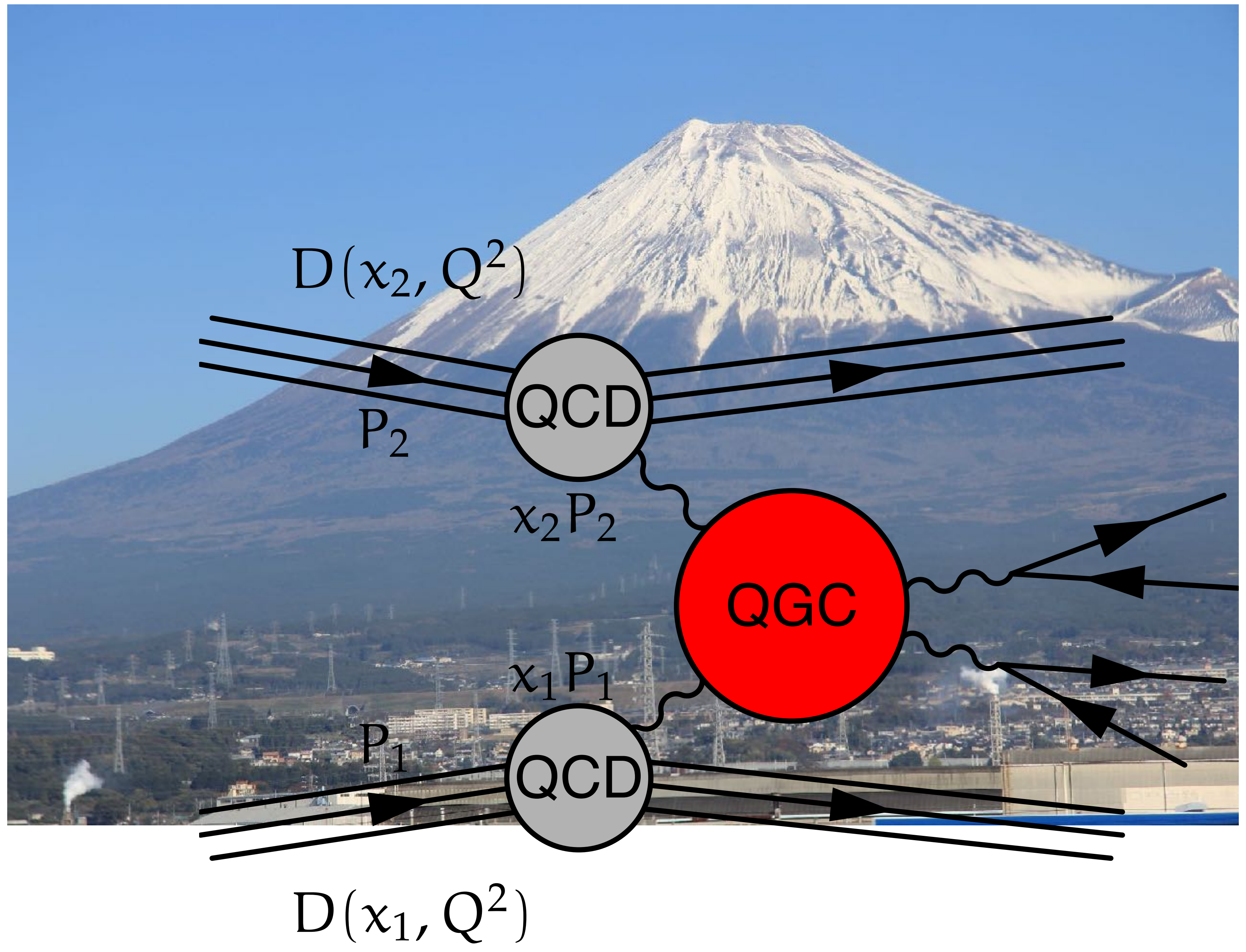
Multiboson Physics for BSM Searches @ LHC & future colliders

50 ICEPP
SINCE 1974
The University of Tokyo

NARODOWE CENTRUM NAUKI
Opus

DESY. HELMHOLTZ



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

EAJADE
Europe-America-Japan Accelerator Development Exchange Programme

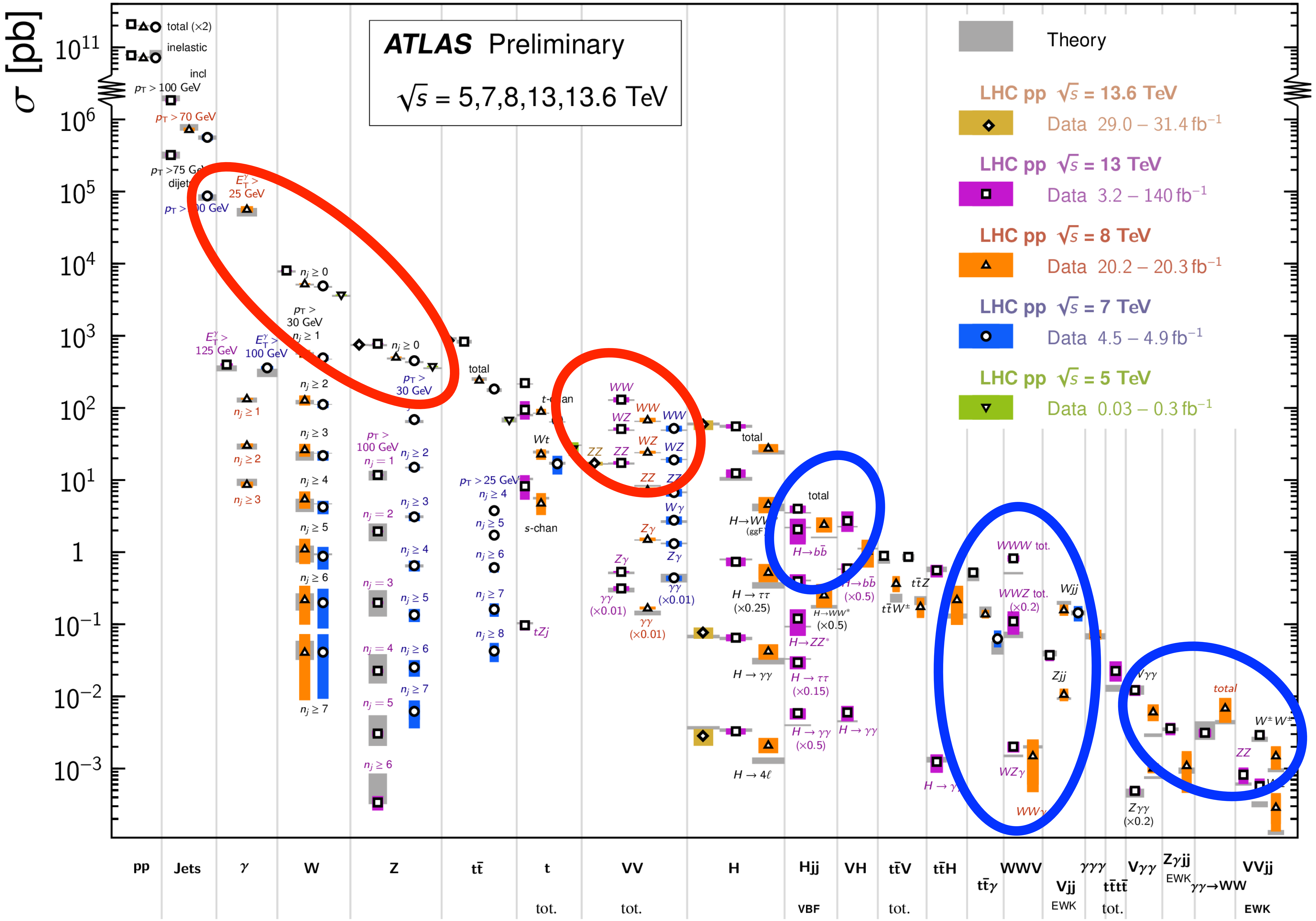
Jürgen R. Reuter

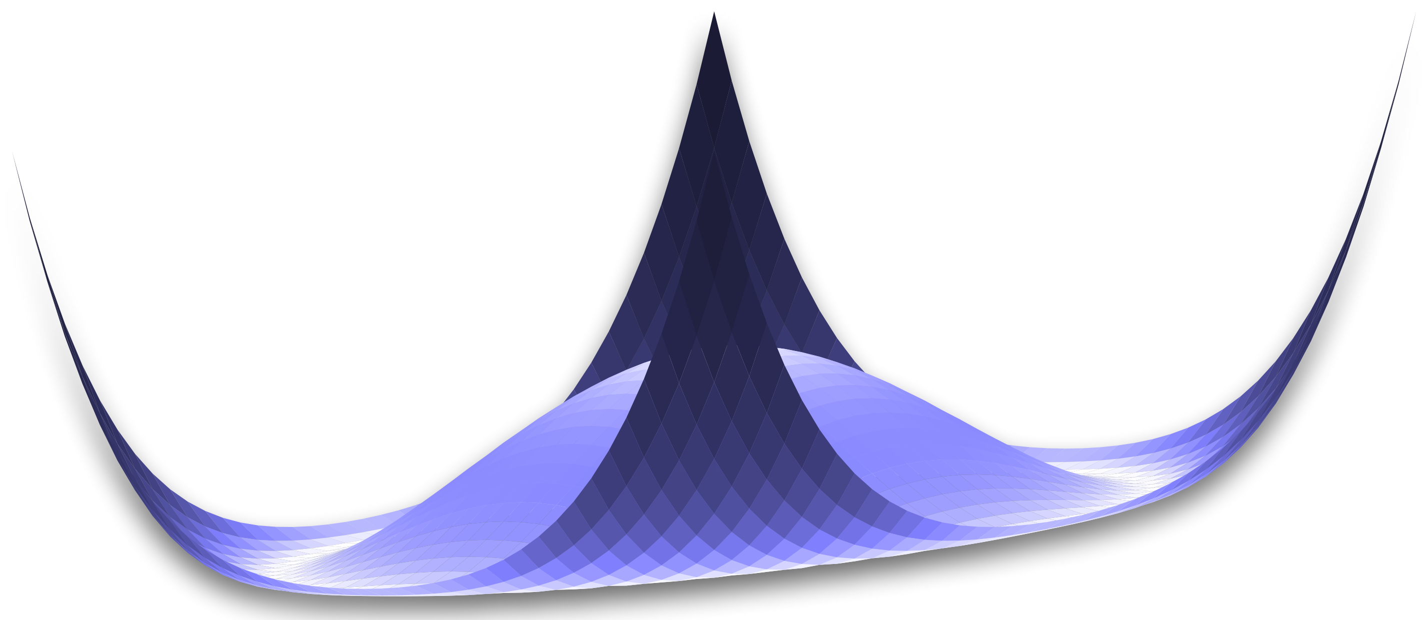
DESY.

The mystery of electroweak interactions

Standard Model Production Cross Section Measurements

Status: October 2023





- **Electroweak physics motivated the LHC**
- Tremendous successes: Higgs discoveries, precision W / Z properties (mass, couplings)
- Missing: **microscopic origin of EWSB**
- Physics of **longitudinal / Goldstone modes**
- Both: **multi-bosons and polarization needed**

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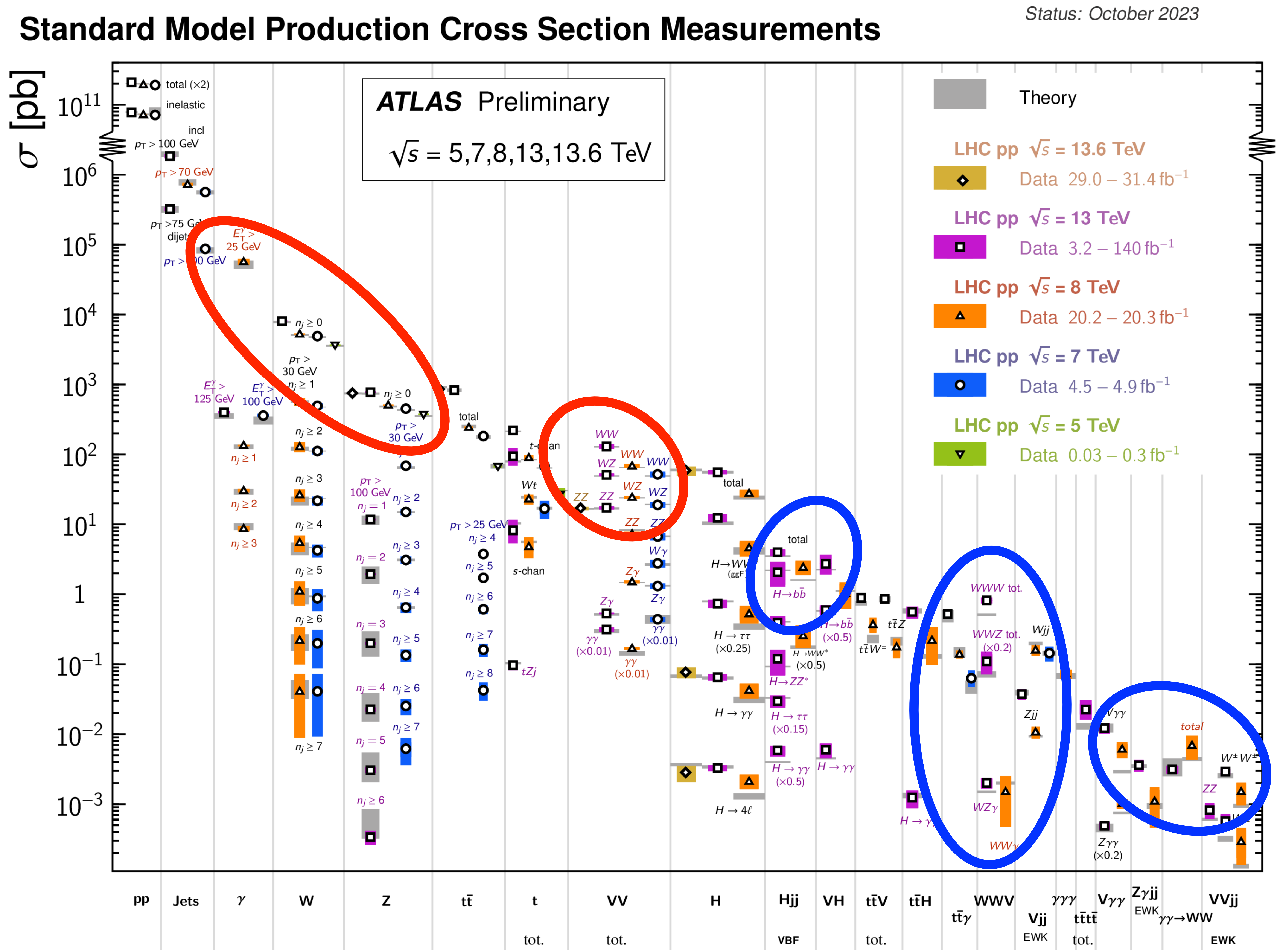

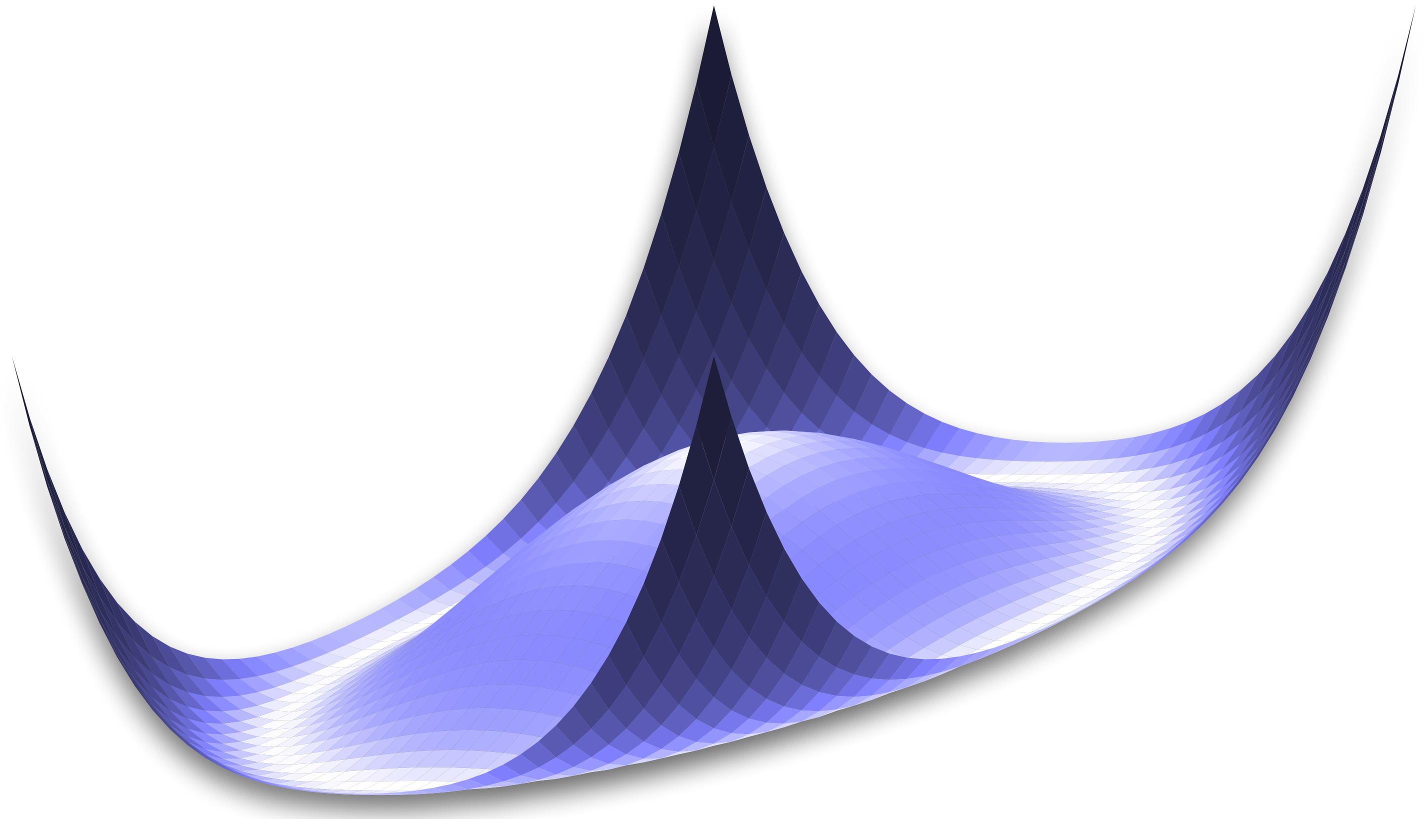

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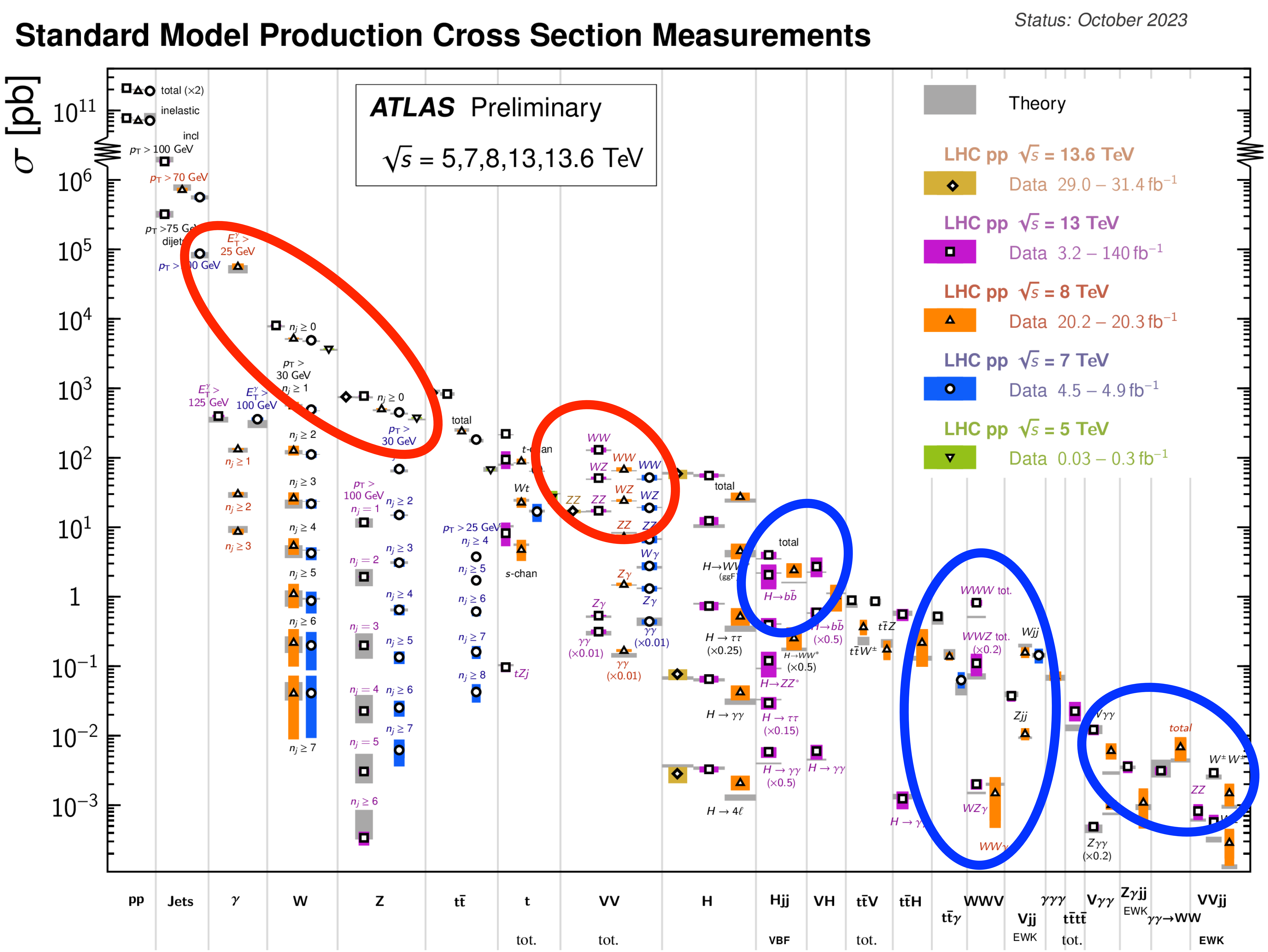

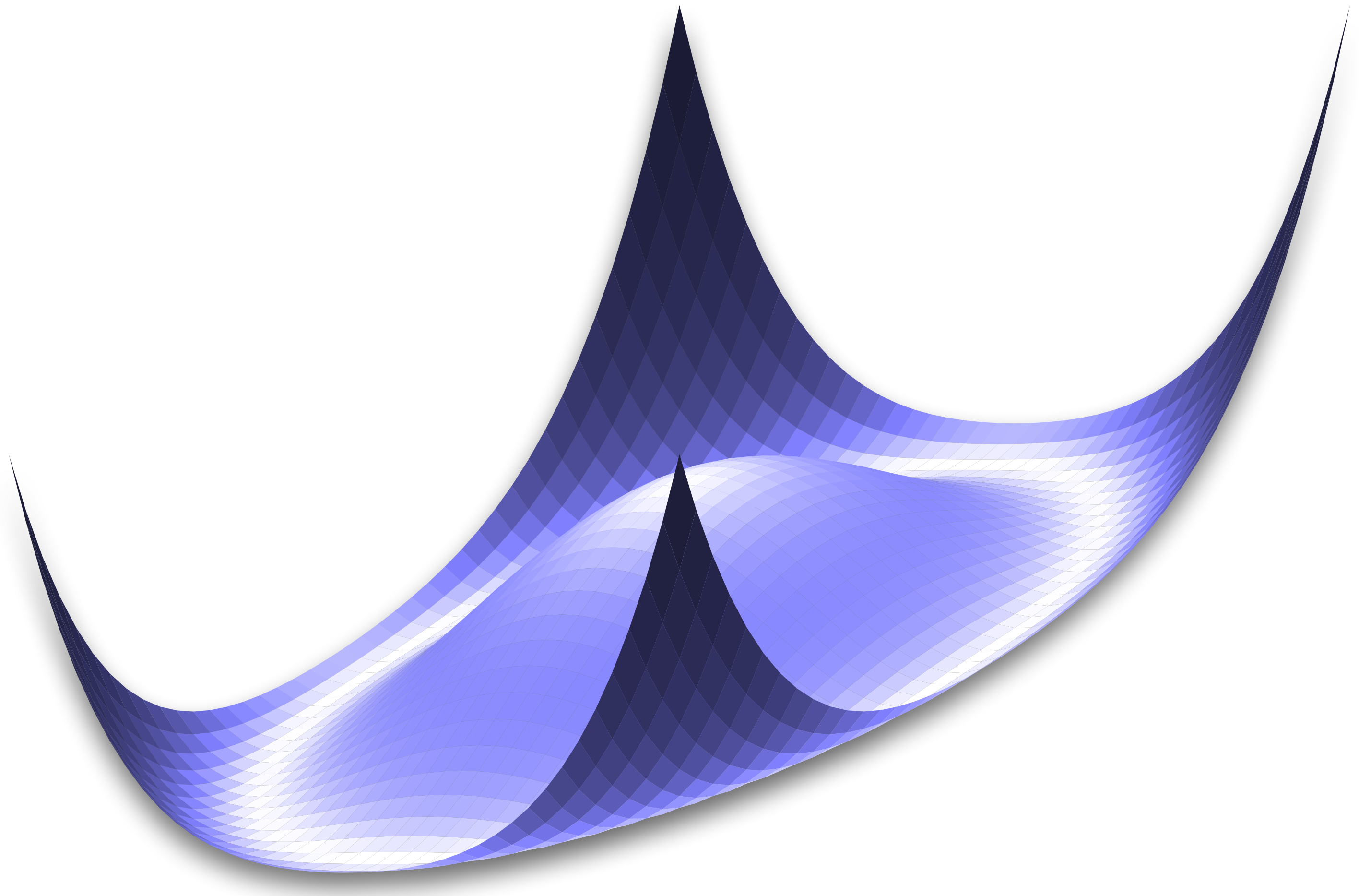

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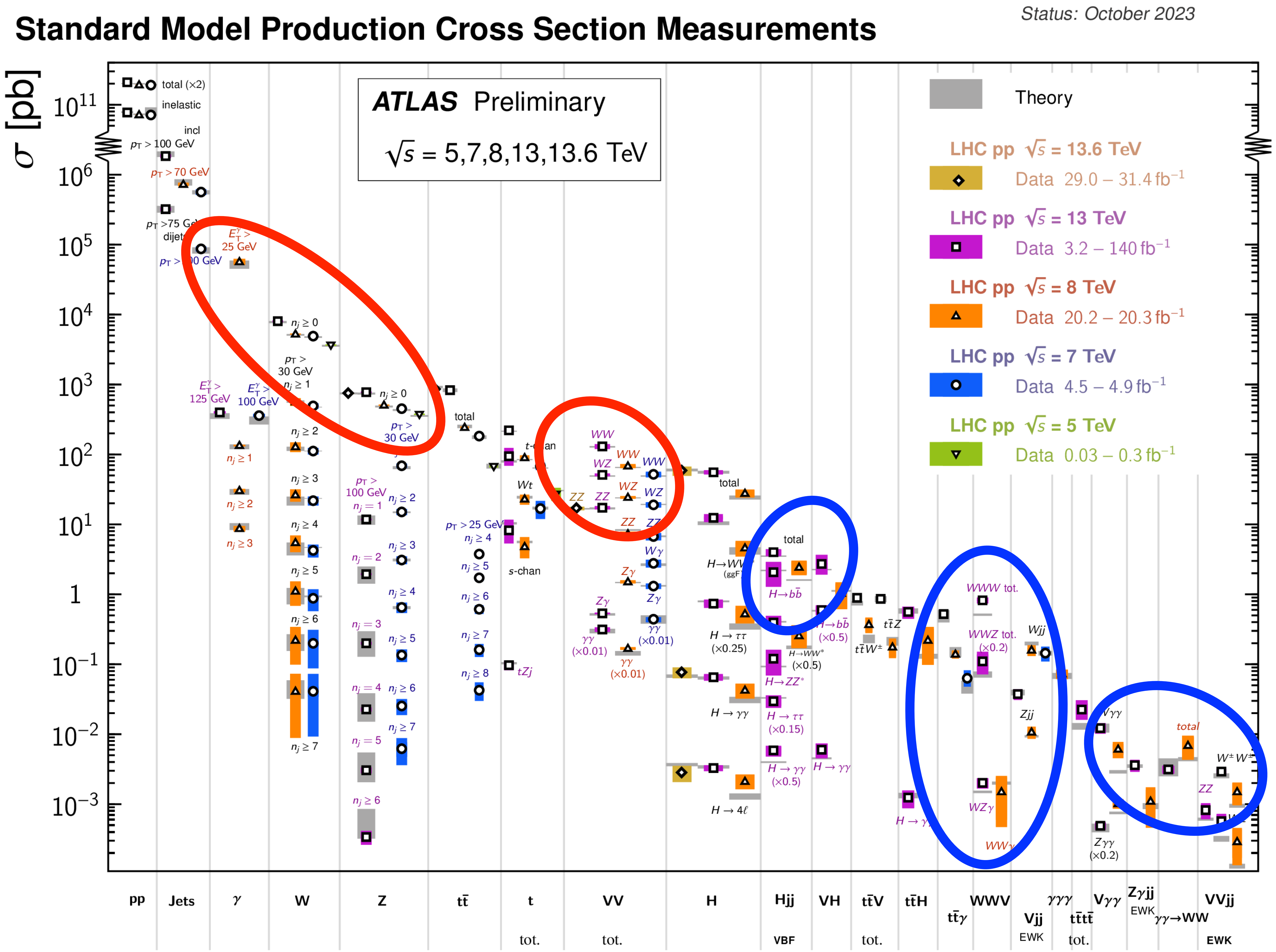

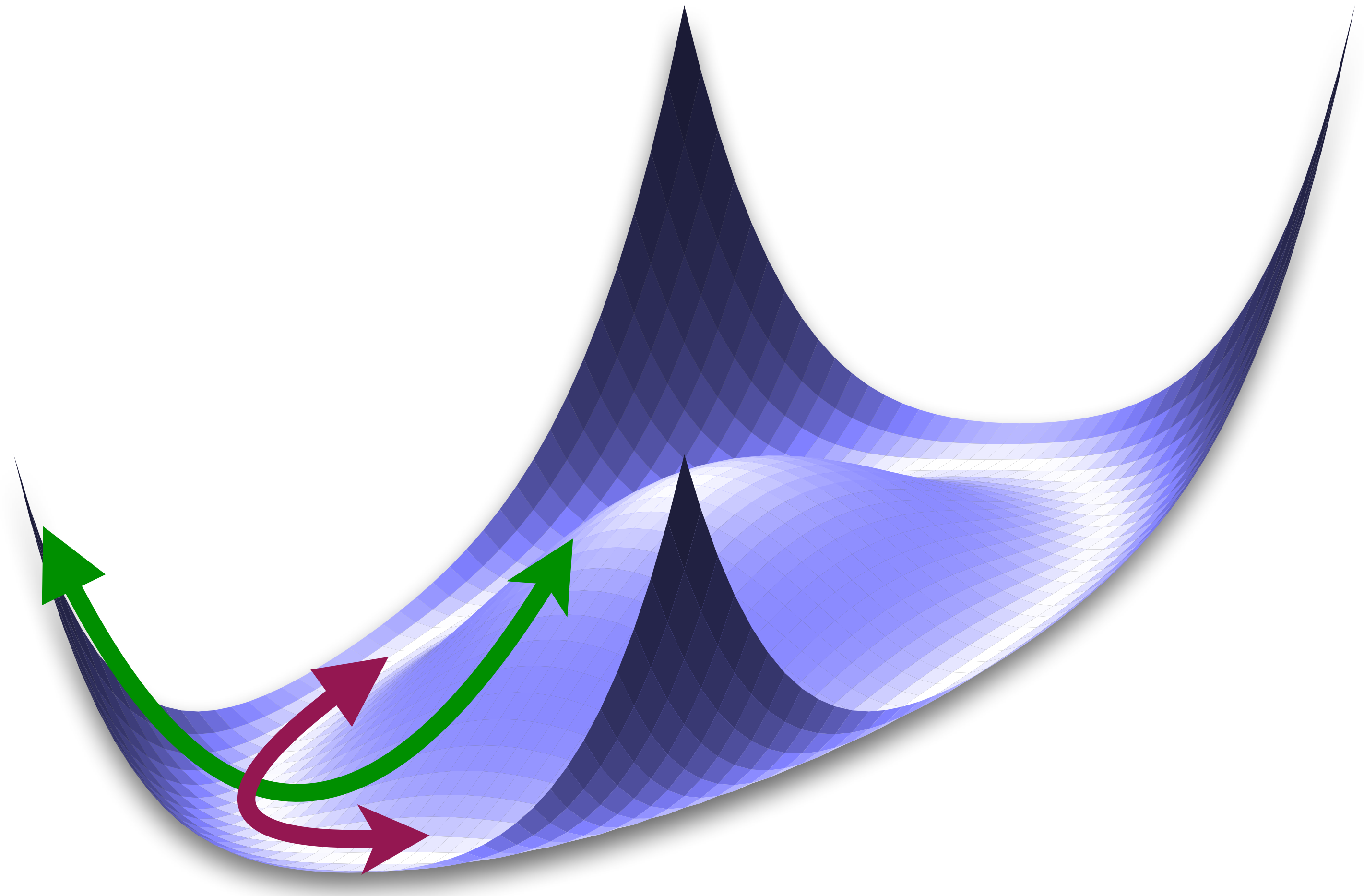

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The importance of multi-bosons

- Di-(multi-) boson seem to have much less statistical power than Drell-Yan
- (Almost) fully inclusive cross sections: $\sigma(WW)/\sigma(DY) \sim 10^{-3}$
- This changes for looking at the high-energy region:

$$\sigma[pp \to W^+W^- \to e^+e^-\nu\nu] \sim 1.5 \text{ pb}$$

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M. Mangano, MBI 22 Summary Talk

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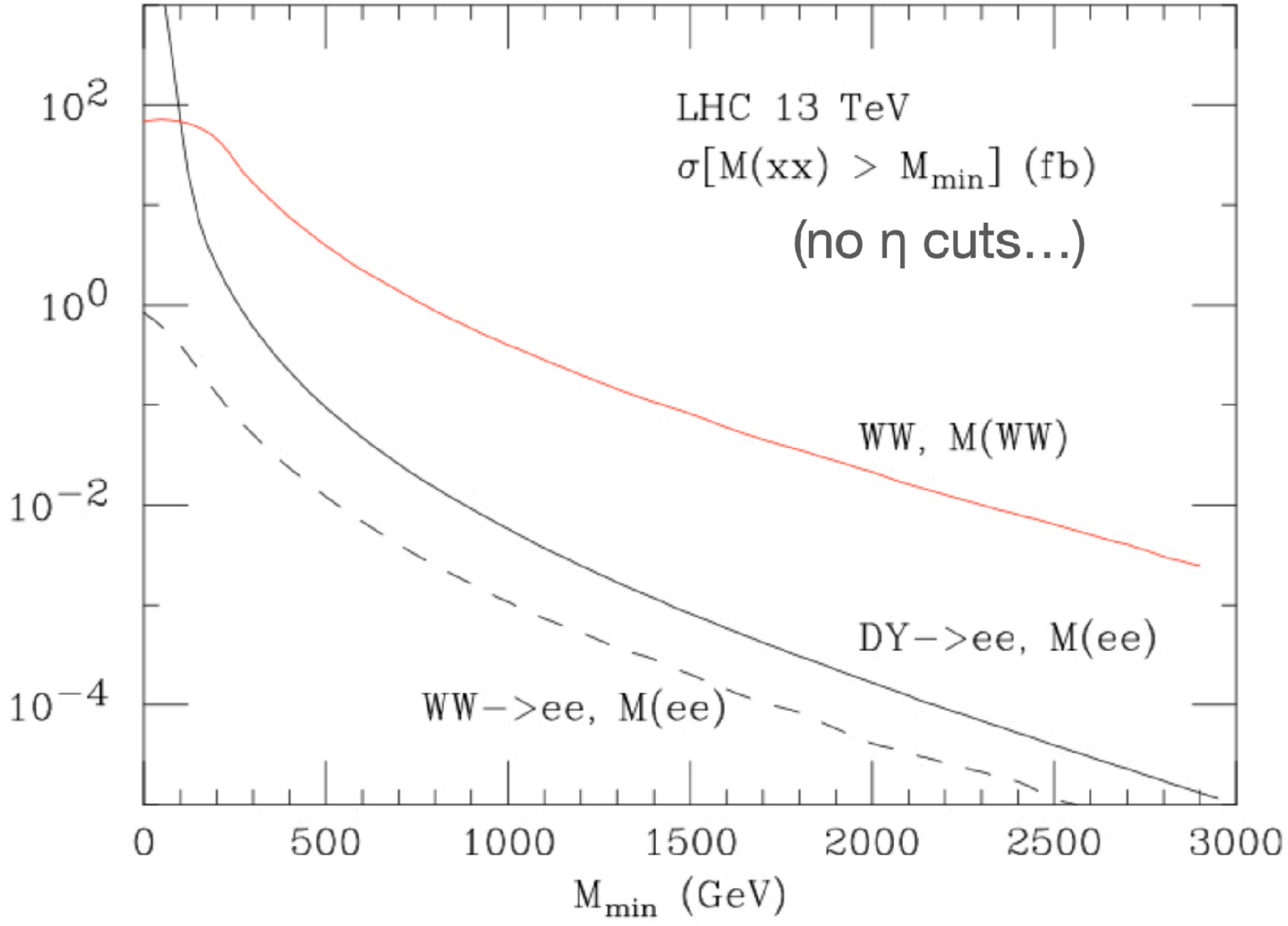
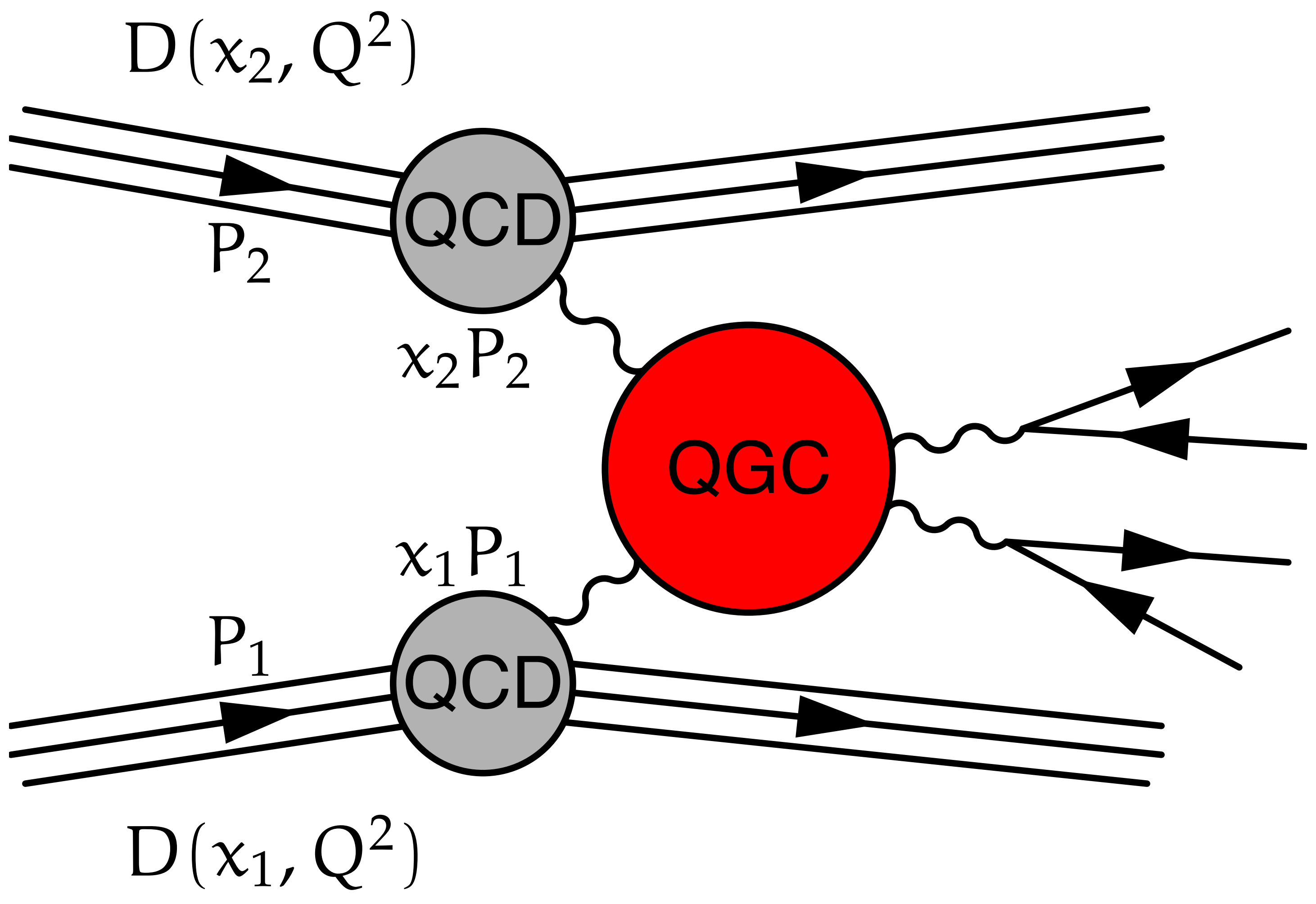
Multibosons are the most sensitive probe of EW interactions in the high-Q2 region



- Di-(multi-) boson supersede DY: *s*- vs. *t*-channel
- Tri- [multi-] bosons usually higher BSM sensitivity
- BSM sensitivity vs. total cross sections
- HL/HE-LHC, MuC, ILC1000, CLIC: tribosons optimal
- Vector Boson Scattering (VBS): pay the price for double weak radiation twice, then universal behavior

M. Mangano, MBI 22 Summary Talk

Vector boson scattering



Fiducial phase space volume:

- $lljj$ tag
- $m_{jj} > 500$ GeV (“jet recoil”)
- $|\Delta y_{jj}|$ > 2.4 (“rapidity distance”)
- Cuts on E_j , $p_T{}^j$
- No / little central jet activity

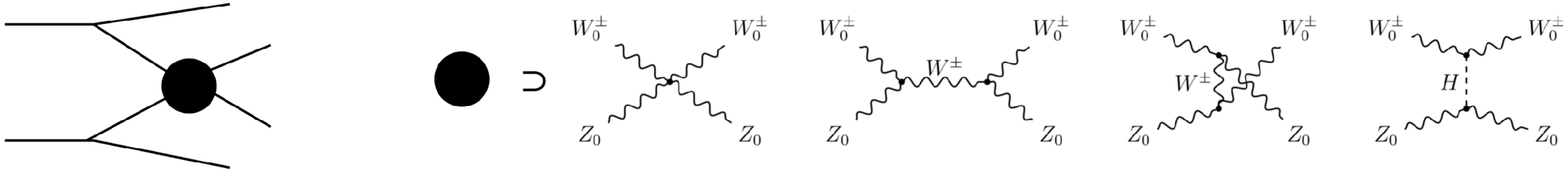
Importance of VBS

○ VBS gives access to pure EW sector

○ No dependence of fermion sector, flavor mixing etc. (almost)

○ Goal: proof relation between Goldstones (W_L , Z_L) and Higgs H

○ Problem: longitudinal modes suppressed compared to transversal (~10%)



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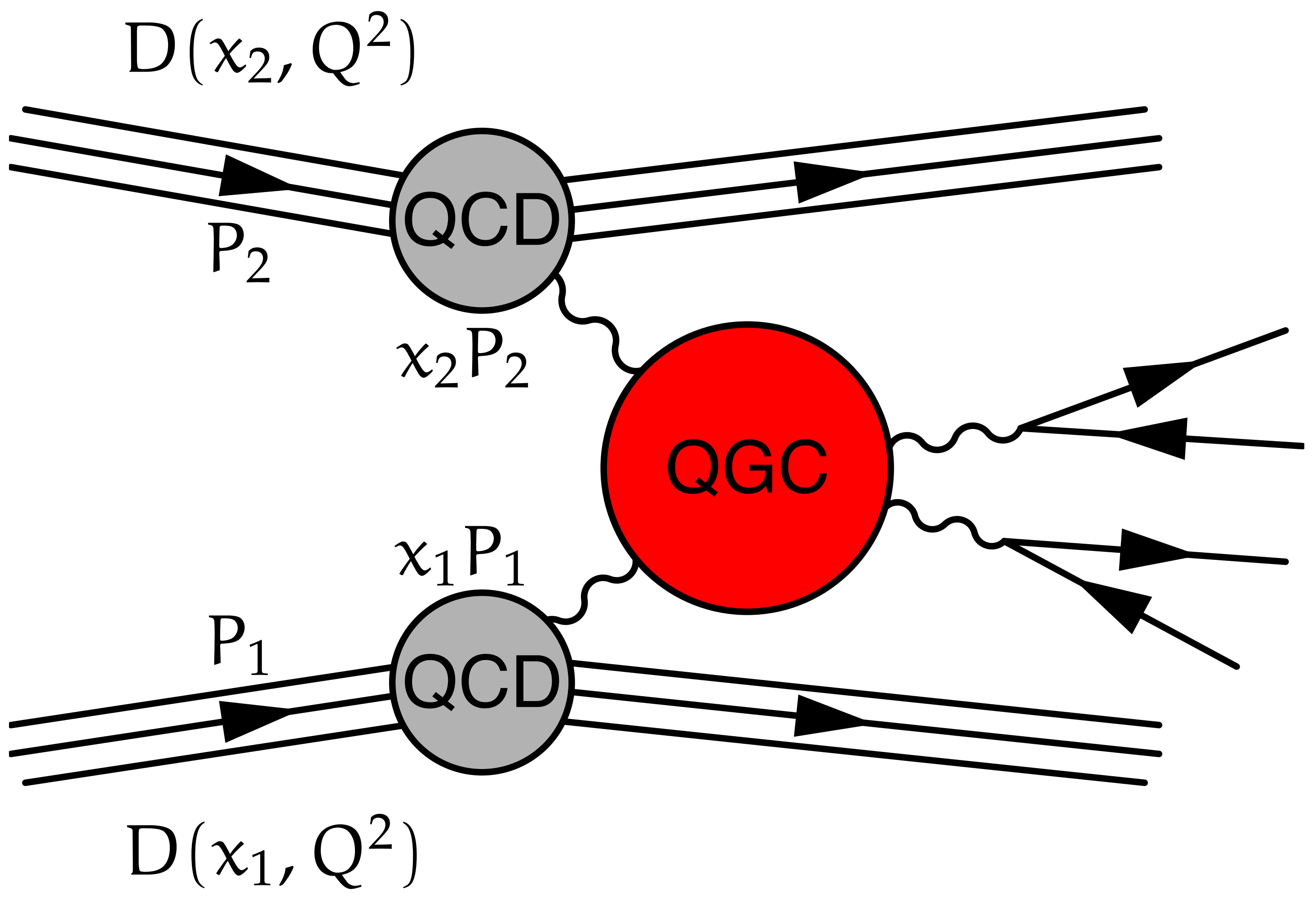

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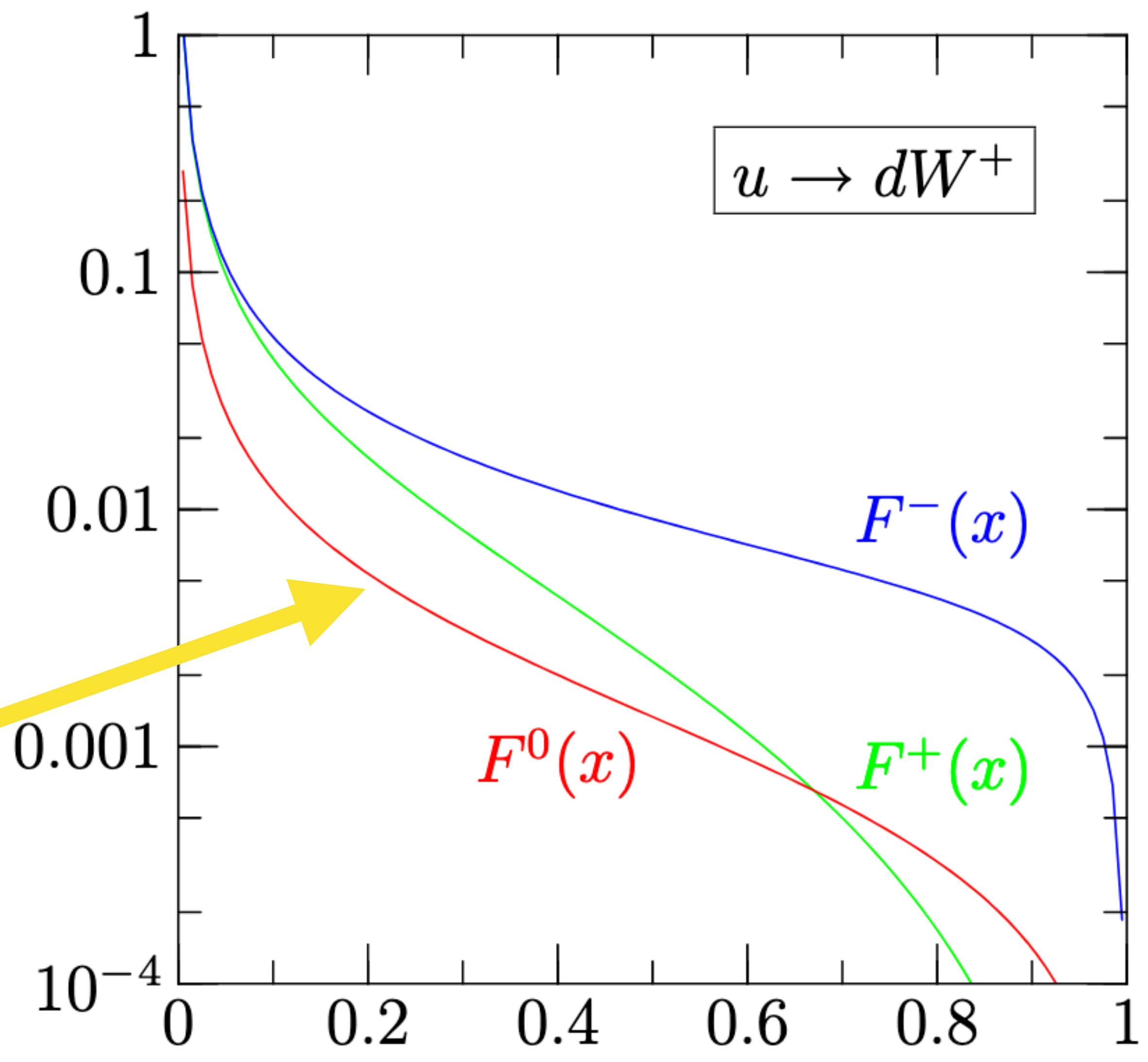
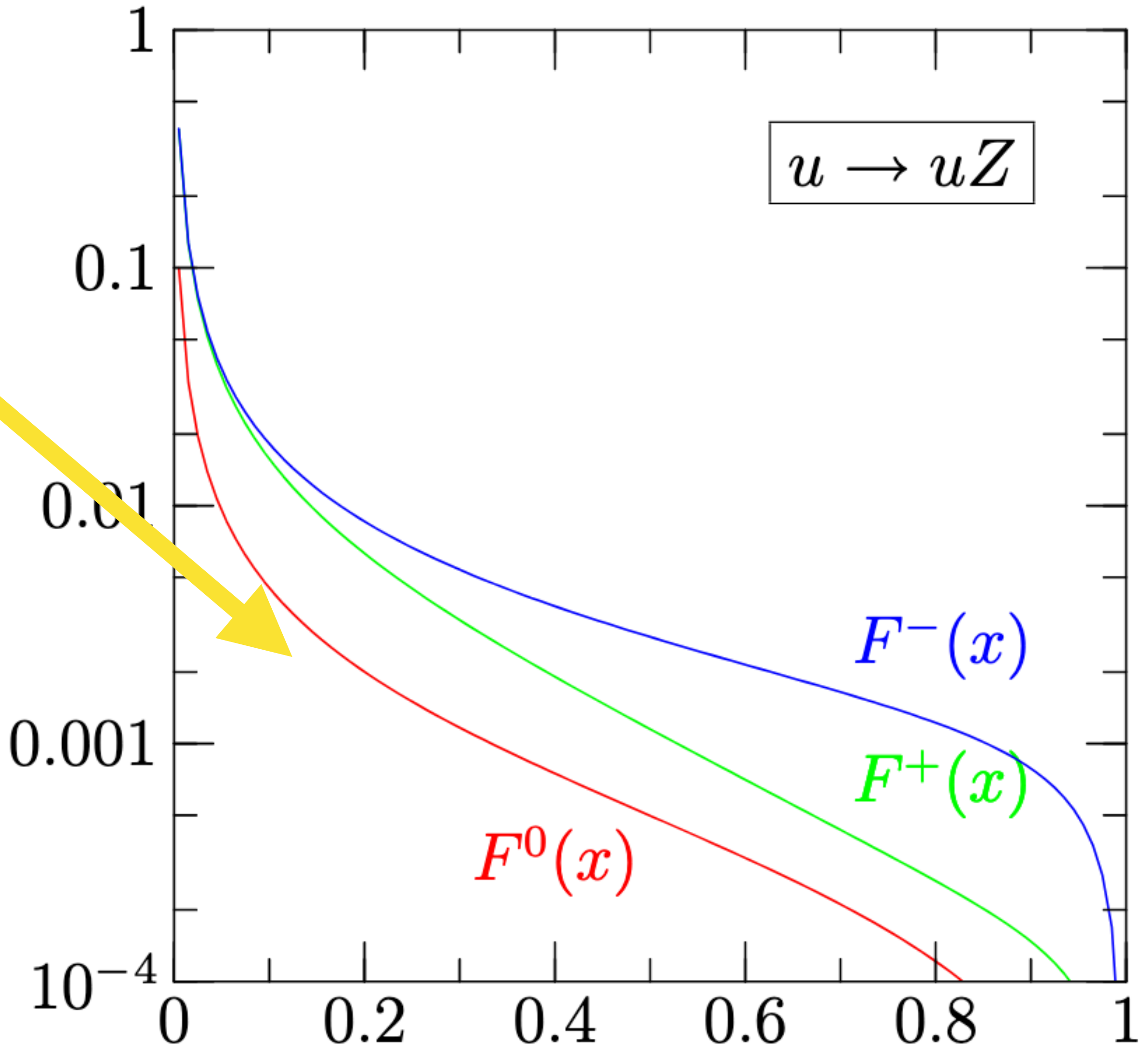
from:
Alboteanu/Kilian/JRR,
0806.4145

EW PDF / Splitting function picture





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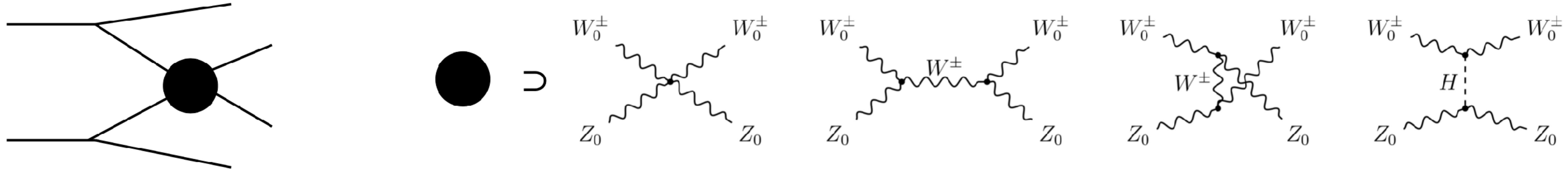
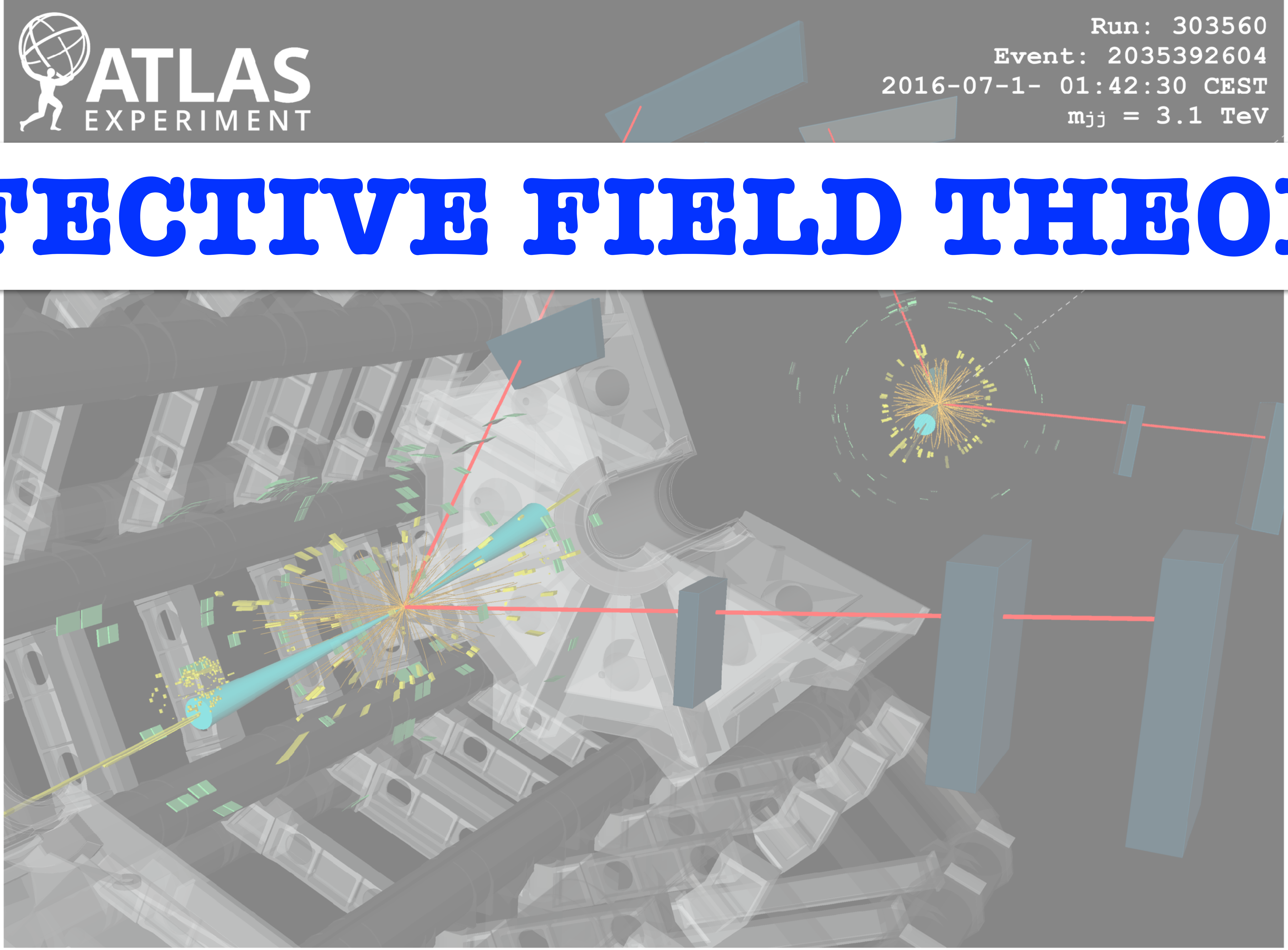


3 LEVELS OF NEW PHYSICS

Increasing generality

1. Effective Field Theories (SMEFT, HEFT, …)
2. Simplified Models (generic EW resonances)
3. UV-(semi-)complete models

Increasing definiteness



EFFECTIVE FIELD THEORIES

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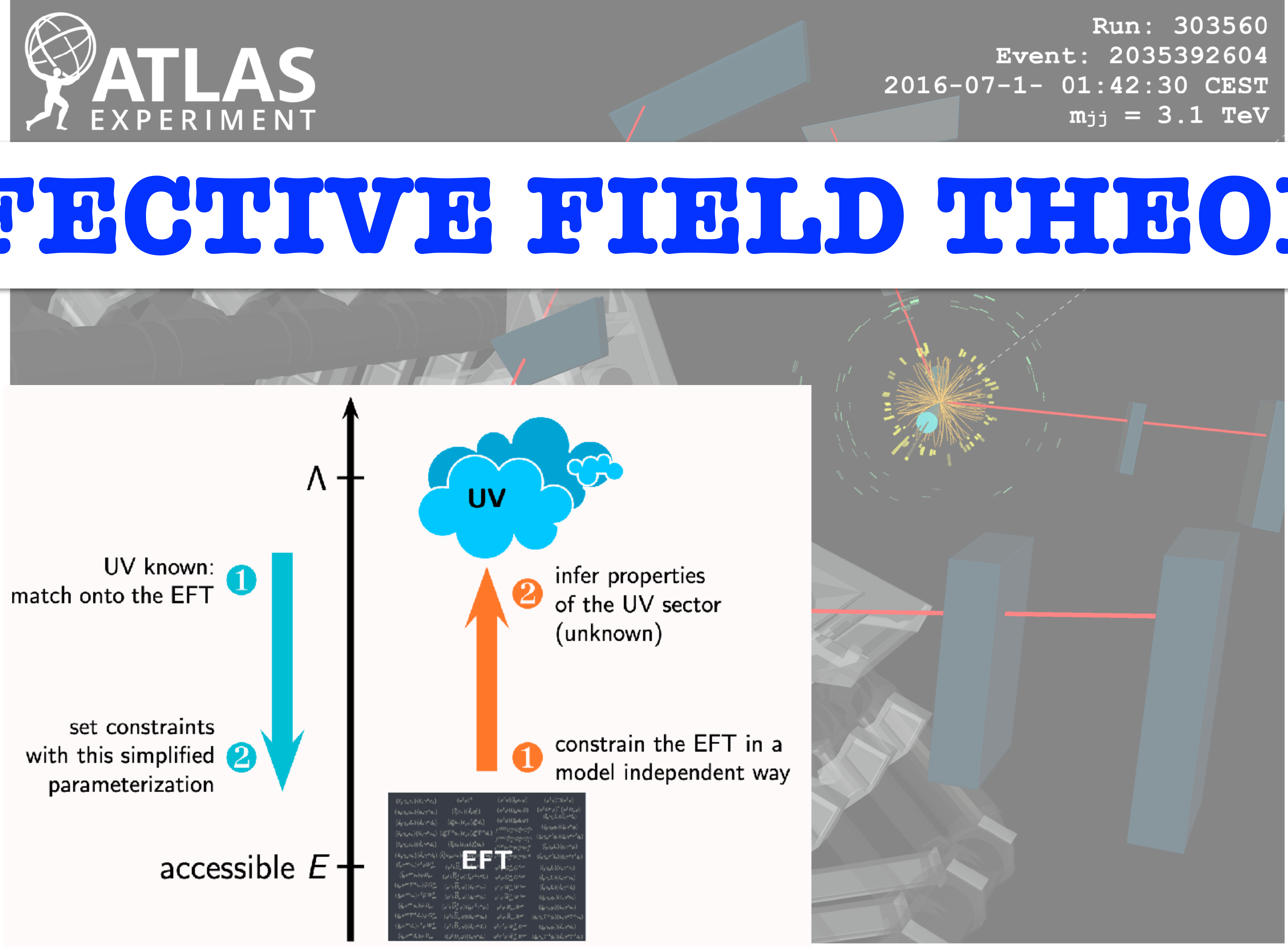

UV known: match onto the EFT ①

set constraints with this simplified parameterization ②

infer properties of the UV sector (unknown) ②

constrain the EFT in a model independent way ①

From the past via present to the future

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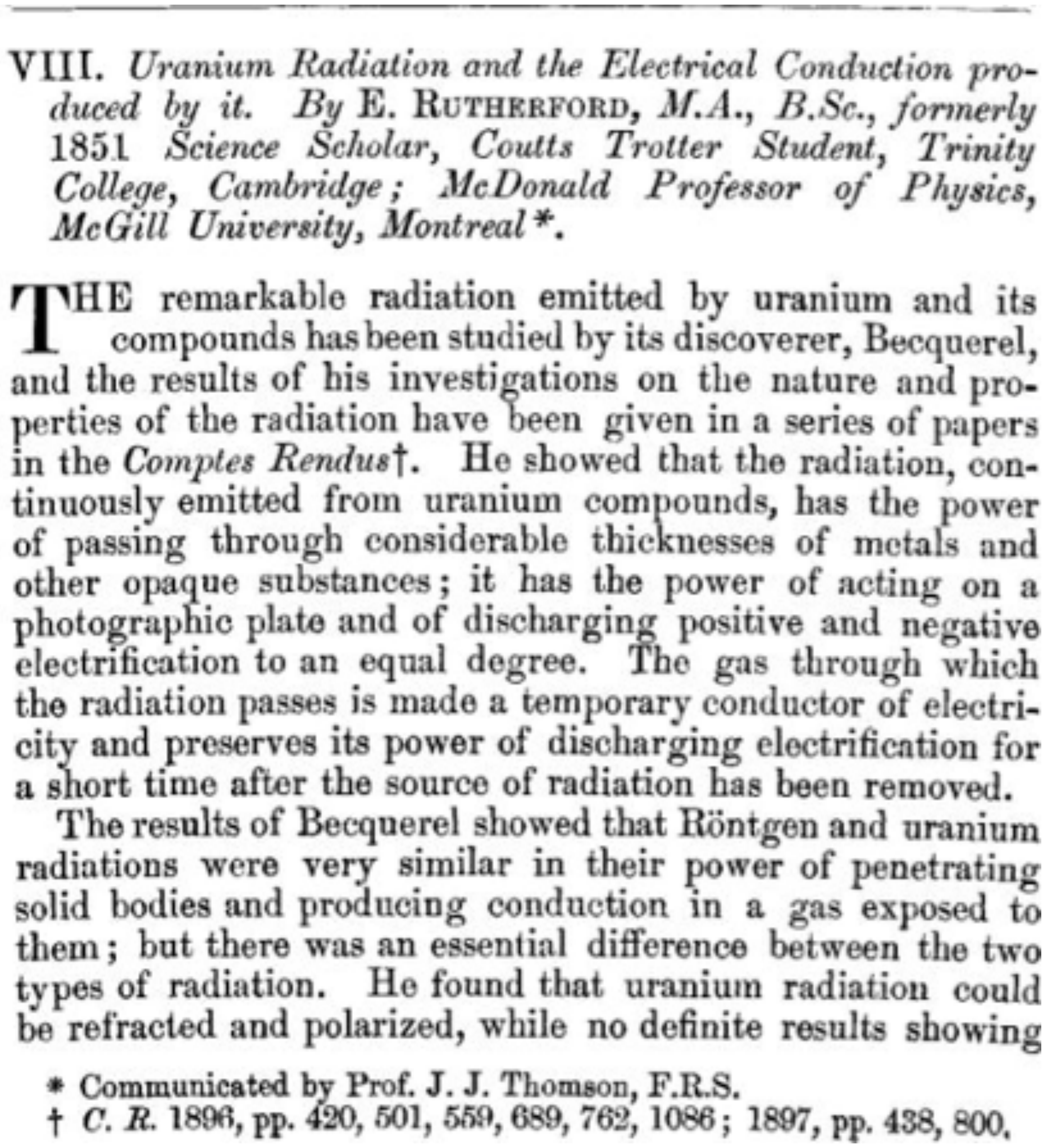
- 1898: Weak interactions known since 1898 (beta decay; virtual *W* exchange [used a new particle discovery, the *electron* !])



VIII. *Uranium Radiation and the Electrical Conduction produced by it.* *By* E. Rutherford, *M.A., B.Sc., formerly* 1851 *Science Scholar, Coutts Trotter Student, Trinity College, Cambridge; McDonald Professor of Physics, McGill University, Montreal* *.

The remarkable radiation emitted by uranium and its compounds has been studied by its discoverer, Becquerel, and the results of his investigations on the nature and properties of the radiation have been given in a series of papers in the *Comptes Rendus*†. He showed that the radiation, continuously emitted from uranium compounds, has the power of passing through considerable thicknesses of metals and other opaque substances; it has the power of acting on a photographic plate and of discharging positive and negative electrification to an equal degree. The gas through which the radiation passes is made a temporary conductor of electricity and preserves its power of discharging electrification for a short time after the source of radiation has been removed.

The results of Becquerel showed that Röntgen and uranium radiations were very similar in their power of penetrating solid bodies and producing conduction in a gas exposed to them; but there was an essential difference between the two types of radiation. He found that uranium radiation could be refracted and polarized, while no definite results showing

* Communicated by Prof. J. J. Thomson, F.R.S.

† *C. R.* 1896, pp. 420, 501, 559, 689, 762, 1086; 1897, pp. 438, 800.

From the past via present to the future

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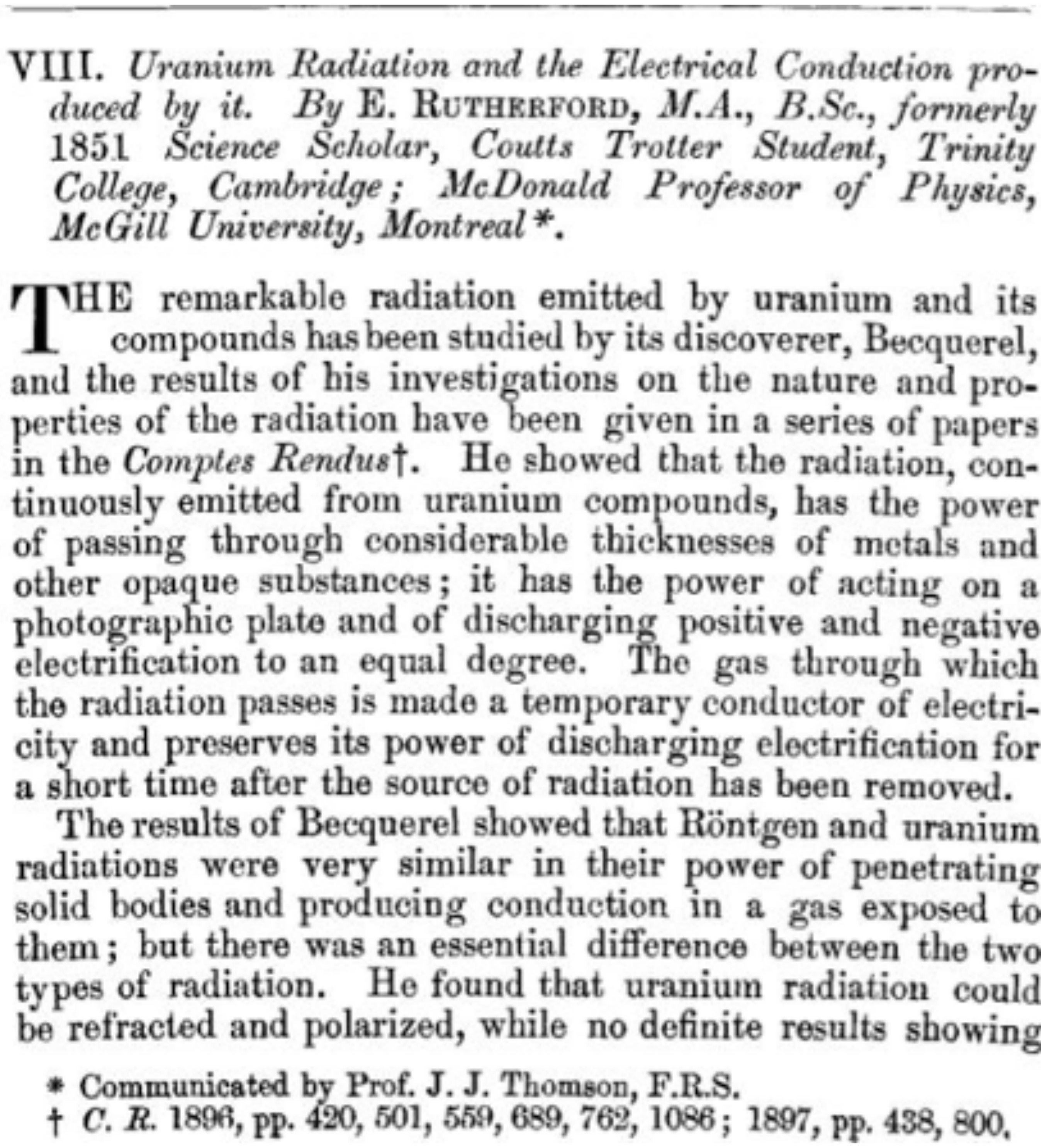
  [used a new particle discovery, the *electron* !])
- 1934: Fermi Effective Field Theory ("FEFT")
  charged current weak processes
  (points to high scale *v*)

$$\boxed{\mathcal{L}_{FEFT} = \frac{c_F}{v^2}\left(\overline{\Psi}_{e,L}\gamma^\mu\Psi_{\nu,L}\right)\left(\overline{\Psi}_{\nu,L}\gamma_\mu\Psi_{e,L}\right)}$$



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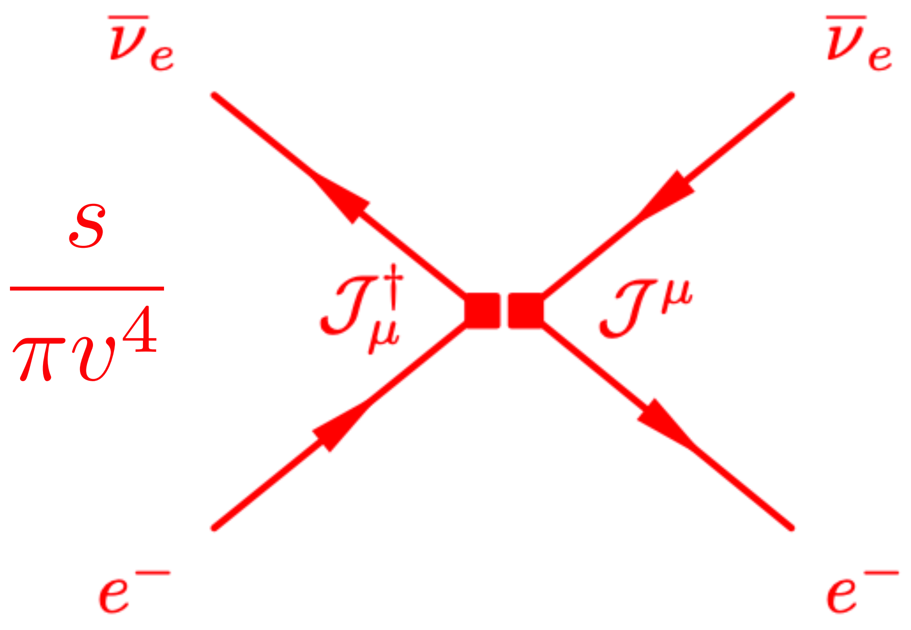
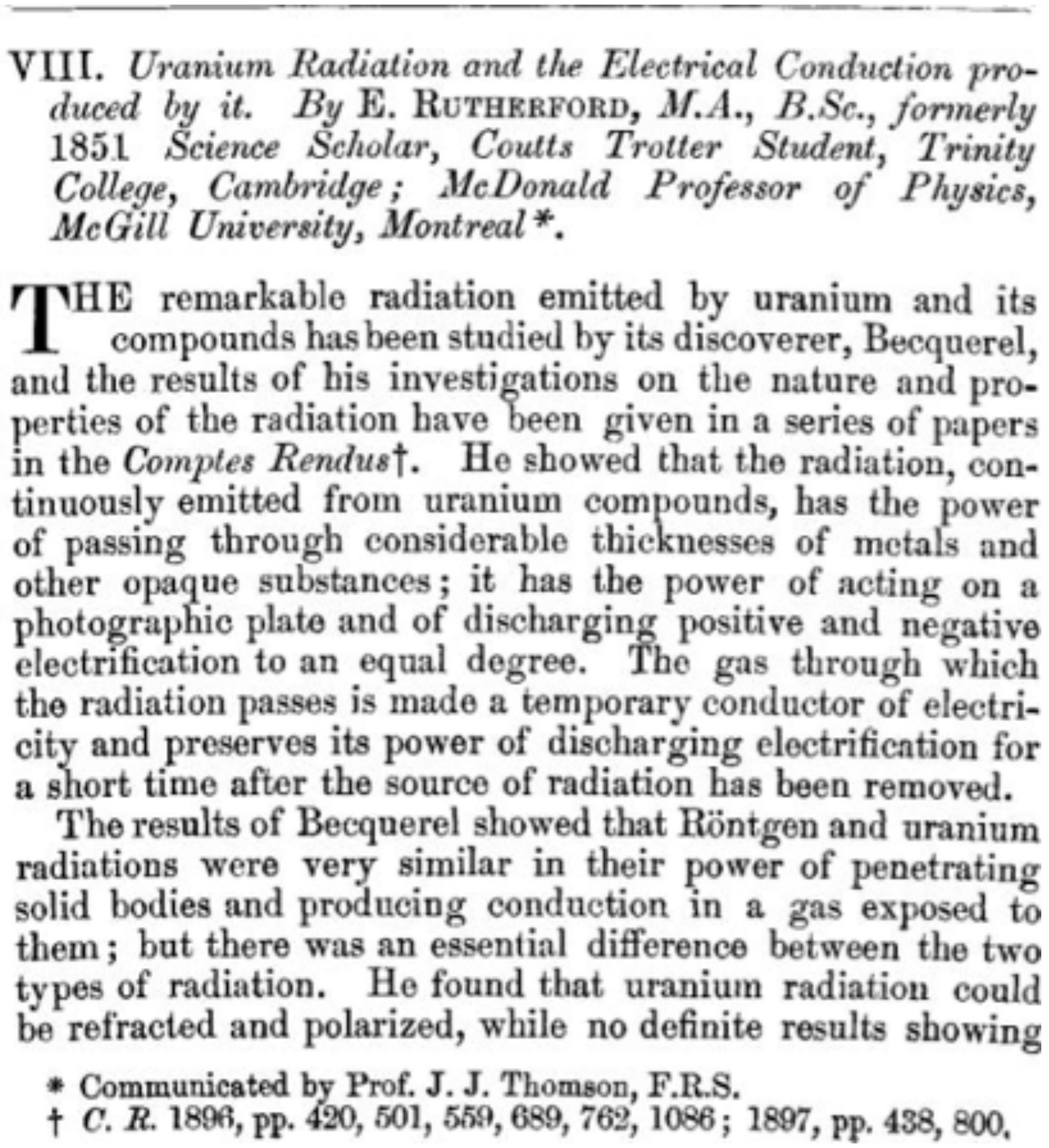


Effective theory leads to invalidity / unitarity violation at higher energies

S-wave unitarity demands: $\sqrt{s} \lesssim 500\,\mathrm{GeV}$



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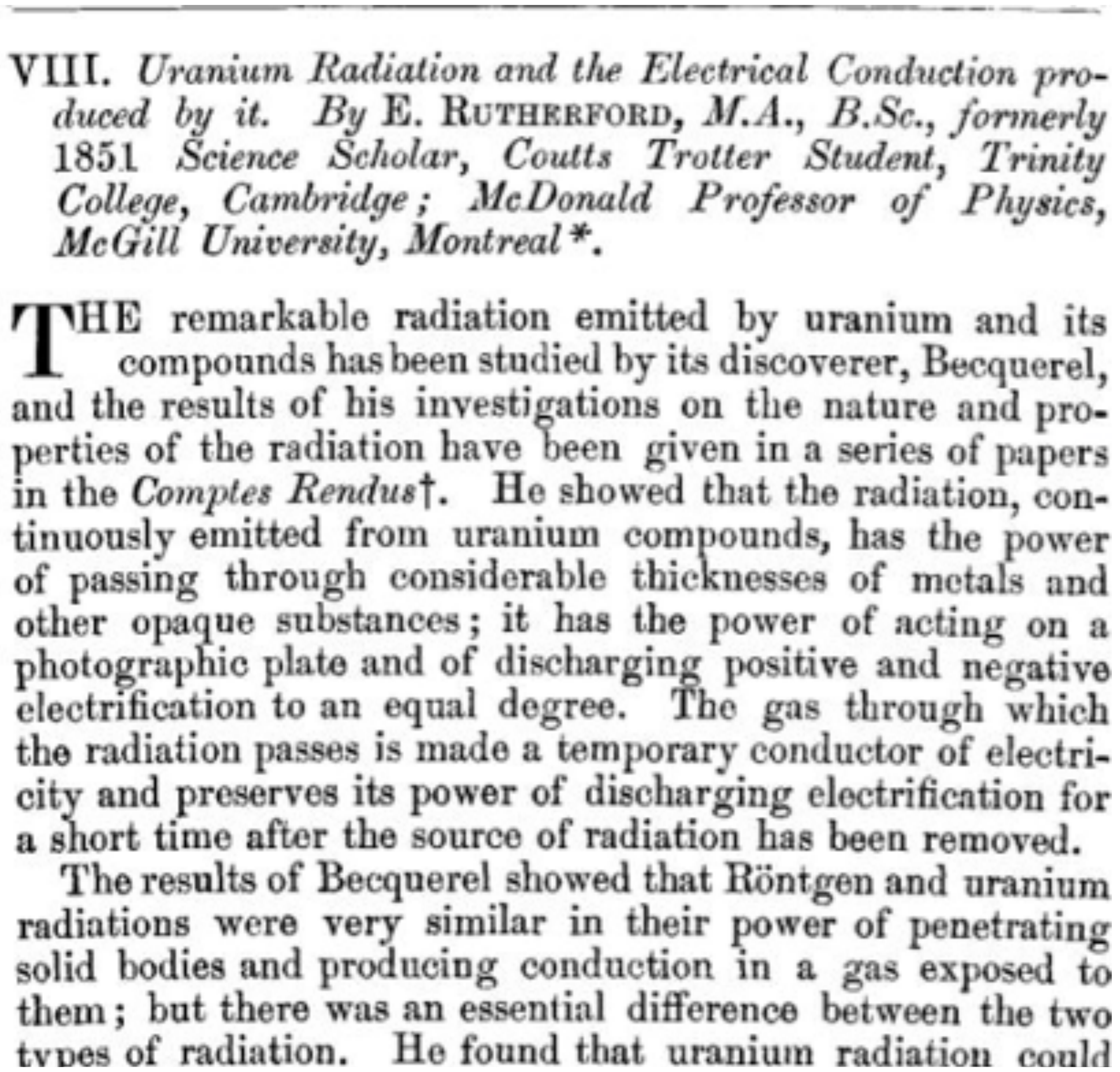

