Preliminary

Event Signatures with Light-Lepton Pairs and Taus at the LHC

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Outline

- Introduction
- Higgs boson production in association with two top quarks, ttH(H→ $\tau\tau$)
  - Multi-lepton channel
  - Higgs boson mass reconstruction
- Searches for charged Higgs boson production, tbH$^+$(WH)(H→ $\tau\tau$)
  - Multi-lepton channel
- Searches for Leptoquark pair-production, $LQ_3^d LQ_3^d \rightarrow t\tau t\tau$ 2lSS1tau
  - Multi-lepton channel
- Higgs boson production in association with a single top quark, tH(H→ $\tau\tau$)
  - Higgs boson mass reconstruction in the multi-lepton channel
- Higgs boson self-coupling
  - Overview
  - Challenges
- Exchange with Czech Technical University in Prague
- Conclusions and Outlook

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LHC proton-proton collisions

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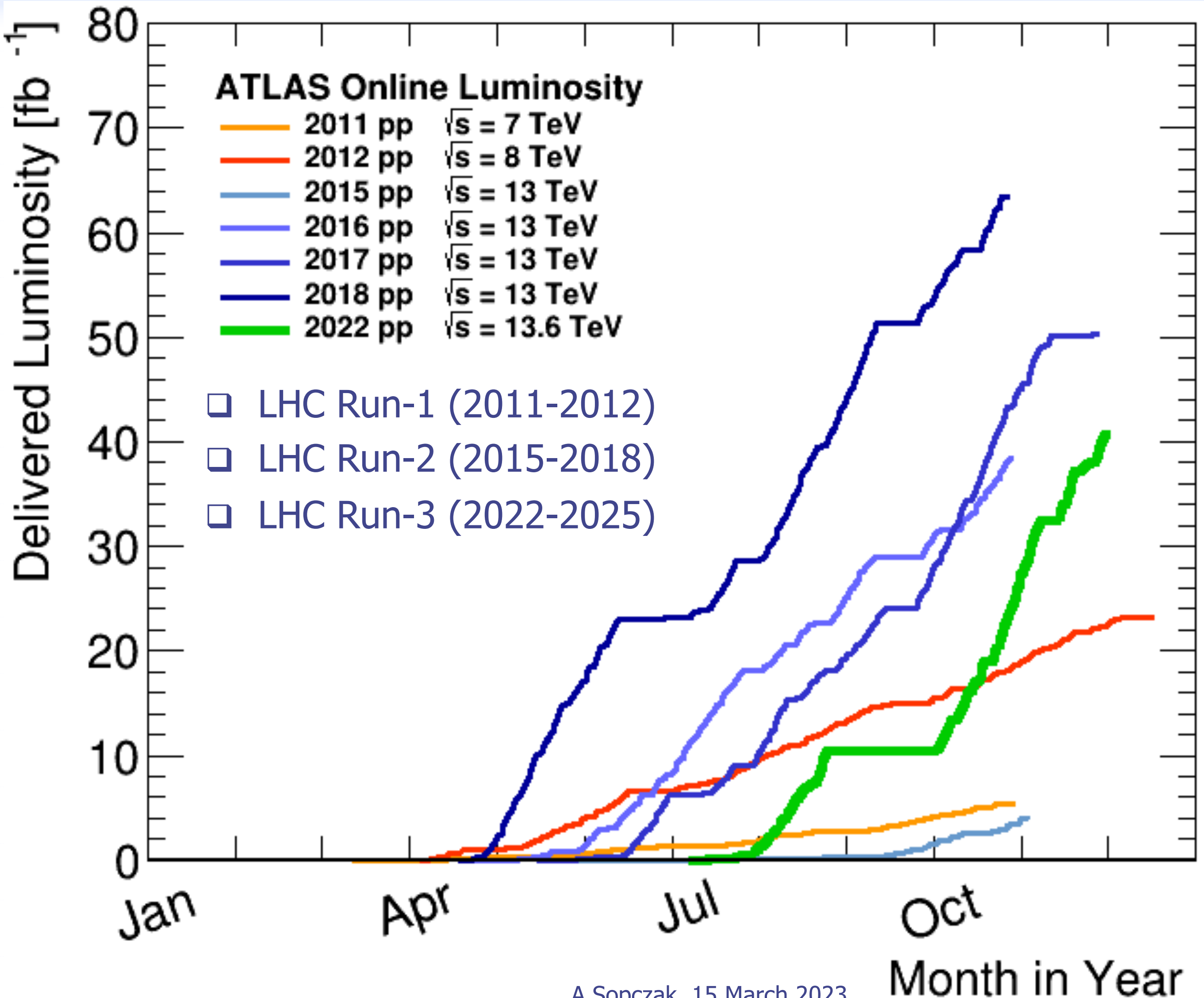

- LHC Run-1 (2011-2012)
- LHC Run-2 (2015-2018)
- LHC Run-3 (2022-2025)

Produced numbers of Higgs bosons in six production modes

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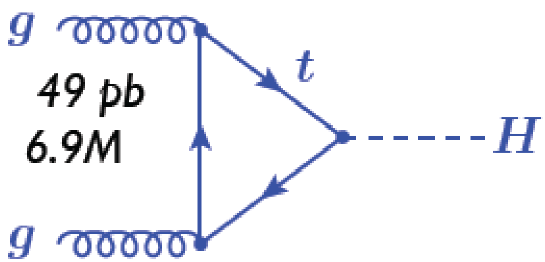
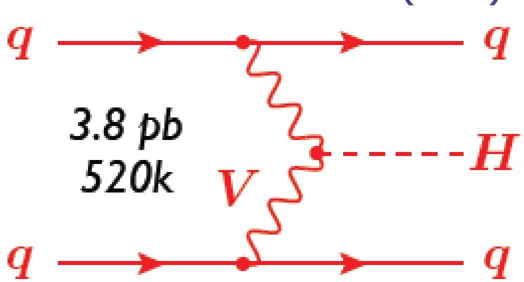
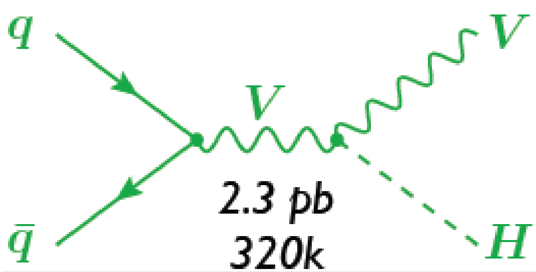
Gluon-gluon fusion (ggF)



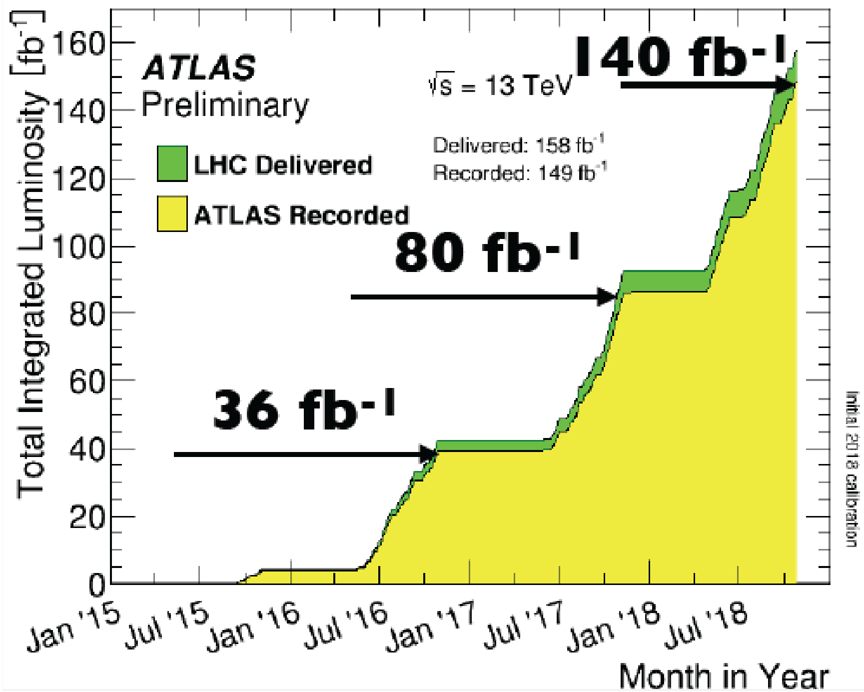
Vector boson fusion (VBF)



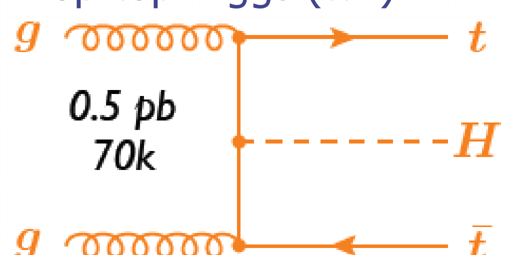
Associated production (VH)



Cross-sections for 13 TeV and number of events for 140 fb^{-1}



Top-top Higgs (ttH)



Single-top Higgs (tH)

0.07 pb, 10k

Di-Higgs (HH)

0.03 pb, 4k

Higgs boson decay branching fraction and expected final states

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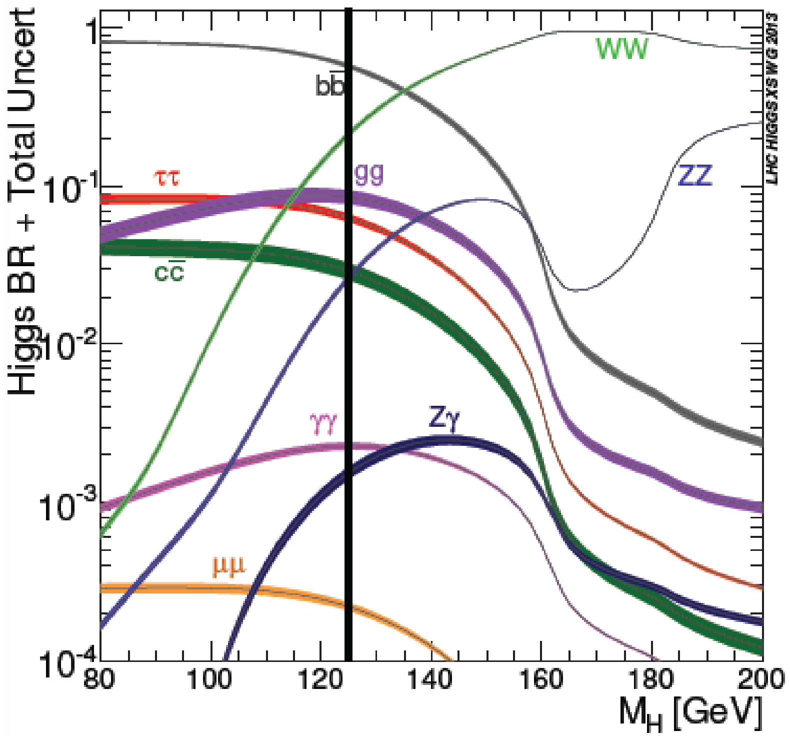
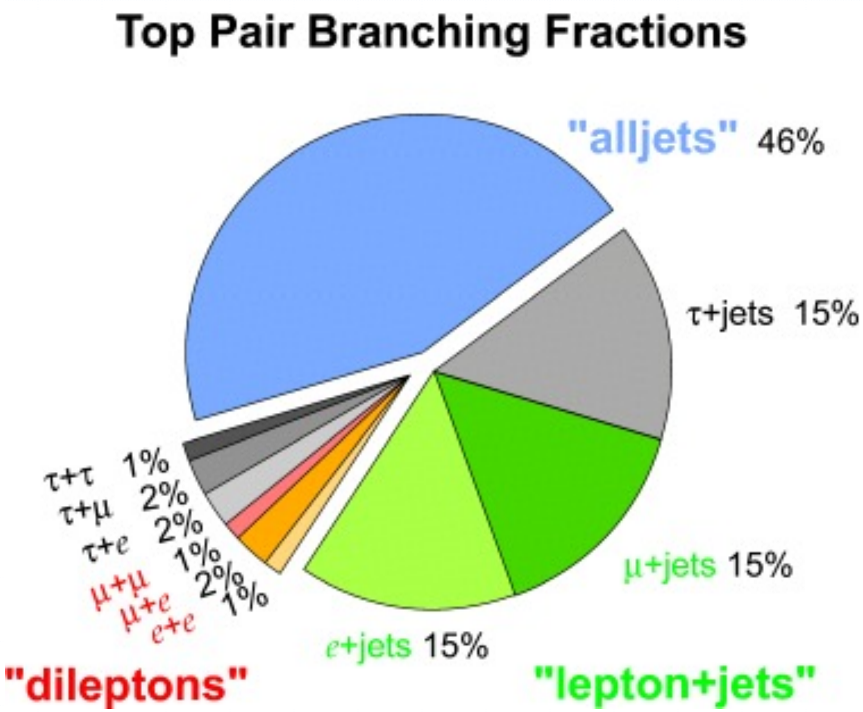


- H → bb: 58%
- H → WW*: 21%
- H → ττ: 6.3%
- H → ZZ*: 2.6%
- H → γγ: 0.23%
- H → Zγ: 0.15%
- H → $\mu\mu$: 0.022%

