Higgs into tau final states at ATLAS

Lidia Dell'Asta
(Boston University)

Outline

- Higgs boson discovery
- Evidence of the decay of the Higgs boson into tau pairs
- Search for Lepton Flavor Violating decays of the Higgs boson

Fermilab - Wine&Cheese seminar - 27.05.2016

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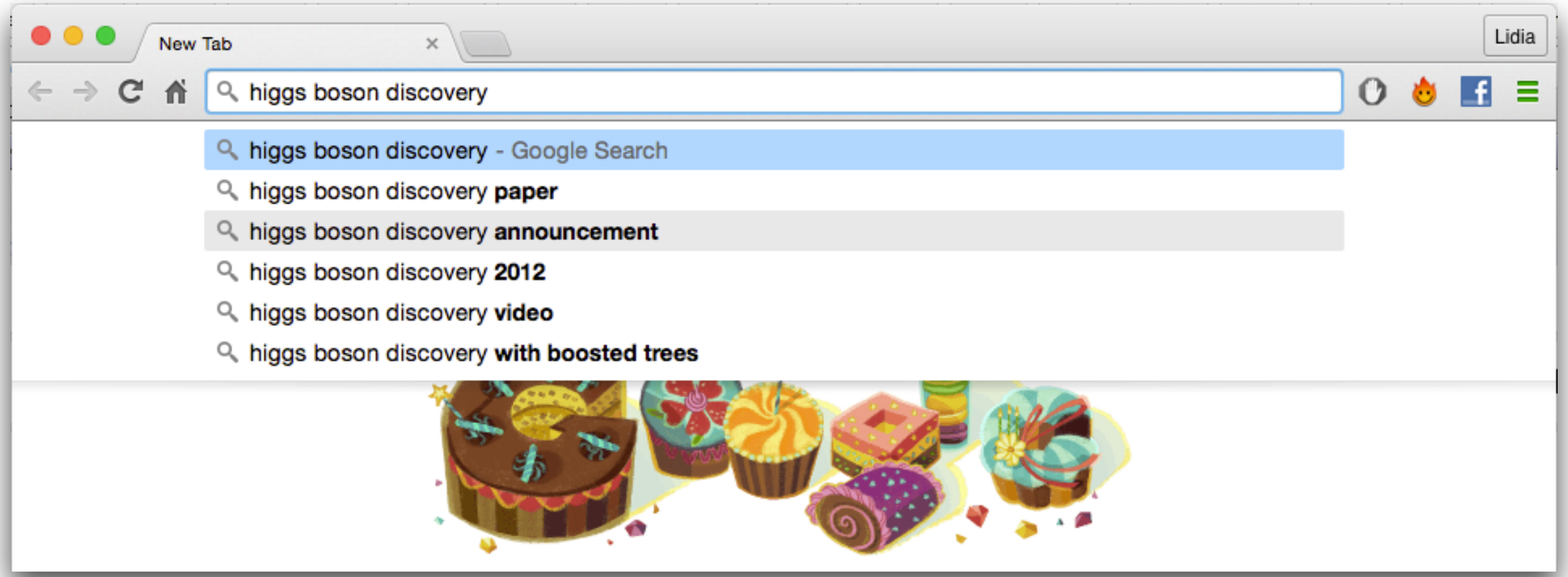

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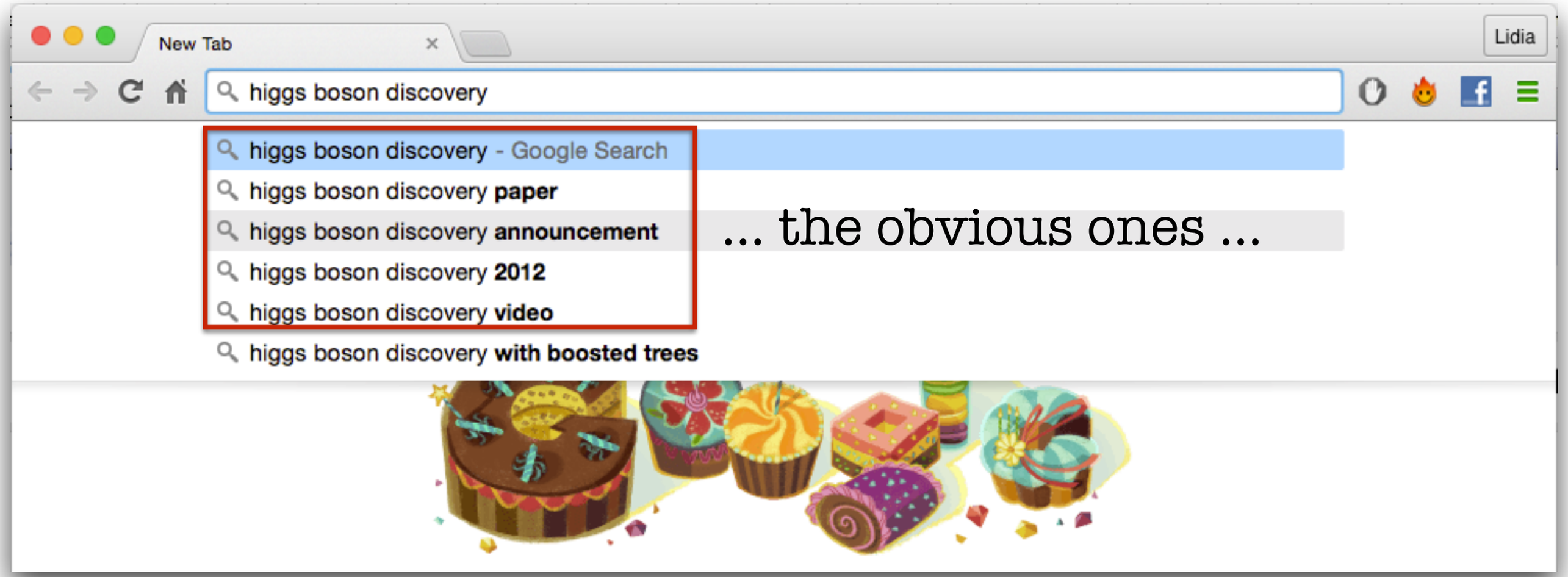

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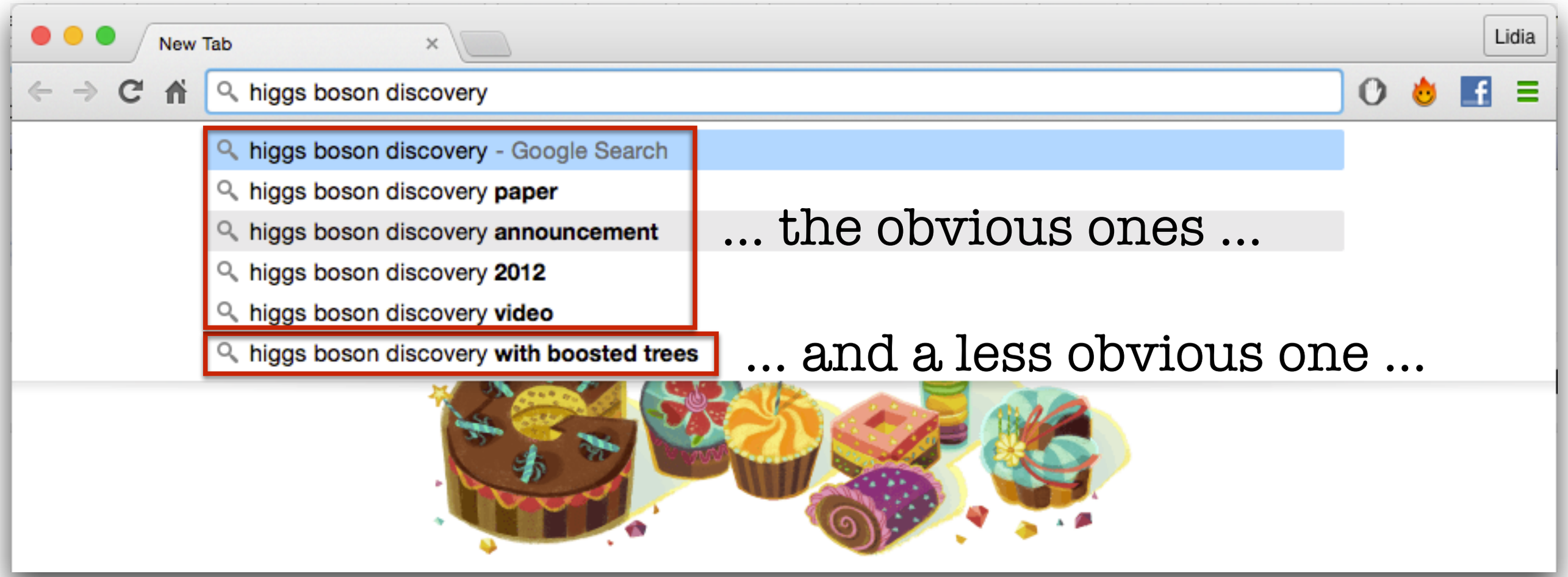

Where? The Large Hadron Collider

		$\sqrt{s}$	$\int Ldt$	peak Lumi
Run1	2010	7 TeV	48.1 pb^{-1}	2.1 10^{32} $cm^{-2}s^{-1}$
	2011	7 TeV	5.46 fb^{-1}	3.8 10^{33} $cm^{-2}s^{-1}$
	2012	8 TeV	22.8 fb^{-1}	7.9 10^{33} $cm^{-2}s^{-1}$
Run2	2015	13 TeV	4.2 fb^{-1}	5 10^{33} $cm^{-2}s^{-1}$
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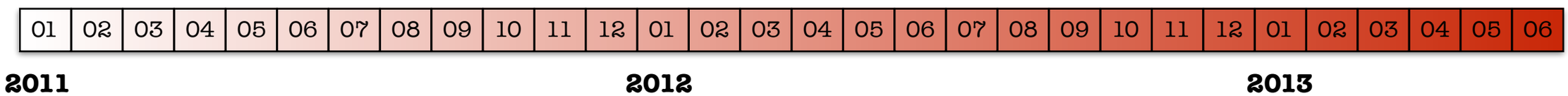
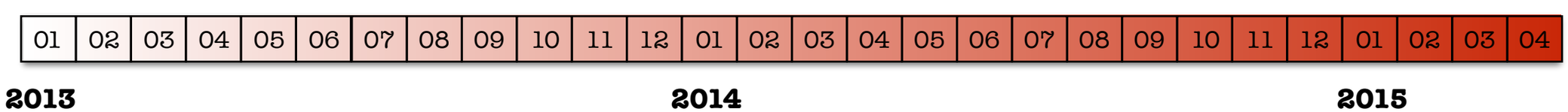
Analyses shown here based on this dataset

Roadmap to the observation





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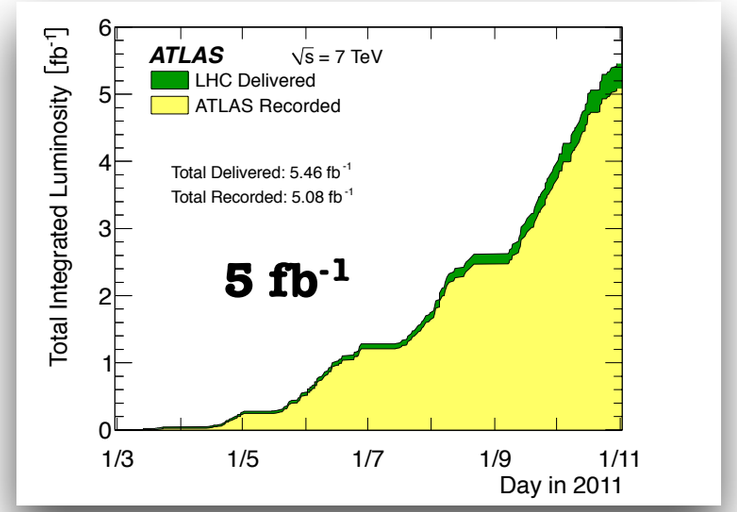

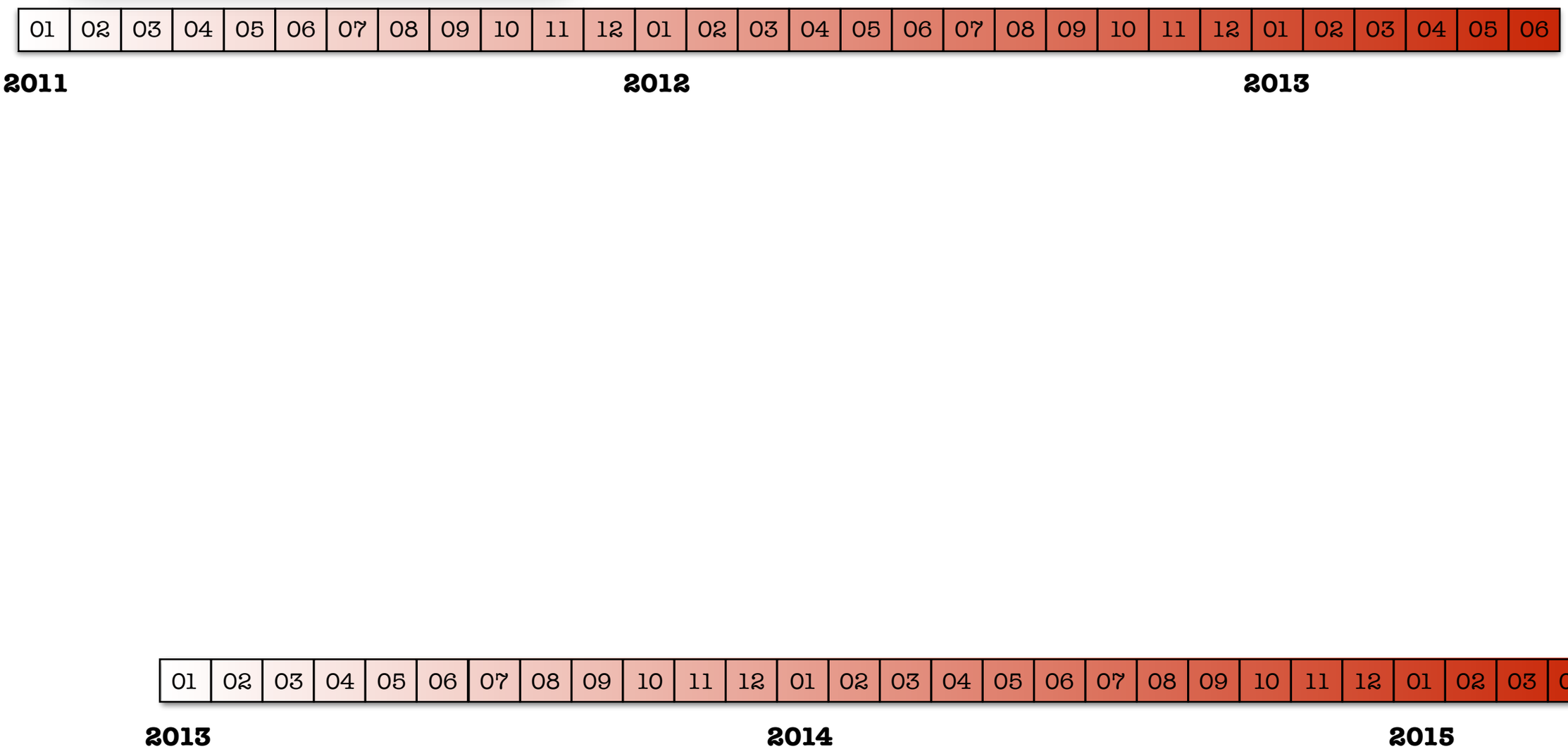

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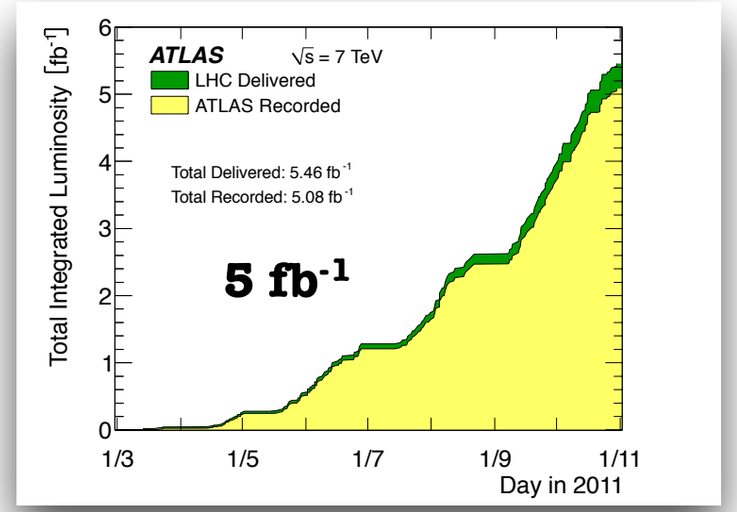

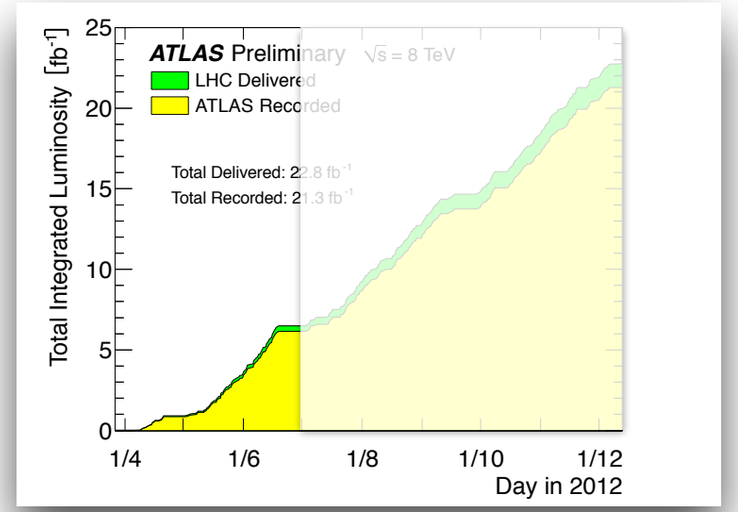

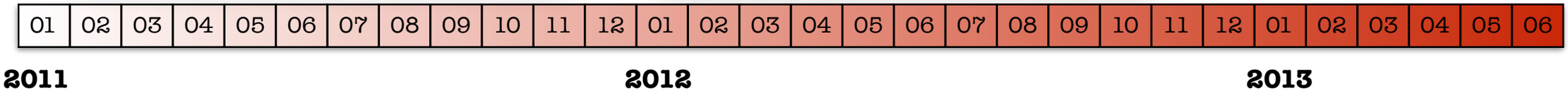

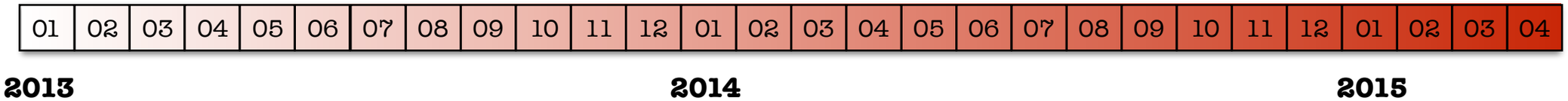

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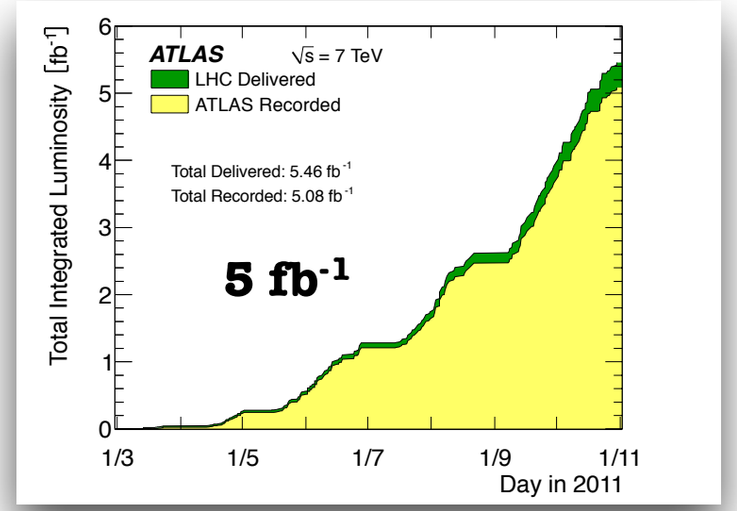

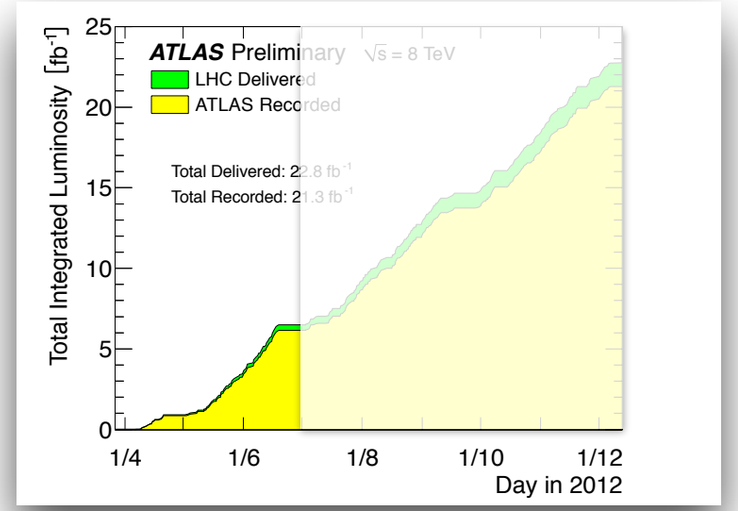

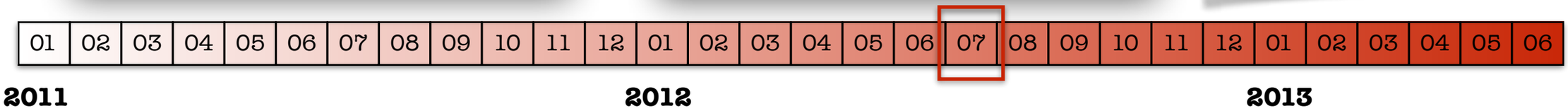

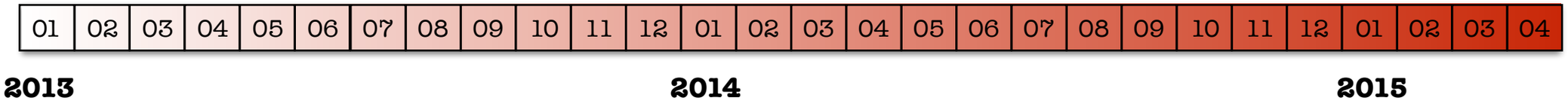

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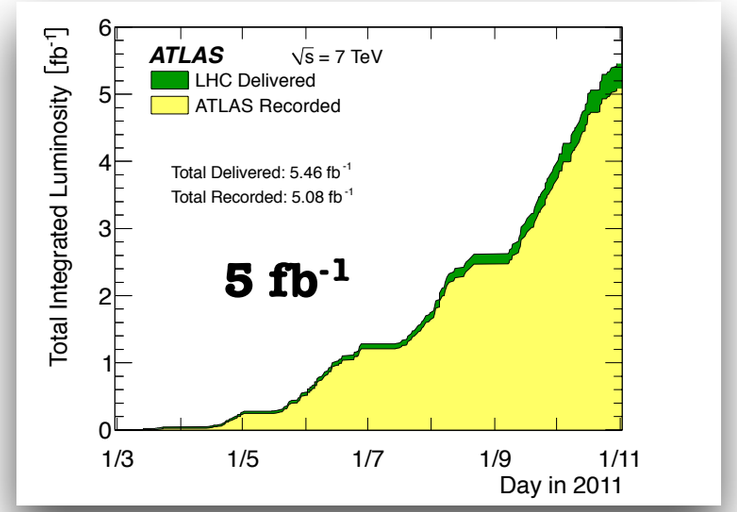

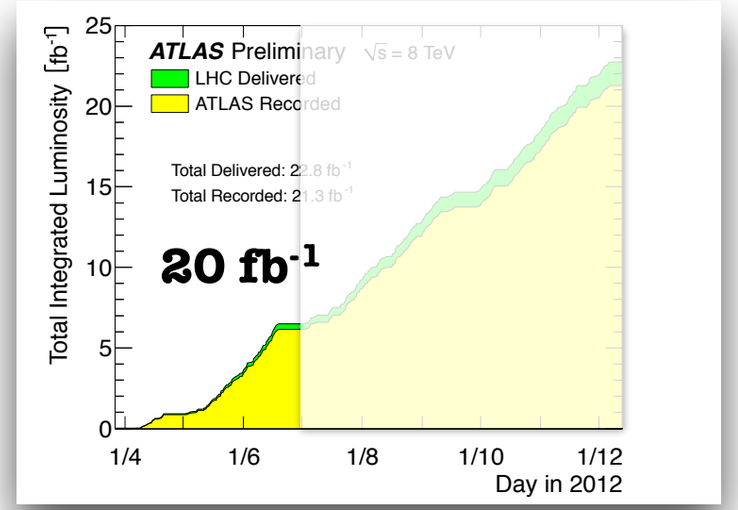

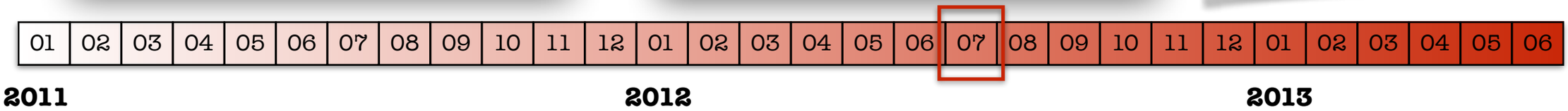

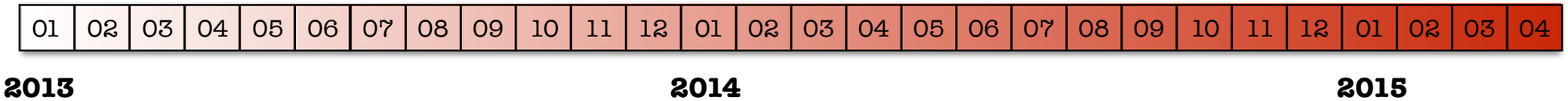

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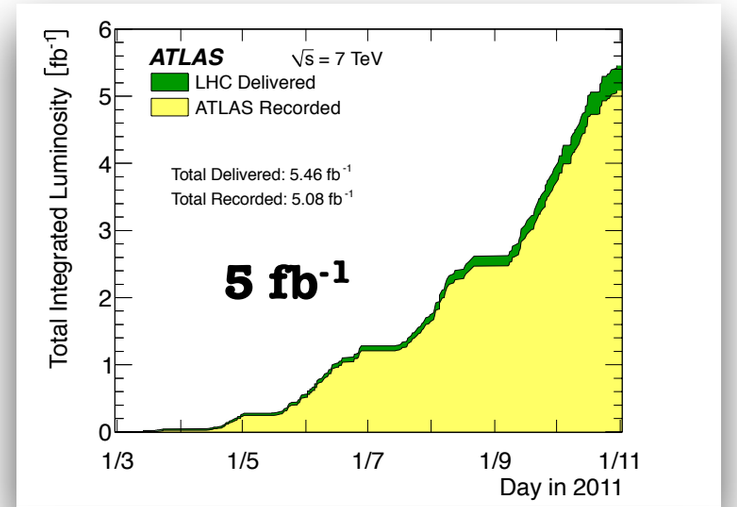

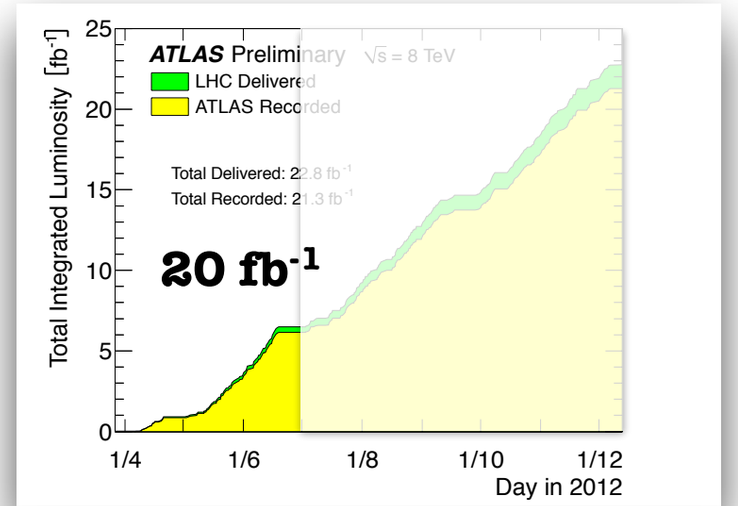

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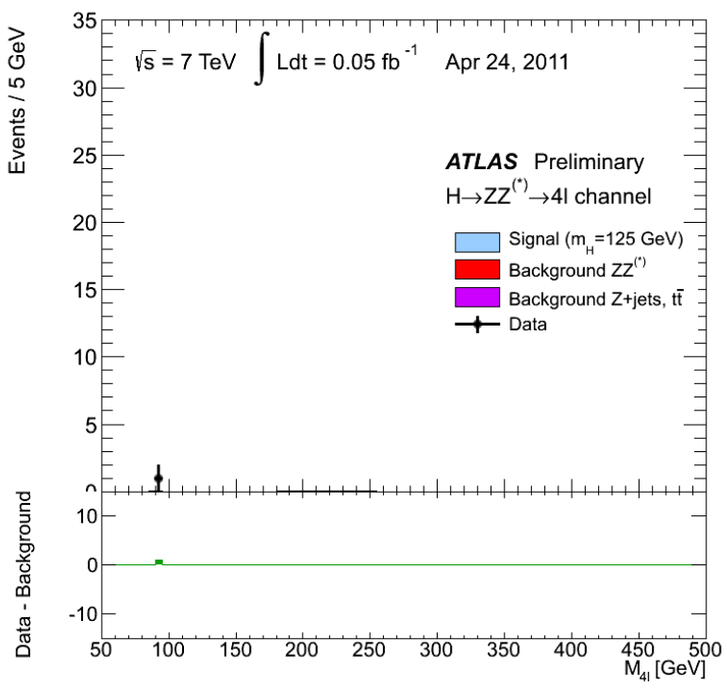
2011 **2012** **2013**



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2013 **2014** **2015**

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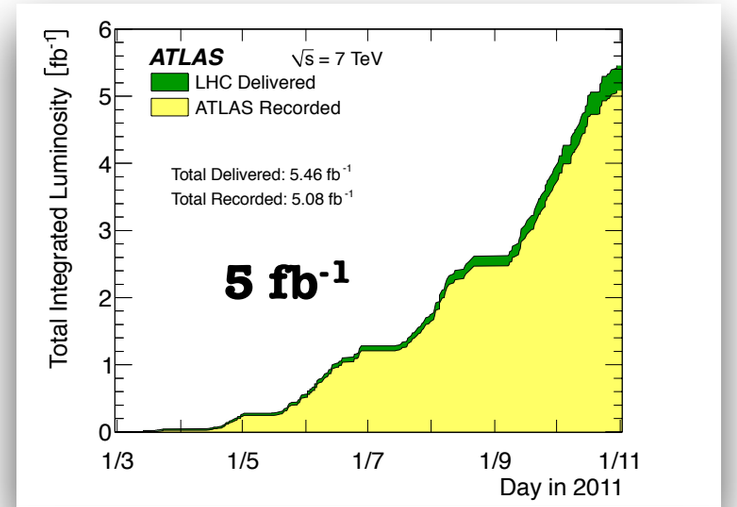

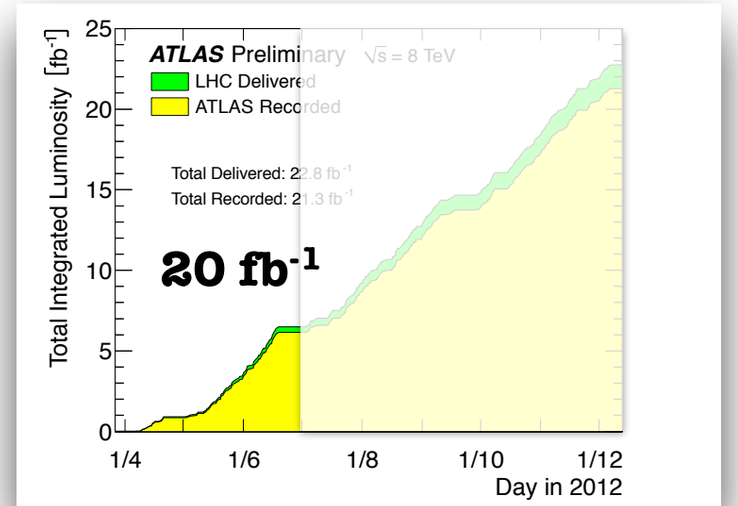

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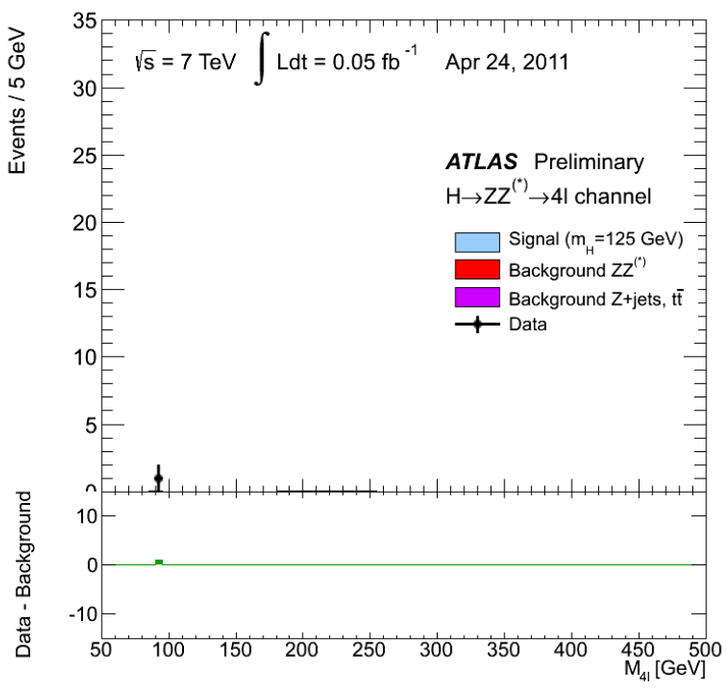

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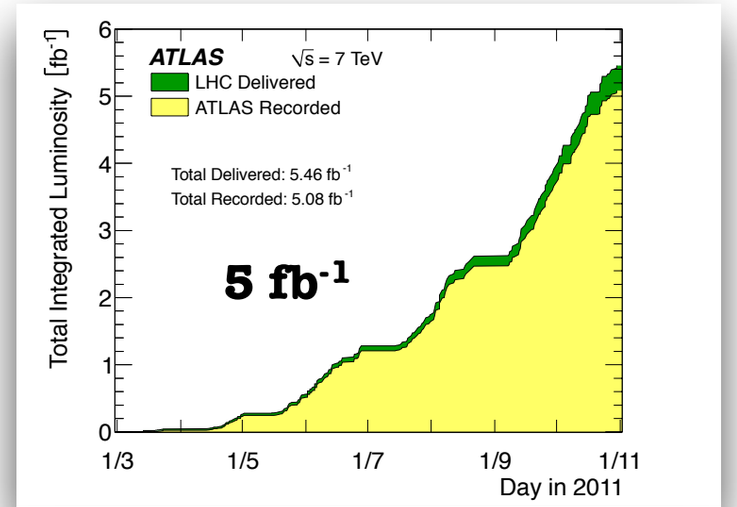

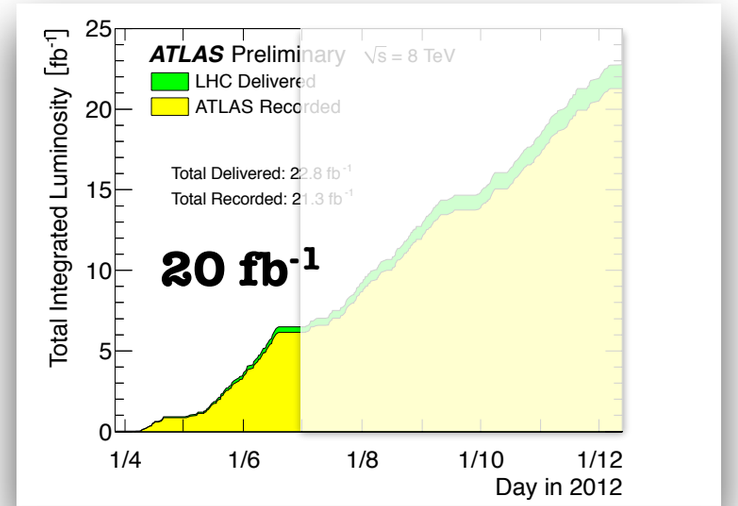

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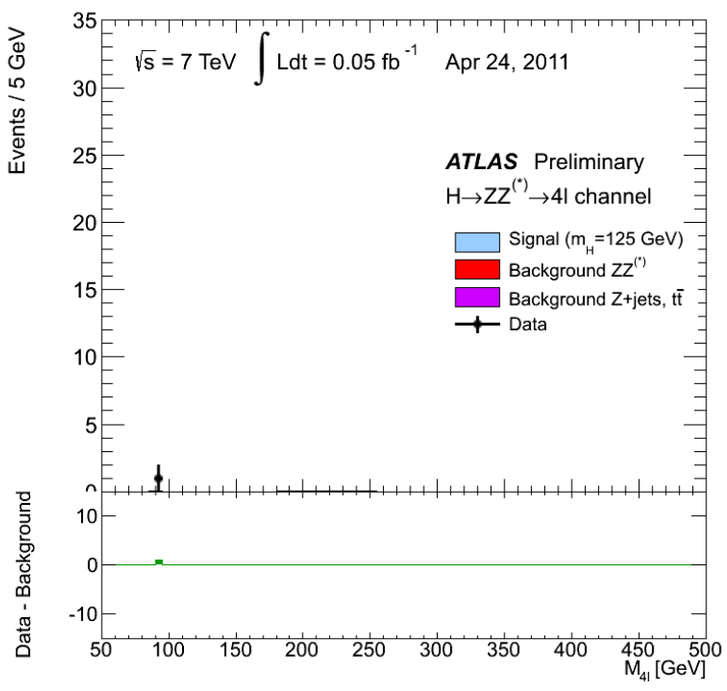

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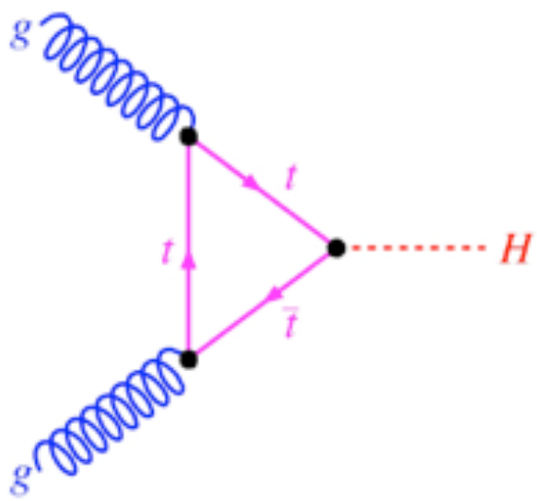
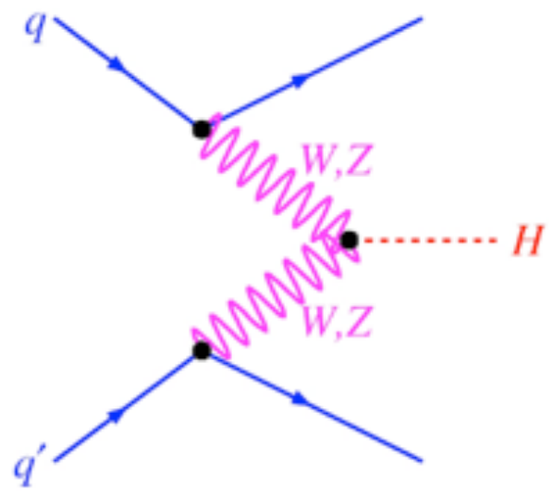
2013 **2014** **2015**

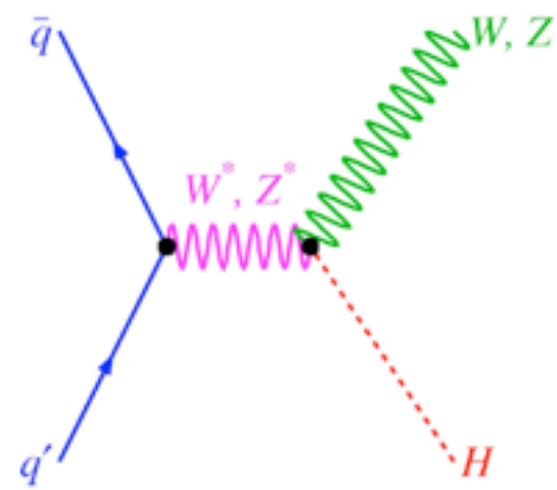
Higgs boson production



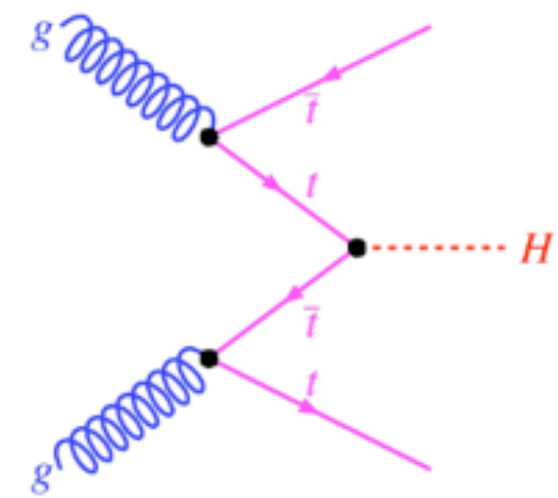
gF



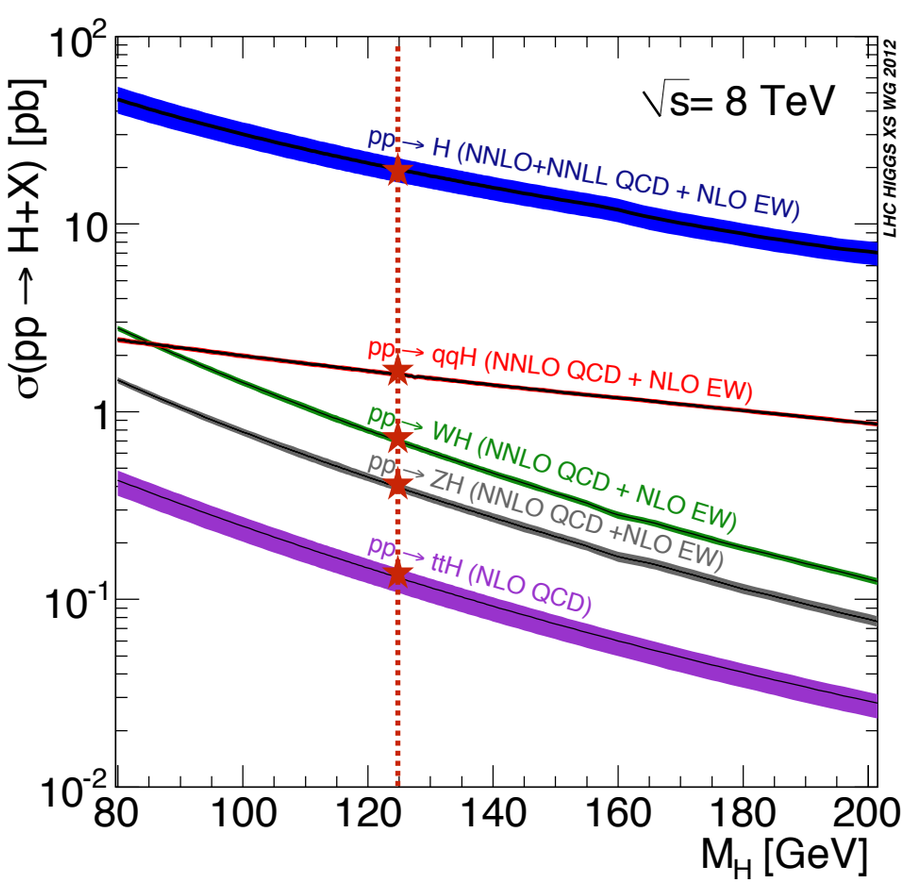
VBF



VH



ttH



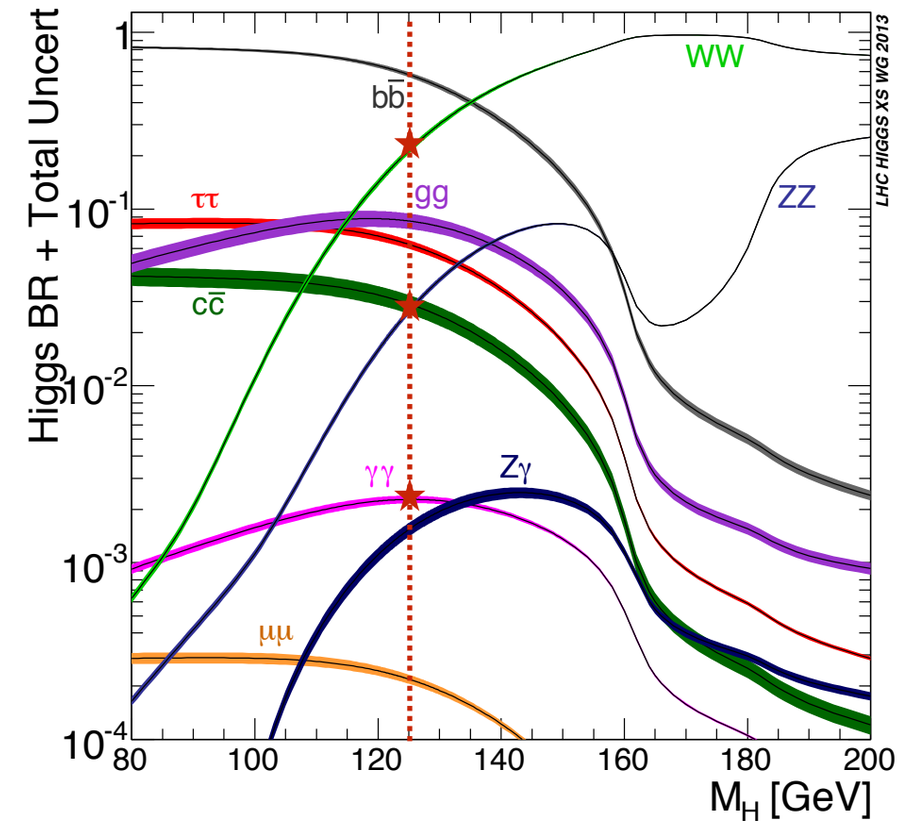
Higgs boson **production** cross sections

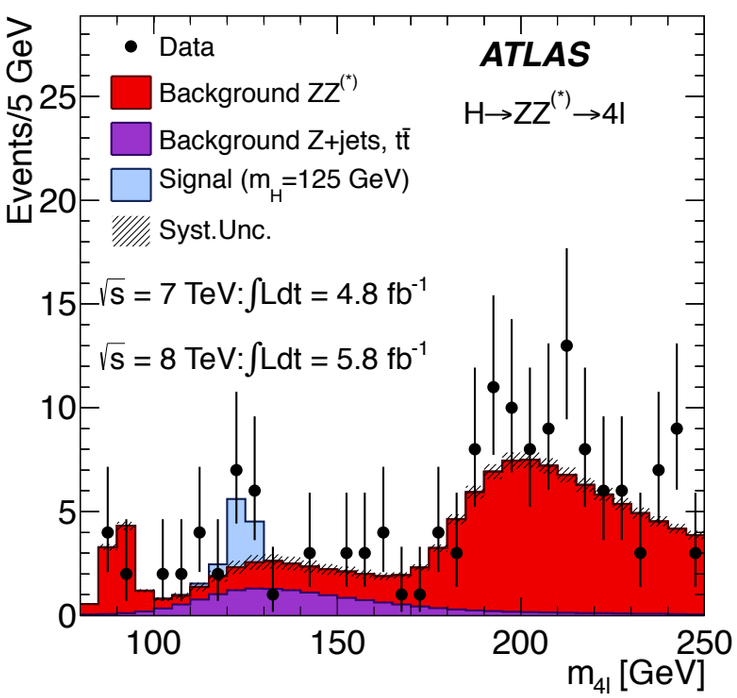
m_H = 125 GeV	gF	VBF	WH	ZH	ttH
7 TeV	15.13 pb	1.22 pb	0.58 pb	0.34 pb	0.09 pb
8 TeV	19.27 pb	1.58 pb	0.70 pb	0.42 pb	0.13 pb
13 TeV	43.92 pb	3.75 pb	1.38 pb	0.87 pb	0.51 pb

