

Preliminary

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

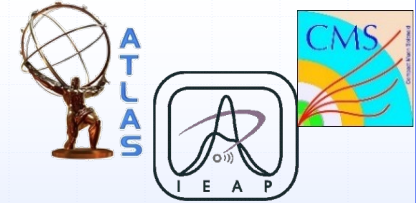


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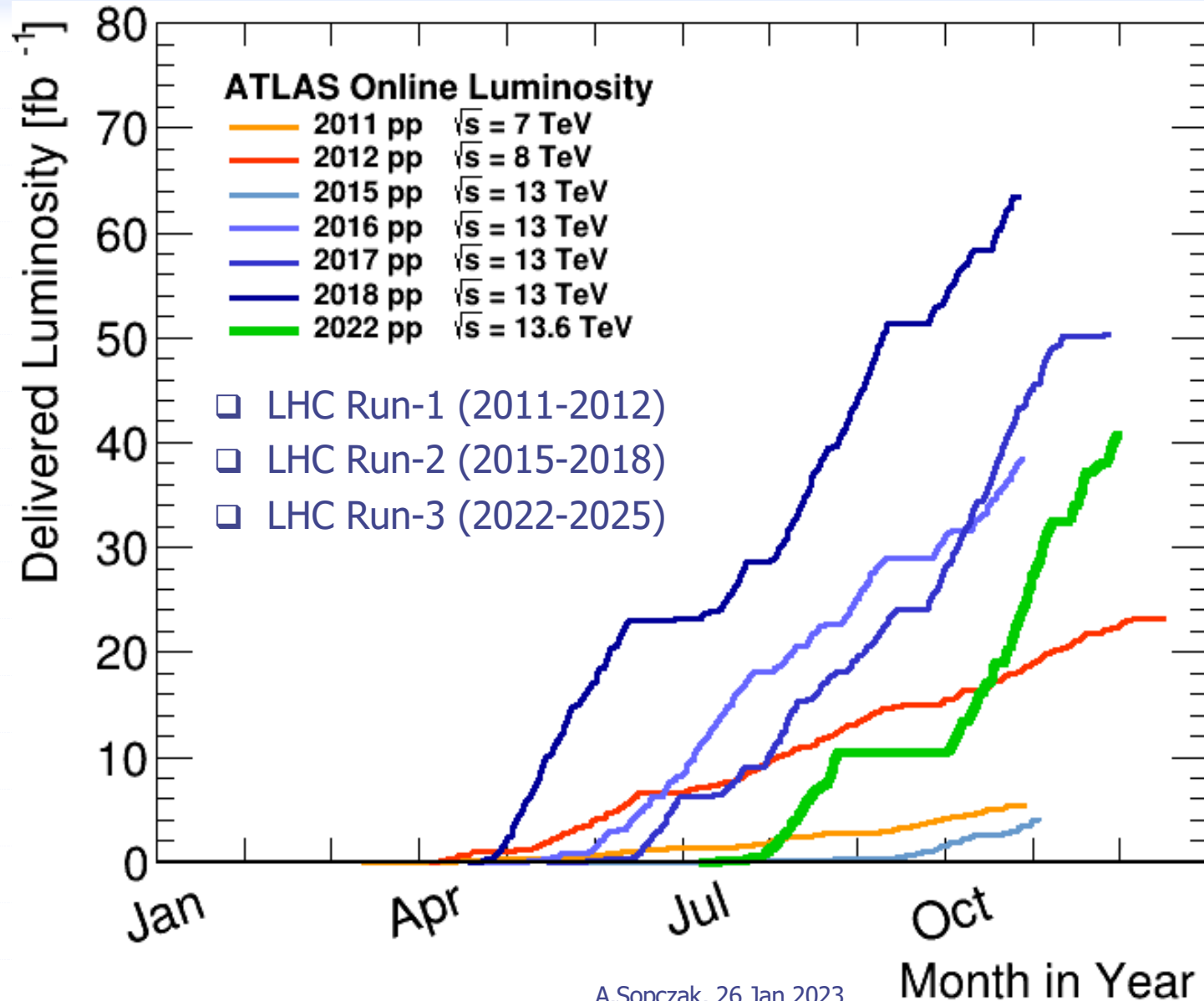
26 January 2023

Outline

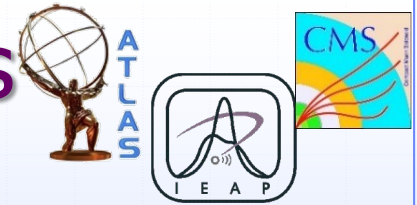


- ❑ Introduction
- ❑ Higgs boson production in association with two top quarks, $ttH(H \rightarrow \tau\tau)$
 - Multi-lepton channel
 - Higgs boson mass reconstruction
- ❑ Searches for charged Higgs boson production, $tbH^+(WH)(H \rightarrow \tau\tau)$
 - Multi-lepton channel
- ❑ Searches for Leptoquark pair-production, $LQ_3^d LQ_3^d \rightarrow t\tau t\tau$ 2ISS1tau
 - Multi-lepton channel
- ❑ Higgs boson production in association with a single top quark, $tH(H \rightarrow \tau\tau)$
 - Higgs boson mass reconstruction in the multi-lepton channel
- ❑ Higgs boson self-coupling
 - Overview
 - Challenges
- ❑ Erasmus exchange with Czech Technical University in Prague
- ❑ Conclusions and Outlook

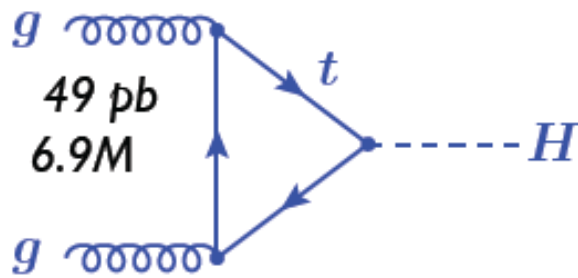
LHC proton-proton collisions



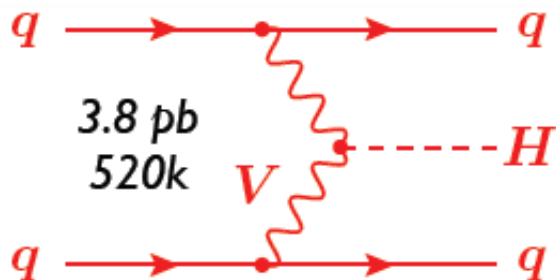
Produced numbers of Higgs bosons in six production modes



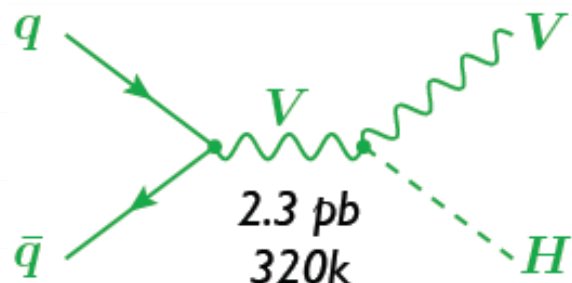
Gluon-gluon fusion (ggF)



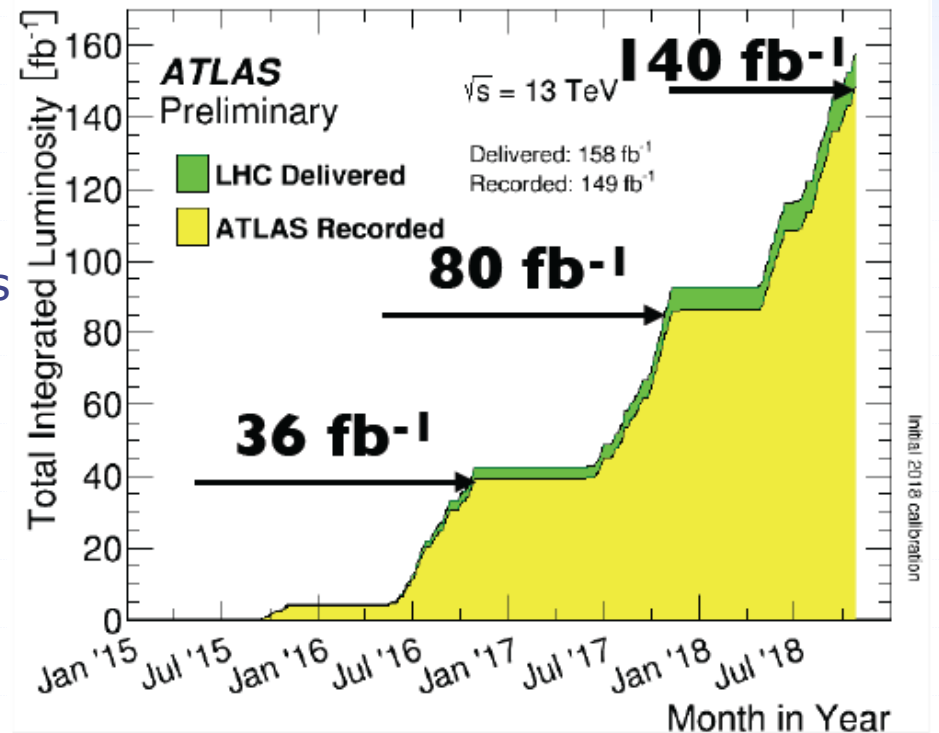
Vector boson fusion (VBF)



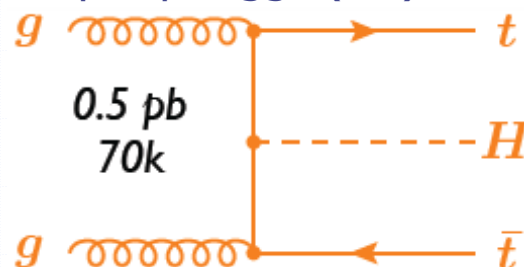
Associated production (VH)



Cross-sections for 13 TeV and number of events for 140 fb⁻¹



Top-top Higgs (ttH)



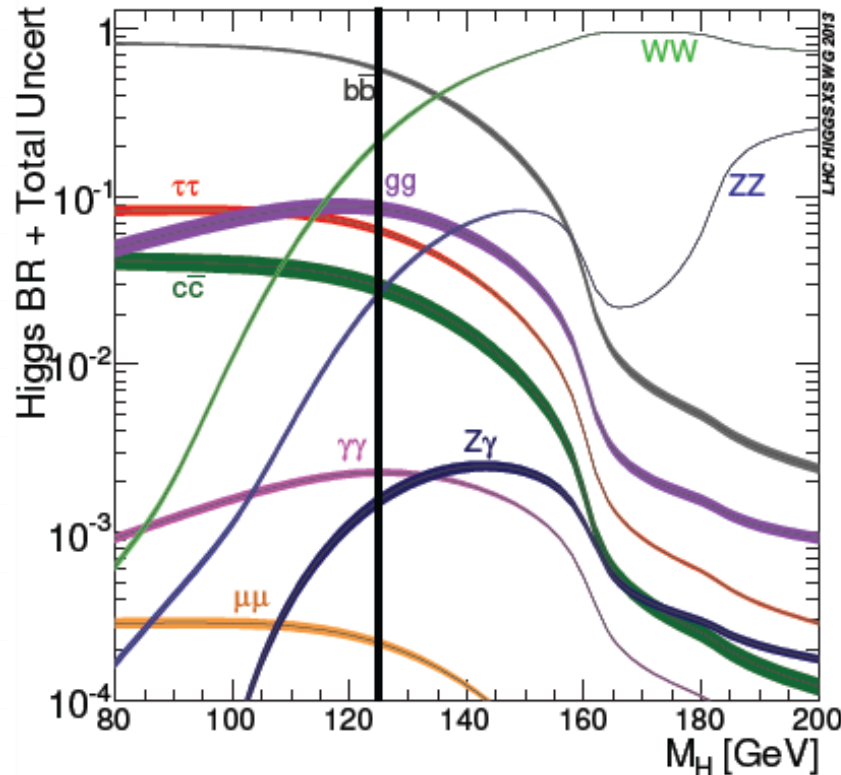
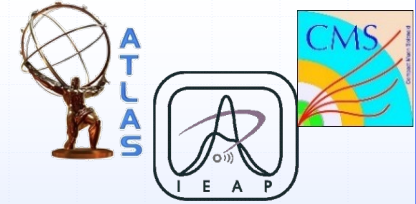
Single-top Higgs (tH)

0.07 pb, 10k

Di-Higgs (HH)

0.03 pb, 4k

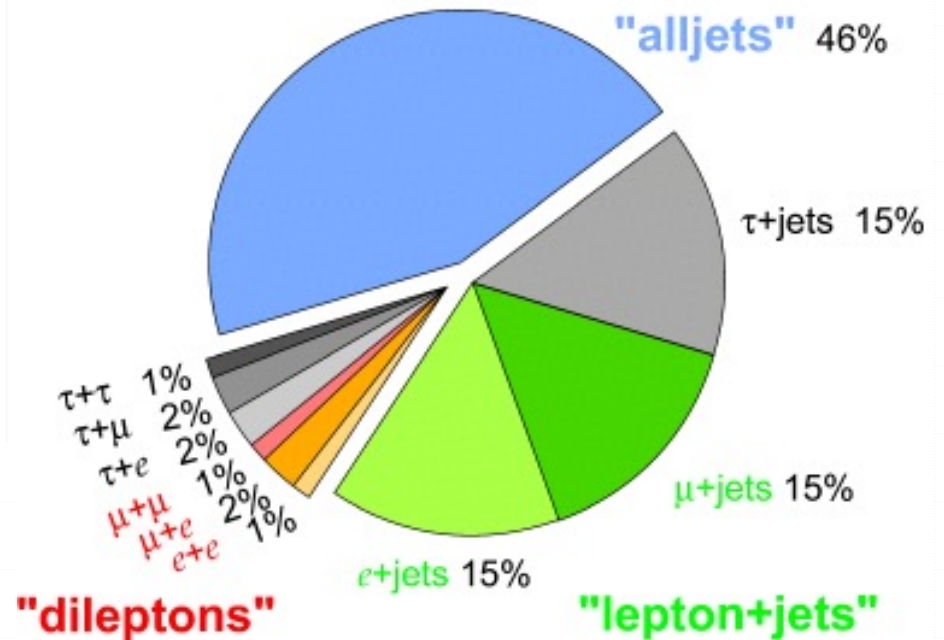
Higgs boson decay branching fraction and expected final states



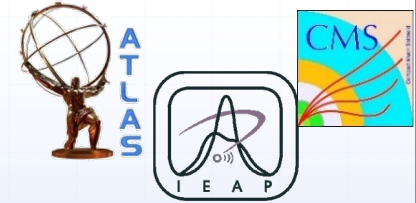
- $H \rightarrow bb$: 58%
- $H \rightarrow WW^*$: 21%
- $H \rightarrow \tau\tau$: 6.3%
- $H \rightarrow ZZ^*$: 2.6%
- $H \rightarrow \gamma\gamma$: 0.23%
- $H \rightarrow Z\gamma$: 0.15%
- $H \rightarrow \mu\mu$: 0.022%