Example:
ttH production and decay



ttH: two same-sign leptons and one hadronic tau final state

ttH observation
ATLAS: 5.8 (4.9) st.dev., PLB 784 (2018) 173
CMS: 5.2 (4.2) st.dev., PRL 120 (2018) 231801

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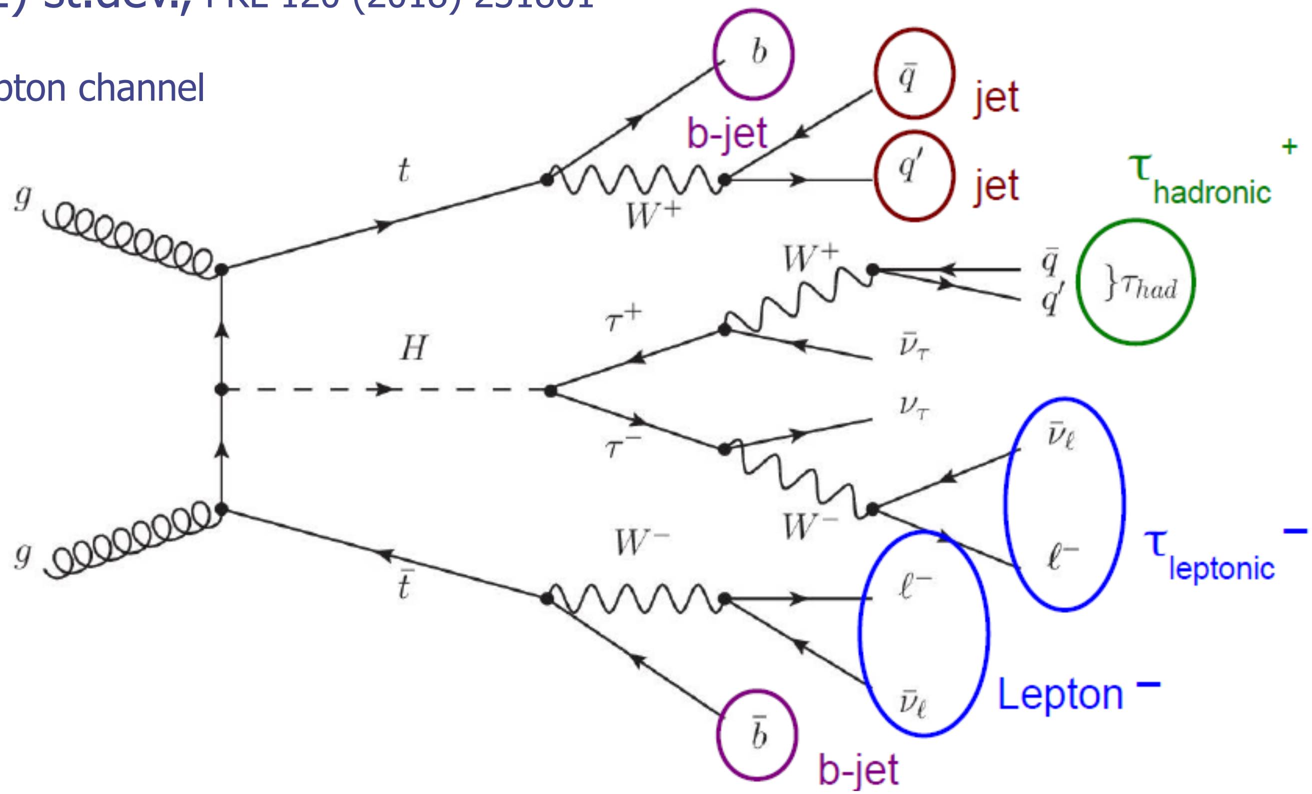
Babar Ali

Example: multilepton channel



- Main backgrounds: tt and ttV
- Fake background estimate determined from data

ttH candidate (multi-leptons) same-sign e and μ and tau-jet

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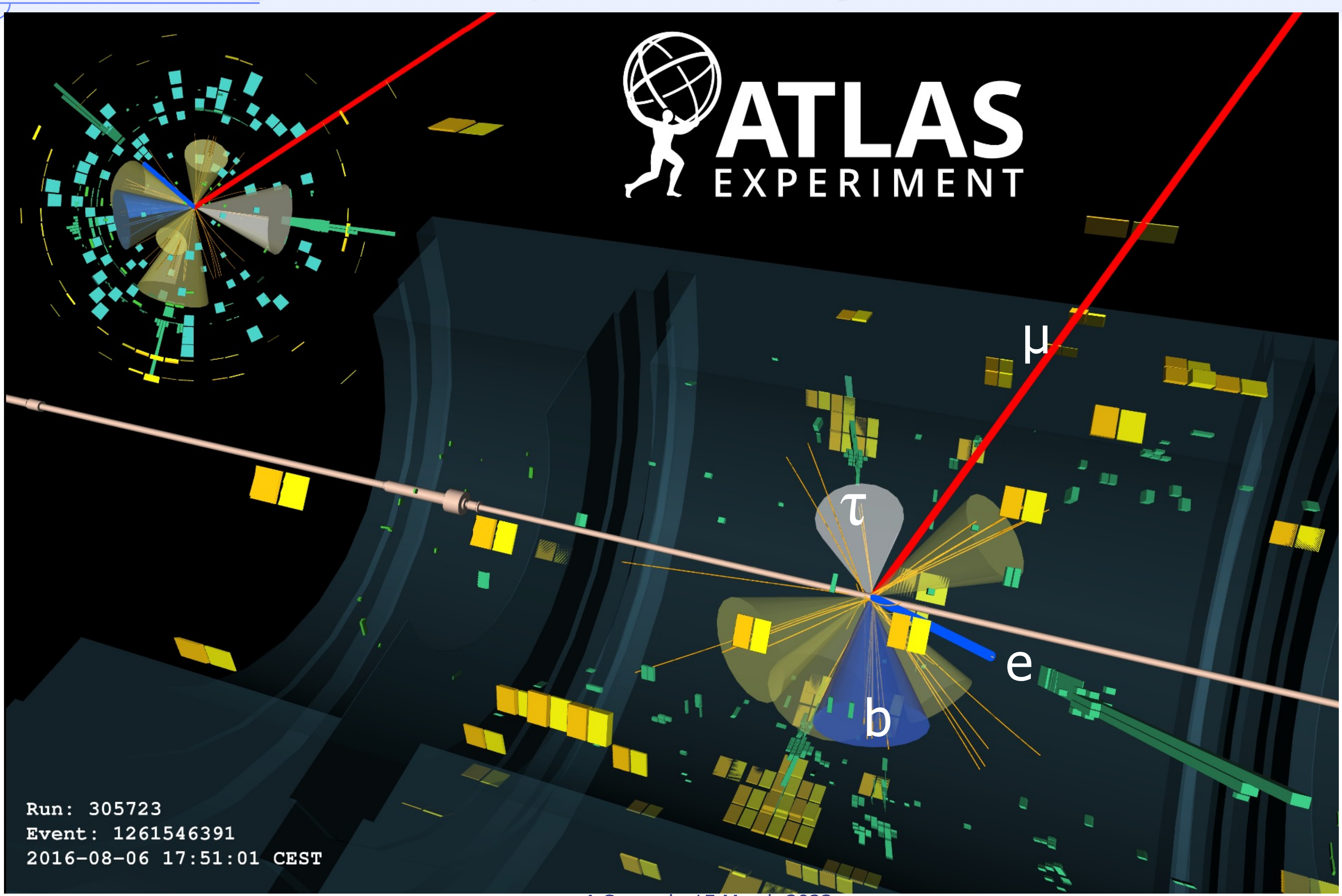

PRD 97 (2018) 072003

Higgs boson couplings to fermions ttH direct probe, leptons

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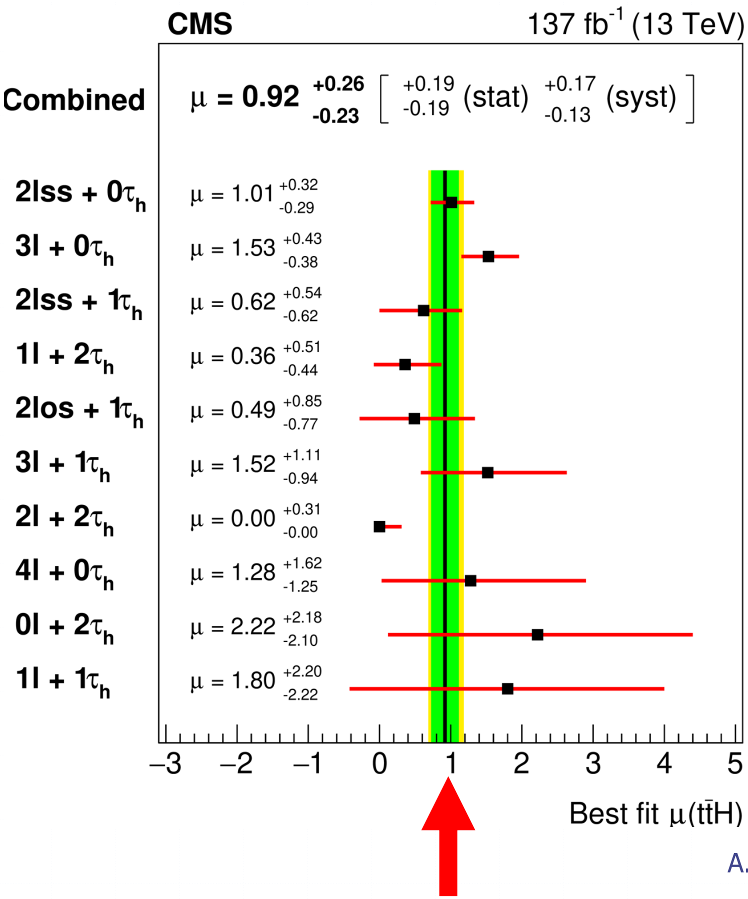
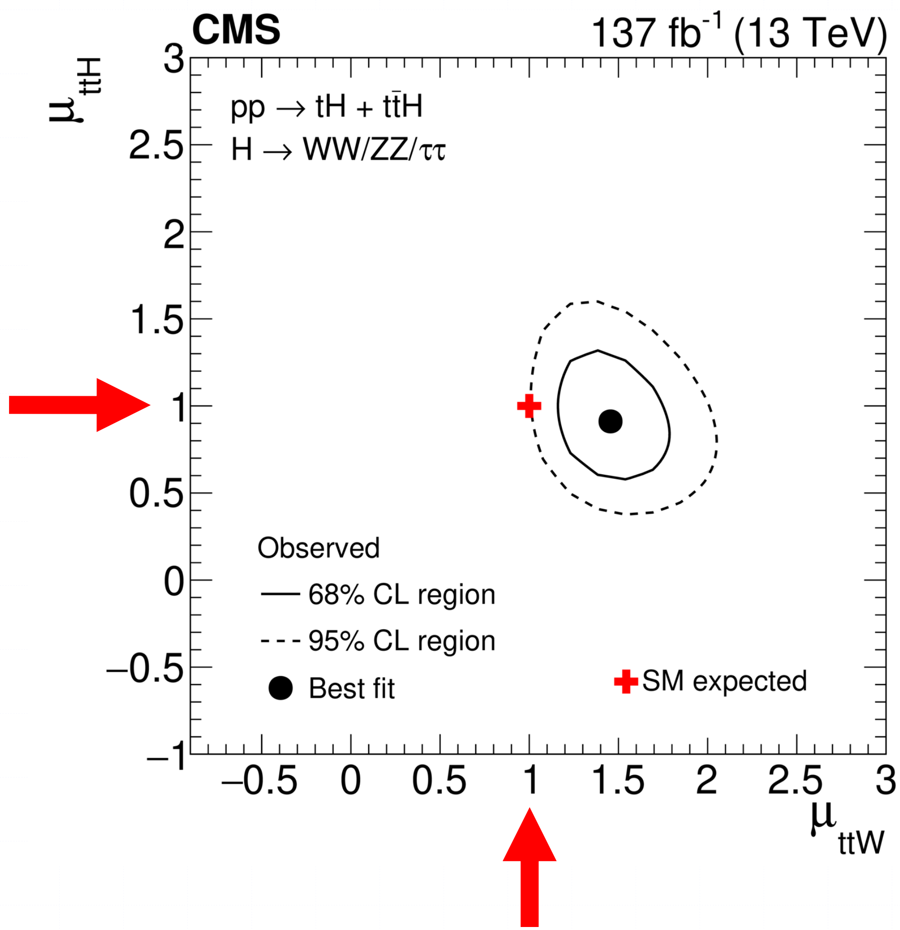
- ttH: multilepton channels with l = e or μ, τ(hadronic decay)
- ATLAS, PRD 97 (2018) 072003 (36.1 fb^{-1})
  ATLAS-CONF-2019-045 (80 fb-1)

1.8 (3.1) st.dev. (multileptons)

EPJ C81 (2021) 378





2lSS1tau, machine learning
Jan Presperín

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- Train a **classification algorithm** to discriminate between signal (ttH) and background (ttW, ttZ, tt, VV, others) events
- **Specific channel:**
  two light leptons, same-sign,
  one hadronically decaying tau lepton,
  at least 4 jets,
  at least one jet tagged as b-jet