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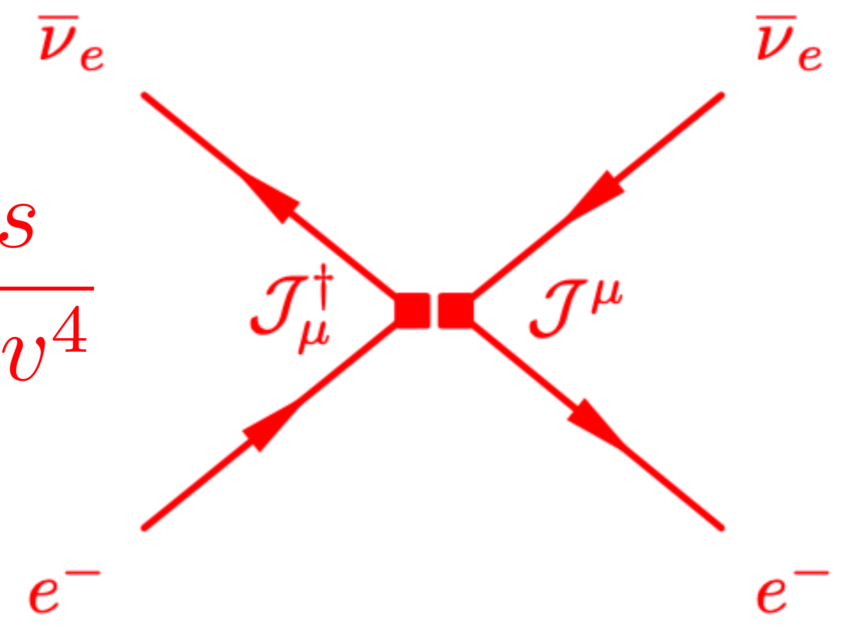

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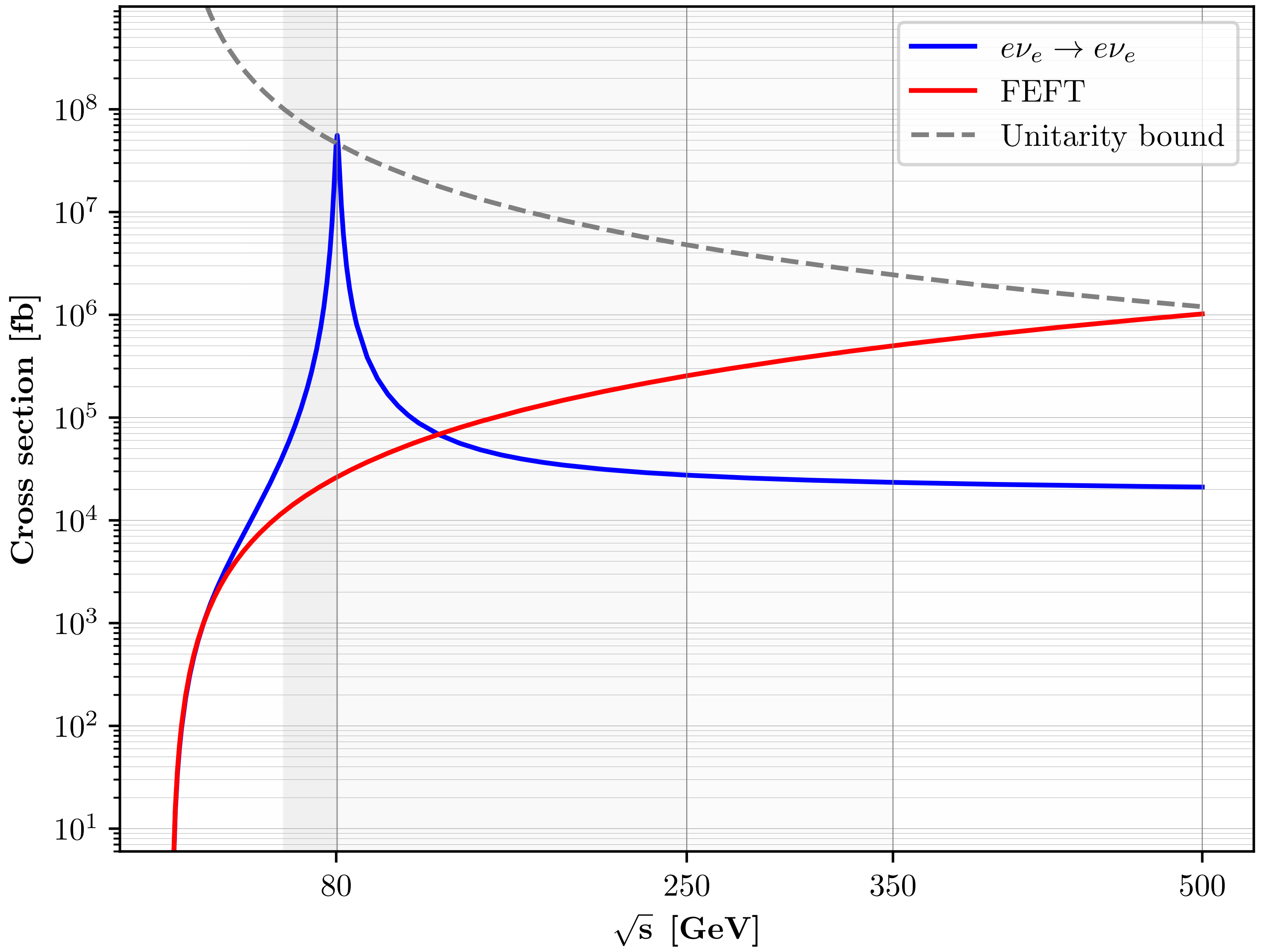
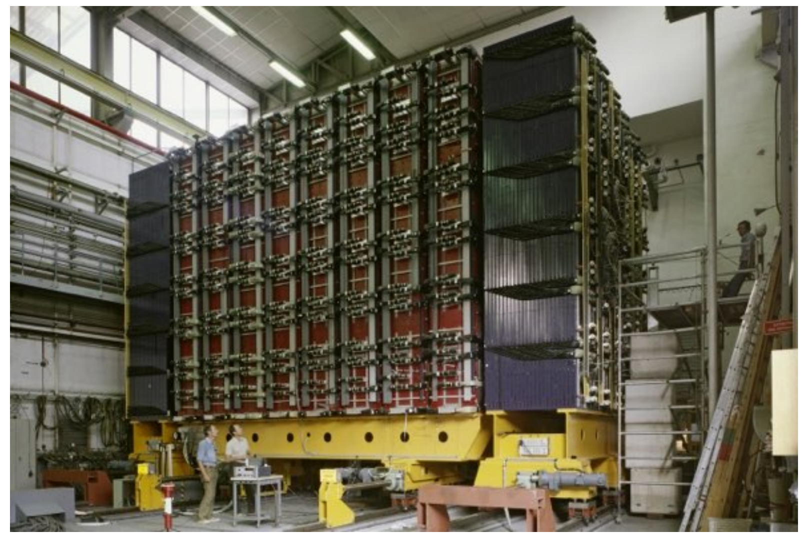
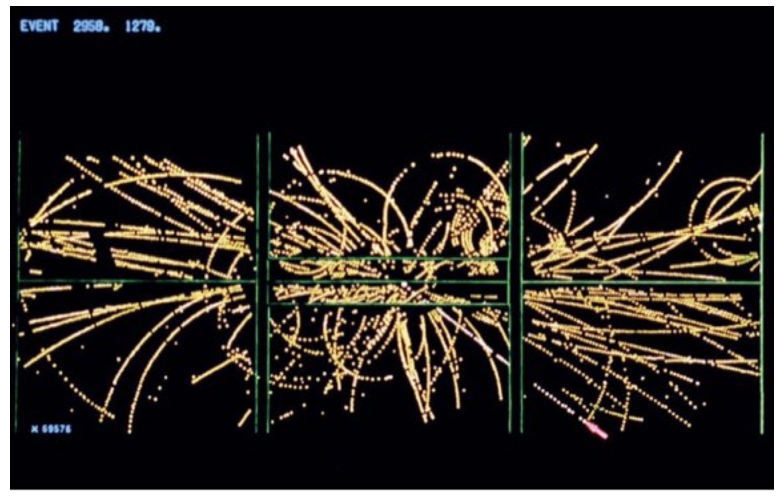


- 1964-1967: Renormalizable spontaneously broken "UV-complete" *SU(2)*
- Discovery of *W/Z* at Sp$\overline{\text{p}}$S@CERN



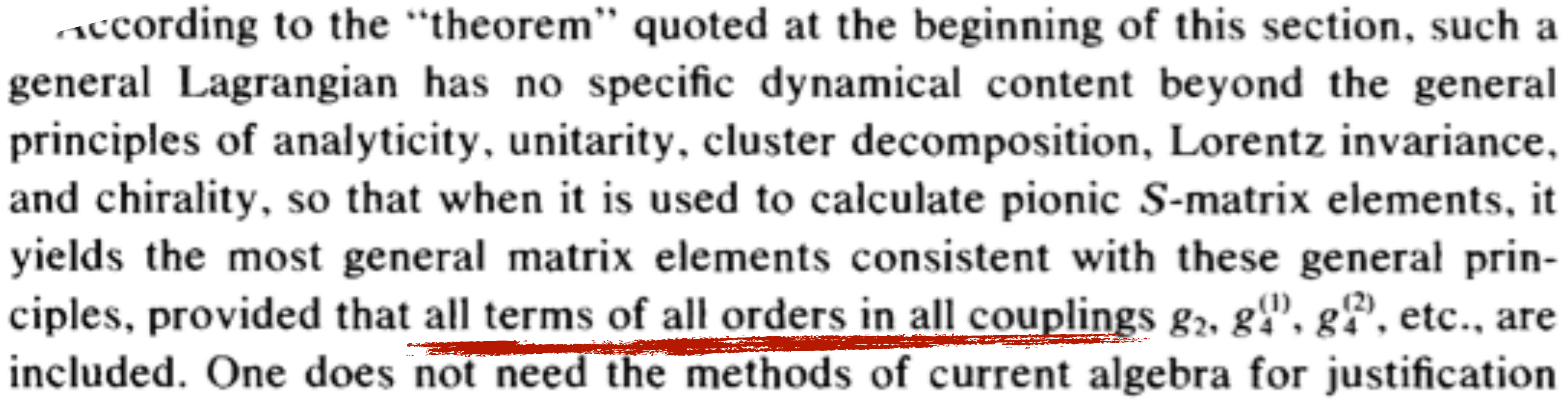


The rationale of Effective Field Theories

- SM contains all dim 2- and dim 4-operators "relevant" for low-energy physics: $\mathcal{L}_{EW} = -\frac{1}{2}\text{tr}\,[W_{\mu\nu}W^{\mu\nu}] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$
  (no fermions or QCD here)

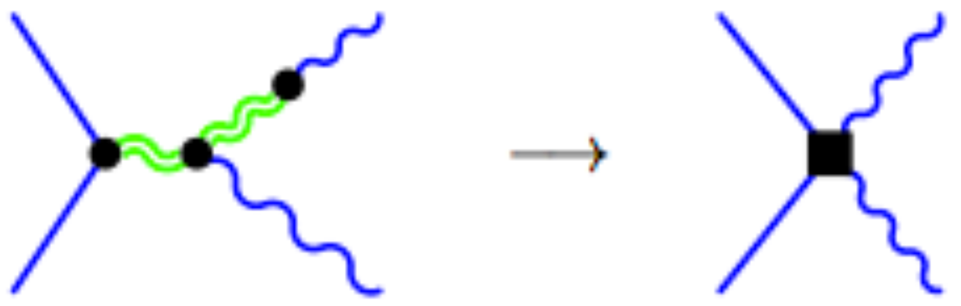
- Add all higher-dimensional operators consisting of SM fields/consistent with SM symmetries

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \boxed{\frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}} + \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \boxed{\frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)}} + \cdots \right]}$$



According to the "theorem" quoted at the beginning of this section, such a general Lagrangian has no specific dynamical content beyond the general principles of analyticity, unitarity, cluster decomposition, Lorentz invariance, and chirality, so that when it is used to calculate pionic S-matrix elements, it yields the most general matrix elements consistent with these general principles, provided that all terms of all orders in all couplings g_2, $g_4^{(1)}$, $g_4^{(2)}$, etc., are included. One does not need the methods of current algebra for justification

S.Weinberg, 1979



- $v \ll \Lambda$: new physics scale; $c_i^{(d)}$: dimensionless Wilson coefficient
- All odd operators involve fermions, all dim 5 and dim 7 violate B and/or L

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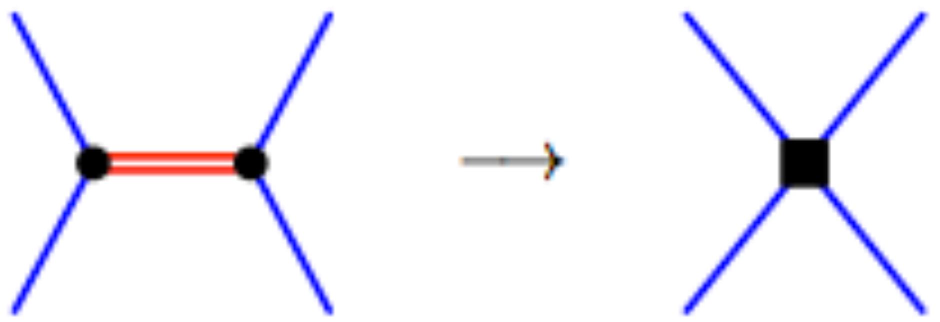

Truncation introduces model dependence again

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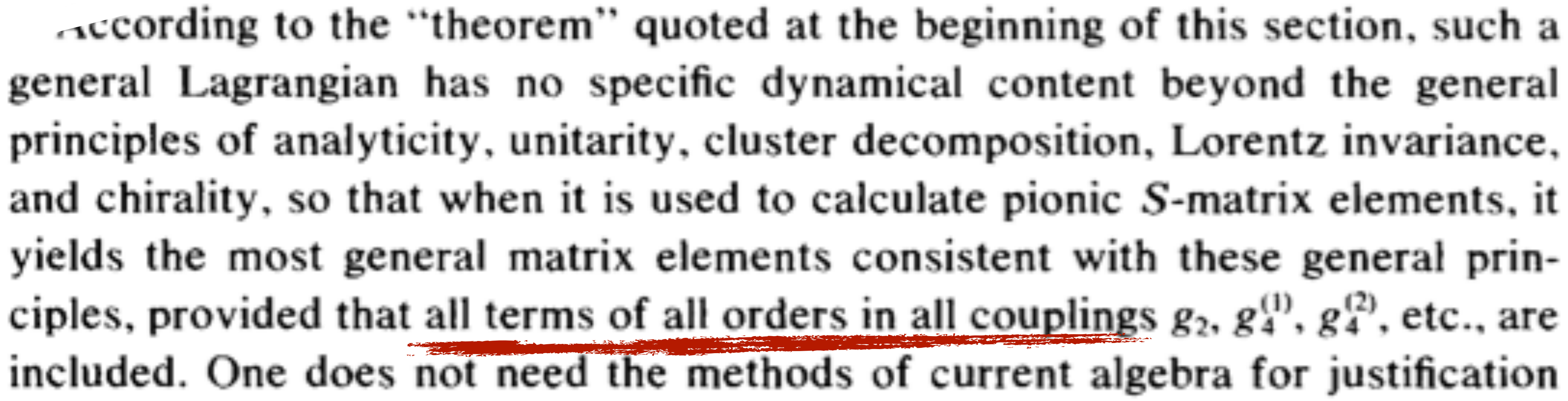

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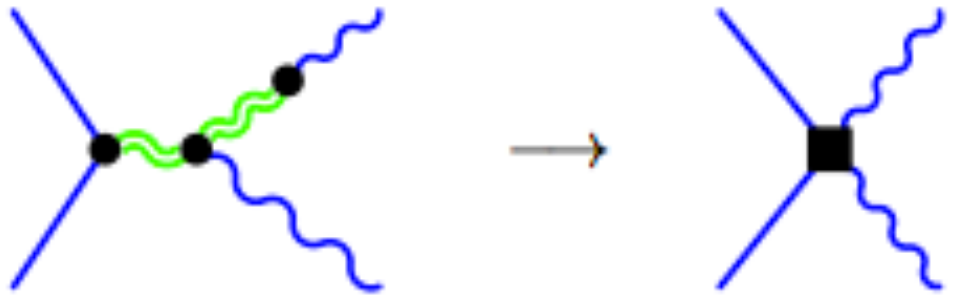

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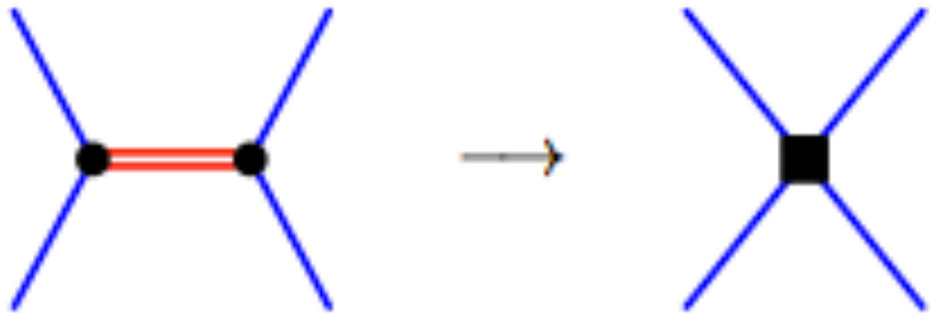


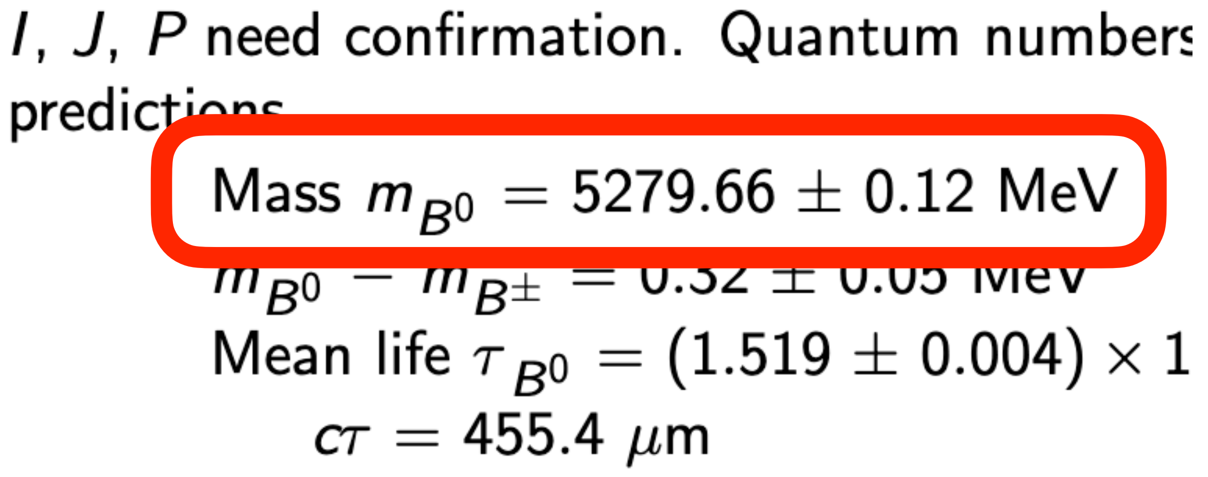
Truncation introduces model dependence again

$$\mathcal{O}'_{WW} = -\frac{1}{\Lambda^2}\frac{1}{2}(\Phi^\dagger\Phi - v^2/2)\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right]$$

$$\mathcal{O}_B = \frac{1}{\Lambda^2}\frac{i}{2}(D_\mu\Phi)^\dagger(D_\nu\Phi)B^{\mu\nu}$$

B^0

$$\boxed{\Lambda_{\text{low}} = m_B}$$



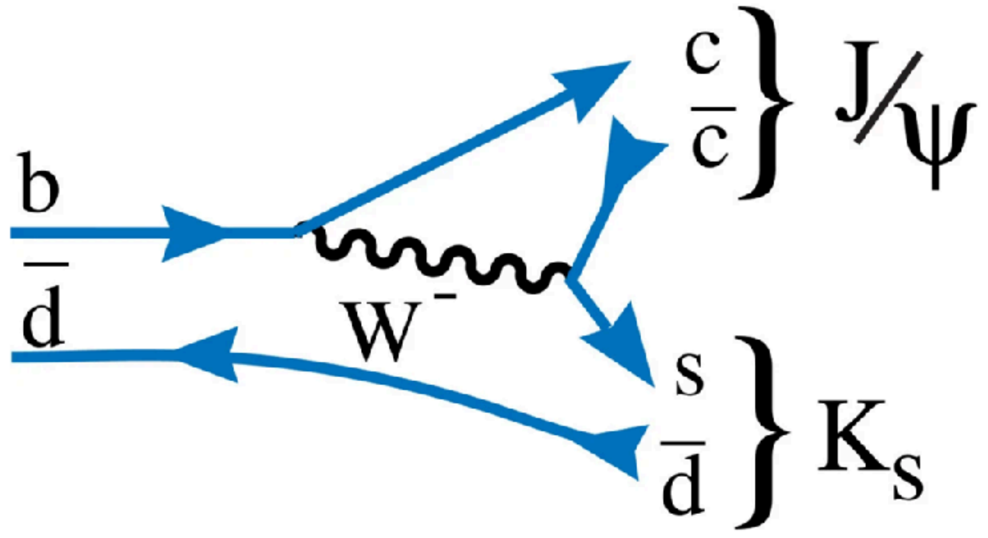
I, J, P need confirmation. Quantum numbers predictions

Mass $m_{B^0} = 5279.66 \pm 0.12$ MeV

$m_{B^0} - m_{B^\pm} = 0.32 \pm 0.05$ MeV

Mean life $\tau_{B^0} = (1.519 \pm 0.004) \times 1$

$c\tau = 455.4\ \mu$m



The rationale of Effective Field Theories

- SM contains all dim 2- and dim 4-operators "relevant" for low-energy physics: $\mathcal{L}_{EW} = -\frac{1}{2}\mathrm{tr}\,[W_{\mu\nu}W^{\mu\nu}] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$
  (no fermions or QCD here)

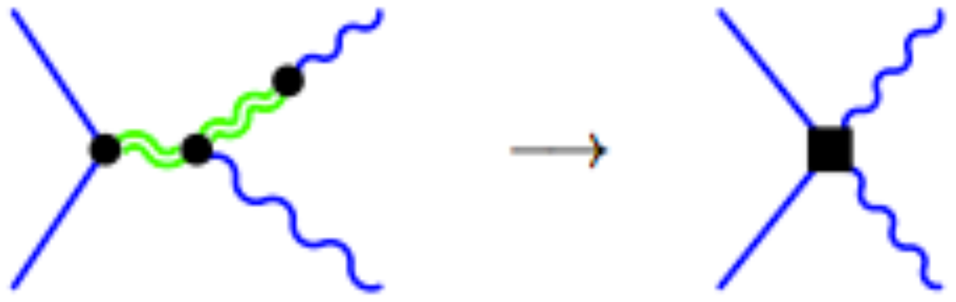
- Add all higher-dimensional operators consisting of SM fields/consistent with SM symmetries

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \boxed{\frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}} + \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \boxed{\frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)}} + \cdots \right]}$$

- $v \ll \Lambda$: new physics scale; $c_i^{(d)}$: dimensionless Wilson coefficient
- All odd operators involve fermions, all dim 5 and dim 7 violate B and/or L

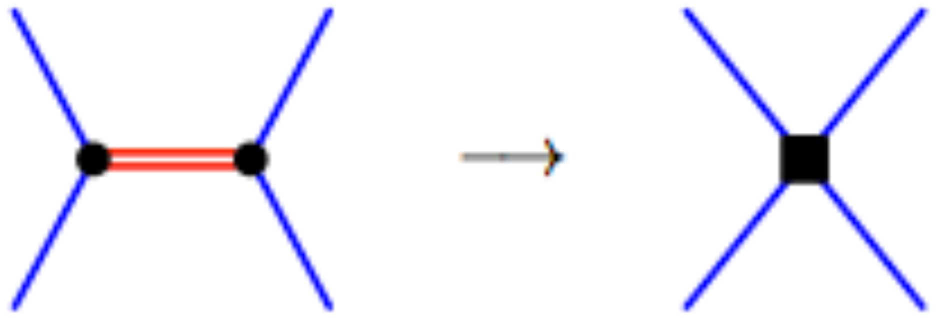
According to the "theorem" quoted at the beginning of this section, such a general Lagrangian has no specific dynamical content beyond the general principles of analyticity, unitarity, cluster decomposition, Lorentz invariance, and chirality, so that when it is used to calculate pionic S-matrix elements, it yields the most general matrix elements consistent with these general principles, provided that all terms of all orders in all couplings g_2, $g_4^{(1)}$, $g_4^{(2)}$, etc., are included. One does not need the methods of current algebra for justification

S. Weinberg, 1979



$$\mathcal{O}'_{\Phi,1} = \frac{1}{\Lambda^2}\left((D\Phi)^\dagger\Phi\right)\cdot\left(\Phi^\dagger(D\Phi)\right) - \frac{v^2}{2}|D\Phi|^2$$

$$\mathcal{O}'_{\Phi\Phi} = \frac{1}{\Lambda^2}(\Phi^\dagger\Phi - v^2/2)\,(D\Phi)^\dagger\cdot(D\Phi)$$



Truncation introduces model dependence again

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$$\boxed{\Lambda_{\text{low}} = m_B}$$

I, J, P need confirmation. Quantum numbers

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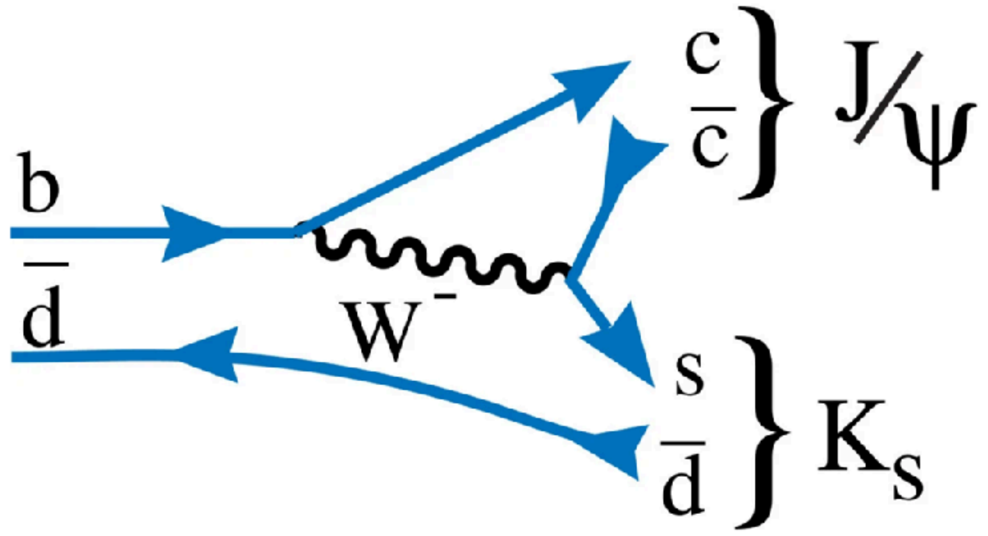
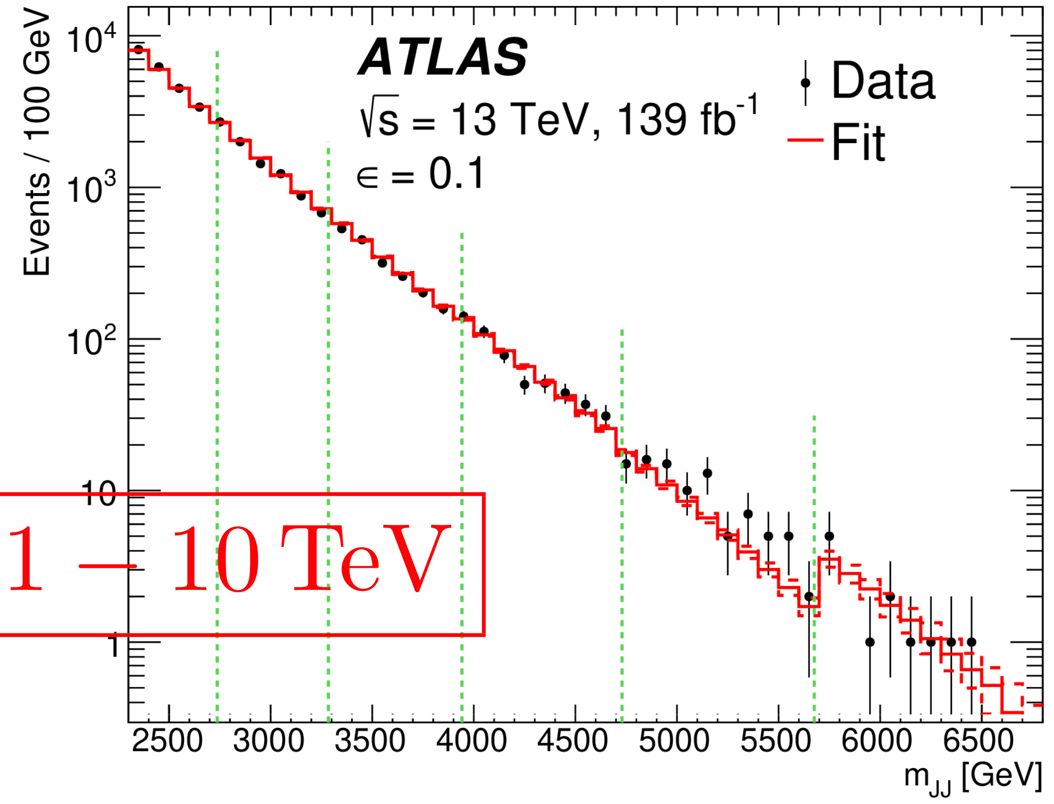


↔

$$\boxed{\Lambda_{\text{low}} \sim .1 - 10 \text{ TeV}}$$



EFT Operators in Multi-Boson Physics @ Dim-6

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\begin{aligned} \mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] & \mathcal{O}_{\partial\Phi} &= \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right) \\ \mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) & \mathcal{O}_{\Phi W} &= \left(\Phi^\dagger\Phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}] \\ \mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) & \mathcal{O}_{\Phi B} &= \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu} \end{aligned}$$

Dimension-6 operators for Multiboson physics (CP-violating)

$$\begin{aligned} \mathcal{O}_{\widetilde{W}W} &= \Phi^\dagger\widetilde{W}_{\mu\nu}W^{\mu\nu}\Phi & \mathcal{O}_{\widetilde{W}WW} &= \mathrm{Tr}[\widetilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\ \mathcal{O}_{\widetilde{B}B} &= \Phi^\dagger\widetilde{B}_{\mu\nu}B^{\mu\nu}\Phi & \mathcal{O}_{\widetilde{W}} &= (D_\mu\Phi)^\dagger\widetilde{W}^{\mu\nu}(D_\nu\Phi) \end{aligned}$$

All operators can change differential rates & polarization fractions!

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{W}$	✓	✓	✓	✓	✓		✓	✓	✓	
$\mathcal{O}_{B}$	✓	✓		✓	✓					
$\mathcal{O}_{\Phi d}$			✓	✓						
$\mathcal{O}_{\Phi W}$			✓	✓	✓	✓				
$\mathcal{O}_{\Phi B}$				✓	✓	✓				
$\mathcal{O}_{\tilde{W}WW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{\tilde{W}}$	✓	✓	✓	✓	✓					
$\mathcal{O}_{\tilde{W}W}$			✓	✓	✓	✓				
$\mathcal{O}_{\tilde{B}B}$				✓	✓	✓				

connected to Higgs physics

- “HISZ” basis: no fermionic operators Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993
- “GIMR” basis: first minimal complete basis Grzadkowski/Iskrzyński/Misiak/Rosiek, 2010
- “SILH” basis: complete basis Giudice/Grojean/Pomarol/Ratazzi, 2007; Elias-Miró et al, 2013
- Dim. 8 operators: Eboli et al., 2006; Kilian/JRR/Ohl/Sekulla, 2014+2015; Hays/Martin/Sanz/Setford, 1808.00442, Li et al., 2005.00008
- “EChL” basis: Dobado/Espriu/Pich et al.; Buchalla/Cata; Kilian/JRR et al.

EFT Operators in Multi-Boson Physics @ Dim-8

Longitudinal operators

$$\begin{aligned} \mathcal{O}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\ \mathcal{O}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \end{aligned}$$

All operators can change differential rates & polarization fractions!

Transversal operators

$$\begin{aligned} \mathcal{O}_{T,0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] \\ \mathcal{O}_{T,1} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] \\ \mathcal{O}_{T,2} &= \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right] \\ \mathcal{O}_{T,5} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot B_{\alpha\beta}B^{\alpha\beta} \\ \mathcal{O}_{T,6} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot B_{\mu\beta}B^{\alpha\nu} \\ \mathcal{O}_{T,7} &= \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot B_{\beta\nu}B^{\nu\alpha} \\ \mathcal{O}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\ \mathcal{O}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \end{aligned}$$

Mixed operators

$$\begin{aligned} \mathcal{O}_{M,0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\ \mathcal{O}_{M,1} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\ \mathcal{O}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\ \mathcal{O}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\ \mathcal{O}_{M,4} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu} D^\mu\Phi\right] \cdot B^{\beta\nu} \\ \mathcal{O}_{M,5} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu} D^\nu\Phi\right] \cdot B^{\beta\mu} \\ \mathcal{O}_{M,6} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu} D^\mu\Phi\right] \\ \mathcal{O}_{M,7} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu} D^\nu\Phi\right] \end{aligned}$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

EFT Operators in Multi-Boson Physics @ Dim-8

Longitudinal operators

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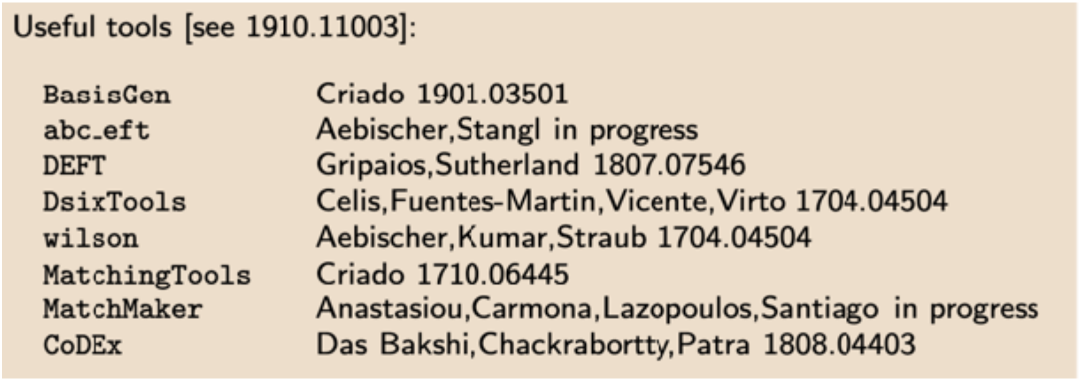
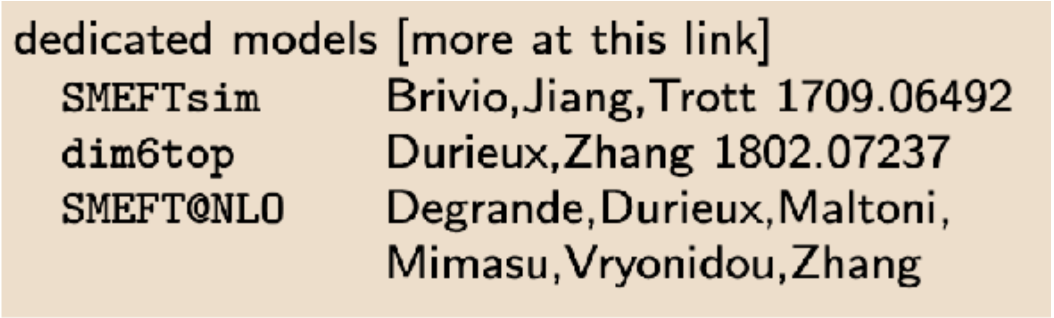
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

Tools:



Useful tools [see 1910.11003]:

`BasisGen`	Criado 1901.03501
`abc_eft`	Aebischer,Stangl in progress
`DEFT`	Gripaios,Sutherland 1807.07546
`DsixTools`	Celis,Fuentes-Martin,Vicente,Virto 1704.04504
`wilson`	Aebischer,Kumar,Straub 1704.04504
`MatchingTools`	Criado 1710.06445
`MatchMaker`	Anastasiou,Carmona,Lazopoulos,Santiago in progress
`CoDEx`	Das Bakshi,Chackrabortty,Patra 1808.04403



dedicated models [more at this link]

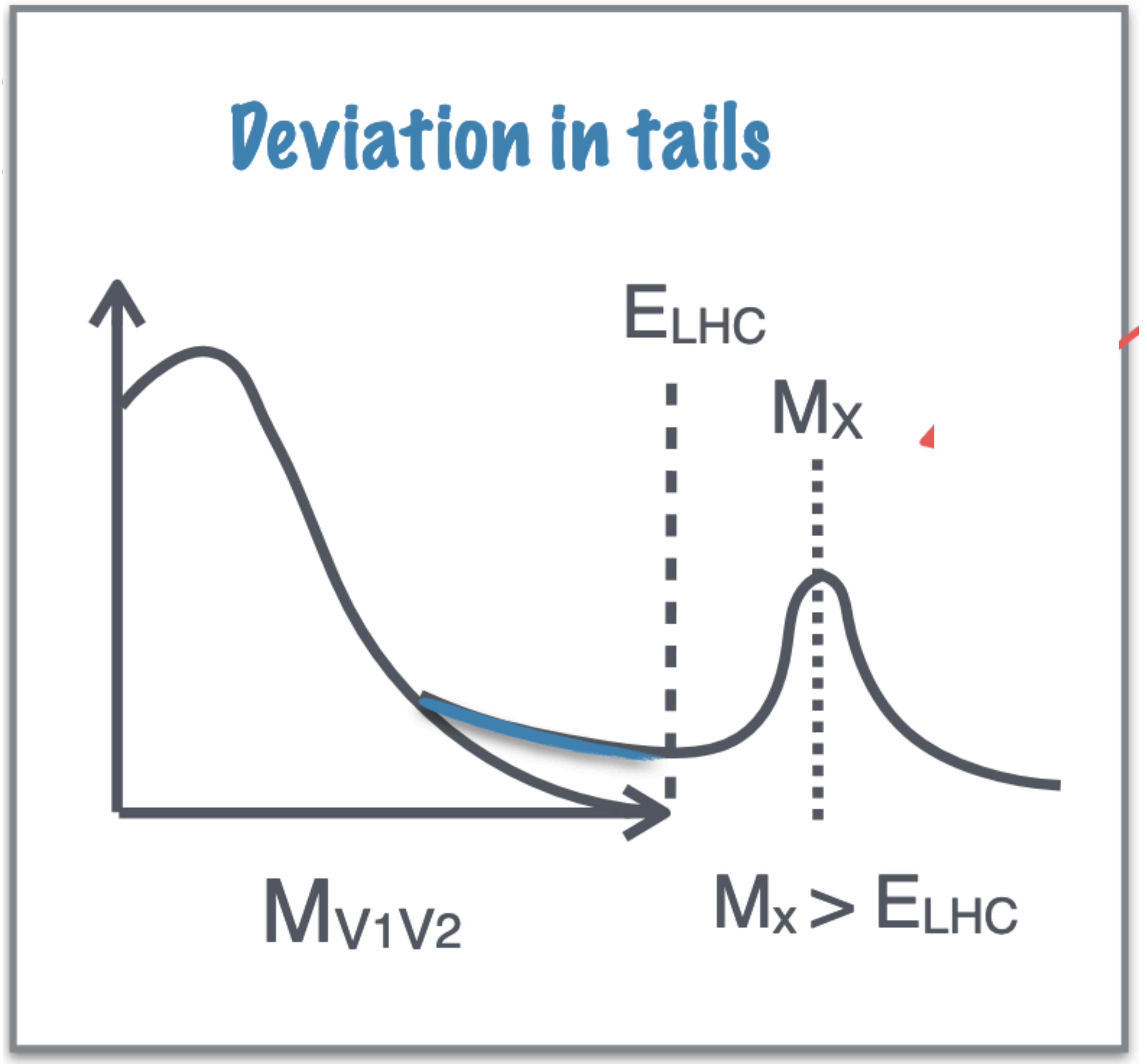
`SMEFTsim`	Brivio,Jiang,Trott 1709.06492
`dim6top`	Durieux,Zhang 1802.07237
`SMEFT@NLO`	Degrande,Durieux,Maltoni, Mimasu,Vryonidou,Zhang

New Physics Searches in VBS - Struggling EFT description

- ☐ **Resonances in direct reach** (not clear: strongly interacting models [e.g. σ resonance]
- ☐ **Estimate of operator coefficients** (difficult for strongly coupled models)

$$\mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-6}} \gtrsim |\mathcal{A}_{\text{dim-6}}|^2 \qquad \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-8}} \gtrsim |\mathcal{A}_{\text{dim-8}}|^2 \qquad \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-6}} \gtrsim \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-8}}$$

- ☐ **Partial wave unitarity:** gives guidance on maximally possible event numbers
- ☐ **Positivity constraints on operator coefficients** (Analyticity: UV-complete or “swampland”)
- ☐ **Size of coefficients:** dichotomy between validity and detectability



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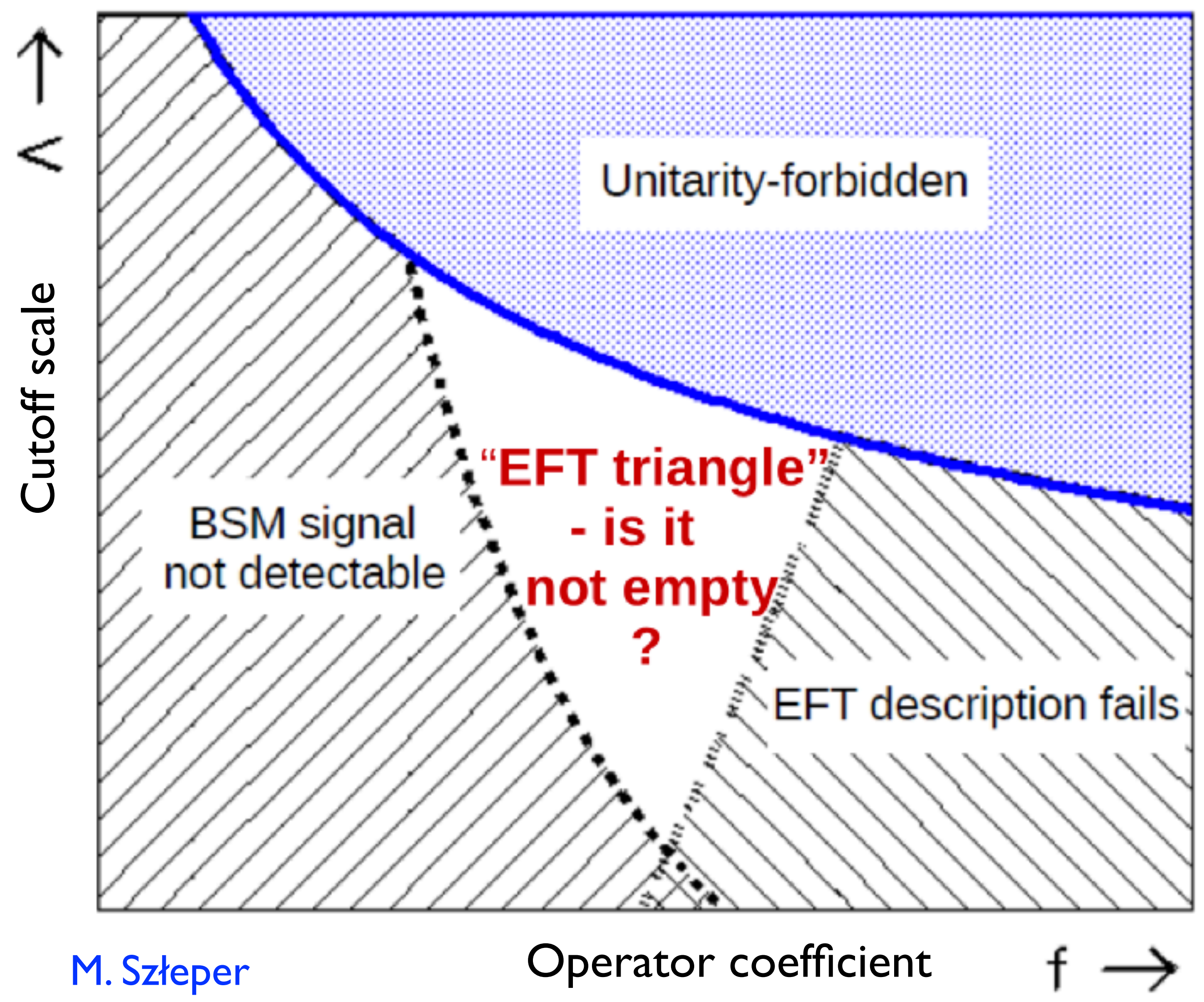

M. Szłeper

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$$\mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-6}} \gtrsim |\mathcal{A}_{\text{dim-6}}|^2 \qquad \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-8}} \gtrsim |\mathcal{A}_{\text{dim-8}}|^2 \qquad \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-6}} \gtrsim \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-8}}$$

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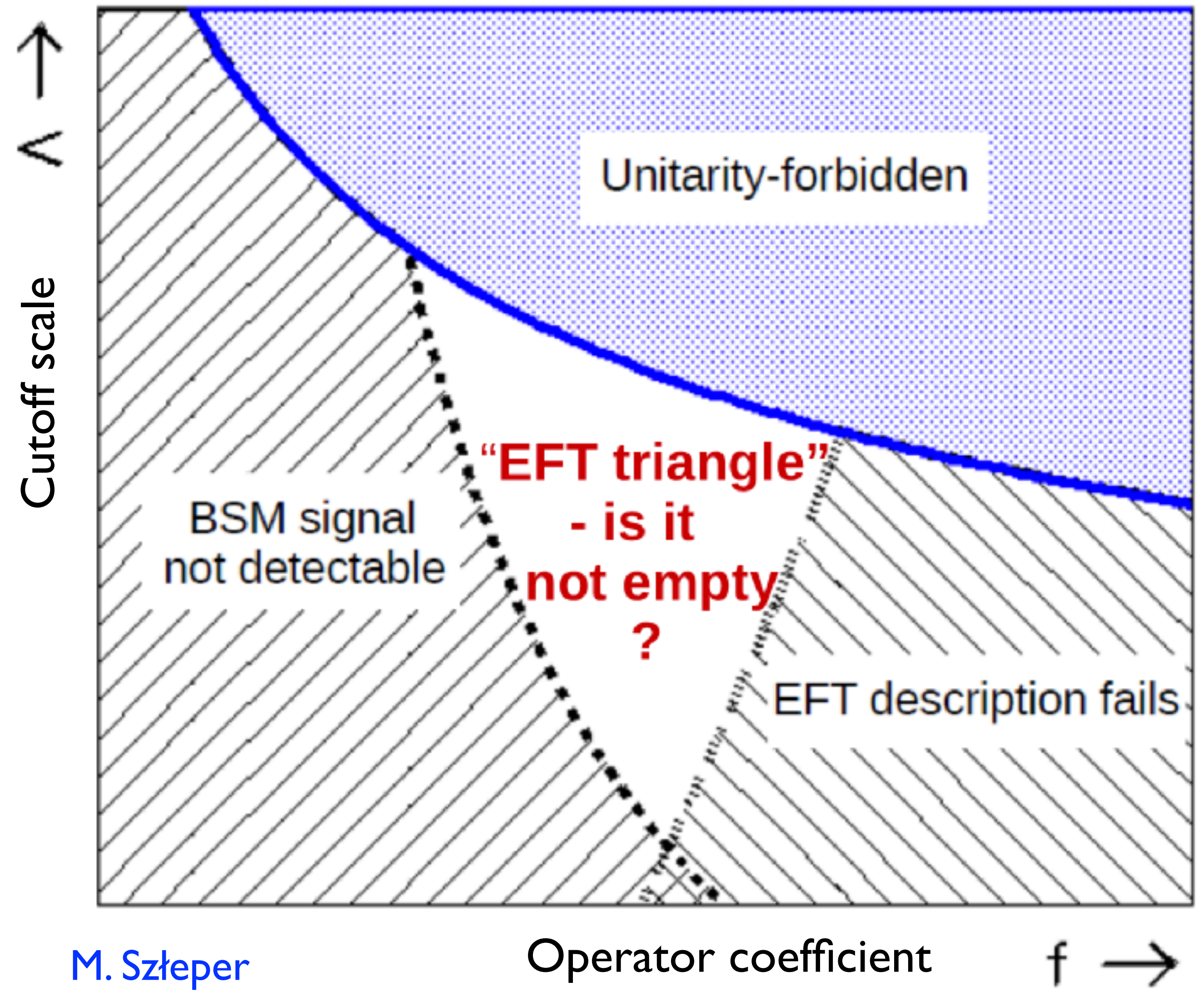
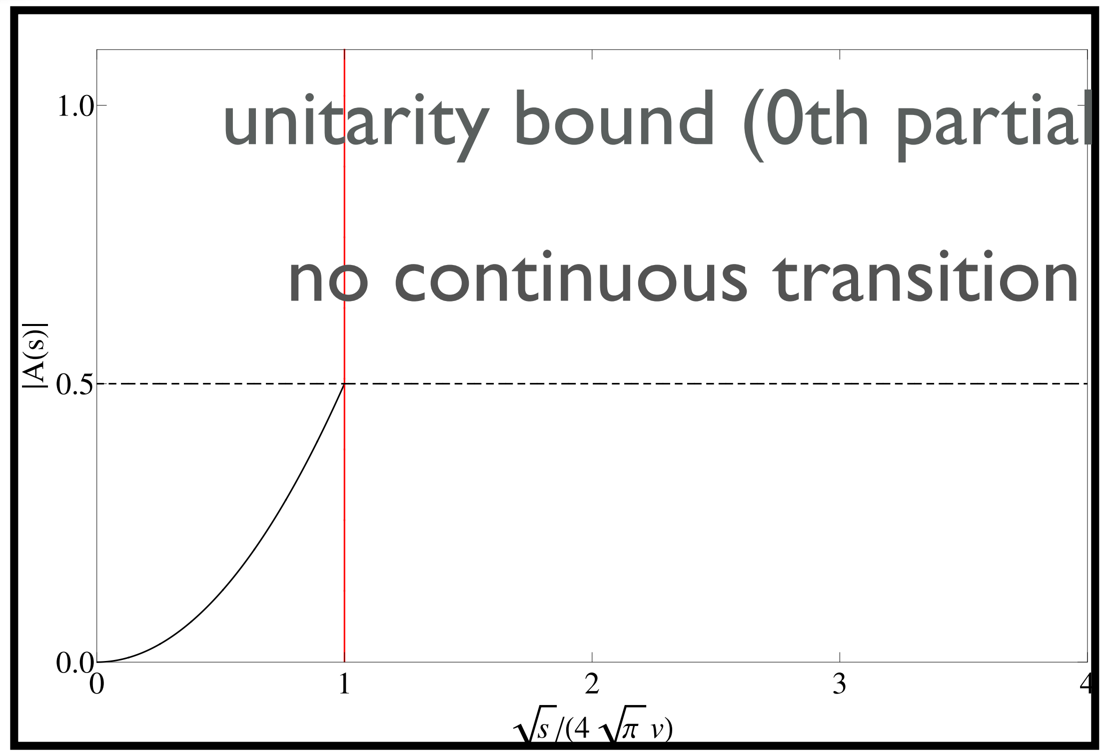


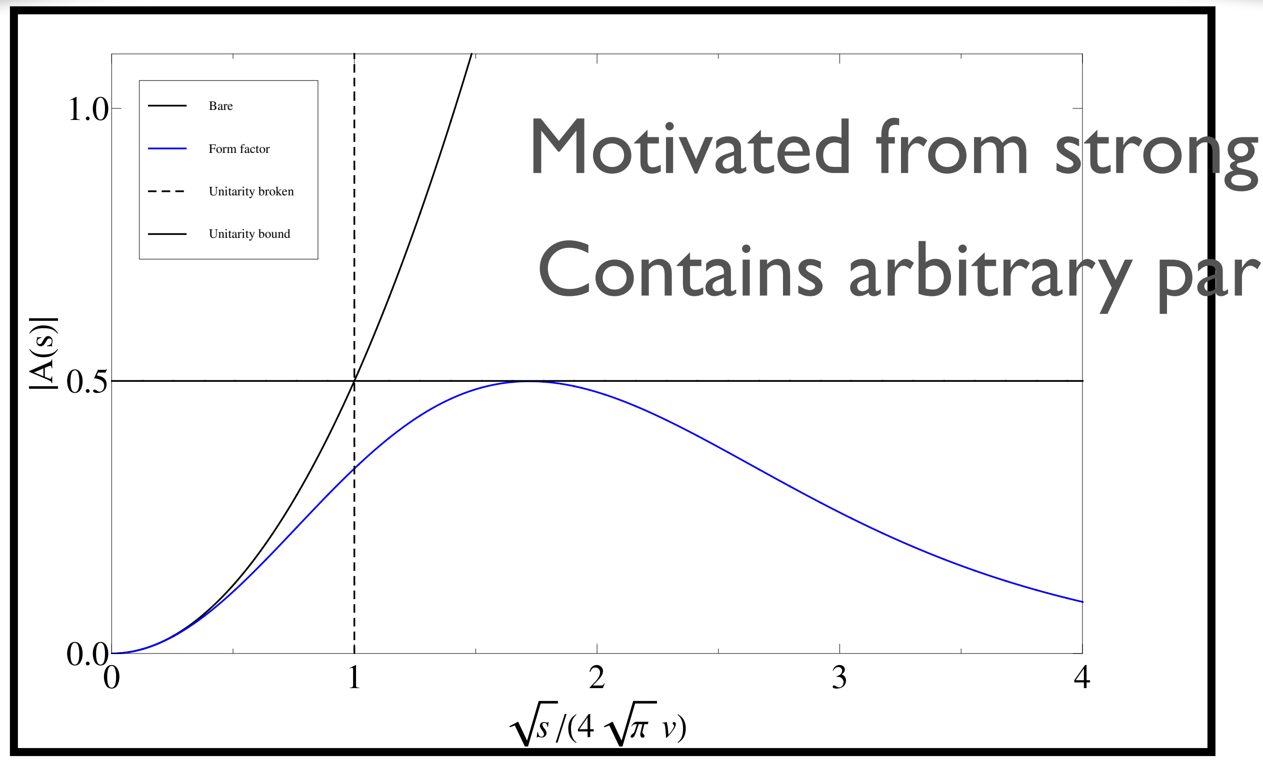
Cut-off (a.k.a. "Event clipping") $\theta(\Lambda_C^2 - s)$



unitarity bound (0th partial wave) at Λ_C

no continuous transition beyond

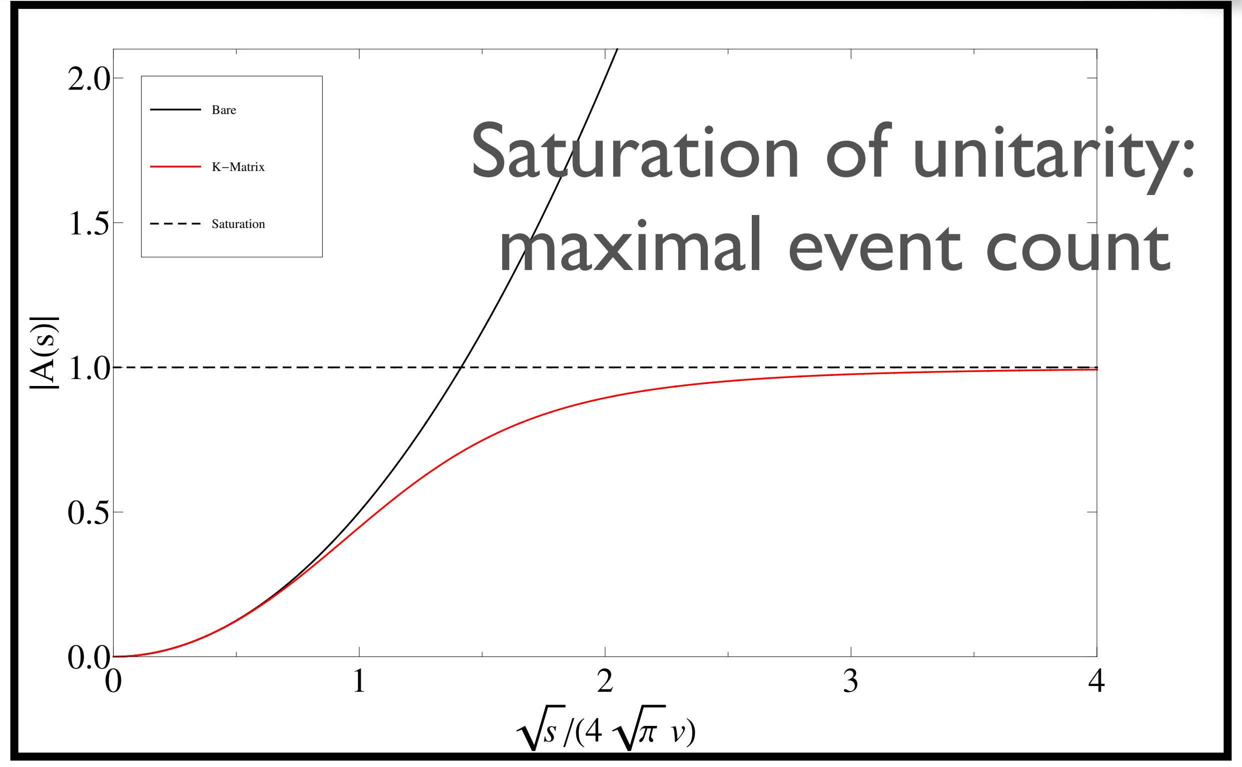
Form factor $\frac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$



Motivated from strong interactions

Contains arbitrary parameters

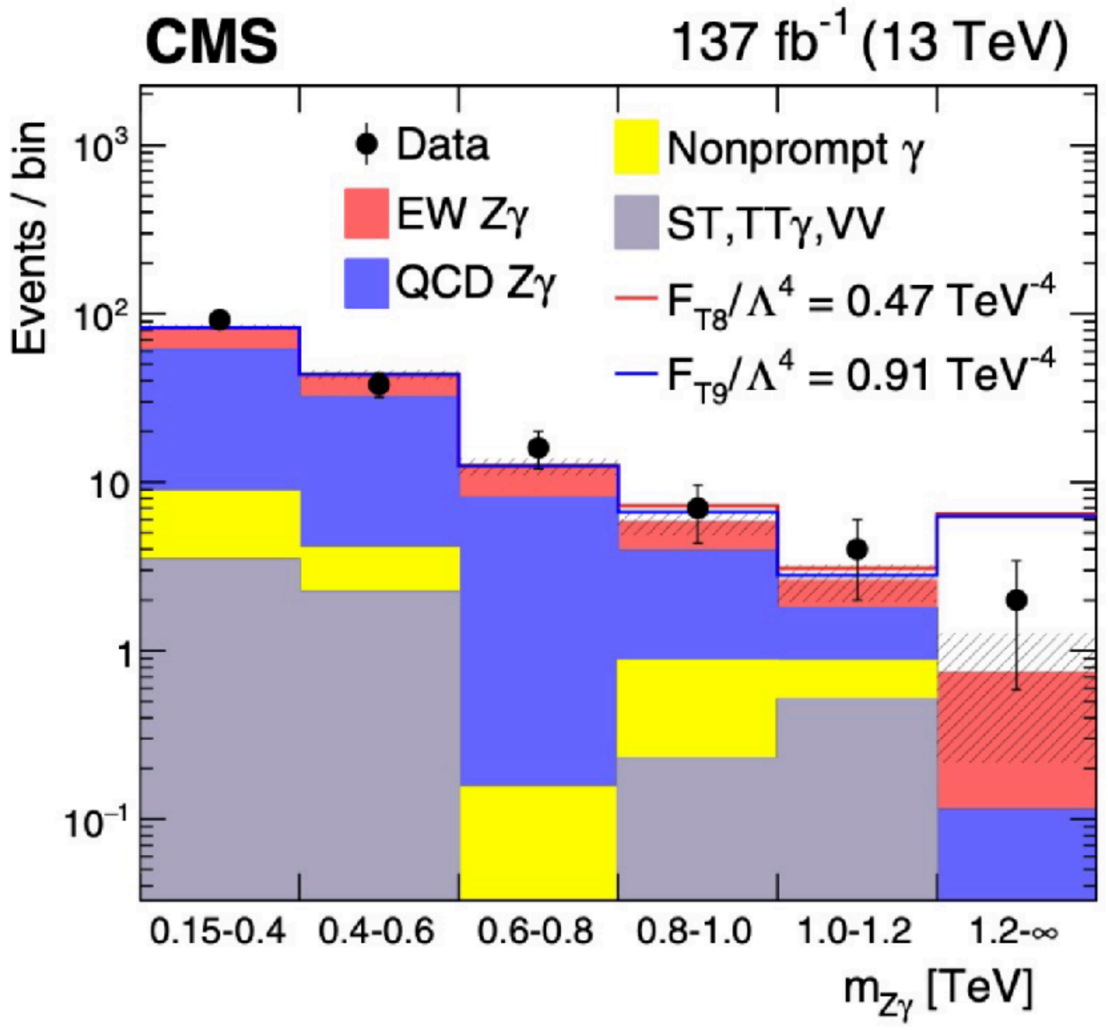
***K*-/*T*-matrix saturation** $a = \frac{1}{\text{Re}\left(\frac{1}{a_0}\right) - \text{i}}$

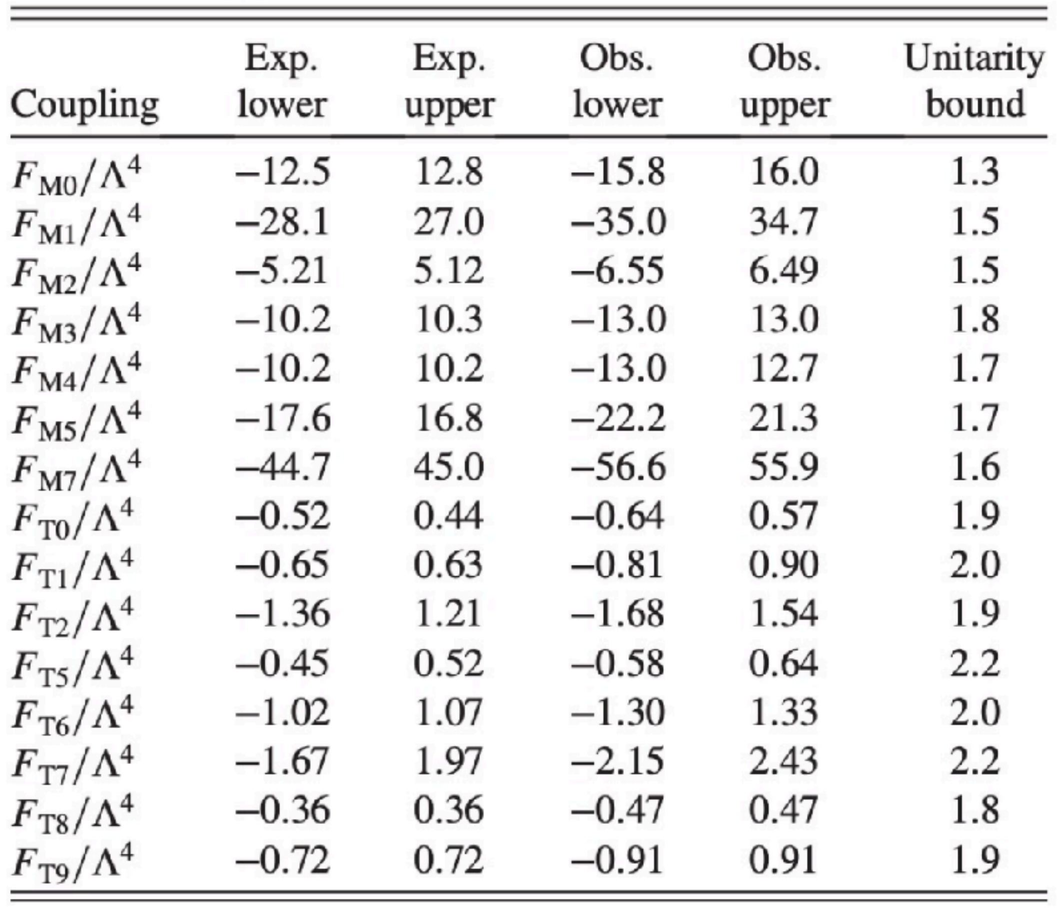


Saturation of unitarity: maximal event count

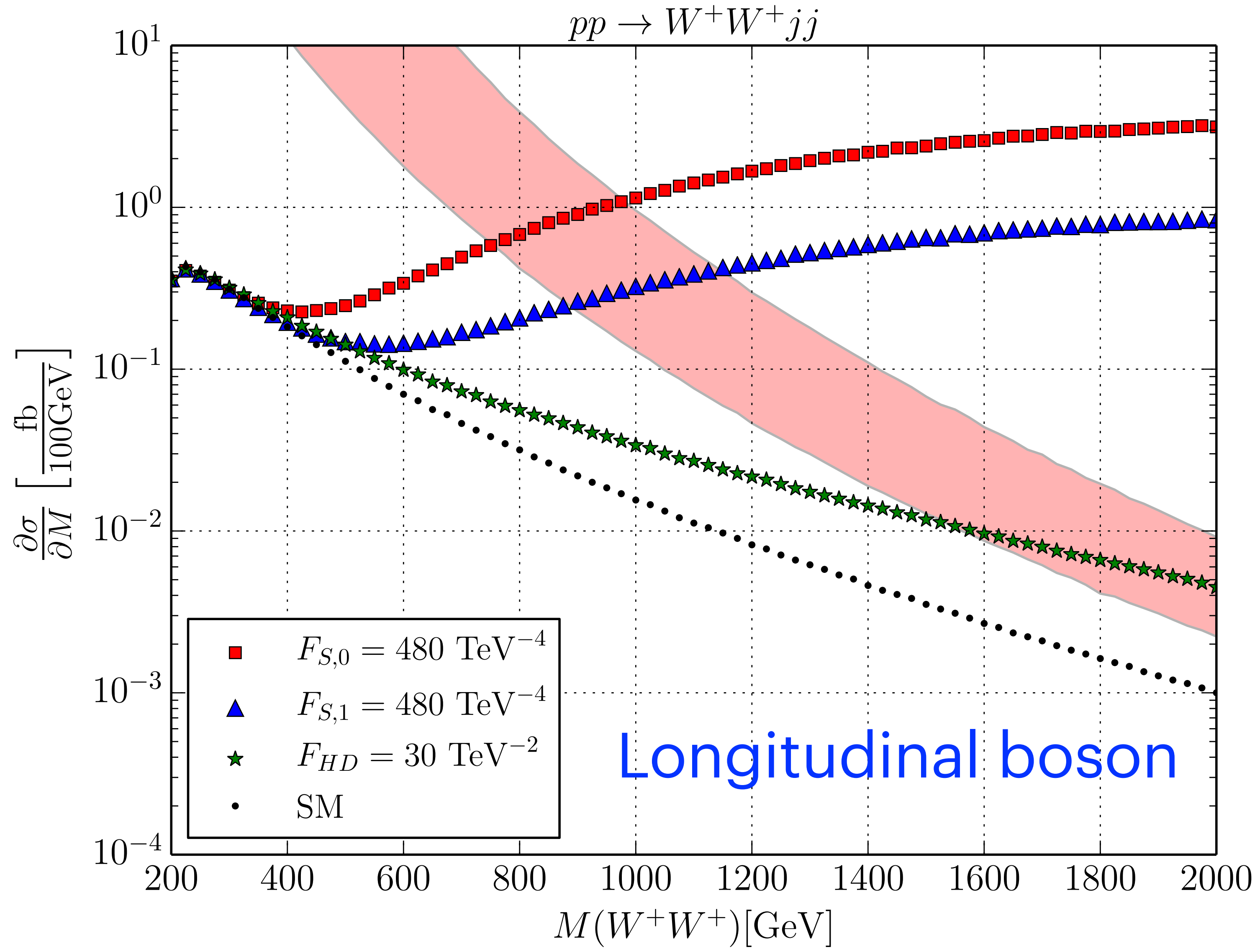
New Physics Searches in VBS/Multi bosons

○ EFT mostly model-independent → Truncation, power-counting introduces model-dependence (cf. LHC EFT WG)





Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9



Longitudinal boson

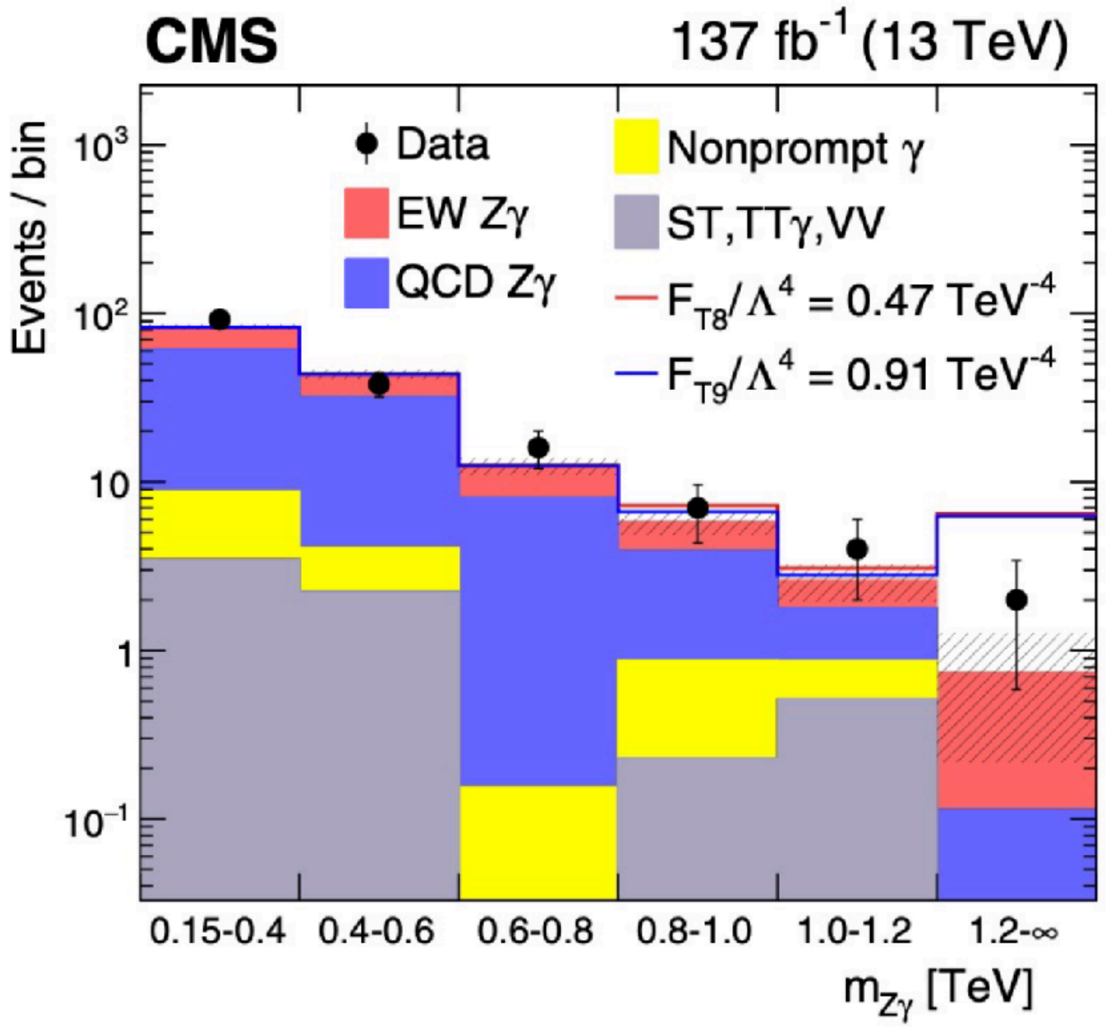
General cuts:

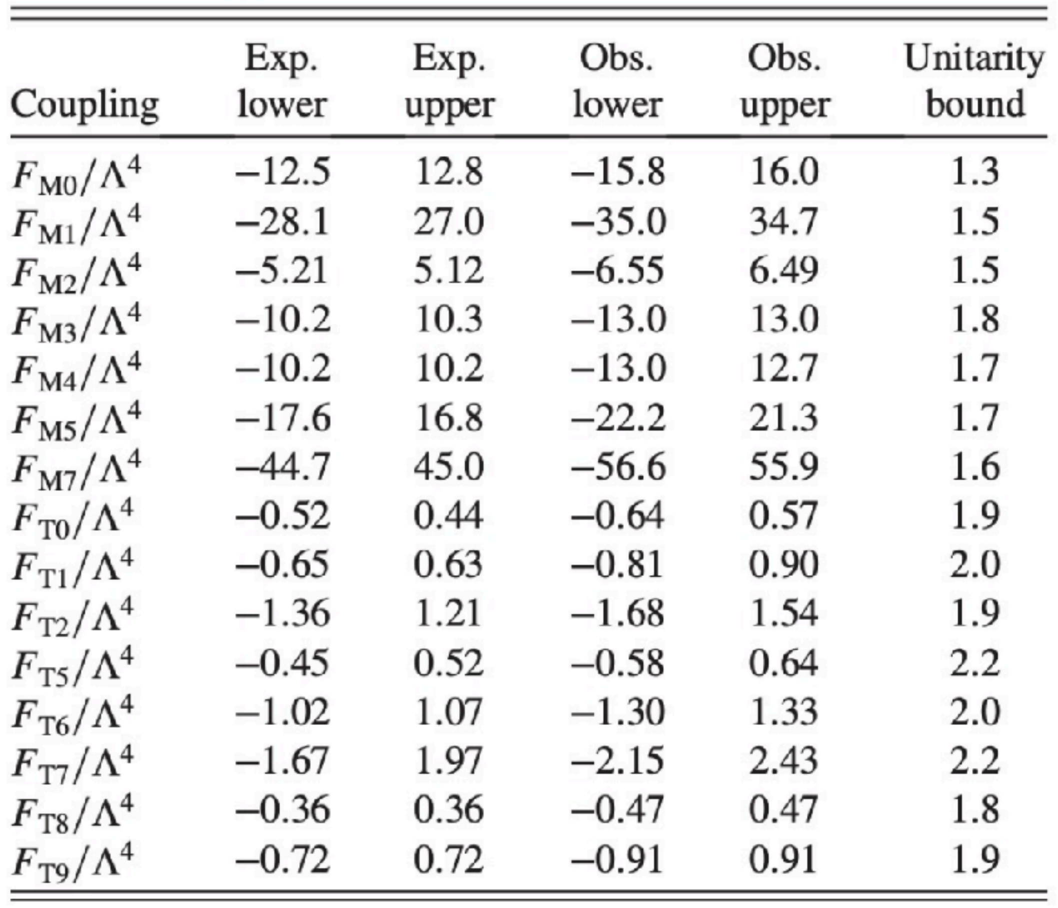
$M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

Kilian/Ohl/JRR/Sekulla, 1511.00022

New Physics Searches in VBS/Multi bosons

- EFT mostly model-independent → Truncation, power-counting introduces model-dependence (cf. LHC EFT WG)





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F_{M0}/Λ^4	–12.5	12.8	–15.8	16.0	1.3
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F_{M2}/Λ^4	–5.21	5.12	–6.55	6.49	1.5
F_{M3}/Λ^4	–10.2	10.3	–13.0	13.0	1.8
F_{M4}/Λ^4	–10.2	10.2	–13.0	12.7	1.7
F_{M5}/Λ^4	–17.6	16.8	–22.2	21.3	1.7
F_{M7}/Λ^4	–44.7	45.0	–56.6	55.9	1.6
F_{T0}/Λ^4	–0.52	0.44	–0.64	0.57	1.9
F_{T1}/Λ^4	–0.65	0.63	–0.81	0.90	2.0
F_{T2}/Λ^4	–1.36	1.21	–1.68	1.54	1.9
F_{T5}/Λ^4	–0.45	0.52	–0.58	0.64	2.2
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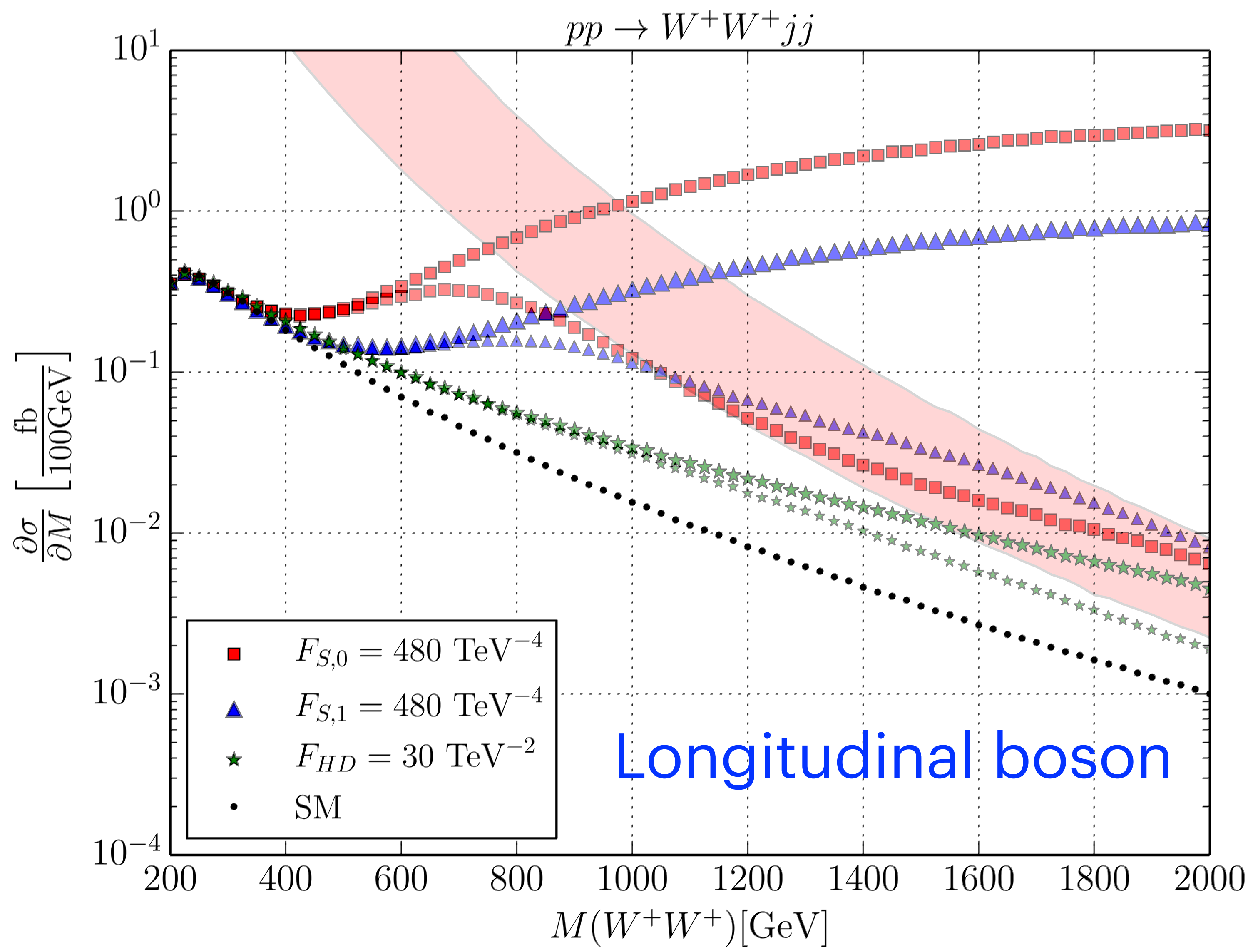

Longitudinal boson

General cuts:

$M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

Kilian/Ohl/JRR/Sekulla, 1511.00022

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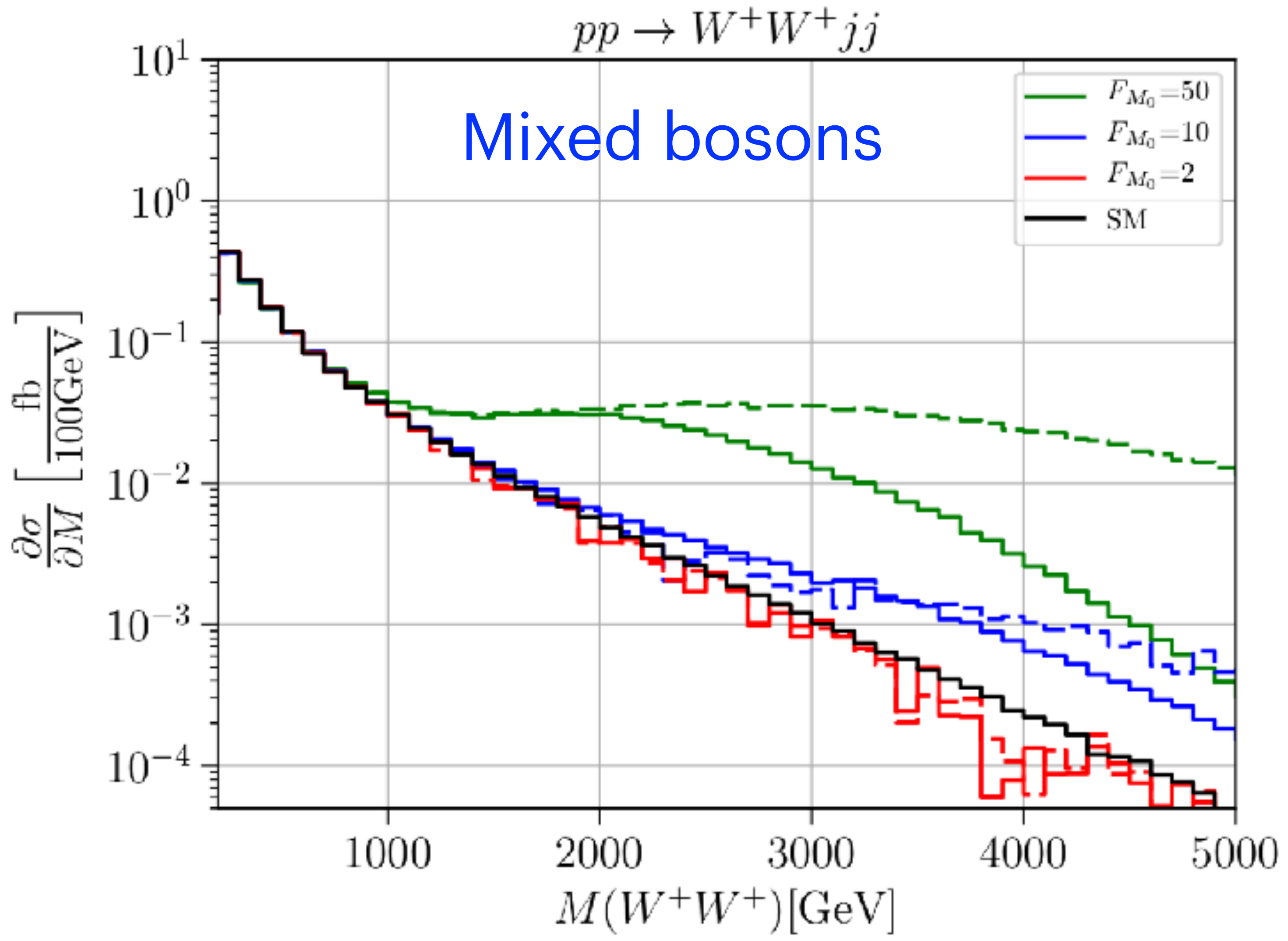