Example:
ttH production and decay

Top Pair Branching Fractions



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



ttH observation

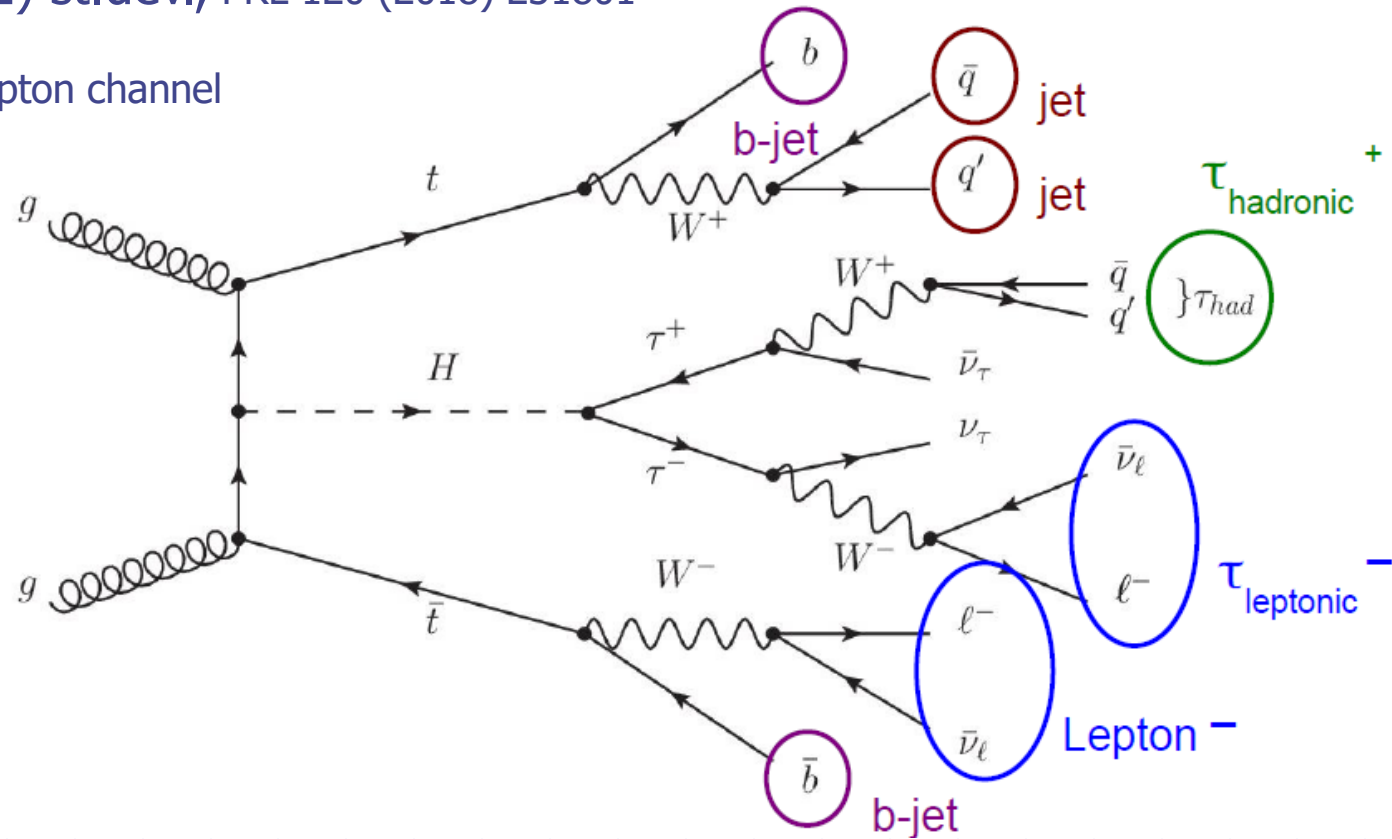
ATLAS: 5.8 (4.9) st.dev., PLB 784 (2018) 173

CMS: 5.2 (4.2) st.dev., PRL 120 (2018) 231801

[CERN-THESIS-2019-419](#)

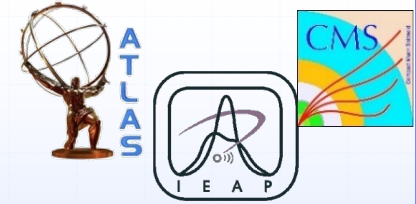
Babar Ali

Example: multilepton channel

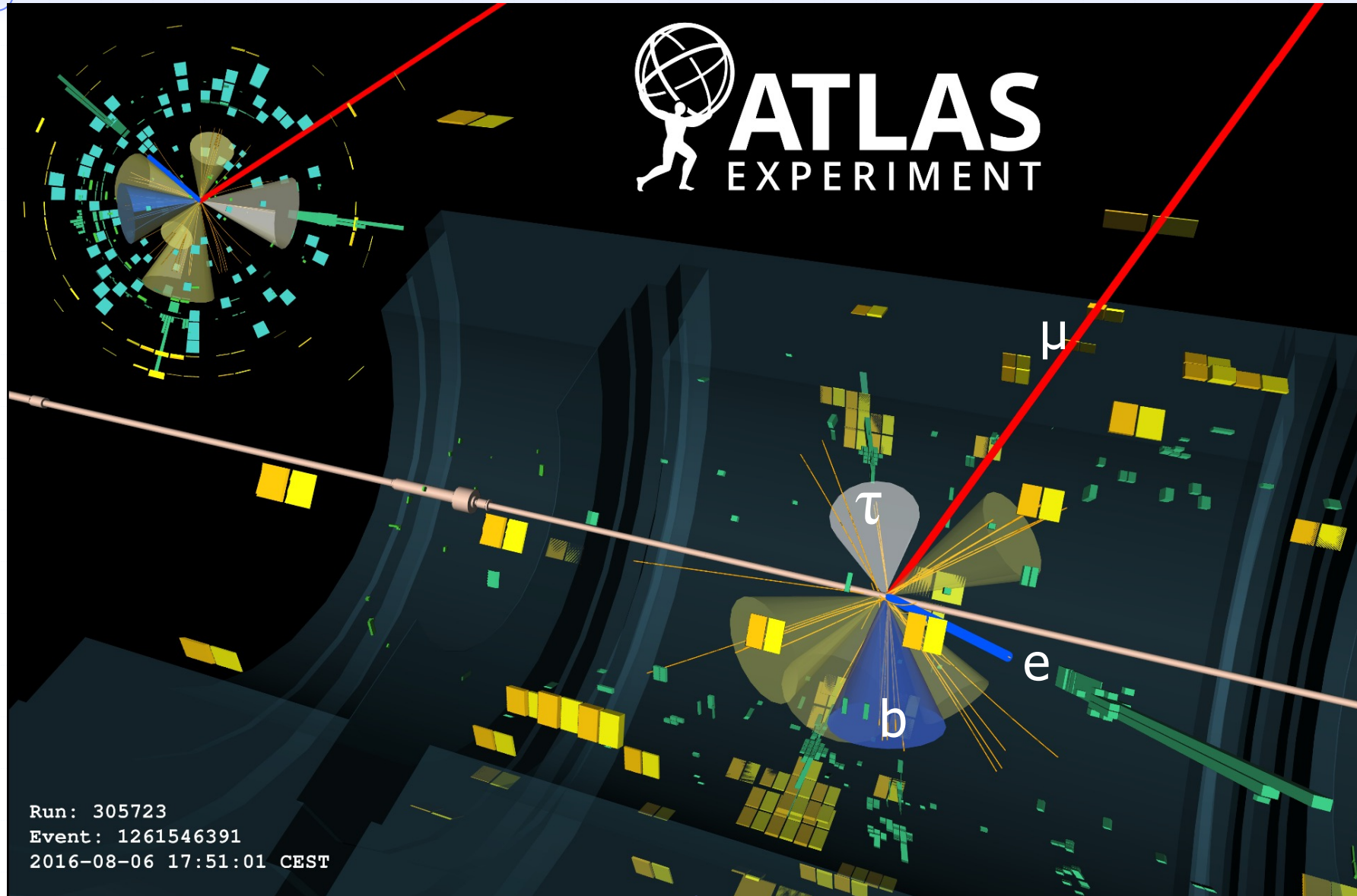


- ❑ Main backgrounds: tt and ttV
- ❑ Fake background estimate determined from data

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

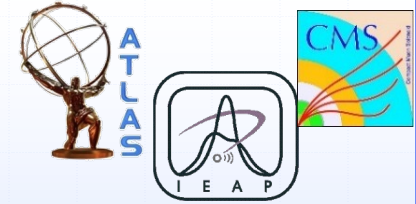


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PRD 97 (2018) 072003

Higgs boson couplings to fermions ttH direct probe, leptons

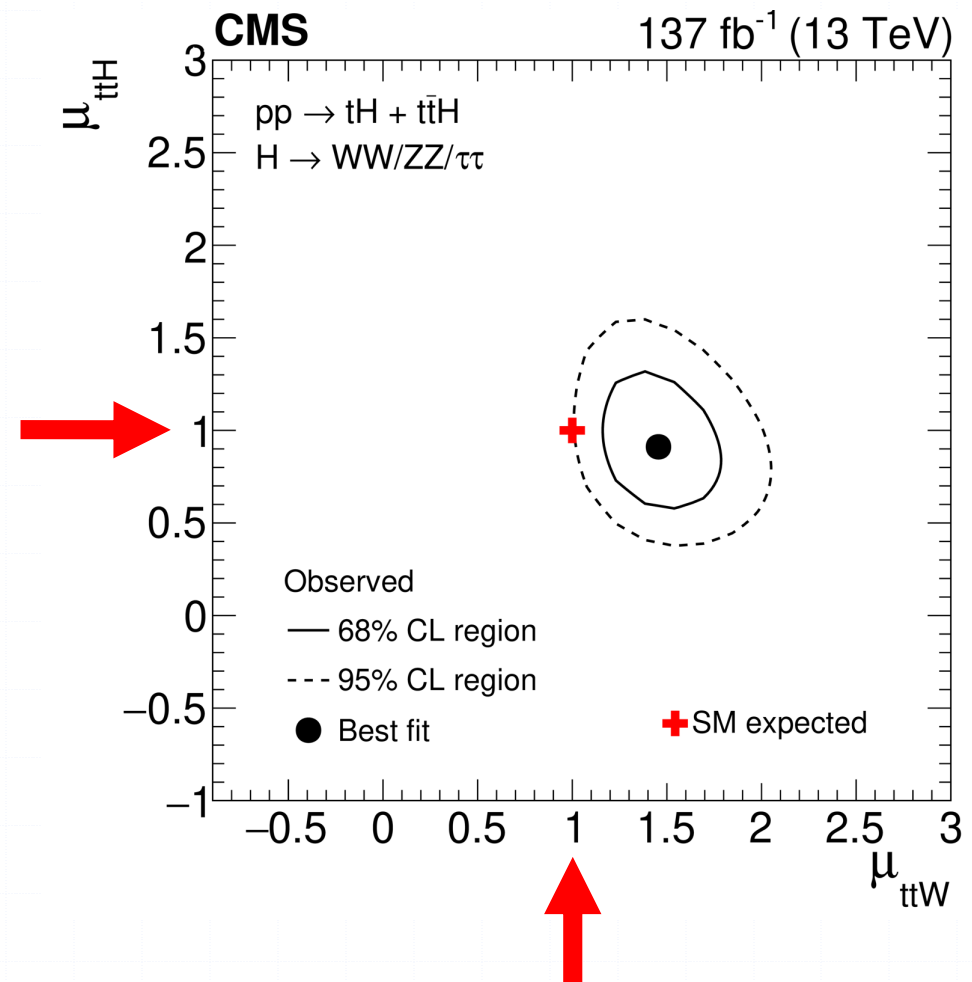
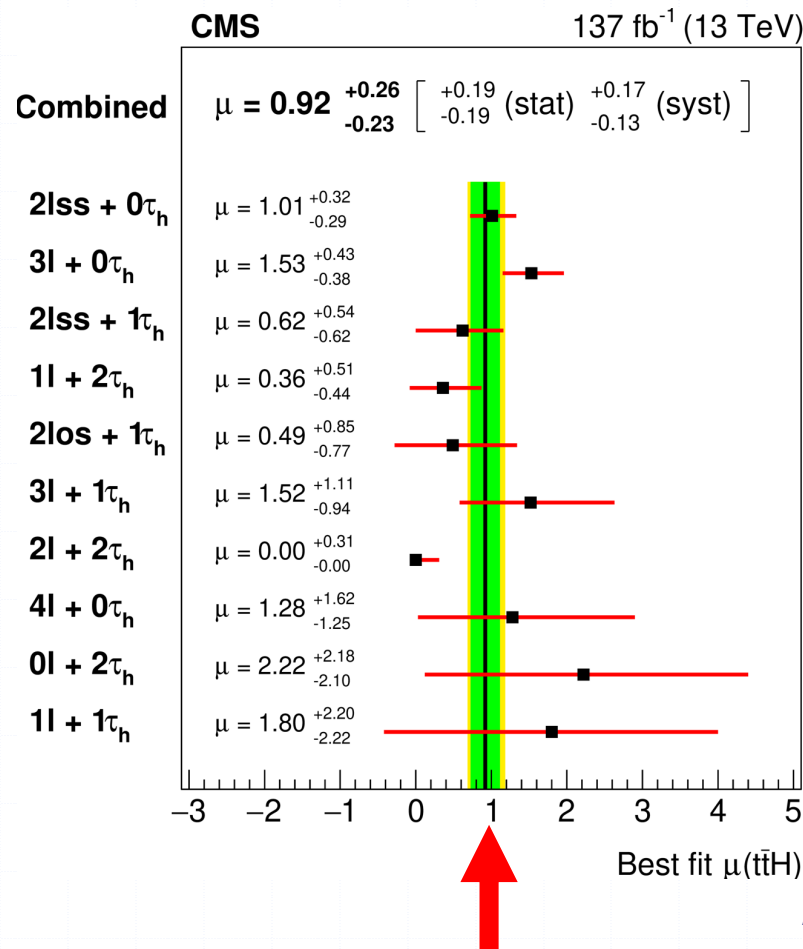


□ ttH: **multilepton channels** with $l = e$ or μ , τ (hadronic decay)

□ ATLAS, PRD 97 (2018) 072003 (36.1 fb⁻¹)
ATLAS-CONF-2019-045 (80 fb⁻¹)

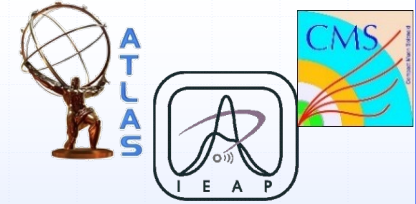
1.8 (3.1) st.dev. (multileptons)

EPJ C81 (2021) 378



2ISS1tau, machine learning

Jan Presperín



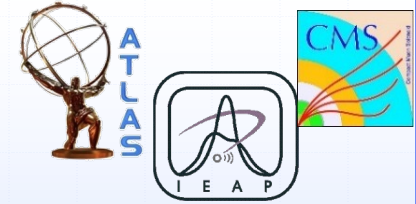
- ❑ Train a **classification algorithm** to discriminate between signal (ttH) and background (ttW, ttZ, tt, VV, others) events
- ❑ **Specific channel:** two light leptons, same-sign, one hadronically decaying tau lepton, at least 4 jets, at least one jet tagged as b-jet
- ❑ **3 sets of features** (low-level, higher-level, all) and **3 different classification algorithms** (TabNet network, XGBoost, MLP)