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- **3 sets of features** (low-level, higher-level, all) and **3 different classification algorithms** (TabNet network, XGBoost, MLP)

classname	number of examples	number of weighted events
tth	29538	22.7
ttw	10289	24.8
ttz	27410	18.2
tt	186	22.1
vv	2805	6.4
other	3142	11.4

network performance - MLP
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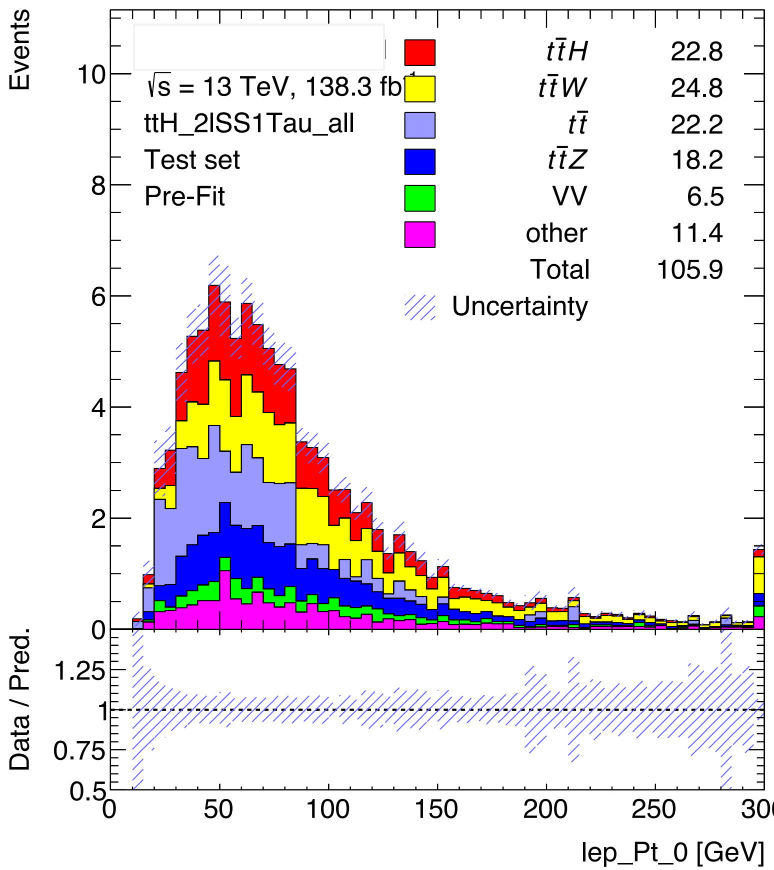
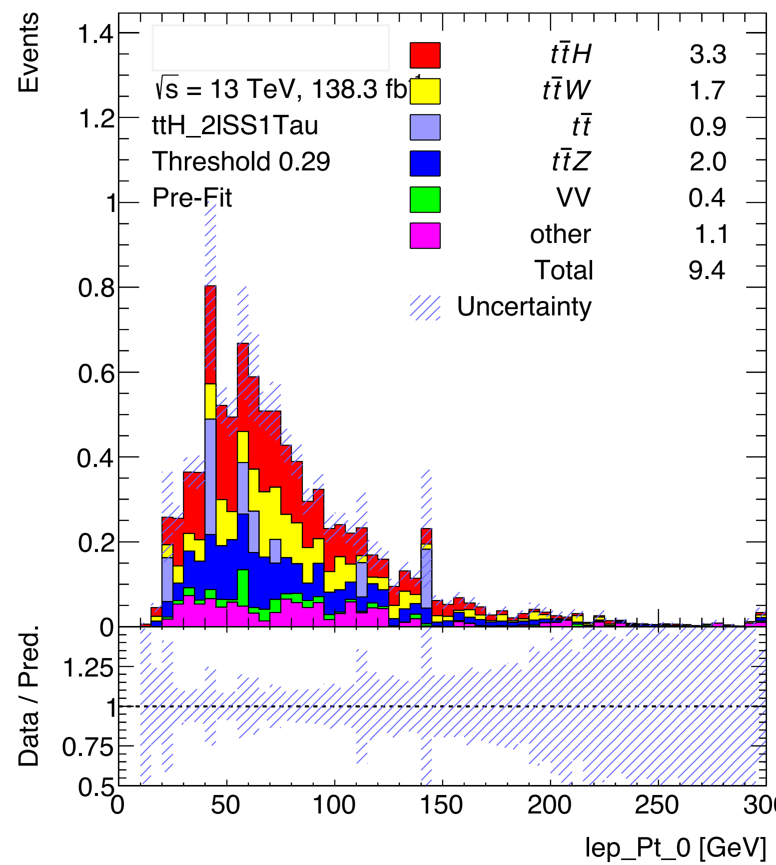
all **training & testing**

testing data (20%) classified by the network as signal





Expected sensitivity - MLP
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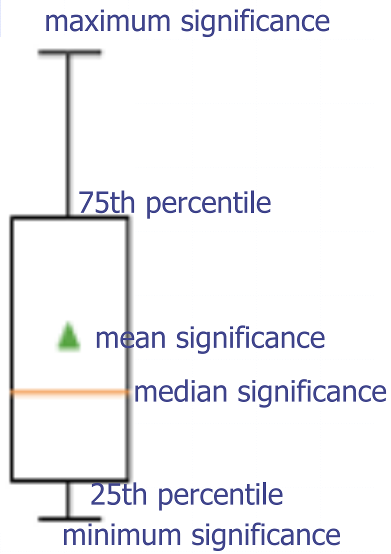
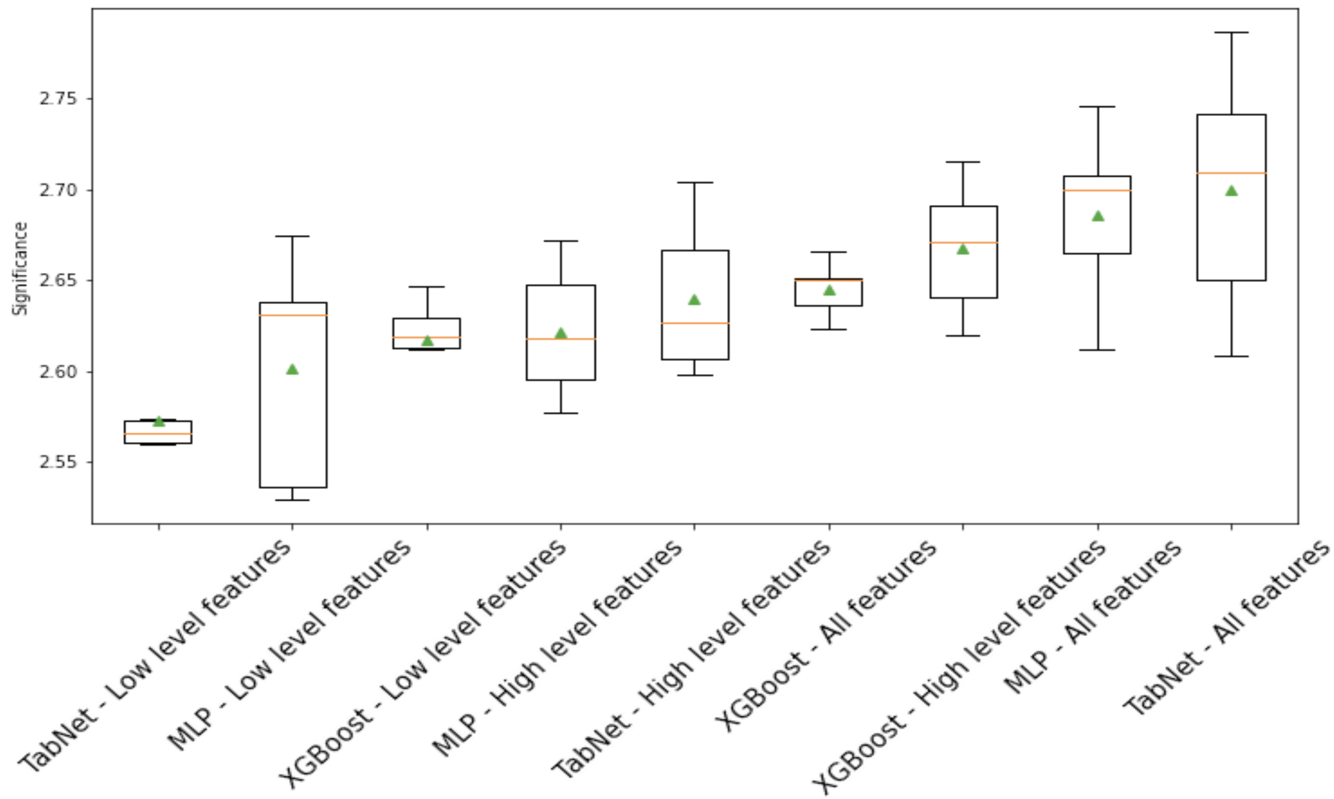
- Significances after running multiple experiments with a particular combination of algorithm and feature set





boxplot:
5 runs of
training+testing

Neural networks performed better than tree algorithms, combining more features always gives better performance

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Higgs boson mass reconstruction in 2lSS1tau channel, Adam Herold

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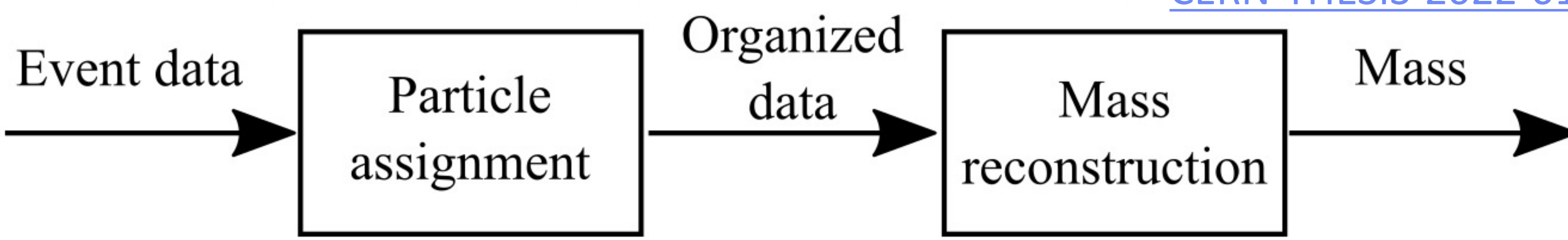
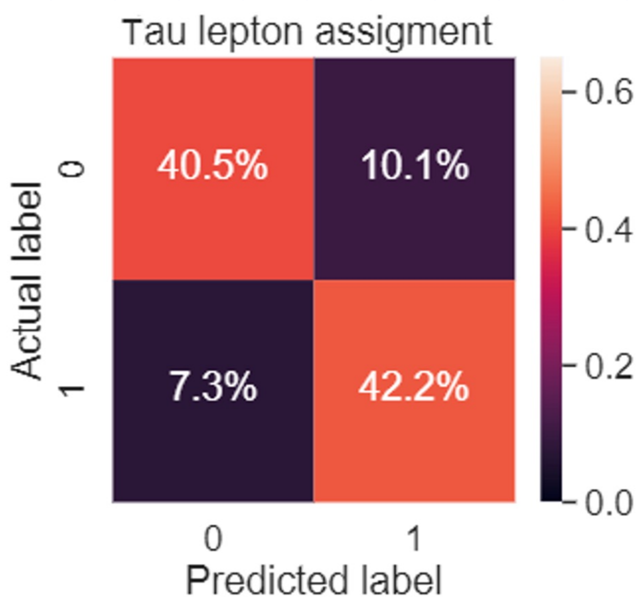
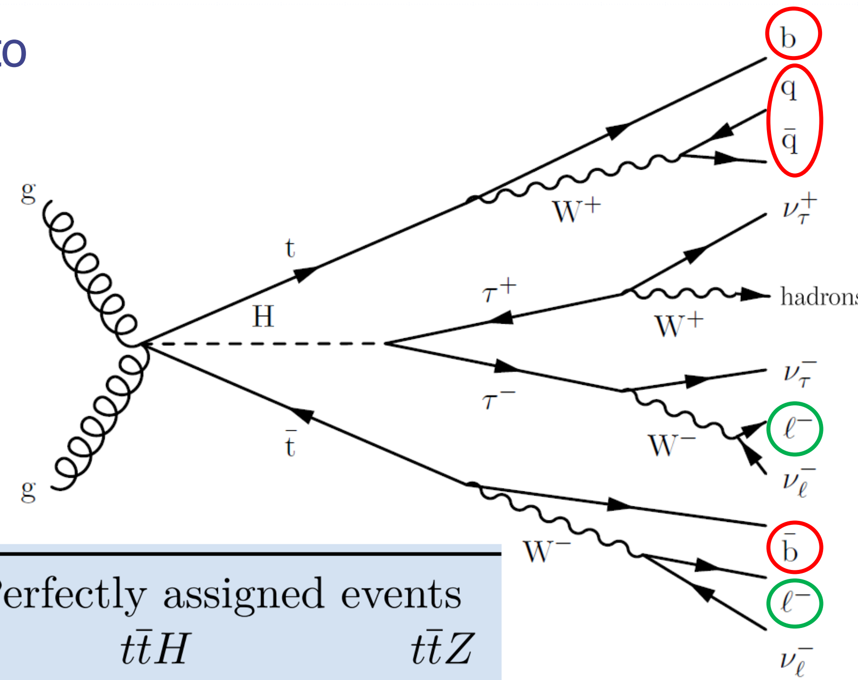