Higgs boson decay

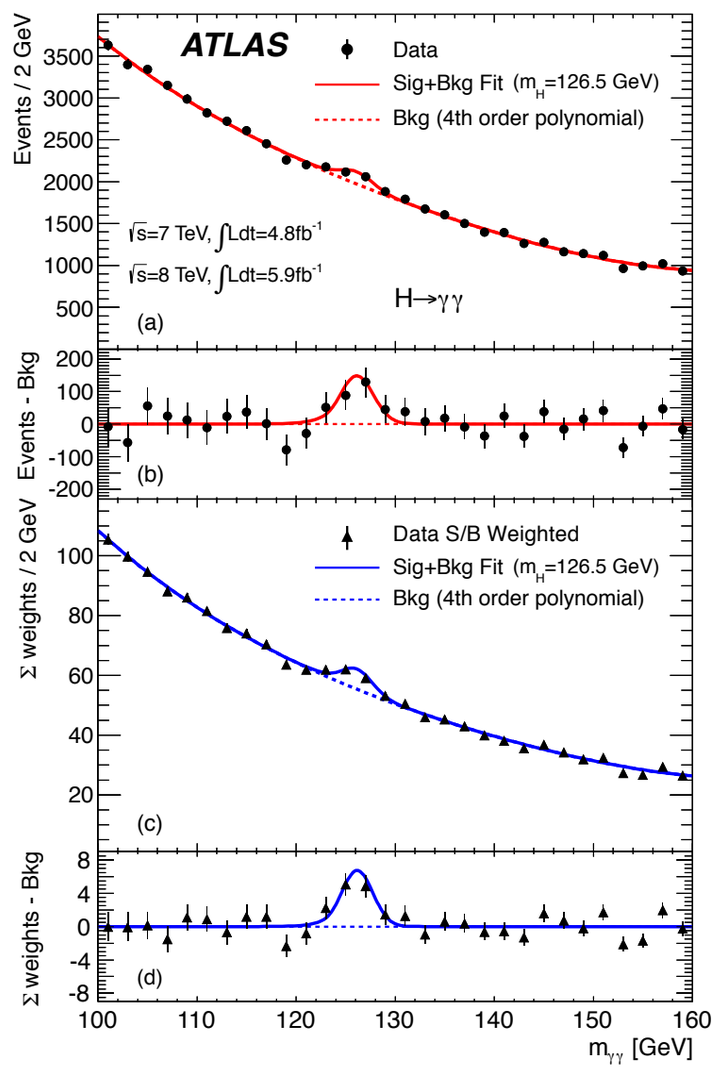
BR for the **decay** of Higgs boson into **bosons**.

m_H = 125 GeV	H→WW	H→ZZ	H→γγ
BR	21.5%	2.64%	0.228%





Phys. Lett. B 716 (2012) 1



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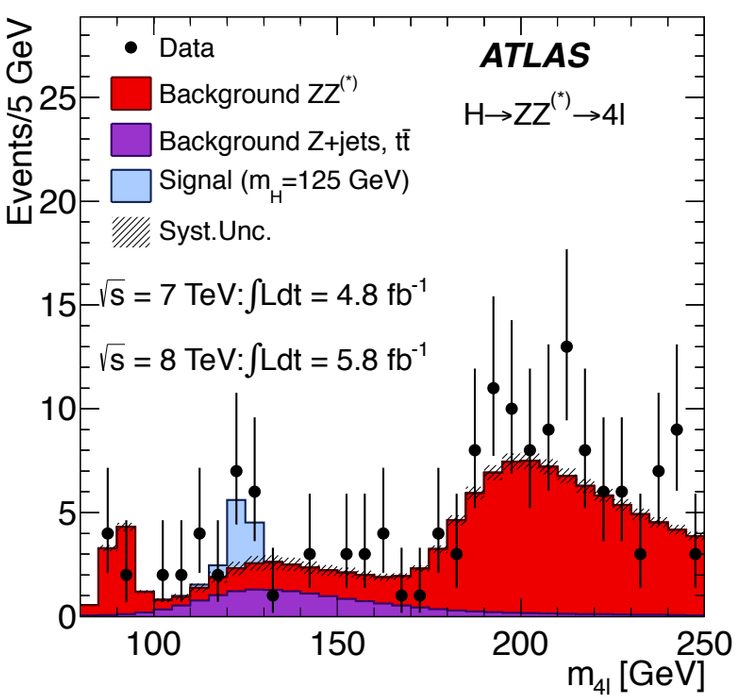

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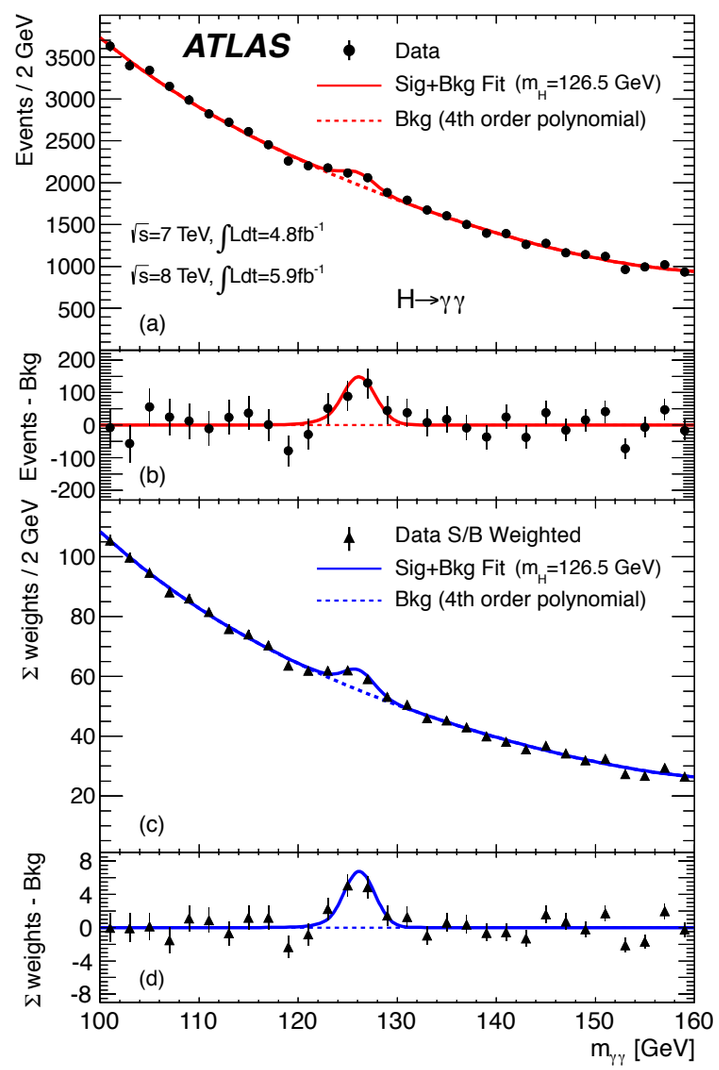
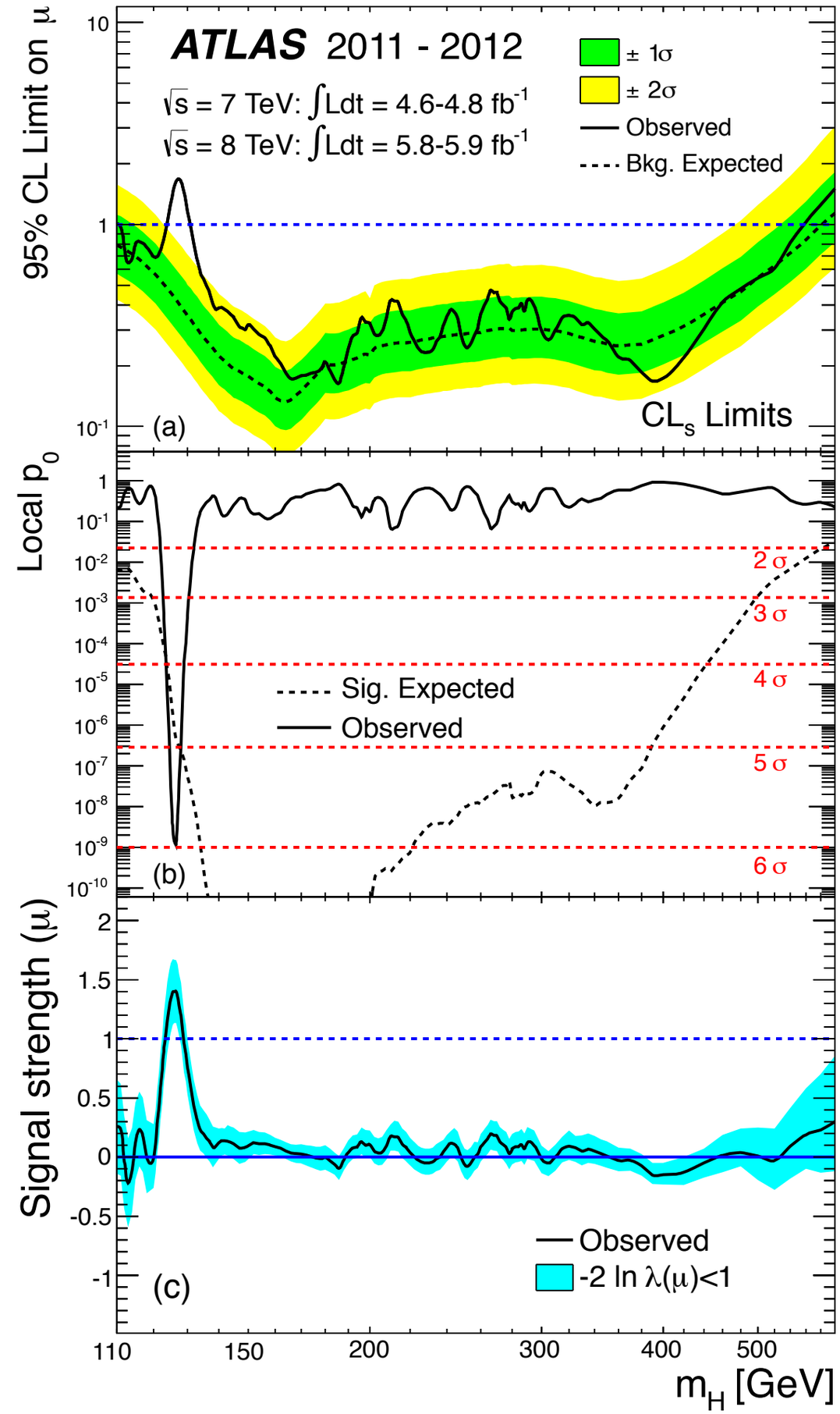
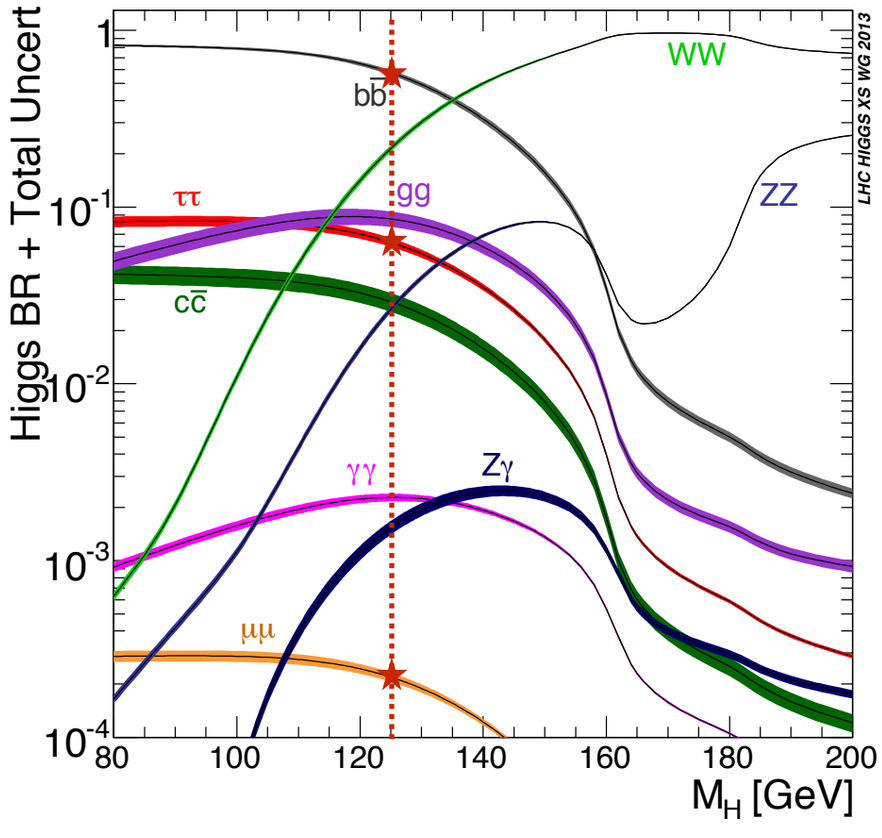




Higgs boson decay

BR for the **decay** of Higgs boson into **fermions**.

m_H = 125 GeV	H→bb	H→ττ	H→μμ
BR	57.7%	6.32%	0.0219%



- **H→bb**: highest branching ratio, looked for in associated production.
  - Tevatron: 3σ excess observed, compatible with Higgs with m_H = 125 GeV [Phys. Rev. D 88 (2013) 052014].
  - ATLAS results from Run1: Eur. Phys. J. C 75 (2015) 349 (ttH) and JHEP 01 (2015) 069 (VH).

- **H→μμ**: cleanest final state but tiny branching ration and overwhelming Z/γ*→μμ background.
  - Possibile with full Run2 statistics.
  - ATLAS results from Run1: Phys. Lett. B 738 (2014) 68.

- **H→ττ**: here!

$H \rightarrow \tau\tau$: analysis strategy

- Analysis performed on 4.5 fb^{-1}@7TeV + 20.3 fb^{-1}@8TeV.
- Multi variate analysis (**MVA**) based on boosted decision trees (BDT).
- Cut-based analysis (**CBA**) as an independent cross check.

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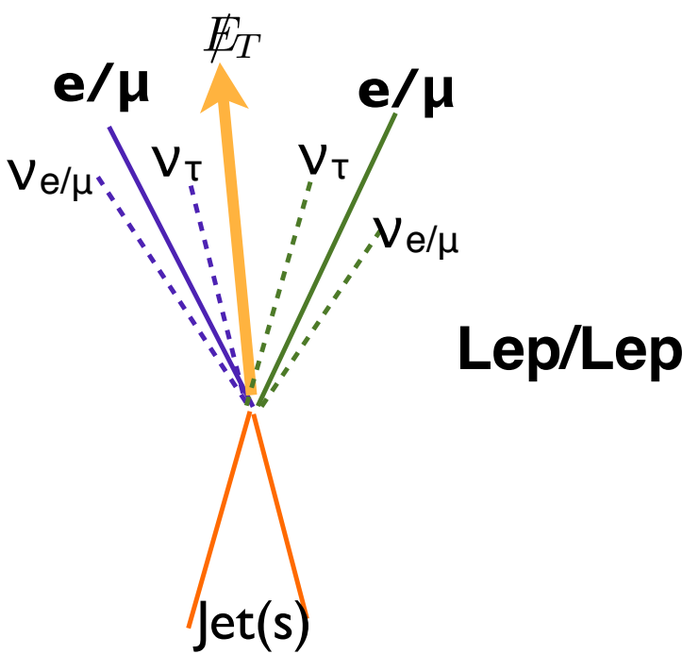
$H \to \tau_{lep}\tau_{lep}$

very clean signature
BR = 12.4%
2 OS leptons
no had taus
trigger: single- or di-lepton



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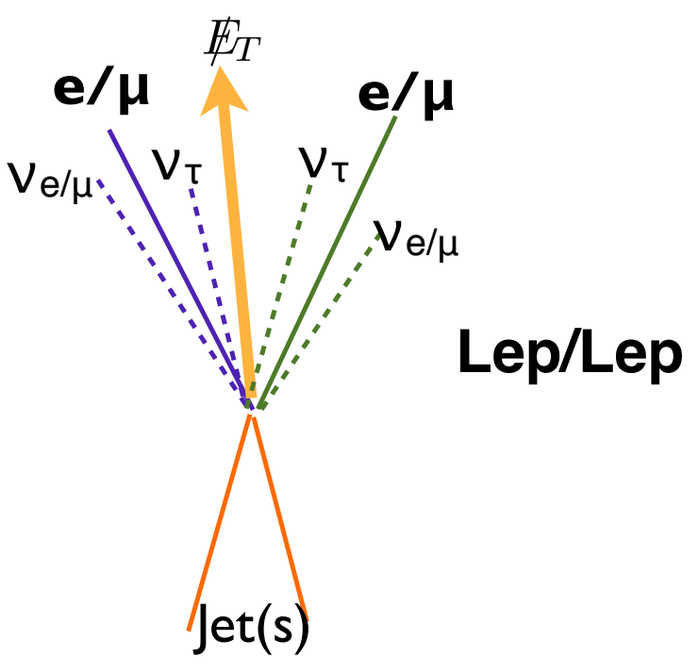
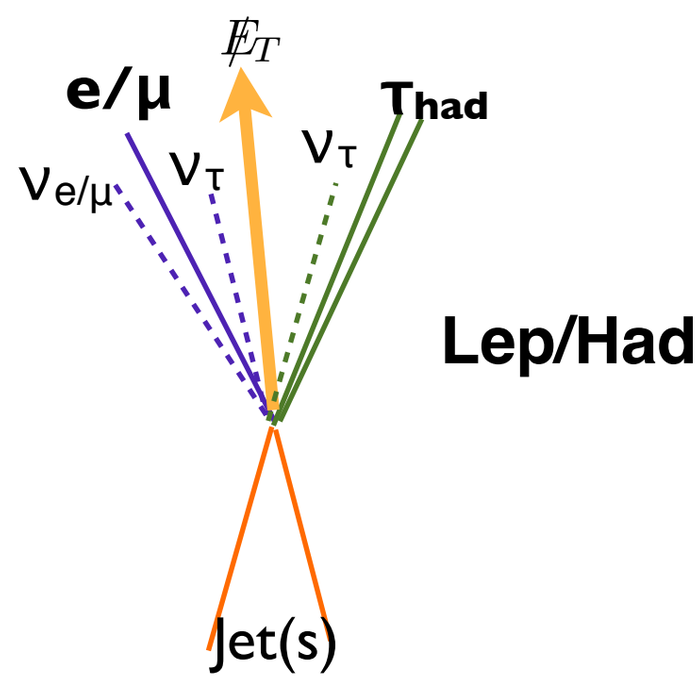
$H \to \tau_{lep}\tau_{lep}$

very clean signature
BR = 12.4%
2 OS leptons
no had taus
trigger: single- or di-lepton

$H \to \tau_{lep}\tau_{had}$

clean signature
BR = 45.6%
1 lepton
1 had tau
trigger: single-lepton





$H \to \tau\tau$: analysis strategy

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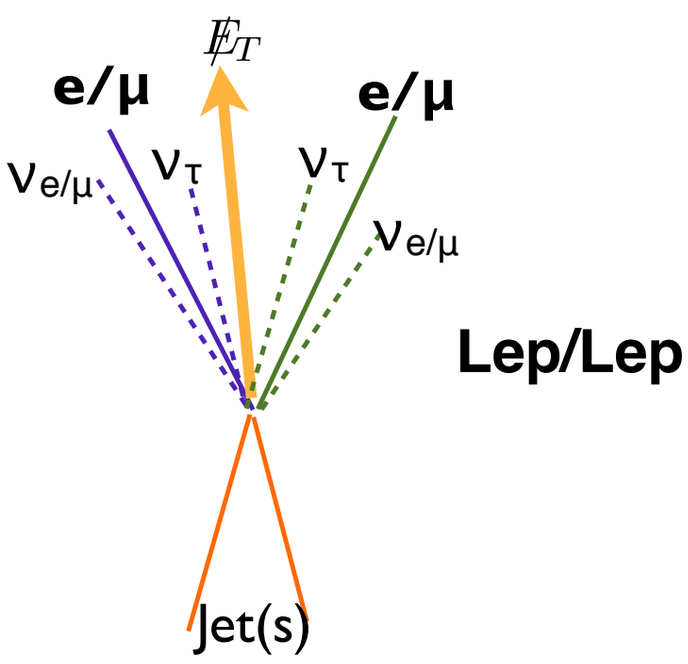
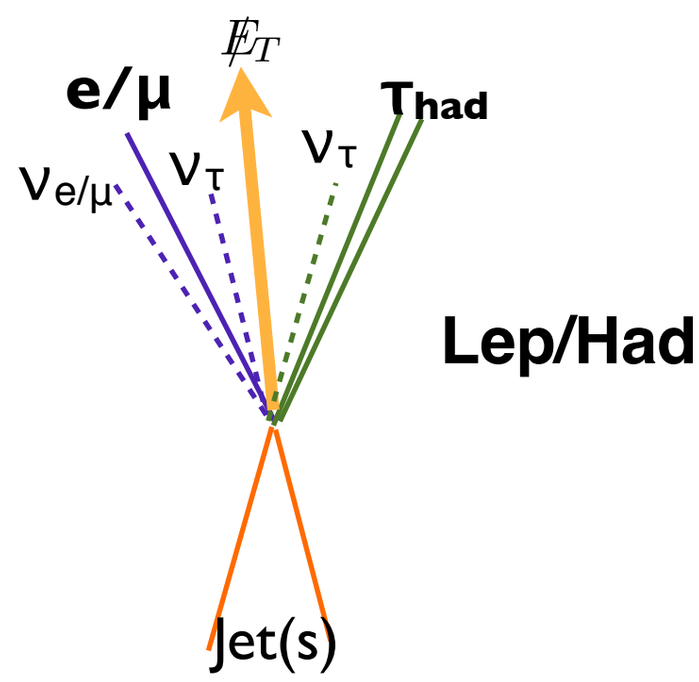
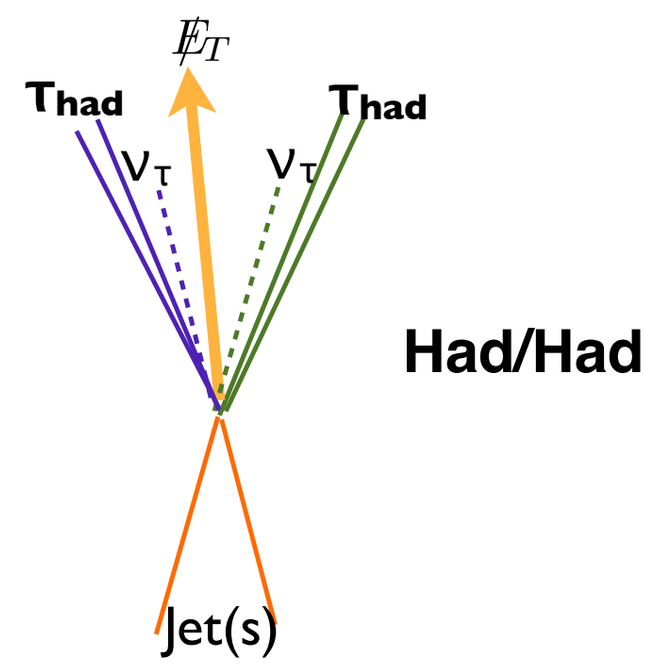
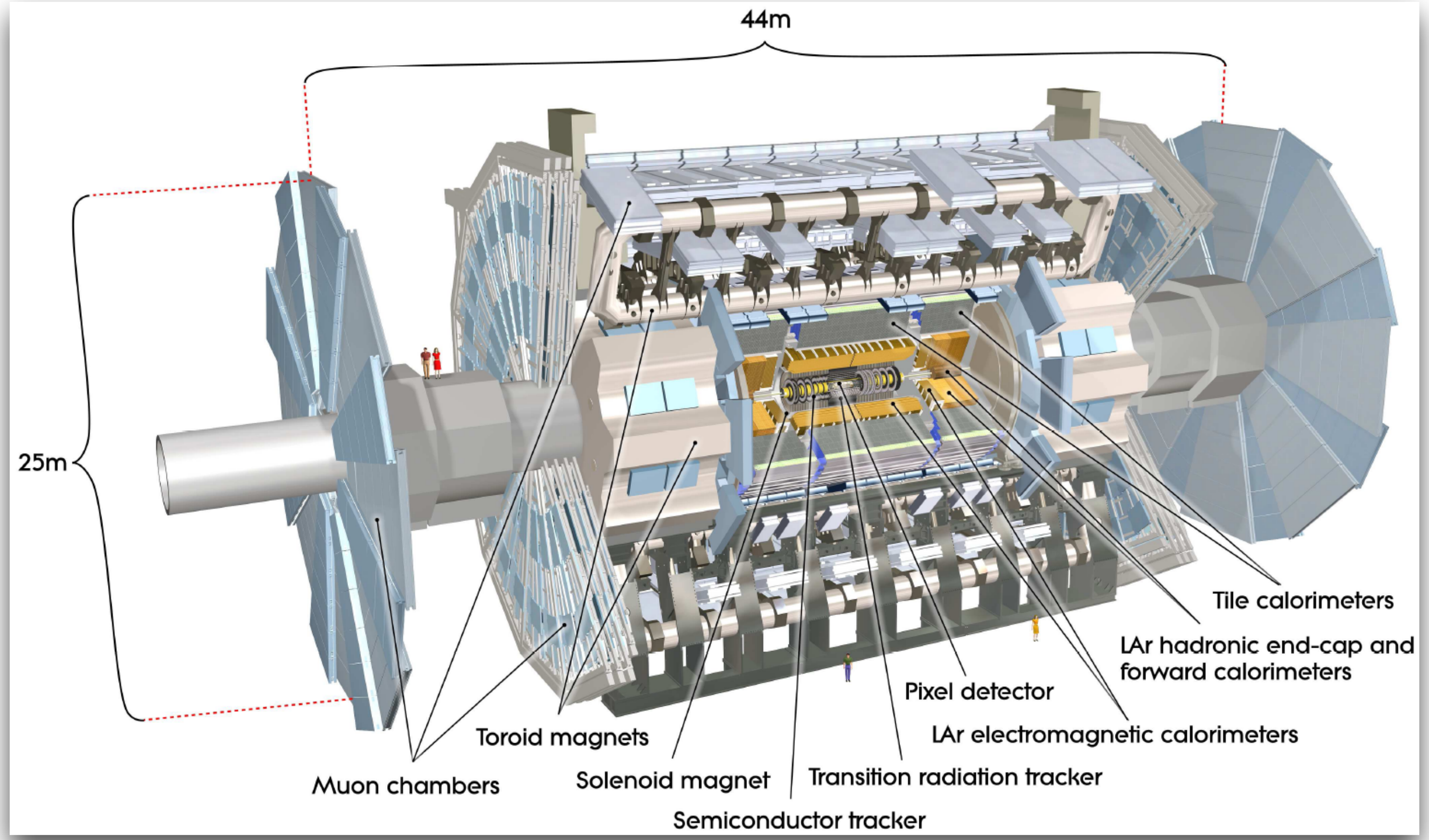
$H \to \tau_{lep}\tau_{lep}$	$H \to \tau_{lep}\tau_{had}$	$H \to \tau_{had}\tau_{had}$
very clean signature	clean signature	high multijet background
BR = 12.4%	BR = 45.6%	BR = 42%
2 OS leptons	1 lepton	2 had taus
no had taus	1 had tau	trigger: di-tau
trigger: single- or di-lepton	trigger: single-lepton	







The ATLAS Experiment



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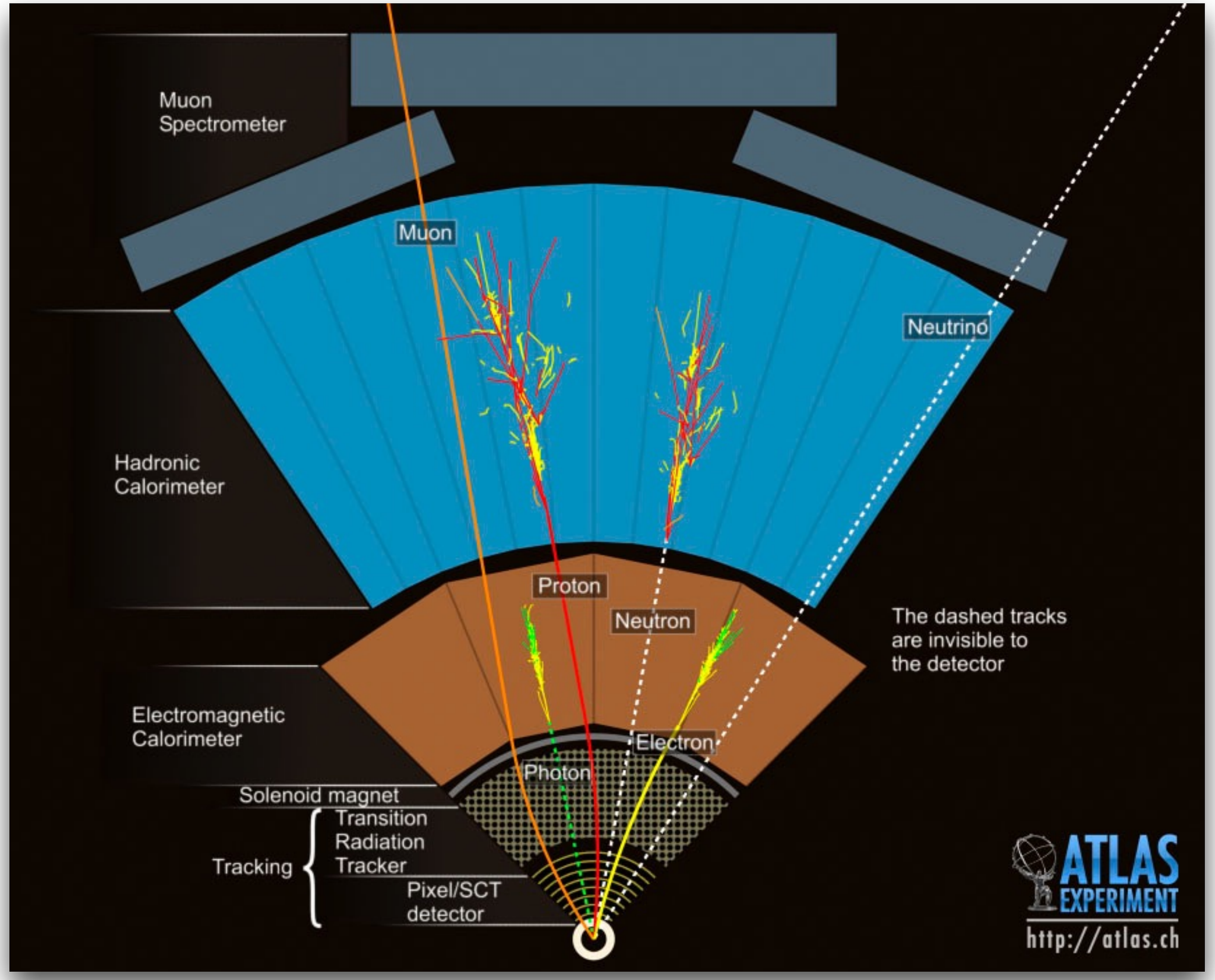

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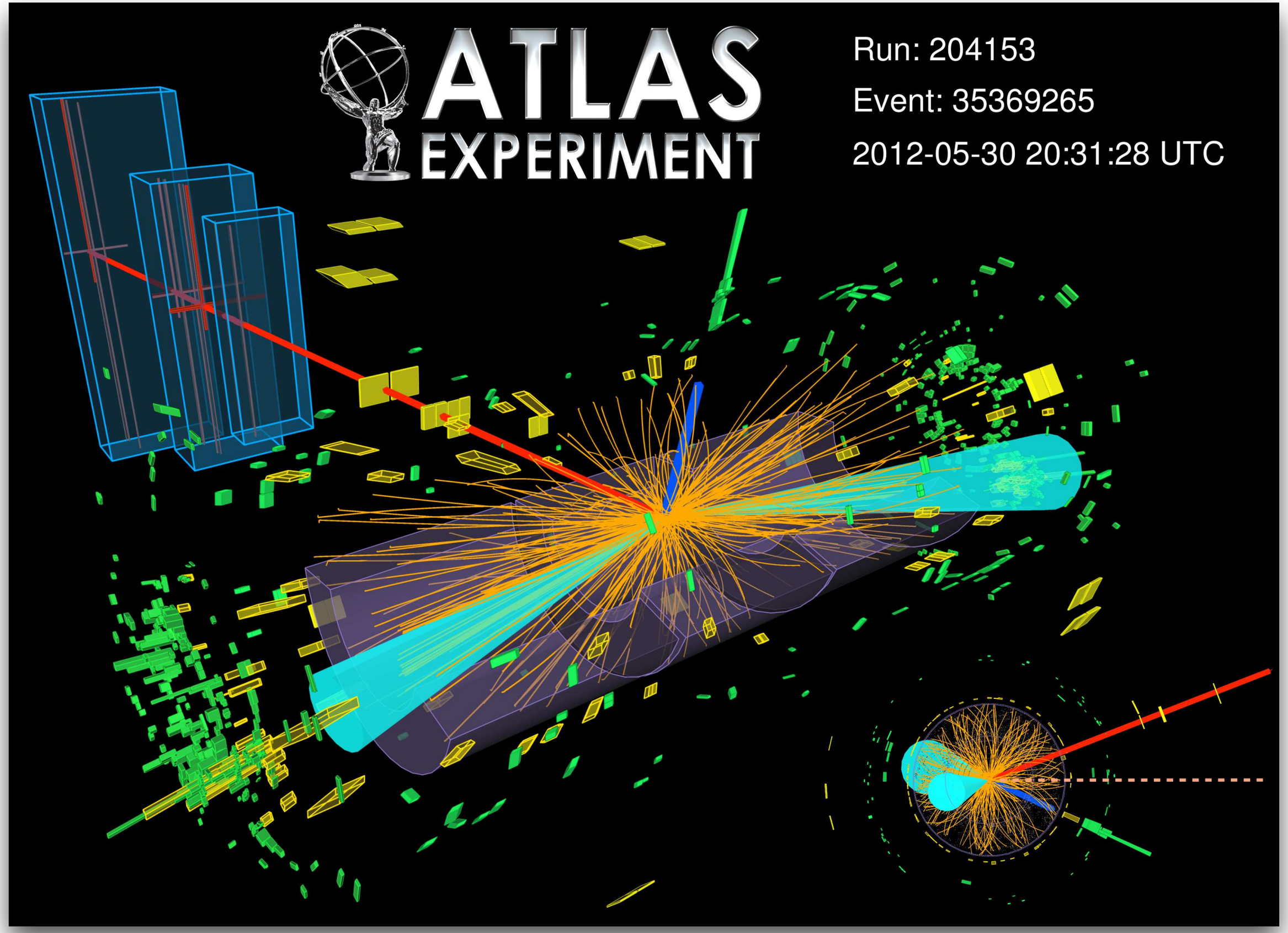
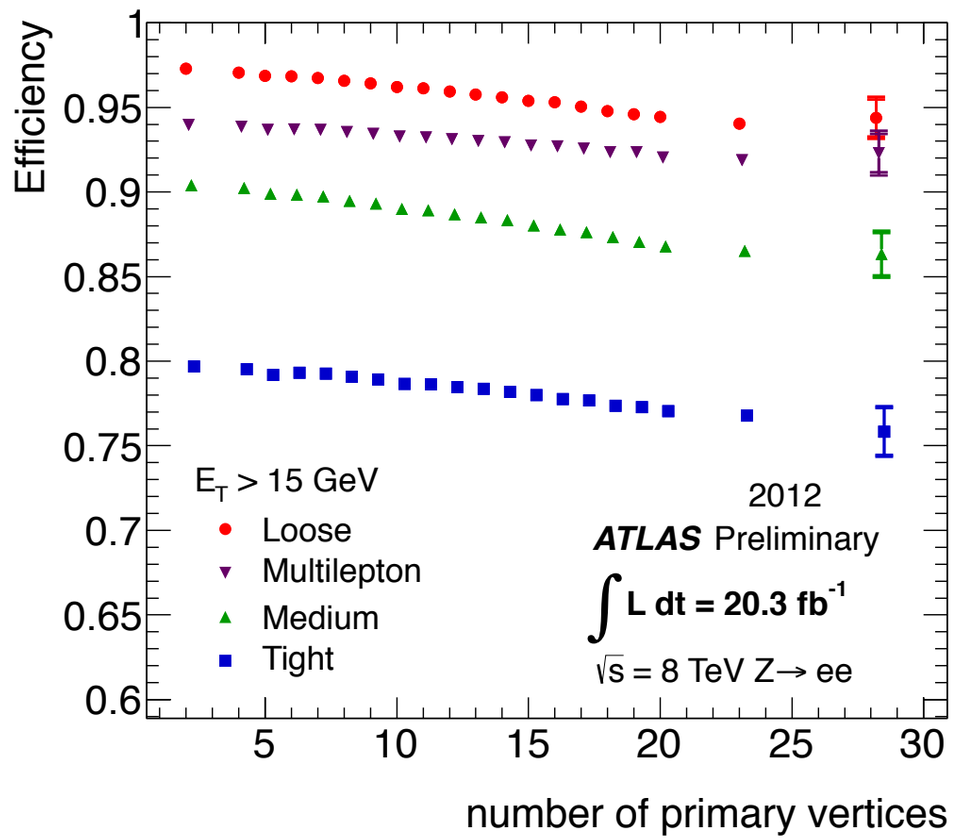
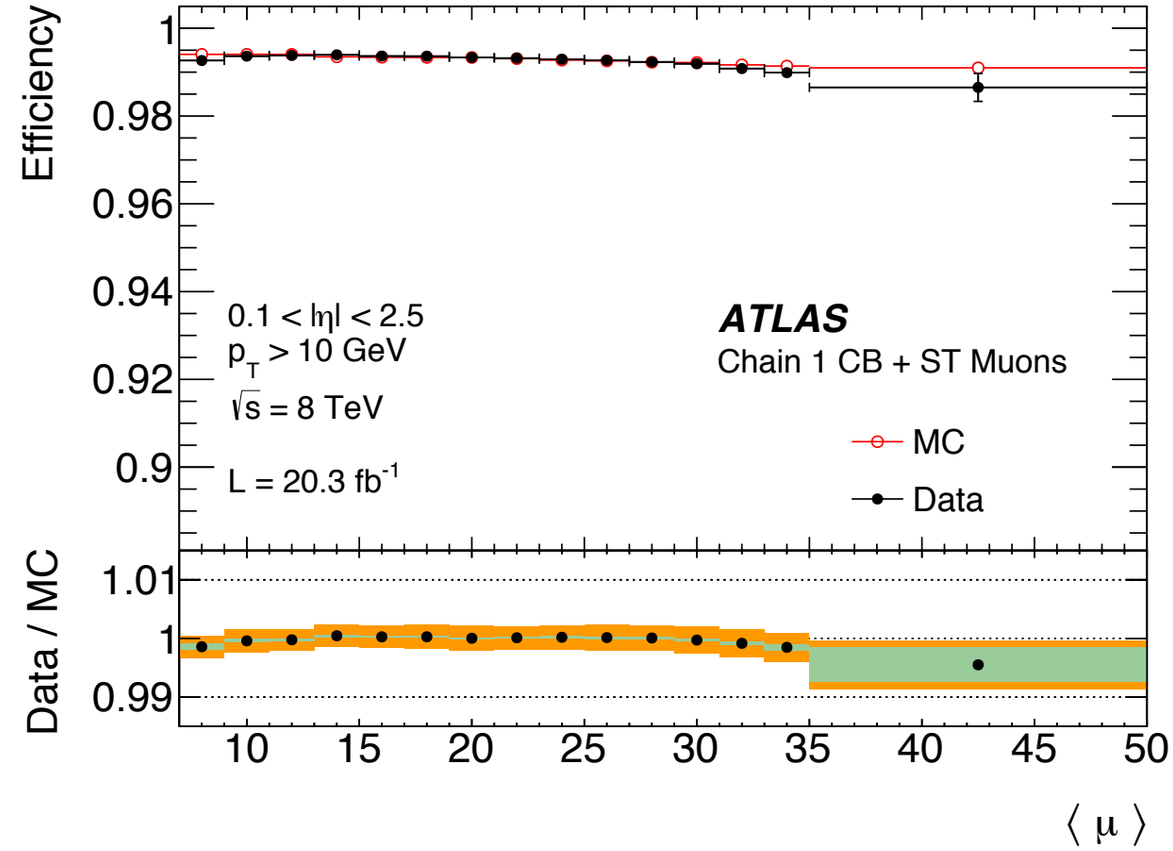


Electron and muon reconstruction





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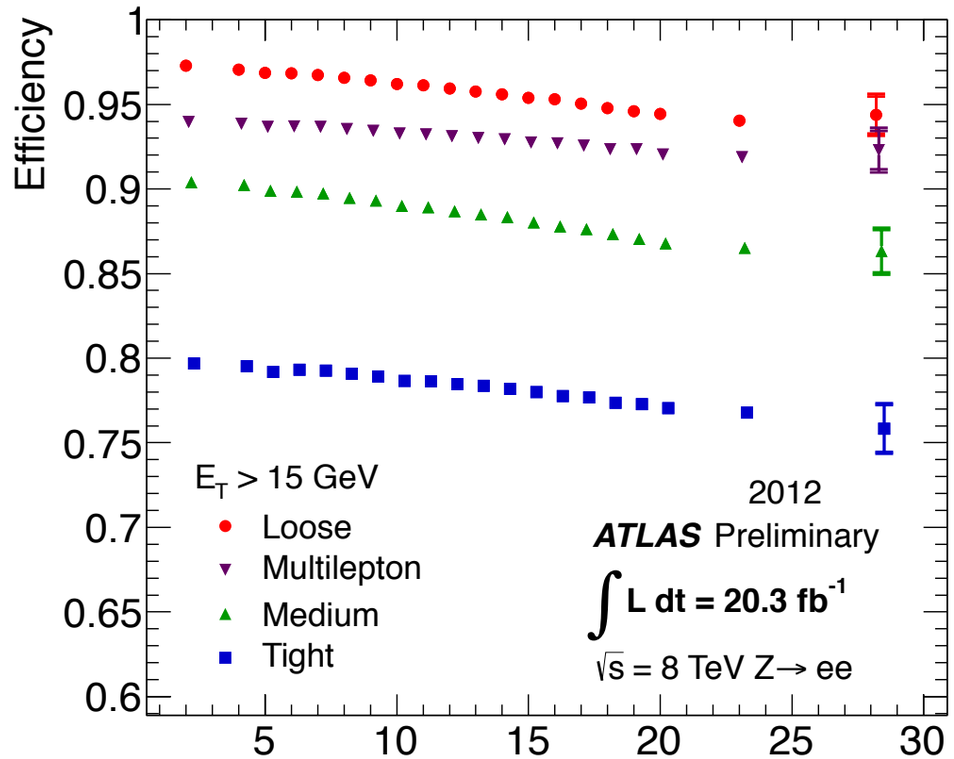