[CERN-THESIS-2022-066](#)

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

Jan Presperín

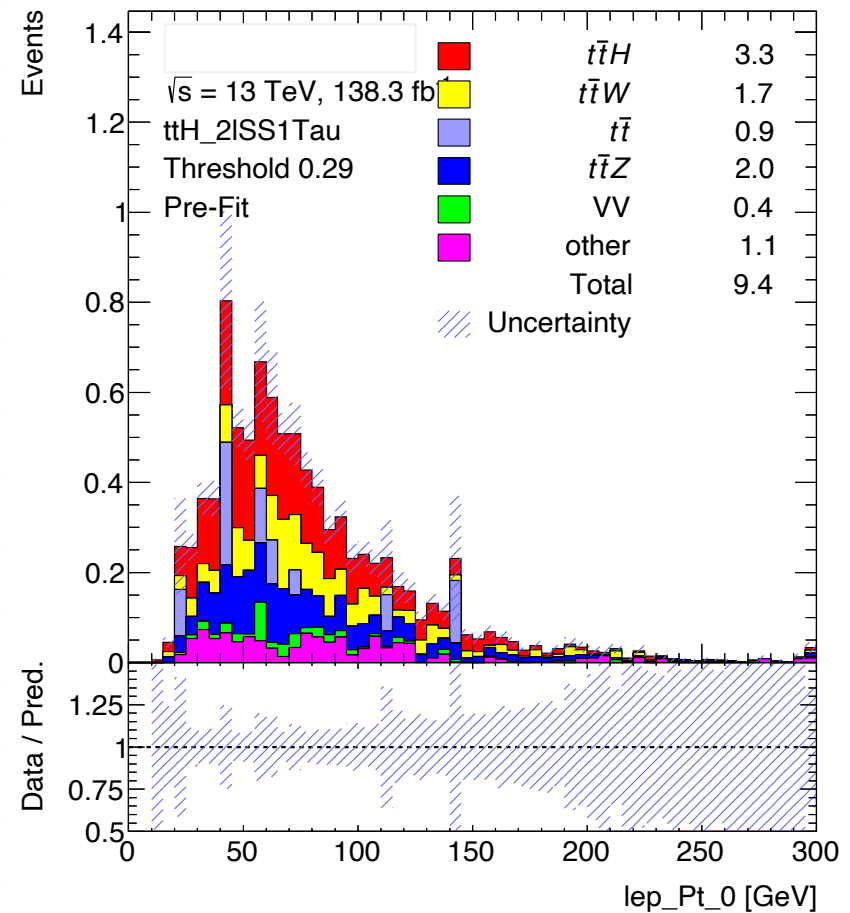
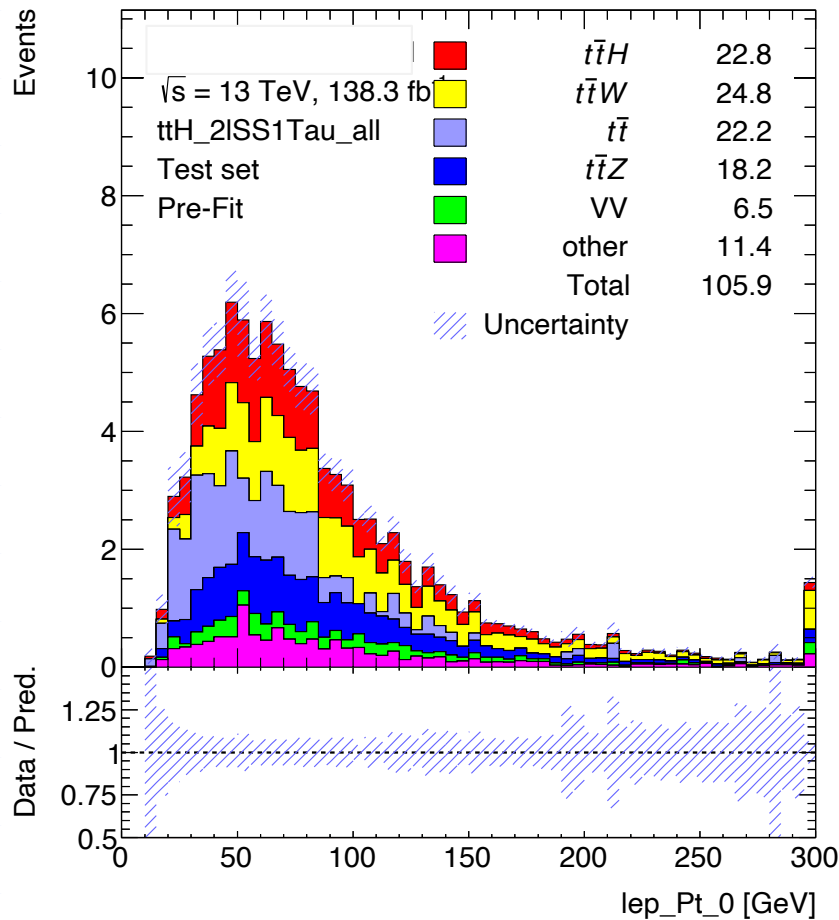


CERN-THESIS-2022-066

all training & testing

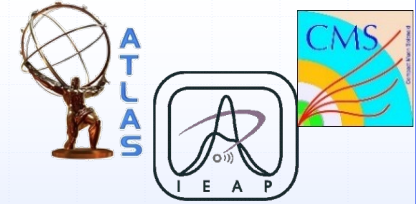


testing data (20%) classified
by the network as signal



Expected sensitivity - MLP

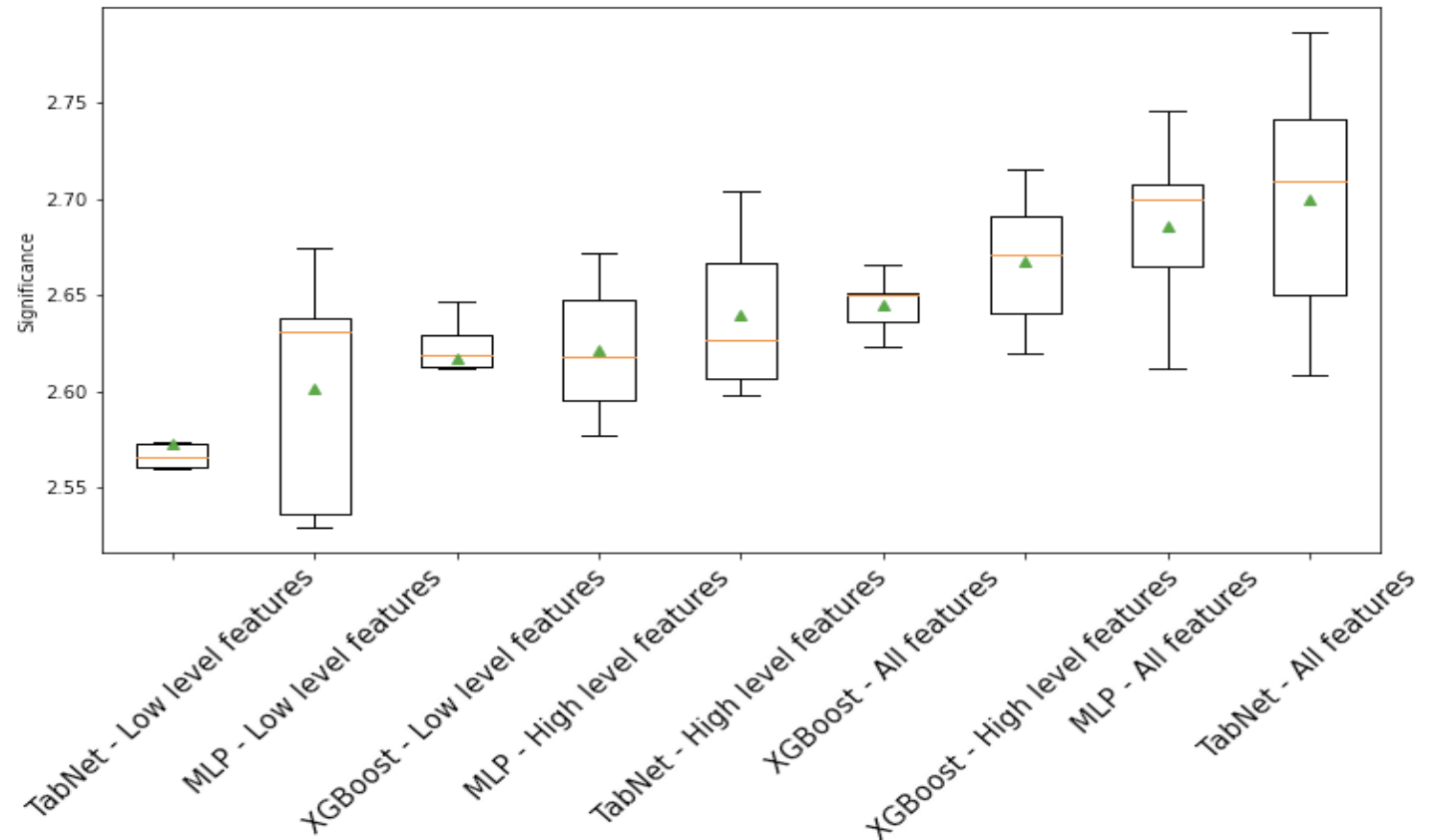
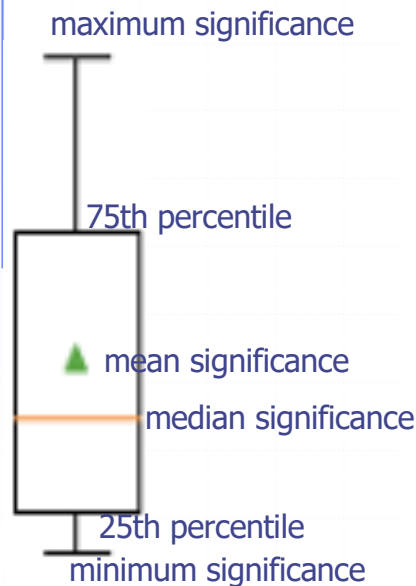
Jan Presperín



CERN-THESIS-2022-066

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

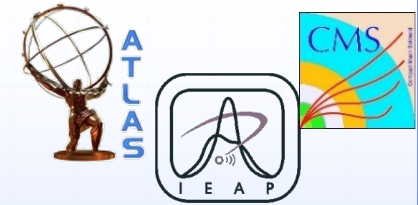
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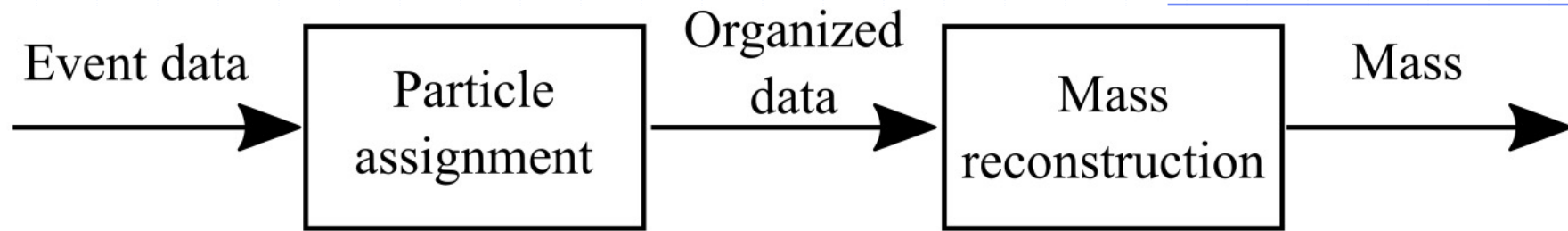
boxplot:
5 runs of
training+testing

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

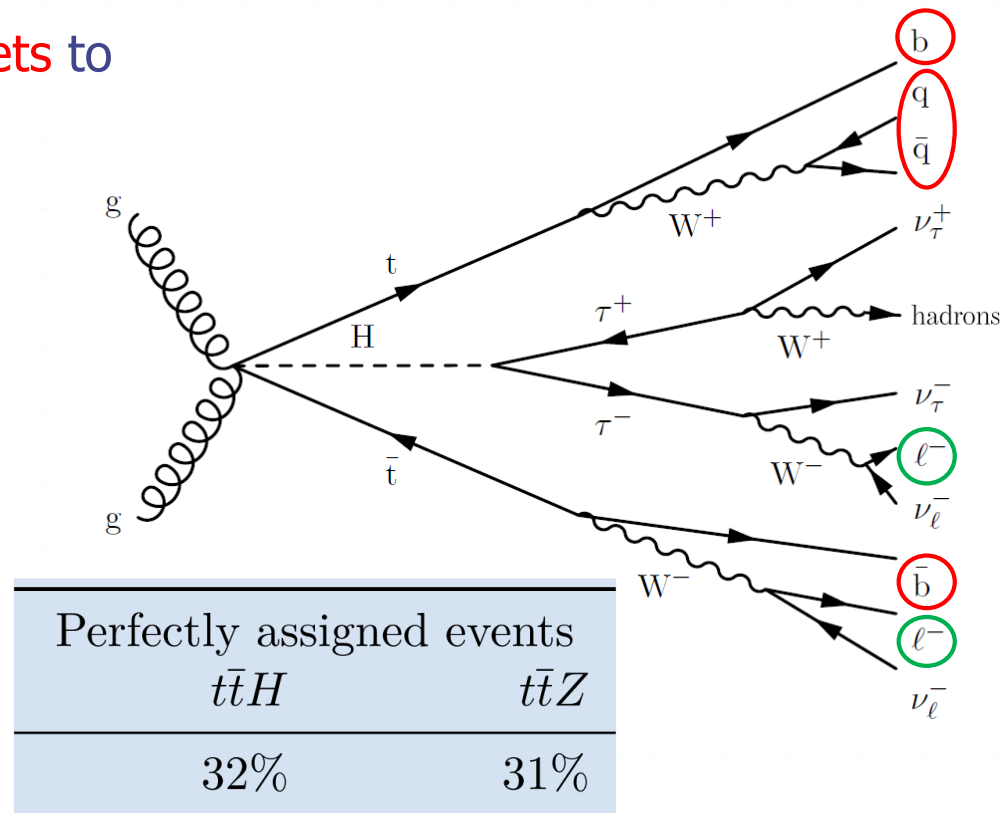
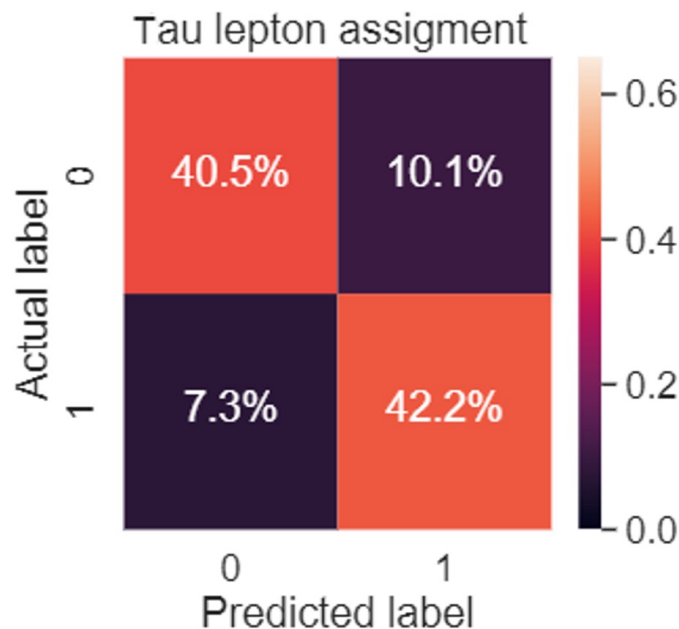
Higgs boson mass reconstruction in $2\text{SS}1\text{tau}$ channel, Adam Herold