- Assign detected leptons and jets to positions in the decay





Perfectly assigned events	
$t\bar{t}H$	$t\bar{t}Z$
32%	31%

Higgs boson mass reconstruction in 2lSS1tau channel, Adam Herold

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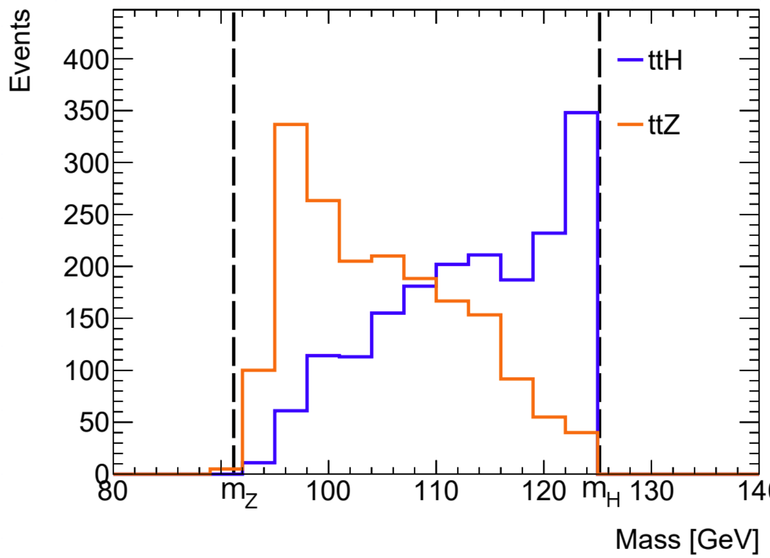
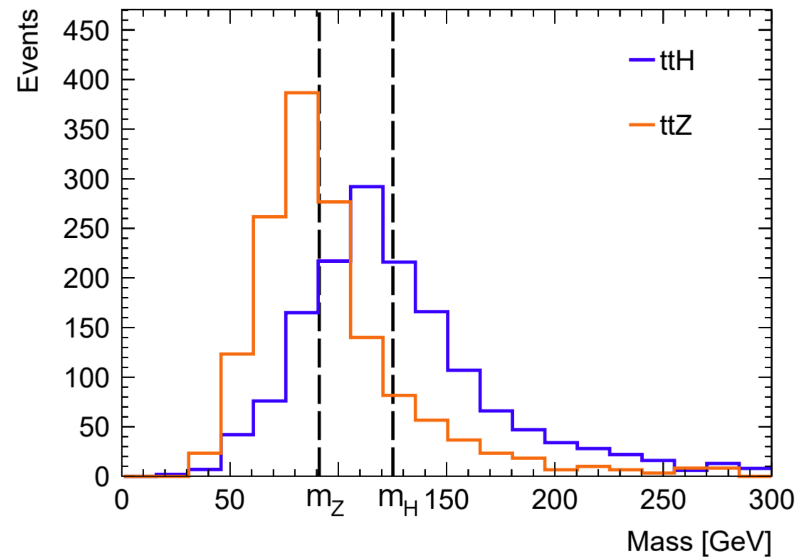
- Separation of ttH and ttZ samples by mass reconstruction



Neural network
distribution of predicted mass

Separation 69.33%



Missing mass calculator
distribution of predicted mass

Separation 67.63%

2lSS1tau, tbH⁺ ($H^+ \to W^+H$, $H \to \tau\tau$)
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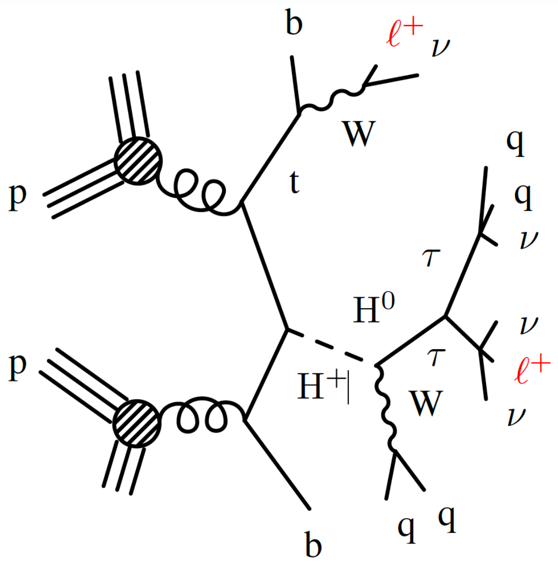

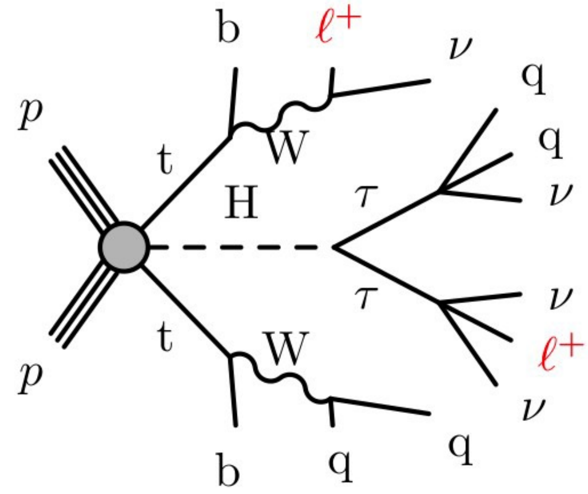

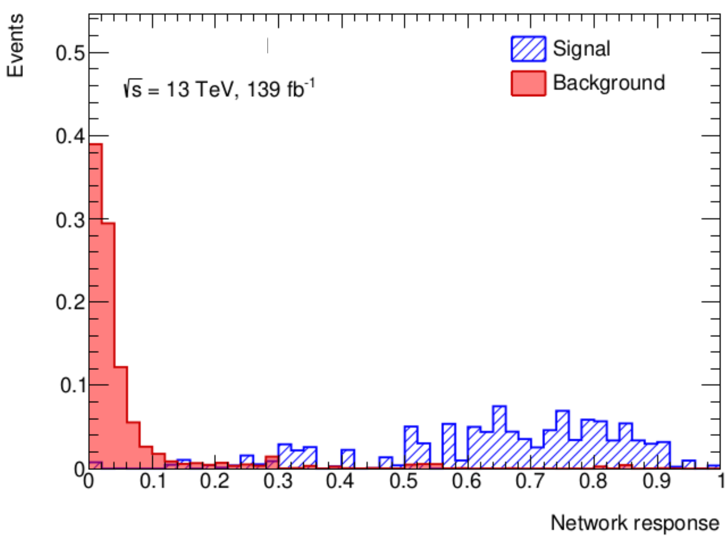

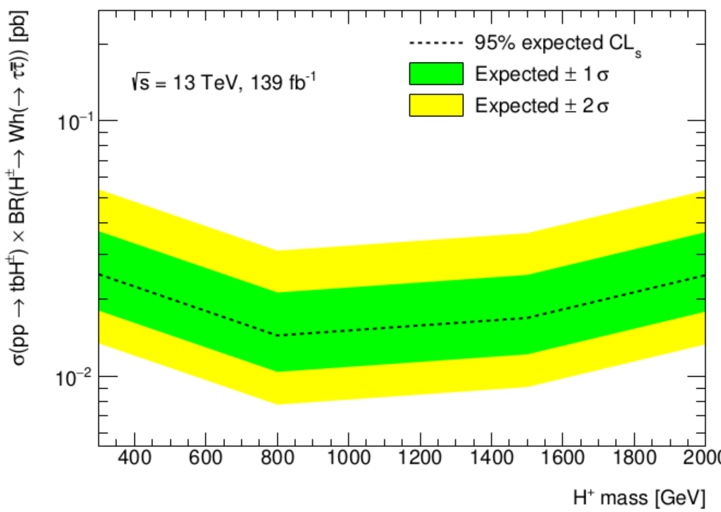

2lSS1tau, tbH$^+$ (H$^+ \rightarrow$ W$^+$H, H$\rightarrow\tau\tau$)
Niklas Düser

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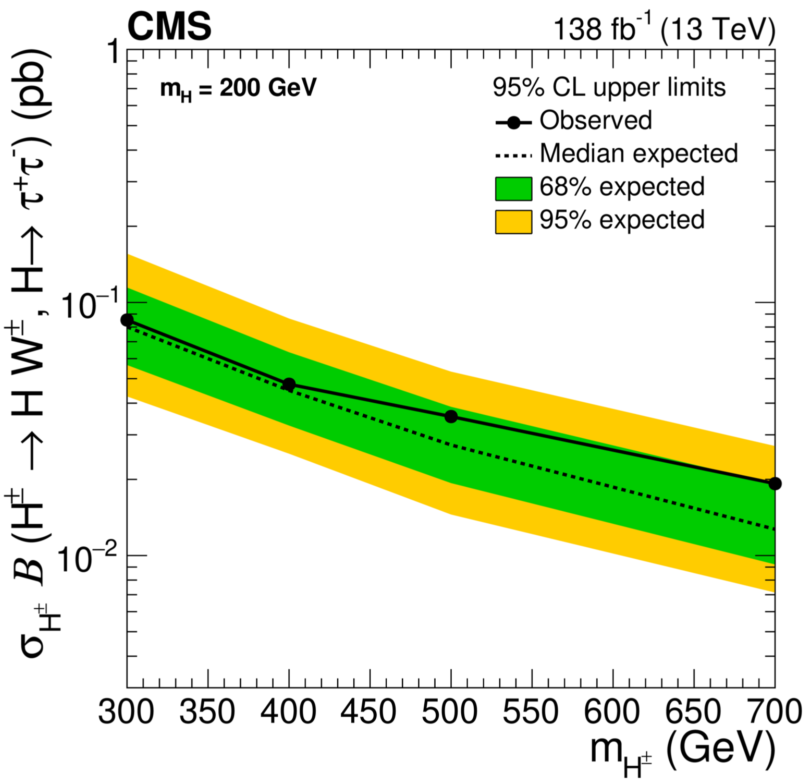

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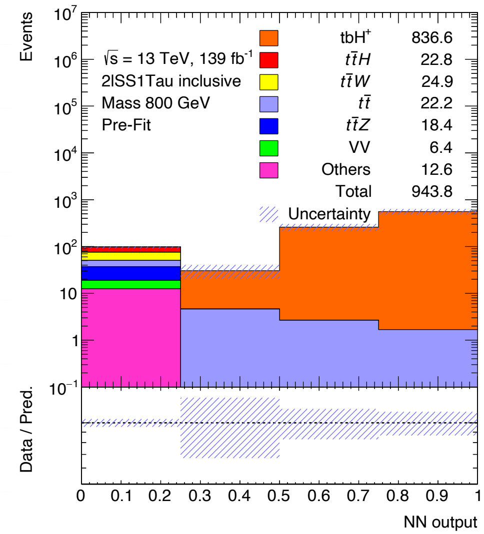