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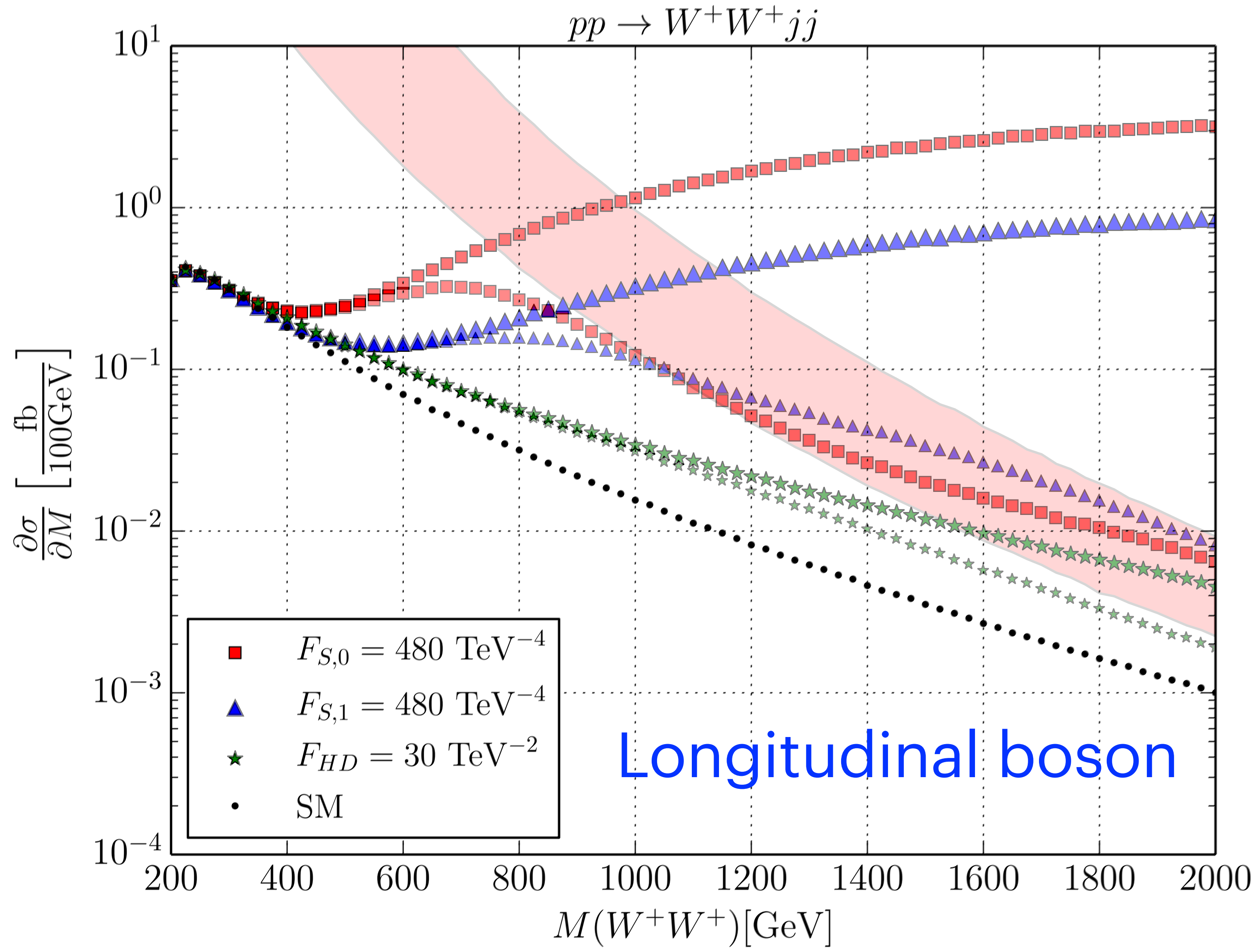

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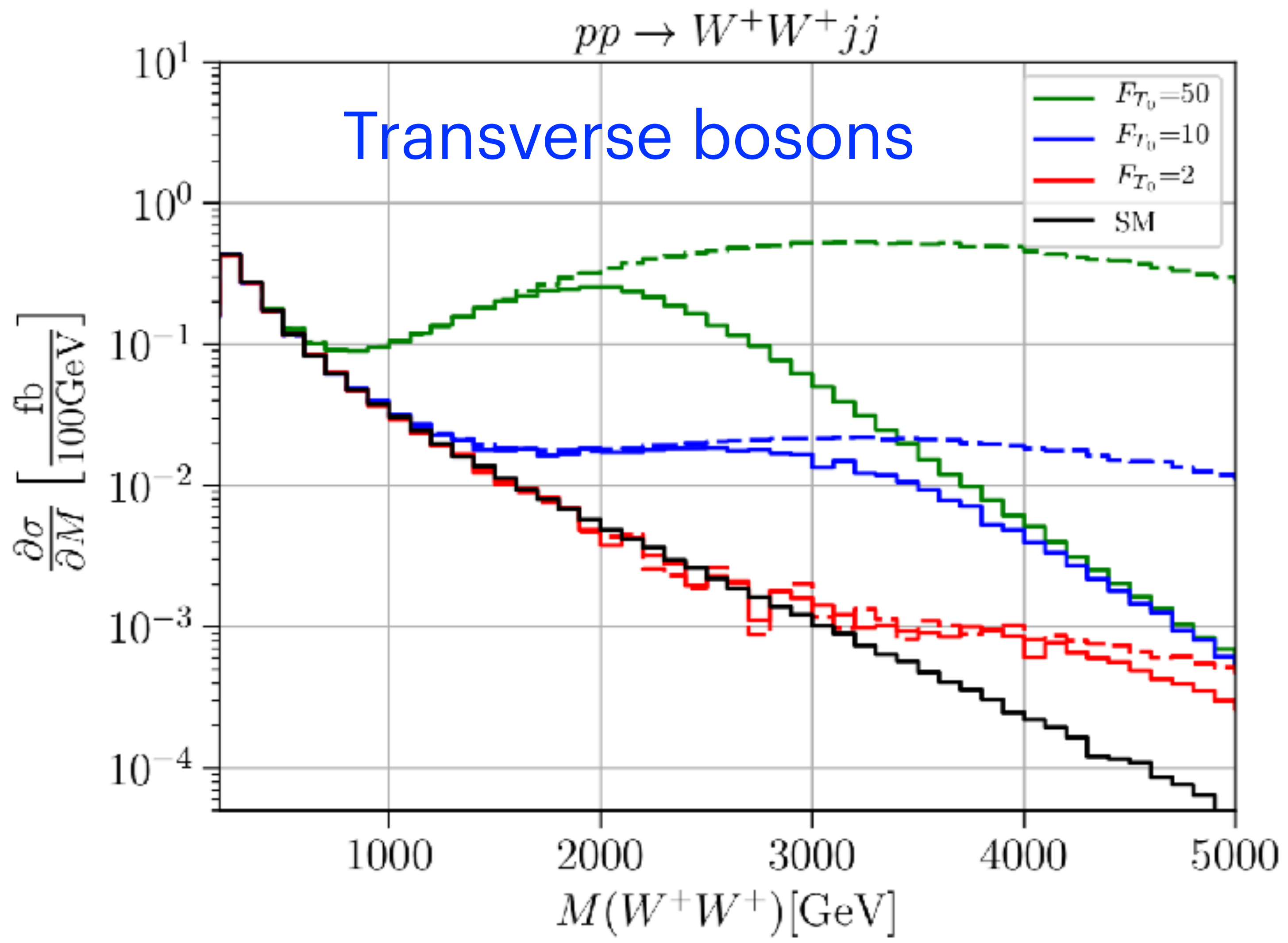

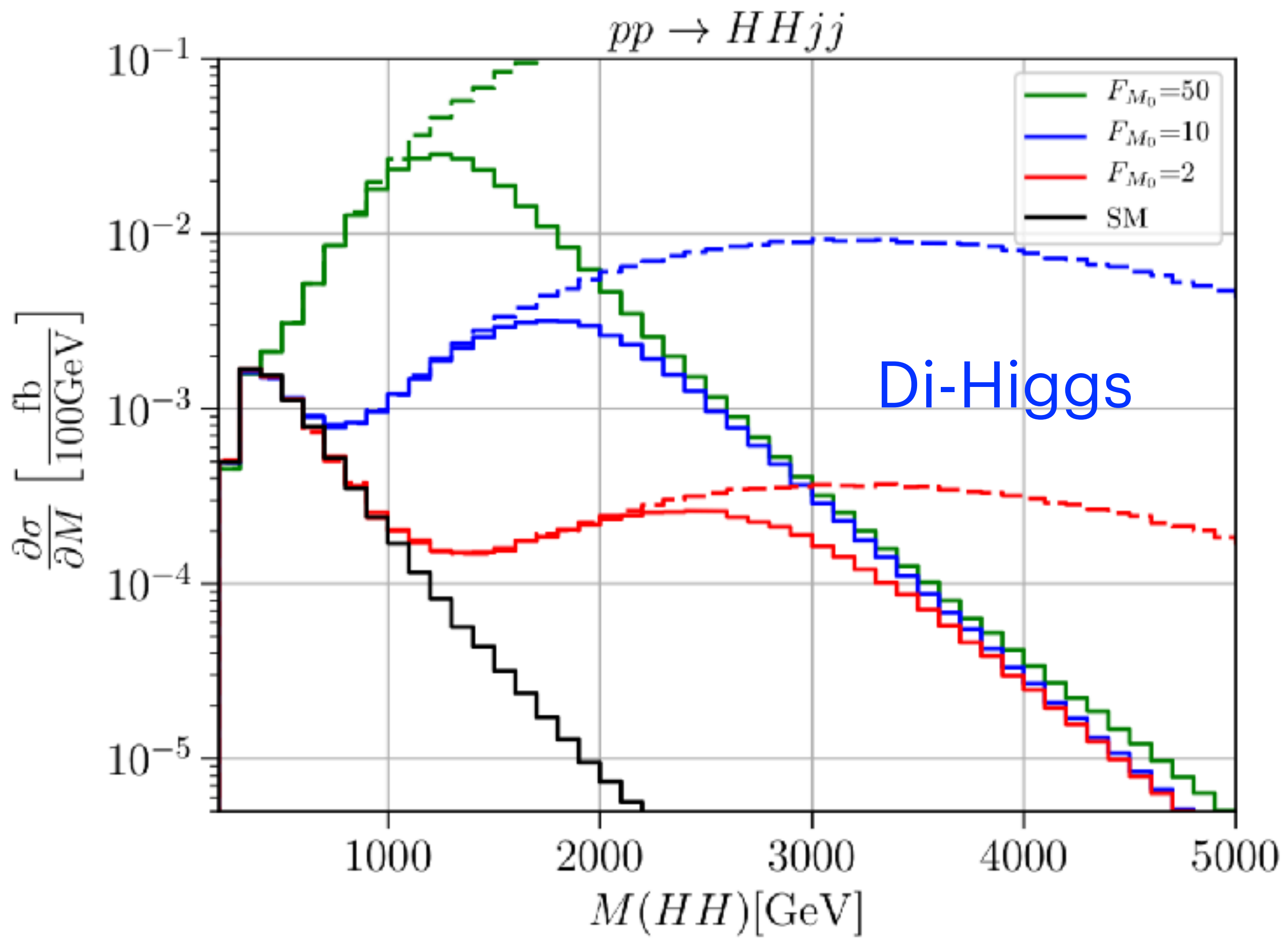

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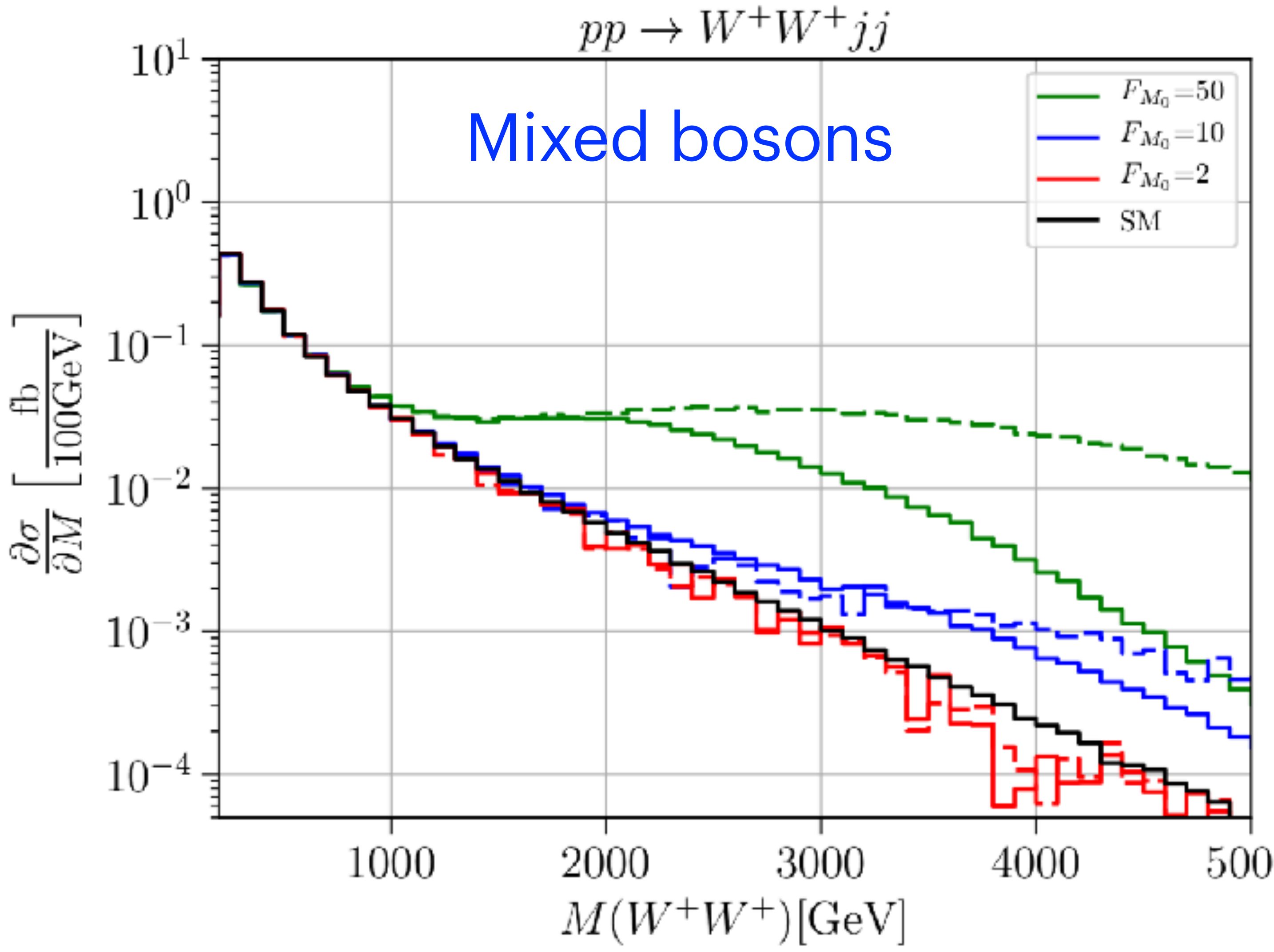

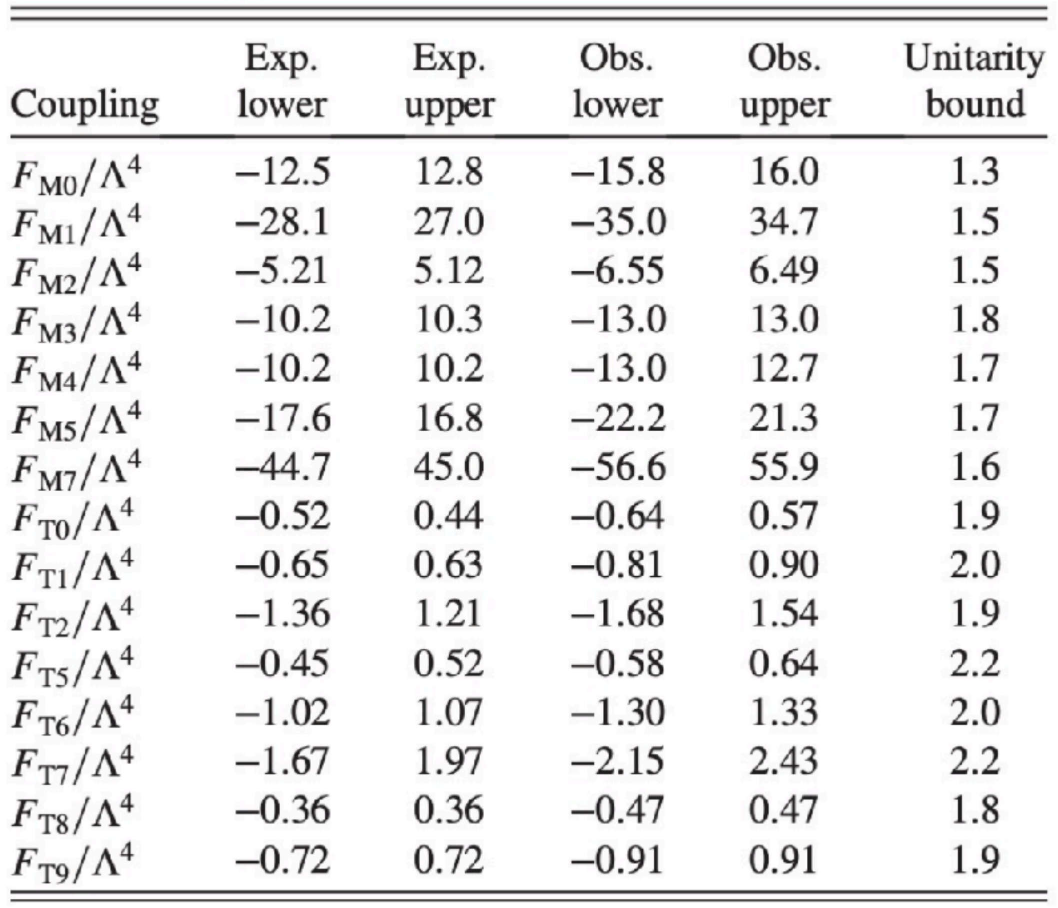

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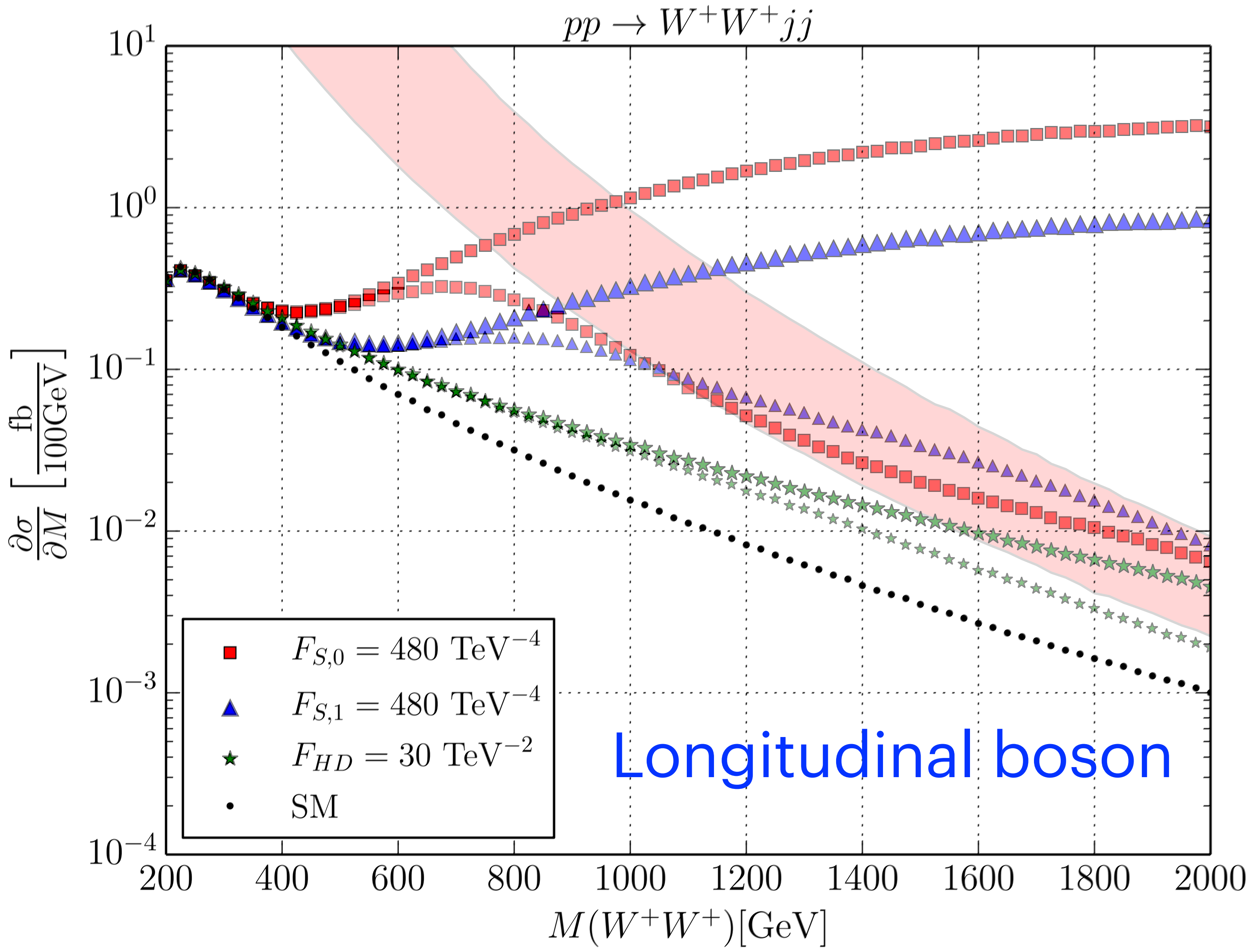

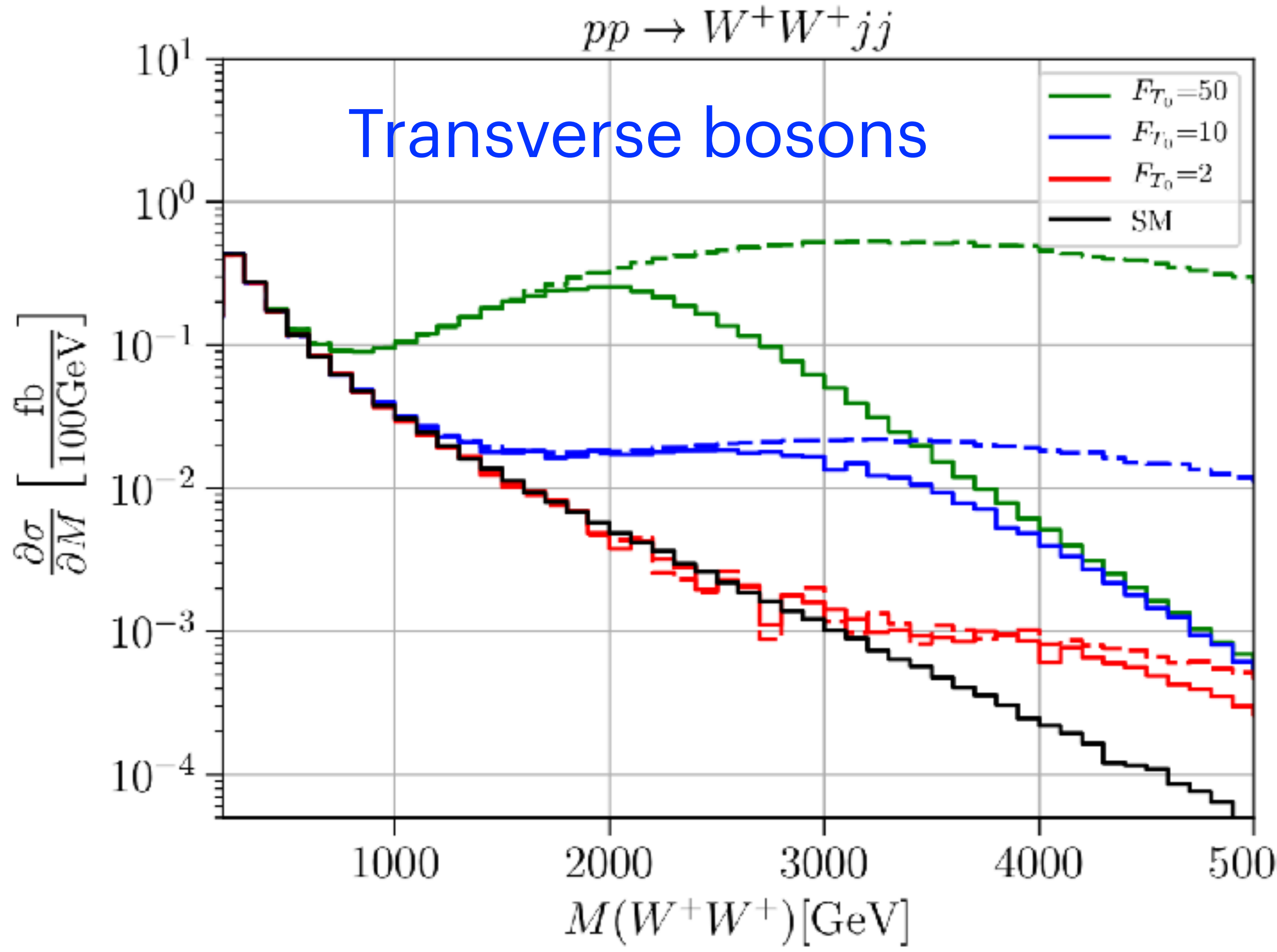

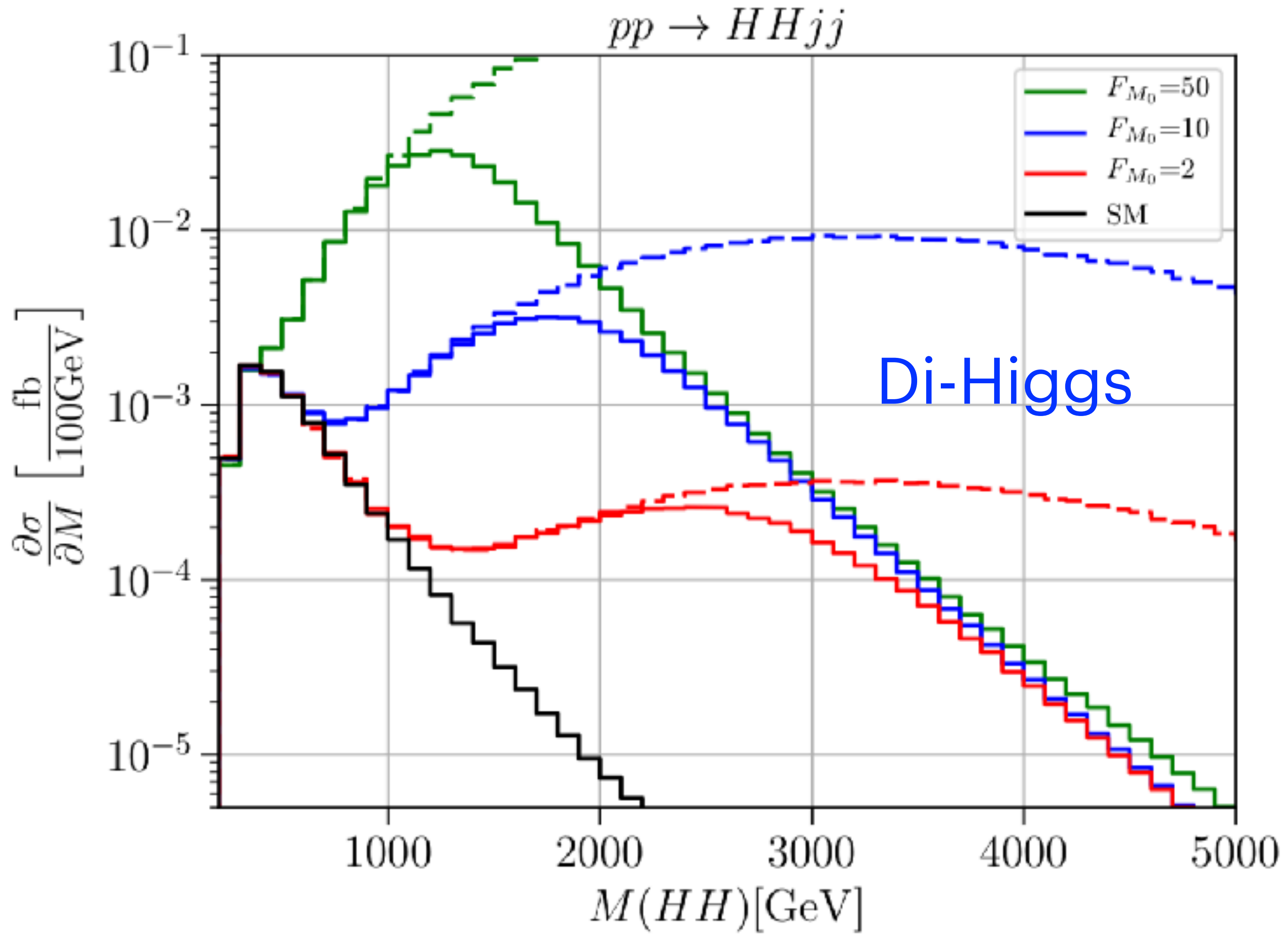

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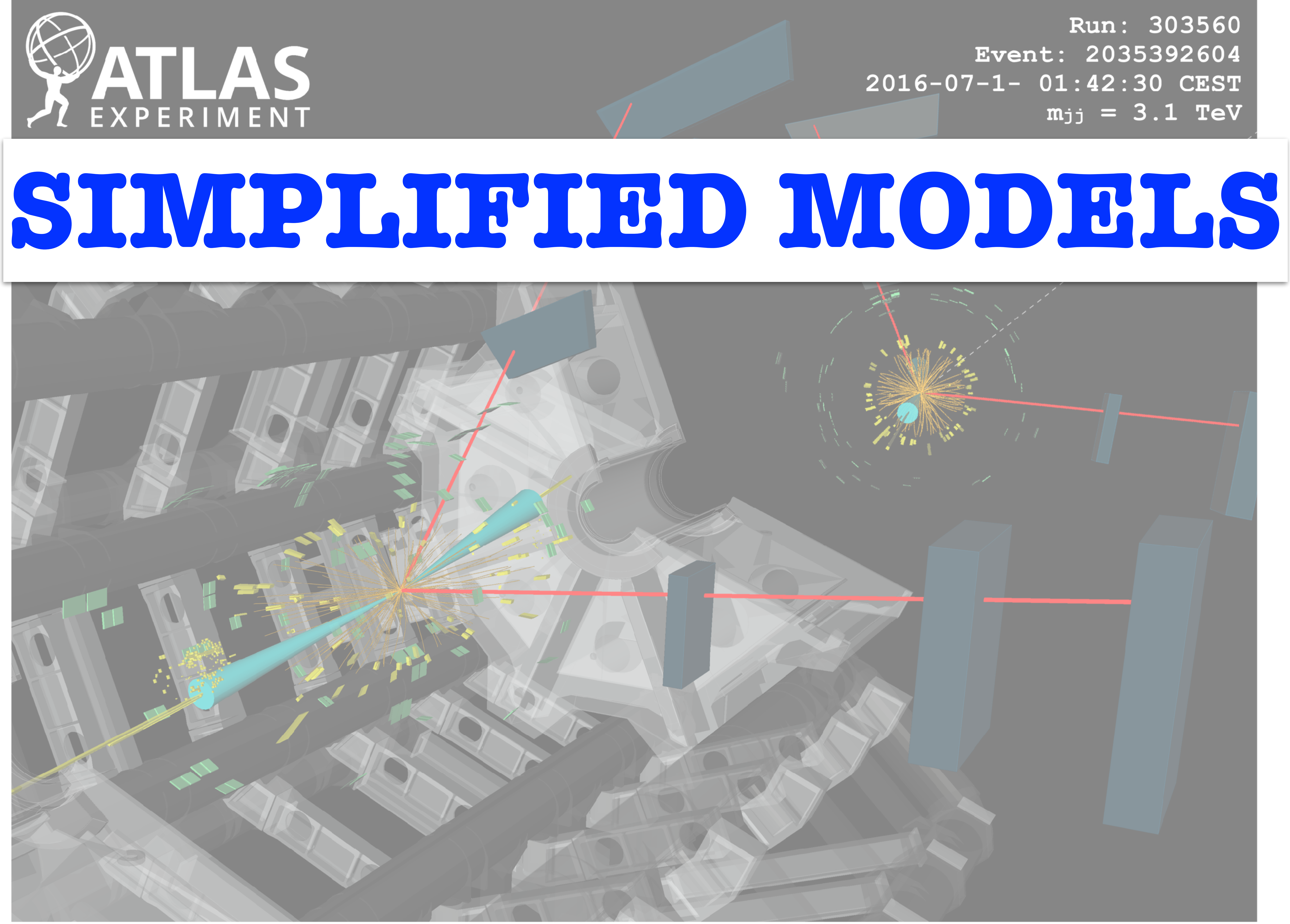
Much more leeway for new physics in transversal gauge bosons and di-Higgs ; longitudinal bosons much closer to unitarity limit

Kilian/Ohl/JRR/Sekulla, 1511.00022



SIMPLIFIED MODELS

Simplified New Physics Models for VBS

- Semi-model-independent: simplified models
- Consider all possible EW diboson resonances
- Very few parameters: $(M_V \, , \, g_{VV}) \, , \, (M_V \, , \, \Gamma_{[VV]})$
- Distinguish weakly/strongly-coupled models

$$\frac{c_i}{\Lambda} \sim \frac{g}{4\pi\Lambda} \quad \text{vs.} \quad \frac{c_i}{\Lambda} \sim \frac{g}{\Lambda}$$

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Alboteanu/Kilian/JRR, 0806.4145; Kilian et al., 1511.00022; Braß et al. , 1807.02512
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Translation into Wilson coefficient below resonance

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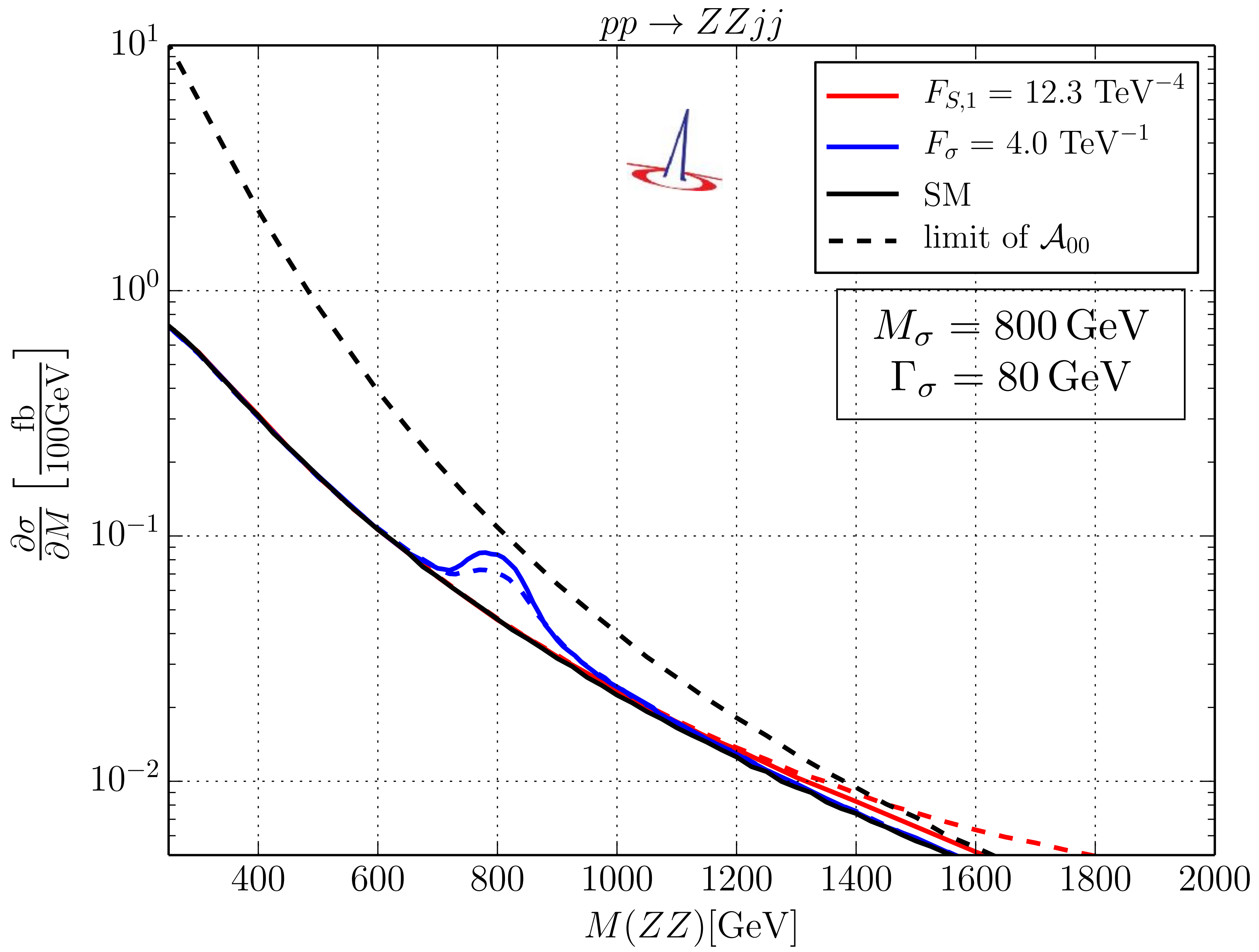

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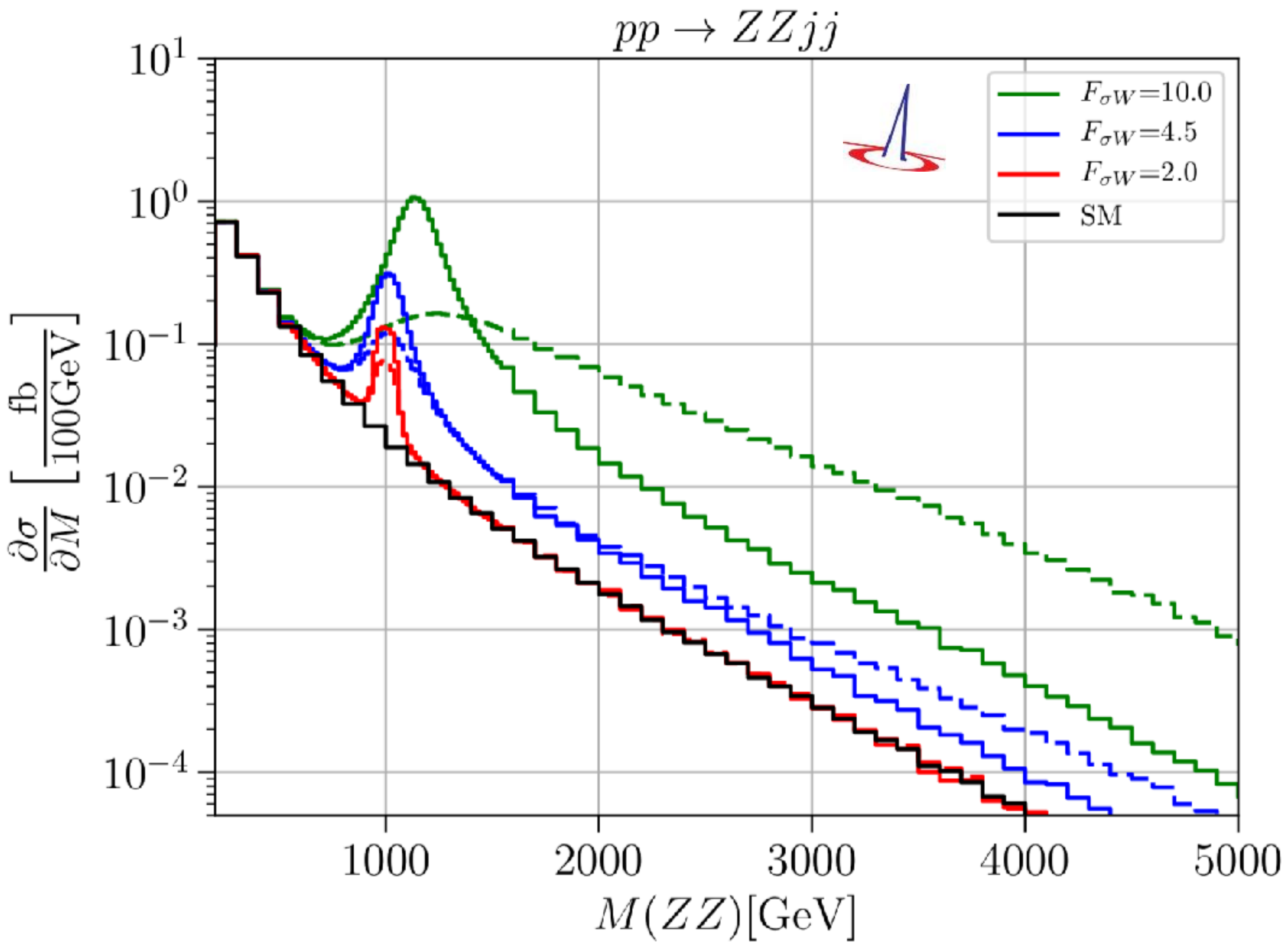

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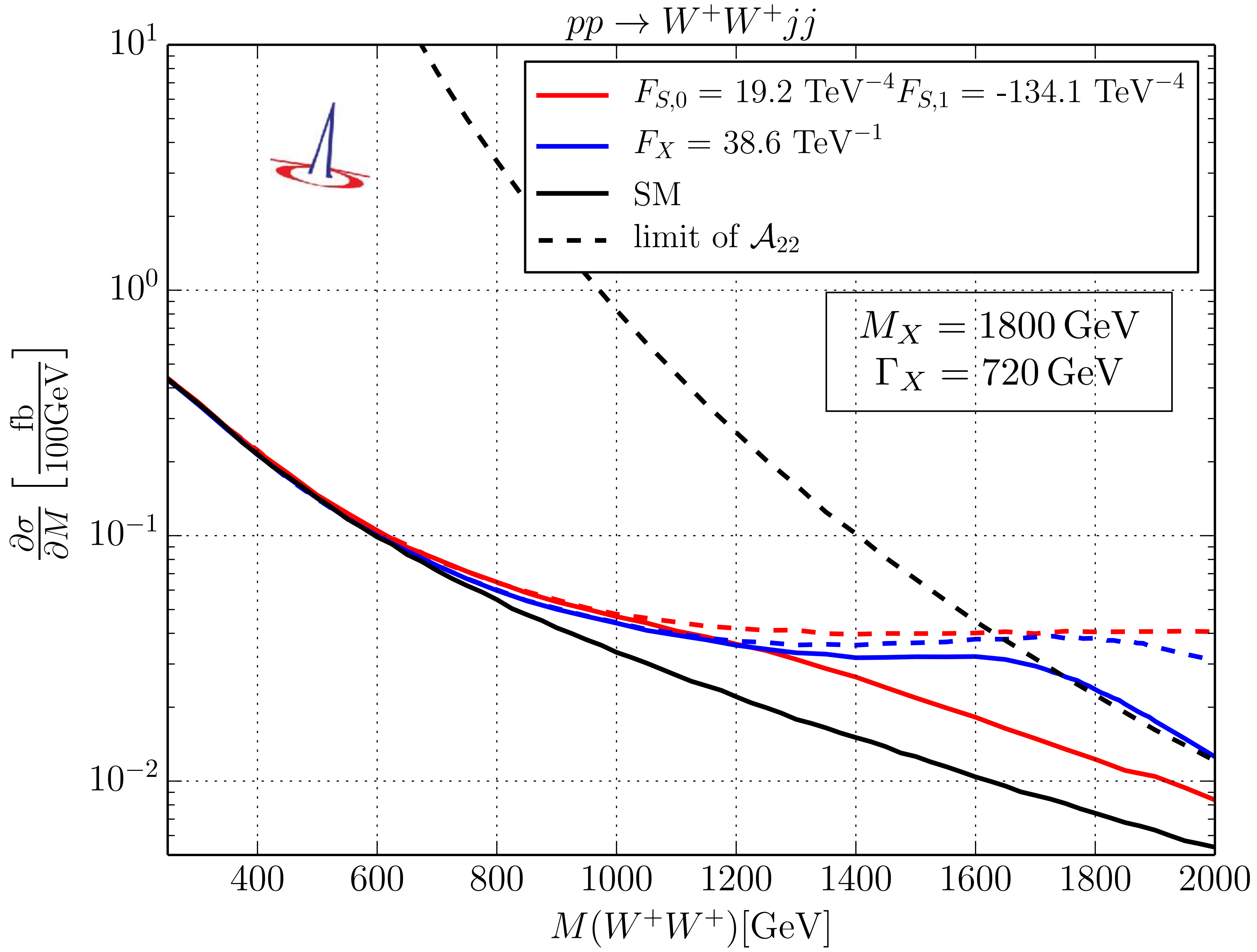

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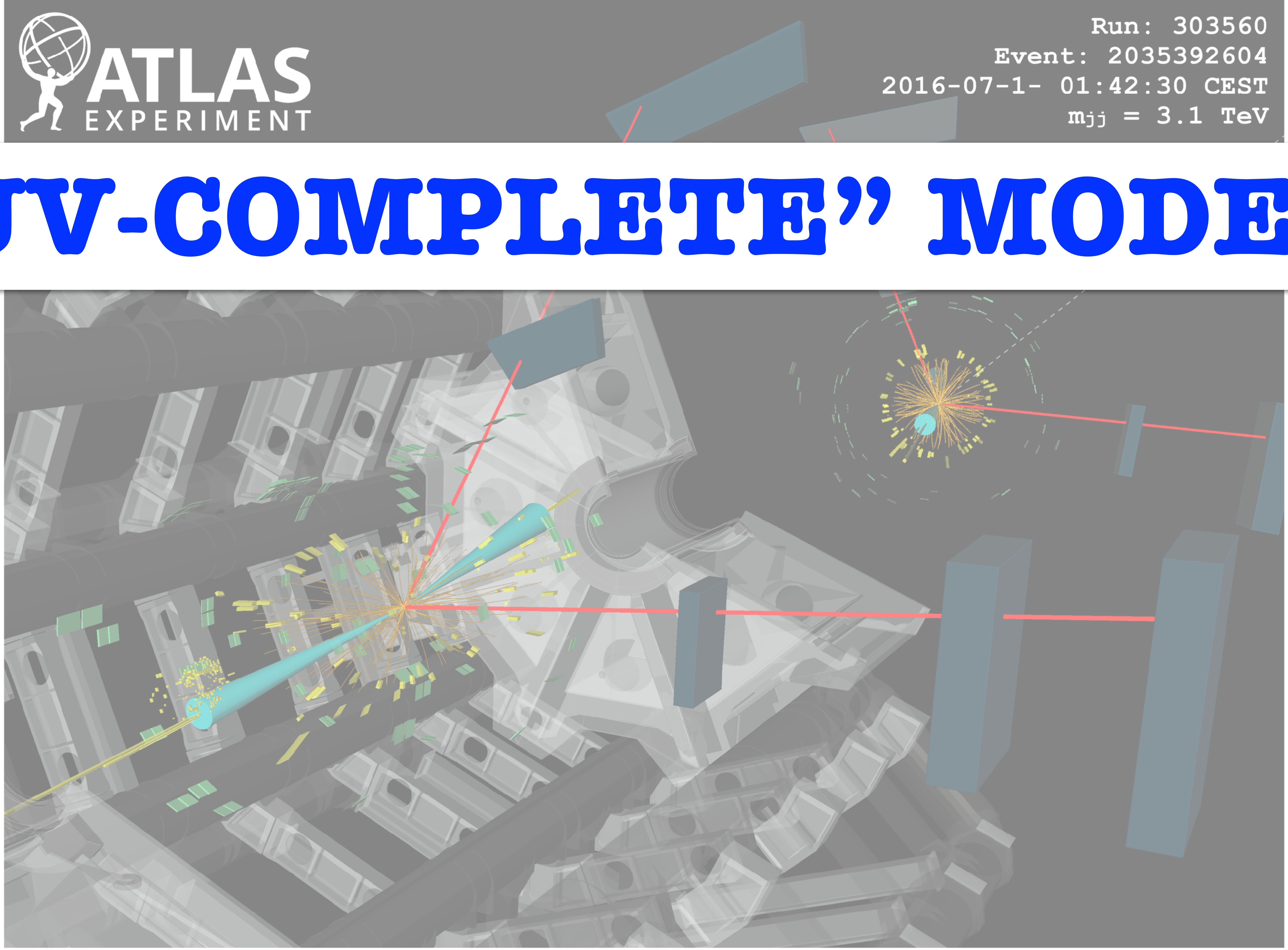


“UV-COMPLETE” MODELS

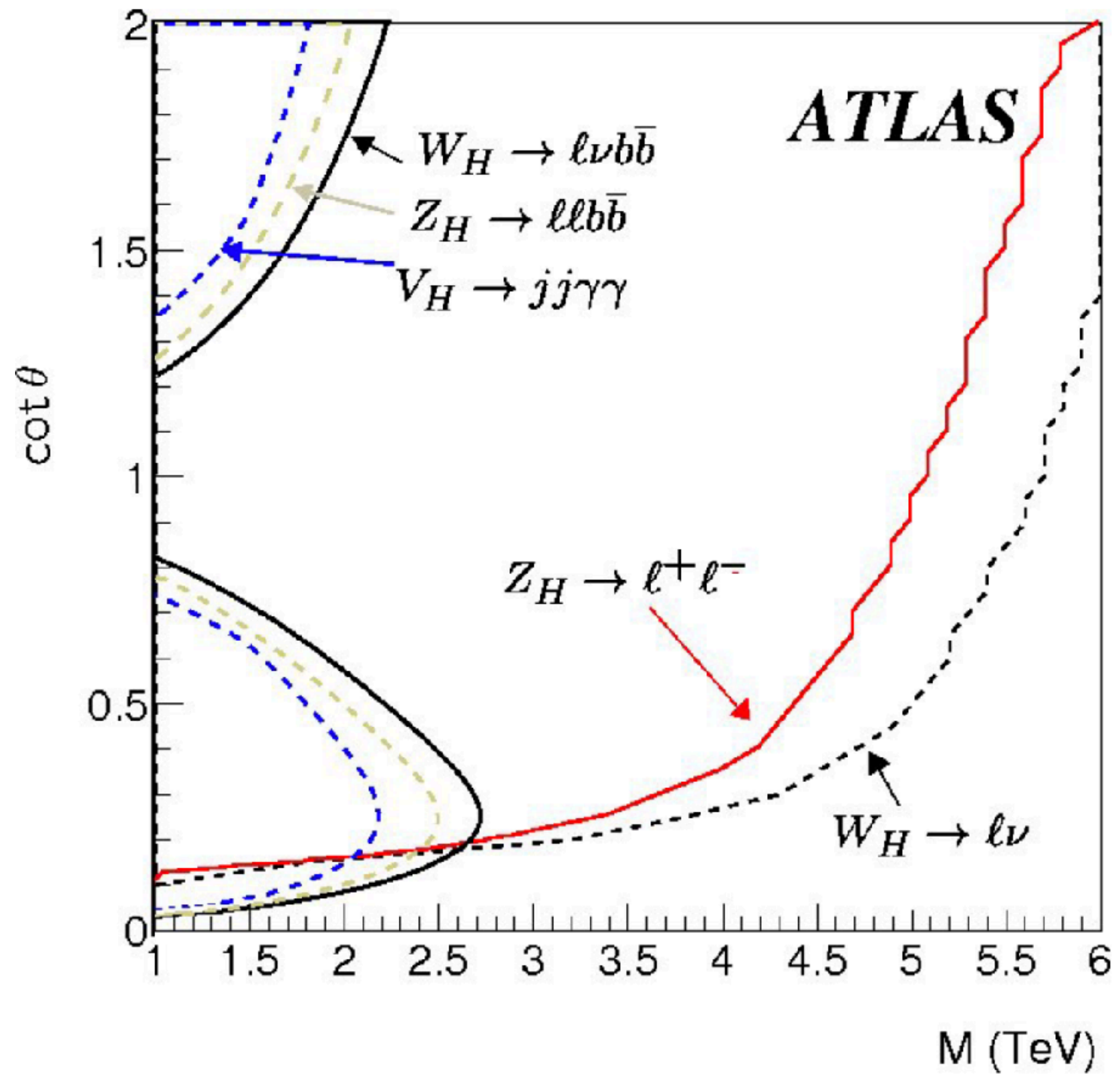
New Physics: Drell-Yan vs. Dibosons vs. VBF/VBS

- New physics in multi bosons: "fermiophobic" resonances, visible in DB/MB, but not in Drell-Yan
- Old example: Littlest Higgs model SN-ATLAS-2004-038
- Small fermion couplings ⟺ small DY xsec (or even forbidden by symmetry)
- I. New scalars (mostly alignment): 2HDM, IDM, N2HDM, Georgi-Machacek, (N)MSSM, etc.

  best signatures in direct or pair production, sometimes in VBF/VBS
- II. New fermions: heavy neutral leptons (HNL), excited fermions, technifermions, SUSY, etc.

  single production = mixing with SM, otherwise pair production
- III. New vectors: composite Higgs, LRSM, U(1), GUT-inspired models, Little Higgs etc.

  mixing with SM = single production/DY , compositeness mostly in multibosons
- IV. light/invisible sectors: ALPs, WISPs, Higgs portals, Neutral naturalness, etc.
- Polarization measurements will be important for determination of quantum numbers and CP



Reconstruction of models from SMEFT

- Assumption: Discovery at LHC at 5σ ⇨ measurement of SMEFT Wilson coefficients
- How well could a specific model be reconstructed from such a measurement
- Important: dedicated comparison of UV-(quasi-)complete model with EFT descriptions
- Example: HVT Bruggisser/Geoffrey/Kilian/Krämer/Luchmann/Plehn/Summ, 2108.01094; Summ, 2103.02487

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$$\begin{aligned}\mathcal{L}_{HVT} &= \mathcal{L}_{SM} - \frac{1}{4}\widetilde{V}^{\mu\nu A}\widetilde{V}^{A}_{\mu\nu} + \frac{\widetilde{m}_V^2}{2}\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu} - \frac{\widetilde{g}_M}{2}\widetilde{V}^{\mu\nu A}\widetilde{W}^{A}_{\mu\nu} \\ &+ \widetilde{g}_H\widetilde{V}^{\mu A}J^{A}_{H\mu} + \widetilde{g}_l\widetilde{V}^{\mu A}J^{A}_{l\mu} + \widetilde{g}_q\widetilde{V}^{\mu A}J^{A}_{q\mu} + \frac{\widetilde{g}_{VH}}{2}|H|^2\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu}\end{aligned}$$

- 5 UV parameters, 1 matching scale Q
- 1-loop matching to 17 dim-6 operators: $\frac{c_i}{\Lambda^2}(\widetilde{g}_M, \widetilde{g}_H, \widetilde{g}_l, \widetilde{g}_q, \widetilde{g}_{VH}, \widetilde{m}_V, Q)$
- Heavy resonance-SMEFT searches poorly constrain such a model
- Large uncertainties from variations of the matching scale:

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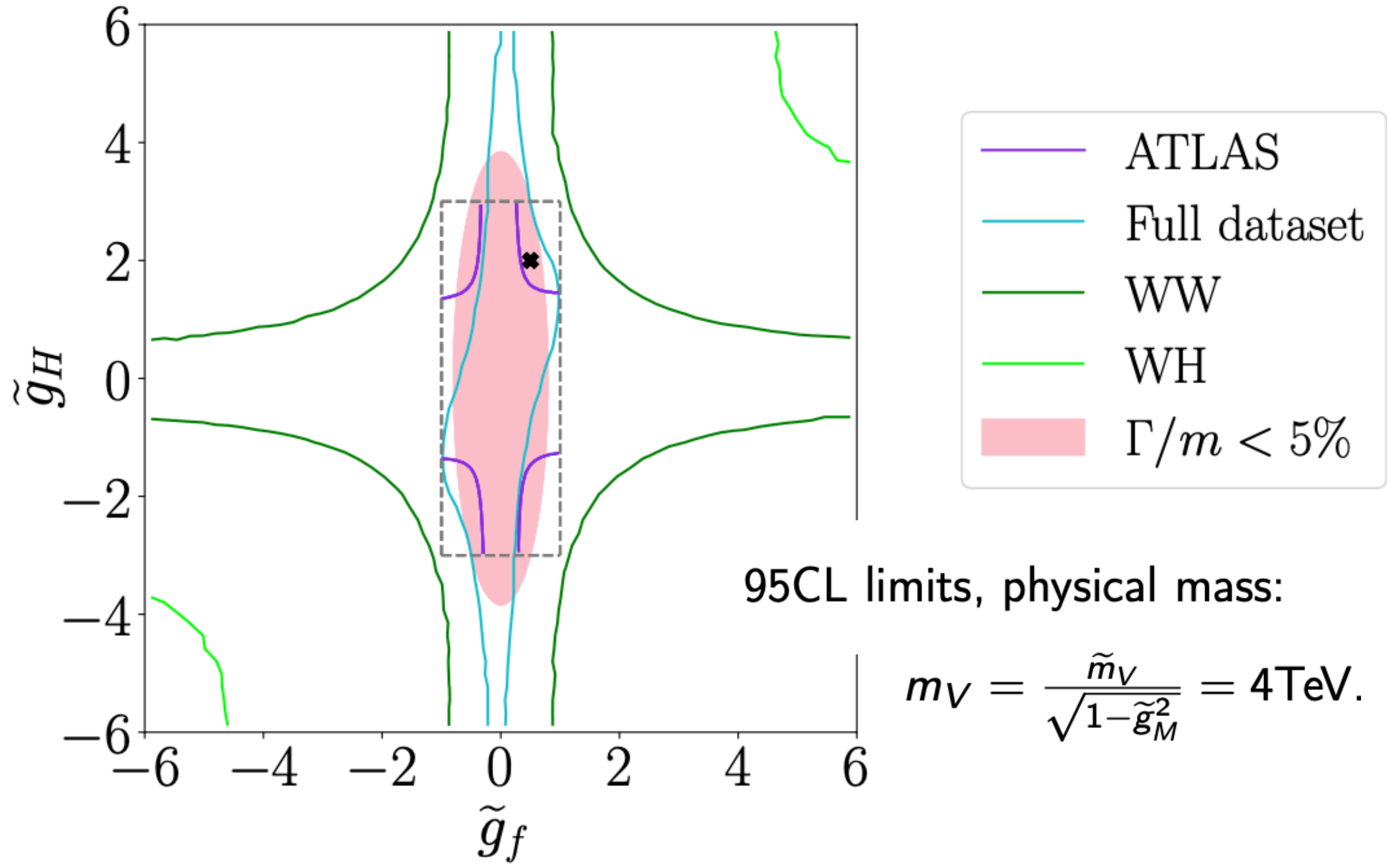

95CL limits, physical mass:

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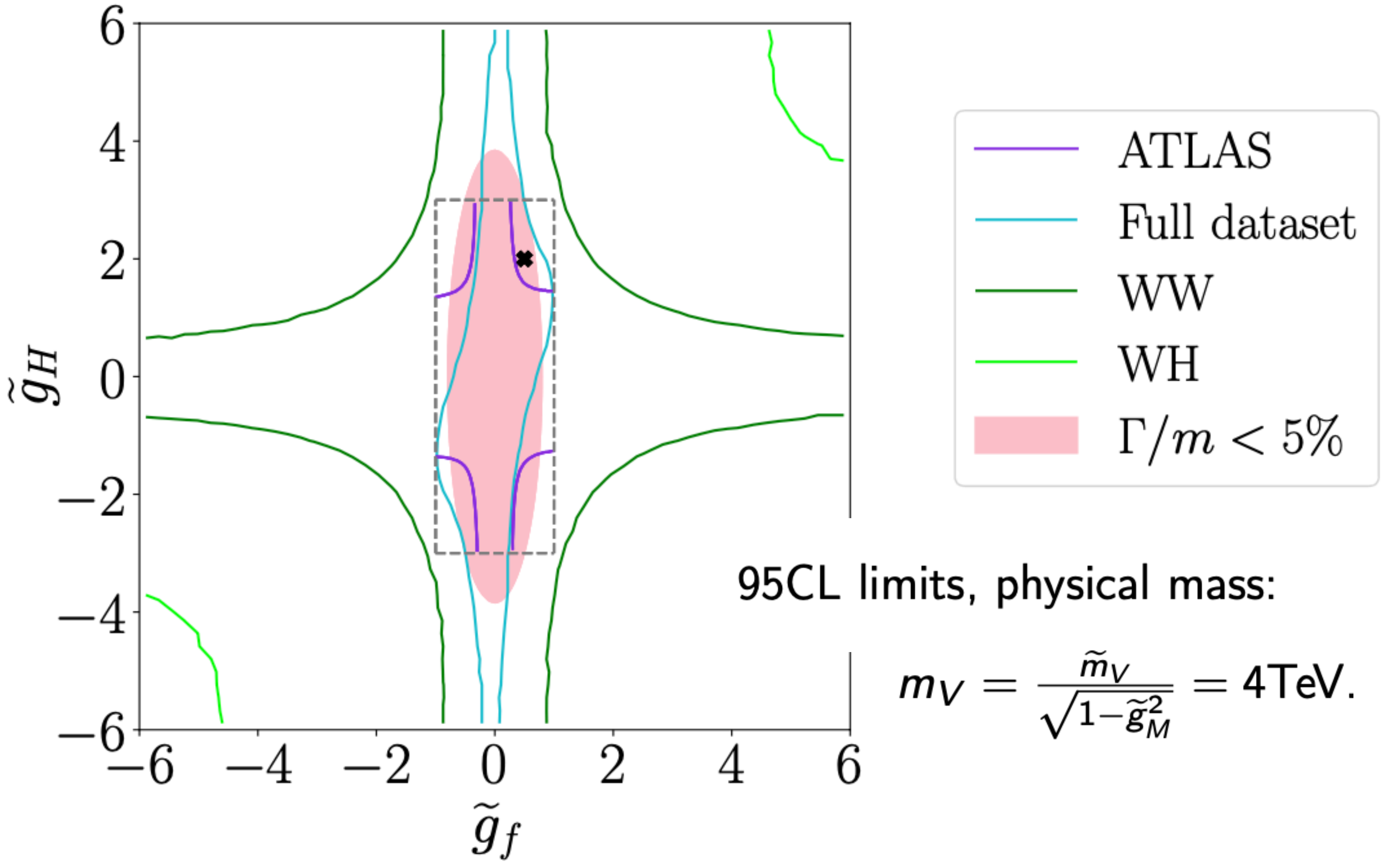
Reconstruction of models from SMEFT

- Assumption: Discovery at LHC at 5σ ⇨ measurement of SMEFT Wilson coefficients
- How well could a specific model be reconstructed from such a measurement
- Important: dedicated comparison of UV-(quasi-)complete model with EFT descriptions
- Example: HVT Bruggisser/Geoffrey/Kilian/Krämer/Luchmann/Plehn/Summ, 2108.01094; Summ, 2103.02487

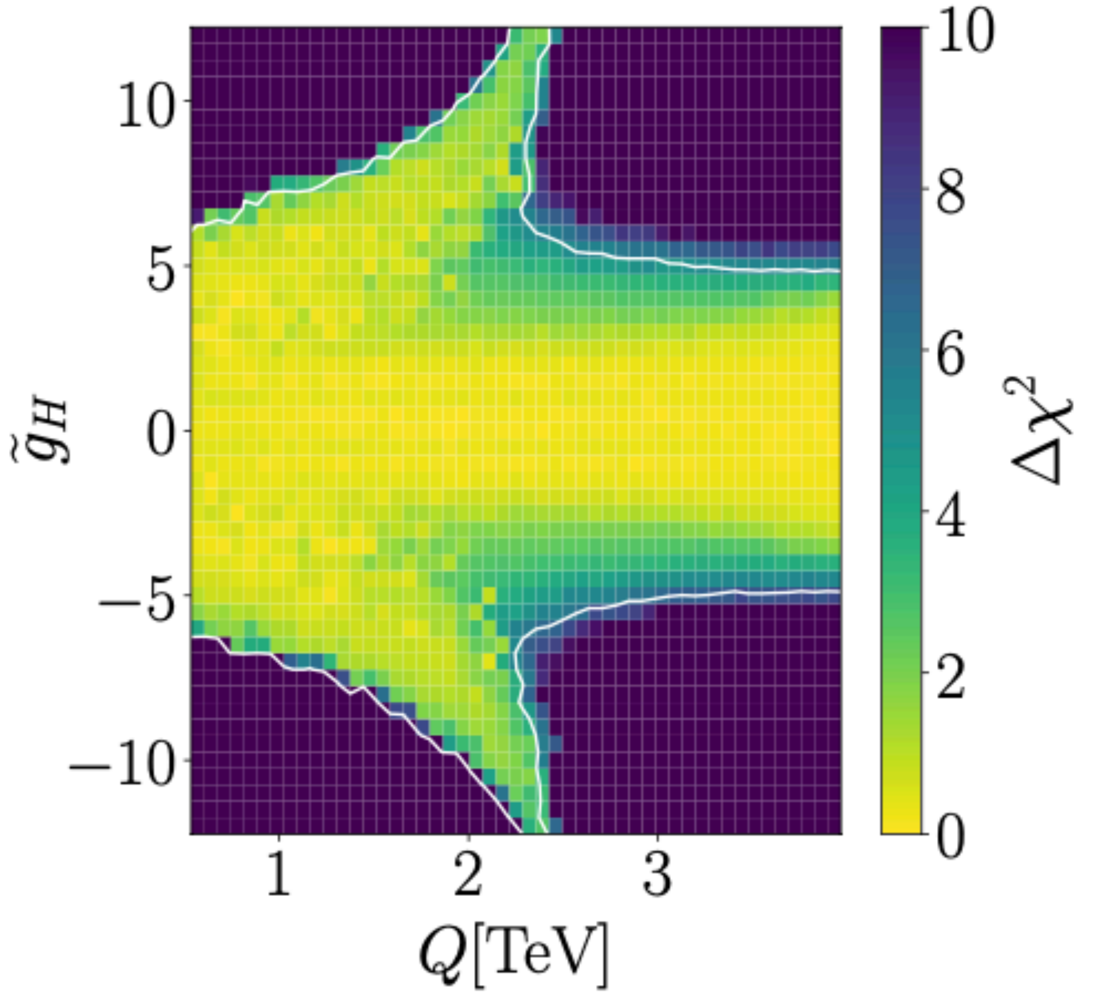
$$\mathcal{L}_{HVT} = \mathcal{L}_{SM} - \frac{1}{4}\widetilde{V}^{\mu\nu A}\widetilde{V}^{A}_{\mu\nu} + \frac{\widetilde{m}_V^2}{2}\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu} - \frac{\widetilde{g}_M}{2}\widetilde{V}^{\mu\nu A}\widetilde{W}^{A}_{\mu\nu} + \widetilde{g}_H\widetilde{V}^{\mu A}J^A_{H\mu} + \widetilde{g}_l\widetilde{V}^{\mu A}J^A_{l\mu} + \widetilde{g}_q\widetilde{V}^{\mu A}J^A_{q\mu} + \frac{\widetilde{g}_{VH}}{2}|H|^2\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu}$$

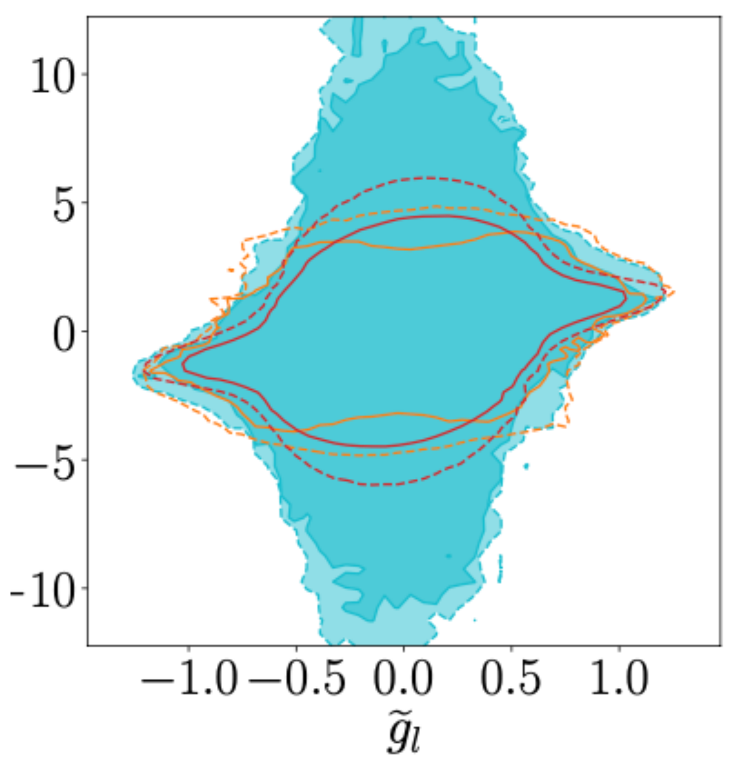
- 5 UV parameters, 1 matching scale Q
- 1-loop matching to 17 dim-6 operators: $\frac{c_i}{\Lambda^2}(\widetilde{g}_M, \widetilde{g}_H, \widetilde{g}_l, \widetilde{g}_q, \widetilde{g}_{VH}, \widetilde{m}_V, Q)$
- Heavy resonance-SMEFT searches poorly constrain such a model
- Large uncertainties from variations of the matching scale: nuisance parameter / theory uncertainty



95CL limits, physical mass:

$$m_V = \frac{\widetilde{m}_V}{\sqrt{1-\widetilde{g}_M^2}} = 4\text{TeV}.$$





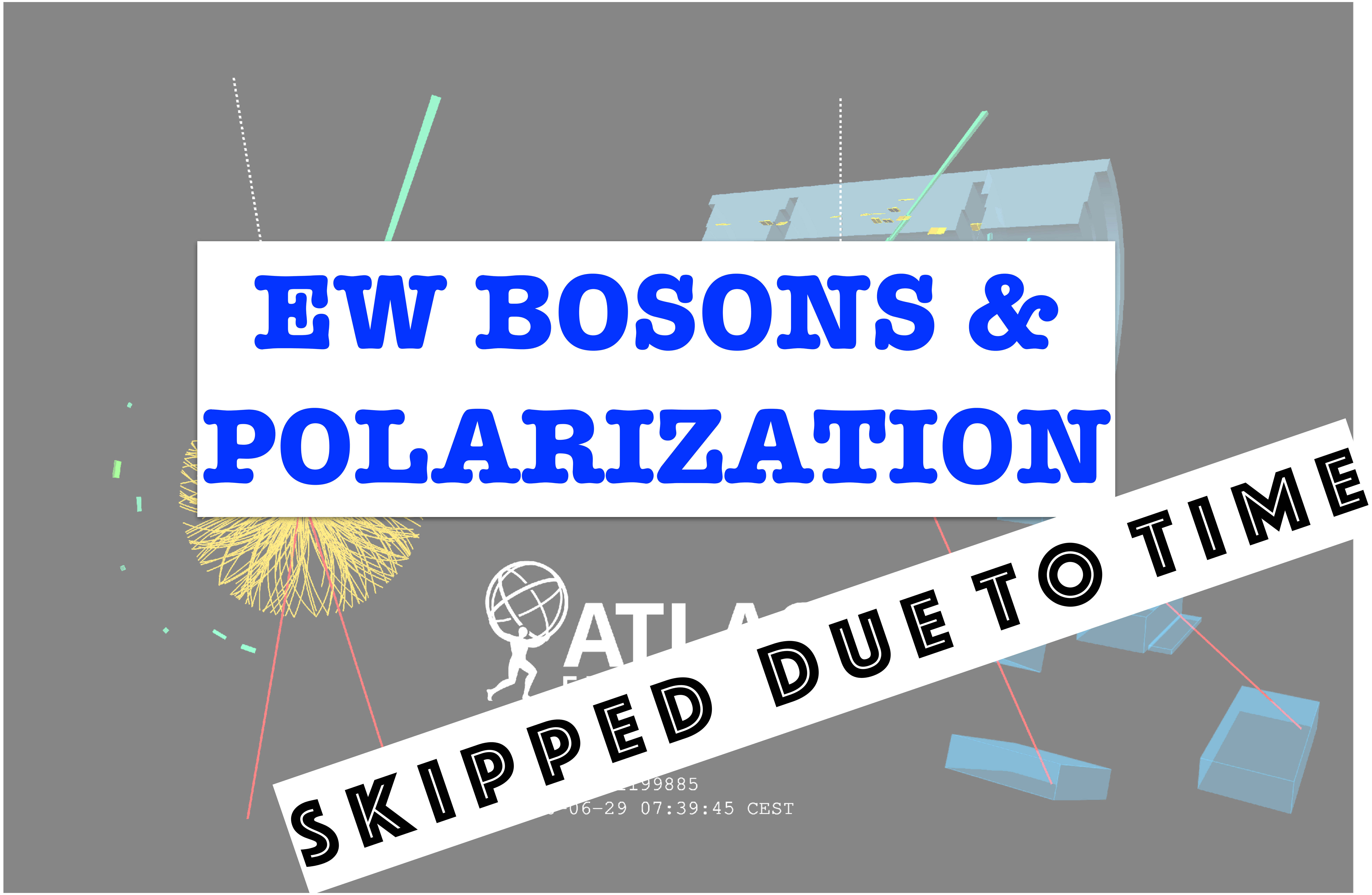
cf. also Dawson, Giardino, Homiller, 2102.02823

Tree level matching

1-loop level matching for $Q = 4$ TeV

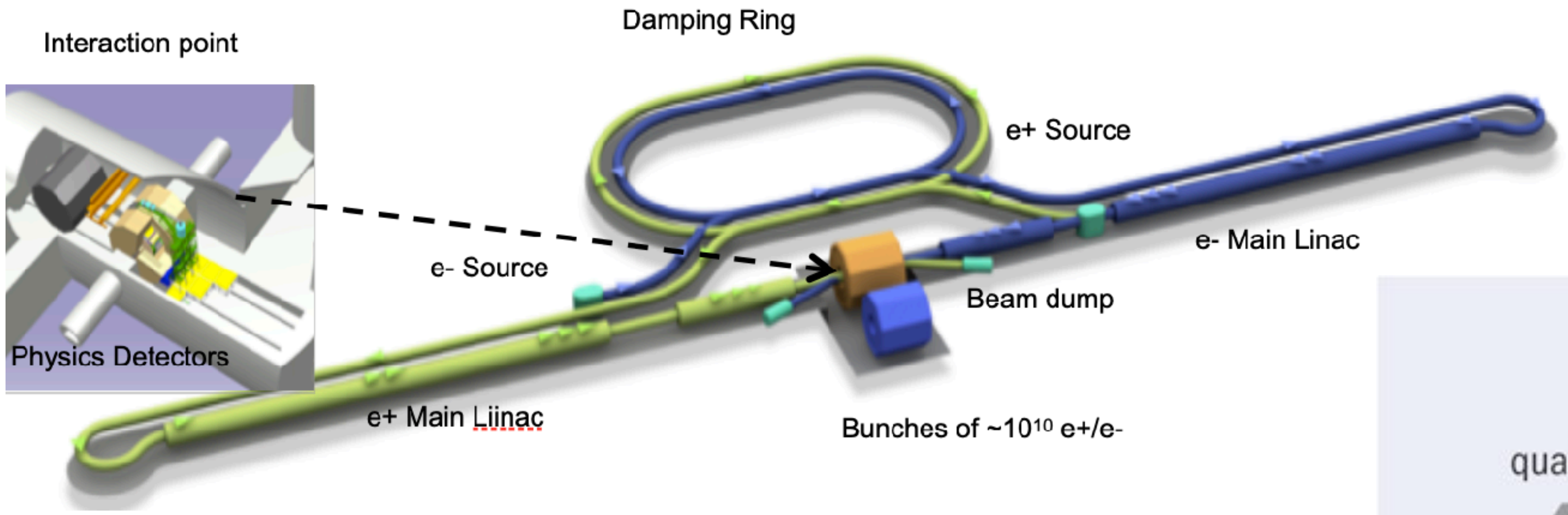
1-loop level matching for $Q \in [0.5, 4]$ TeV

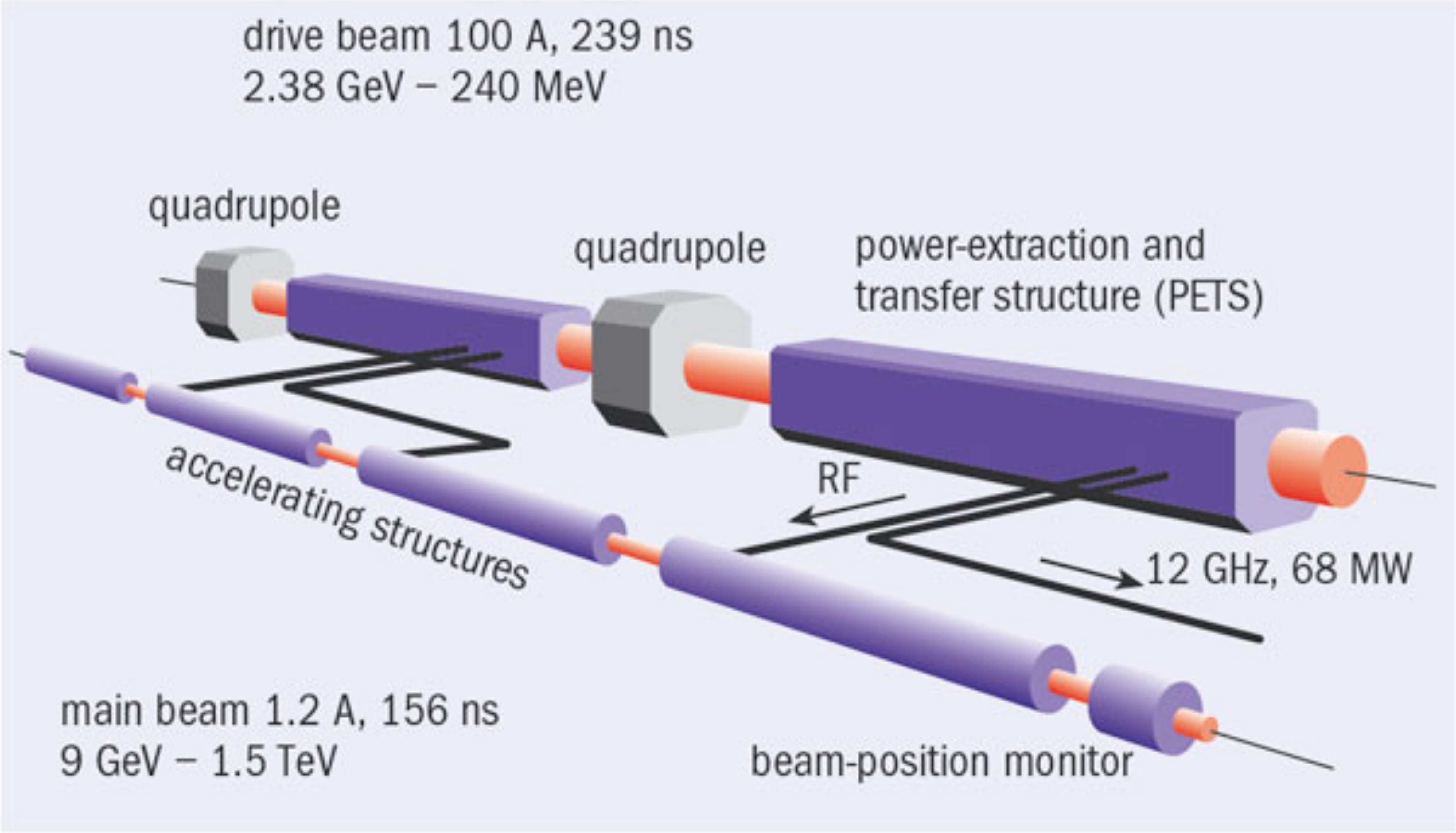
EW BOSONS & POLARIZATION



SKIPPED DUE TO TIME

VBS AT E+E- COLLIDERS

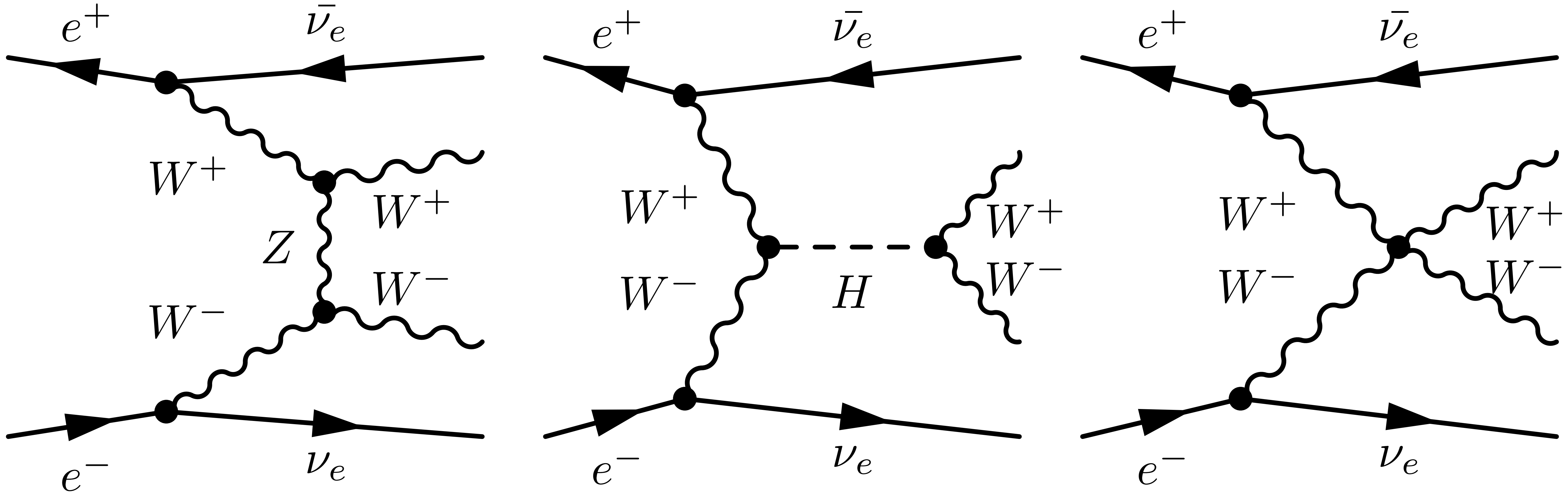




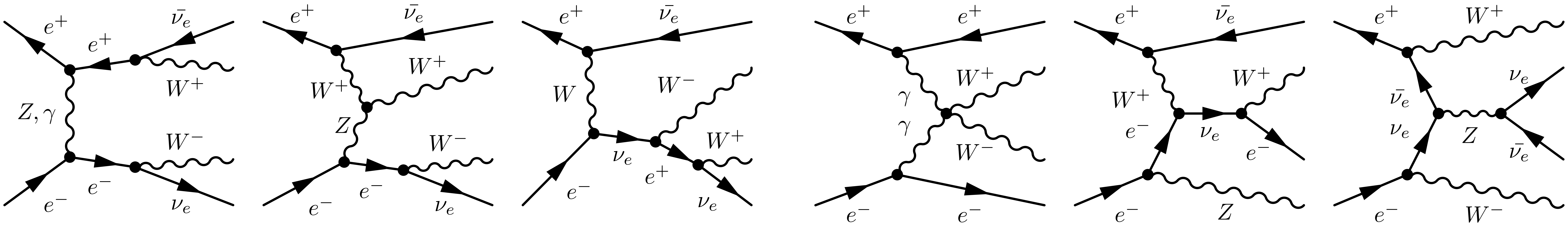
New Physics in VBS at e^+e^- colliders

Fleper/Kilian/JRR/Sekulla: Eur.Phys.J. C77 (2017) no.2, 120

Signal process: triple gauge couplings, Higgs-*V*-*V* couplings, quartic gauge



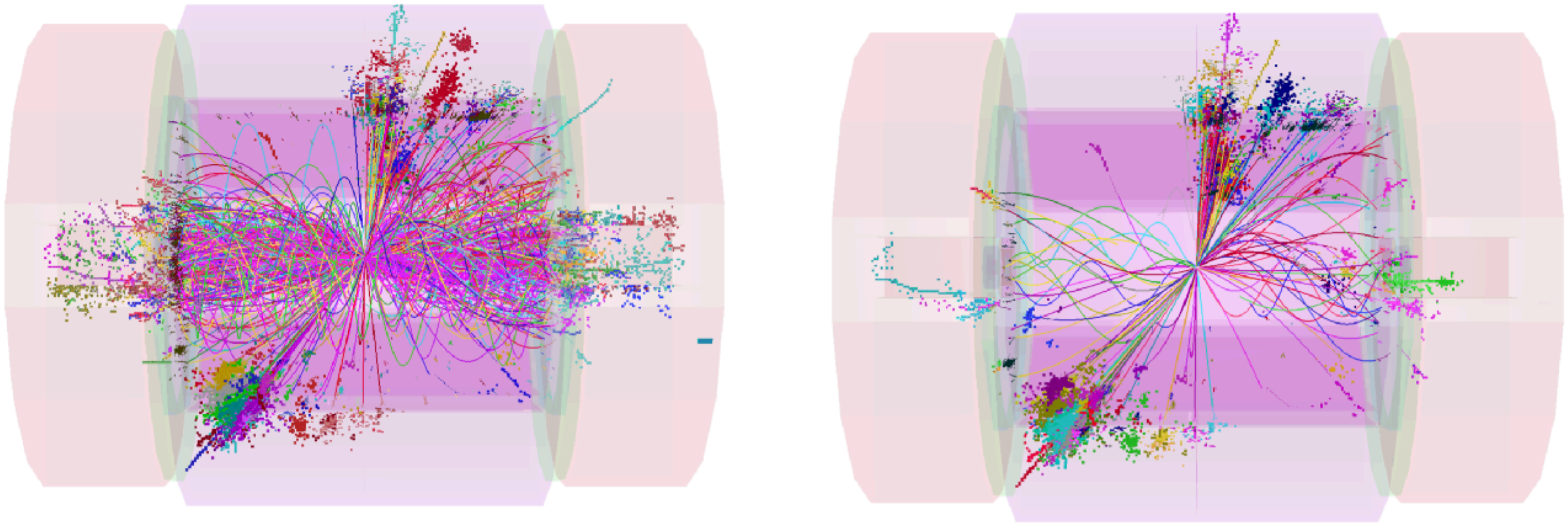
Background: difermions with EW radiation, single *W*, tribosons, radiative



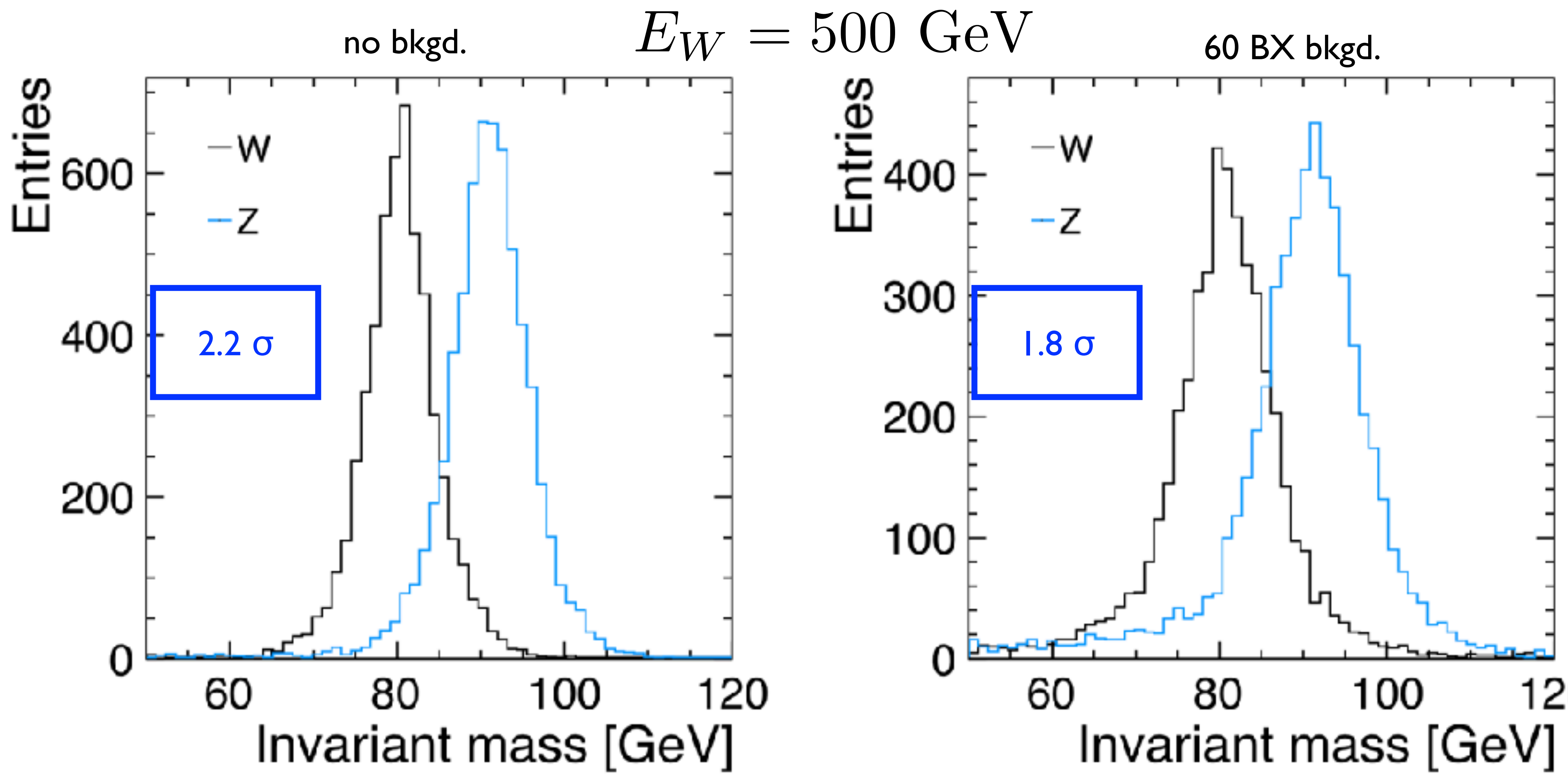
Identification of hadronic *W* / *Z*

J. S. Marshall / A. Münnich / M. A. Thomson , arXiv: 1209.4039

Particle Flow Algorithm (PFA) allows very good particle ID for ILD detector



`Tight PFO` removes
photon-induced
background from
1.2 TeV to 100 GeV



$E_W = 500$ GeV

no bkgd.