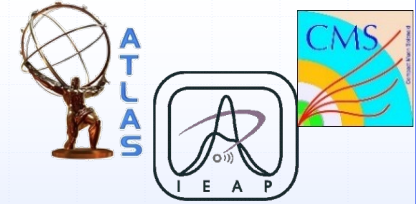
CERN-THESIS-2022-012



- Assign detected leptons and jets to positions in the decay

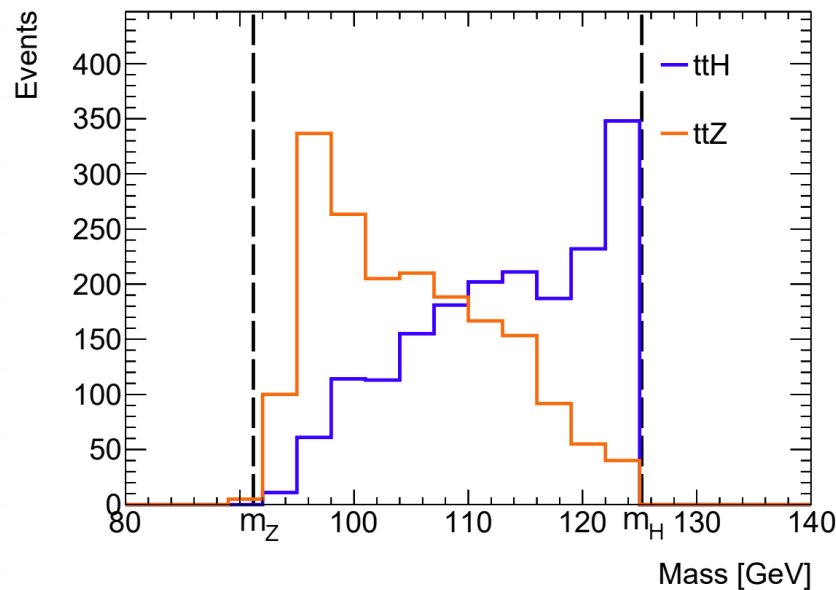


Higgs boson mass reconstruction in 2ISS1tau channel, Adam Herold



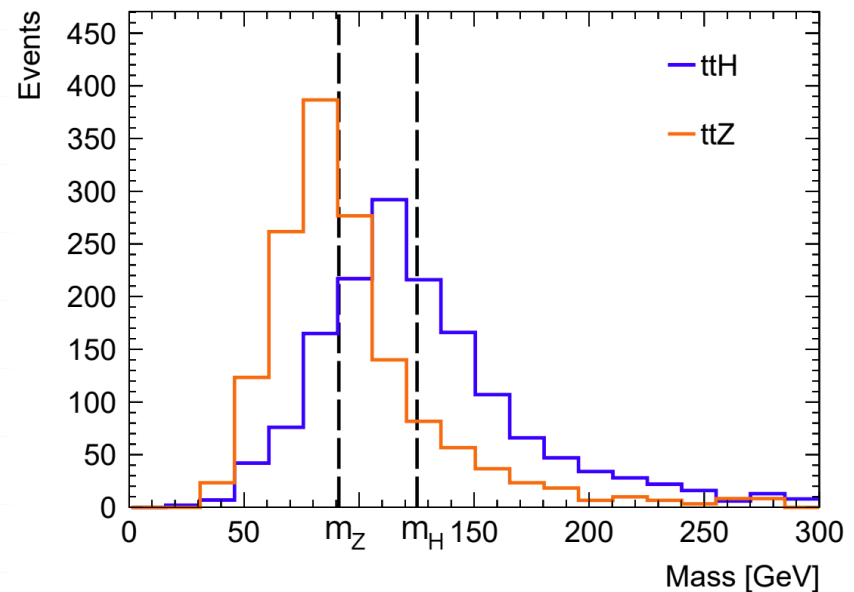
CERN-THESIS-2022-012

- Separation of ttH and ttZ samples by mass reconstruction



Neural network
distribution of predicted mass

Separation 69.33%

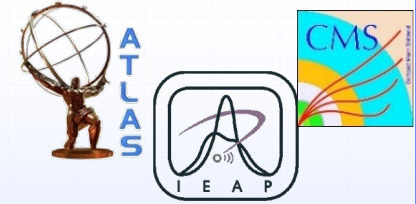


Missing mass calculator
distribution of predicted mass

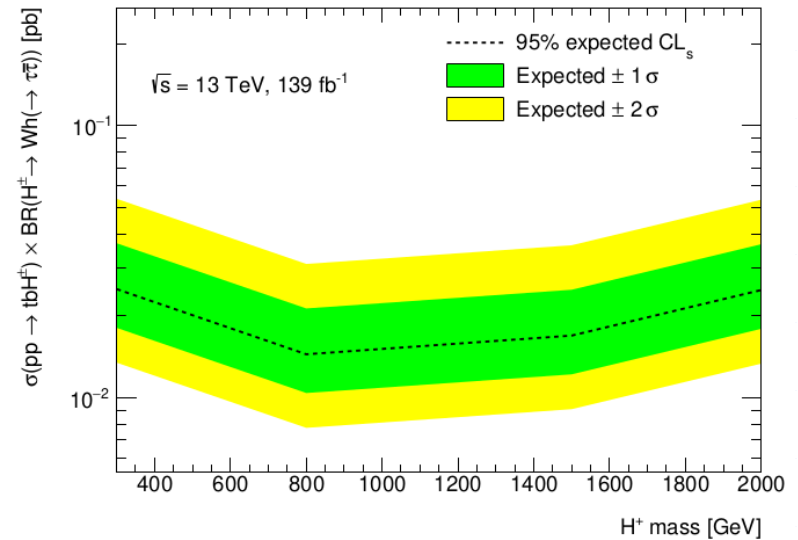
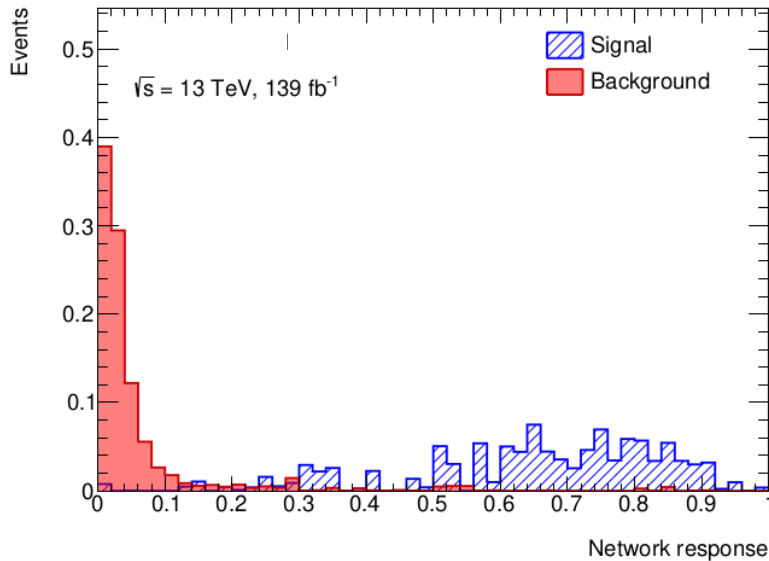
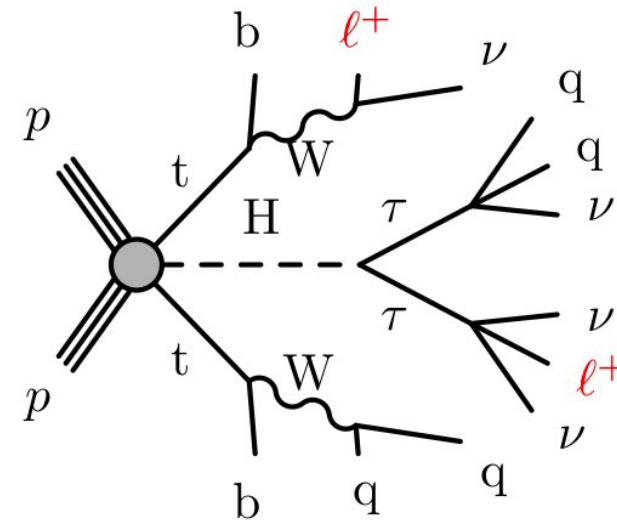
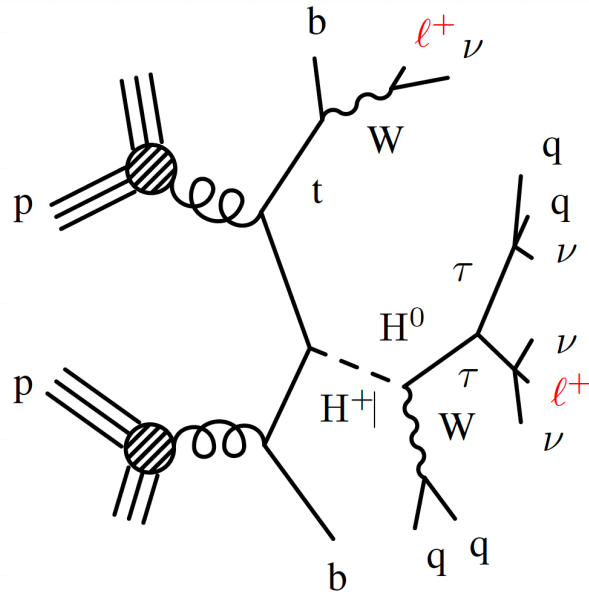
Separation 67.63%

2lSS1tau, tbH⁺ (H⁺ → W⁺H, H → ττ)

Jiří Pospisil



CERN-THESIS-2022-065

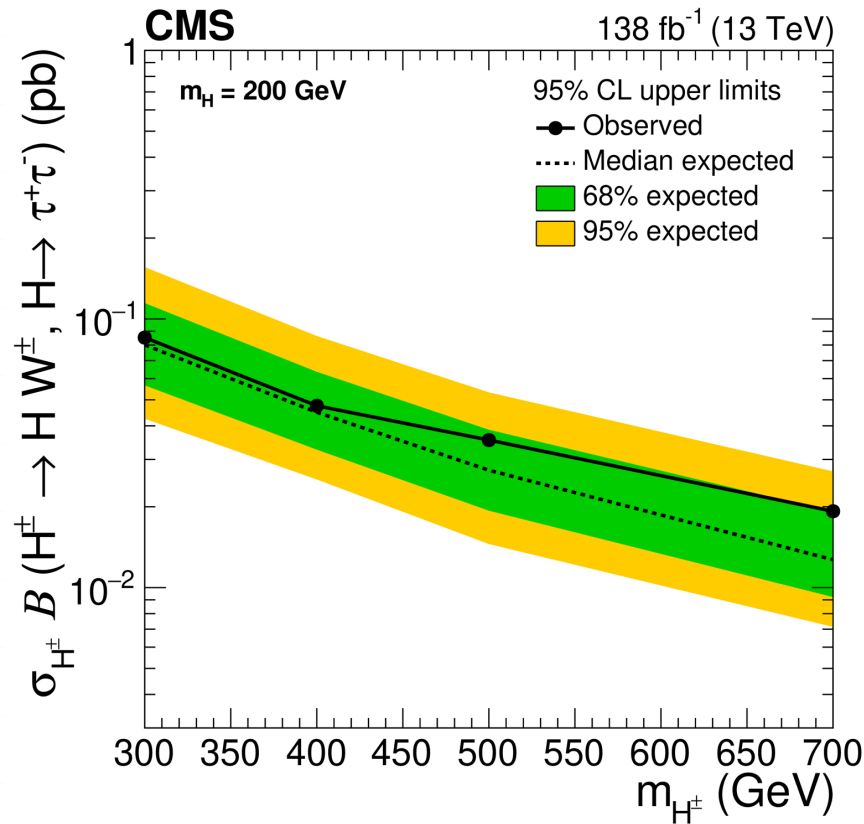


2ISS1tau, tbH[±] (H[±] → W[±]H, H → ττ)

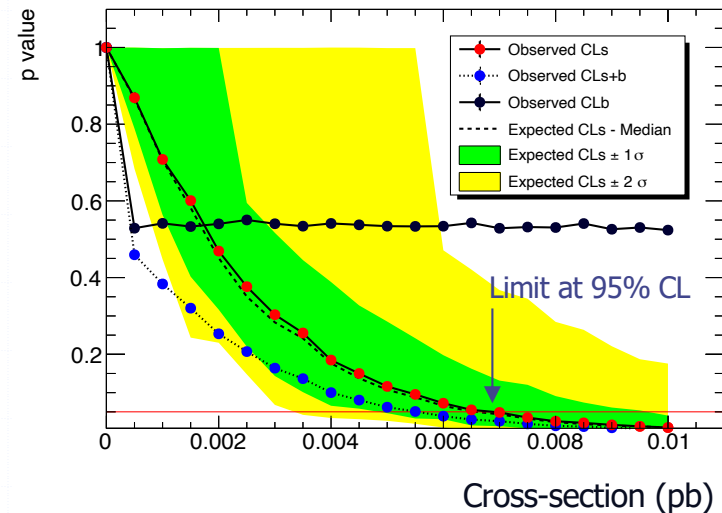
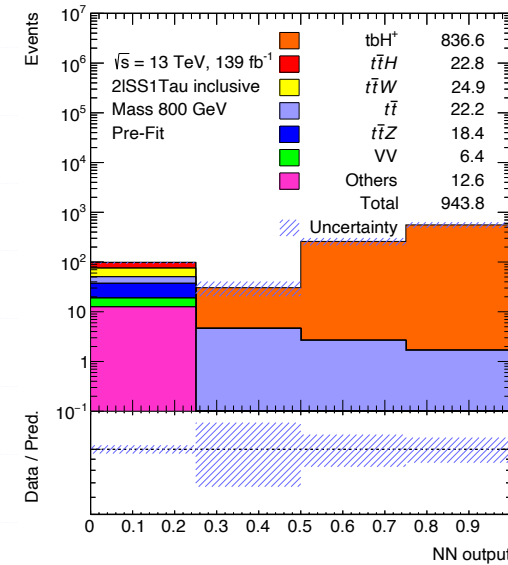
Niklas Düser



