LPNHE
PARIS

Evidence for Higgs boson decays to $\tau^+\tau^-$ final states with ATLAS

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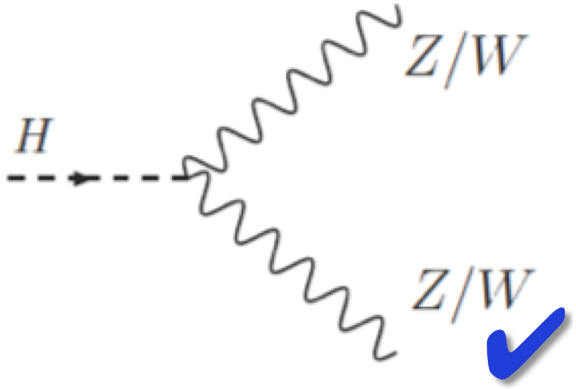
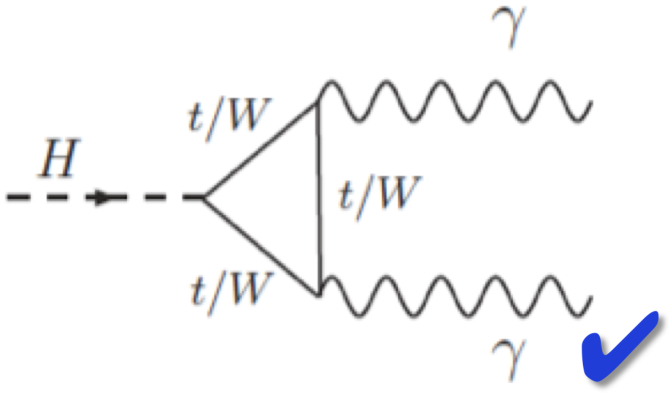
Palaiseau, Ecole Polytechnique, June 3rd 2014

What did we discover exactly?

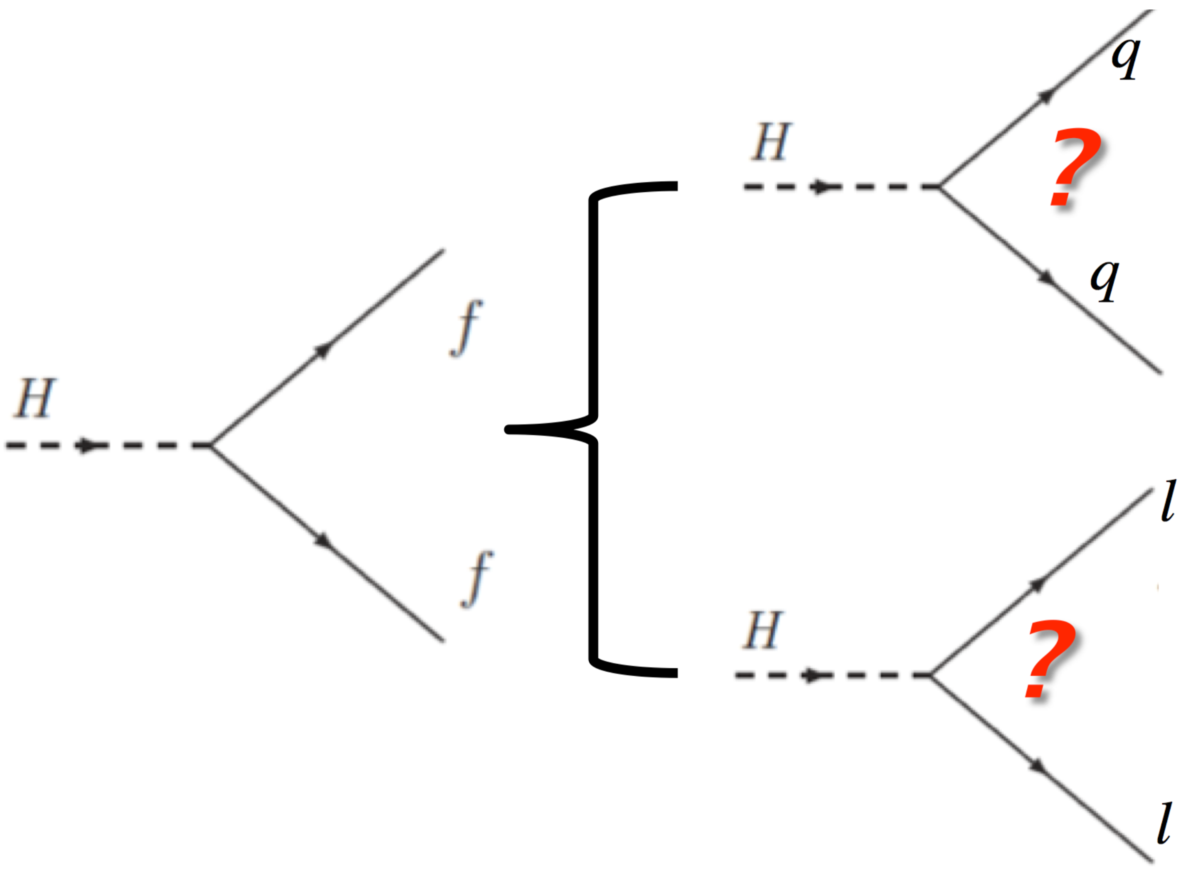
- Observation via ZZ*, WW* and γγ decay modes





- Results strongly favour $J^P=0^+$ quantum numbers, consistent with Standard Model predictions

- Is the discovered Higgs boson coupling to fermions?



- quarks?

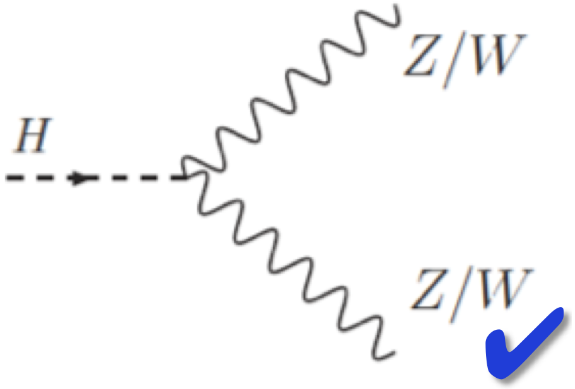
Most likely yes, because of the quark loop in gg-fusion/photon decay. Nevertheless a direct measurement to quarks is necessary (H→bb)

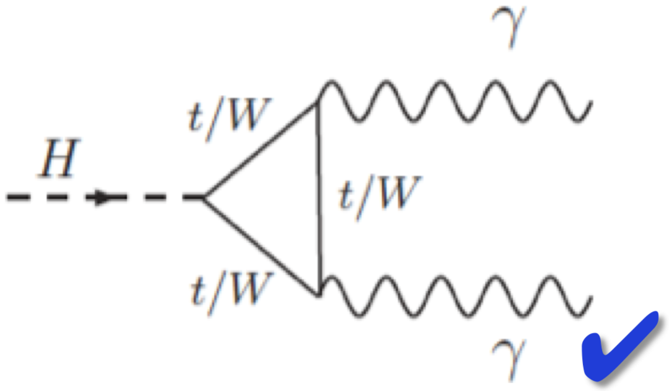
- leptons?

<u>This is the question that the H→ττ analysis is addressing</u>

What did we discover exactly?

- Observation via ZZ^*, WW^* and γγ decay modes





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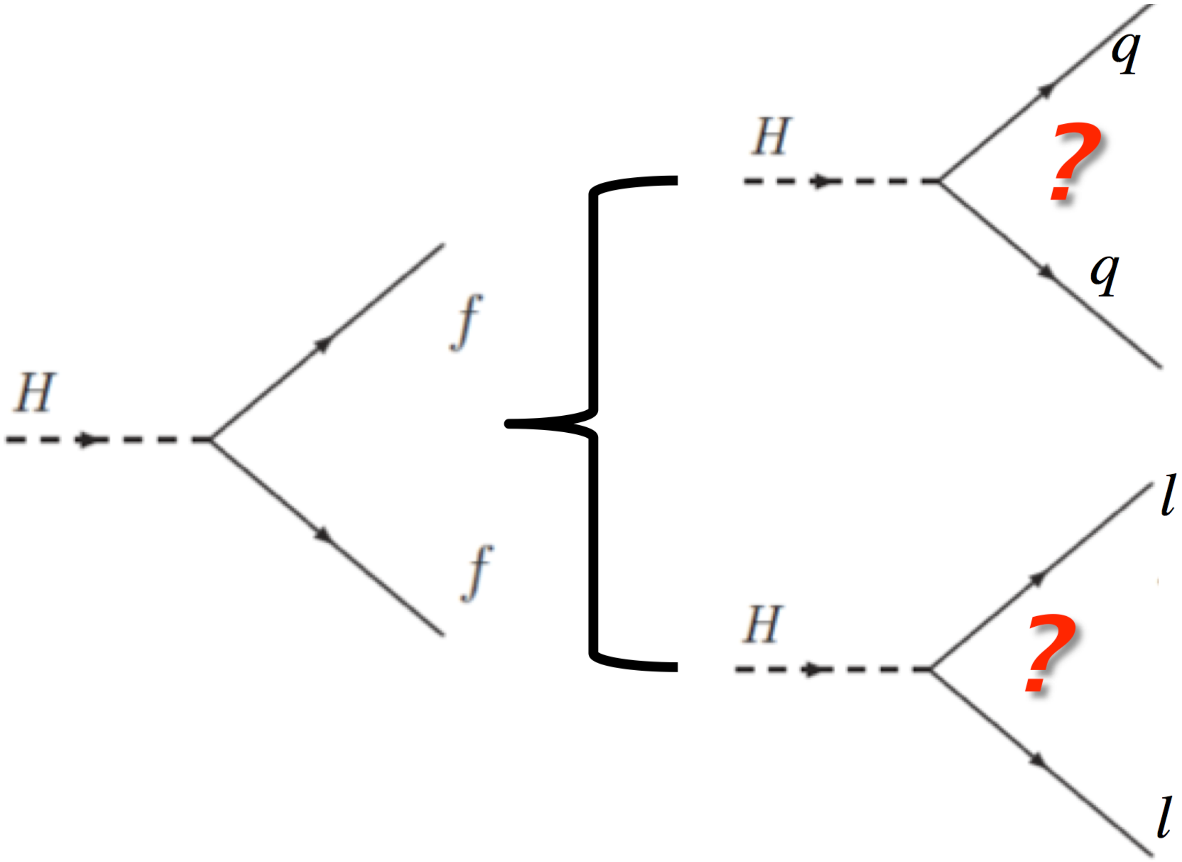

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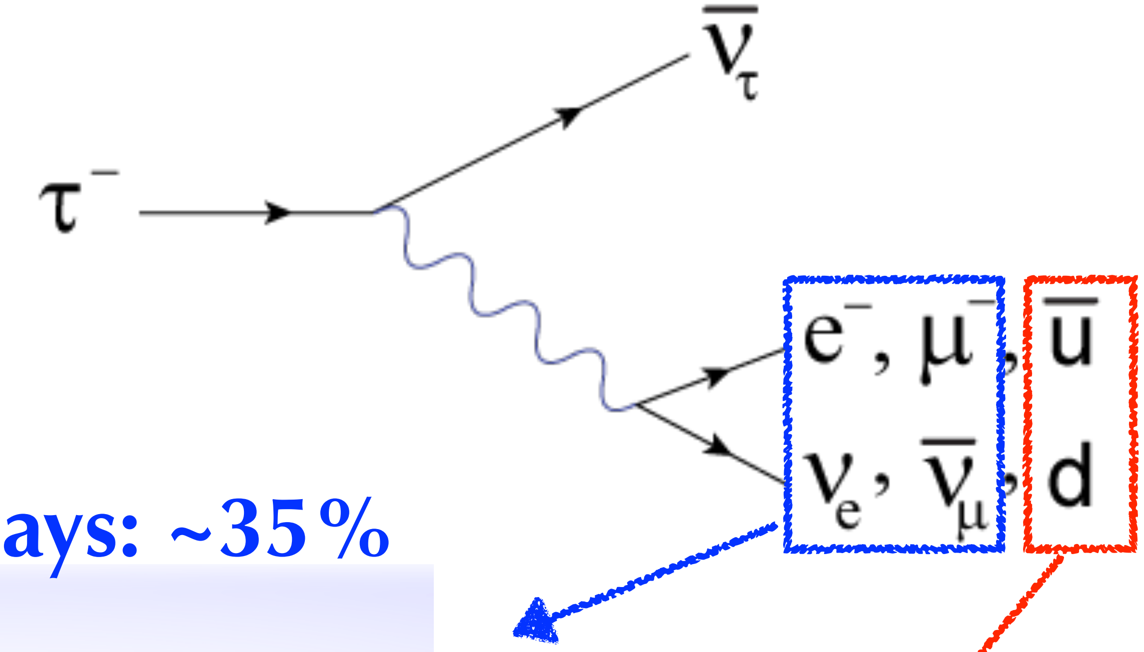
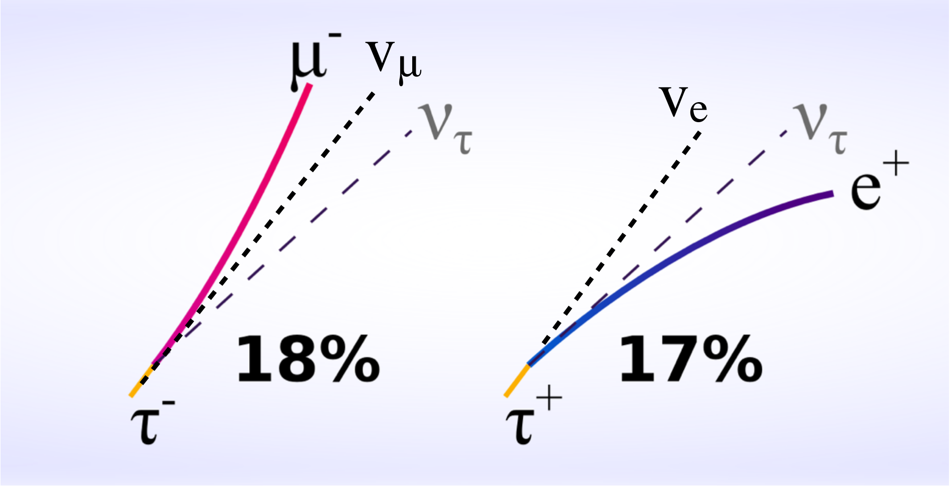
m	ττ	VH(bb)	μμ
σ×BR [pb]	**~1.4**	**~0.08**	**~0.0002**

Tau lepton trivia

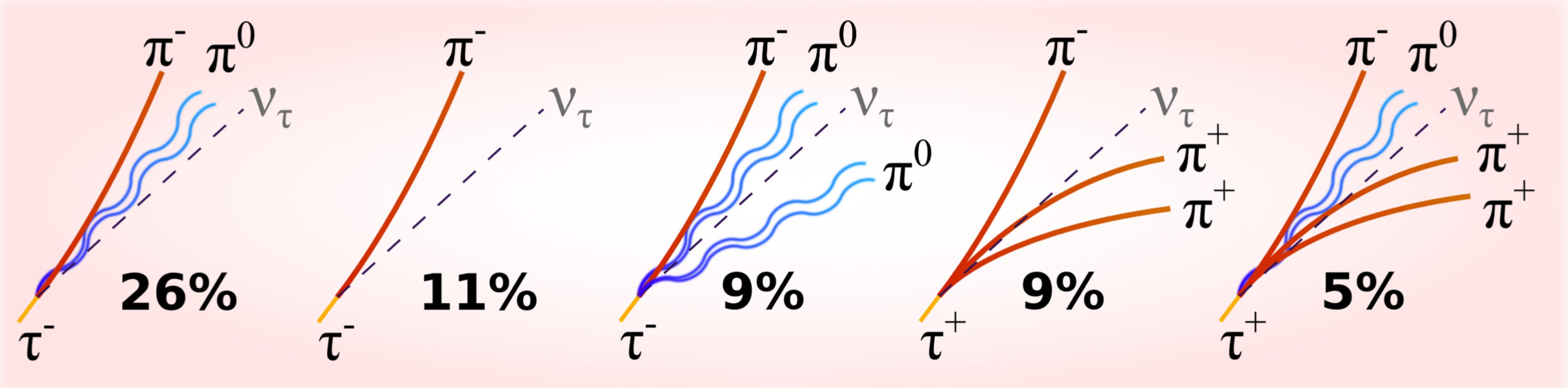
- Mass: 1.8 GeV
- cτ: 87 μm
  - Decays within the beam-pipe



Leptonic decays: ~35%

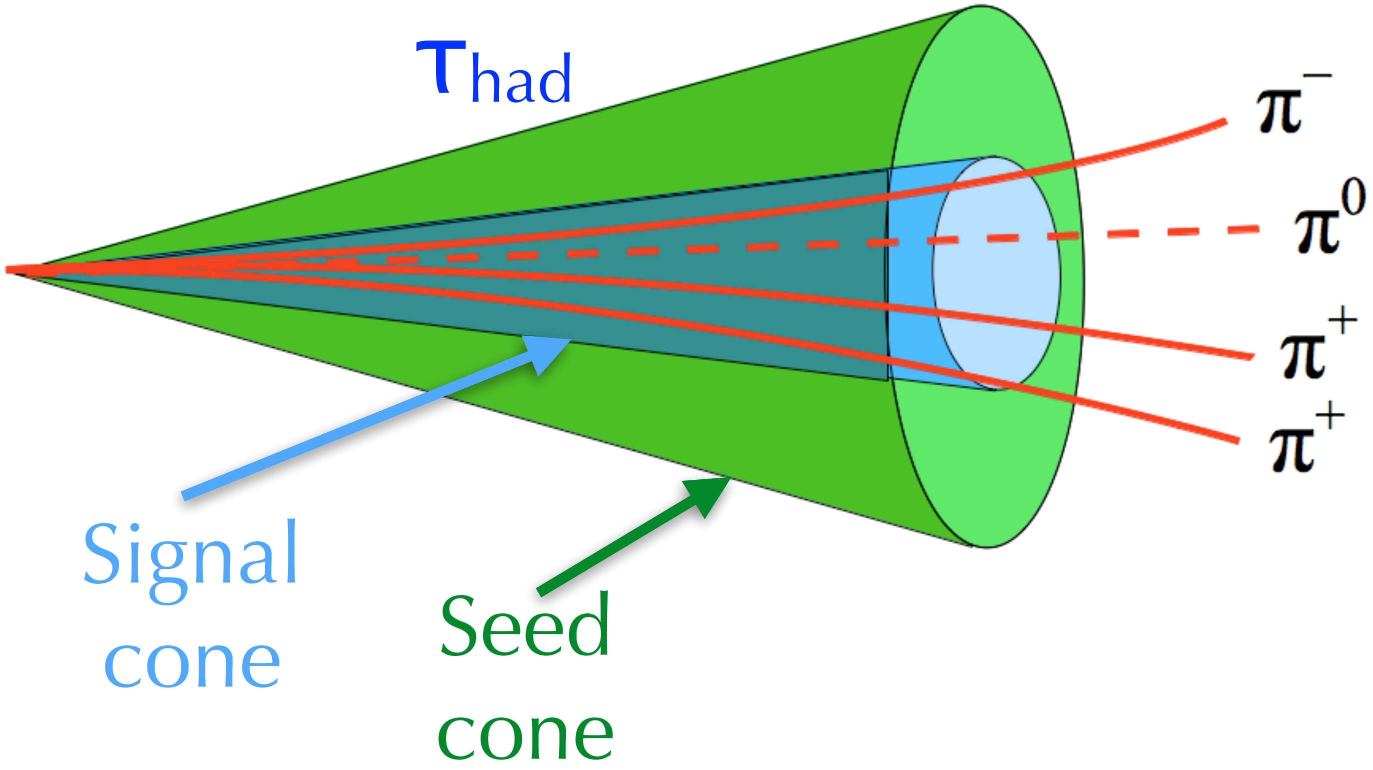


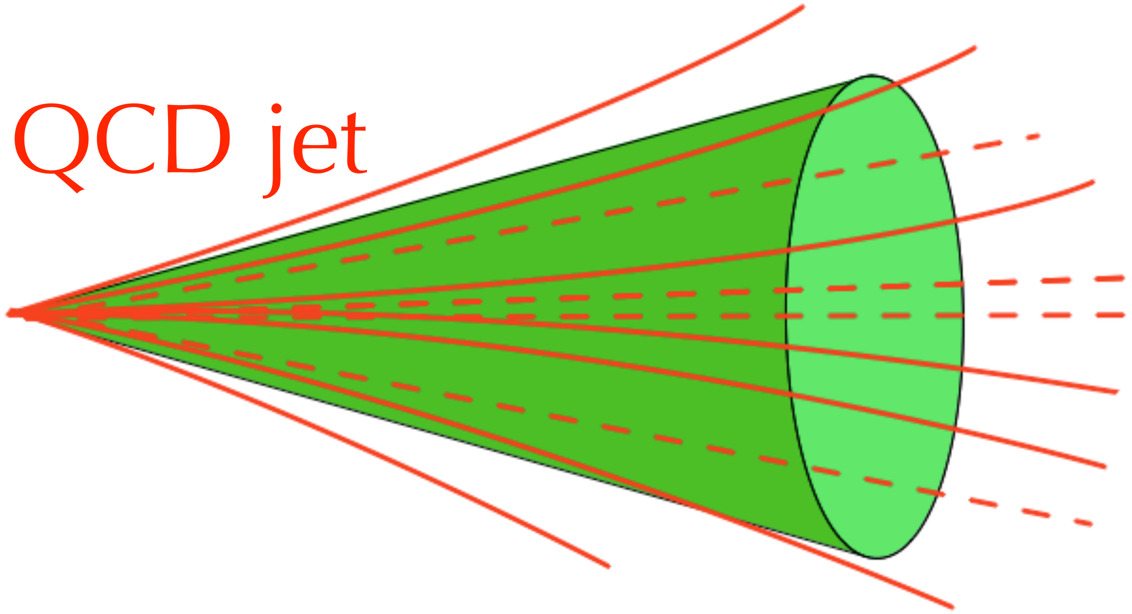
Hadronic decays: ~65%



Tau (τ_{had}) reconstruction in ATLAS

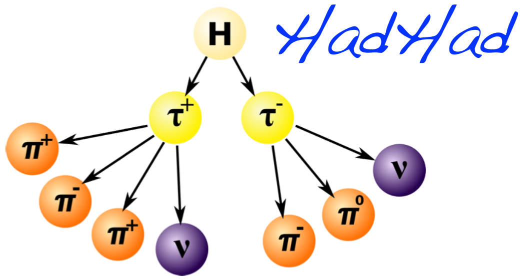
- τ_{had} seed: All jets (cone $\Delta R<0.4$) that fall within the tracker ($|\eta|>2.5$, $p_T>10$ GeV)
- Classify τ_{had}: count number of tracks in signal cone of $\Delta R<0.2$ around the jet seed
- τ_{had} energy: Energy from calo topological clusters in $\Delta R<0.2$
- Tau Identification: MVA to separate τ_{had} from QCD jets & electrons
- τ_{had} appears as a narrow jet



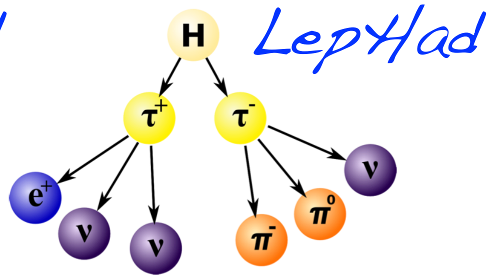


H→ττ search: Analysis concept

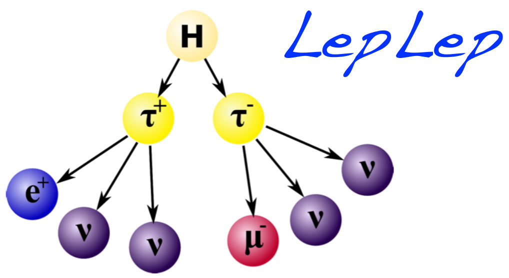
- **Does the Higgs boson with $m_H \simeq 125.5$ GeV decay to a pair of τ-leptons?**
- Analysis strategy
  - Achieve maximum sensitivity by performing a **multivariate analysis: Boosted Decision Trees (BDT)**
  - Analyse full **2012** LHC dataset: **20.3 fb^{-1}** @ 8 TeV ➠ ATLAS-CONF-2013-108
- Perform analysis in **3 channels** according to the τ lepton decay



$\tau_{had}\tau_{had}$
hadronic-hadronic
42%



$\tau_{lep}\tau_{had}$
leptonic-hadronic
46%



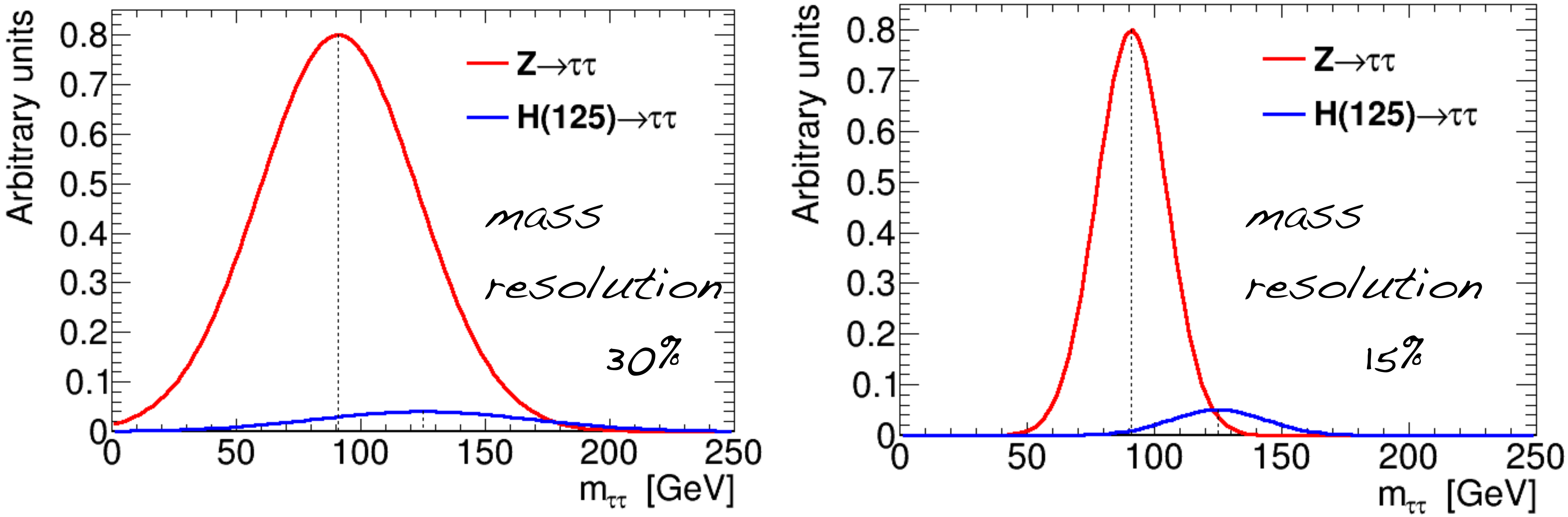
$\tau_{lep}\tau_{lep}$
leptonic-leptonic
12%

- And in **2 categories** per channel
  - **VBF:** 2 jets with leading(sub-leading) p_T>50(30) GeV, $\Delta\eta(jj)$>3
  - **Boosted:** $p_T(H)$>100 GeV , $p_T(H)$: $\vec{E}_T^{miss} + \vec{p}_T(\tau_1) + \vec{p}_T(\tau_2)$
- Different **BDT** per channel and per category: **6** BDT's
  - Keep simple selection and let the **BDT separate signal and background**
  - **Final discriminant: BDT score**

DiTau mass reconstruction: MMC

- **Challenge**: **Separate** the **signal** from the **dominant** irreducible **$Z \rightarrow \tau\tau$**
- Most **efficient way**: Precise estimation of the **mass of the system di-τ: $m_{\tau\tau}$**
  - **Challenging task** because **neutrinos** escape detection
    - The only way: Rely on **E_T^{miss}** to get an estimation of the **transverse energy** of the neutrinos

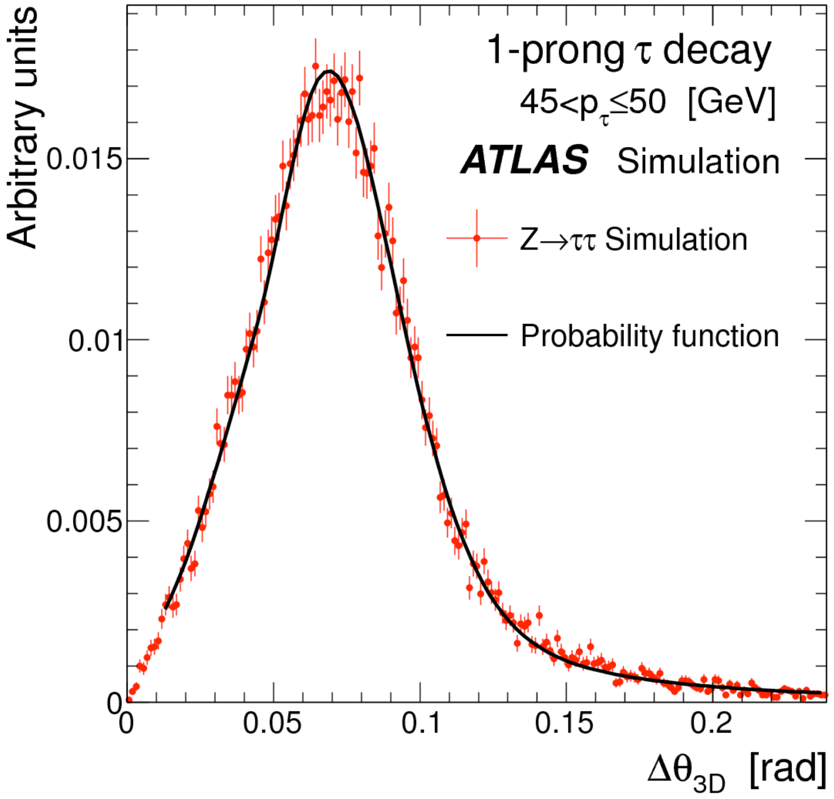
illustration purpose

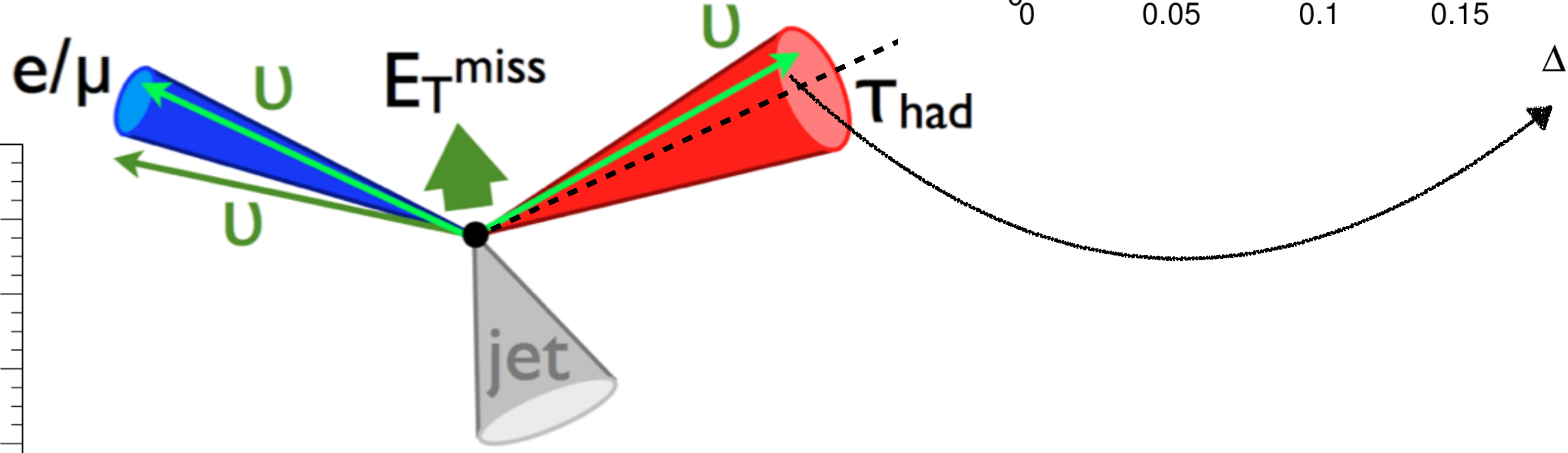


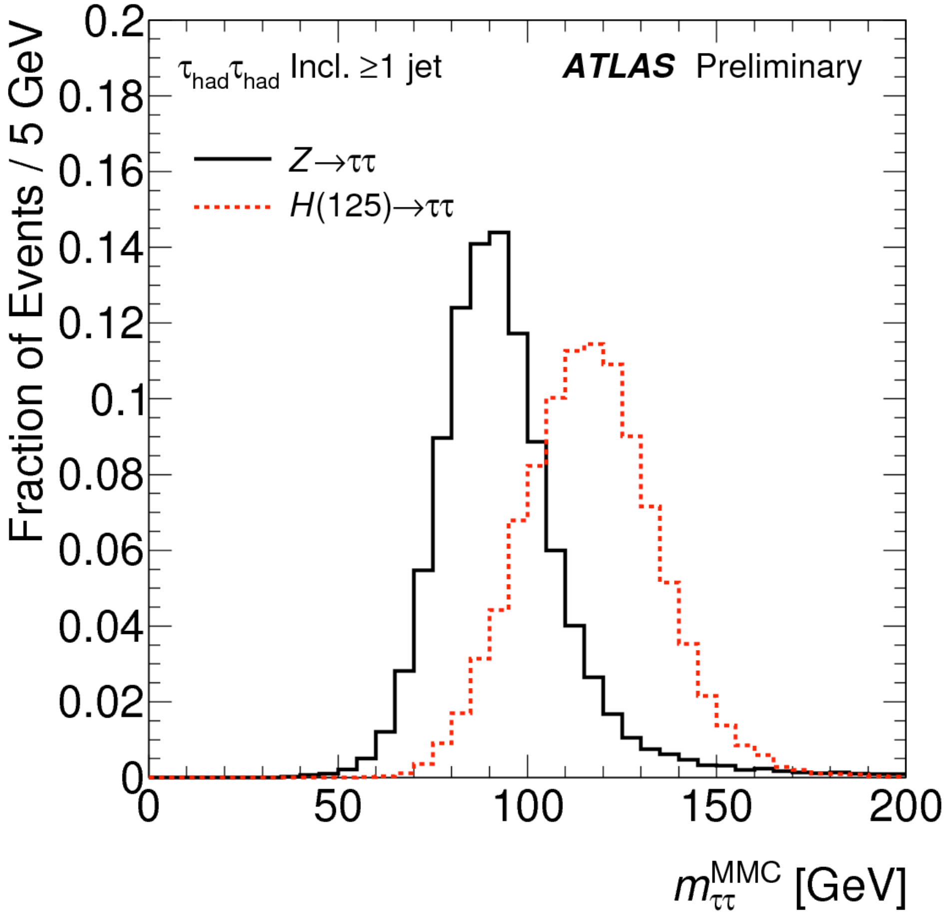
A good mass reconstruction is **essential** for the $H \rightarrow \tau\tau$ search

DiTau mass reconstruction: MMC

- Missing Mass Calculator **(MMC)**: **Mass reconstruction of original ττ system** despite the presence of undetectable neutrinos
  - ✦ Solve under-constrained system of kinematic equations by selecting the **most likely solution** given a **parameterisation** of 3D angle of tau visible and invisible decay products, and a E_T^{miss} scan



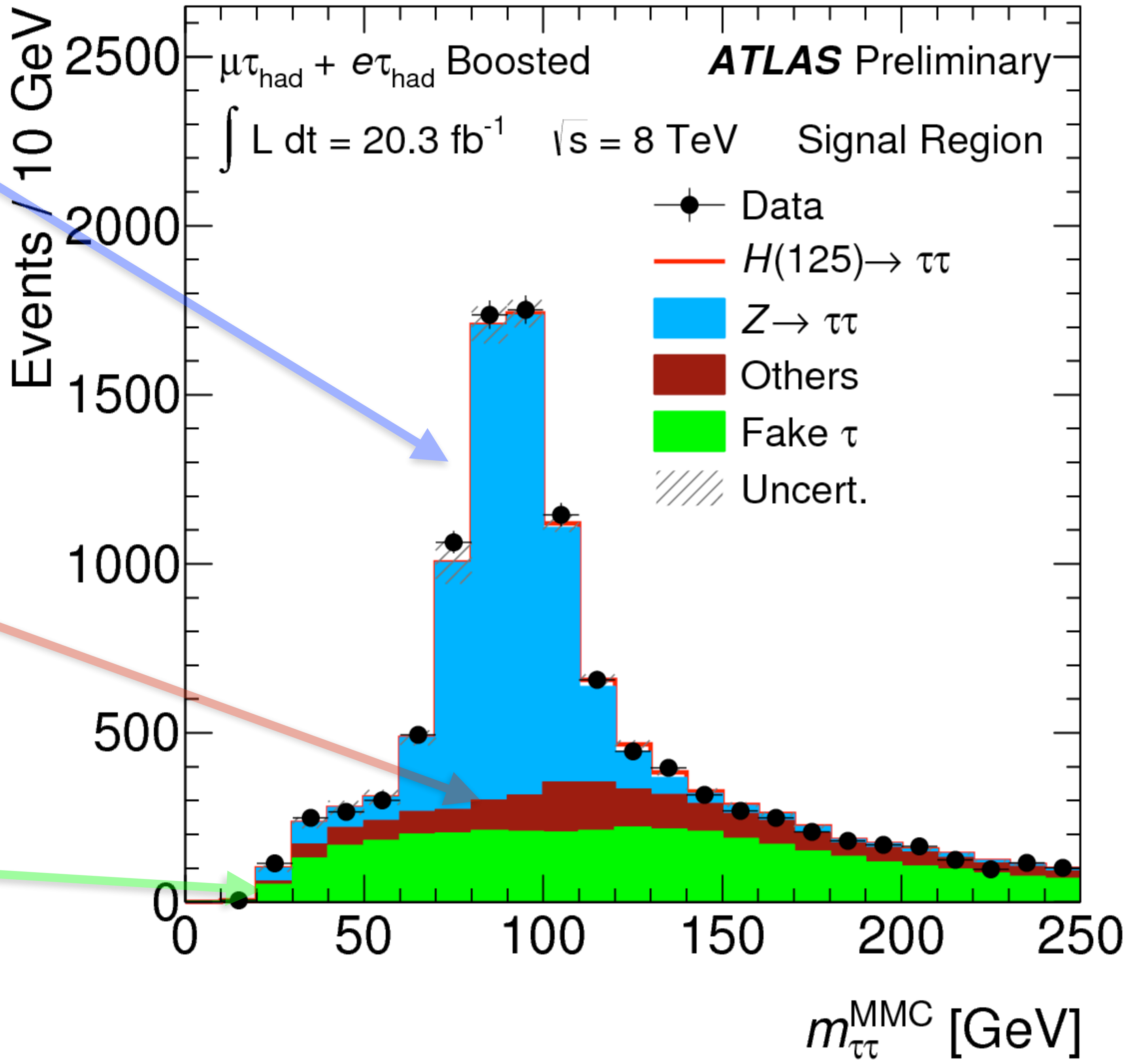




- **Correct peak position**, **reduced tails**
- Resolution **14%-22%** depending on channel and topology