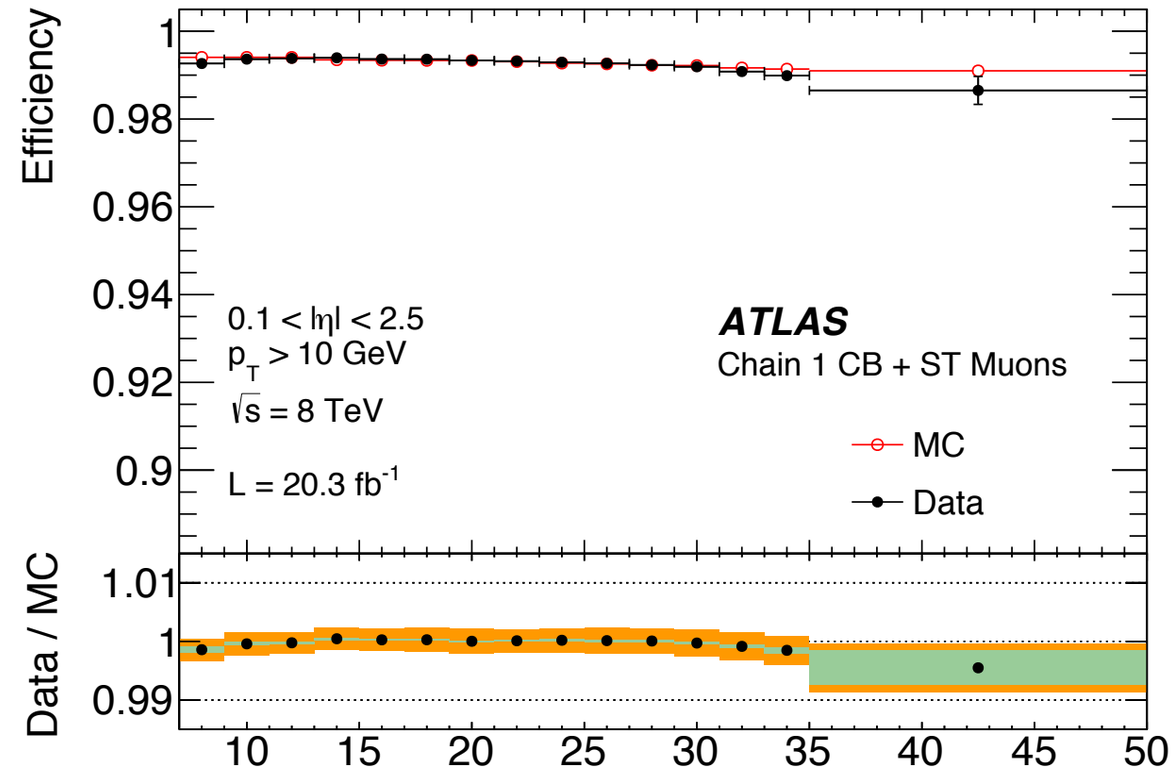

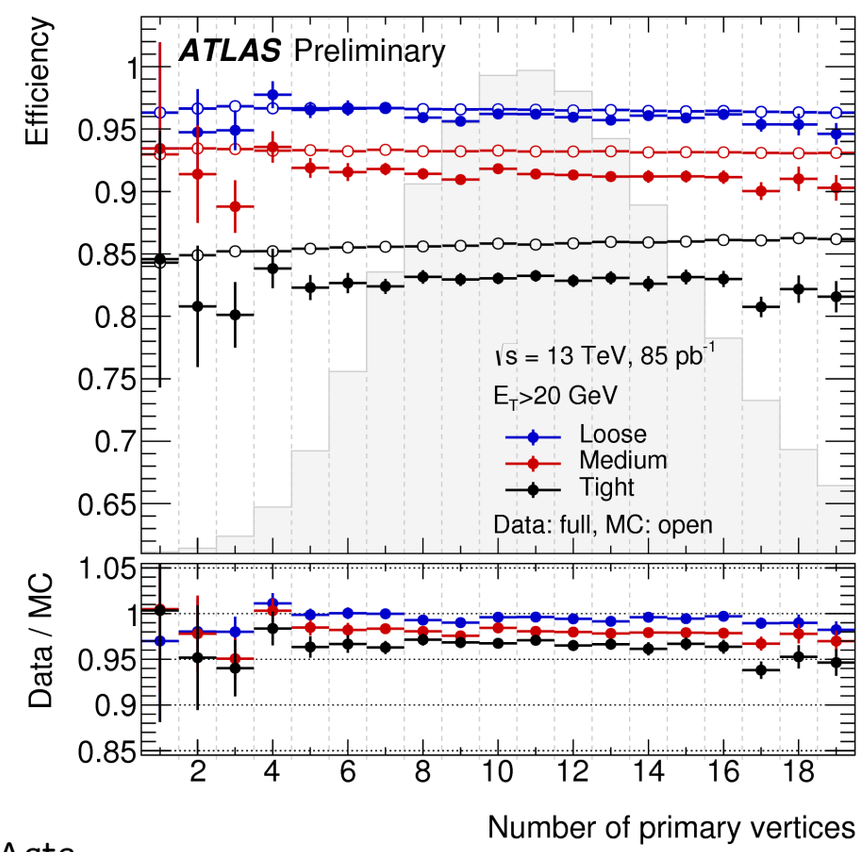

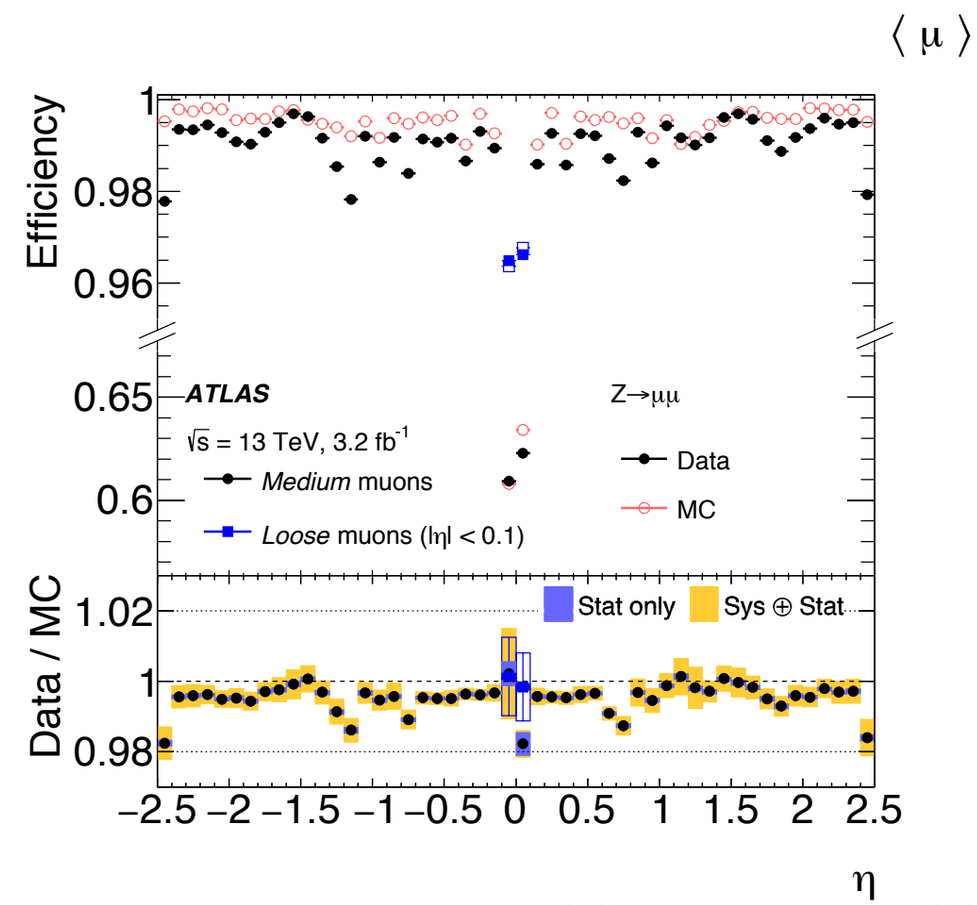

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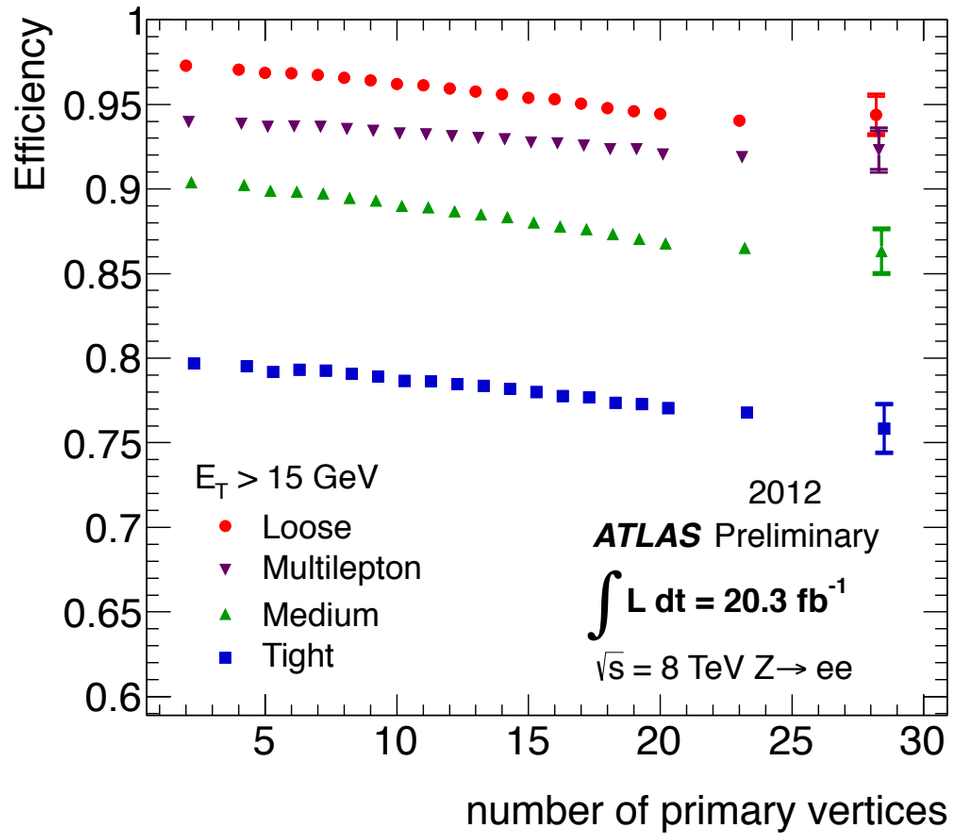
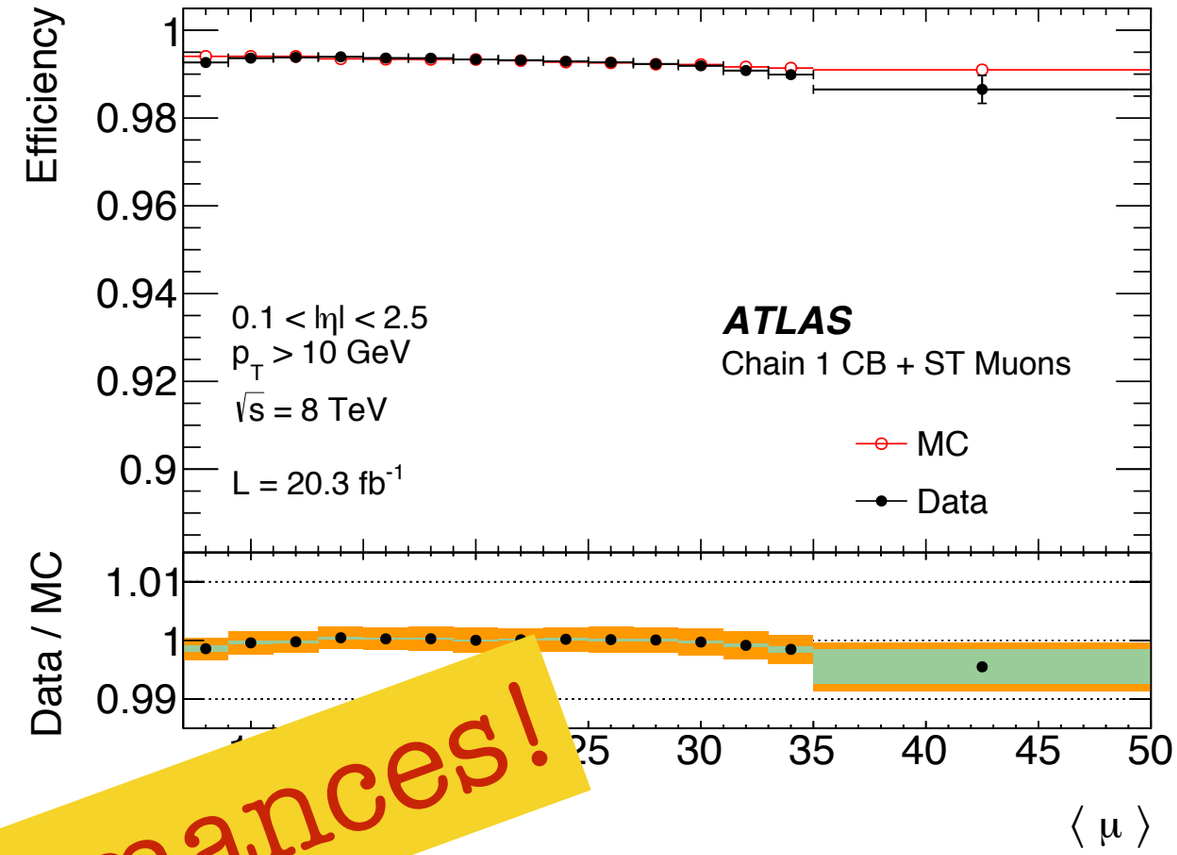
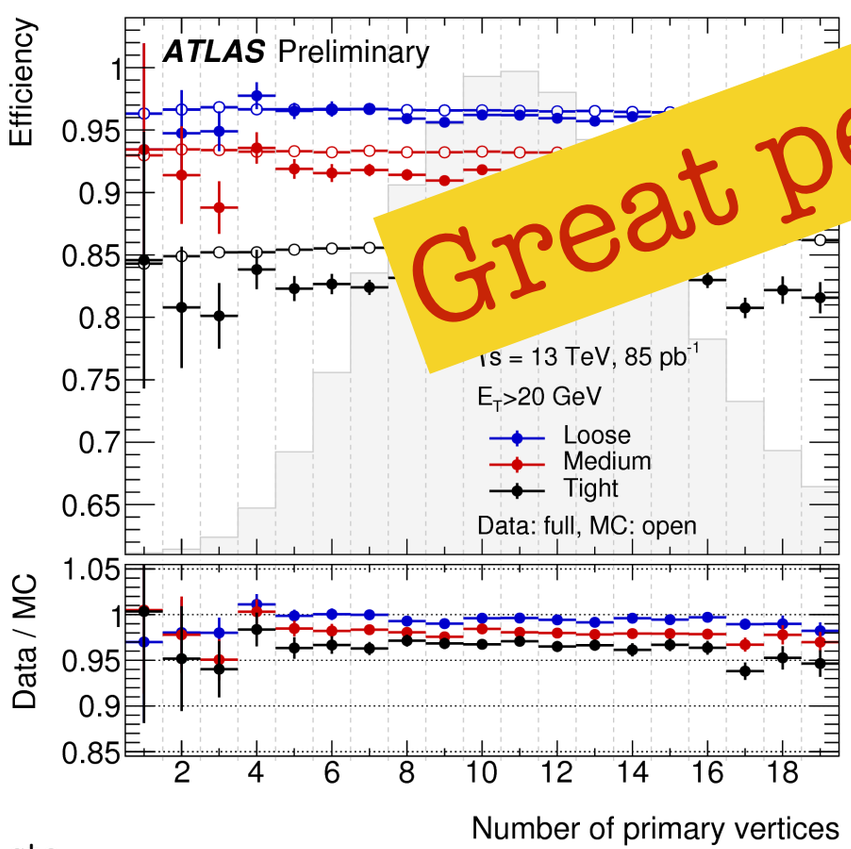
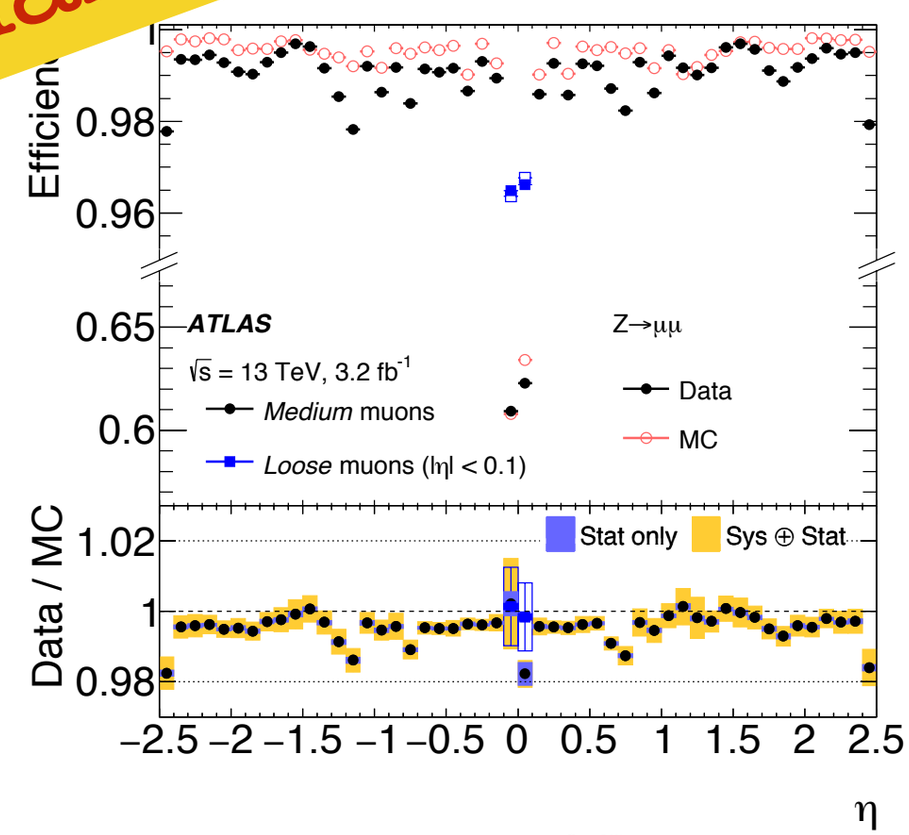


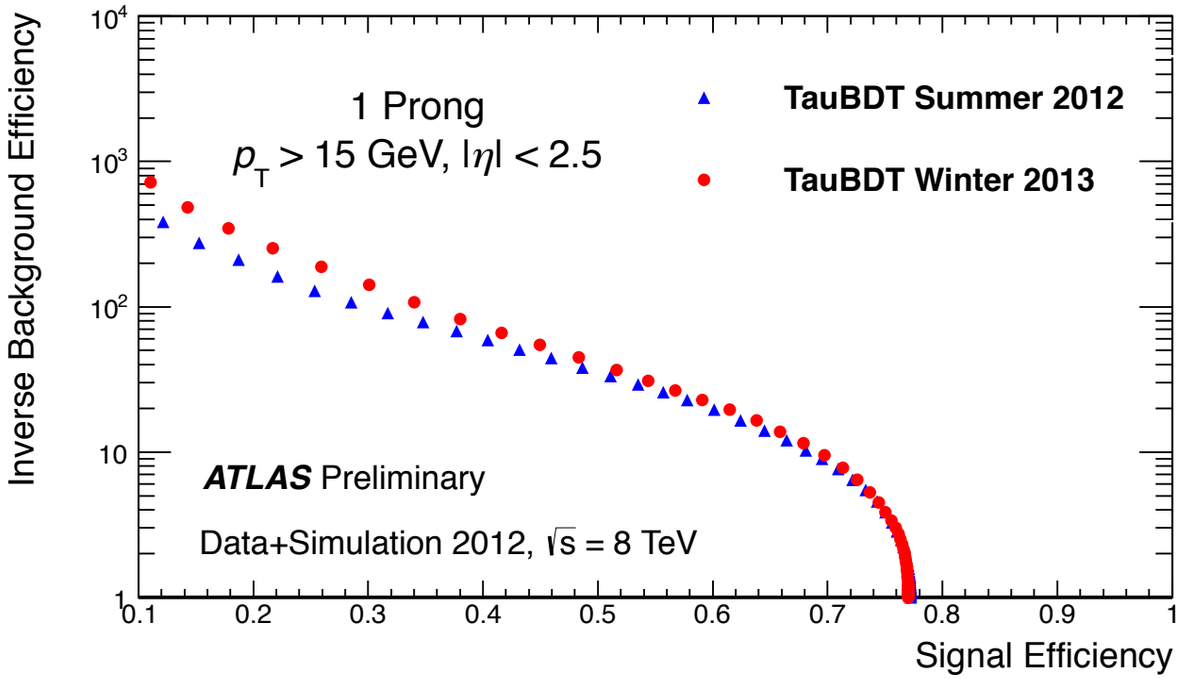


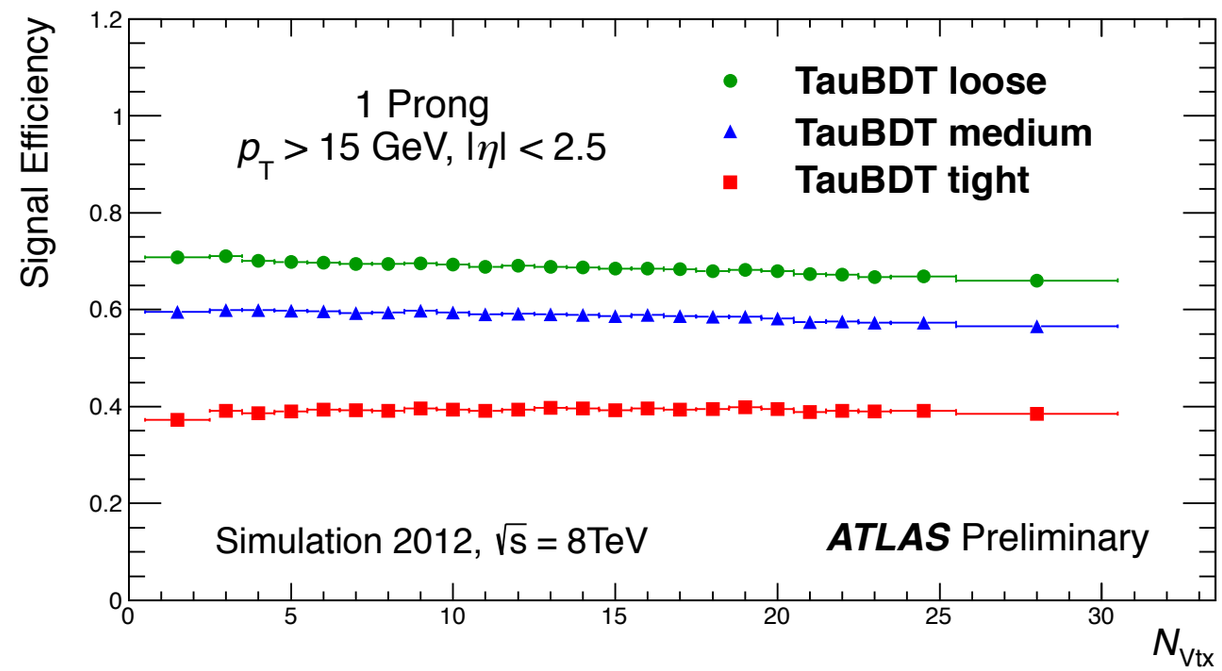
Great performances!

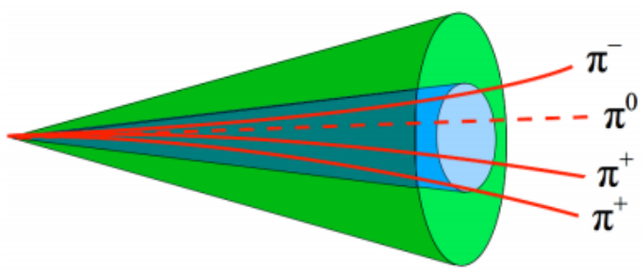


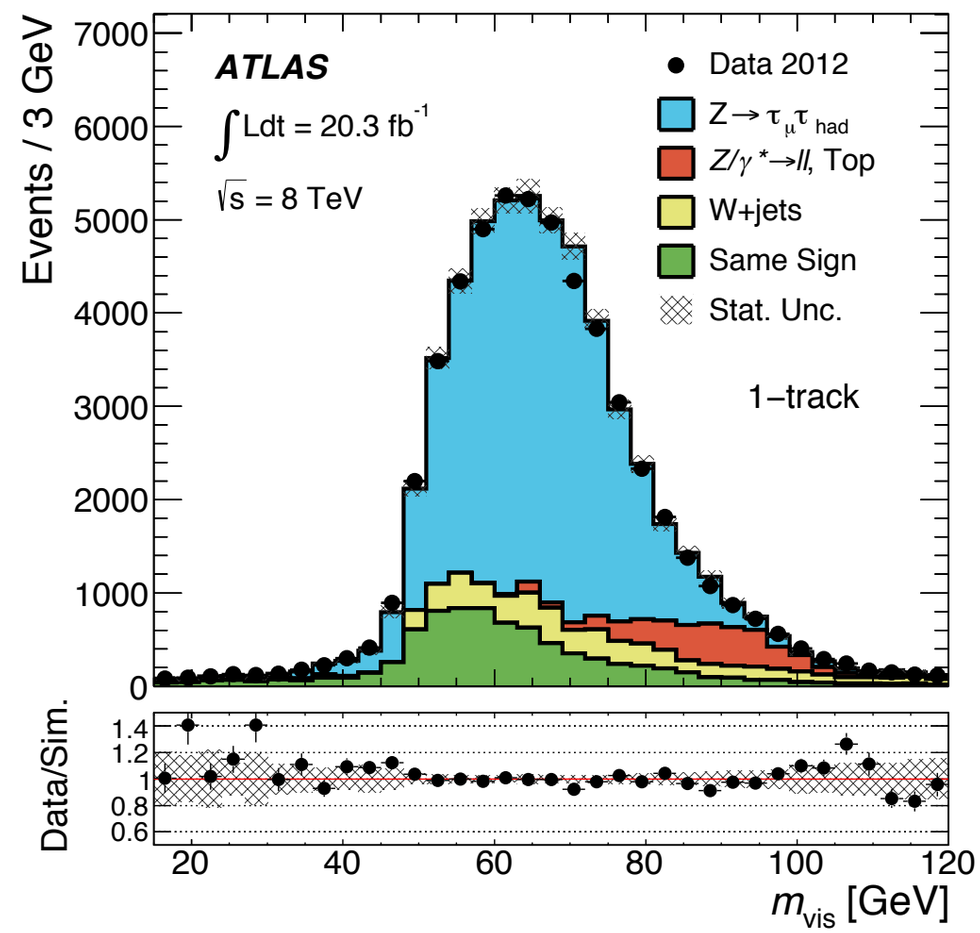


Hadronic tau reconstruction









- Multivariate hadronic tau identification.
  - Use information about shower shape in calorimeter and tracking detectors.
  - TauID systematic uncertainties: 2.5% for 1-prong taus,
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- Tau energy scale (TES) derived using in situ calibration based on $Z \to \tau\tau$ peak position.

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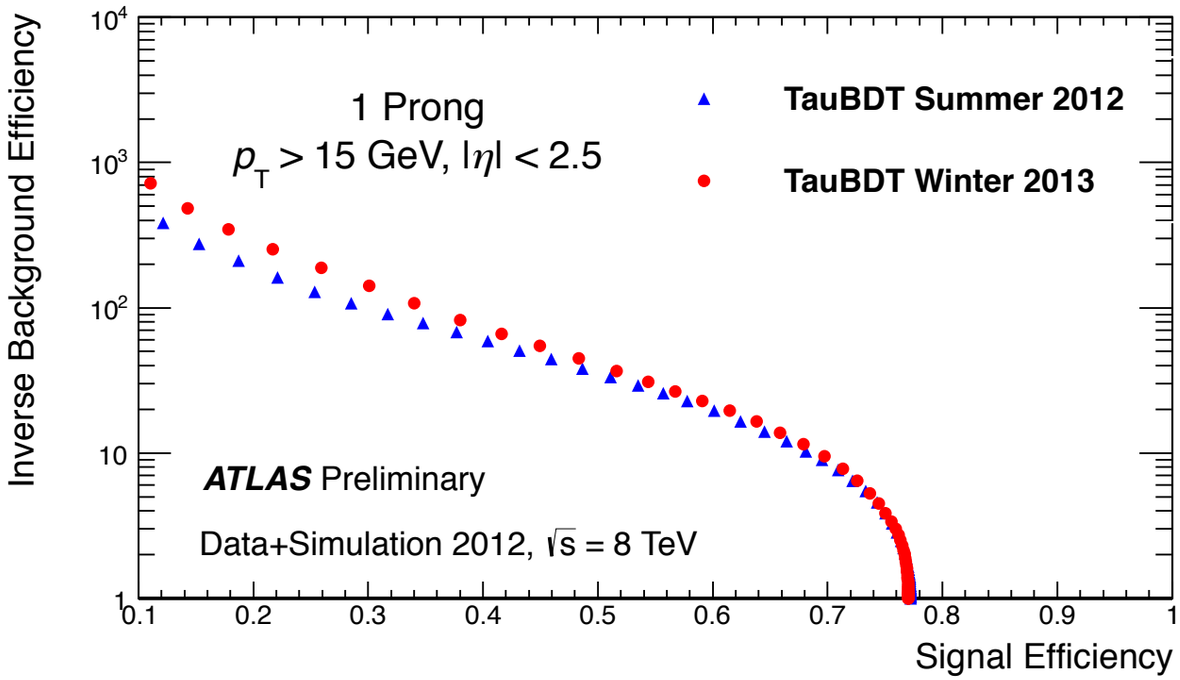

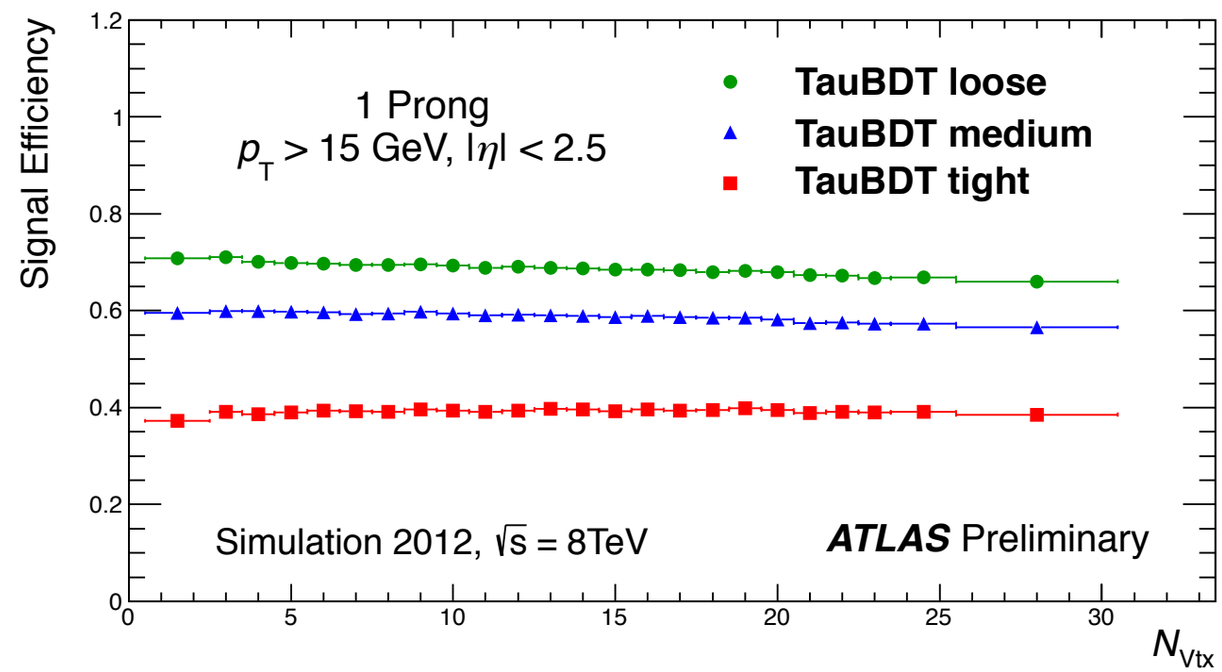

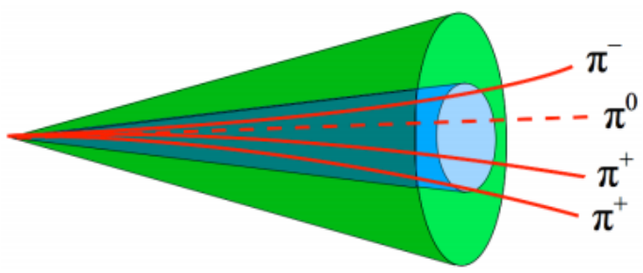

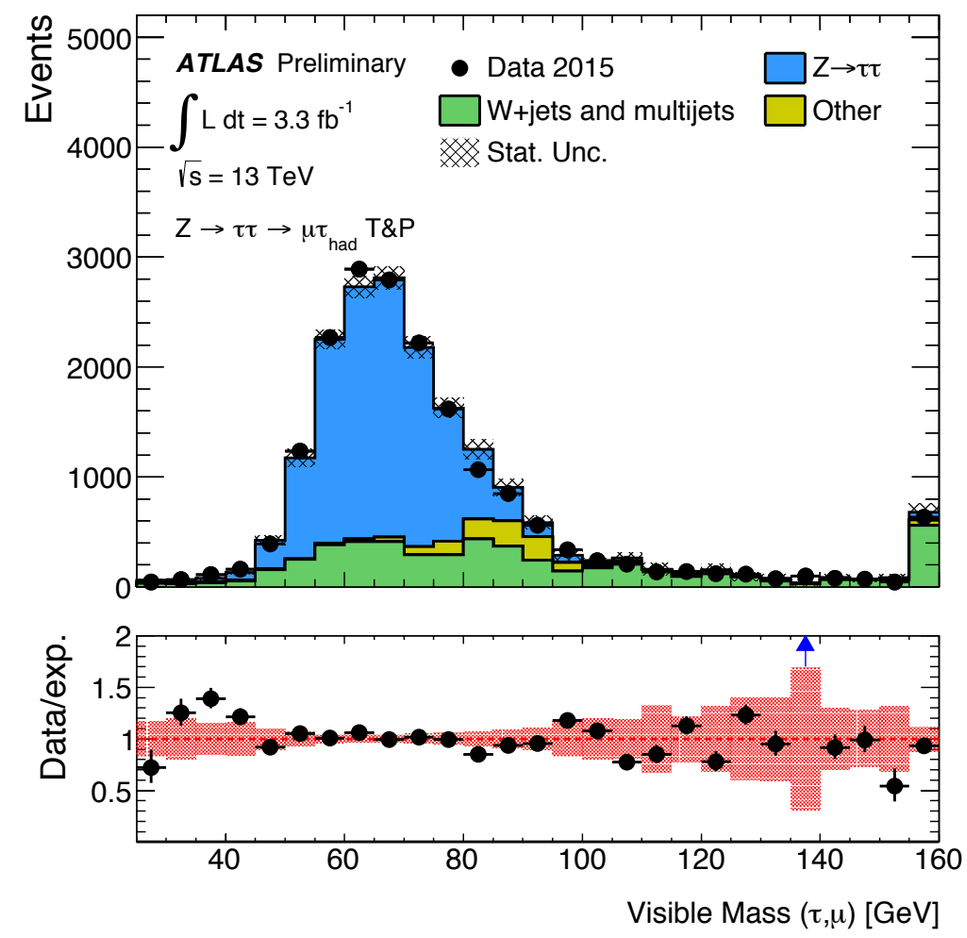

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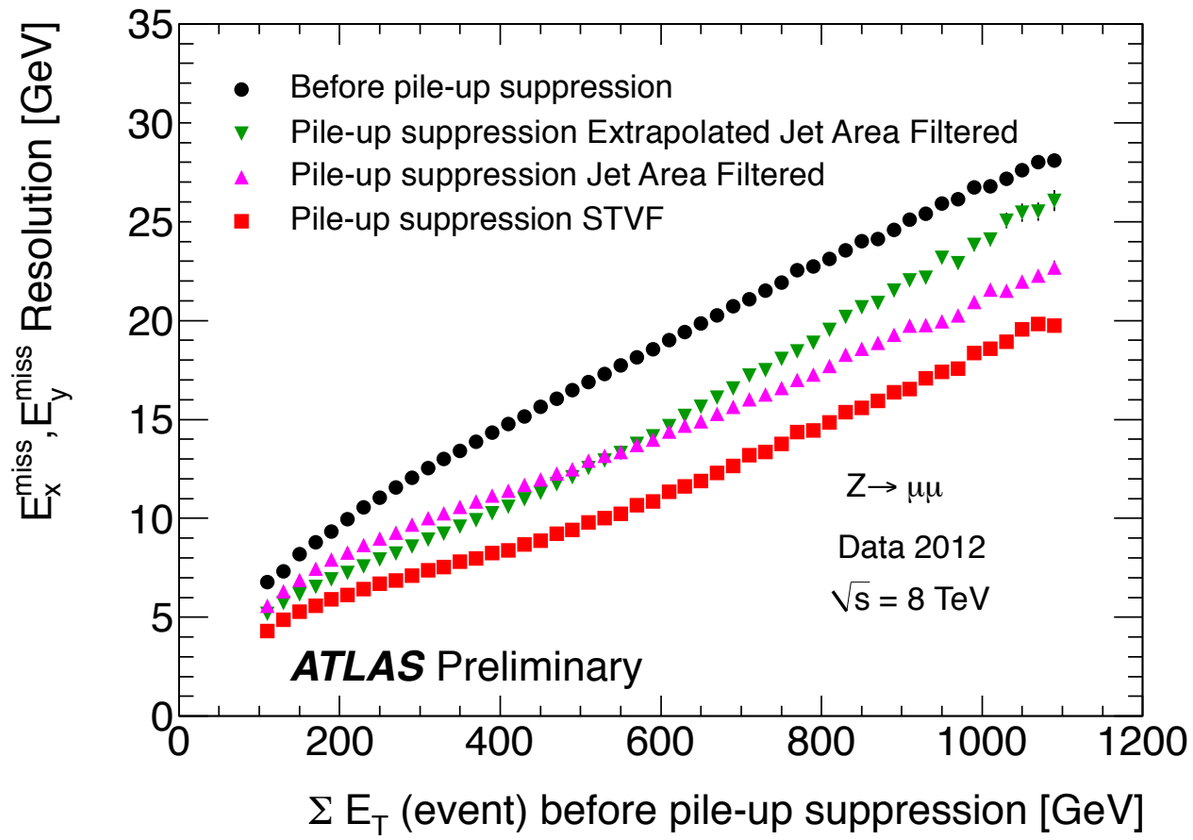
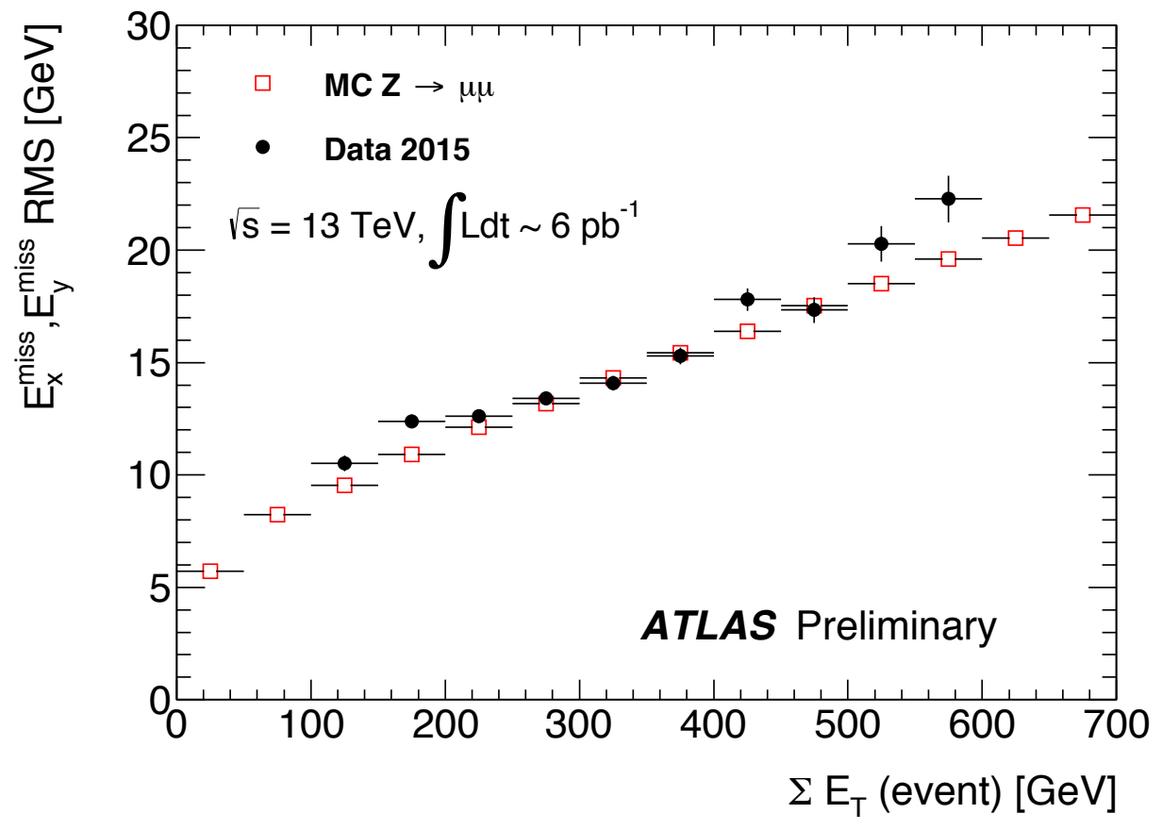
Missing energy





- Good MET resolution very important for $H \to \tau\tau$ search.
  - MET is used in event selection and in $M_{\tau\tau}$ reconstruction.

$H \rightarrow \tau\tau$

Outline

- Higgs boson discovery
- Evidence of the decay of the Higgs boson into tau pairs
- Search for Lepton Flavor Violating decays of the Higgs boson

Event Selection & Categorization

- **Basic** event **selection** based on final state.
- Additional (minimal) requirements to suppress specific backgrounds (channel dependent).
  - The **signal/bkg separation** is provided by the **MVA** analysis.
- Two **categories** are defined for each channel:
  - **VBF**: two jets with high η separation.
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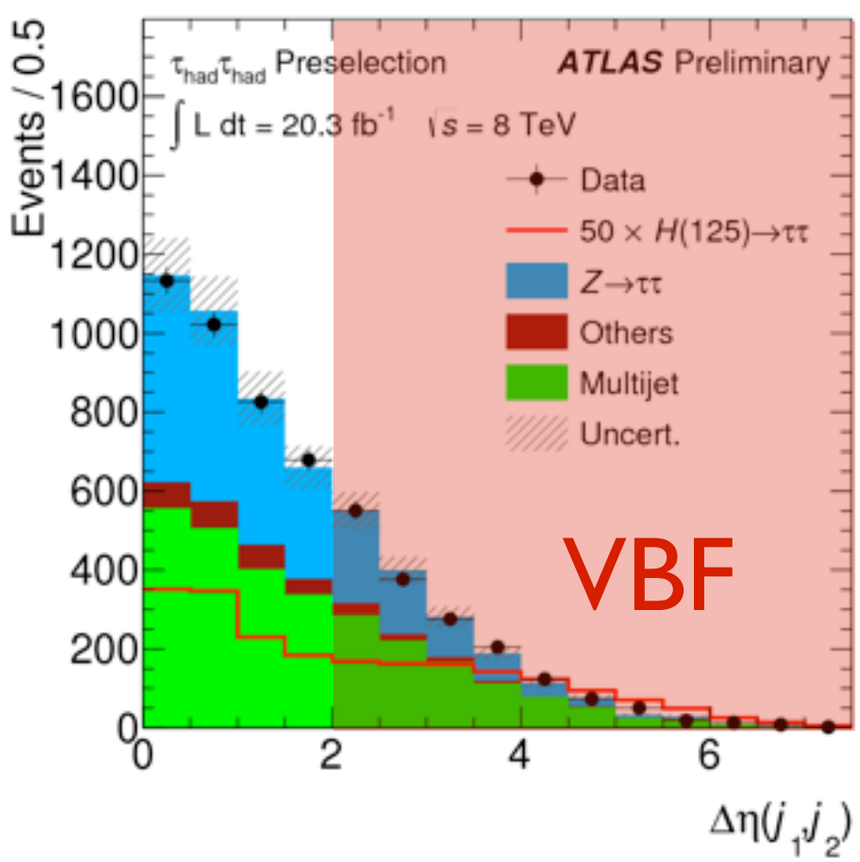

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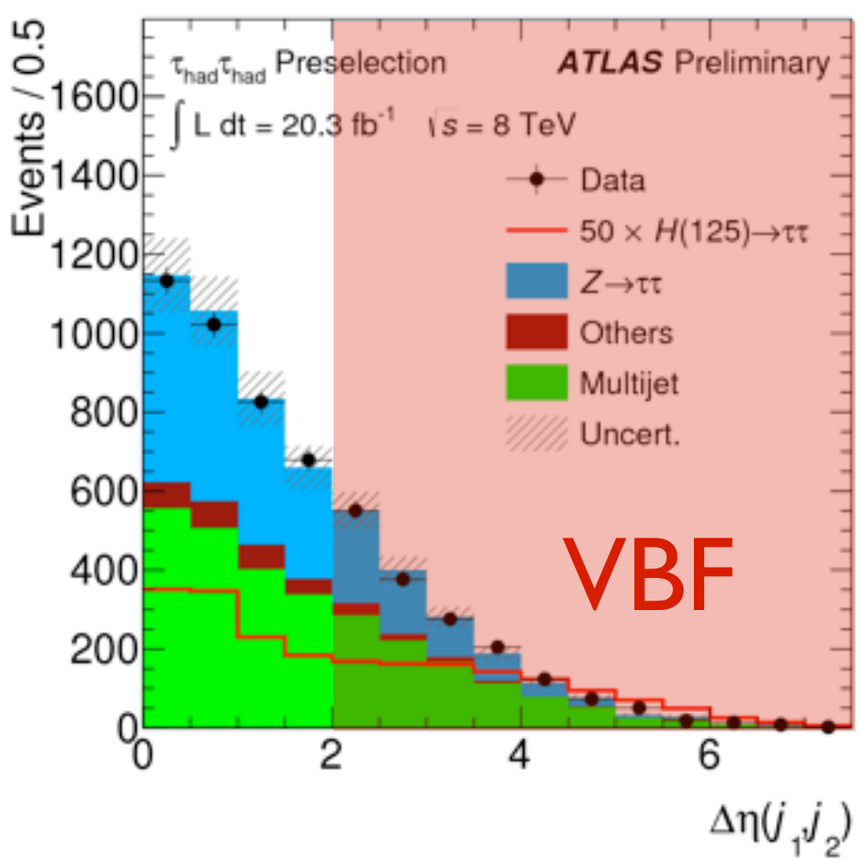

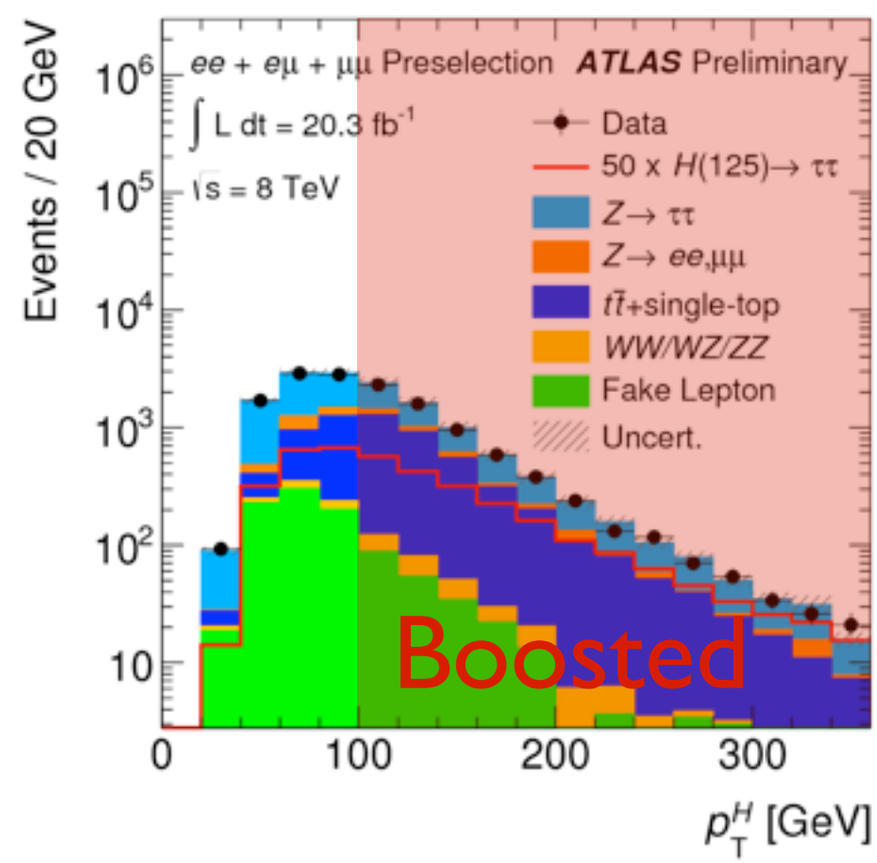

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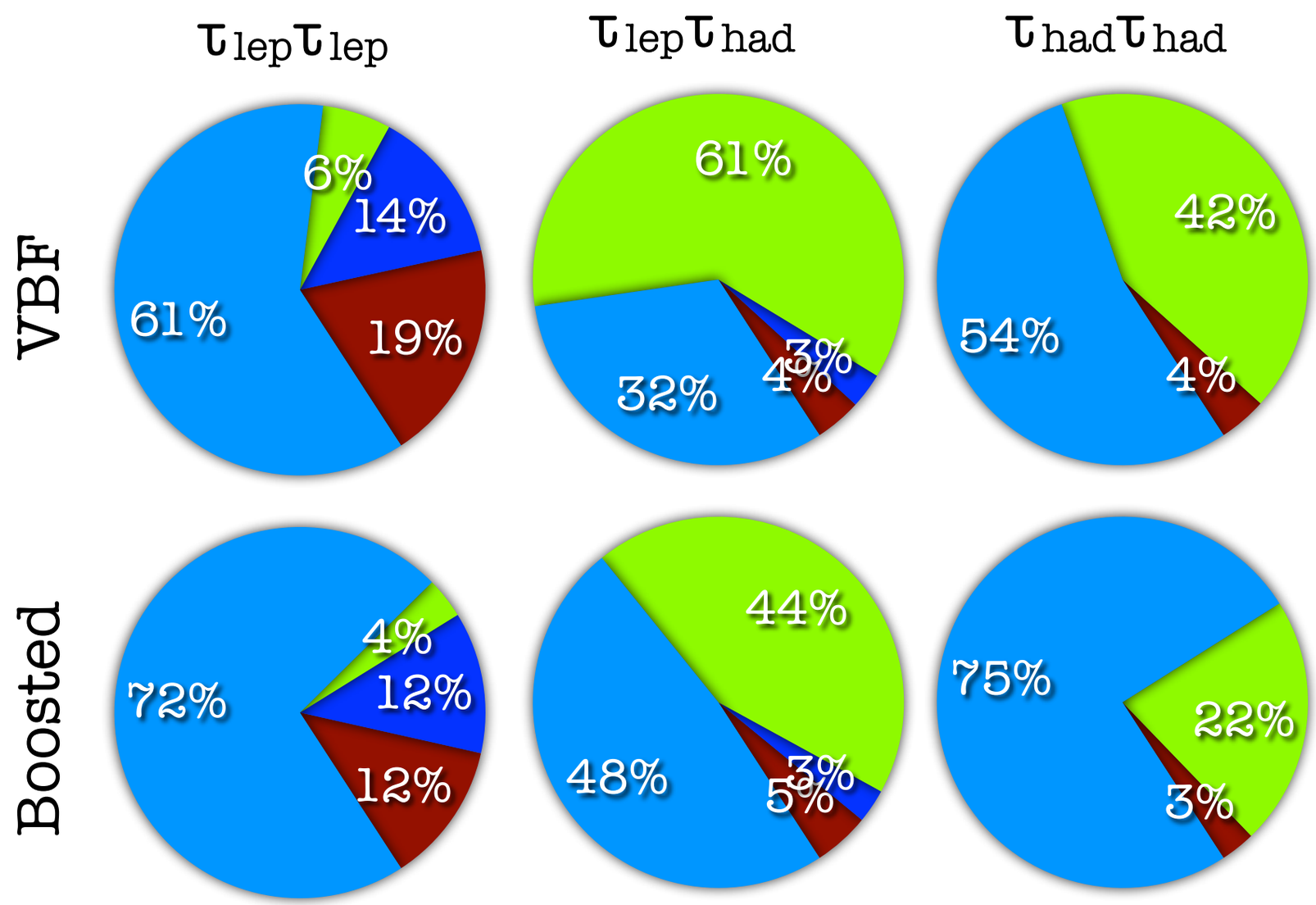
	VBF	Boosted
$\tau_{lep}\tau_{lep}$	VBF: 55% ggf: 41%	VBF: 17% ggf: 64%
$\tau_{lep}\tau_{had}$	VBF: 65% ggf: 33%	VBF: 18% ggf: 67%
$\tau_{had}\tau_{had}$	VBF: 60% ggf: 40%	VBF: 18.5% ggf: 62%

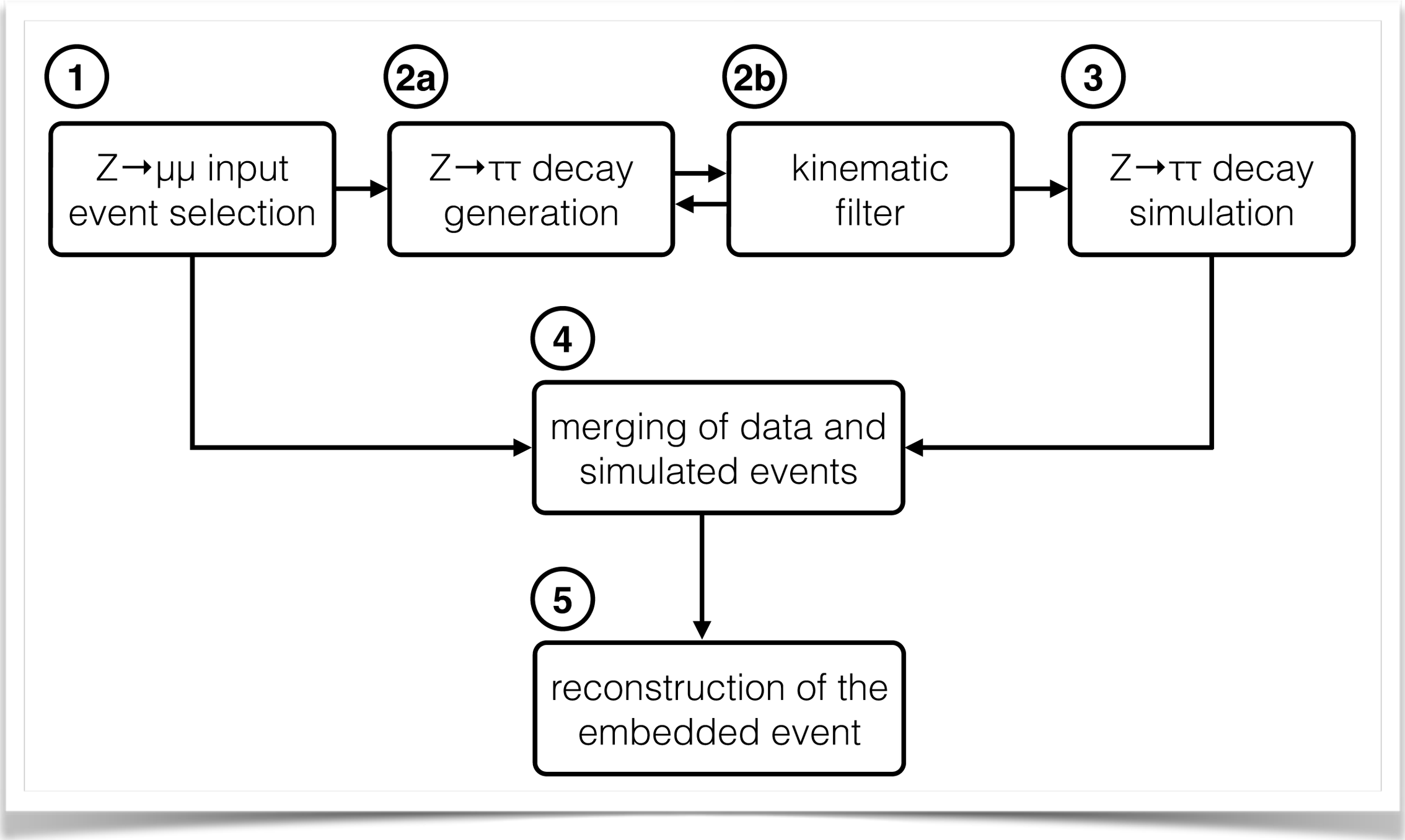
Background composition

- Quite **different** background **composition** across channels and categories.
- Mainly $Z \to \tau\tau$, misidentified leptons and τ_{had}, top.
- Different background estimation strategies: data-driven methods and MC simulation.
- **Normalization** of the background components done in **control regions** (CRs) when possible. Otherwise normalized to the theoretical cross section.