60 BX bkgd.

- *W*/*Z* discrimination: 88% efficiency
- With γ-induced bkgd: 71 — 79 %

VBS in e^+e^-: SM rates & backgrounds (I)

Experimentally: study all processes that lead to VBS–like signatures [1 TeV]:

[80% e^-, 40% e^+ polarization]

Vector-Boson Scattering

Triboson Production

Vector-Boson Scattering / Radiative Bhabha

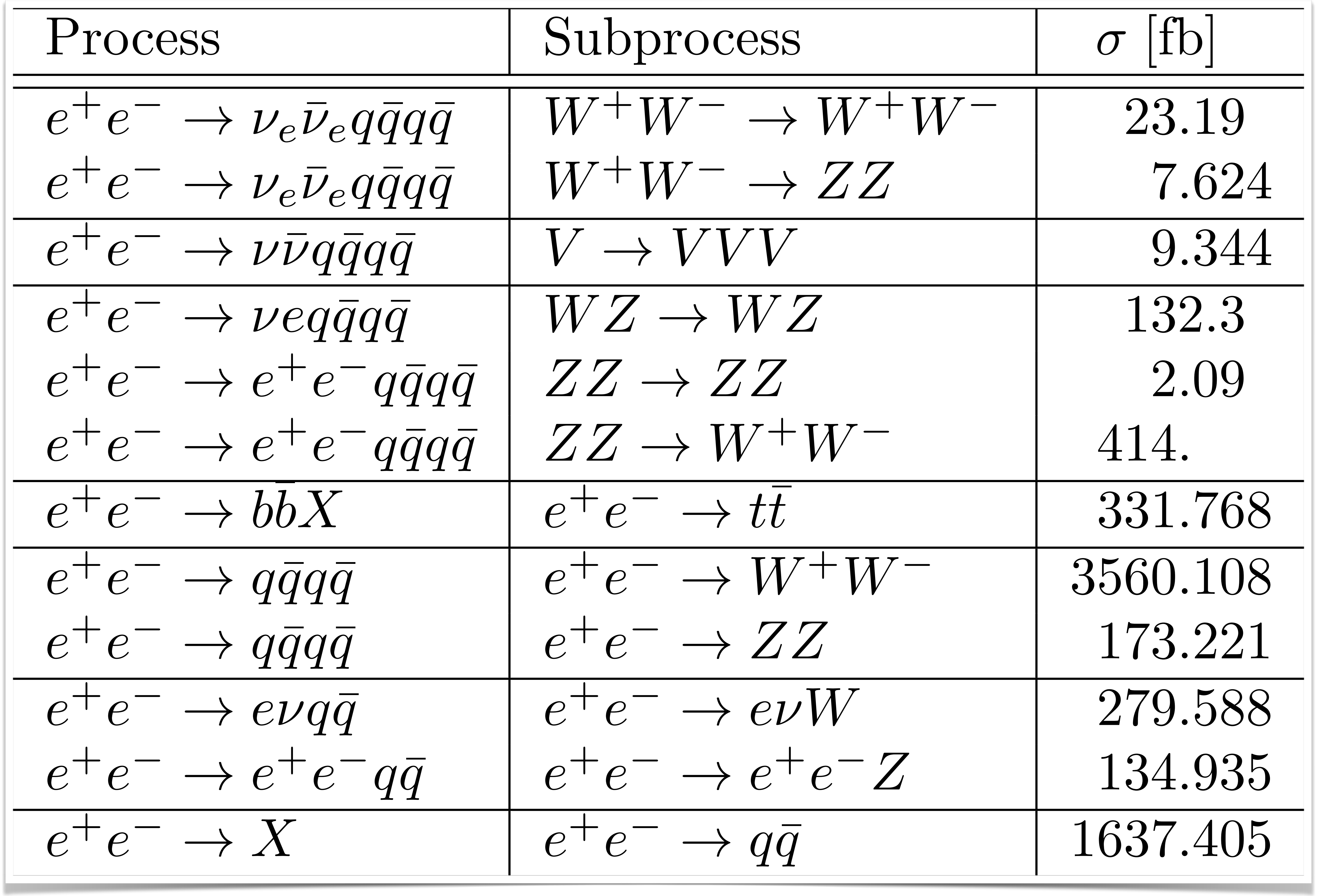
Top pair production

Diboson Production

Single *W* Production

Radiative *Z* Production

QCD Di-/Multijets



Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$W^+W^- \to W^+W^-$	23.19
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$W^+W^- \to ZZ$	7.624
$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to ZZ$	2.09
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to W^+W^-$	414.
$e^+e^- \to b\bar{b}X$	$e^+e^- \to t\bar{t}$	331.768
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to W^+W^-$	3560.108
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to ZZ$	173.221
$e^+e^- \to e\nu q\bar{q}$	$e^+e^- \to e\nu W$	279.588
$e^+e^- \to e^+e^- q\bar{q}$	$e^+e^- \to e^+e^- Z$	134.935
$e^+e^- \to X$	$e^+e^- \to q\bar{q}$	1637.405

[Beyer/Kilian/Krstonošić/Mönig/JRR/Schmidt/Schröder, EPJC48 (2006) 353]

VBS in e^+e^-: SM rates & backgrounds (II)

Process	1400 GeV	3000 GeV	Factor
$W^+W^-\nu\bar\nu$	47.1	132	1
$W^+W^-e^+e^-$	1570	3820	1
$W^\pm Z e^\mp \nu$	138	408	0.136
ZZe^+e^-	3.78	4.70	0.019
$W^+W^-(Z \to \nu\bar\nu)$	11.7	9.35	1
$ZZ\nu\bar\nu$	15.7	57.5	1
ZZe^+e^-	3.78	4.70	1
$W^\pm Z e^\mp \nu$	138	408	0.136
$W^+W^-e^+e^-$	1570	3820	0.019
$ZZ(Z \to \nu\bar\nu)$	0.484	0.237	1

Total cross sections [fb], no cuts

Mismatched hadronic vector bosons

Triboson background

[80% e^-, 0% e^+ polarization]

Fleper/Kilian/JRR/Sekulla: 1607.03030

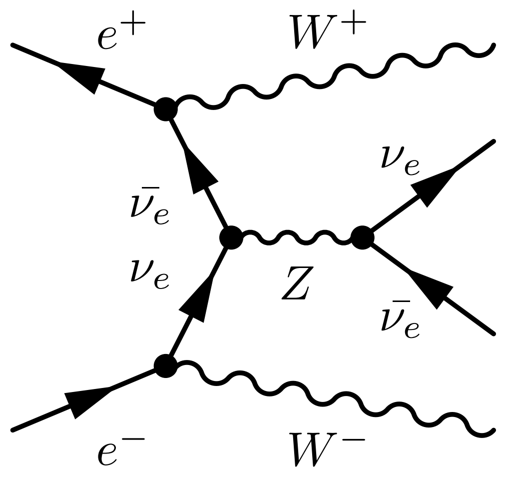
- ☑ Signal cross sections rise factor 3–4 from 1.4 to 3 TeV
- ☑ Mistagging from *W/Z* conversions in hadronic bosons: severe for *WZ* scattering
- ☑ Irreducible backgrounds from tribosons (Gauge invariance connects full processes)

VBS in e^+e^-: selection / isolation cuts

Color coding: **Cuts for** 1 TeV ILC — 1.4 TeV CLIC — 3 TeV CLIC

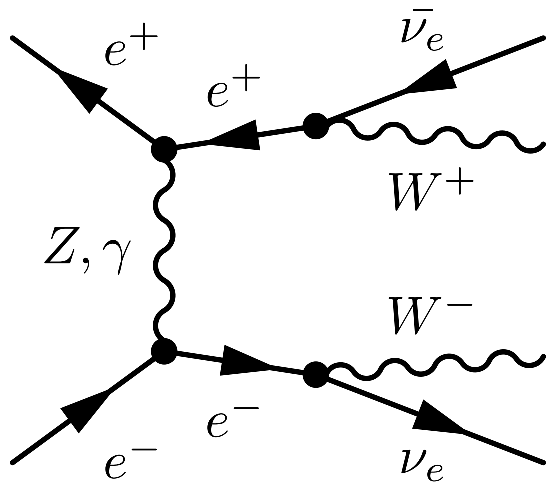
- **Suppression of background from Z → $\nu\nu$, W⁺W⁻, and QCD 4-jet production**

$M_{inv}(\bar{\nu}\nu) > 150\,\text{GeV}$	$M_{inv}(\bar{\nu}\nu) > 175\,\text{GeV}$	$M_{inv}(\bar{\nu}\nu) > 230\,\text{GeV}$



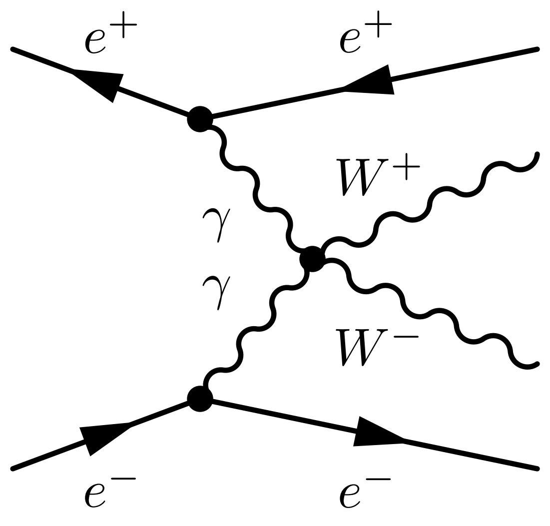
- **Suppression of background from t–channel exchange in subprocess**

$p_{\perp,W/Z} > 150\,\text{GeV}$	$p_{\perp,W/Z} > 180\,\text{GeV}$	$p_{\perp,W/Z} > 300\,\text{GeV}$
$\lvert\cos\theta(W/Z)\rvert < 0.8$	$\lvert\cos\theta(W/Z)\rvert < 0.8$	$\lvert\cos\theta(W/Z)\rvert < 0.8$



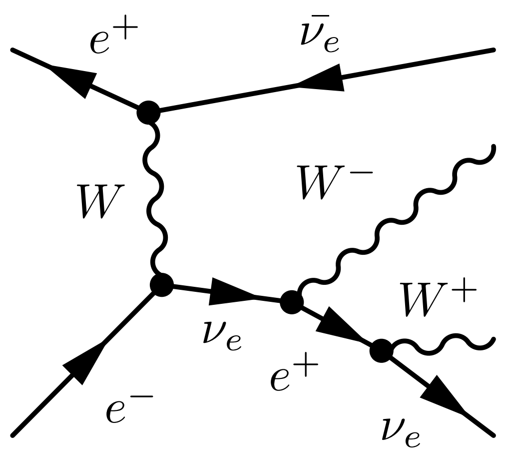
- **Suppression of $\gamma\gamma$–fusion induced backgrounds**

$p_\perp(WW) > 45\,\text{GeV}$	$p_\perp(WW) > 50\,\text{GeV}$	$p_\perp(WW) > 100\,\text{GeV}$
$p_\perp(ZZ) > 40\,\text{GeV}$	$p_\perp(ZZ) > 40\,\text{GeV}$	$p_\perp(ZZ) > 60\,\text{GeV}$
$\theta(e) > 15\,\text{mrad}$	$\theta(e) > 15\,\text{mrad}$	$\theta(e) > 15\,\text{mrad}$



- **Suppression of non-scattering vector boson processes [i.e. massive EW radiation]**

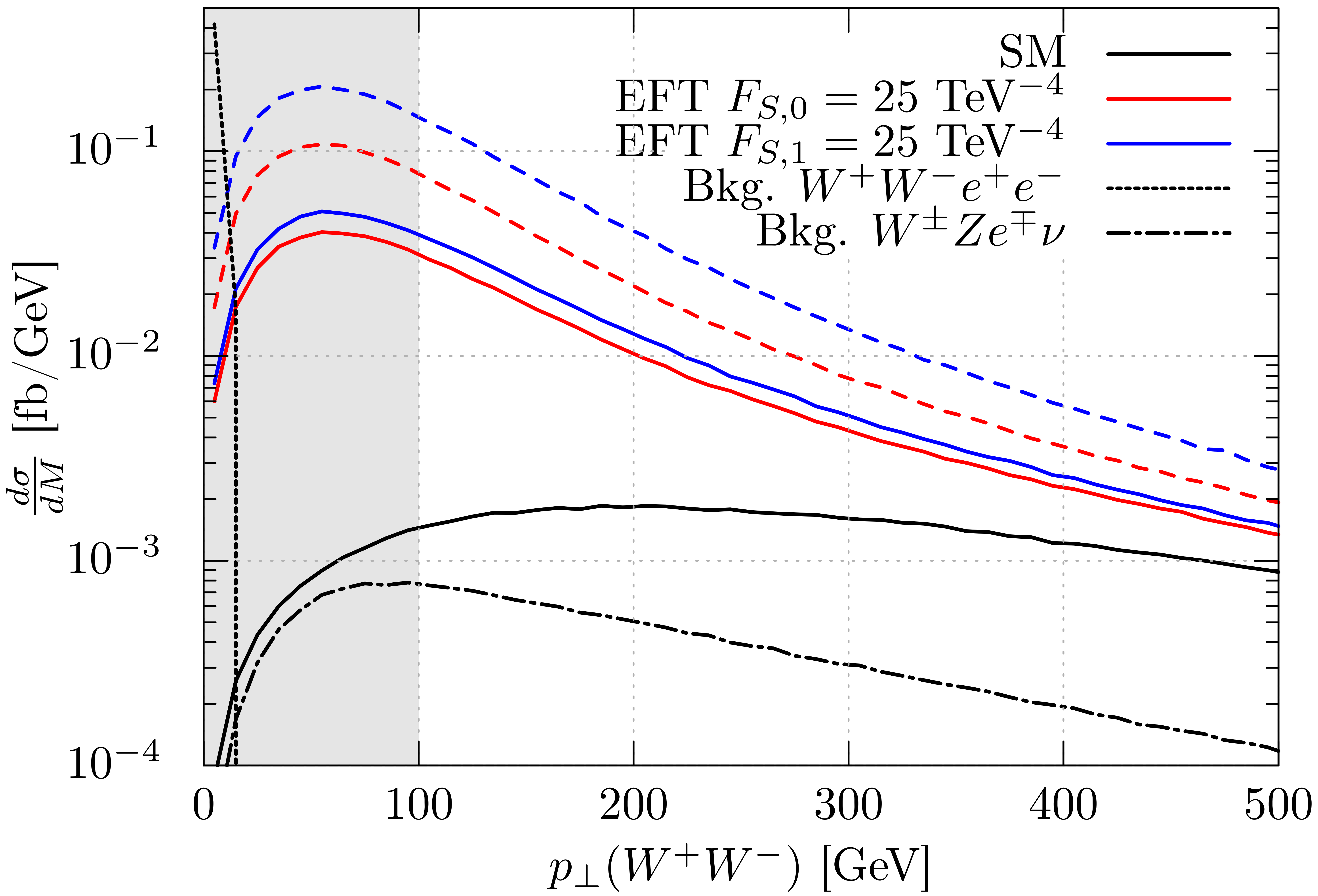
$M_{inv}^{WW} \in [575, 800]\,\text{GeV}$	$M_{inv}^{WW} \in [800, 1175]\,\text{GeV}$	$M_{inv}^{WW} \in [900, 1900]\,\text{GeV}$
$M_{inv}^{ZZ} \in [600, 800]\,\text{GeV}$	$M_{inv}^{ZZ} \in [800, 1175]\,\text{GeV}$	$M_{inv}^{ZZ} \in [850, 1900]\,\text{GeV}$



Longitudinal VBS in e^+e^-

$e^+e^- \to \bar{\nu}\nu W^+W^-$

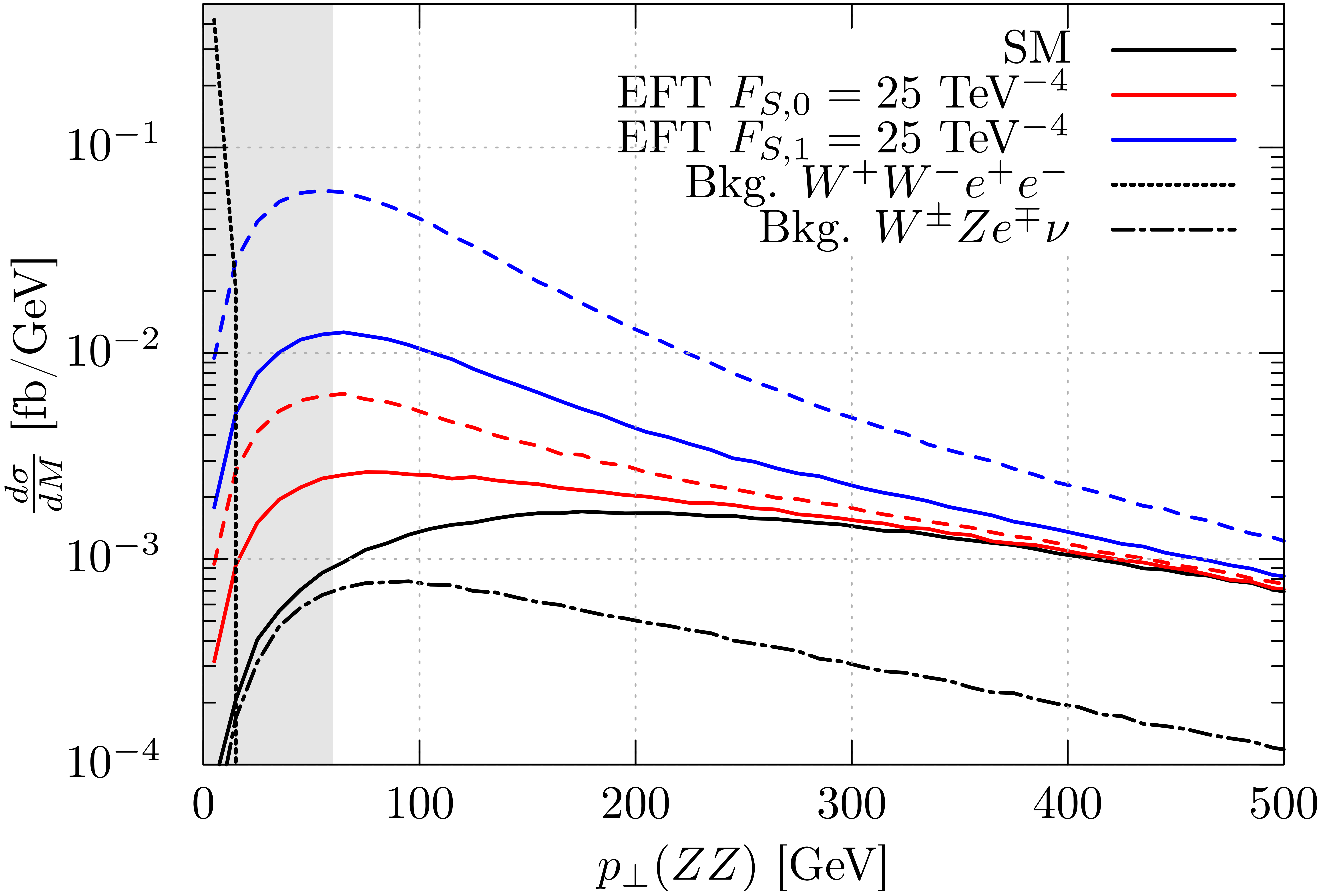
CLIC 3 TeV



Longitudinal VBS in e^+e^-

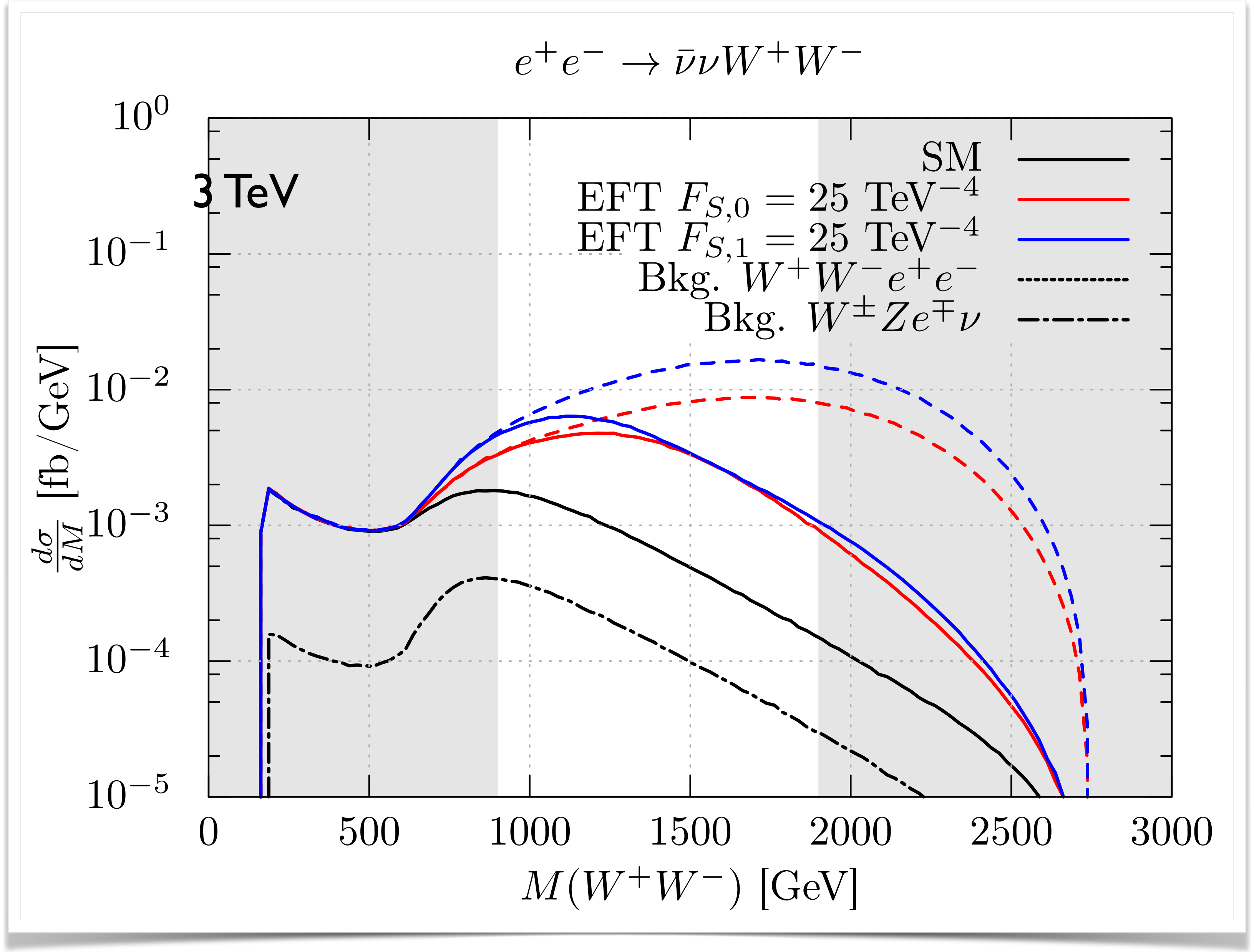
CLIC 3 TeV

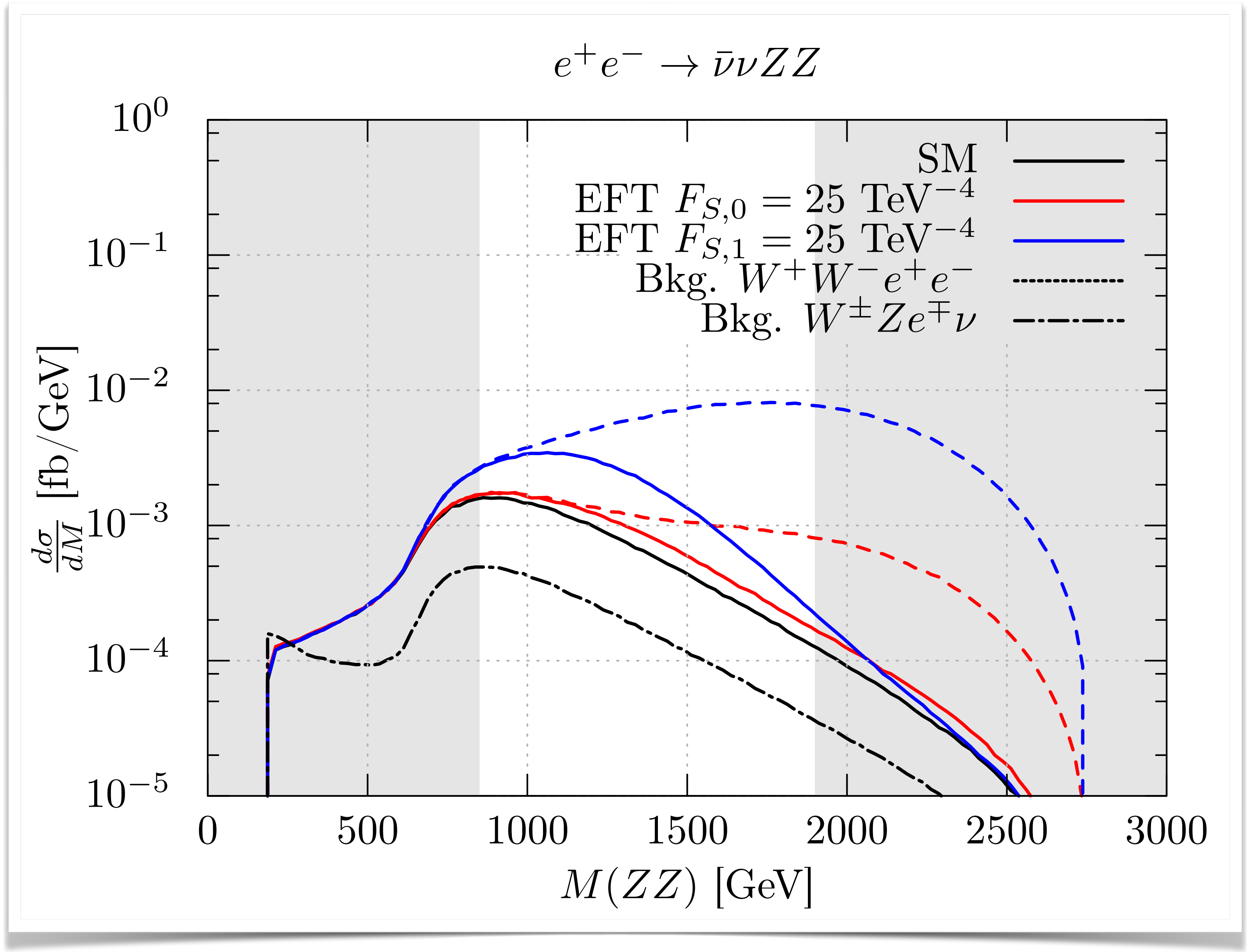
$e^+e^- \to \bar{\nu}\nu ZZ$

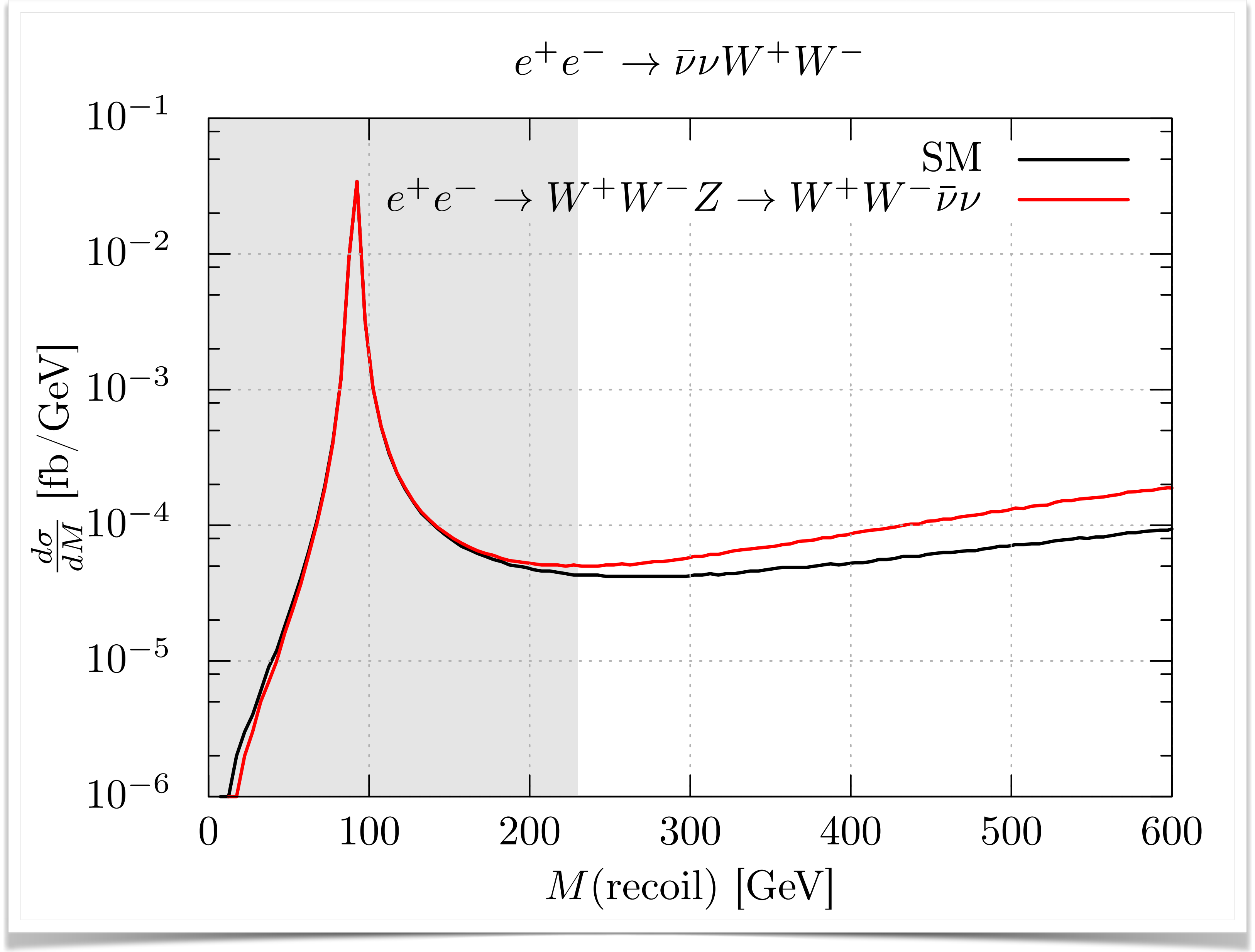


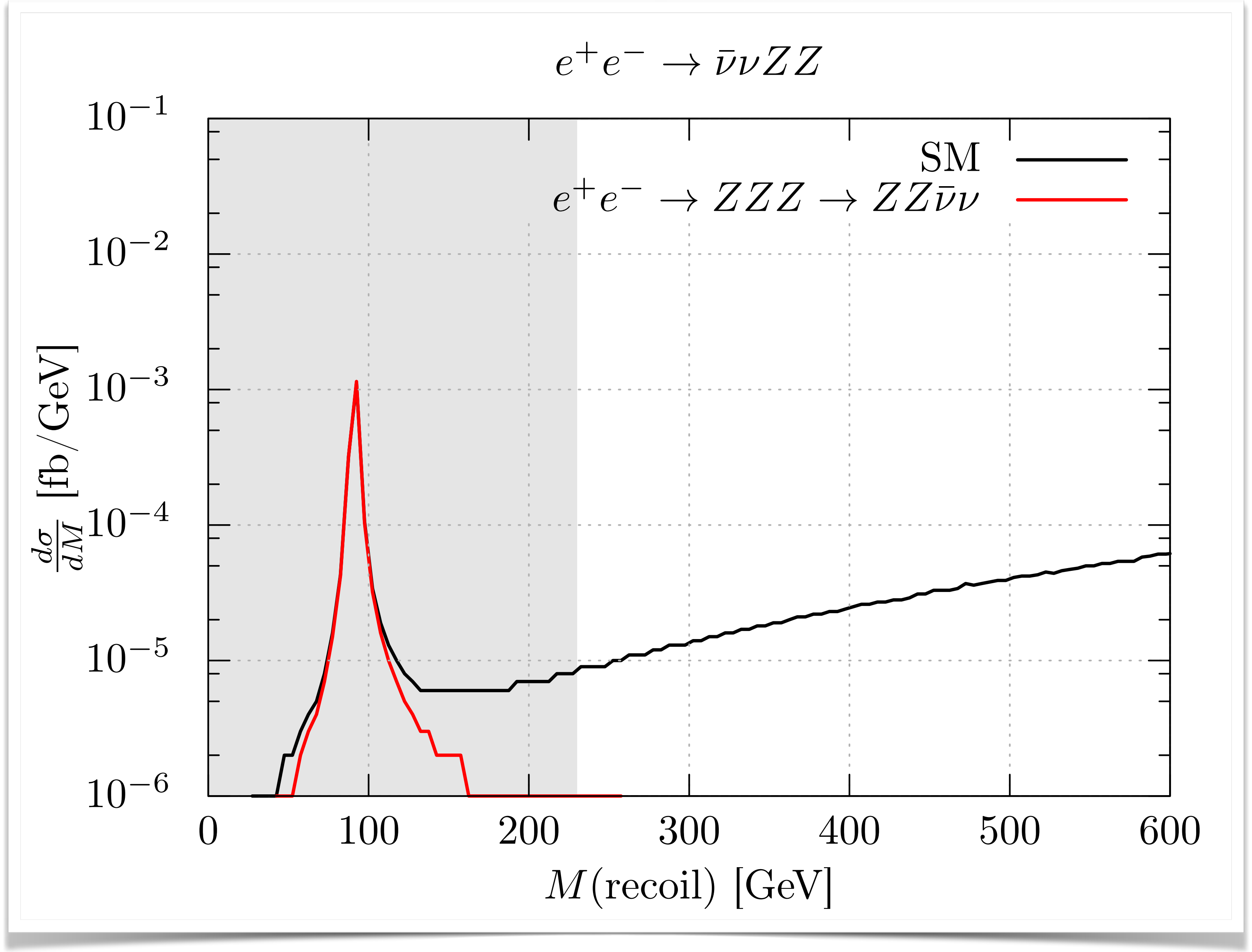
Separability of signal and triboson backgrounds

3 TeV



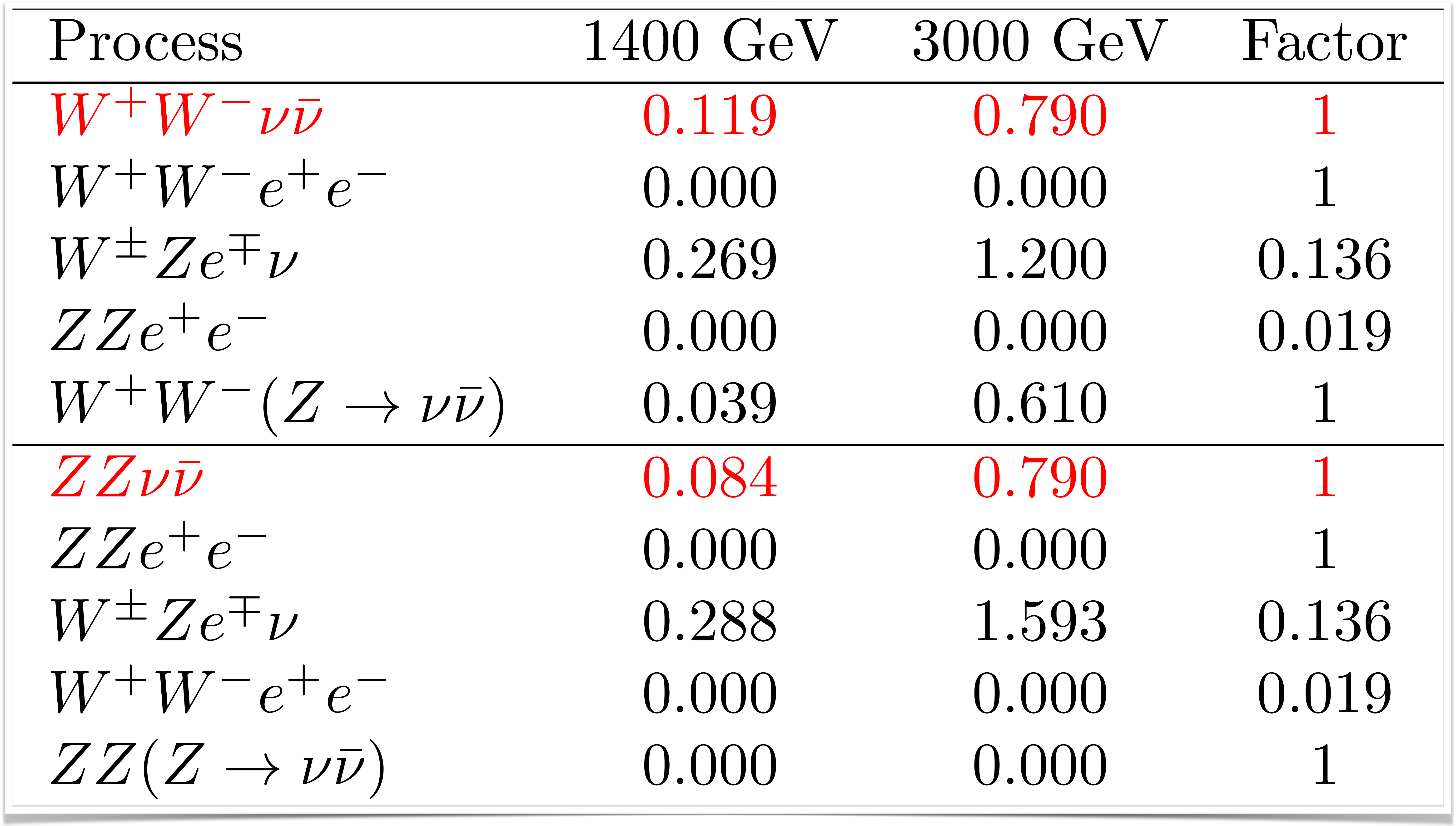






VBS in e^+e^-: SM rates & backgrounds (II)

Fleper/Kilian/JRR/Sekulla: 1607.03030

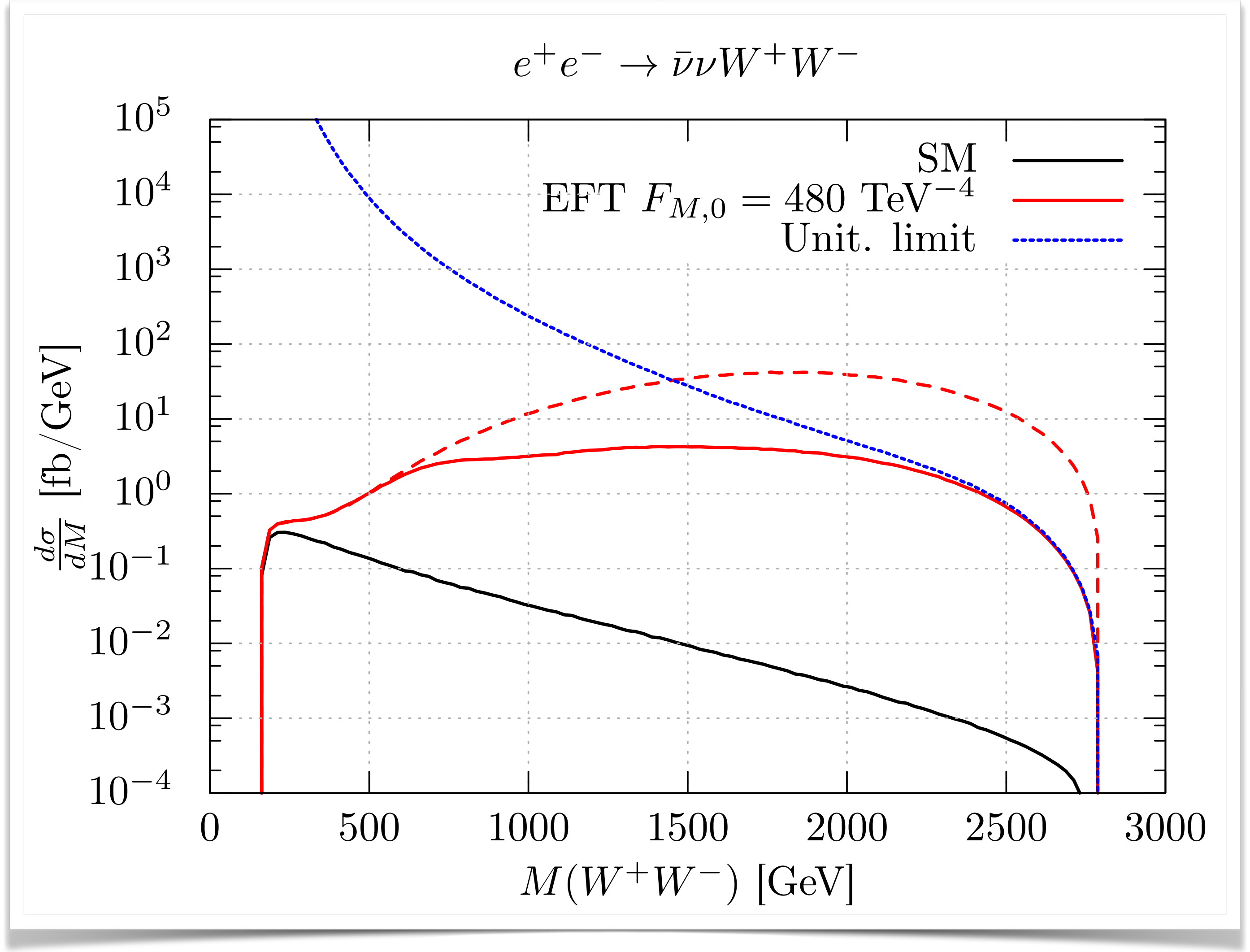


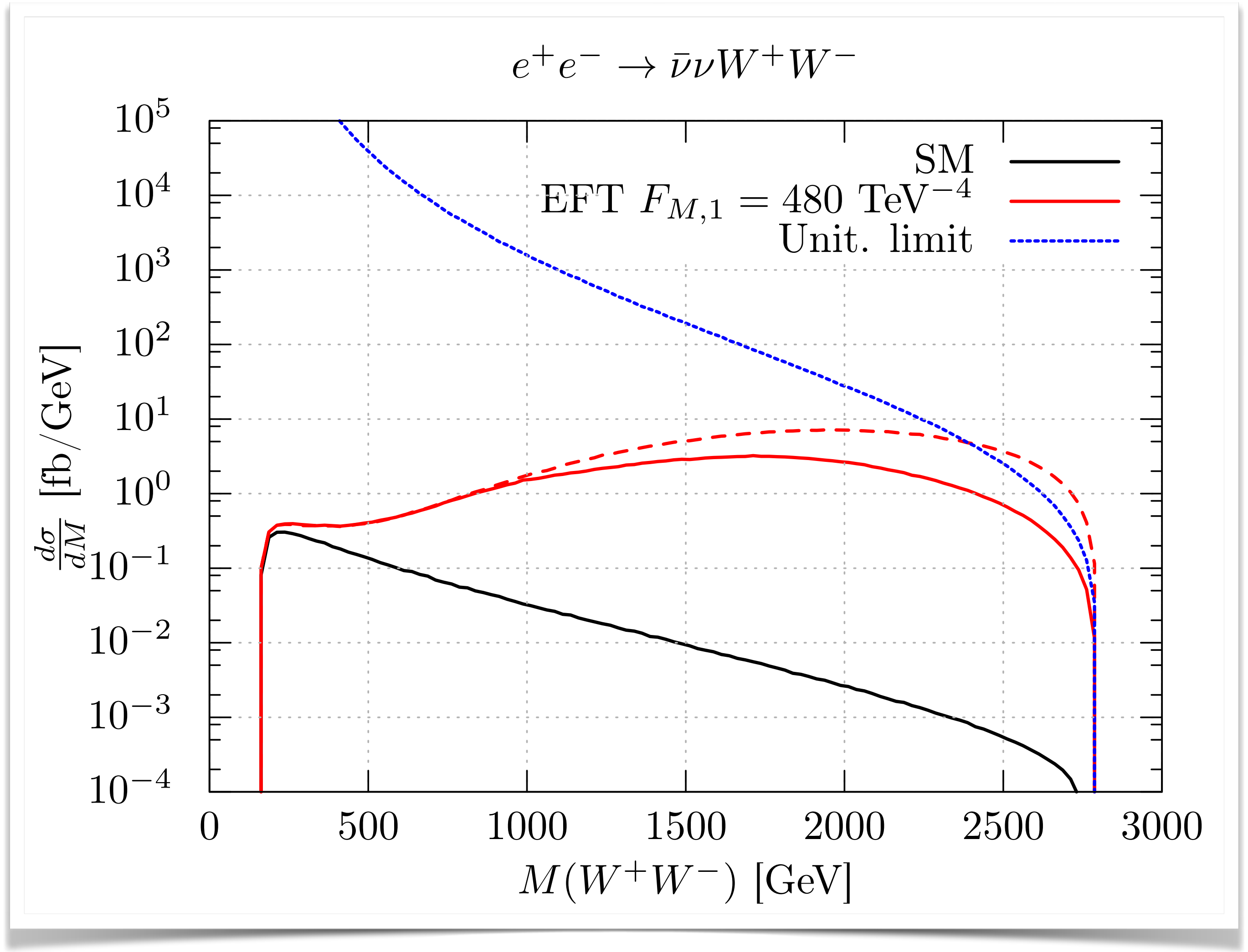
Process	1400 GeV	3000 GeV	Factor
$W^+W^-\nu\bar{\nu}$	0.119	0.790	1
$W^+W^-e^+e^-$	0.000	0.000	1
$W^\pm Ze^\mp\nu$	0.269	1.200	0.136
ZZe^+e^-	0.000	0.000	0.019
$W^+W^-(Z \to \nu\bar{\nu})$	0.039	0.610	1
$ZZ\nu\bar{\nu}$	0.084	0.790	1
ZZe^+e^-	0.000	0.000	1
$W^\pm Ze^\mp\nu$	0.288	1.593	0.136
$W^+W^-e^+e^-$	0.000	0.000	0.019
$ZZ(Z \to \nu\bar{\nu})$	0.000	0.000	1

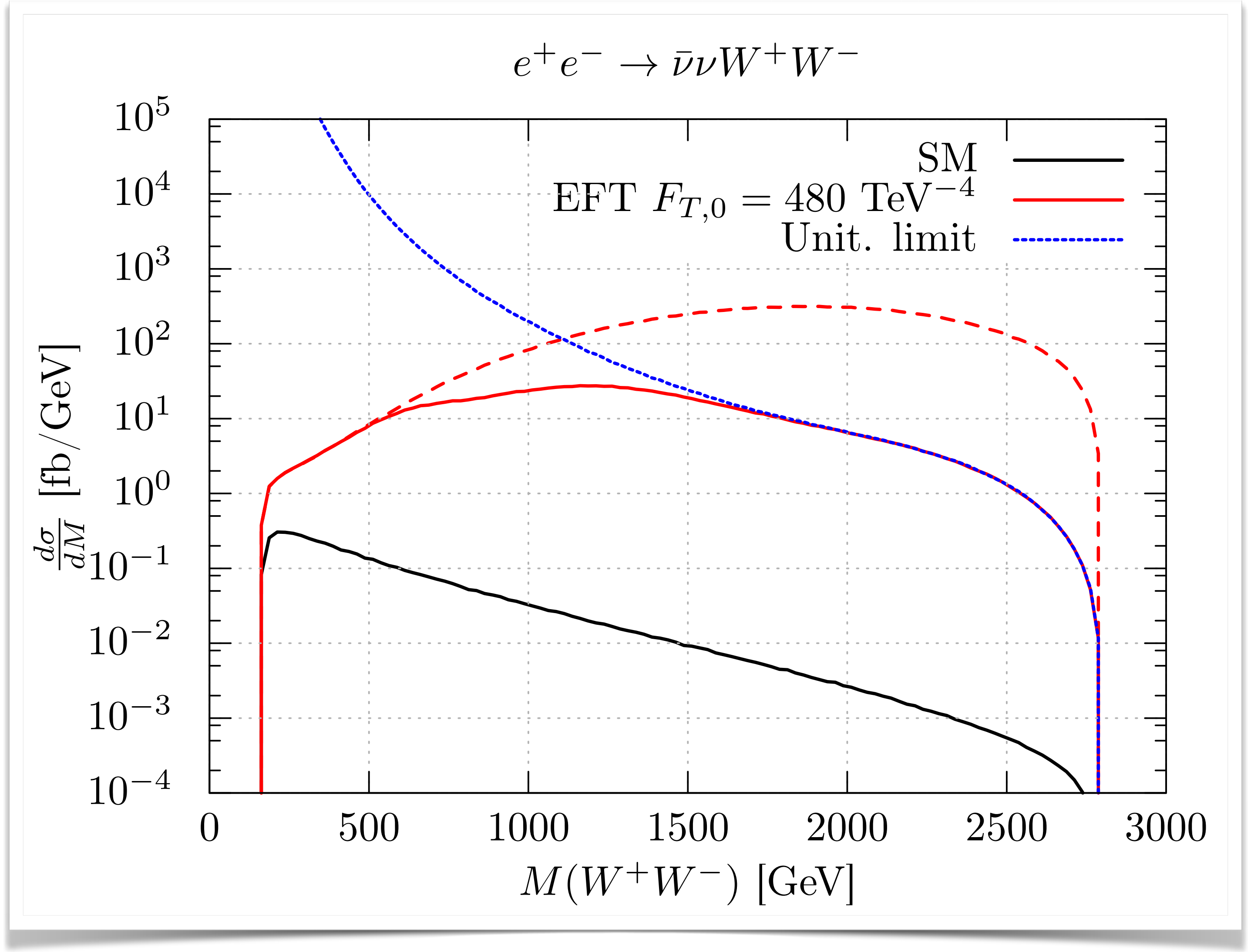
Total cross sections
[fb], all cuts

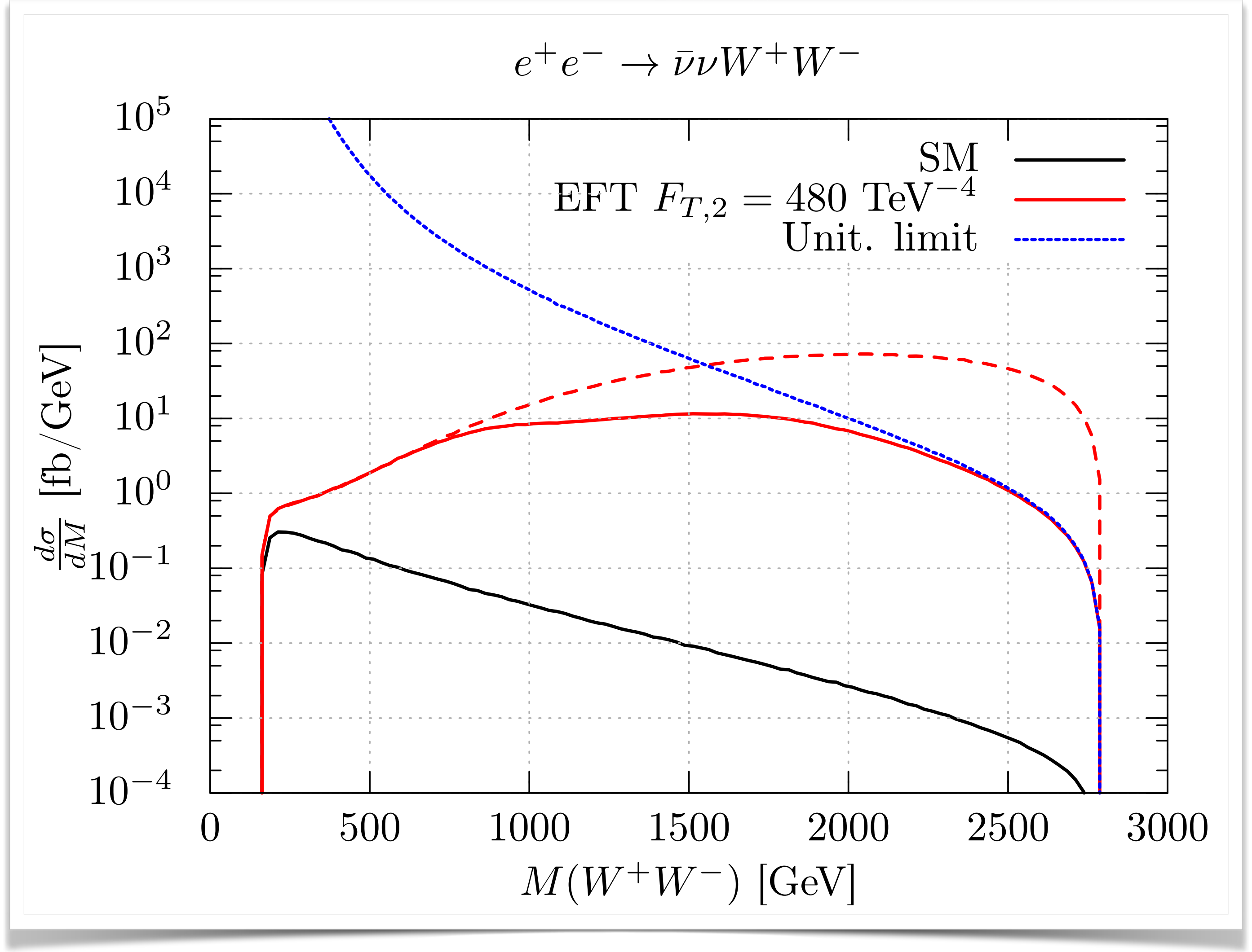
MC error are
≈ 1% on average

SMEFT dim. 8: longitudinal vs. mixed operators vs. Resonances

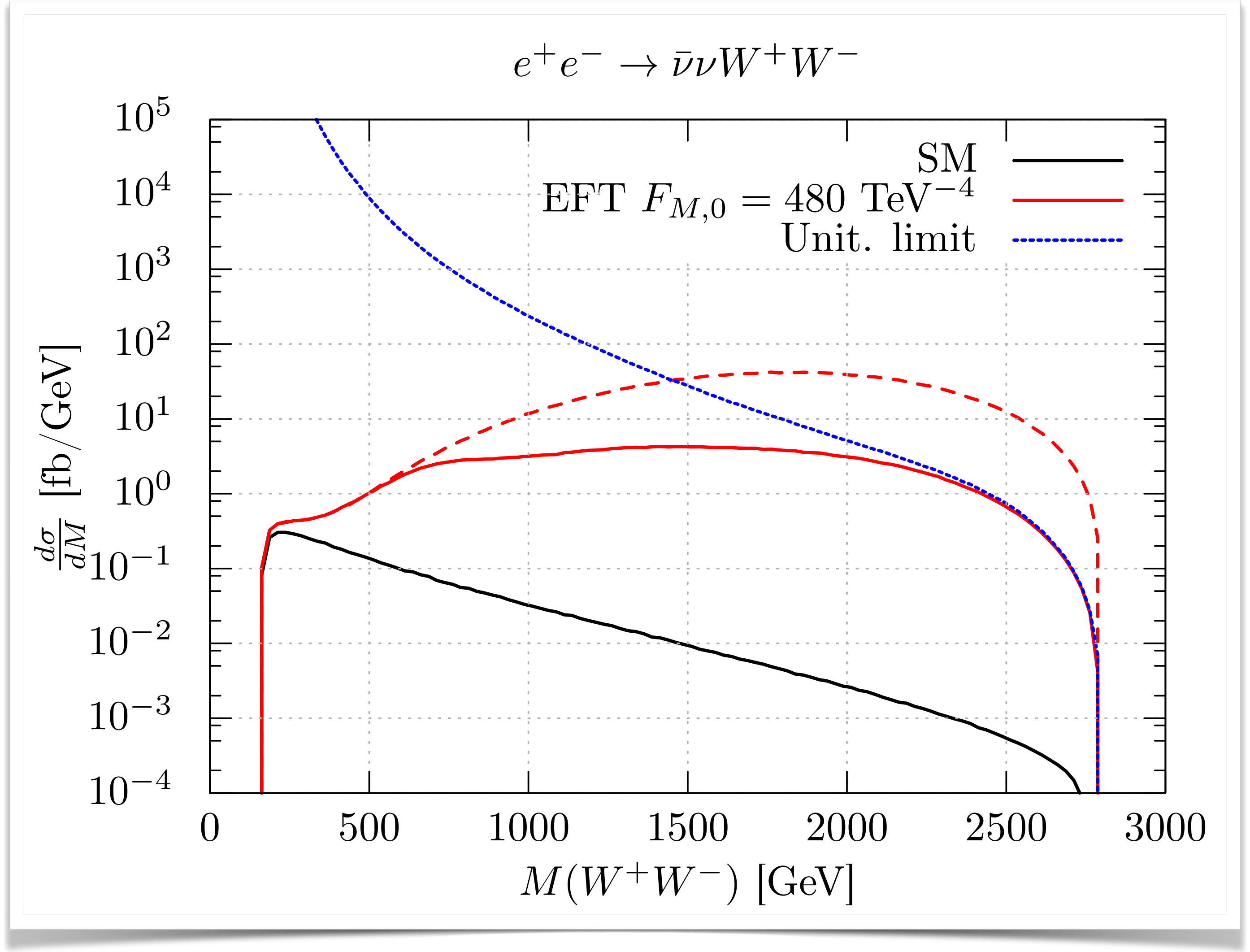


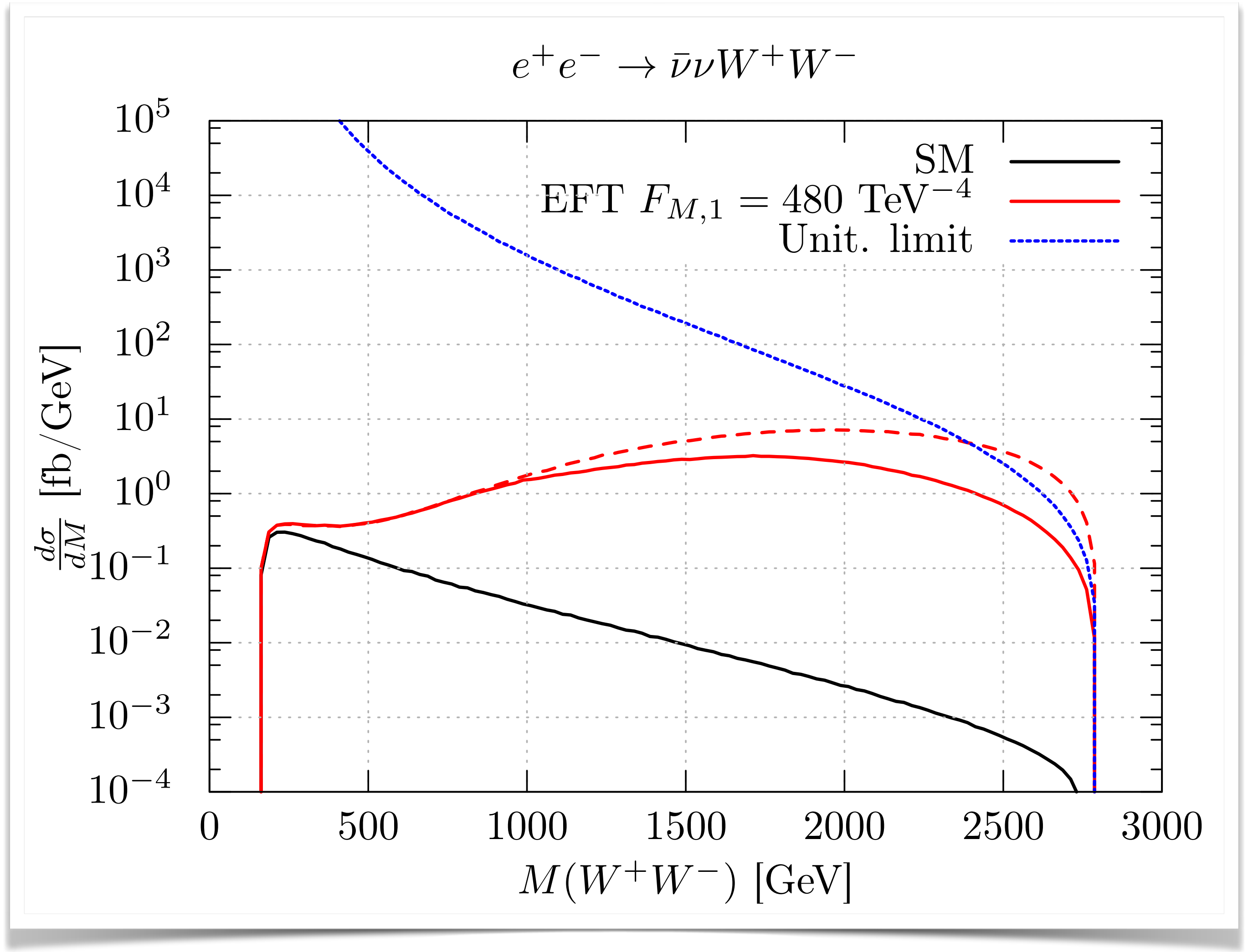


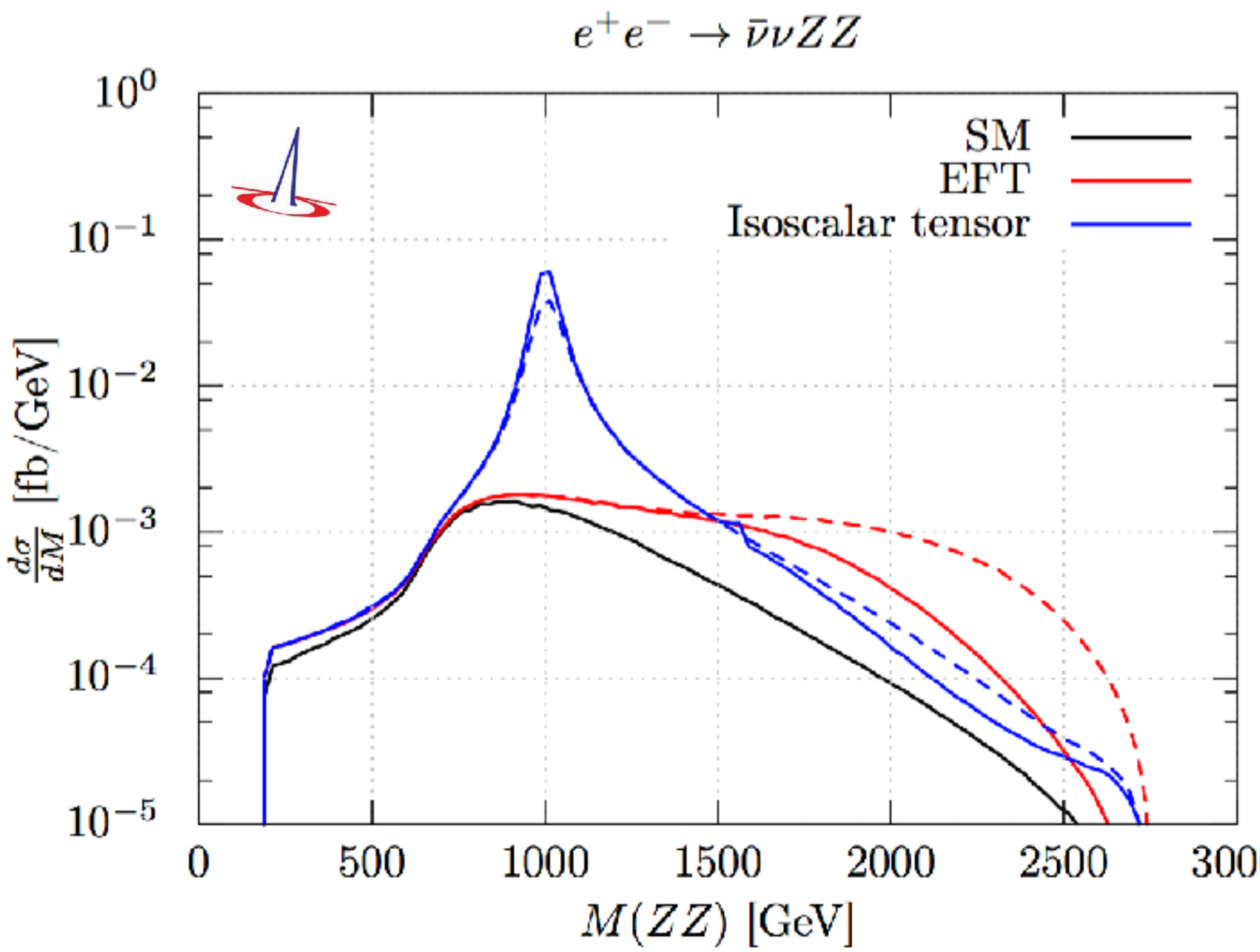


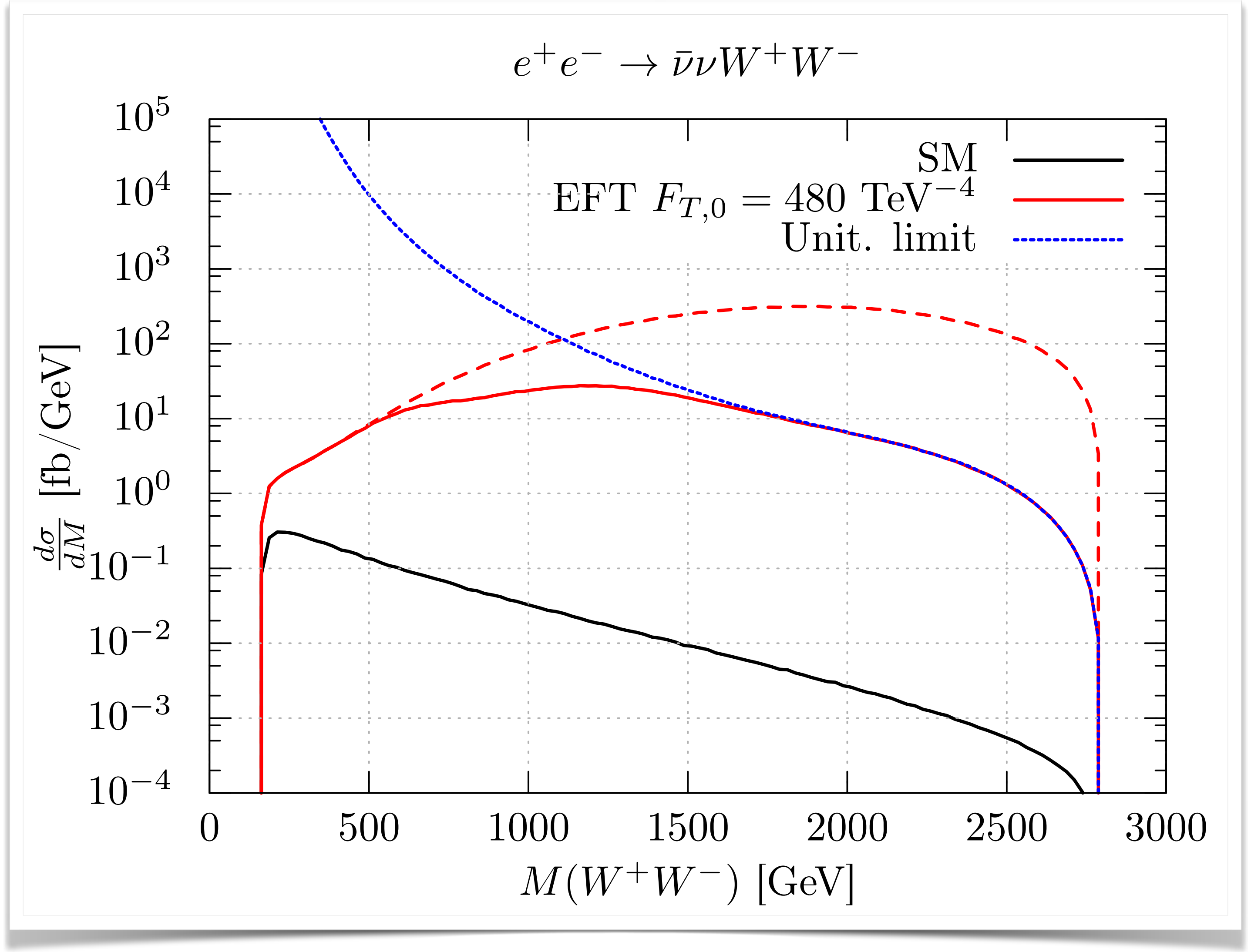


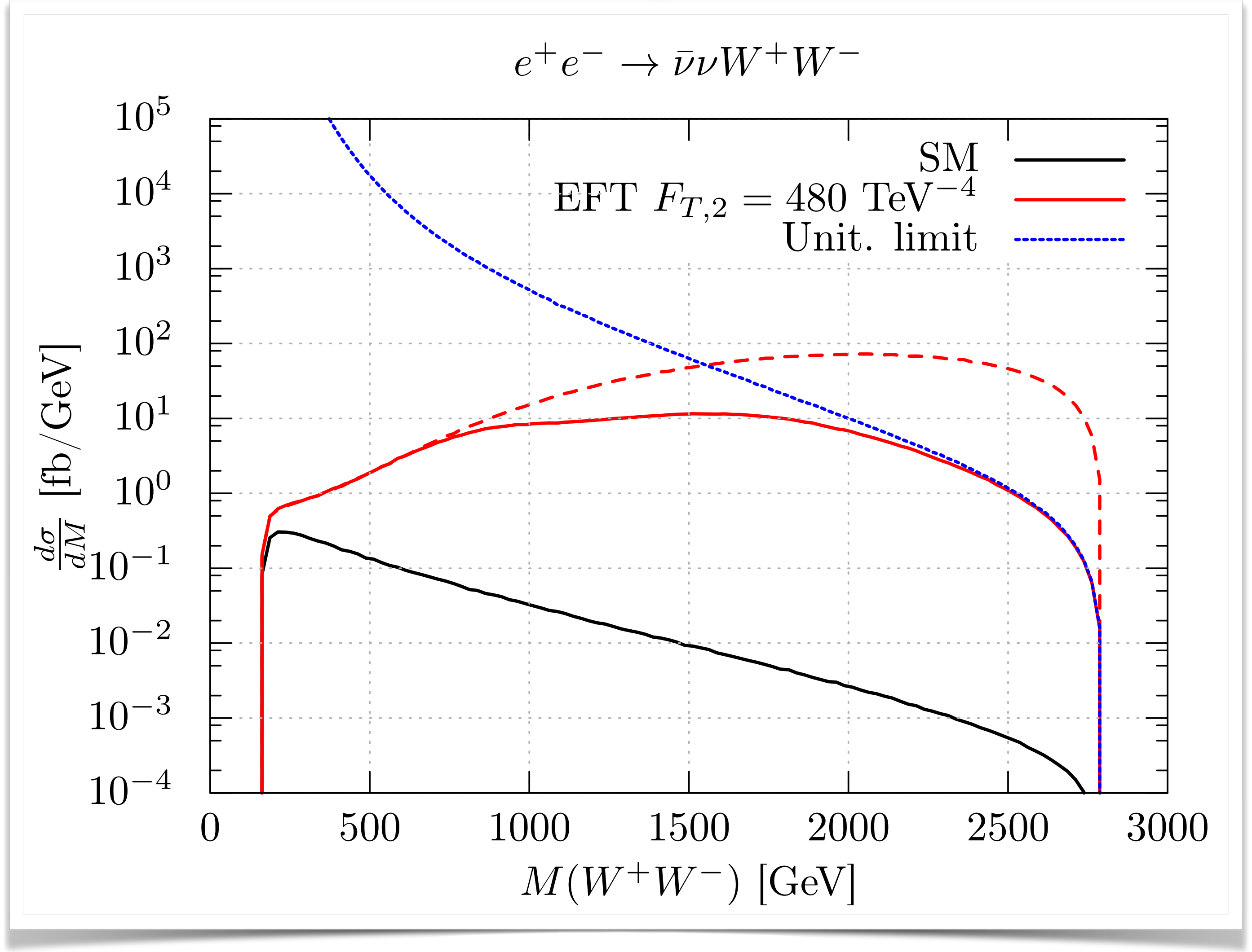
SMEFT dim. 8: longitudinal vs. mixed operators vs. Resonances











Exclusion sensitivies

5 ab^{-1} ⟸

Continuum model matched to low-energy SMEFT with two Dim 8-coefficients at 3 TeV, 2 ab^{-1}

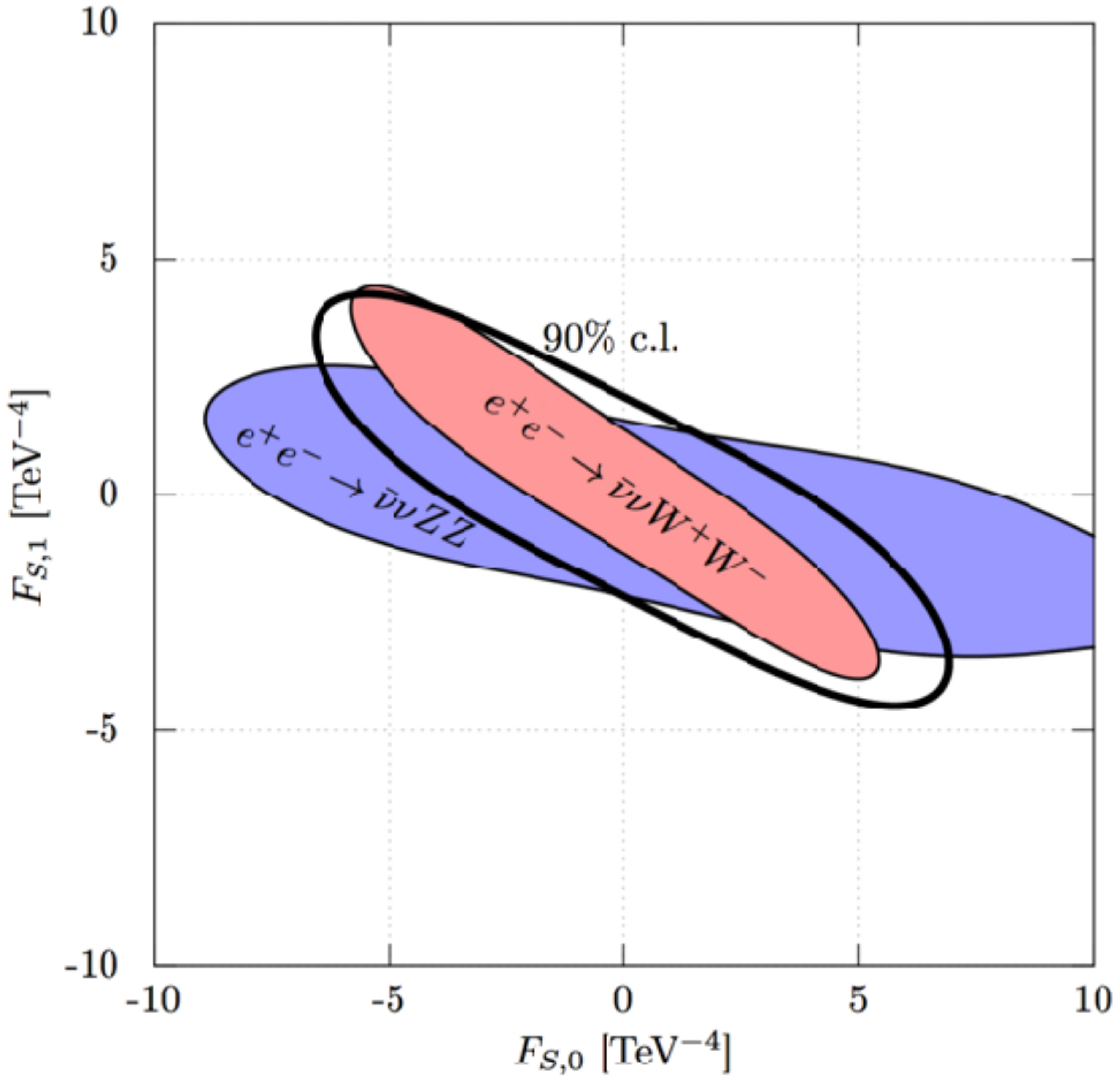
- All cuts have been applied
- Detector efficiencies are included
- All cross sections use T-matrix unitarization