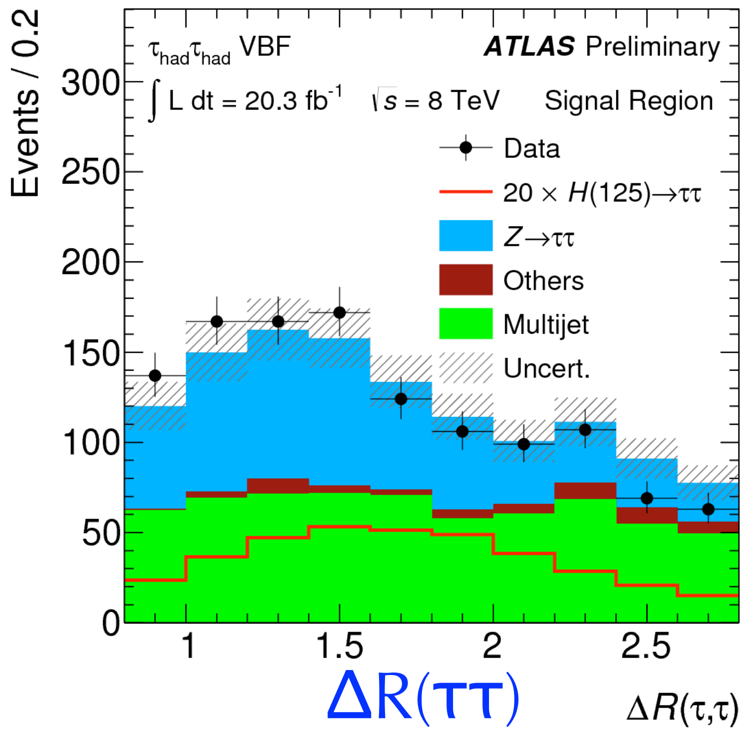
Estimating the backgrounds

- Dominant Z→ττ
  - Embedded samples: Except for tau decays, all event properties are taken from data Z→μμ events
- Others
  - Di-boson, Z→ee/μμ, top
  - H→WW for LepLep channel
  - Shape from simulation, normalisation from data
- Fake τ
  - Multijet, W+jets
  - Data-driven methods

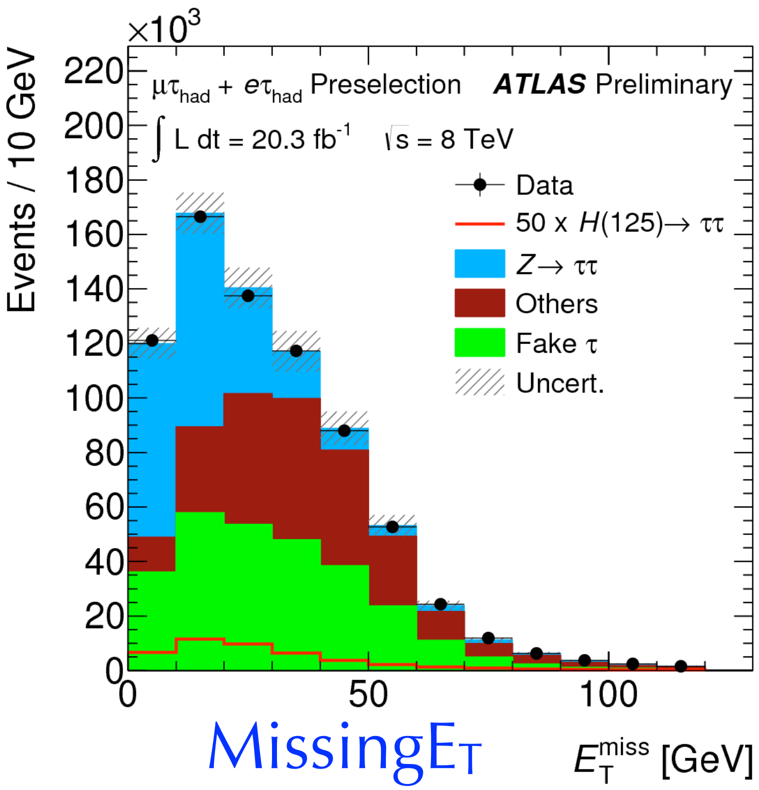


Input variables to BDT

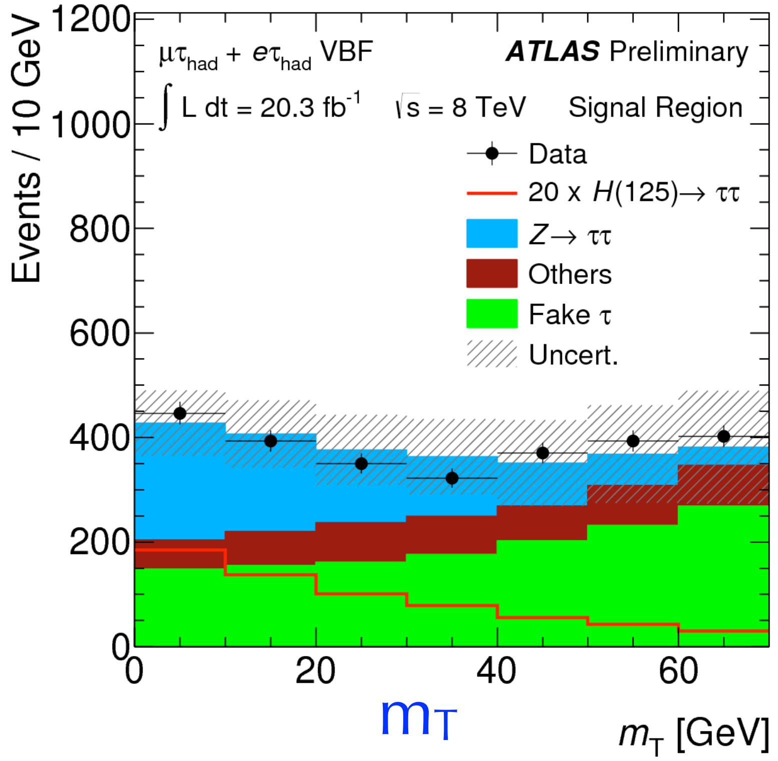
- Probe resonance properties
  - ✦ $m_{MMC}(\tau\tau)$, $\Delta R(\tau\tau)$
- Explore event topology
  - ✦ MissingE$_T$, m_T, object centralities, high p_T objects sum
- VBF specific, for the 2 VBF jets:
  - ✦ Different hemispheres $\eta_{j1}\times\eta_{j2}$
  - ✦ Separation $|\eta_{j1}-\eta_{j2}|$
  - ✦ Invariant mass m_{j1j2}



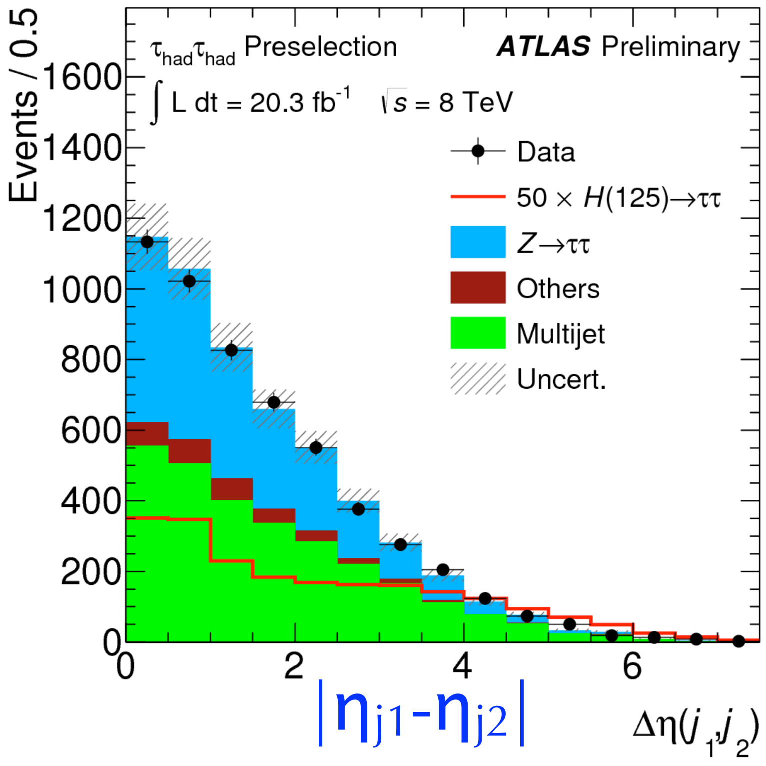
ΔR(ττ)



MissingE$_T$



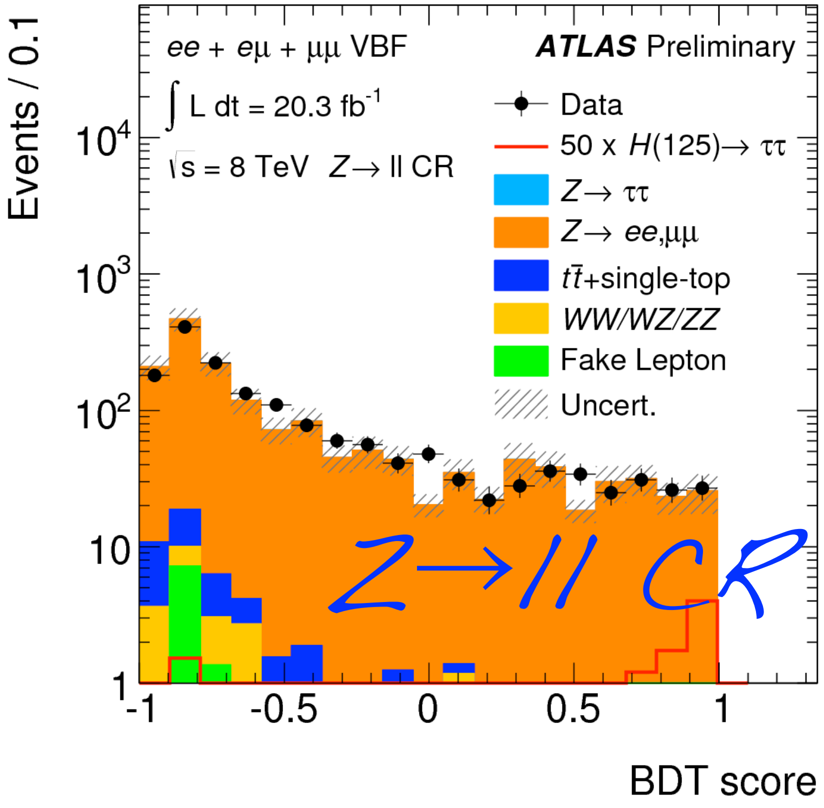
m_T

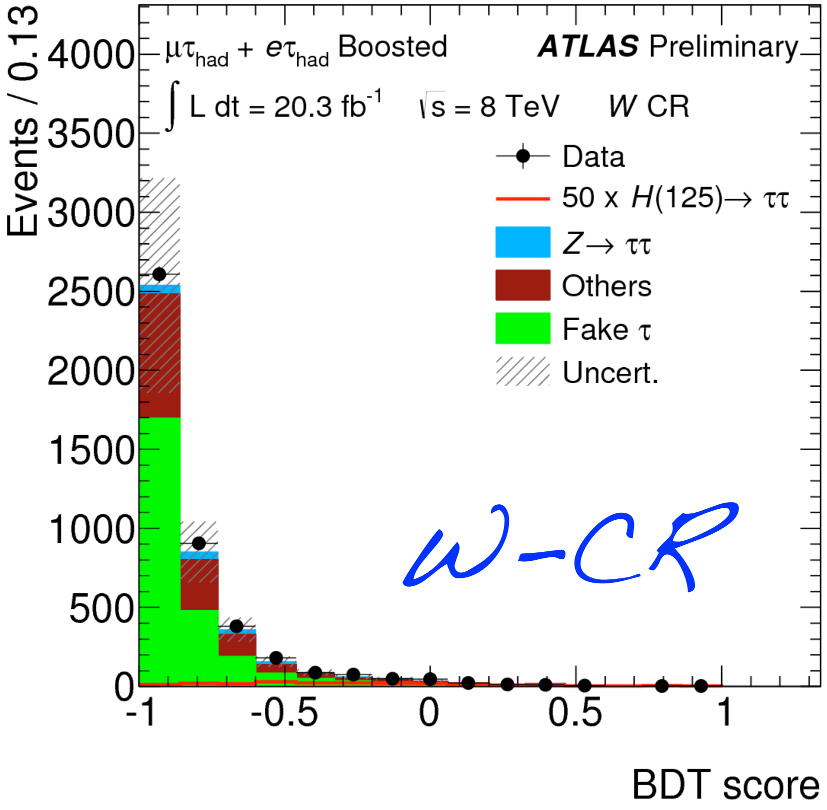


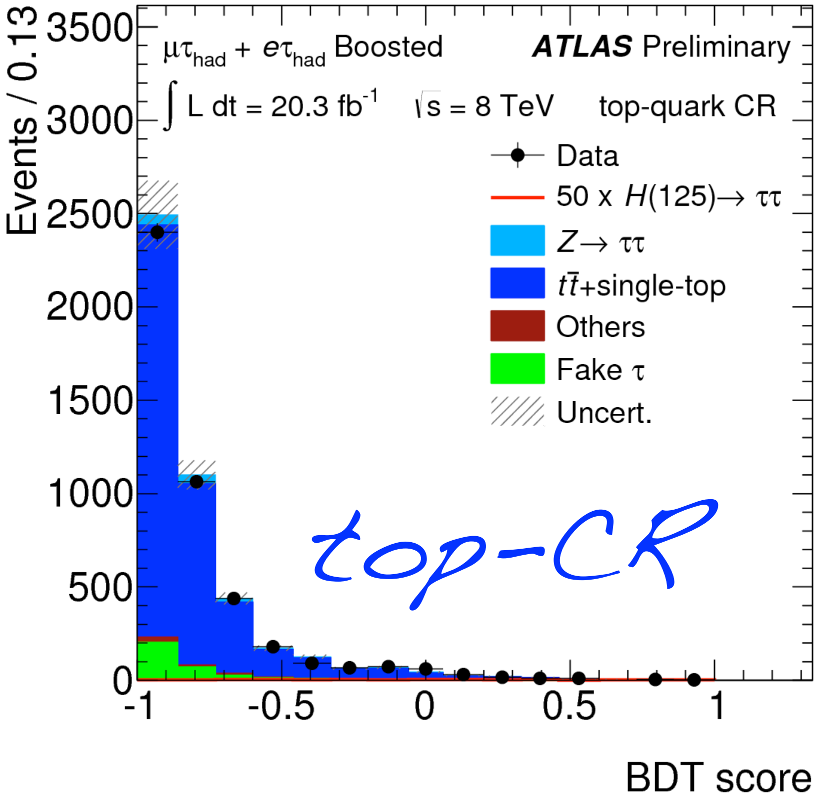
$|\eta_{j1}-\eta_{j2}|$

Building trust in the background model

- Checked modelling of all input variables at preselection, signal regions, control regions
- Checked the BDT score in control regions







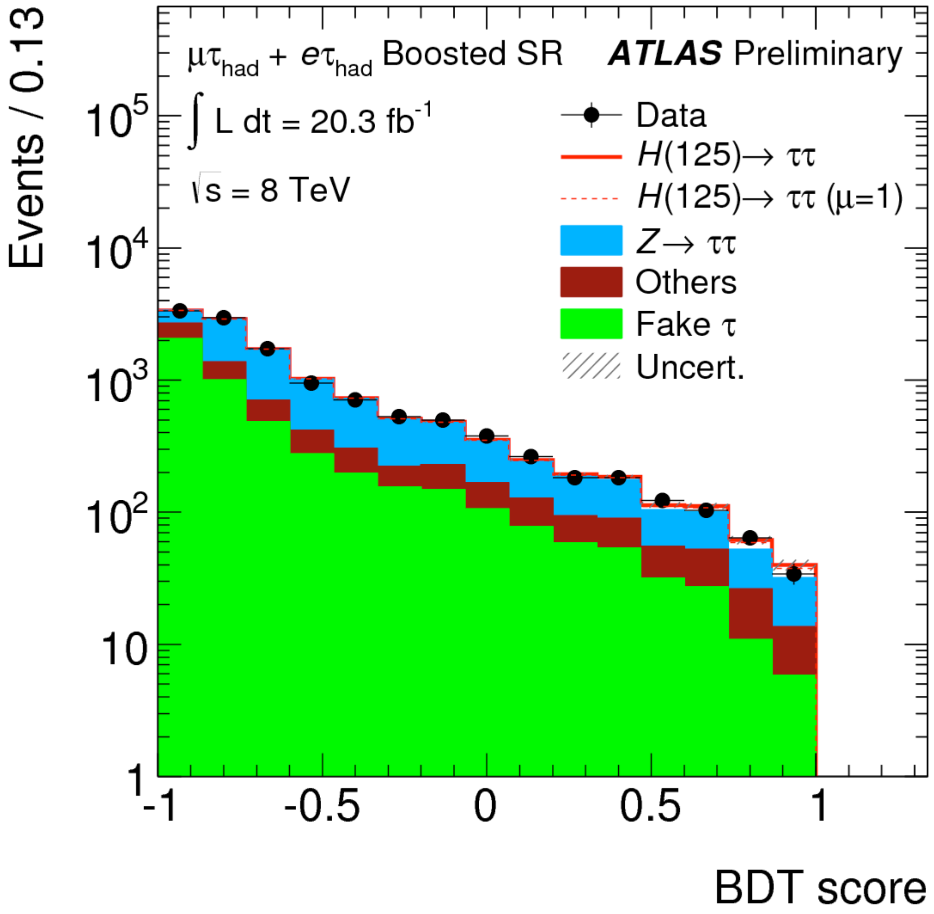
Good agreement in all BDT distributions

Signal extraction using the BDT score

- We fit the **Background** + **μ**×**Signal** model to the data using the BDT score distributions

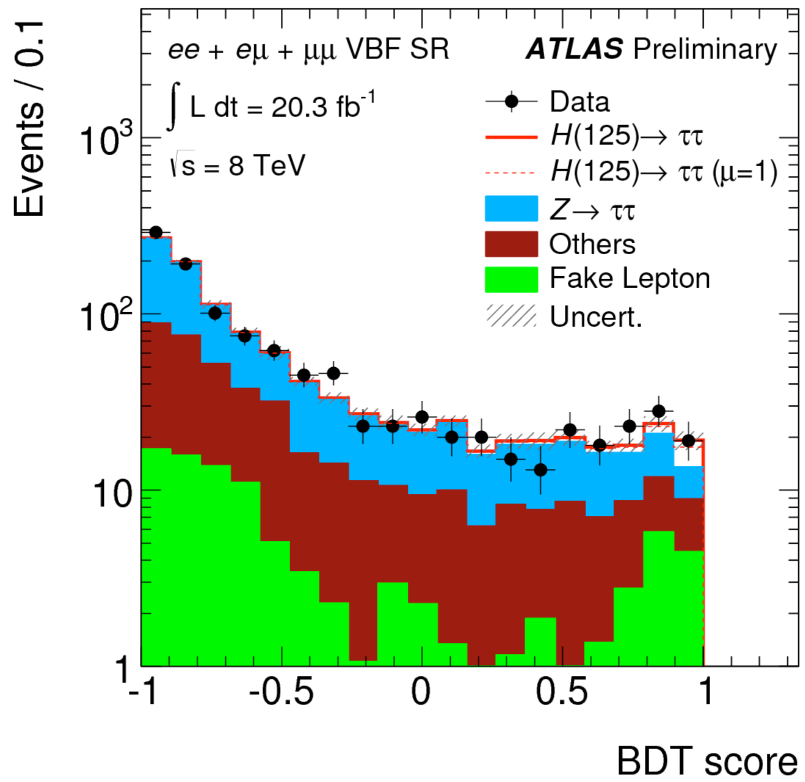
parameter of interest: $\mu = \frac{\sigma_{measured}}{\sigma_{SM}}$

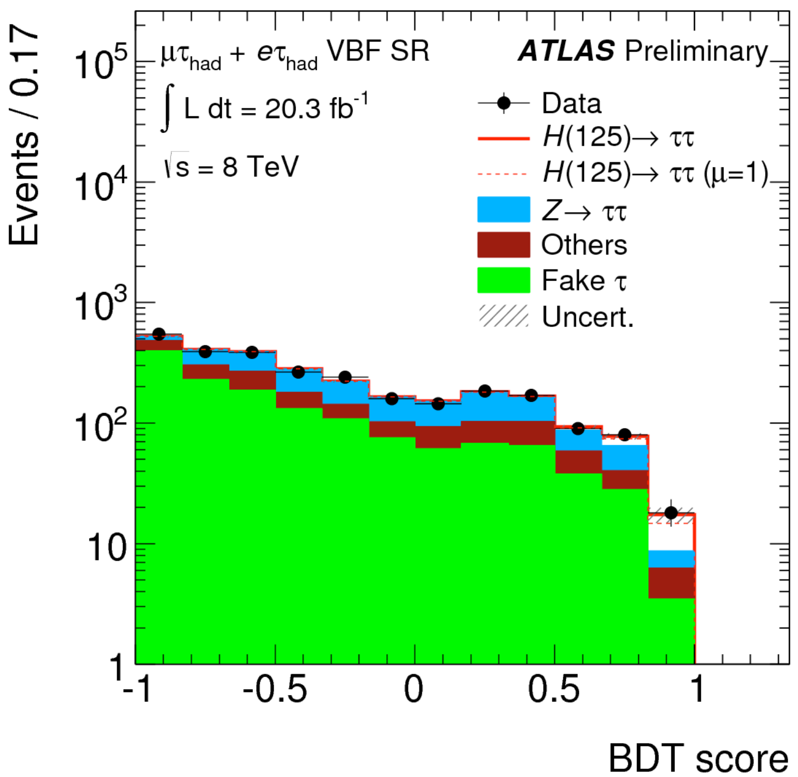
- Bins in the BDT score are ordered by signal purity. **Signal** like events populate the **highest BDT score bins**
- Simultaneous fit in **6 SR** and **5 CR** with common systematic nuisance parameters

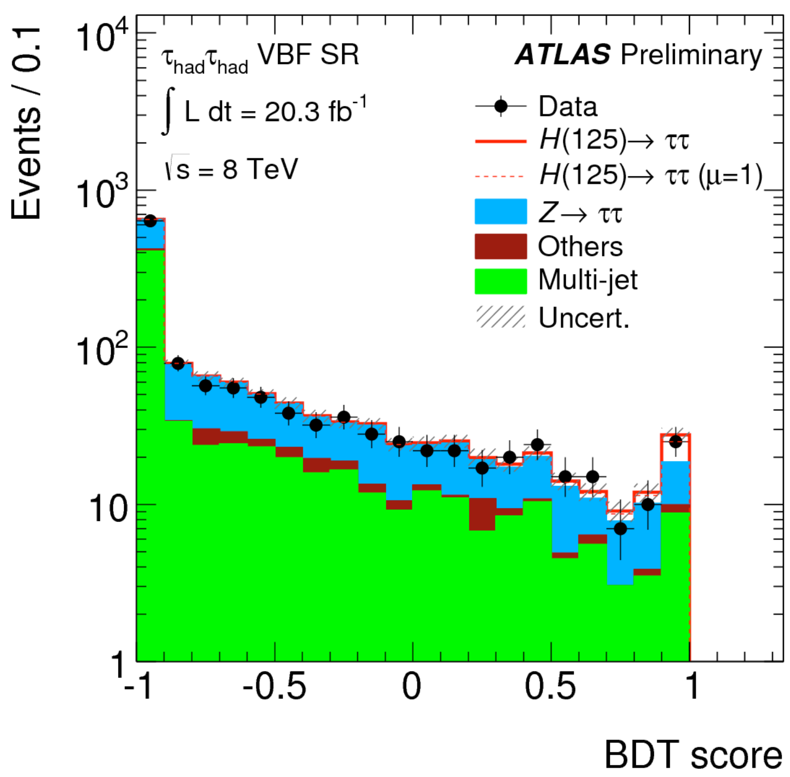


	VBF Category		Boosted Category		Non VBF, Non Boosted
	SR	CR	SR	CR	CR
H→$\tau_{lep}\tau_{lep}$	✔	✔ Z→ll (1 bin) & Top (1 bin)	✔	✔ Z→ll (1 bin) & Top (1 bin)	✘
H→$\tau_{lep}\tau_{had}$	✔	✔ Z→ll (1 bin) & Top (1 bin)	✔	✔ Z→ll (1 bin) & Top (1 bin)	✘
H→$\tau_{had}\tau_{had}$	✔	✘	✔	✘	✔ $\Delta\eta(\tau_1,\tau_2)$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