S/B	VBF	Boosted
$\tau_{lep}\tau_{lep}$	0.024	0.011
$\tau_{lep}\tau_{had}$	0.017	0.007
$\tau_{had}\tau_{had}$	0.023	0.011

Z→ττ background - Embedding



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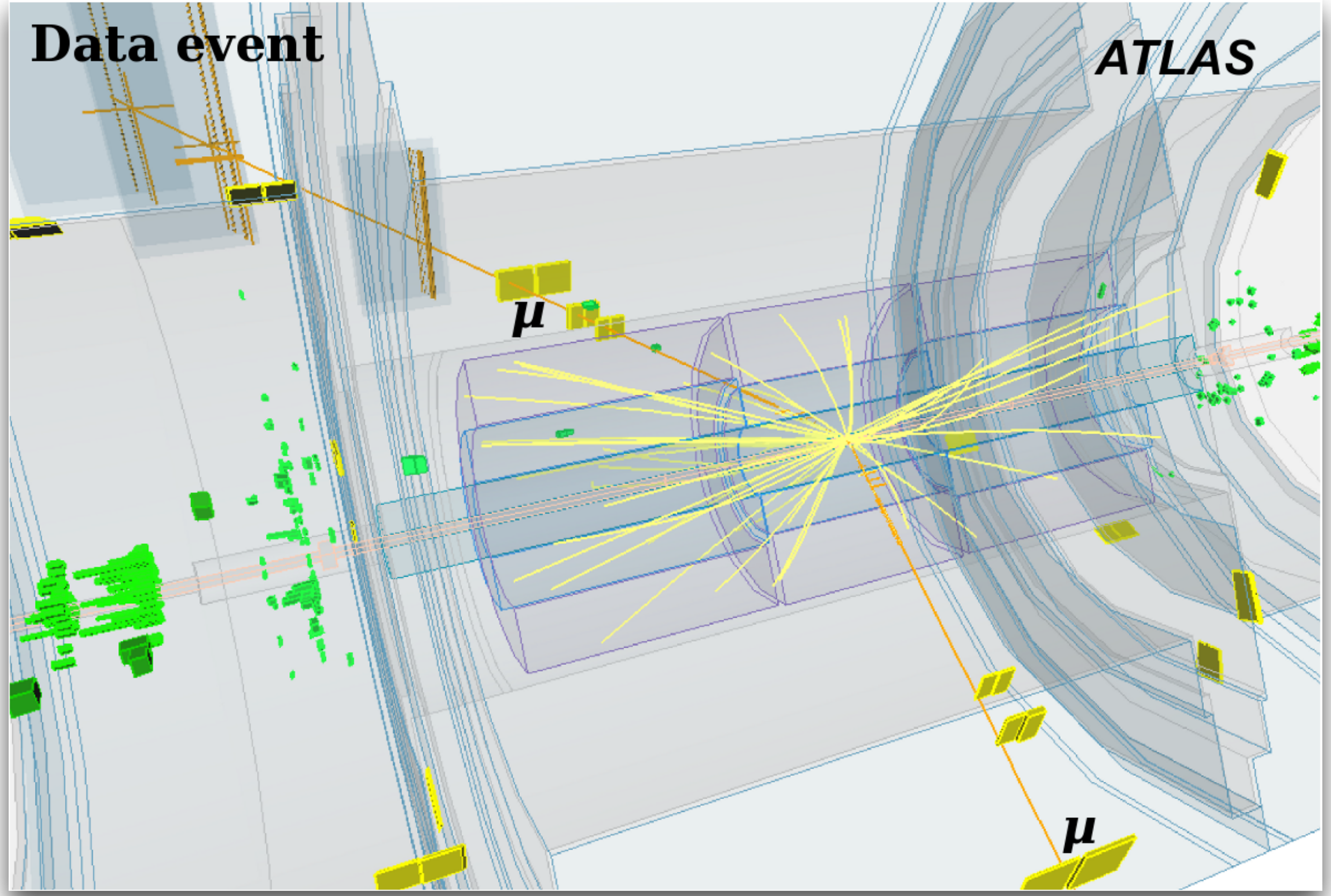
Z→ττ background - Embedding

JINST 10 (2015) P09018



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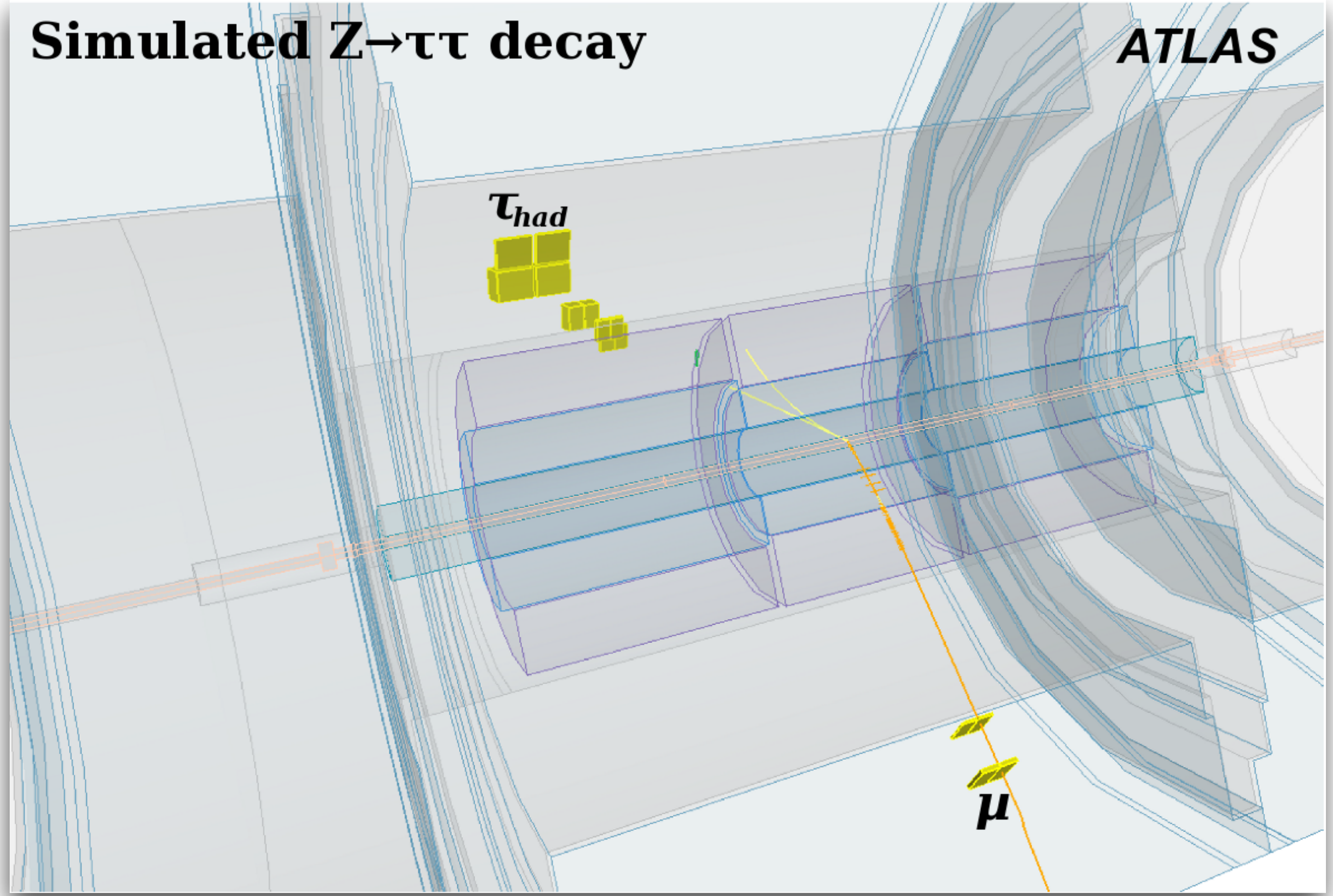
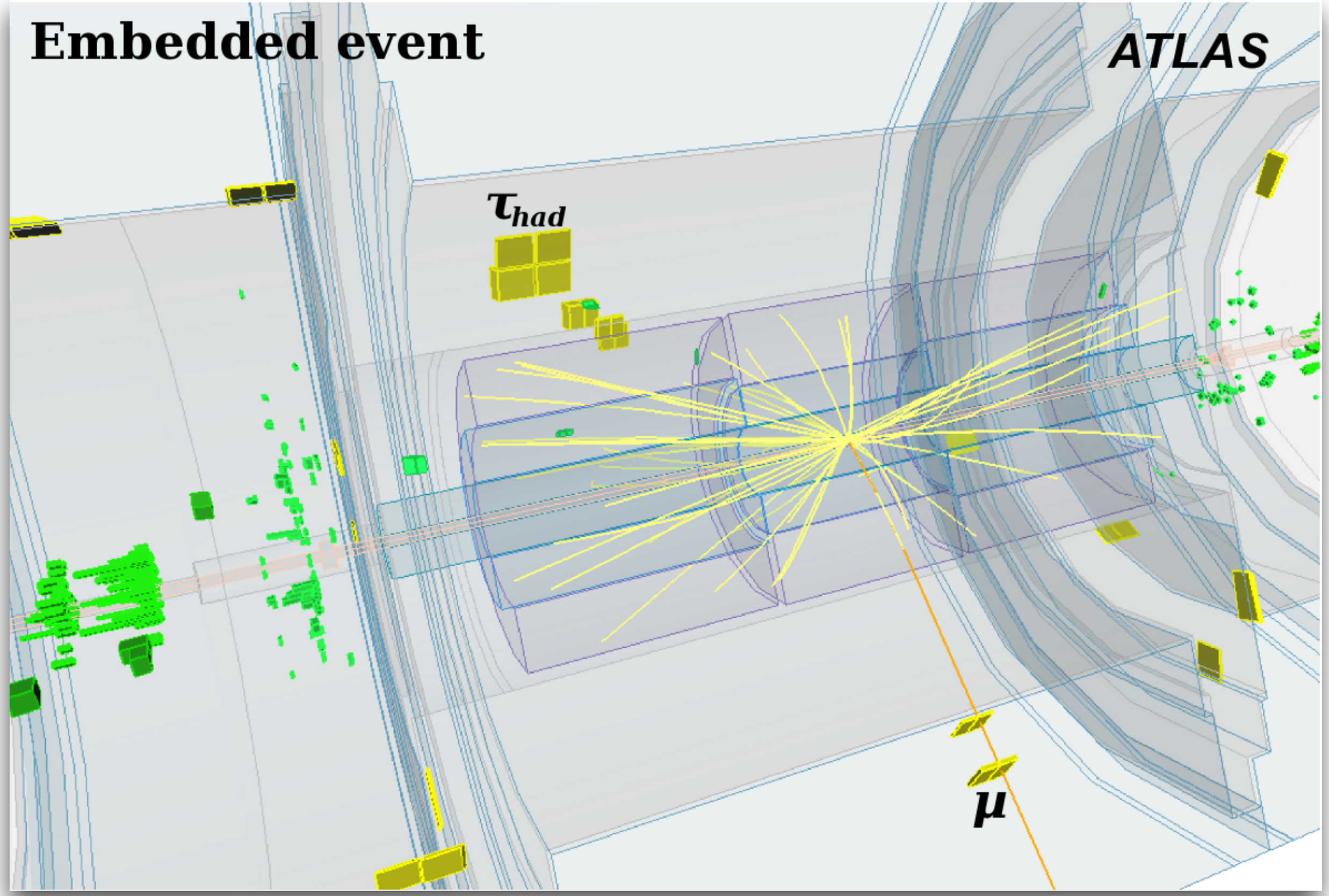


$Z \to \tau\tau$ background - Embedding

JINST 10 (2015) P09018



$Z \to \tau\tau$ background - Embedding

- Apart from τ-decays, all properties of a $Z \to \tau\tau$ event are modeled by actual $Z \to \mu\mu$ data.
- Major advantages of embedding: Z-boson kinematics, jets, MET resolution, pile-up, and VBF/EWK production are directly modeled by data.

Variables used in the Boosted Decision Tree

- Separate BDTs are trained for each channel and category.
  - Trained on 8 TeV samples and applied to both 7 and 8 TeV analyses.
- Signal with m_H = 125 GeV is used.

- Variable chosen according to:
  - resonance properties: $m(\tau\tau)$, $\Delta R(\tau\tau)$, et al.
  - VBF topology: $m(jj)$, $\Delta\eta(jj)$, et al.
  - event activity: scalar & vector p_T-sum.
  - event topology: m_T, object centralities, $p_T(\tau_1)/p_T(\tau_2)$, et al.

- Using 6 to 9 variables per channel per category.

Cross checks

- Need to carefully check all **input variables** fed into the BDT.
  - All input variables are checked in validation regions enriched in major backgrounds.
  - All input variables are checked in the signal regions after categorization (MMC in low BDT score region).
  - All input variable correlations are validated.

- Need also to check that the **BDT output** is sensible.
  - BDT distributions are checked in validation regions enriched in major backgrounds.
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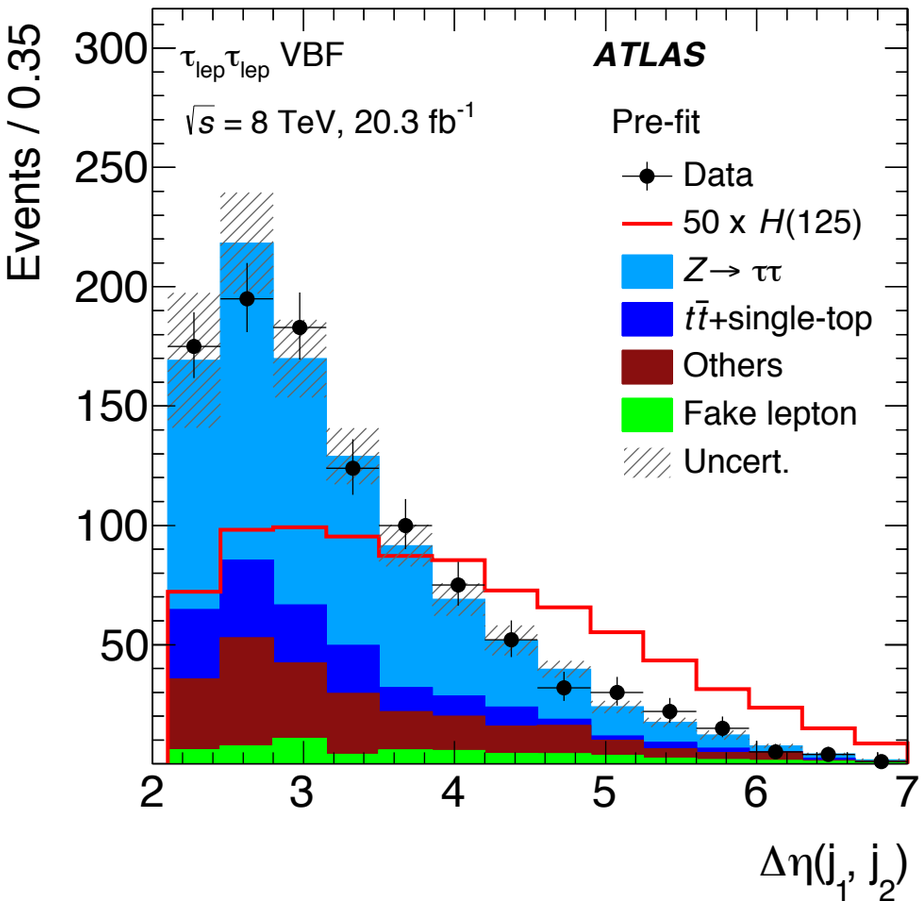
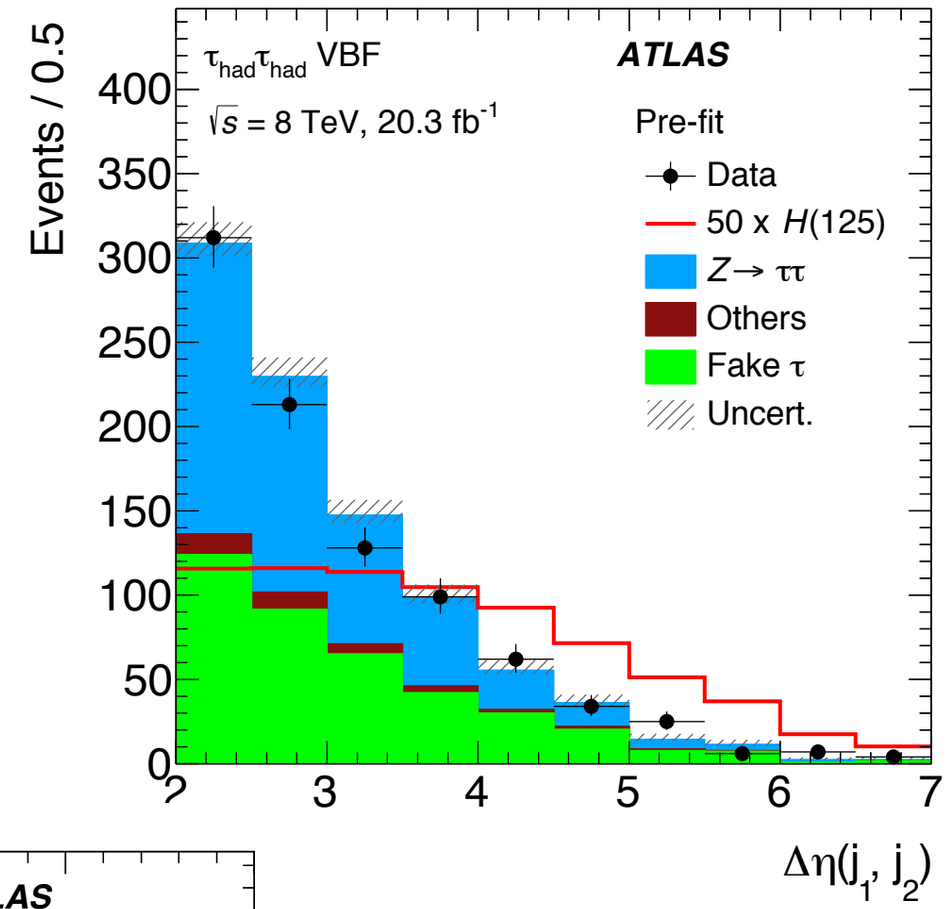
Looking at BDT input variables in signal regions





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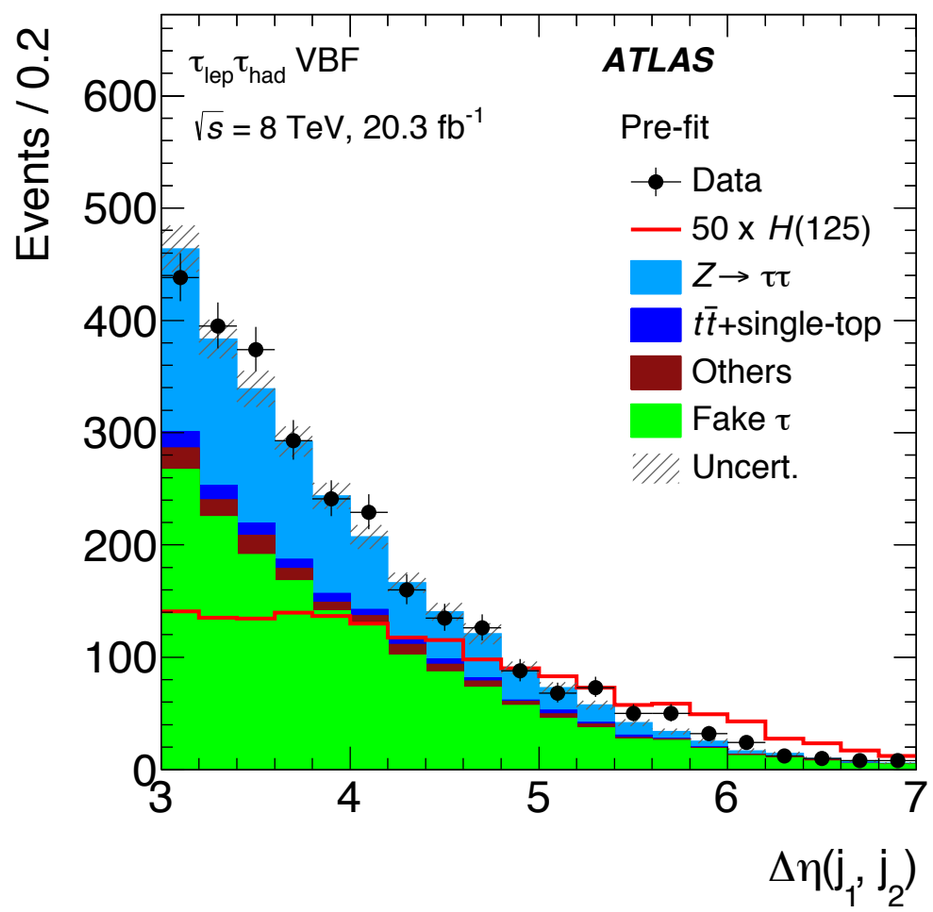
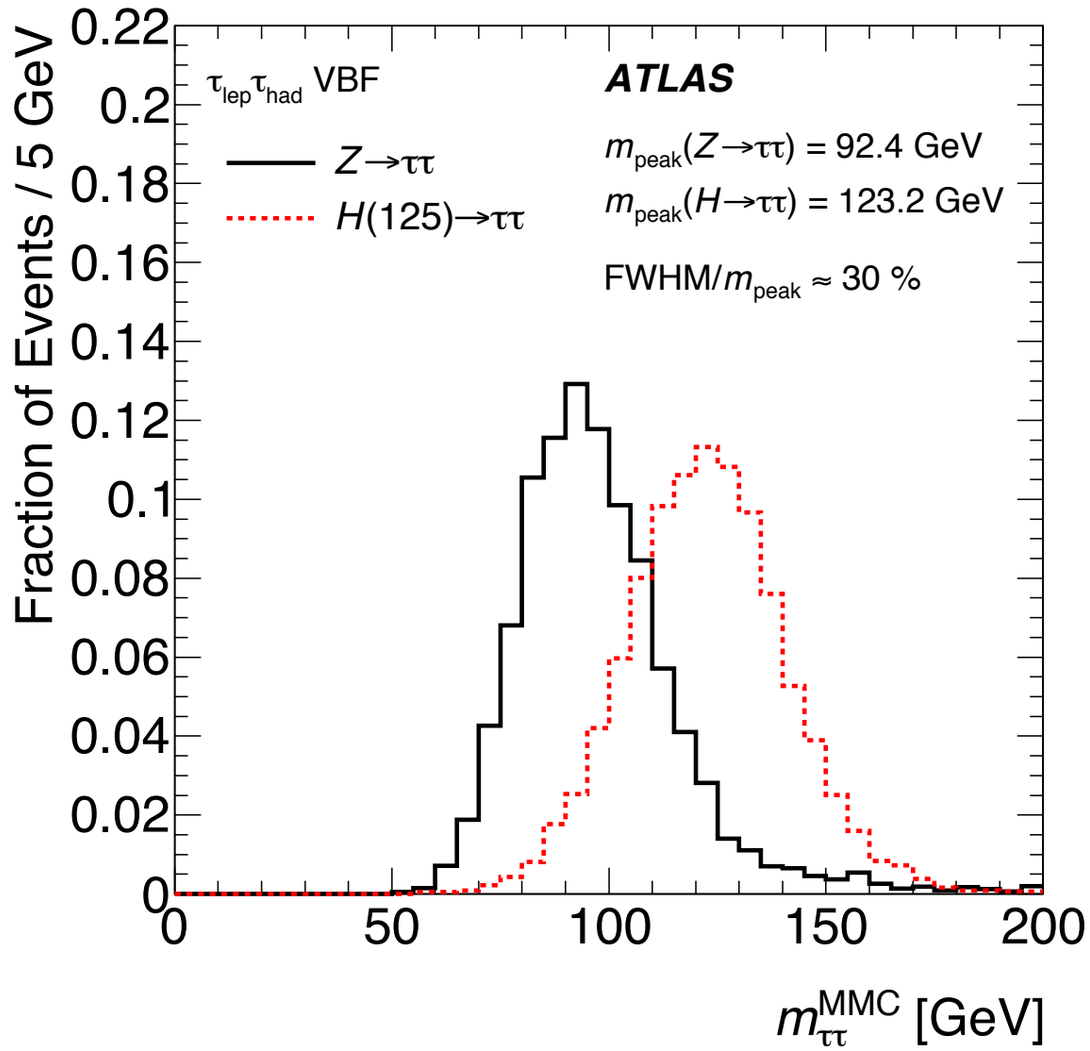


Mass reconstruction - Missing Mass Calculator



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- Good m(ττ) resolution most effective tool against Z→ττ.
  - m(ττ): most highly ranked BDT input variables.
- m(ττ) reconstructed by Missing Mass Calculator (MMC).
  - MMC is sophisticated technique to reconstruct m(ττ) in presence of neutrinos from τ-decays.
    - Requirement that mutual orientations of the neutrinos and other decay products are consistent with the mass and decay kinematics of a tau lepton.
  - Better than the collinear mass (collinear approximation not always holds).

Looking at BDT input variables

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$\tau_{lep}\tau_{lep}$

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$\tau_{lep}\tau_{lep}$

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$\tau_{had}\tau_{had}$

Looking at BDT input variables

Looking at BDT input variables

VBF Category

Looking at BDT input variables

VBF Category

Boosted Category

Looking at MMC

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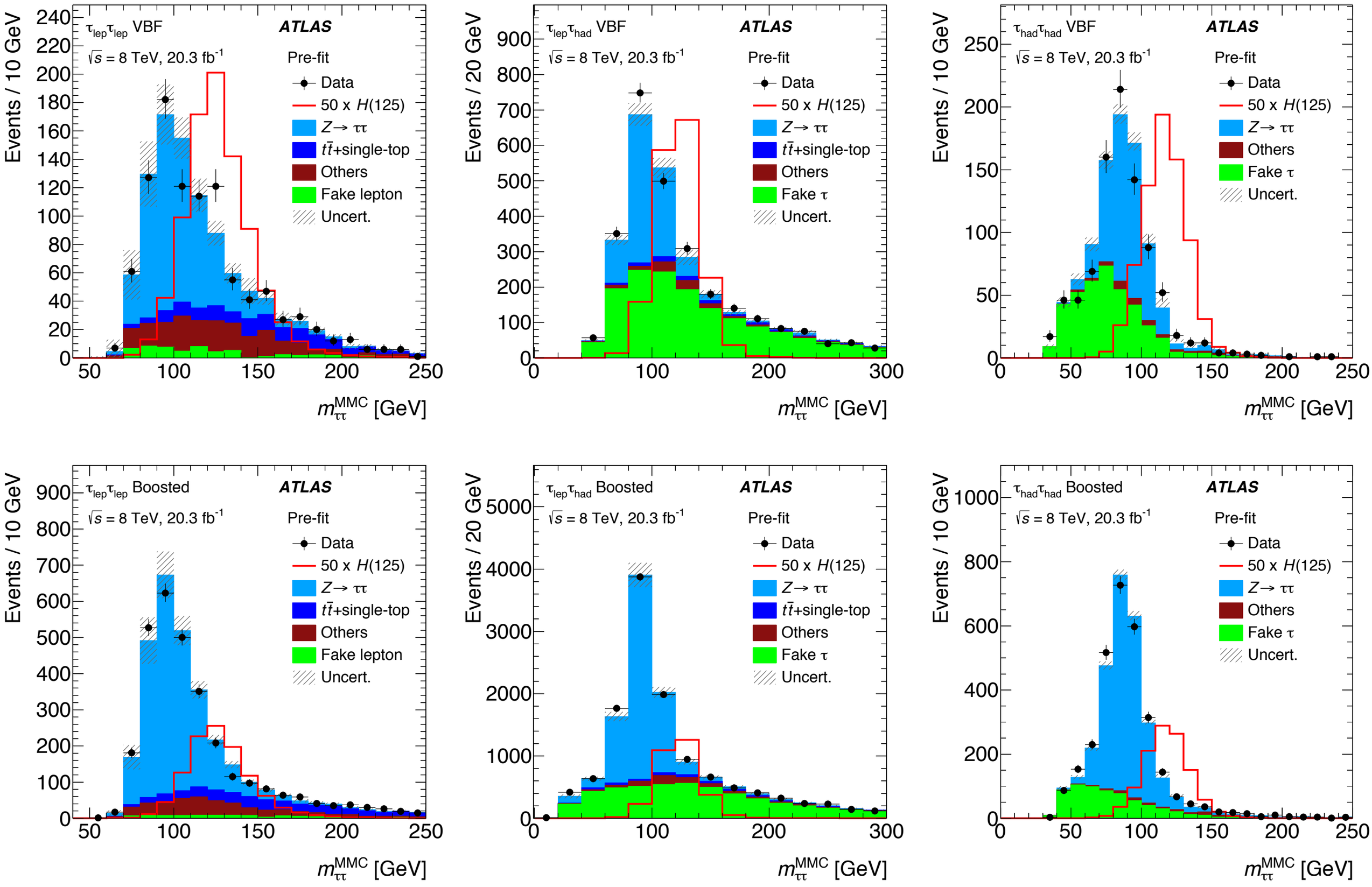

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Background modeling checks

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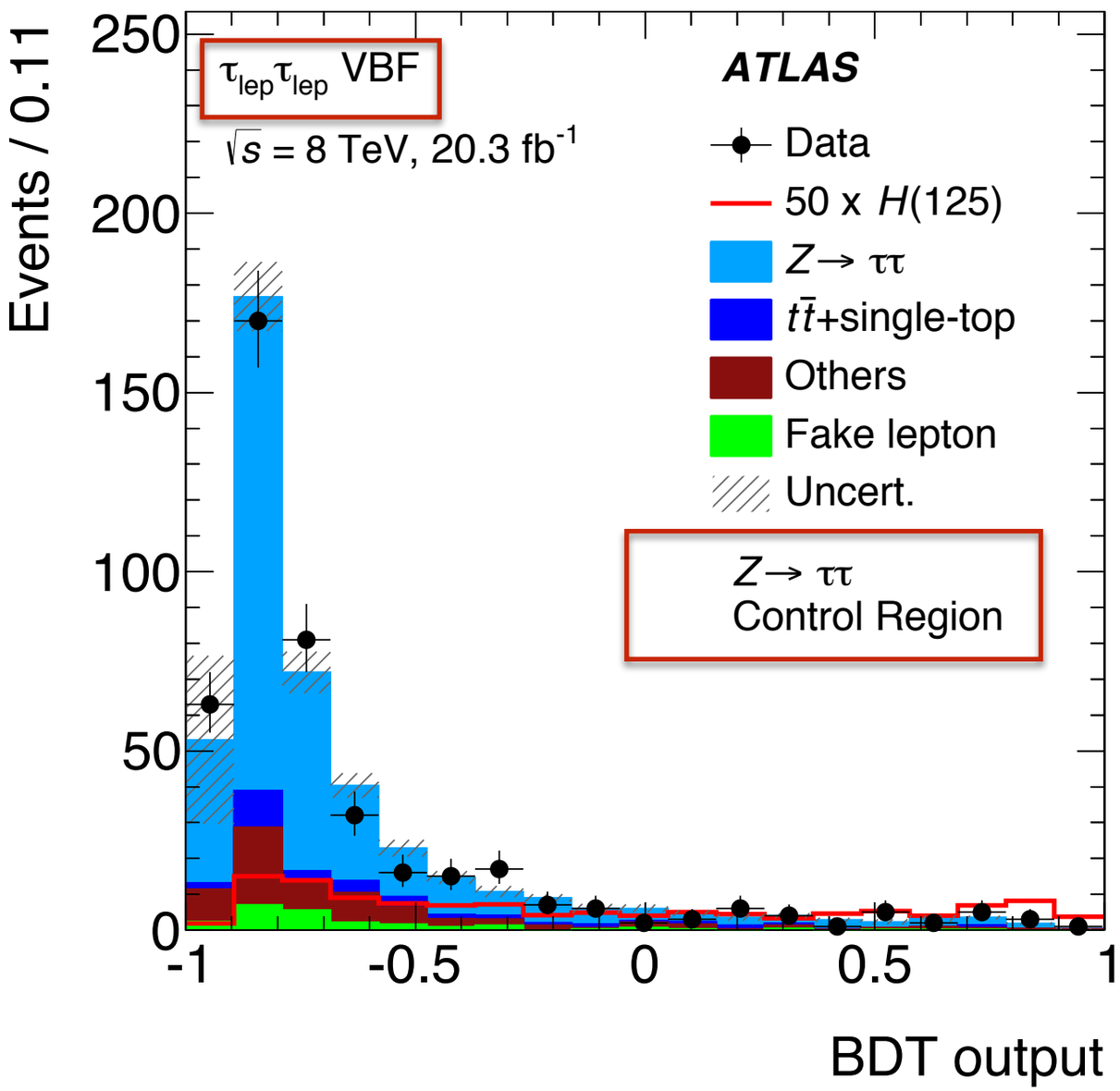

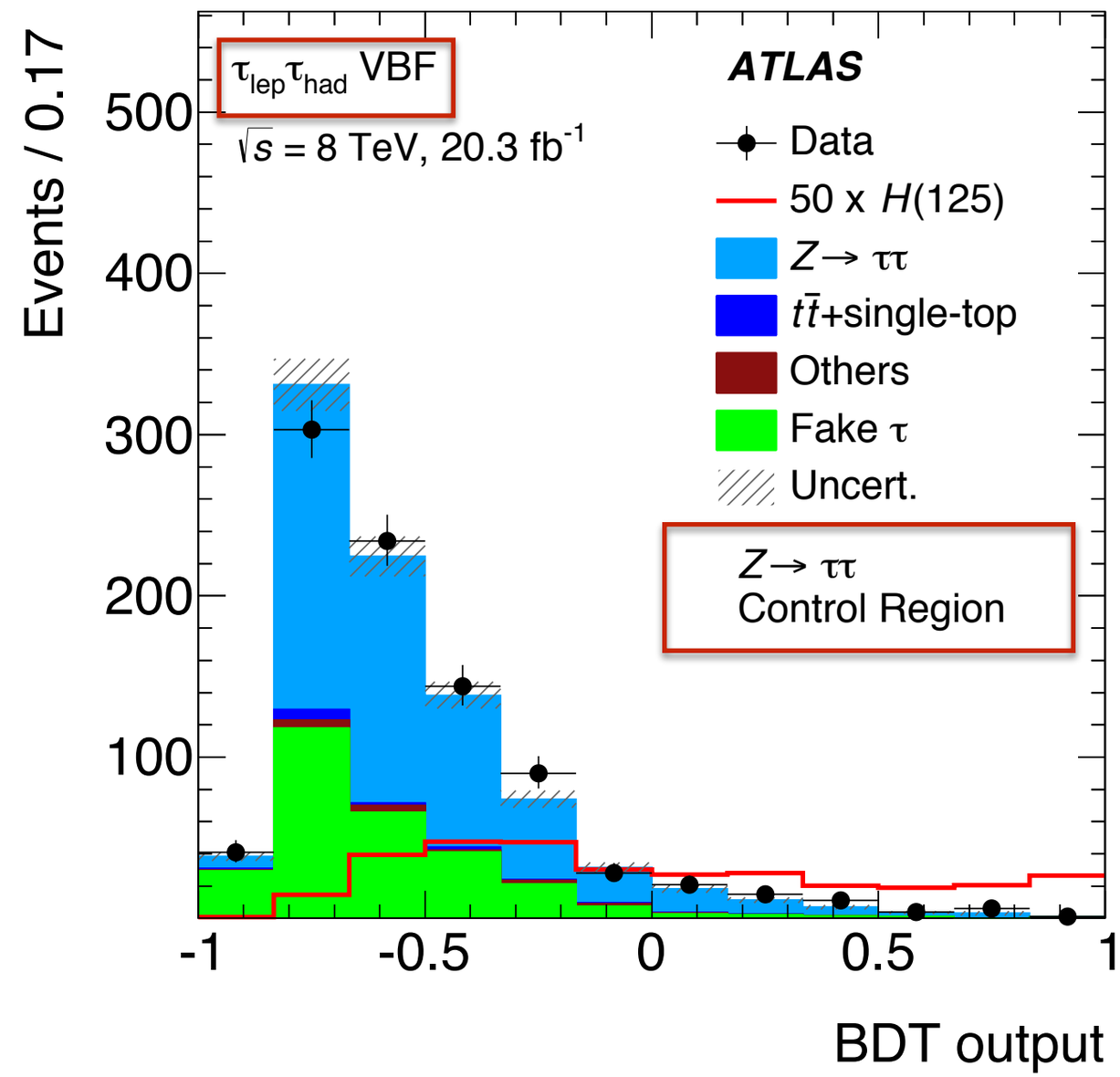

Signal extraction

- Final **discriminant** of the analysis: **BDT** output.
- Maximum-likelihood fit performed on all categories to extract the **signal strength μ**.
- 6 SR + 7 CR included in the fit.

	VBF		Boosted		Rest
	SR	CR	SR	CR	CR
$\tau_{lep}\tau_{lep}$	✔	✔ Z→ll (1 bin) & Top (1 bin)	✔	✔ Z→ll (1 bin) & Top (1 bin)	✘
$\tau_{lep}\tau_{had}$	✔	✔ Top (1 bin)	✔	✔ Top (1 bin)	✘
$\tau_{had}\tau_{had}$	✔	✘	✔	✘	✔ $\Delta\eta(\tau_1,\tau_2)$ (shape)

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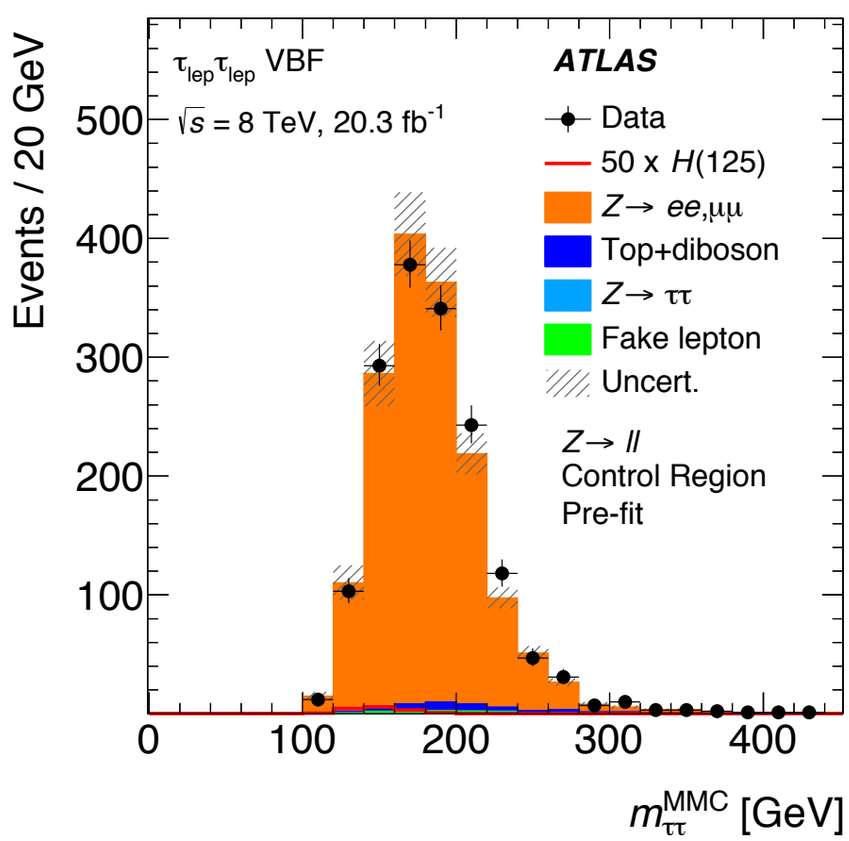
$\tau_{had}\tau_{had}$	✔	✘	✔	✘	✔ $\Delta\eta(\tau_1,\tau_2)$ (shape)



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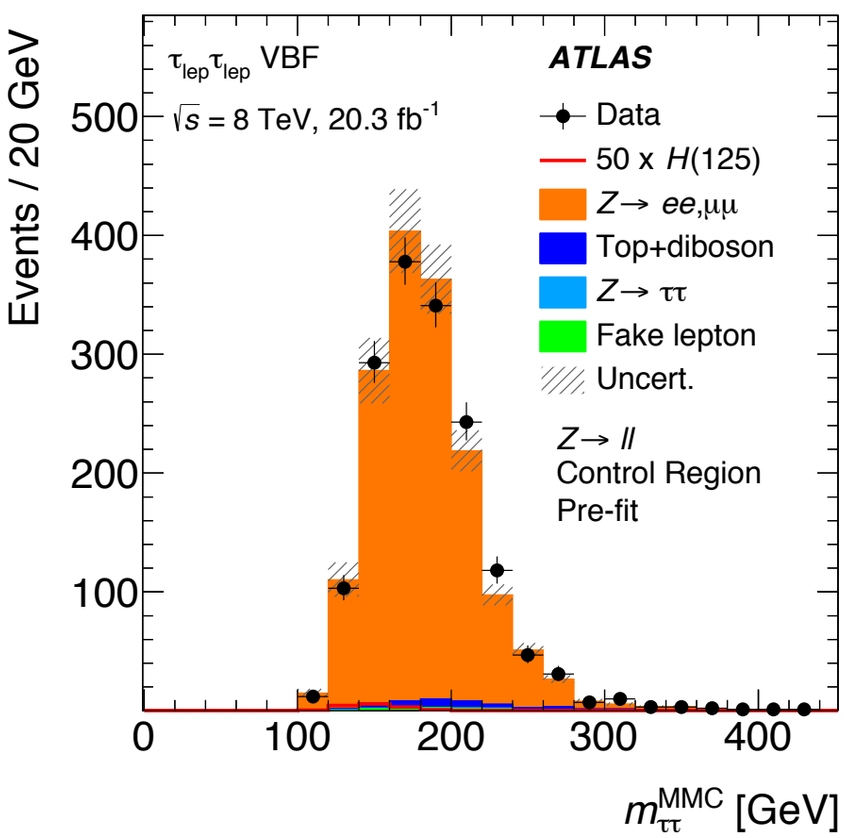
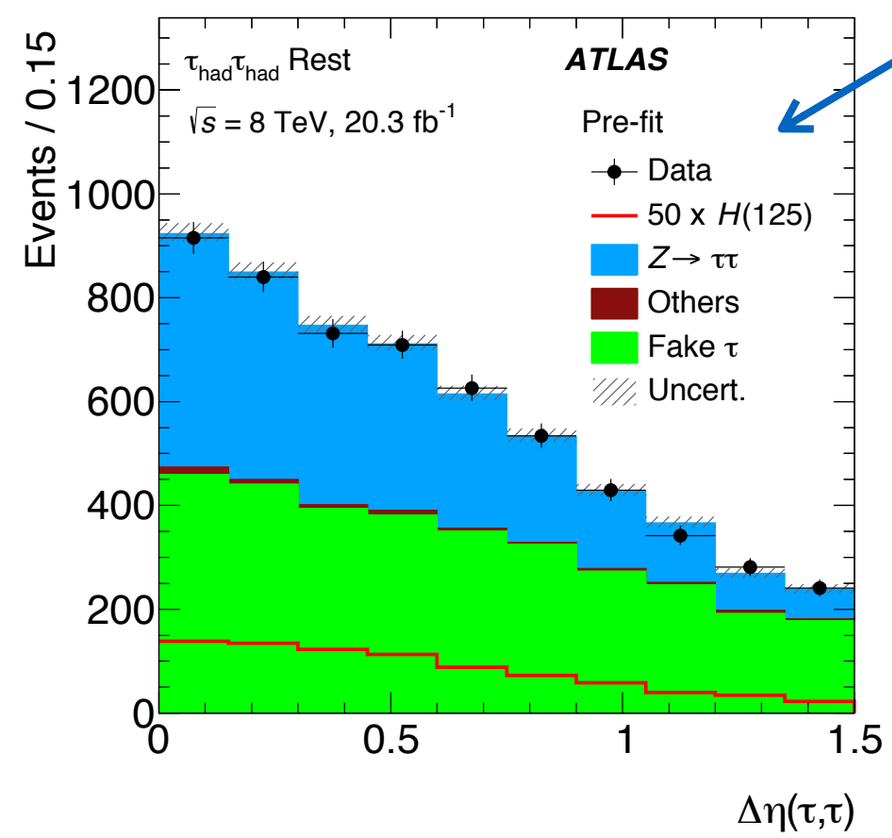
	SR	CR	SR	CR	CR
$\tau_{lep}\tau_{lep}$	✔	✔ Z→ll (1 bin) & Top (1 bin)	✔	✔ Z→ll (1 bin) & Top (1 bin)	✘
$\tau_{lep}\tau_{had}$	✔	✔ Top (1 bin)	✔	✔ Top (1 bin)	✘
$\tau_{had}\tau_{had}$	✔	✘	✔	✘	✔ $\Delta\eta(\tau_1,\tau_2)$ (shape)





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Final discriminant in signal regions

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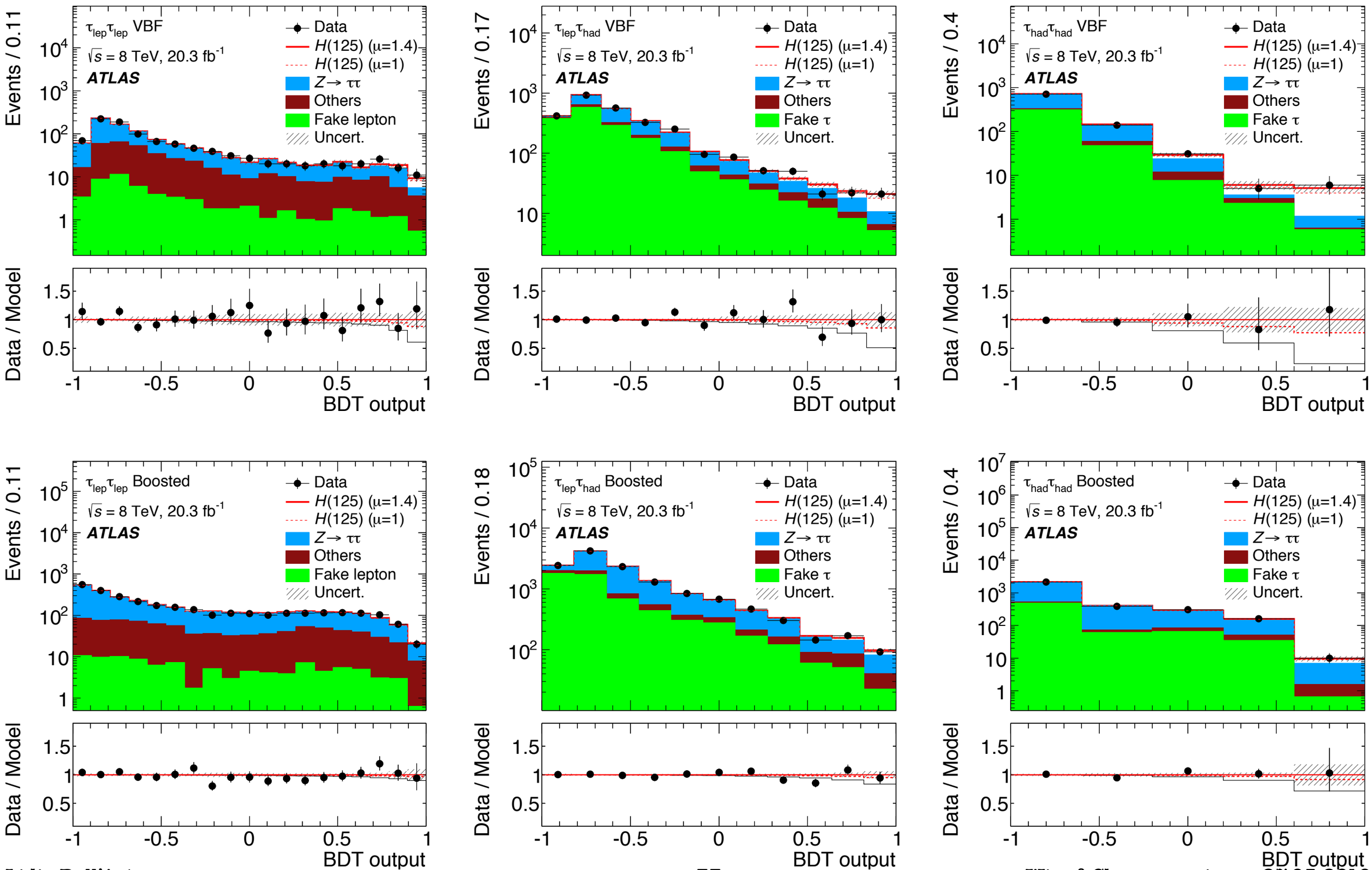
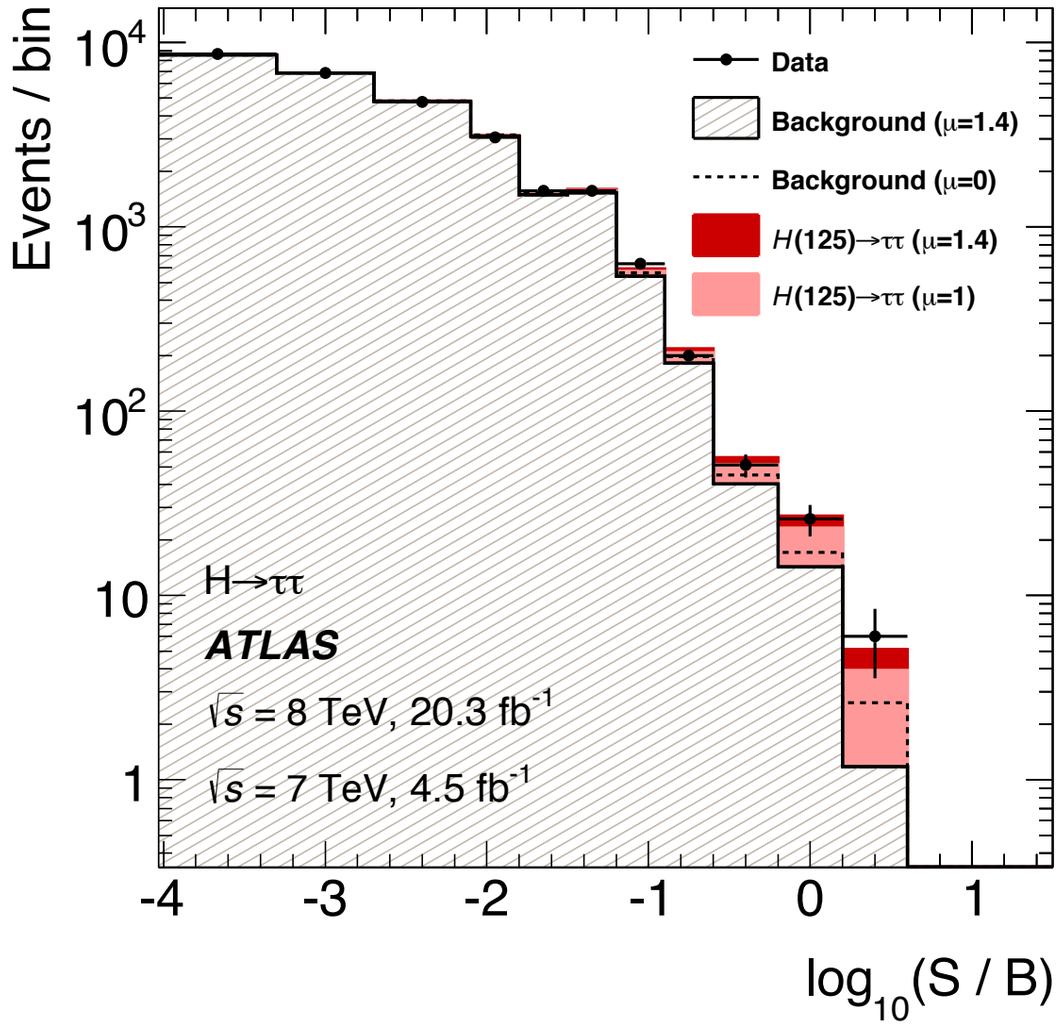


Results



- Significant **excess** of data events in high S/B region.
- **Observed** (expected) **significance** at m_H=125 GeV corresponds to **4.5σ** (3.4σ).