- Confirmed by full simulation [CLICdp]

Exclusion sensitivies

5 ab^{-1} ⟸

Continuum model matched to low-energy SMEFT with two Dim 8-coefficients at 3 TeV, 2 ab^{-1}



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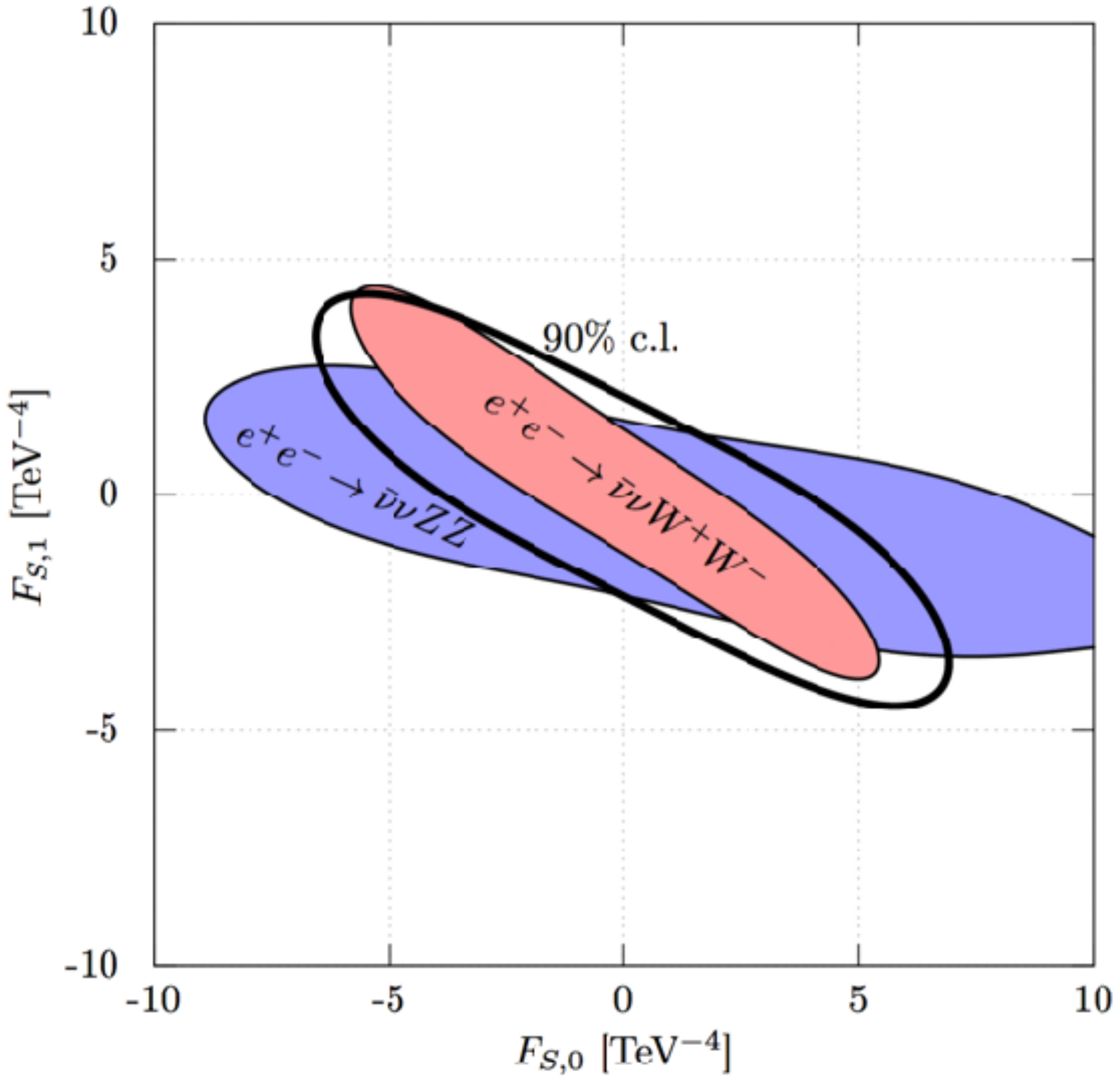
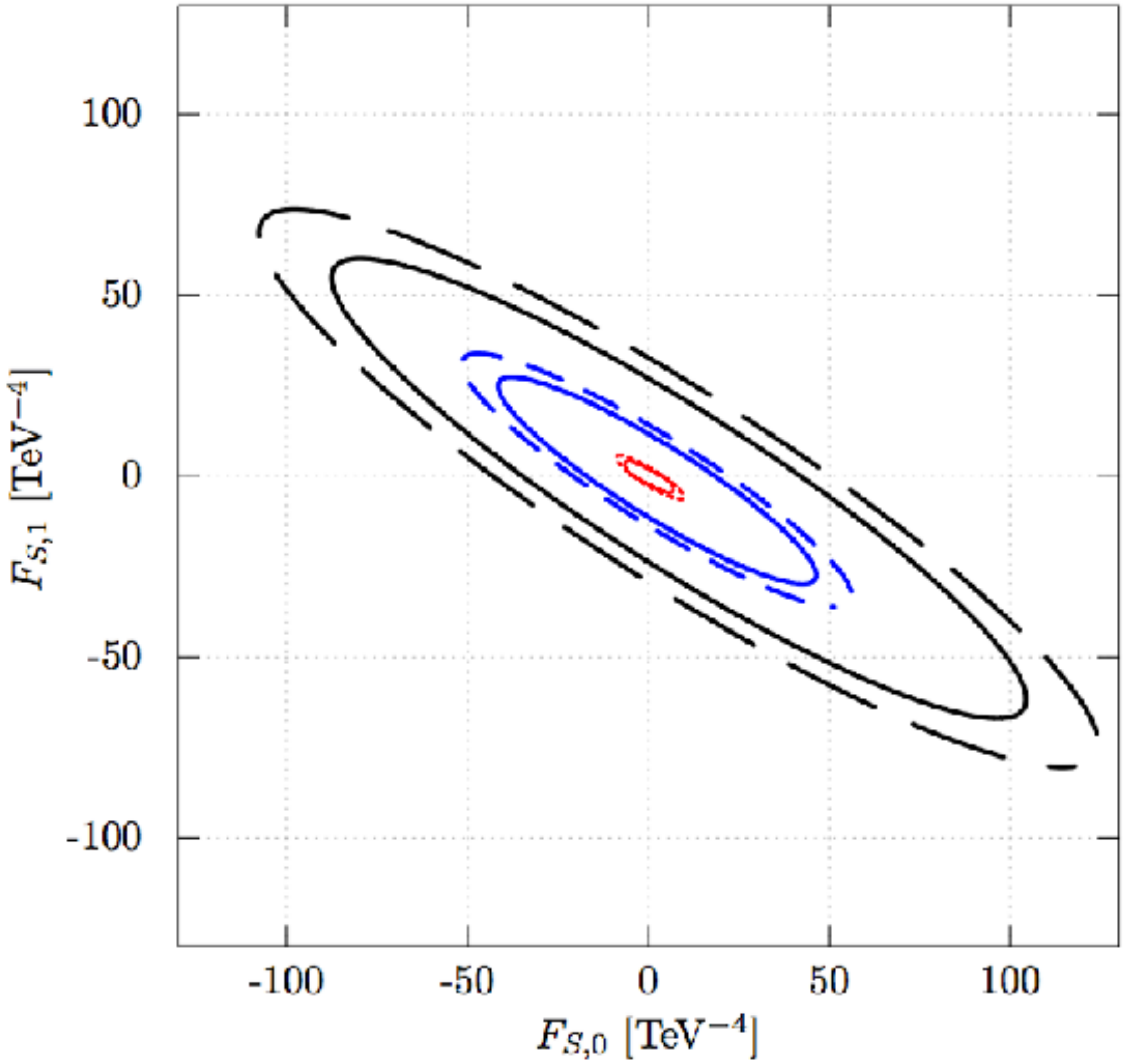


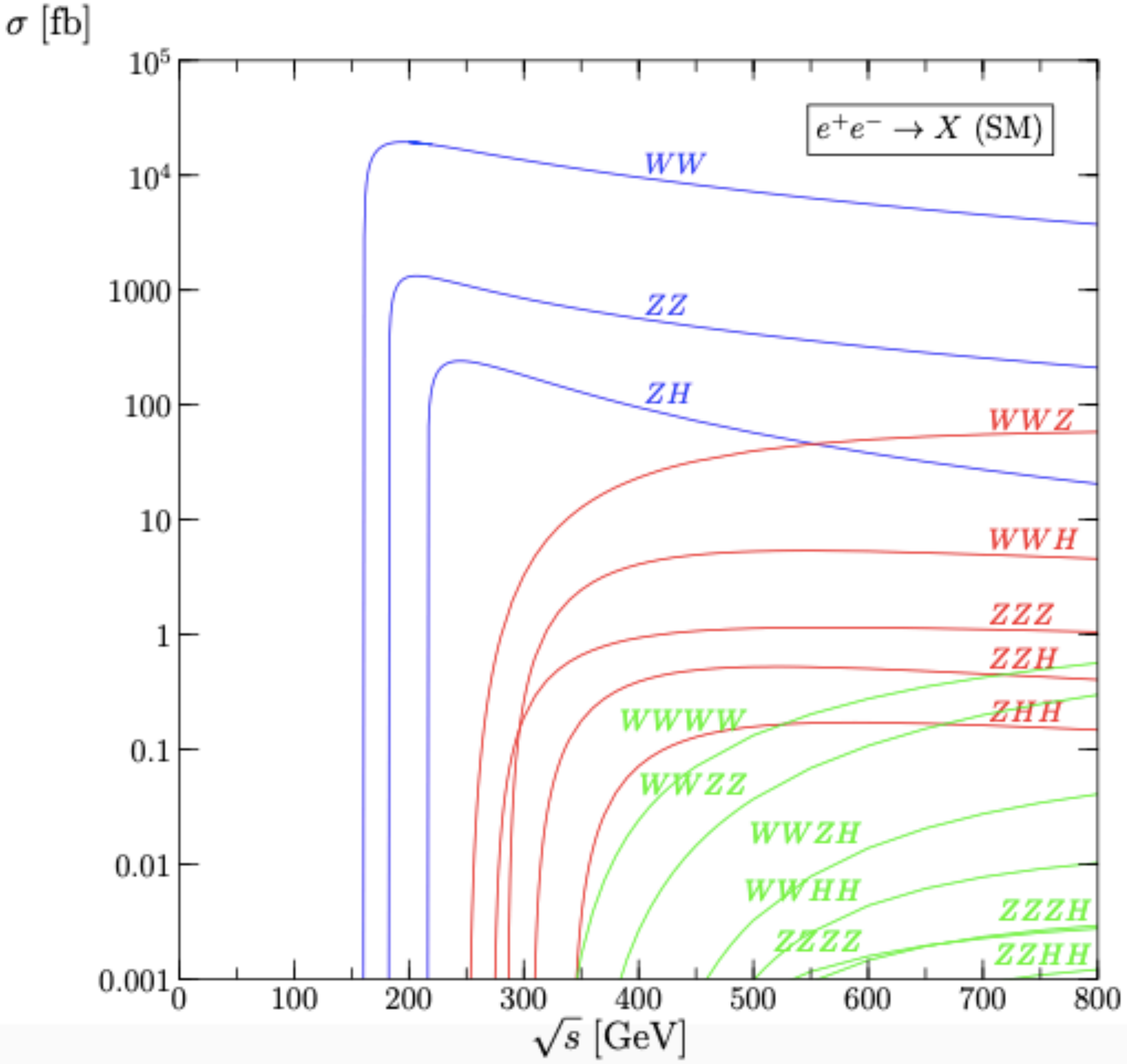


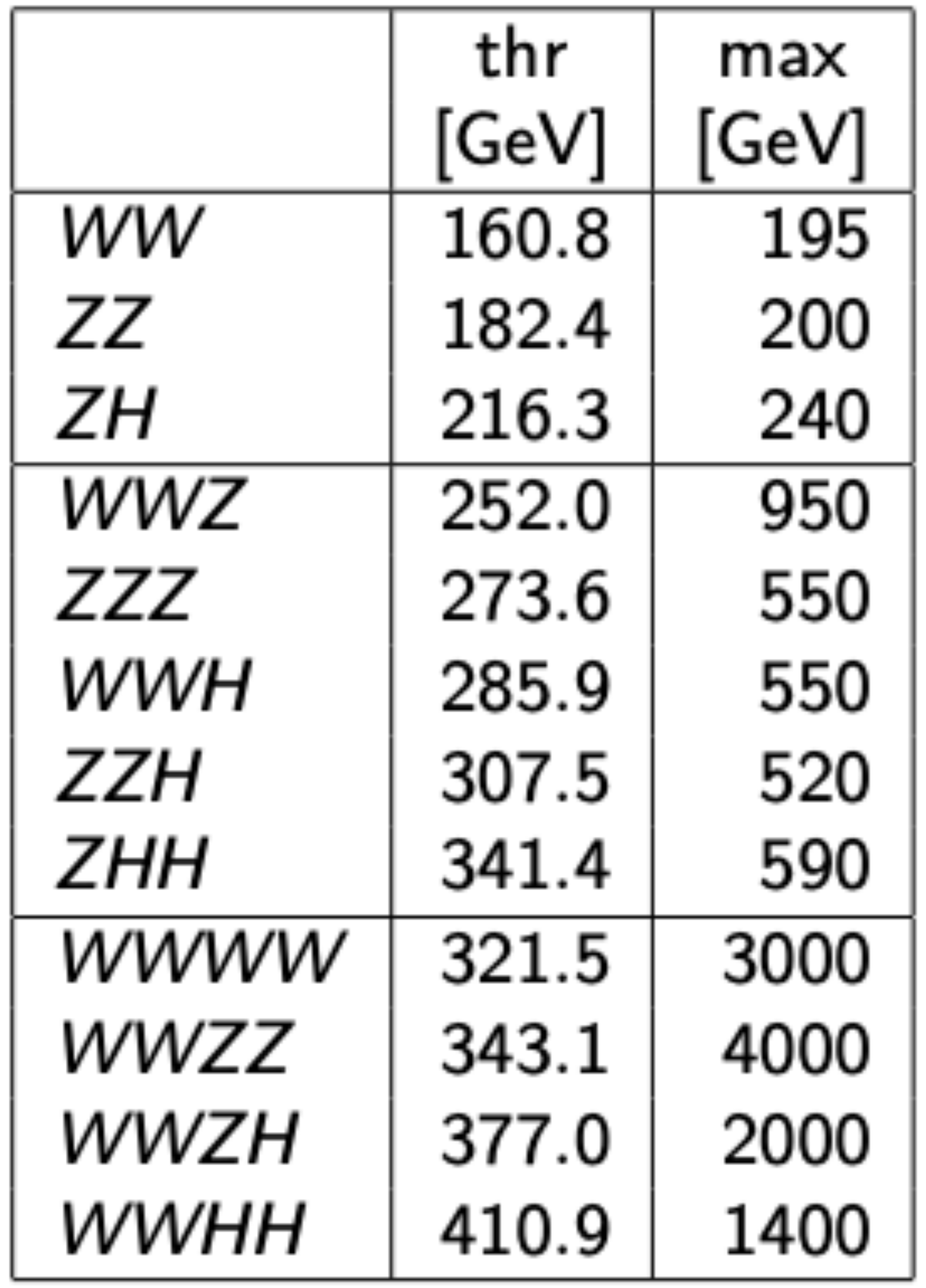
- All cuts have been applied
- Detector efficiencies are included
- All cross sections use *T*-matrix unitarization

- Confirmed by full simulation [CLICdp]

New Physics in VBS at TeV-e^+e^- colliders

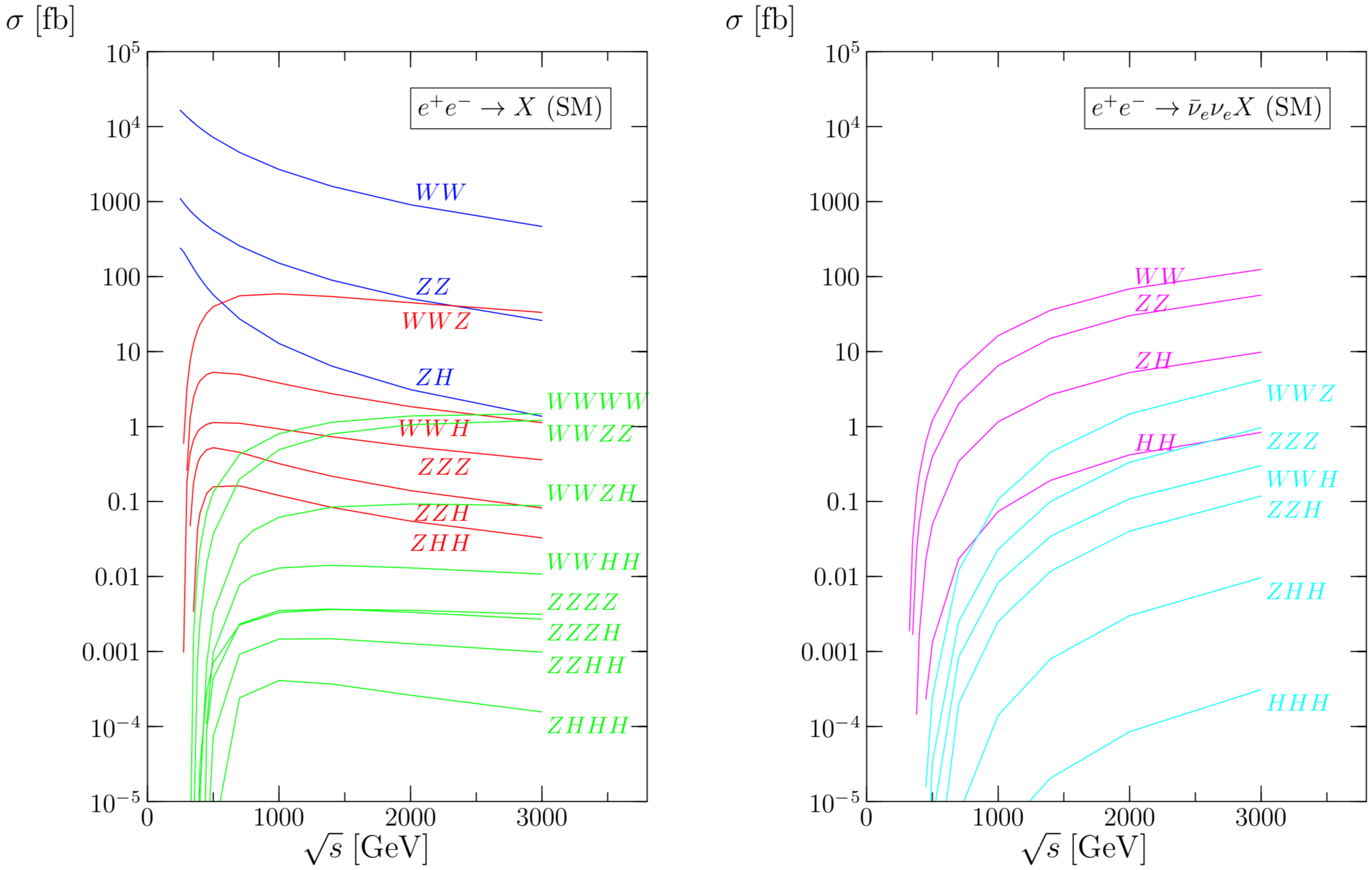
- ☑ 6-, 8-, 10-fermion final states studied trigger-less and fully exclusive in all observables
- ☑ Main issues: hadronic separation of *W*, *Z*, *H*; jet charge ($W^\pm$) ; combinatorics
- ☑ Low rates in clean environments: statistics dominated





	thr [GeV]	max [GeV]
WW	160.8	195
ZZ	182.4	200
ZH	216.3	240
WWZ	252.0	950
ZZZ	273.6	550
WWH	285.9	550
ZZH	307.5	520
ZHH	341.4	590
WWWW	321.5	3000
WWZZ	343.1	4000
WWZH	377.0	2000
WWHH	410.9	1400

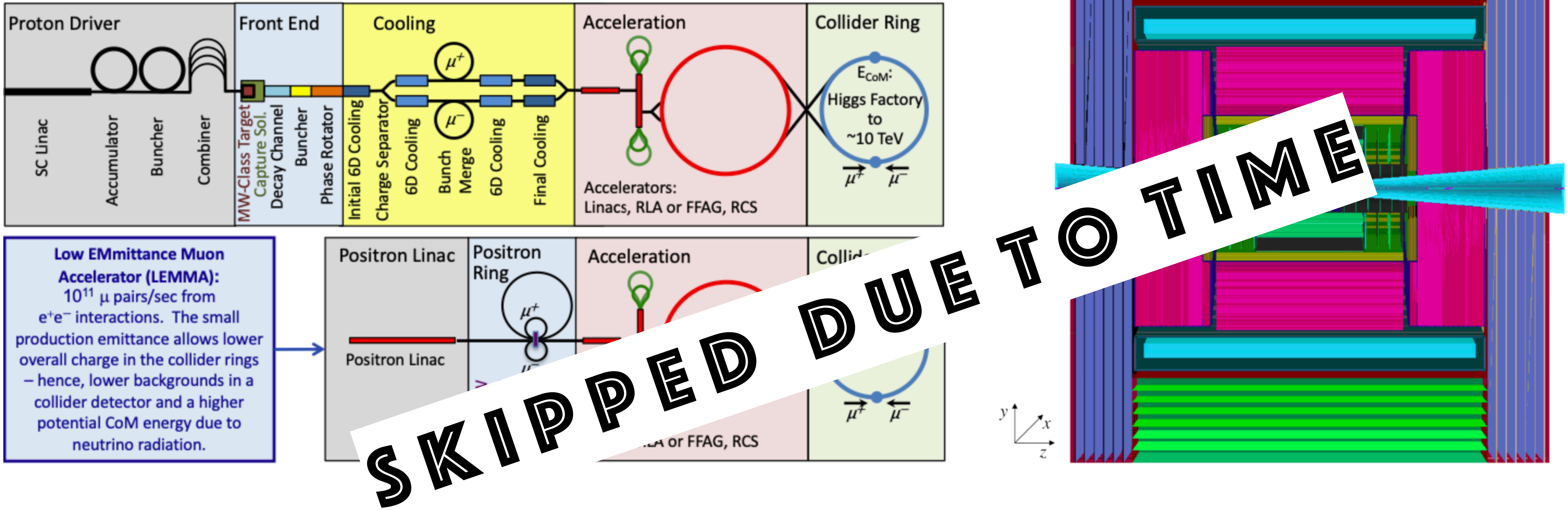
New Physics in VBS at TeV-e^+e^-colliders



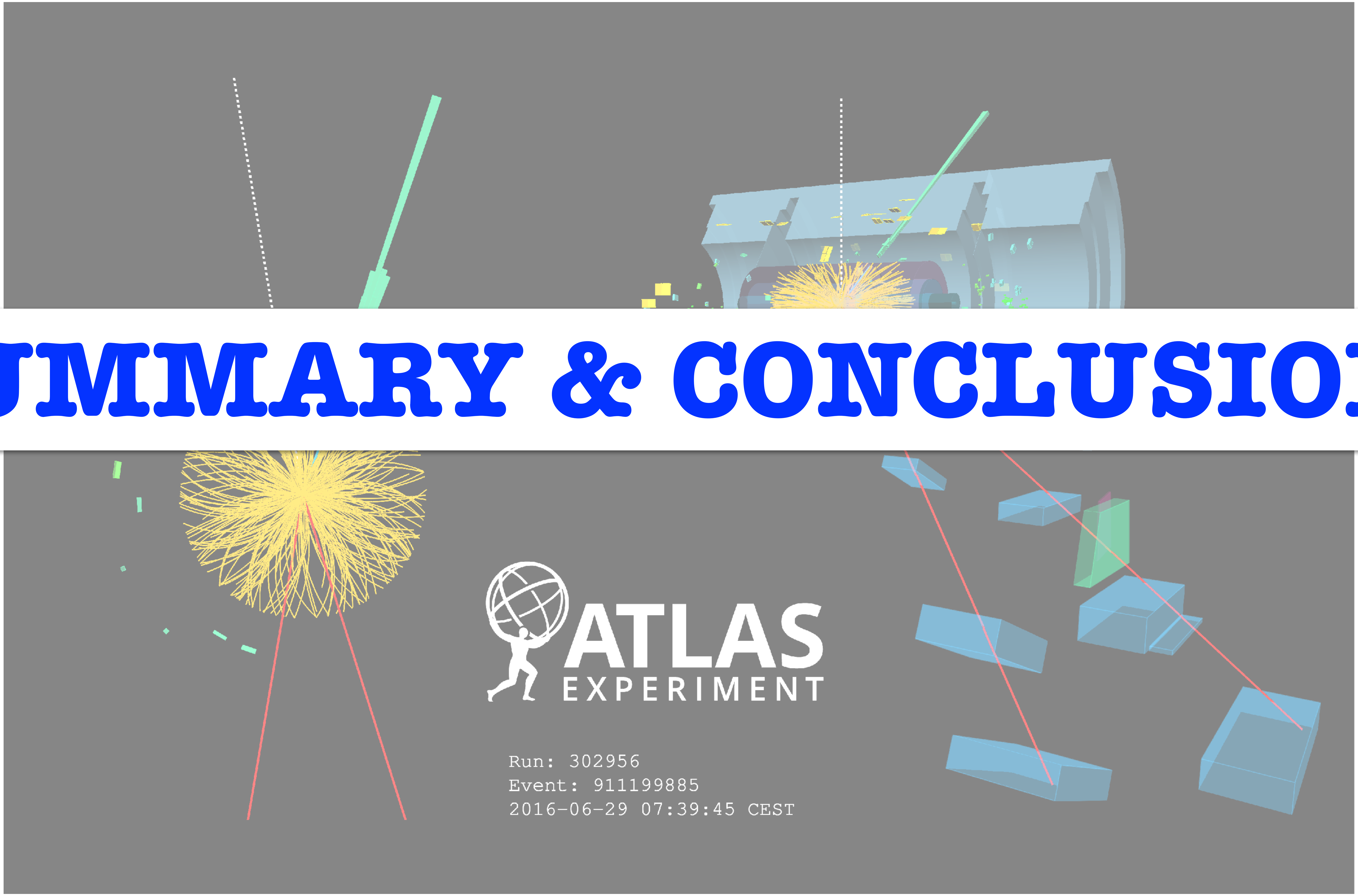
VBS beats multi-boson at high energies

1812.02093; Brass/Kilian/Kreher/JRR

EW BOSONS
@ MUON COLLIDERS



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



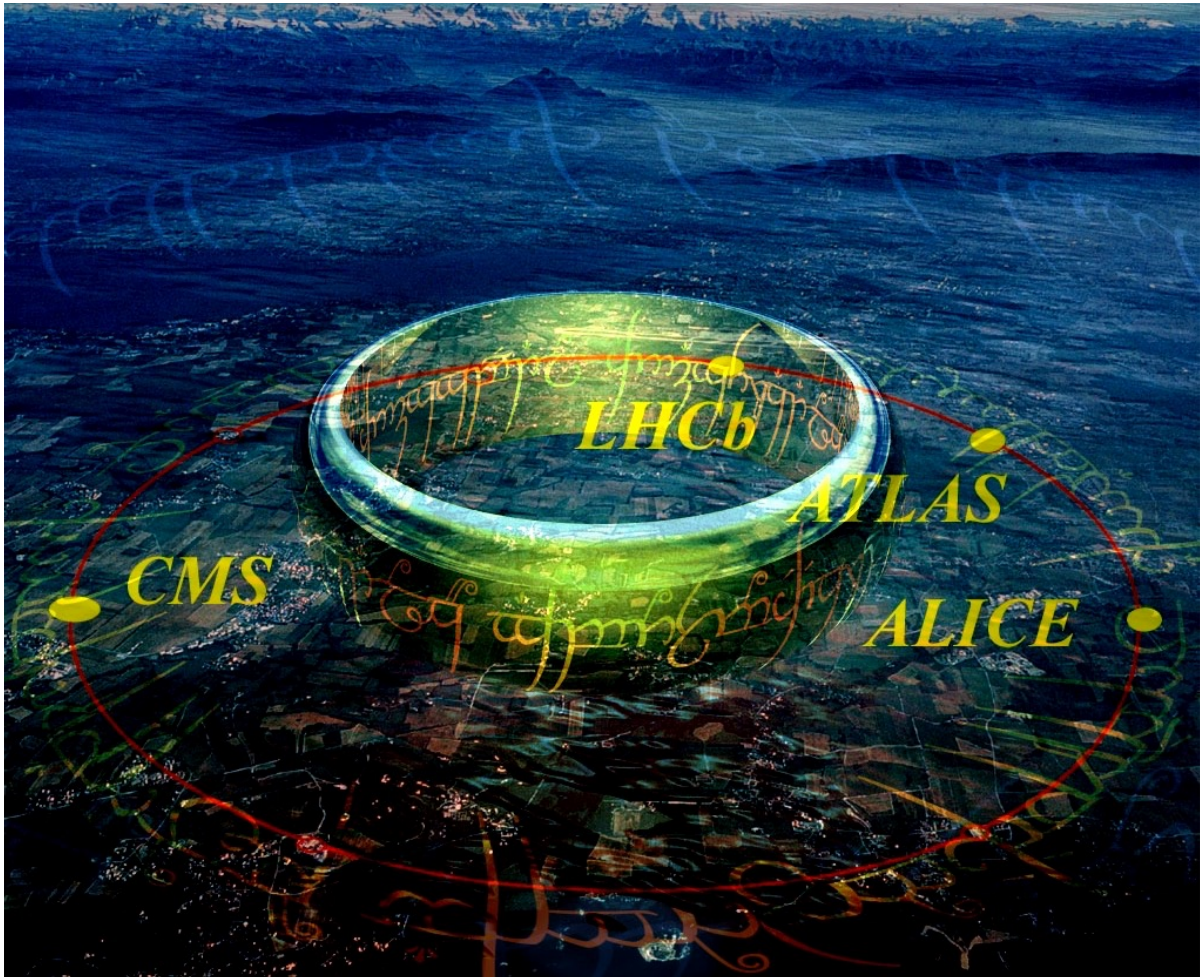
SUMMARY & CONCLUSION

Conclusions & Outlook

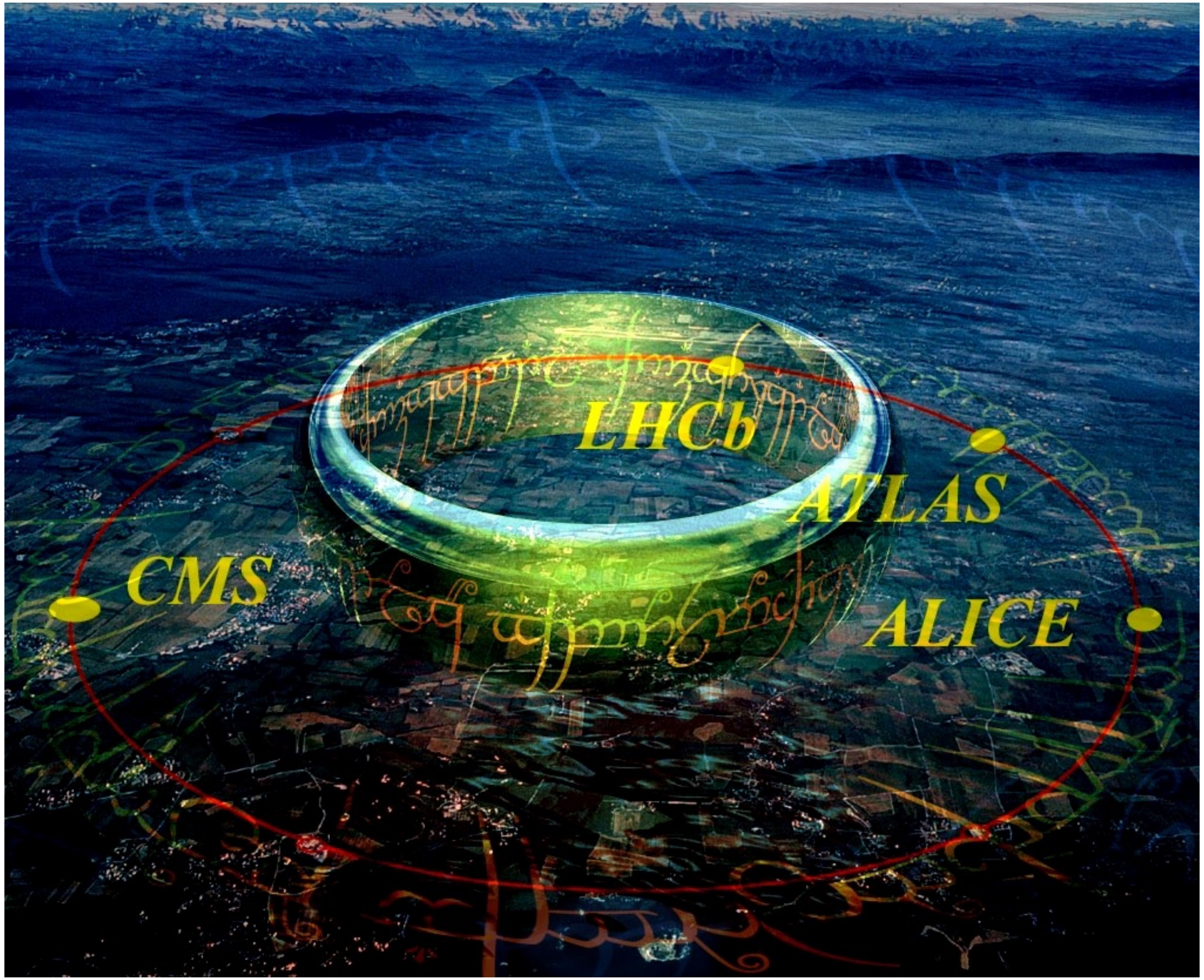
- Multi-boson + Higgs final states: multi-messenger detectors for EWSB+EW sector will shine in Run 3
- Three different levels of BSM parameterizations: EFT — Simplified Models — “UV complete” models
- EFT: limit-driven — Simplified Models: quantum number-driven — Models: symmetry-driven
- Heavy New Physics: Drell-Yan/diboson (“fermiophilic”) vs. VBF/VBS (“fermiophobic”)
- Signal models always need to be consistent with quantum field unitary (unitarity, positivity)
- Reconstruction of UV-complete models difficult (due to unknown matching scale)
- [Polarization measurement crucial: discriminate extended Higgs sector from axion-like particles]
- Combination of *V, VH, VV, VVV, VVjj* processes: lots of correlations, lots of power !!
- Multi-boson physics at e^+e^- colliders: hadronic channels fully usable; crucial *W/Z* separation
- Separation of VBS and di/tribosons only possible through cuts (gauge invariance!)
- Polarization and energy play an important role for constraining Wilson coefficients at lepton colliders

One Ring, 3 Runs

One Ring To Find Them,



One Ring To Rule Them Out



BACKUP

Unitarity in (VBS) Scattering Amplitudes

Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)/2$$

Partial wave amplitudes:

$$\mathcal{M}(s,t,u) = 32\pi \sum_\ell (2\ell+1)\mathcal{A}_\ell(s) P_\ell(\cos\theta)$$ (“Power spectrum”)

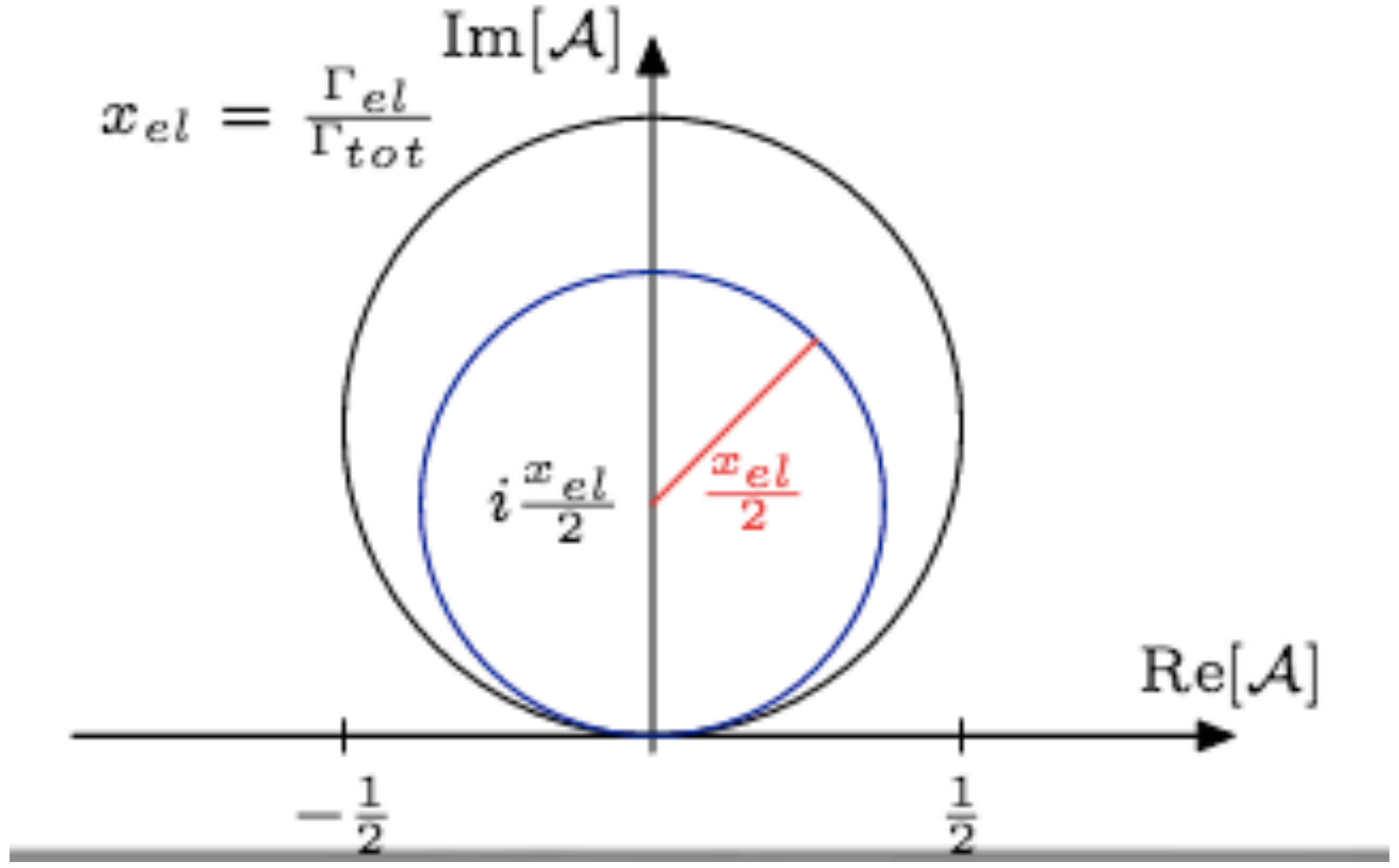
Unitarity in (VBS) Scattering Amplitudes

Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)/2$$

Partial wave amplitudes:

$$\mathcal{M}(s,t,u) = 32\pi\sum_\ell (2\ell+1)\mathcal{A}_\ell(s) P_\ell(\cos\theta)$$ ("Power spectrum")



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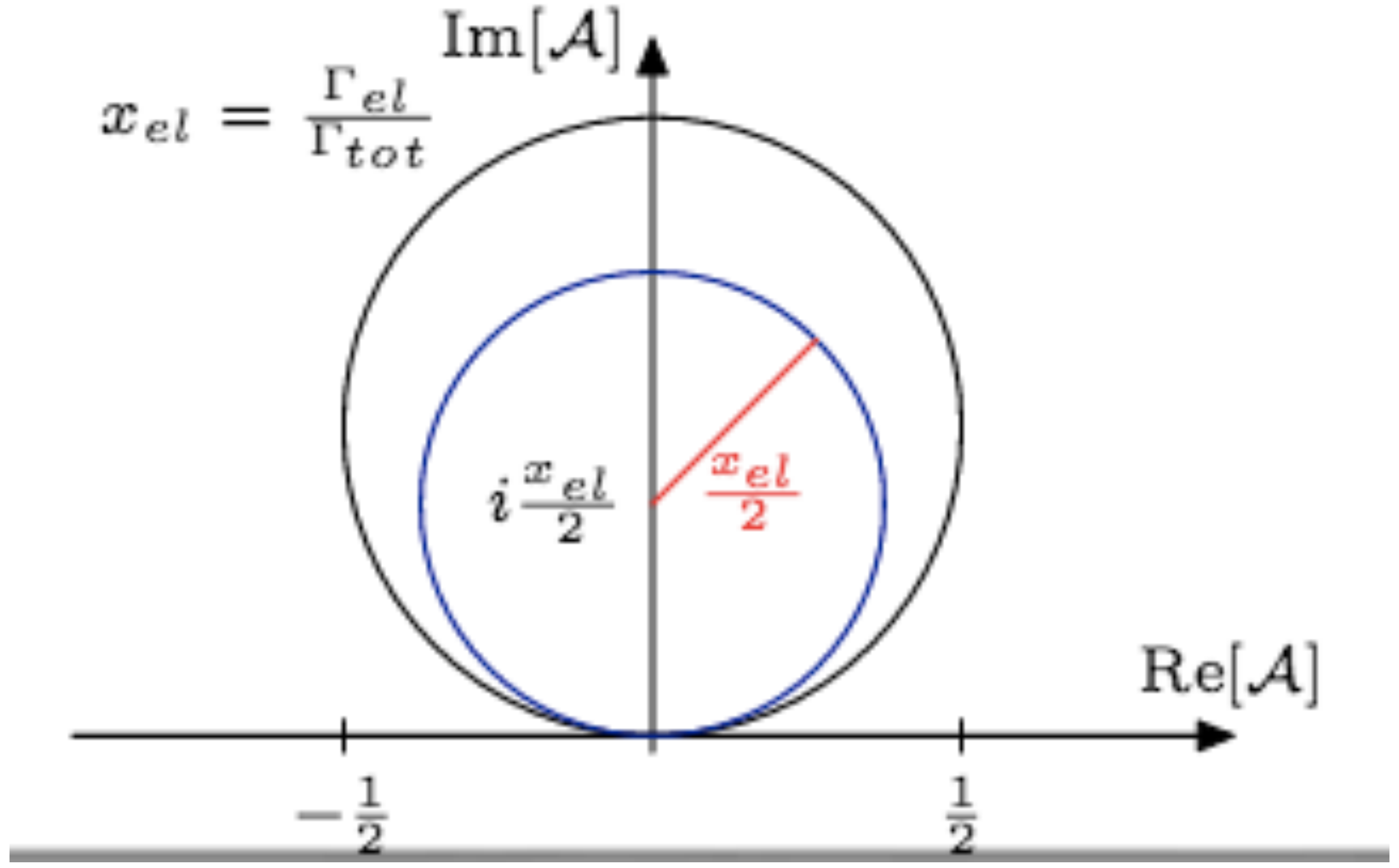

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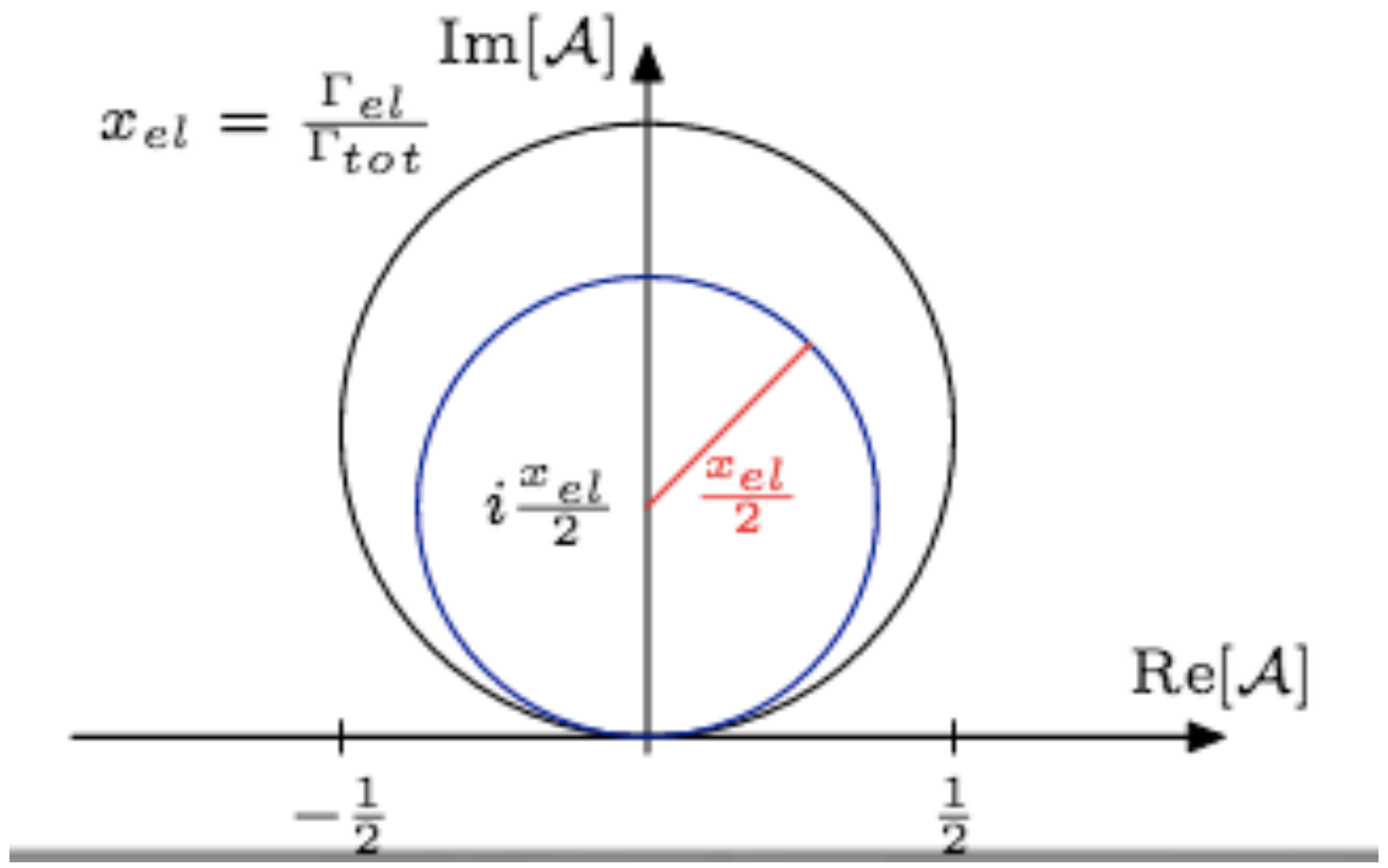


Lee/Quigg/Thacker, 1973

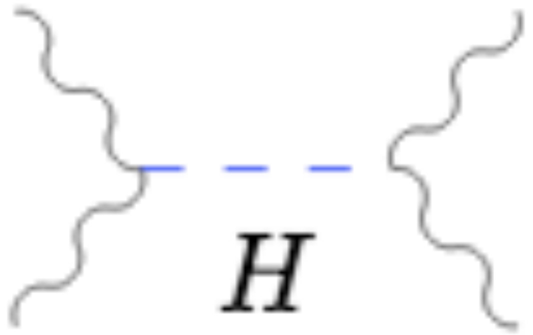
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

$$I = 0: \qquad E \sim \sqrt{8\pi}v = 1.2\,\text{TeV}$$

$$I = 1: \qquad E \sim \sqrt{48\pi}v = 3.5\,\text{TeV}$$

$$I = 2: \qquad E \sim \sqrt{16\pi}v = 1.7\,\text{TeV}$$

Higgs exchange:

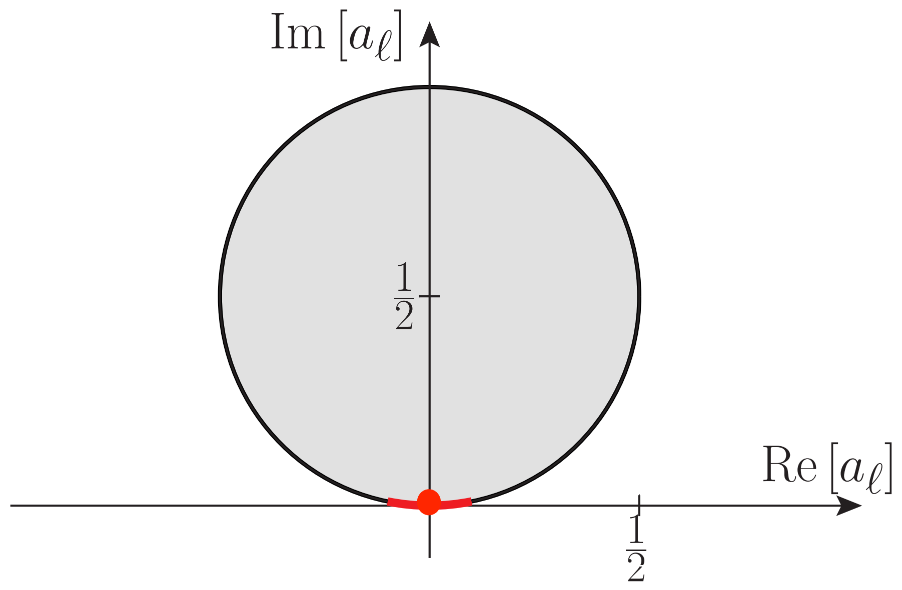


$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

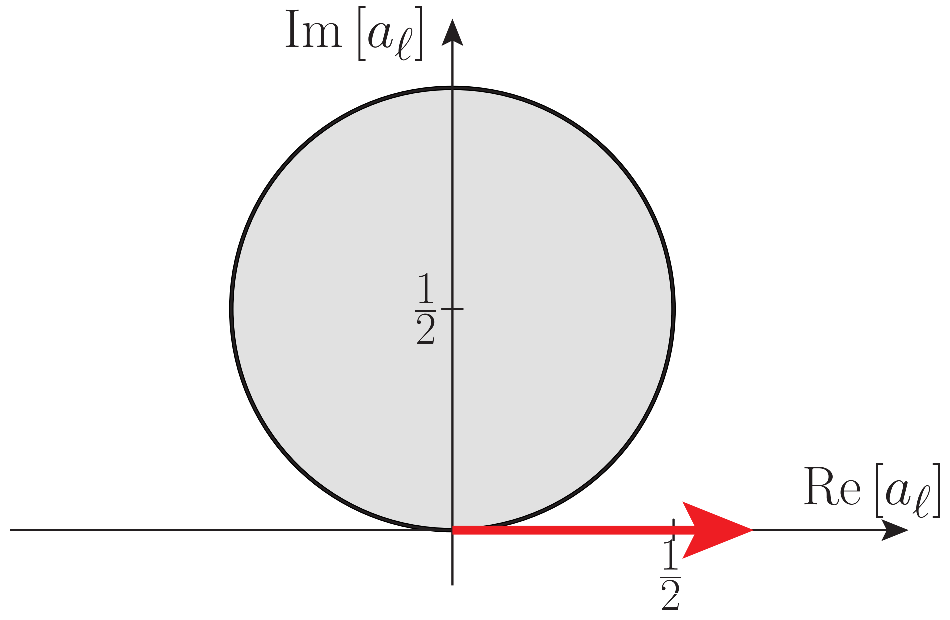
Unitarity: $M_H \lesssim \sqrt{8\pi}v \sim 1.2\,\text{TeV}$

Scenarios for New Physics in VBS

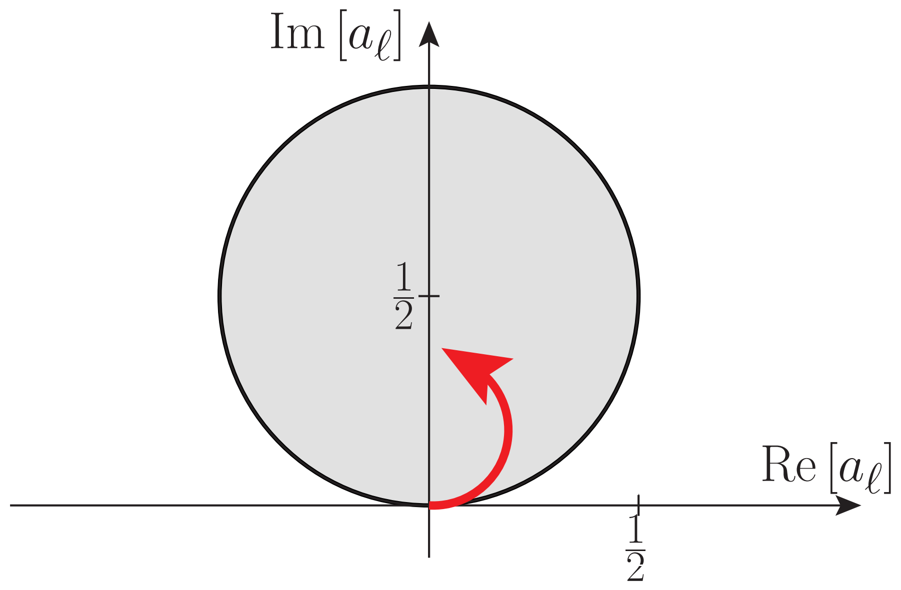
1. SM or weakly coupled physics (e.g. 2HDM):
   amplitude remains close to origin



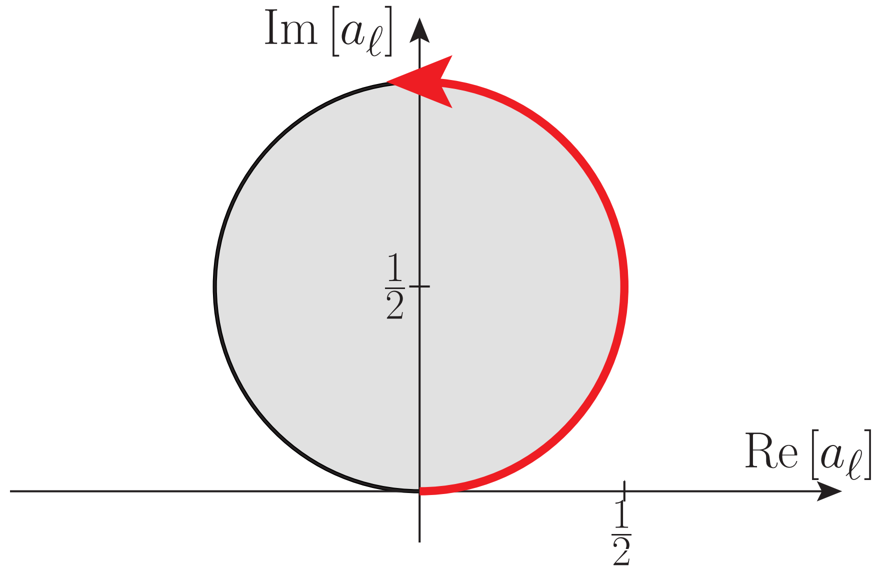
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.], strongly interacting regime



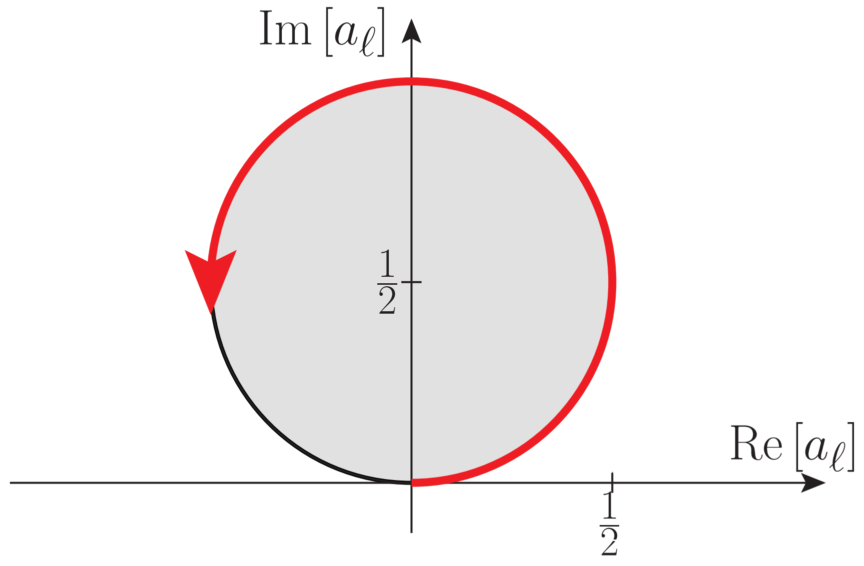
3. Inelastic channel opens (form-factor description):
   new channels open out, multi-boson final states



4. Saturation of amplitude: maximal amplitude, strongly interacting continuum, K-/T-matrix unitarization



5. New resonance: amplitude turns over



Tensor Resonances (in VBS)

- Symmetric tensor $f_{\mu\nu}$
- On-shell conditions: 10 → 5 components
- Tracelessness: ${f_\mu}^\mu = 0$
- Transversality: $\partial_\mu f^{\mu\nu} = 0$

How to deal with *off-shell* tensor in realistic processes?

- Start with Fierz-Pauli Lagrangian for symmetric tensor

$$\boxed{\begin{aligned}\mathcal{L}_{\mathrm{FP}} =& \frac{1}{2}\partial_\alpha f_{\mu\nu}\partial^\alpha f^{\mu\nu} - \frac{1}{2}m^2 f_{\mu\nu}f^{\mu\nu} - \frac{1}{2}\partial_\alpha f^\mu_\mu \partial^\alpha f^\nu_\nu + \frac{1}{2}m^2 f^\mu_\mu f^\nu_\nu \\ &- \partial^\alpha f_{\alpha\mu}\partial_\beta f^{\beta\mu} - f^\alpha_\alpha \partial^\mu\partial^\nu f_{\mu\nu} + f_{\mu\nu}J_f^{\mu\nu}\end{aligned}}$$

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- ϕ: $\partial_\mu \partial_\nu f^{\mu\nu}$
- A^μ: $\partial_\nu f^{\mu\nu}$
- σ: $f^\mu{}_\mu$

Gauge fixing: $\sigma = -\phi$

$$\begin{aligned}\mathcal{L} =& \frac{1}{2} f_{f\mu\nu}\left(-\partial^2 - m_f^2\right) f_f^{\mu\nu} + \frac{1}{2} f_f{}^\mu{}_\mu \left(-\frac{1}{2}\left(-\partial^2 - m_f^2\right)\right) f_f{}^\nu{}_\nu \\ &+ \frac{1}{2} A_{f\mu}\left(\partial^2 + m_f^2\right) A_f^\mu + \frac{1}{2}\sigma_f\left(-\partial^2 - m_f^2\right)\sigma_f \\ &+ \left(f_{\mu\nu} - \frac{1}{\sqrt{6}}\sigma_f g_{\mu\nu}\right) J_f^{\mu\nu} \\ &- \left(\frac{1}{\sqrt{2} m_f}\left(A_{f\mu}\partial_\nu + A_{f\nu}\partial_\mu\right) - \frac{\sqrt{2}}{\sqrt{3} m_f^2}\sigma_f \partial_\mu \partial_\nu\right) J_f^{\mu\nu}\end{aligned}$$

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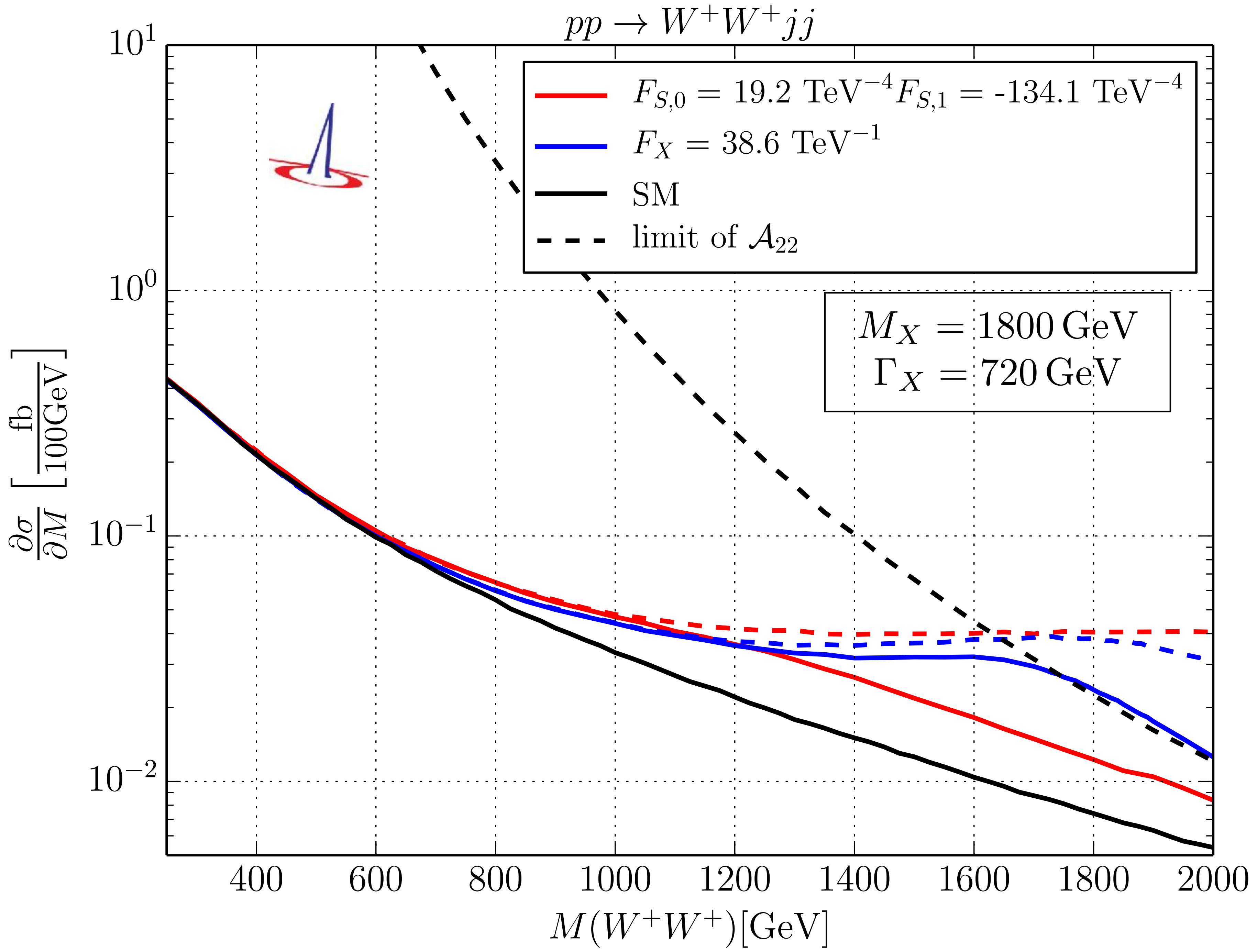
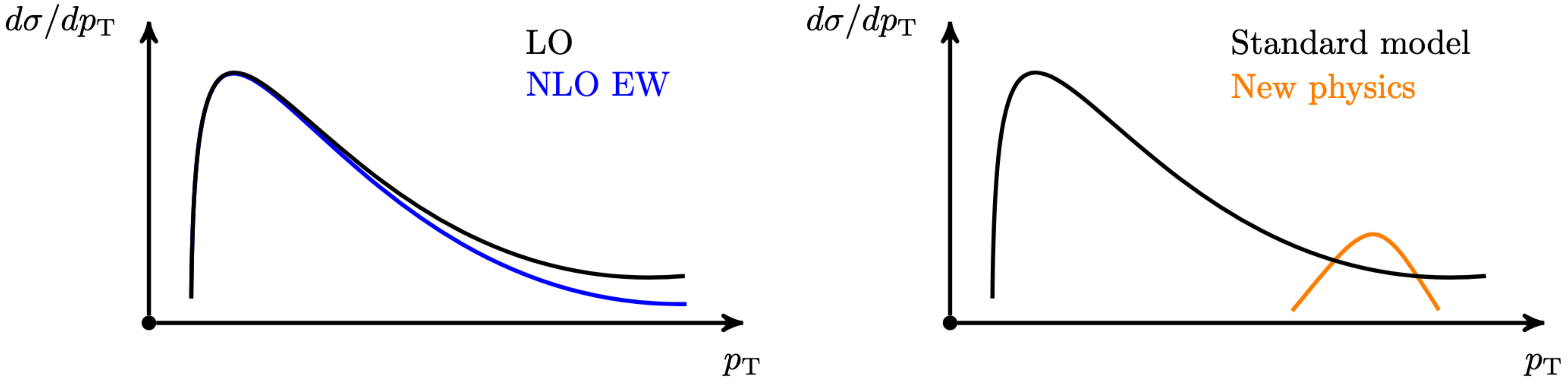
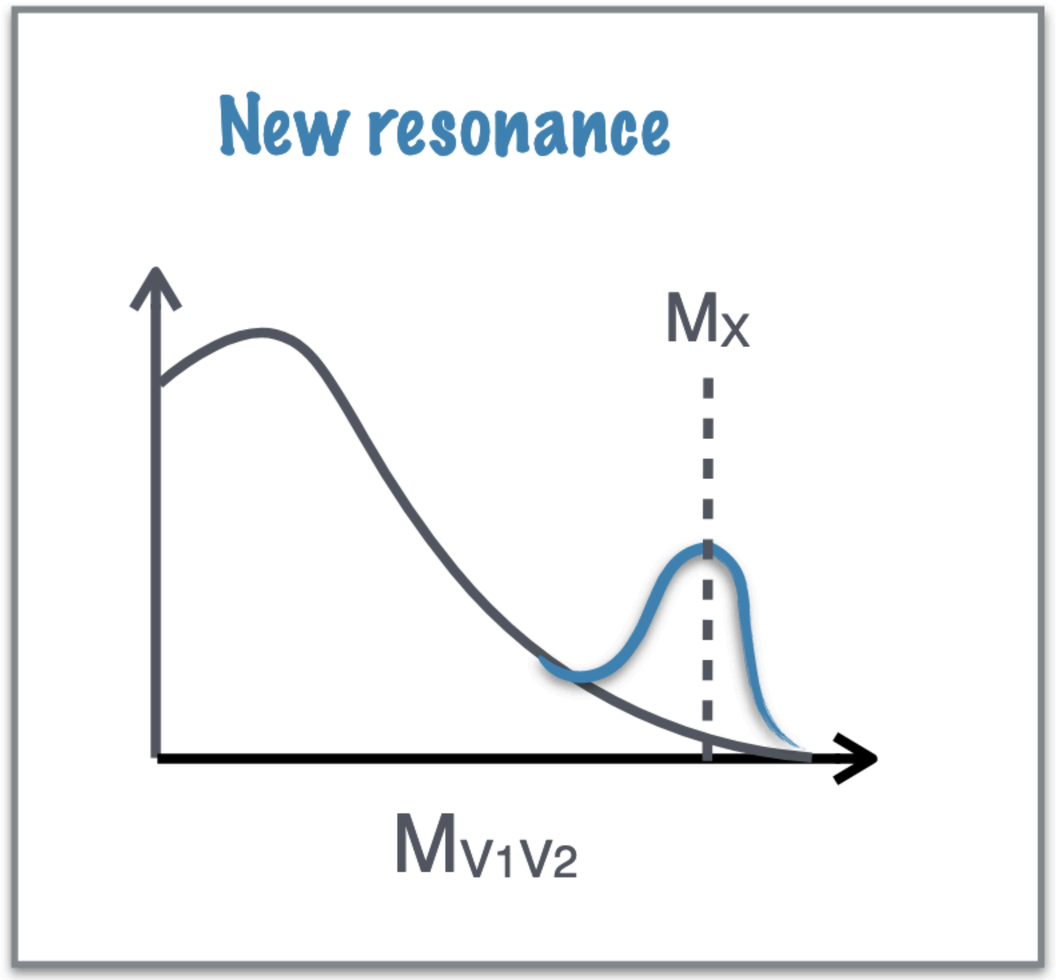


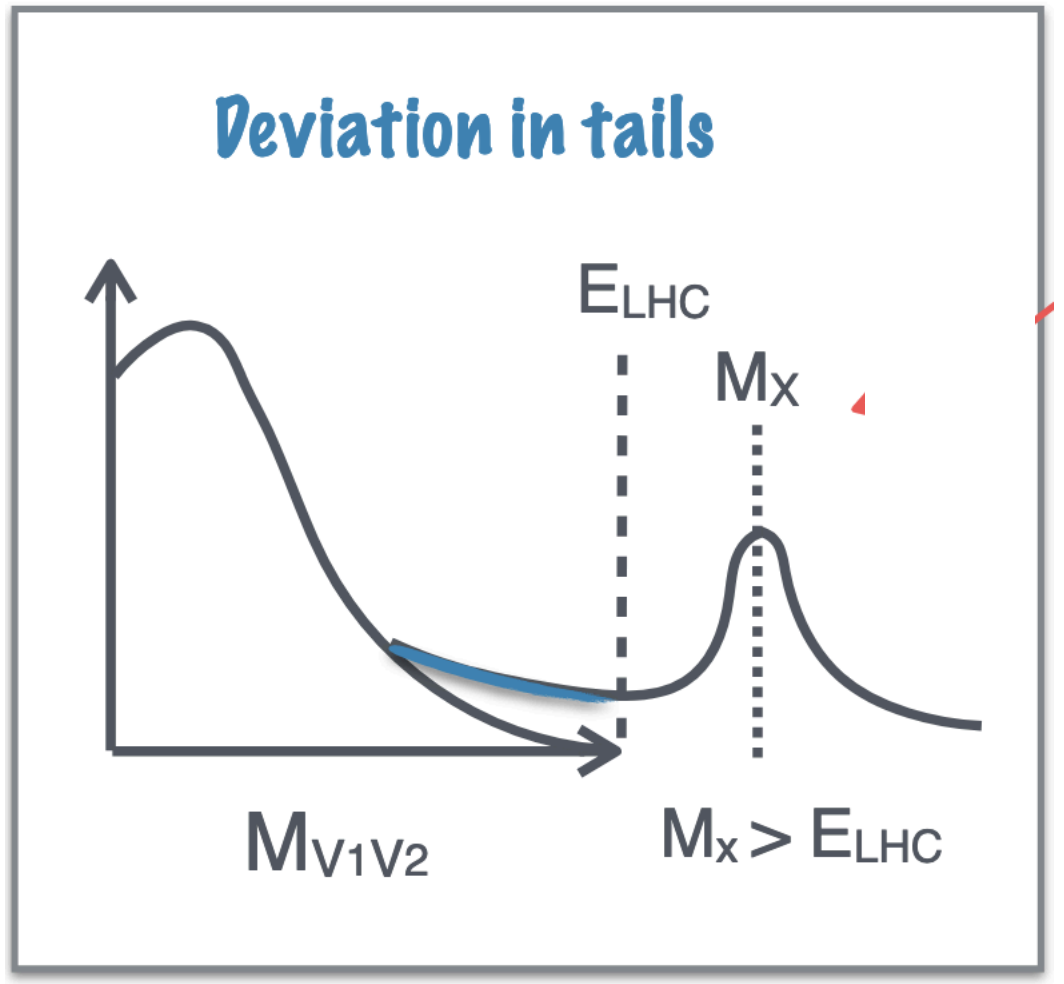
Precision in Vector Boson Scattering

- Search for New Physics in tails: onset of resonances
- NLO EW(+QCD) corrections important for those tails

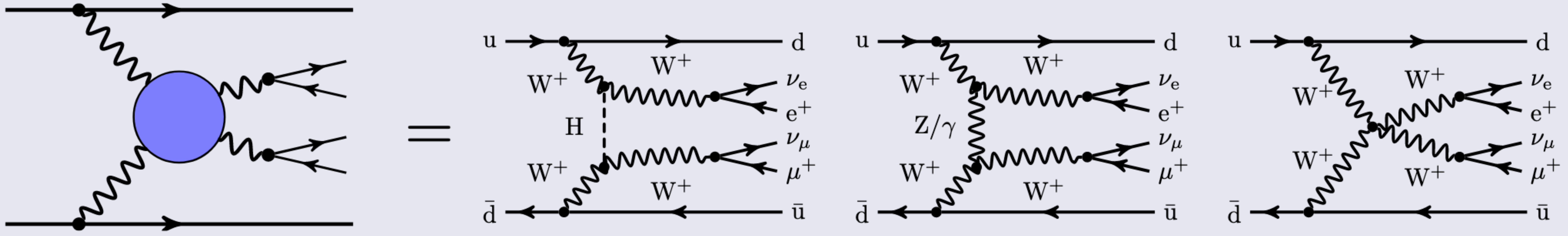


adapted from M. Pellen, MBI 2022



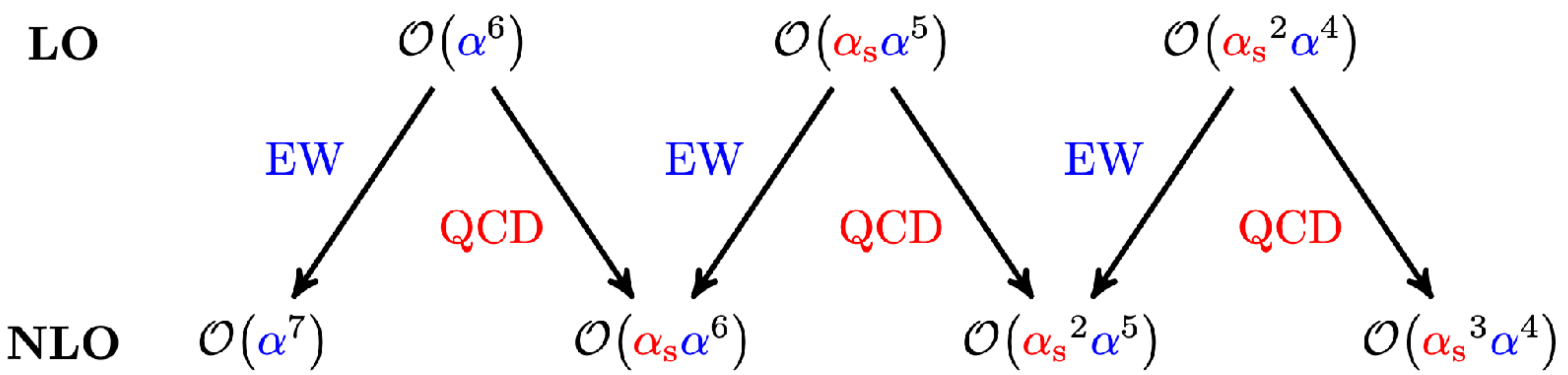


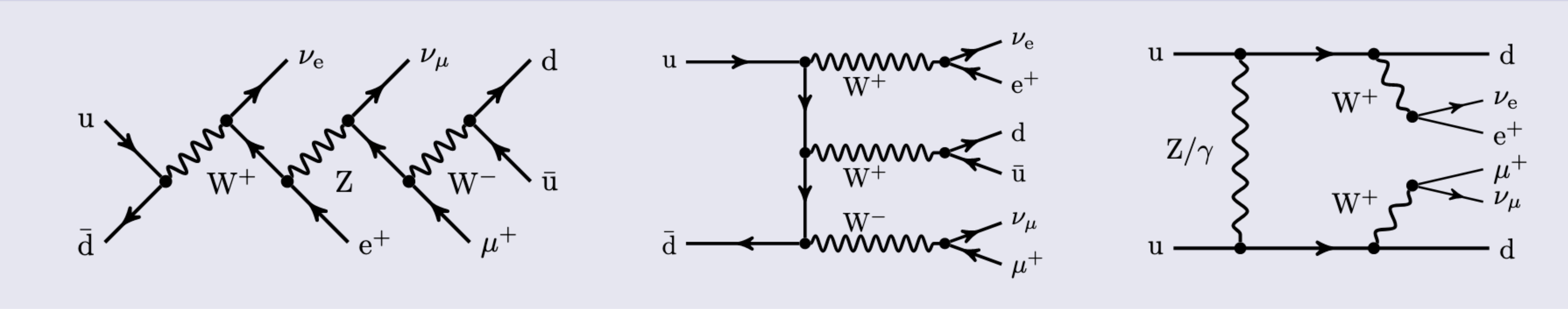
VBS diagrams



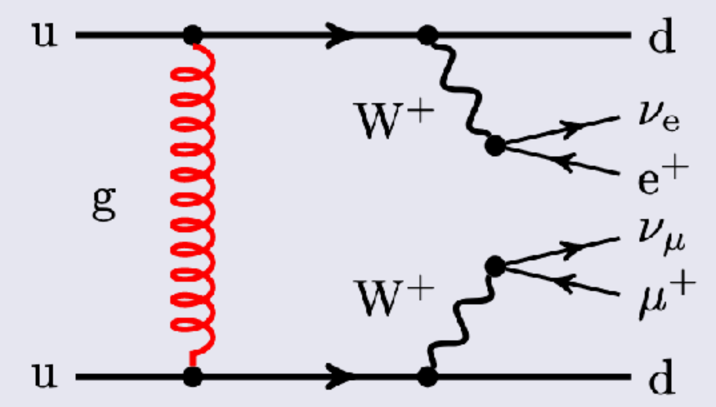
VBS LO+NLO:
Biedermann, Denner, Pellen, 1708.00268 ; Denner, Dittmaier, Maierhöfer, Pellen, Schwan, 1611.02951; Ballestrero et al., 1803.07943; Denner, Franken, Pellen, Schmidt, 2107.10688;

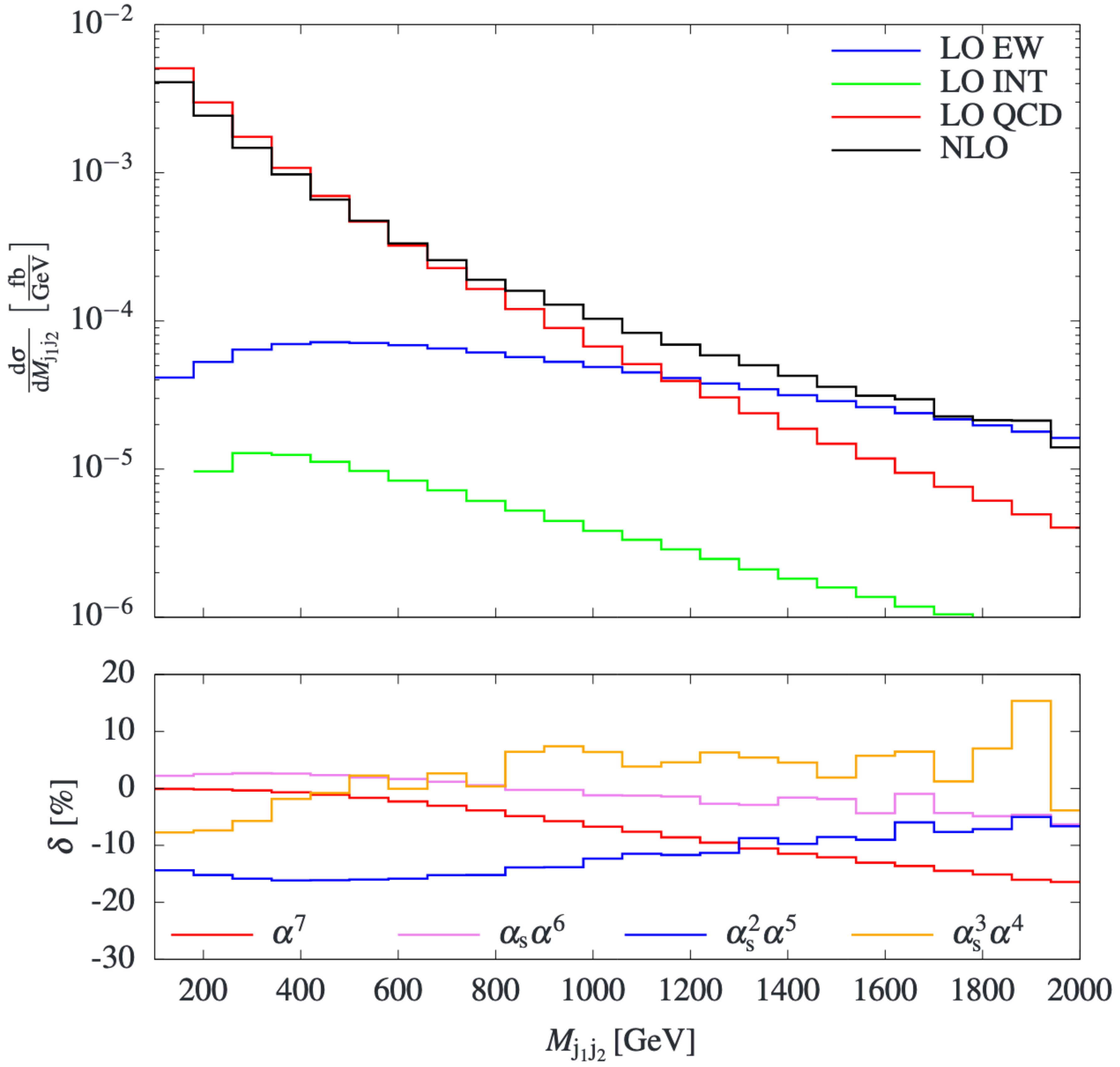
Precision in Vector Boson Scattering





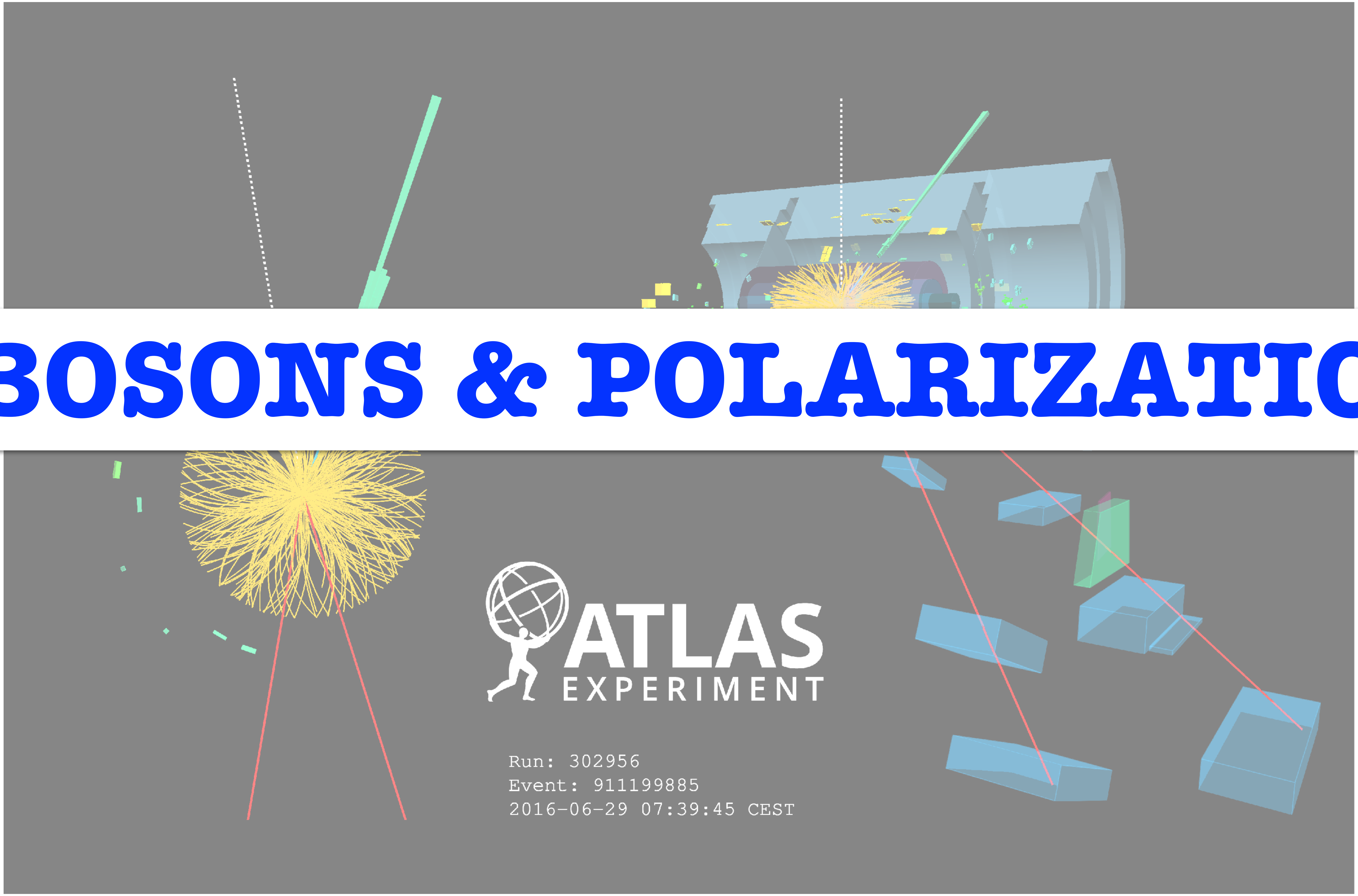
Even more (QCD) diagrams ...





