Two-Photon Pair Production at High Energy Colliders

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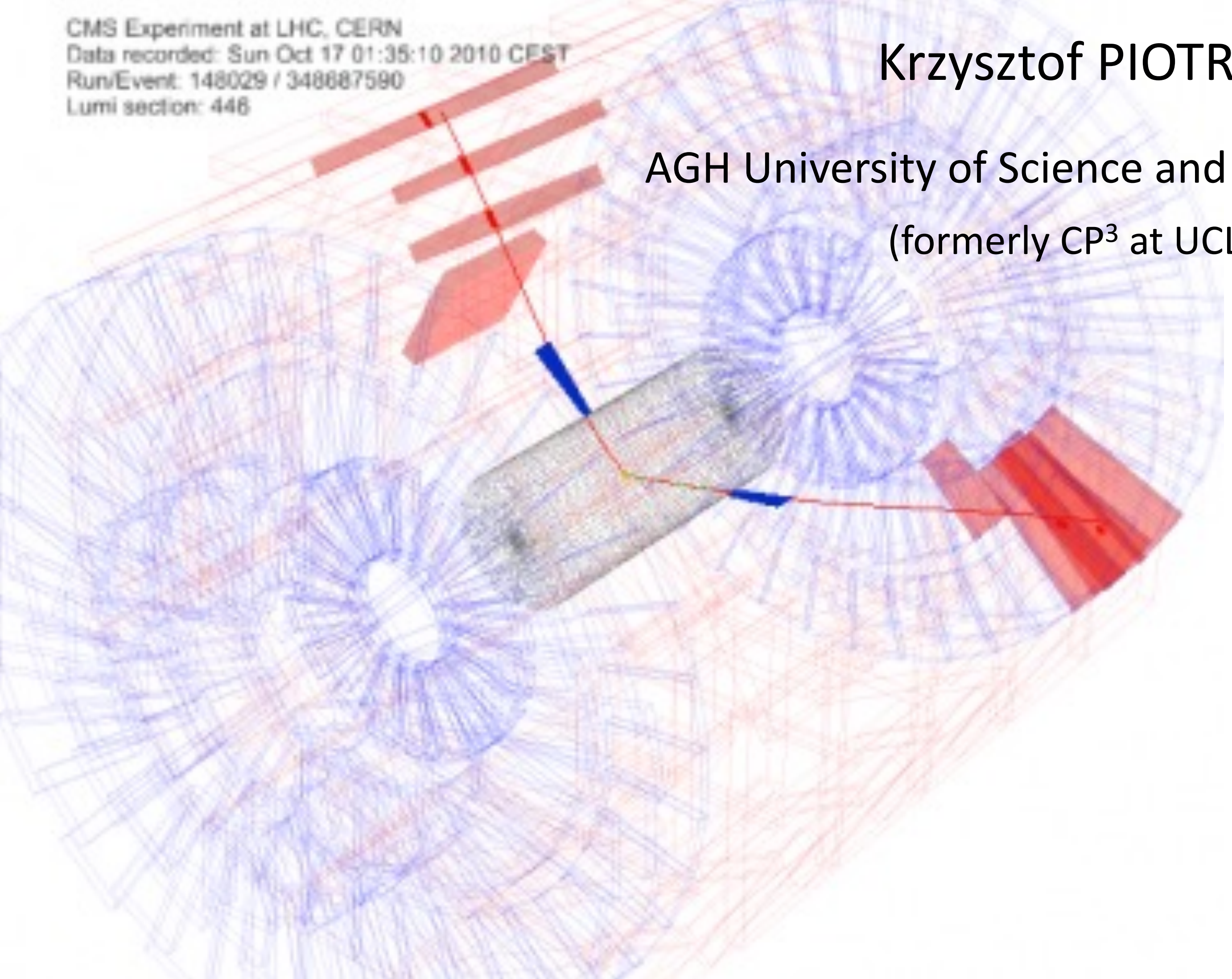
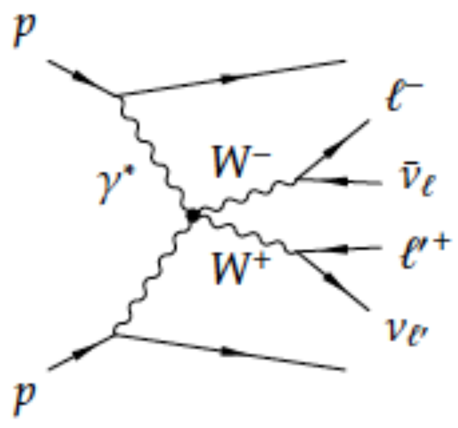
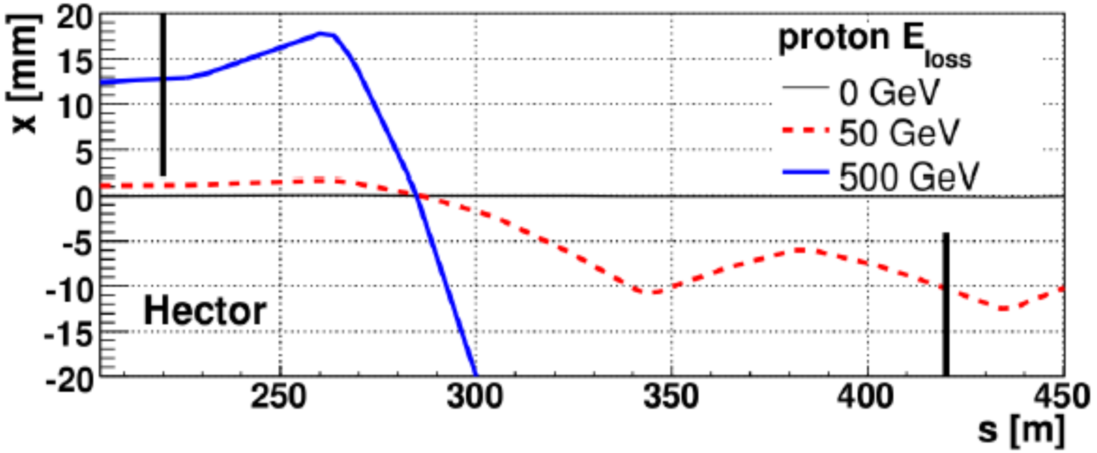
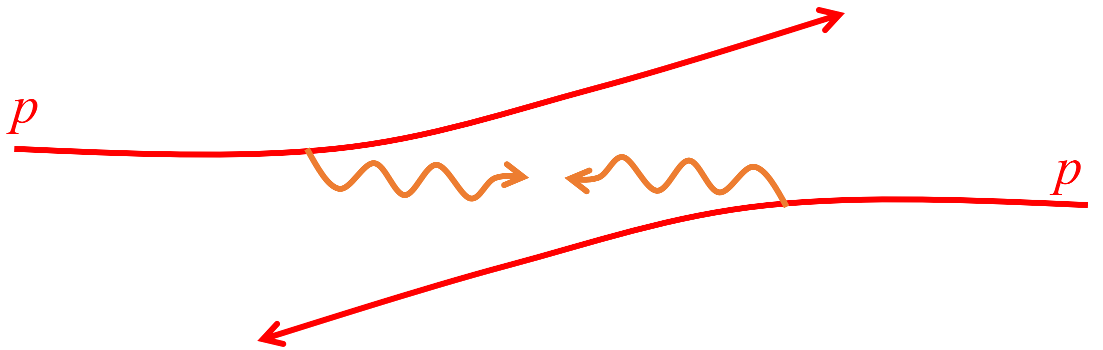






As an Introduction: LHC as a High Energy $\gamma\gamma$ Collider



Phys. Rev. **D63** (2001) 071502(R)
hep-ex/0201027

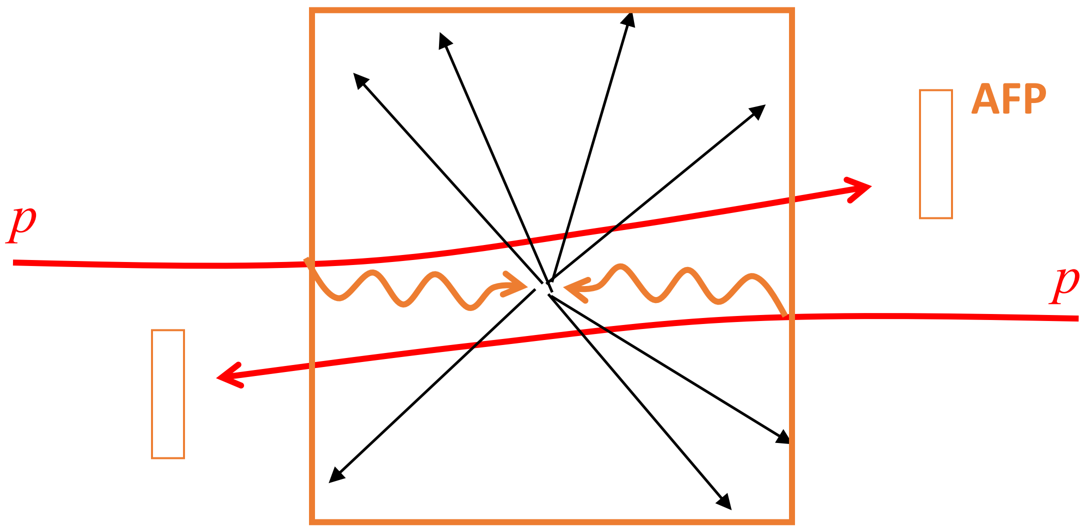
Initial observation:
Provided efficient measurement of very forward-scattered protons one can study high-energy $\gamma\gamma$ collisions at the LHC

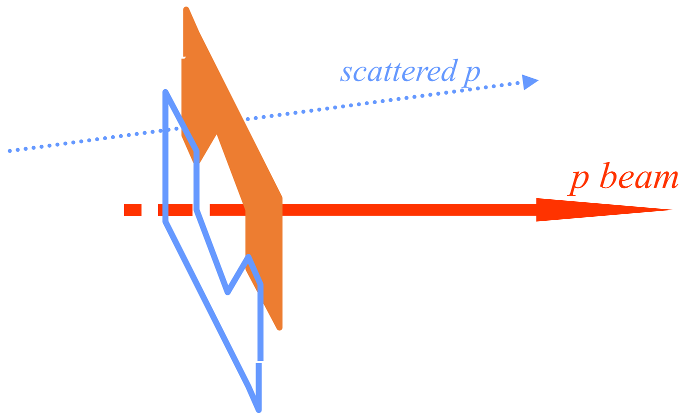
Highlights:

- **$\gamma\gamma$ CM energy *W* up to/beyond 1 TeV (and under control)**
- **Large (quasi-real) photon flux *F* therefore significant (effective) $\gamma\gamma$ luminosity**
- **Complementary (and "clean") physics to *pp* interactions, e.g. studies of exclusive production of heavy particles might be possible ➡ opening new field of high energy $\gamma\gamma$ physics**

How to measure these events?

Measure $(\gamma\gamma \rightarrow)$ X in the **ATLAS** or **CMS** detector and the scattered protons using dedicated **very forward detectors** (thanks to the proton energy loss)

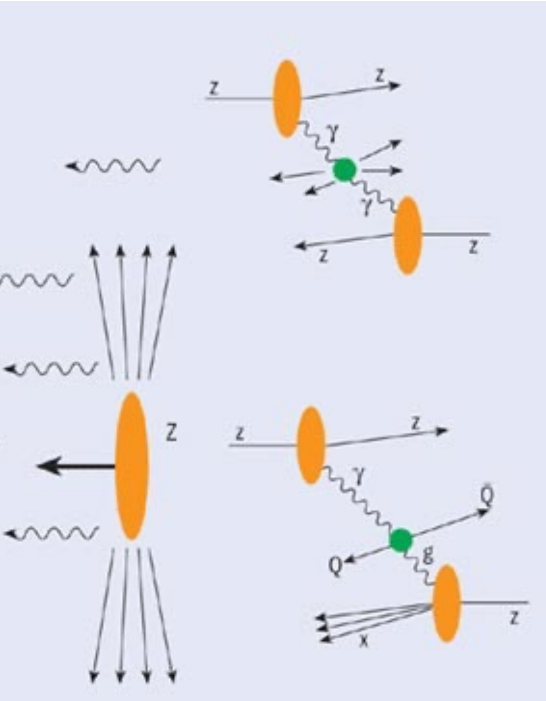




Very forward detectors needed – capable of running at high luminosity, installed as far (> 100 m) from IP and as close to the beam (≥2 mm) as possible.

Nota bene: no event pileup included at that time

Beyond Weizsäcker-Williams: *Equivalent Photon Approximation* (EPA)



In EPA the photon spectrum is a function of the photon energy ω and its virtuality Q^2 [1]:

$$\mathrm{d}N = \frac{\alpha}{\pi}\frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}Q^2}{Q^2}\left[\left(1-\frac{\omega}{E}\right)\left(1-\frac{Q^2_{min}}{Q^2}\right)F_E + \frac{\omega^2}{2E^2}F_M\right], \qquad (1)$$

where α is the fine-structure constant, E is the incoming proton energy and the minimum photon virtuality $Q^2_{min} \simeq [M_N^2 E/(E-\omega) - M_p^2]\omega/E$, where M_p is the proton mass and M_N is the invariant mass of the final state N. For the elastic production, assuming the dipole approximation for proton form factors, $F_M = G_M^2$ and $F_E = (4M_p^2 G_E^2 + Q^2 G_M^2)/(4M_p^2 + Q^2)$, and $G_E^2 = G_M^2/7.78 = (1+Q^2/0.71\mathrm{GeV}^2)^{-4}$. For the inelastic production $F_M = \int \mathrm{d}x F_2/x^3$ and $F_E = \int \mathrm{d}x F_2/x$, where $F_2(x, Q^2)$ is the proton structure function and $x \simeq Q^2/M_N^2$.

Physics Reports, Volume 15, Issue 4, January 1975, Pages 181-282

***Elastic* (or fully exclusive) production + *Inelastic*, when proton dissociates**

EPA: Kinematics/γγ Luminosity

Virtuality Q^2 of colliding photons vary between kinematical minimum = $M_p^2 x^2/(1-x)$ where x is fraction of proton momentum carried by a photon, and $Q^2_{max} \sim 1/\text{proton radius}^2$

$$W^2 = s\, x_1\, x_2$$

(where $W \equiv M_X$)

Phys. Rev. **D63** (2001) 071502(R)

Photon flux $\propto 1/Q^2$

$Q^2 - Q^2_{min} \approx s\theta^2/4$

protons scattered at
`zero-degree' angle

$S_{\gamma\gamma}(W) = N_\gamma(x_1) \otimes N_\gamma(x_2)$

$\sigma_{pp} = \int S\, \sigma_{\gamma\gamma}\, dW$

Use EPA à la *Budnev et al.**

* *error found in the elastic (Q^2 integrated) γ flux for protons!*

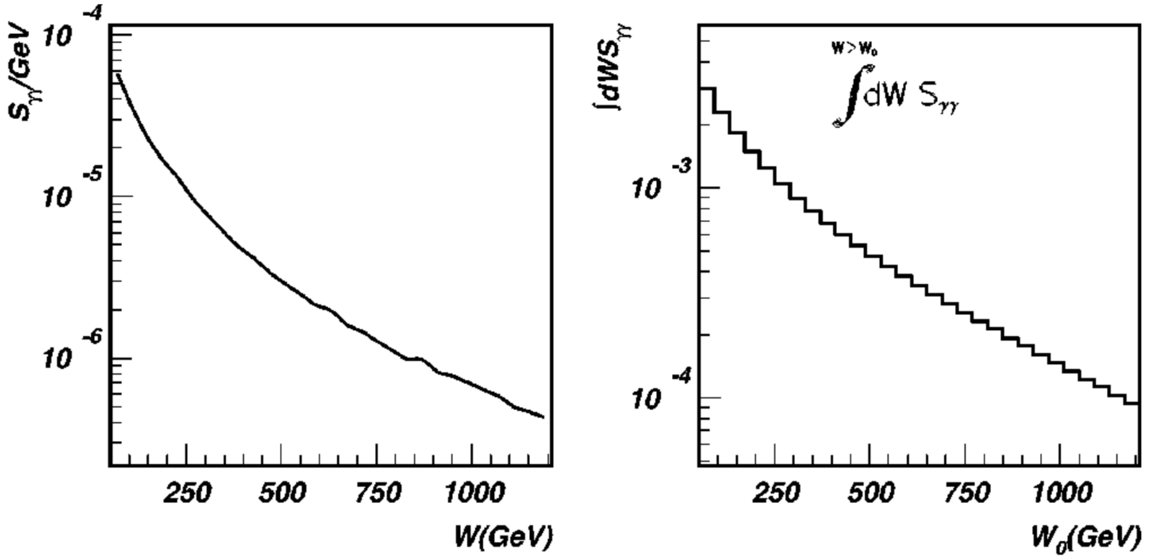


FIG. 1. Elastic $\gamma\gamma$ luminosity spectrum and its integral $\int^{W>W_0} dWS_{\gamma\gamma}$ at the LHC, for the range of photon energy and virtuality, 5 GeV$<\omega<$7000 GeV and $Q^2_{min}<Q^2<2$ GeV^2.