BDT scores in Signal Regions



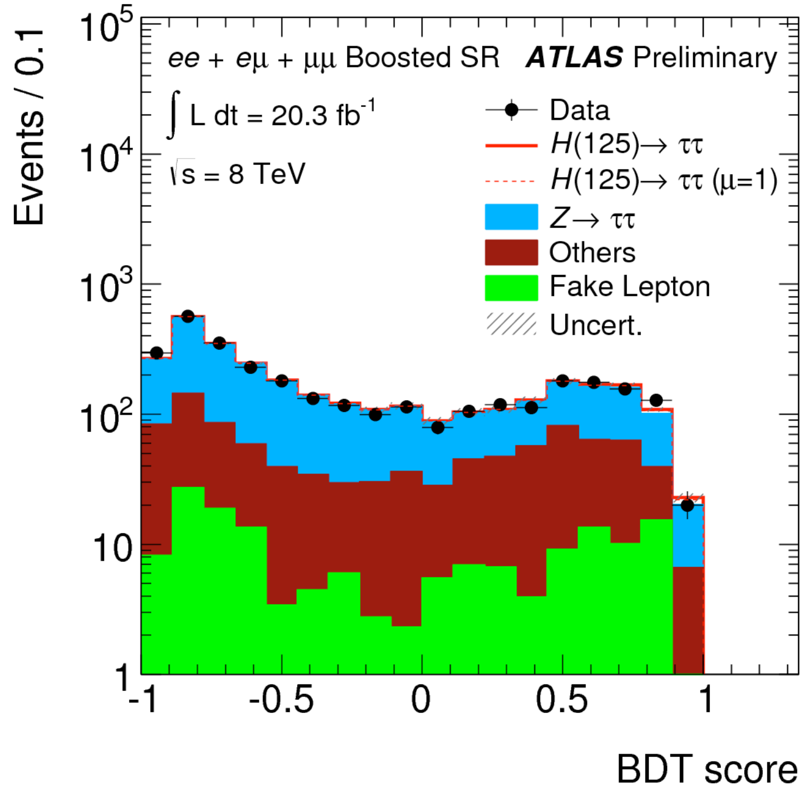


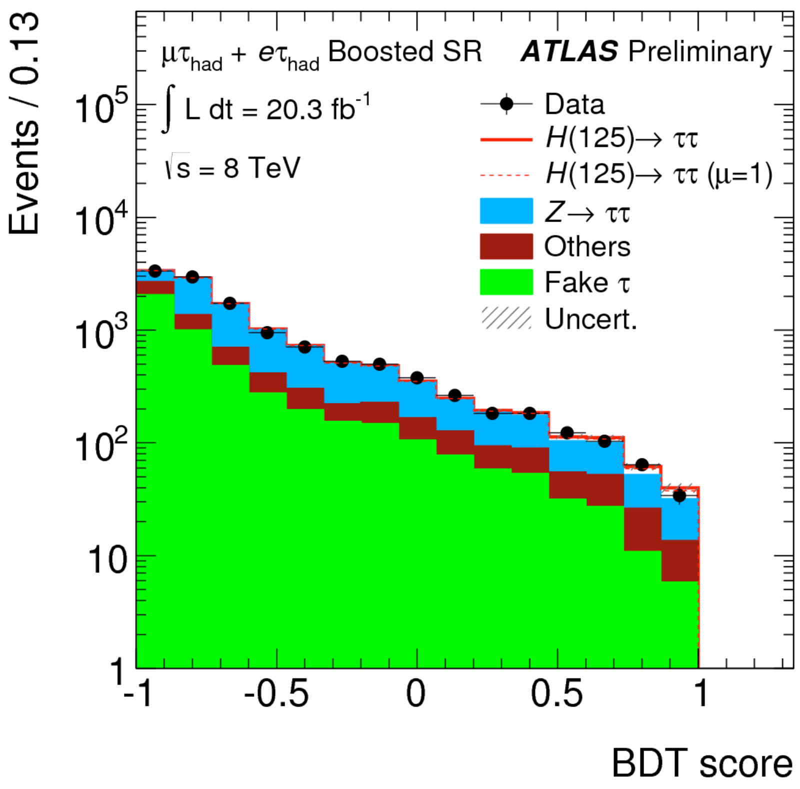


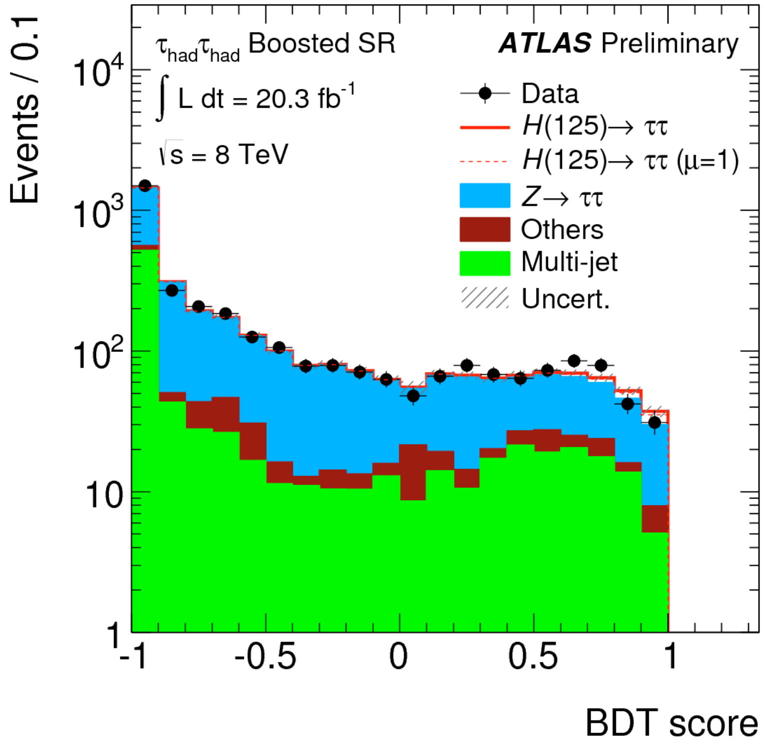
LepLep

LepHad

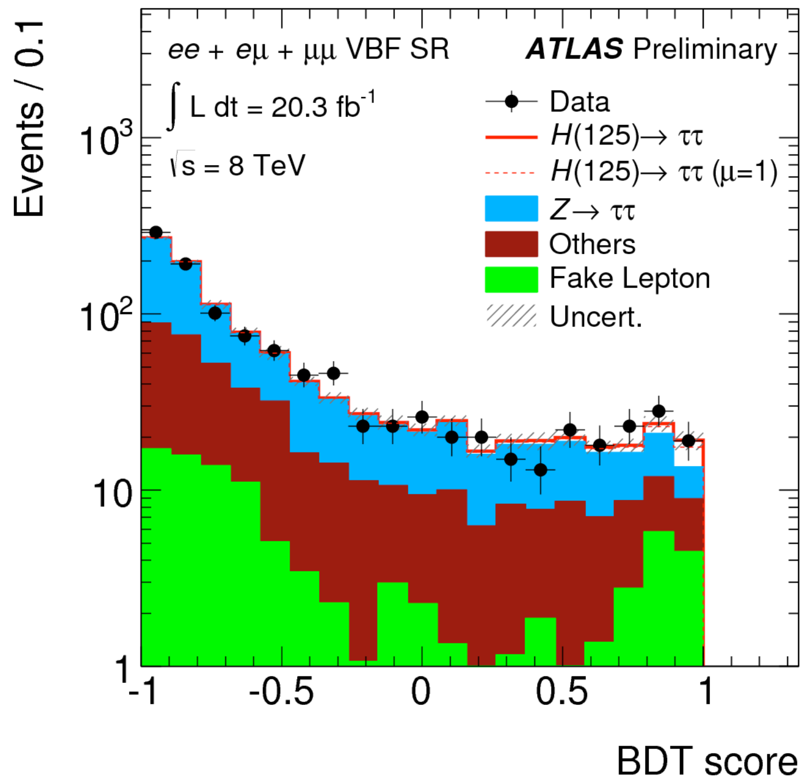
HadHad

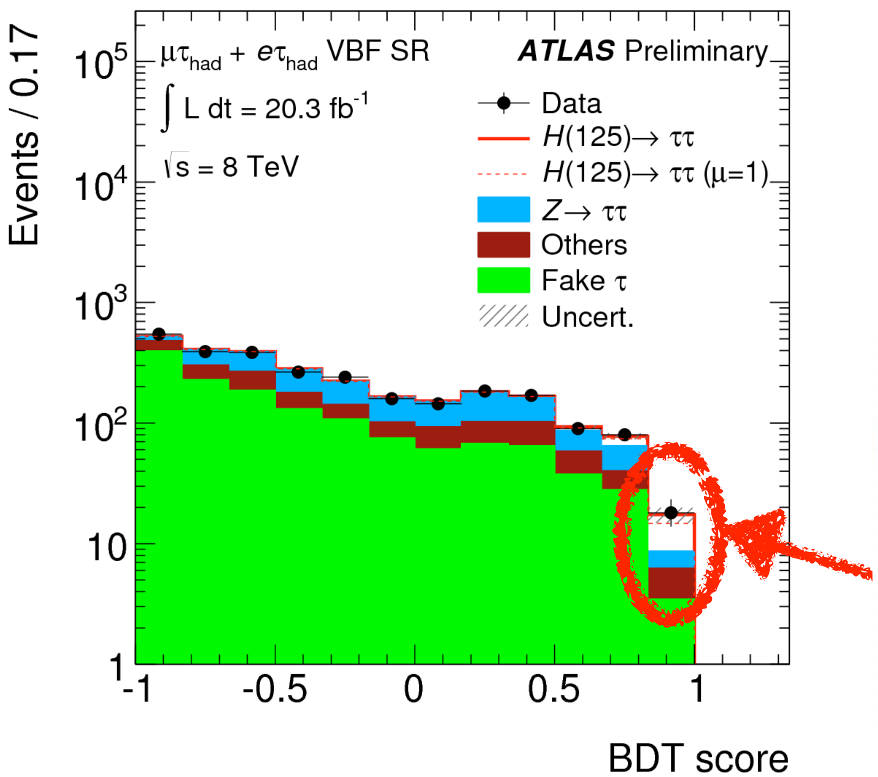


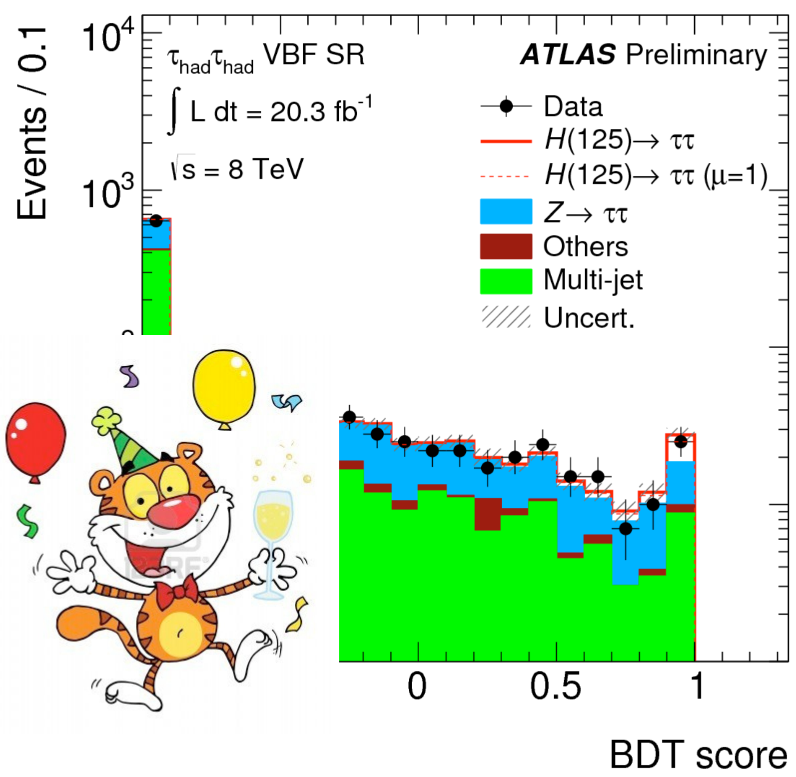




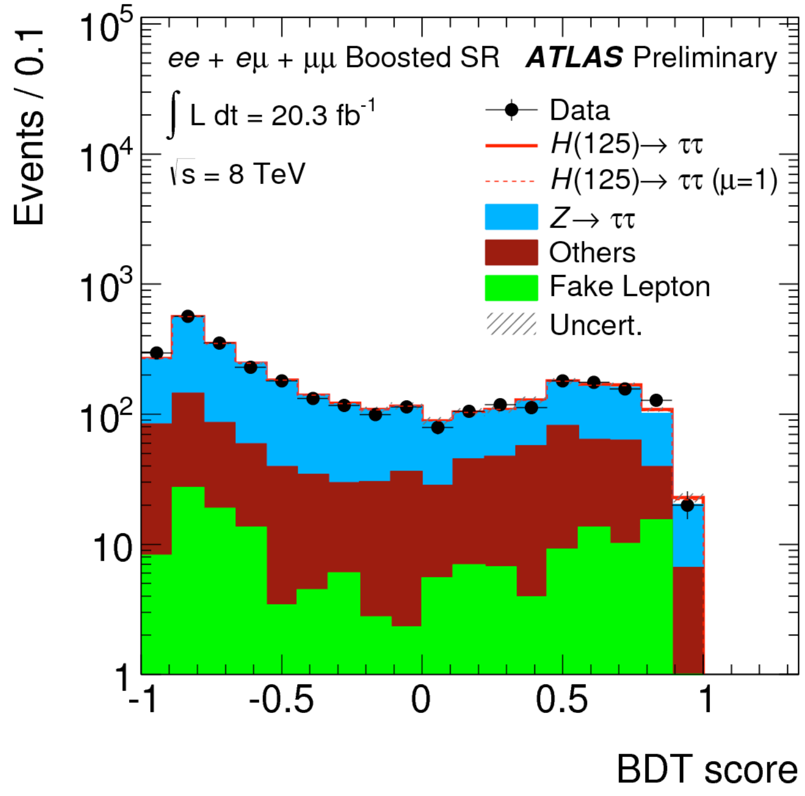
BDT scores in Signal Regions

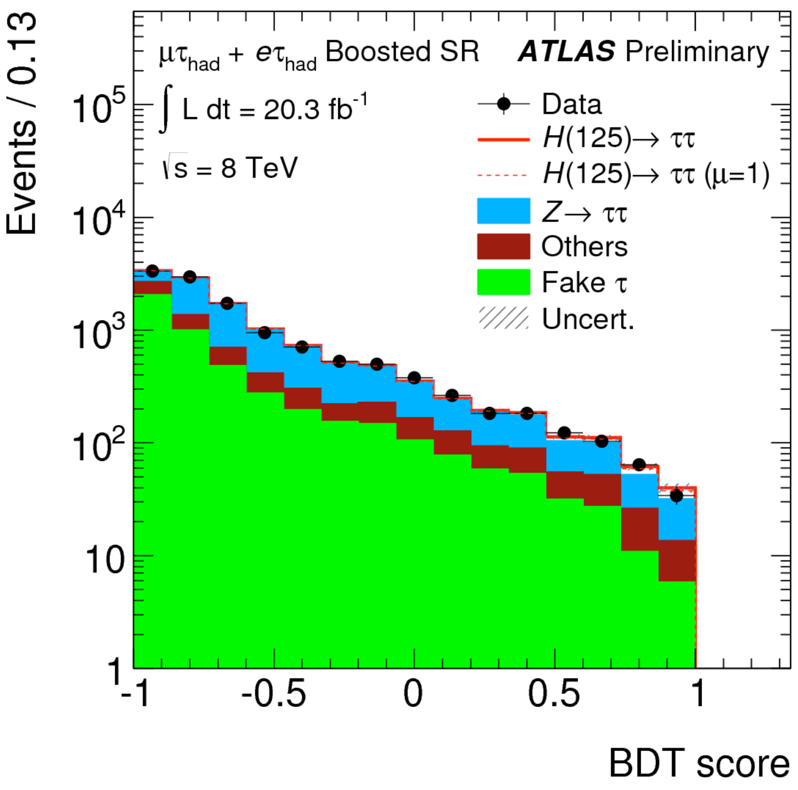


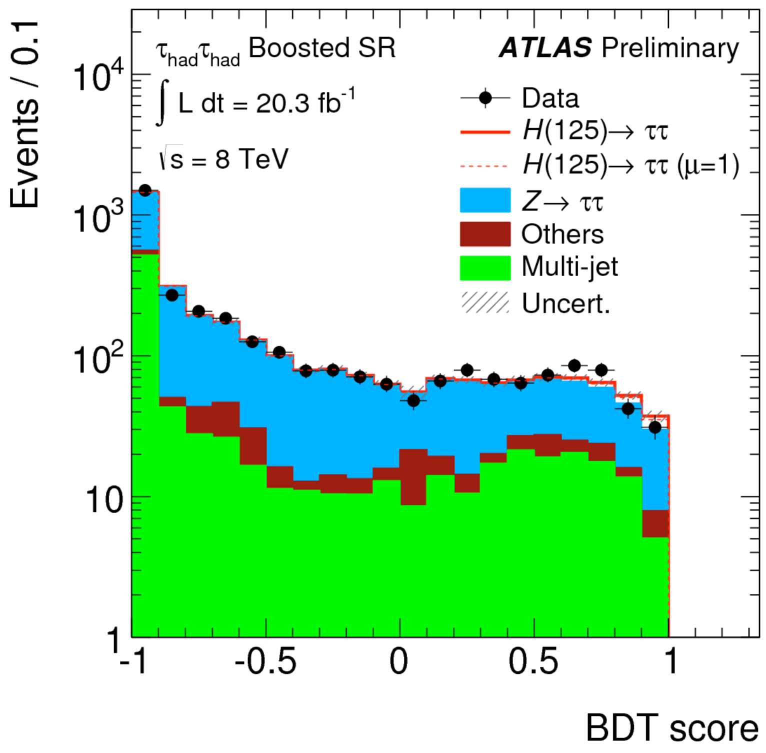




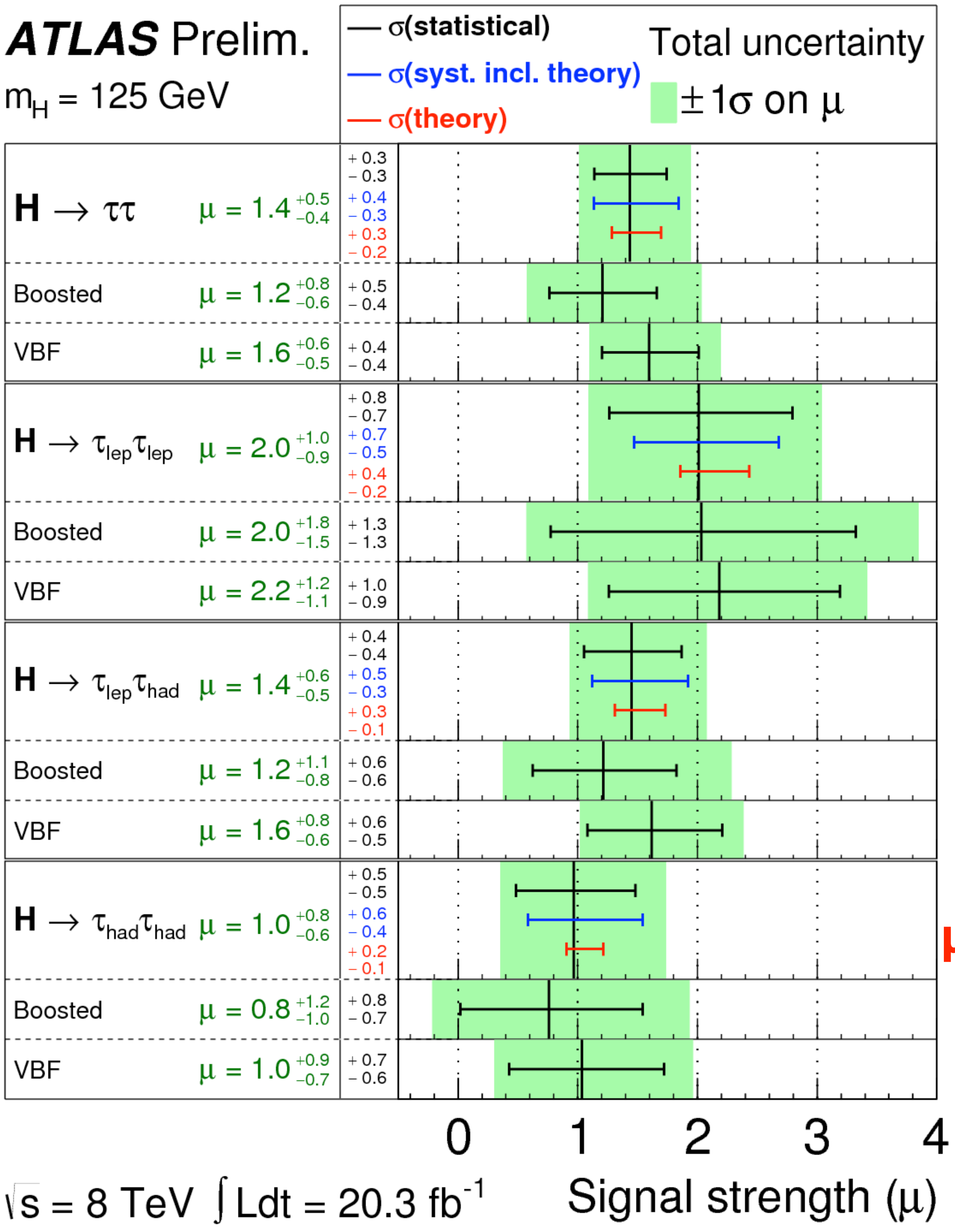
LepLep LepHad HadHad







Signal Strength μ



- Measured signal strength
  - ✦ **$\mu = 1.4^{+0.5}_{-0.4}$**
  - ✦ Boosted category: **$\mu = 1.2^{+0.8}_{-0.6}$**
  - ✦ VBF category: **$\mu = 1.6^{+0.6}_{-0.5}$**

Consistent with SM Higgs boson predictions !

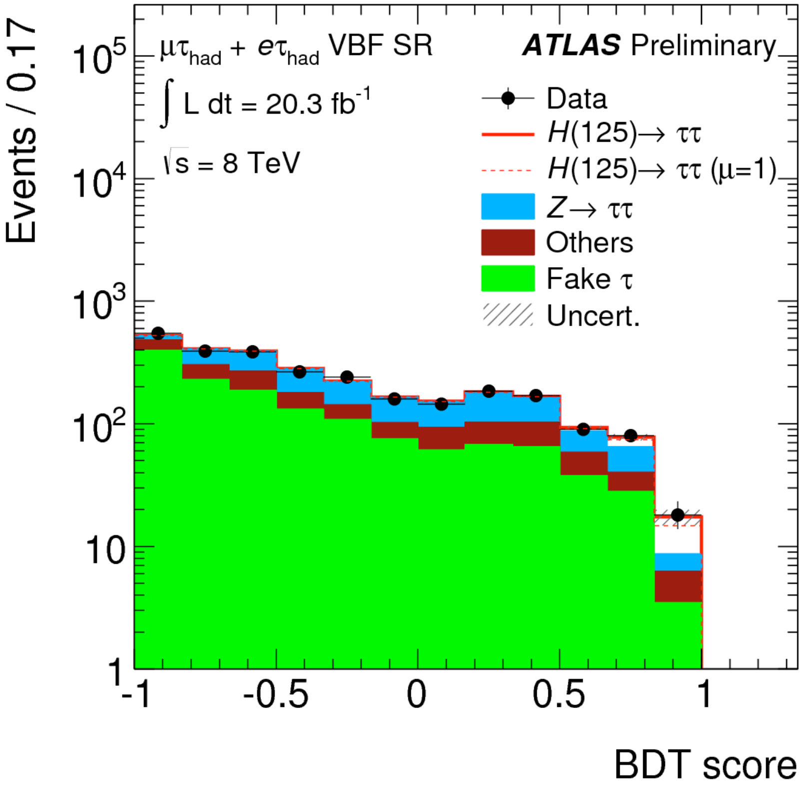
- Breakdown of the uncertainties

$\mu = 1.4 \pm 0.3(\text{stat.})\ ^{+0.3}_{-0.2}(\text{syst.})\ ^{+0.3}_{-0.2}(\text{theory})$

Leading Uncertainties

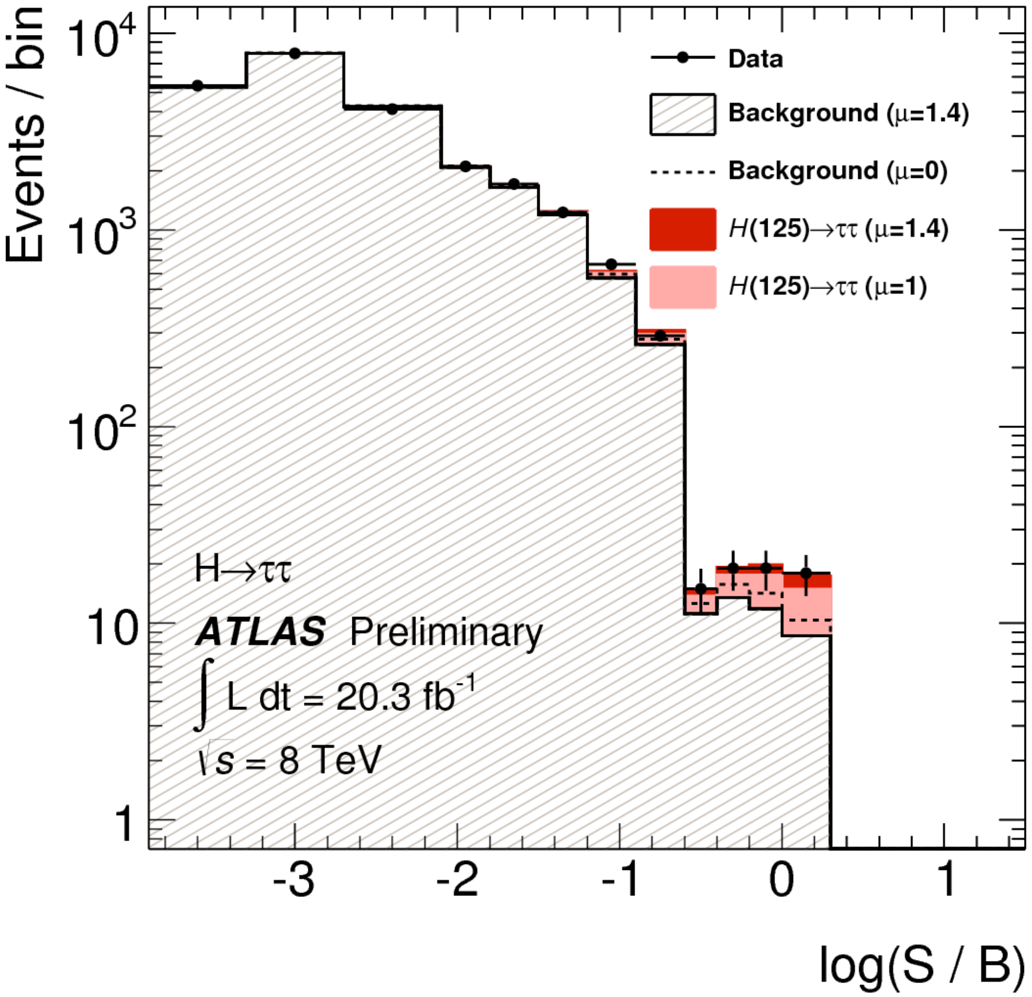
Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	0.30
$Z \to \ell\ell$ normalization ($\tau_{\text{lep}}\tau_{\text{had}}$ boosted)	0.13
ggF $d\sigma/dp_T^H$	0.12
JES η calibration	0.12
Top normalization ($\tau_{\text{lep}}\tau_{\text{had}}$ VBF)	0.12
Top normalization ($\tau_{\text{lep}}\tau_{\text{had}}$ boosted)	0.12
$Z \to \ell\ell$ normalization ($\tau_{\text{lep}}\tau_{\text{had}}$ VBF)	0.12
QCD scale	0.07
di-τ_{had} trigger efficiency	0.07
Fake backgrounds ($\tau_{\text{lep}}\tau_{\text{lep}}$)	0.07
τ_{had} identification efficiency	0.06
$Z \to \tau^+\tau^-$ normalization ($\tau_{\text{lep}}\tau_{\text{had}}$)	0.06
τ_{had} energy scale	0.06

$\mu = 1.4^{+0.5}_{-0.4}$



- Leading uncertainty due to **little statics** in the **high BDT score bins** that drive the best fit value
- **Theory uncertainty** ranked high
- Leading experimental uncertainties come from the **background normalisation**

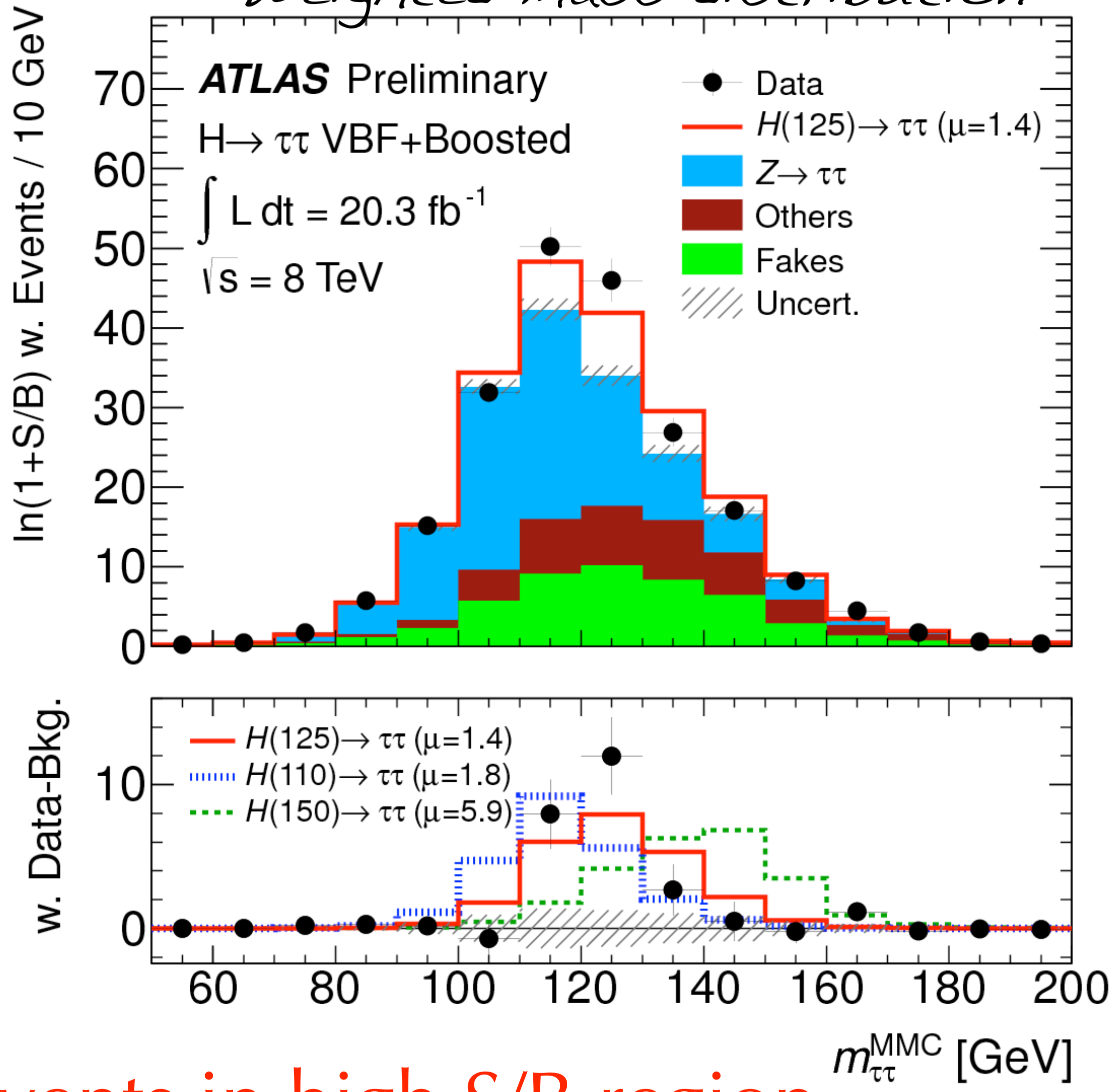
$H\rightarrow\tau\tau$ significant excess observed



Number of events in highest BDT-score bin

VBF	LepHad
Signal	8.7±2.5
Bckgr.	8.7±2.4
Data	19

Weighted mass distribution

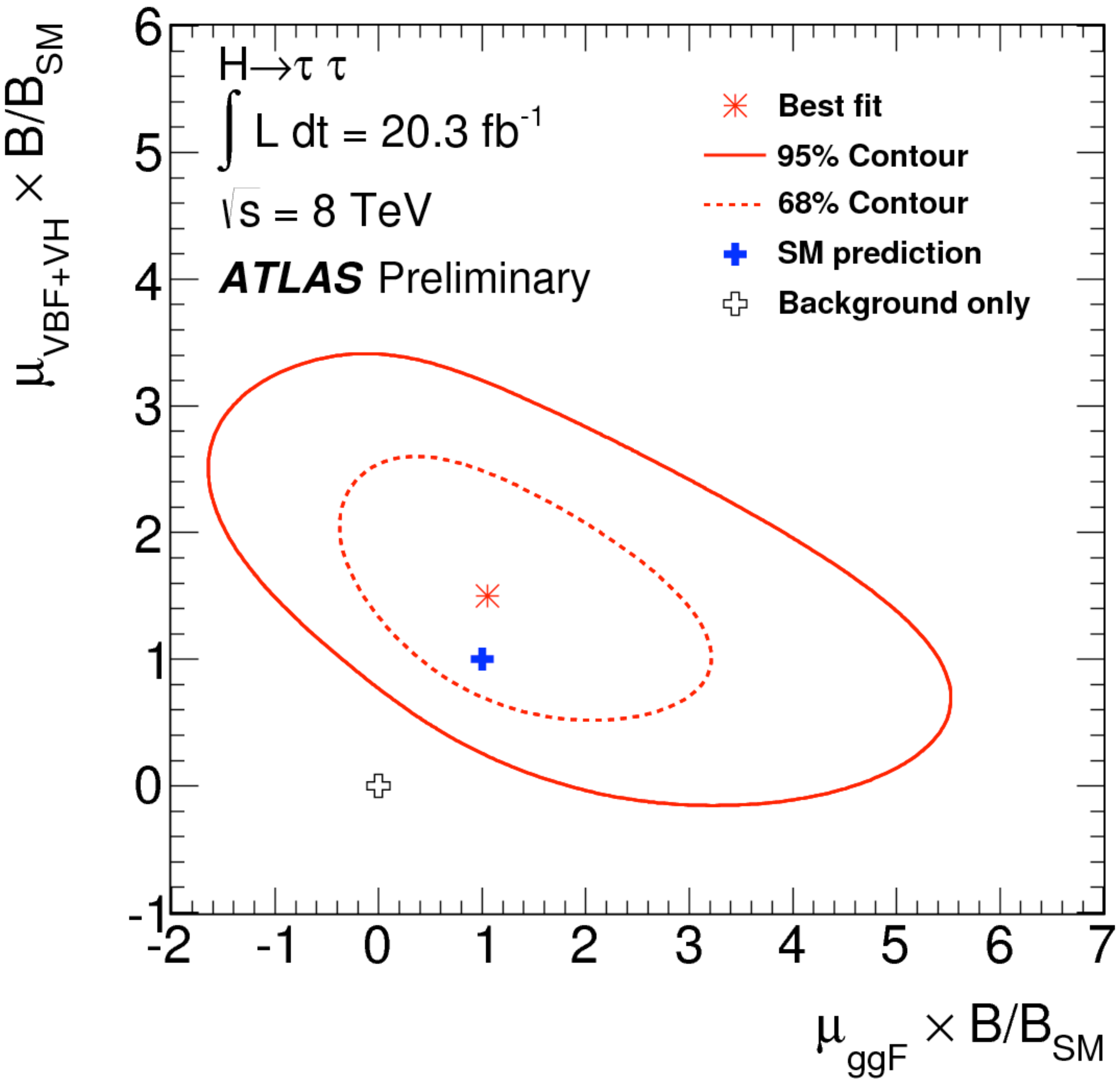


- ATLAS observes significant excess of data events in high S/B region
  - ✦ **Expected** significance @ m_H=125 GeV : **3.2σ** (Probability: **6.6×10^{-4}**)
  - ✦ **Observed** significance @ m_H=125 GeV : **4.1σ** (Probability: **2×10^{-5}**)
  - ✦ Excess observed in all three channels
  - ✦ **Observed signal compatible with m_H=125 GeV**
- **Direct evidence of 4.1σ that the Higgs boson couples to leptons**

Production Mechanisms

- Best fit sits comfortably away from null hypothesis

- **Compatible with Standard Model expectation within the 68% contour**



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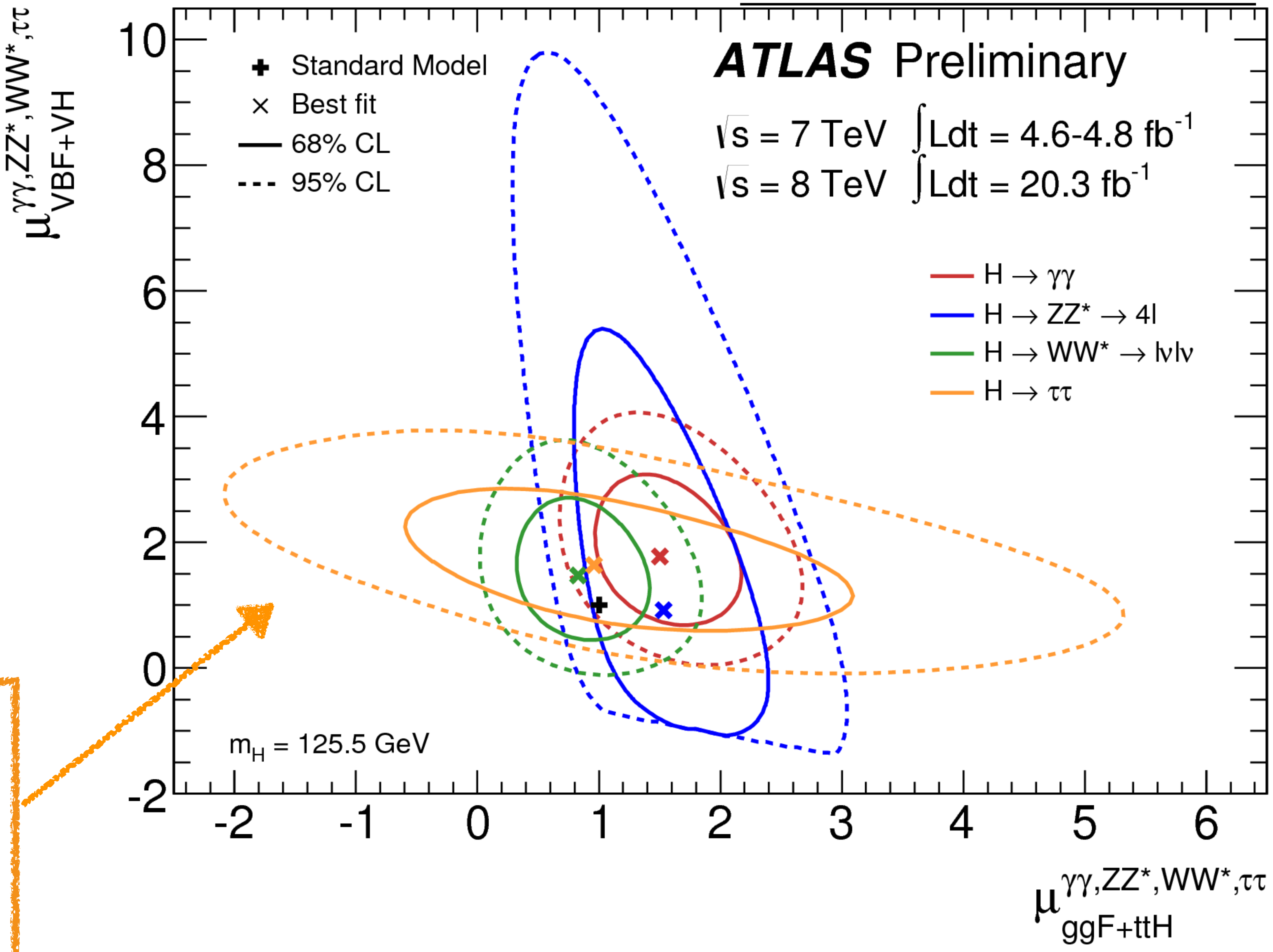
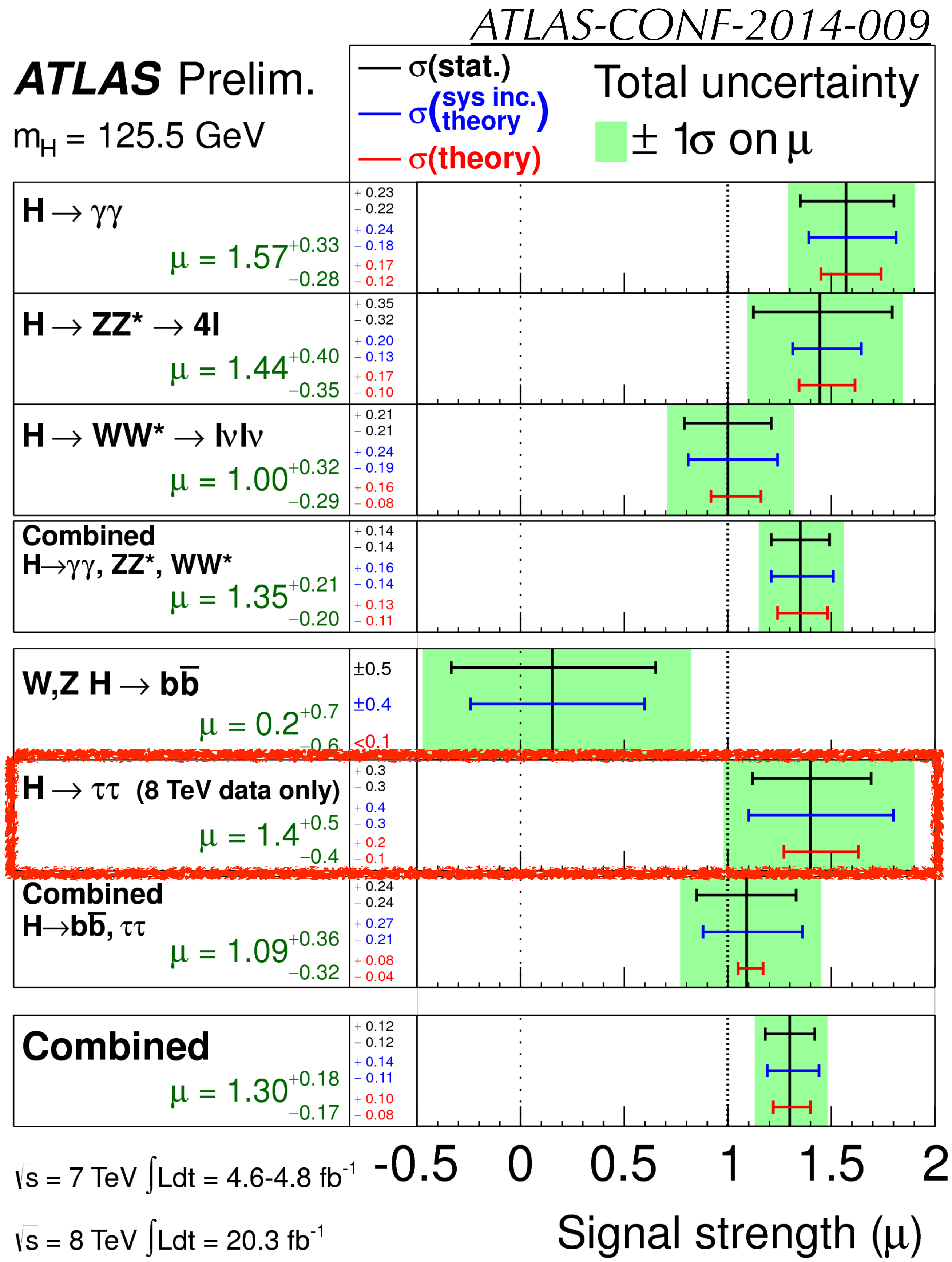


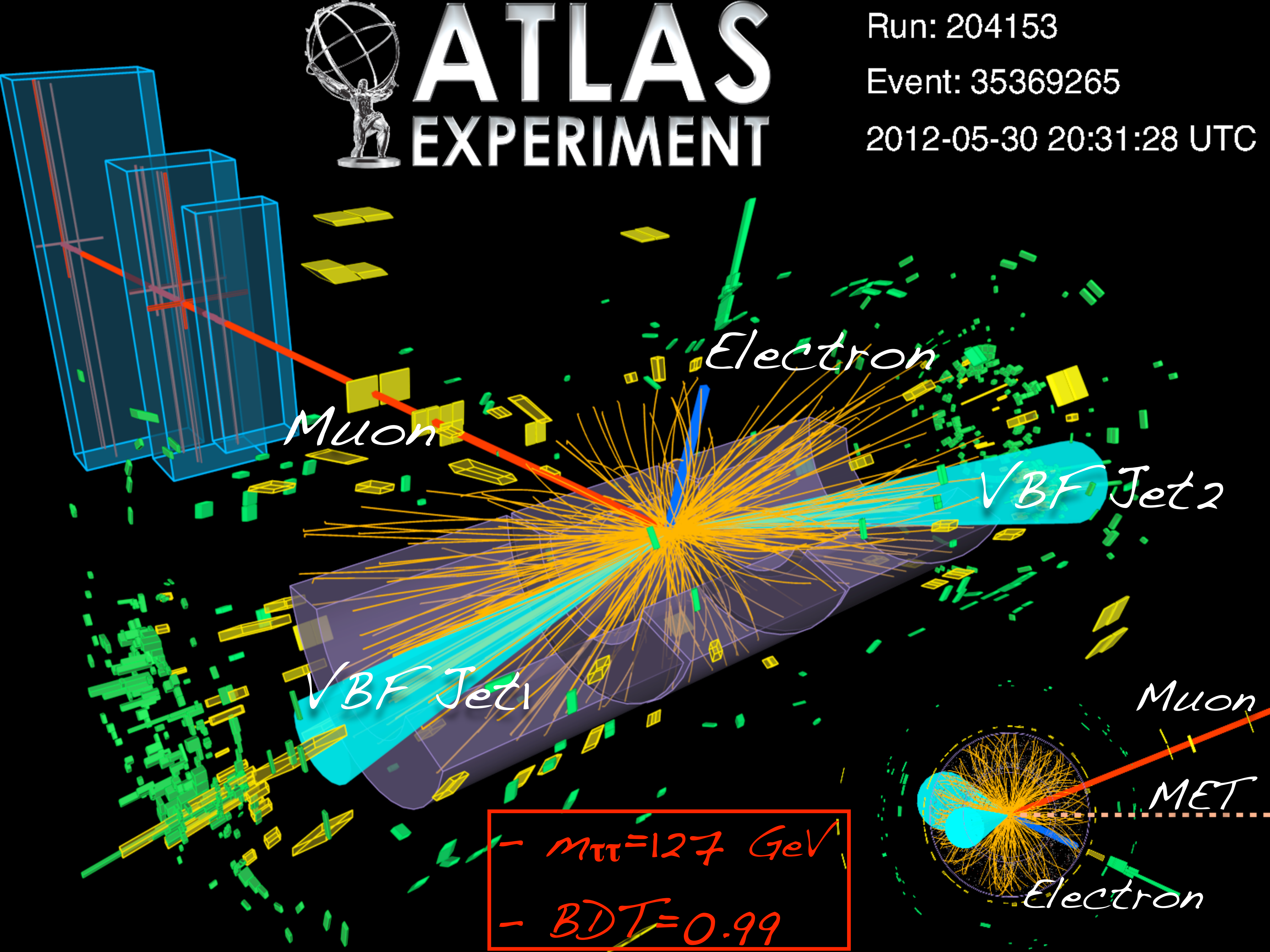
ATLAS-CONF-2014-009

- H→ττ most sensitive to the VBF mode (good constraint for the ATLAS combination)

Epilogue



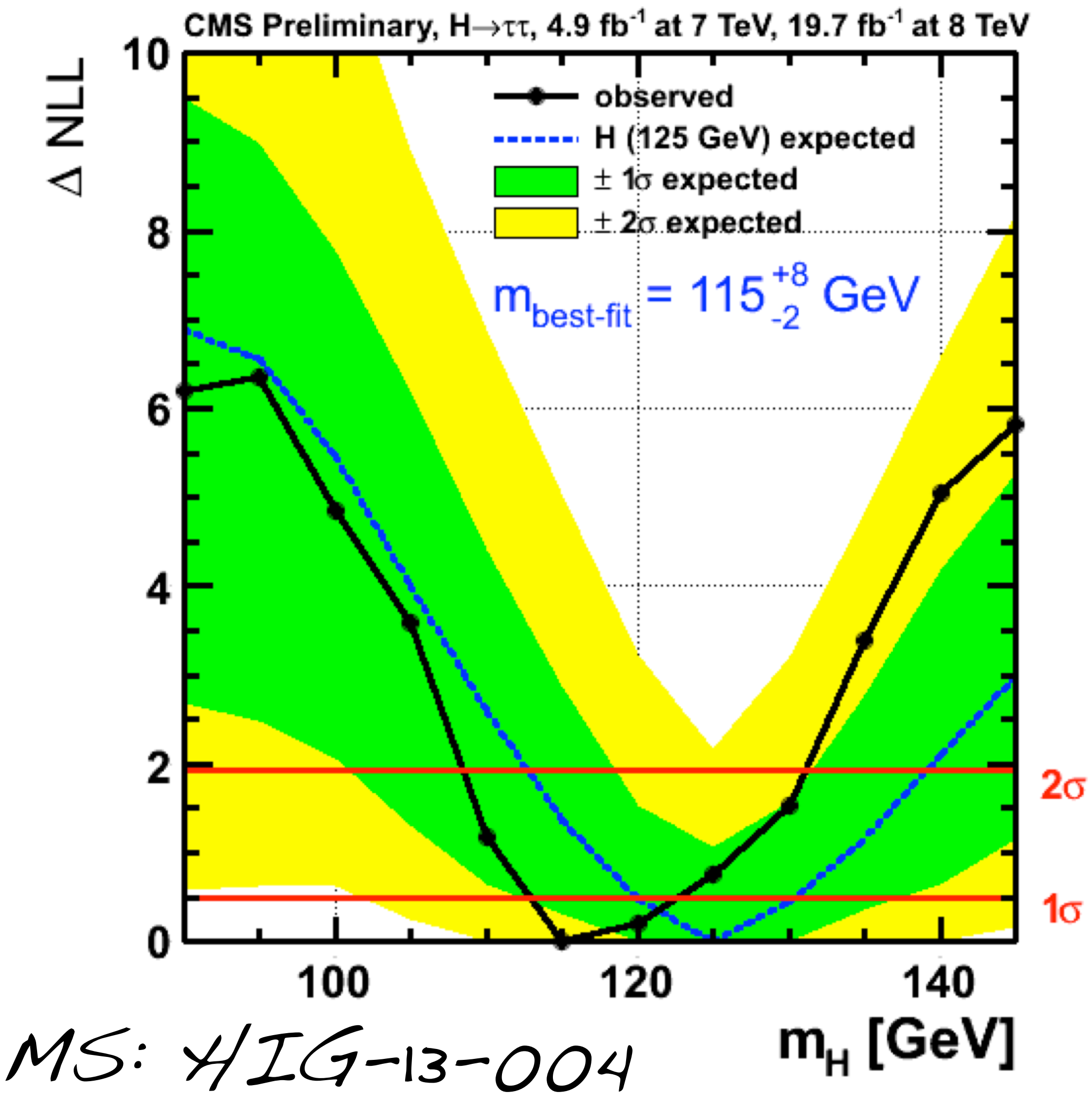
- **ATLAS observed 4.1σ evidence for H→ττ decays,** consistent with SM Higgs boson predictions
- This analysis paves the road for H→ττ property measurements during Run II



- $m_{\tau\tau}=127$ GeV
- BDT=0.99

Back-up index

ATLAS Vs CMS



CMS: HIG-13-004

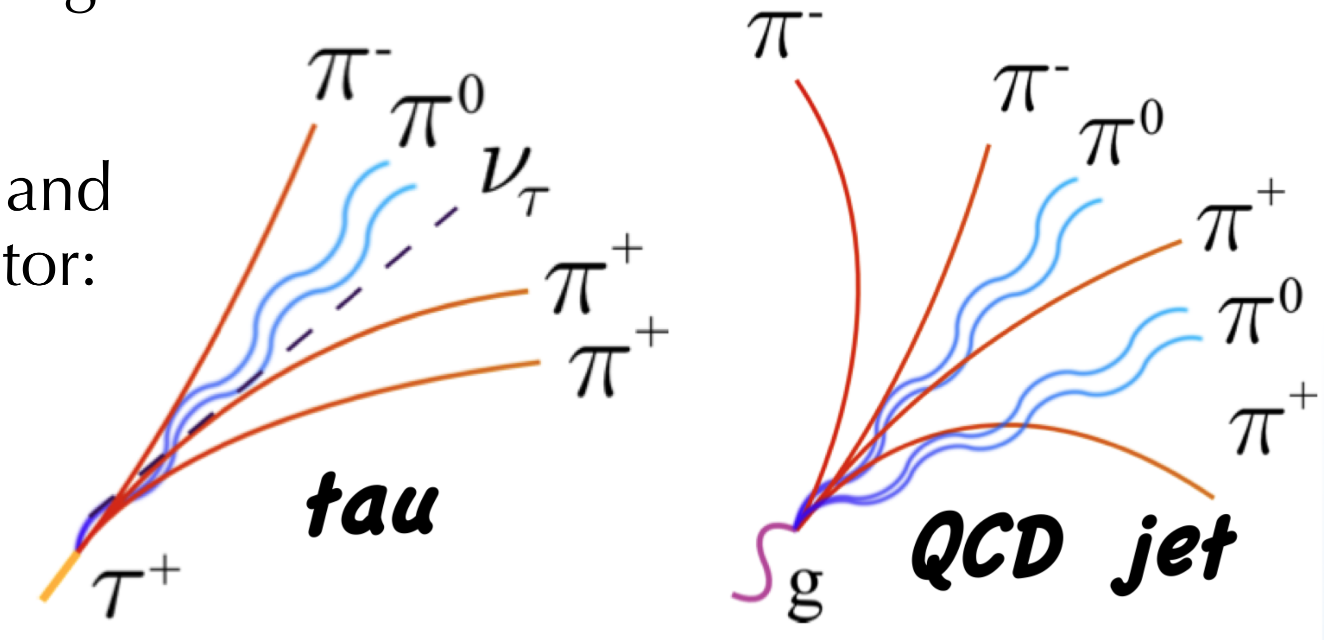
	CMS	ATLAS
obs. p	3.4	4.1
exp. p	3.6	3.2
signal strength μ	0.9 ± 0.3	μ = 1.4