Process	W^+W^+	W^+Z	ZZ	W^+W^- (VBS setup)	W^+W^- (Higgs setup)
$\Delta\sigma^{\alpha^7}_{\mathrm{NLO}}$[fb]	−0.2169(3)	−0.04091(2)	−0.015573(5)	−0.307(1)	−0.103(1)
$\sigma^{\alpha^6}_{\mathrm{LO}}$[fb]	1.4178(2)	0.25511(1)	0.097683(2)	2.6988(3)	1.5322(2)
δ^{α^7}[%]	−15.3	−16.0	−15.9	−11.4	−6.7

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s{}^2\alpha^5)$	$\mathcal{O}(\alpha_s{}^3\alpha^4)$
NLO	✓	✓	✓	✓
NLO+PS	✓	✓*	✗	✓



DIBOSONS & POLARIZATION

Polarization in dibosons and VBS: LO and NLO

Vast theory literature (non-exhaustive) from 2010+

Omissions are my fault !!

Polarization for single bosons

Bern et al., 1103.5445; Stirling, Vryonidou, 1204.6427; Belyaev, Ross, 1303.3297; Pellen, Poncelet, Popescu, 2109.14336

Polarization in dibosons: NLO QCD / NLO EW

Baglio, Le Duc, 1810.11034; Rahama, Singh, 1810.11657; Baglio, Le Duc, 1910.13746; Rahama, Singh, 1911.03111; Denner, Pellicciol, 2006.14867 + 2107.06579; Rahama, Singh, 2109.09345; Denner, Pellicciol, 2010.07149; Le Duc, Baglio, 2203.01470; Le Duc, Baglio, Dao, 2208.09232

Polarization in dibosons: NNLO QCD

Poncelet/Popoescu, 2102.13583

Polarization in VBS: LO yet

Kilian, Ohl, JRR, Sekulla, 1408.6207; Ballestrero, Maina, Pellicciol, 1710.09339; Ballestrero, Maina, Pellicciol, 1907.04722; Buarque Franzosi, Mattelaer, Ruiz, Shil, 1912.01725; Ballestrero, Maina, Pellicciol, 2007.07133

Polarization in dibosons and VBS

Courtesy to René Poncelet for many polarization figures/plots

Polarized bosons discriminate between “gauge” and “Goldstone” modes: “Yang-Mills vs. EWSB”

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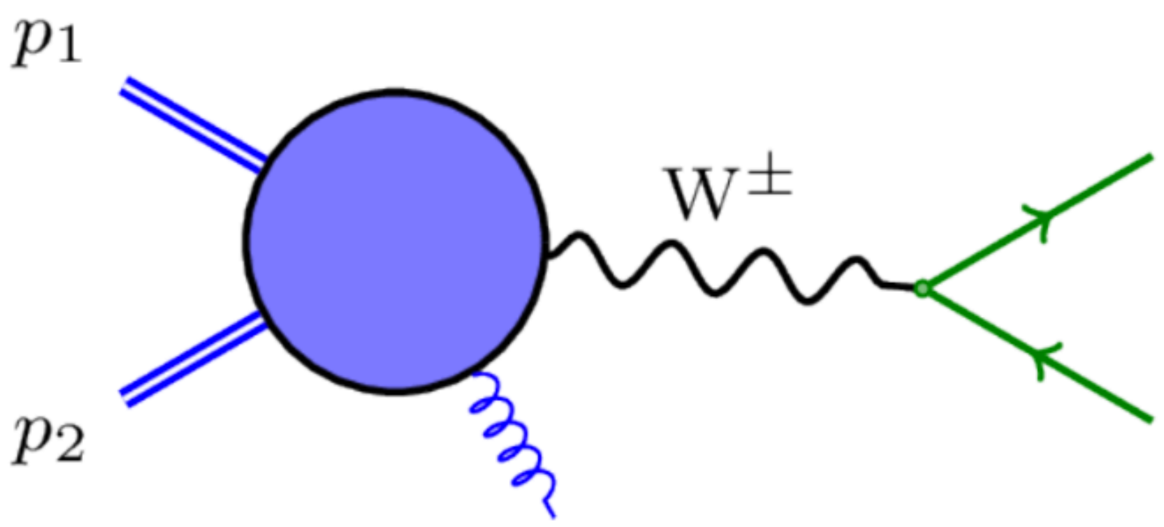
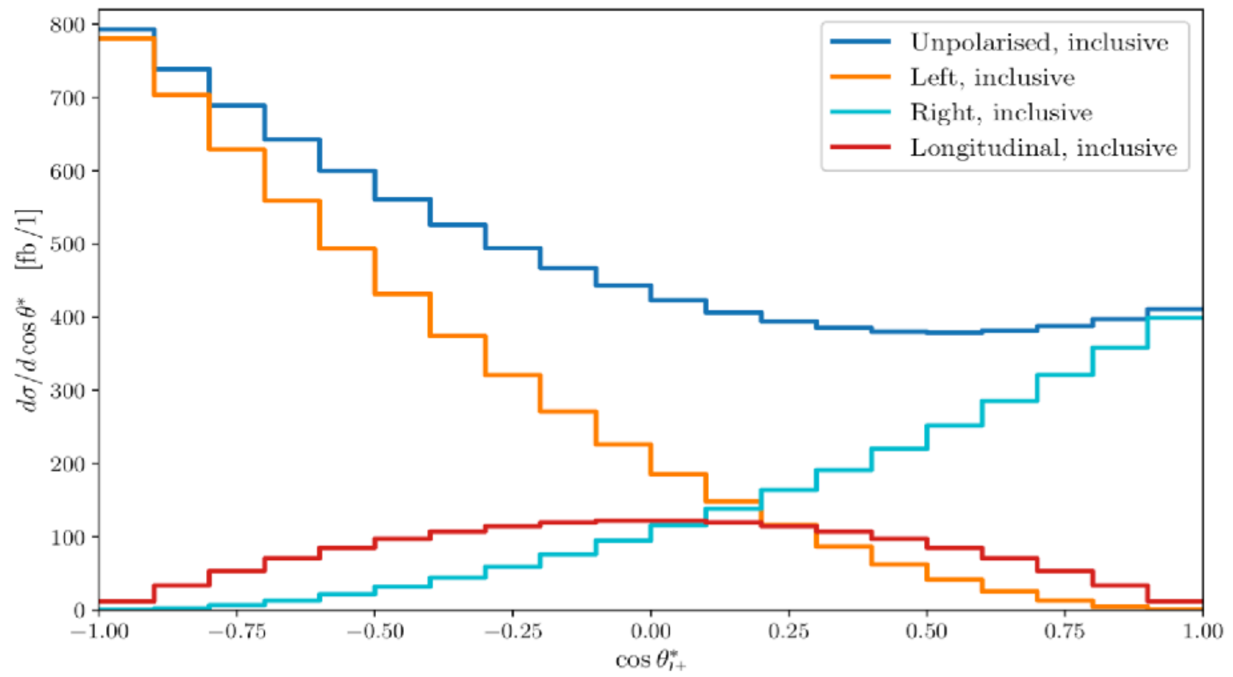
Polarization only accessible via decay products; definition of polarizations “as on-shell as possible”



$$M_\lambda = \mathbf{P}_\mu \cdot \frac{-g_{\mu\nu} + \frac{k^\mu k^\nu}{k^2}}{k^2 - M_V^2 + i M_V \Gamma_V} \cdot \mathbf{D}_\nu$$

$$-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2} \longrightarrow \sum_\lambda \epsilon_\lambda^{\mu\,*} \epsilon_\lambda^\nu$$

On-shell vector bosons (NWA or DPA)



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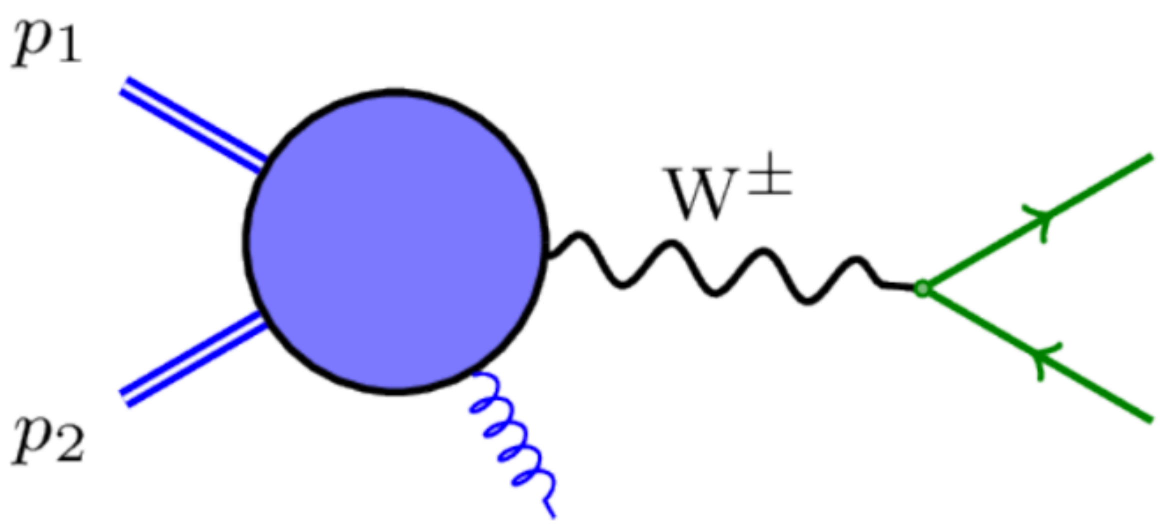

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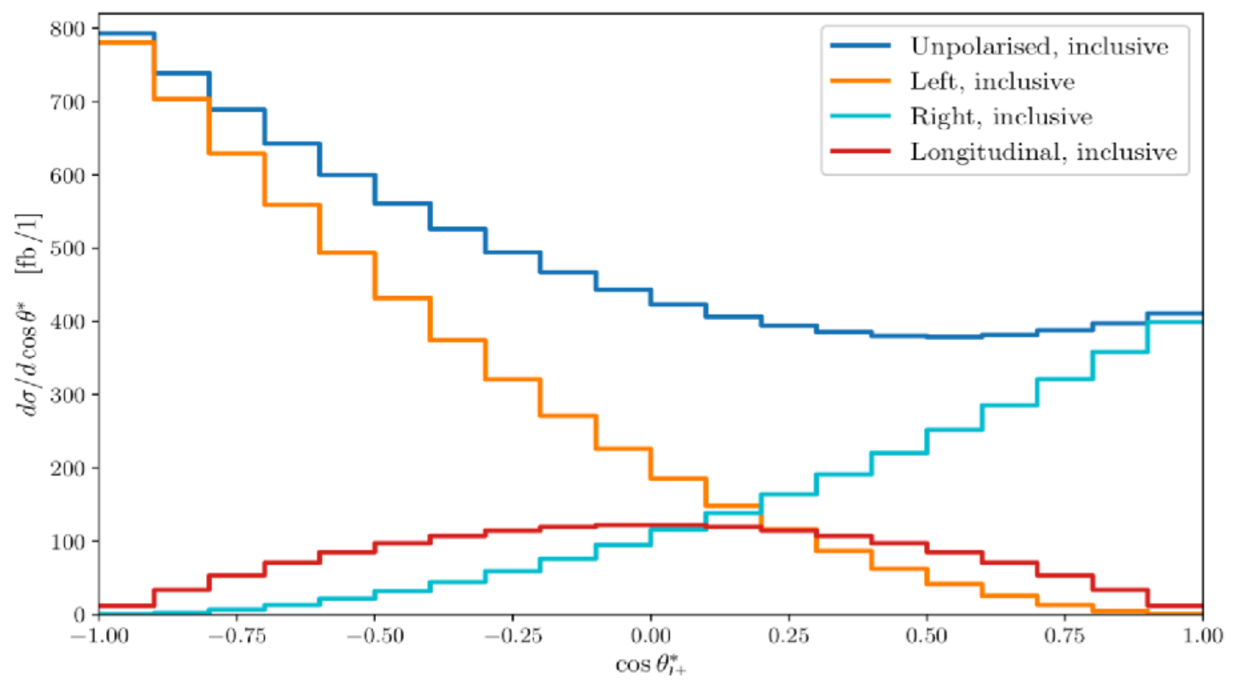

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\cos\theta^*} = \frac{3}{4}\sin\theta^* f_0 + \frac{3}{8}(1-\cos\theta^*)^2 f_L + \frac{3}{8}(1+\cos\theta^*)^2 f_R$$

Extract polarization fractions via projections and/or fits

Decay angle in vector boson rest frame $\cos\theta^*$

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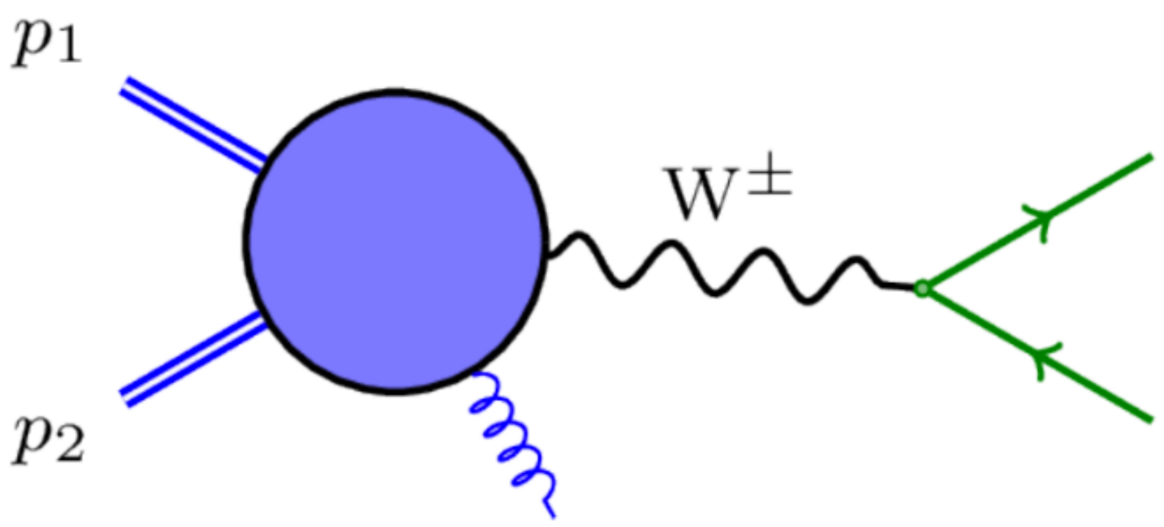

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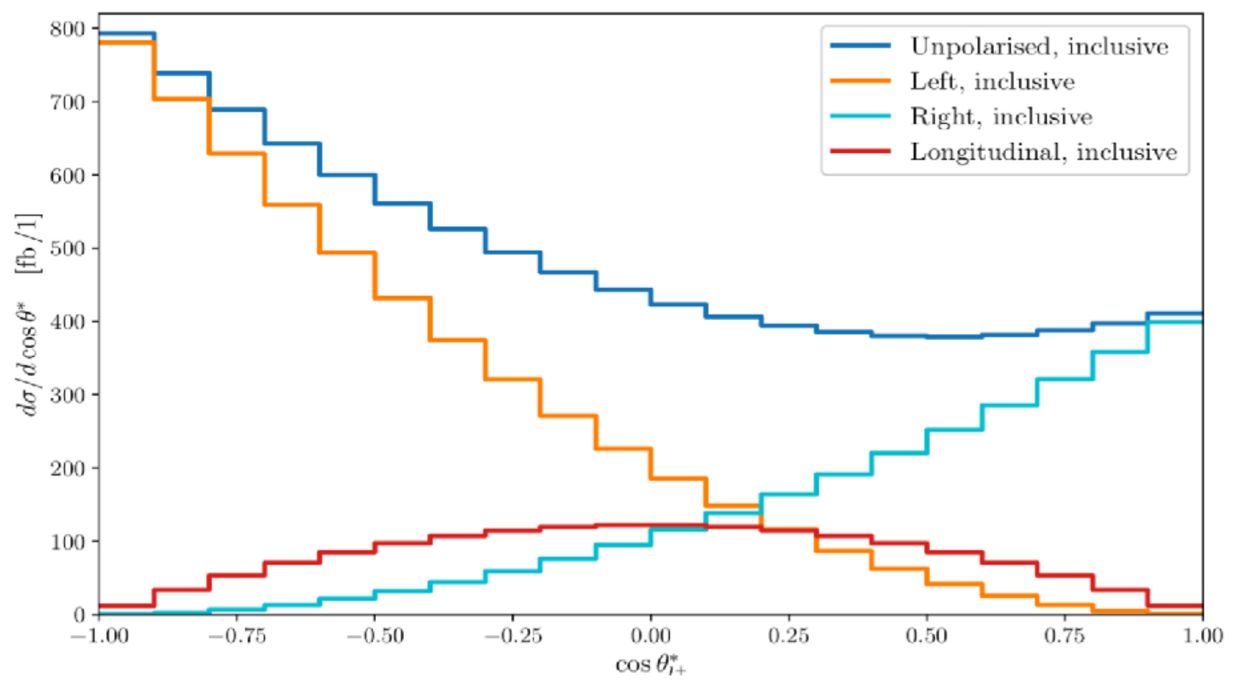

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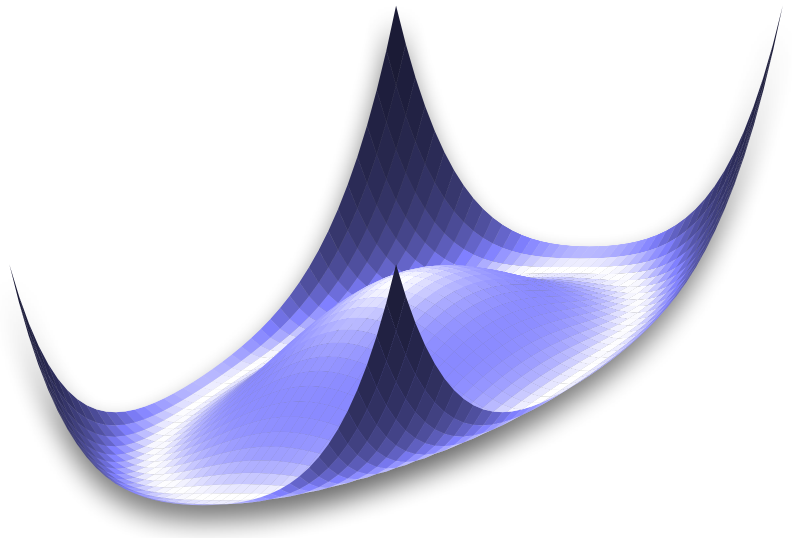
Problems

- ○ Fiducial cuts on leptons: disturb relations between angular correlations and polarization fractions
- ○ Decay: Higher order corrections affect ang. decomposition
- ○ Vector boson rest frame ok for *Z*, difficult for *W*



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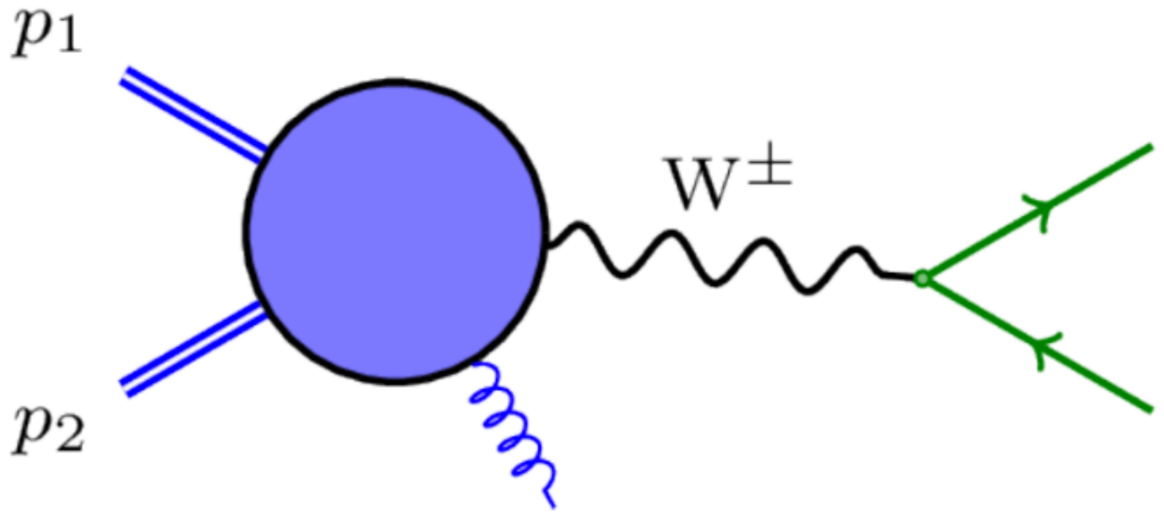

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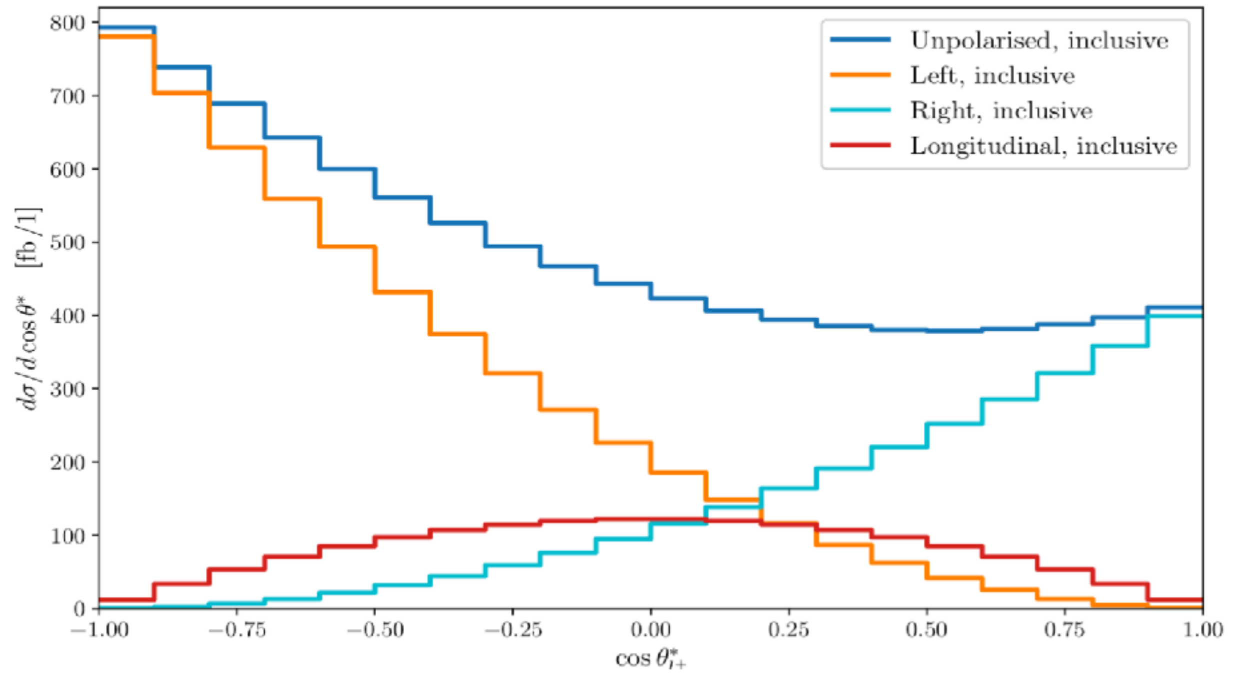

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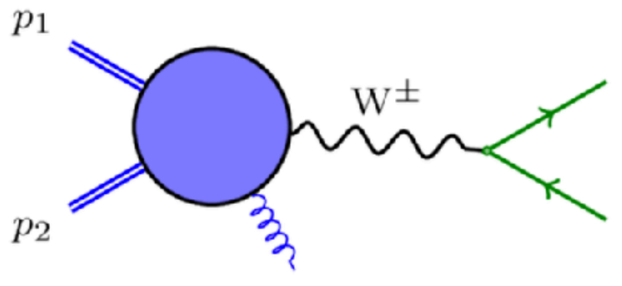
Better: use signal model with polarized events

Problems

- Fiducial cuts on leptons: disturb relations between angular correlations and polarization fractions
- Decay: Higher order corrections affect ang. decomposition
- Vector boson rest frame ok for *Z*, difficult for *W*

Definition of polarized vector bosons



$$M_\lambda = \mathbf{P}_\mu \cdot \frac{-g_{\mu\nu} + \frac{k^\mu k^\nu}{k^2}}{k^2 - M_V^2 + iM_V\Gamma_V} \cdot \mathbf{D}_\nu$$

$$|M|^2 = \underbrace{\sum_\lambda |M_\lambda|^2}_{\text{Polarized cross section/ squared matrix element}} + \underbrace{\sum_{\lambda\neq\lambda'} M_\lambda^* M_\lambda}_{\text{Spin correlations/ interferences}}$$

$$\boxed{\frac{d\sigma}{d\mathcal{O}} = f_L \frac{d\sigma_L}{d\mathcal{O}} + f_R \frac{d\sigma_R}{d\mathcal{O}} + f_0 \frac{d\sigma_0}{d\mathcal{O}} \quad \left[+ f_{corr.} \frac{d\sigma_{corr.}}{d\mathcal{O}} \right]}$$

Again: fit to the measurement the fractions f_L , f_R , f_0

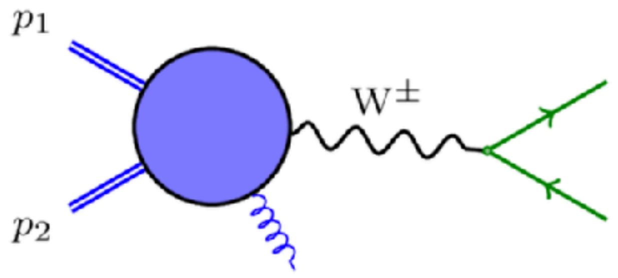
Impact of higher order/spin correlations ?

- ☑ Spin correlations can be included
- ☑ Any observable $\mathcal{O}$ can be used (lab frame!)
- ☑ $d\sigma$ / $d\mathcal{O}$ can be systematically improved (N[N]LO etc.)

$$\frac{d\sigma}{d\mathcal{O}} = f_\perp \frac{d\sigma_\perp}{d\mathcal{O}} + f_\parallel \frac{d\sigma_\parallel}{d\mathcal{O}} \qquad \left[\cancel{+ f_{corr.} \frac{d\sigma_{corr.}}{d\mathcal{O}}} \right]$$

select regions with small/tiny interferences

Definition of polarized vector bosons



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Polarized cross section/ squared matrix element

Spin correlations/ interferences

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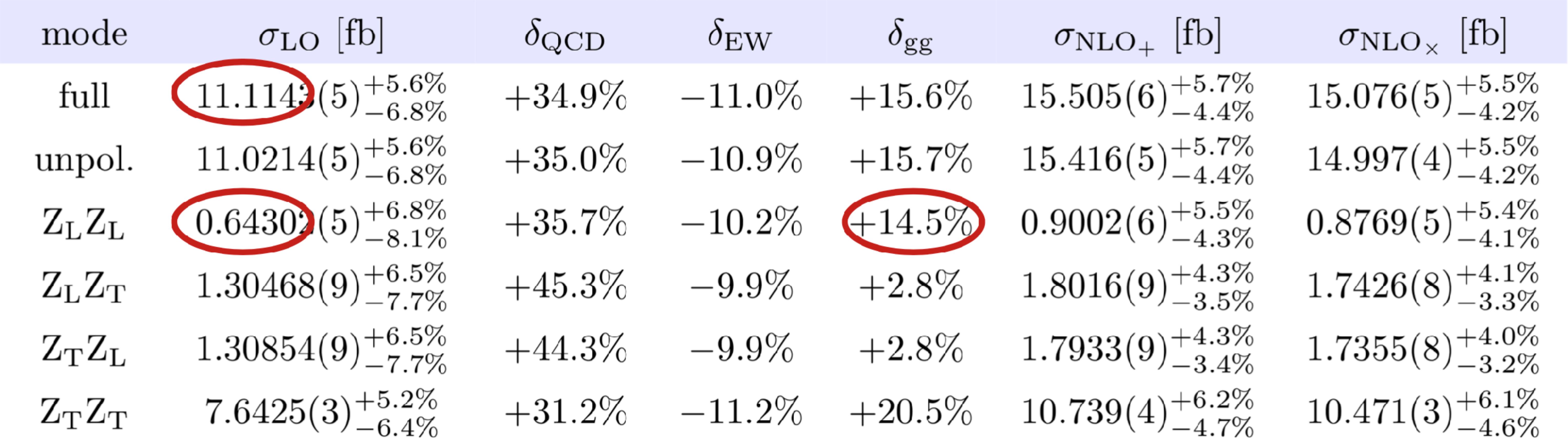
select regions with small/tiny interferences

$pp \to ZZ \to \ell\ell\ell\ell + X$	polarized; NLO QCD / EW	Denner, Pellicciolli, 2107.06579
$pp \to W^+W^- \to e^-\overline{\nu}_e\mu^+\nu_\mu + X$	polarized; NNLO QCD	Poncelet, Popescu, 2102.13583
$pp \to W^+Z \to e^+\nu_e\mu^+\mu^- + X$	polarized; NLO QCD / EW	Duc, Baglio, 2203.01470
$pp \to Wj \to \ell\nu_\ell j + X$	polarized; NNLO QCD	Pellen, Poncelet, Popescu, 2109.14336
$pp \to e^+\nu_e\mu^-\overline{\nu}_\mu jj + X$	polarized; LO	Ballestrero, Maina, Pellicciolli, 2007.07133

$pp \to ZZ \to 4l + X$ NLO QCD + EW

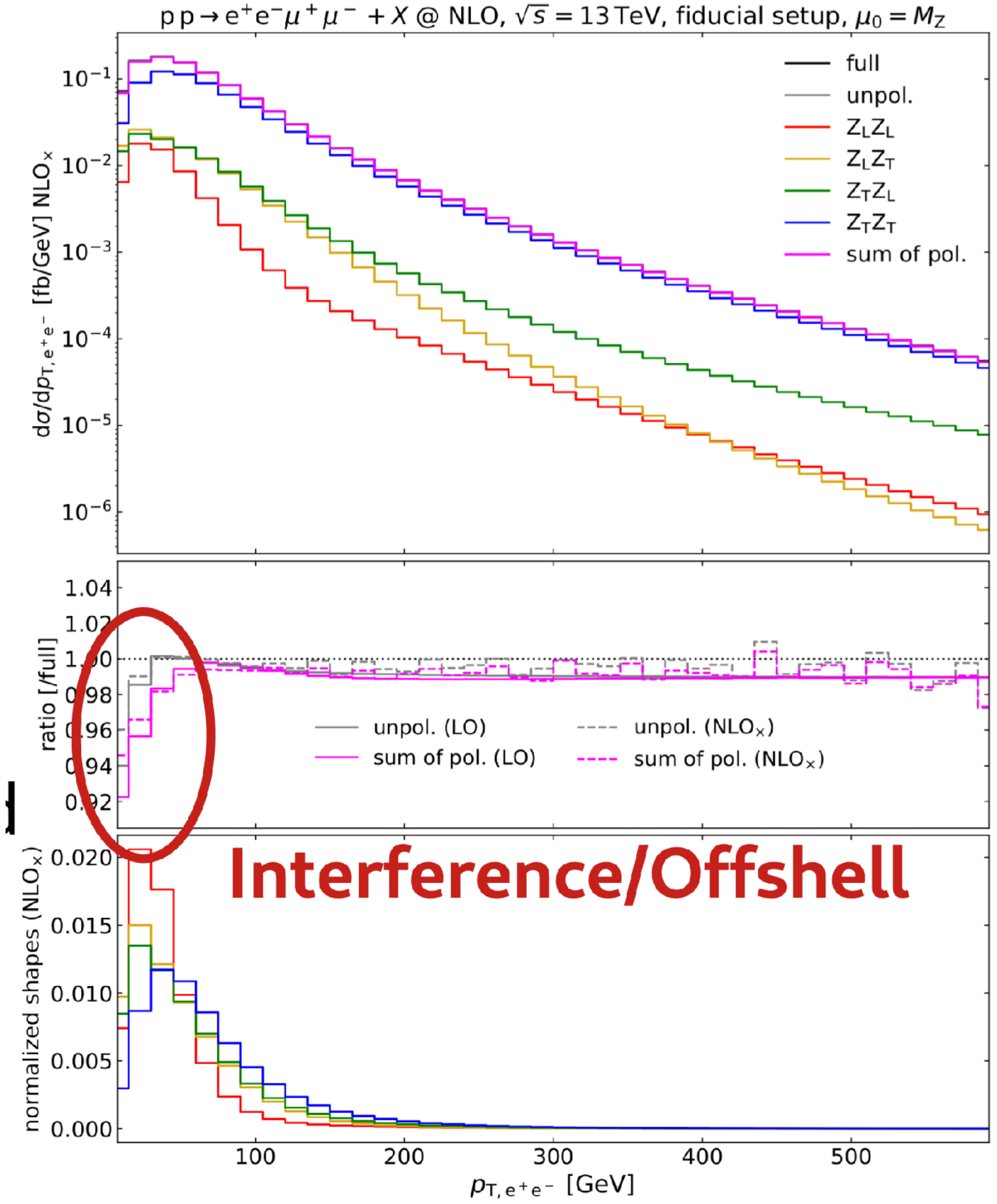
Denner, Pelliccioli, 2107.06579



mode	σ_{LO} [fb]	δ_{QCD}	δ_{EW}	δ_{gg}	σ_{NLO_+} [fb]	$\sigma_{\text{NLO}_\times}$ [fb]
full	$11.1143(5)^{+5.6\%}_{-6.8\%}$	$+34.9\%$	-11.0%	$+15.6\%$	$15.505(6)^{+5.7\%}_{-4.4\%}$	$15.076(5)^{+5.5\%}_{-4.2\%}$
unpol.	$11.0214(5)^{+5.6\%}_{-6.8\%}$	$+35.0\%$	-10.9%	$+15.7\%$	$15.416(5)^{+5.7\%}_{-4.4\%}$	$14.997(4)^{+5.5\%}_{-4.2\%}$
$\text{Z}_\text{L}\text{Z}_\text{L}$	$0.64302(5)^{+6.8\%}_{-8.1\%}$	$+35.7\%$	-10.2%	$+14.5\%$	$0.9002(6)^{+5.5\%}_{-4.3\%}$	$0.8769(5)^{+5.4\%}_{-4.1\%}$
$\text{Z}_\text{L}\text{Z}_\text{T}$	$1.30468(9)^{+6.5\%}_{-7.7\%}$	$+45.3\%$	-9.9%	$+2.8\%$	$1.8016(9)^{+4.3\%}_{-3.5\%}$	$1.7426(8)^{+4.1\%}_{-3.3\%}$
$\text{Z}_\text{T}\text{Z}_\text{L}$	$1.30854(9)^{+6.5\%}_{-7.7\%}$	$+44.3\%$	-9.9%	$+2.8\%$	$1.7933(9)^{+4.3\%}_{-3.4\%}$	$1.7355(8)^{+4.0\%}_{-3.2\%}$
$\text{Z}_\text{T}\text{Z}_\text{T}$	$7.6425(3)^{+5.2\%}_{-6.4\%}$	$+31.2\%$	-11.2%	$+20.5\%$	$10.739(4)^{+6.2\%}_{-4.7\%}$	$10.471(3)^{+6.1\%}_{-4.6\%}$

Total cross sections

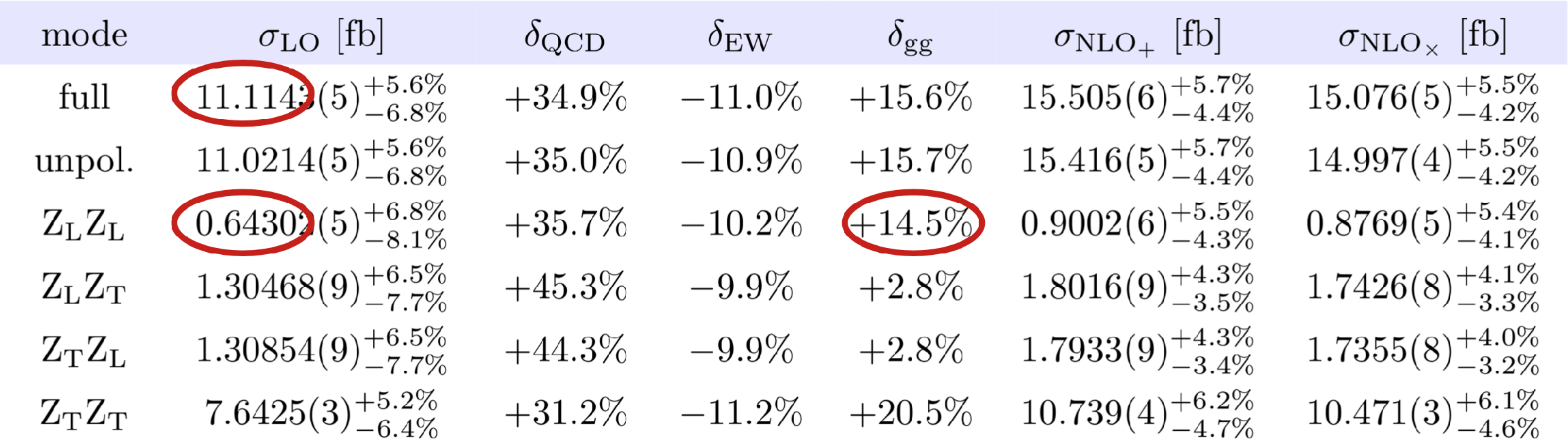
- Small LL contribution, TT dominates
- Quite sizable NLO and EW corrections
- Large *gg*-loop induced (LI) contribution
- Pol. fractions preserved from LO to NLO
- Similar for NLO QCD/EW for *WZ* , *WW*



Interference/Offshell

$pp \to ZZ \to 4l + X$ NLO QCD + EW

Denner, Pellicciolі, 2107.06579



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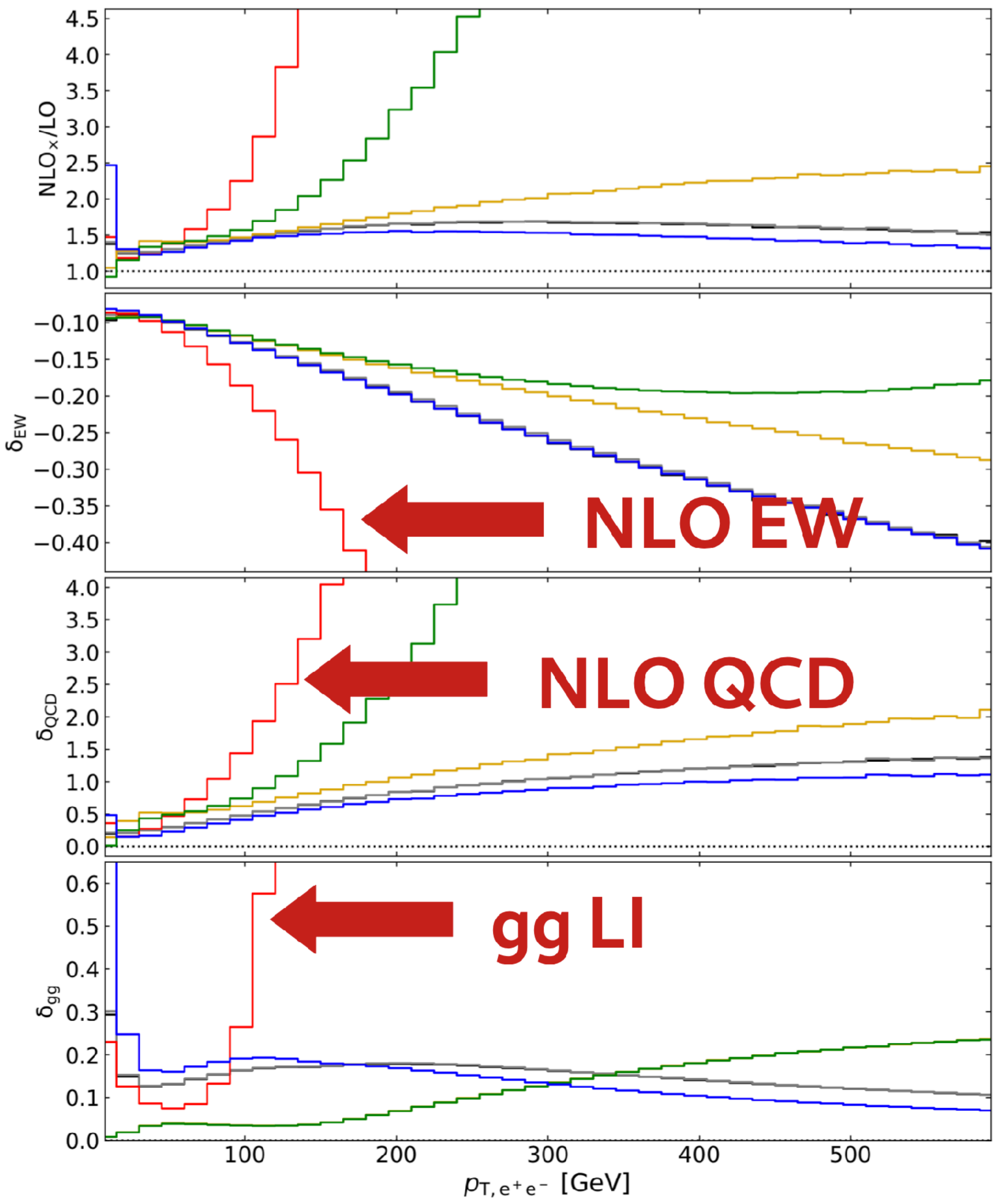


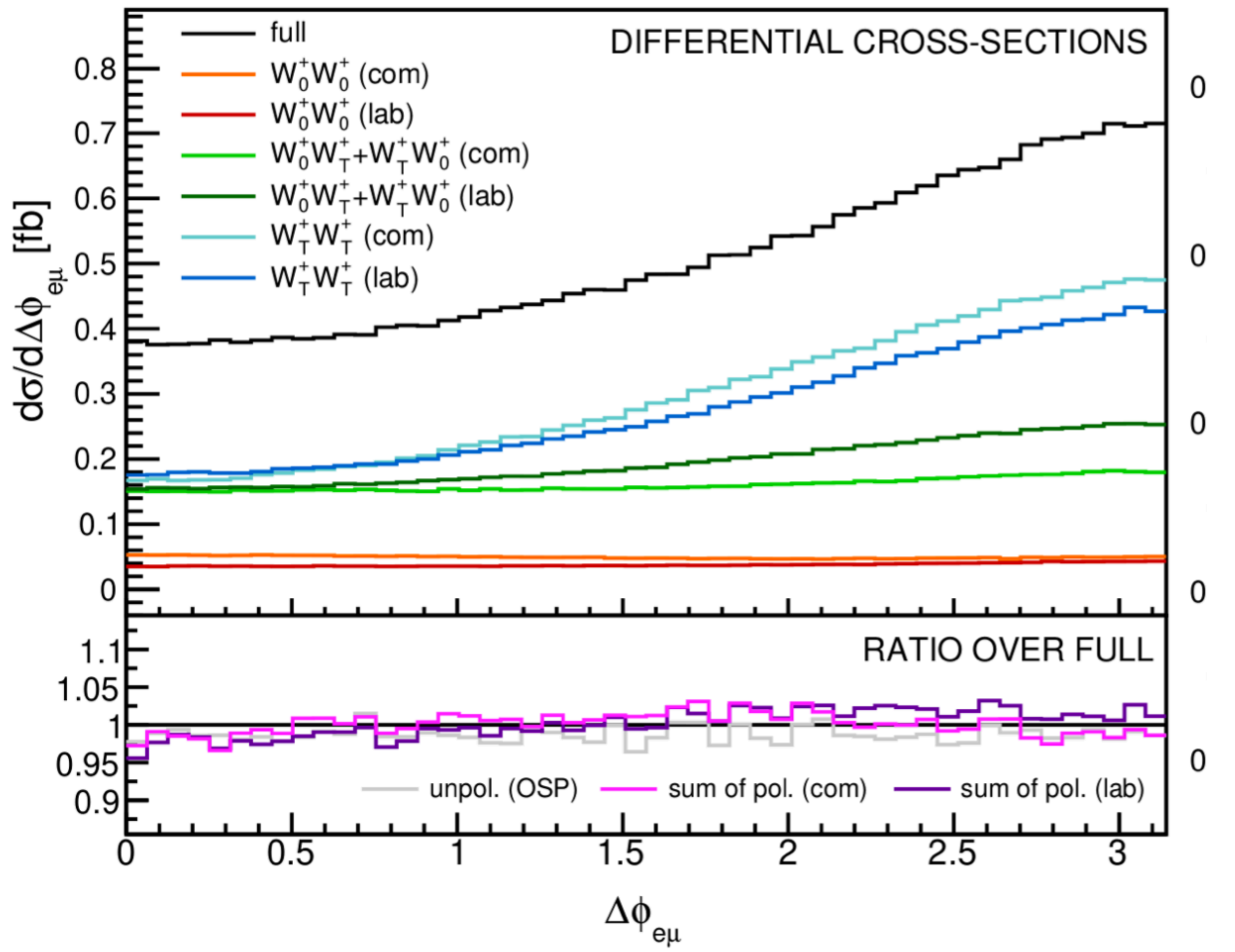
Differential distributions

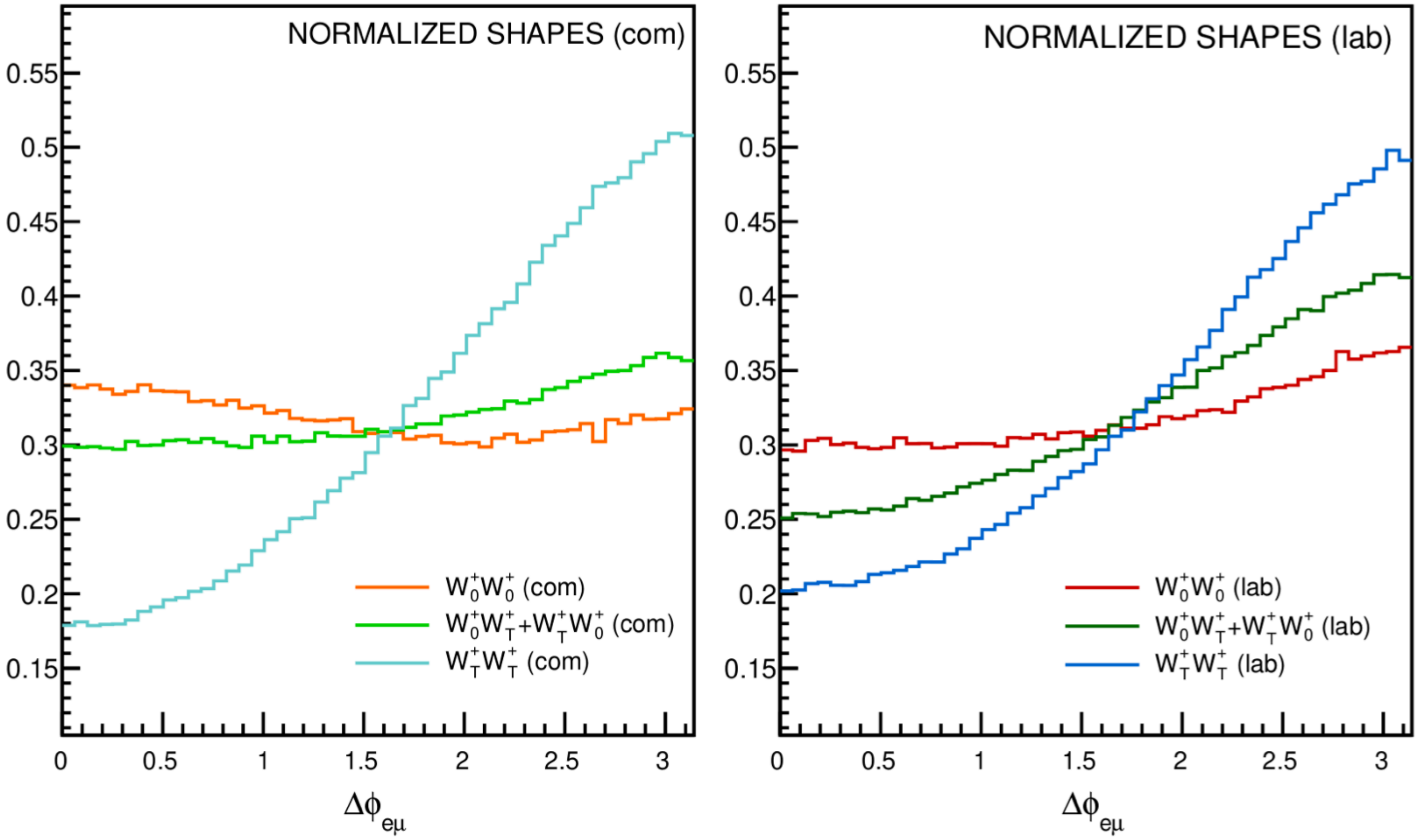
- ○ Low region: off-shell effects and spin correlations
- ○ Very large NLO QCD corrections
- ○ New polarization from e.g. *gq* →*ZZq*
- ○ Great care with such observables, e.g. in fits
- ○ Never use without prescription from local theorist!

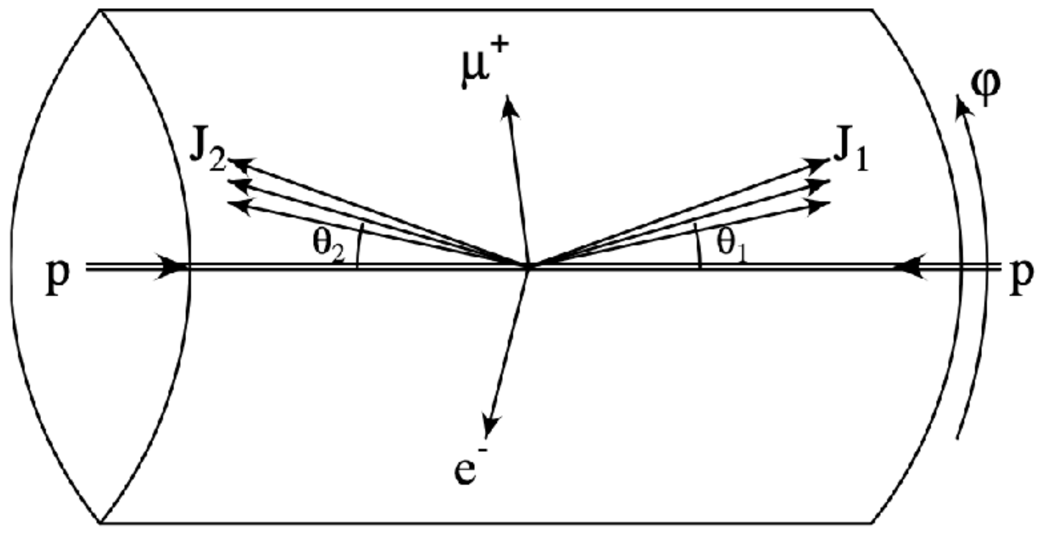
Polarized Vector boson scattering

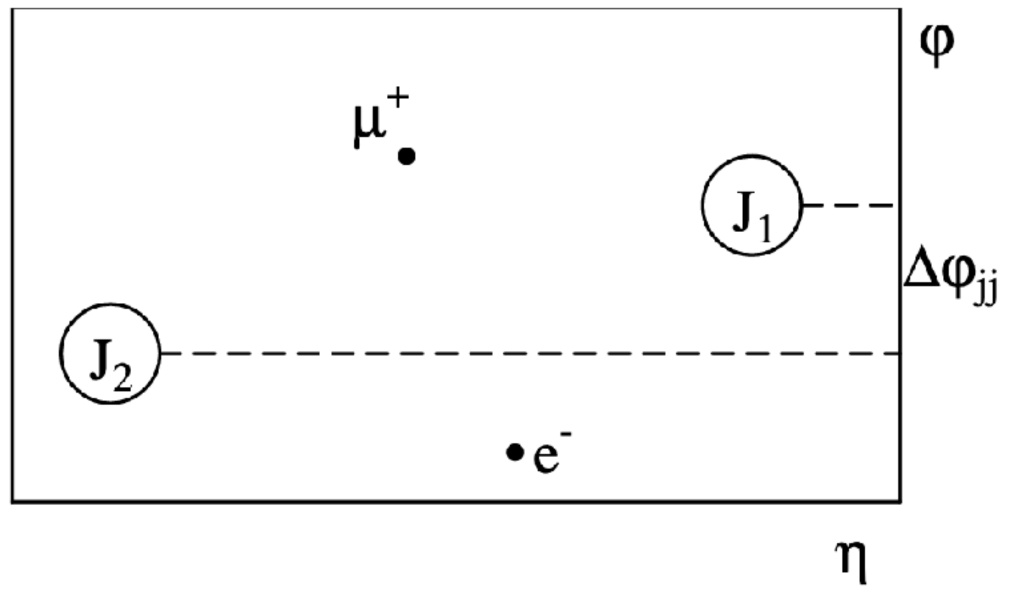
- ☑ Many LO tools available: MG5_*aMC@NLO, PHANTOM, WHIZARD*
- ☑ Singly-/doubly-polarized VBS studied at LO
- ☑ Frame of polarization definition
- ☑ Impact of fiducial selection criteria
- ☑ Study of off-shell effects / spin correlations (“interferences”)

Ballestrero, Maina, Pellicciioli, 2007.07133

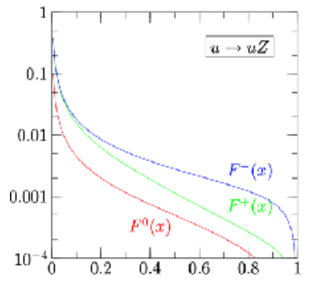








- ○ Small total double-longitudinal (LL) contribution (~10%)
- ○ Drastically different angular correlations (***$\Delta\phi_{e\mu}$***) for LL



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Ballestrero, Maina, Pelliccioli, 2007.07133

W+W+

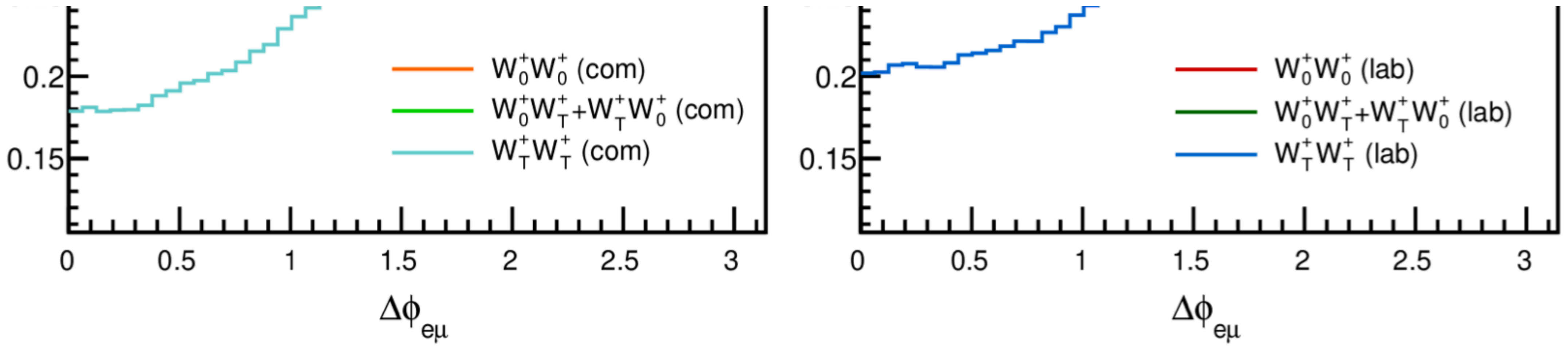
	Lab	WW CoM	ratio
full	3.185(3)		-
unpol	3.167(2)		-
0-unpol	0.8772(8)	0.8374(9)	0.95
T-unpol	2.287(2)	2.329(2)	1.02
0-0	0.2573(3)	0.3275(4)	1.27
0-T,T-0	0.6199(6)	0.5081(5)	0.82
T-T	1.666(1)	1.820(1)	1.09

W+W-

	Lab	WW CoM	ratio
full	4.651(2)		-
unpol	4.641(2)		-
0-unpol	1.186(1)	1.146(1)	0.97
T-unpol	3.456(2)	3.494(2)	1.01
unpol-0	1.2226(4)	1.1905(5)	0.97
unpol-T	3.418(1)	3.450(1)	1.01
0-0	0.3314(2)	0.3786(3)	1.14
0-T	0.8545(4)	0.7669(3)	0.90
T-0	0.8912(4)	0.8119(4)	0.91
T-T	2.563(1)	2.683(1)	1.05

WZ

	Lab	WZ CoM	ratio
full	0.5253(3)		-
unpol	0.5210(3)		-
0-unpol	0.1216(1)	0.1292(1)	1.06
T-unpol	0.3992(2)	0.3918(3)	0.98
unpol-0	0.1370(1)	0.1436(1)	1.05
unpol-T	0.3839(2)	0.3773(2)	0.98
0-0	0.03236(3)	0.03993(5)	1.23
0-T	0.08923(8)	0.08926(8)	1.00
T-0	0.1045(1)	0.1039(1)	0.99
T-T	0.2948(2)	0.2876(2)	0.98



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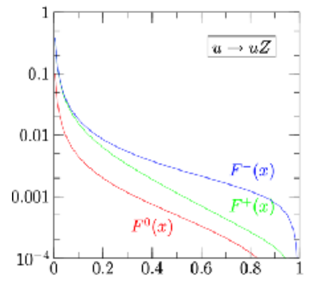
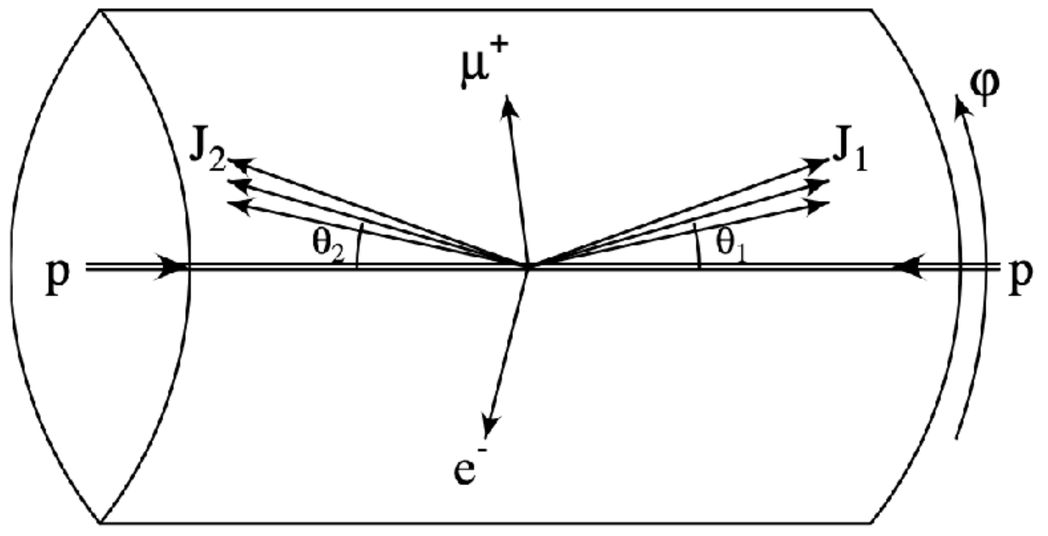
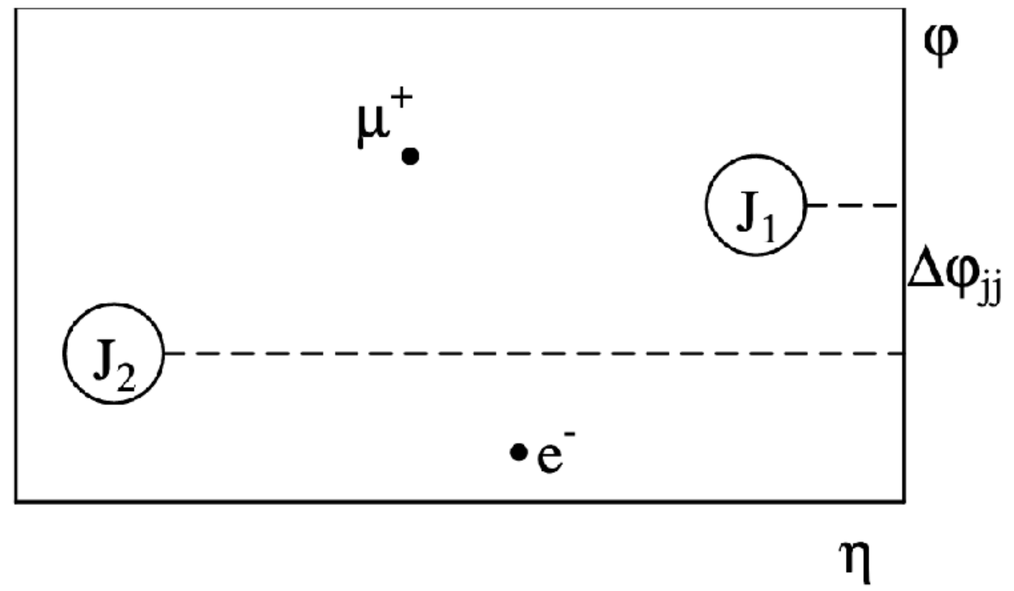
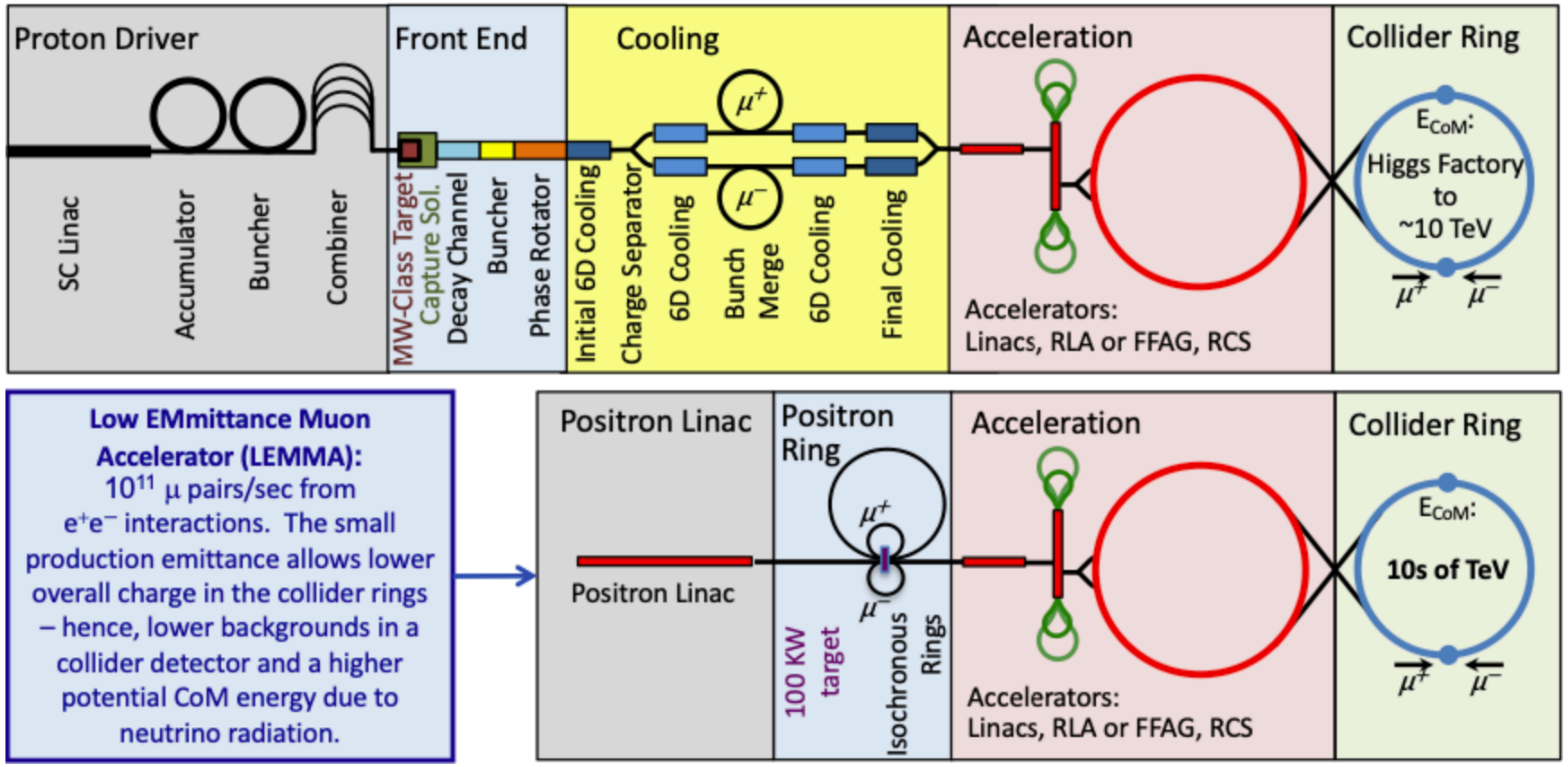






EW BOSONS
@ MUON COLLIDERS



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

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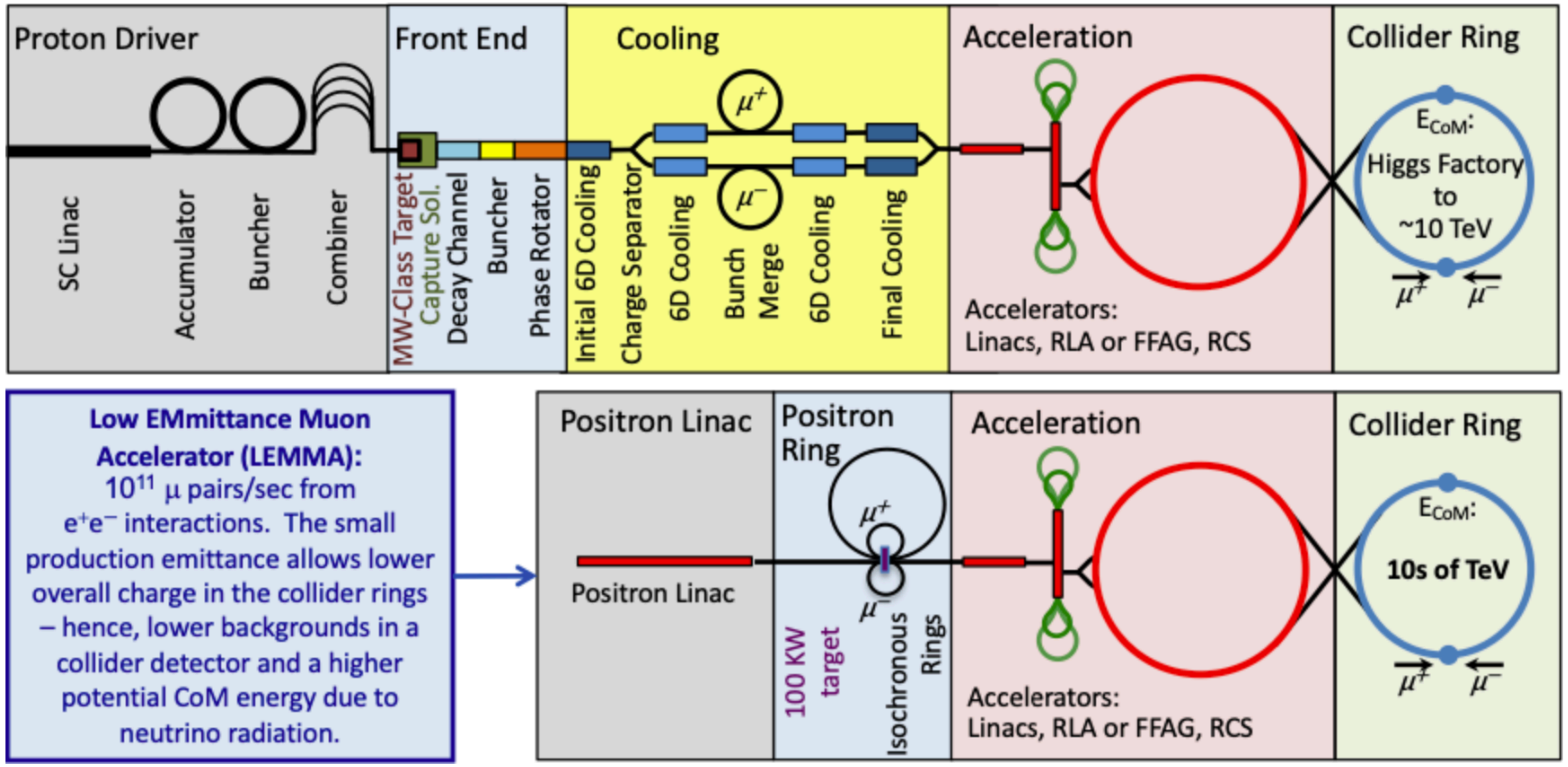

Proton Driver

SC Linac

Accumulator

Buncher

Combiner

Front End

MW-Class Target

Capture Sol.

Decay Channel

Buncher

Phase Rotator

Cooling

Initial 6D Cooling

Charge Separator

6D Cooling

μ^+

μ^-

Bunch Merge

6D Cooling

Final Cooling

Acceleration

Accelerators:
Linacs, RLA or FFAG, RCS

Collider Ring

E_{CoM}:
Higgs Factory
to
~10 TeV

μ^+ μ^-

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Positron Linac

Positron Linac

Positron Ring

100 KW target

μ^+

μ^-

Isochronous Rings

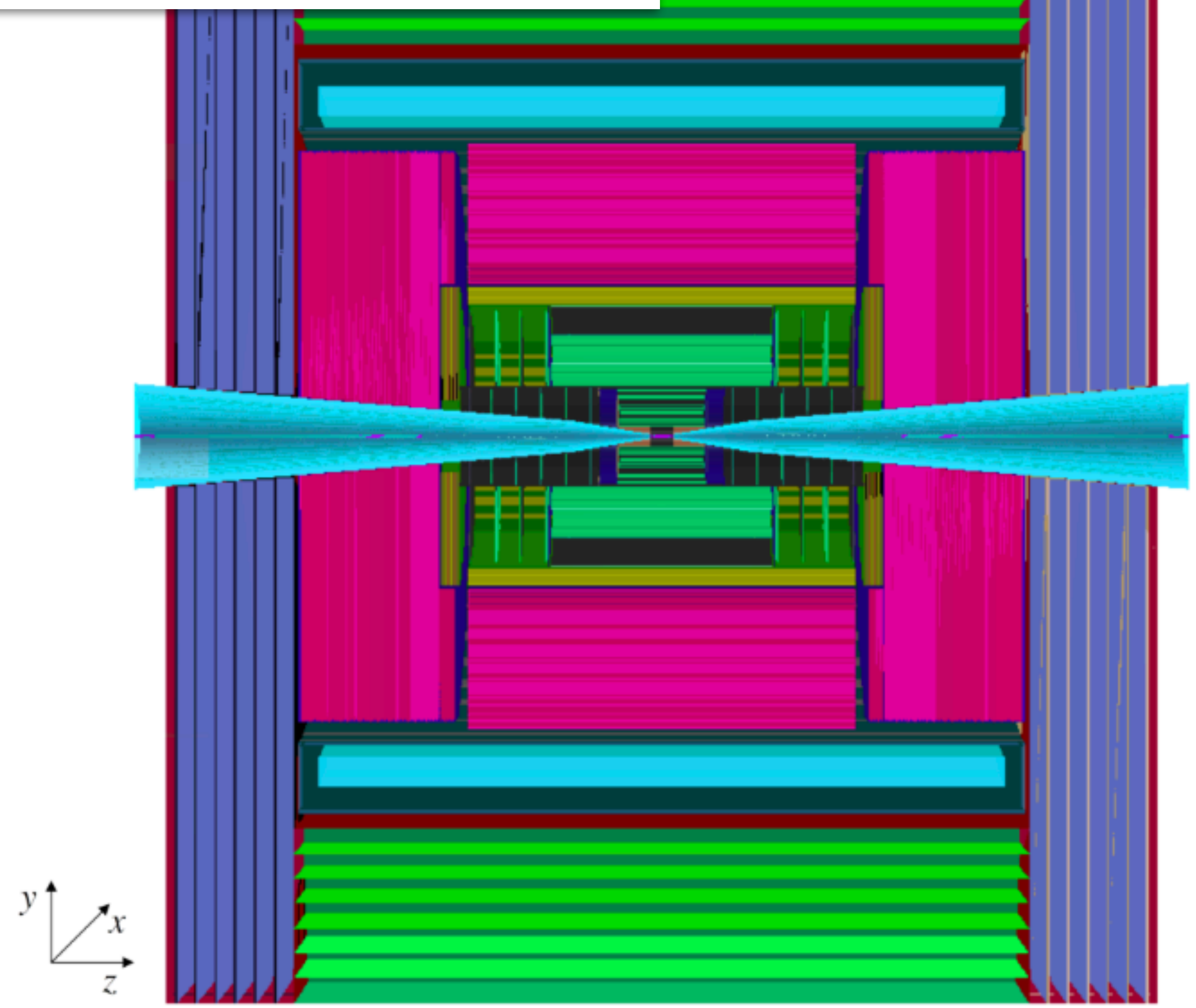
Acceleration

Accelerators:
Linacs, RLA or FFAG, RCS

Collider Ring

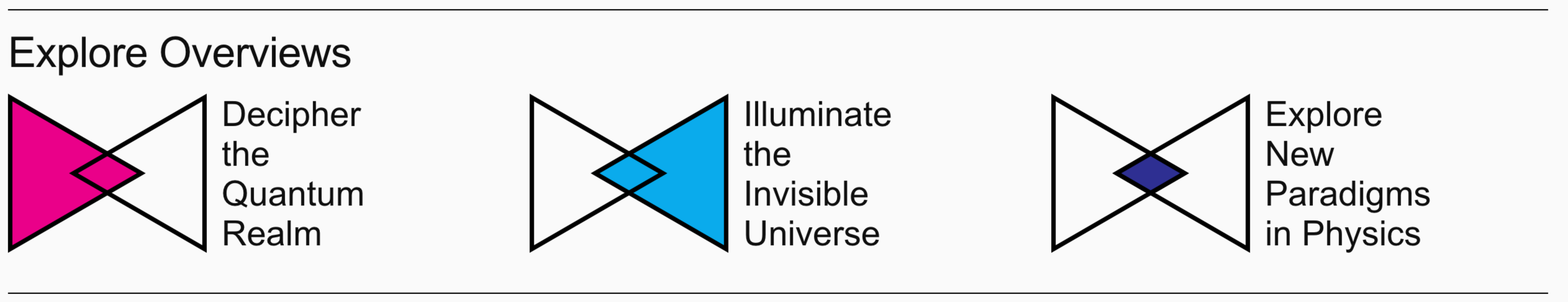
E_{CoM}:
10s of TeV

μ^+ μ^-



The Muon Shot

- EPPSU 2020: MuC R&D (accelerator roadmap) ⟹ start of IMCC

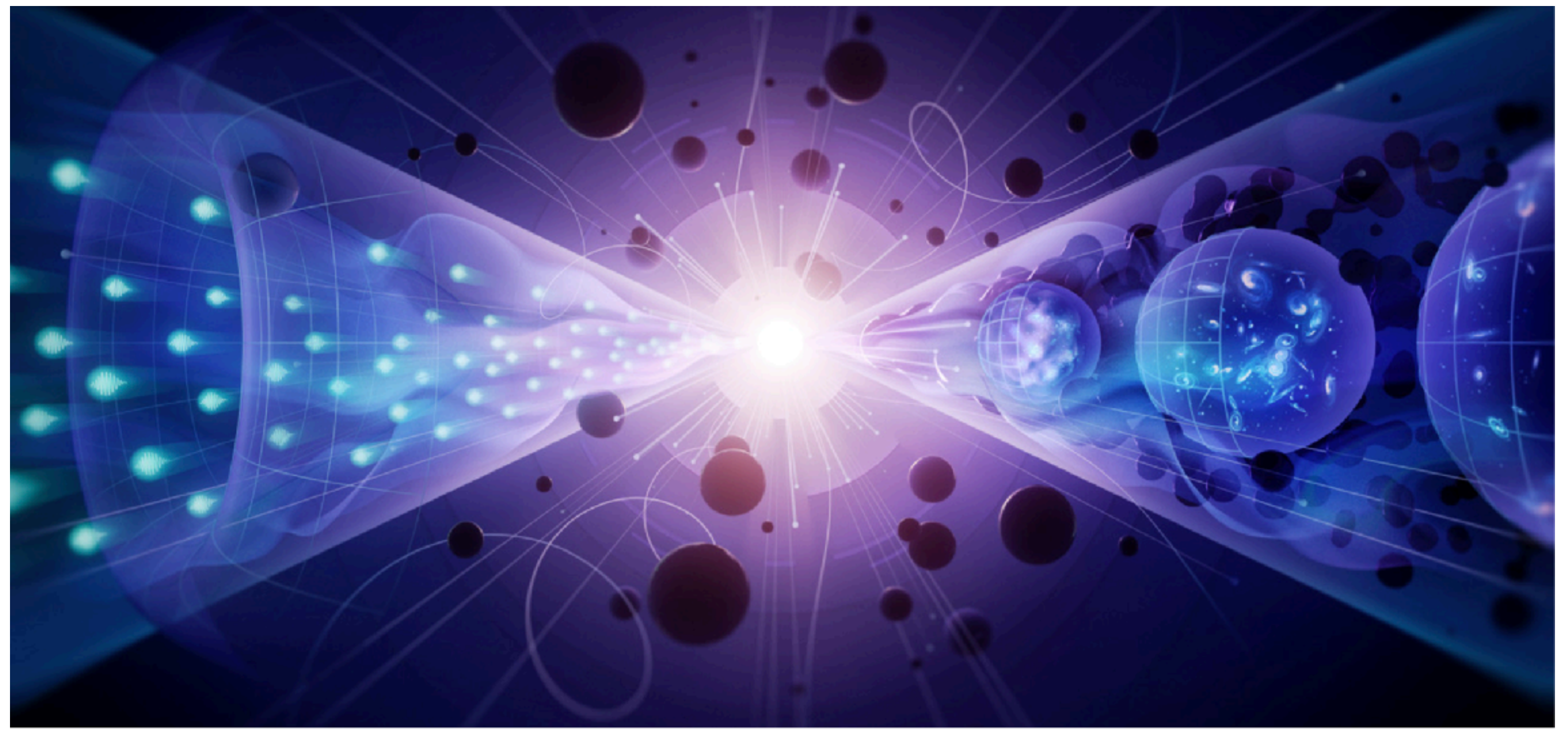


Explore Overviews

Decipher the Quantum Realm

Illuminate the Invisible Universe

Explore New Paradigms in Physics



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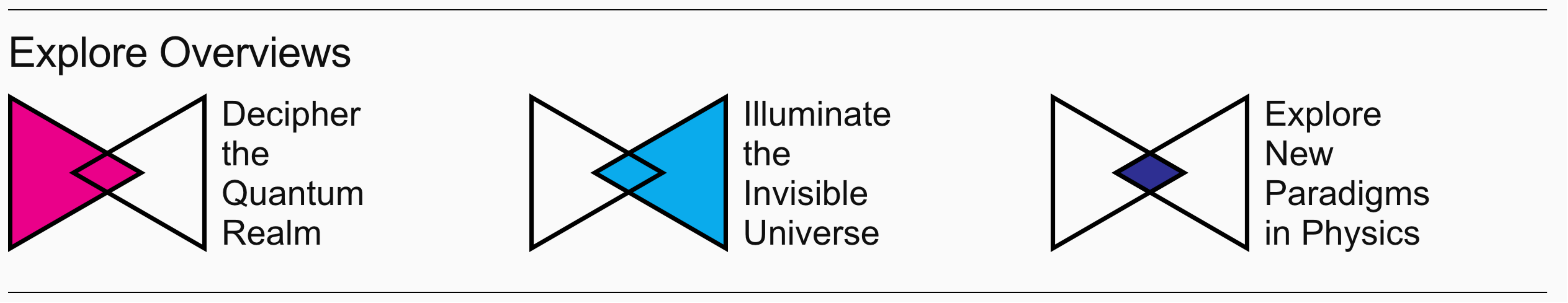

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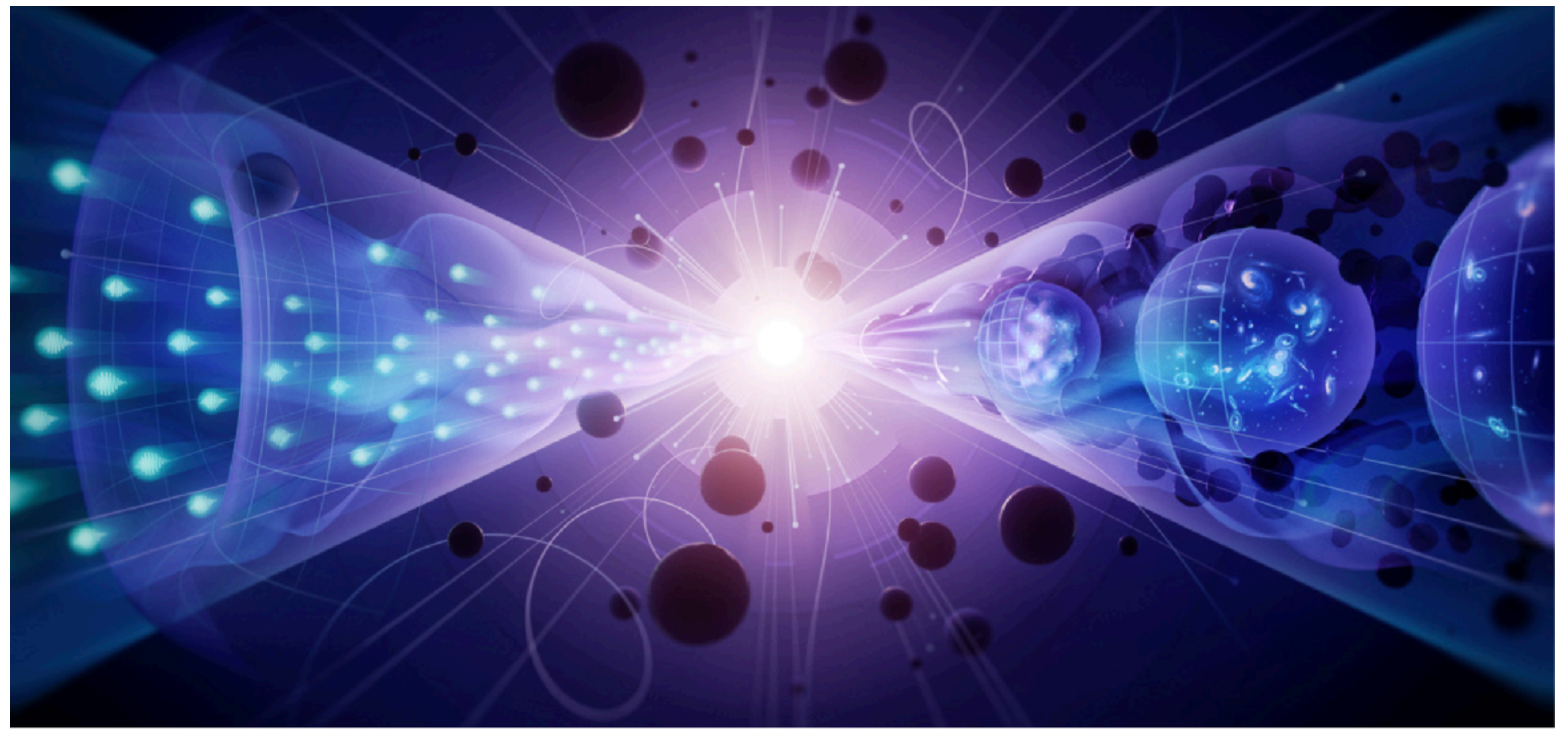

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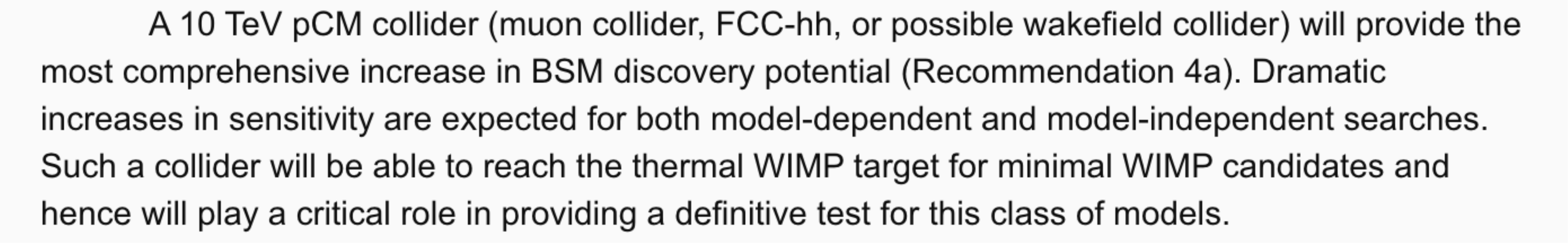
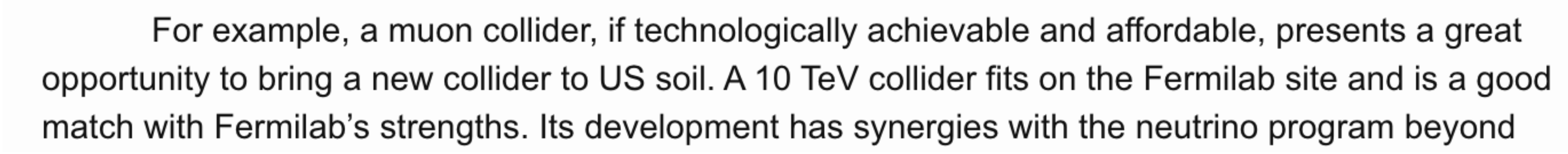


A 10 TeV pCM collider (muon collider, FCC-hh, or possible wakefield collider) will provide the most comprehensive increase in BSM discovery potential (Recommendation 4a). Dramatic increases in sensitivity are expected for both model-dependent and model-independent searches. Such a collider will be able to reach the thermal WIMP target for minimal WIMP candidates and hence will play a critical role in providing a definitive test for this class of models.