$\int dWS_{\gamma\gamma}$ = *'γγ : pp luminosity'*

Note: it's few times larger if one of protons is allowed to break up

LHC as a $\gamma\gamma$ collider

At high energies two-photon exclusive pair production cross-section is given by:

particle **charge, mass and spin**

for given mass and charge it is largest for vector particles, then for fermions,

$\gamma\gamma \rightarrow$ WW pair production has a very sizable cross-section at the LHC of $\sim$100 fb (and at least $\times$ 4, if inelastic production included)!

Massive fermions have sizable $\gamma\gamma$ cross-sections up to about 200 GeV masses, for scalars cross-sections are about 5 times smaller, but there is H^{++} case, for example

$\sigma \propto Z^4 \Rightarrow \sigma \times 16$!

LHC as a $\gamma\gamma$ collider

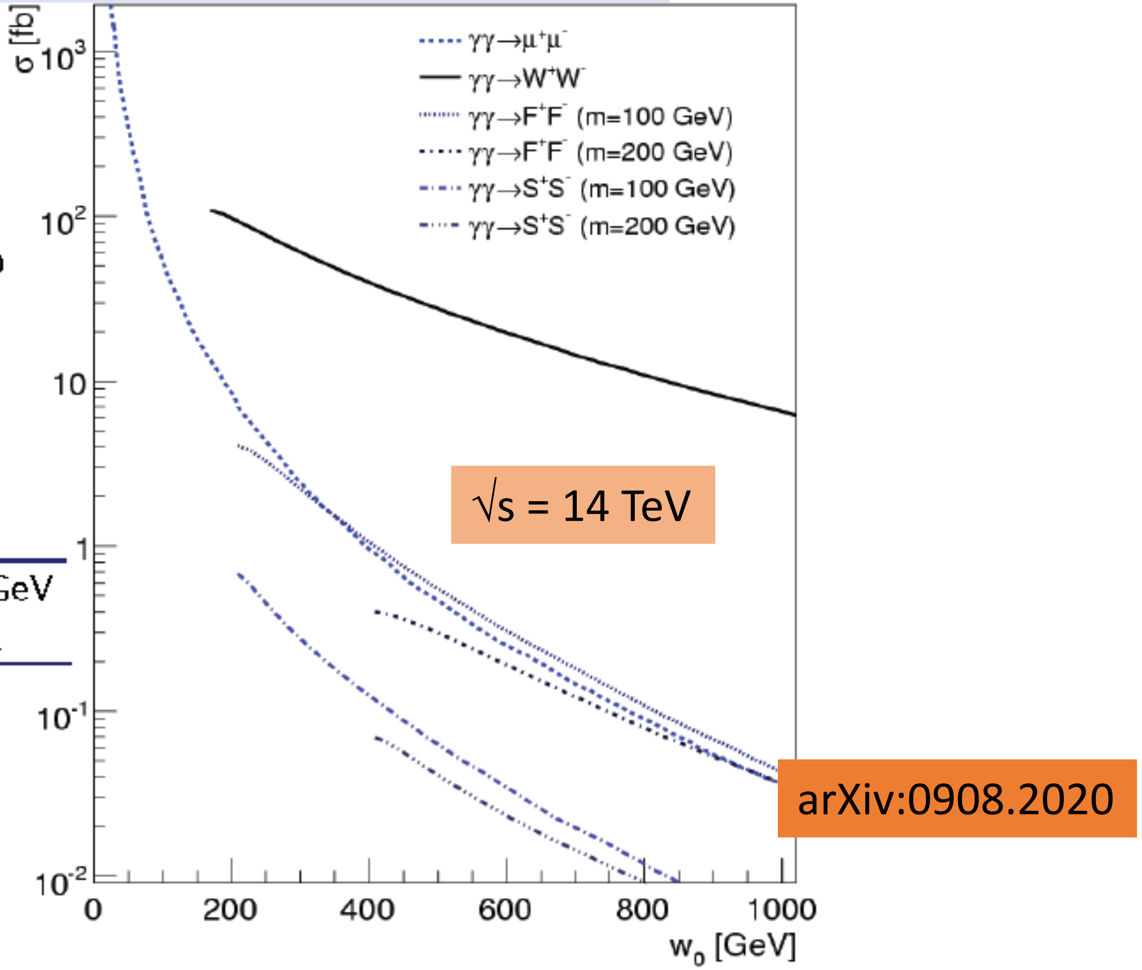
- $\gamma\gamma \rightarrow \mu\mu$ first $\gamma\gamma$ process to be seen
- $\gamma\gamma \rightarrow W^+W^-$ very interesting SM process 108fb
- New physics !

Processes		[fb]	Generator
$\gamma\gamma \rightarrow \mu\mu$		72 500	LPAIR pt > 2 GeV $\lvert\eta\rvert < 3.1$
$\gamma\gamma \rightarrow$ WW		108	
$\rightarrow$ FF	(m=100GeV)	4.06	MadGraph
$\rightarrow$ FF	(m=200GeV)	0.40	/
$\rightarrow$ SS	(m=100GeV)	0.68	MadEvent
$\rightarrow$ SS	(m=200GeV)	0.07	

moreover :

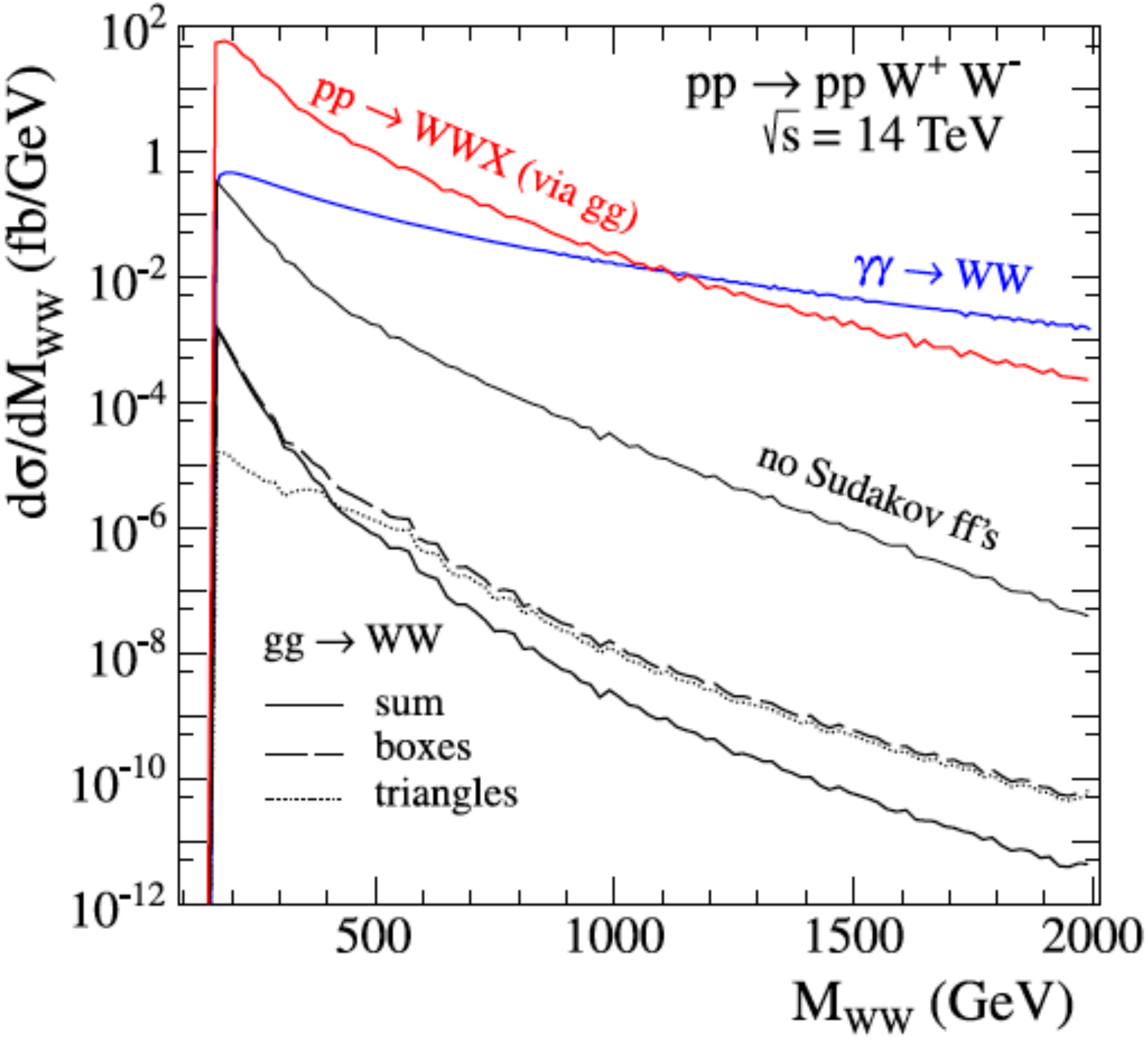
lepton final states

clear signature – background suppression



Cross sections for $\gamma\gamma$ processes as a function of the minimal $\gamma\gamma$ cms energy W_0

WW pair production @ LHC



At very high energy $\gamma\gamma$ wins over 'inclusive' production !!

*Nucl. Phys. B **867** (2013) 61*

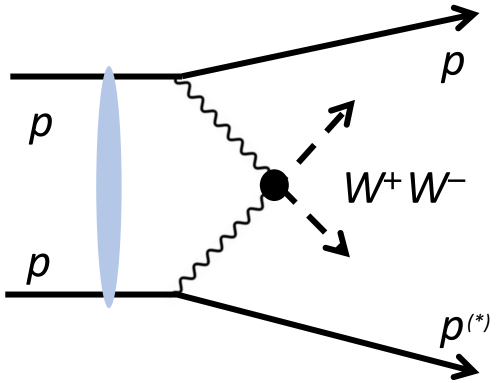
EPA and absorption corrections

EPA assumes **full** factorization of the long range (→ photon fluxes) and short range (→ $\gamma\gamma$ fusion) physics; values of the impact parameter *b* are the best check of a regime one works with – they are different for the proton elastic and dissociative cases, though the flux *b* dependence is similar, $dn \propto bdb$.

If one takes the 8 TeV beam and $x = 0.01$ (corresponding to W = 160 GeV) then:

Elastic: $b_{max} \approx 20$ fm and $b_{min} \approx 0.6$ fm

Inelastic (dissociative): typ. $b_{max} \approx 0.1$ fm and $b_{min} \approx 0.01$ fm



Note:

For two-photon exchange one deals with two impact parameters, so one can approximate

$$b \approx b_1 + b_2$$

EPA and absorption corrections

For two-photon exchange one deals with two impact parameters, hence one can approximate $b \approx b_1 + b_2$

Therefore, relatively small absorption are expected both for fully exclusive (*elastic-elastic*) as well as single dissociative SD (2x *elastic-inelastic*) and **BIG** one for DD case (*inelastic-inelastic*)

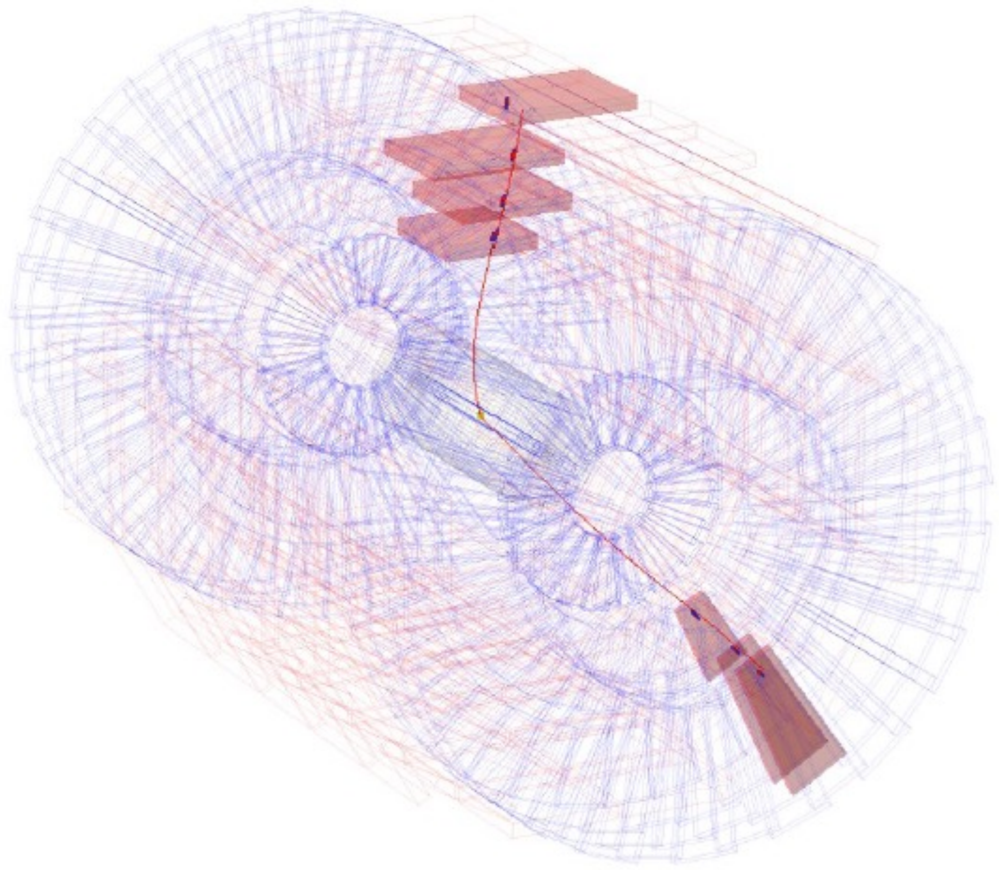
Three important comments regarding two-photon *lepton pair production*:

- Lepton pair acoplanarity is a good measure of the relevant impact parameters involved; if there is significant absorption it must distort the acoplanarity

- Absorption should increase with increase of W (since b_{max} **decreases**)

- Fully exclusive pairs die fast with increasing pair p_T; so above 1 GeV/c one is left with SD+DD only

Untagged $\gamma\gamma$: Special Exclusivity Conditions and Lepton Pairs



Exclusivity in initial (very) low luminosity era:
2 muons and “nothing else“
in the tracker **and** calorimeters

In 2010, each event of interest was accompanied by extra “PileUp” events within the same bunch crossing:
~ 2-3 pileup interactions