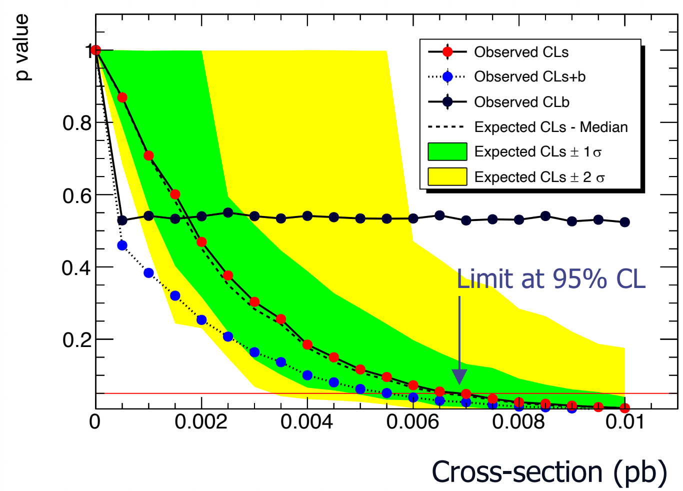

2lSS1tau, Leptoquark signature, Lucas Viceník

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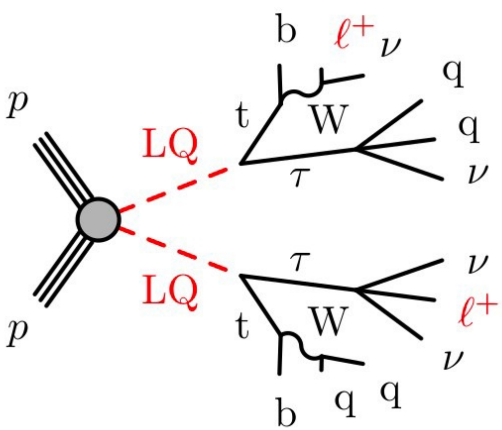
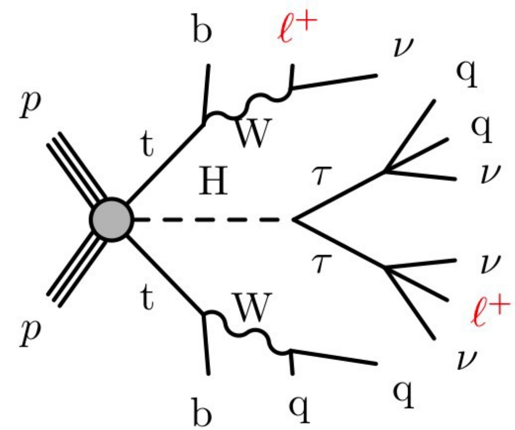
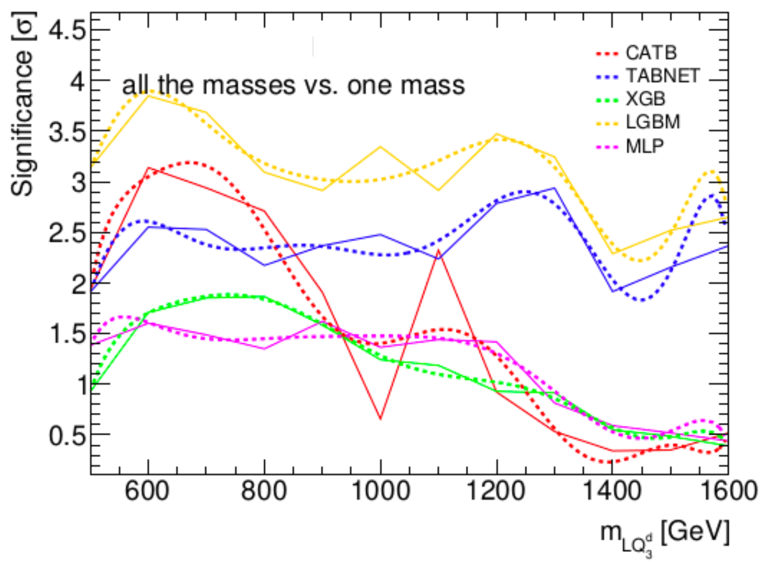
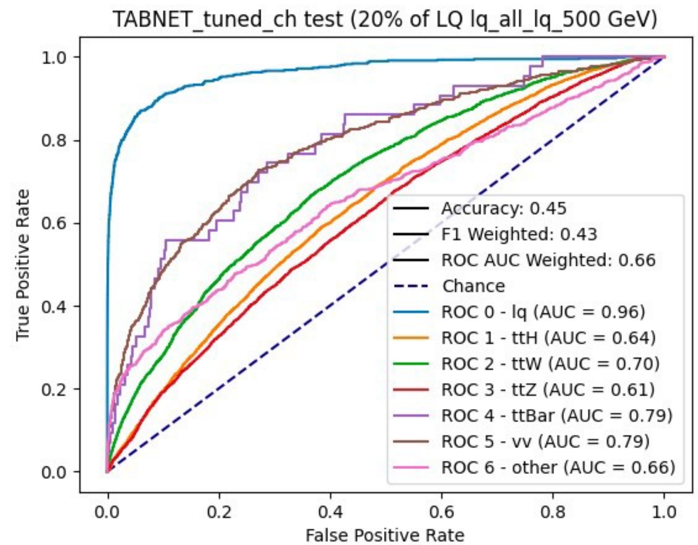
CERN-THESIS-2022-064









2lSS1tau, Leptoquark signature, Lucas Viceník

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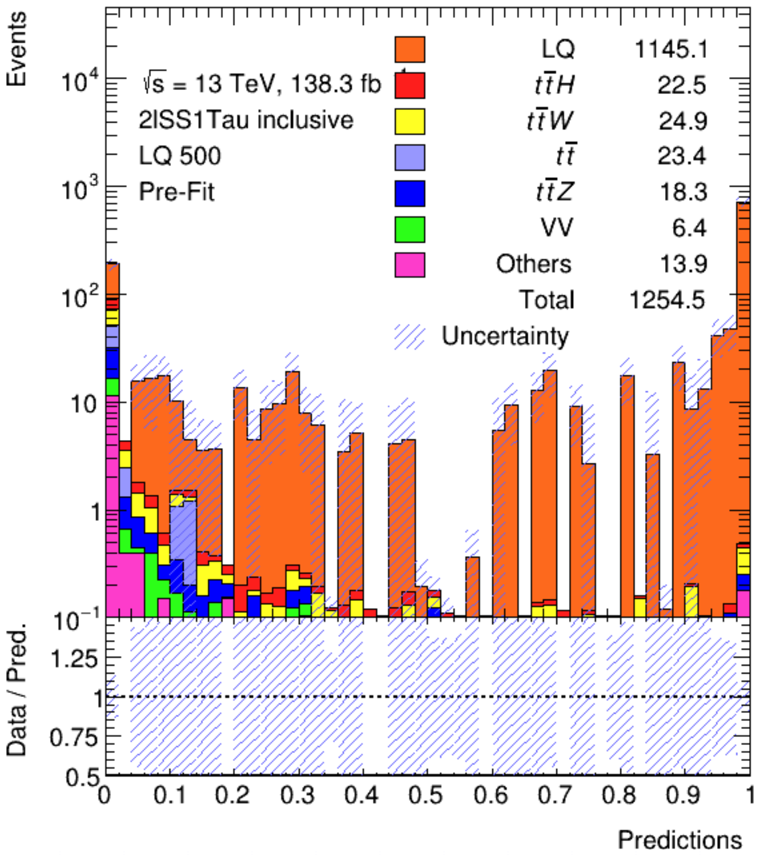

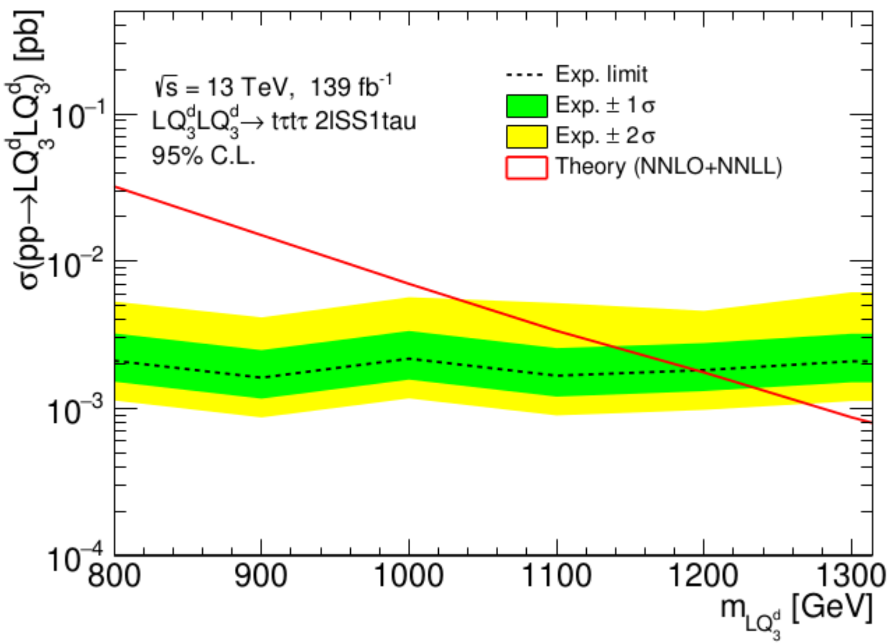

Single top and Higgs boson production tH

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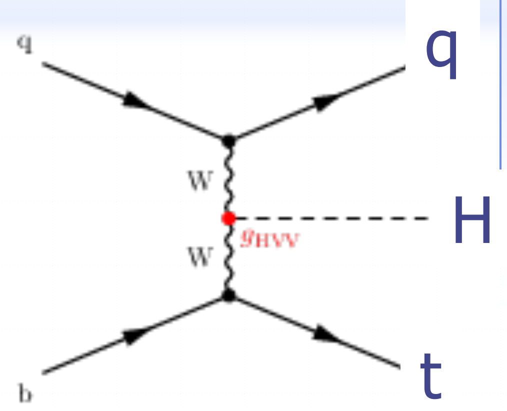
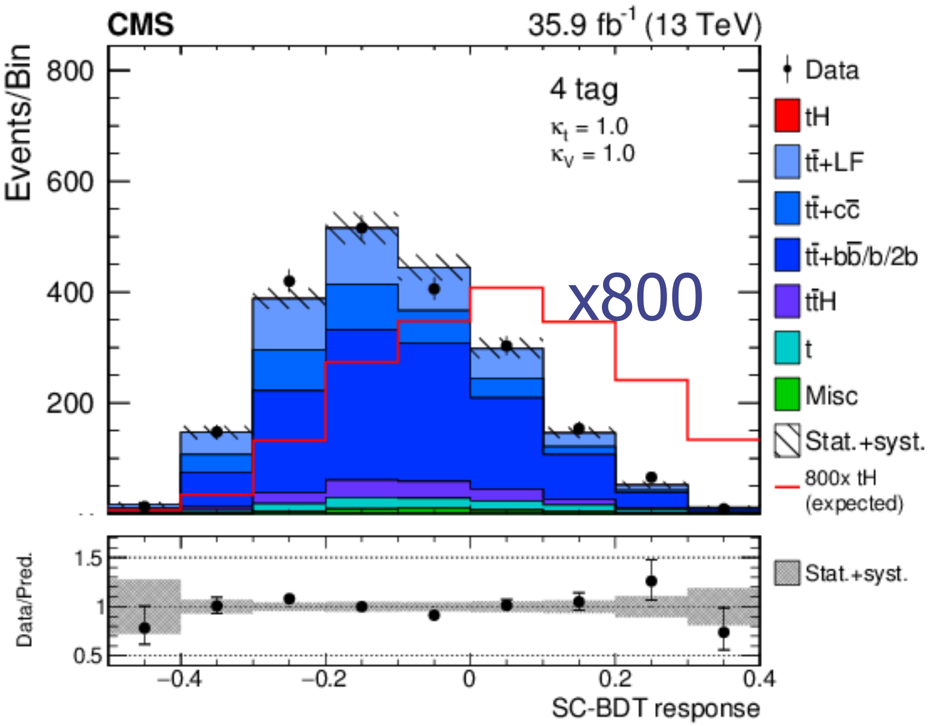
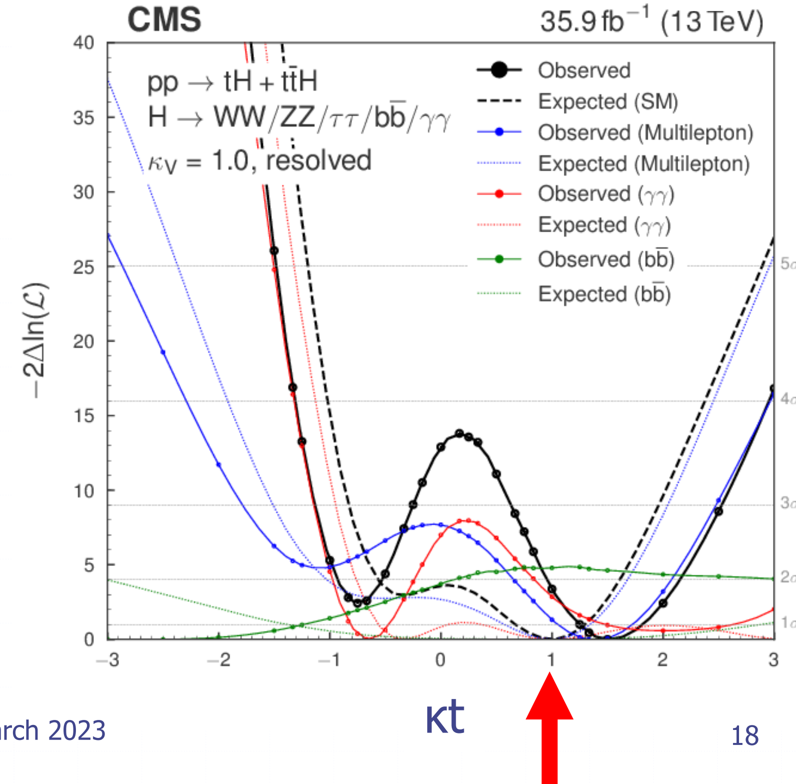
- tH, H → WW/ZZ/ττ and H → bb

PRD 99 (2019) 092005

- Combination with ttH, H → γγ
- Sensitive to absolute values top quark Yukawa coupling, the Higgs boson coupling to vector bosons, gHVV, and uniquely their relative sign
- SM κt = 1.0 over κt = −1.0 by > 1.5 st.dev.