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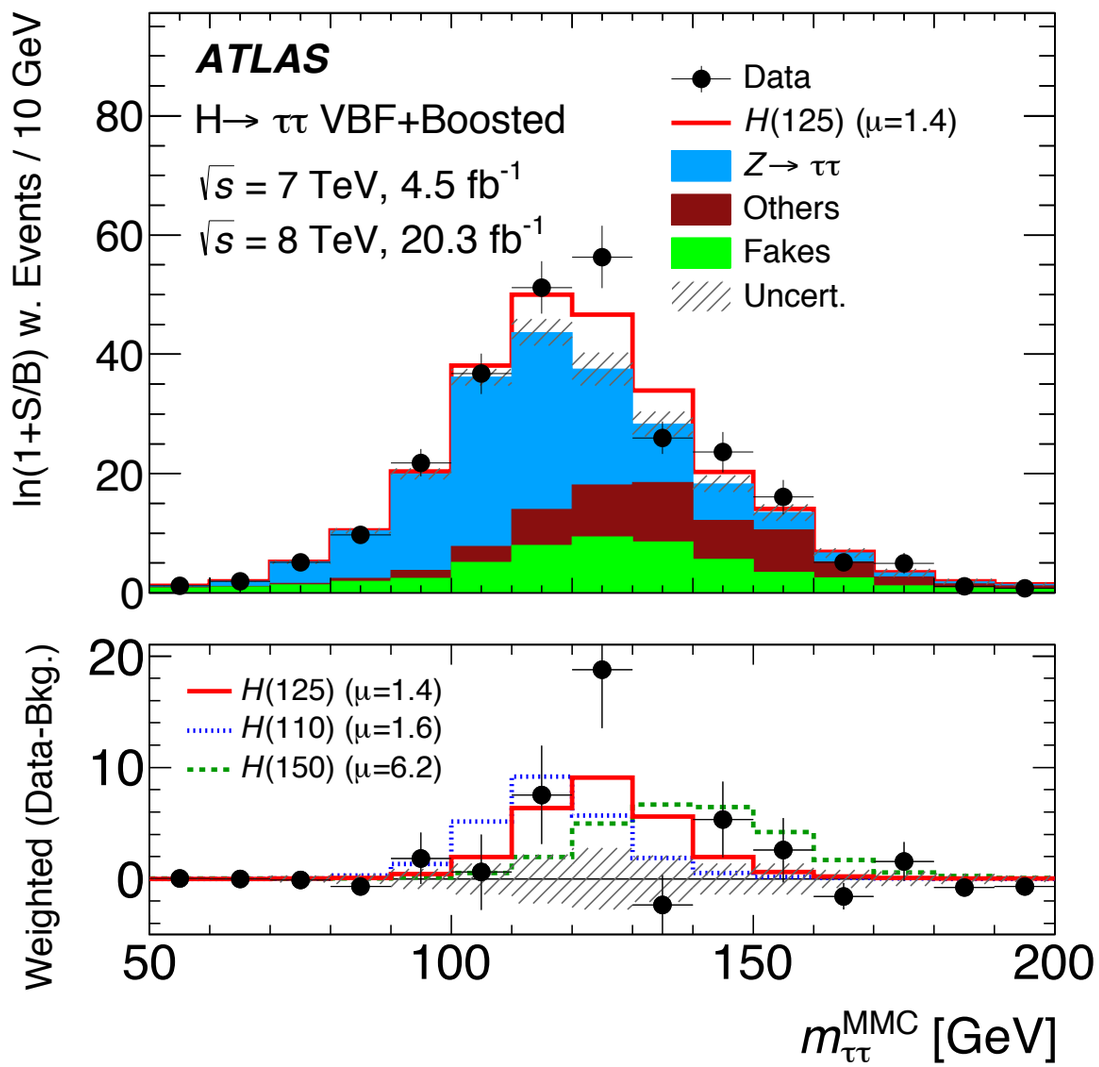
Channel and Category	Expected Significance (σ)	Observed Significance (σ)
$\tau_{lep}\tau_{lep}$ VBF	1.15	1.88
$\tau_{lep}\tau_{lep}$ Boosted	0.57	1.72
$\tau_{lep}\tau_{lep}$ Total	1.25	2.40
$\tau_{lep}\tau_{had}$ VBF	2.11	2.23
$\tau_{lep}\tau_{had}$ Boosted	1.11	1.01
$\tau_{lep}\tau_{had}$ Total	2.33	2.33
$\tau_{had}\tau_{had}$ VBF	1.70	2.23
$\tau_{had}\tau_{had}$ Boosted	0.82	2.56
$\tau_{had}\tau_{had}$ Total	1.99	3.25
Combined	3.43	4.54

Results



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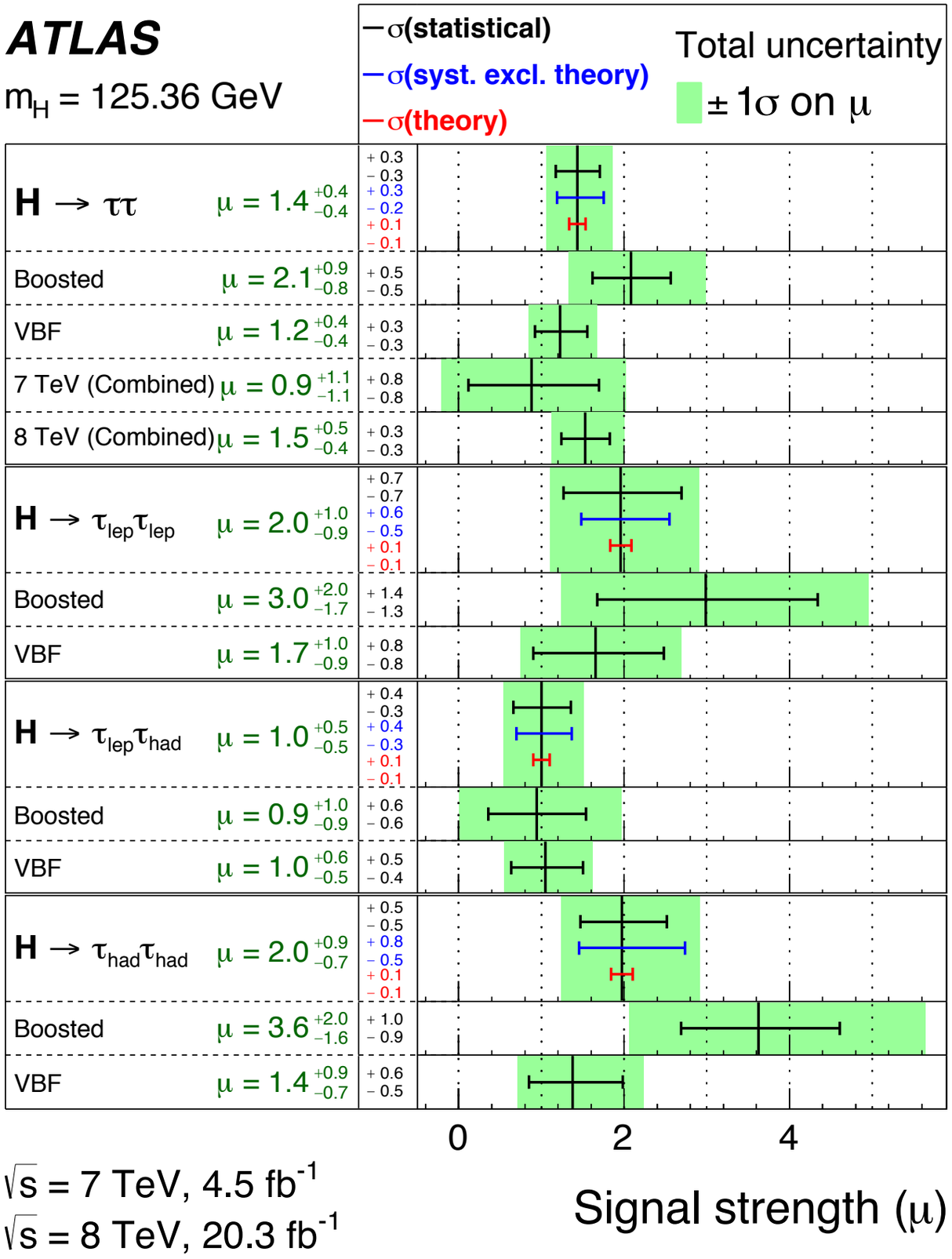
- Each event is weighted by ln(1+S/B) for corresponding bin in BDT-score.
- Excess of data events is **consistent** with presence of **Higgs** at **125 GeV**.

Results



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$$\mu = 1.43\ ^{+0.27}_{-0.26}(\text{stat.})\ ^{+0.32}_{-0.25}(\text{syst.})\ \pm 0.09(\text{theory syst.})$$

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.13
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR ($H \to \tau\tau$)	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03
Total sys.	$^{+0.33}_{-0.26}$
Total	$^{+0.43}_{-0.37}$

Results

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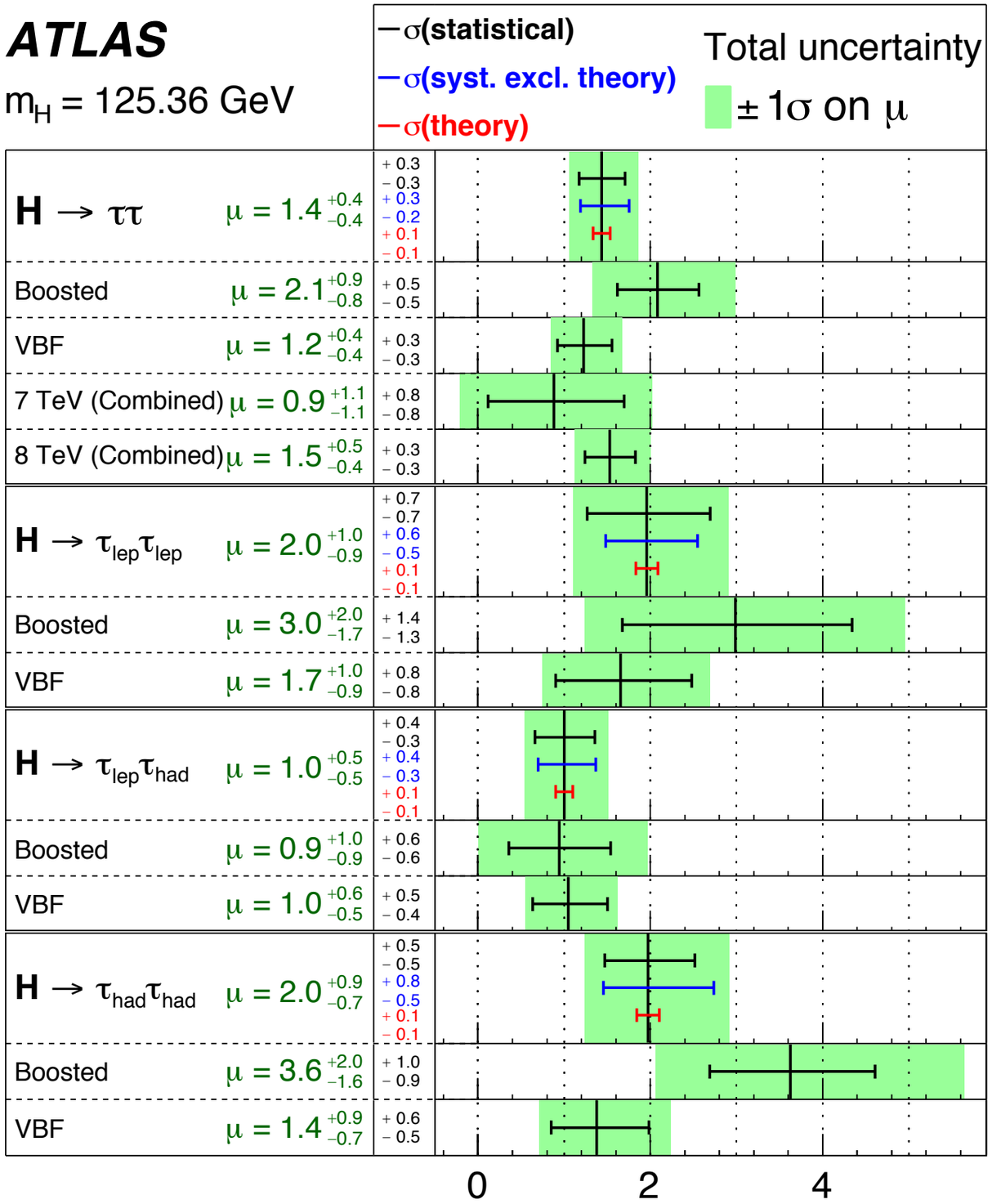

$\sqrt{s}$ = 7 TeV, 4.5 fb^{-1}

$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}

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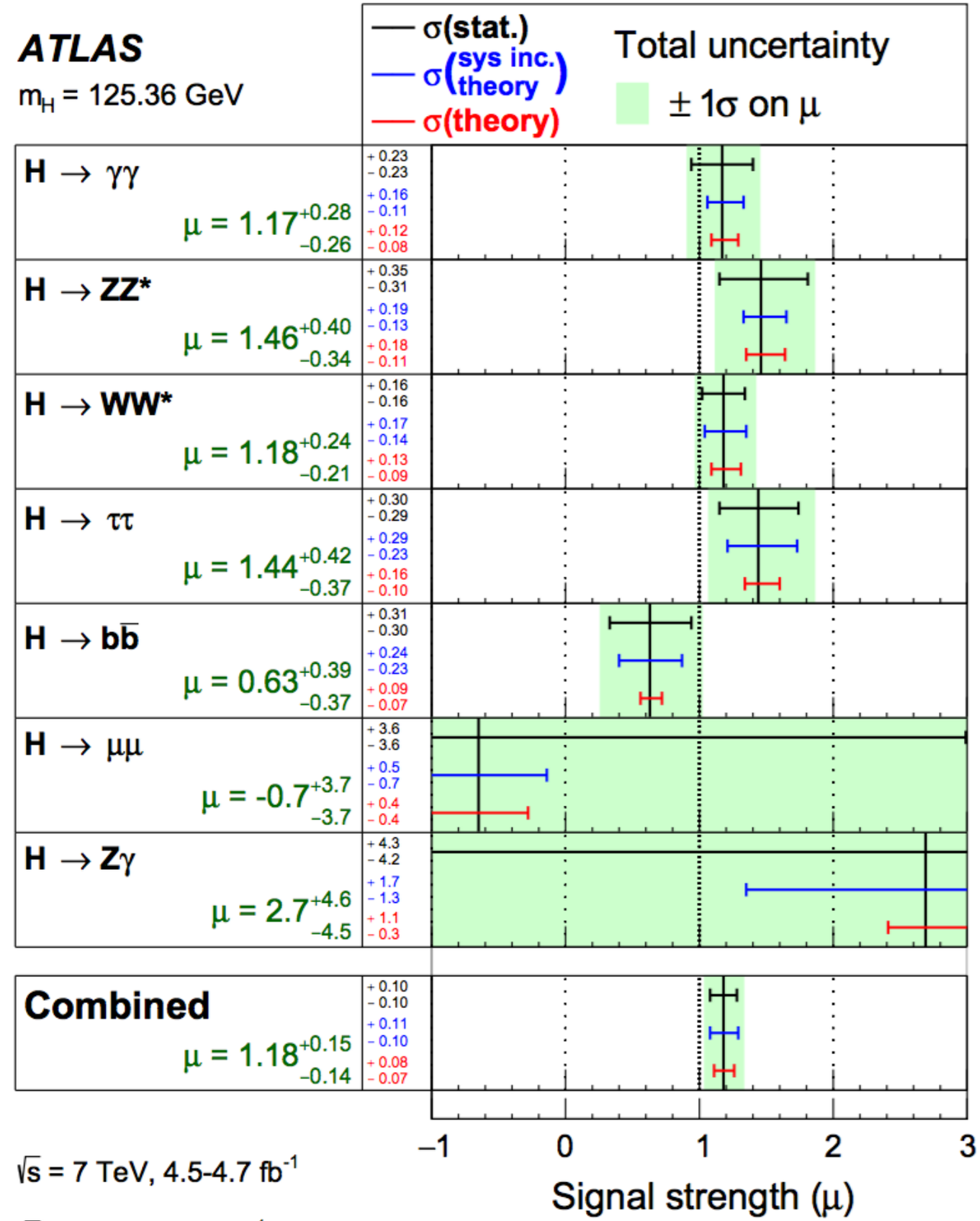
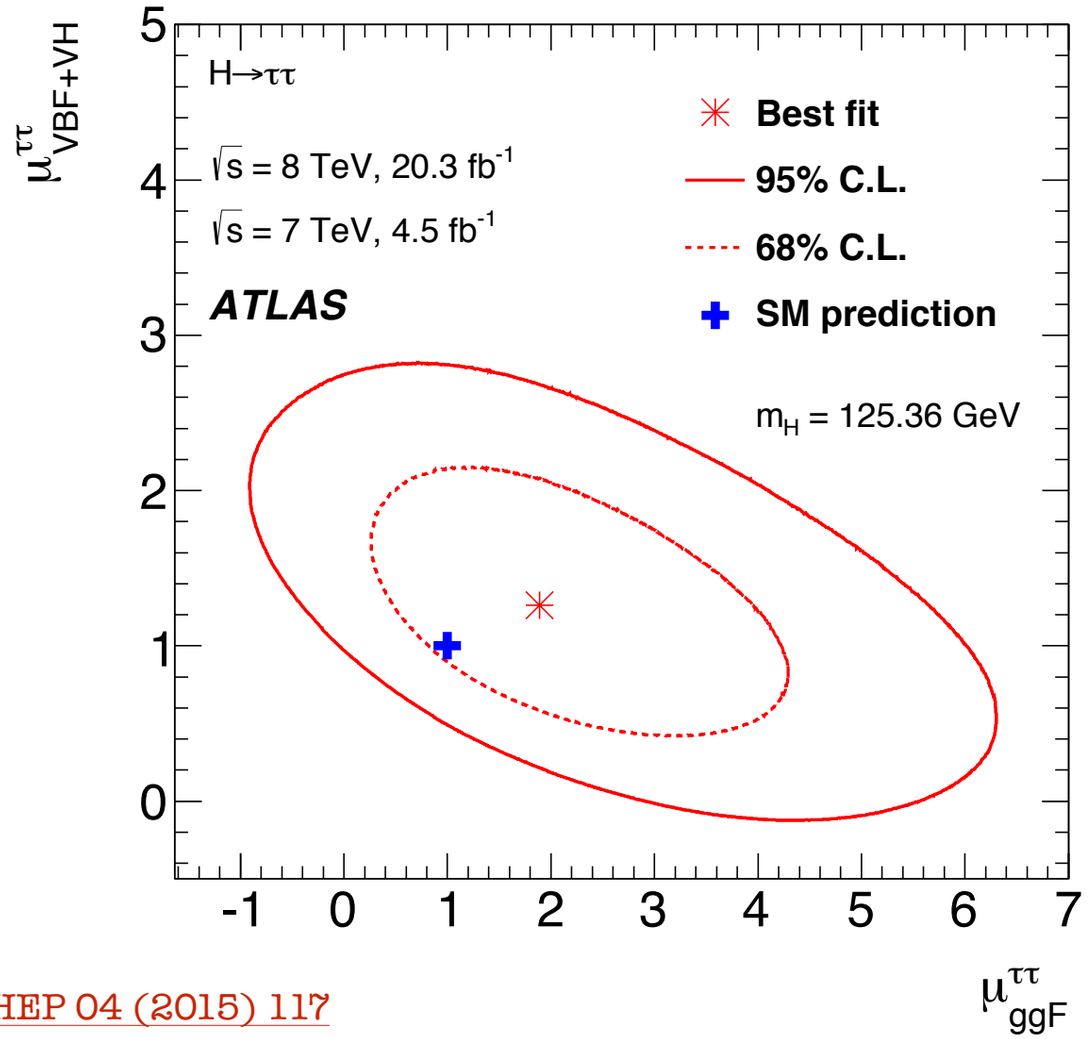


$\sqrt{s}$ = 7 TeV, 4.5-4.7 fb^{-1}

$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}

Results



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- Best fitted values:

$$\mu^{\tau\tau}_{ggF} = 1.1^{+1.3}_{-1.1}$$

$$\mu^{\tau\tau}_{VH+VBF} = 1.6^{+0.8}_{-0.7}$$

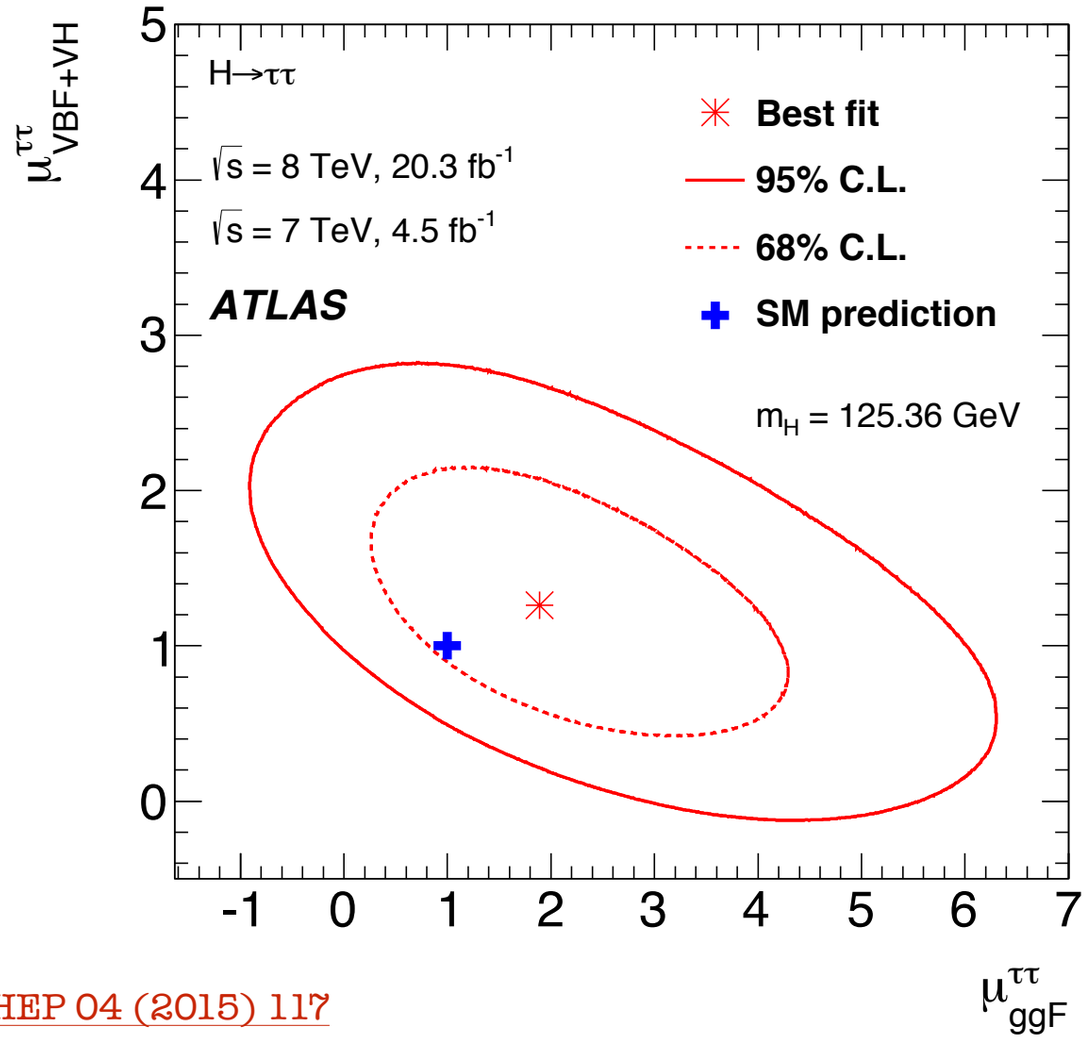
- Observed (expected) significances:

ggF: 1.74σ (0.95σ)
VBF+VH: 2.25σ (1.72σ)

- Results are consistent with SM predictions within 68% CL contour.

	Measured $\sigma\times$BR [pb]	Predicted $\sigma\times$BR [pb]
7 TeV	$1.0\ ^{+0.9}_{-0.8}(\text{stat.})^{+0.9}_{-0.8}(\text{syst.})$	1.09 ± 0.11
8 TeV	$2.1 \pm 0.4(\text{stat.})^{+0.5}_{-0.4}(\text{syst.})$	1.39 ± 0.14
Gluon fusion, 8 TeV	$1.7 \pm 1.1(\text{stat.})^{+1.5}_{-1.1}(\text{syst.})$	1.22 ± 0.14
VBF+VH, 8 TeV	$0.26 \pm 0.09(\text{stat.})^{+0.06}_{-0.05}(\text{syst.})$	0.17 ± 0.01

Results



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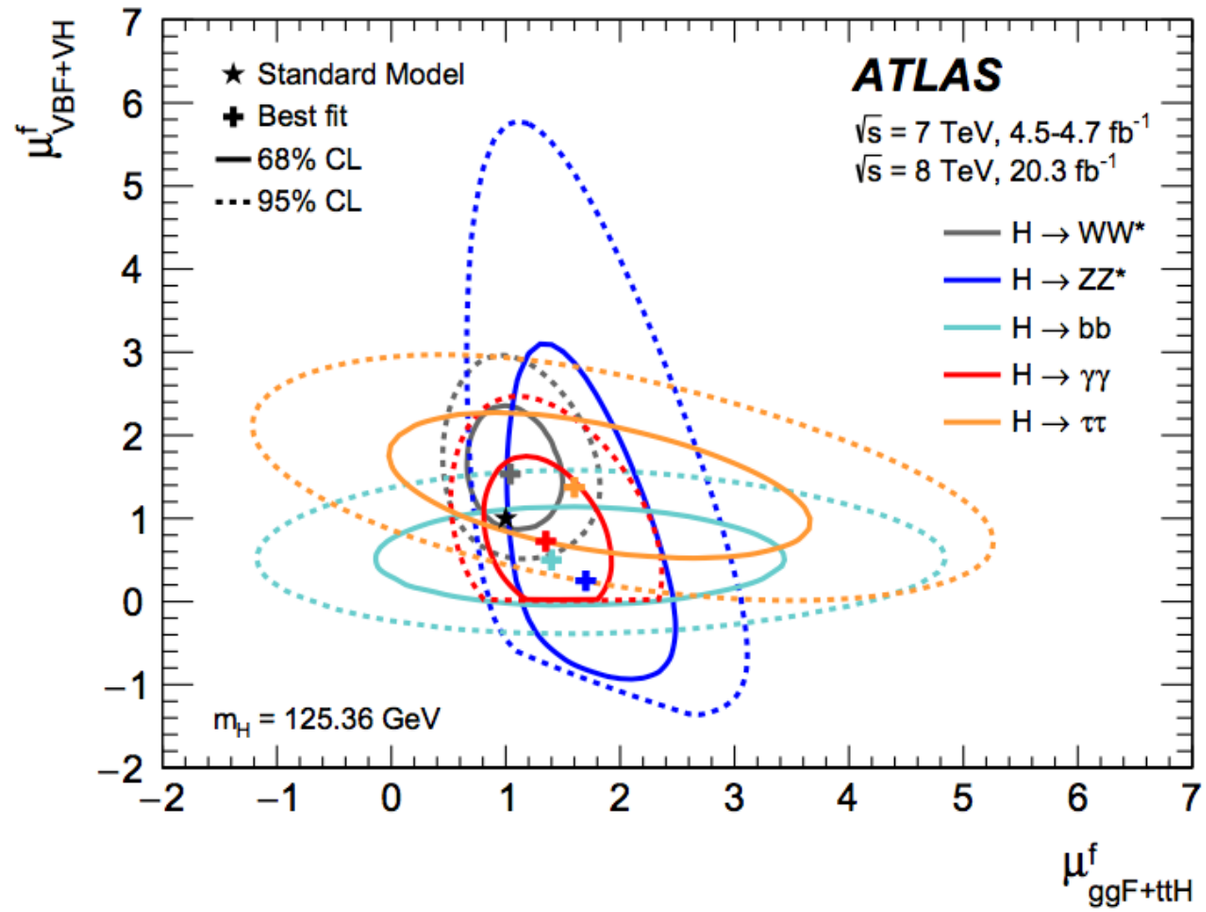
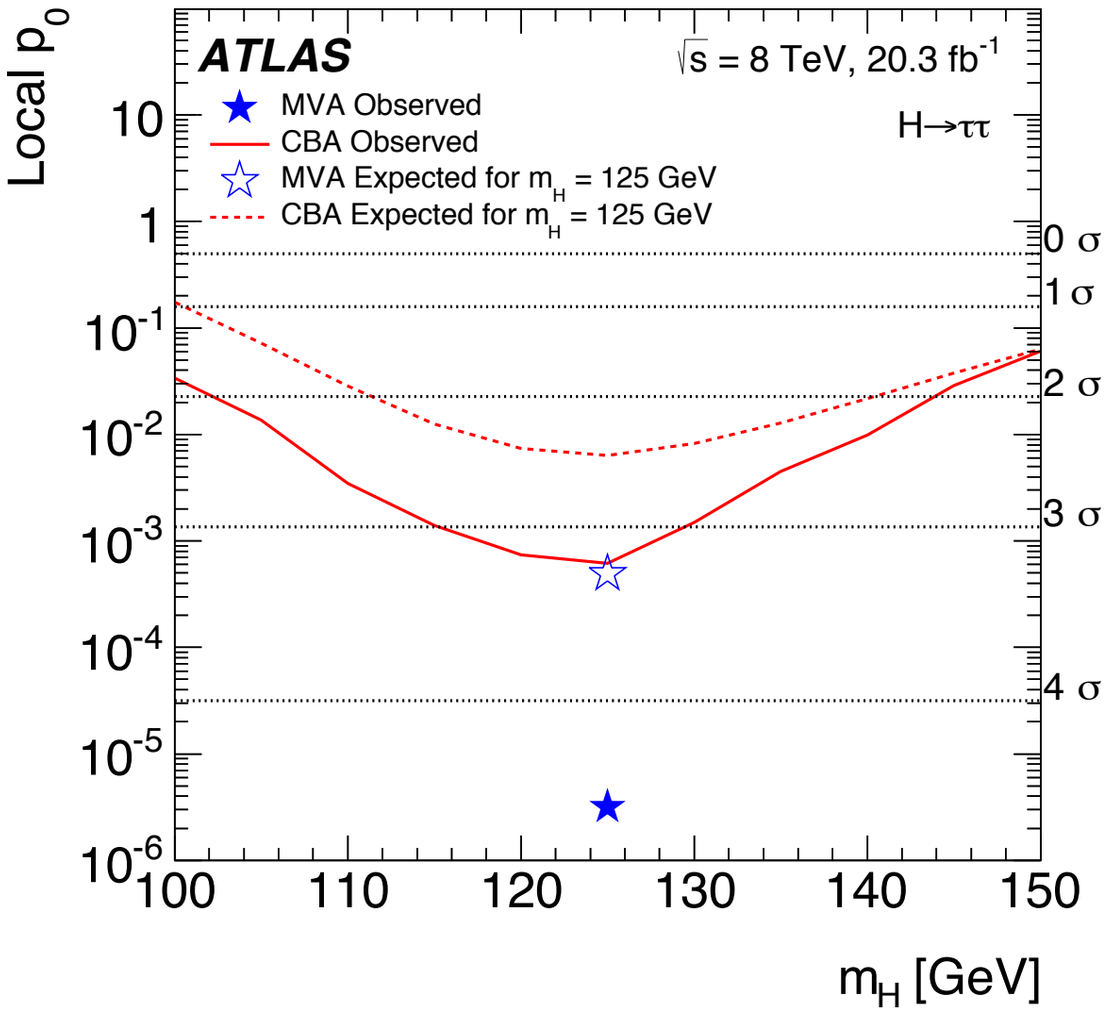
Eur. Phys. J. C76 (2016) 6



- Results are consistent with SM predictions within 68% CL contour.

	Measured $\sigma\times$BR [pb]	Predicted $\sigma\times$BR [pb]
7 TeV	$1.0\ ^{+0.9}_{-0.8}(\text{stat.})^{+0.9}_{-0.8}(\text{syst.})$	1.09 ± 0.11
8 TeV	$2.1 \pm 0.4(\text{stat.})^{+0.5}_{-0.4}(\text{syst.})$	1.39 ± 0.14
Gluon fusion, 8 TeV	$1.7 \pm 1.1(\text{stat.})^{+1.5}_{-1.1}(\text{syst.})$	1.22 ± 0.14
VBF+VH, 8 TeV	$0.26 \pm 0.09(\text{stat.})^{+0.06}_{-0.05}(\text{syst.})$	0.17 ± 0.01

Results - A cut based cross check



- Cut based analysis performed on 8 TeV data as a cross check of the MVA analysis.
- Compatible results are observed.

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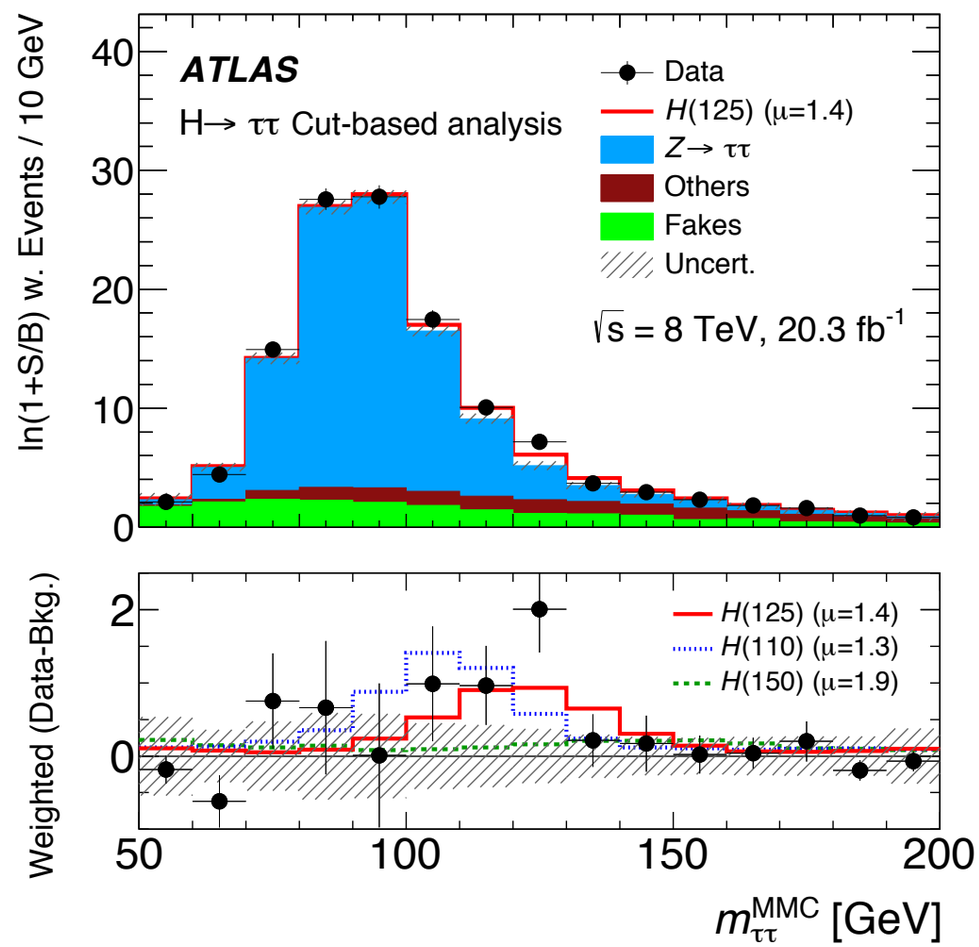
Observed (expected) significances are 3.2σ (2.5σ)



LFV Higgs decays

Outline

- Higgs boson discovery
- Evidence of the decay of the Higgs boson into tau pairs
- Search for Lepton Flavor Violating decays of the Higgs boson

Introduction

- In the SM, lepton flavor violating (LFV) decays are forbidden.
- If the theory is re-normalizable up to a finite mass scale, LFV couplings may be introduced.
- LFV decays can occur naturally in several BSM models.

- Indirect experimental constraints are reviewed and translated into constraints on $Br(H \to e\mu, \mu\tau, e\tau)$.

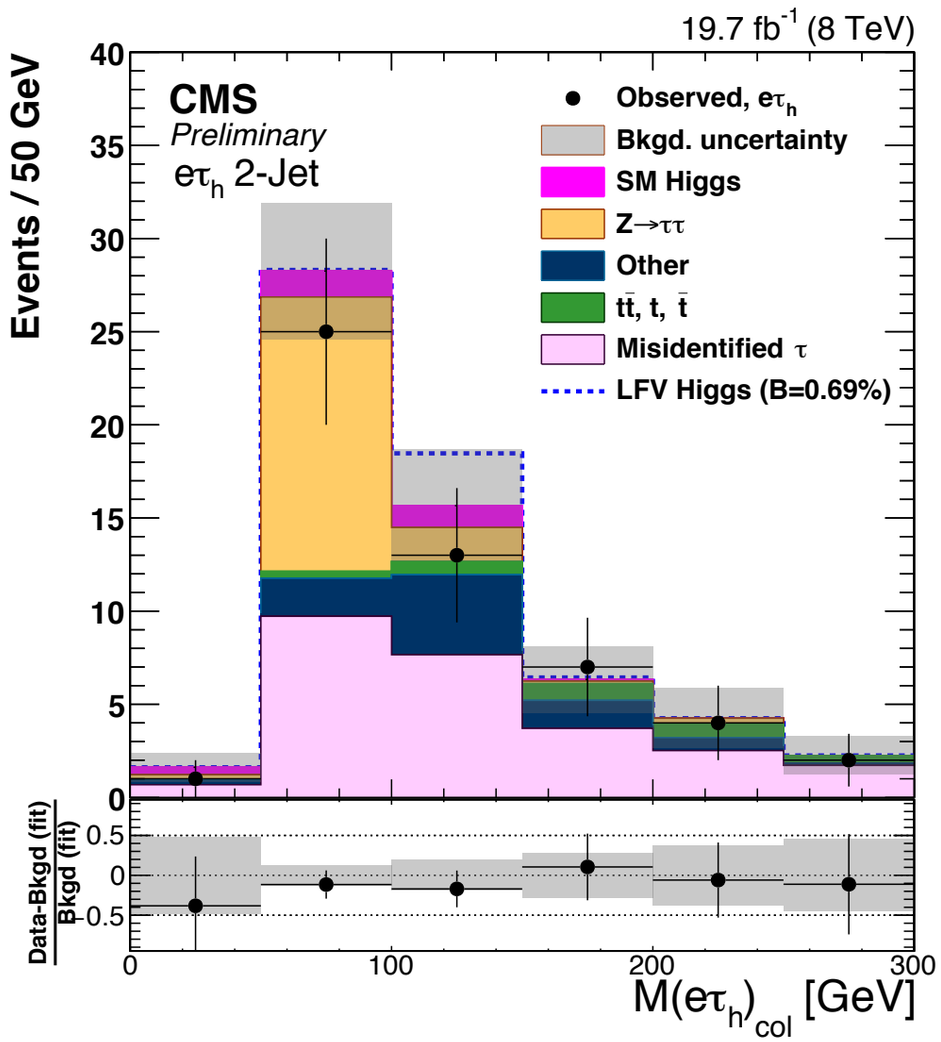
LFV decay: limits on BR	$BR(H \to \mu e) < O(10^{-8})$ $BR(H \to \tau e) < O(10\%)$ $BR(H \to \tau \mu) < O(10\%)$

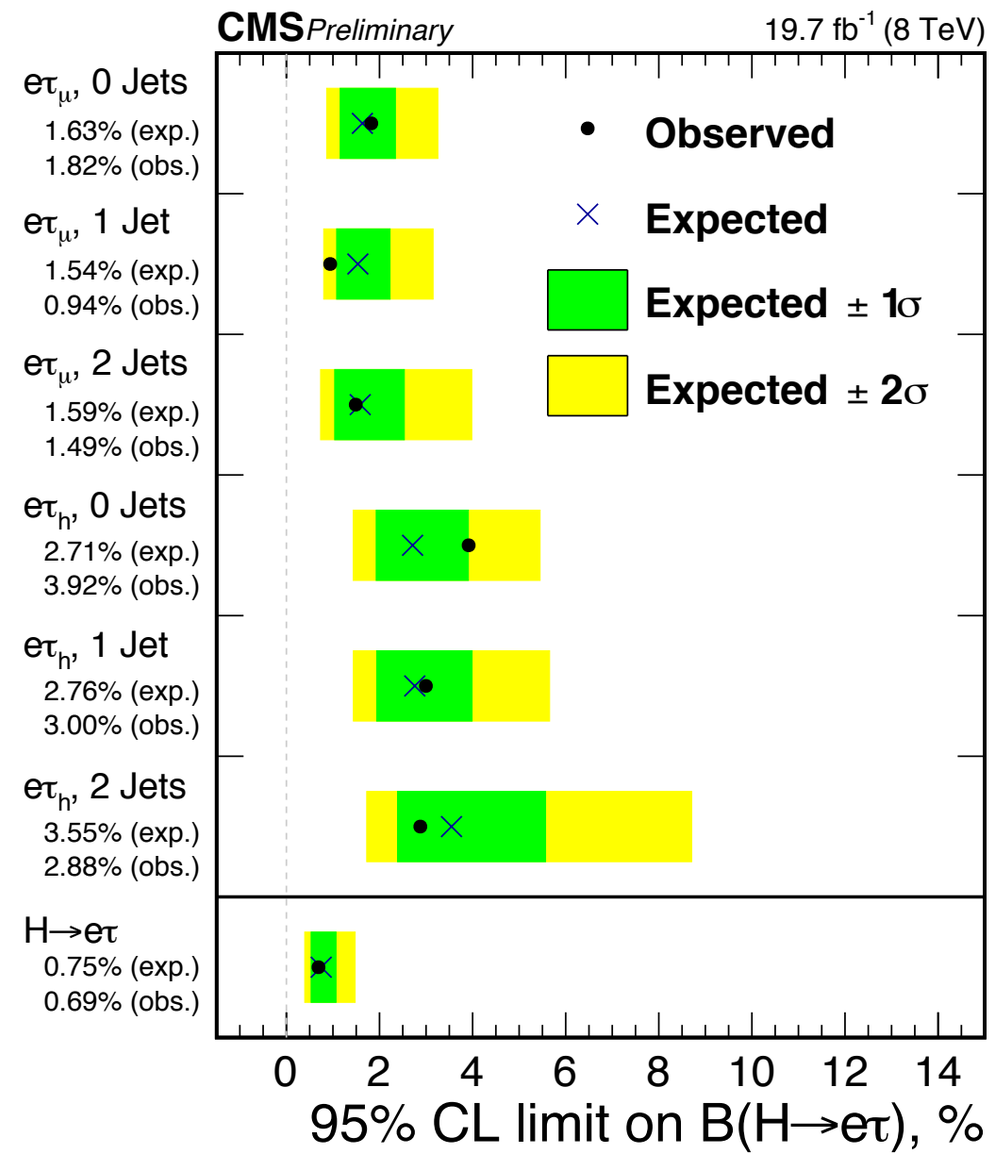
There is room at the LHC to improve $H \to \tau e$ and $H \to \tau \mu$ limits.

- Signature very similar to SM $H \to \tau\tau$ decays, but:
  - lepton from LFV Higgs decay tends to have a larger momentum than in SM case,
  - neutrinos are collinear with the tau decay products.