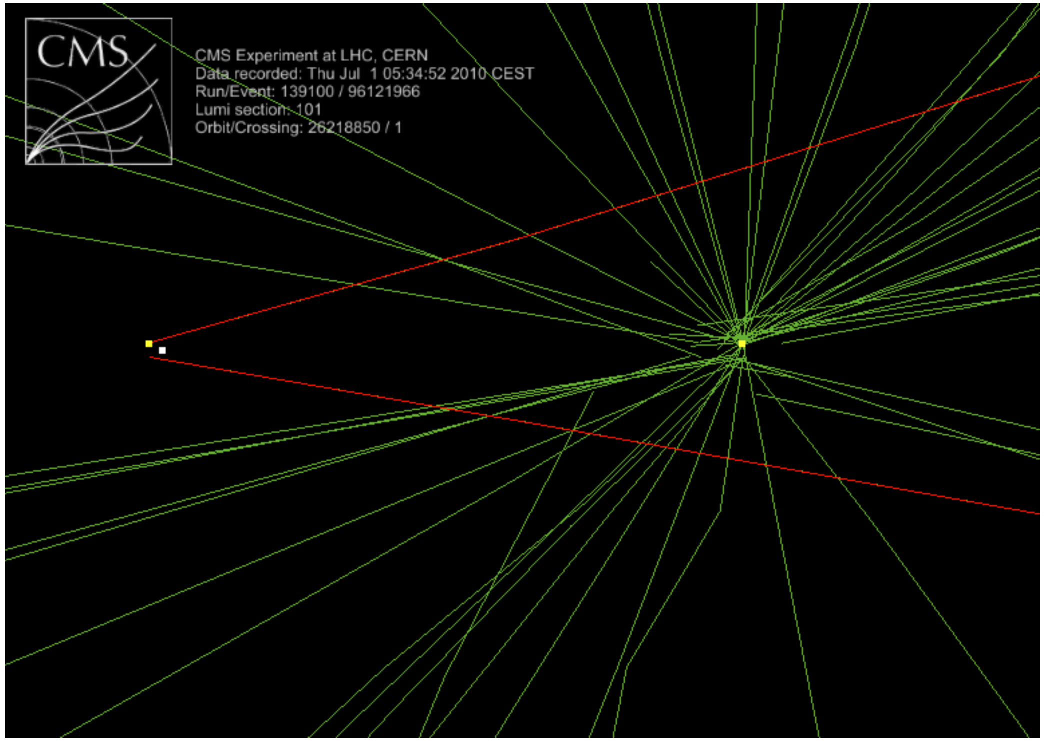
In 2011, roughly 7-10 PU per crossing

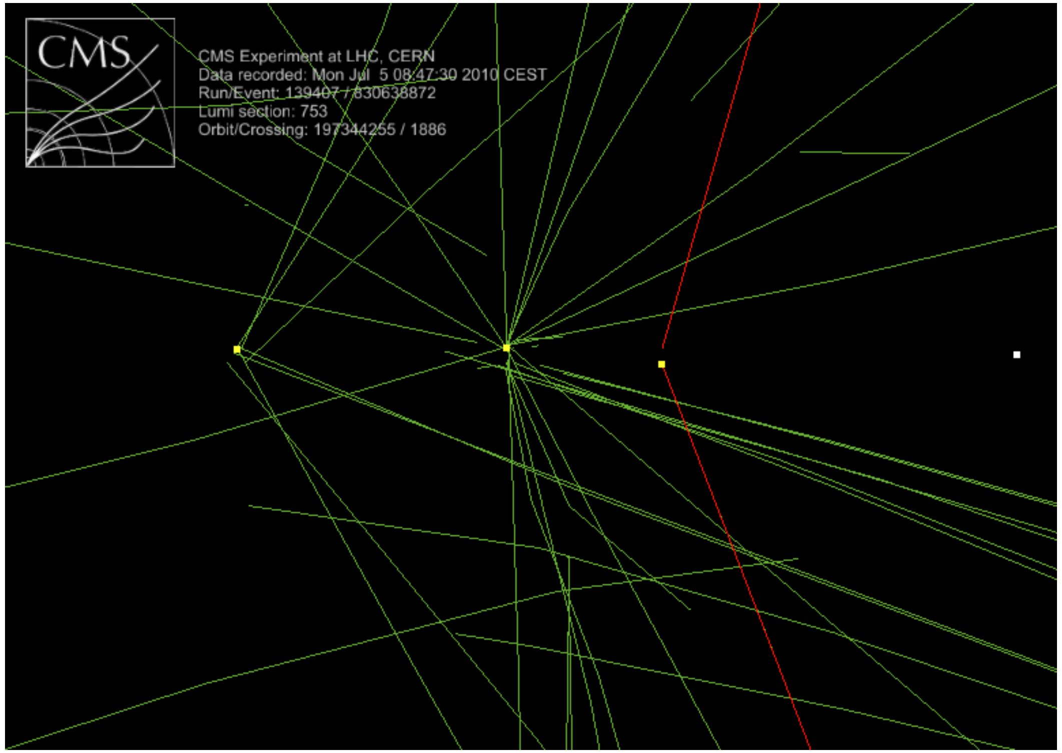
In 2012, PU =25 put the method to a very limit…

Restricting the analysis to single interactions only would have reduced the data sample a very small fraction of the total $\rightarrow$ **impose exclusivity using tracking only**

Question: How to select exclusive events in high pileup environment?

Answer: Use tracking only and zoom-in onto the vertices!





Proof-of-principle: Exclusive $\gamma\gamma \to \mu^+\mu^-$

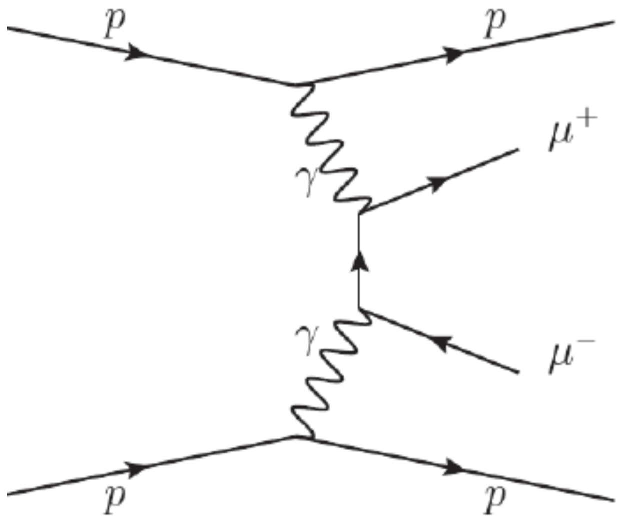
Exclusive muon pairs *aka* standard candle:

“***Pure” QED process:***

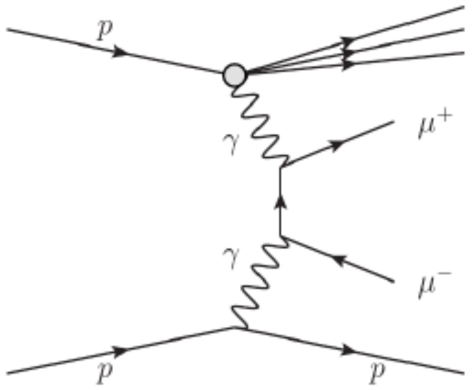
- Only electromagnetic form-factors enter
- Small theoretical uncertainties

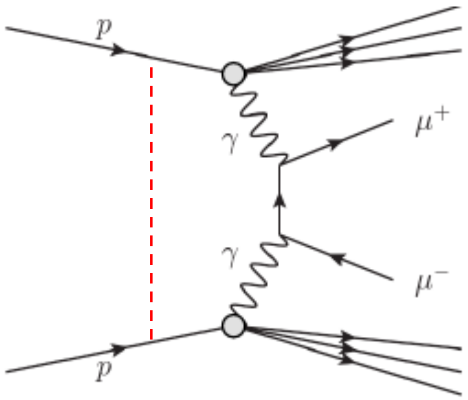
Striking kinematic distributions:

- Thanks to very small virtuality of the exchanged photons



Largest background arises from *semi-exclusive* **two-photon** production due to single and double proton dissociative (or inelastic) photon exchange:





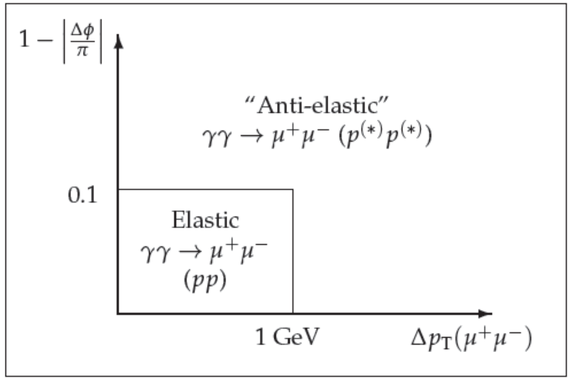
CMS Analysis Note

The content of this note is intended for CMS internal use and distribution only

2011/06/19

Measurement of exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production at $\sqrt{s} = 7$ TeV

Jonathan Hollar, Krzysztof Piotrzkowski, and Nicolas Schul
Center for Cosmology, Particle Physics and Phenomenology (CP3)
Universite catholique de Louvain, Belgium



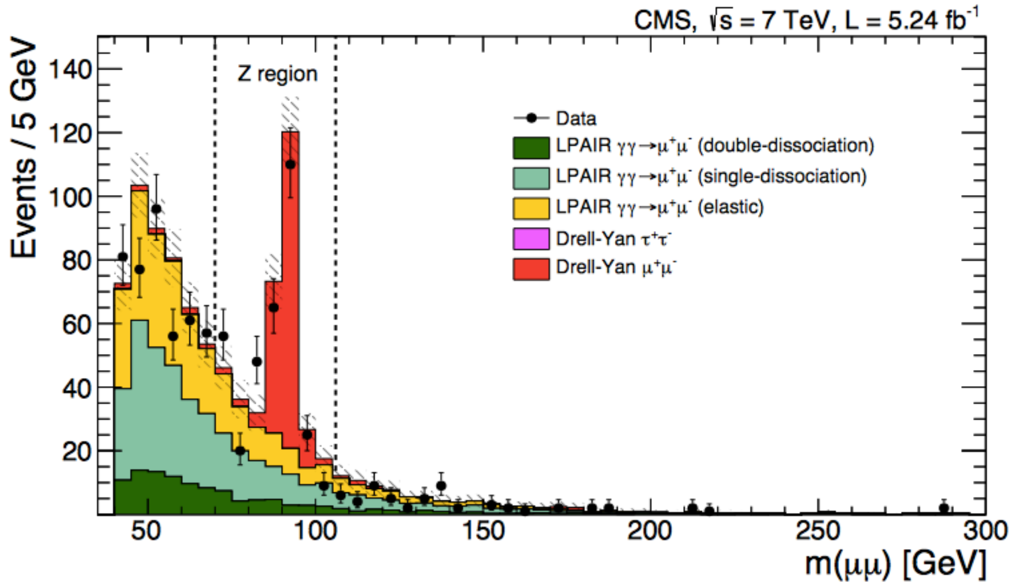


Figure 3: Invariant mass distribution of the muon pairs for the elastic selection with no additional track on the dimuon vertex. The dashed lines indicate the Z-peak region. The hatched bands indicate the statistical uncertainty in the simulation.

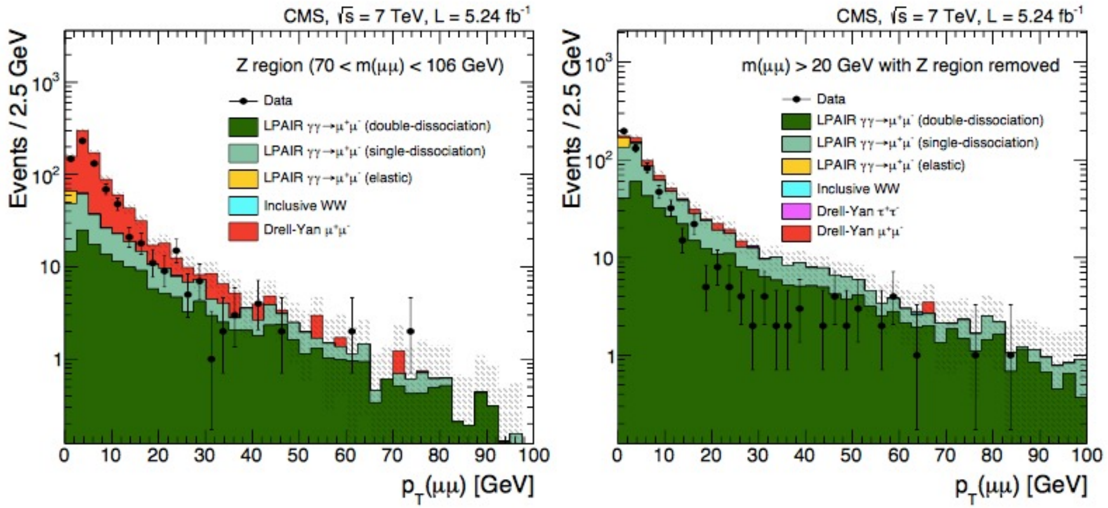
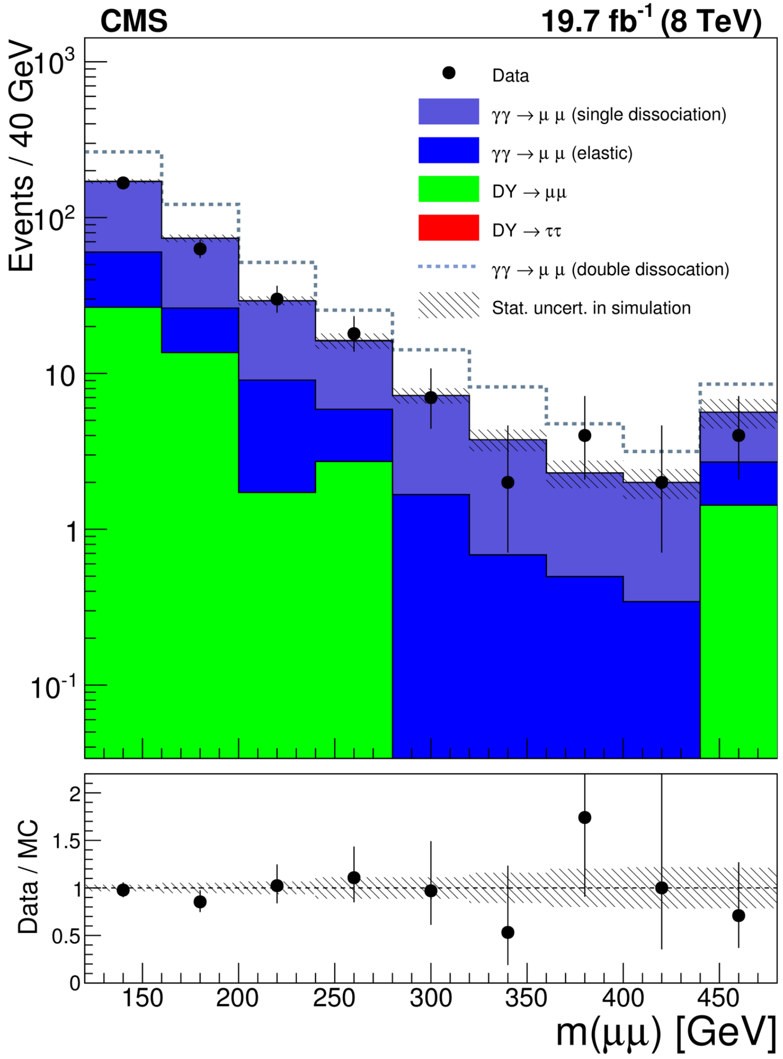
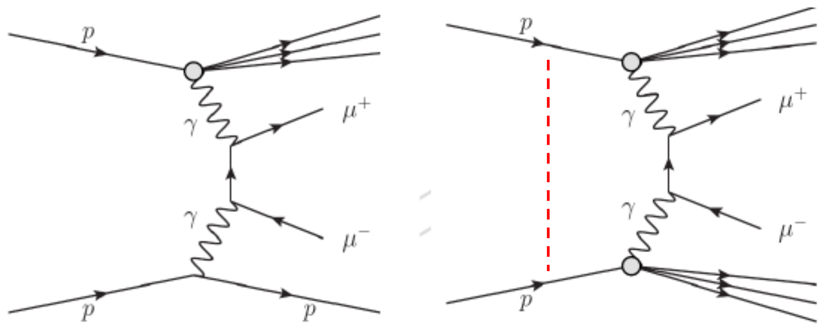


Figure 6: Transverse momentum distribution for $\mu^+\mu^-$ pairs with zero extra tracks passing the dissociation selection, for the Z region only (left), and with the Z region removed (right). The hatched bands indicate the statistical uncertainty in the simulation.