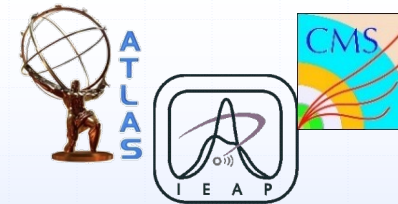
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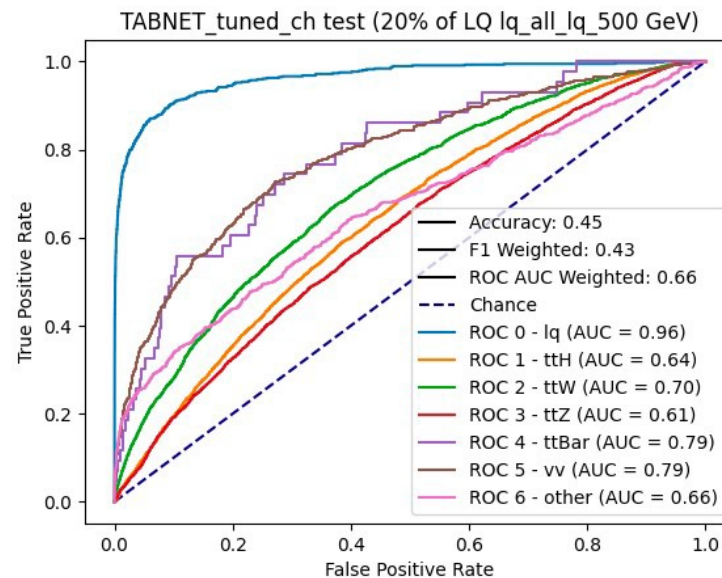
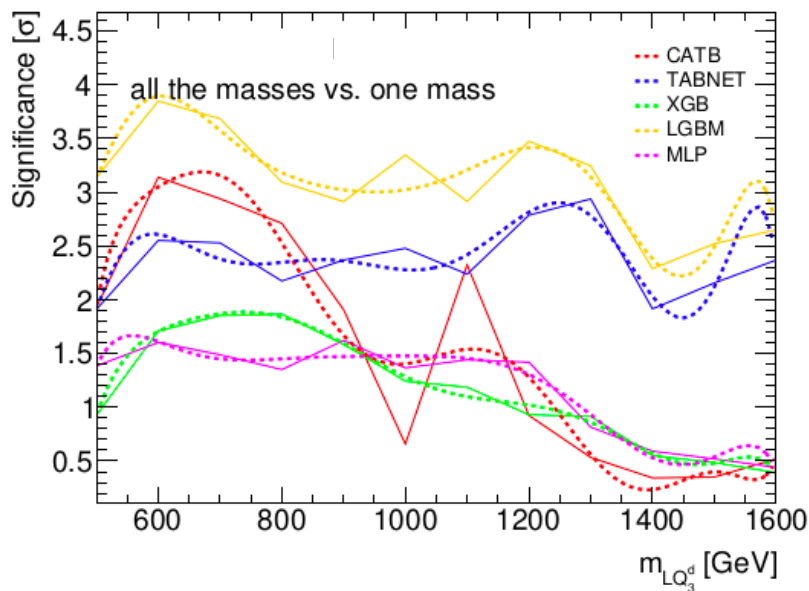
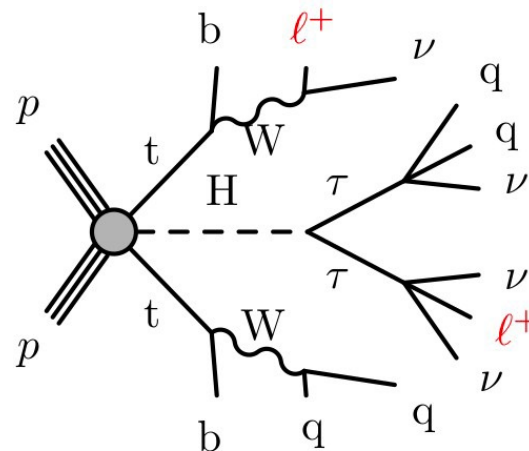
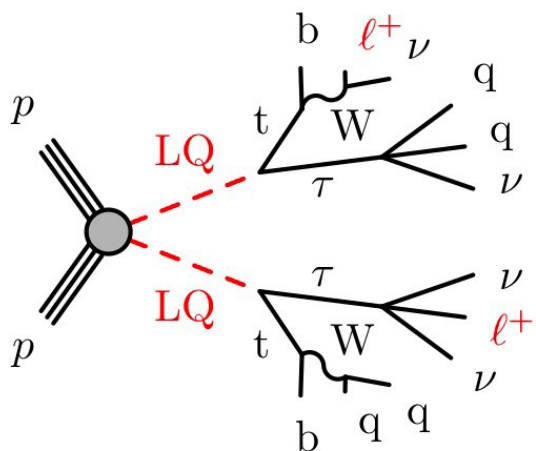
CERN-STUDENTS-Note-2022-222



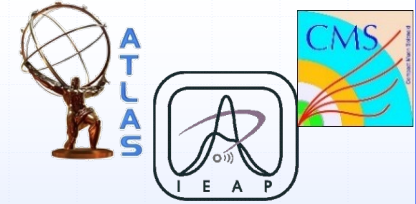
2lSS1tau, Leptoquark signature, Lucas Viceník



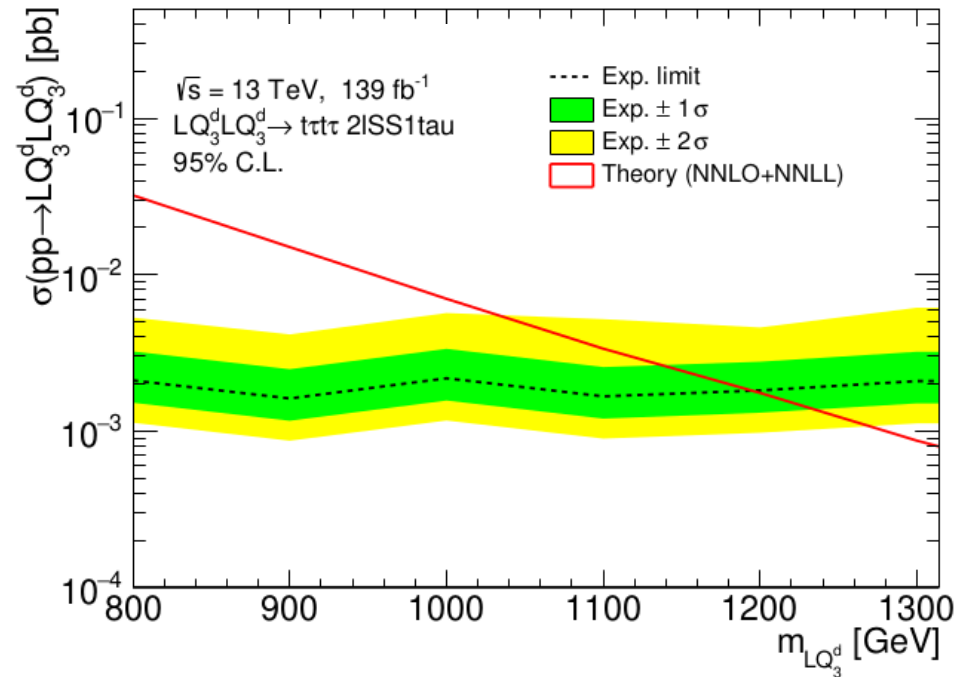
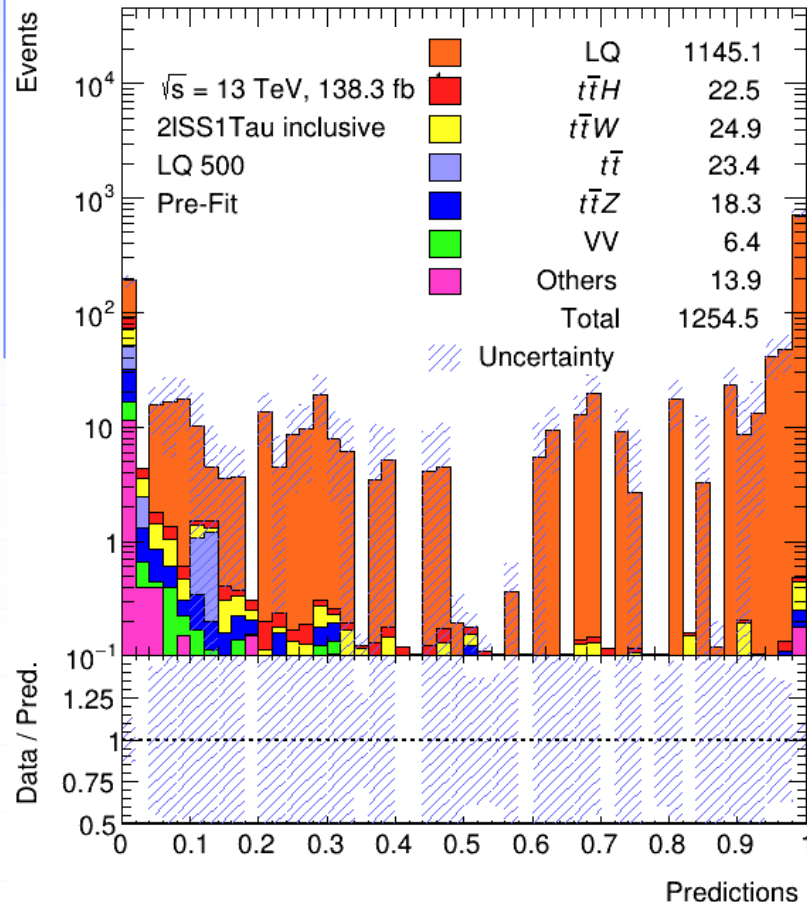
CERN-THESIS-2022-064



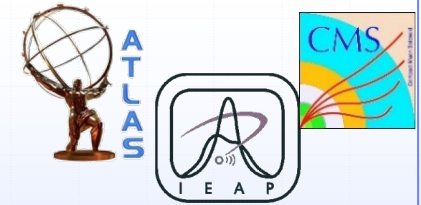
2ISS1tau, Leptoquark signature, Lucas Viceník



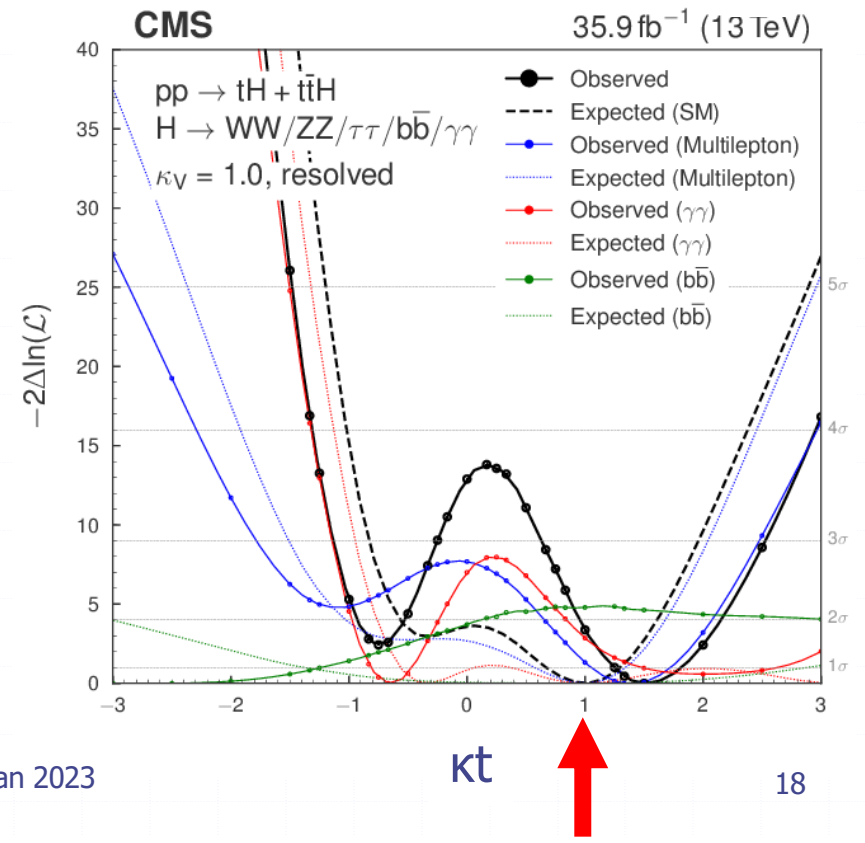
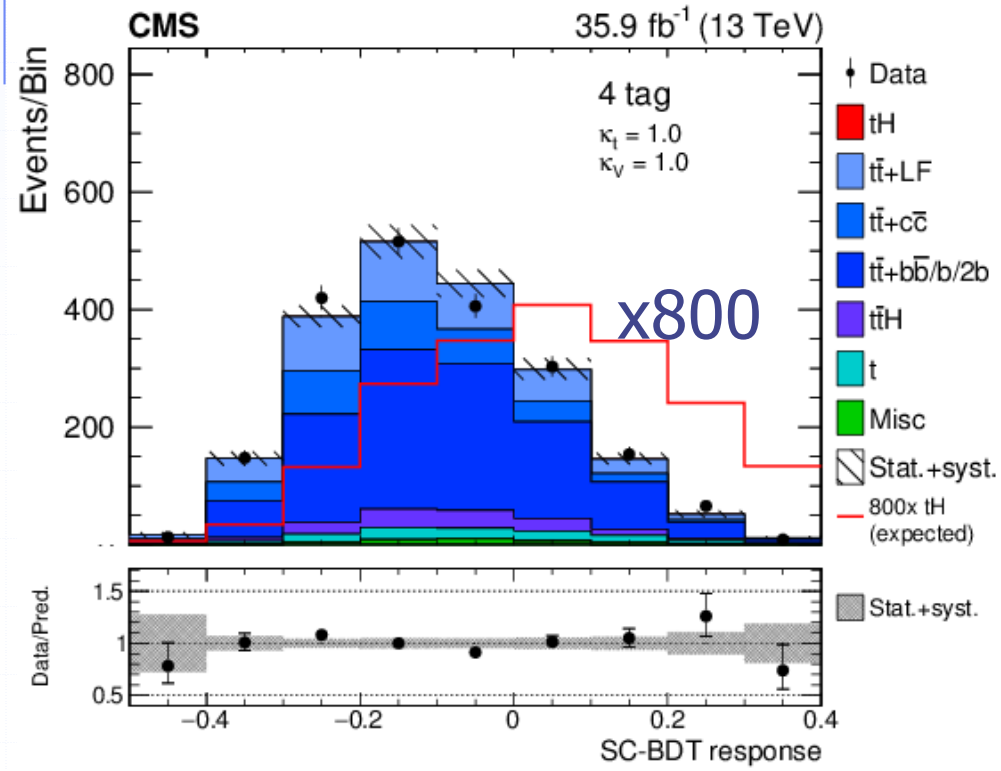
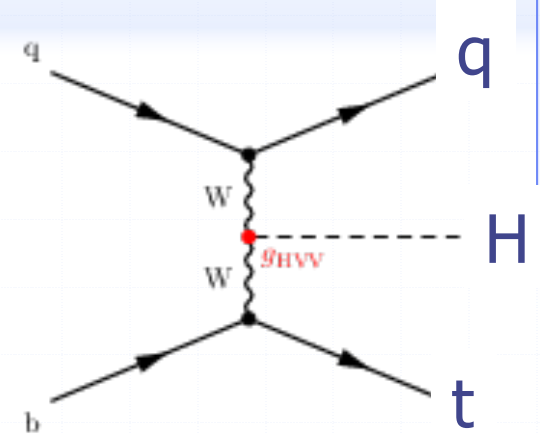
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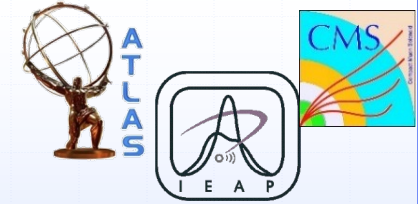
Single top and Higgs boson production tH