For example, a muon collider, if technologically achievable and affordable, presents a great opportunity to bring a new collider to US soil. A 10 TeV collider fits on the Fermilab site and is a good match with Fermilab's strengths. Its development has synergies with the neutrino program beyond

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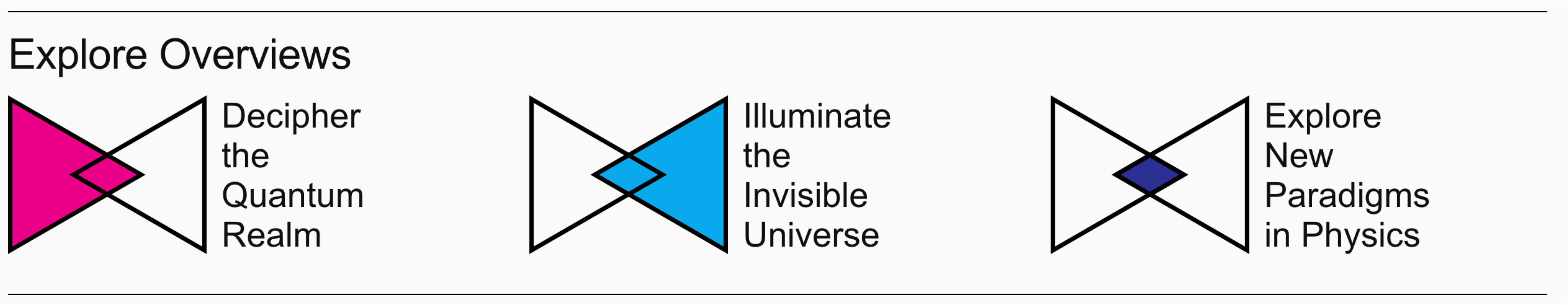

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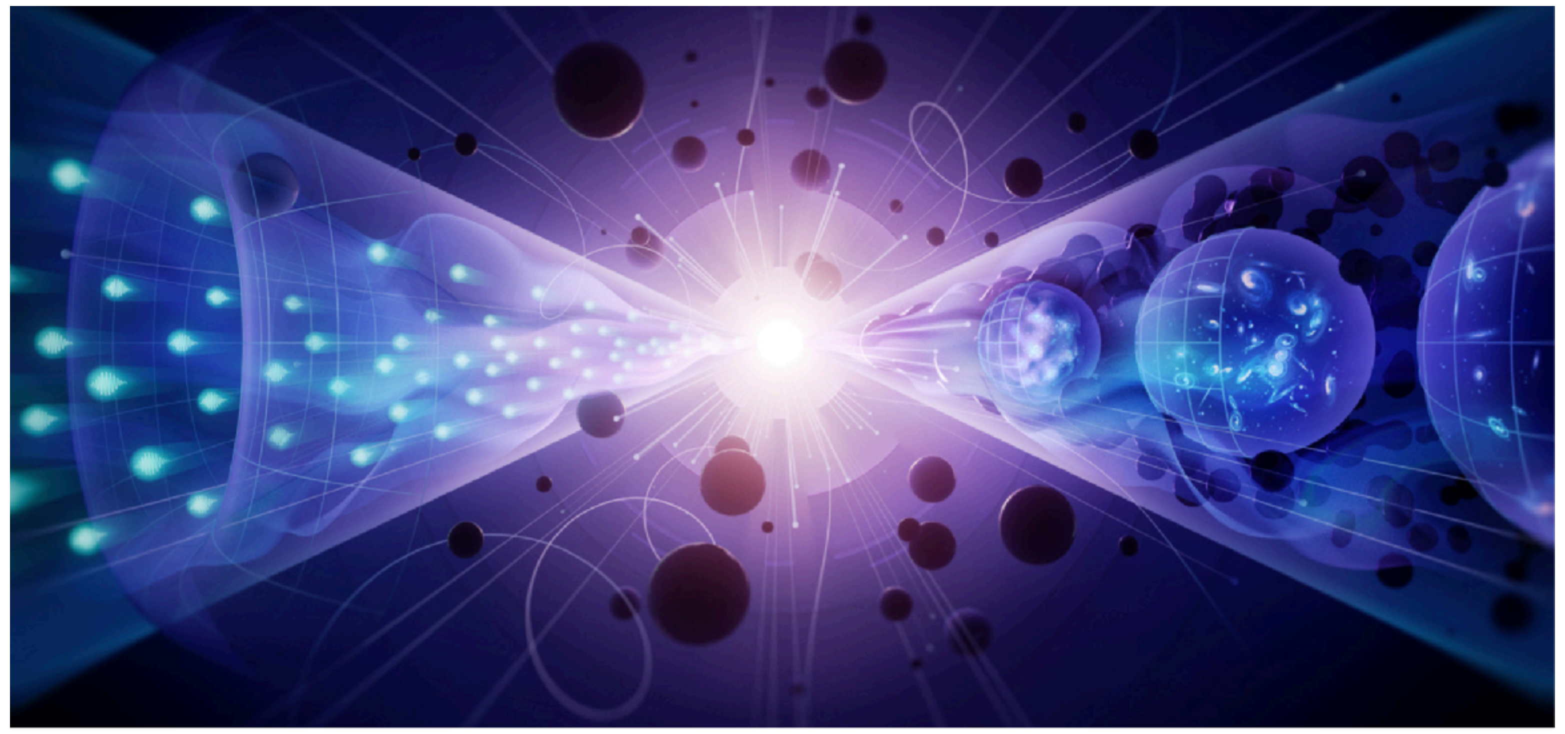

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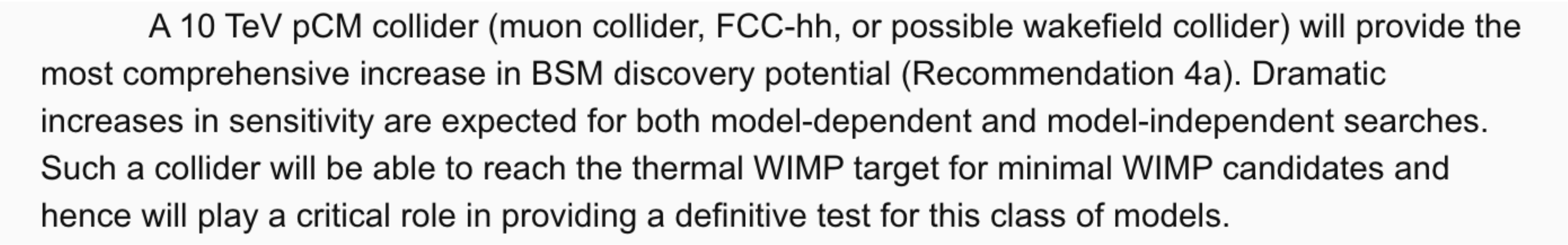

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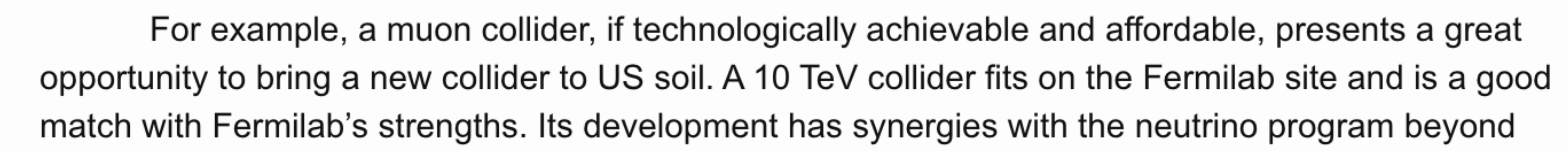

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$$m_\mu = 0.1056\,\mathrm{GeV} \approx 207 \cdot m_e$$

$$\Gamma_\mu = 3 \cdot 10^{-19}\,\mathrm{GeV} \qquad \tau_\mu = 2.2\,\mu\mathrm{s}$$

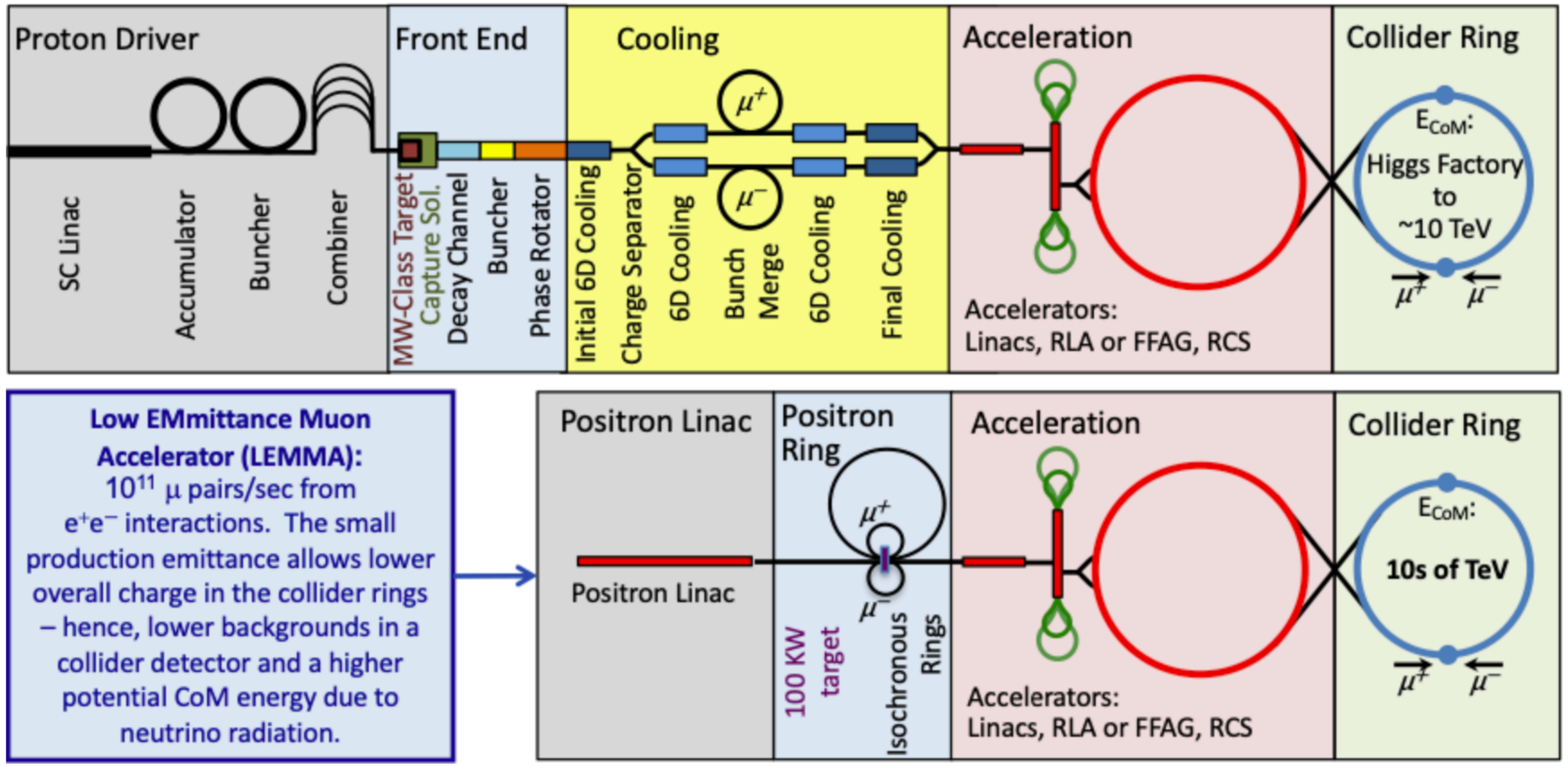
$$c\tau_\mu \approx 660\,\mathrm{m}$$

The glory of a muon collider

- ☑ Muons pointlike objects: cleaner environment than hh
- ☑ Much less synchrotron radiation than electrons
- ☑ Much smaller beam energy spread: $\Delta E \approx 0.1 - 0.001\%$

- ☐ Short lifetime: difficult to get high-quality/lumi beams
- ☐ Difficult cooling of beams

  considerable progress: MICE collaboration
- ☐ Beam-induced bkgds (BIP) from decay @ IP
- ☐ Radiation hazard from beam dump (neutrinos)



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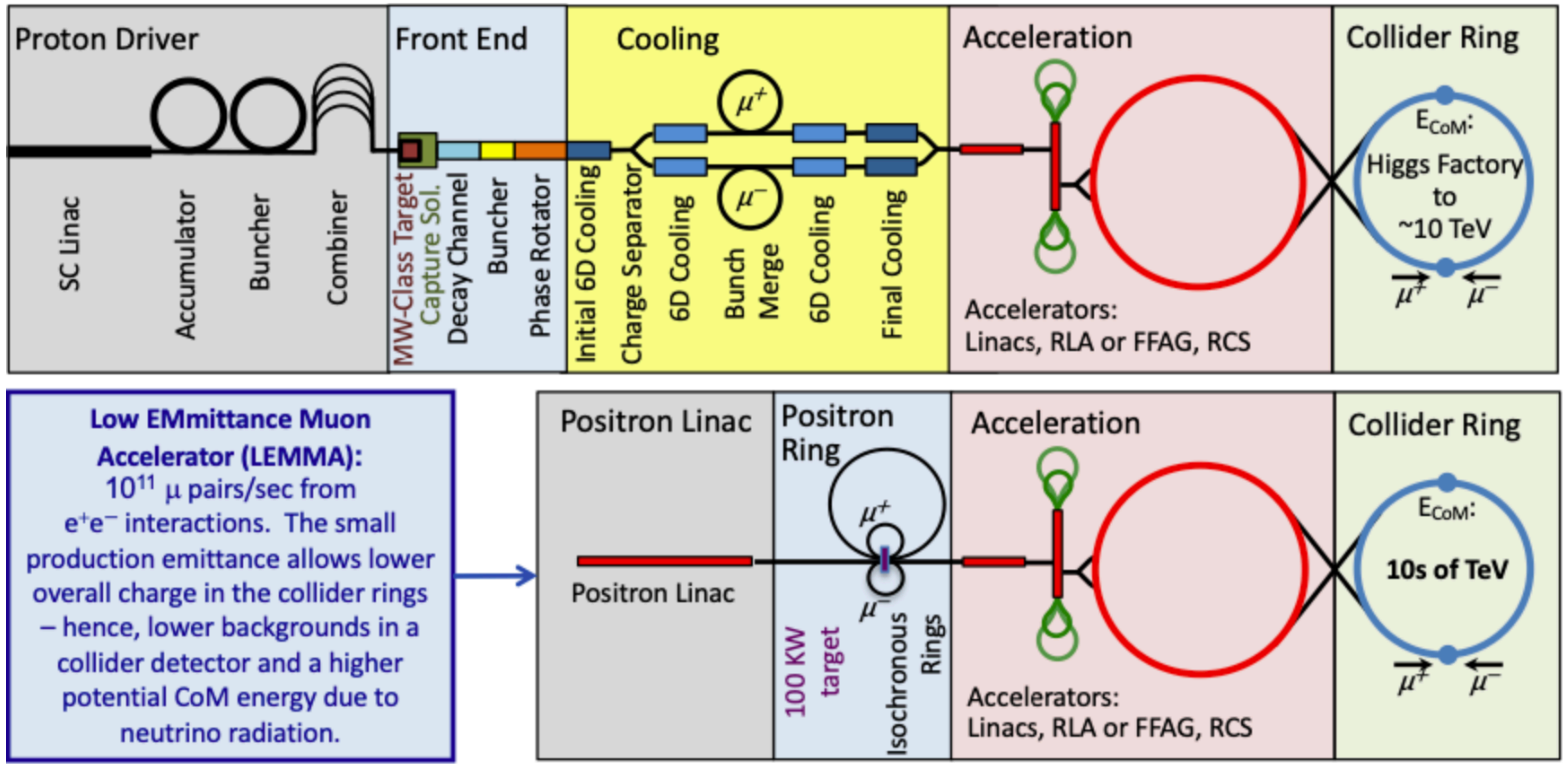


Low EMmittance Muon Accelerator (LEMMA): 10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

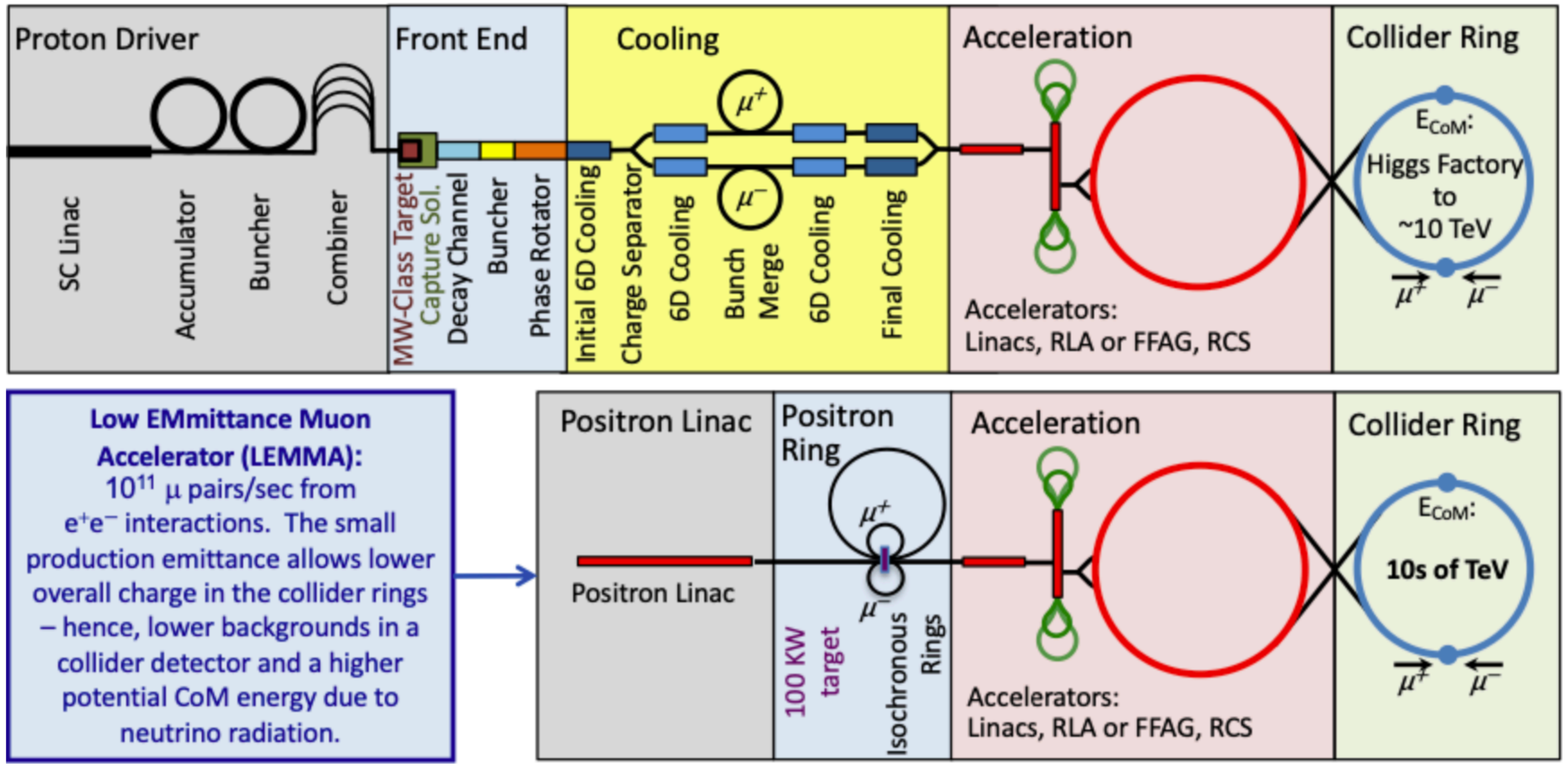
1901.06150; 2001.04431;
PoS(ICHEP2020)703; Nat.Phys.17, 289-292;
IMCC study group

The glory of a muon collider

- ☑ Muons pointlike objects: cleaner environment than hh
- ☑ Much less synchrotron radiation than electrons
- ☑ Much smaller beam energy spread: *ΔE ≈ 0.1 — 0.001%*

- ☐ Short lifetime: difficult to get high-quality/lumi beams
- ☐ Difficult cooling of beams

  considerable progress: MICE collaboration
- ☐ Beam-induced bkgds (BIP) from decay @ IP
- ☐ Radiation hazard from beam dump (neutrinos)



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1901.06150; 2001.04431;
PoS(ICHEP2020)703; Nat.Phys.17, 289-29
IMCC study group

credit: A. Wulzer

The (high-energy) muon collider

Site filler Accelerator

- Largest Radius is ~2.65 km
  - ~16.5 km Circumference
    - ~2/3 LHC

~RCS accelerator

If B_{ave} = 3 T → E_μ = 2.4 TeV

(B_{max} = 8T, B_{pulse} =±2T)

Doubled ?

B_{ave} = 6.3 T → E_μ = 5 TeV

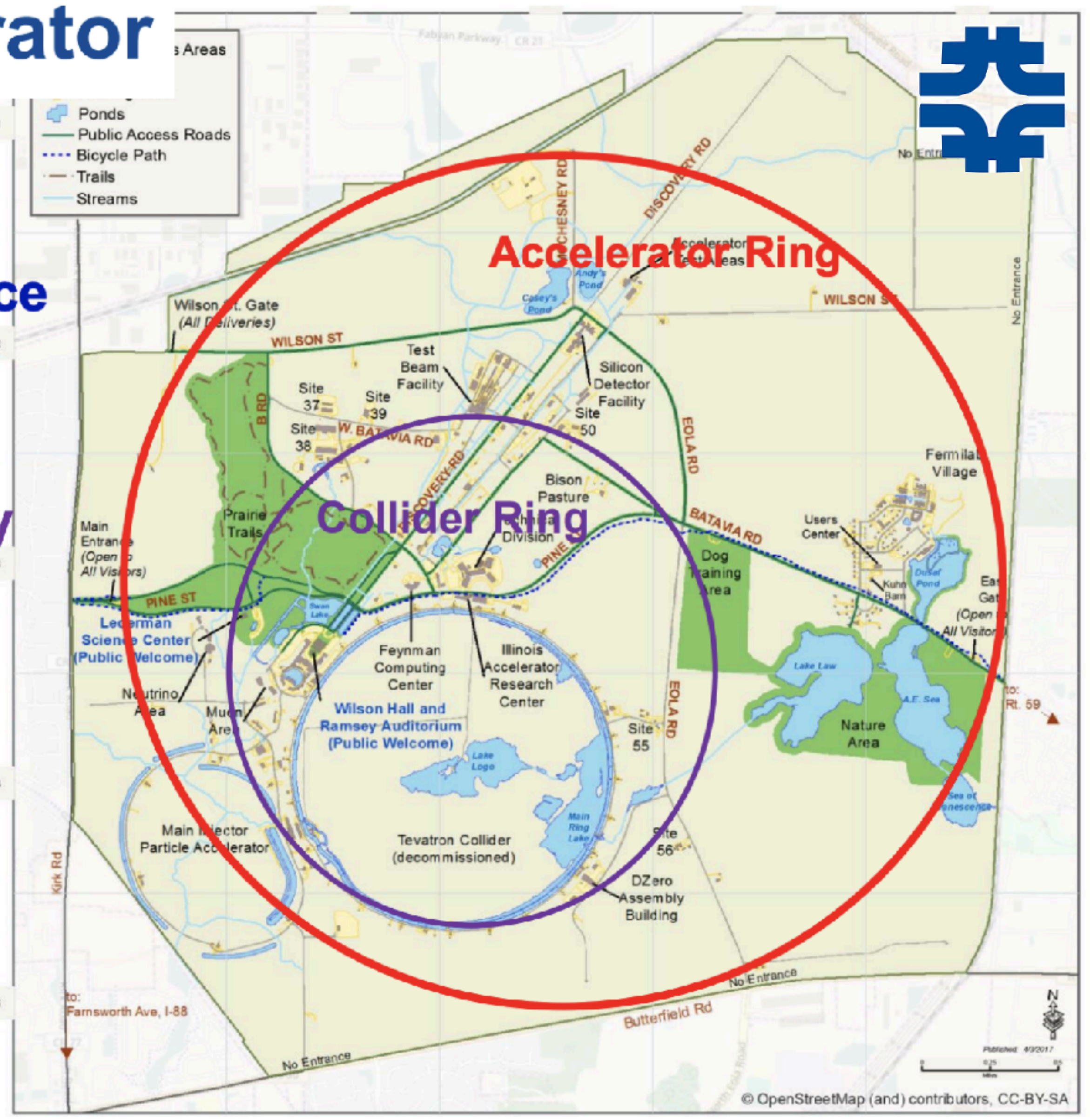
(B_{max} = 16T, B_{pulse} =±4T)

10 TeV collider

Collider Ring ~10 km

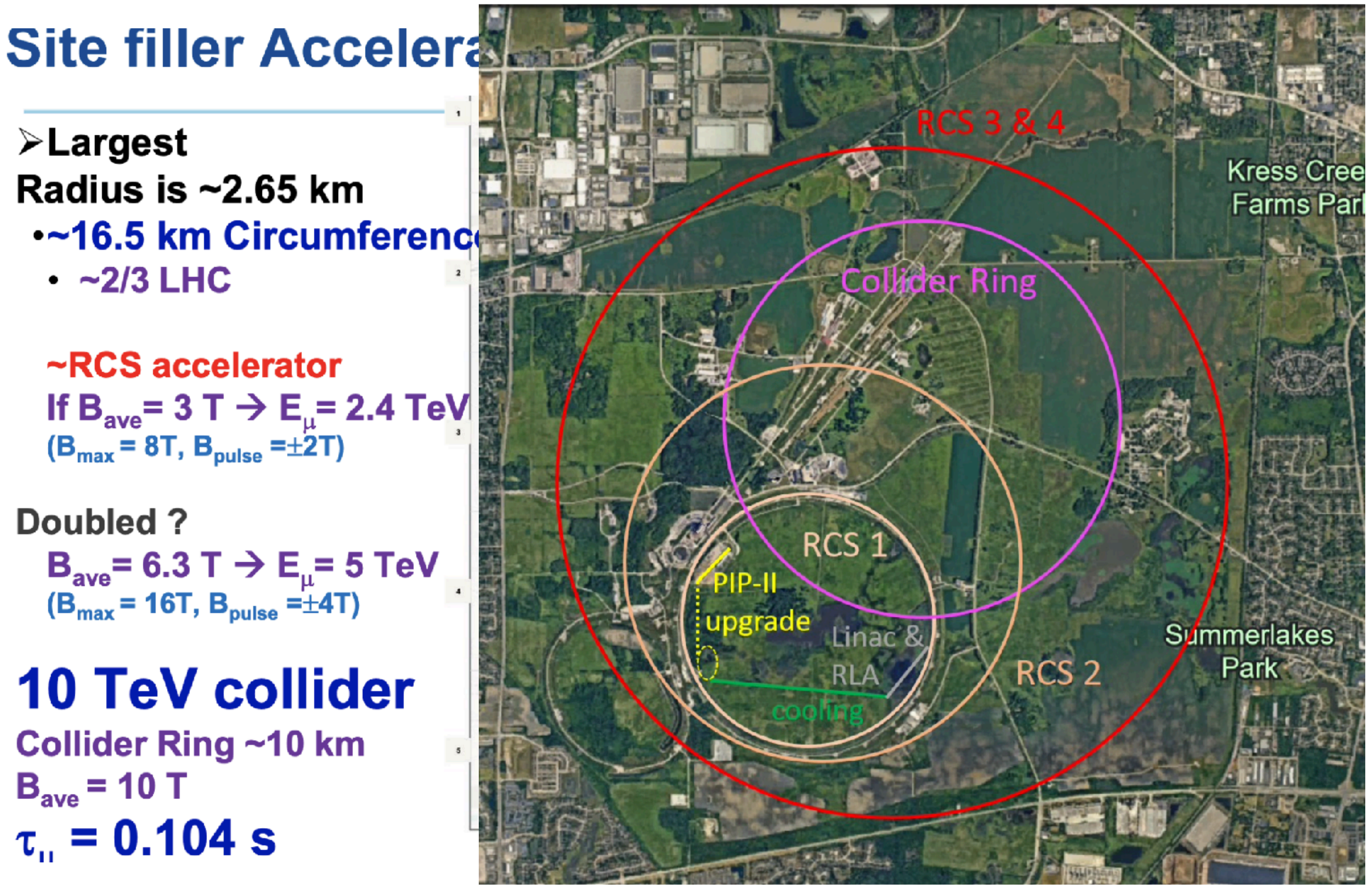
B_{ave} = 10 T

τ_μ = 0.104 s



Siting at FNAL

The (high-energy) muon collider



Site filler Accelera

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Radius is ~2.65 km
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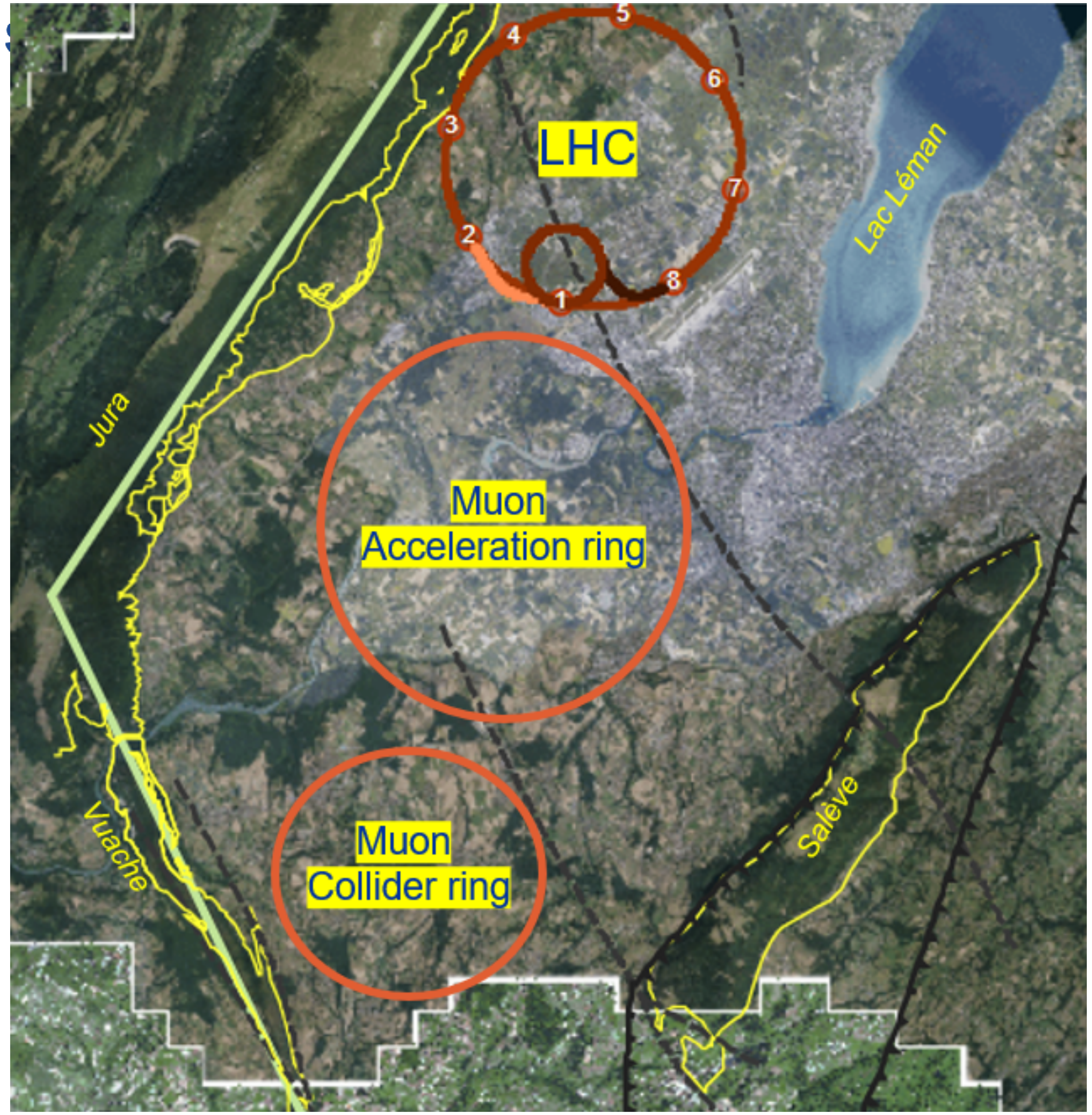
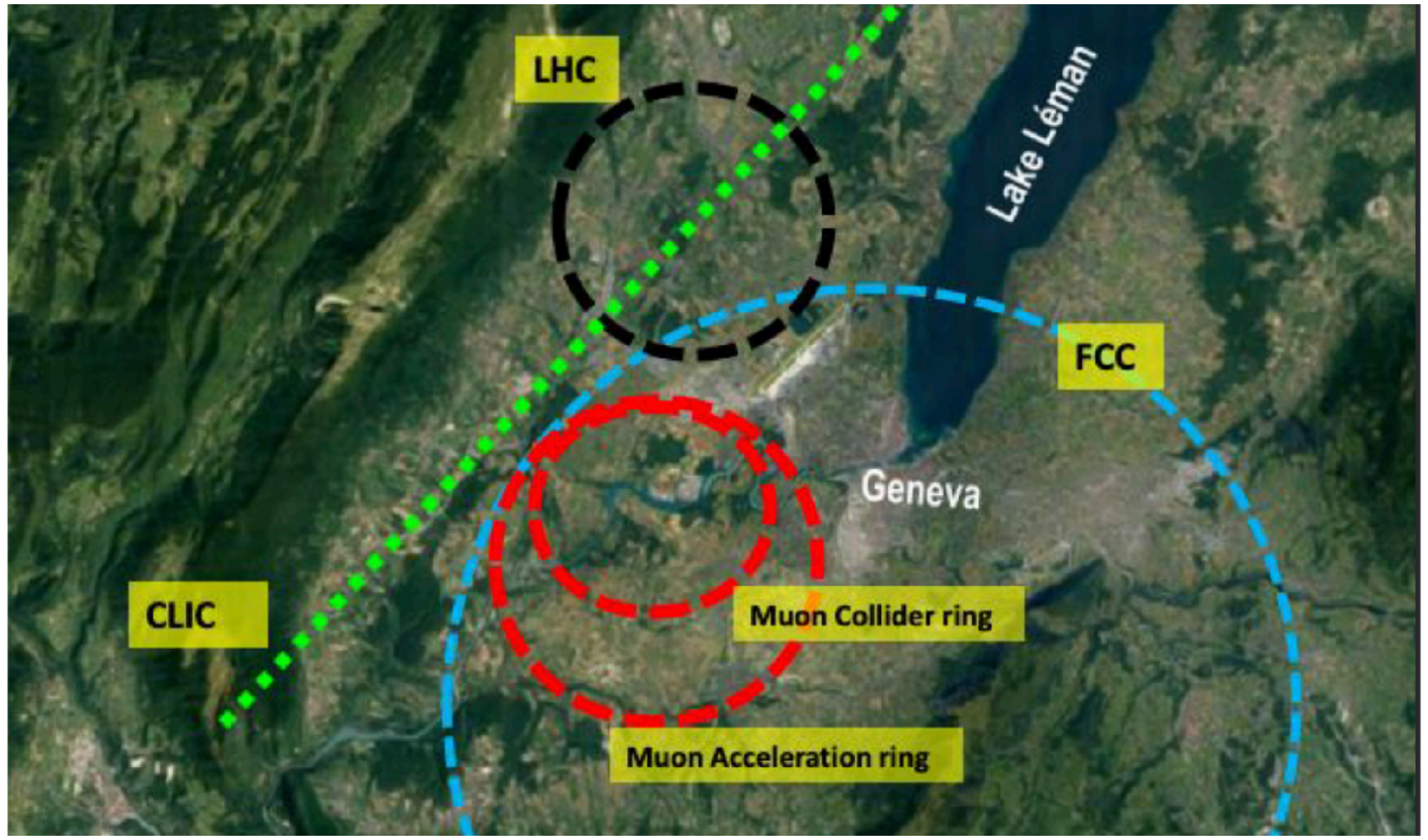
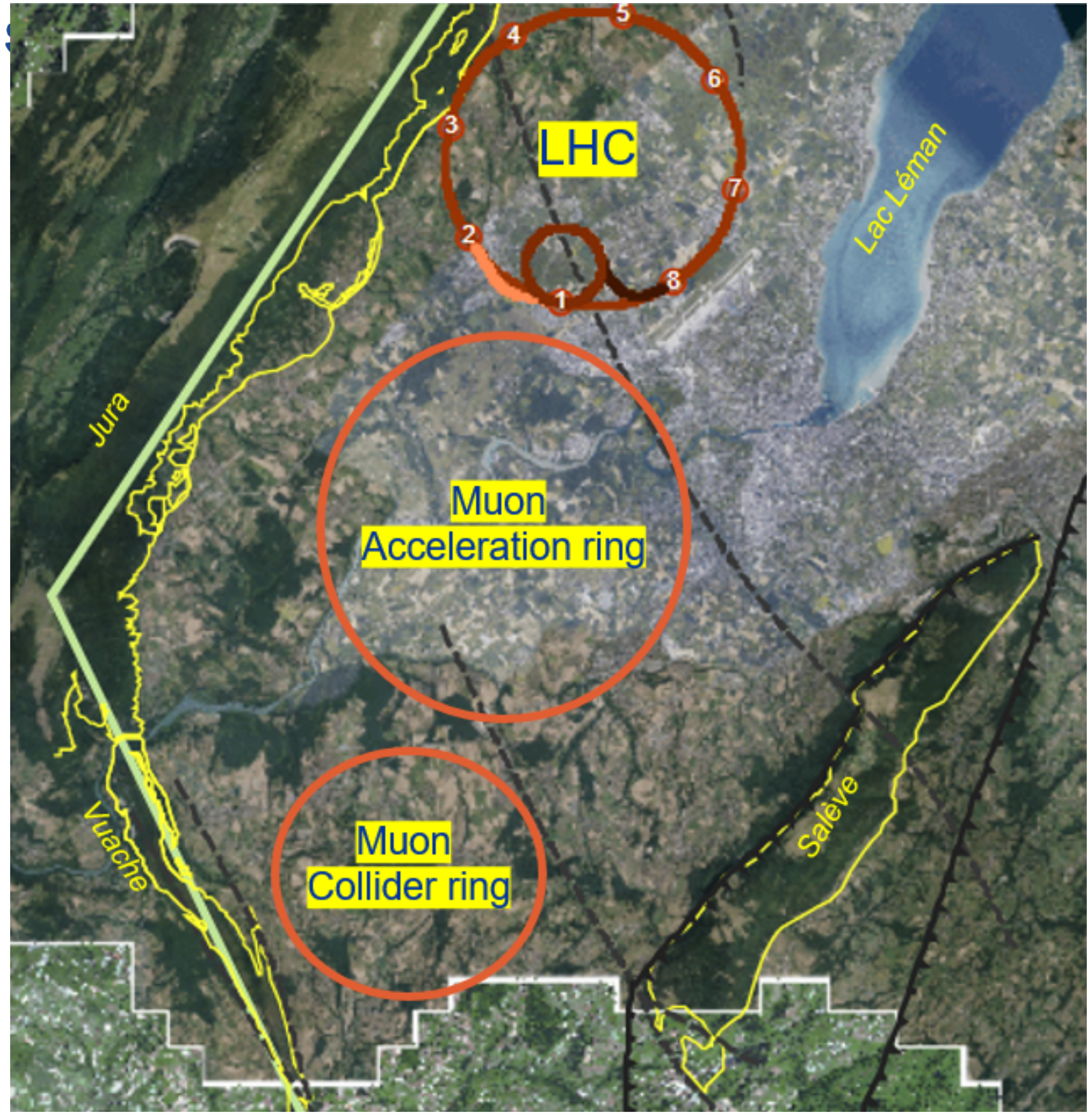


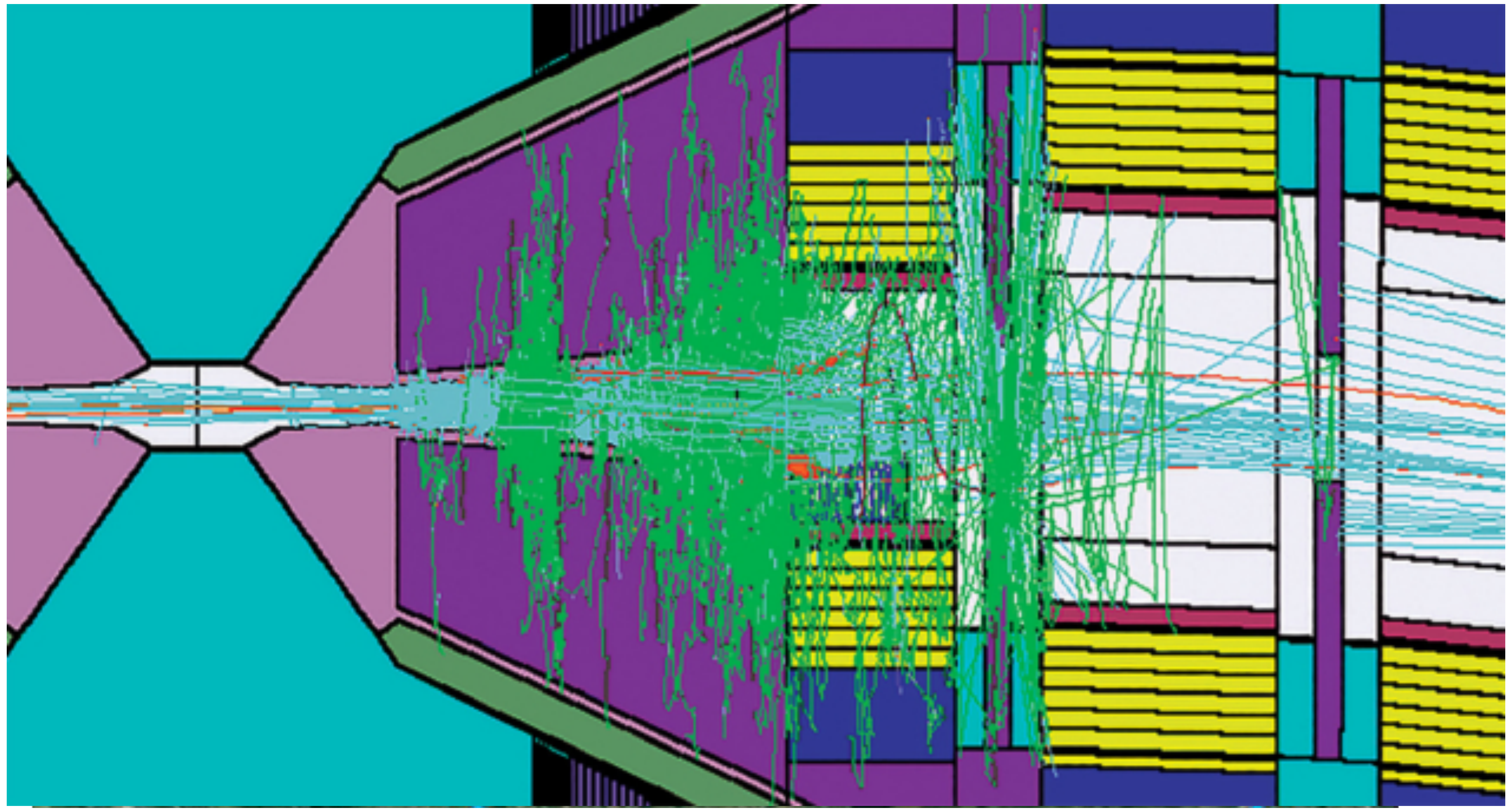


Siting at CERN

The (high-energy) muon collider

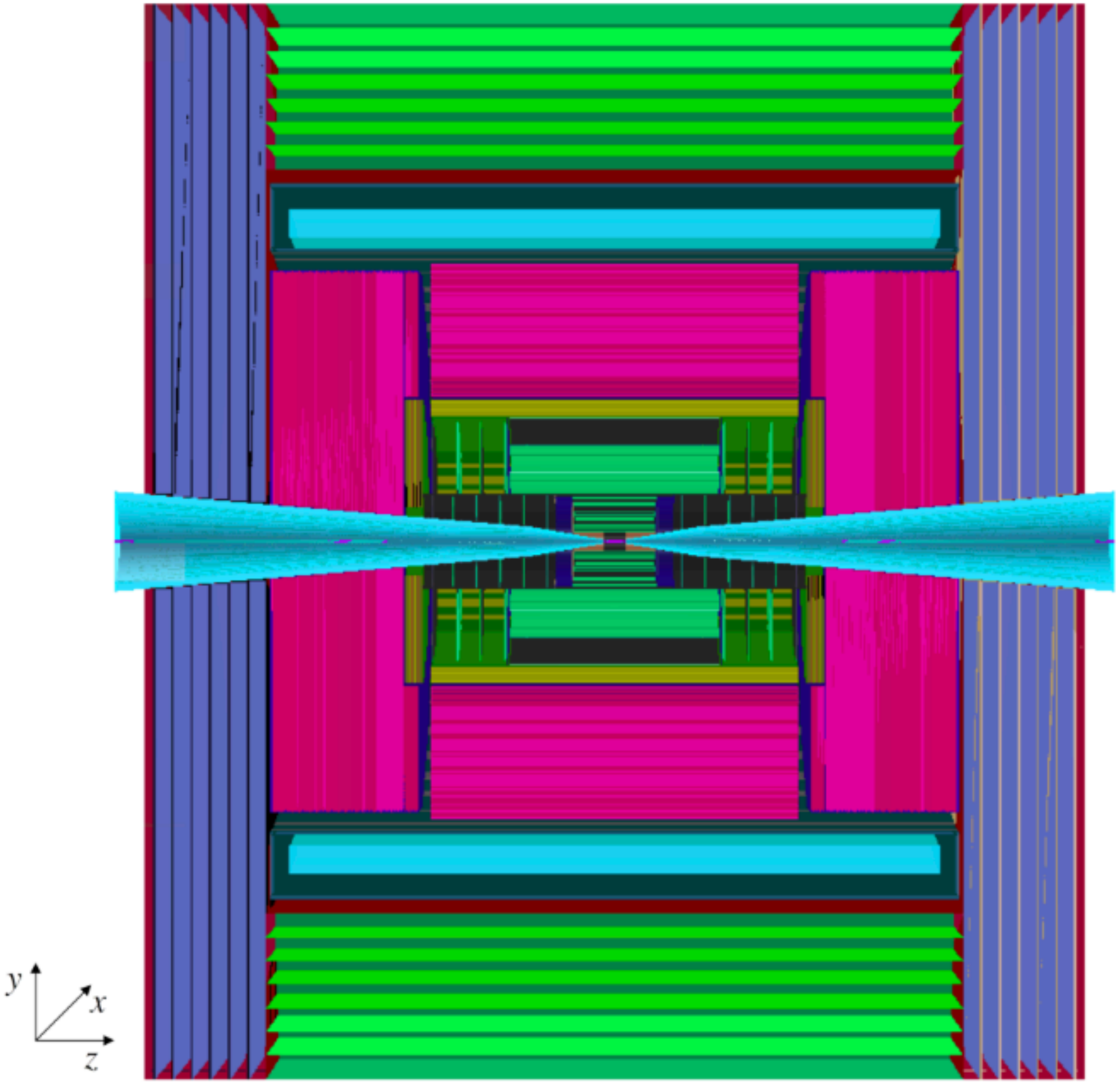


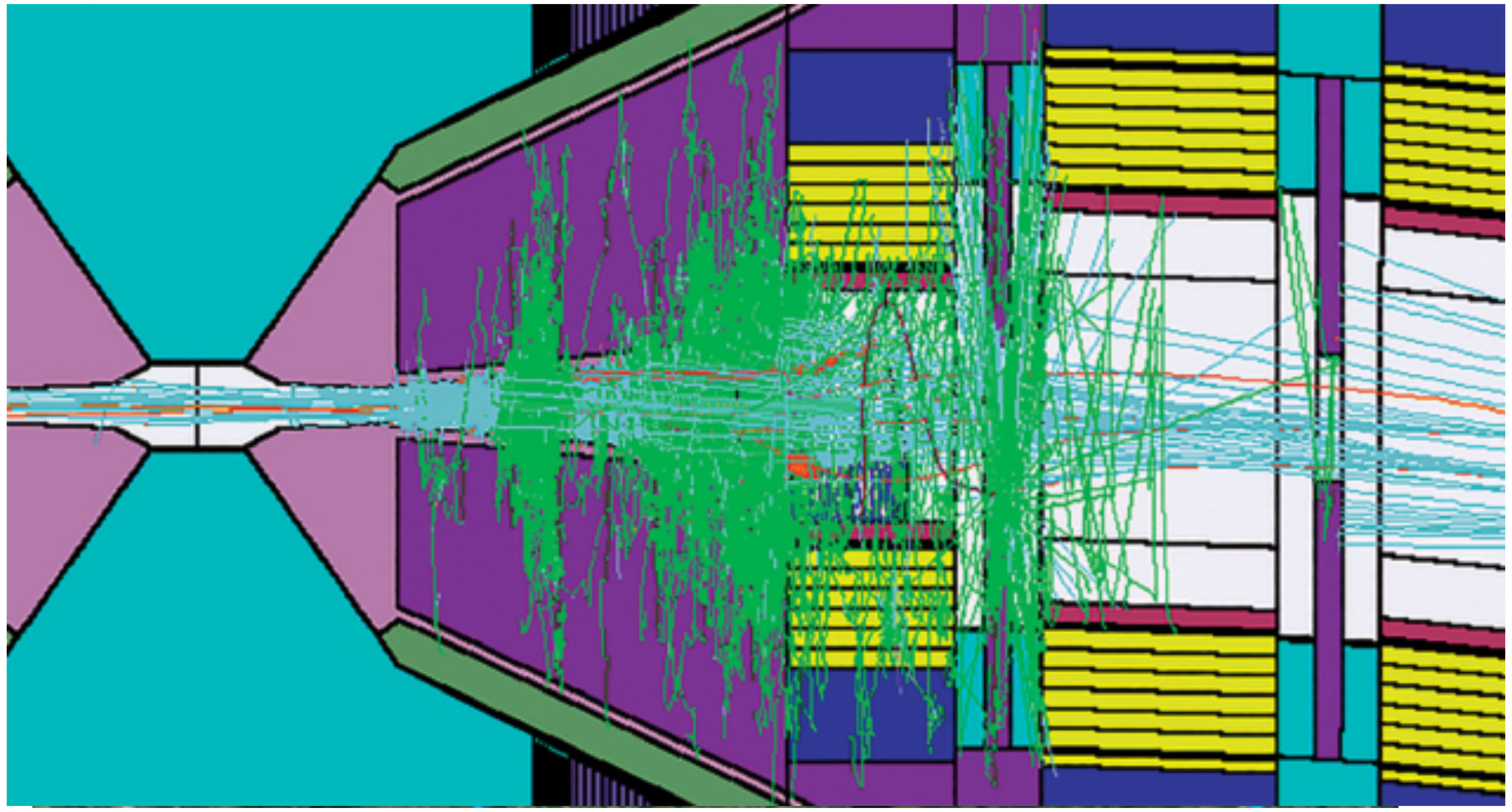
Siting at CERN



Beam-induced background for the machine-detector interface (MDI)

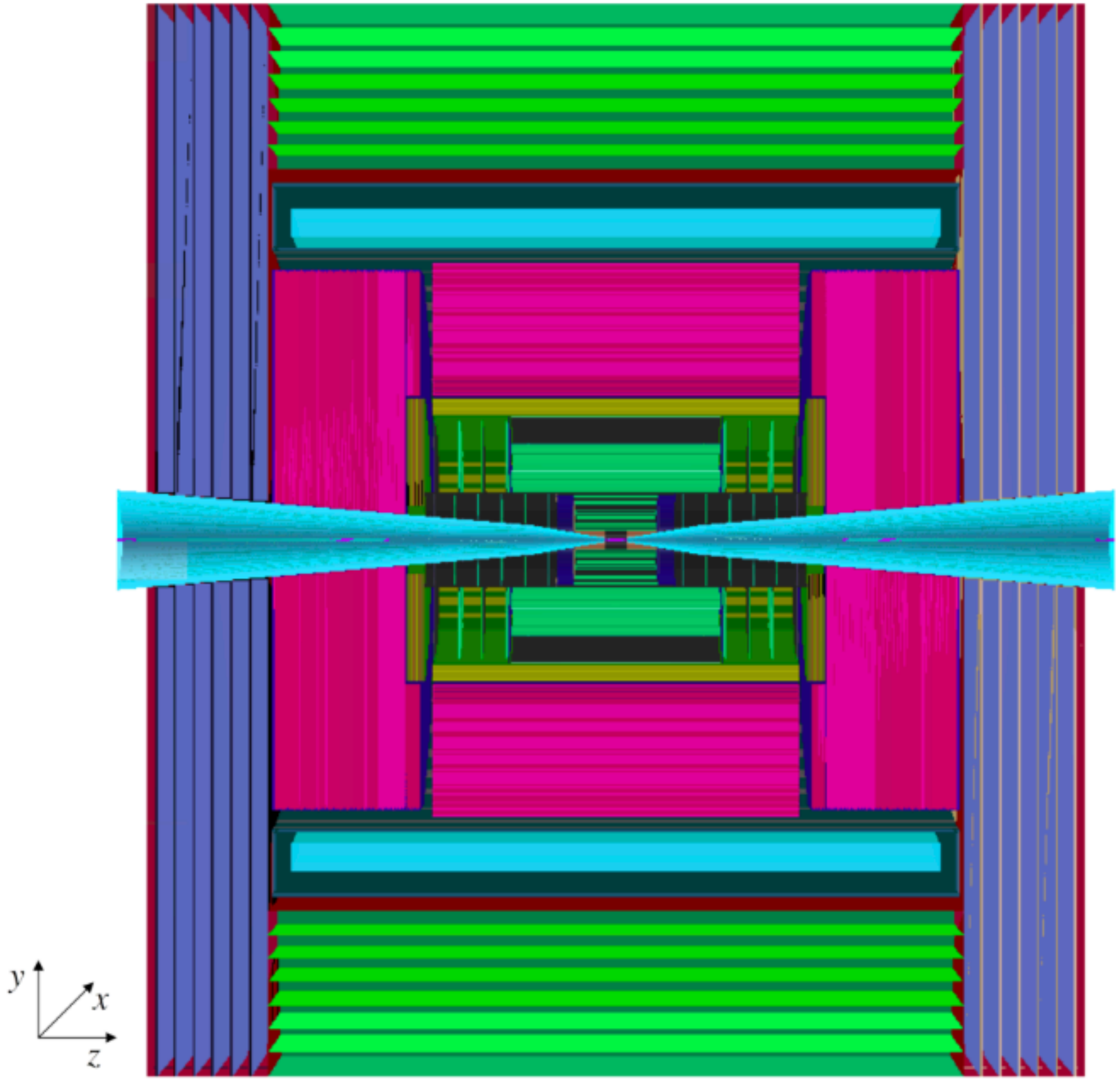
The (high-energy) muon collider

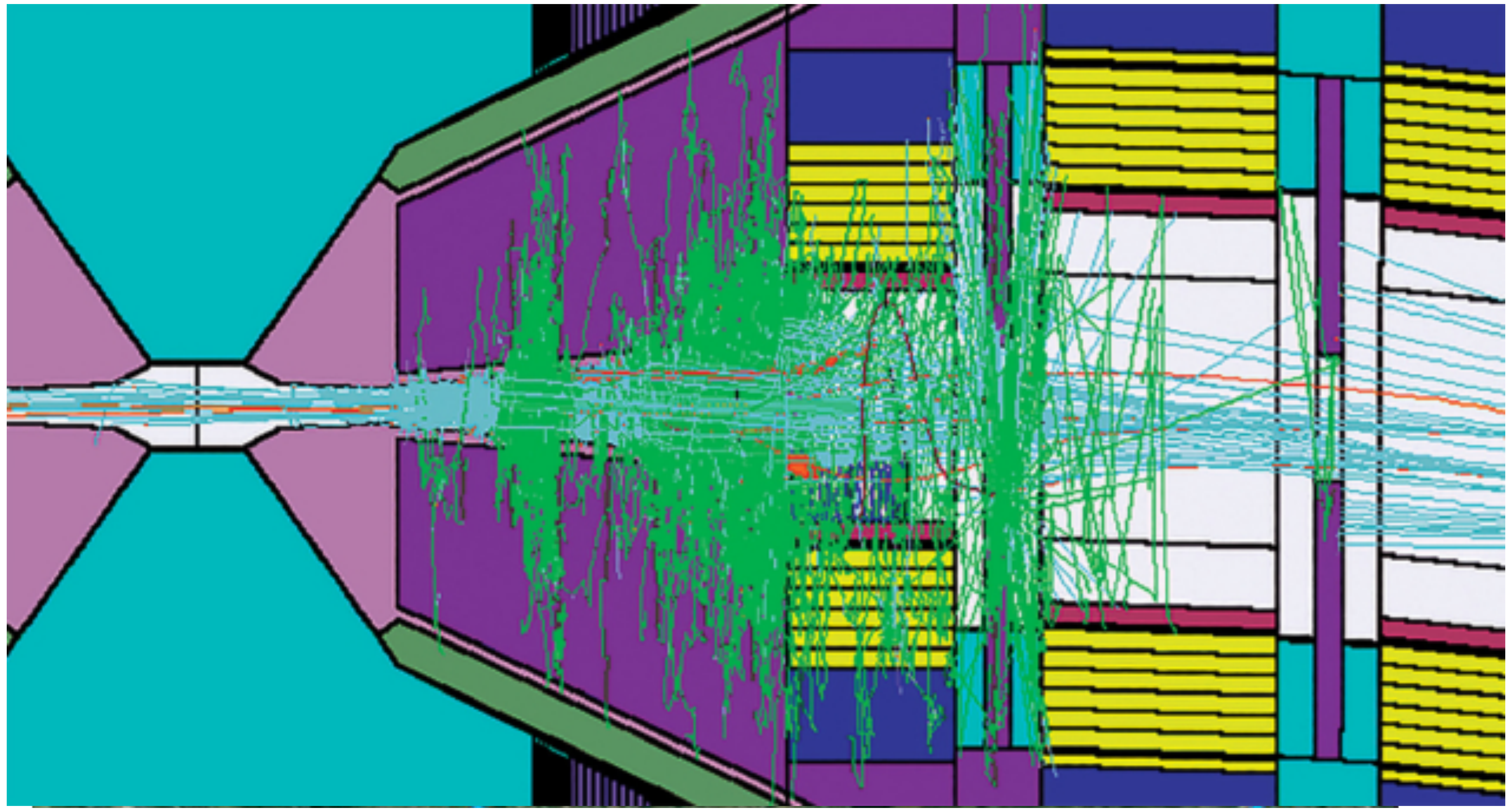




Beam-induced background for the machine-detector interface (MDI)

The (high-energy) muon collider





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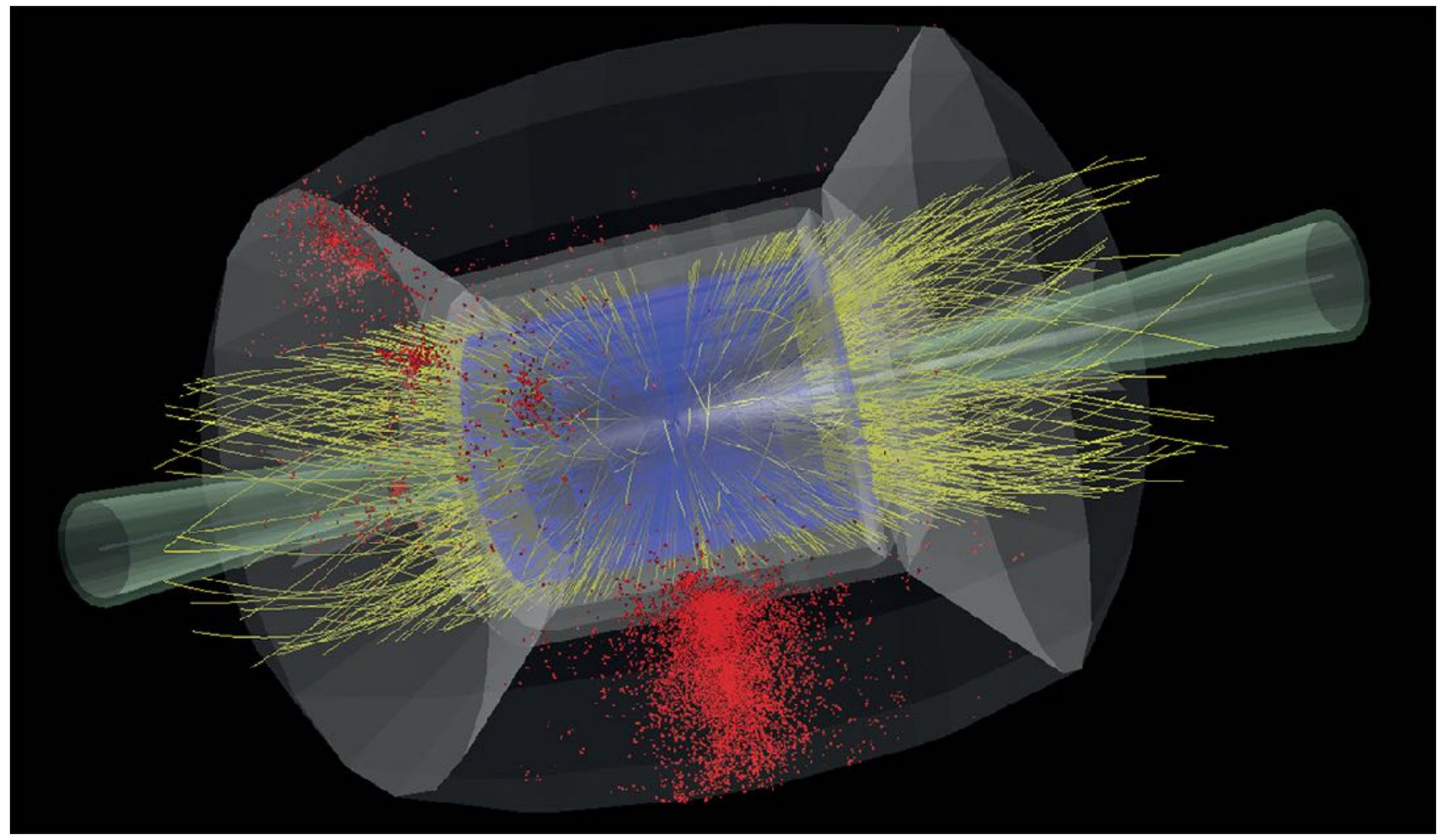
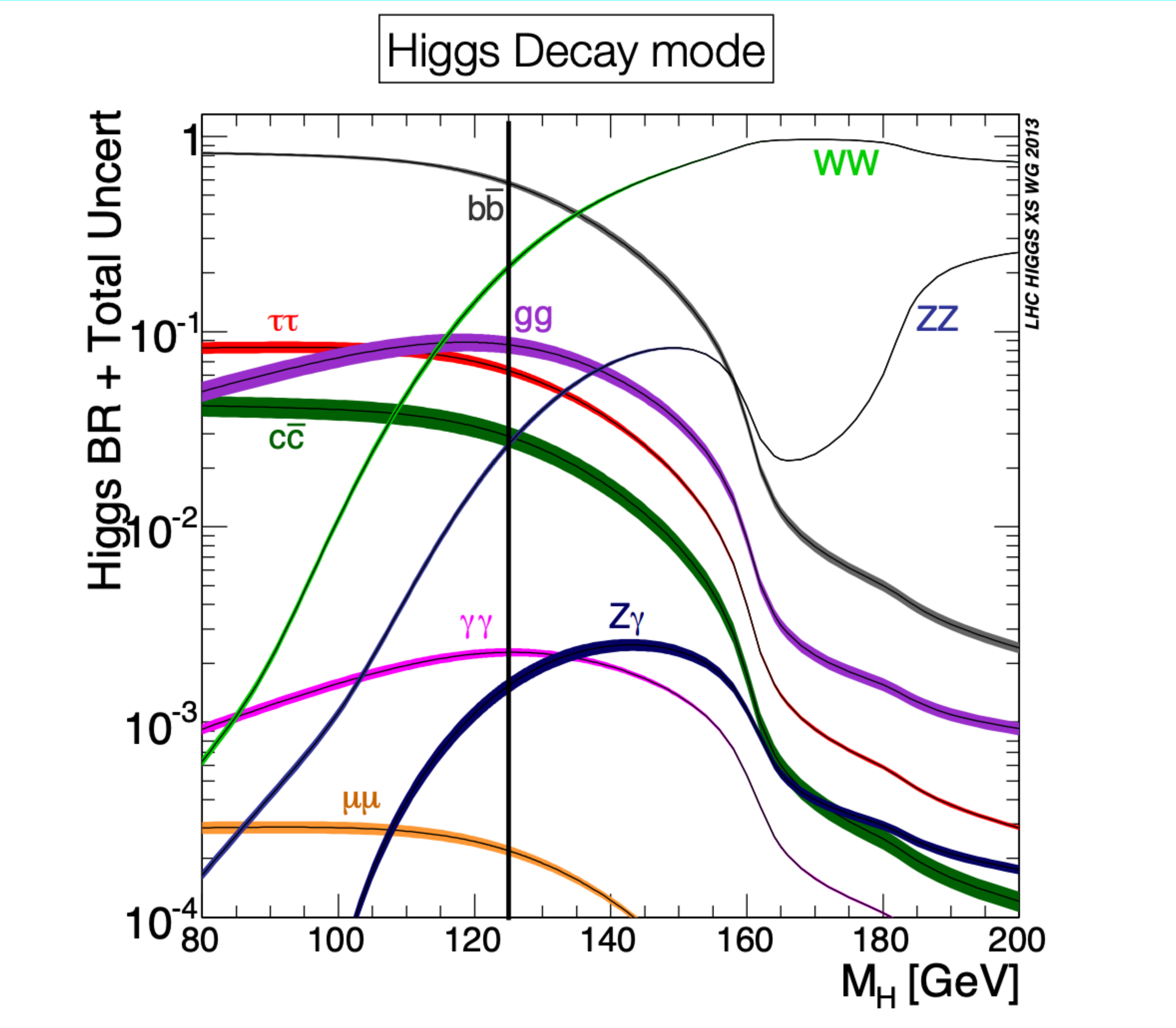
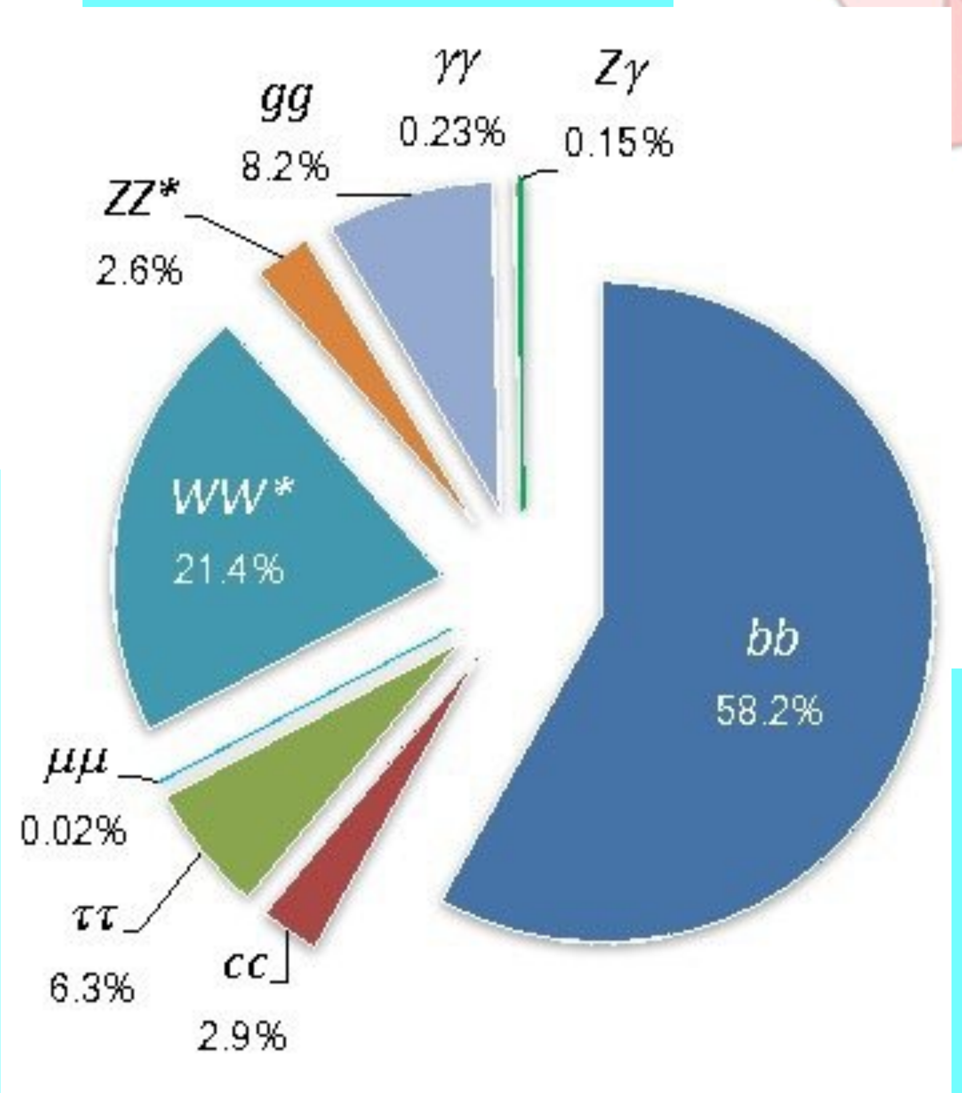
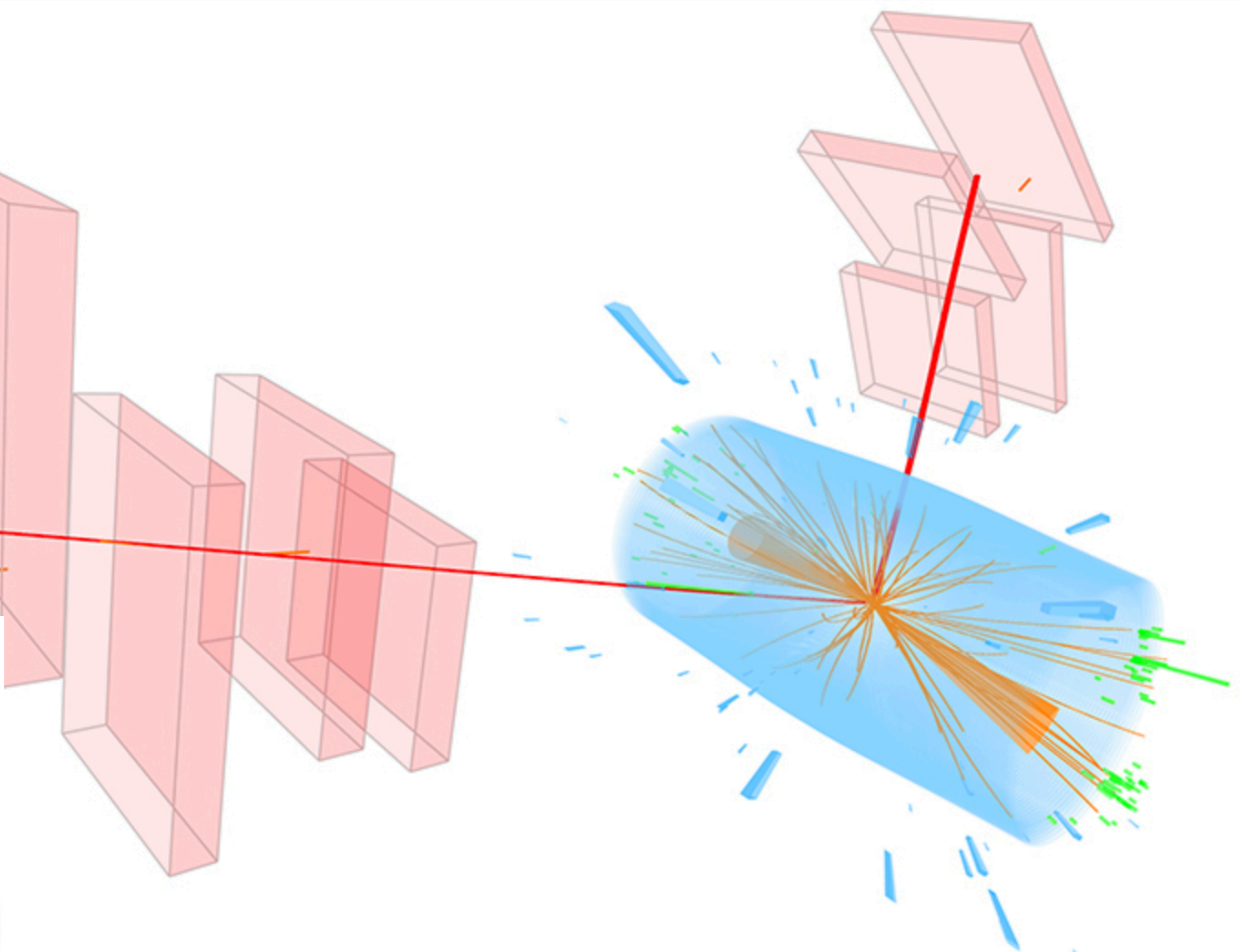


VBF Higgs

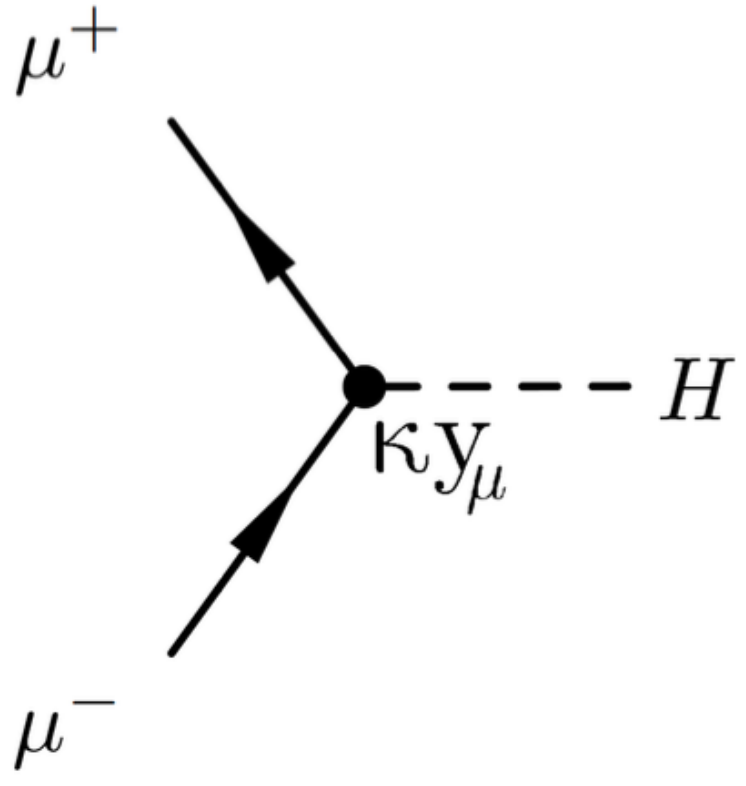
Multi-Bosons: Elusive couplings







EFT Modelling of SM μ-H coupling deviations

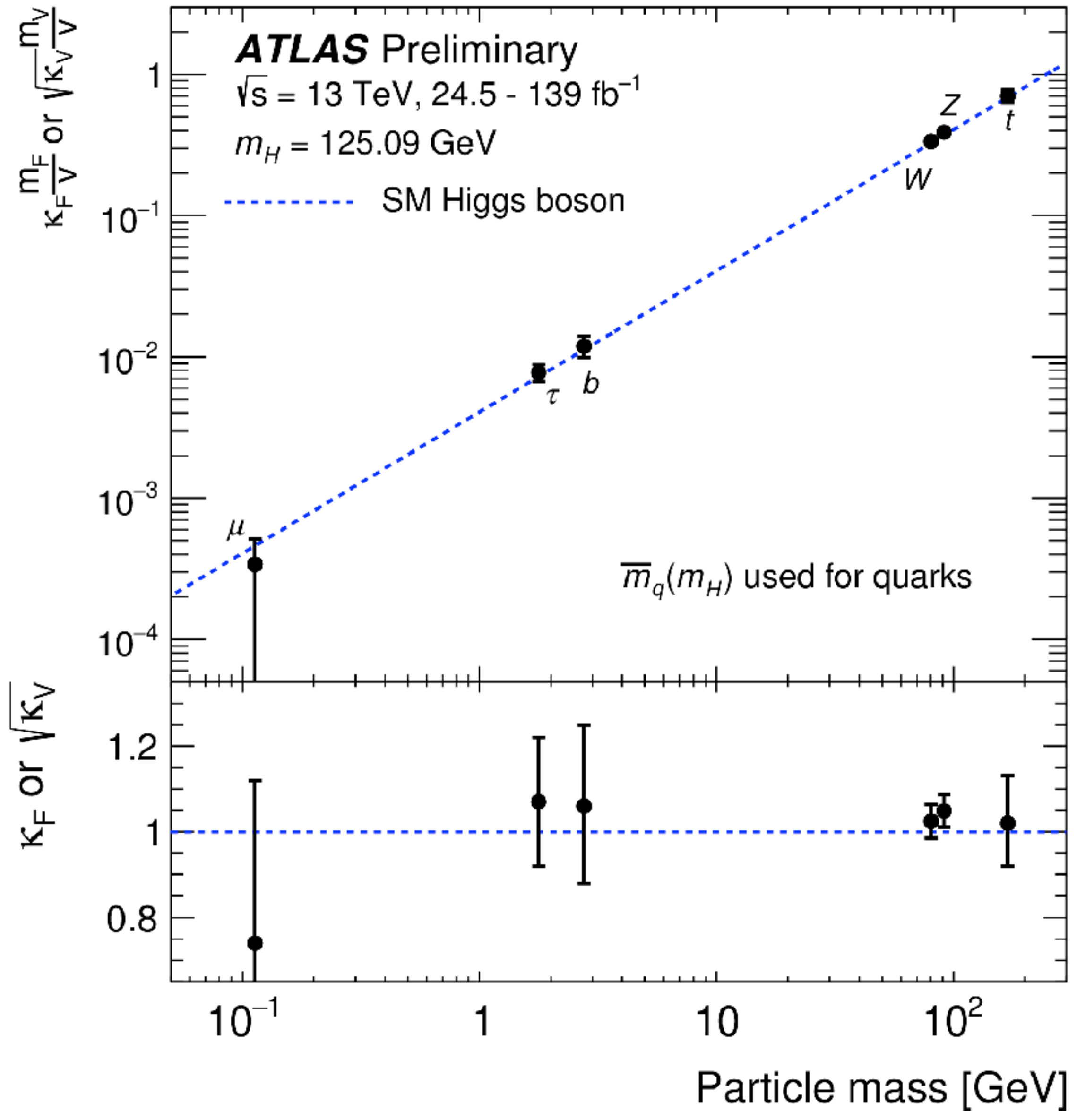


- Evidence for muon Yukawa coupling at LHC (not yet 5σ) [ATLAS: 2007.07830 ; CMS: 2009.04363]
- Projections for the high-luminosity LHC (HL-LHC): (model-dependent) sensitivity with precision of 5-10% [ATLAS-PHYS-PUB-2014-016]