γγ lepton pairs @ 8 TeV





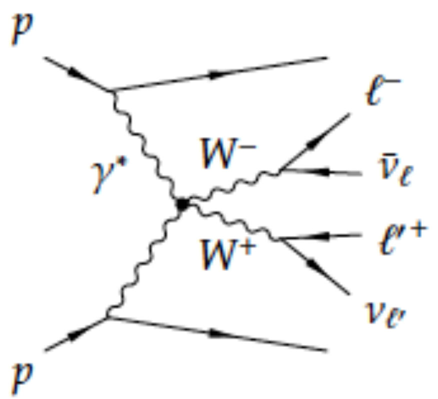
Untagged data show **a very strong suppression of double dissociative events** and not (yet) visible re-scattering effects for single dissociation

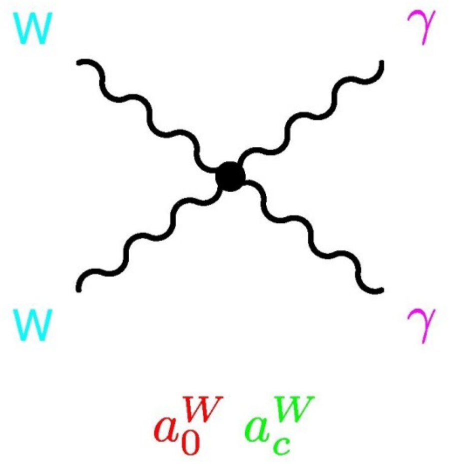
μμ studies are **essential** for establishing $S_{\gamma\gamma}$, including survival probability, however suffer from lack of statistics at large *W*

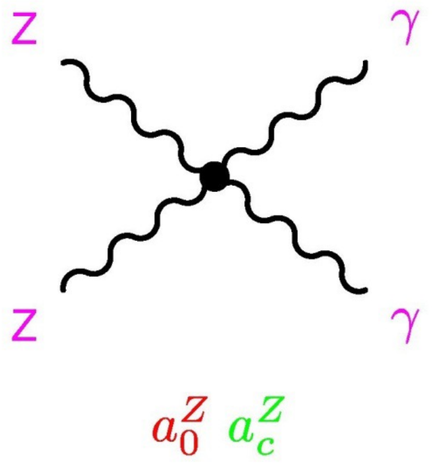
Physics with $\gamma\gamma \to$ WW (and ZZ)

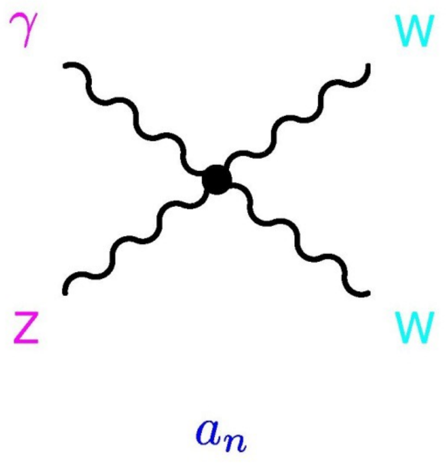
$\gamma\gamma \to$ WW and ZZ (=0 at tree level in SM) pairs as a powerful test bench for the gauge boson sector at the LHC

Search for anomalous quartic couplings









$$\gamma\gamma \rightarrow WW \rightarrow \mu e \nu \nu$$

LHC PHYSICS

CMS sees first direct evidence for $\gamma\gamma \rightarrow WW$

In a small fraction of proton collisions at the LHC, the two colliding protons interact only electromagnetically, radiating high-energy photons that subsequently interact or "fuse" to produce a pair of heavy charged particles. Fully exclusive production of such pairs takes place when quasi-real photons are emitted coherently by the protons rather than by their quarks, which survive the interaction. The ability to select such events opens up the exciting possibility of transforming the LHC into a high-energy photon–photon collider and of performing complementary or unique studies of the Standard Model and its possible extensions.

The CMS collaboration has made use of this opportunity by employing a novel method to select "exclusive" events based only on tracking information. The selection is made by requesting that two – and only two – tracks originate from a candidate vertex for the exclusive two-photon production. The power of this method, which was first developed for the pioneering measurement of exclusive production of muon and electron pairs, lies in its effectiveness even in difficult high-luminosity conditions with large event pile-up at the LHC.

The collaboration has recently used this approach to analyse the full data sample collected at $\sqrt{s}$=7 TeV and to obtain the first direct evidence of the $\gamma\gamma \rightarrow WW$ process. Fully leptonic W-boson decays have been measured in final states characterized by opposite-sign and opposite-flavour lepton pairs where one W decays into an electron and a neutrino, the other into a muon and a neutrino (both neutrinos leave undetected). The leptons were required to have: transverse momenta p_T>20 GeV/c and pseudorapidity $|\eta|$ < 2.1; no extra track associated with their vertex; and for the pair, a total p_T>30 GeV/c. After applying all selection criteria, only two events remained – compared with an expectation of 3.2 events: 2.2 from $\gamma\gamma \rightarrow WW$ and 1 from background (figure 2).

The lack of events observed at large values of transverse momentum for the pair, which would be expected within the Standard Model, allows stringent limits on anomalous quartic $\gamma\gamma WW$ couplings to be derived. These surpass the previous best limits, set at the Large Electron–Positron collider and at the Tevatron, by up to two orders of magnitude (figure 3).

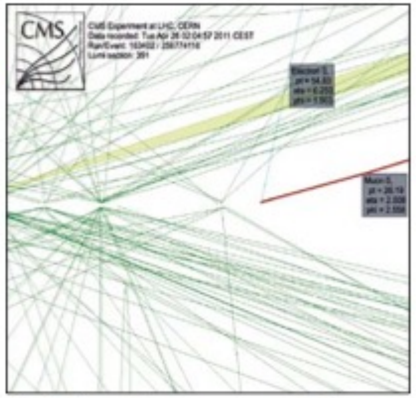


Fig. 1. Above: Proton–proton collisions recorded by CMS at $\sqrt{s}$=7 TeV, featuring candidates for the exclusive two-photon production of a W^+W^- pair, where one W boson has decayed into an electron and a neutrino, the other into a muon and a neutrino.

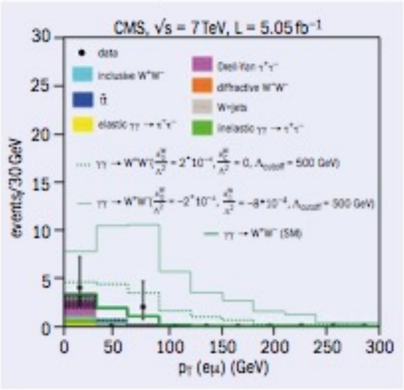


Fig. 2. Top right: The p_T distribution of eμ pairs in events with no extra tracks compared with the Standard Model expectation (thick green line) and predictions for anomalous quartic gauge couplings (dashed green histograms).

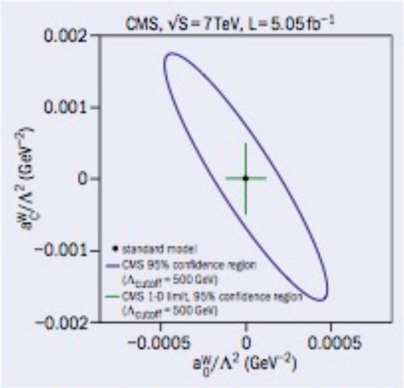


Fig. 3. Right: Limits on anomalous quartic $\gamma\gamma WW$ couplings.

● **Further reading**

CMS collaboration 2013 arXiv:1305.5596 [hep-ex], submitted to *JHEP*.

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERNCOURIER

VOLUME 53 NUMBER 6 JULY/AUGUST 2013

Hot news back in 2013…

LHC as a high energy $\gamma\gamma$ collider: **power of modern tracking**

CMS breakthrough in 2011-13 (without tagging):

Track-based only exclusivity selection for charged *dilepton* final states at high event pileup (PU) – resulted in significantly higher $\gamma\gamma$ luminosity thanks to *quasi-exclusive* contributions, but also in no direct control of *W*

Search for the exclusive two-photon production of W^+W^- pairs in pp collisions at 7 TeV

The CMS Collaboration

DRAFT

Abstract

A search for exclusive or semi-exclusive W^+W^- production, $pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}$, at $\sqrt{s} = 7$ TeV is reported using data corresponding to an integrated luminosity of 5.05 fb^{-1}. Two events passing all selections are observed in data, compared to a Standard Model expectation of 2.7 ± 0.5 signal events with 0.84 ± 0.13 background. The region of high dilepton transverse momentum, $p_T(\mu^\pm e^\mp) > 100$ GeV, is studied for deviations from the Standard Model. No events are observed in this region, and the resulting upper limits are compared to predictions assuming anomalous quartic gauge couplings.

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PDFAuthor: Jonathan J. Hollar, Laurent Forthomme, Krzysztof Piotrzkowski, Gustavo Gil Da Silveira, Finn Rebassoo

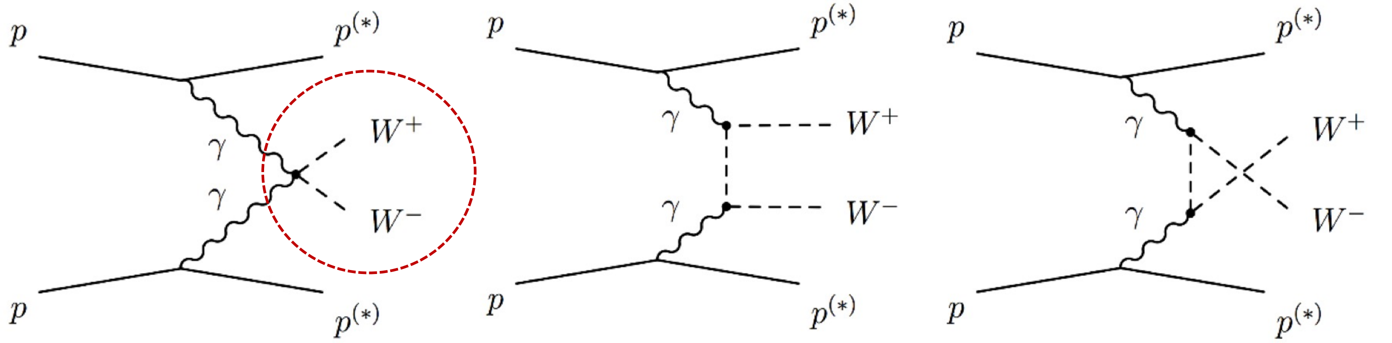


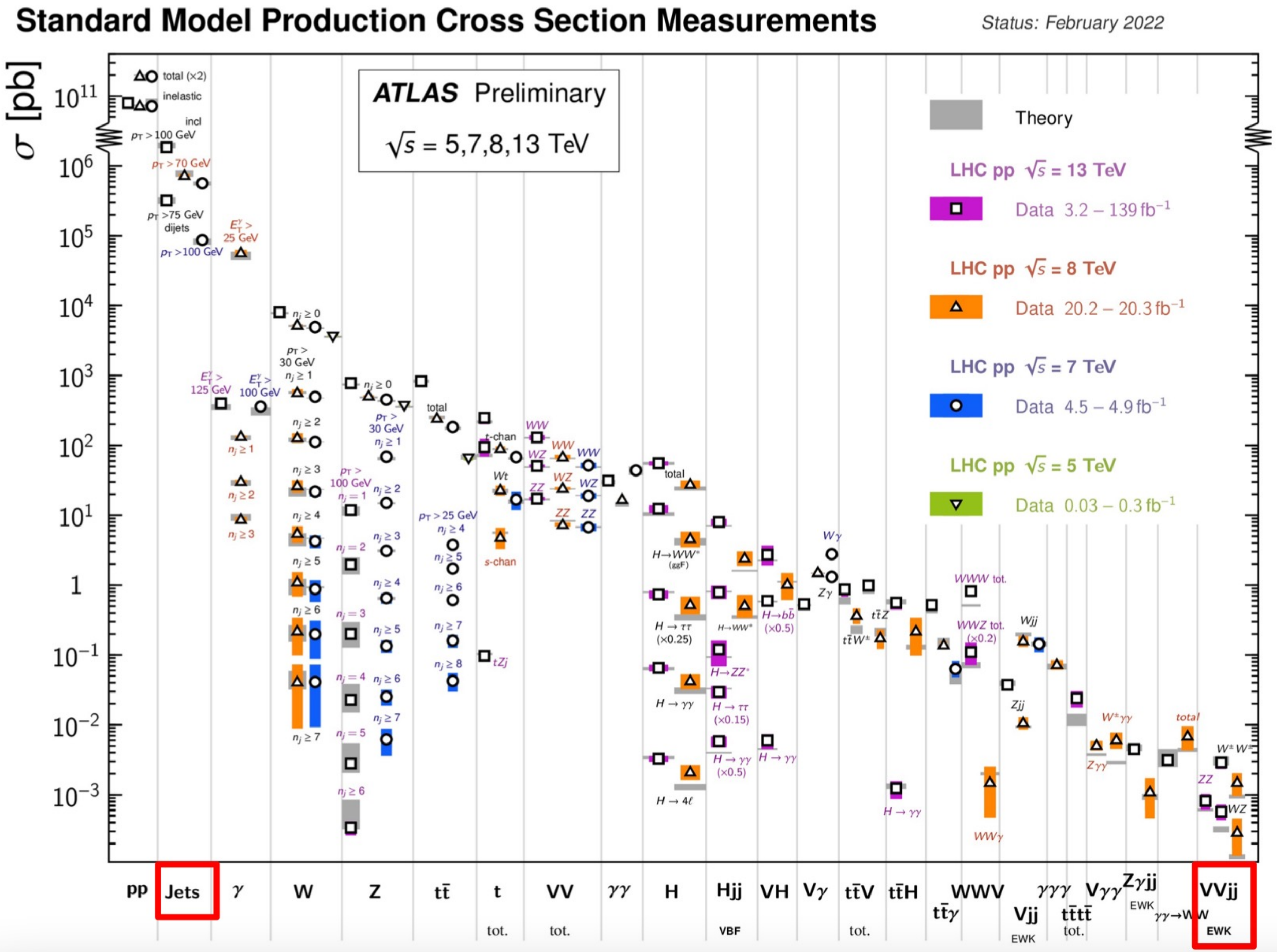
Figure 1. Quartic (left), t-channel (center), and u-channel (right) diagrams contributing to the $\gamma\gamma \to W^+W^-$ process at leading order in the SM. The $p^{(*)}$ indicates that the final state proton(s) remain intact ("exclusive" or "elastic" production), or dissociate ("quasi-exclusive" production).

$$W^+W^- \to e^\pm\nu\mu^\mp\nu$$

CMS Run 1 final result at 7/8 TeV (for mean event PU ≈ 7):

"Upper limits on the anomalous quartic gauge coupling operators $a_{W0,C}$ (dimension-6) and $f_{M0,1,2,3}$ (dimension-8), the **most stringent to date**, are derived from the measured dilepton transverse momentum spectrum."

doi: 10.1007/JHEP08(2016)119



Standard Model Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
$\sqrt{s}$ = 5,7,8,13 TeV
σ [pb]
Theory
LHC pp $\sqrt{s}$ = 13 TeV
Data 3.2 – 139 fb^{-1}
LHC pp $\sqrt{s}$ = 8 TeV
Data 20.2 – 20.3 fb^{-1}
LHC pp $\sqrt{s}$ = 7 TeV
Data 4.5 – 4.9 fb^{-1}
LHC pp $\sqrt{s}$ = 5 TeV
Data 0.03 – 0.3 fb^{-1}
pp
Jets
γ
W
Z
$t\bar{t}$
t
tot.
VV
tot.
γγ
H
Hjj
VBF
VH
Vγ
$t\bar{t}V$
tot.
$t\bar{t}H$
$t\bar{t}γ$
WWV
Vjj
EWK
γγγ
$t\bar{t}t\bar{t}$
tot.
Vγγ
Zγjj
EWK
γγ→WW
VVjj
EWK