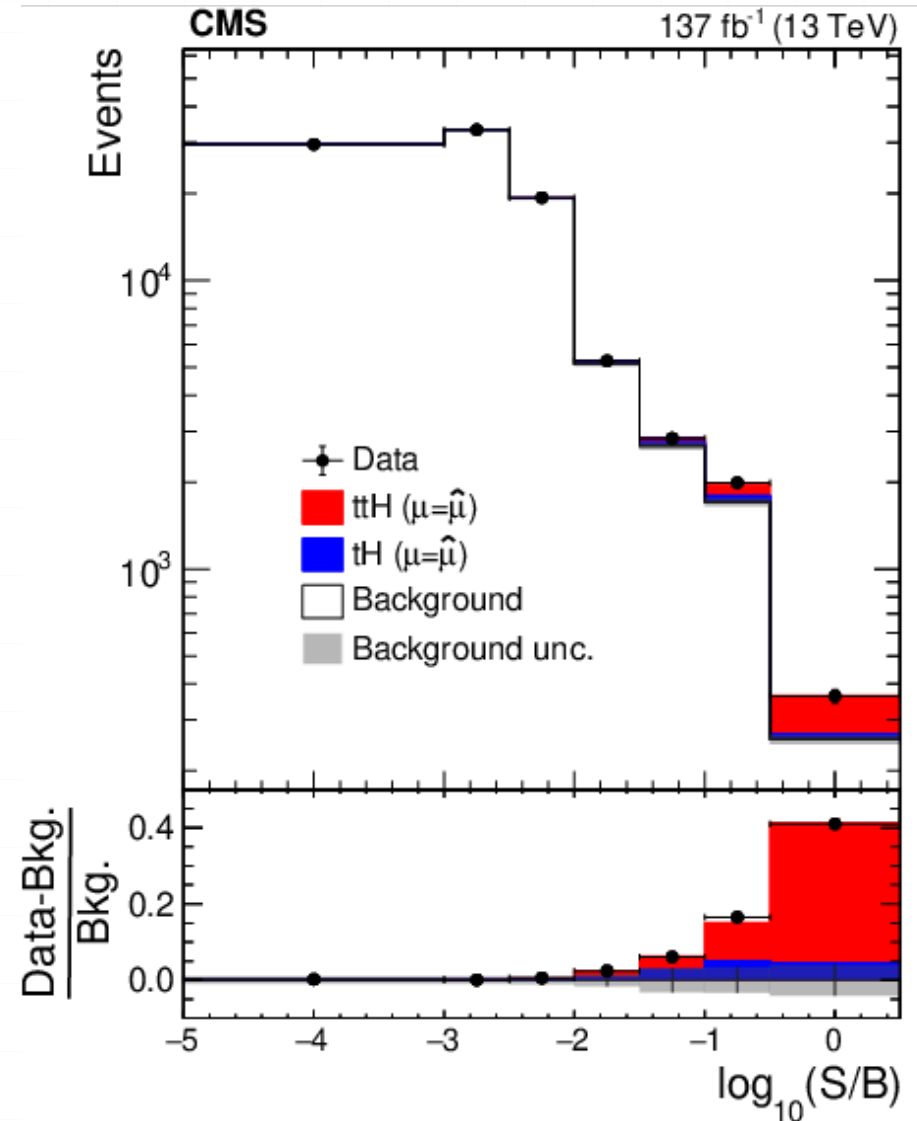
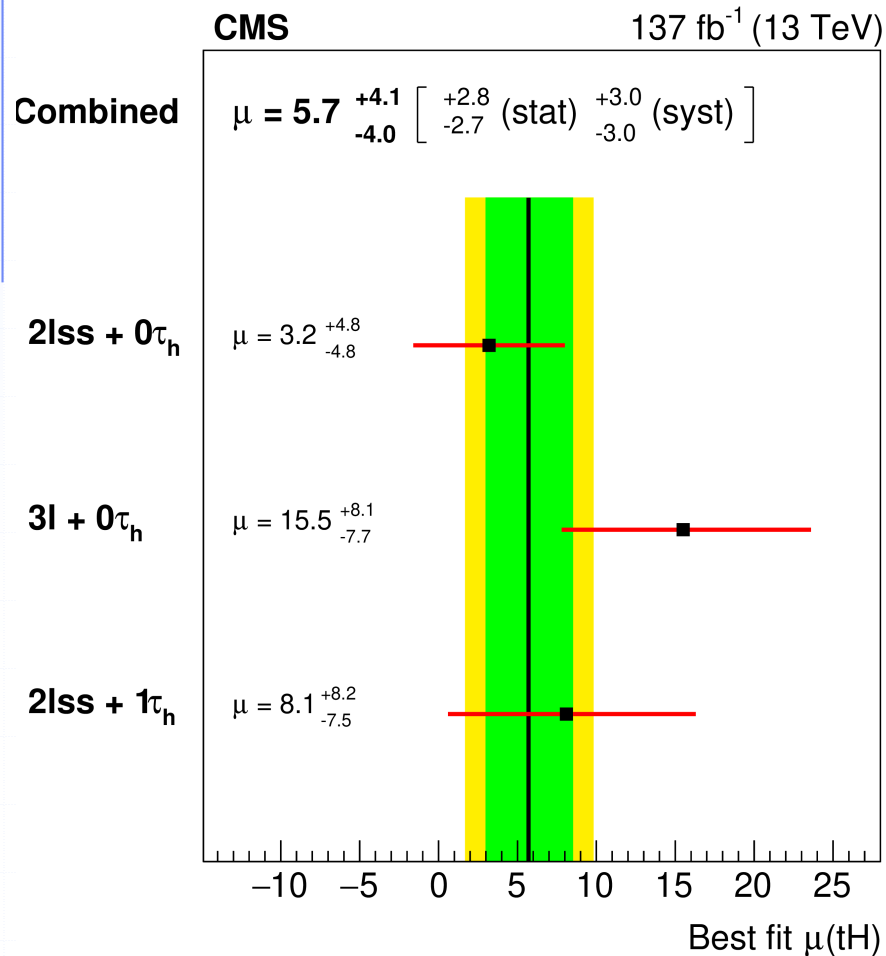
- ❑ tH, H → WW/ZZ/ττ and H → bb PRD 99 (2019) 092005
- ❑ Combination with ttH, H → γγ
- ❑ Sensitive to absolute values top quark Yukawa coupling, the Higgs boson coupling to vector bosons, g_{HVV}, and uniquely their relative sign
- ❑ SM κ_t = 1.0 over κ_t = -1.0 by > 1.5 st.dev.



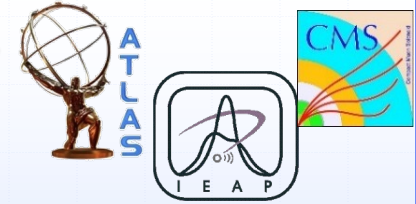
Single top and Higgs boson production tH



- With respective SM expectations:
 $\mu = 5.7 \pm 2.7(\text{stat}) \pm 3.0(\text{syst})$
- **Significance 1.4 (0.3)** EPJ C81 (2021) 378



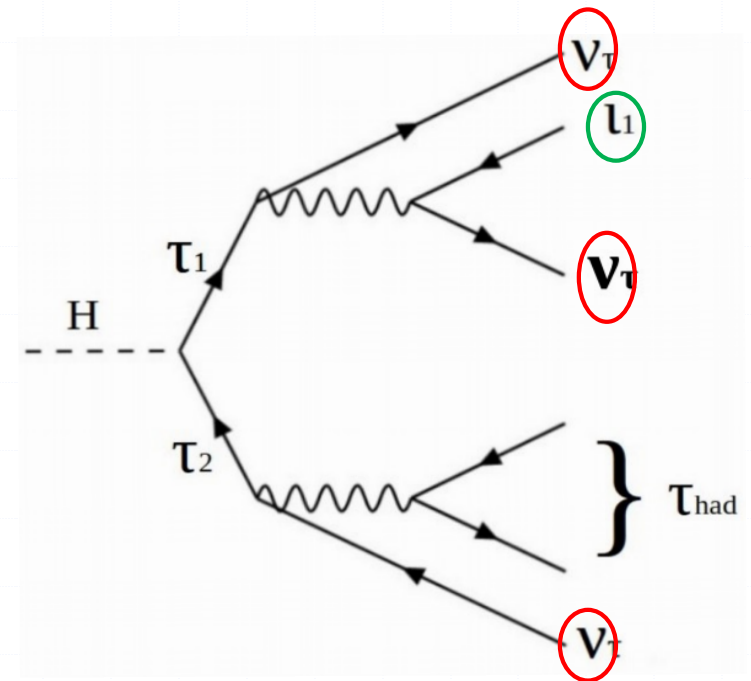
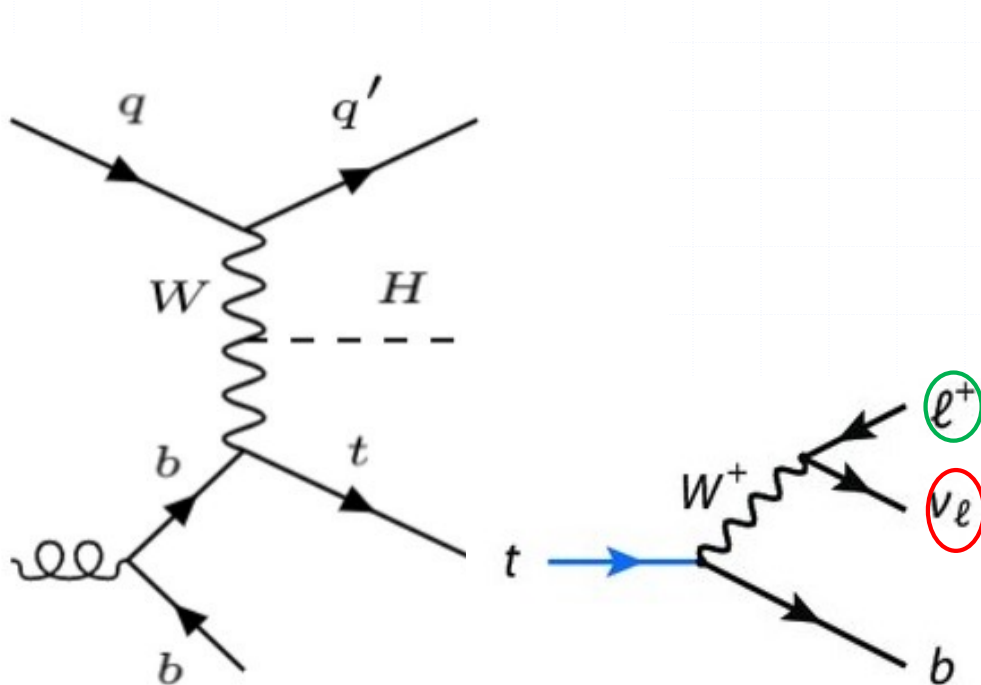
tH: 2 light leptons & 1 hadronically decaying tau, Cyrus Walther



[Erasmus seminar, IEAP CTU, 15.02.22](#)

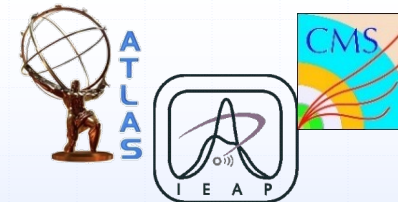
Challenges for Higgs boson mass reconstruction:

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

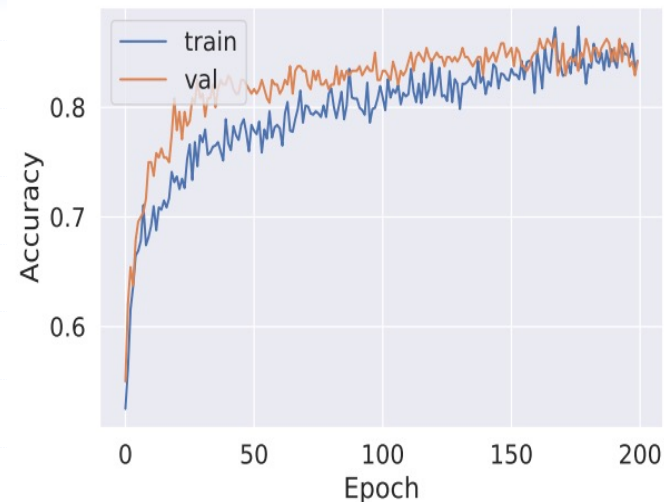


Association of the leptons

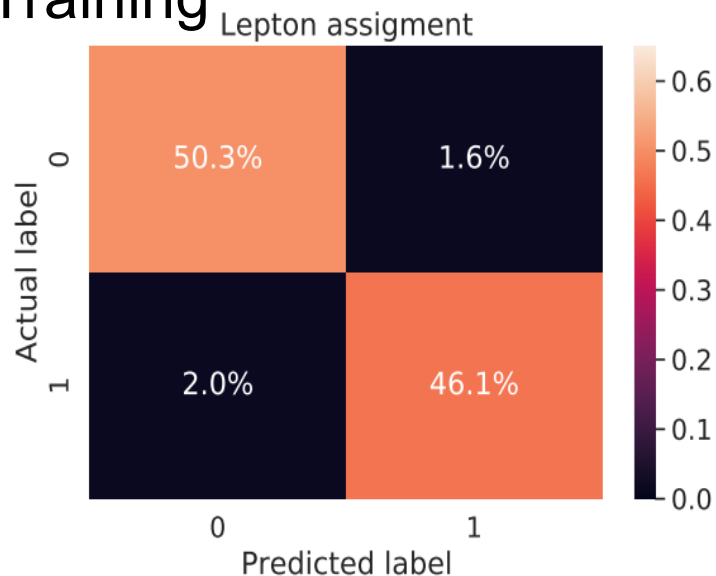
Cyrus Walther



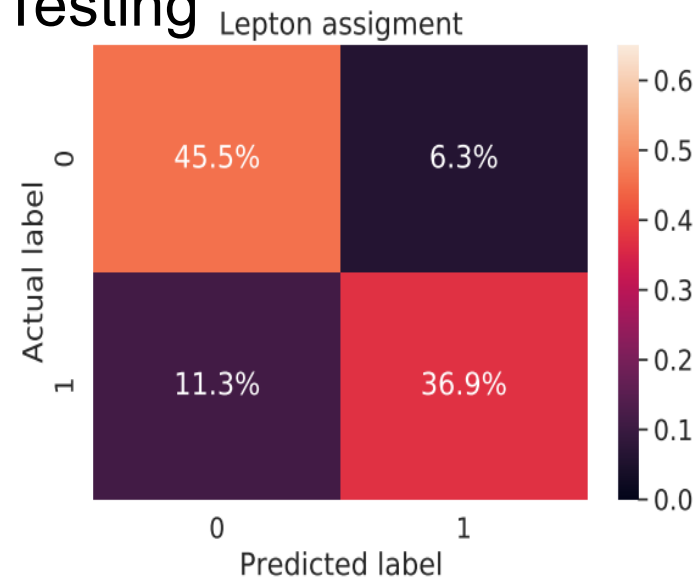
- ❑ Training and testing performance of network
- ❑ 82% correct lepton association