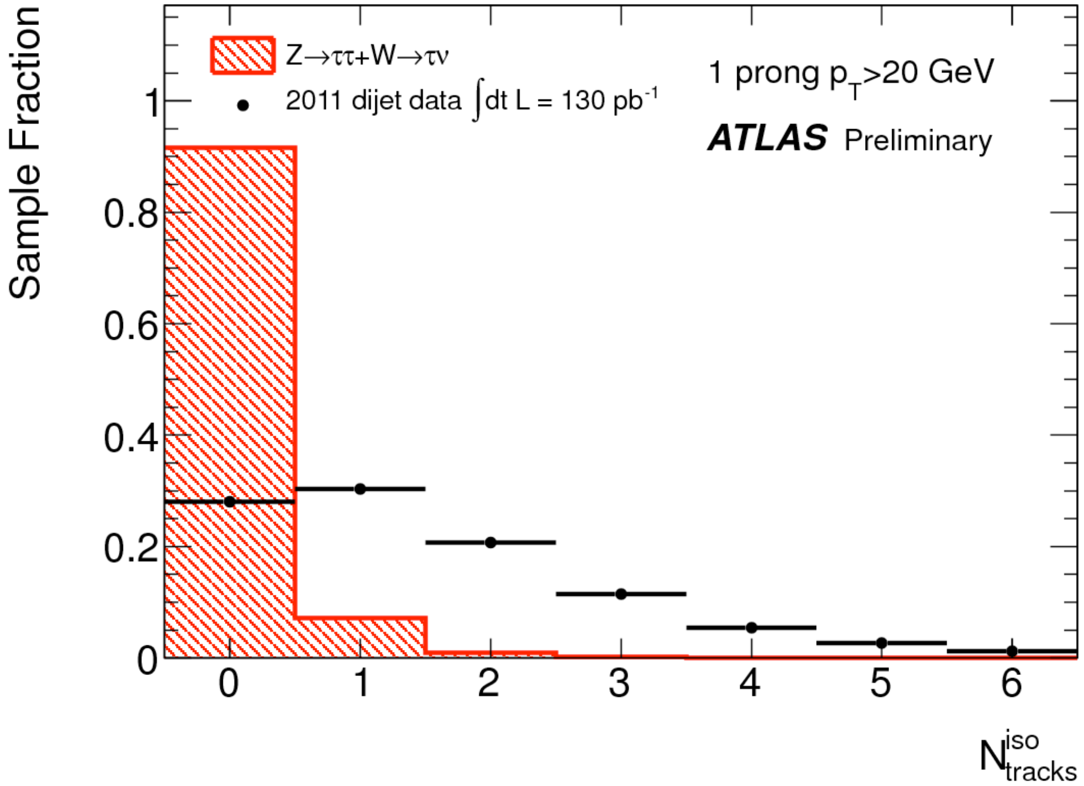
- **Results** of two experiments are **similar**
- Both **ATLAS** and **CMS** observe an **evidence** of the **H→ττ**
- **Excess** is **compatible** with **SM** H→ττ within **1σ** for both cases

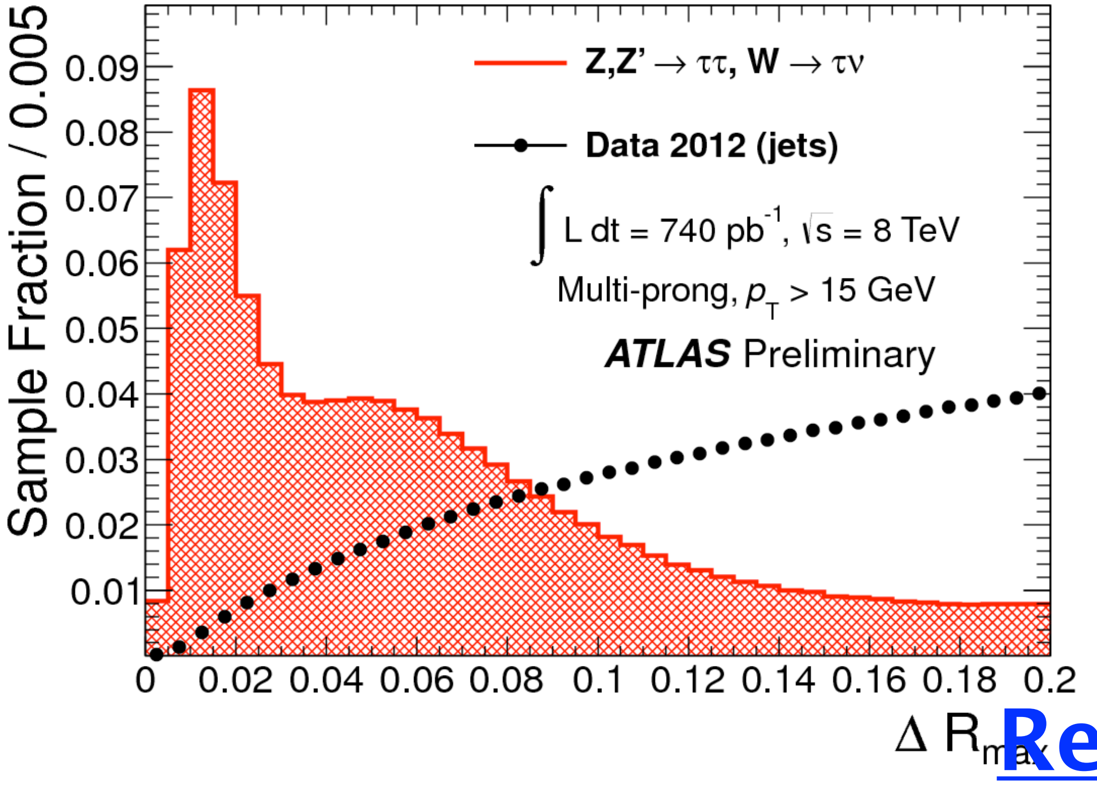
- Hard to compare in detail, analyses approach differs
- **ATLAS** uses an **MVA**, while **CMS** a **cut-based**
  - ✦ **CMS** performs a mass measurement: **$m_H = 115^{+8}_{-2}$ GeV**
- Other important differences
  - ✦ **CMS** has analysed **2011 dataset** as well and **includes** additional **VH channels** with **V** decaying **leptonically**

Tau Identification (TauID)

- **TauID: Distinguish τ_{had} from QCD jets and electrons**
- Use a number of discriminating variables based on tau properties: isolation, energy profiles, fractions of EM & Had energy, angular distances
- Combine all variables separately for 1p and 3p tau decays using an MVA discriminator: BDT



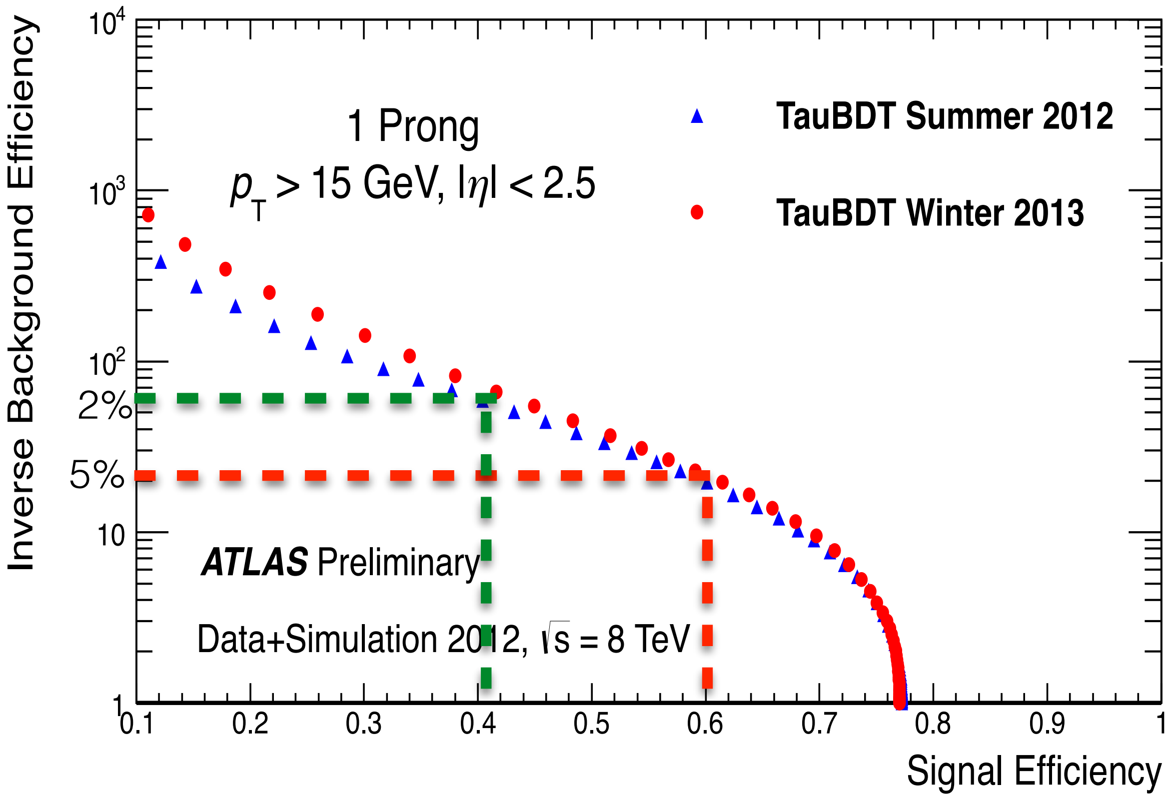


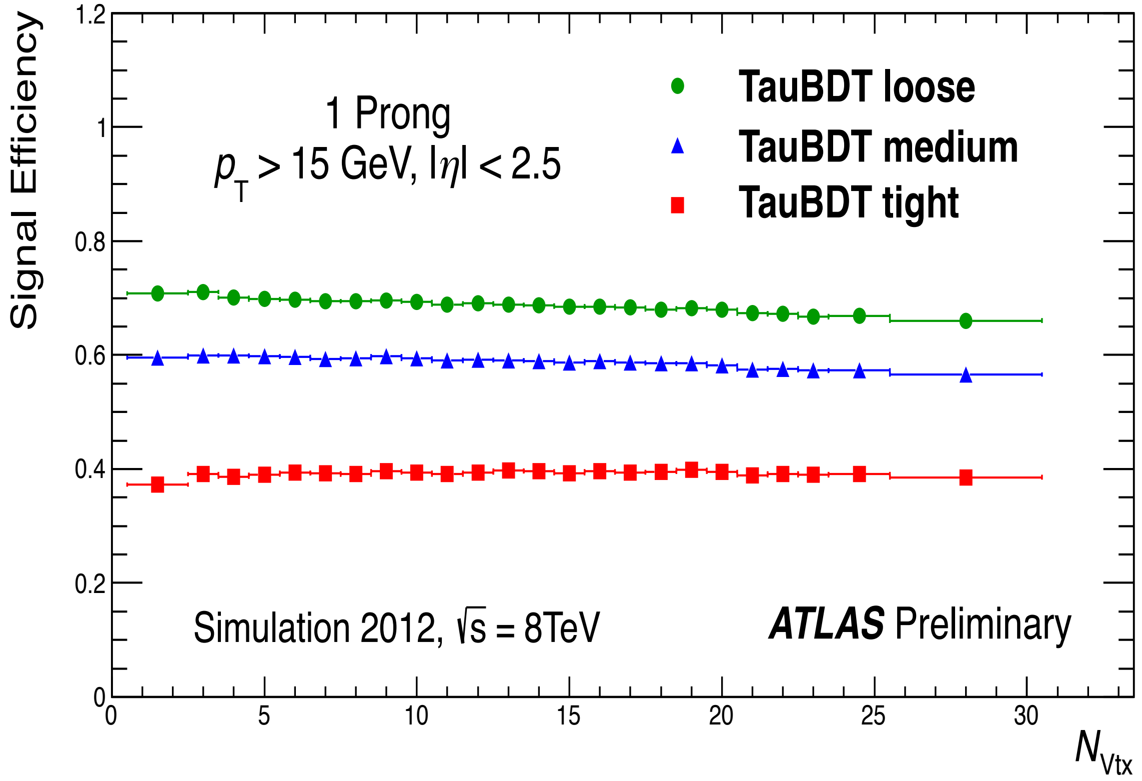


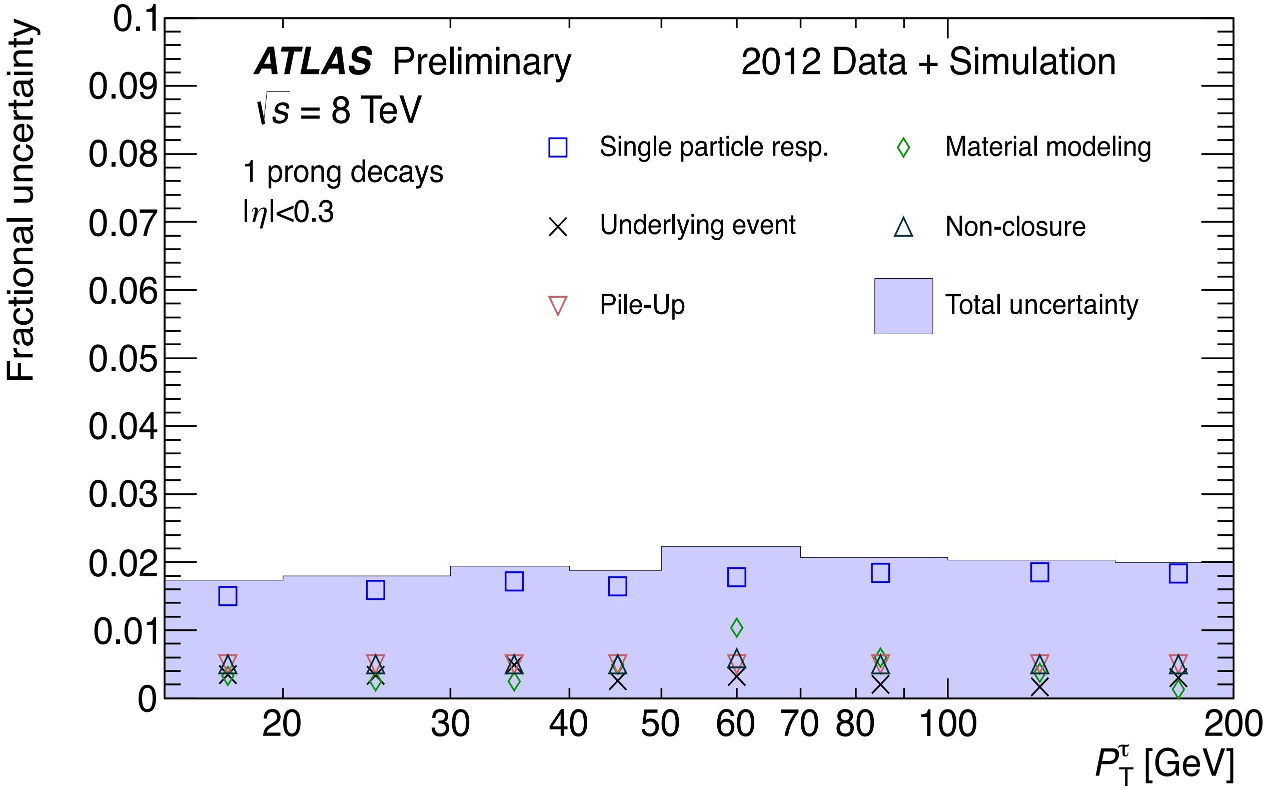
Return

TauID efficiency, energy scale

- **H→ττ uses ~60% and ~40% signal efficiency working points**
- TauID robust against pile-up
- Overall tau energy scale uncertainty 2-3%
  - ✦ Derived from MC and test-beam data
  - ✦ Single particle response the largest contribution

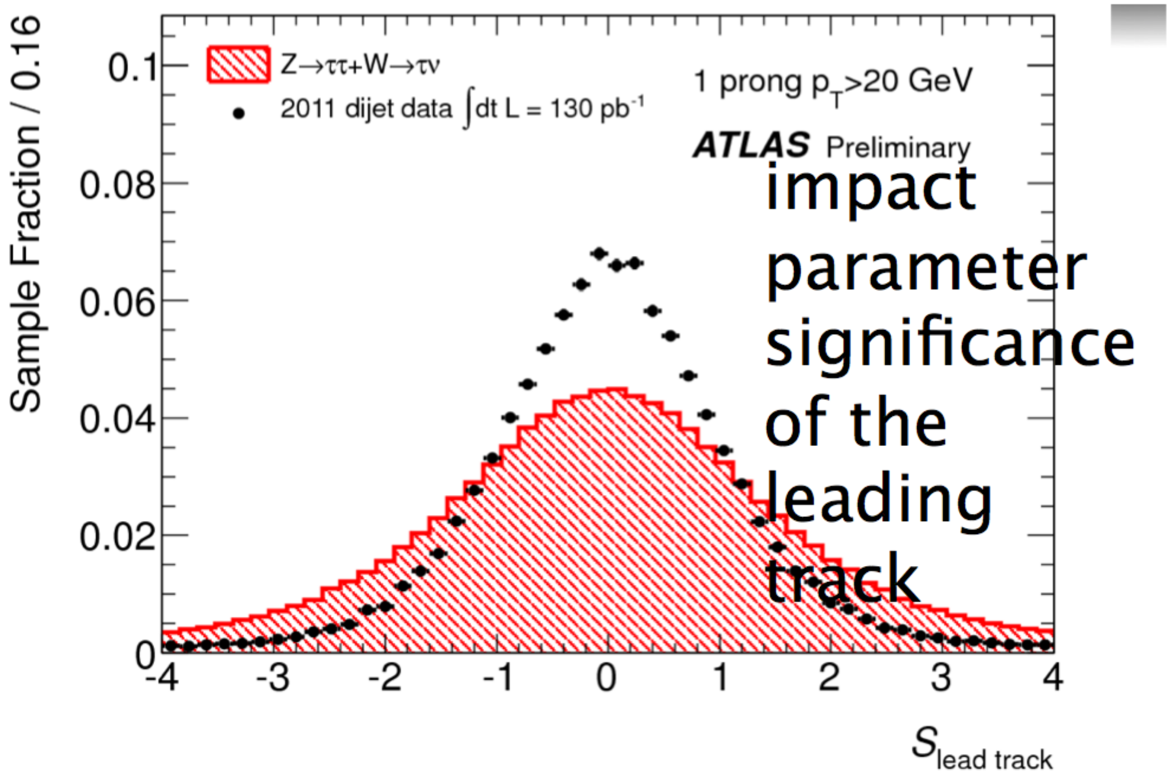




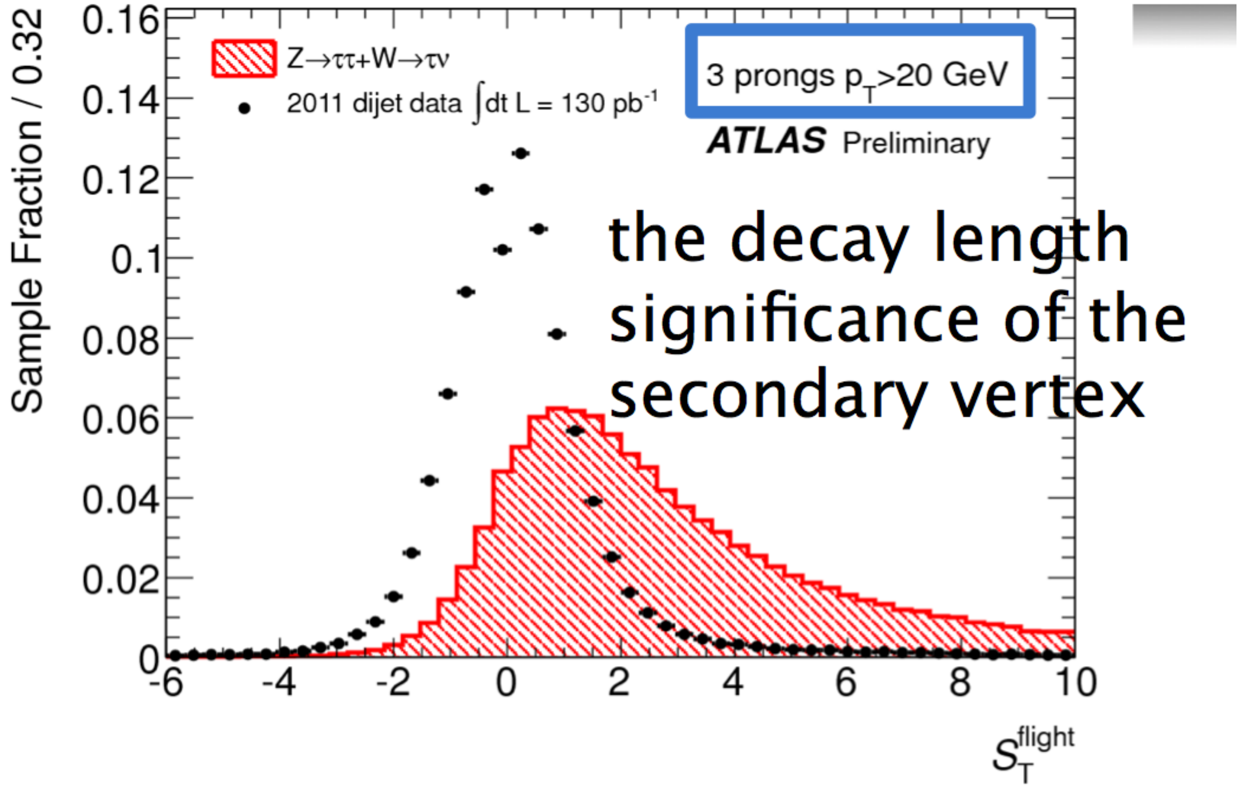


Return

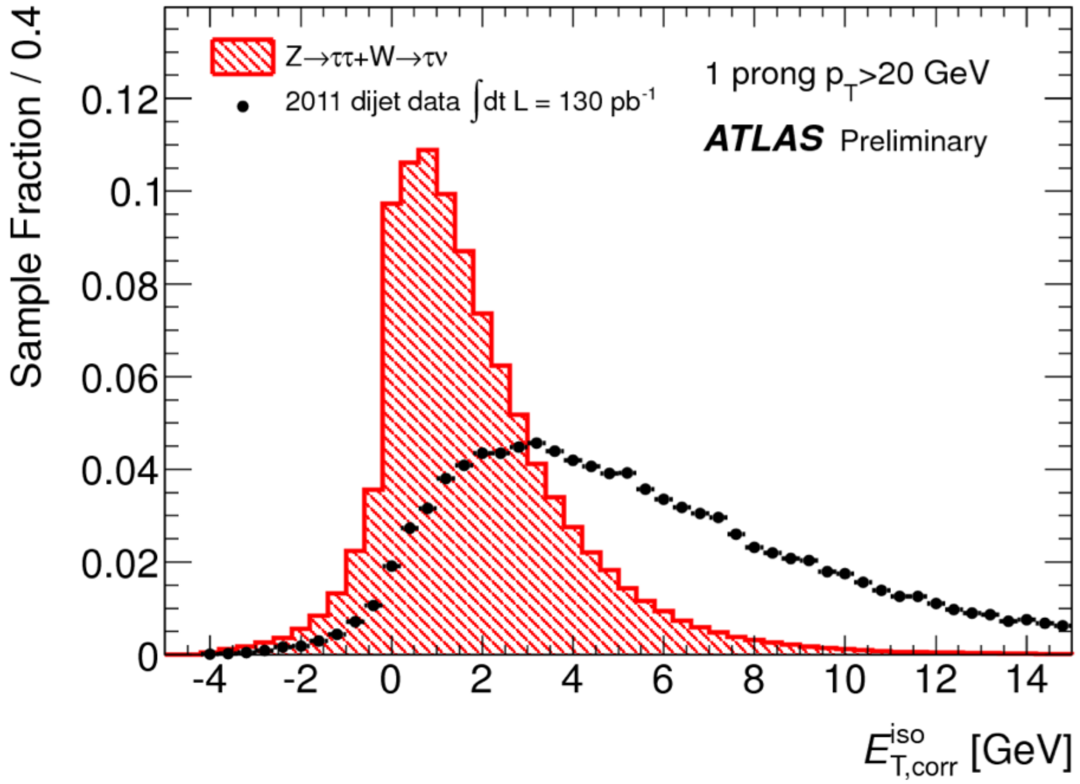
TauID variables

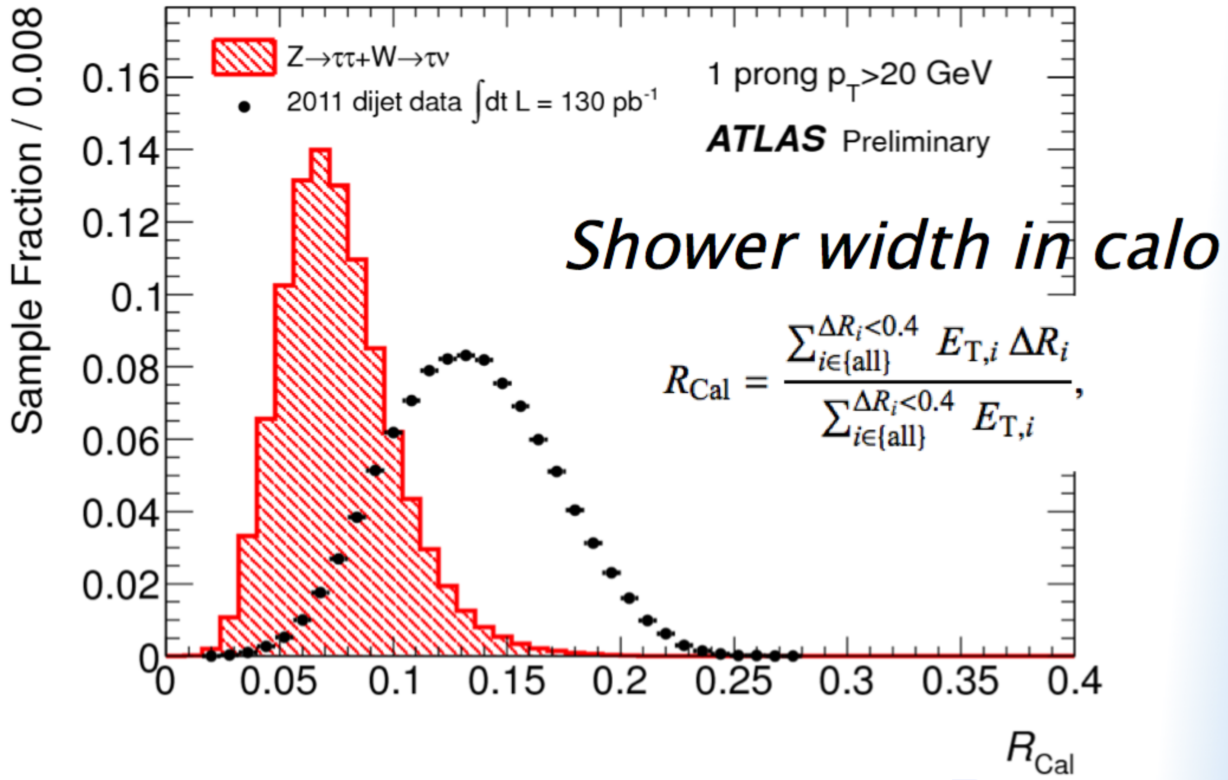


impact parameter significance of the leading track



the decay length significance of the secondary vertex



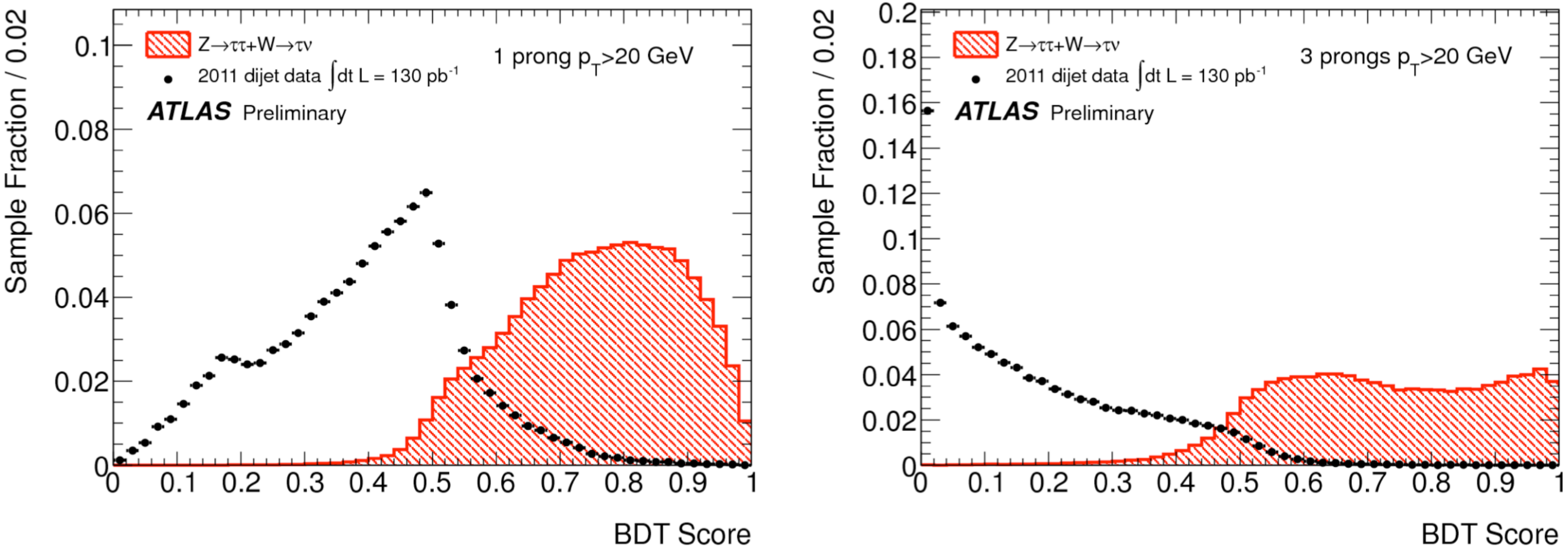


Shower width in calo

$$R_{\text{Cal}} = \frac{\sum_{i\in\{\text{all}\}}^{\Delta R_i<0.4} E_{\text{T},i}\,\Delta R_i}{\sum_{i\in\{\text{all}\}}^{\Delta R_i<0.4} E_{\text{T},i}},$$

Return

TauBDT score



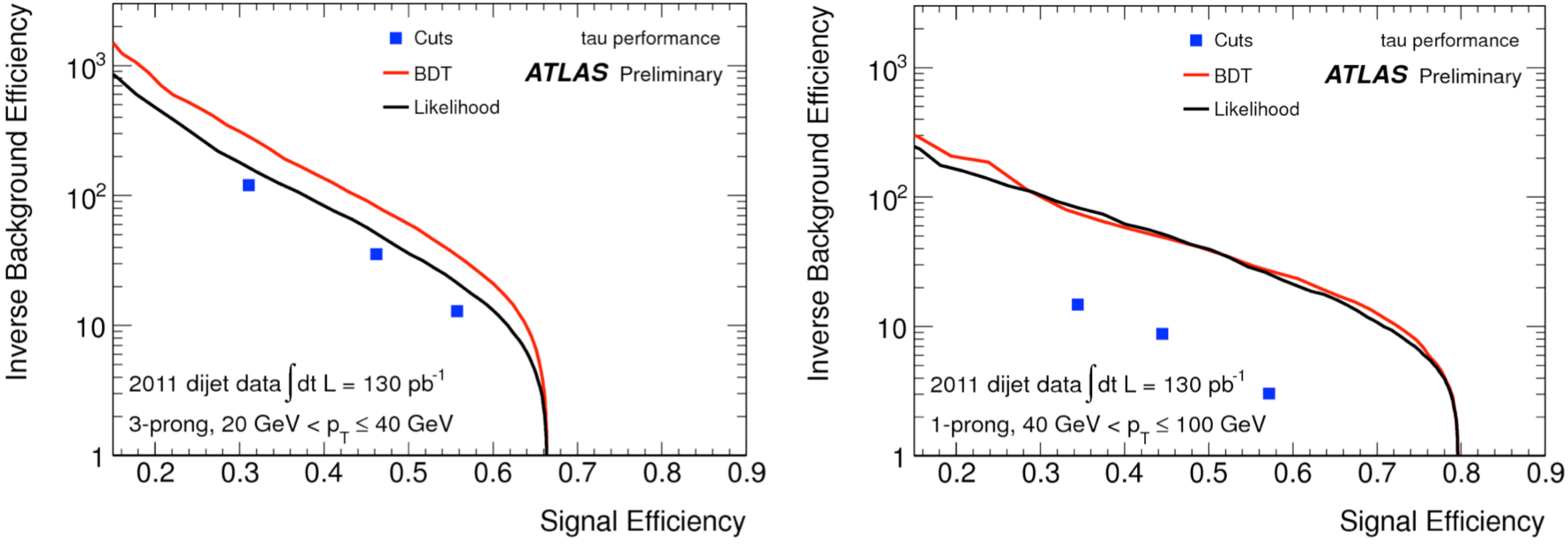
TauID efficiency

Signal efficiency: MC: Z→ττ , W→τν

$$\varepsilon_{\text{sig}}^{n\text{-prong}} = \frac{(\#\text{ of tau candidates with } n \text{ reconstructed tracks, passing ID})}{(\#\text{ of true visible hadronic tau decays with } n \text{ prongs})}$$

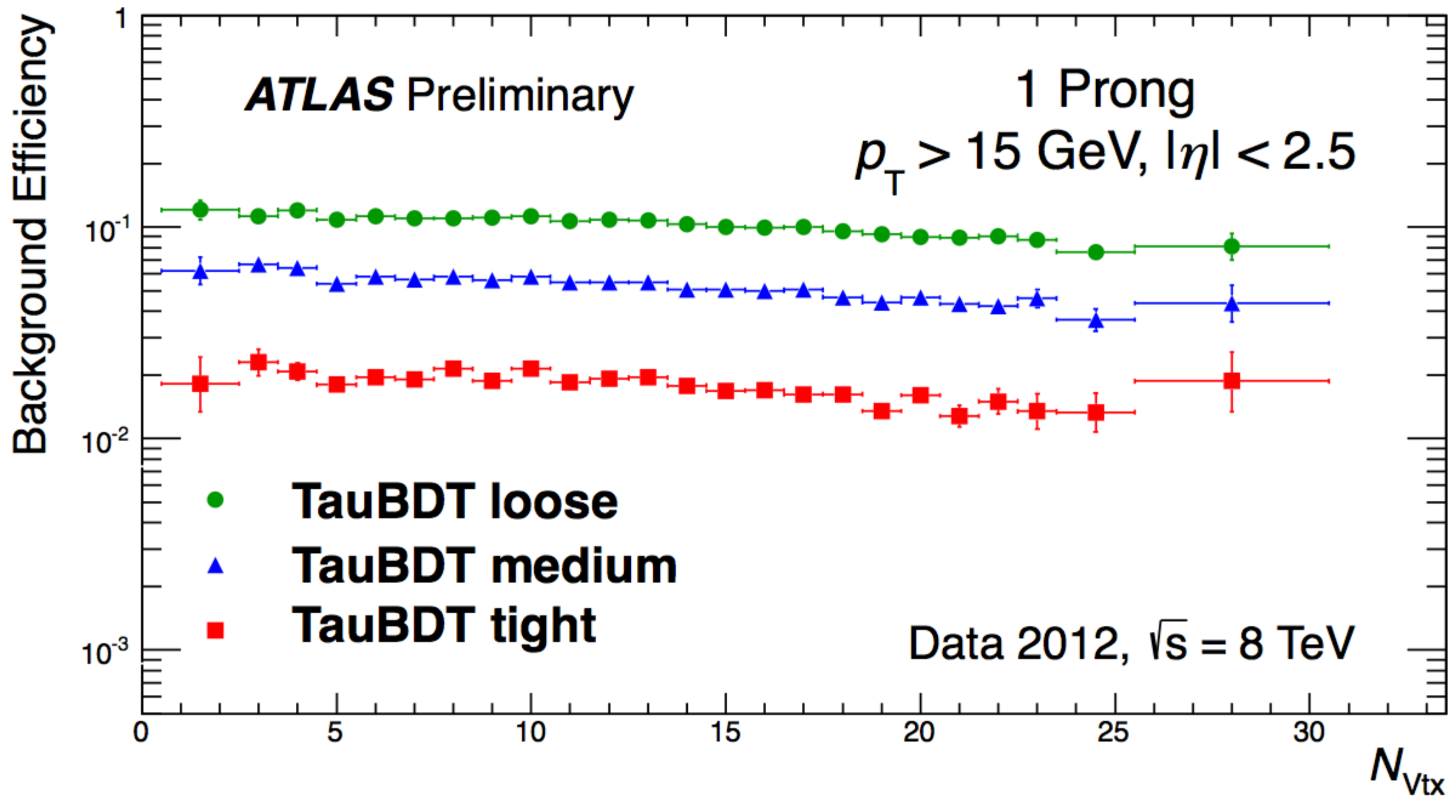
Background efficiency: Data: Dijet sample