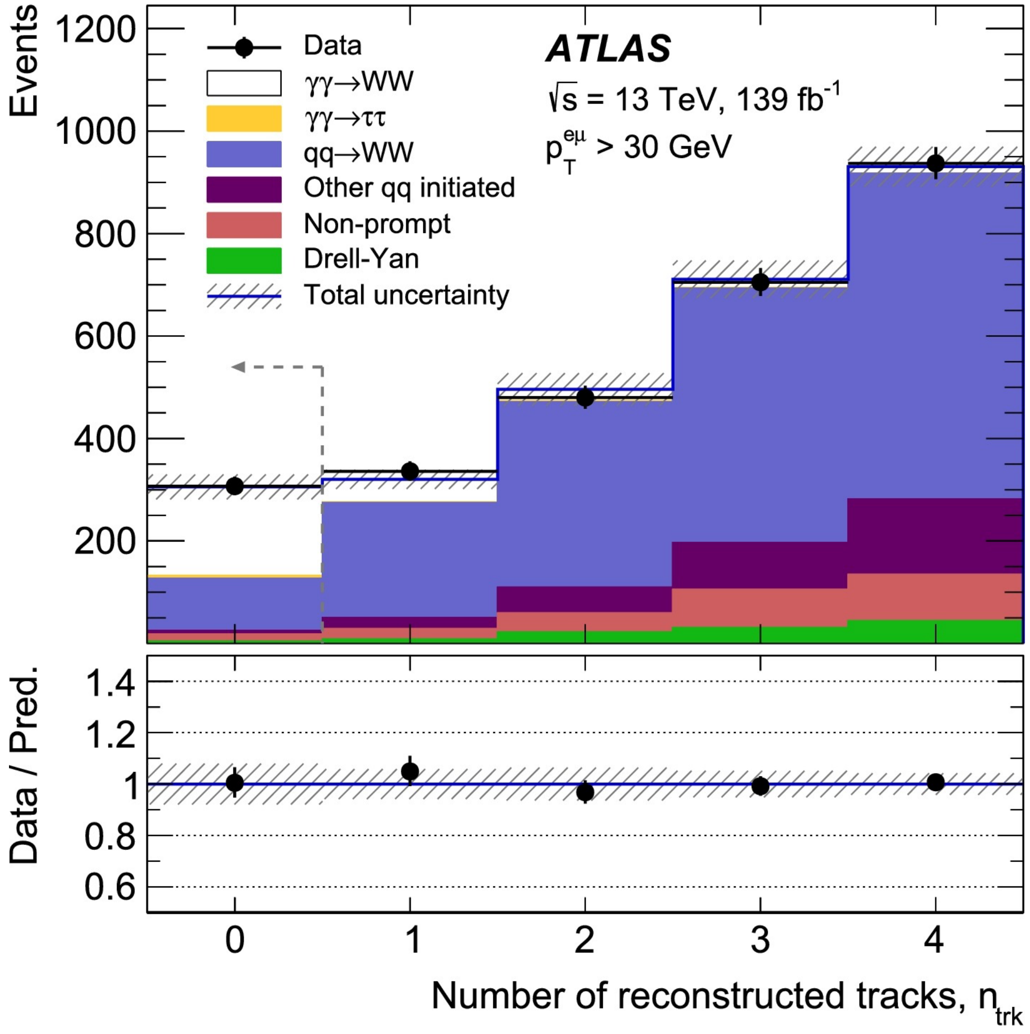
LHC as a high energy $\gamma\gamma$ collider: **recent results**

$$W^+W^- \to e^\pm \nu \mu^\mp \nu$$

ATLAS Run 2 final result at 13 TeV (average event **PU ≈ 34**):

"The data yield in the signal region is 307, compared with 132 background events predicted by the best-fit result. […] This measurement constitutes **the observation of photon-induced *WW* production in *pp* collisions**, a process for which only evidence was previously reported."

doi: 10.1016/j.physletb.2021.136190



Note: in spite of almost 5 times bigger PU, a similar S/B was achieved, as for Run 1 analyses, thanks to improved tracking/ vertexing **and** significantly higher $S_{\gamma\gamma}$ at 13 TeV.

LHC as a high energy $\gamma\gamma$ collider: **recent results II**

"The observation of forward proton scattering in association with lepton pairs ($e^+e^- + p$ or $\mu^+\mu^- + p$) produced via photon fusion is presented. The **scattered proton is detected by the ATLAS Forward Proton spectrometer**, while the leptons are reconstructed by the central ATLAS detector. Proton-proton collision data recorded in 2017 at a center-of-mass energy of $\sqrt{s}$ = 13 TeV are analyzed, corresponding to an integrated luminosity of **14.6 fb⁻¹**."
doi: 10.1103/PhysRevLett.125.261801

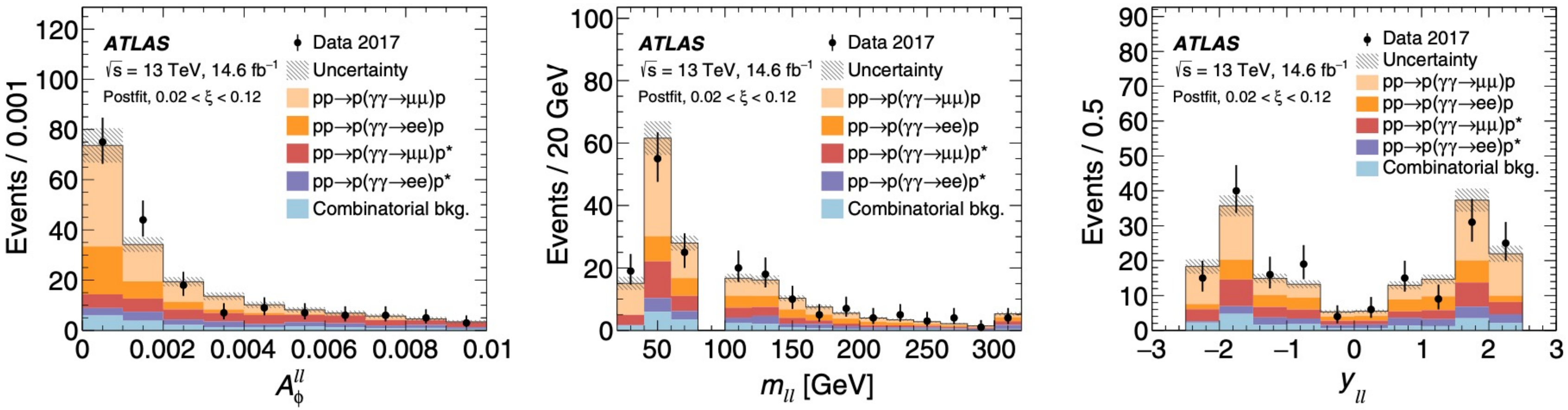
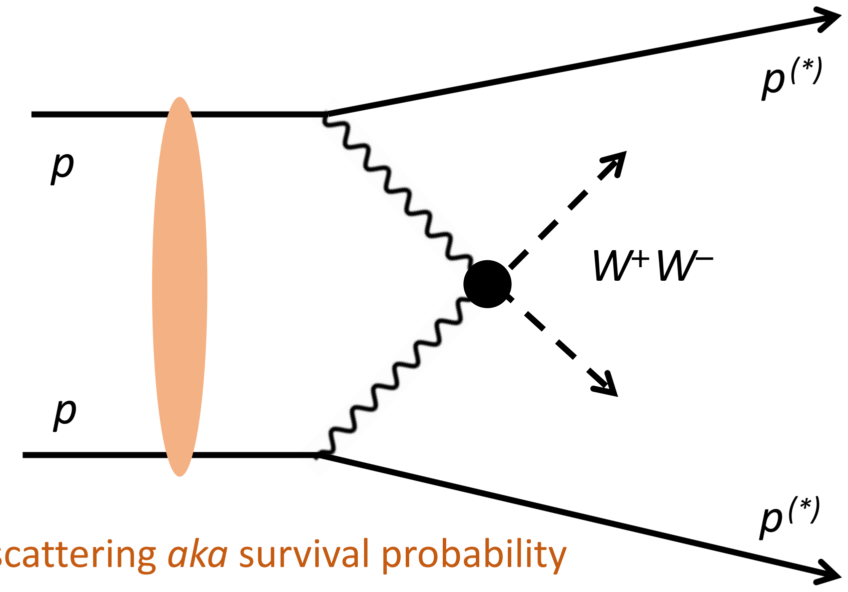


FIG. 3. Distributions of dilepton acoplanarity $A_\phi^{\ell\ell}$ (left), invariant mass $m_{\ell\ell}$ (center), rapidity $y_{\ell\ell}$ (right) satisfying $\xi_{\ell\ell}, \xi_{\rm AFP} \in [0.02, 0.12]$, and $|\xi_{\rm AFP} - \xi_{\ell\ell}| < 0.005$ for at least one AFP side. Events with $70 < m_{\ell\ell} < 105$ GeV are vetoed. The total prediction comprises the signal and combinatorial background processes, where p^* denotes a dissociated proton. The simulated predictions are normalized to data to illustrate the expected signal composition. The rightmost bin of the $m_{\ell\ell}$ distribution includes overflow. The hatched band indicates the combined statistical and systematic uncertainties of the prediction. Error bars denote statistical uncertainties of the data.

HL-LHC as a high energy $\gamma\gamma$ collider: **challenges**



re-scattering *aka* survival probability

HL-LHC will provide 10 times bigger integrated luminosity, but:

- $S_{\gamma\gamma}$ only marginally higher (thanks to 13 → 14 TeV increase)
- PU yet 4 times higher (≈ 140) than for Run 2 – but new tracking exclusivity might be more performant
- Very high event pileup will make tagging with forward protons even more tricky – **ps resolution timing detectors** are a must – however, the problem of overall efficiency loss still persists
- New ps timing in central detectors could provide much needed handle to further suppress accidental coincidences!

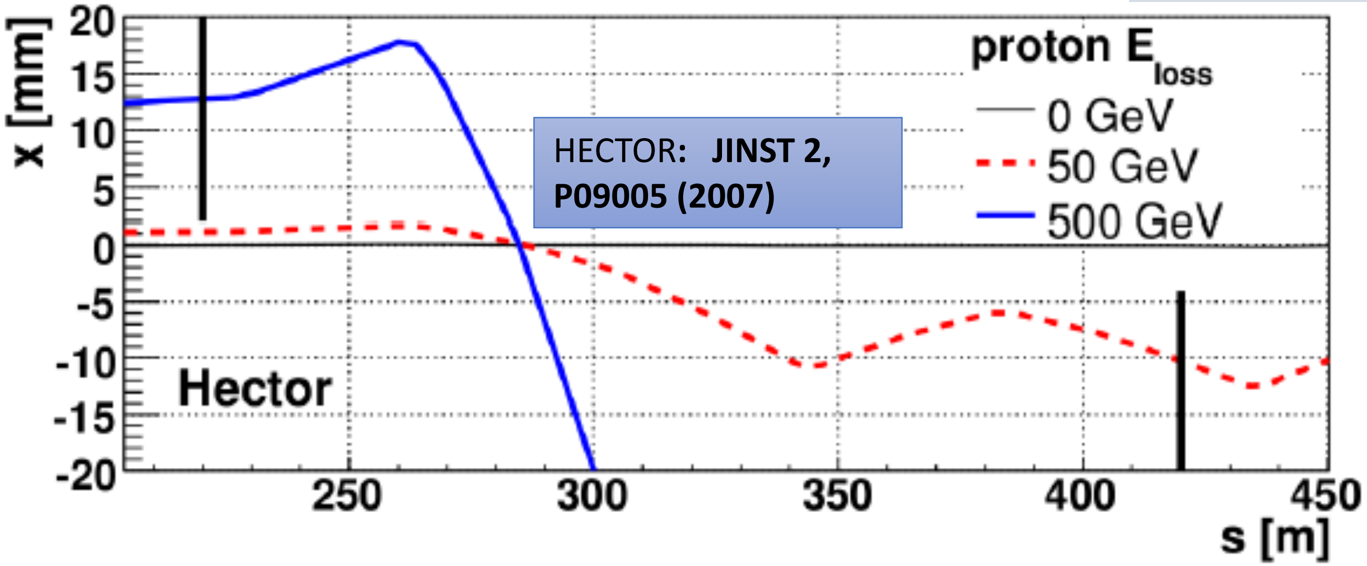
Major challenges for the high luminosity LHC $\gamma\gamma$ collider:

- **Only** tracks can be used for the selection of (quasi-)exclusive production
- **Only** exclusive charged dilepton states could be successfully measured so far (after 10-year efforts)
- And, the **re-scattering suppression** is large and uncertain, especially at very large *W*

Picosecond ToF detectors @ LHC

Use very fast ToF detectors to measure *longitudinal vertex position* by *z-by-timing* from forward proton arrival time difference:

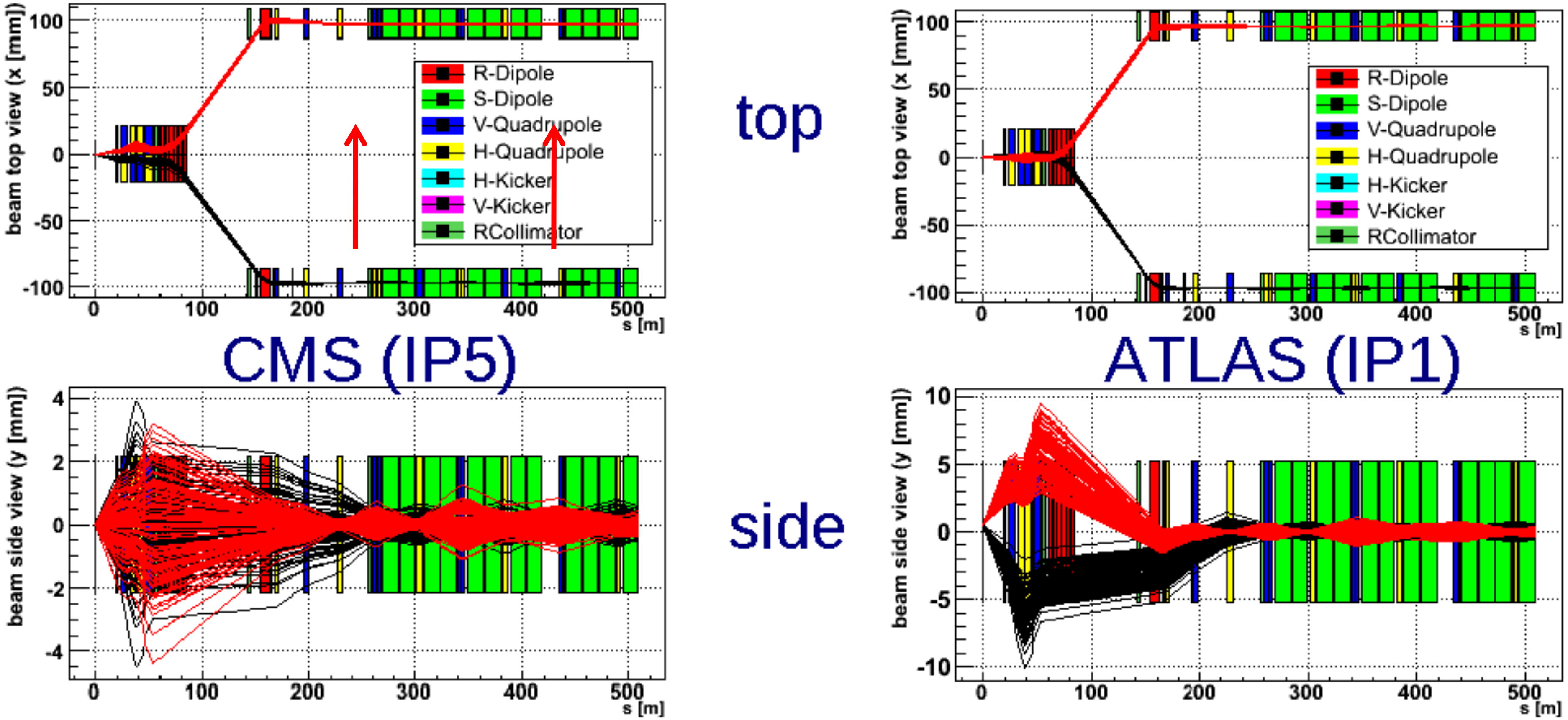
$z = (t_1 - t_2)/2c$



Path length differences are very small for forward protons at LHC, typically << 100 μm corresponding to sub-picosecond time differences.