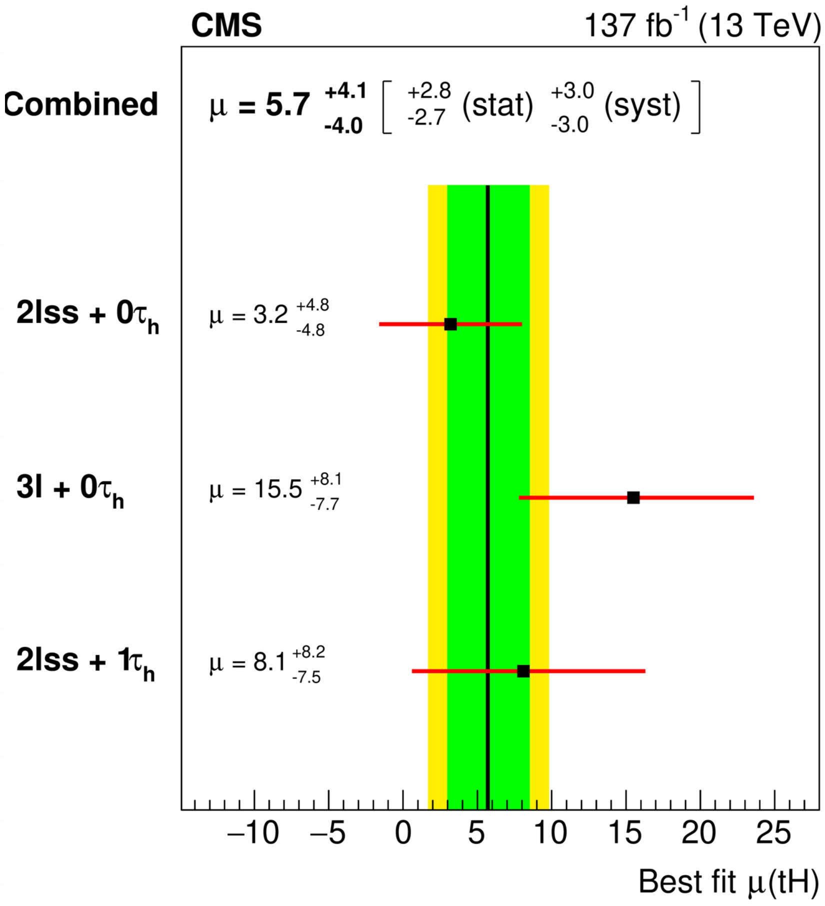


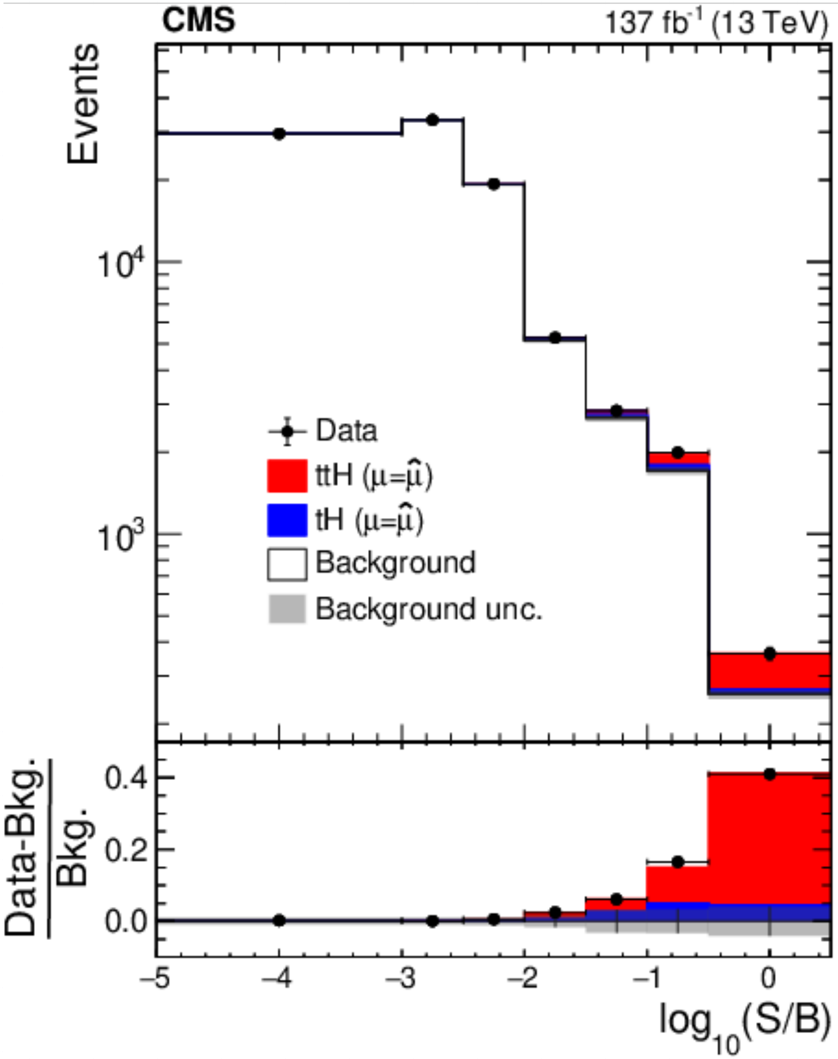




Single top and Higgs boson production tH

- With respective SM expectations: μ =5.7±2.7(stat)±3.0(syst)
- Significance 1.4 (0.3) EPJ C81 (2021) 378





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tH: 2 light leptons & 1 hadronically decaying tau, Cyrus Walther

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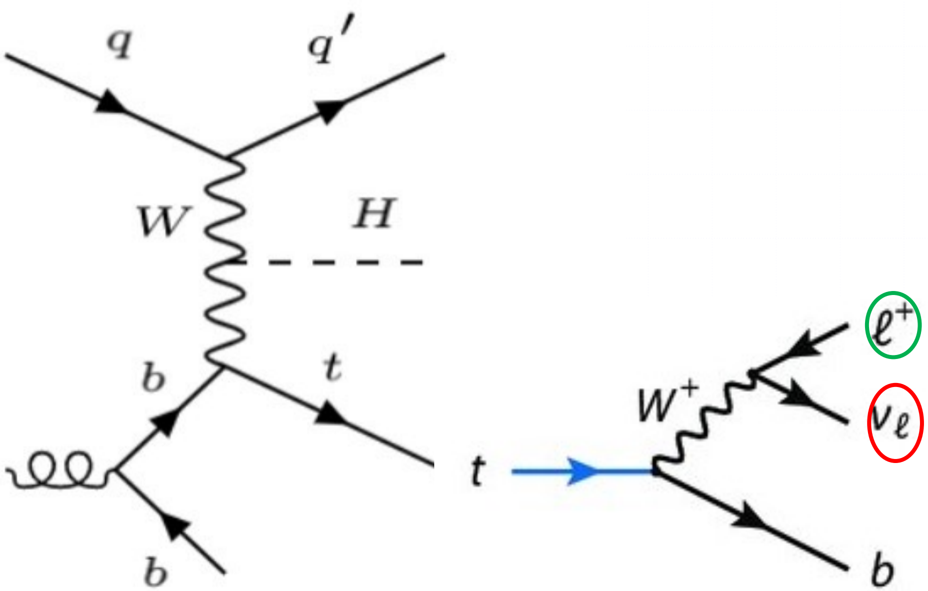
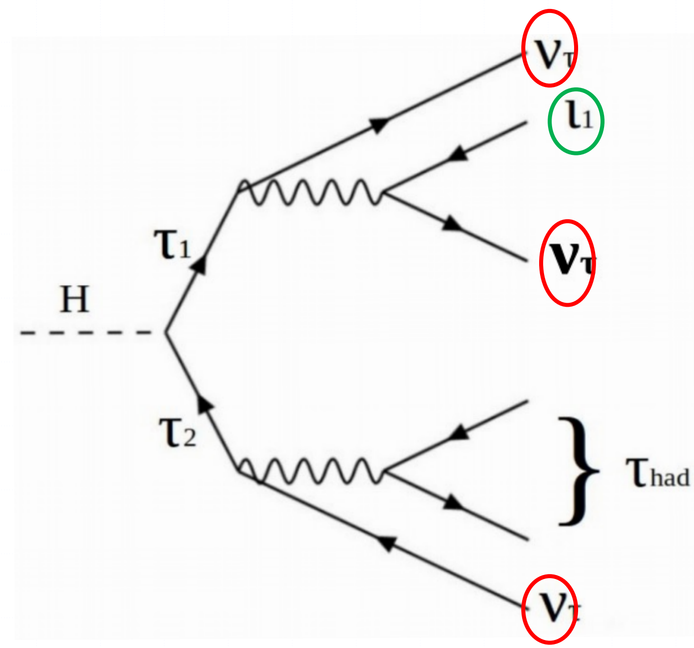
Erasmus seminar, IEAP CTU, 15.02.22

Challenges for Higgs boson mass reconstruction:

- associate correct light lepton to Higgs boson decay
- neutrinos in mass reconstruction neural network





Association of the leptons
Cyrus Walther

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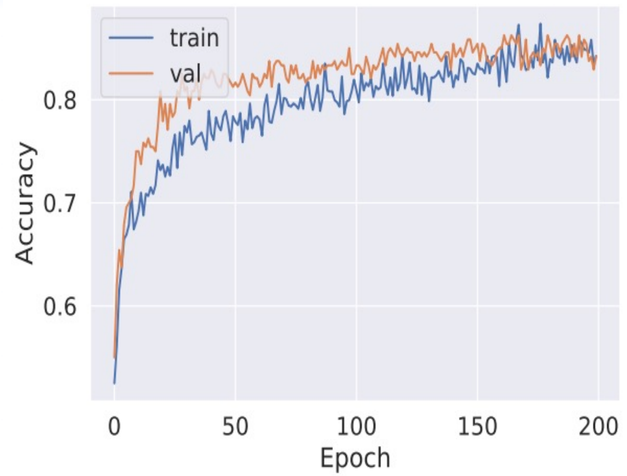
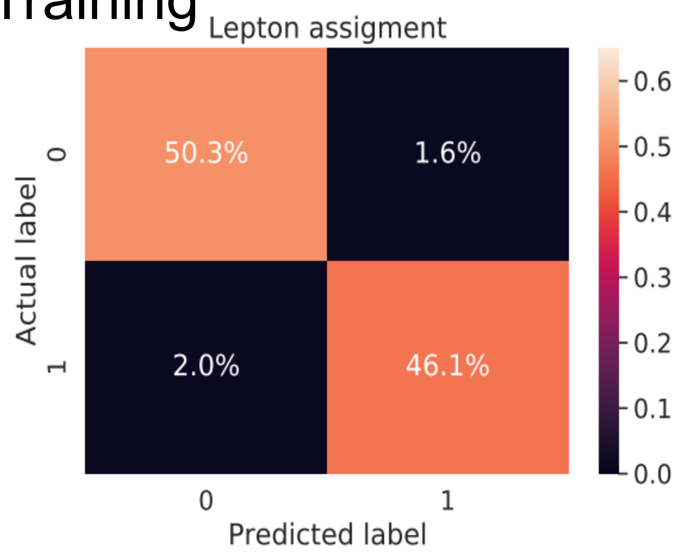
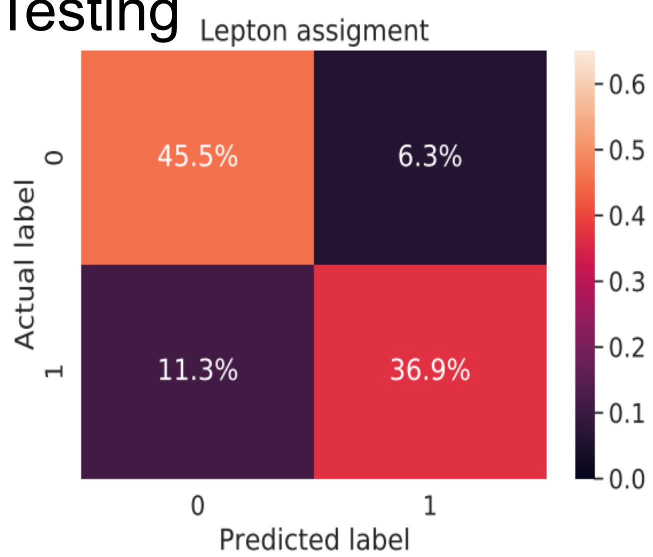
- Training and testing performance of network
- 82% correct lepton association



- Training



- Testing



Higgs boson mass reconstruction, Cyrus Walther

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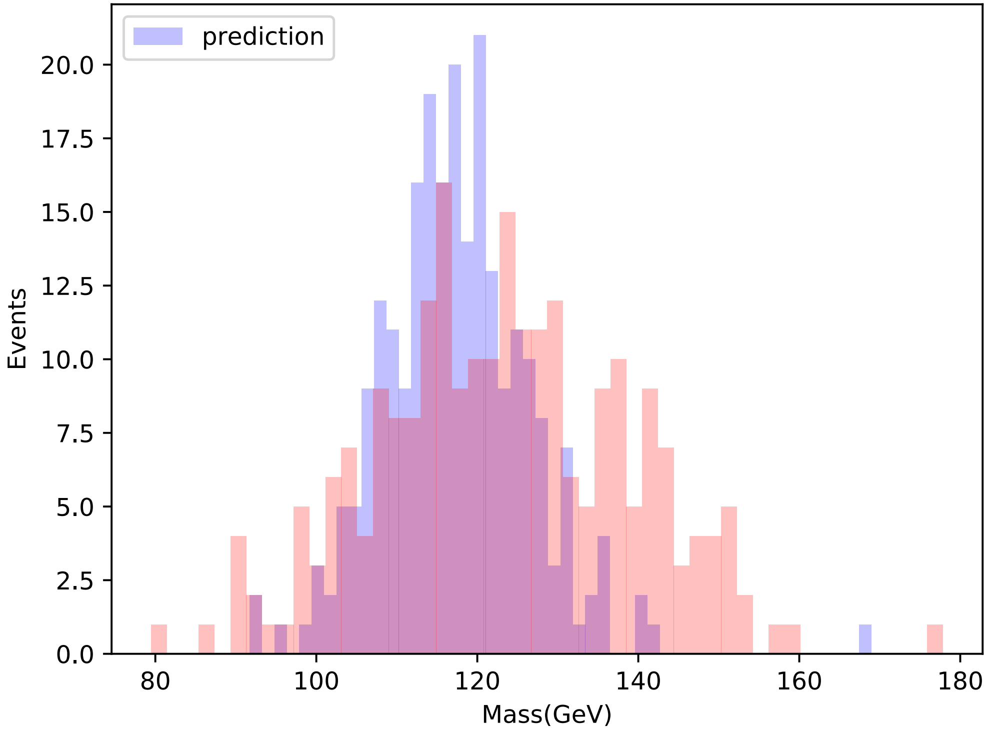
- Higgs boson mass is a constant
- Neural networks learn constants and easy relation
- More complex or random influences are needed to disengage the label from the true Higgs boson mass
- Gaussian smearing is used with σ=15 GeV