State of the art - H→eτ

CMS-PAS-HIG-14-040

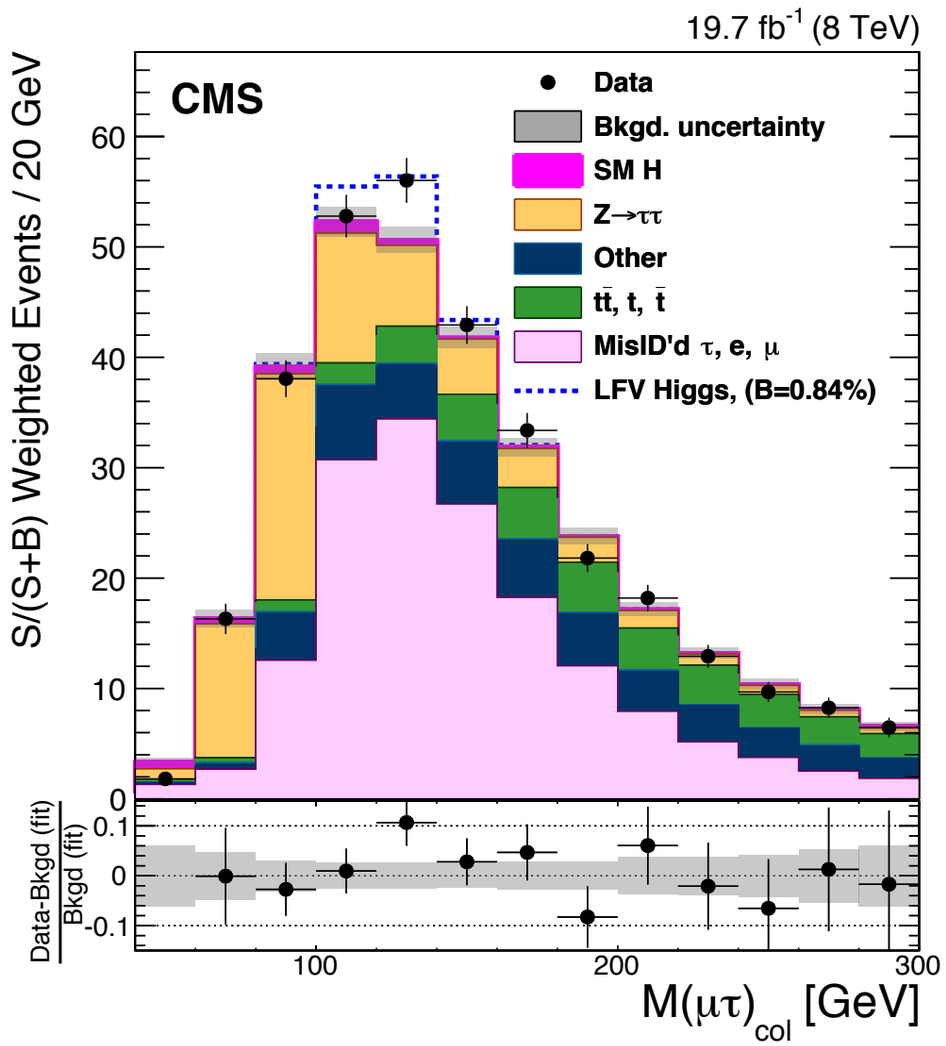


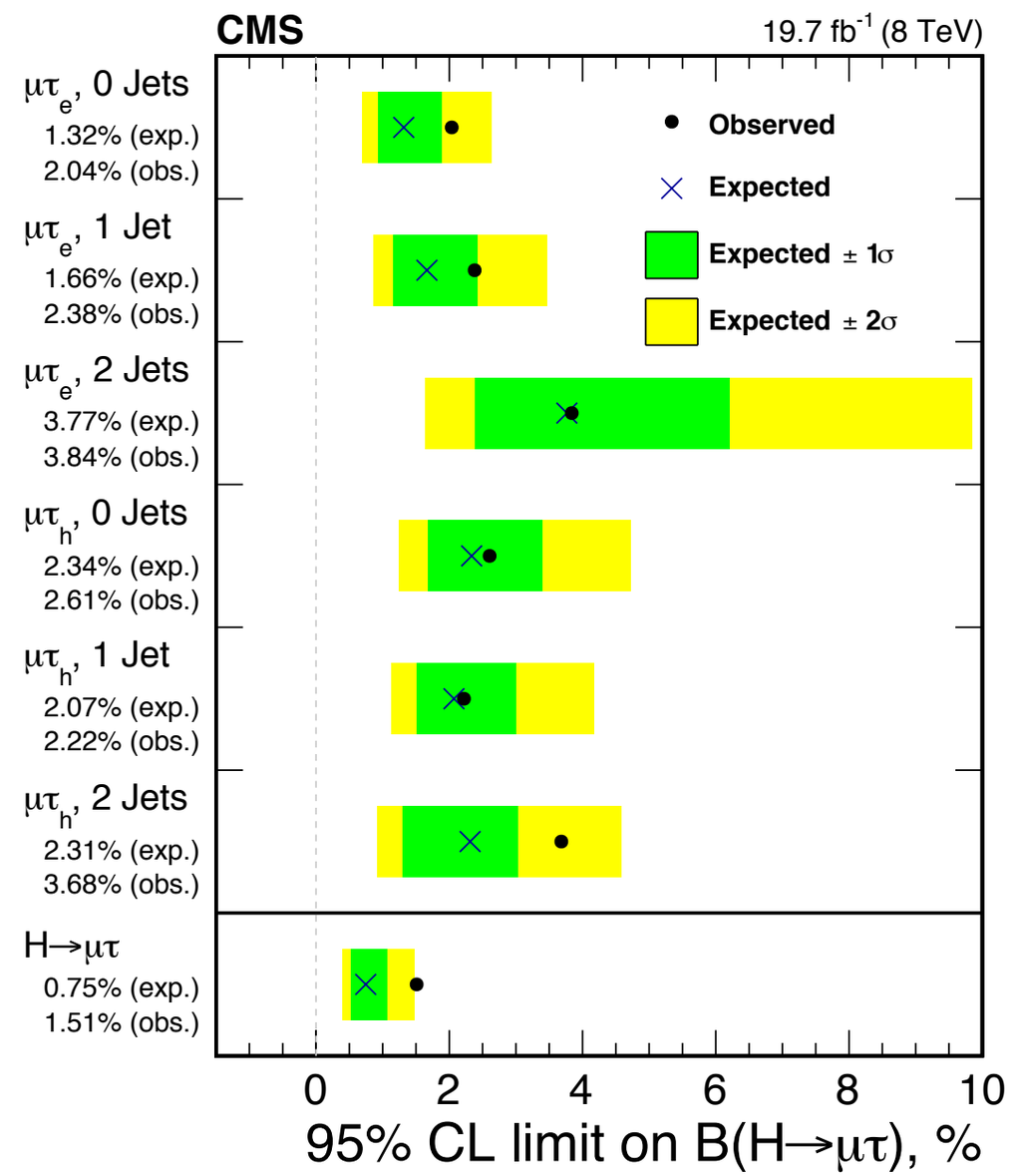


observed 95% CL upper limit on BR:
Br(H→eτ) < 0.69%

State of the art - H→μτ (a.k.a. CMS excess)

Phys. Lett. B 749 (2015) 337





observed 95% CL upper limit on BR:
Br(H→μτ) < 1.51%
while expected is: Br(H→μτ) < (0.75 ± 0.38) %
slight excess (2.4σ)

Best fit:
Br(H→μτ) = $(0.84^{+0.39}_{-0.37})$%

Analysis strategy

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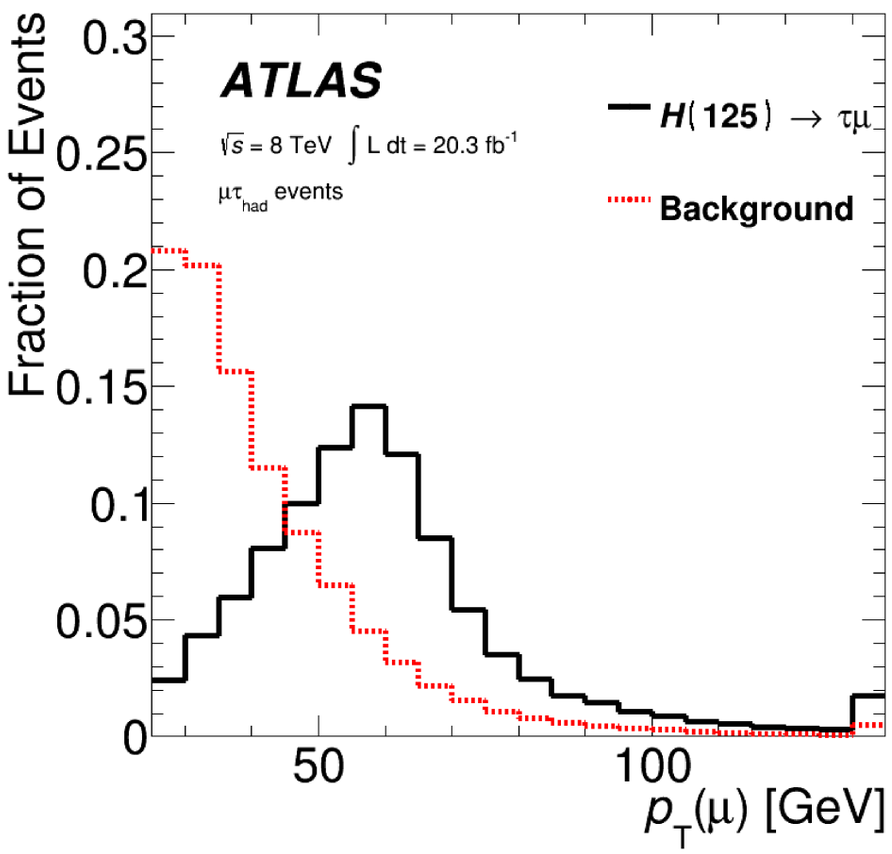
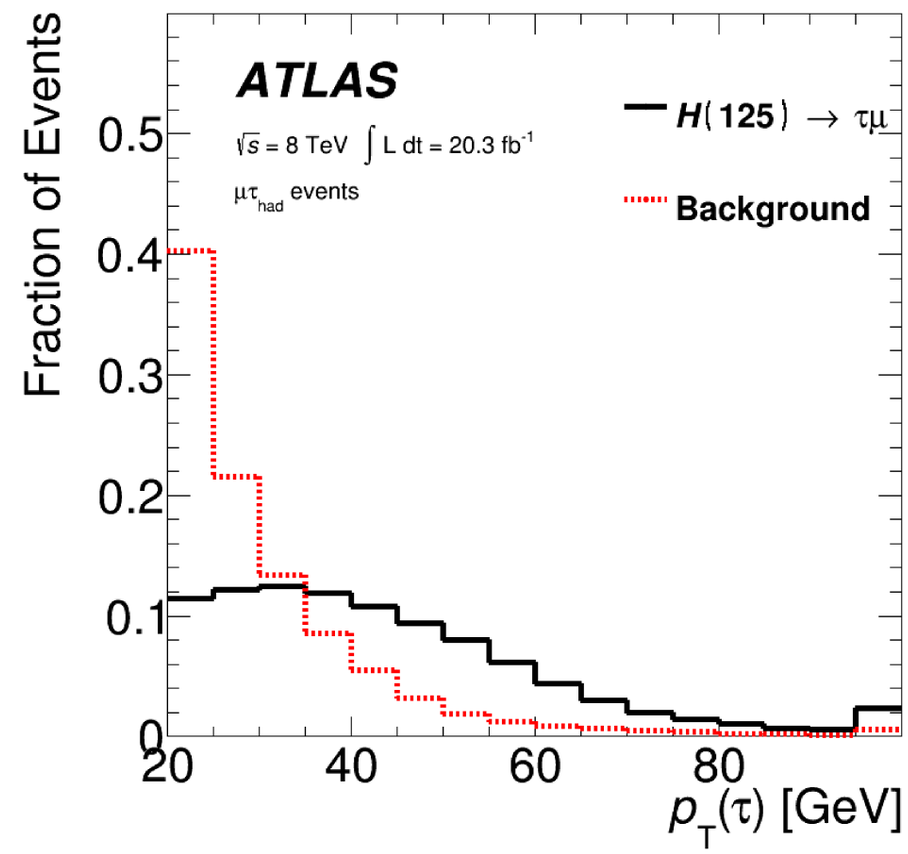
- Very similar to the H→ττ analysis.
  - Same background estimation strategies.
  - Use of MMC (also used as final discriminant).
- Different signal and control regions.

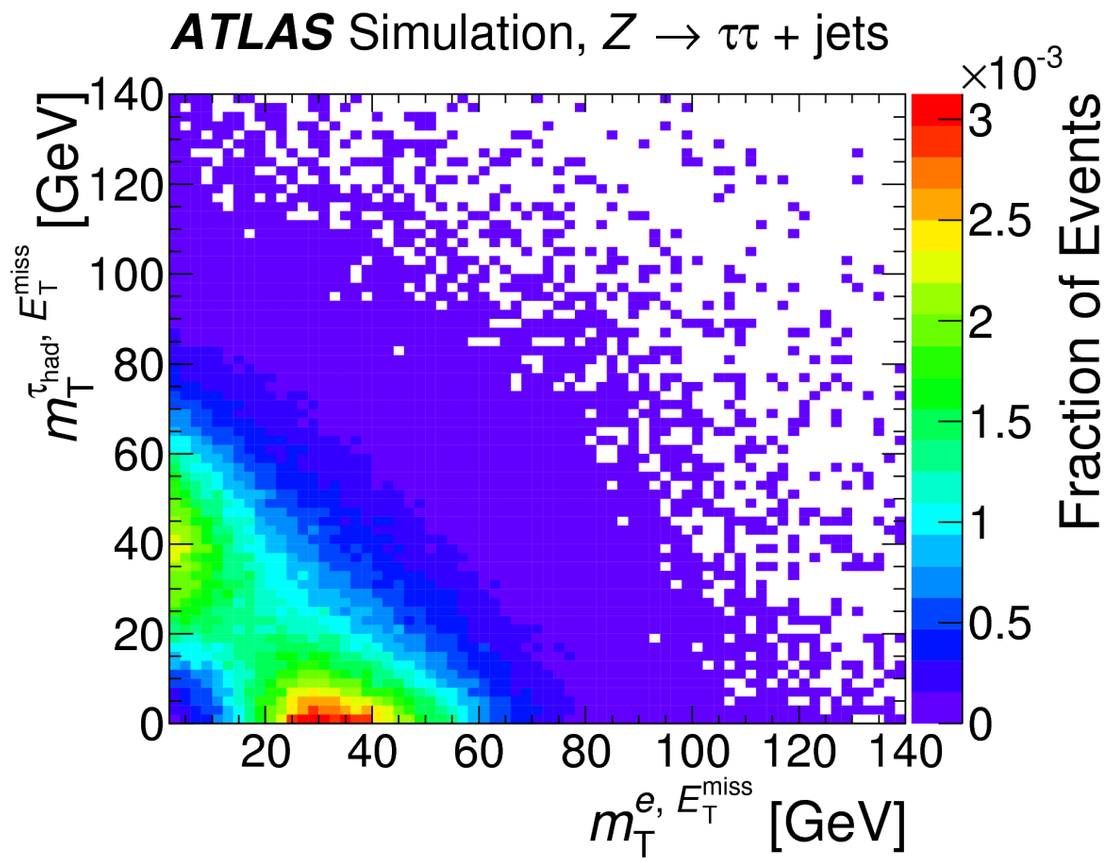
Cut	SR1	SR2	WCR	TCR
$p_{\mathrm{T}}(\mu)$	>26 GeV	>26 GeV	>26 GeV	>26 GeV
$p_{\mathrm{T}}(\tau_{\mathrm{had}})$	>45 GeV	>45 GeV	>45 GeV	>45 GeV
$m_{\mathrm{T}}(\mu, E_{\mathrm{T}}^{\mathrm{miss}})$	>40 GeV	<40 GeV	>60 GeV	–
$m_{\mathrm{T}}(\tau_{\mathrm{had}}, E_{\mathrm{T}}^{\mathrm{miss}})$	<30 GeV	<60 GeV	>40 GeV	–
$\lvert\eta(\mu) - \eta(\tau_{\mathrm{had}})\rvert$	<2	<2	<2	<2
N_{jet}	–	–	–	>1
$N_{b-\mathrm{jet}}$	0	0	0	>0

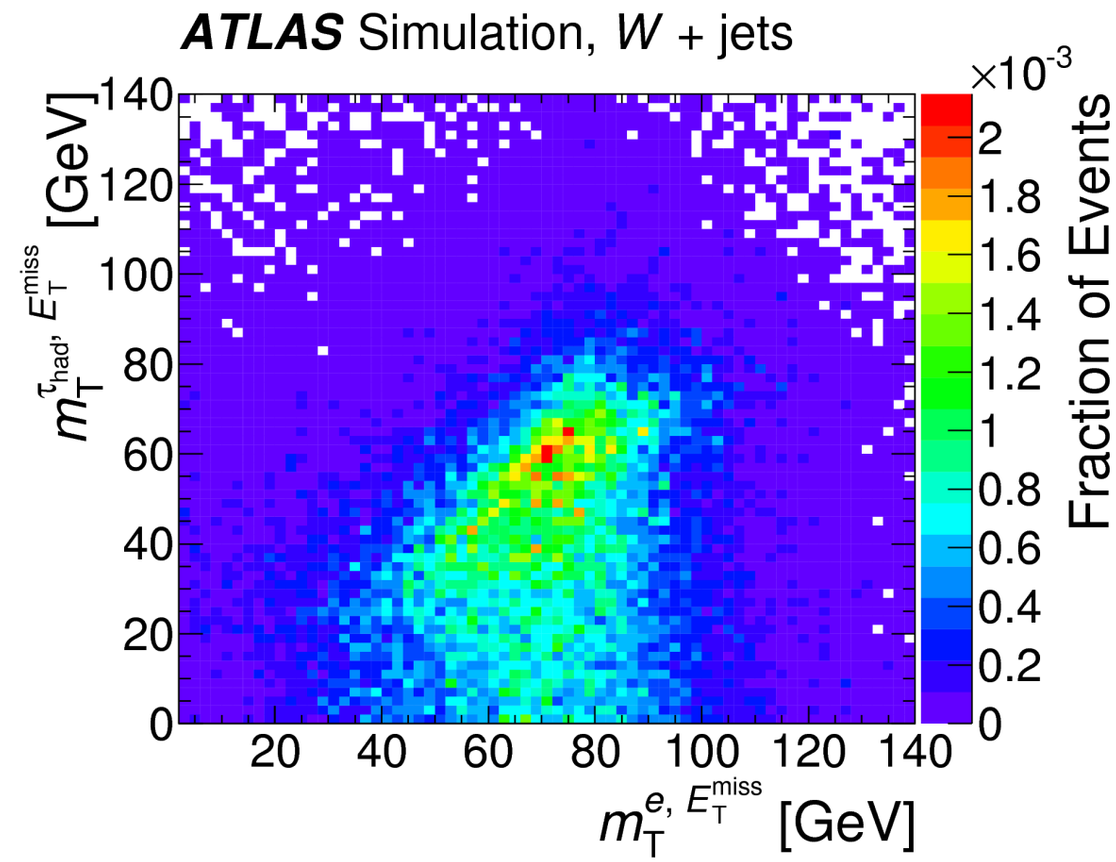


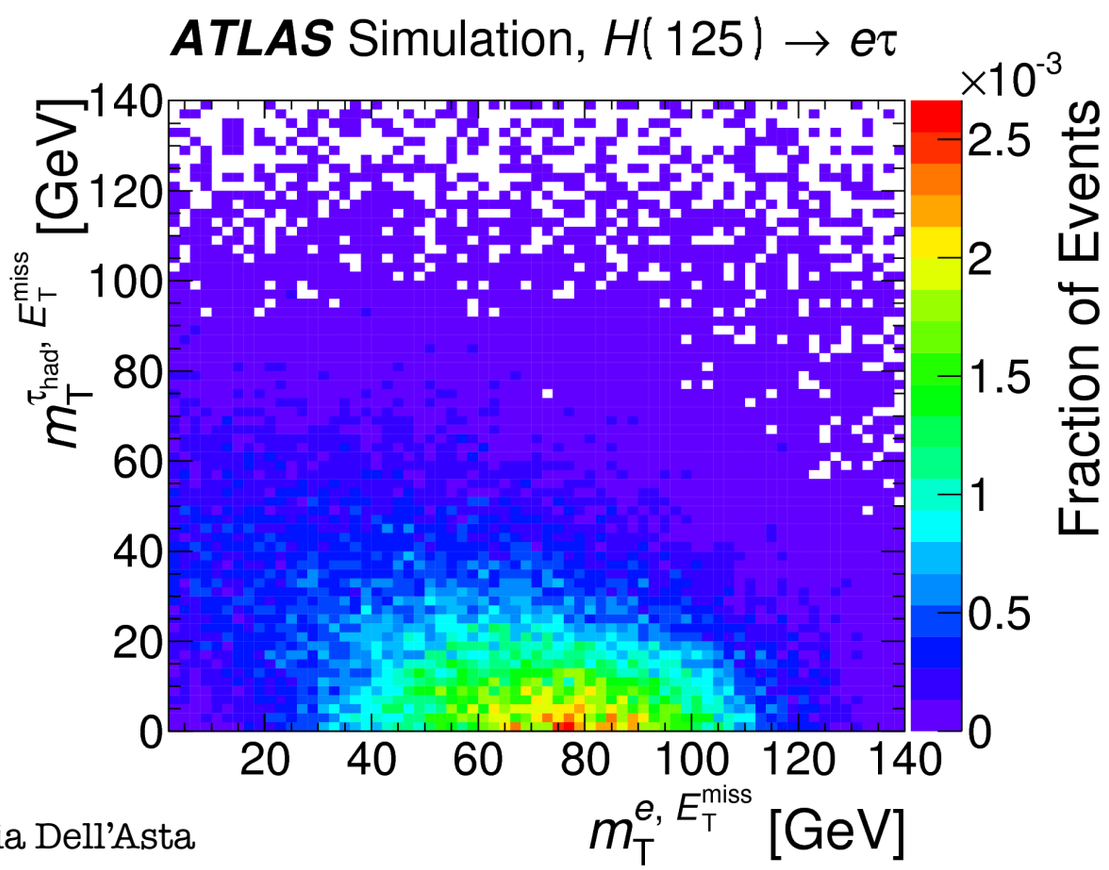


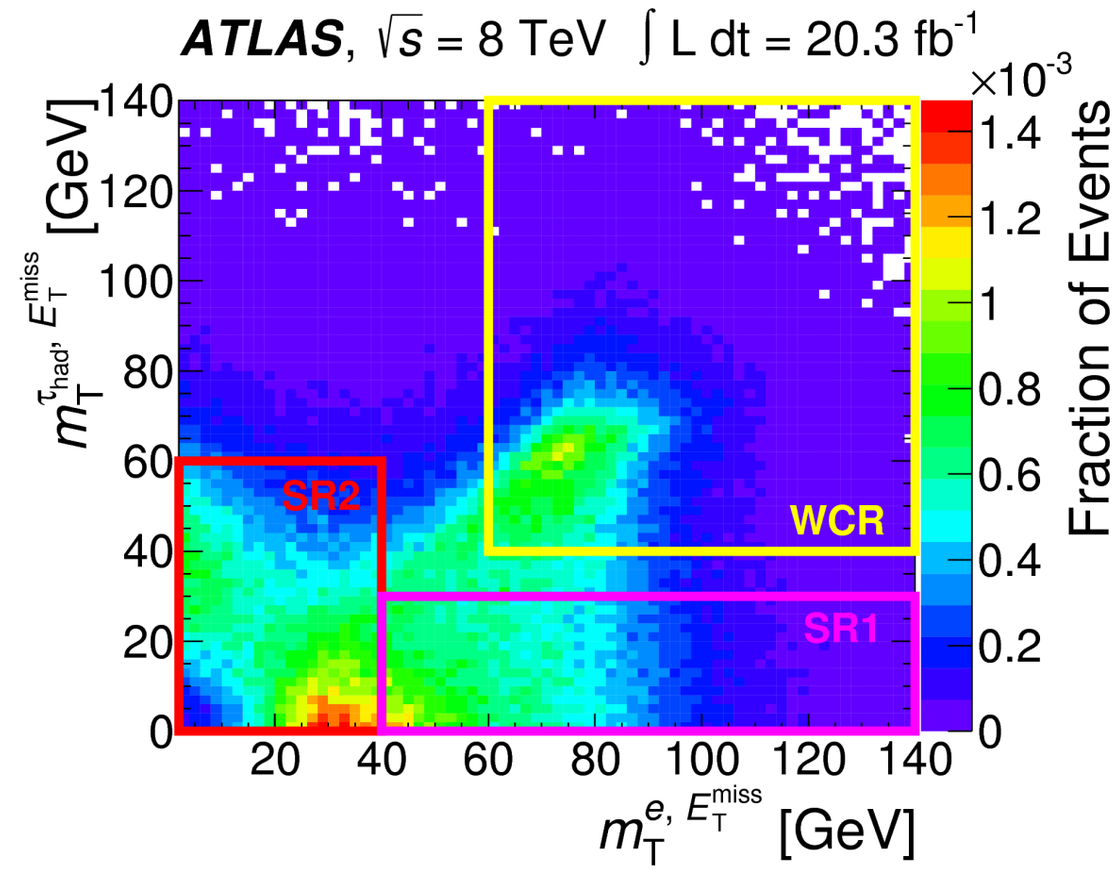
Analysis strategy

arXiv:1604.07730



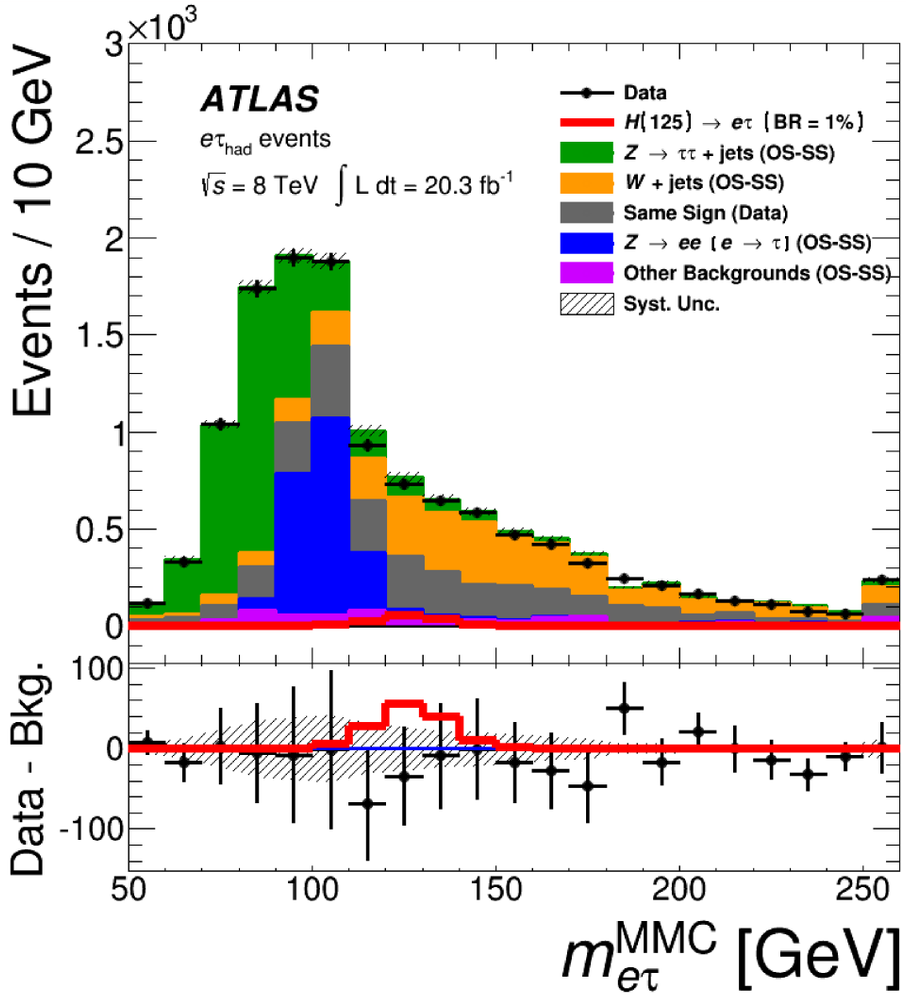


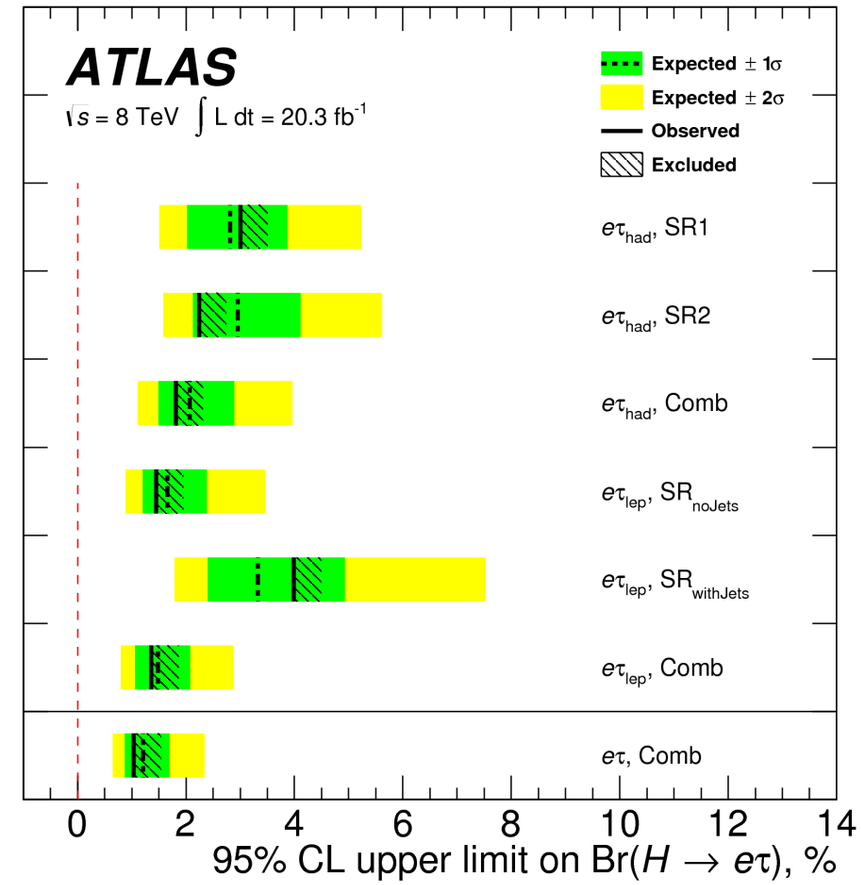




H→eτ channel

observed 95% CL upper limit on BR:
Br(H→eτ) < 1.04%

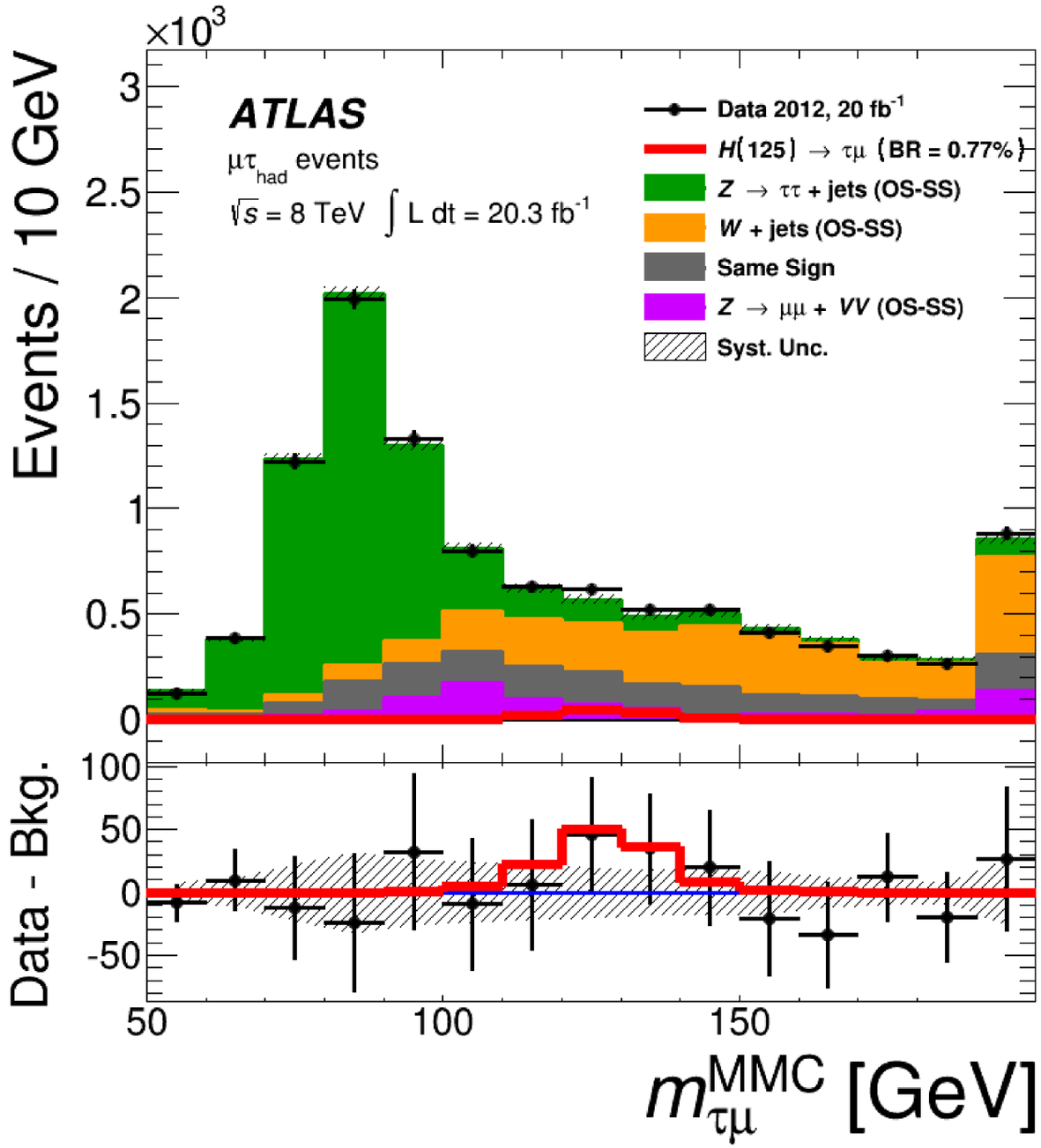


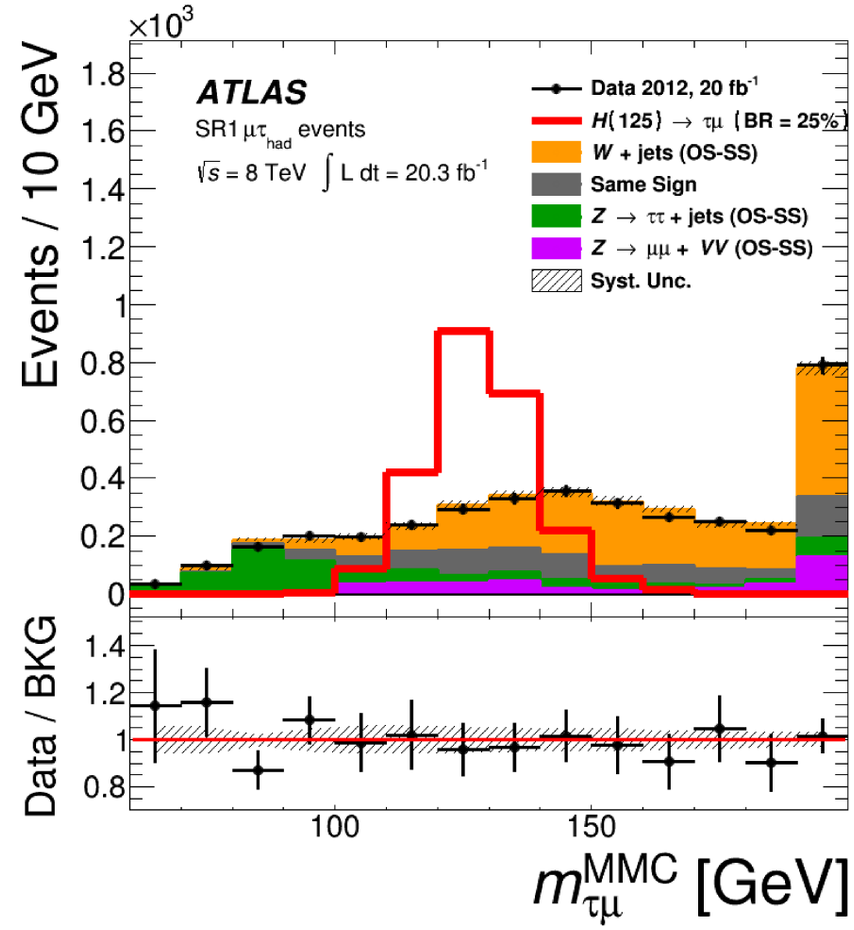


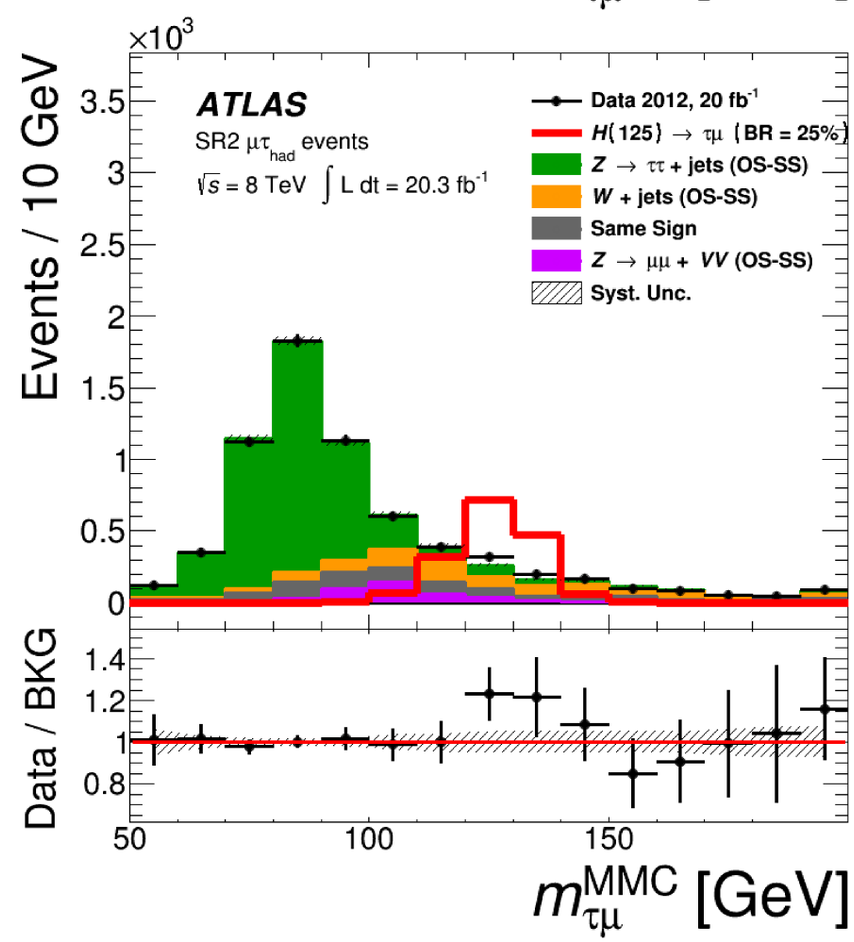
Channel	Category	Expected limit [%]	Observed limit [%]	Best fit Br [%]
$H \to e\tau_{\text{had}}$	SR1	$2.81^{+1.06}_{-0.79}$	3.0	$0.33^{+1.48}_{-1.59}$
	SR2	$2.95^{+1.16}_{-0.82}$	2.24	$-1.33^{+1.56}_{-1.80}$
	Combined	$2.07^{+0.82}_{-0.58}$	1.81	$-0.47^{+1.08}_{-1.18}$
$H \to e\tau_{\text{lep}}$	$\text{SR}_{\text{noJets}}$	$1.66^{+0.72}_{-0.46}$	1.45	$-0.45^{+0.89}_{-0.97}$
	$\text{SR}_{\text{withJets}}$	$3.33^{+1.60}_{-0.93}$	3.99	$0.74^{+1.59}_{-1.62}$
	Combined	$1.48^{+0.60}_{-0.42}$	1.36	$-0.26^{+0.79}_{-0.82}$
$H \to e\tau$	Combined	$1.21^{+0.49}_{-0.34}$	1.04	$-0.34^{+0.64}_{-0.66}$

arXiv:1604.07730

H→μτ channel







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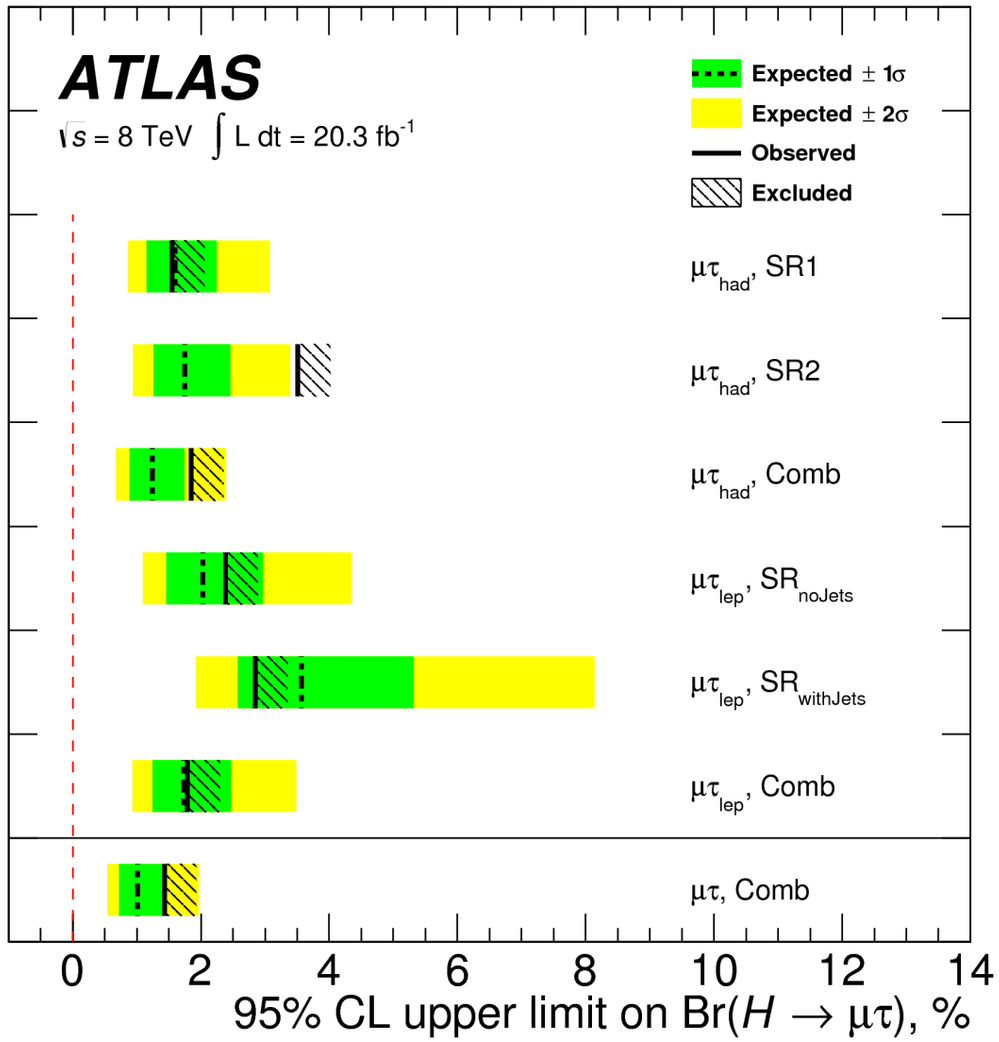
H→μτ channel



observed 95% CL upper limit on BR:
$Br(H\to\mu\tau) < 1.43\%$
while expected is: $Br(H\to\mu\tau) < (1.01^{+0.40}_{-0.39})$ %
very small excess (1σ) driven by $\mu\tau_{had}$ channel

Best fit:
$Br(H\to\mu\tau) = (0.53 \pm 0.51)\%$

arXiv:1604.07730

Channel	Category	Expected limit [%]	Observed limit [%]	Best fit Br [%]
$H \to \mu\tau_{\rm had}$	SR1	$1.60^{+0.64}_{-0.45}$	1.55	$-0.07^{+0.81}_{-0.86}$
	SR2	$1.75^{+0.71}_{-0.49}$	3.51	$1.94^{+0.92}_{-0.89}$
	Combined	$1.24^{+0.50}_{-0.35}$	1.85	$0.77^{+0.62}_{-0.62}$
$H \to \mu\tau_{\rm lep}$	$\rm SR_{noJets}$	$2.03^{+0.93}_{-0.57}$	2.38	$0.31^{+1.06}_{-0.99}$
	$\rm SR_{withJets}$	$3.57^{+1.74}_{-1.00}$	2.85	$-1.03^{+1.66}_{-1.82}$
	Combined	$1.73^{+0.74}_{-0.49}$	1.79	$0.03^{+0.88}_{-0.86}$
$H \to \mu\tau$	Combined	$1.01^{+0.40}_{-0.29}$	1.43	$0.53^{+0.51}_{-0.51}$

Conclusions

To conclude...

- **Run1** has been **fantastic**.
  - Thanks to LHC's great performance.
- **Discovery** of a new particle with mass around 125 GeV and compatible with **Higgs** boson predicted by the Standard Model.
  - So far, no deviation from SM observed.

- **H→ττ** channel: **coupling** to **fermions**.
  - excess with observed (expected) significance of 4.5σ (3.4σ).
- Higgs decay in final states with taus useful to **search** for **lepton flavor violating decays**.

- **Run2** has just **started**.
  - **Challenging** environment.
- Small excess from Run1 for LFV decays can be confirmed or ruled out already this year.
  - Stay tuned!

References

1. ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1

2. ATLAS Collaboration, Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector, JHEP 04 (2015) 117

3. ATLAS Collaboration, Modelling $Z \to \tau\tau$ processes in ATLAS with τ-embedded $Z \to \mu\mu$ data, JINST 10 (2015) P09018

4. ATLAS Collaboration, Search for lepton-flavour-violating $H \to \mu\tau$ decays of the Higgs boson with the ATLAS detector, JHEP 11 (2015) 211

5. ATLAS Collaboration, Search for lepton-flavour-violating decays of the Higgs and Z bosons with the ATLAS detector, submitted to EPJC, arXiv:1604.07730

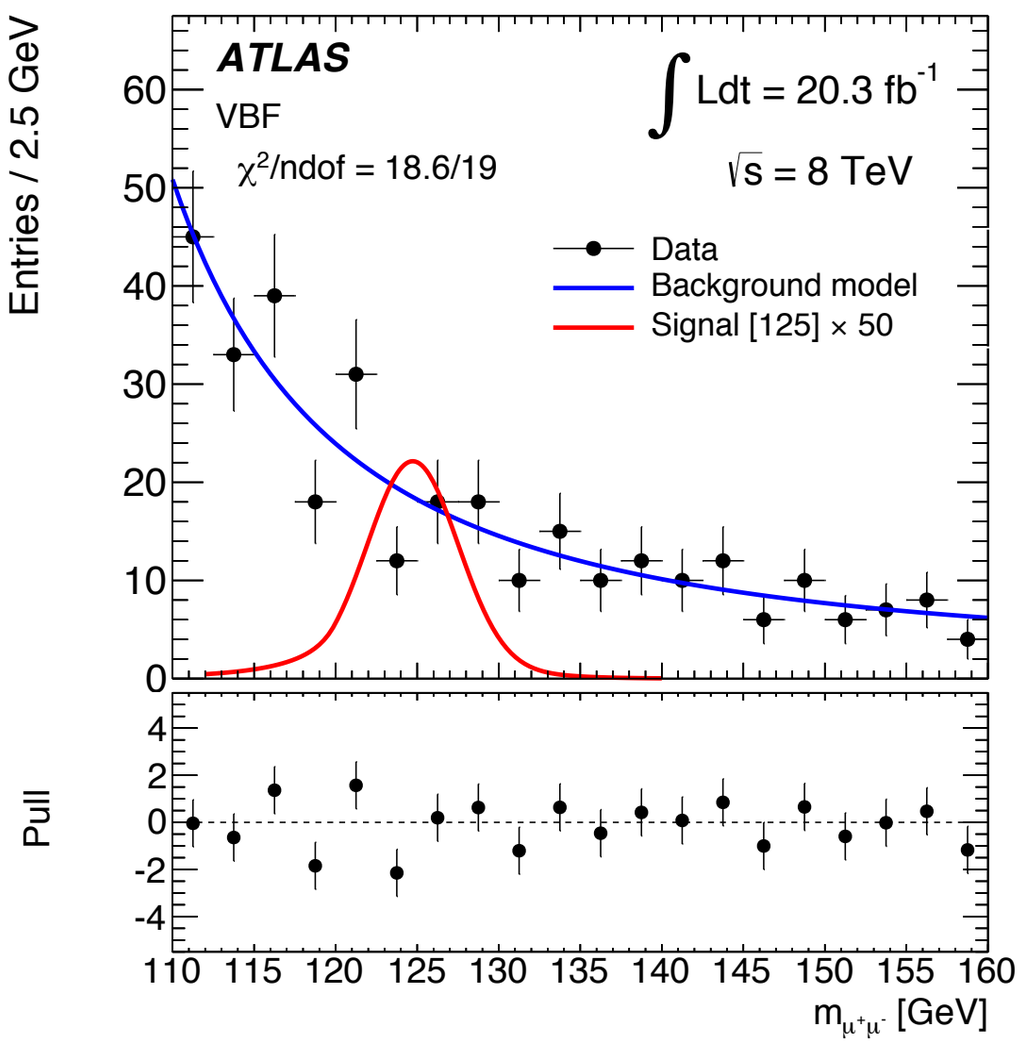
BackUp

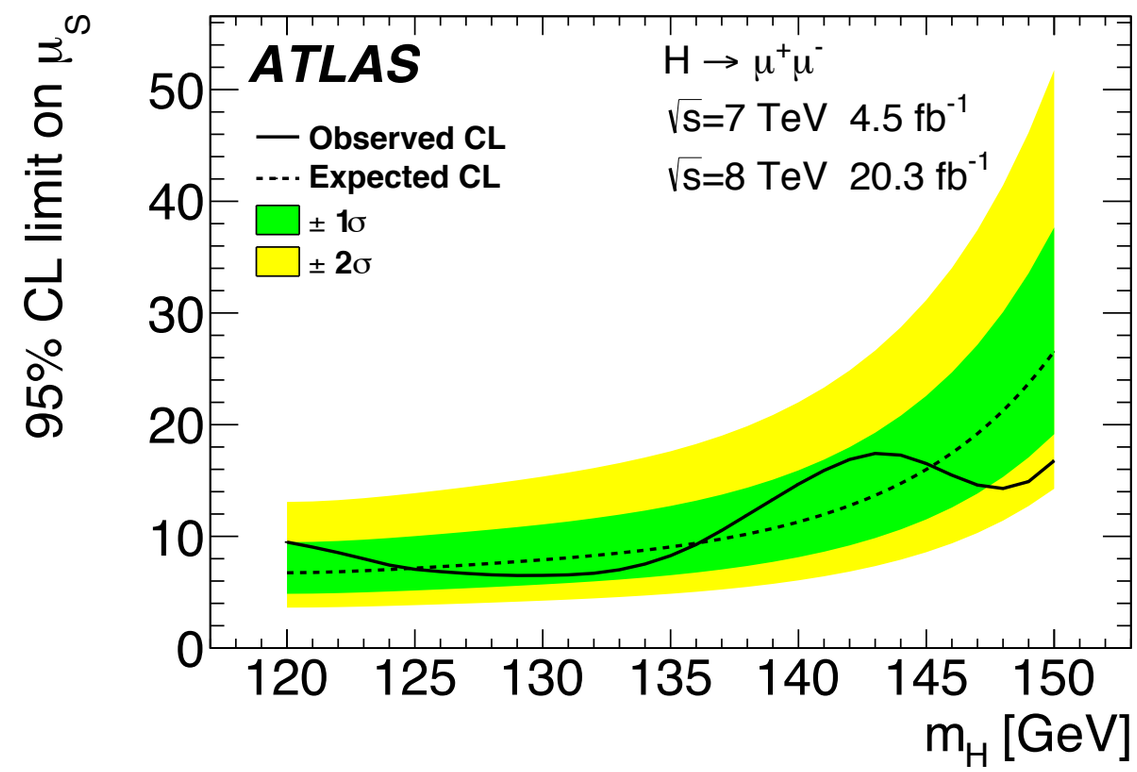
H→μμ

Phys. Lett. B 738 (2014) 68

Higgs boson coupling to **second generation** fermions.
Test if the coupling is flavor universal or proportional to the lepton mass, as predicted by the SM.

- **Clean** final state, but **small BR** and **overwhelming Z/γ*** →μμ background.
- Event **categorization** based on jet multiplicity, $p_T(\mu\mu)$ and m(μμ) resolution.
- Cut based analysis with fit of m(μμ) with analytical bkg/signal shapes.