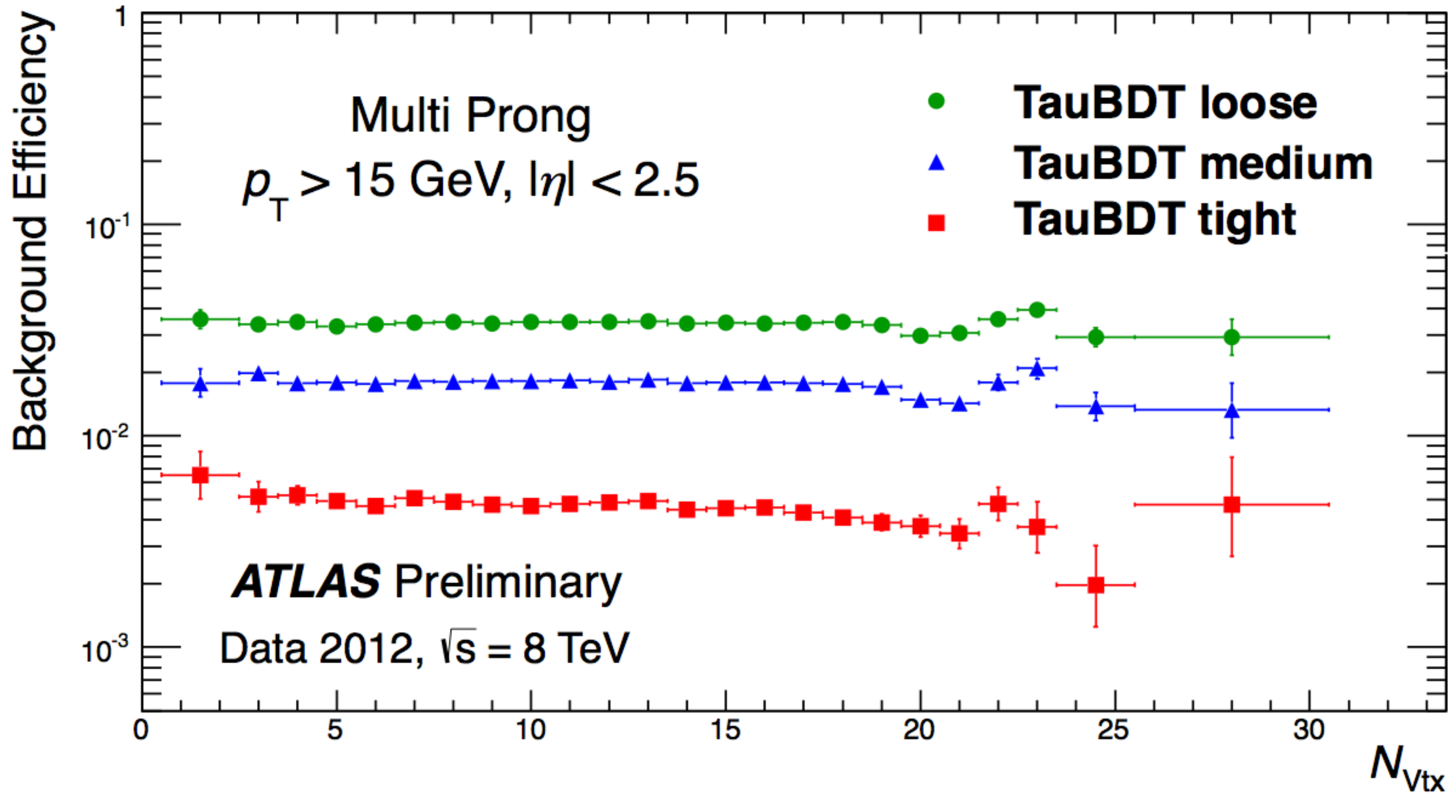
$$\varepsilon_{\text{bkg}}^{n\text{-prong}} = \frac{(\#\text{ of tau candidates with } n \text{ reconstructed tracks, passing ID})}{(\#\text{ of tau candidates with } n \text{ reconstructed tracks})}$$



[Return](#)

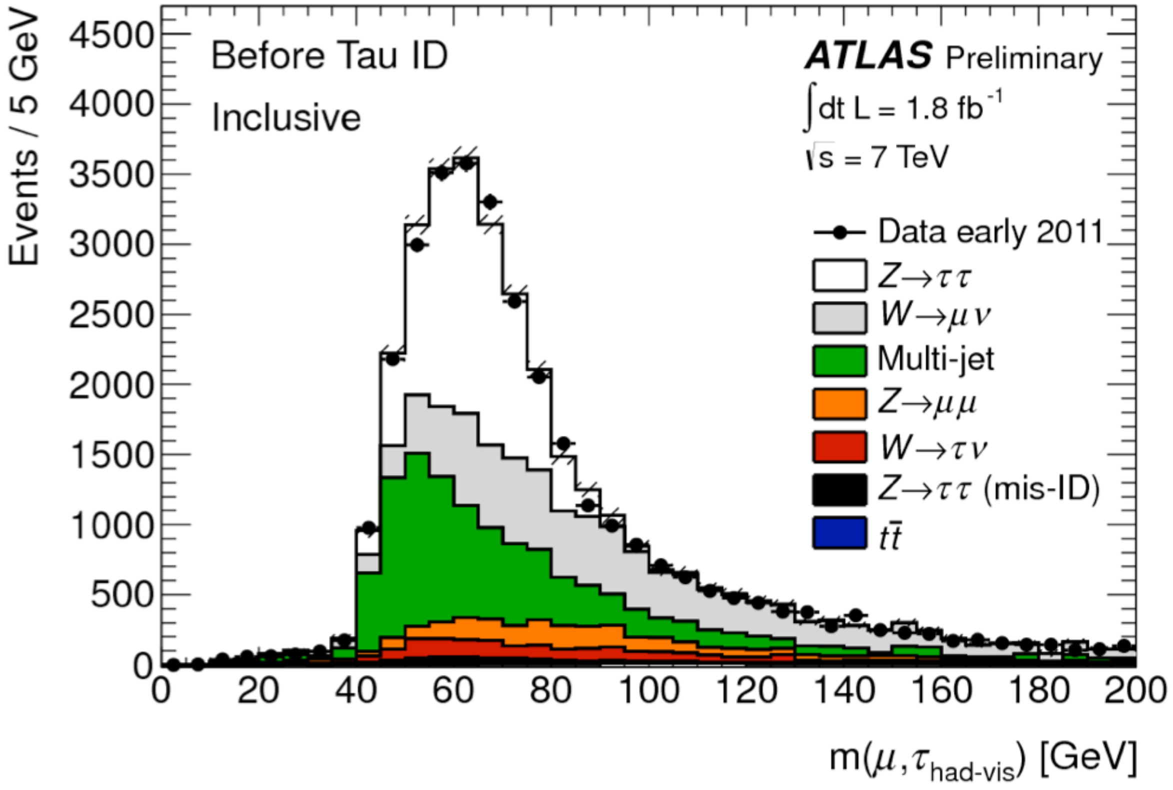
TauID Pile-Up

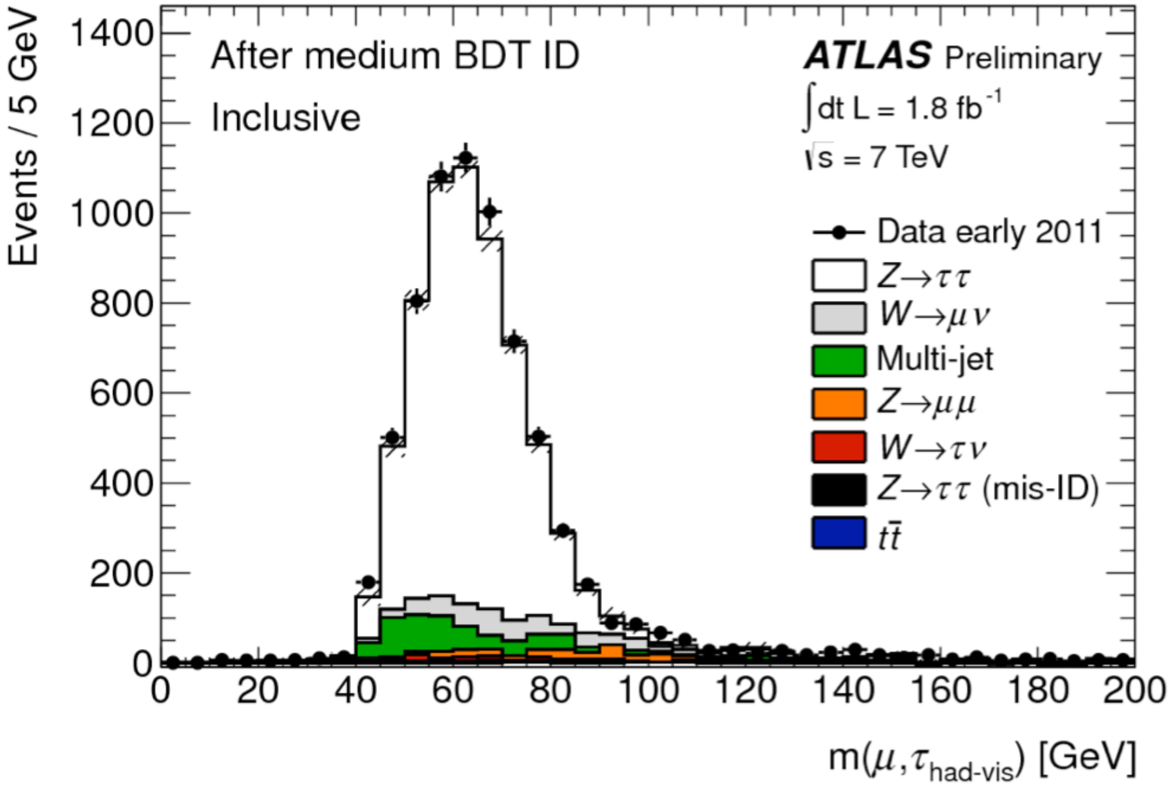




Return

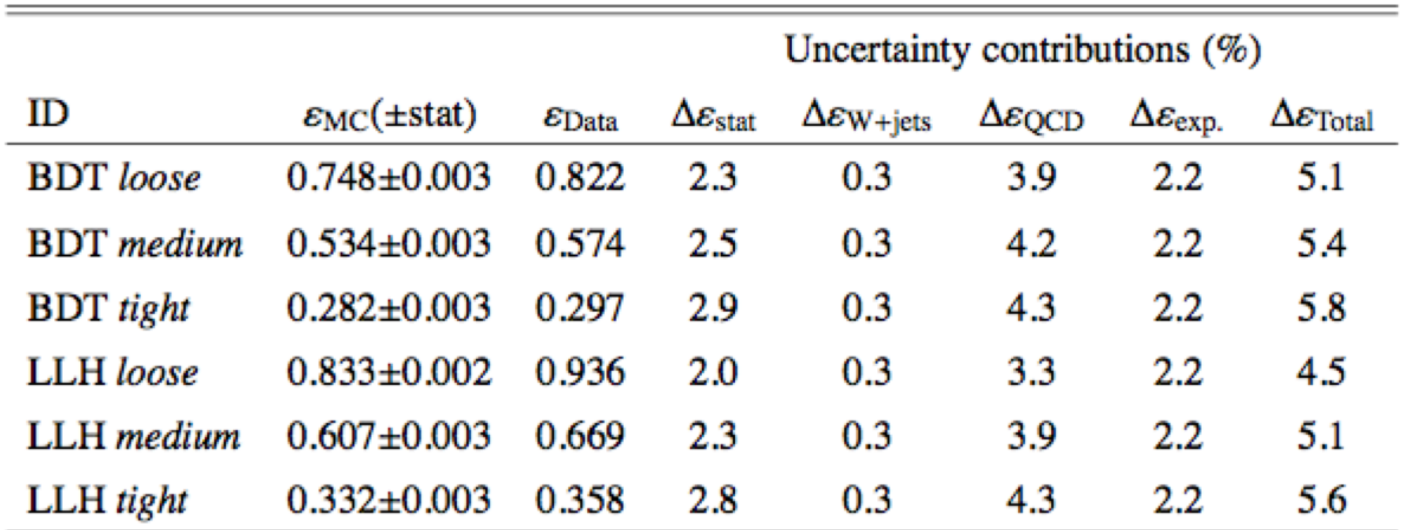
TauID Efficiency measurement





- Use well-known SM processes to test Data-MC agreement, using tag-probe
- $Z \rightarrow \tau_{had}\tau_{l}$ Use lepton to tag and tau to probe
- Good purity achieved

$$C^{\mathrm{id}}_{\mathrm{data/MC}} = \frac{\varepsilon^{\mathrm{id}}_{\mathrm{Data}}}{\varepsilon^{\mathrm{id}}_{\mathrm{MC}}}$$



			Uncertainty contributions (%)				
ID	$\varepsilon_{\mathrm{MC}}(\pm\mathrm{stat})$	$\varepsilon_{\mathrm{Data}}$	$\Delta\varepsilon_{\mathrm{stat}}$	$\Delta\varepsilon_{\mathrm{W+jets}}$	$\Delta\varepsilon_{\mathrm{QCD}}$	$\Delta\varepsilon_{\mathrm{exp.}}$	$\Delta\varepsilon_{\mathrm{Total}}$
BDT *loose*	0.748±0.003	0.822	2.3	0.3	3.9	2.2	5.1
BDT *medium*	0.534±0.003	0.574	2.5	0.3	4.2	2.2	5.4
BDT *tight*	0.282±0.003	0.297	2.9	0.3	4.3	2.2	5.8
LLH *loose*	0.833±0.002	0.936	2.0	0.3	3.3	2.2	4.5
LLH *medium*	0.607±0.003	0.669	2.3	0.3	3.9	2.2	5.1
LLH *tight*	0.332±0.003	0.358	2.8	0.3	4.3	2.2	5.6

Return

TES response

- $Z \rightarrow \tau\tau$, $W \rightarrow \tau\nu$, $Z' \rightarrow \tau\tau$
- At least 1 reco τ candidate
- $p_T > 10$ GeV, no jet $p_T > 15$ GeV within $\Delta R < 0.5$
- Tau's passing loose criteria

- TES accounts for energy contribution from pileup

$$E^\tau = \frac{E^\tau_{LC} - E_{pileup}}{\mathcal{R}(E^\tau_{LC}, |\eta^\tau_{reco}|, n_p)}.$$

- Response:

$$\mathcal{R} = \langle E^\tau_{LC} / E^{vis\text{-}\tau}_{truth} \rangle$$

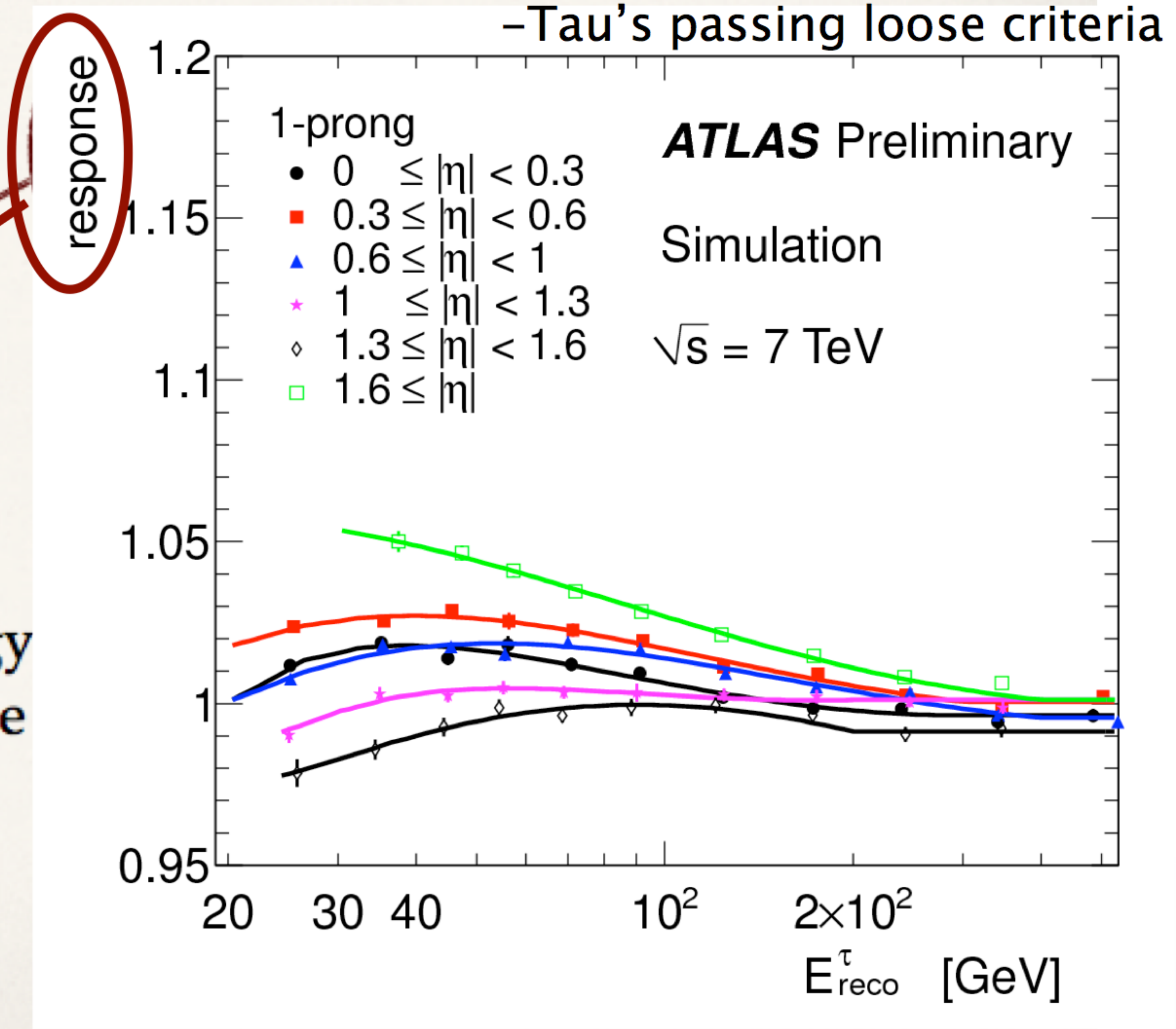
- E^τ = tau energy after TES

E^τ_{LC} = reconstructed tau energy

$E^{vis\text{-}\tau}_{truth}$ = generated tau visible energy

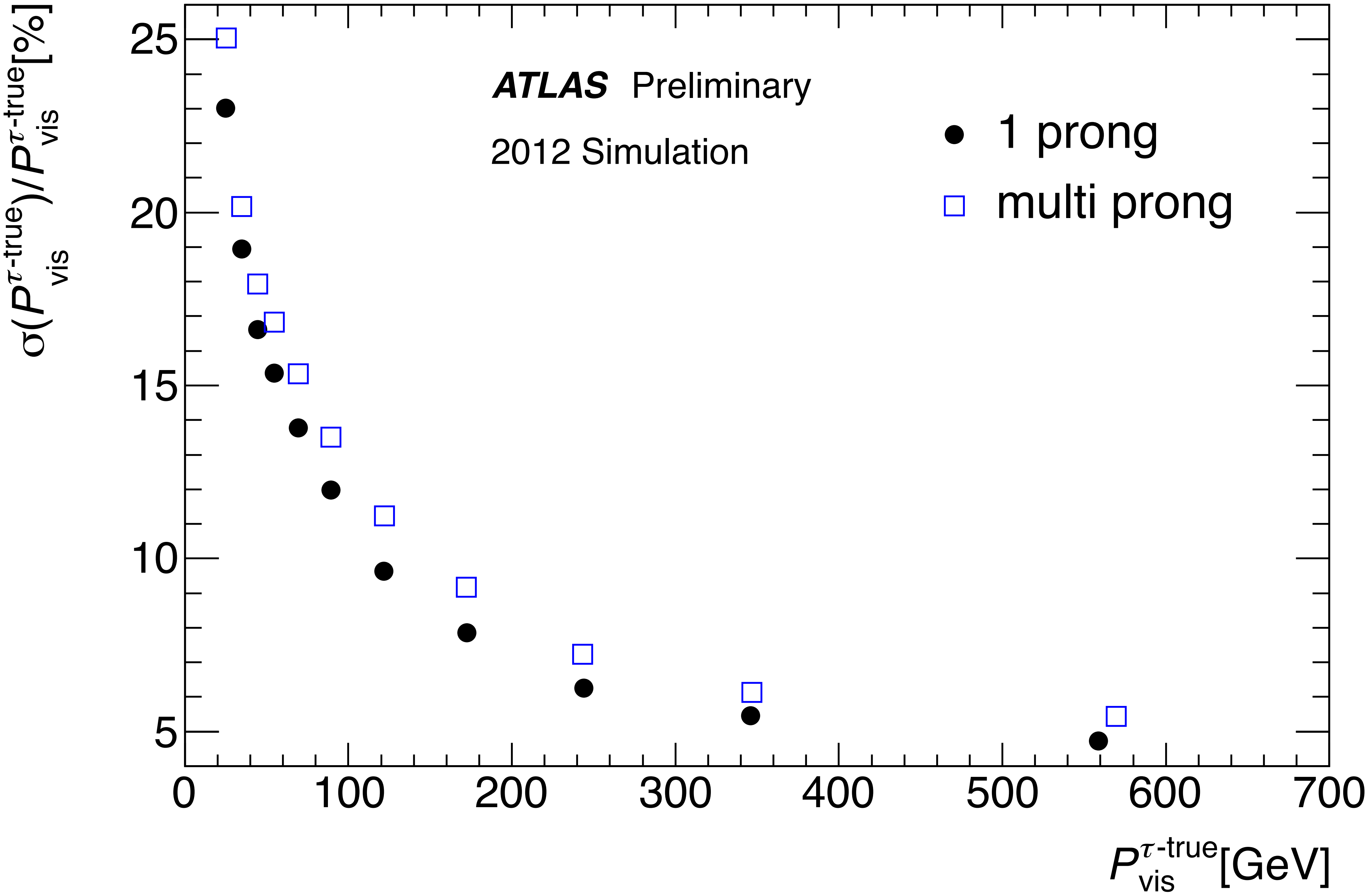
$|\eta^\tau_{reco}|$ = reconstructed pseudorapidity

n_p = number of prong



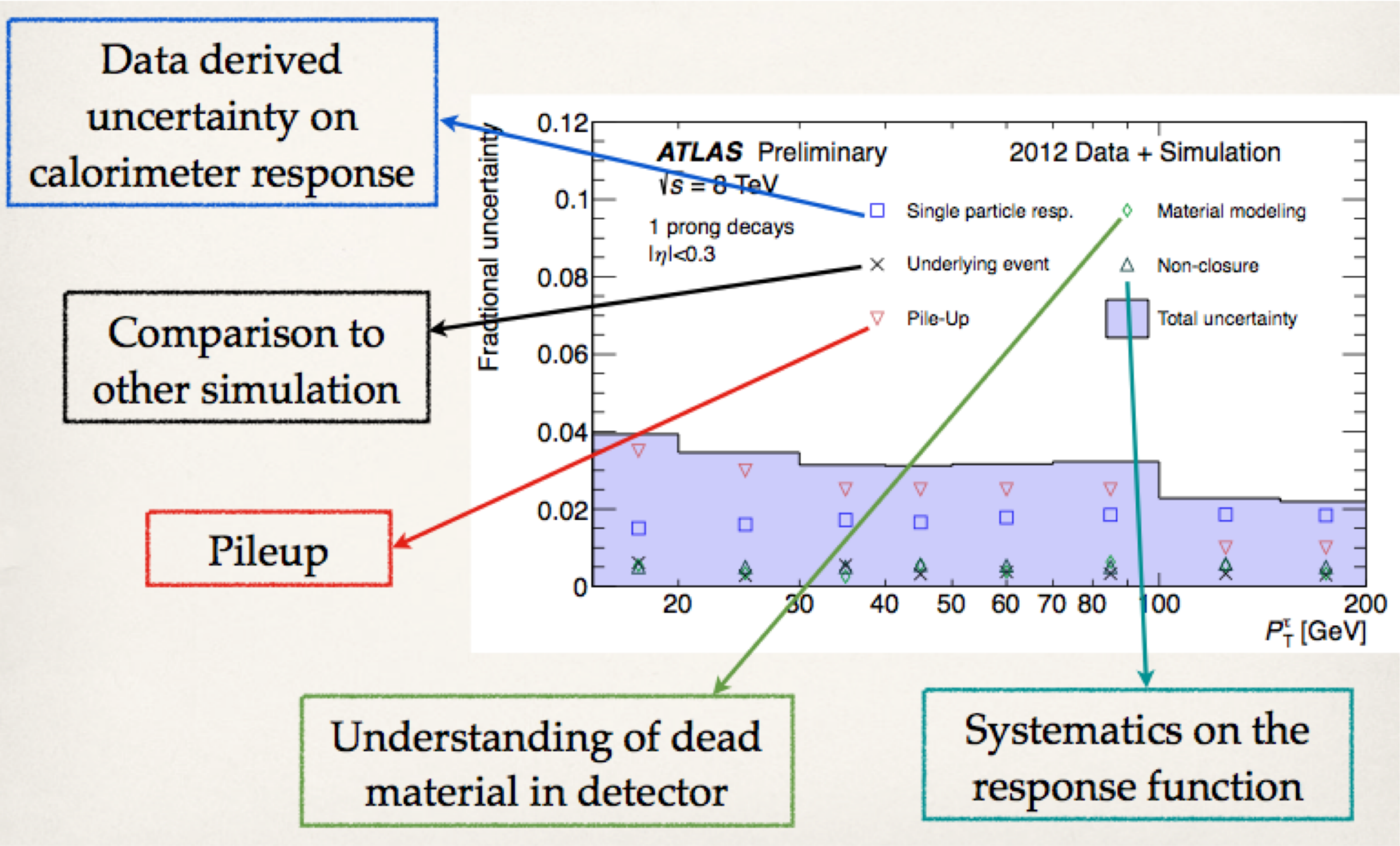
Return

Tau energy resolution



Return

TES systematics



Data derived uncertainty on calorimeter response

Comparison to other simulation

Pileup

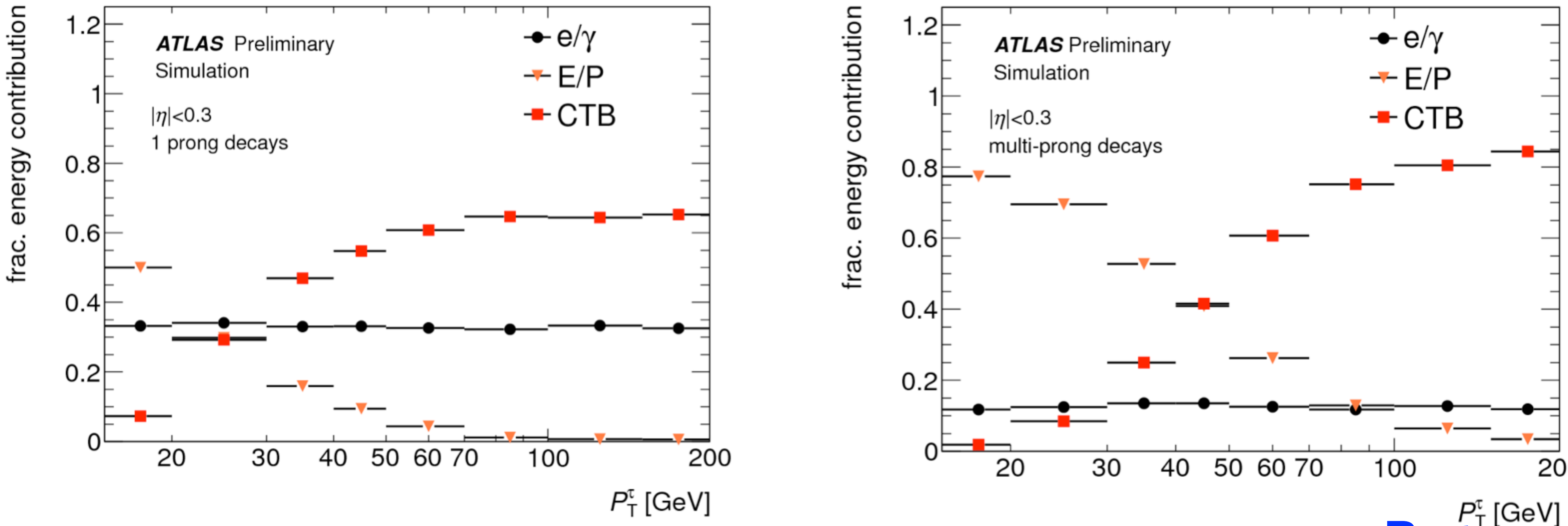
Understanding of dead material in detector

Systematics on the response function

Return

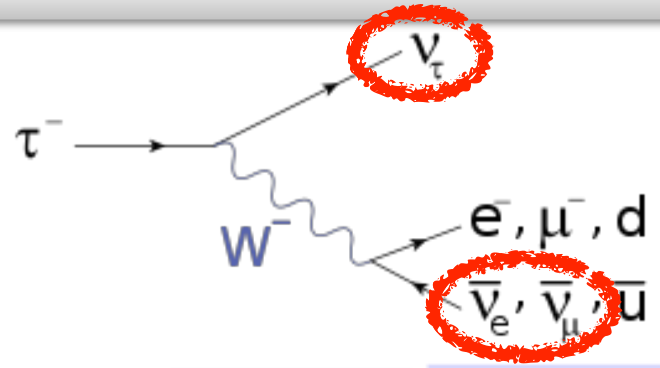
Single particle response

- Determine calorimeter response uncertainty using single particle response, by decomposing the the tau to its decay products and convolving the constituents' response with the tau particle composition
- The response of the calorimeter to single charged pions is derived from one of three sources depending on the particle kinematics
  - P<20GeV for |η|<1.7 and P<60GeV for 1.7<|η|<2.5: in-situ ⟨E/P⟩ measurements
  - High momentum in central region |η|<0.8, combined test beam
  - High momentum outside central region (|η|>0.8) use simulation

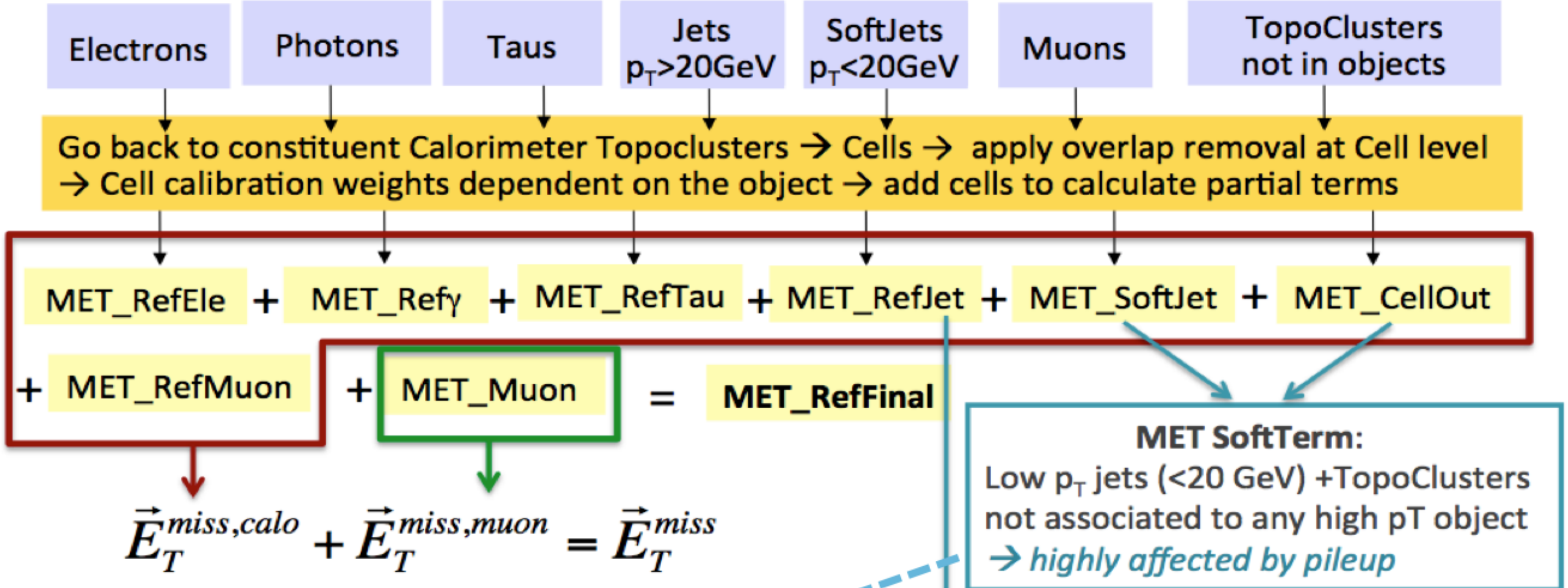


Return

E_T^{miss} reconstruction



- **Neutrinos** from tau decay⇒ Real E_T^{miss}
- $E_T^{miss} = -\Sigma E_T^{visible}$



Electrons | Photons | Taus | Jets p_T>20GeV | SoftJets p_T<20GeV | Muons | TopoClusters not in objects

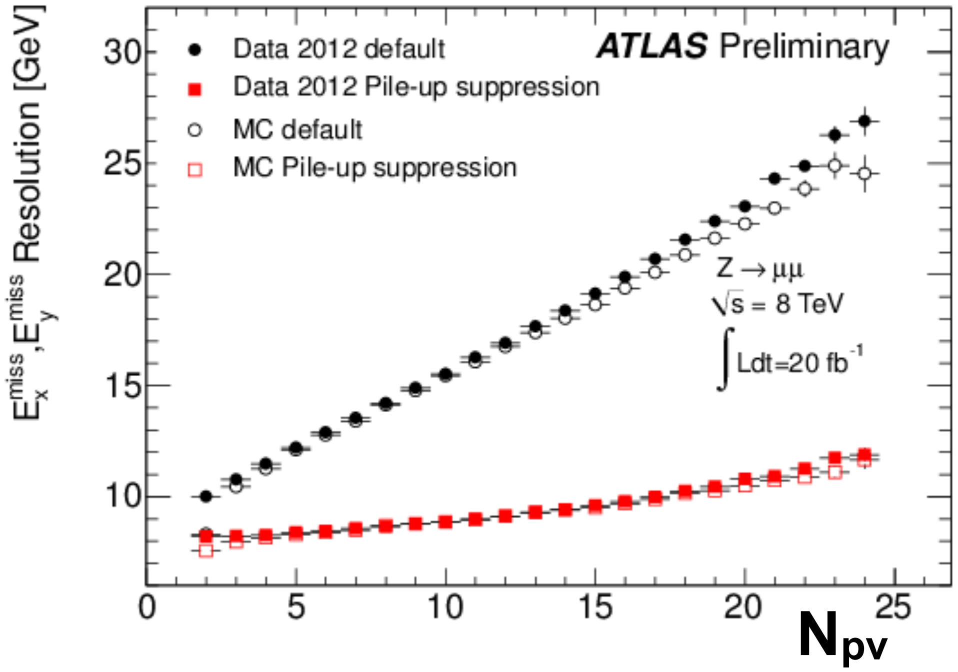
Go back to constituent Calorimeter Topoclusters → Cells → apply overlap removal at Cell level → Cell calibration weights dependent on the object → add cells to calculate partial terms

MET_RefEle + MET_Refγ + MET_RefTau + MET_RefJet + MET_SoftJet + MET_CellOut + MET_RefMuon + MET_Muon = **MET_RefFinal**

$$\vec{E}_T^{miss,calo} + \vec{E}_T^{miss,muon} = \vec{E}_T^{miss}$$

MET SoftTerm:
Low p_T jets (<20 GeV) +TopoClusters not associated to any high pT object
→ *highly affected by pileup*

→ *highly affected by pileup*



Pile-up suppression using tracks

- STVF, JVF: $\sum_{track,PV} p_T / \sum_{track} p_T$

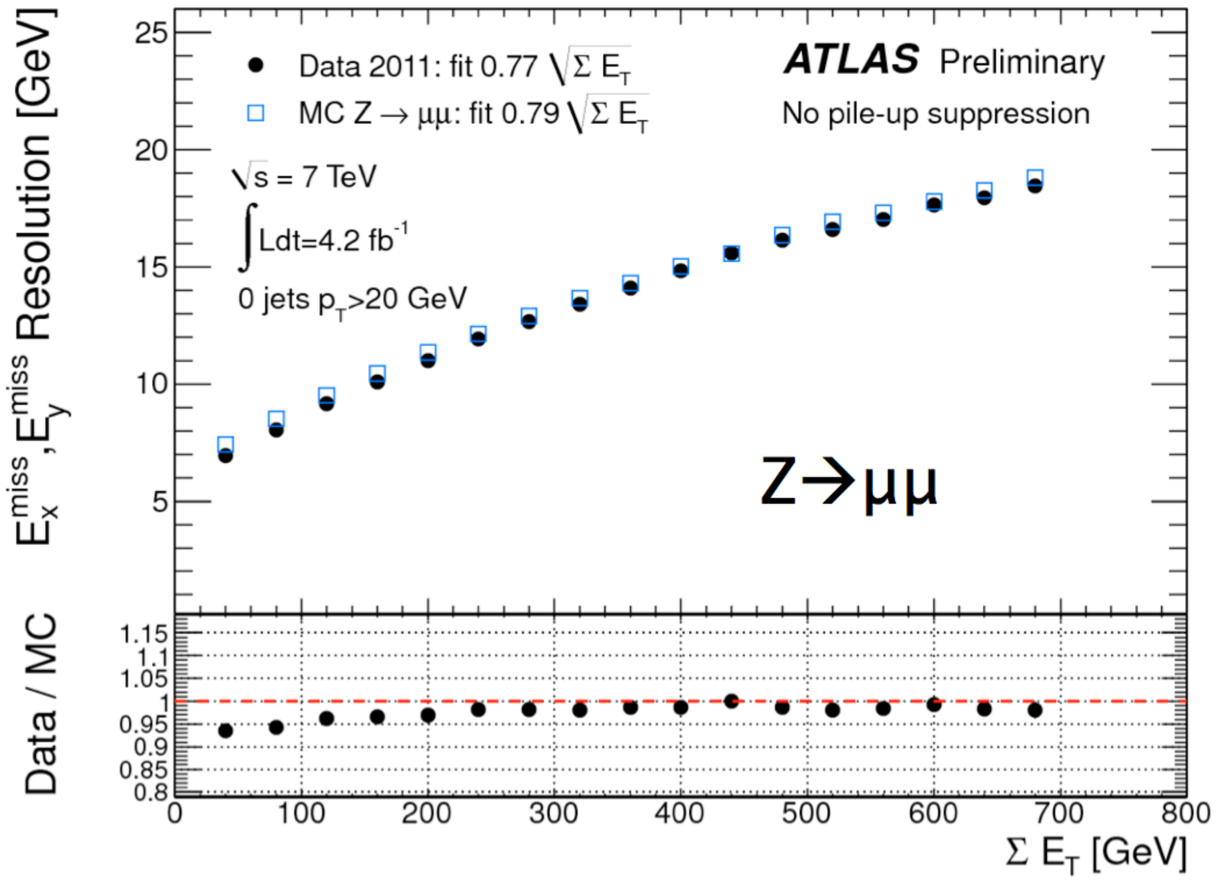
*For **clusters/jets** with associated tracks within tracker coverage $|\eta|<2.5$:*

➡ Soft term: (STVF)× $E_T^{miss,SoftTerm}$
➡ Jet term: (JVF)× $E_T^{miss,JetTerm}$

Return

E_T^{miss} systematics

- Uncertainties on the scale and resolution of objects (leptons/taus/jets need are propagated to the MET
- Soft term uncertainty is evaluated separately



- Mean Data/MC discrepancy as the systematic uncertainty
- 5% in MET scale and 2% in MET resolution, treated uncorrelated (conservative approach)
- Data/MC ratios have weak dependence on pile-up
- Pile-up affects resolution but well described in MC