- Higgs muon Yukawa coupling — connected to muon mass [in the SM!]
- Model-independent test for this coupling; directly, not relying on decays
- Sensitivity to the sign (and maybe phase) of coupling

SM: $\varkappa = 1$

or $\Delta\varkappa = 0$

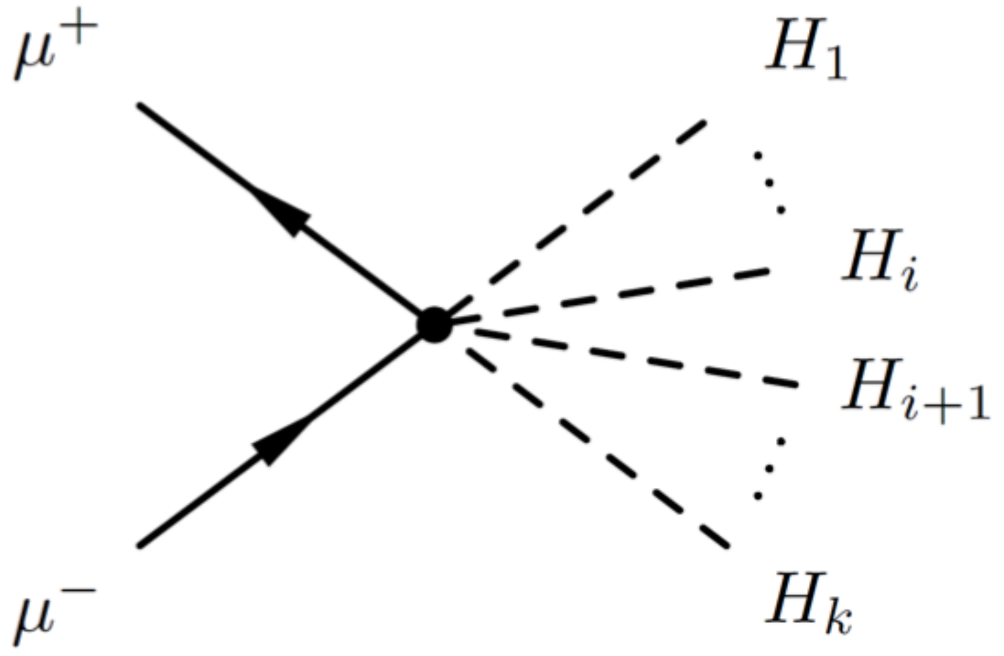


Non-linear representation (HEFT) vs. Linear representation ([truncated] SMEFT)

H doublet $$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + H + i\phi^0 \end{pmatrix} \qquad \mathcal{L}_\varphi = \left[-\bar{\mu}_L y_\mu \varphi \mu_R + \sum_{n=1}^{N} \frac{C_{\mu\varphi}^{(n)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^n \bar{\mu}_L \varphi \mu_R + \text{h.c.} \right]$$

Generalized (μ) Yukawa sector

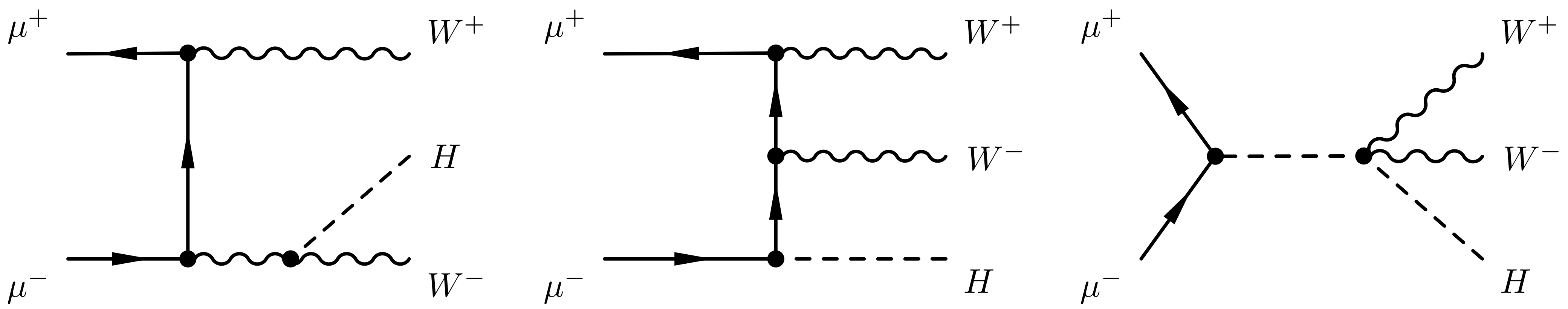
$$-i\frac{k!}{\sqrt{2}} \left[Y_\ell \delta_{k,1} - \sum_{n=n_k}^{M-1} \frac{C_{\mu\varphi}^{(n)}}{\Lambda^{2n}} \binom{2n+1}{k} \frac{v^{2n+1-k}}{2^n} \right] = 0 \quad =$$



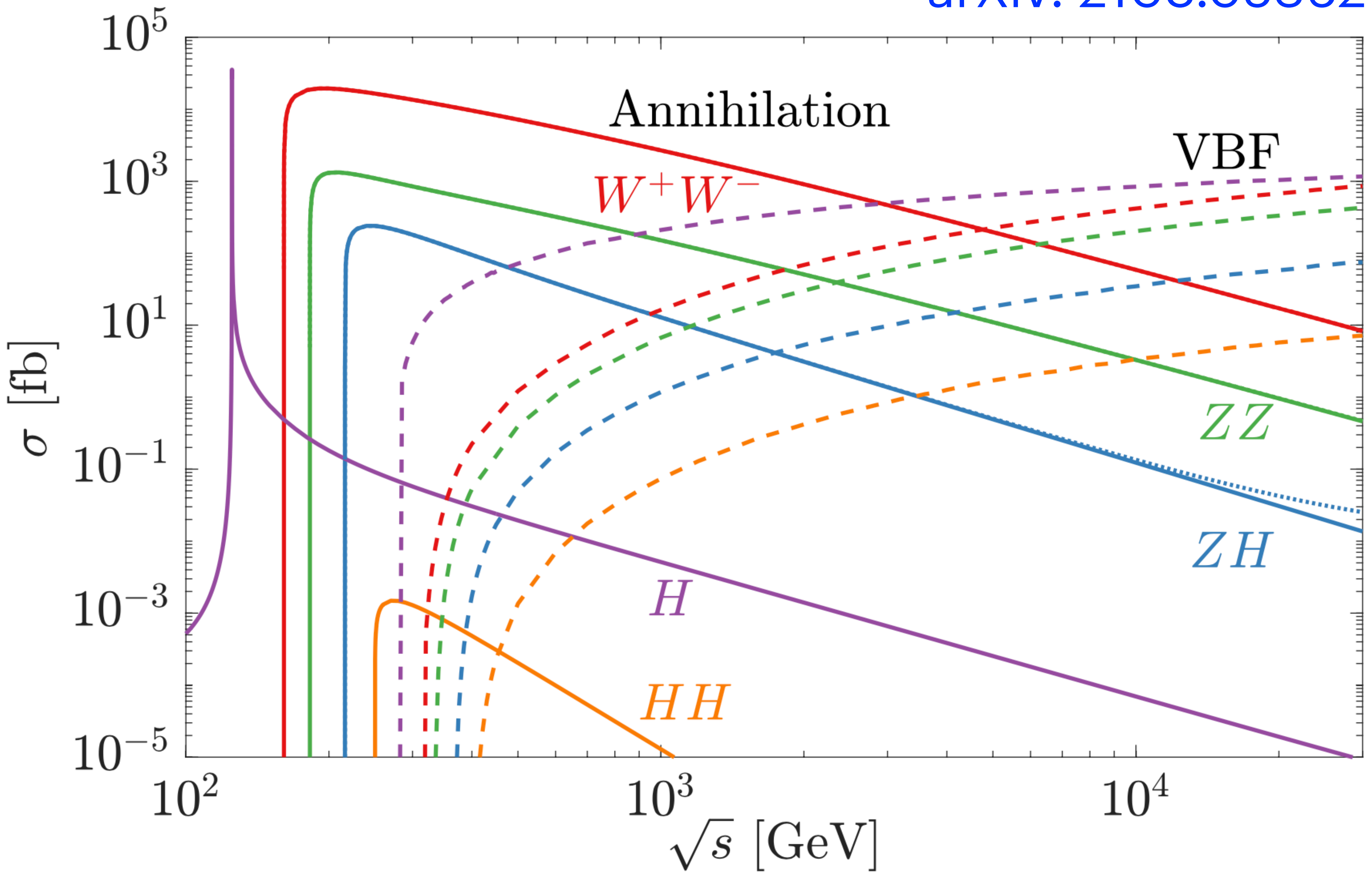
Benchmark scenario: “matched” case

Multi-boson final states

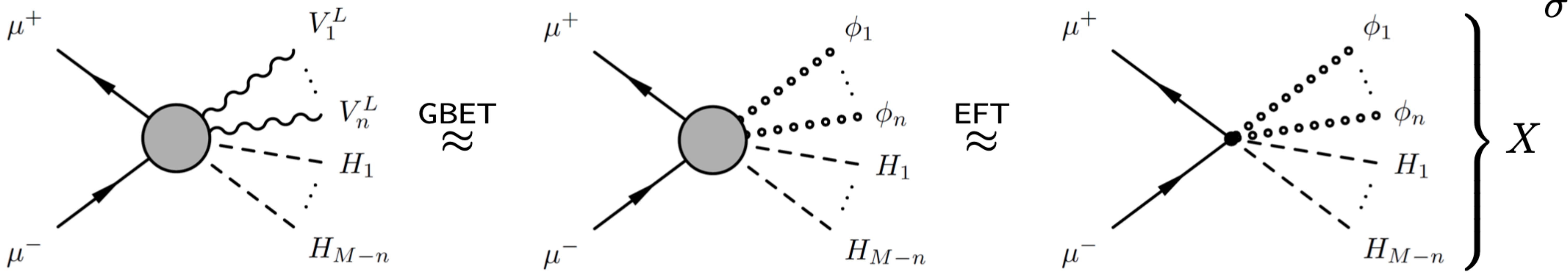
- Subtle cancellation between Yukawa coupling and multi-boson final states [hep-ph/0106281]



arXiv: 2108.05362



- (Multi-) boson final states: longitudal polarizations dominate high energies
- Analytic calculations can be approximated by Goldstone-boson Equivalence Theorem (GBET) [NPB261(1985) 379; PRD34(1986) 379]
- New physics parameterized by EFT operator insertions (Wilson coeff. C_X)



$$\sigma_X \approx \frac{1}{4}\left(\frac{\pi}{2(2\pi)^4}\right)^{M-1} \frac{s^{M-2}}{\Gamma(M)\Gamma(M-1)}|C_X|^2 \left(\prod_{j\in J_X}\frac{1}{n_j!}\right)$$

Cross section ratios: $$R = \frac{\sigma_X}{\sigma_Y} \approx \frac{|C_X|^2 \left(\prod_{j\in J_X}\frac{1}{n_j!}\right)}{|C_Y|^2 \left(\prod_{j\in J_Y}\frac{1}{n_j!}\right)}$$

Simulation, Consistency, Unitarity & Cross Sections

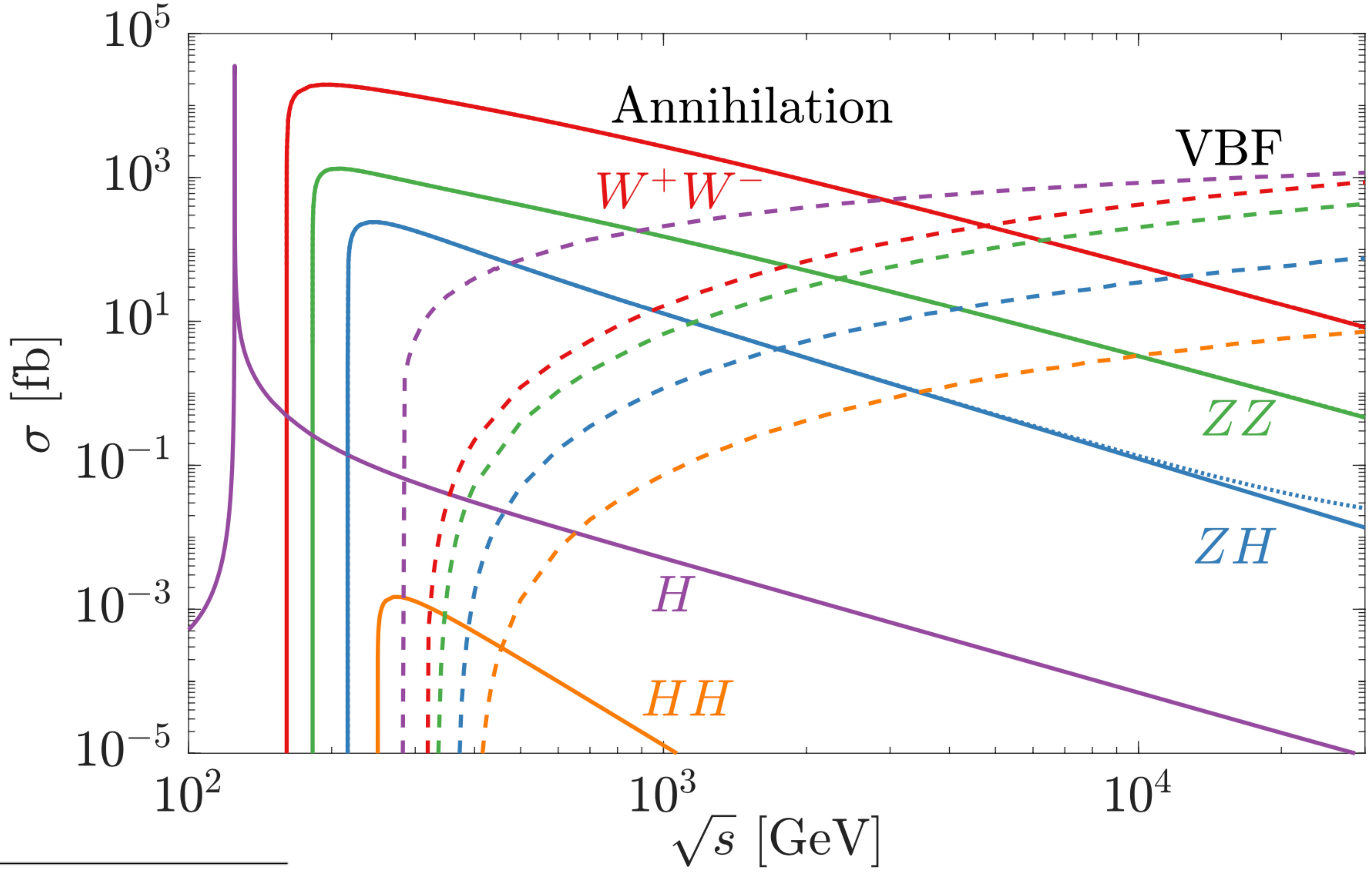
☑ Analytical calculations checked independently by 3 groups

☑ Validation of analytic calculation with 2 different MCs

☑ Final simulation: using UFO files in `WHIZARD`

States with multiplicity 2

- Different cases: dim 6 alone, dim 8 alone, dim 6+8 combined
- Matched case: combination such that Yukawa coupling is zero



	$\Delta\sigma^X/\Delta\sigma^{W^+W^-}$					
	SMEFT				HEFT	
X	$\dim_6$	$\dim_8$	$\dim_{6,8}$	$\dim_{6,8}^{\text{matched}}$	$\dim_\infty$	$\dim_\infty^{\text{matched}}$
W^+W^-	1	1	1	1	1	1
ZZ	1/2	1/2	1/2	1/2	1/2	1/2
ZH	1	1/2	1	1	$R^{\text{HEFT}}_{(2),1}$	1
HH	9/2	25/2	$R^{\text{SMEFT}}_{(2),1}/2$	0	$2\,R^{\text{HEFT}}_{(2),2}$	0

Simulation, Consistency, Unitarity & Cross Sections

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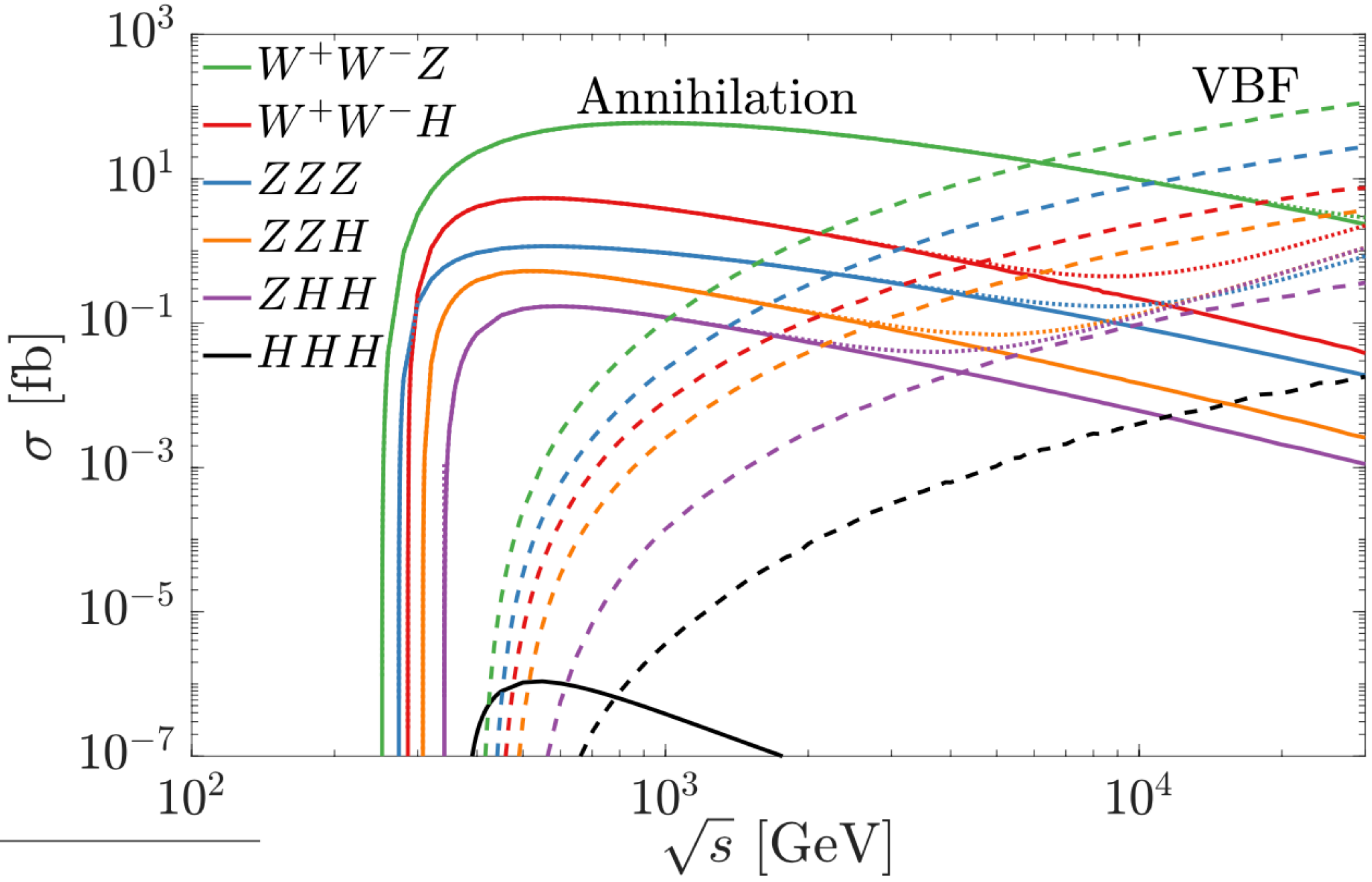
States with multiplicity 3

- Different cases: dim 6 alone, dim 8 alone, dim 6+8 combined
- Matched case: combination such that Yukawa coupling is zero



	$\Delta\sigma^X/\Delta\sigma^{W^+W^-H}$					
	SMEFT				HEFT	
$\mu^+\mu^- \to X$	$\dim_6$	$\dim_8$	$\dim_{6,8}$	$\dim_{6,8}^{\text{matched}}$	$\dim_\infty$	$\dim_\infty^{\text{matched}}$
WWZ	1	$1/9$	$R^{\text{SMEFT}}_{(3),1}$	$1/4$	$R^{\text{HEFT}}_{(3),1}/9$	$1/4$
ZZZ	$3/2$	$1/6$	$3\,R^{\text{SMEFT}}_{(3),1}/2$	$3/8$	$R^{\text{HEFT}}_{(3),1}/6$	$3/8$
WWH	1	1	1	1	1	1
ZZH	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$
ZHH	$1/2$	$1/2$	$1/2$	$1/2$	$2\,R^{\text{HEFT}}_{(3),2}$	$1/2$
HHH	$3/2$	$25/6$	$3\,R^{\text{SMEFT}}_{(3),2}/2$	$75/8$	$6\,R^{\text{HEFT}}_{(3),3}$	0

Simulation, Consistency, Unitarity & Cross Sections

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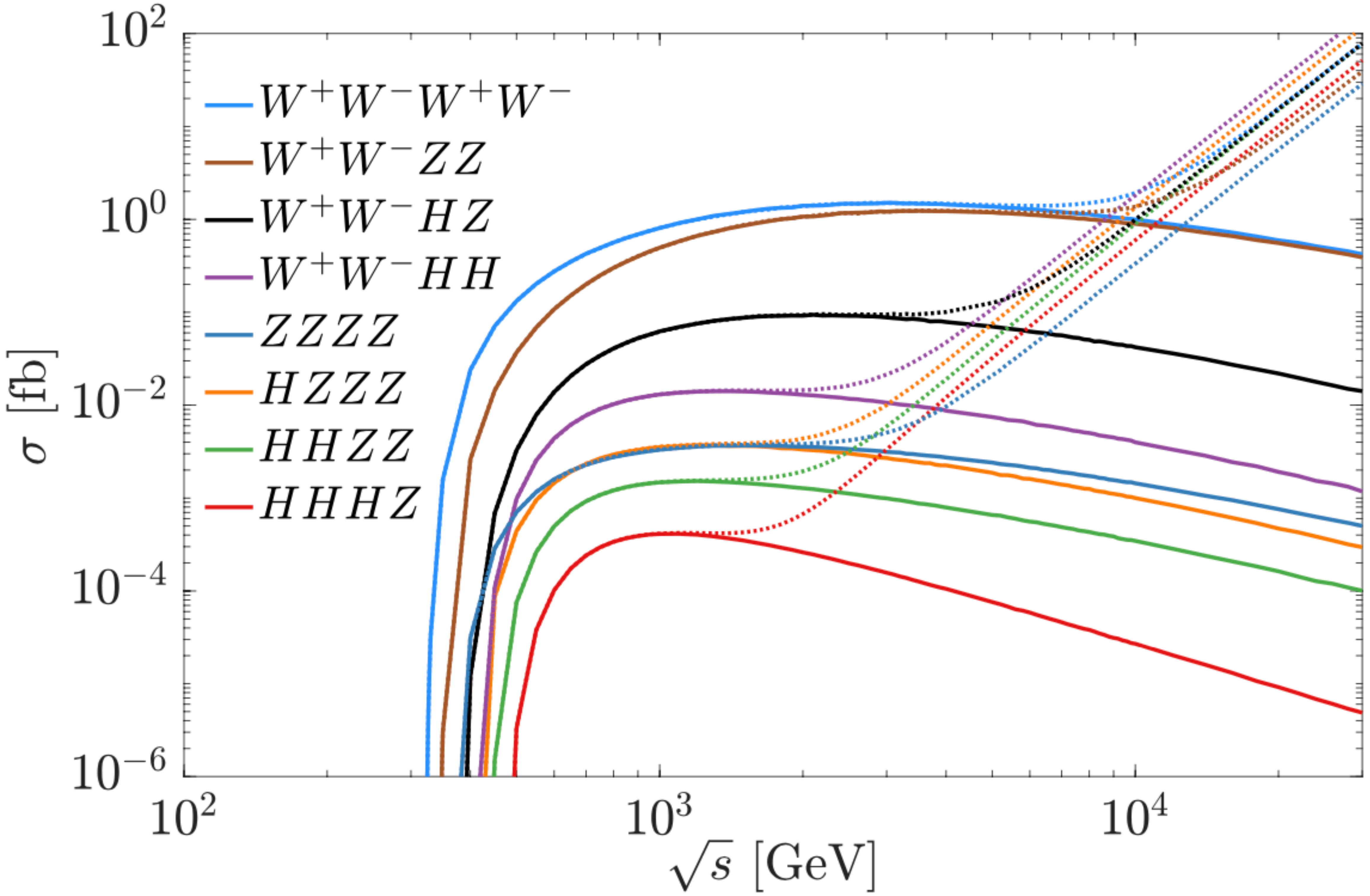
States with multiplicity 4

- Different cases: dim 6 alone, dim 8 alone, dim 6+8 combined
- Matched case: combination such that Yukawa coupling is zero



	SMEFT				HEFT	
$\mu^+\mu^- \to X$	$\mathrm{dim}_{6,8}$	dim_{10}	$\mathrm{dim}_{6,8,10}$	$\mathrm{dim}^{\mathrm{matched}}_{6,8,10}$	dim_{∞}	$\mathrm{dim}^{\mathrm{matched}}_{\infty}$
$WWWW$	$2/9$	$2/25$	$2\,R^{\mathrm{SMEFT}}_{(4),1}/9$	$1/2$	$R^{\mathrm{HEFT}}_{(4),1}/18$	$1/2$
$WWZZ$	$1/9$	$1/25$	$R^{\mathrm{SMEFT}}_{(4),1}/9$	$1/4$	$R^{\mathrm{HEFT}}_{(4),1}/36$	$1/4$
$ZZZZ$	$1/12$	$3/100$	$R^{\mathrm{SMEFT}}_{(4),1}/12$	$3/16$	$R^{\mathrm{HEFT}}_{(4),1}/48$	$3/16$
$WWZH$	$2/9$	$2/25$	$2\,R^{\mathrm{SMEFT}}_{(4),1}/9$	$1/2$	$R^{\mathrm{HEFT}}_{(4),2}/8$	$1/2$
$WWHH$	1	1	1	1	1	1
$ZZZH$	$1/3$	$3/25$	$R^{\mathrm{SMEFT}}_{(4),1}/3$	$3/4$	$R^{\mathrm{HEFT}}_{(4),2}/12$	$3/4$
$ZZHH$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$
$ZHHH$	$1/3$	$1/3$	$1/3$	$1/3$	$3\,R^{\mathrm{HEFT}}_{(4),3}$	$1/3$
$HHHH$	$25/12$	$49/12$	$25\,R^{\mathrm{SMEFT}}_{(4),2}/12$	$1225/48$	$12\,R^{\mathrm{HEFT}}_{(4),4}$	0

Simulation, Consistency, Unitarity & Cross Sections

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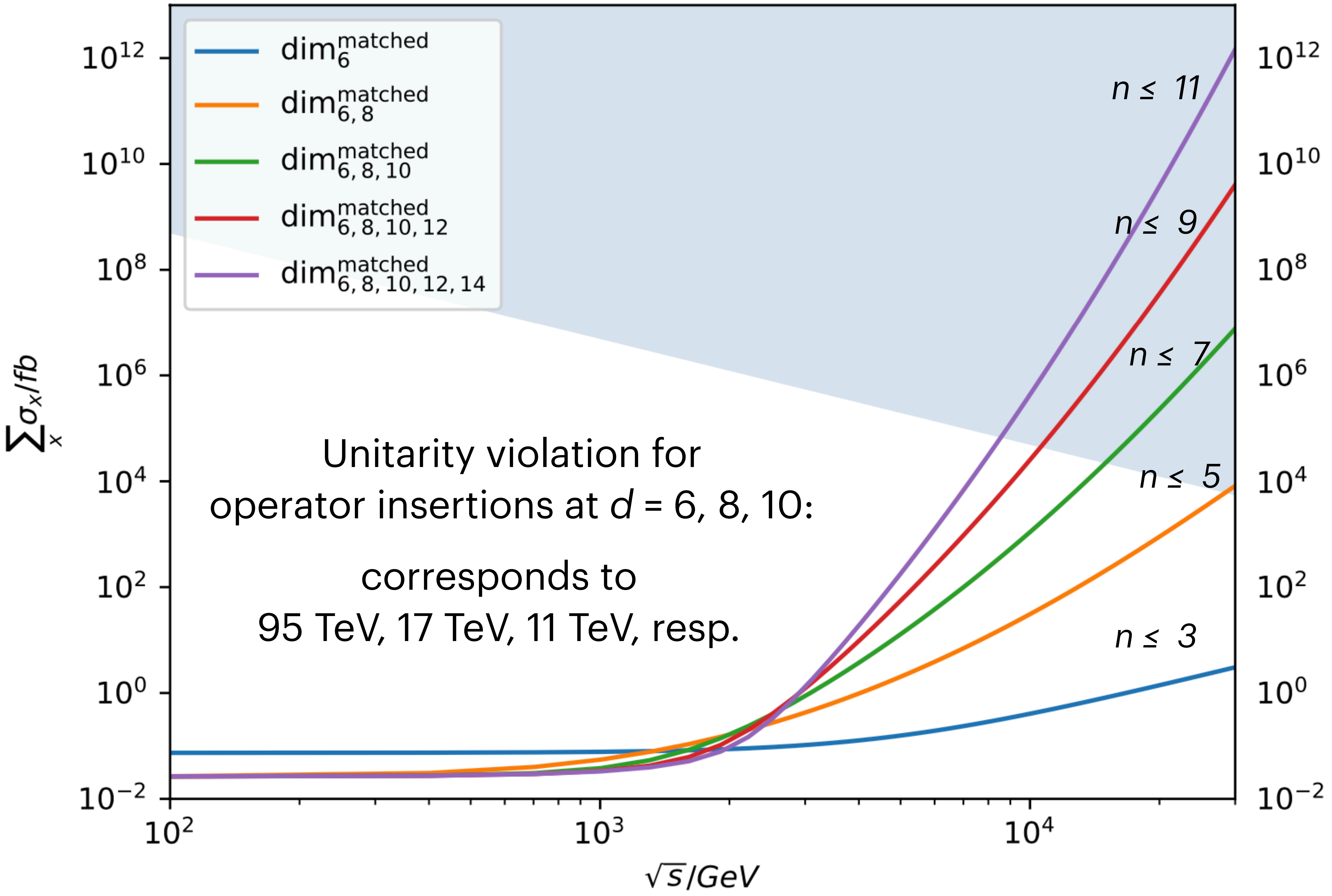
States with multiplicity 4

- Different cases: dim 6 alone, dim 8 alone, dim 6+8 combined
- Matched case: combination such that Yukawa coupling is zero



Unitarity violation for operator insertions at d = 6, 8, 10:

corresponds to 95 TeV, 17 TeV, 11 TeV, resp.

	SMEFT					
$\mu^+\mu^- \to X$	$\text{dim}_{6,8}$	dim_{10}	$\text{dim}_{6,8,10}$	$\text{dim}_{6,8,10}^{\text{matched}}$		
$WWWW$	$2/9$	$2/25$	$2\,R^{\text{SMEFT}}_{(4),1}/9$	$1/2$	R	
$WWZZ$	$1/9$	$1/25$	$R^{\text{SMEFT}}_{(4),1}/9$	$1/4$	R	
$ZZZZ$	$1/12$	$3/100$	$R^{\text{SMEFT}}_{(4),1}/12$	$3/16$	$R^{\text{HEFT}}_{(4),1}/48$	$3/16$
$WWZH$	$2/9$	$2/25$	$2\,R^{\text{SMEFT}}_{(4),1}/9$	$1/2$	$R^{\text{HEFT}}_{(4),2}/8$	$1/2$
$WWHH$	1	1	1	1	1	1
$ZZZH$	$1/3$	$3/25$	$R^{\text{SMEFT}}_{(4),1}/3$	$3/4$	$R^{\text{HEFT}}_{(4),2}/12$	$3/4$
$ZZHH$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$
$ZHHH$	$1/3$	$1/3$	$1/3$	$1/3$	$3\,R^{\text{HEFT}}_{(4),3}$	$1/3$
$HHHH$	$25/12$	$49/12$	$25\,R^{\text{SMEFT}}_{(4),2}/12$	$1225/48$	$12\,R^{\text{HEFT}}_{(4),4}$	0

Unitarity bound for final states $X \neq \mu\mu$:

$$\boxed{\sum_X \sigma_{\mu^+\mu^-\to X}(s) \le \frac{4\pi}{s}}$$

hep-ph/0106281

Kinematic separation of signal

$\mu^+\mu^- \to W^+W^-H$

Kinematic separation between multi-boson direct production and VBF, e.g. 10 TeV: arXiv: 2108.05362

QED ISR

- *WWZ* largest cross section, but small deviation
- *WWH* large cross section and considerable deviation
- *ZZH* smaller/-ish cross section, but largest (relative) deviation
- Direct production has almost full energy (except for ISR) $\Longrightarrow$ M_{3B}
- VBF generates mostly forward bosons $\Longrightarrow$ Θ_B
- Separation criterion for final state bosons $\Longrightarrow$ ΔR_{BB}

Cut flow	$\kappa_\mu = 1$	w/o ISR	$\kappa_\mu = 0$ (2)	CVBF	NVBF
σ [fb]	WWH				
No cut	0.24	0.21	0.47	2.3	7.2
$M_{3B} > 0.8\sqrt{s}$	0.20	0.21	0.42	$5.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-2}$
$10° < \theta_B < 170°$	0.092	0.096	0.30	$2.5 \cdot 10^{-4}$	$2.7 \cdot 10^{-4}$
$\Delta R_{BB} > 0.4$	0.074	0.077	0.28	$2.1 \cdot 10^{-4}$	$2.4 \cdot 10^{-4}$
# of events	740	770	2800	2.1	2.4
S/B	2.8				

Results and final projections

Muon collider with energy range $1 < \sqrt{s} < 30\ \mathrm{TeV}$ and luminosity $\mathcal{L} = \left(\frac{\sqrt{s}}{10\ \mathrm{TeV}}\right)^2 10\ \mathrm{ab}^{-1}$

1901.06150; 2001.04431;
PoS(ICHEP2020)703; Nat.Phys.17, 289-292

- ☑ Sensitivity to (deviations of) the muon Yukawa coupling
- ☑ Definition of # signal events: $S = N_{\kappa_\mu} - N_{\kappa_\mu=1}$
- ☑ Definition of # background events: $B = N_{\kappa_\mu=1} + N_{\mathrm{VBF}}$
- ☑ Statistical significance of anom. muon Yukawa couplings:

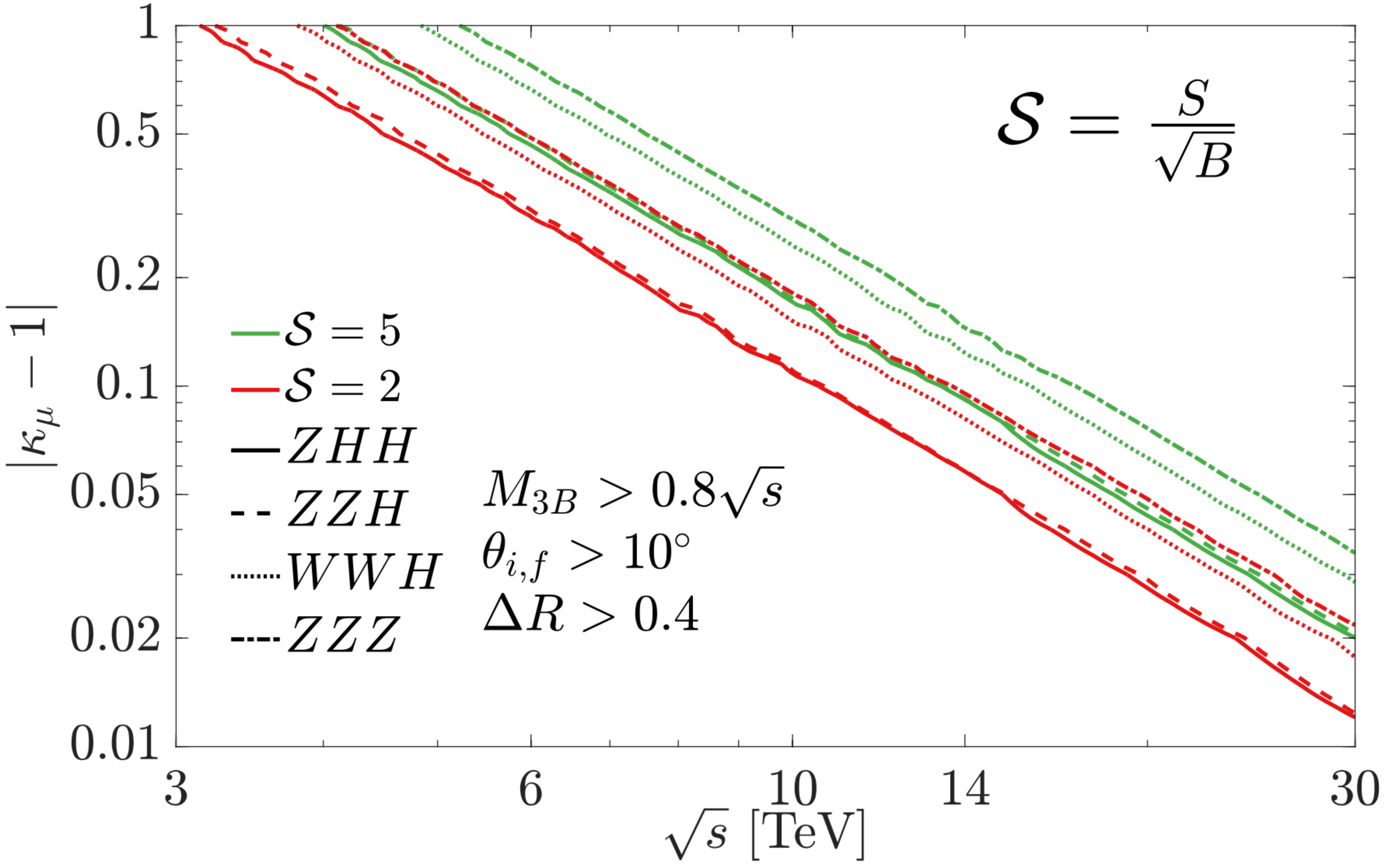
$$\mathcal{S} = \frac{S}{\sqrt{B}}$$

(note that always: $N_{\kappa_\mu} \geq N_{\kappa_\mu=1}$)

$$\sigma|_{\kappa_\mu=1+\delta} = \sigma|_{\kappa_\mu=1-\delta} \quad \Longrightarrow \quad \mathcal{S}|_{\kappa_\mu=1+\delta} = \mathcal{S}|_{\kappa_\mu=1-\delta}$$

- 5σ sensitivity to 20% @ 10 TeV .... 2% @ 30 TeV
- Sensitivity to κ translates to new physics scale Λ

$$\Lambda > 10\ \text{TeV}\sqrt{\frac{g}{\Delta\kappa_\mu}}$$



arXiv: 2108.05362

Multi-Higgs/V processes

Celada/Han/Kilian/Kreher/Ma/Maltoni/Pagani/JRR/Striegl/Xie, arXiv:2312.13082

- EFT setup generating multi-boson vertices of higher multiplicity
- Paradigmatic BSM implementations: scalar singlet *S* / vector-like fermions $E_{L/R}$
- Vertex parameterizations (can be expressed by HEFT or SMEFT operators):

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- Paradigmatic BSM implementations: scalar singlet *S* / vector-like fermions $E_{L/R}$
- Vertex parameterizations (can be expressed by HEFT or SMEFT operators):

$$\mathcal{L} \supset -\frac{m_H^2}{2}H^2 - m_\mu \bar{\mu}\mu - \sum_{n=3}^{\infty} \beta_n \frac{\lambda}{v^{n-4}} H^n - \sum_{n=1}^{\infty} \alpha_n \frac{m_\mu}{v^n} \bar{\mu}\mu H^n.$$

$$y_{\mu,n} = \frac{\sqrt{2}m_\mu}{v}\alpha_n, \qquad f_{V,n} = \beta_n \lambda$$

$$\alpha_1 = \frac{v}{\sqrt{2}m_\mu} y_{l,1} = 1 + \frac{v^3}{\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{v^5}{\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{3v^7}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_2 = \frac{v}{\sqrt{2}m_\mu} y_{l,2} = \frac{3v^3}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_3 = \frac{v}{\sqrt{2}m_\mu} y_{l,3} = \frac{v^3}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_4 = \frac{v}{\sqrt{2}m_\mu} y_{l,4} = \frac{5v^5}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_5 = \frac{v}{\sqrt{2}m_\mu} y_{l,5} = \frac{v^5}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

Multi-Higgs/V processes

Celada/Han/Kilian/Kreher/Ma/Maltoni/Pagani/JRR/Striegl/Xie, arXiv:2312.13082

- EFT setup generating multi-boson vertices of higher multiplicity
- Paradigmatic BSM implementations: scalar singlet S / vector-like fermions $E_{L/R}$
- Vertex parameterizations (can be expressed by HEFT or SMEFT operators):

$$\mathcal{L} \supset -\frac{m_H^2}{2}H^2 - m_\mu \bar{\mu}\mu - \sum_{n=3}^{\infty} \beta_n \frac{\lambda}{v^{n-4}} H^n - \sum_{n=1}^{\infty} \alpha_n \frac{m_\mu}{v^n} \bar{\mu}\mu H^n .$$

$$y_{\mu,n} = \frac{\sqrt{2}m_\mu}{v}\alpha_n, \qquad\qquad f_{V,n} = \beta_n \lambda$$

$$\alpha_1 = \frac{v}{\sqrt{2}m_\mu} y_{l,1} = 1 + \frac{v^3}{\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{v^5}{\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{3v^7}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

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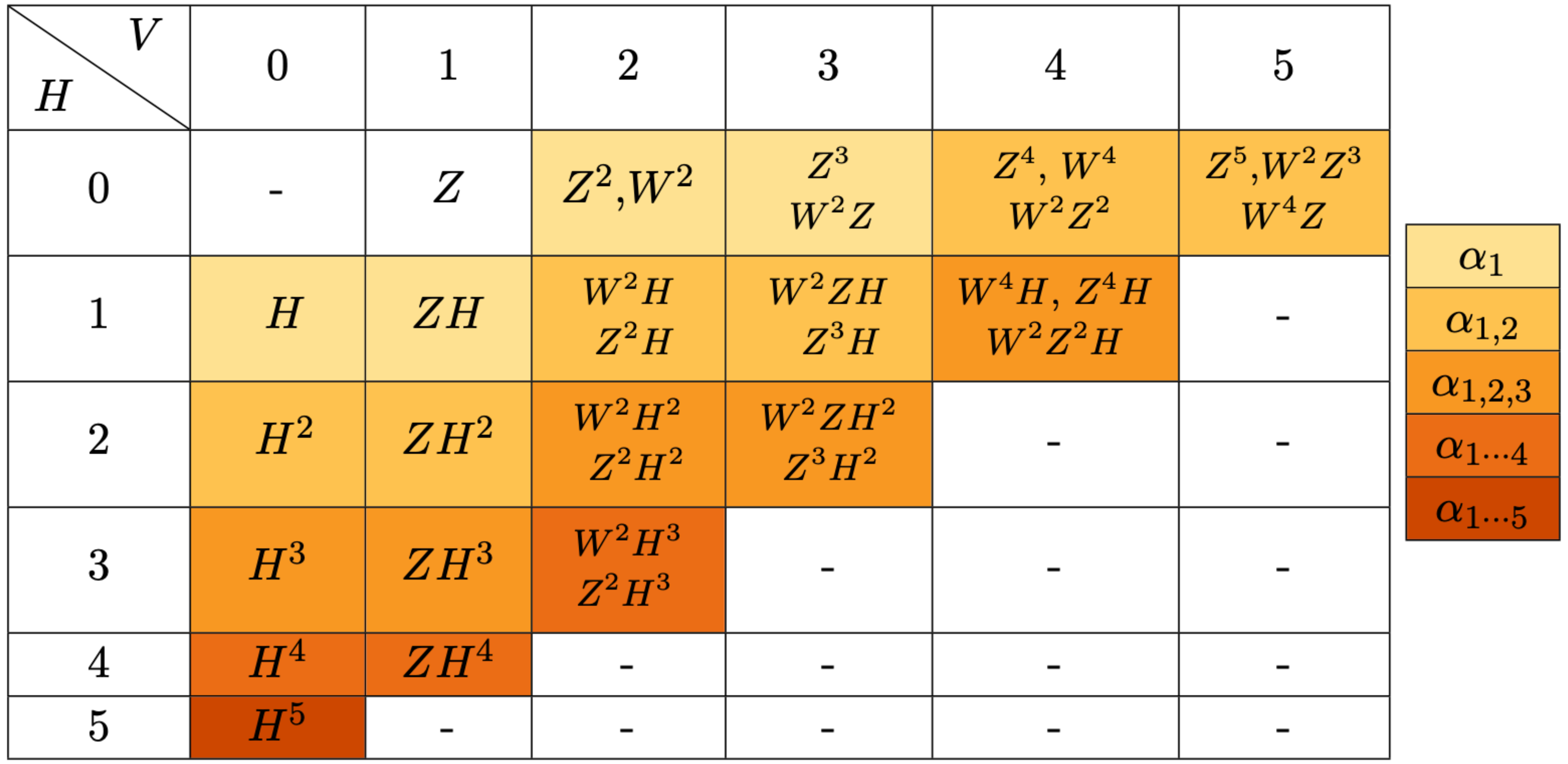

H \ V	0	1	2	3	4	5
0	-	Z	Z^2,W^2	Z^3 W^2Z	Z^4, W^4 W^2Z^2	Z^5,W^2Z^3 W^4Z
1	H	ZH	W^2H Z^2H	W^2ZH Z^3H	W^4H, Z^4H W^2Z^2H	-
2	H^2	ZH^2	W^2H^2 Z^2H^2	W^2ZH^2 Z^3H^2	-	-
3	H^3	ZH^3	W^2H^3 Z^2H^3	-	-	-
4	H^4	ZH^4	-	-	-	-
5	H^5	-	-	-	-	-

α_1

$\alpha_{1,2}$

$\alpha_{1,2,3}$

$\alpha_{1\ldots4}$

$\alpha_{1\ldots5}$

Multi-Higgs/V processes

Celada/Han/Kilian/Kreher/Ma/Maltoni/Pagani/JRR/Striegl/Xie, arXiv:2312.13082

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$$y_{\mu,n} = \frac{\sqrt{2} m_\mu}{v} \alpha_n , \qquad f_{V,n} = \beta_n \lambda$$

$$\alpha_1 = \frac{v}{\sqrt{2} m_\mu} y_{l,1} = 1 + \frac{v^3}{\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{v^5}{\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{3v^7}{4\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_2 = \frac{v}{\sqrt{2} m_\mu} y_{l,2} = \frac{3v^3}{2\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_3 = \frac{v}{\sqrt{2} m_\mu} y_{l,3} = \frac{v^3}{2\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

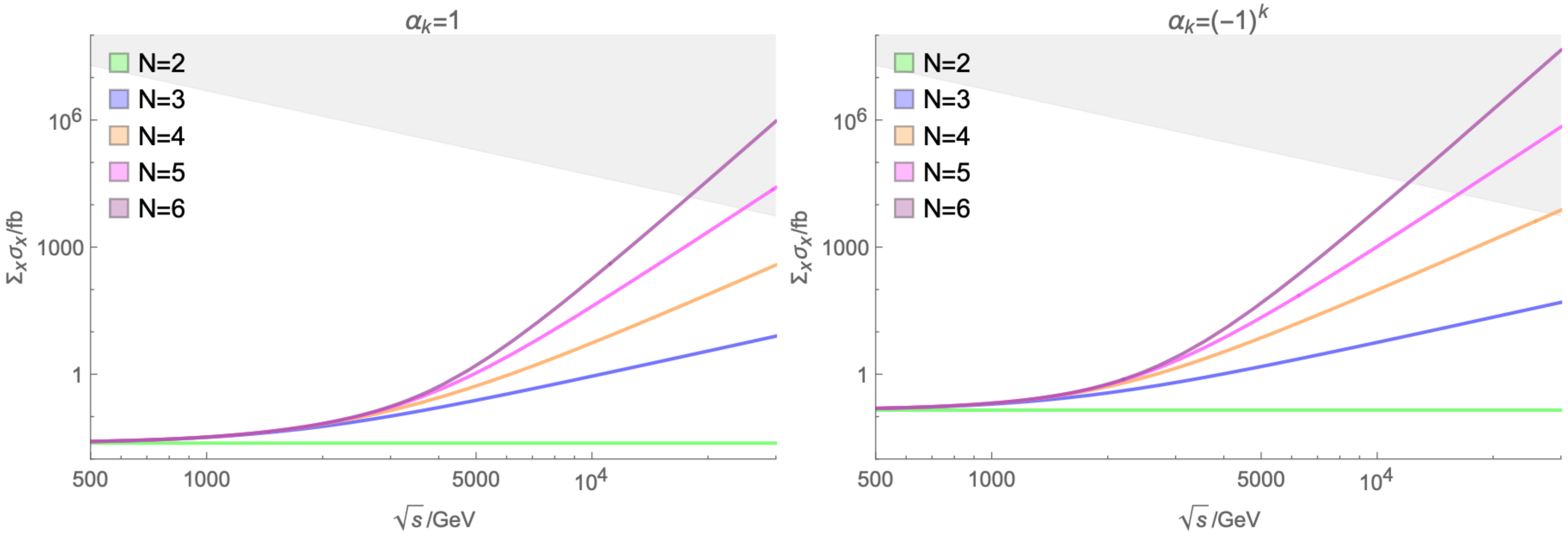
$$\alpha_4 = \frac{v}{\sqrt{2} m_\mu} y_{l,4} = \frac{5v^5}{4\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_5 = \frac{v}{\sqrt{2} m_\mu} y_{l,5} = \frac{v^5}{4\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2} m_\mu} \frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

H \ V	0	1	2	3	4	5
0	-	Z	Z^2,W^2	Z^3 W^2Z	Z^4, W^4 W^2Z^2	Z^5,W^2Z^3 W^4Z
1	H	ZH	W^2H Z^2H	W^2ZH Z^3H	W^4H, Z^4H W^2Z^2H	-
2	H^2	ZH^2	W^2H^2 Z^2H^2	W^2ZH^2 Z^3H^2	-	-
3	H^3	ZH^3	W^2H^3 Z^2H^3	-	-	-
4	H^4	ZH^4	-	-	-	-
5	H^5	-	-	-	-	-

α_1
$\alpha_{1,2}$
$\alpha_{1,2,3}$
$\alpha_{1\ldots4}$
$\alpha_{1\ldots5}$

Perturbative Unitarity bound



Results for $\mu^+\mu^- \to V^k H^l$

Cut flow: signal and background events

$\sqrt{s}$	3 TeV				10 TeV			
	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF
σ [fb]	$2H$							
No cut	$2.4 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	0.951	$2.4 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.2 \cdot 10^{-4}$	3.80
$M_F > 0.8\sqrt{s}$	$2.4 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	$6.12 \cdot 10^{-4}$	$2.4 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.2 \cdot 10^{-4}$	$6.50 \cdot 10^{-4}$
$\lvert\theta_{iB}\rvert > 10^\circ$	$2.3 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	$1.18 \cdot 10^{-4}$	$2.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.1 \cdot 10^{-4}$	$3.46 \cdot 10^{-5}$
event #	23	–	2.6	0.12	230	–	4.1	0.3
σ [fb]	$3H$							
No cut	$3.1 \cdot 10^{-2}$	$3.0 \cdot 10^{-8}$	$1.1 \cdot 10^{-5}$	$3.69 \cdot 10^{-4}$	$3.7 \cdot 10^{-1}$	$2.3 \cdot 10^{-9}$	$1.7 \cdot 10^{-6}$	$5.52 \cdot 10^{-3}$
$M_F > 0.8\sqrt{s}$	$3.1 \cdot 10^{-2}$	$3.0 \cdot 10^{-8}$	$1.1 \cdot 10^{-5}$	$2.84 \cdot 10^{-6}$	$3.7 \cdot 10^{-1}$	$2.3 \cdot 10^{-9}$	$1.7 \cdot 10^{-6}$	$7.85 \cdot 10^{-5}$
$\lvert\theta_{iB}\rvert > 10^\circ$	$3.0 \cdot 10^{-2}$	$2.8 \cdot 10^{-8}$	$1.1 \cdot 10^{-5}$	$6.82 \cdot 10^{-7}$	$3.5 \cdot 10^{-1}$	$2.2 \cdot 10^{-9}$	$1.7 \cdot 10^{-6}$	$7.37 \cdot 10^{-5}$
$\Delta R_{BB} > 0.4$	$2.9 \cdot 10^{-2}$	$2.7 \cdot 10^{-8}$	$8.1 \cdot 10^{-6}$	$6.07 \cdot 10^{-7}$	$3.4 \cdot 10^{-1}$	$2.1 \cdot 10^{-9}$	$6.8 \cdot 10^{-7}$	$7.22 \cdot 10^{-5}$
event #	29	–	–	–	3400	–	–	0.7

Results for $\mu^+\mu^- \to V^k H^l$

Cut flow: signal and background events

$\sqrt{s}$	3 TeV				10 TeV			
	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF
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No cut	$2.4 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	0.951	$2.4 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.2 \cdot 10^{-4}$	3.80
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$\|\theta_{iB}\| > 10°$	$2.3 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	$1.18 \cdot 10^{-4}$	$2.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.1 \cdot 10^{-4}$	$3.46 \cdot 10^{-5}$
event #	23	–	2.6	0.12	230	–	4.1	0.3
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No cut	$3.1 \cdot 10^{-2}$	$3.0 \cdot 10^{-8}$	$1.1 \cdot 10^{-5}$	$3.69 \cdot 10^{-4}$	$3.7 \cdot 10^{-1}$	$2.3 \cdot 10^{-9}$	$1.7 \cdot 10^{-6}$	$5.52 \cdot 10^{-3}$
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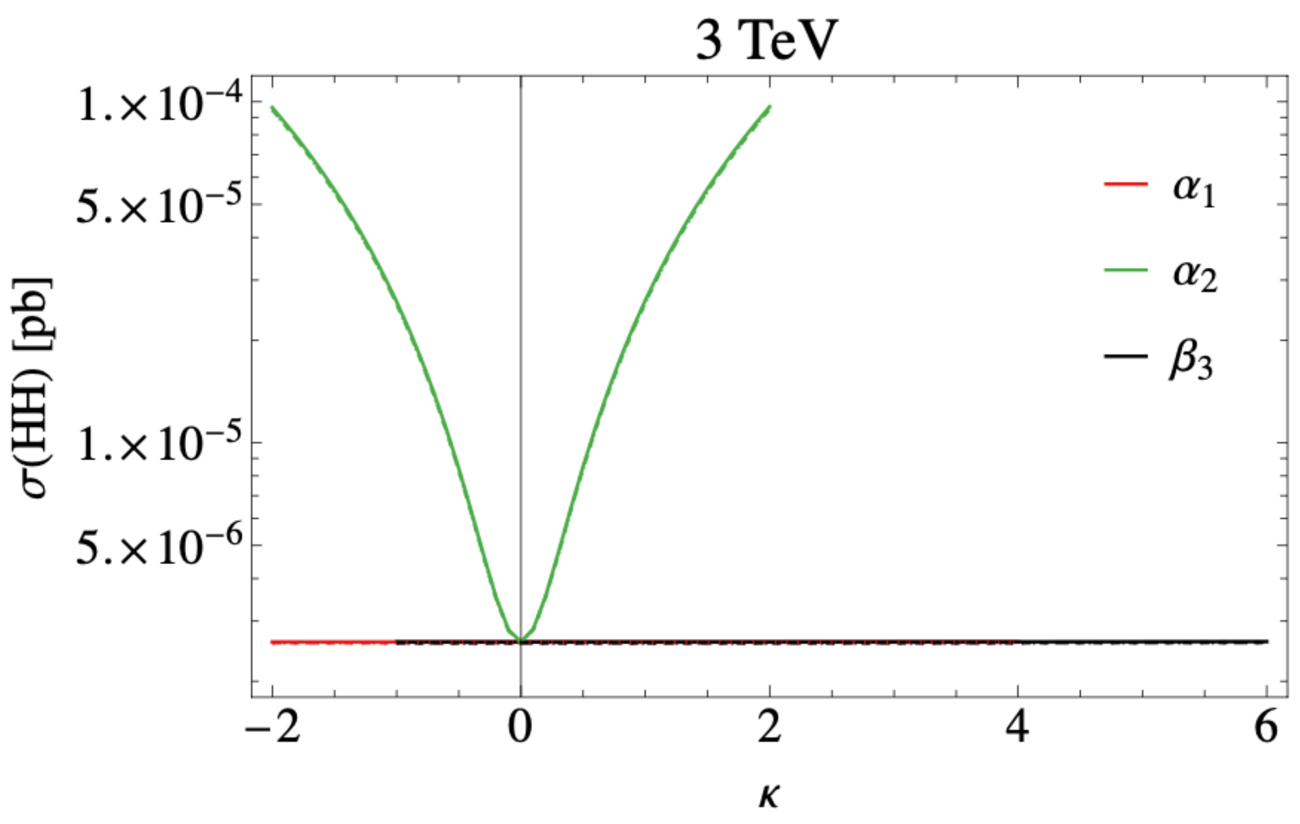
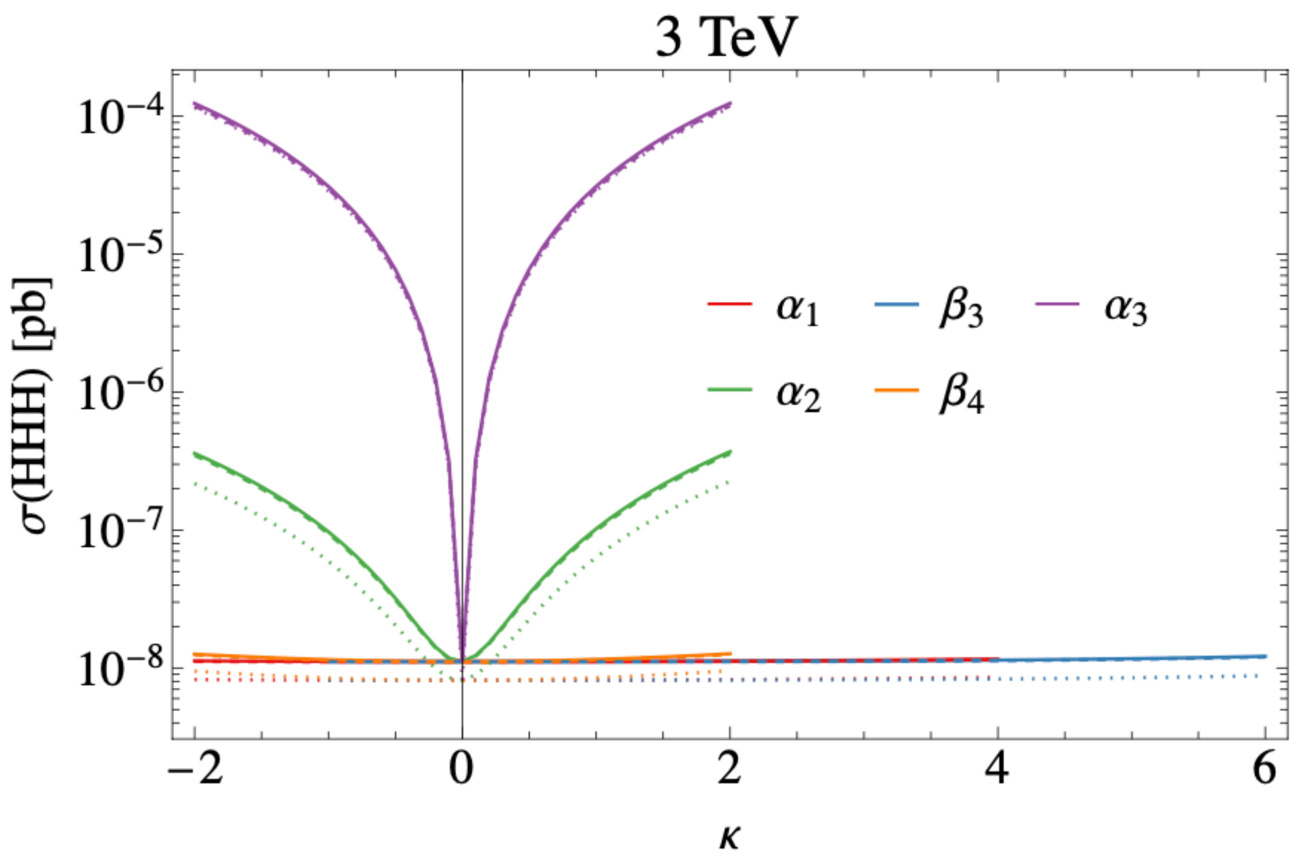
event #	29	–	–	–	3400	–	–	0.7





Results for $\mu^+\mu^- \to V^k H^l$

Cut flow: signal and background events

$\sqrt{s}$	3 TeV				10 TeV			
	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF
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$\lvert\theta_{iB}\rvert > 10°$	$2.3 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	$1.18 \cdot 10^{-4}$	$2.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.1 \cdot 10^{-4}$	$3.46 \cdot 10^{-5}$
event #	23	–	2.6	0.12	230	–	4.1	0.3
σ [fb]	$3H$							
No cut	$3.1 \cdot 10^{-2}$	$3.0 \cdot 10^{-8}$	$1.1 \cdot 10^{-5}$	$3.69 \cdot 10^{-4}$	$3.7 \cdot 10^{-1}$	$2.3 \cdot 10^{-9}$	$1.7 \cdot 10^{-6}$	$5.52 \cdot 10^{-3}$
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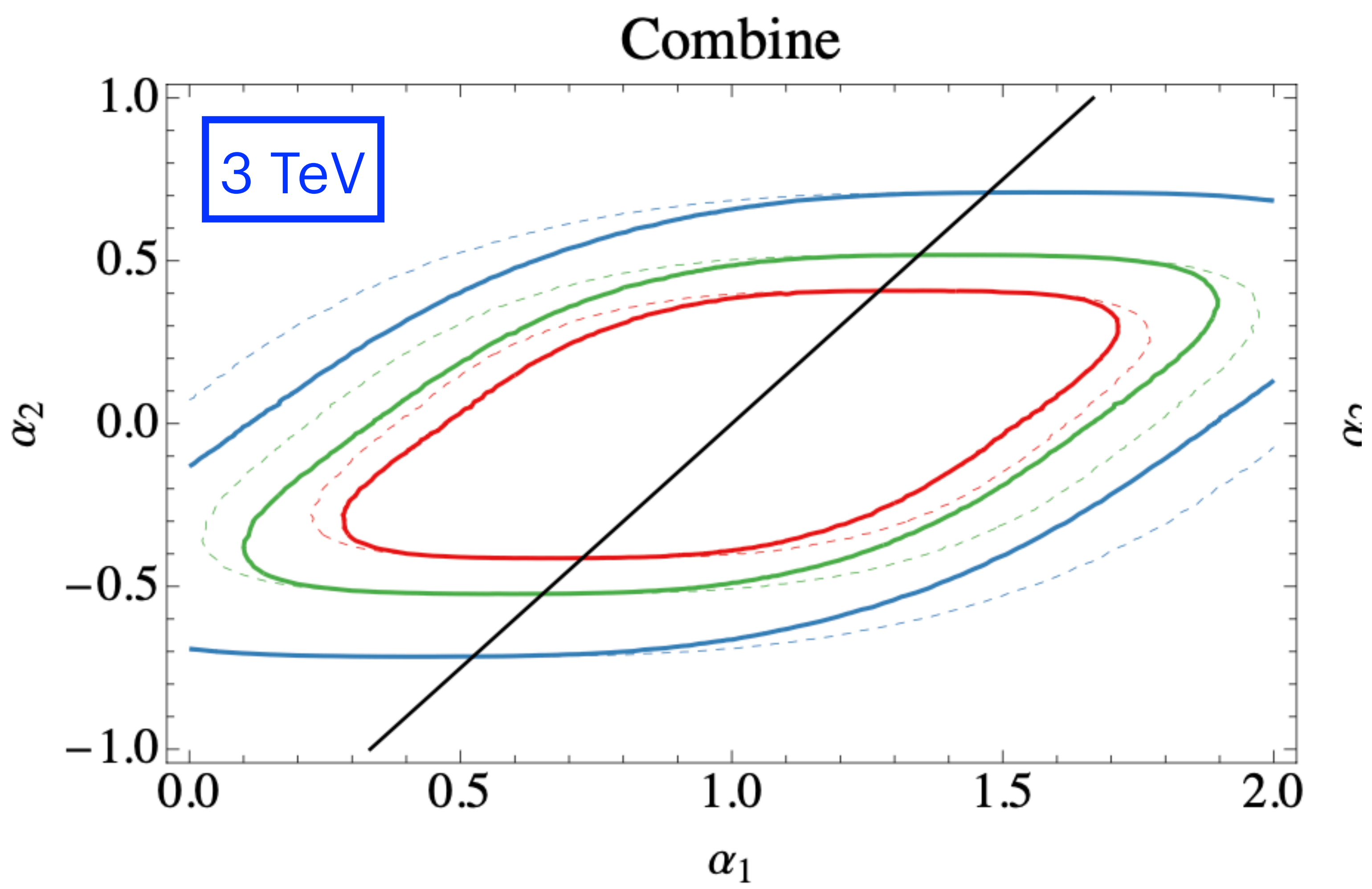
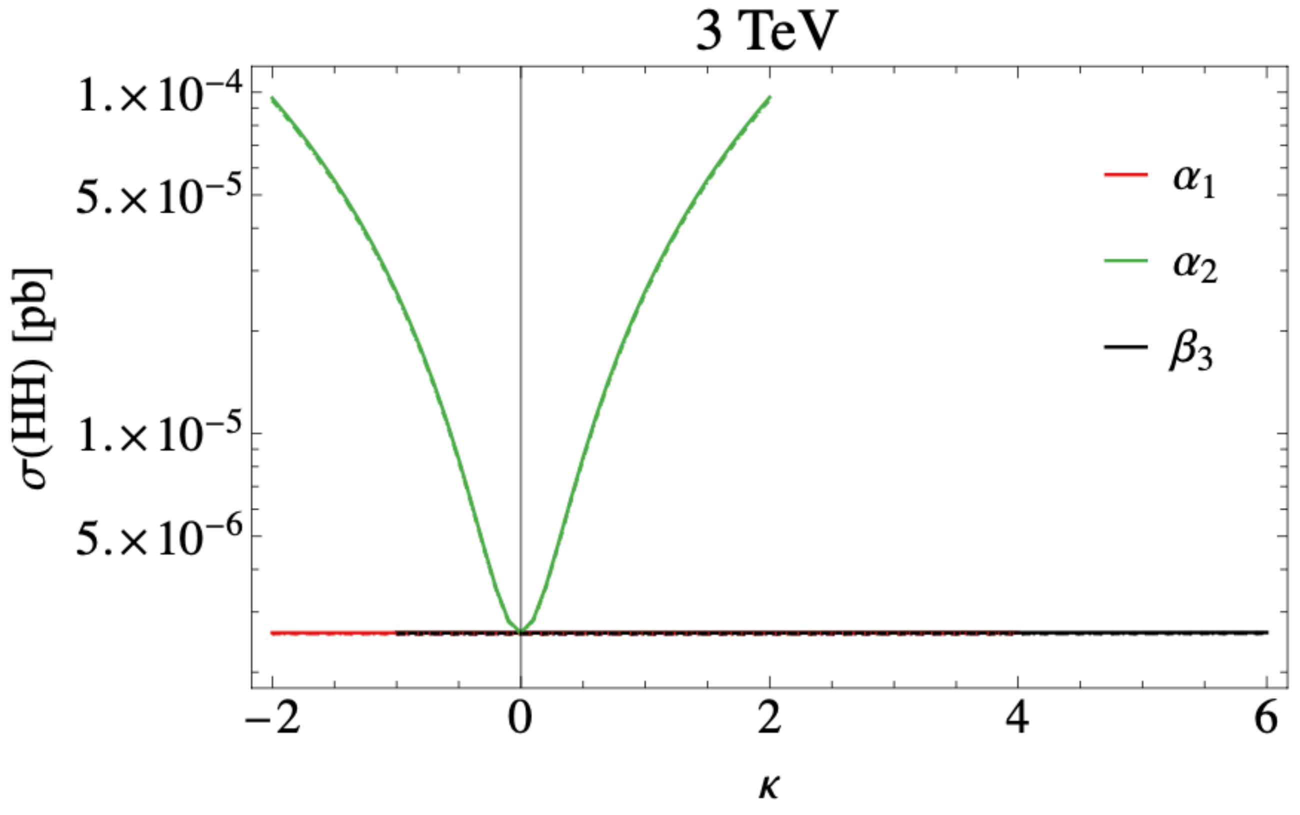
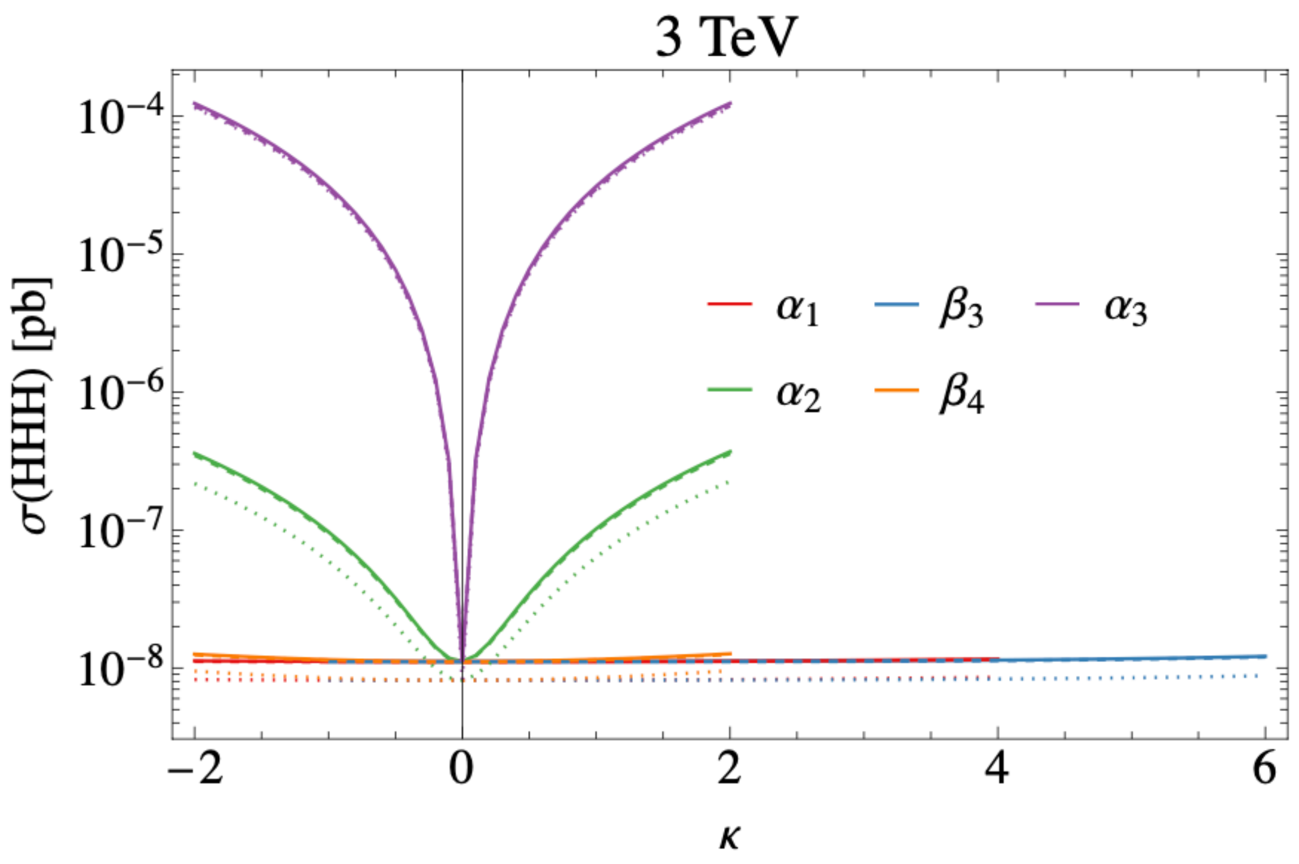
event #	29	–	–	–	3400	–	–	0.7

Combination of $\mu\mu \to HH, HVV, V^k$







Results for $\mu^+\mu^- \to V^k H^l$

Cut flow: signal and background events

$\sqrt{s}$	3 TeV				10 TeV			
	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF	$\alpha_{2(3)} = 1^\dagger$	SM LO	Loop	VBF
σ [fb]	$2H$							
No cut	$2.4 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	0.951	$2.4 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.2 \cdot 10^{-4}$	3.80
$M_F > 0.8\sqrt{s}$	$2.4 \cdot 10^{-2}$	$1.6 \cdot 10^{-7}$	$2.6 \cdot 10^{-3}$	$6.12 \cdot 10^{-4}$	$2.4 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$	$4.2 \cdot 10^{-4}$	$6.50 \cdot 10^{-4}$
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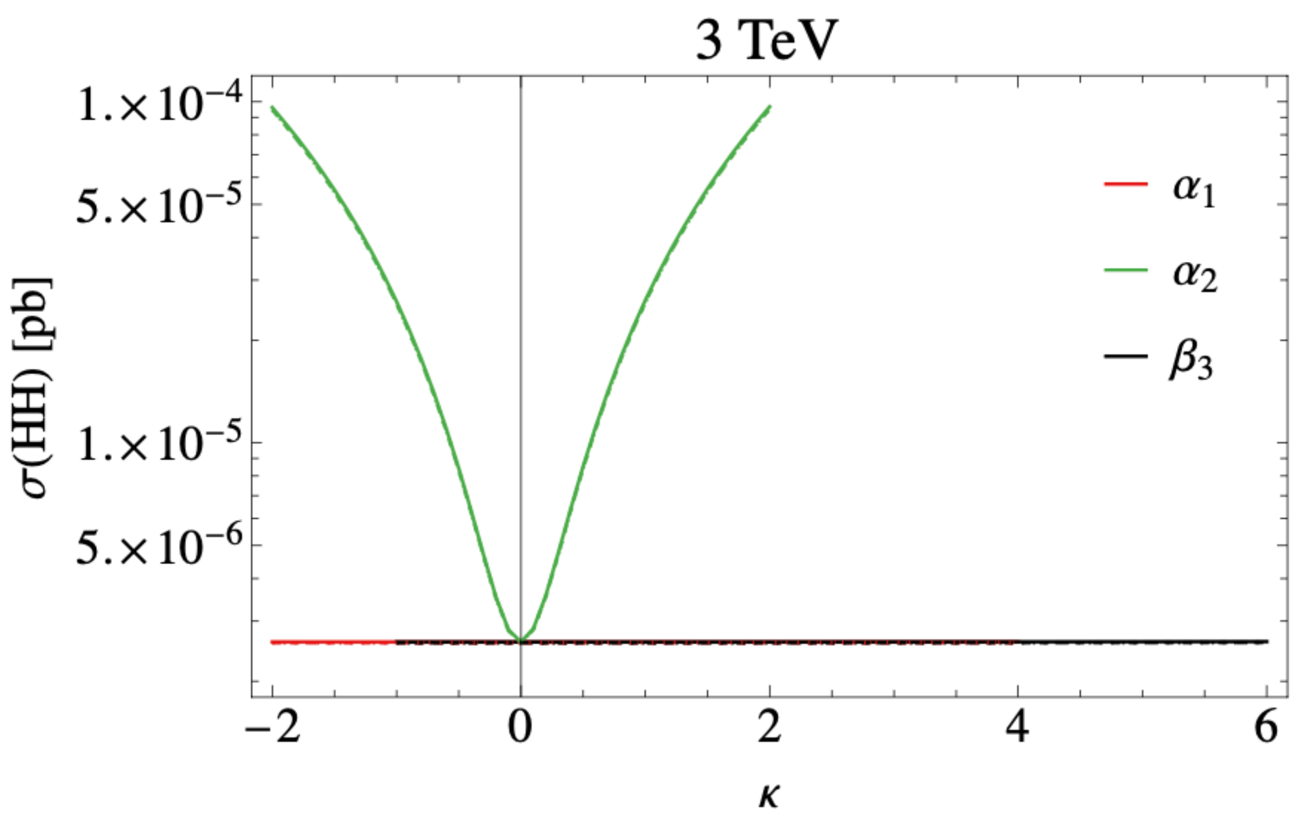
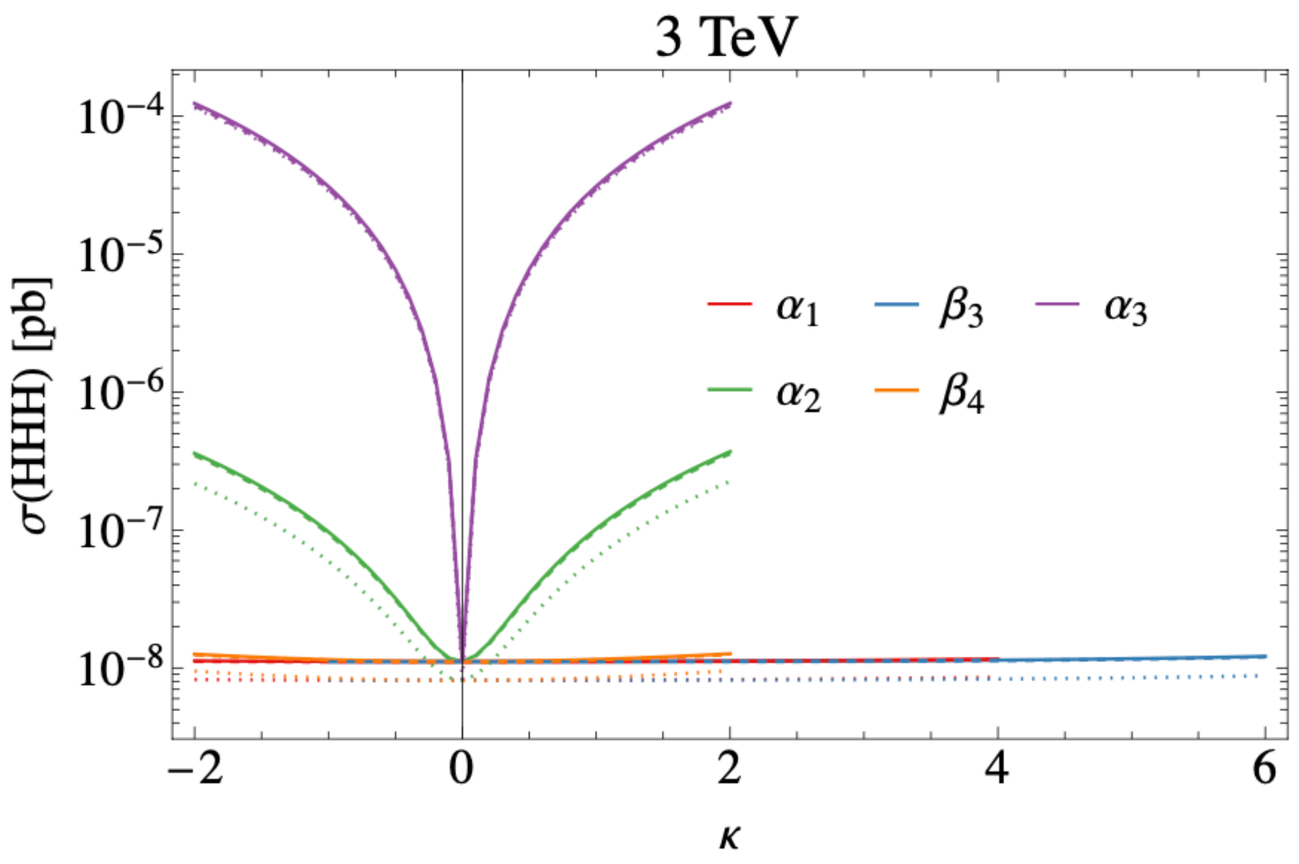
event #	29	–	–	–	3400	–	–	0.7





Combination of $\mu\mu \to HH, HVV, V^k$