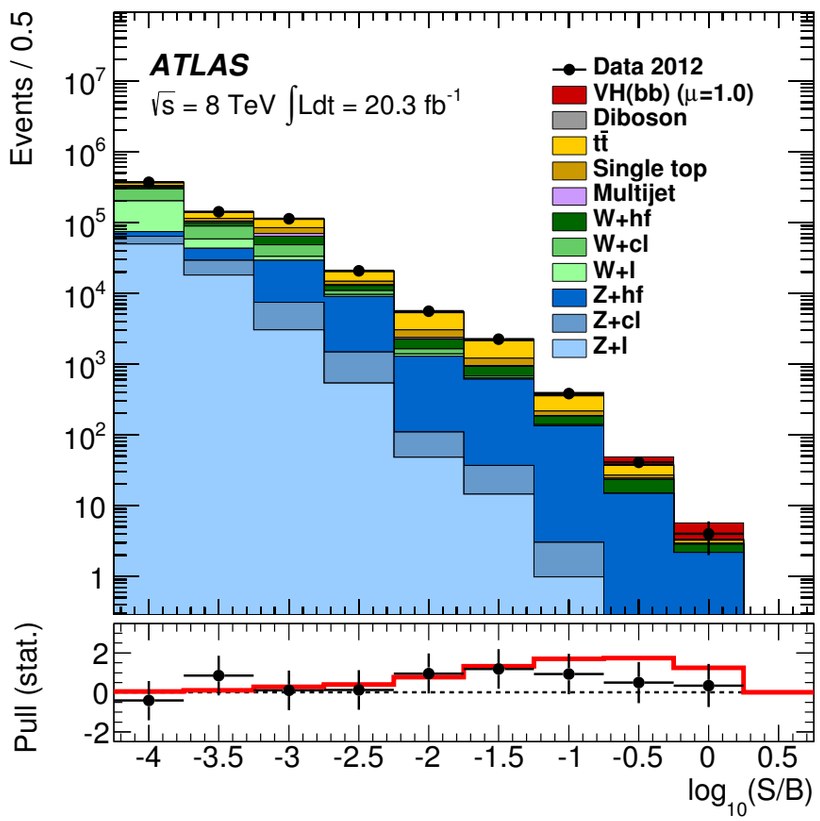




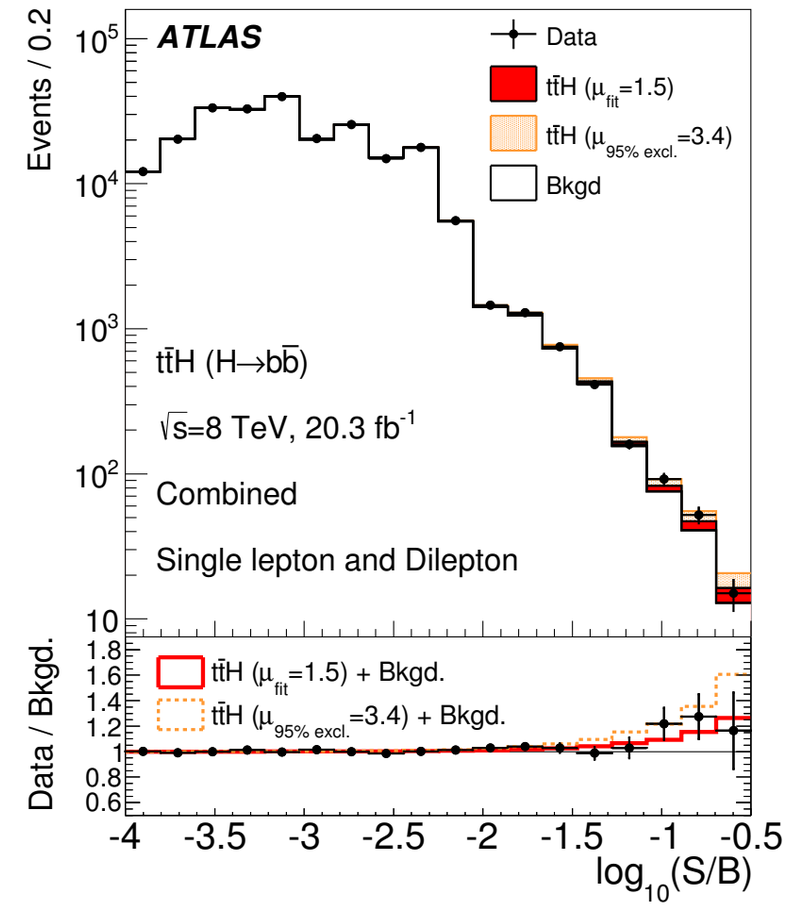
obs (exp) 95% CL limit on μ @ 125 GeV:
ATLAS: 7.0 (7.2) x SM

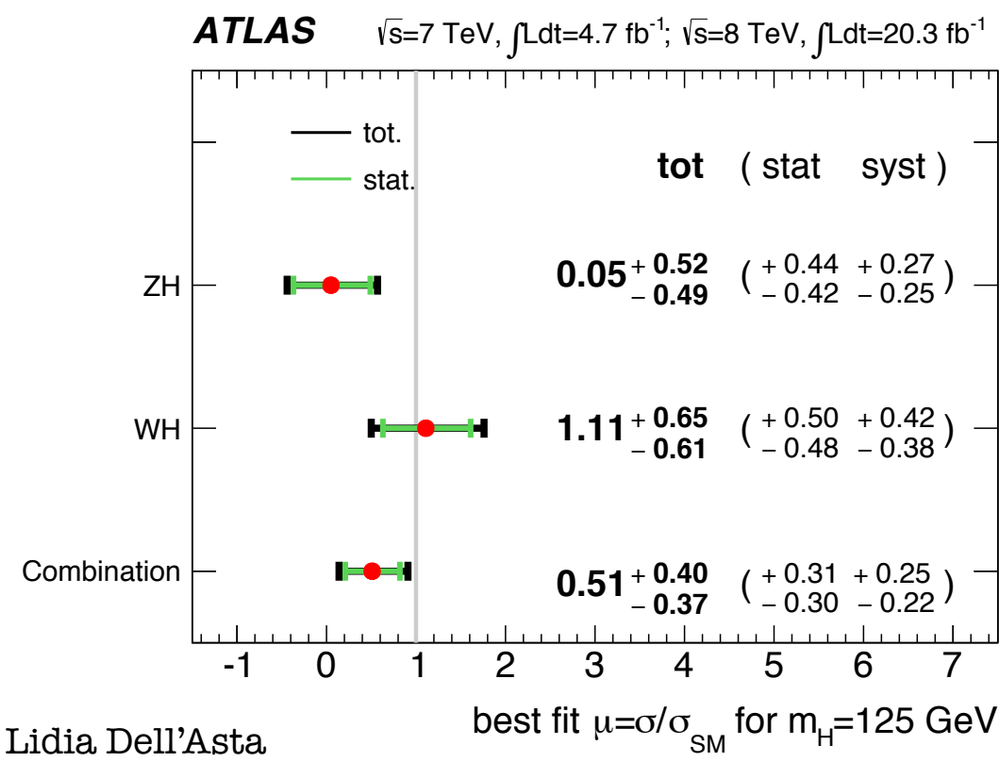
H→bb

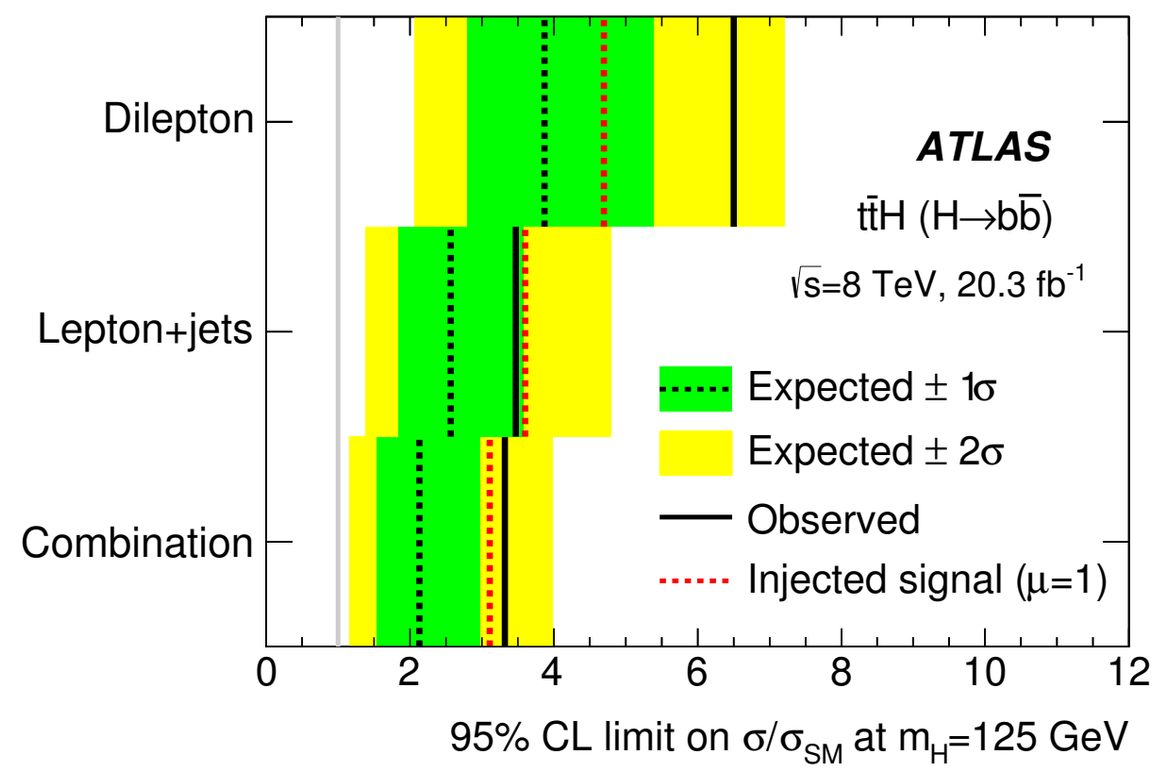
VH: JHEP 01 (2015) 069
ttH: Eur. Phys. J. C 75 (2015) 349



First direct test of interaction of the Higgs boson with the **quark sector**, as the coupling to the top quark has only been tested through loop effects.







Event Selection & Categorization

Channel	Preselection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	Exactly two isolated opposite-sign leptons Events with $\tau_{\rm had}$ candidates are rejected 30 GeV$< m_{\tau\tau}^{\rm vis} <$ 100 (75) GeV for DF (SF) events $\Delta\phi_{\ell\ell} < 2.5$ $E_{\rm T}^{\rm miss} >$ 20 (40) GeV for DF (SF) events $E_{\rm T}^{\rm miss,HPTO} >$ 40 GeV for SF events $p_{\rm T}^{\ell_1} + p_{\rm T}^{\ell_2} >$ 35 GeV Events with a b-tagged jet with $p_{\rm T} >$ 25 GeV are rejected $0.1 < x_{\tau_1}, x_{\tau_2} < 1$ $m_{\tau\tau}^{\rm coll} > m_Z -$ 25 GeV
$\tau_{\rm lep}\tau_{\rm had}$	Exactly one isolated lepton and one medium $\tau_{\rm had}$ candidate with opposite charges $m_{\rm T} <$ 70 GeV Events with a b-tagged jet with $p_{\rm T} >$ 30 GeV are rejected
$\tau_{\rm had}\tau_{\rm had}$	One isolated medium and one isolated tight opposite-sign $\tau_{\rm had}$-candidate Events with leptons are vetoed $E_{\rm T}^{\rm miss} >$ 20 GeV $E_{\rm T}^{\rm miss}$ points between the two visible taus in ϕ, or $\min[\Delta\phi(\tau, E_{\rm T}^{\rm miss})] < \pi/4$ $0.8 < \Delta R(\tau_{\rm had_1}, \tau_{\rm had_2}) < 2.4$ $\Delta\eta(\tau_{\rm had_1}, \tau_{\rm had_2}) < 1.5$

Channel	VBF category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_{\rm T}^{j1} >$ 40 GeV and $p_{\rm T}^{j2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j1} >$ 50 GeV and $p_{\rm T}^{j2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\rm vis} >$ 40 GeV
$\tau_{\rm had}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j1} >$ 50 GeV and $p_{\rm T}^{j2} >$ 30 GeV $p_{\rm T}^{j2} >$ 35 GeV for jets with $\lvert\eta\rvert > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$

Channel	Boosted category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least one jet with $p_{\rm T} >$ 40 GeV
All	Failing the VBF selection $p_{\rm T}^{H} >$ 100 GeV

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Variables used in the Boosted Decision Tree

Variable	VBF			Boosted		
	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$
$m_{\tau\tau}^{\rm MMC}$	●	●	●	●	●	●
$\Delta R(\tau_1, \tau_2)$	●	●	●		●	●
$\Delta\eta(j_1, j_2)$	●	●	●			
m_{j_1,j_2}	●	●	●			
$\eta_{j_1} \times \eta_{j_2}$		●	●			
$p_{\rm T}^{\rm Total}$		●	●			
Sum $p_{\rm T}$					●	●
$p_{\rm T}^{\tau_1}/p_{\rm T}^{\tau_2}$					●	●
$E_{\rm T}^{\rm miss}\phi$ centrality		●	●	●	●	●
m_{ℓ,ℓ,j_1}				●		
m_{ℓ_1,ℓ_2}				●		
$\Delta\phi(\ell_1, \ell_2)$				●		
Sphericity				●		
$p_{\rm T}^{\ell_1}$				●		
$p_{\rm T}^{j_1}$				●		
$E_{\rm T}^{\rm miss}/p_{\rm T}^{\ell_2}$				●		
$m_{\rm T}$		●			●	
$\min(\Delta\eta_{\ell_1\ell_2,\rm jets})$	●					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	●					
$C_{\eta_1,\eta_2}(\eta_\ell)$		●				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	●					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			●			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			●			

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Variables used in the Boosted Decision Tree

- $E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality: a variable that quantifies the relative angular position of the missing transverse momentum with respect to the visible tau decay products in the transverse plane. The transverse plane is transformed such that the direction of the tau decay products are orthogonal, and that the smaller ϕ angle between the tau decay products defines the positive quadrant of the transformed plane. The $E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality is defined as the sum of the x- and y-components of the $E_{\mathrm{T}}^{\mathrm{miss}}$ unit vector in this transformed plane.

- Sphericity: a variable that describes the isotropy of the energy flow in the event [101]. It is based on the quadratic momentum tensor

$$S^{\alpha\beta} = \frac{\sum_i p_i^{\alpha} p_i^{\beta}}{\sum_i |\vec{p_i}^2|}. \tag{5.1}$$

In this equation, α and β are the indices of the tensor. The summation is performed over the momenta of the selected leptons and jets in the event. The sphericity of the event (S) is then defined in terms of the two smallest eigenvalues of this tensor, λ_2 and λ_3,

$$S = \frac{3}{2}(\lambda_2 + \lambda_3). \tag{5.2}$$

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Variables used in the Boosted Decision Tree

- Object η centrality: a variable that quantifies the η position of an object (an isolated lepton, a τ_{had} candidate or a jet) with respect to the two leading jets in the event. It is defined as

$$C_{\eta_1,\eta_2}(\eta) = \exp\left[\frac{-4}{(\eta_1-\eta_2)^2}\left(\eta - \frac{\eta_1+\eta_2}{2}\right)^2\right], \tag{5.3}$$

where η, η_1 and η_2 are the pseudorapidities of the object and the two leading jets respectively. This variable has a value of 1 when the object is halfway in η between the two jets, 1/e when the object is aligned with one of the jets, and $< 1/\text{e}$ when the object is not between the jets in η. In the $\tau_{\text{lep}}\tau_{\text{lep}}$ channel the η centrality of a third jet in the event, $C_{\eta_1,\eta_2}(\eta_{j_3})$, and the product of the η centralities of the two leptons are used as BDT input variables, while in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel the η centrality of the lepton, $C_{\eta_1,\eta_2}(\eta_\ell)$, is used, and in the $\tau_{\text{had}}\tau_{\text{had}}$ channel the η centrality of each τ, $C_{\eta_1,\eta_2}(\eta_{\tau_1})$ and $C_{\eta_1,\eta_2}(\eta_{\tau_2})$, is used. Events with only two jets are assigned a dummy value of -0.5 for $C_{\eta_1,\eta_2}(\eta_{j_3})$.

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Input Variables - $\tau_{lep}\tau_{lep}$ - VBF category

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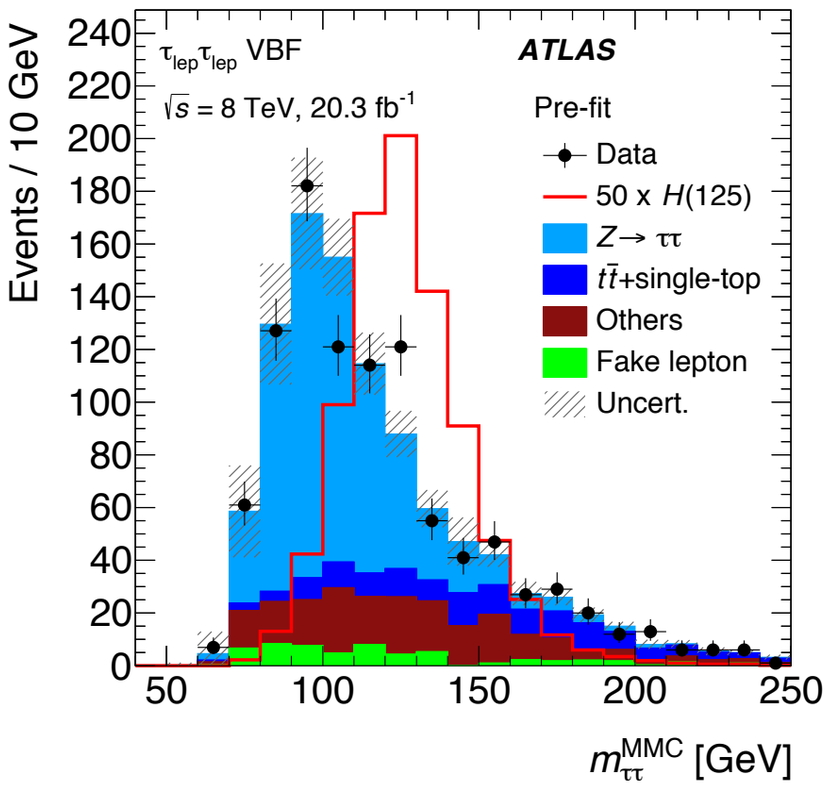
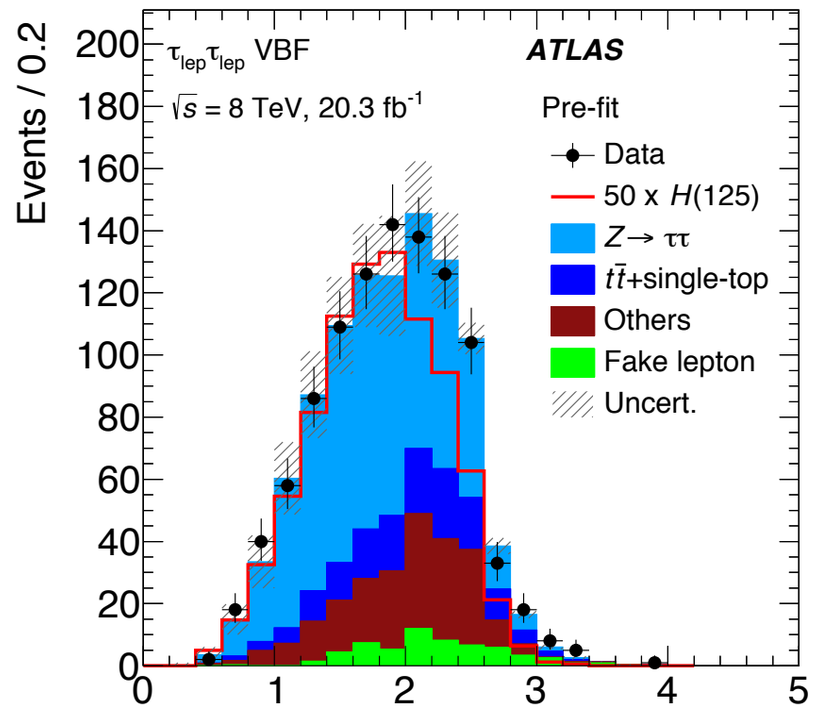
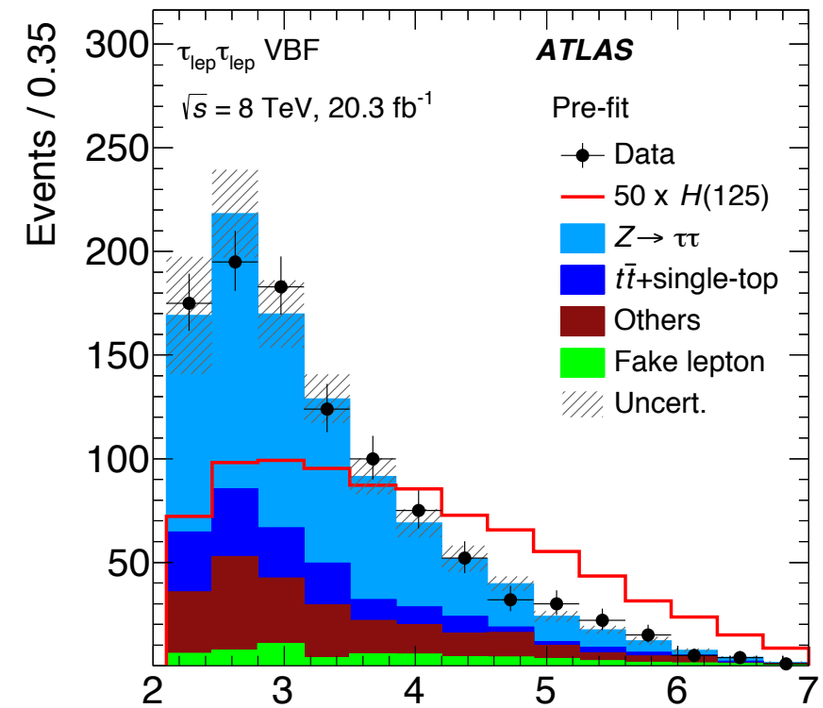
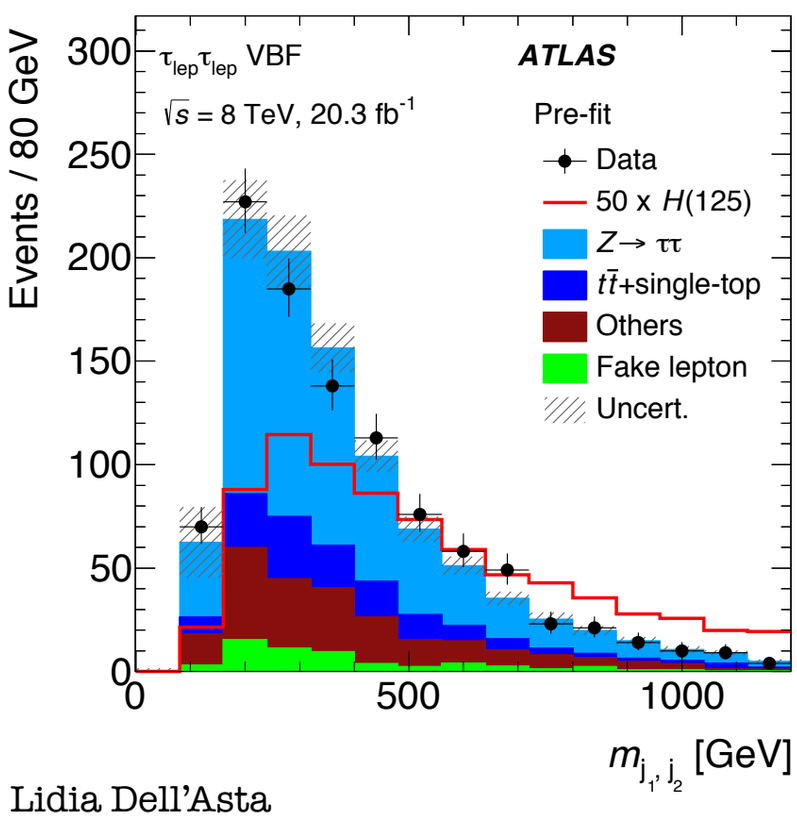
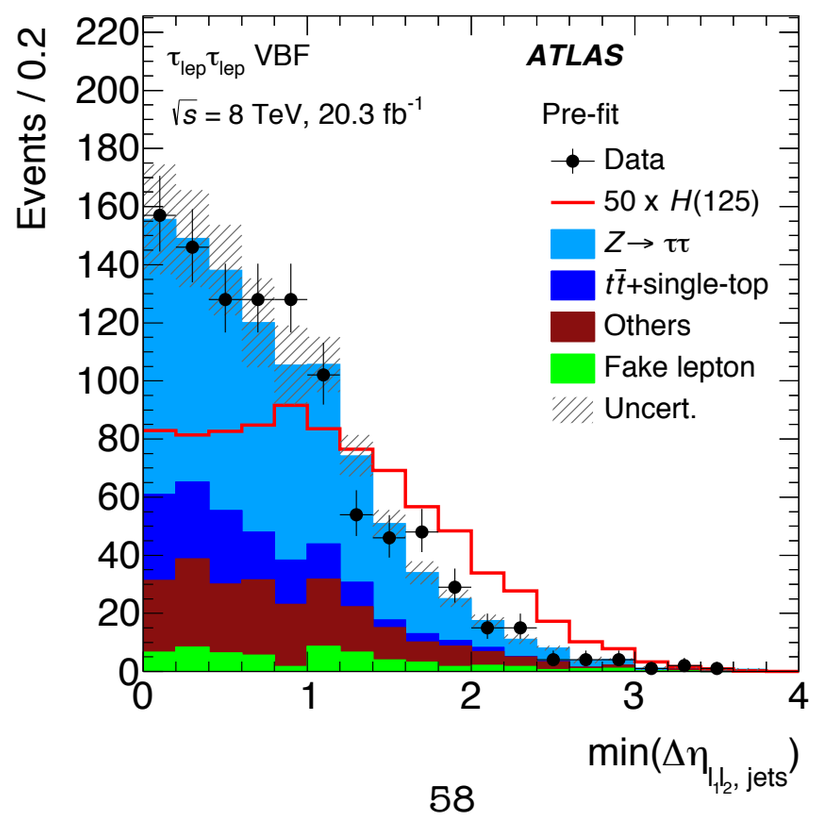
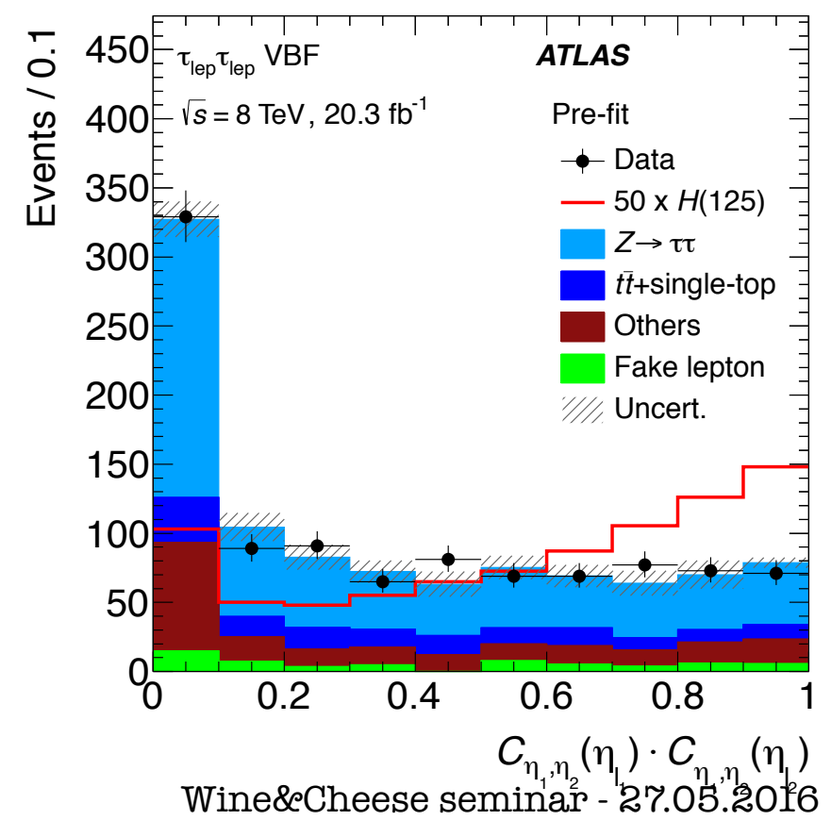




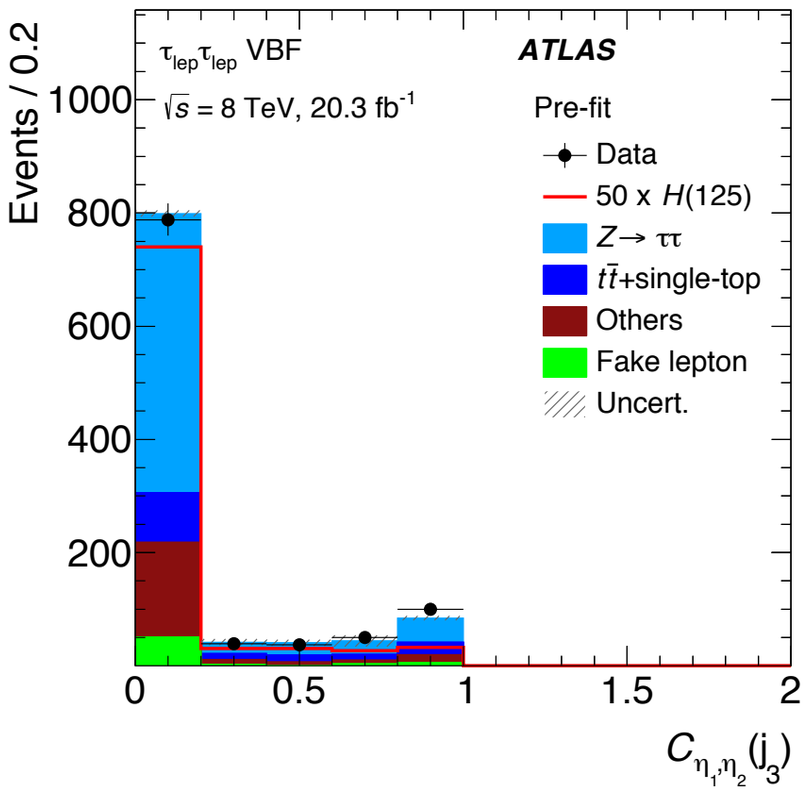








Input Variables - $\tau_{lep}\tau_{lep}$ - VBF category



Input Variables - $\tau_{lep}\tau_{lep}$ - Boosted category

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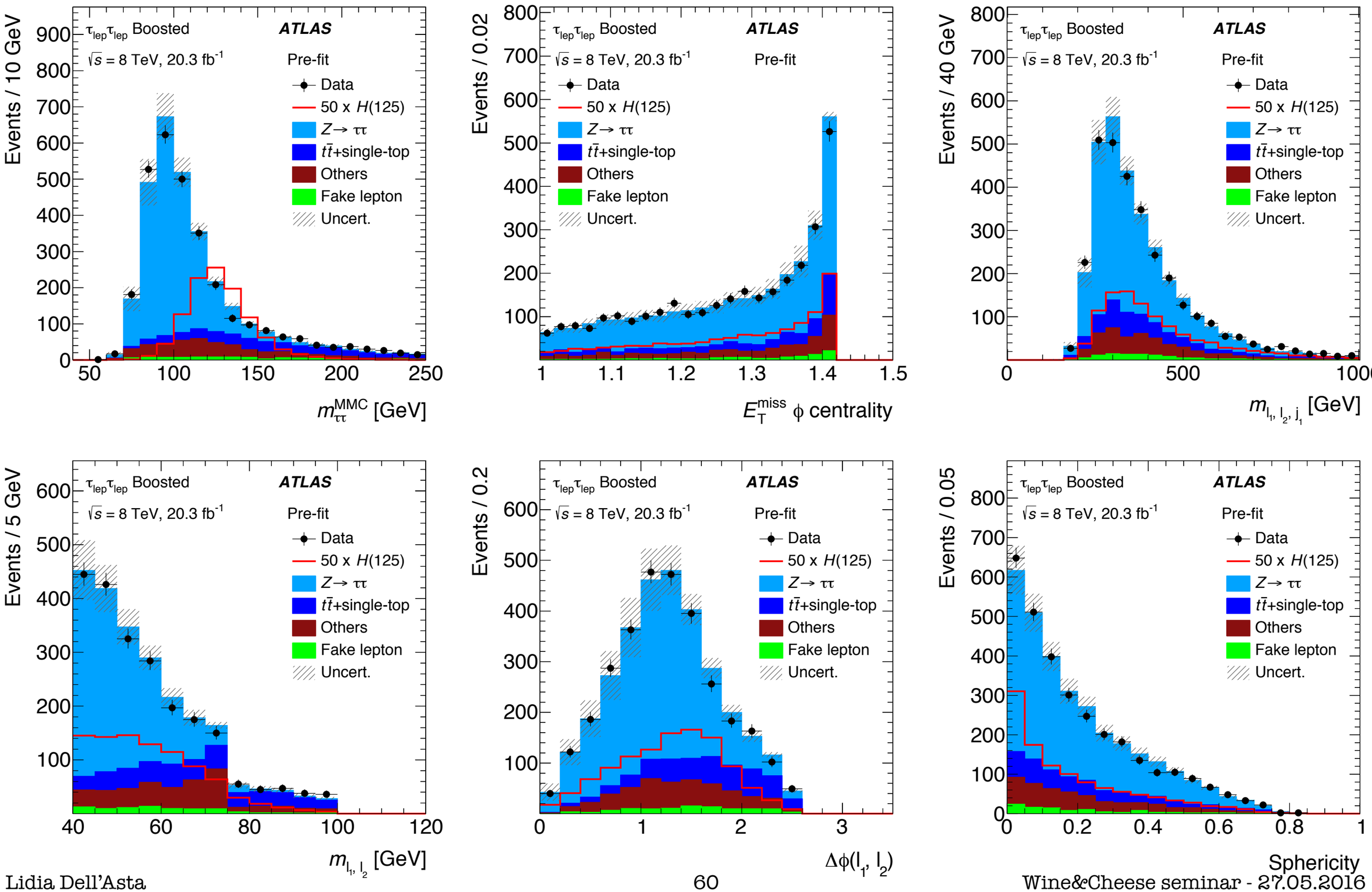

Input Variables - $\tau_{lep}\tau_{lep}$ - Boosted category

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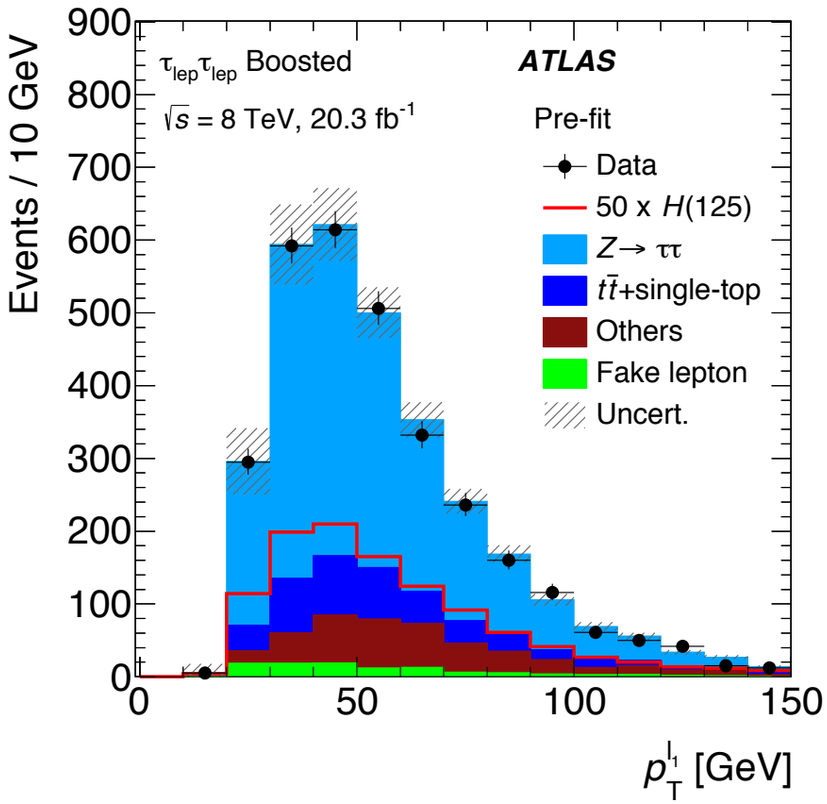
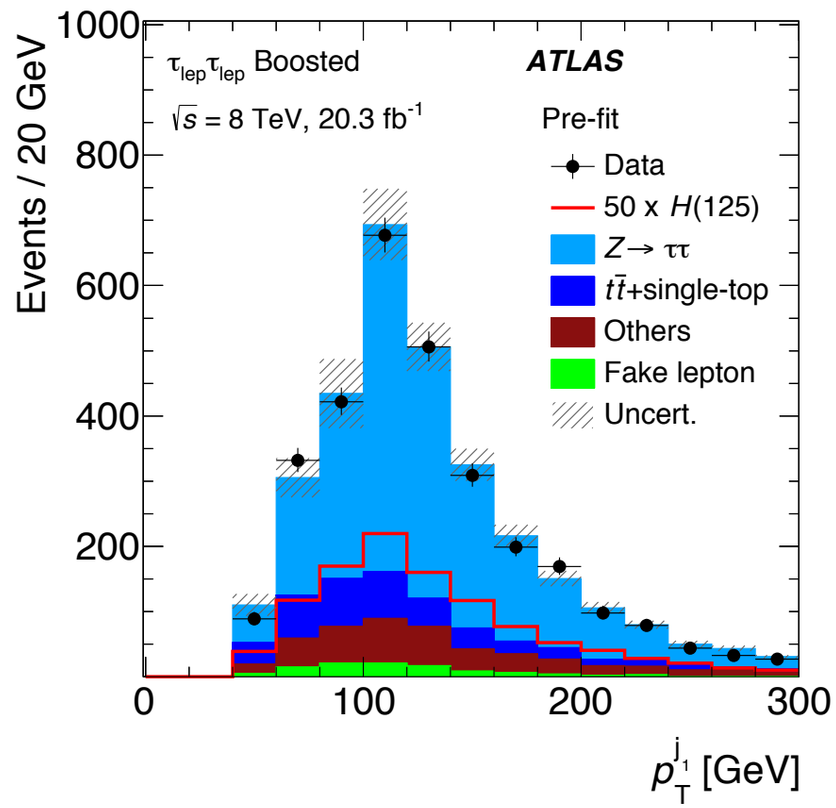
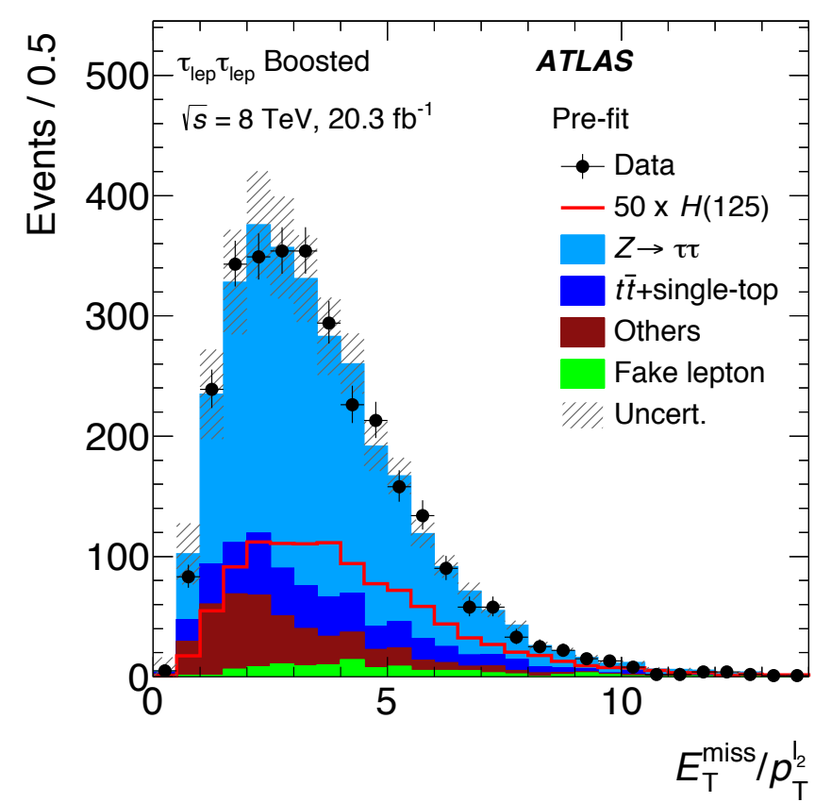
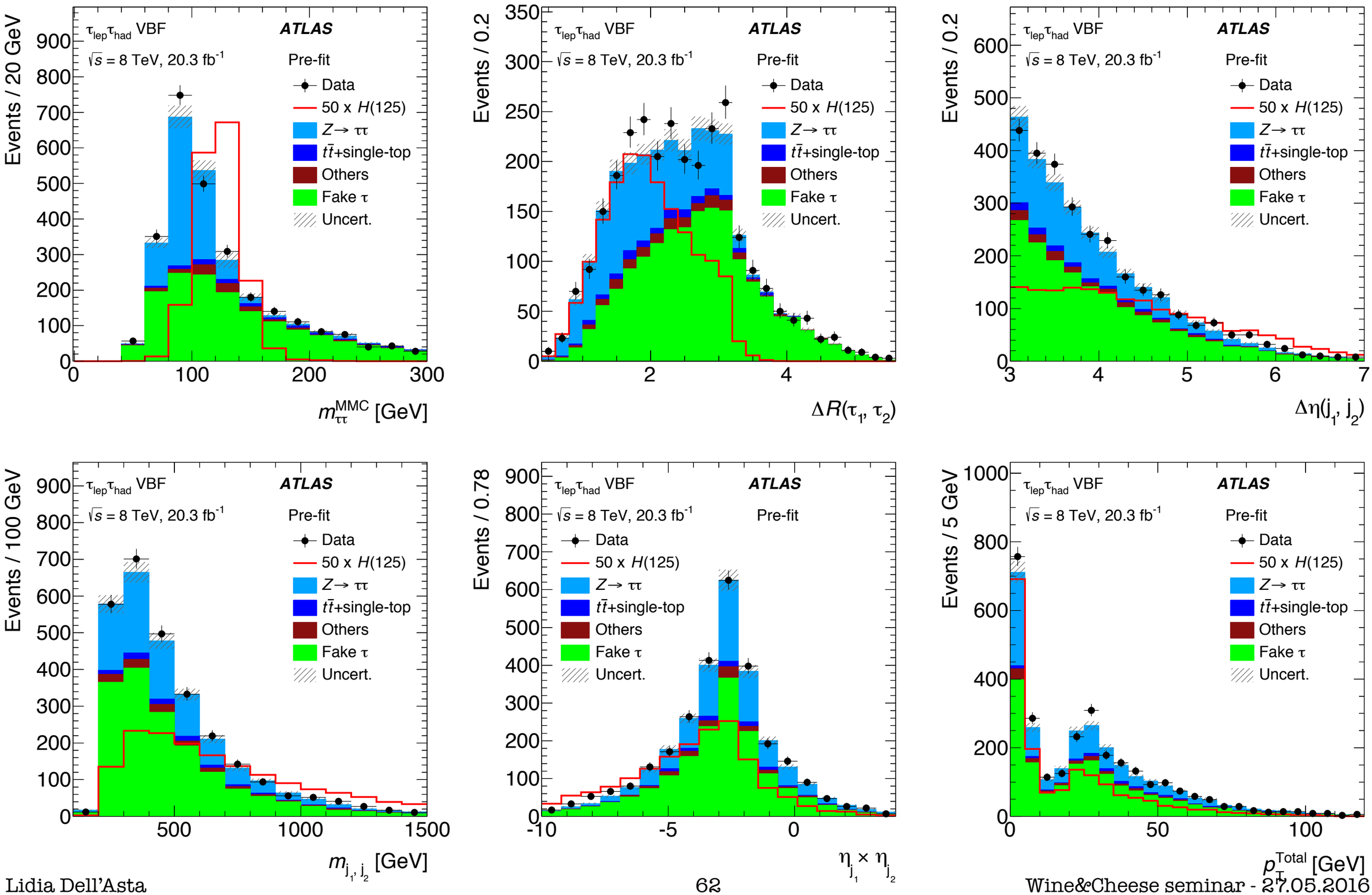






Input Variables - $\tau_{lep}\tau_{had}$ - VBF category



Input Variables - $\tau_{lep}\tau_{had}$ - VBF category

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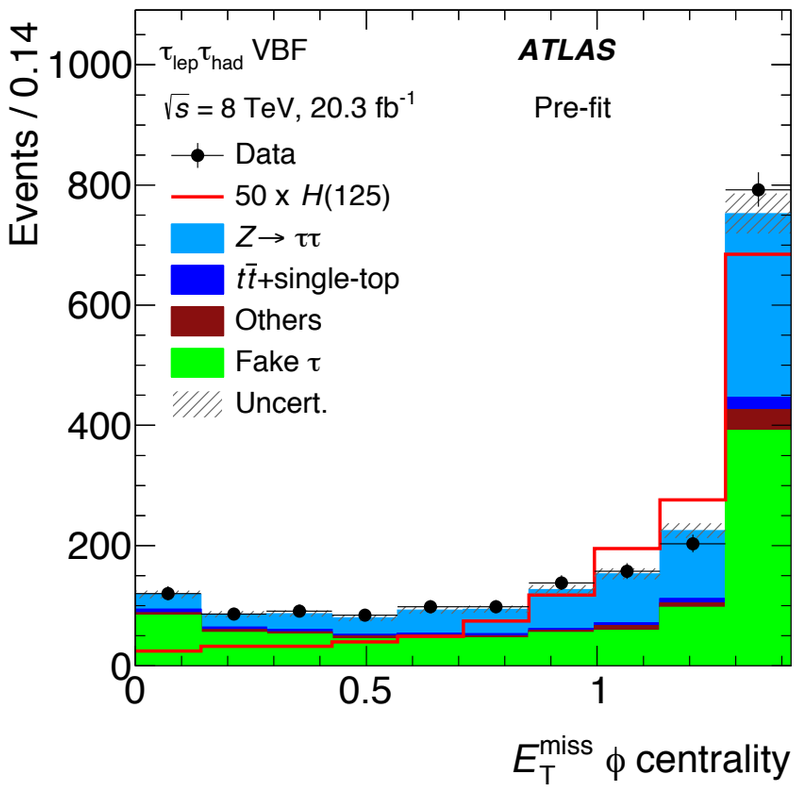