Higgs boson pair-production HH

$$V(H) = \frac{1}{2} m_3^2 H^2 + \lambda_3 H^3 + \frac{1}{4} \lambda_4 H^4 + O(H^5)$$

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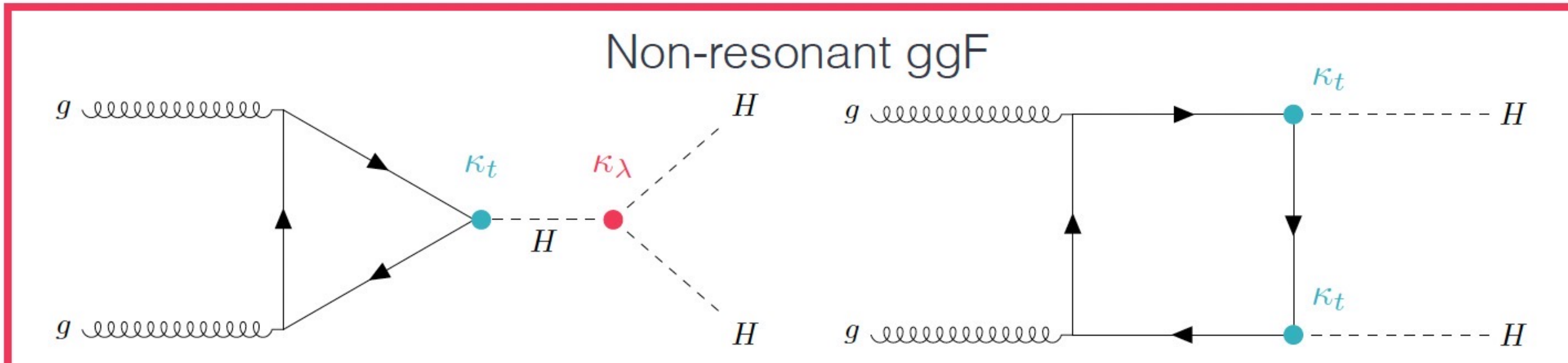
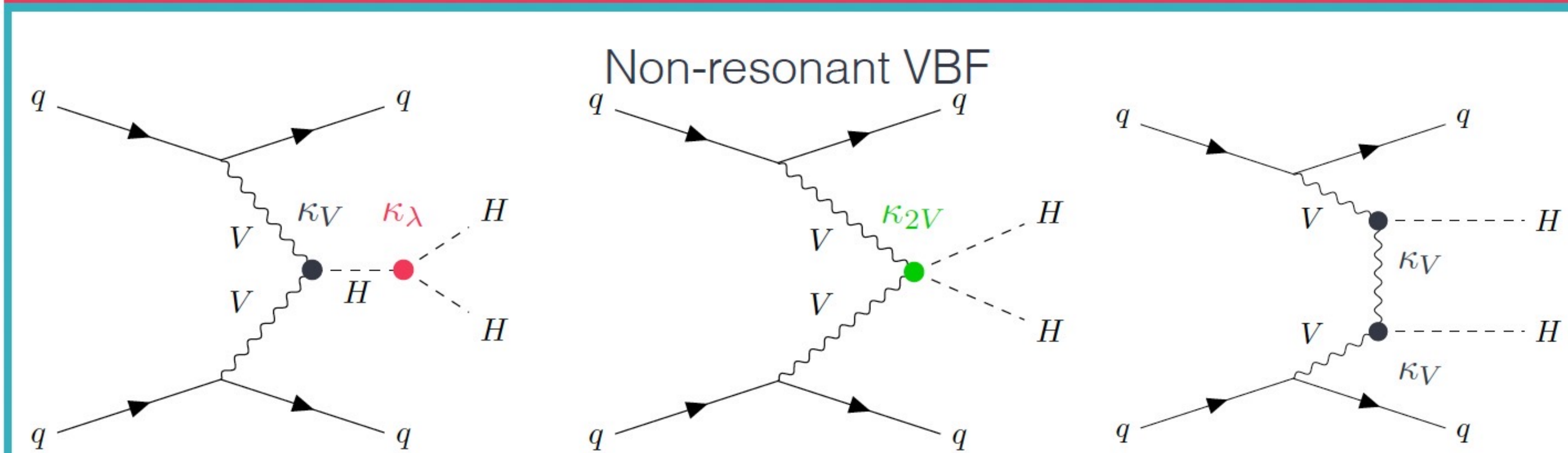
- Higgs self-coupling $\kappa_\lambda = \lambda_3 / \lambda_{3,SM}$





31.1 fb ggF: destructive interference between the two diagrams

1.7 fb VBF: rare process, sensitivity to κ_{2V}

Higgs boson pair-production HH
Many decay modes

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- H$\rightarrow bb, WW, \tau\tau, ZZ, \gamma\gamma$

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Higgs boson pair-production HH with bb signature

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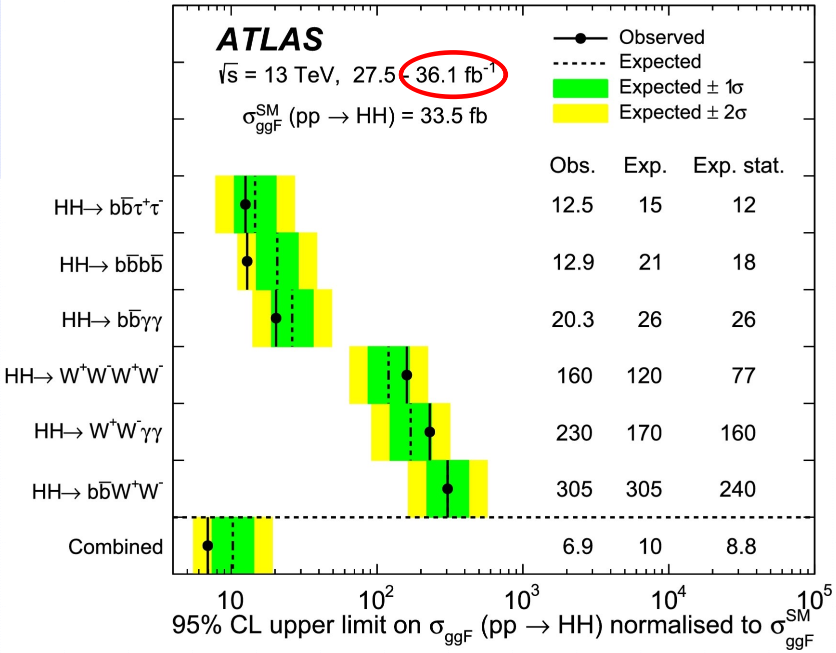
ATLAS:

- HH → bbbb, bbττ, bbγγ, bbWW, …
  < 6.9 (10) x SM at 95% CL

PLB 800 (2020) 135103

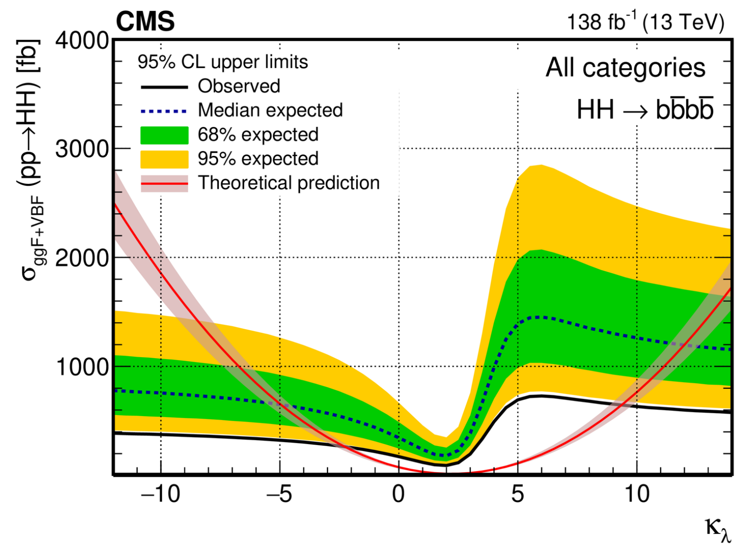


Sensitivity statistically limited.

- HH → bbττ, 139 fb^{-1}
  < 4.7 (3.9) x SM at 95% CL

CMS:

- HH → bbbb, 138 fb^{-1} HIG-20-005
  < 3.6 (7.3) x SM at 95% CL
- HH → bbVV, 139 fb^{-1} PLB 801 (2020) 135145
  < 40 (29) x SM at 95% CL
- HH → bbZZ →bb4l, 137 fb^{-1} HIG-20-004
  < 30 (37) x SM at 95% CL



PRL(2022)129(8):081802

−2.3 (−5.0) < κ_λ < 9.4 (12.0) at 95% CL

2lSS1tau: Fake rate determination from tt production, Josefine Robl

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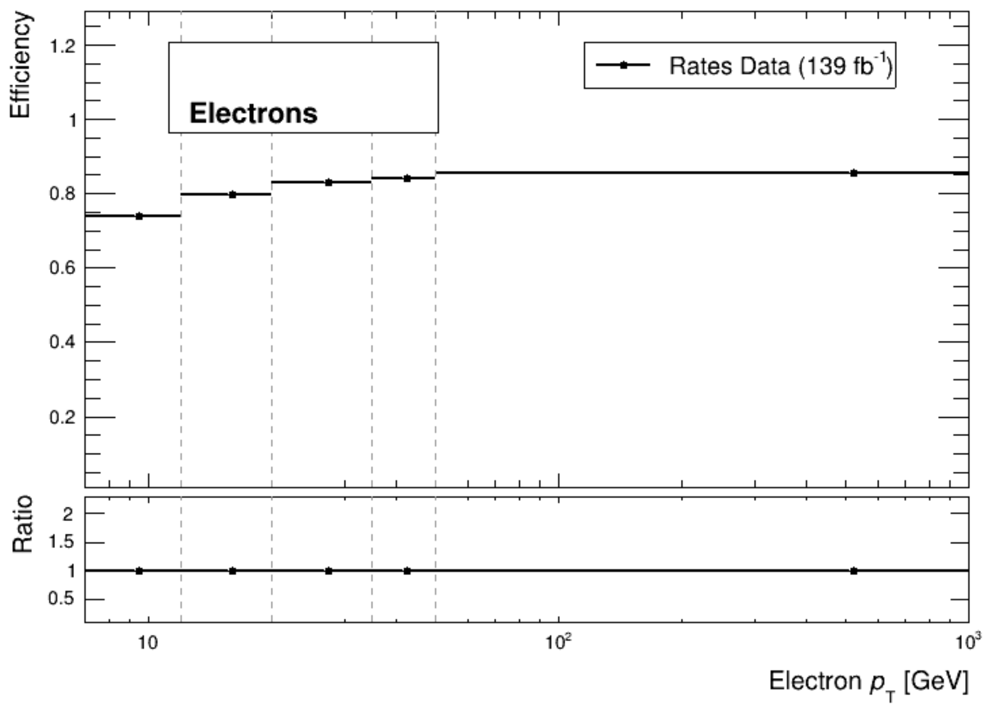
- Matrix Method to determine the Fake Rate
- pp⟶tt is dominant reaction, sub-leading lepton
- Dominant reason for fake leptons, semi-leptonic B decays
- Determine rate from recoded data (control region) instead of simulation
- Real and fake efficiency determination for Matrix Method as function of pt



2lSS1tau: closure test, Josefine Robl

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CERN-STUDENTS-Note-2021-233

- Closure test: apply Matrix Method on simulated data, where the true origin of the particles are known
- Compare Matrix Method result with true origin
- Difference of Matrix Method prediction and true origin of fake rate indicate the systematic uncertainty of the method