Return

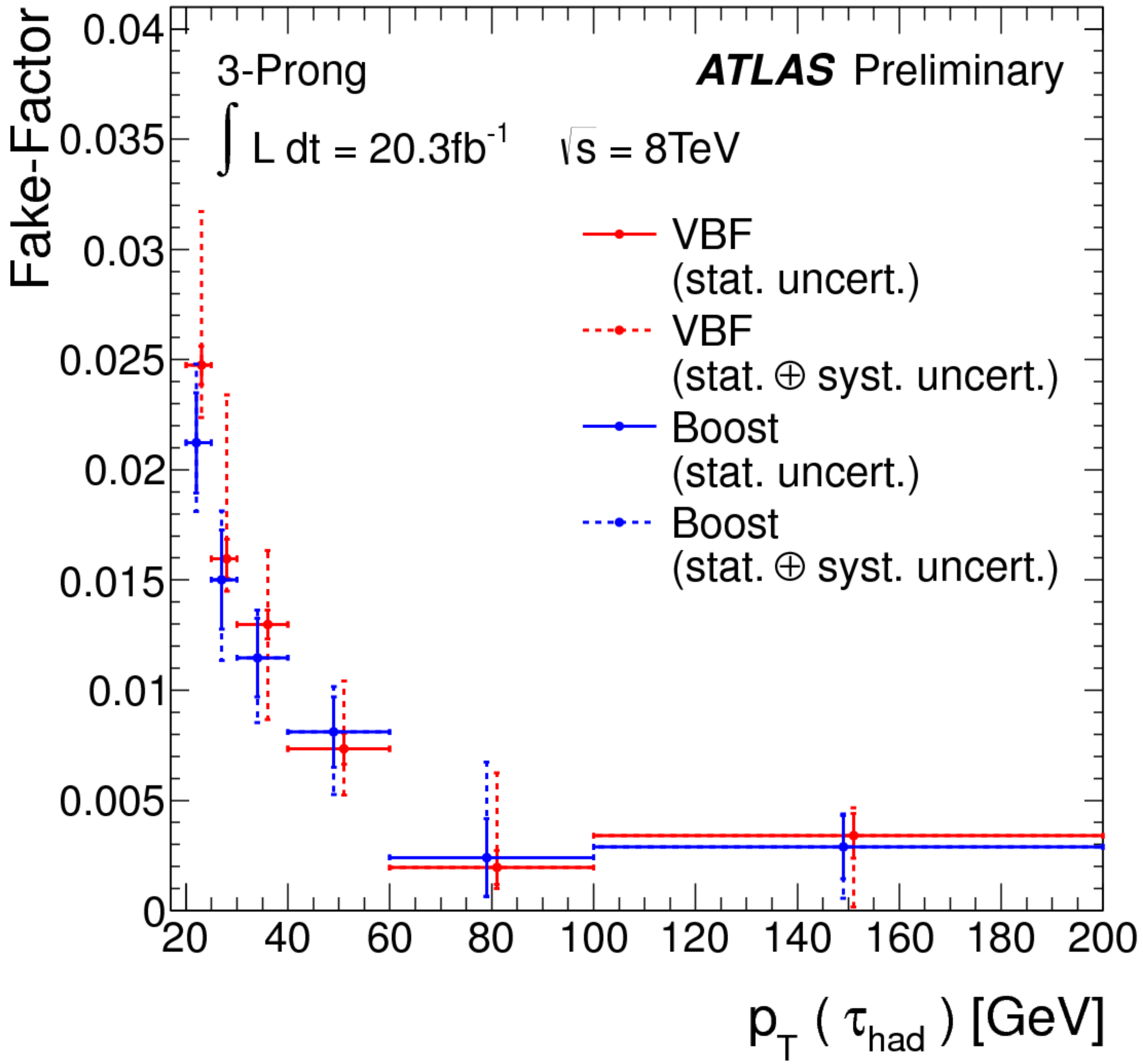
Fake Factor method

- Tight selection: not enough events left to estimate background
- $Z \to \tau\tau$, $Z \to ll$
  - Using MC Alpgen VBF-filtered samples: certain VBF jet cuts applied in generator level
    - $|\Delta\eta_{jj}|$ re-weighted to correct differences between data and MC
- W, QCD, top
  - Using fake factor (FF) method: $N^{Est.}_{Bkg.} = N_{\text{anti}-\tau} \times FF \; , \; FF = \frac{N_{\text{identified}-\tau}}{N_{\text{anti}-\tau}}$
  - $N_{\text{anti}-\tau}$ in a CR similar to VBF, with the τ-candidate failing tau-id
  - FF separated into FF_{QCD} and FF_W for gluon-rich and quark-rich samples
    - FF_W measured in W control region $m_T > 70$ TeV
    - FF_{QCD} measured in CR with loose leptons

Return

Fake Factor method

- Tight selection: not enough events left to estimate background
- Z
  - es: certain VBF jet cuts
  - es between data and MC
- W
  - $N_{\text{anti}-\tau} \times FF$, $FF = \frac{N_{\text{identified}-\tau}}{N_{\text{anti}-\tau}}$
  - τ–candidate failing tau–id
  - luon–rich and quark–rich
  - 70 TeV
  - ns

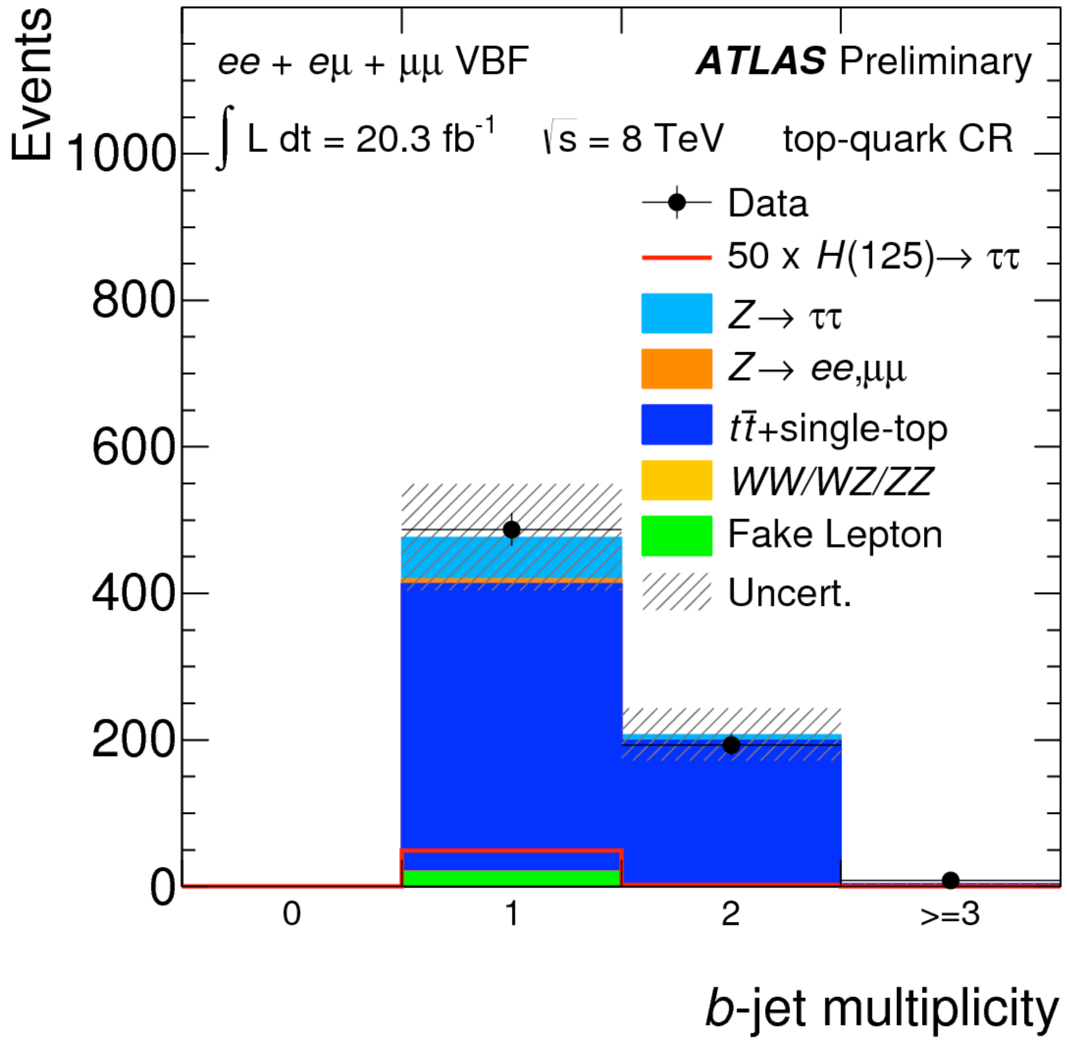


Return

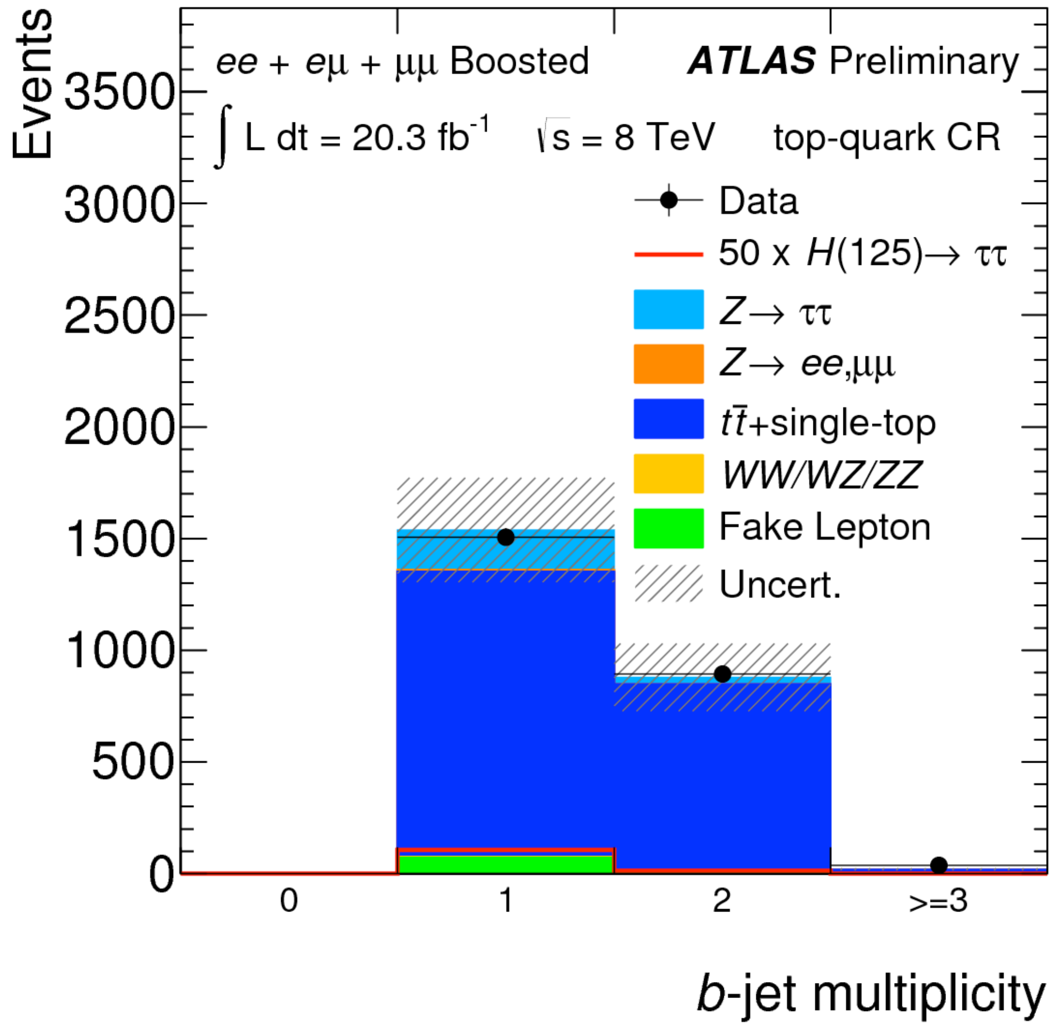
Top background

- Shape from simulation
- Normalisation from data control region
  - ✦ Done separately for Boosted and VBF categories

VBF



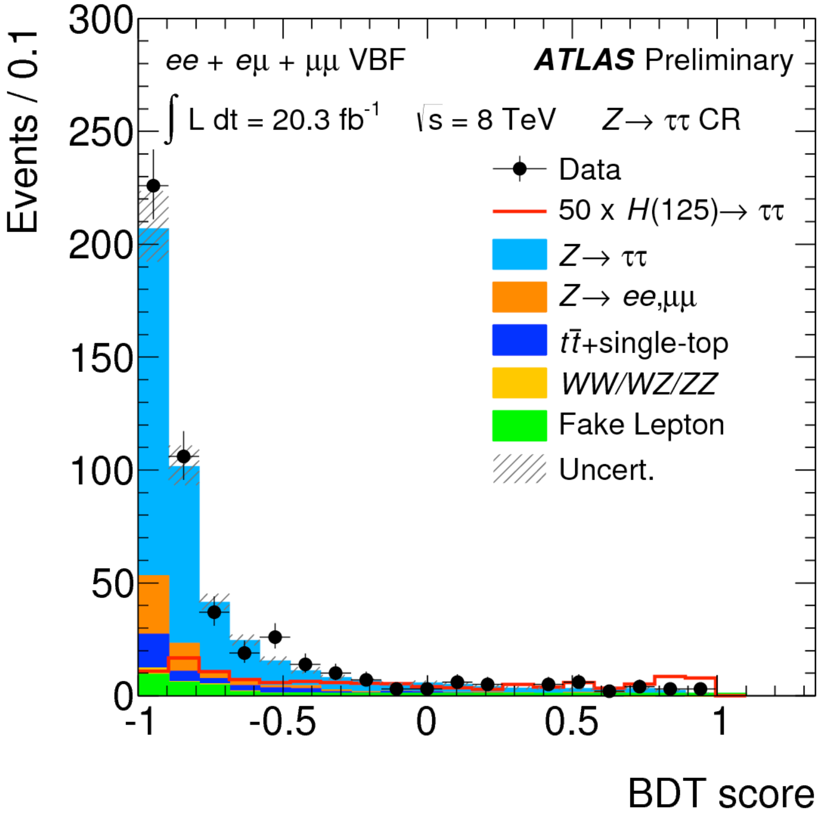
Boosted

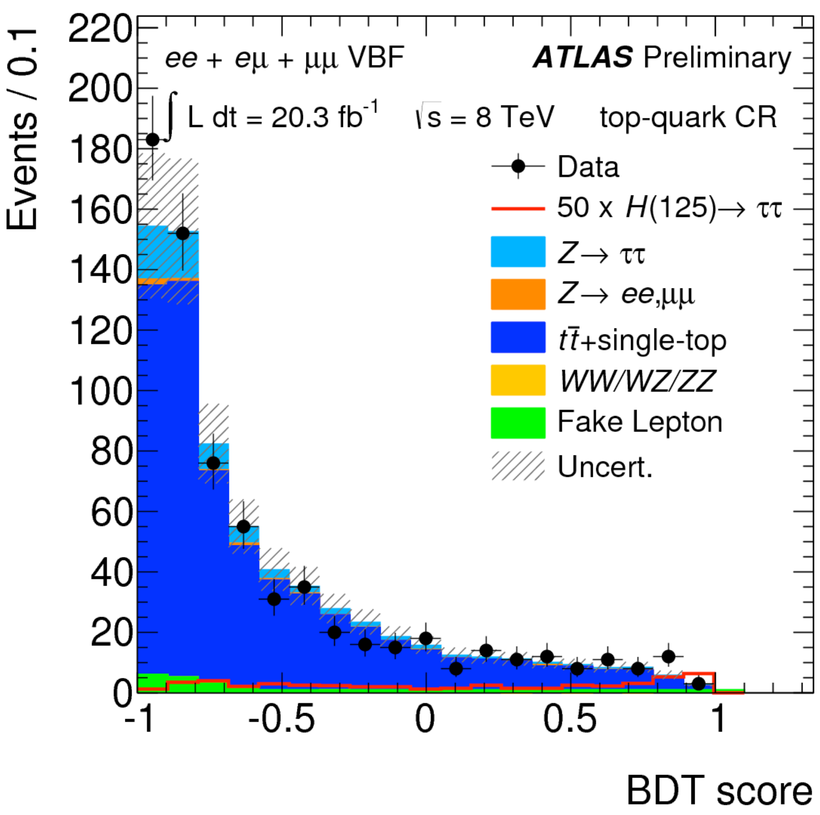


Return

LepLep Control Regions

- $Z \rightarrow \ell\ell$**-enriched**: for same-flavour events, the $m_{\tau\tau}^{\text{vis}}$ selection is changed to 80 GeV $< m_{\tau\tau}^{\text{vis}} <$ 100 GeV.
- $Z \rightarrow \tau\tau$**-enriched**: $m_{\tau\tau}^{\text{HPTO}} <$ 100 GeV, where $m_{\tau\tau}^{\text{HPTO}}$ is the invariant mass, obtained using the collinear approximation, calculated only with high p_{T} objects.
- $t\bar{t}$ **-enriched**: invert b–jet veto.
- **Fake-enriched**: same sign lepton events.
- **Low BDT score**.

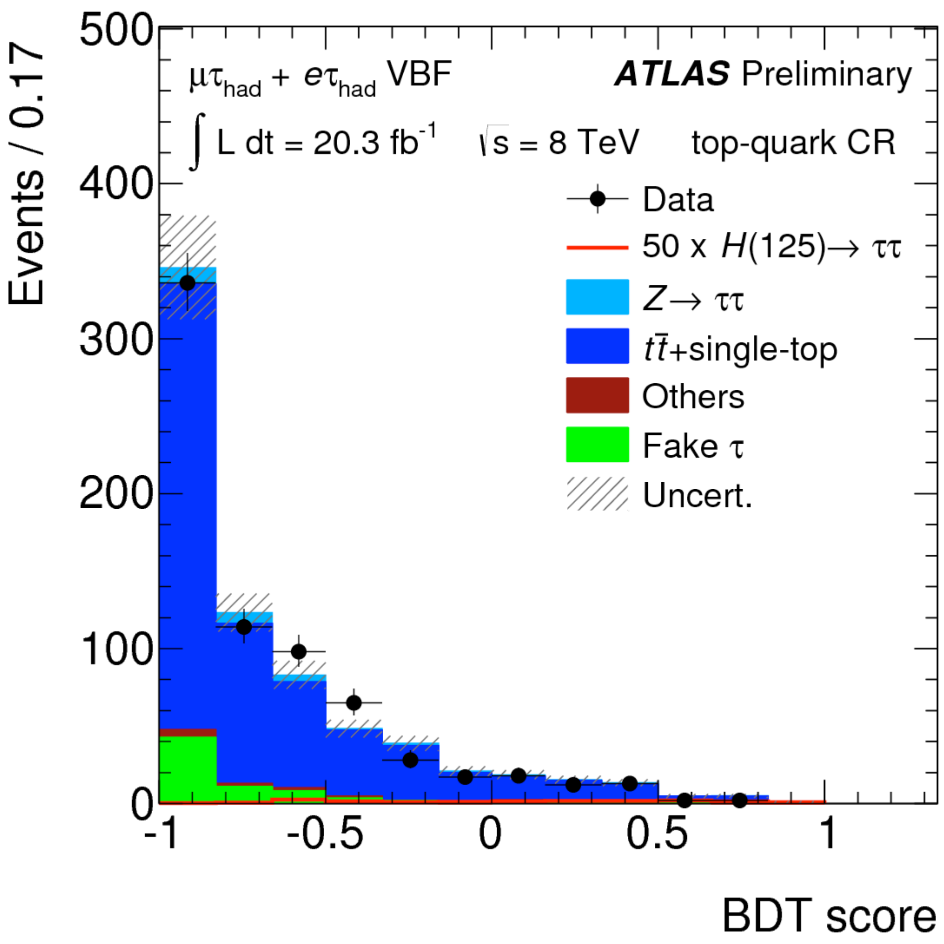


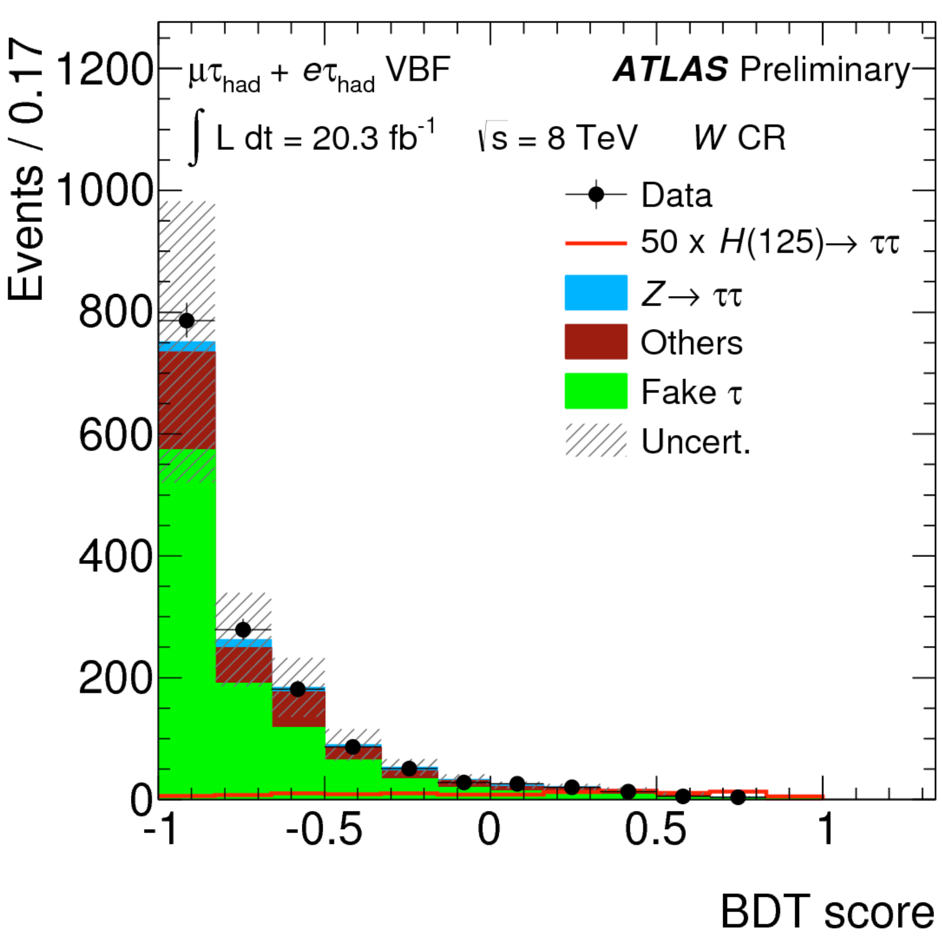


Return

LepHad Control Regions

- **$Z \rightarrow \tau\tau$-enriched**: $m_T < 40$ GeV and $m_{\tau\tau}^{\text{MMC}} < 110$ GeV.
- **W-enriched**: $m_T > 70$ GeV.
- **$t\bar{t}$ -enriched**: invert b-jet veto and $m_T > 50$ GeV.
- **Low BDT score**.

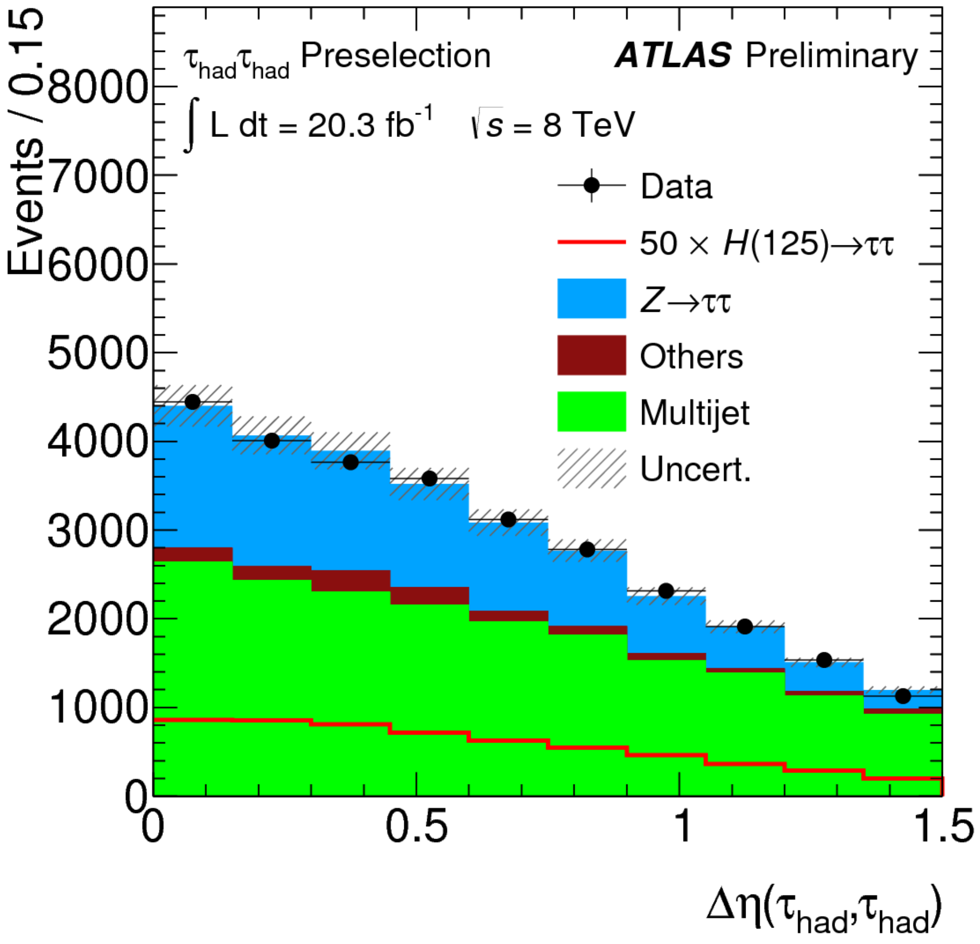


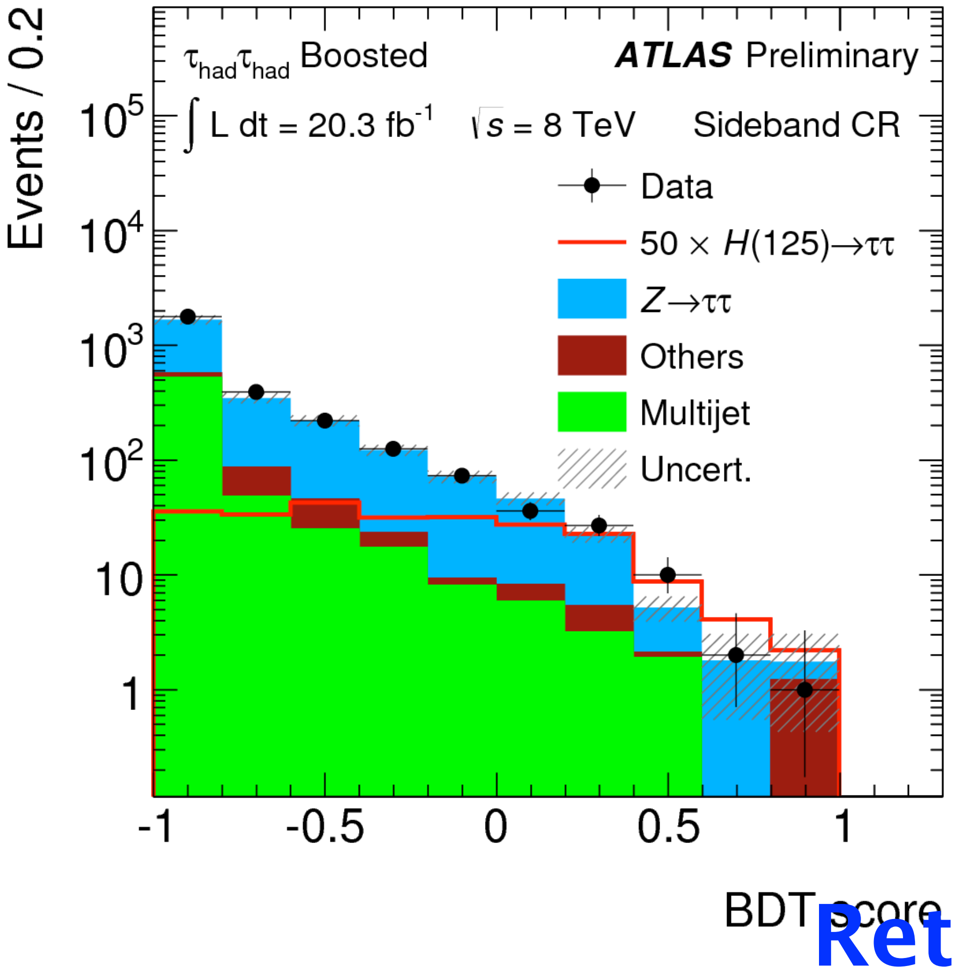


Return

HadHad Control Regions

- **Mass sideband**: $m_{\tau\tau}^{\text{MMC}} < 100\,$ GeV or $m_{\tau\tau}^{\text{MMC}} > 140\,$ GeV.
- **Multijet-enriched**: inverted signal region $\Delta\eta$ selection: $\Delta\eta(\tau_{\text{had}}, \tau_{\text{had}}) > 1.5$.
- **Rest category**: events that pass preselection but fail the VBF and boosted category selections. This region is used in the global likelihood fit to determine the $Z \to \tau^+\tau^-$ and the multijet background normalizations.
- **Low BDT score**.





Return

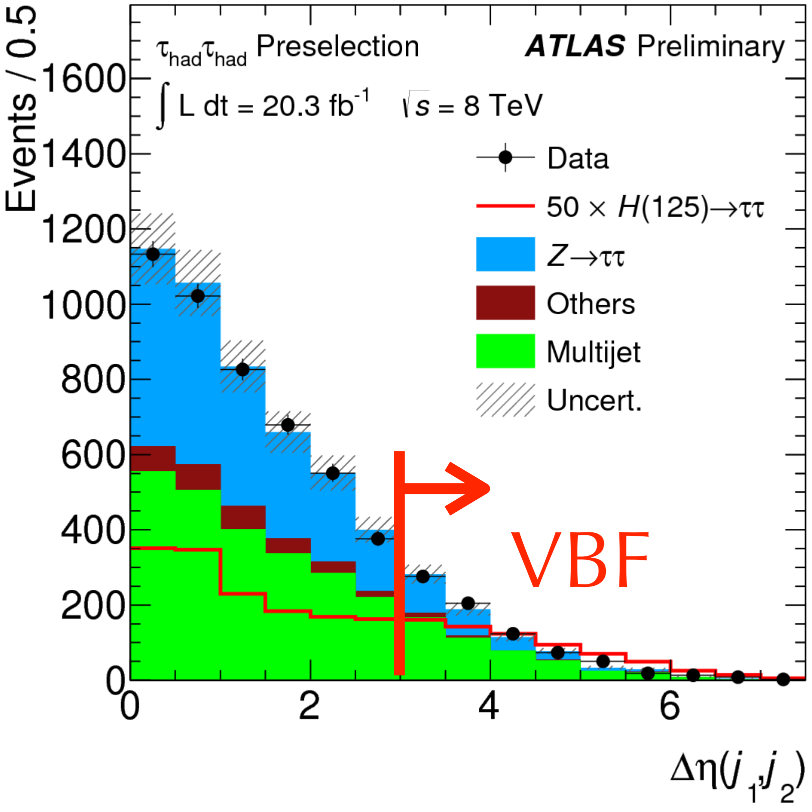
Analysis cross-checks

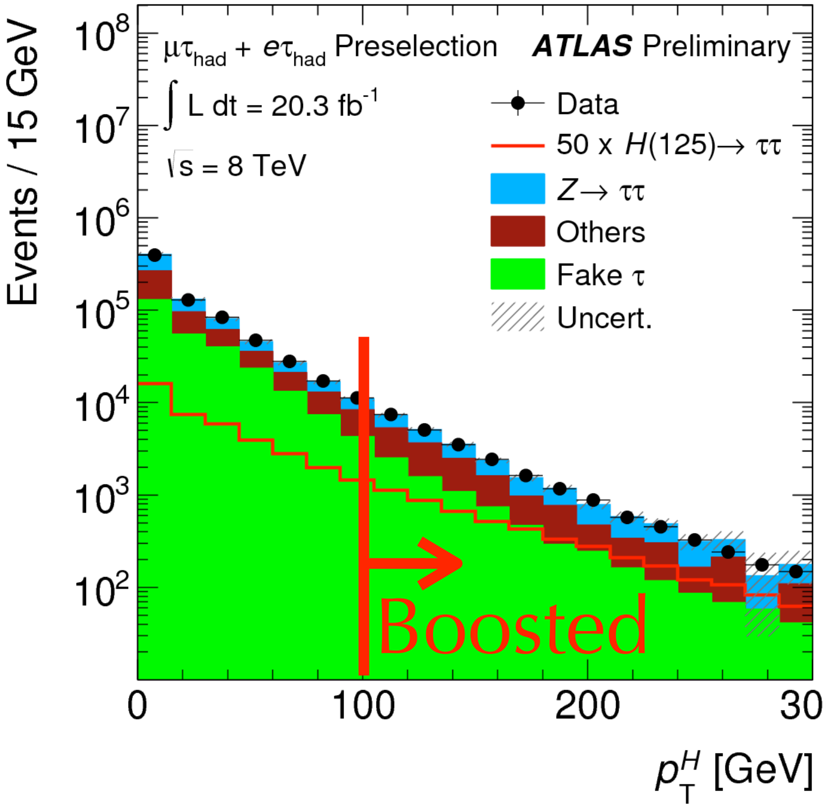
- Rigorous checks of background model and fitting technique
  - ✓ Check modeling of all input variables
  - ✓ Check modeling of correlation between each pair of input variables: $\langle V_i \rangle$ vs V_j
  - ✓ Dedicated control regions (CR) for all major backgrounds
    - **$Z \rightarrow ee/\mu\mu$ + jets CR** in lep-lep & lep-had
    - **Top CR** in lep-lep & lep-had
    - **W+jets CR** in lep-had
    - **"Fakes"-enriched CR** in lep-lep
    - **QCD-enriched CR** in had-had
  - ✓ Perform fit in mass sidebands (outside 100-140 GeV window)
    - Check of $Z \rightarrow \tau\tau$ background and overall background model
  - ✓ Study each constrained or pulled fit nuisance parameter

Return

Analysis Categorisation

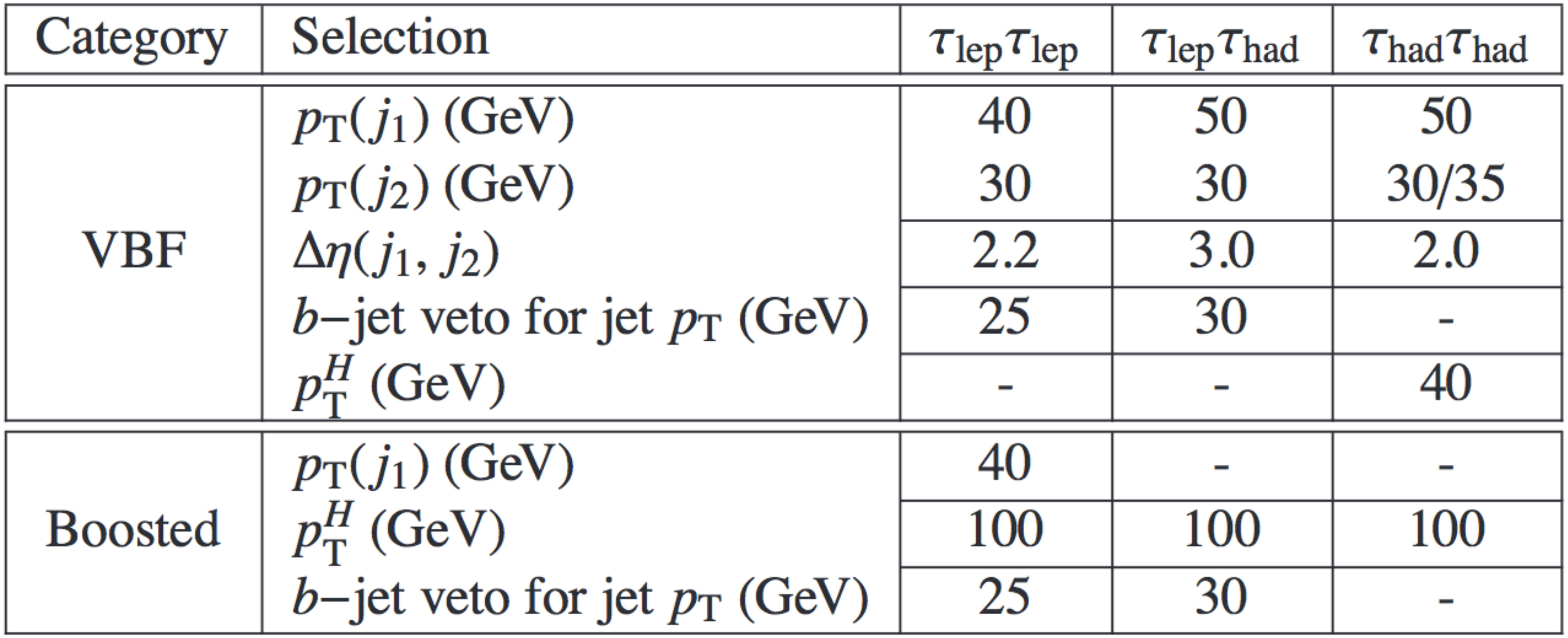
- Separate the clearly distinct signal topologies
  - ✦ Isolate production mechanisms
  - ✦ Use variables that are relevant to each mechanism
- Analysis is performed in **2 categories**
  - ✦ **VBF**: 2 jets with leading(sub-leading) p_T>50(30) GeV, Δη(jj)>3
    - ❖ VBF signal fraction ~60%
  - ✦ **Boosted**: $p_T(H)$>100 GeV , $p_T(H)=\vec{E}_T^{miss} + \vec{\tau_1} + \vec{\tau_2}$
    - ❖ Dominated by gg-fusion (~70%)





Return

Jet related cuts to define categories



Category	Selection	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$
VBF	$p_{\rm T}(j_1)$ (GeV)	40	50	50
	$p_{\rm T}(j_2)$ (GeV)	30	30	30/35
	$\Delta\eta(j_1, j_2)$	2.2	3.0	2.0
	b–jet veto for jet $p_{\rm T}$ (GeV)	25	30	-
	$p_{\rm T}^{H}$ (GeV)	-	-	40
Boosted	$p_{\rm T}(j_1)$ (GeV)	40	-	-
	$p_{\rm T}^{H}$ (GeV)	100	100	100
	b–jet veto for jet $p_{\rm T}$ (GeV)	25	30	-

Return

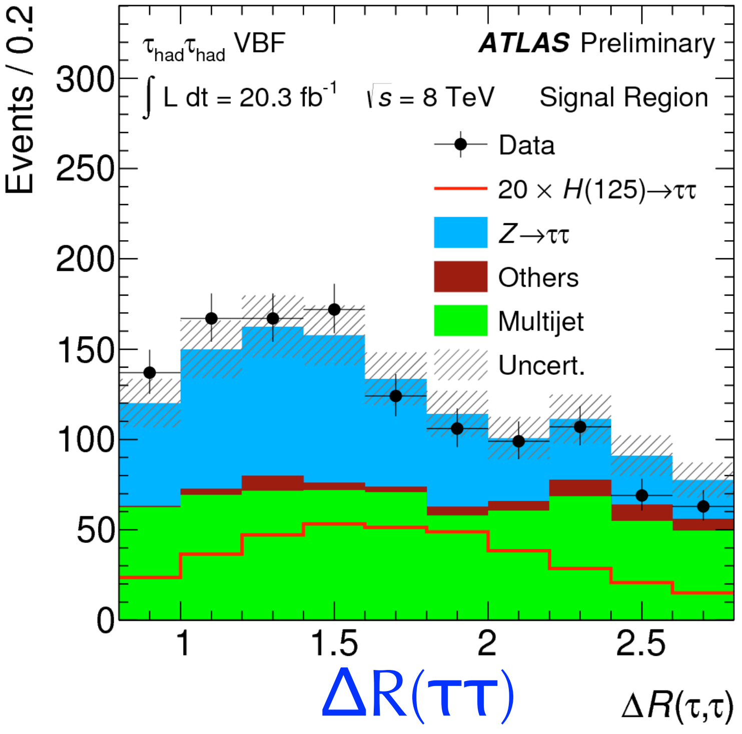
How we use BDT's

- We train separate BDTs in each channel and category (see following pages).
- The BDT is trained against a mix of all backgrounds in nature's proportions. Signal is VBF-only in the VBF category and a mix elsewhere.
- Training is performed on each half of the events and applied to the other half (cross-evaluation) such that all events appear in the final plots.
- The BDT score is used as the final discriminant in the fit model.