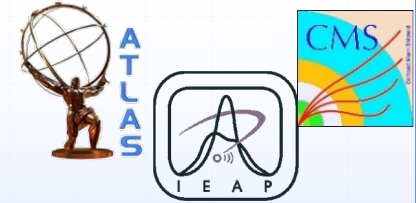
• Training



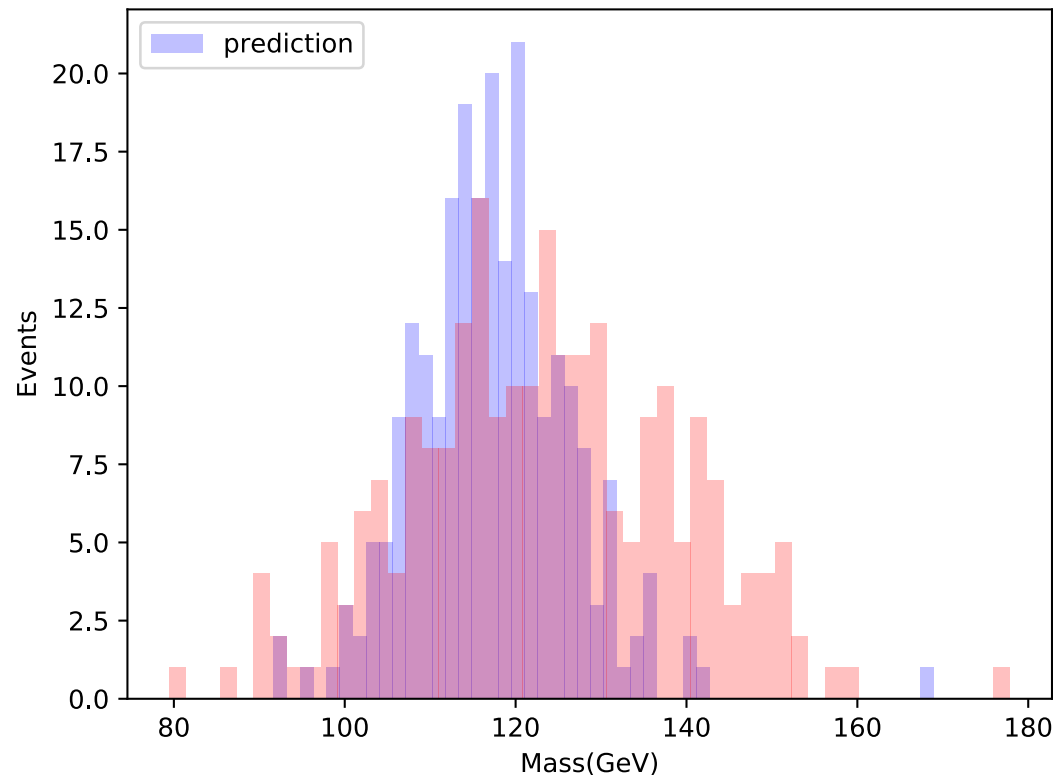
• Testing



Higgs boson mass reconstruction, Cyrus Walther



- ❑ 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 $\sigma=15$ GeV

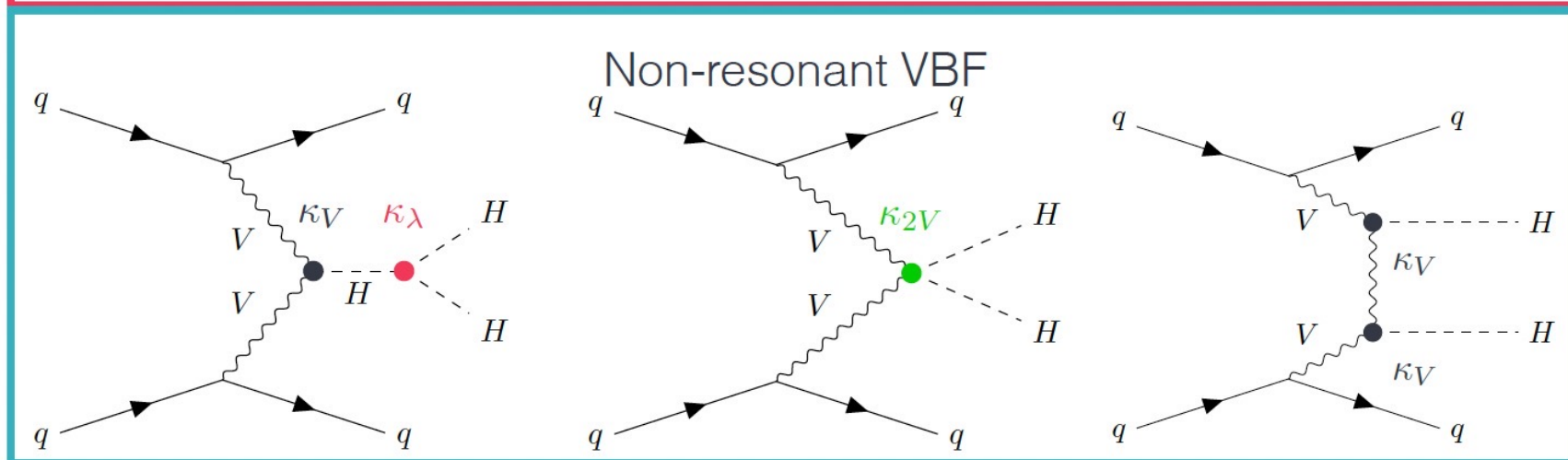
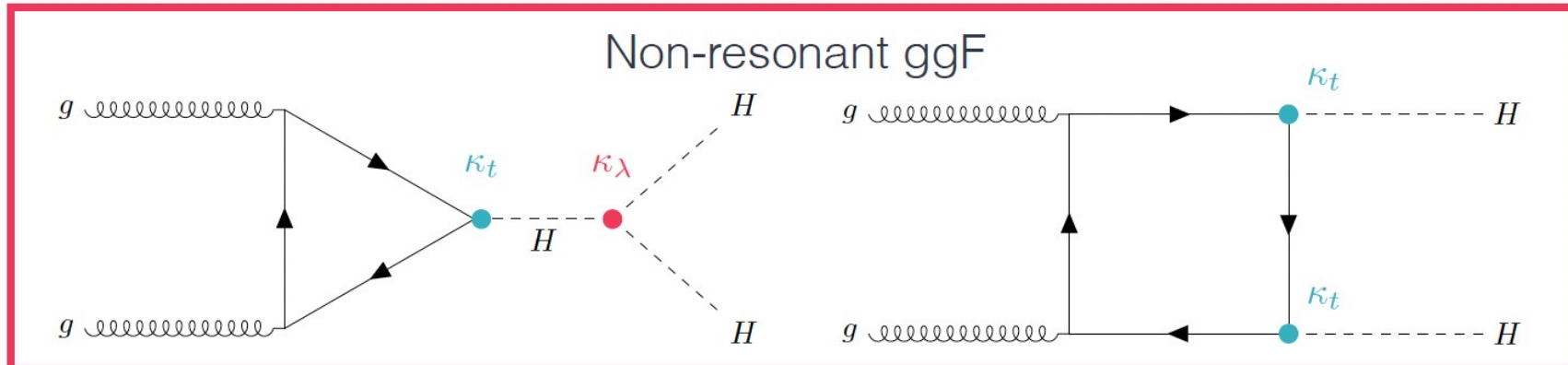


Higgs boson pair-production HH

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



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

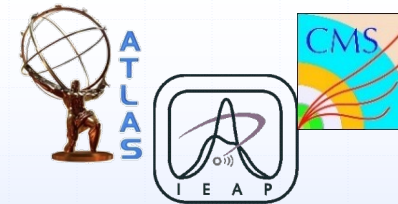


31.1 fb ggF: **destructive interference between the two diagrams**

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

Higgs boson pair-production HH

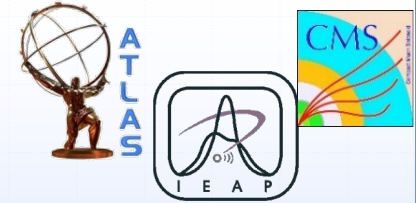
Many decay modes



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

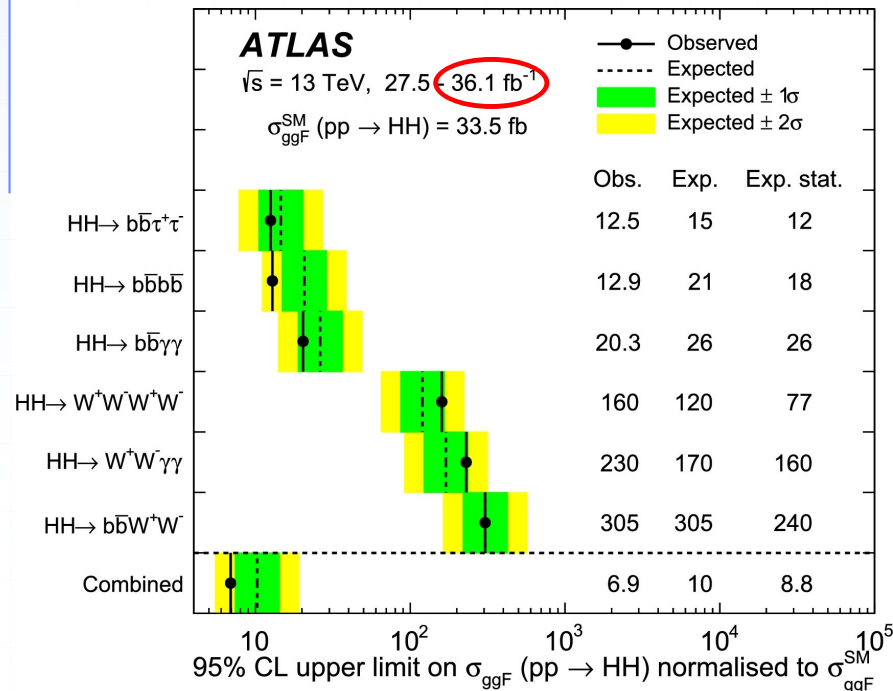
	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
$\tau\tau$	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
$\gamma\gamma$	0.26%	0.10%	0.029%	0.013%	0.0005%

Higgs boson pair-production HH with bb signature



ATLAS:

- $HH \rightarrow bbbb, bb\tau\tau, bb\gamma\gamma, bbWW, \dots$
 $< 6.9 (10) \times SM$ at 95% CL
 PLB 800 (2020) 135103

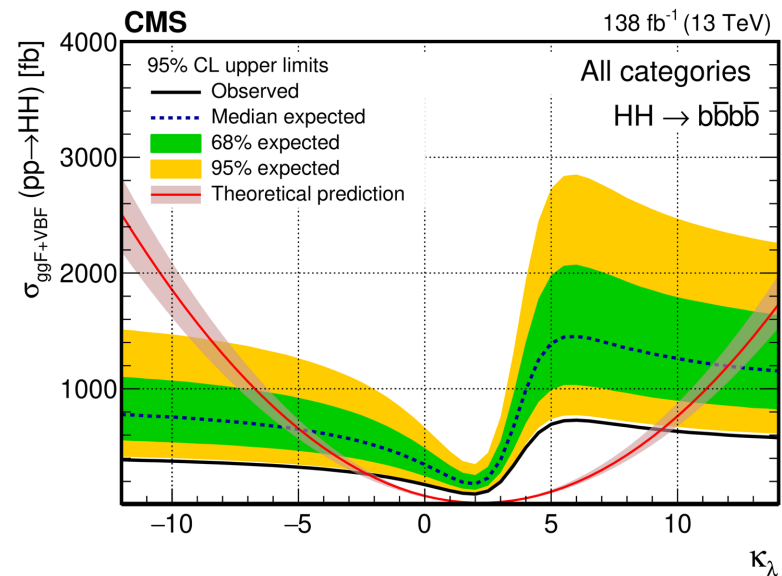


Sensitivity statistically limited.

- $HH \rightarrow bb\tau\tau, 139 \text{ fb}^{-1}$
 $< 4.7 (3.9) \times SM$ at 95% CL

CMS:

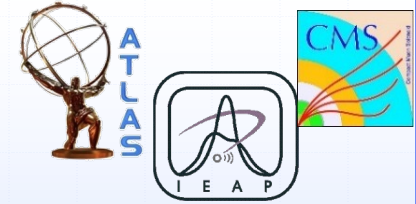
- $HH \rightarrow bbbb, 138 \text{ fb}^{-1}$ HIG-20-005
 $< 3.6 (7.3) \times SM$ at 95% CL
- $HH \rightarrow bbVV, 139 \text{ fb}^{-1}$ PLB 801 (2020) 135145
 $< 40 (29) \times SM$ at 95% CL
- $HH \rightarrow bbZZ \rightarrow bb4l, 137 \text{ fb}^{-1}$ HIG-20-004
 $< 30 (37) \times SM$ at 95% CL



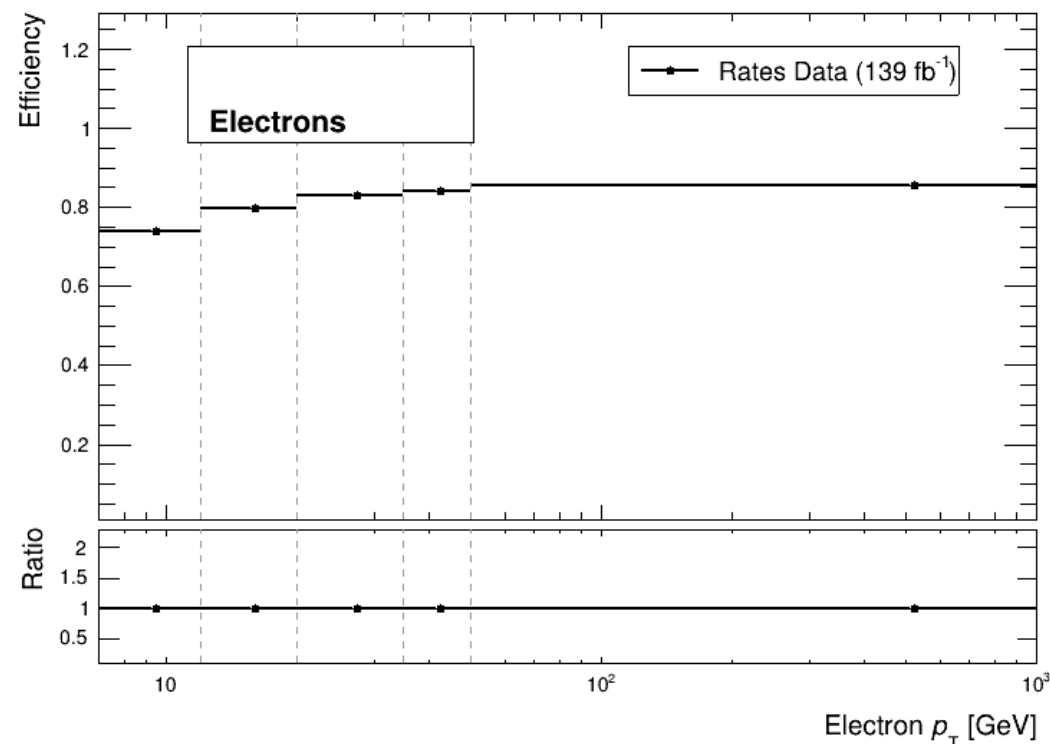
PRL(2022)129(8):081802

$-2.3 (-5.0) < \kappa_\lambda < 9.4 (12.0)$ at 95% CL

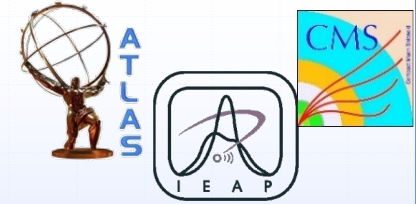
2ISS1tau: Fake rate determination from tt production, Josefine Robl