Ultra fast timing detectors are essential for measuring the exclusive production at LHC, JINST 4 (2009) T10001

Optimal places for tagging Exclusive Production at LHC: @ 220/240m and 420m from IP

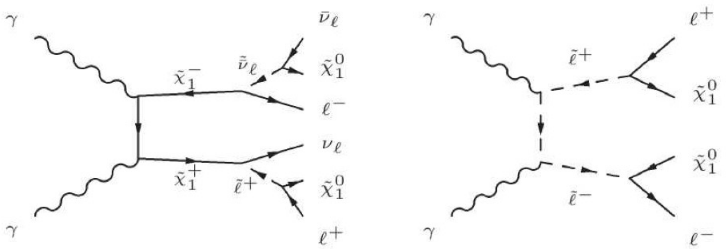


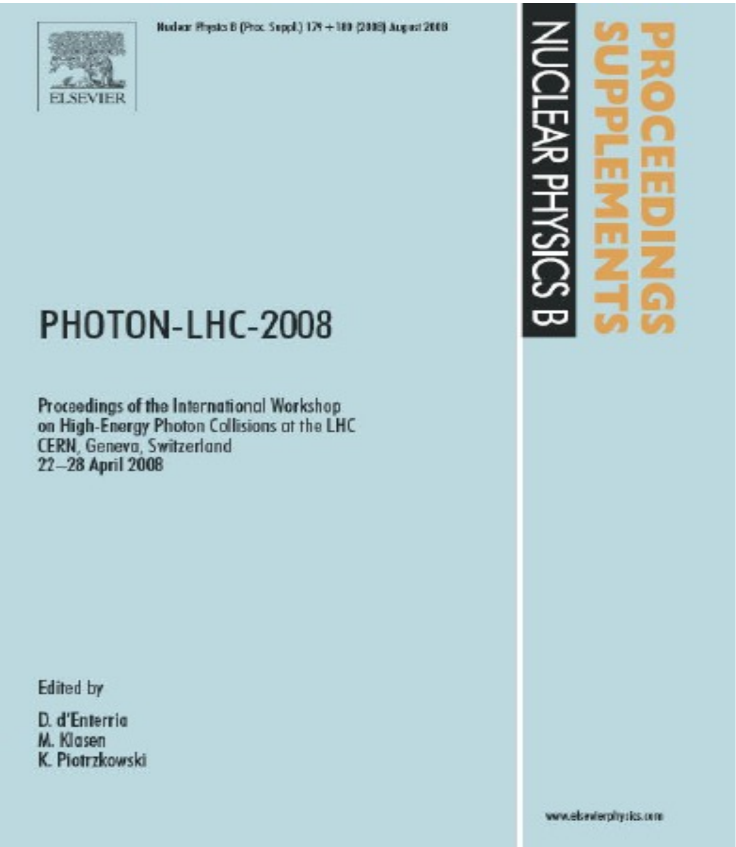
Horizontal crossing plane

Vertical crossing plane

HECTOR: **JINST 2, P09005 (2007)**
For <u>nominal</u> low-β LHC optics

HL-LHC as a high energy $\gamma\gamma$ collider: new physics?





Detection of two-photon exclusive production of supersymmetric pairs at the LHC

Nicolas Schul[a] * and Krzysztof Piotrzkowski[a]

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The detection of pairs of sleptons, charginos and charged higgs bosons produced via photon-photon fusion at the LHC is studied, assuming a couple of benchmark points of the MSSM model. Due to low cross sections, it requires large integrated luminosity, but thanks to the striking signature of these exclusive processes the backgrounds are low, and are well known. Very forward proton detectors can be used to measure the photon energies, allowing for direct determination of masses of the lightest SUSY particle, of selectrons and smuons with a few GeV resolution. Finally, the detection and mass measurement of quasi-stable particles predicted by the so-called sweet spot supersymmetry is discussed.

Table 1
Cross sections for several examples of the exclusive two-photon pair production at the LHC. (F for fermion, S for scalar). [1]

Produced pairs	mass [GeV]	σ [fb]
W^+W^-	80	108.5
F^+F^-	100	4.064
F^+F^-	200	0.399
S^+S^-	100	0.680
S^+S^-	200	0.069

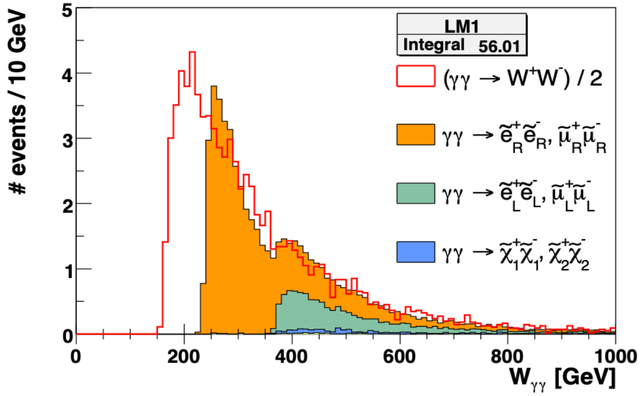


Figure 2. Distribution of two-photon invariant mass $W_{\gamma\gamma}$ for the LM1 benchmark and integrated luminosity L = 100 fb^{-1}. Two visible peaks are due to production thresholds of $\tilde{\ell}_R^+\tilde{\ell}_R^-$ and $\tilde{\ell}_L^+\tilde{\ell}_L^-$ pairs. Verious contribution are added cumulatively. The background distribution of WW pairs is shown separately, and is rescaled to obtain similar size as signal.

HL-LHC as a high energy γγ collider: new physics?

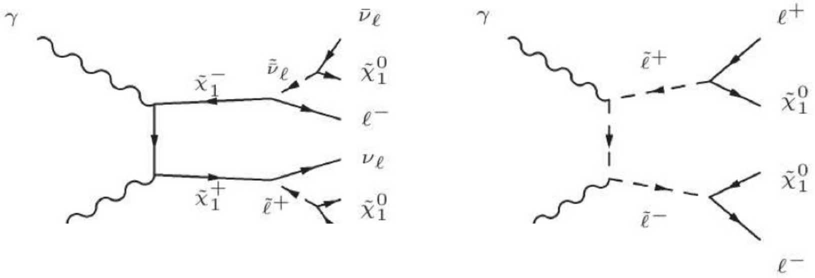
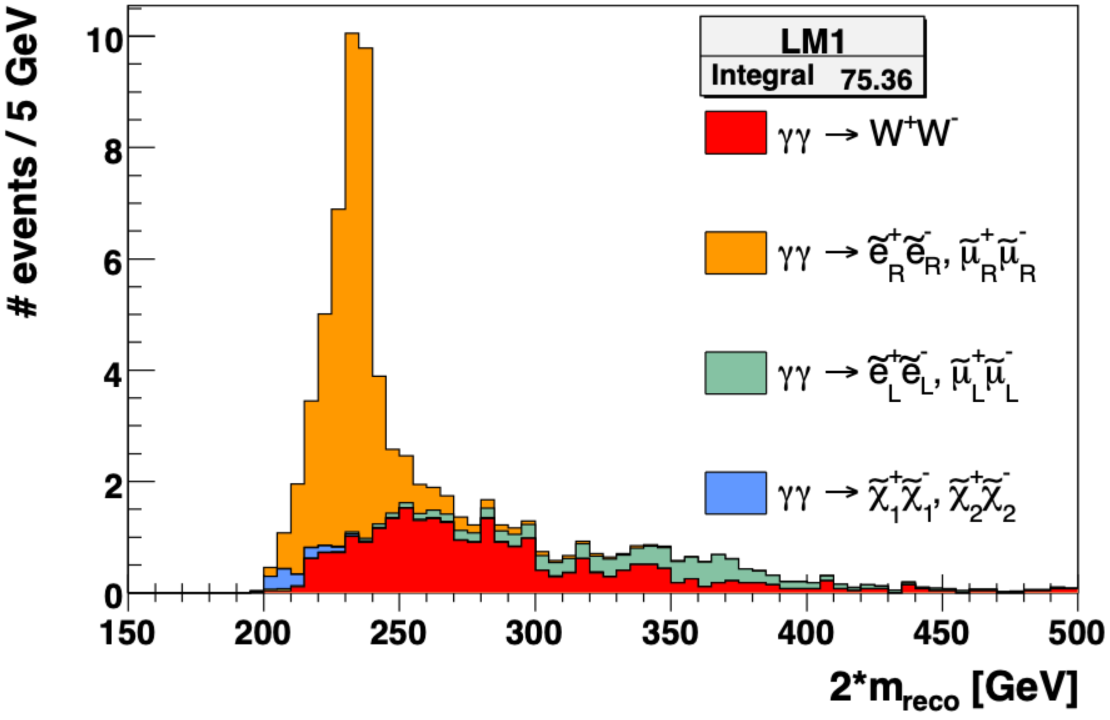


Table 3
LM1 signal and WW background cross sections before and after the acceptance cuts (including the flavor selection), and after the analysis cuts. Values are given in fb. ($\ell = e, \mu$. $i = 1, 2$).

Processes	σ	σ_{acc}	$\sigma_{acc+ana}$
$\gamma\gamma \to \tilde{\ell}_R^+\tilde{\ell}_R^-$	0.798	0.522	0.403
$\gamma\gamma \to \tilde{\ell}_L^+\tilde{\ell}_L^-$	0.183	0.135	0.089
$\gamma\gamma \to \tilde{\tau}_i^+\tilde{\tau}_i^-$	0.604	0.054	0.003
$\gamma\gamma \to \tilde{\chi}_i^+\tilde{\chi}_i^-$	0.642	0.043	0.014
$\gamma\gamma \to H^+H^-$	0.004	/	/
$\gamma\gamma \to W^+W^-$	108.5	3.820	0.255



https://doi.org/10.1016/j.nuclphysbps.2008.07.036

Figure 6. Cumulative distributions of the reconstructed mass $2m_{reco}$ for the LM1 signal and the WW background for the intergrated luminosity L = 100 fb^{-1}.

Need updating for HL-LHC/recent BSM models

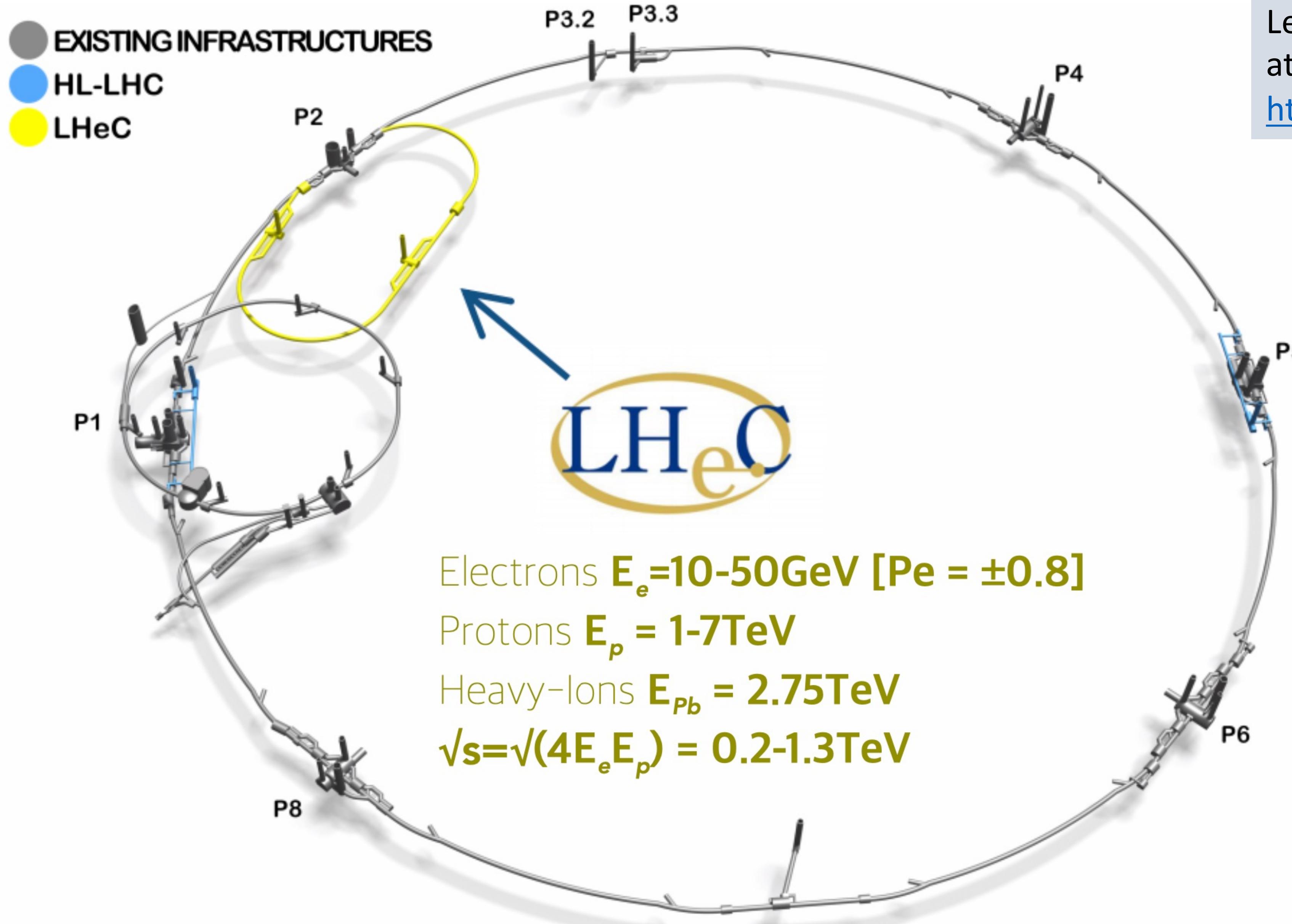
(HL-)LHC as a high energy $\gamma\gamma$ collider: **summary**

High energy $\gamma\gamma$ physics can be successfully studied at the LHC!

- Fundamental role of exclusive $\mu\mu$ (and *ee*) pairs – they serve as a **standard candle** in many ways: as a precise calibration tool & acceptance verification + a photon-flux-meter
- Use of very forward proton detectors (**AFP!**) is essential for full exploration of $\gamma\gamma$ physics at the LHC – perhaps new channels as semi-leptonic WW can be studied already in Run 3
- HL-LHC opens new horizons in this exploration – to properly profit from that, the development of **dedicated ps resolution timing detectors** is mandatory (+ studies of the potential impact of ps timing in central detectors)
- Precise studies of high-mass diffraction at the LHC are **crucial** for optimal extraction of the $\gamma\gamma$ signals using very forward proton detectors

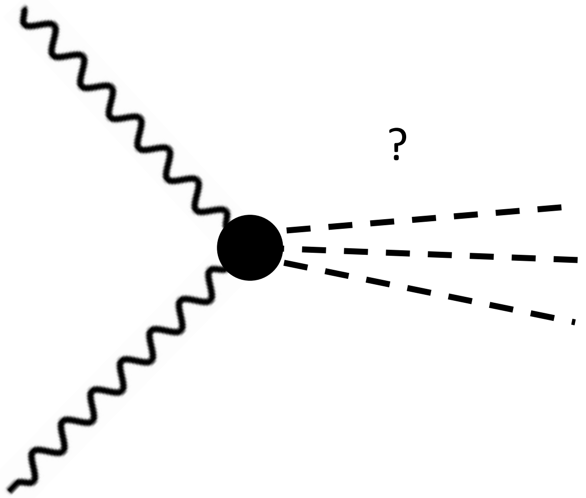
New electroweak opportunities at the LHeC

Learn more about LHeC this Friday at KEK, at IPNS Physics and Detector Seminar: https://kds.kek.jp/event/43635/



LHeC

Electrons E_e=10-50GeV [Pe = ±0.8]
Protons E_p = 1-7TeV
Heavy-Ions E_{Pb} = 2.75TeV
$\sqrt{s}=\sqrt{(4E_eE_p)}$ = 0.2-1.3TeV



Large Hadron electron Collider

ERL, or the on-going revolution in high energy electron acceleration techniques

Machine Parameters and Operation - ep

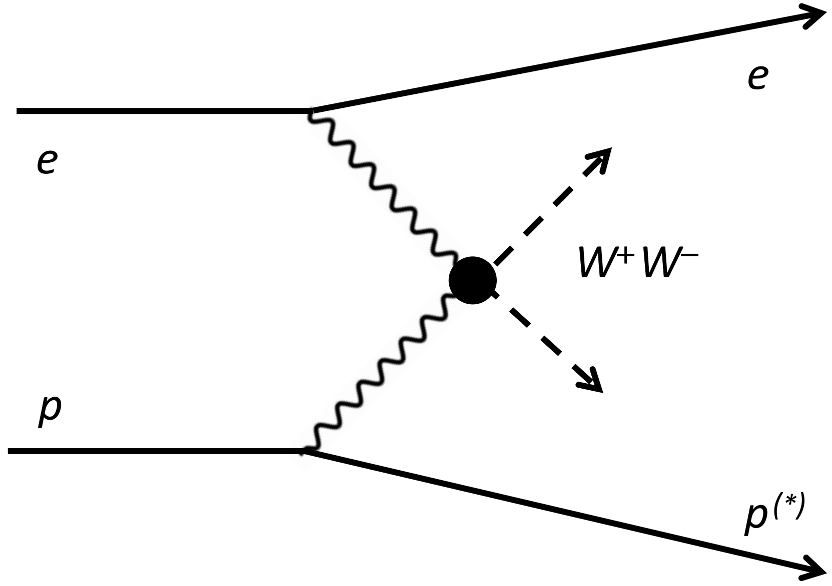
arXiv:2007.14401

Parameter	Unit	LHeC			
		CDR	Run 5	Run 6	Dedicated
E_e	GeV	60	30	50	50
N_p	10^{11}	1.7	2.2	2.2	2.2
ϵ_p	μm	3.7	2.5	2.5	2.5
I_e	mA	6.4	15	20	50
N_e	10^9	1	2.3	3.1	7.8
β^*	cm	10	10	7	7
Luminosity	10^{33} cm^{-2}s^{-1}	1	5	9	23