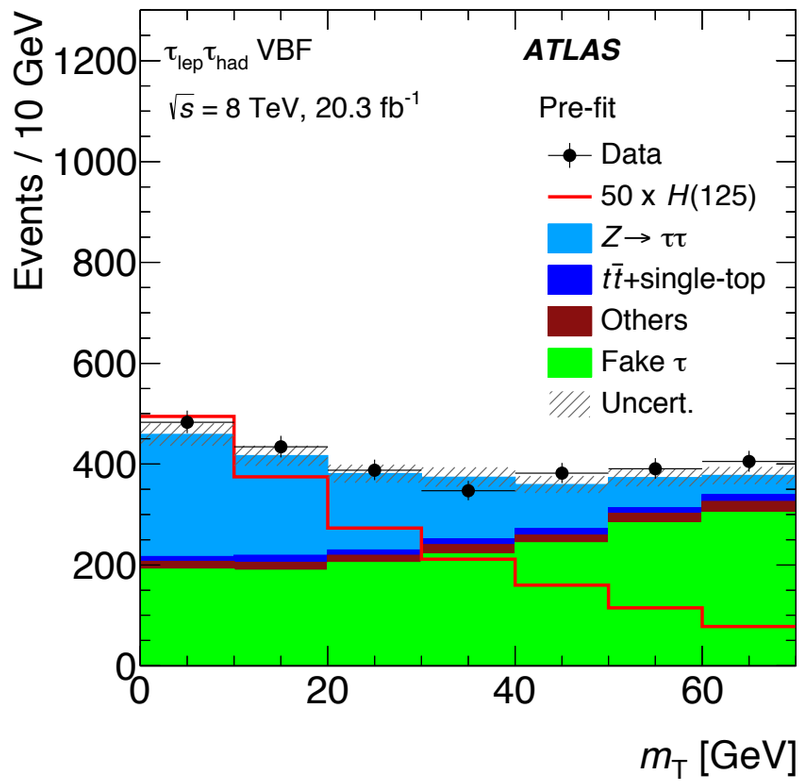

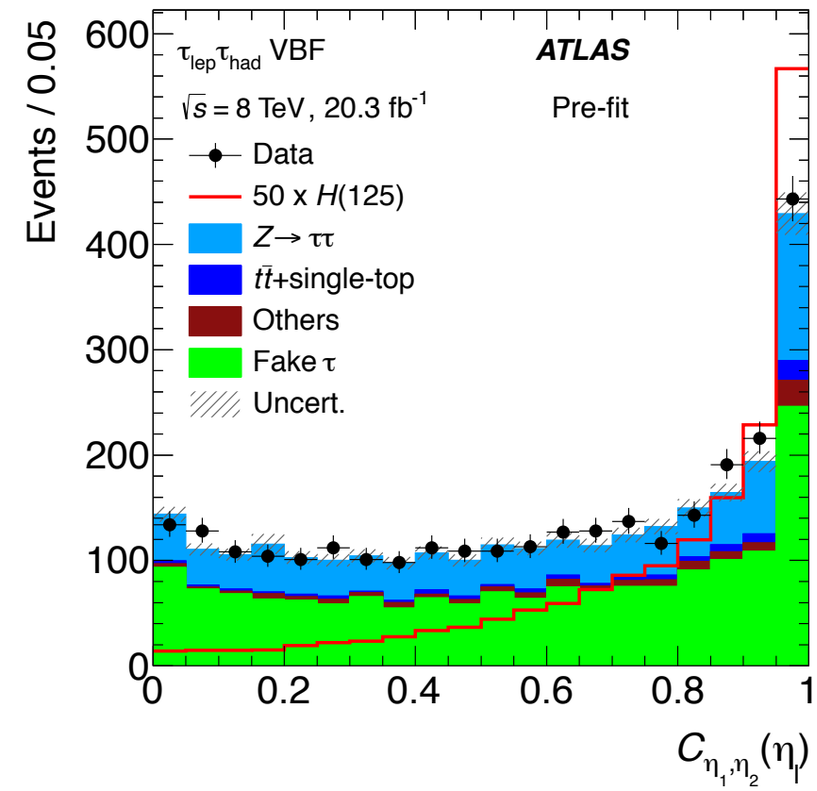

Input Variables - $\tau_{lep}\tau_{had}$ - Boosted category

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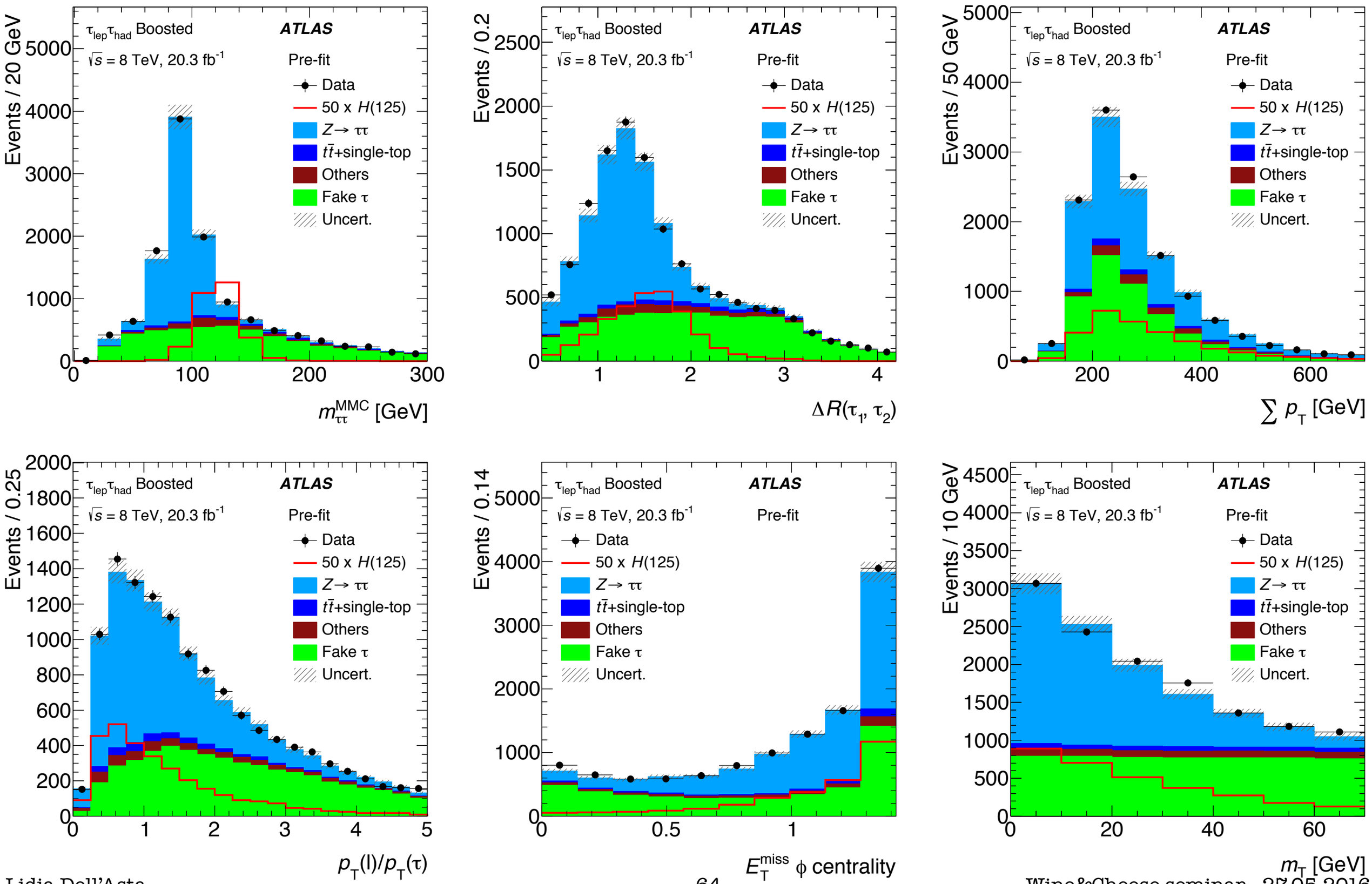

Input Variables - $\tau_{had}\tau_{had}$ - VBF category

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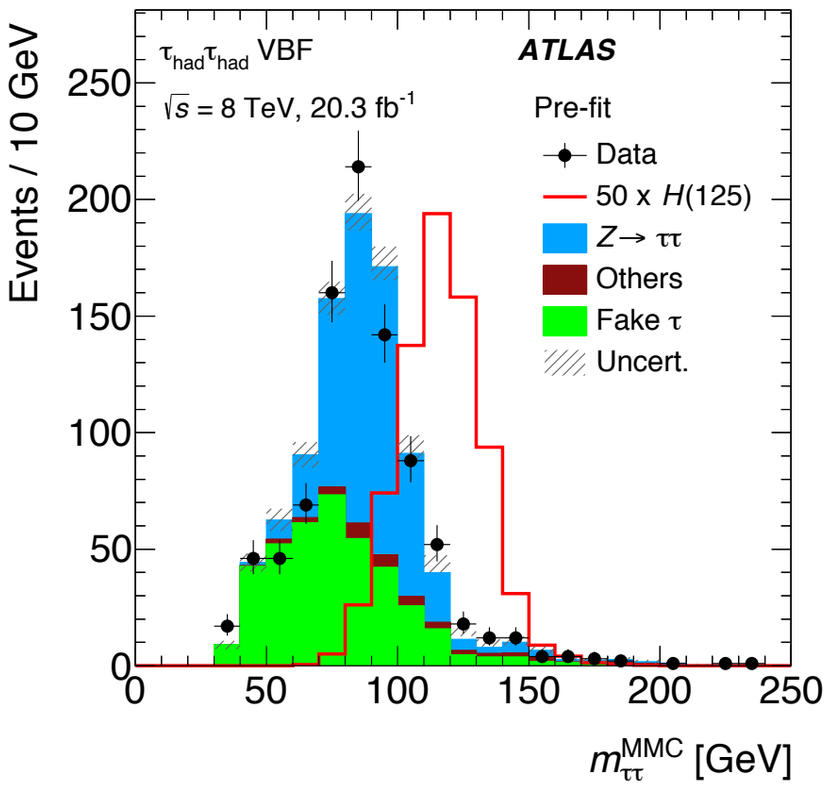

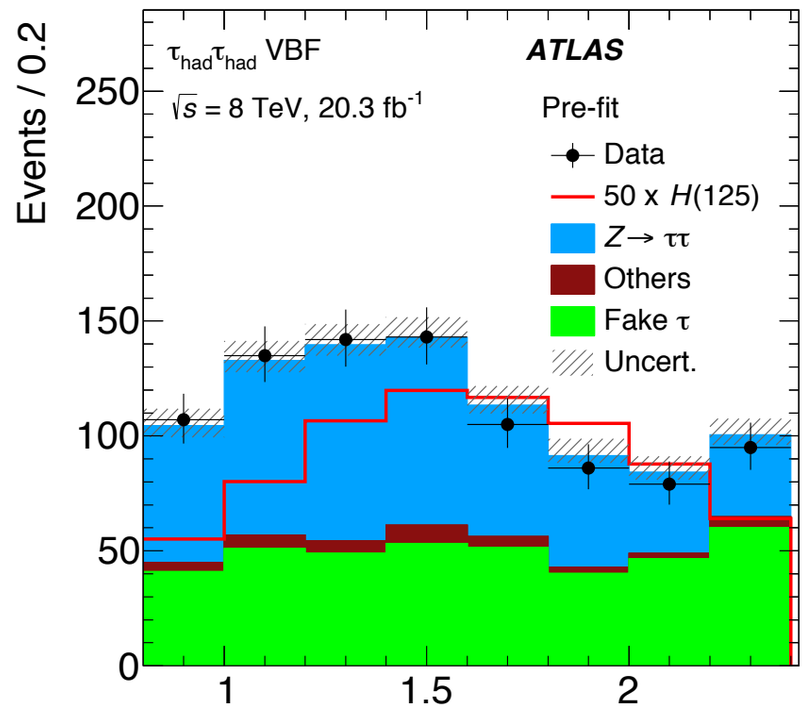

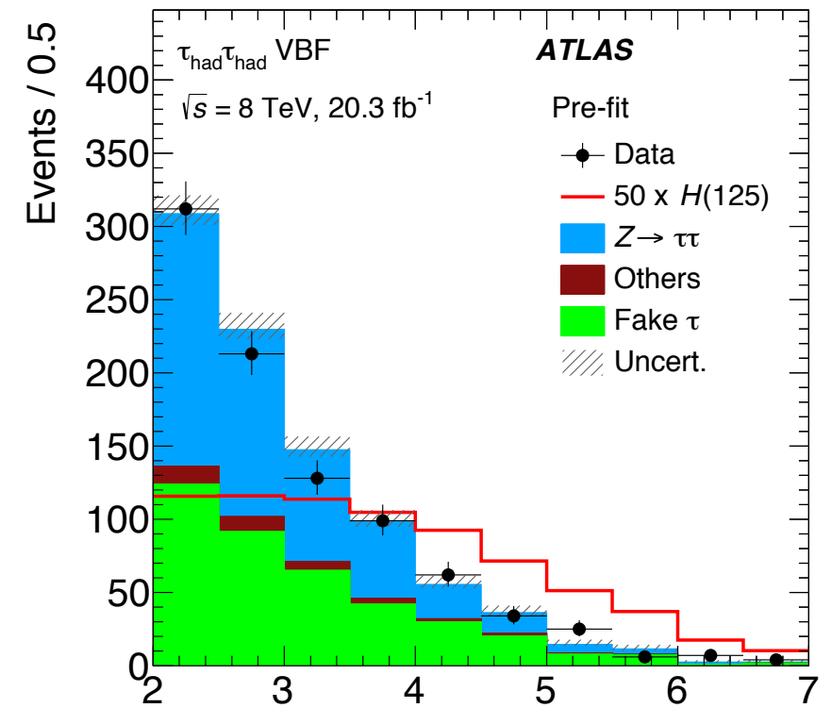

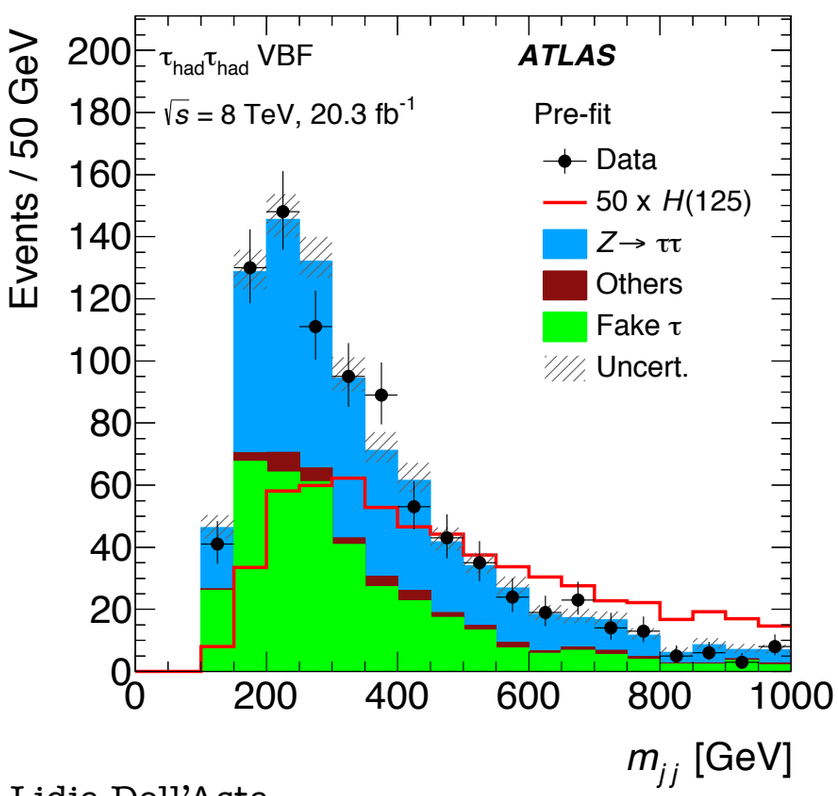

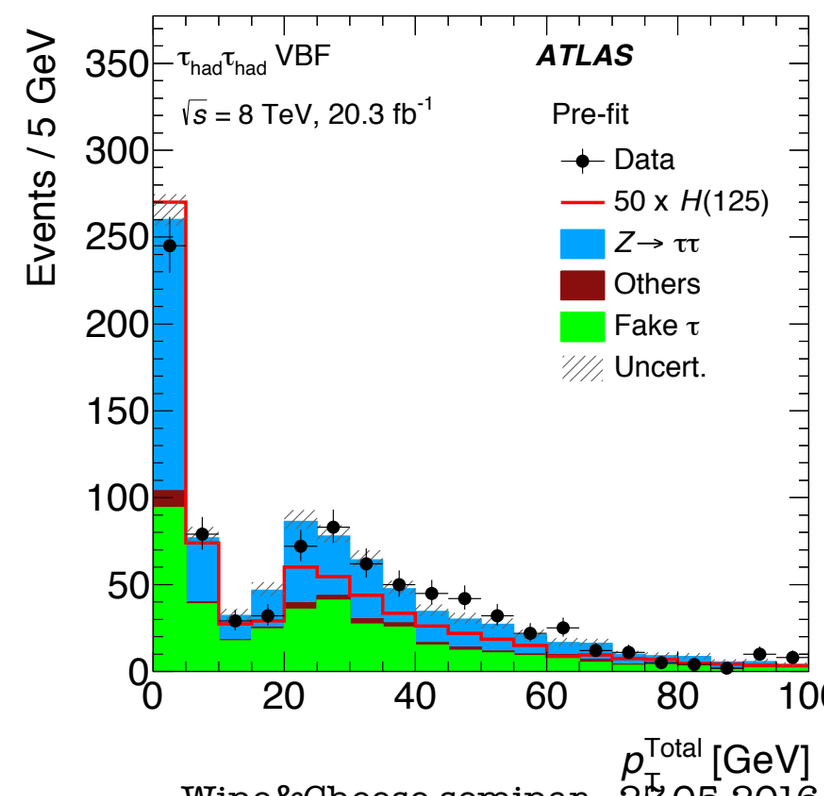

Input Variables - $\tau_{had}\tau_{had}$ - VBF category

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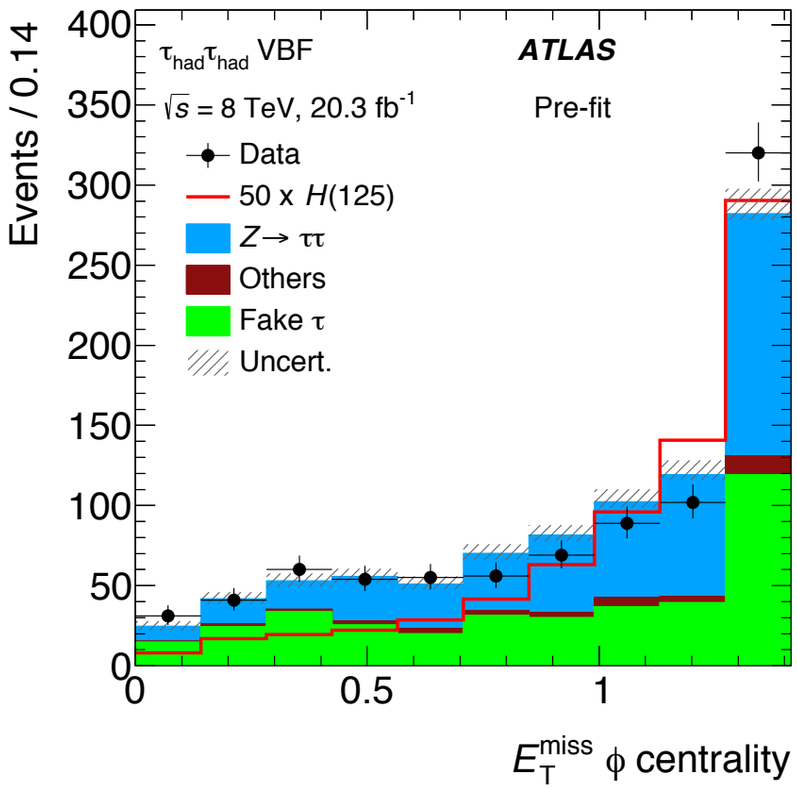

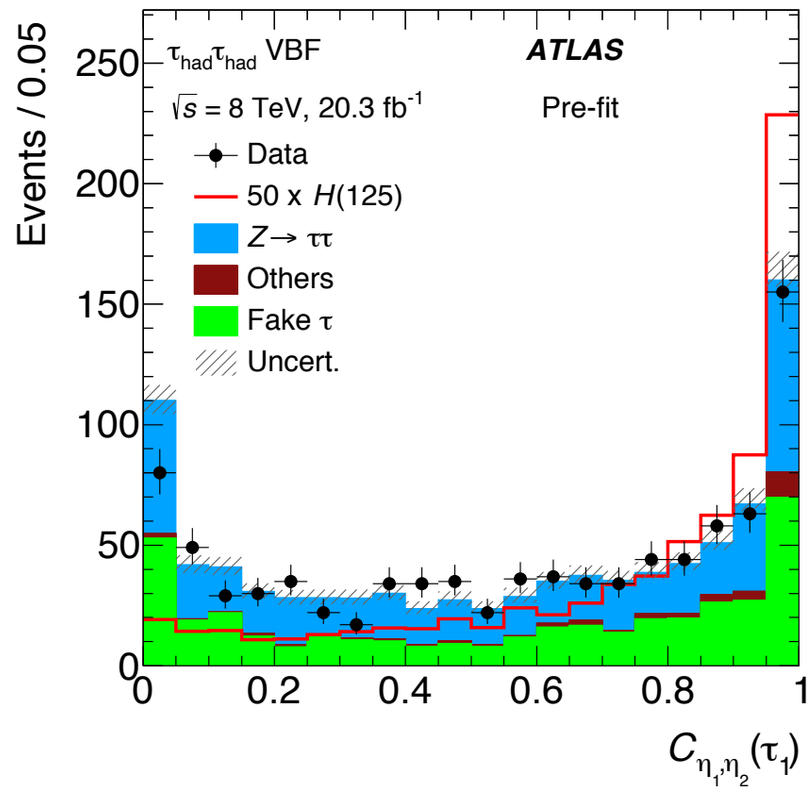

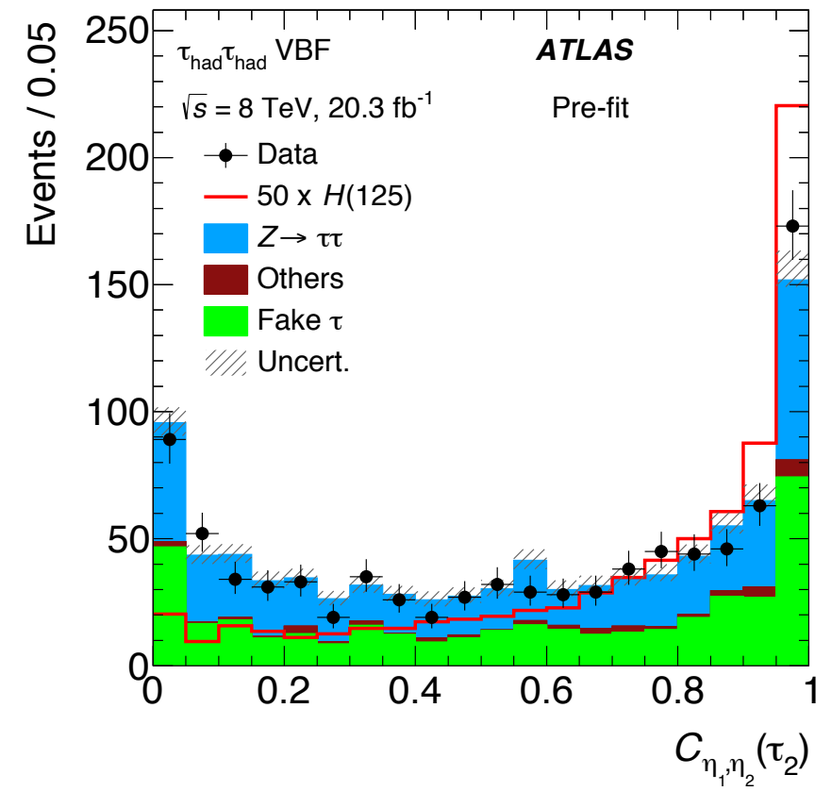

Input Variables - $\tau_{had}\tau_{had}$ - Boosted category

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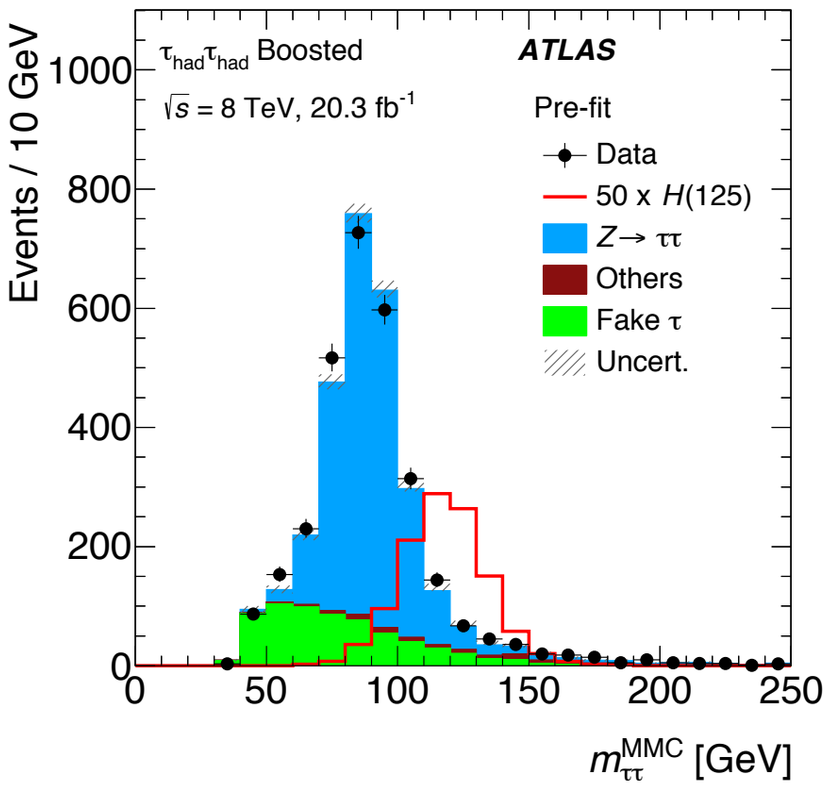

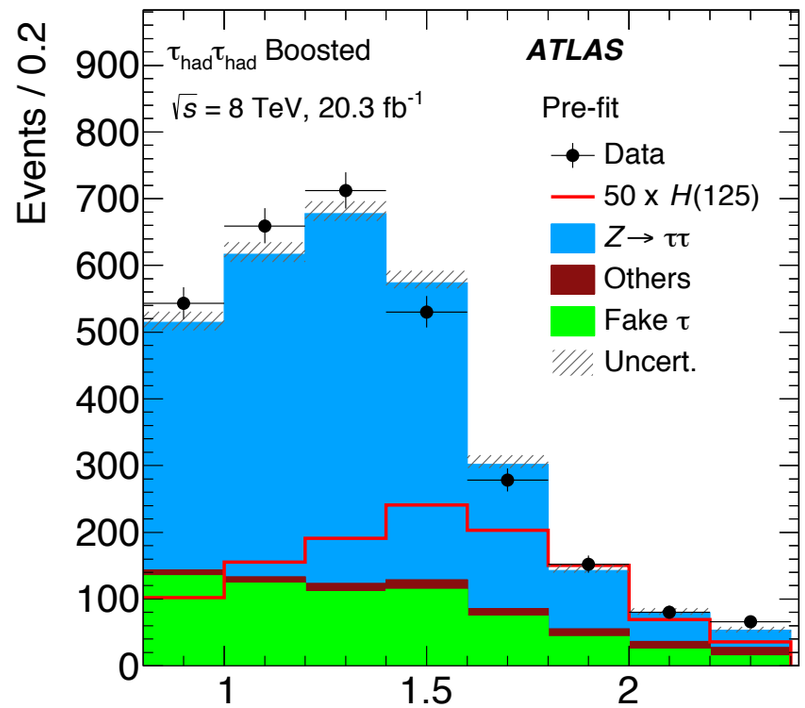

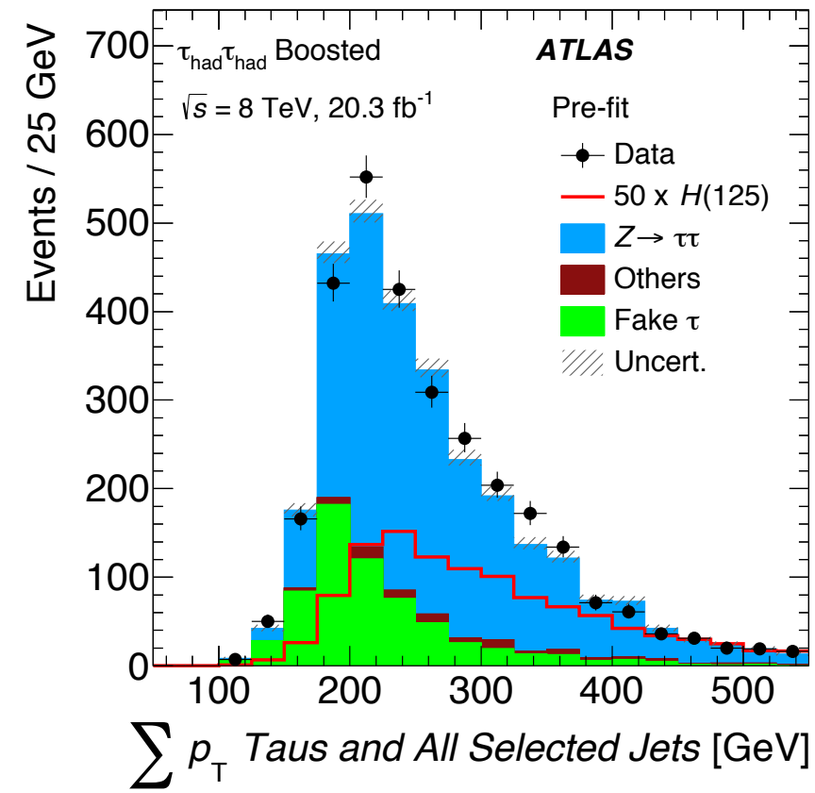

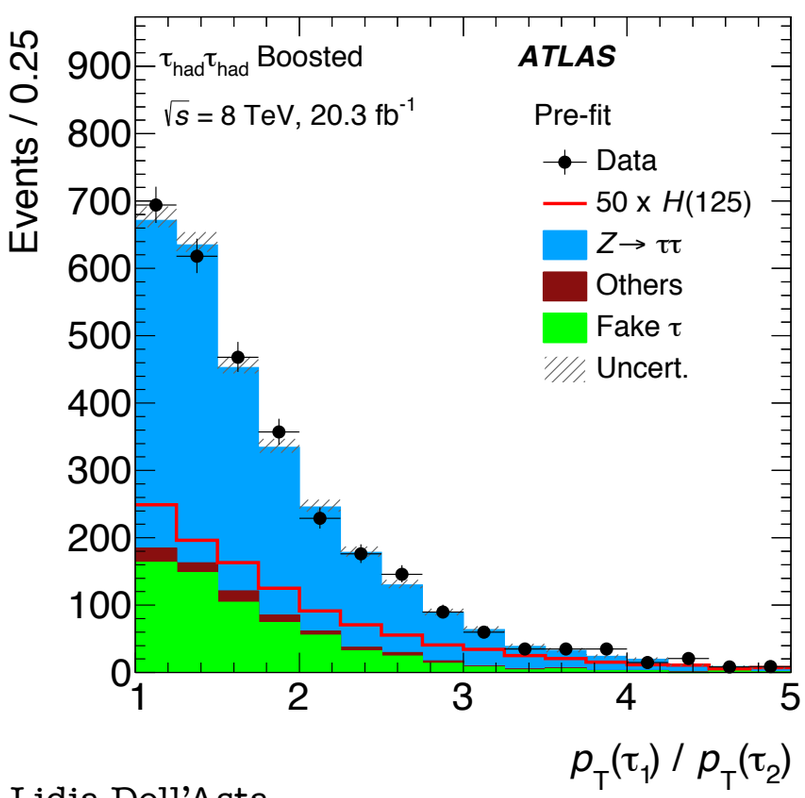

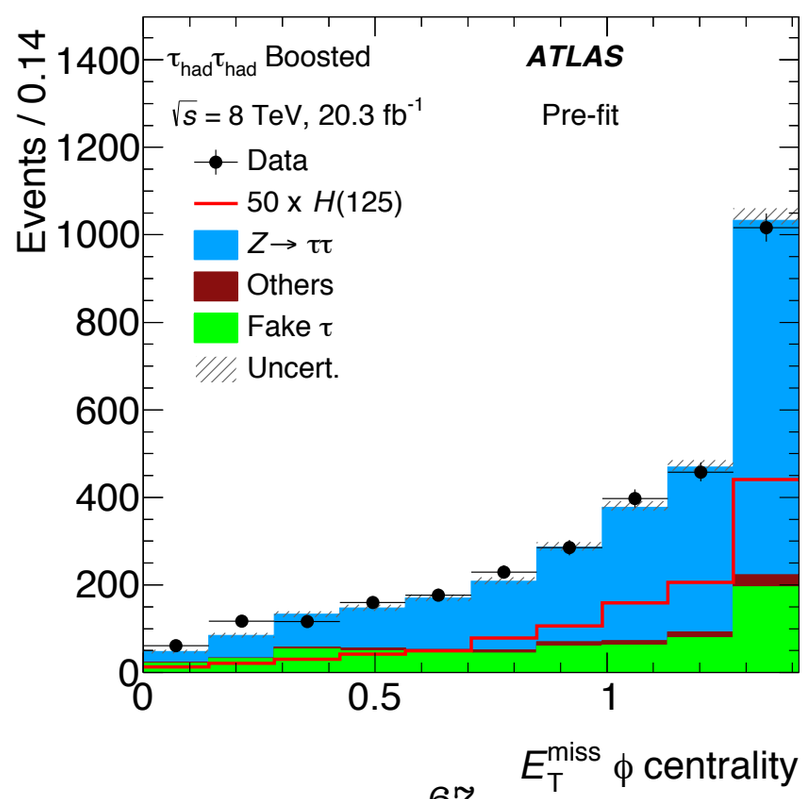

Event yields - $\tau_{lep}\tau_{lep}$

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
$Z \to \tau\tau$	589 ± 24	9.7 ± 1.0	1.99 ± 0.34	2190 ± 80	33.7 ± 2.3	11.3 ± 1.3
Fake background	57 ± 12	1.2 ± 0.6	0.55 ± 0.35	100 ± 40	2.9 ± 1.3	0.6 ± 0.4
Top	131 ± 19	0.9 ± 0.4	0.89 ± 0.33	380 ± 50	9.8 ± 2.1	4.3 ± 1.0
Others	196 ± 17	3.0 ± 0.4	1.7 ± 0.6	400 ± 40	8.3 ± 1.6	2.6 ± 0.7
ggF: $H \to WW \quad (m_H = 125\ GeV)$	2.9 ± 0.8	0.12 ± 0.04	0.11 ± 0.04	7.7 ± 2.3	0.43 ± 0.13	0.24 ± 0.08
VBF: $H \to WW$	3.4 ± 0.4	0.40 ± 0.06	0.38 ± 0.08	1.65 ± 0.18	0.102 ± 0.017	< 0.1
$WH: \ H \to WW$	< 0.1	< 0.1	< 0.1	0.90 ± 0.10	< 0.1	< 0.1
$ZH: \ H \to WW$	< 0.1	< 0.1	< 0.1	0.59 ± 0.07	< 0.1	< 0.1
ggF: $H \to \tau\tau \ (m_H = 125GeV)$	9.8 ± 3.4	0.73 ± 0.26	0.35 ± 0.14	21 ± 8	2.4 ± 0.9	1.3 ± 0.5
VBF: $H \to \tau\tau$	13.3 ± 4.0	2.7 ± 0.7	3.3 ± 0.9	5.5 ± 1.5	0.95 ± 0.26	0.49 ± 0.13
$WH: \ H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	3.8 ± 1.0	0.44 ± 0.12	0.22 ± 0.06
$ZH: \ H \to \tau\tau$	0.14 ± 0.04	< 0.1	< 0.1	2.0 ± 0.5	0.21 ± 0.06	0.113 ± 0.031
Total background	980 ± 22	15.4 ± 1.8	5.6 ± 1.4	3080 ± 50	55 ± 4	19.2 ± 2.1
Total signal	24 ± 6	3.5 ± 0.9	3.6 ± 1.0	33 ± 10	4.0 ± 1.2	2.1 ± 0.6
Data	1014	16	11	3095	61	20

Event yields - $\tau_{lep}\tau_{had}$

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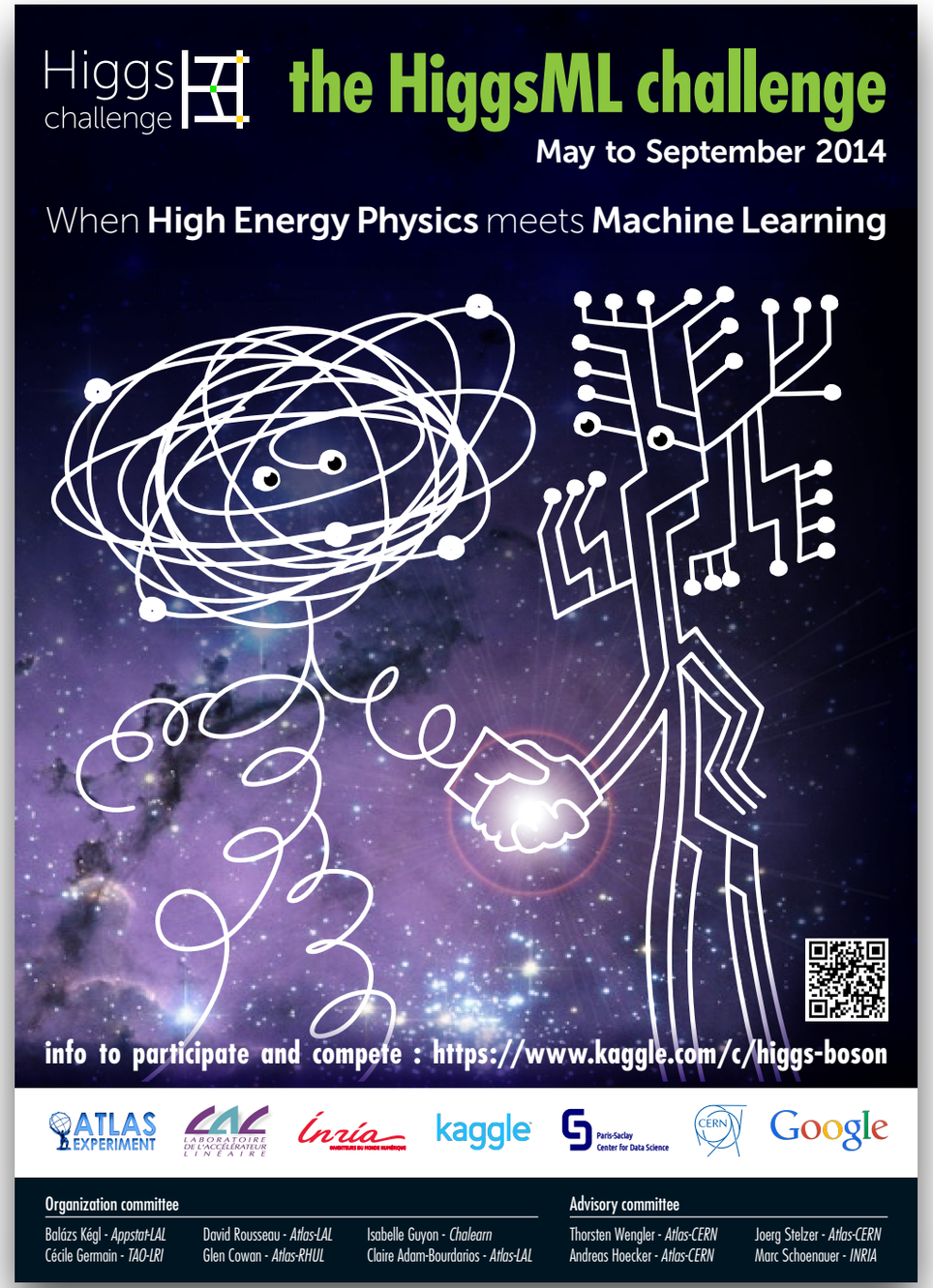
Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	1680 ± 50	8.2 ± 0.9	5.2 ± 0.7	5640 ± 160	51.0 ± 2.5	22.3 ± 1.8
$Z \to \tau\tau$	877 ± 29	7.6 ± 0.9	4.2 ± 0.7	6210 ± 170	57.5 ± 2.8	41.1 ± 3.2
Top	82 ± 15	0.3 ± 0.4	0.5 ± 0.4	380 ± 50	12 ± 4	4.8 ± 1.5
$Z \to \ell\ell(\ell \to \tau_{\text{had}})$	54 ± 26	1.0 ± 0.7	0.30 ± 0.28	200 ± 50	13 ± 4	8.6 ± 3.5
Diboson	63 ± 11	1.0 ± 0.4	0.48 ± 0.20	430 ± 40	9.7 ± 2.2	4.7 ± 1.6
ggF: $H \to \tau\tau$ $(m_H = 125GeV)$	16 ± 6	1.0 ± 0.4	1.2 ± 0.6	60 ± 20	9.2 ± 3.2	10.1 ± 3.4
VBF: $H \to \tau\tau$	31 ± 8	4.5 ± 1.1	9.1 ± 2.2	16 ± 4	2.5 ± 0.6	2.9 ± 0.7
$WH: \ H \to \tau\tau$	0.6 ± 0.4	< 0.1	< 0.1	9.1 ± 2.3	1.3 ± 0.4	1.9 ± 0.5
$ZH: \ H \to \tau\tau$	0.16 ± 0.07	< 0.1	< 0.1	4.6 ± 1.2	0.77 ± 0.20	0.93 ± 0.24
Total background	2760 ± 40	18.1 ± 2.3	10.7 ± 2.7	12860 ± 110	143 ± 6	82 ± 6
Total signal	48 ± 12	5.5 ± 1.3	10.3 ± 2.5	89 ± 26	14 ± 4	16 ± 4
Data	2830	22	21	12952	170	92

Event yields - $\tau_{had}\tau_{had}$

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	370 ± 18	2.3 ± 0.9	0.57 ± 0.29	645 ± 26	35 ± 4	0.65 ± 0.33
Others	37 ± 5	0.67 ± 0.22	< 0.1	89 ± 11	15.9 ± 2.0	0.92 ± 0.22
$Z \to \tau\tau$	475 ± 16	0.6 ± 0.7	0.6 ± 0.4	2230 ± 70	93 ± 4	5.4 ± 1.6
ggF: $H \to \tau\tau$ $(m_H = 125GeV)$	8.0 ± 2.7	0.67 ± 0.23	0.53 ± 0.20	21 ± 8	9.1 ± 3.3	1.6 ± 0.6
VBF: $H \to \tau\tau$	12.0 ± 3.1	1.8 ± 0.5	3.4 ± 0.9	6.3 ± 1.6	2.8 ± 0.7	0.52 ± 0.13
$WH : H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	4.0 ± 1.1	1.9 ± 0.5	0.41 ± 0.11
$ZH : H \to \tau\tau$	0.16 ± 0.04	< 0.1	< 0.1	2.4 ± 0.6	1.13 ± 0.30	0.23 ± 0.06
Total background	883 ± 18	3.6 ± 1.3	1.2 ± 1.0	2960 ± 50	143 ± 6	7.0 ± 1.8
Total signal	20 ± 5	2.5 ± 0.6	3.9 ± 1.0	34 ± 10	15 ± 4	2.7 ± 0.8
Data	892	5	6	3020	161	10

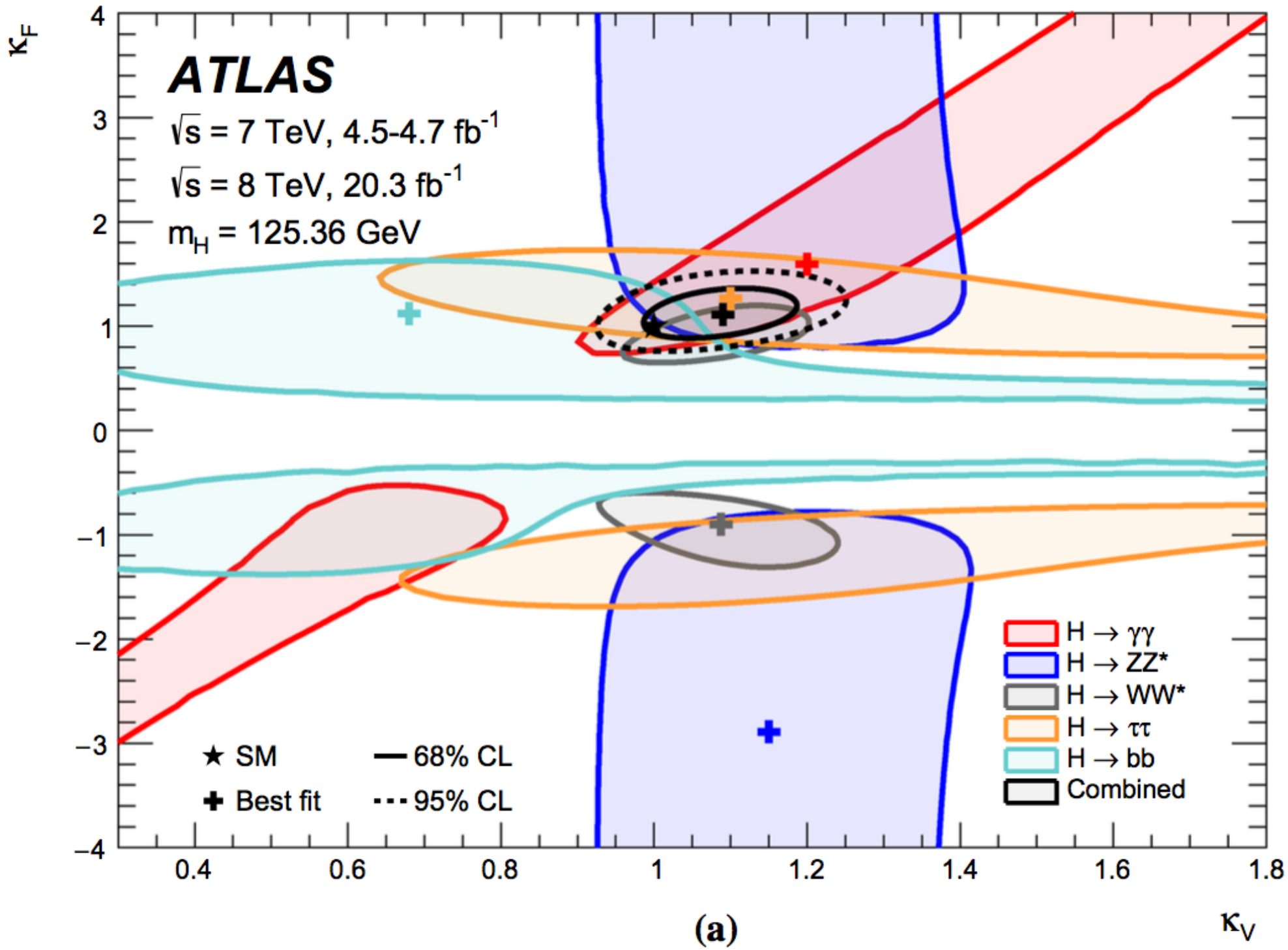
Machine Learning Challenge

- The latest $H \to \tau\tau$ results are based on a Multivariate analysis.
  - We might not be using the MVA with the highest performance.
  - Why not put some ATLAS simulated data on the web and ask data scientists to find the best machine learning algorithm to find the Higgs?
- The challenge:
  - the sample: mixture of $H \to \tau\tau$ signal and corresponding background, from official GEANT4 ATLAS simulation,
  - the variables: the one used in the analysis + some "low level" vars,
  - some simplifications: no systematics, only one signal region, no data driven bkg et al.
- The results:
  - great participation: 1785 teams (1942 people) have participated (i.e. submitted at least one solution), 35772 solutions uploaded, 136 forum topics with 1100 posts...
  - 20% gain w.r.t. to untuned TMVA.
    - More discussion with participants is ongoing.
- Will we use MVA more intensively in Run2?

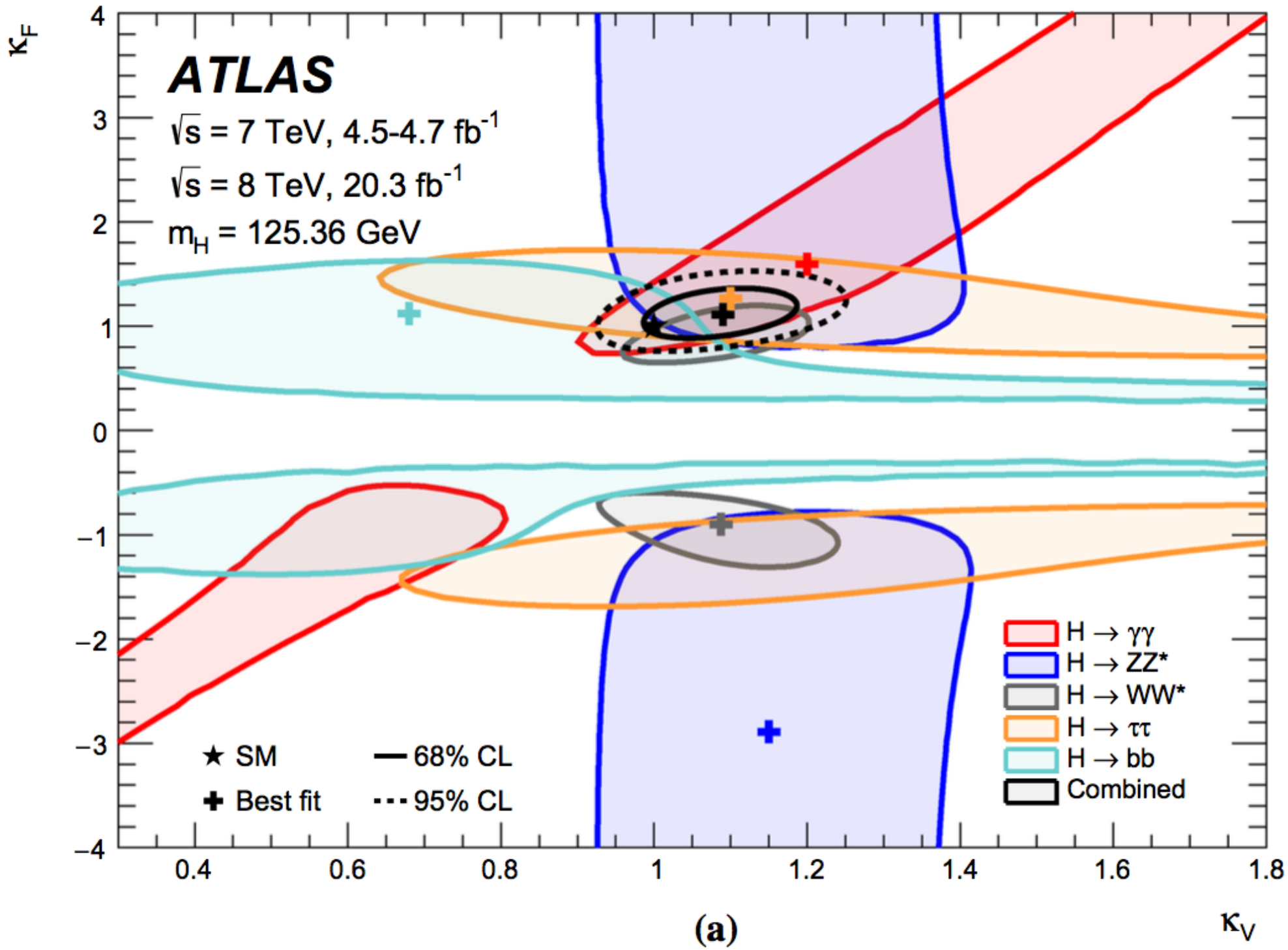


https://higgsml.lal.in2p3.fr/

Results


ATLAS
√s = 7 TeV, 4.5-4.7 fb-1
√s = 8 TeV, 20.3 fb-1
mH = 125.36 GeV
κF
κV
SM
Best fit
68% CL
95% CL
H → γγ
H → ZZ*
H → WW*
H → ττ
H → bb
Combined

(a)

Results

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