- ❑ Matrix Method to determine the Fake Rate [CERN-STUDENTS-Note-2021-233](#)
- ❑ $pp \rightarrow tt$ 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 p_T



2ISS1tau: closure test, Josefine Robl



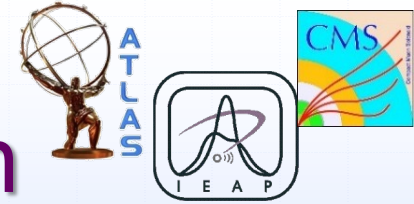
[CERN-STUDENTS-Note-2021-233](#)

- ❑ 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

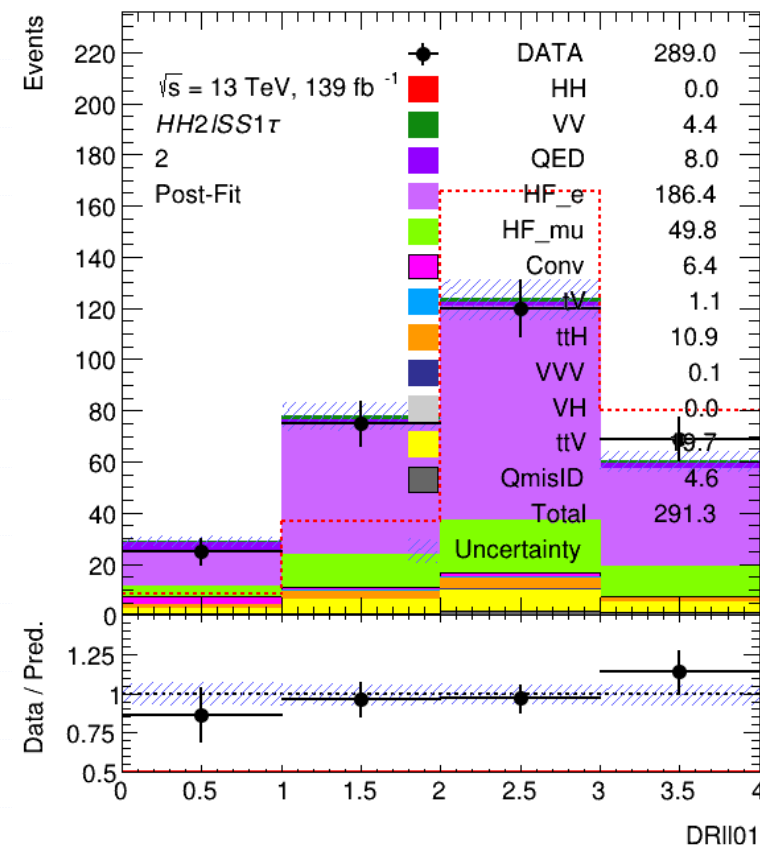
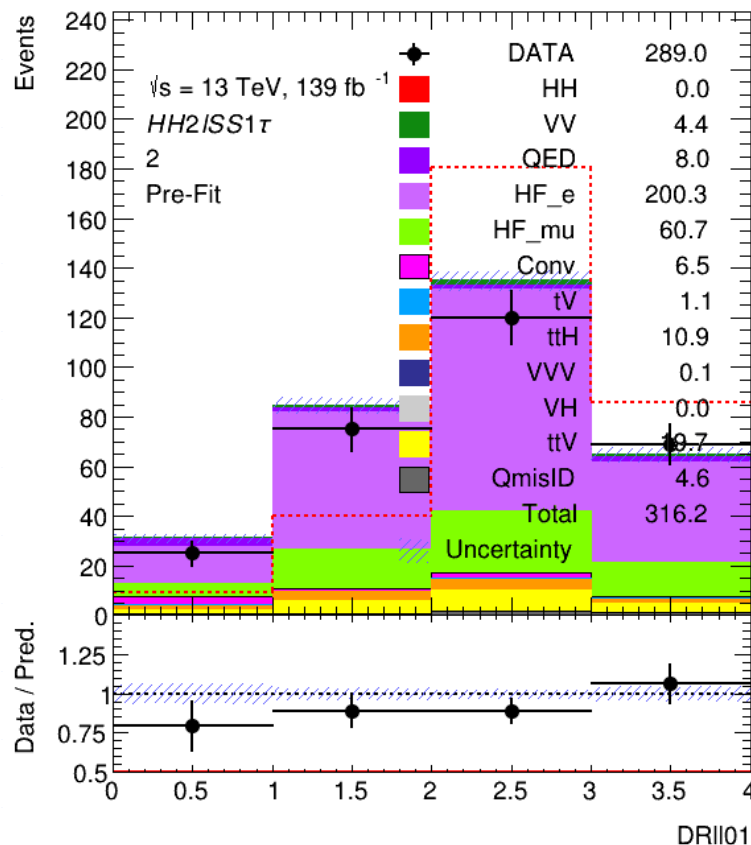
- ❑ Maximum of deviation from unity and statistical uncertainty is taken as systematic uncertainty.
- ❑ Result:
For the signal region: 8%
For the control region: 6%
- ❑ Method used for background determination in HH analysis.

2ISS1tau: Fake rate determination tt production, Thibault Fleischmann



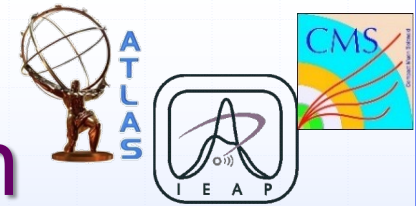
[CERN-STUDENTS-Note-2022-226](#)

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

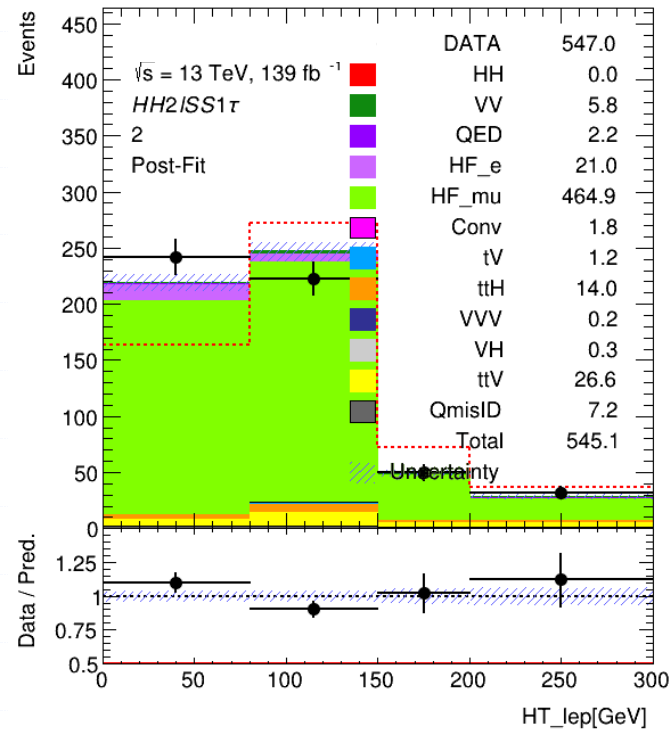
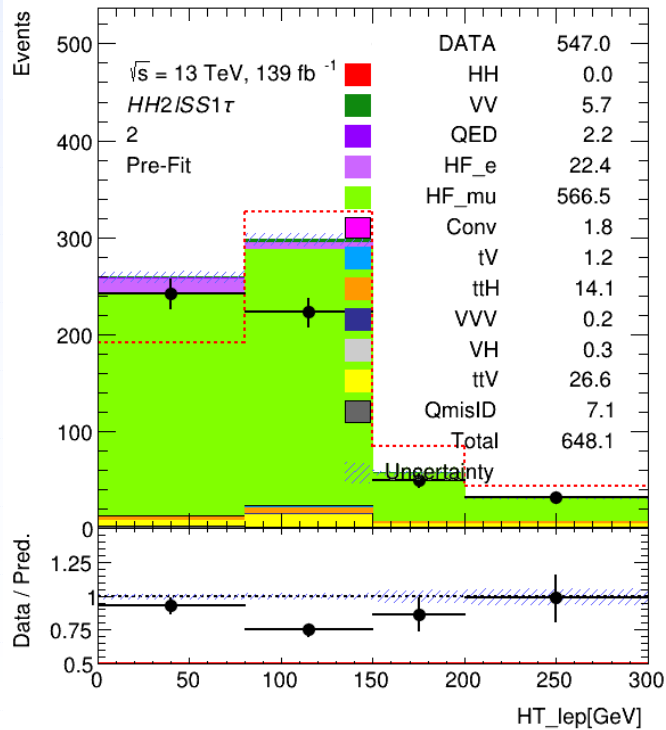


- ❑ ee enhanced sample

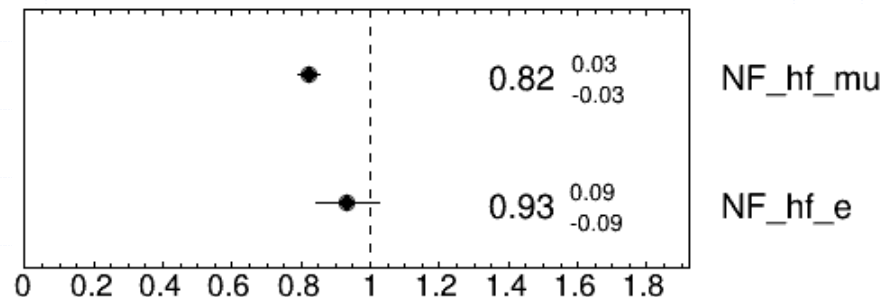
2ISS1tau: Fake rate determination tt production, Thibault Fleischmann

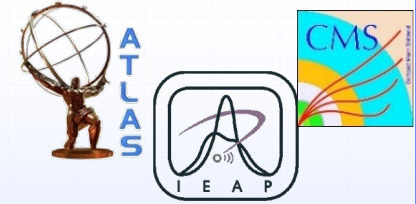


CERN-STUDENTS-Note-2022-226



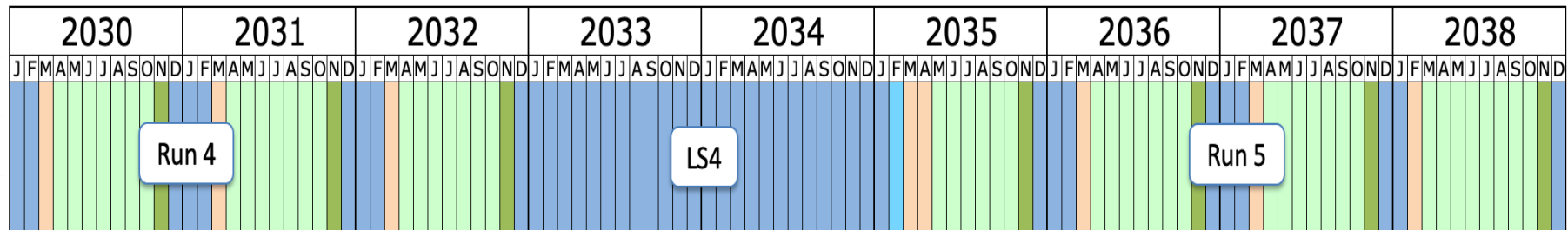
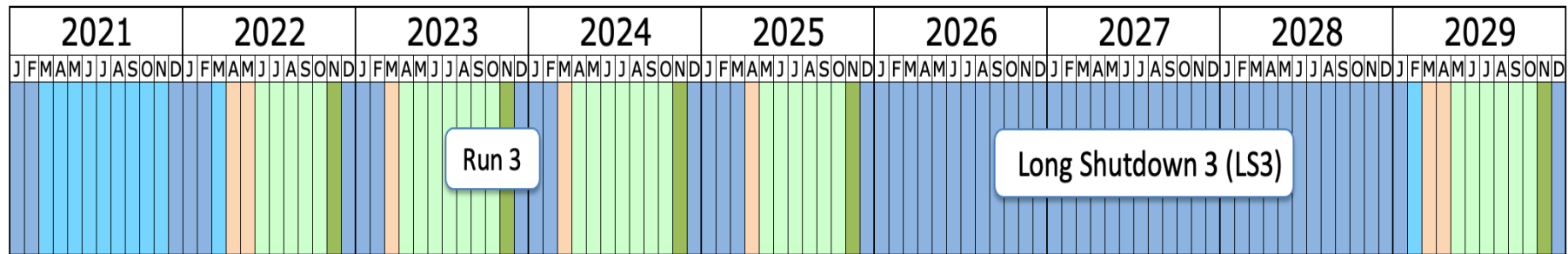
- $\mu\mu$ enhanced sample
- Normalization factors





LHC long-term planning

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



Last updated: January 2022

- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training

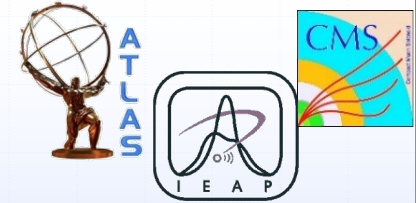
Erasmus exchange program with TU Dortmund - CTU in Prague

- ❑ Established 2021, up to 2027/2028
- ❑ First exchange student WS 2021/2022
- ❑ Contact in Dortmund: Chris Malena Delitzsch
- ❑ Courses at CTU in Prague (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



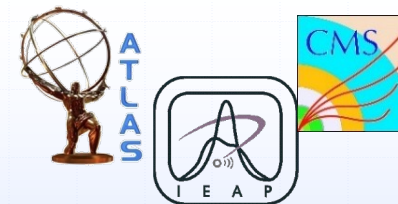
- ❑ Very successful **LHC operation, most analyses with complete Run-2 data**
- ❑ Measurements of **ttH production consistent with SM prediction within 20%**
- ❑ **tbH⁺ production search in 2ISS1tau final state**
- ❑ **Leptoquarks search in same 2ISS1tau final state**
- ❑ Sensitivity for **tH to determine 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**
- ❑ **Erasmus Program TU Dortmund – CTU in Prague**

Acknowledgement



The project is supported
by the Ministry of Education, Youth and Sports
of the Czech Republic
under the project numbers
LM2015058 and LTT17018.