Energy Recovery Linac technology resulted in the major breakthrough for the LHeC:

> 20 luminosity increase

LHeC as a high energy $\gamma\gamma$ collider



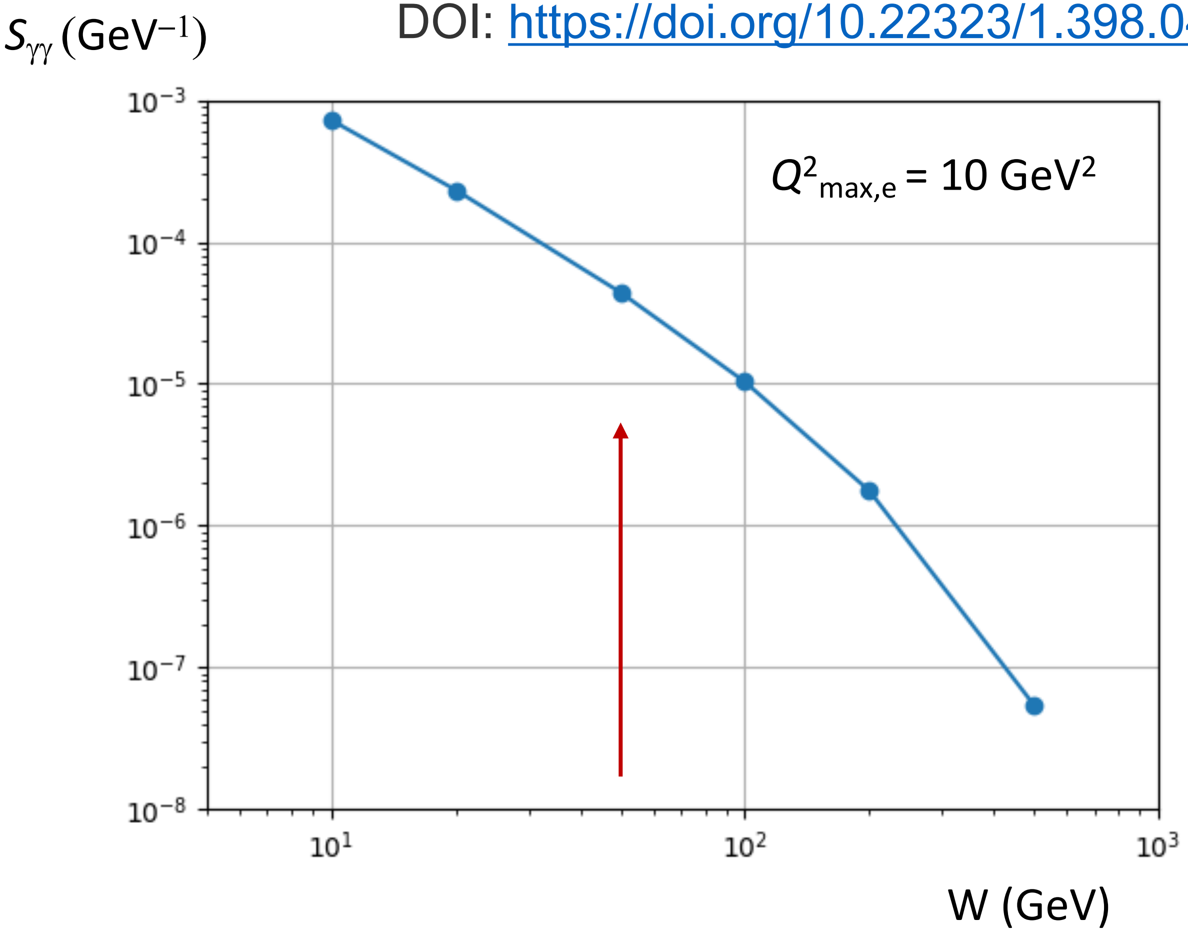
Very high LHeC luminosity is the key here ⇒ more than **1 ab^{-1}** (= 1000 fb^{-1}) is expected for *ep* collisions.

Electrons will have “only” 50 GeV, but **higher** photon flux, as approximately:

$$S_{\gamma\gamma} \propto \ln(Q^2_{max,e}/Q^2_{min,e})\ln(Q^2_{max,p}/Q^2_{min,p})$$

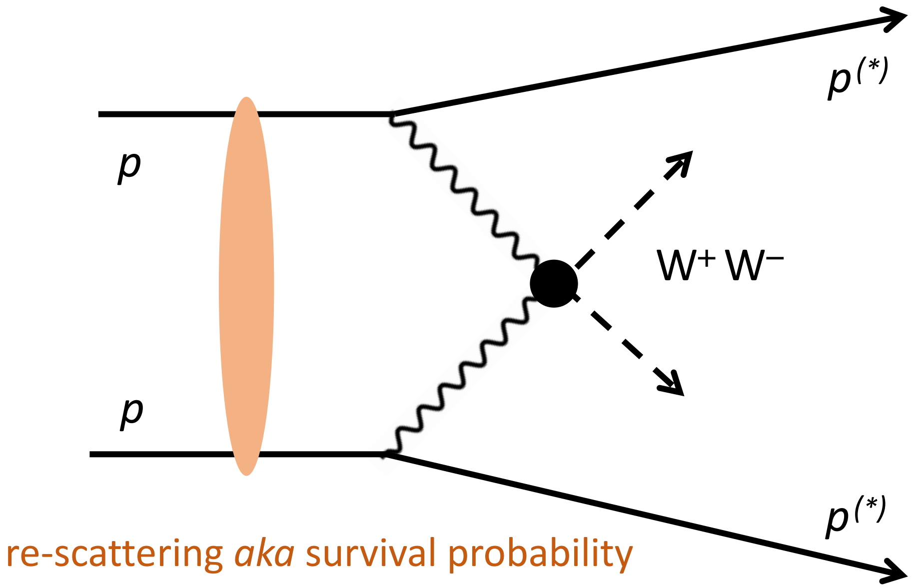
where $Q^2_{min} \propto m^2$, and $Q^2_{max,e}$ can be very high

DOI: https://doi.org/10.22323/1.398.0486

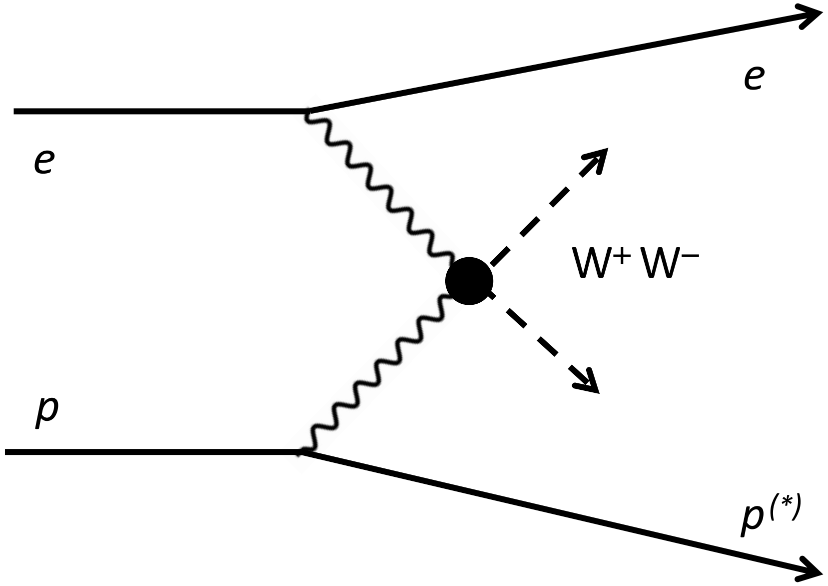


For $W < 50$ GeV the *fully* exclusive $\gamma\gamma$ luminosity spectrum is **higher** at the LHeC than at the HL-LHC!

HL-LHC vs. LHeC as high energy $\gamma\gamma$ colliders



vs.

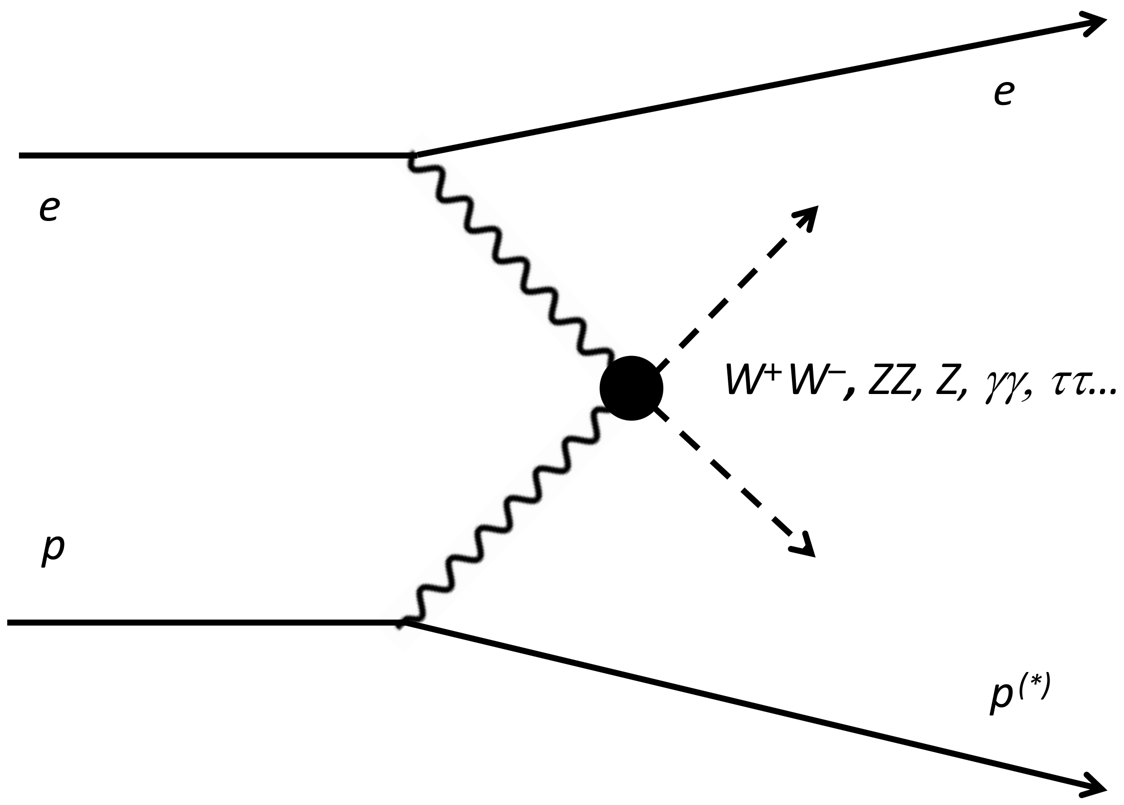


Energy reach for $\gamma\gamma$ interactions is higher at the LHC, however at the highest *W* tagging is not possible and the suppression due to re-scattering becomes large.

Event **pileup is very low at the LHeC** – it is **only 5 %** at the highest *ep* luminosity of **2.3×10^{34} $cm^{-2}s^{-1}$**.

This is not only allowing to **use calorimetry for the selection** of exclusive production, but will also significantly **increase** detection efficiency, including $\gamma\gamma$ tagging, and **suppress** backgrounds!

LHeC as a very unique, generic high energy $\gamma\gamma$ collider

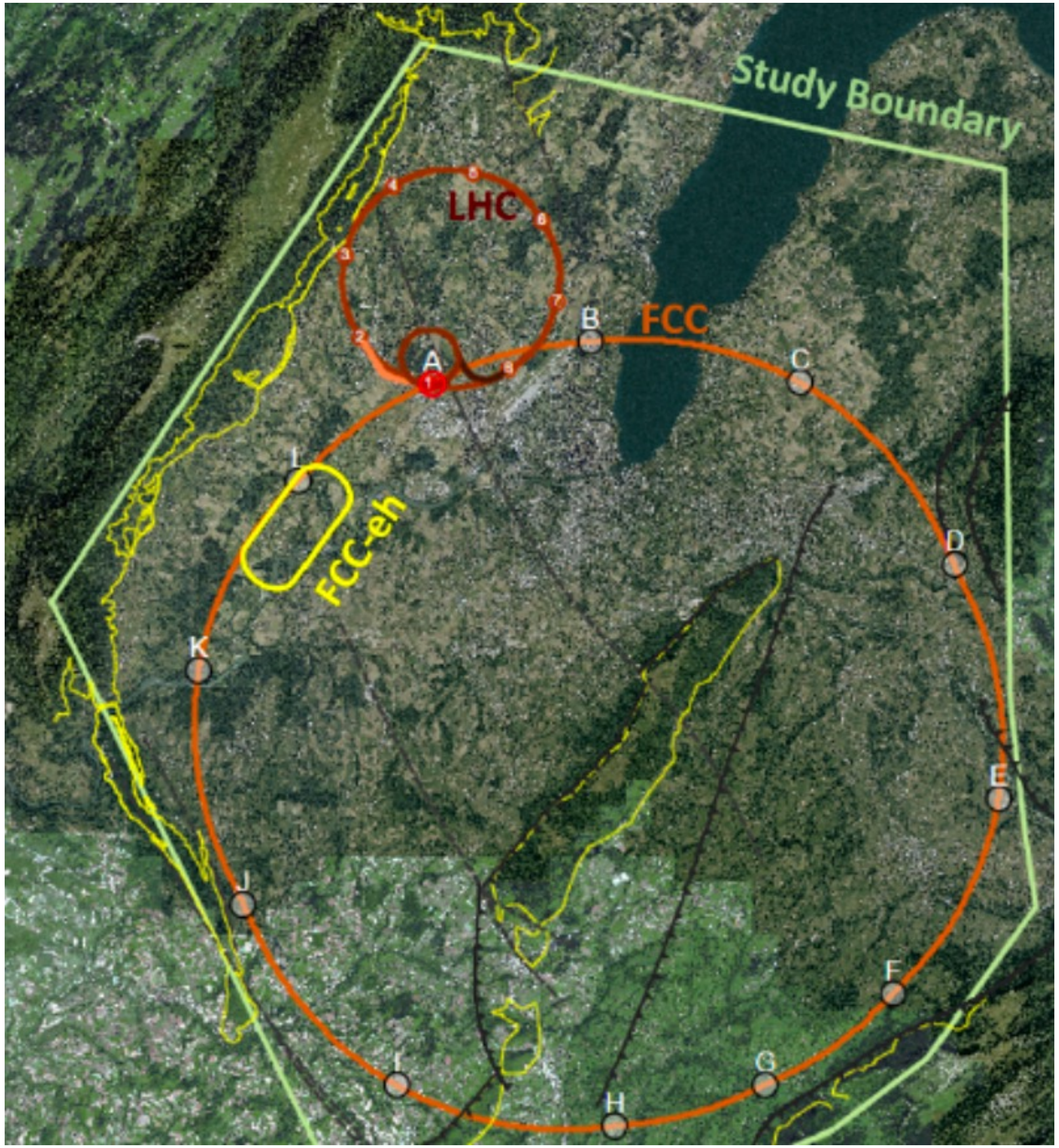


Wide spectrum of $\gamma\gamma$ processes will be studied at the LHeC:

- $\gamma\gamma \rightarrow \gamma\gamma$: orders of magnitude higher statistics than for *PbPb* at the HL-LHC + $\gamma\gamma$ tagging ⇒ kinematic fitting
- $\gamma\gamma \rightarrow \tau^+\tau^-$: orders of magnitude higher statistics than for *PbPb* at the HL-LHC + $\gamma\gamma$ tagging ⇒ new decay modes
- $\gamma\gamma \rightarrow Z$: search for the anomalous single Z boson exclusive production
- $\gamma\gamma \rightarrow ZZ$: possibility of first ever detection + stringent limits on anomalous quartic gauge couplings (aQGCs) using semi-leptonic decay modes, ZZ $\rightarrow l^+l^-jj$
- $\gamma\gamma \rightarrow W^+W^-$: measurements of semi-leptonic decay modes, $W^+W^- \rightarrow l\nu jj$, will allow for a use of Optimal Observable methods (even with single $\gamma\gamma$ tagging) for probing aQGCs; yet high statistics (≈ as at the HL-LHC) is expected for fully leptonic W^+W^- decays + tagging

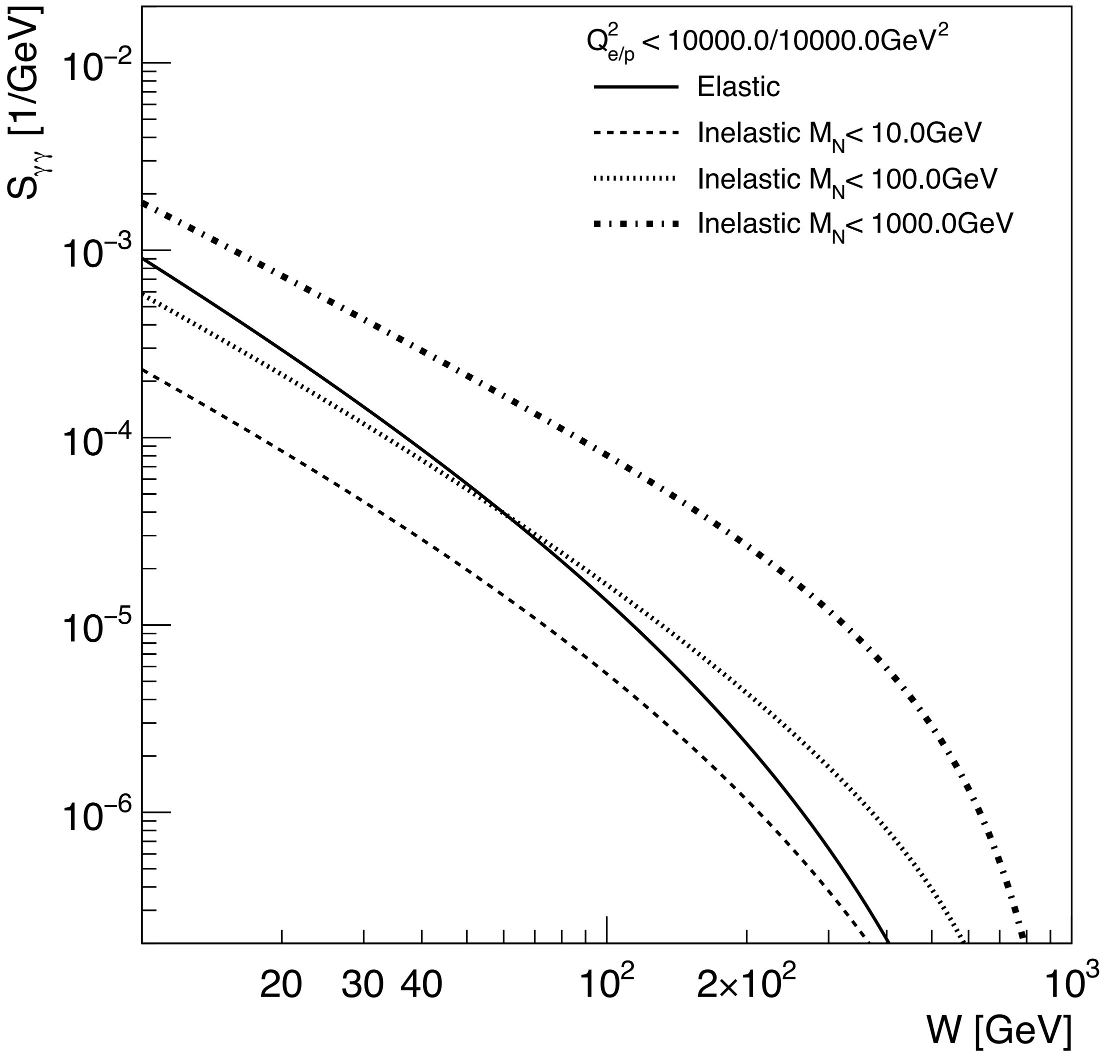
FCC-eh case

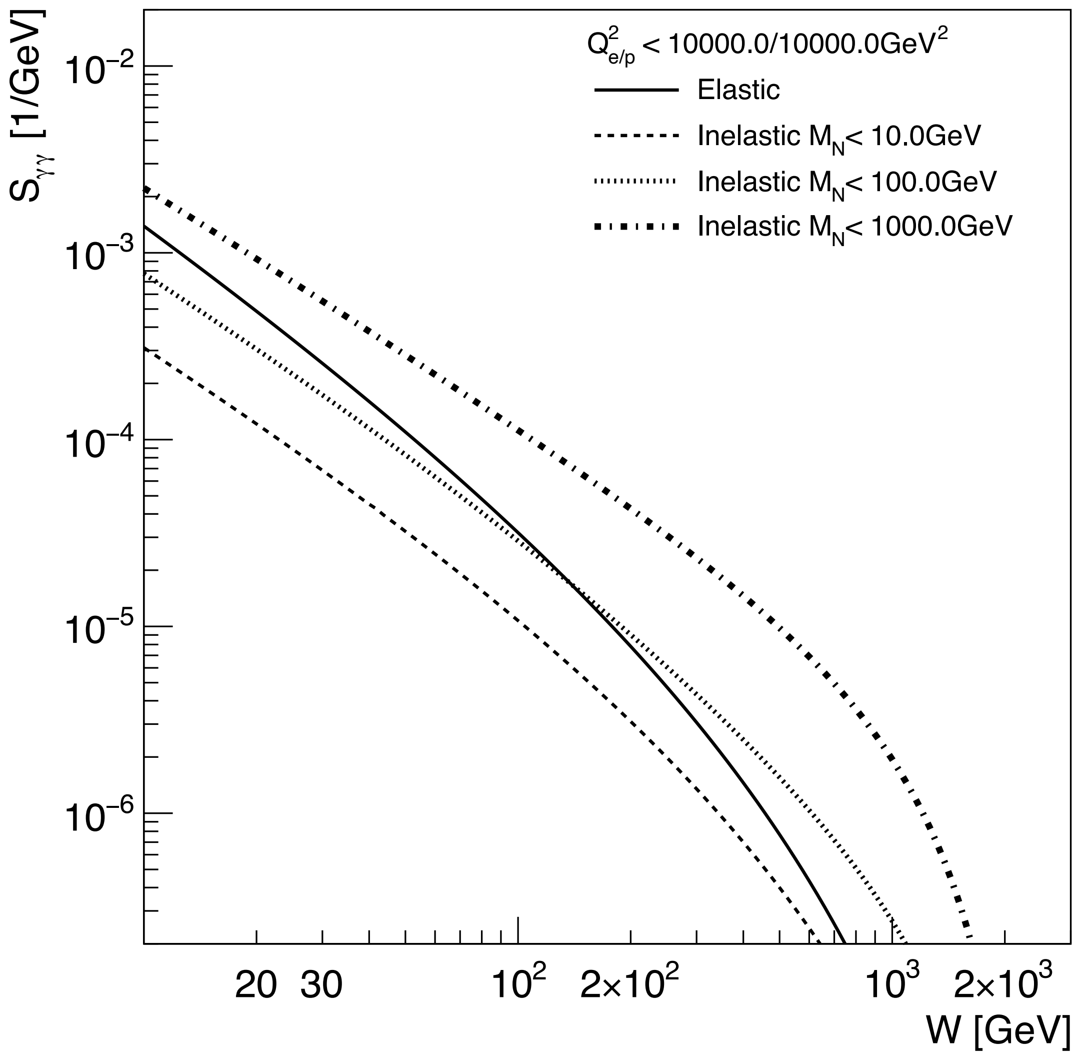
60 × 50000 GeV^2 → **3.5 TeV *ep* collider**
delivering very high luminosity
concurrently with *pp* collisions



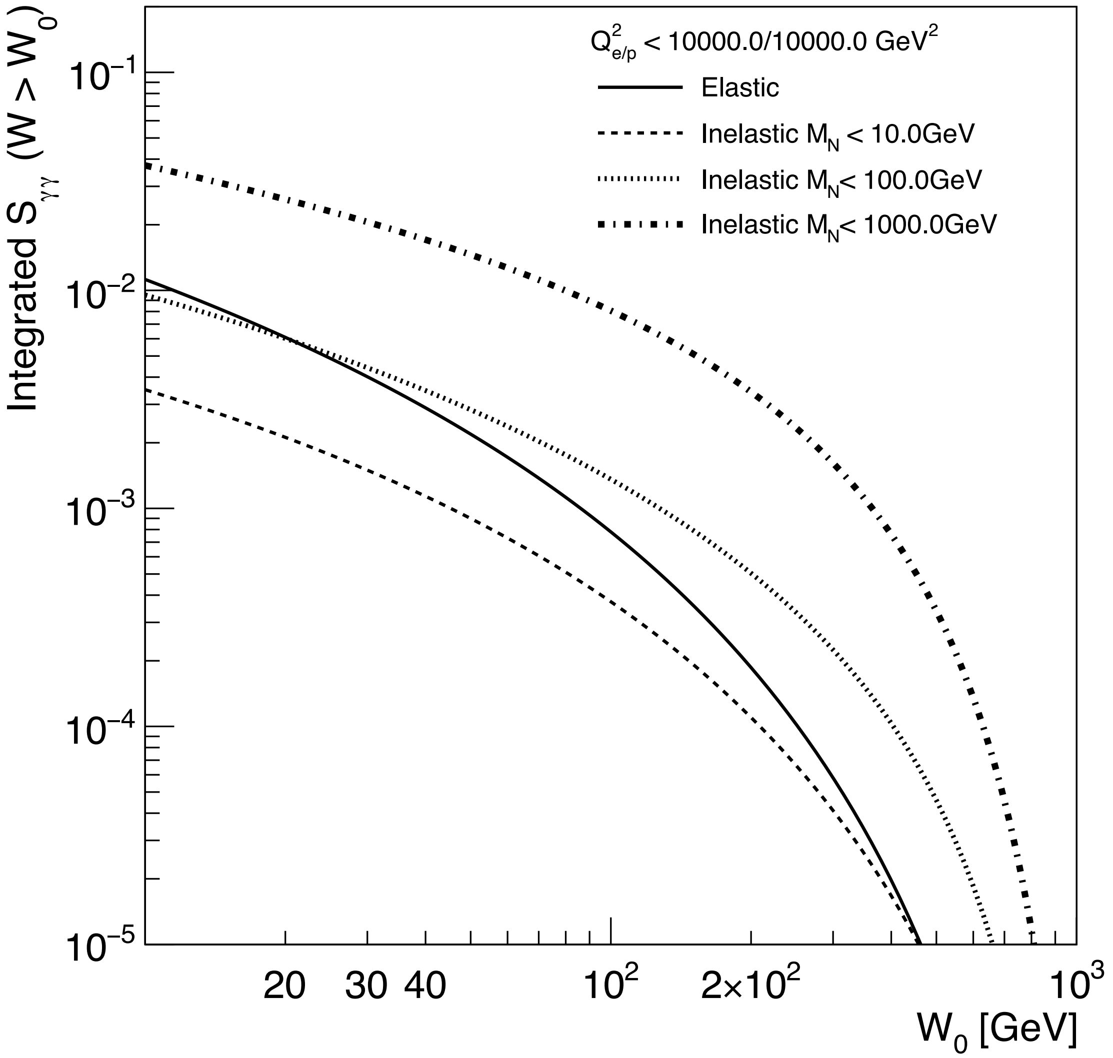
https://indico.cern.ch/event/1072533/contributions/4779225/

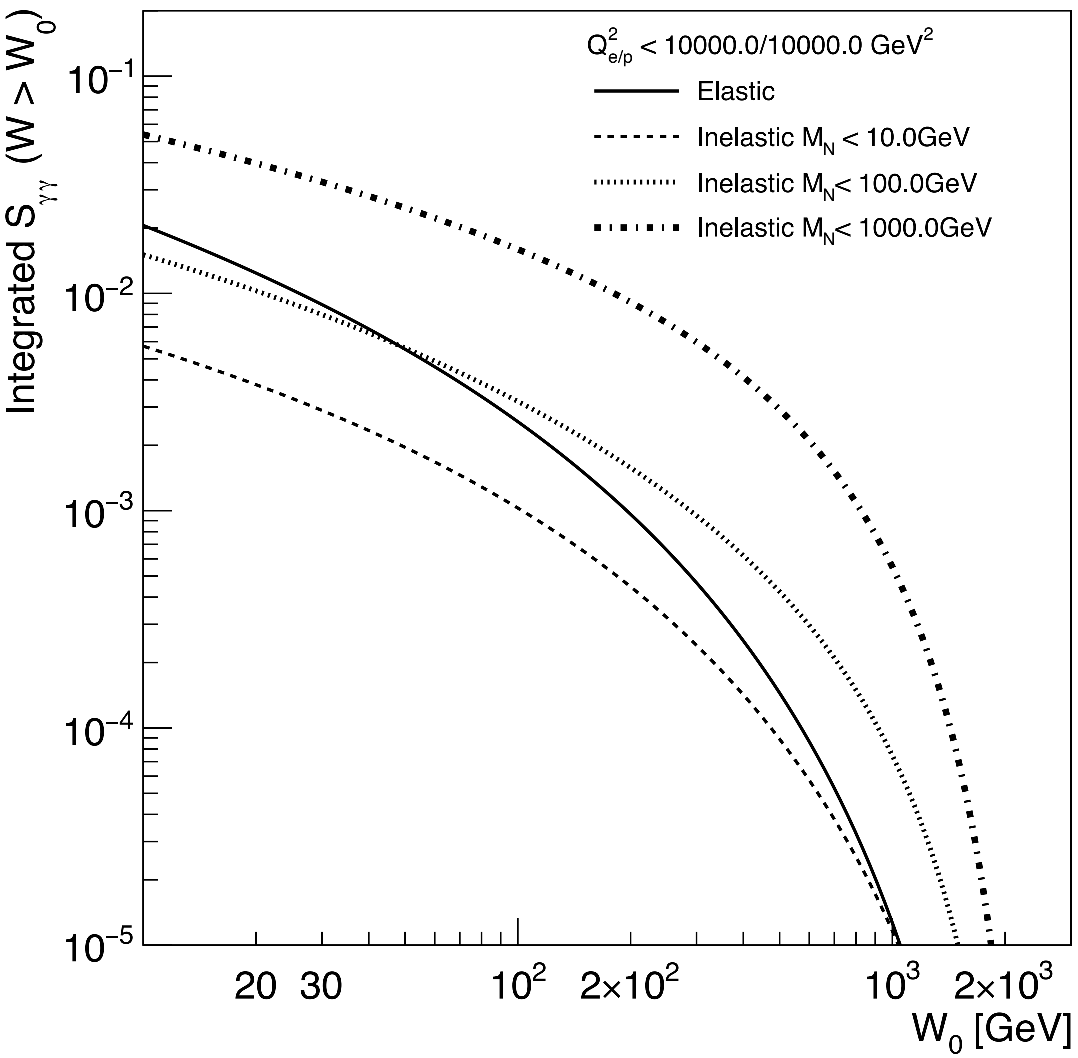
LH*e*C *vs.* FCC-*eh*





LHeC *vs.* FCC-*eh*





LHeC as an extraordinary $\gamma\gamma$ collider: summary & outlook

LHeC will complete the HL-LHC science in a very profound and relevant way, both in the QCD and Electroweak sectors

LHeC offers practically ideal conditions for studying high energy $\gamma\gamma$ interactions

Scientific potential of $\gamma\gamma$ physics at the LHeC, both in testing the electroweak theory and for searches of New Physics signals, will be deeply explored in the near future

Stay tuned!

https://kds.kek.jp/event/43635/

Thank you for attention!