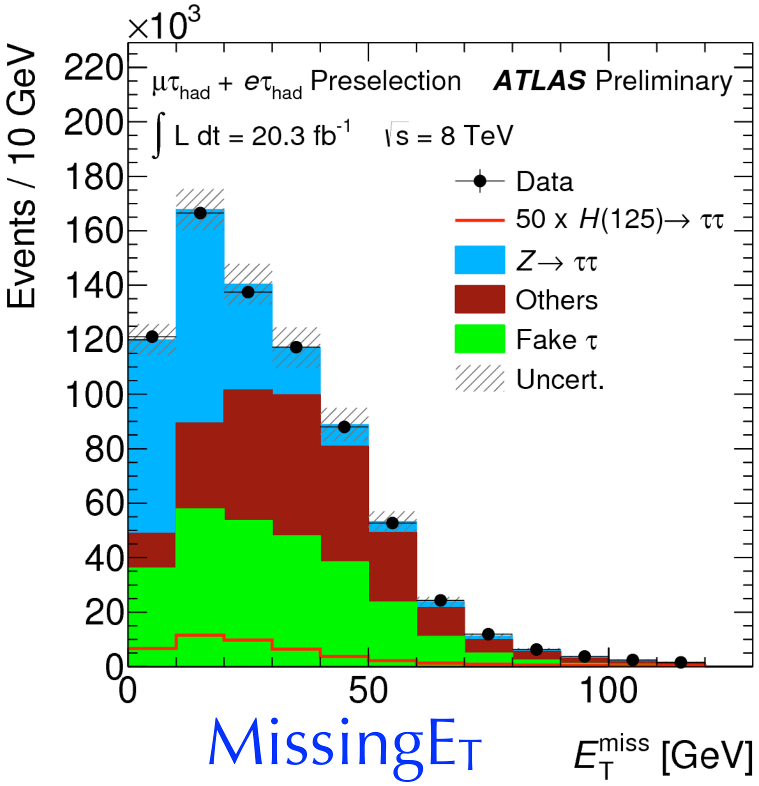
Return

Input variables to BDT

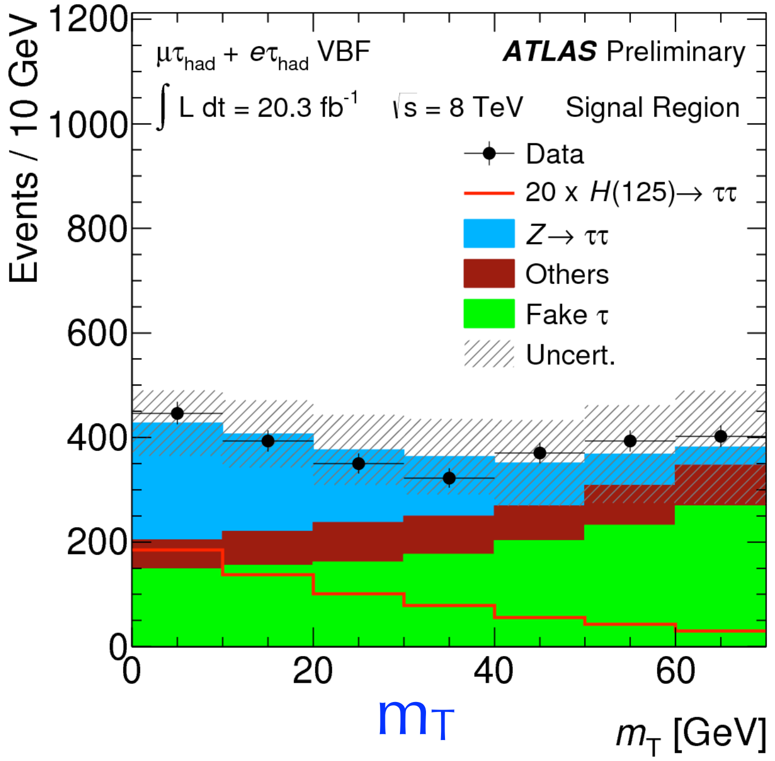
- Probe resonance properties
  - **$m_{MMC}(\tau\tau)$, $\Delta R(\tau\tau)$**
- Explore event topology
  - **E_T^{miss}**, **m_T**, object **centralities**, high **p_T** objects **sum**
- VBF specific, for the 2 VBF jets:
  - Different hemispheres **$\eta_{j1}\times\eta_{j2}$**
  - Separation **$|\eta_{j1}-\eta_{j2}|$**
  - Invariant mass **m_{j1j2}**



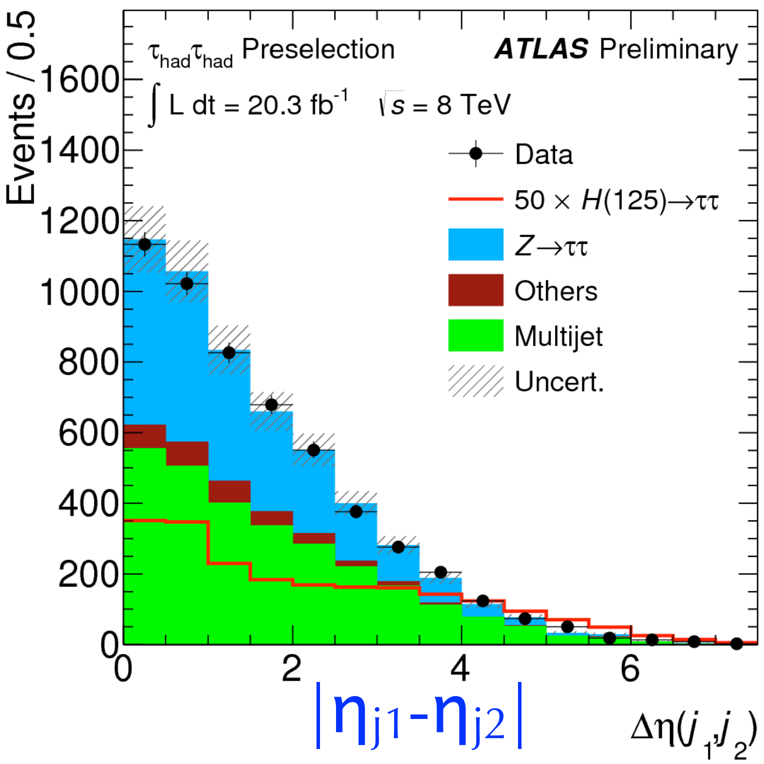
$\Delta R(\tau\tau)$



MissingE_T



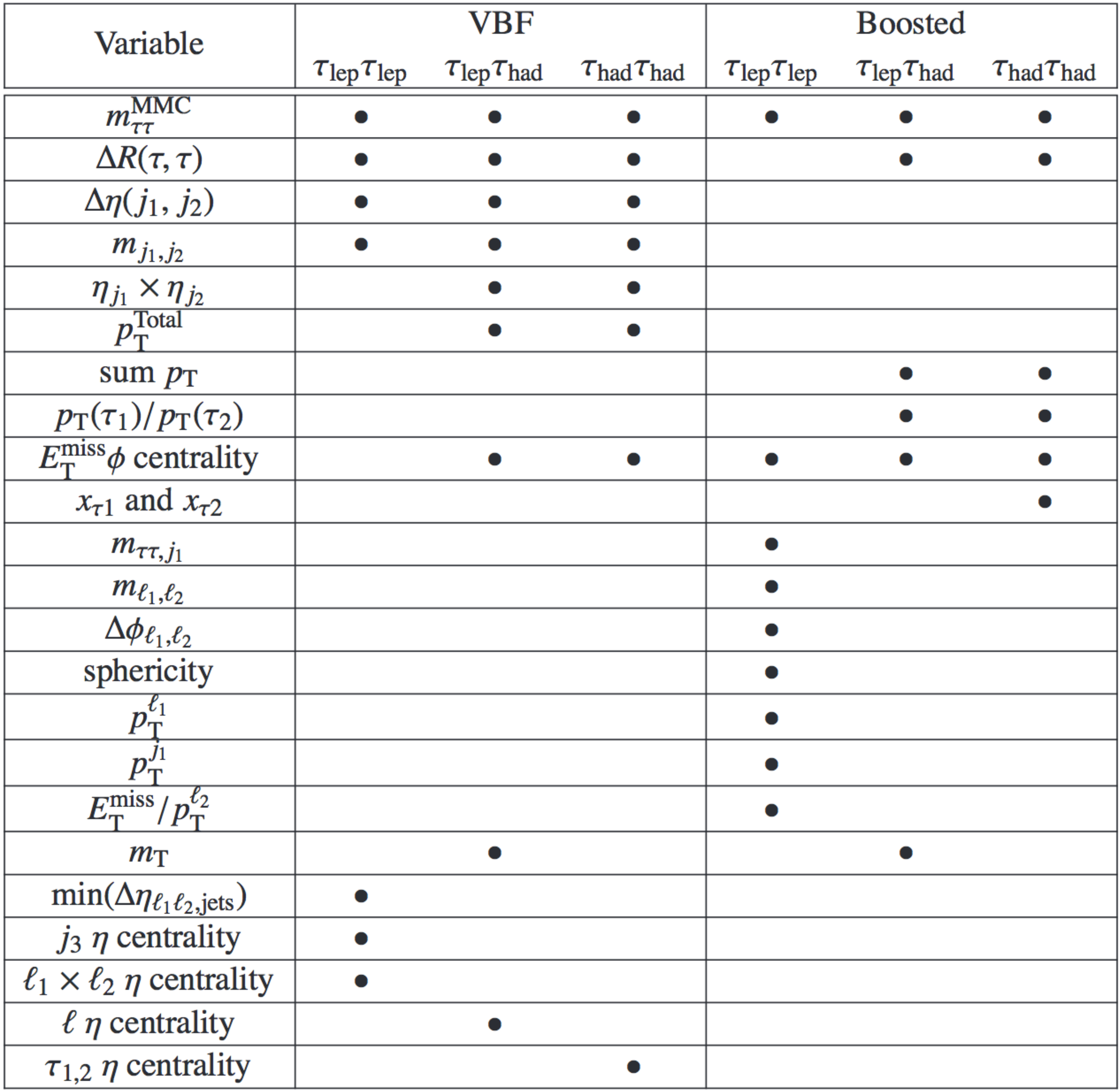
m_T



$|\eta_{j1}-\eta_{j2}|$

Return

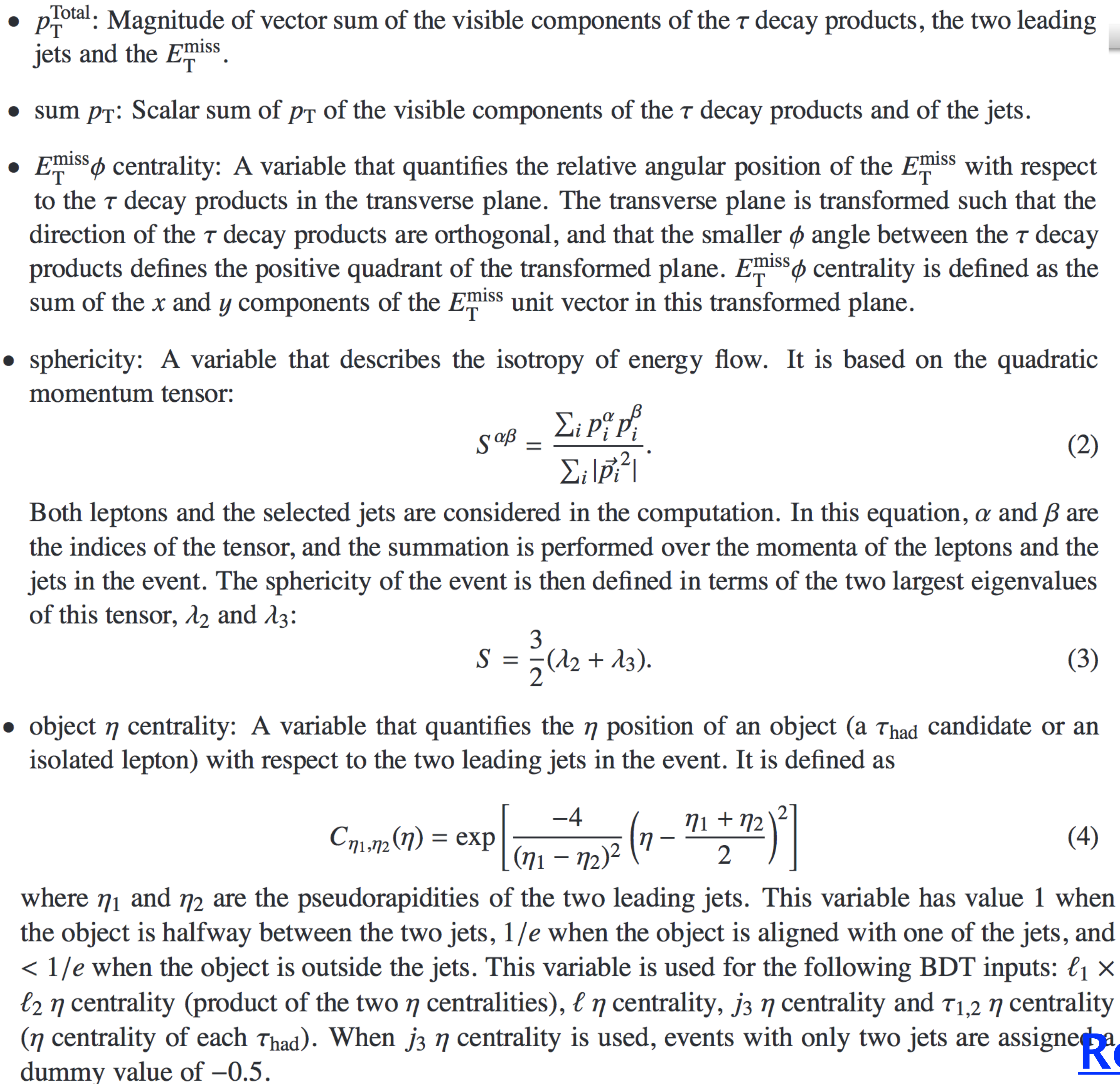
Input variables to BDT



Variable	VBF			Boosted		
	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$m_{\tau\tau}^{\text{MMC}}$	●	●	●	●	●	●
$\Delta R(\tau, \tau)$	●	●	●		●	●
$\Delta\eta(j_1, j_2)$	●	●	●			
m_{j_1,j_2}	●	●	●			
$\eta_{j_1} \times \eta_{j_2}$		●	●			
$p_{\text{T}}^{\text{Total}}$		●	●			
sum p_{T}					●	●
$p_{\text{T}}(\tau_1)/p_{\text{T}}(\tau_2)$					●	●
$E_{\text{T}}^{\text{miss}}\phi$ centrality		●	●	●	●	●
$x_{\tau 1}$ and $x_{\tau 2}$						●
$m_{\tau\tau,j_1}$				●		
m_{ℓ_1,ℓ_2}				●		
$\Delta\phi_{\ell_1,\ell_2}$				●		
sphericity				●		
$p_{\text{T}}^{\ell_1}$				●		
$p_{\text{T}}^{j_1}$				●		
$E_{\text{T}}^{\text{miss}}/p_{\text{T}}^{\ell_2}$				●		
m_{T}		●			●	
$\min(\Delta\eta_{\ell_1\ell_2,\text{jets}})$	●					
j_3 η centrality	●					
$\ell_1 \times \ell_2$ η centrality	●					
ℓ η centrality		●				
$\tau_{1,2}$ η centrality			●			

Return

Variables definition



- $p_{\mathrm{T}}^{\mathrm{Total}}$: Magnitude of vector sum of the visible components of the τ decay products, the two leading jets and the $E_{\mathrm{T}}^{\mathrm{miss}}$.

- sum p_{T}: Scalar sum of p_{T} of the visible components of the τ decay products and of the jets.

- $E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality: A variable that quantifies the relative angular position of the $E_{\mathrm{T}}^{\mathrm{miss}}$ with respect to the τ decay products in the transverse plane. The transverse plane is transformed such that the direction of the τ decay products are orthogonal, and that the smaller ϕ angle between the τ decay products defines the positive quadrant of the transformed plane. $E_{\mathrm{T}}^{\mathrm{miss}}\phi$ 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 energy flow. It is based on the quadratic momentum tensor:

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

  Both leptons and the selected jets are considered in the computation. In this equation, α and β are the indices of the tensor, and the summation is performed over the momenta of the leptons and the jets in the event. The sphericity of the event is then defined in terms of the two largest eigenvalues of this tensor, λ_2 and λ_3:

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

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

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

where η_1 and η_2 are the pseudorapidities of the two leading jets. This variable has value 1 when the object is halfway between the two jets, $1/e$ when the object is aligned with one of the jets, and $< 1/e$ when the object is outside the jets. This variable is used for the following BDT inputs: $\ell_1 \times \ell_2$ η centrality (product of the two η centralities), ℓ η centrality, j_3 η centrality and $\tau_{1,2}$ η centrality (η centrality of each τ_{had}). When j_3 η centrality is used, events with only two jets are assigned a dummy value of -0.5.

Return

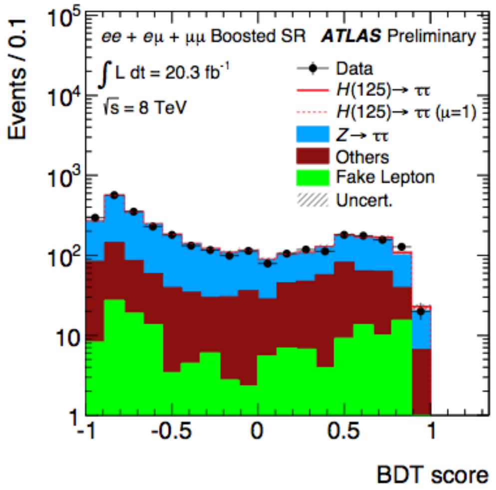
Fit model

Lep-lep & Lep-had channels

Signal region (BDT shape)

Z→*ll* CR (1 bin)

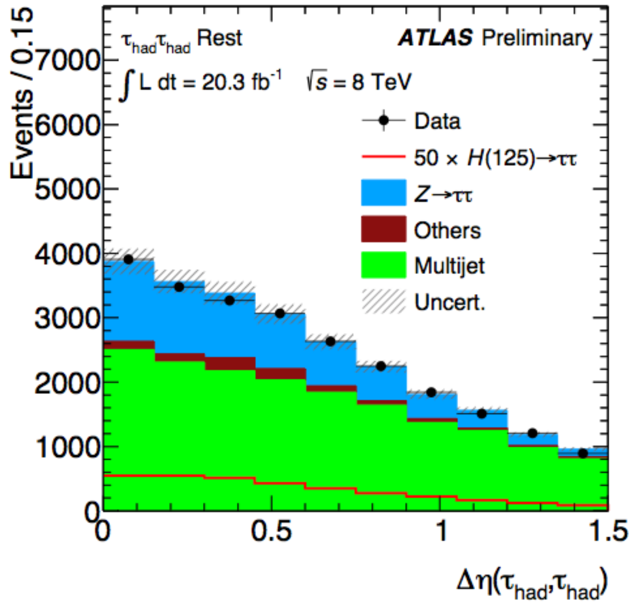
Top CR (1 bin)



Had-had channels

Signal region (BDT shape)

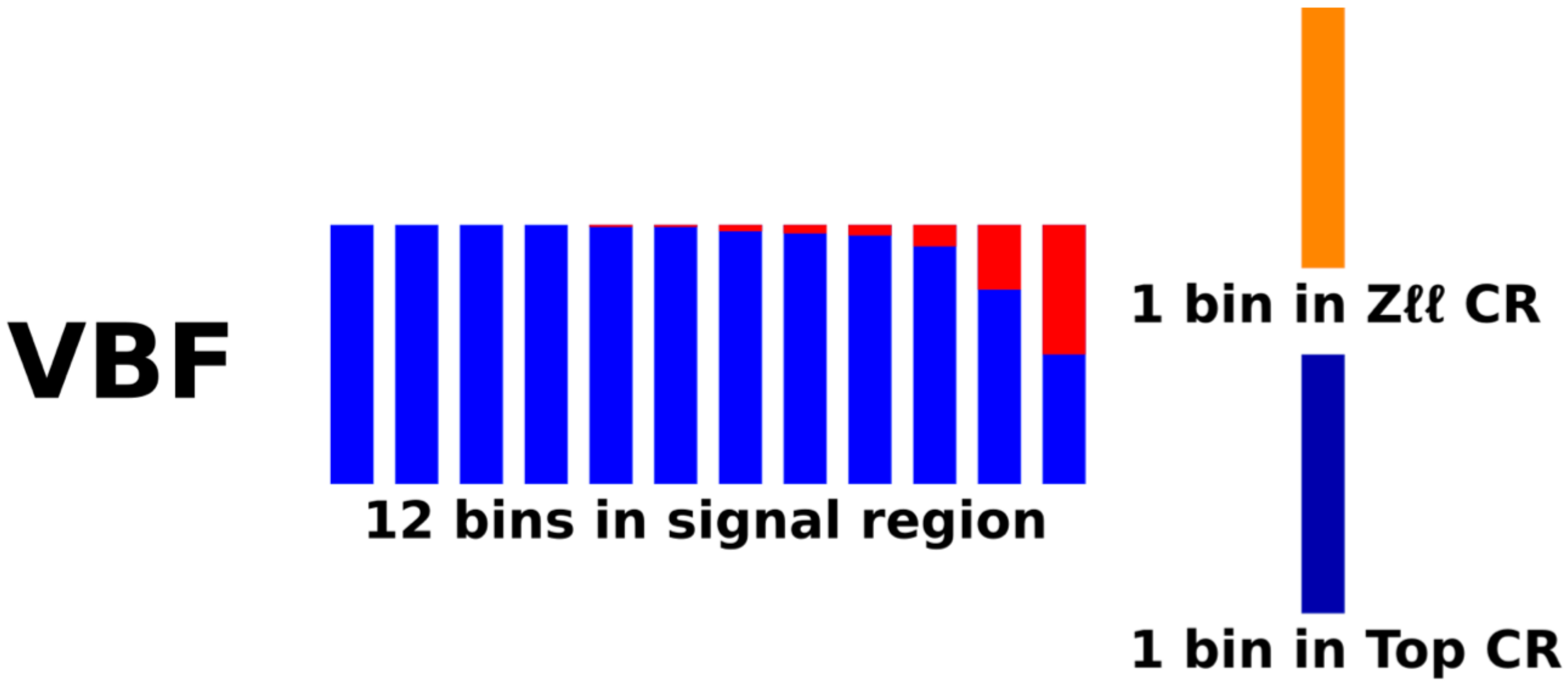
Rest category Δη(ττ) shape



- **Fit BDT shape with signal+background templates**
  - Simultaneous fit in 6 SR and 5 CR with common systematics NP's
  - Z→ττ, Top, multijet (in had-had) & Z→ll normalizations are free in the fit
    - Control regions to constrain normalization of Top & Z→ll
    - **Had-had channel:** multijet & Z→ττ constrained in Rest category

Return

Fit model

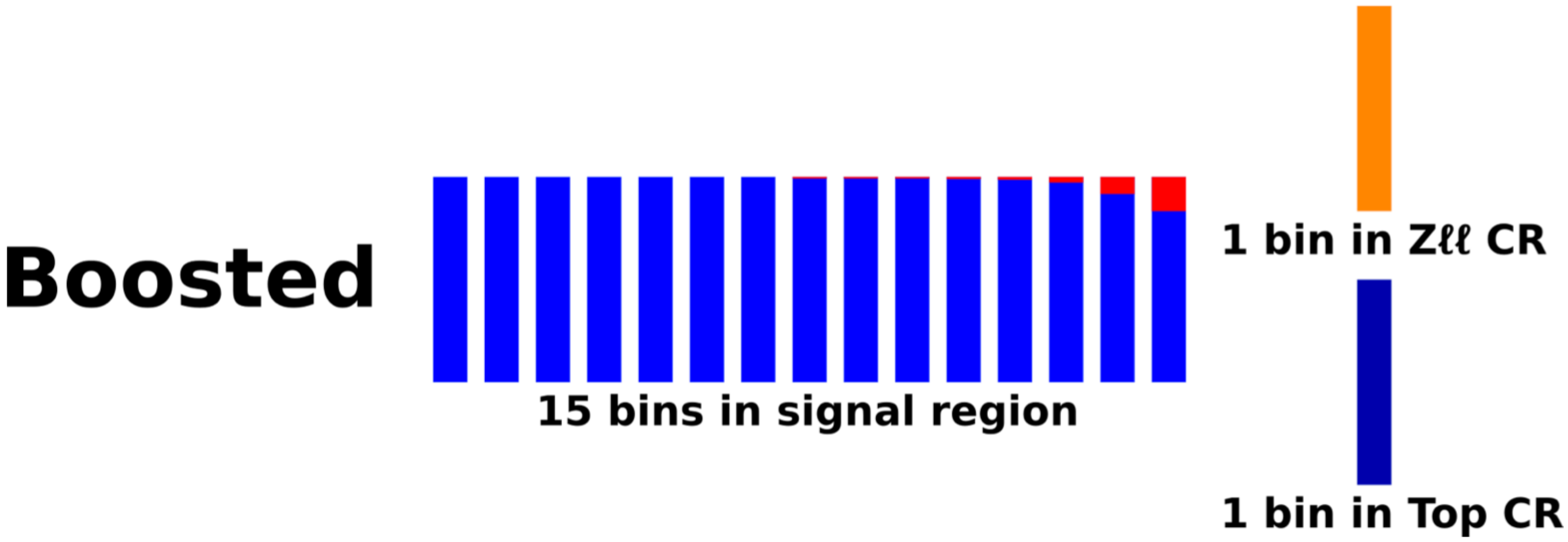


VBF

12 bins in signal region

1 bin in $Z\ell\ell$ CR

1 bin in Top CR



Boosted

15 bins in signal region

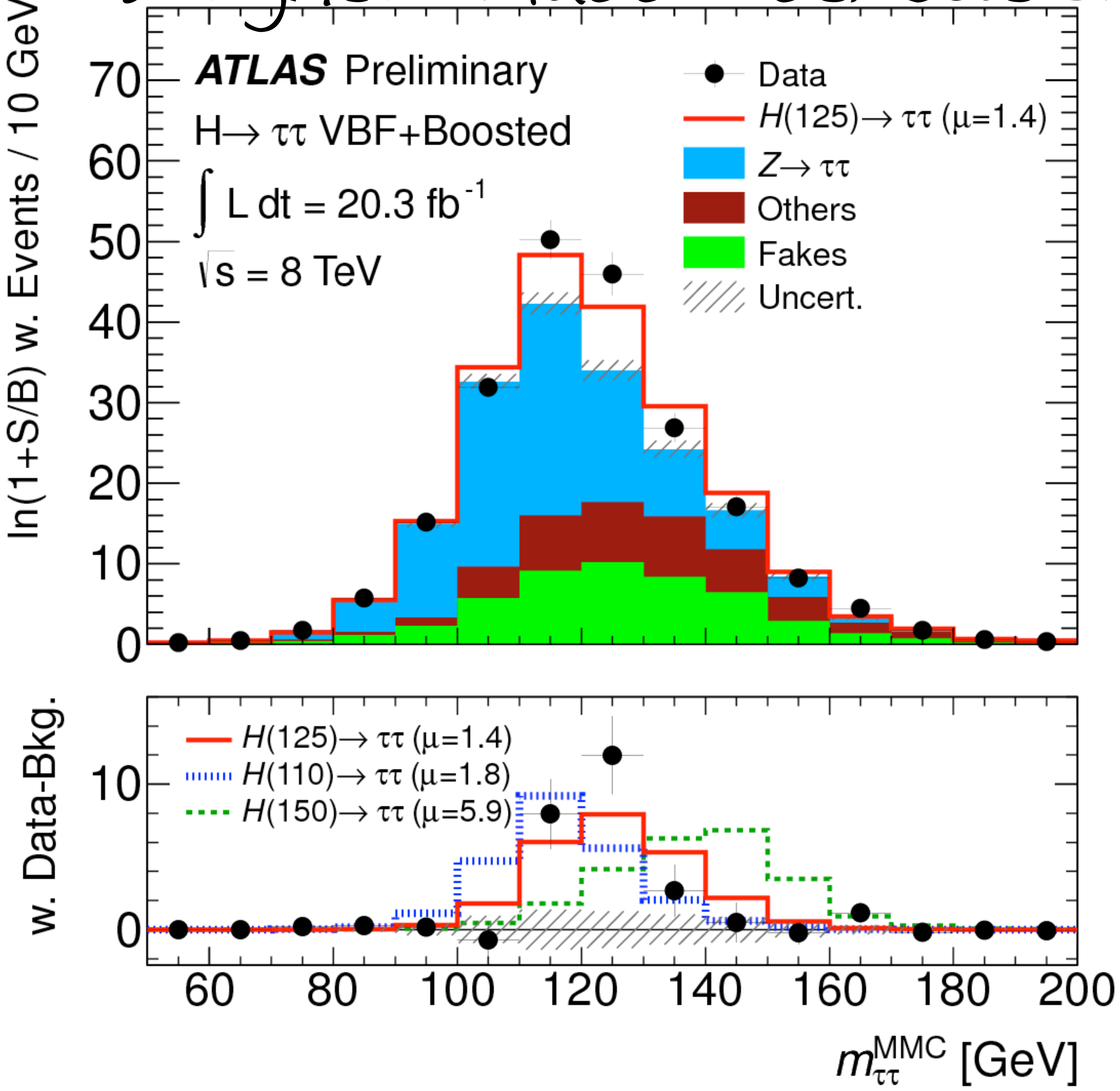
1 bin in $Z\ell\ell$ CR

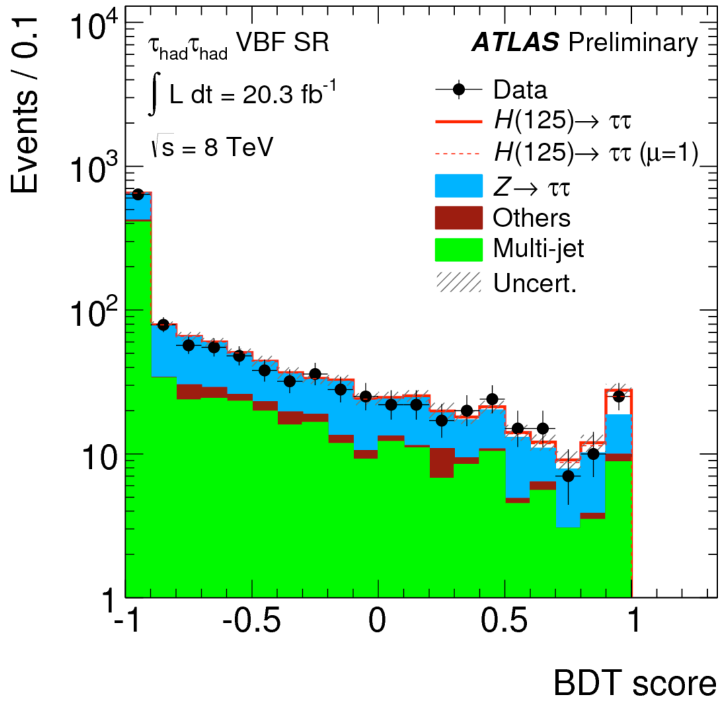
1 bin in Top CR

We run a simultaneous fit on all these (along with the bins from $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{lep}}$)

Is the excess compatible with a m_H=125 GeV Higgs boson?

Weighted mass distribution





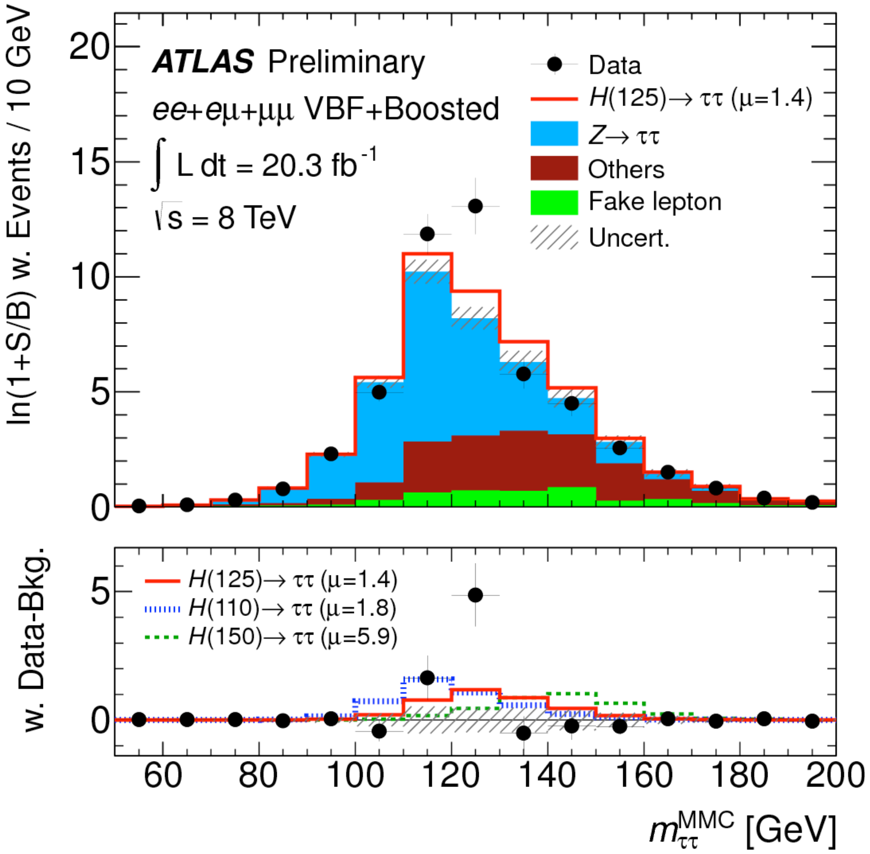
- Each event is weighted by ***ln(1 + n_S/n_B)***, given the bin of the BDT-Score, in which it is contained to