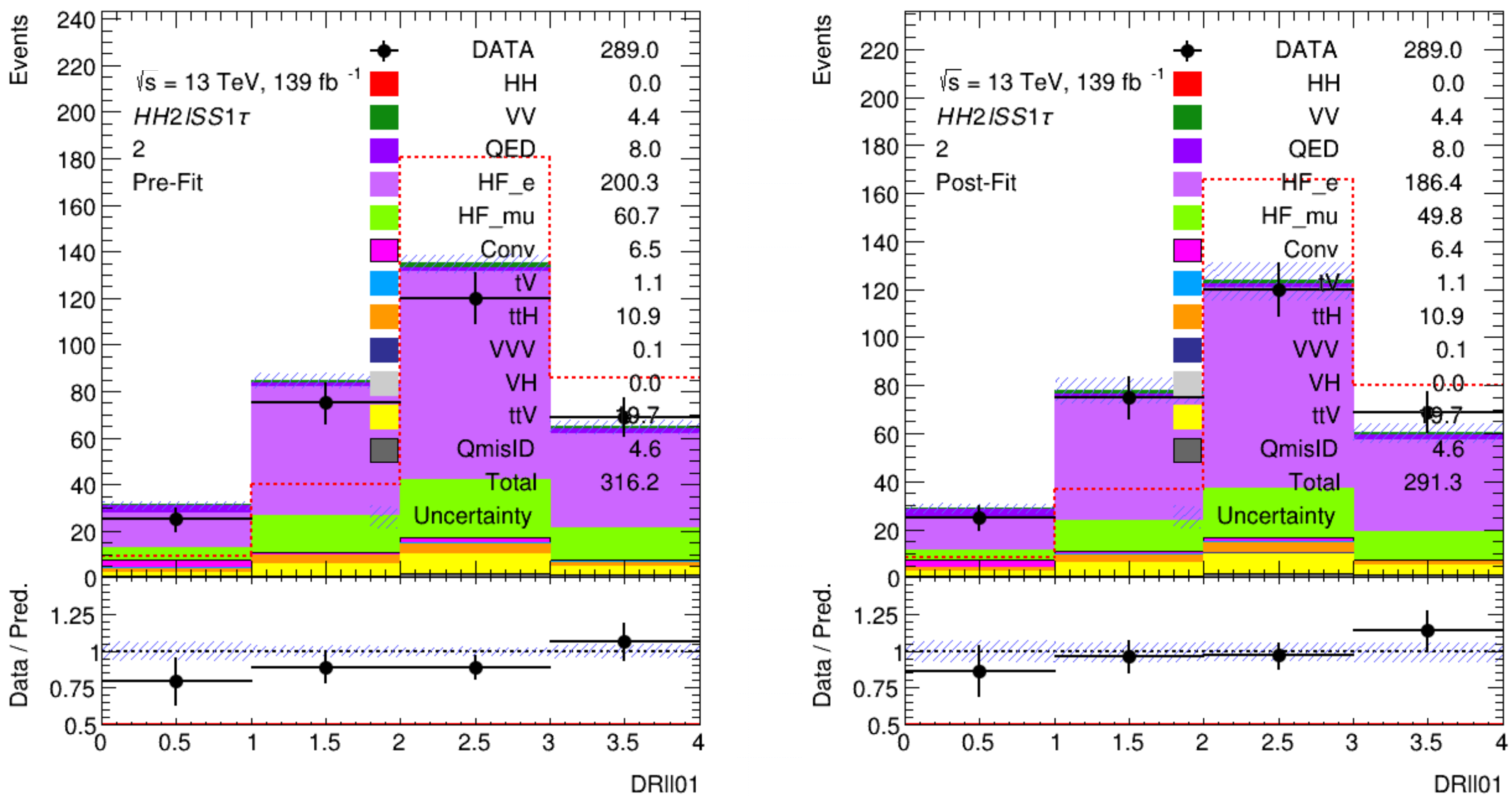
Combined flavours	SR [$t\bar{t}$ events]	CR [$t\bar{t}$ events]
MC $t\bar{t}$	48.7 ± 2.6	130.4 ± 4.2
MM $t\bar{t}$	51.2 ± 3.4	126.9 ± 5.6
Ratio	0.95 ± 0.08	1.03 ± 0.06

- Maximum of deviation from unity and statistical uncertainty is taken as systematic uncertainty.
- Result:
  For the signal region: 8%
  For the control region: 6%
- Method used for background determination in HH analysis.

2lSS1tau: Fake rate determination tt production, Thibault Fleischmann

CERN-STUDENTS-Note-2022-226

- Template Fit (TF) adjusts normalization of simulated background reaction to match recorded data.
- Select electron enhance and muon enhance samples.



- ee enhanced sample

2lSS1tau: Fake rate determination tt production, Thibault Fleischmann

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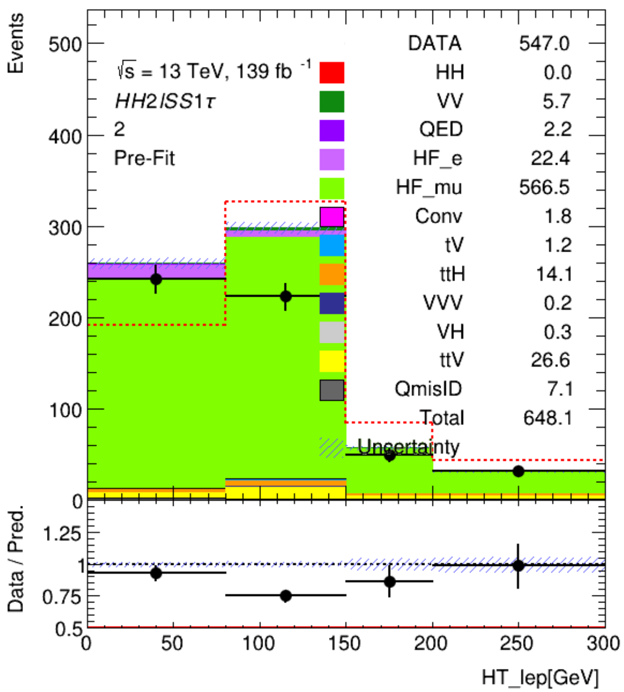
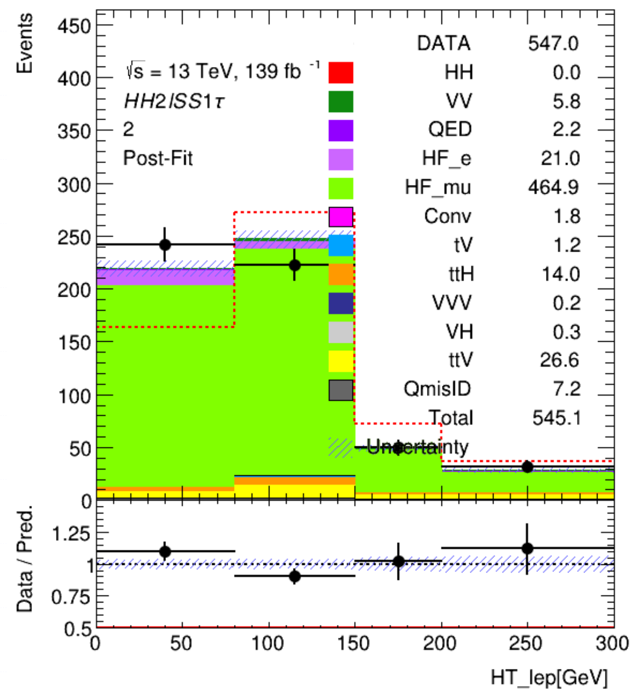
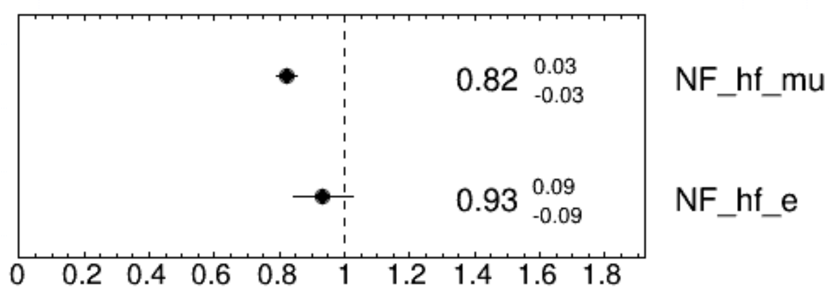


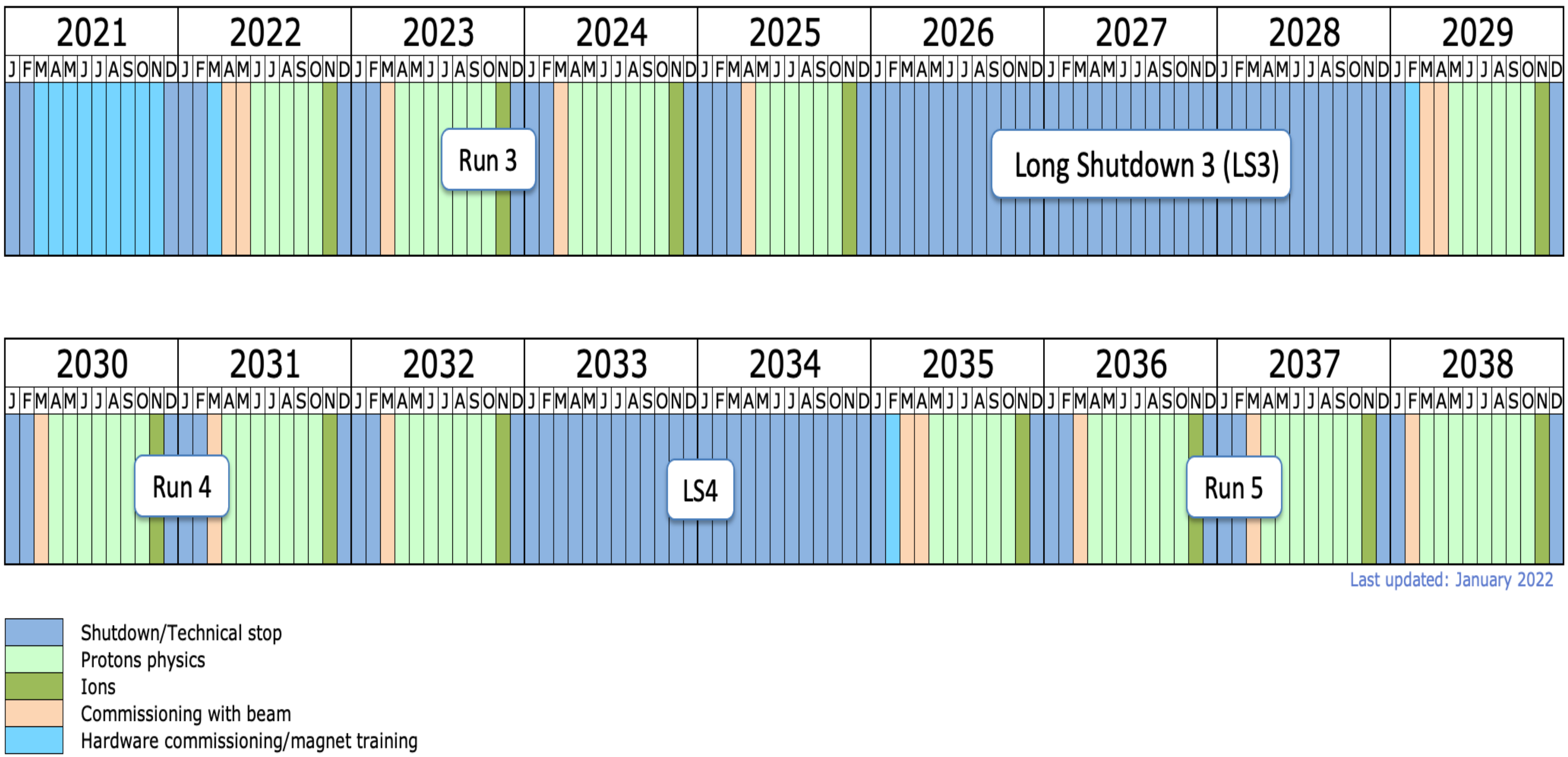


- ❑ $\mu\mu$ enhanced sample
- ❑ Normalization factors



LHC long-term planning

https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm



Exchange program with UTokyo- CTU in Prague

- CTU in Prague has several international agreements, not yet with UTokyo
- Courses at CTU in Prague in English (www.cvut.cz)
  - Faculty of Nuclear Sciences and Physical Engineering
  - Faculty of Information Technology
  - Faculty of Electrical Engineering
- Project on ATLAS physics: Higgs boson, new particles or forward detectors application

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Conclusions – Outlook

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Czech Technical University in Prague

- Very successful **LHC operation, most analyses with complete Run-2 data**
- Measurements of **ttH production consistent with SM prediction within 20%**
- **tbH$^+$ production search in 2lSS1tau final state**
- **Leptoquarks search in same 2lSS1tau final state**
- Sensitivity for **tH to determine sign of coupling**
- Higgs-top and self-coupling **particular theoretical interest**
- Establishing Higgs boson **self-coupling as long-term goal**

- For all analyses **high-level machine learning improves sensitivity**

Outlook

- Completing all analyses with **full LHC Run-2 data set**
- **Combination of ATLAS and CMS results**: increase of sensitivities
- **LHC Run-3** anticipate 300 fb^{-1} (2022 to 2025)
- HL-LHC anticipate 3000 fb^{-1} (2027 -): **new eras of measurement precision**
- **Exchange Program UTokyo – CTU in Prague possibilities**

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