- **Observed signal compatible with m_H=125 GeV**

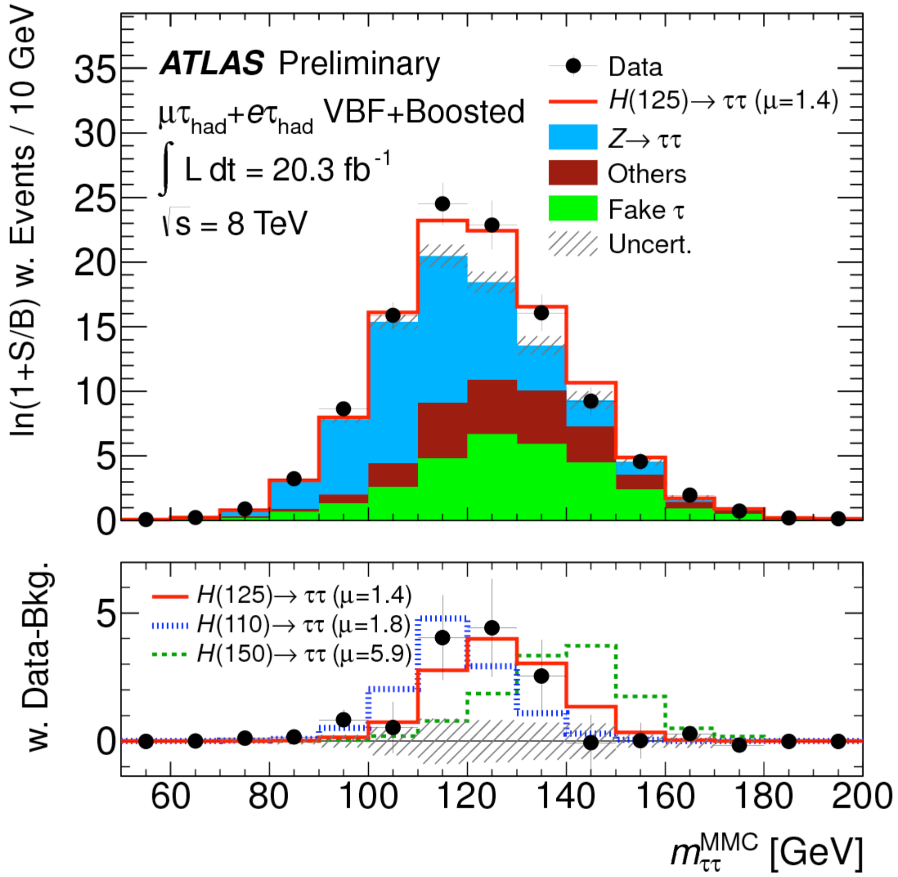
Return

Weighted Mass plots

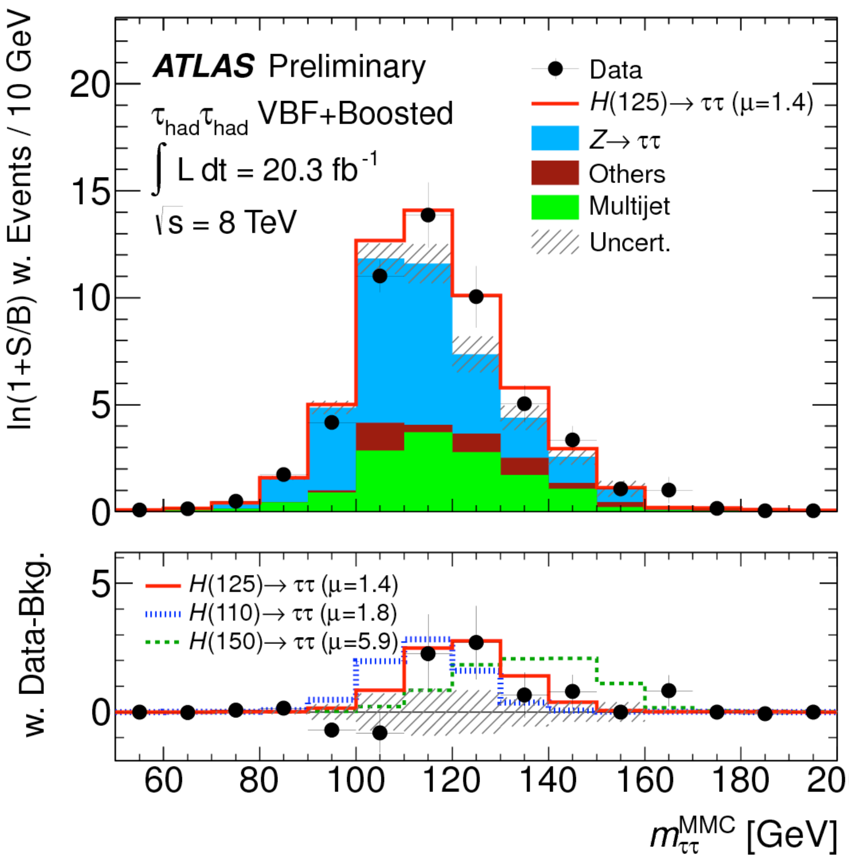
LepLep



LepHad



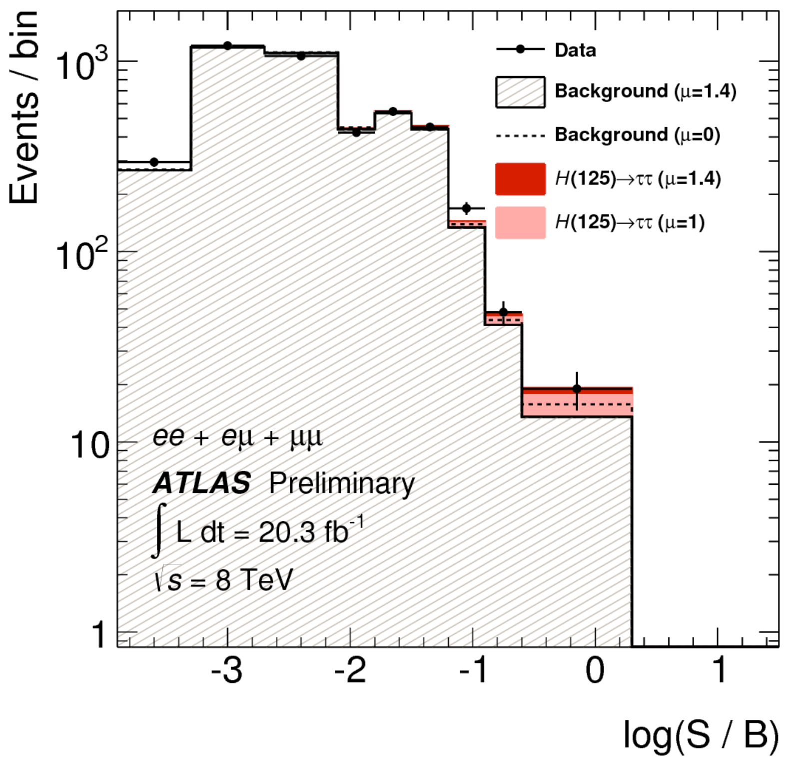
HadHad



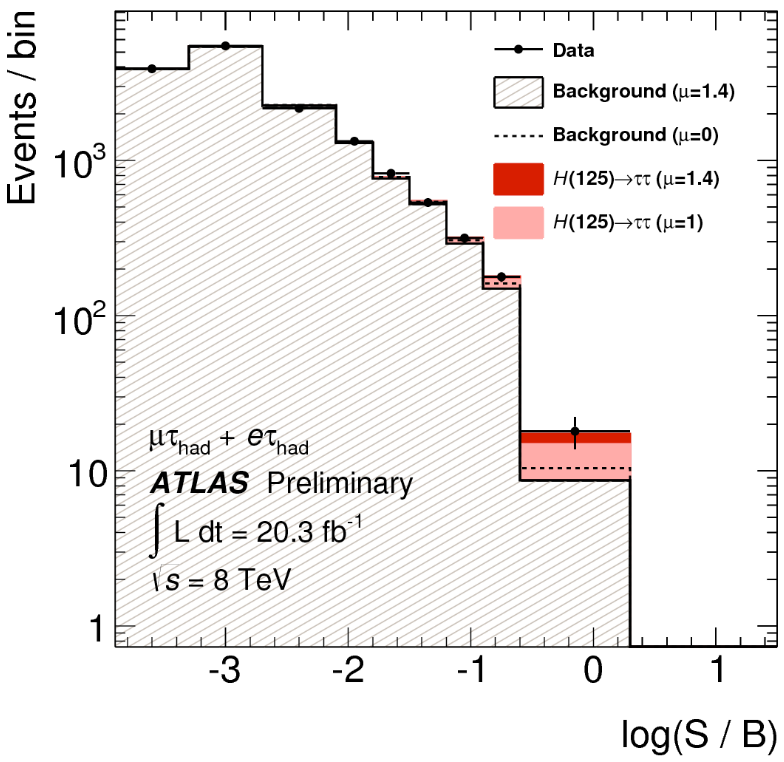
Return

Log(S/B) plots

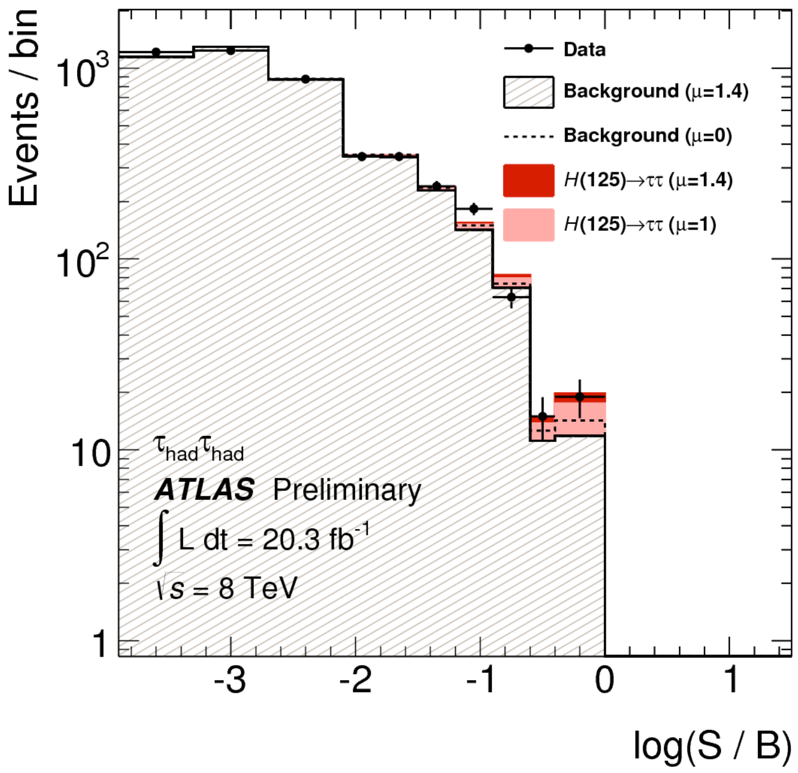
LepLep



LepHad

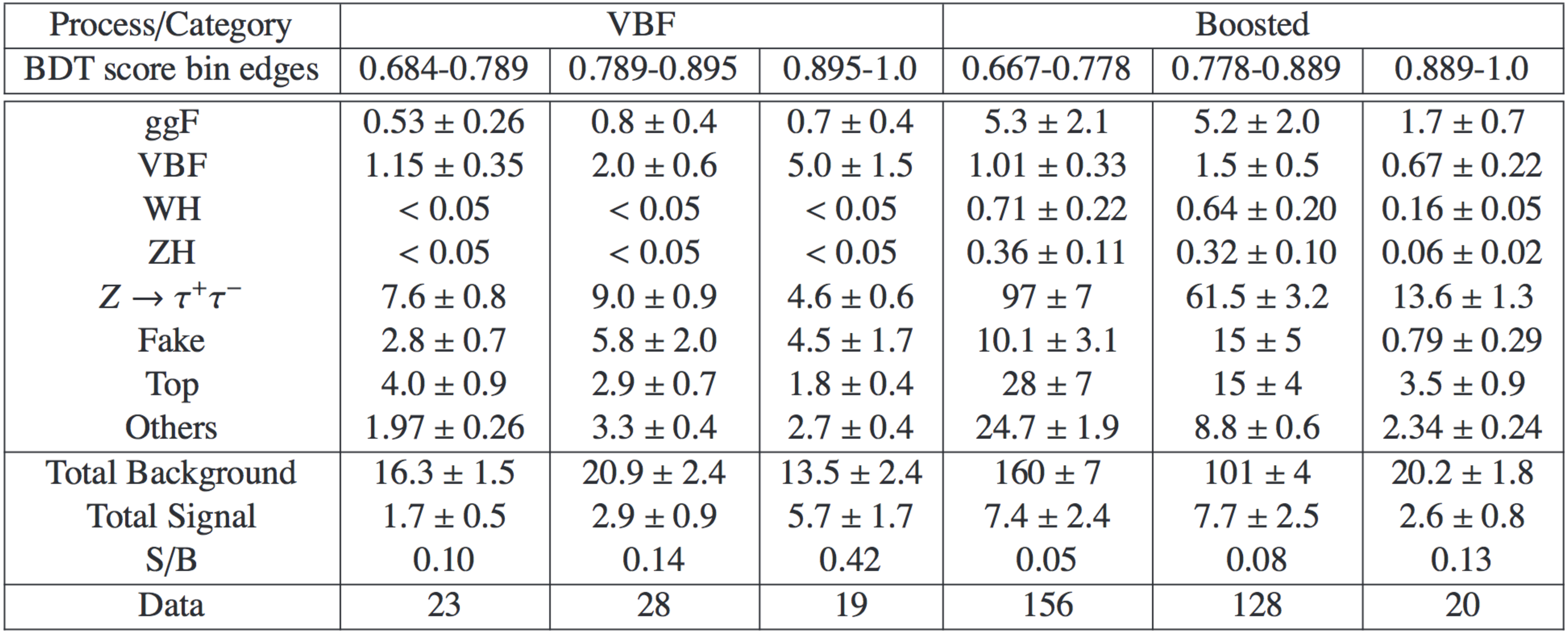


HadHad



Return

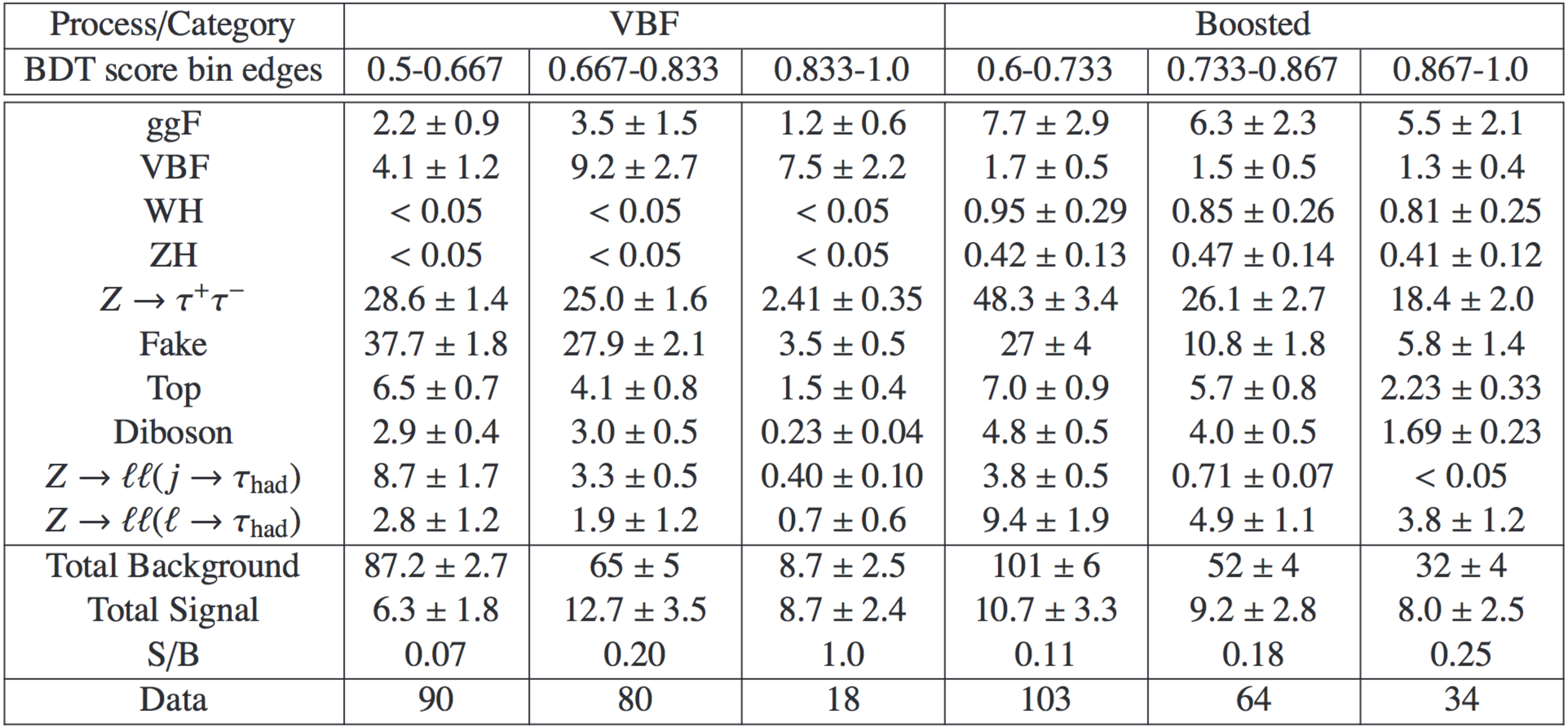
Event Yields in LepLep



Process/Category	VBF			Boosted		
BDT score bin edges	0.684-0.789	0.789-0.895	0.895-1.0	0.667-0.778	0.778-0.889	0.889-1.0
ggF	0.53 ± 0.26	0.8 ± 0.4	0.7 ± 0.4	5.3 ± 2.1	5.2 ± 2.0	1.7 ± 0.7
VBF	1.15 ± 0.35	2.0 ± 0.6	5.0 ± 1.5	1.01 ± 0.33	1.5 ± 0.5	0.67 ± 0.22
WH	< 0.05	< 0.05	< 0.05	0.71 ± 0.22	0.64 ± 0.20	0.16 ± 0.05
ZH	< 0.05	< 0.05	< 0.05	0.36 ± 0.11	0.32 ± 0.10	0.06 ± 0.02
$Z \to \tau^+\tau^-$	7.6 ± 0.8	9.0 ± 0.9	4.6 ± 0.6	97 ± 7	61.5 ± 3.2	13.6 ± 1.3
Fake	2.8 ± 0.7	5.8 ± 2.0	4.5 ± 1.7	10.1 ± 3.1	15 ± 5	0.79 ± 0.29
Top	4.0 ± 0.9	2.9 ± 0.7	1.8 ± 0.4	28 ± 7	15 ± 4	3.5 ± 0.9
Others	1.97 ± 0.26	3.3 ± 0.4	2.7 ± 0.4	24.7 ± 1.9	8.8 ± 0.6	2.34 ± 0.24
Total Background	16.3 ± 1.5	20.9 ± 2.4	13.5 ± 2.4	160 ± 7	101 ± 4	20.2 ± 1.8
Total Signal	1.7 ± 0.5	2.9 ± 0.9	5.7 ± 1.7	7.4 ± 2.4	7.7 ± 2.5	2.6 ± 0.8
S/B	0.10	0.14	0.42	0.05	0.08	0.13
Data	23	28	19	156	128	20

Return

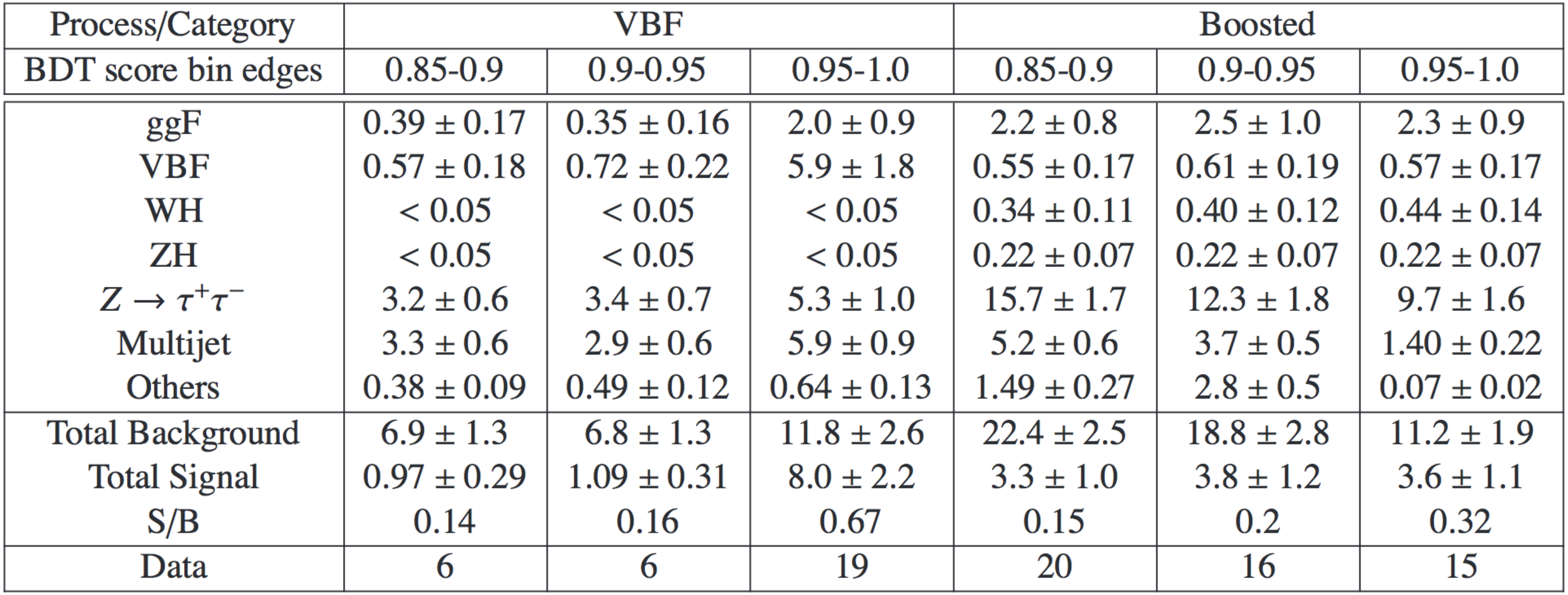
Event Yields in LepHad



Process/Category	VBF			Boosted		
BDT score bin edges	0.5-0.667	0.667-0.833	0.833-1.0	0.6-0.733	0.733-0.867	0.867-1.0
ggF	2.2 ± 0.9	3.5 ± 1.5	1.2 ± 0.6	7.7 ± 2.9	6.3 ± 2.3	5.5 ± 2.1
VBF	4.1 ± 1.2	9.2 ± 2.7	7.5 ± 2.2	1.7 ± 0.5	1.5 ± 0.5	1.3 ± 0.4
WH	< 0.05	< 0.05	< 0.05	0.95 ± 0.29	0.85 ± 0.26	0.81 ± 0.25
ZH	< 0.05	< 0.05	< 0.05	0.42 ± 0.13	0.47 ± 0.14	0.41 ± 0.12
$Z \rightarrow \tau^+\tau^-$	28.6 ± 1.4	25.0 ± 1.6	2.41 ± 0.35	48.3 ± 3.4	26.1 ± 2.7	18.4 ± 2.0
Fake	37.7 ± 1.8	27.9 ± 2.1	3.5 ± 0.5	27 ± 4	10.8 ± 1.8	5.8 ± 1.4
Top	6.5 ± 0.7	4.1 ± 0.8	1.5 ± 0.4	7.0 ± 0.9	5.7 ± 0.8	2.23 ± 0.33
Diboson	2.9 ± 0.4	3.0 ± 0.5	0.23 ± 0.04	4.8 ± 0.5	4.0 ± 0.5	1.69 ± 0.23
$Z \rightarrow \ell\ell(j \rightarrow \tau_{\text{had}})$	8.7 ± 1.7	3.3 ± 0.5	0.40 ± 0.10	3.8 ± 0.5	0.71 ± 0.07	< 0.05
$Z \rightarrow \ell\ell(\ell \rightarrow \tau_{\text{had}})$	2.8 ± 1.2	1.9 ± 1.2	0.7 ± 0.6	9.4 ± 1.9	4.9 ± 1.1	3.8 ± 1.2
Total Background	87.2 ± 2.7	65 ± 5	8.7 ± 2.5	101 ± 6	52 ± 4	32 ± 4
Total Signal	6.3 ± 1.8	12.7 ± 3.5	8.7 ± 2.4	10.7 ± 3.3	9.2 ± 2.8	8.0 ± 2.5
S/B	0.07	0.20	1.0	0.11	0.18	0.25
Data	90	80	18	103	64	34

Return

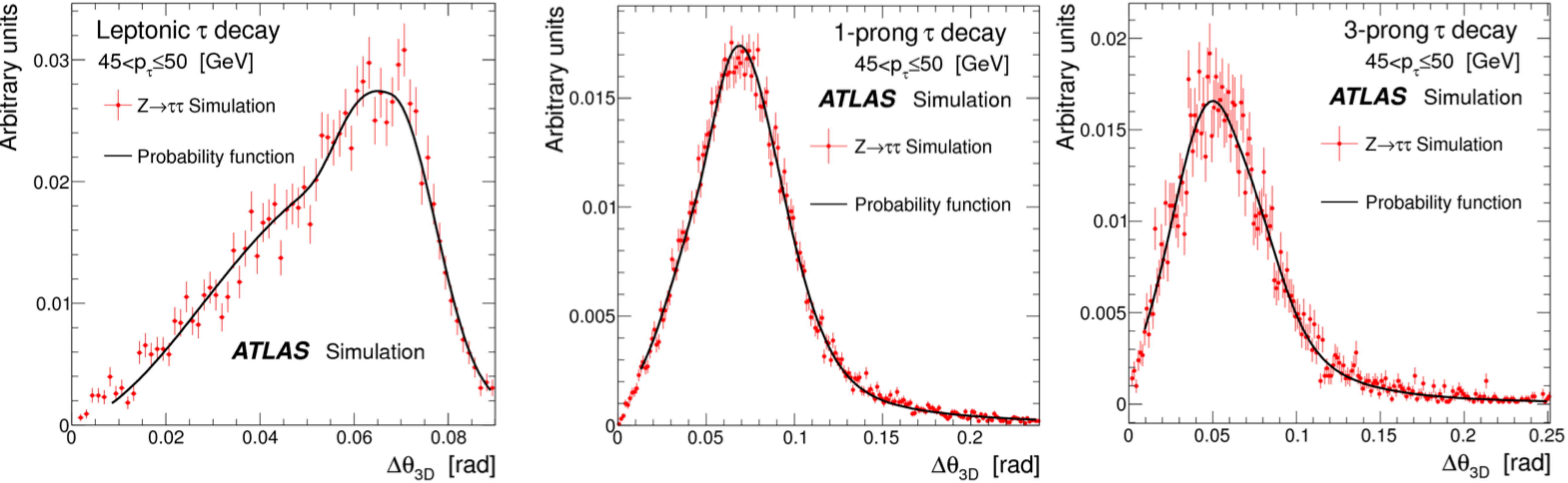
Event Yields in HadHad



Process/Category	VBF			Boosted		
BDT score bin edges	0.85-0.9	0.9-0.95	0.95-1.0	0.85-0.9	0.9-0.95	0.95-1.0
ggF	0.39 ± 0.17	0.35 ± 0.16	2.0 ± 0.9	2.2 ± 0.8	2.5 ± 1.0	2.3 ± 0.9
VBF	0.57 ± 0.18	0.72 ± 0.22	5.9 ± 1.8	0.55 ± 0.17	0.61 ± 0.19	0.57 ± 0.17
WH	< 0.05	< 0.05	< 0.05	0.34 ± 0.11	0.40 ± 0.12	0.44 ± 0.14
ZH	< 0.05	< 0.05	< 0.05	0.22 ± 0.07	0.22 ± 0.07	0.22 ± 0.07
$Z \to \tau^+\tau^-$	3.2 ± 0.6	3.4 ± 0.7	5.3 ± 1.0	15.7 ± 1.7	12.3 ± 1.8	9.7 ± 1.6
Multijet	3.3 ± 0.6	2.9 ± 0.6	5.9 ± 0.9	5.2 ± 0.6	3.7 ± 0.5	1.40 ± 0.22
Others	0.38 ± 0.09	0.49 ± 0.12	0.64 ± 0.13	1.49 ± 0.27	2.8 ± 0.5	0.07 ± 0.02
Total Background	6.9 ± 1.3	6.8 ± 1.3	11.8 ± 2.6	22.4 ± 2.5	18.8 ± 2.8	11.2 ± 1.9
Total Signal	0.97 ± 0.29	1.09 ± 0.31	8.0 ± 2.2	3.3 ± 1.0	3.8 ± 1.2	3.6 ± 1.1
S/B	0.14	0.16	0.67	0.15	0.2	0.32
Data	6	6	19	20	16	15

MMC

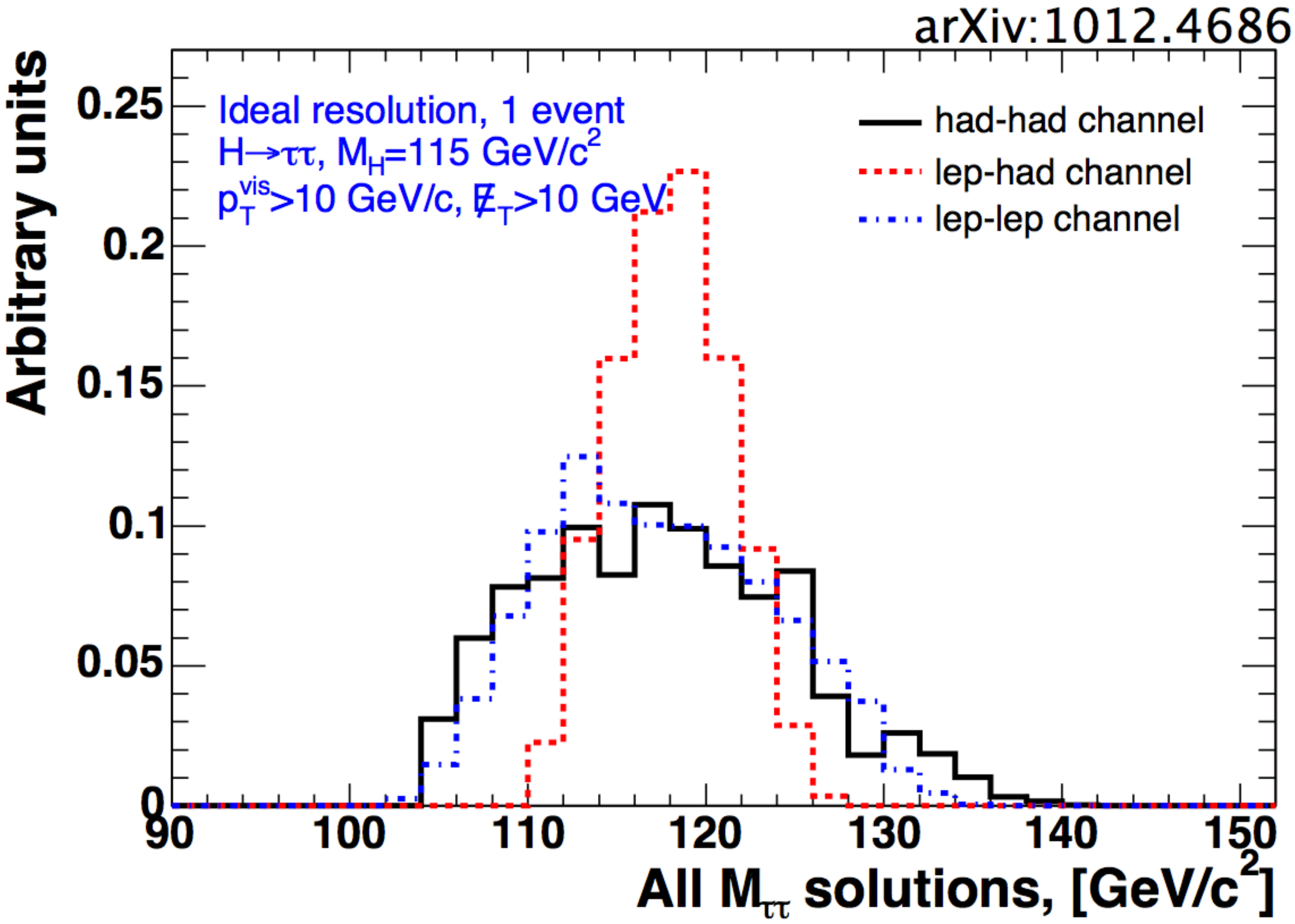
- Based on **Nucl.Instrum.Meth. A654:481-489,2011** Sasha Pranko et al. [arXiv:1012.4686]
- Parameterize $\Delta\theta_{3D}$(visible τ,neutrino[s]) in MC
- Solve τ, E_T^{miss} kinematics equations for each point of the Δφ(vis,neutrino[s]) parameter space
- Use $\Delta\theta_{3D}$(vis,neutrino[s]) parameterization to weight the solutions in Δφ (vis,neutrino[s]) grid, put weighted solutions to histogram
- Peak most probable value as the $M_{\tau\tau}^{MMC}$ estimator



Fit: Gauss × Landau (6 parameters)

Return

MMC

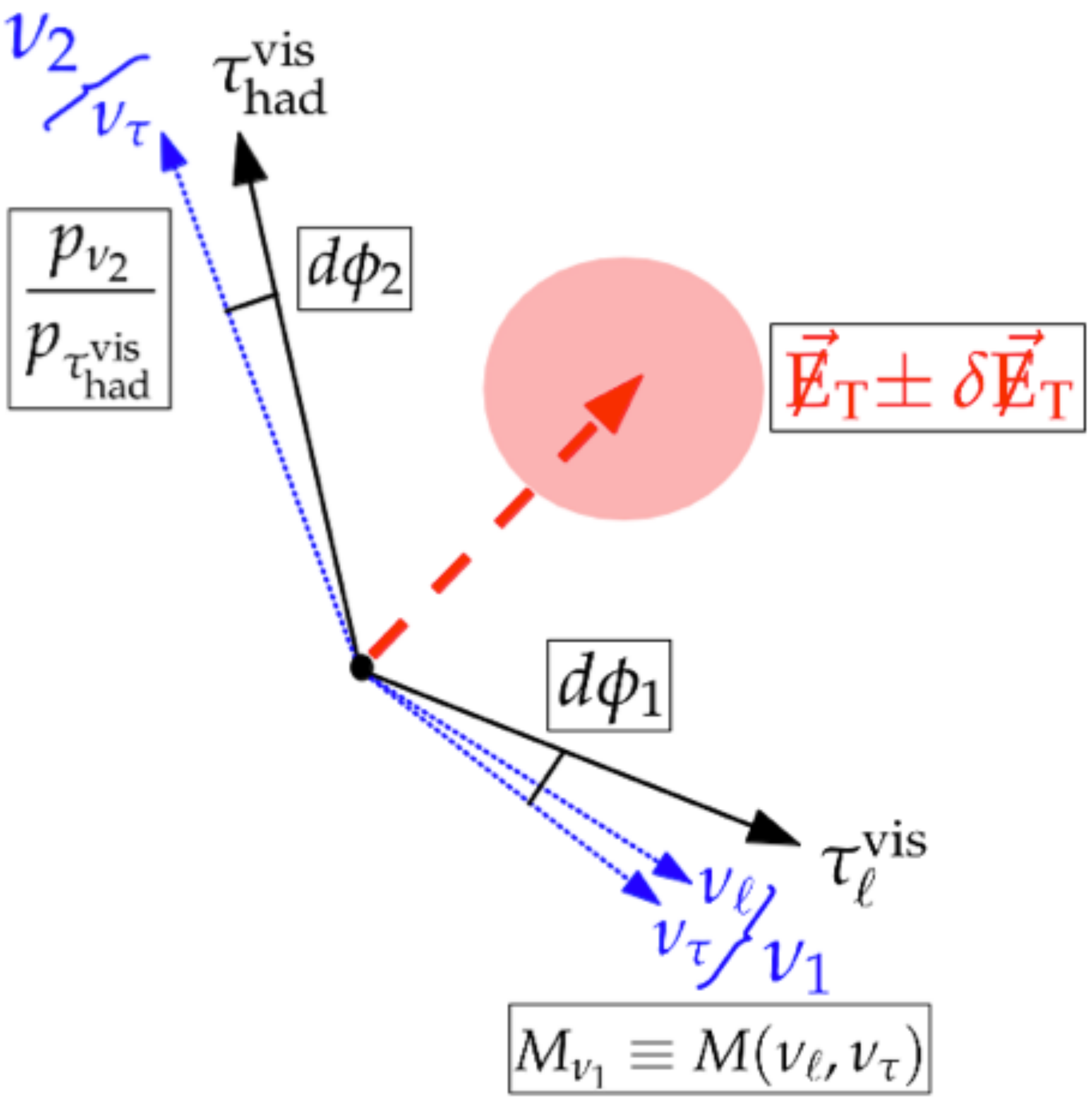


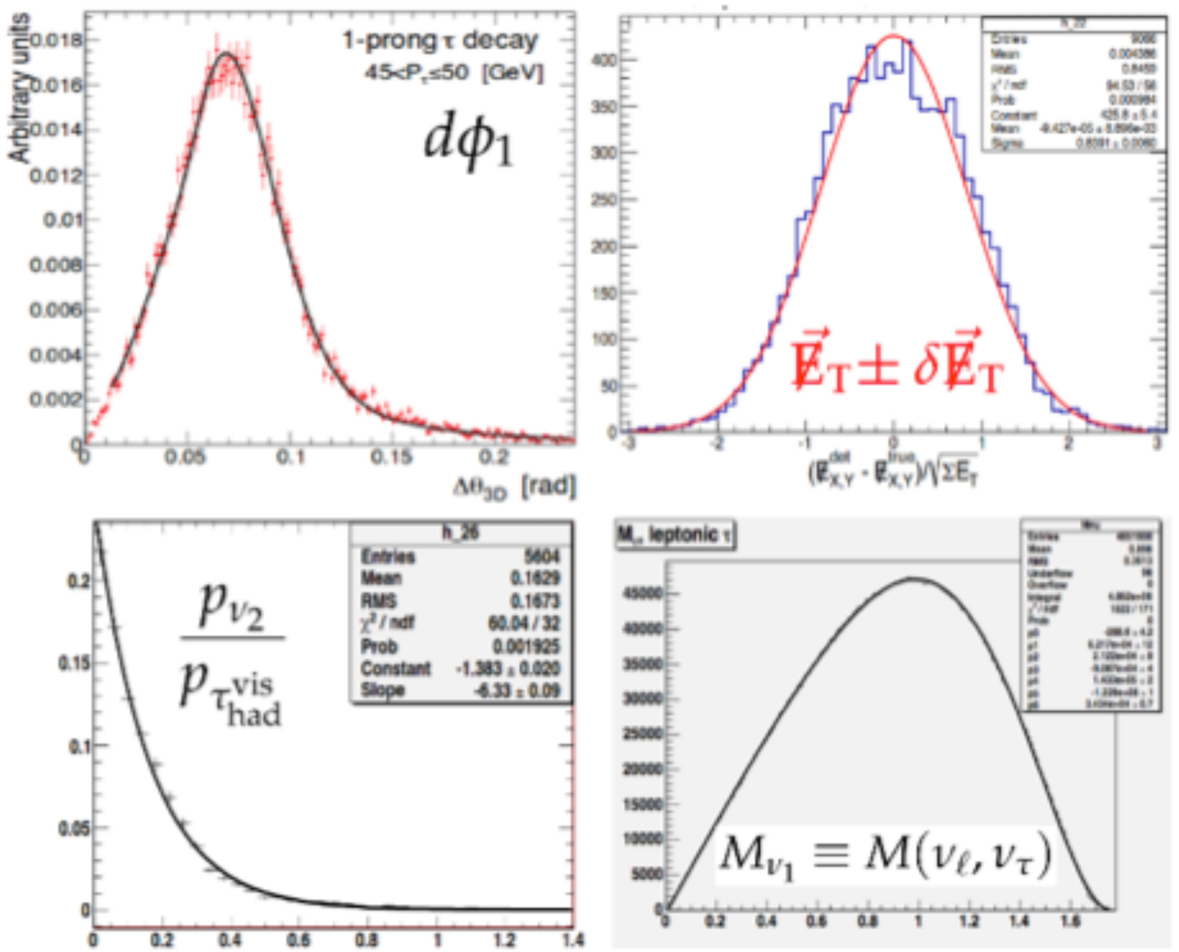
Example of solutions for all points on $[\Delta\varphi_1; \Delta\varphi_2]$ grid for a single Higgs event

- solutions weighted by corresponding $P_{solution}$ probabilities

Return

MMC





☐ = unknown value

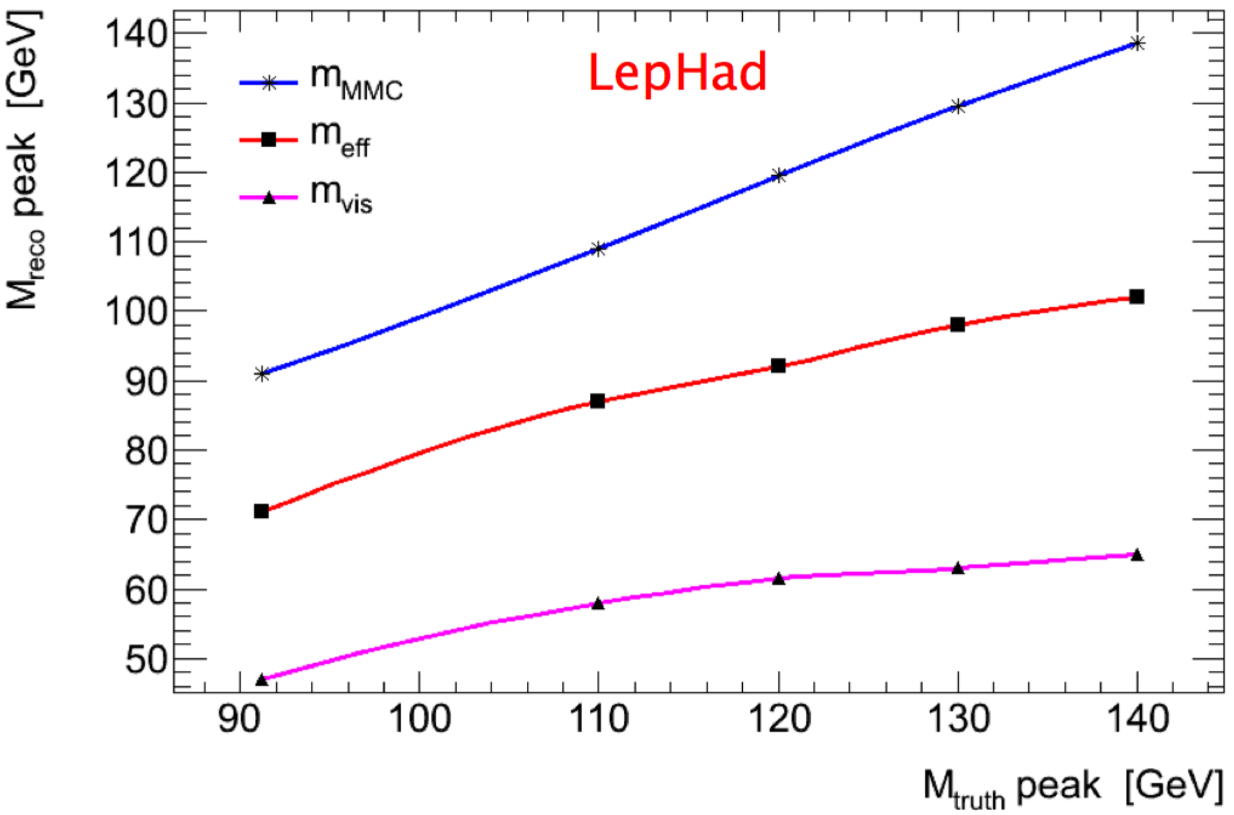
(1) **Perform a scan** over the unknowns, ie choose a config : q = (dΦ$_1$, dΦ$_2$, M$_{\nu 1}$, mET, p$_\nu$/p$_\tau$)

(2) For each configuration q$_i$: compute the **full invariant mass** m$_i$

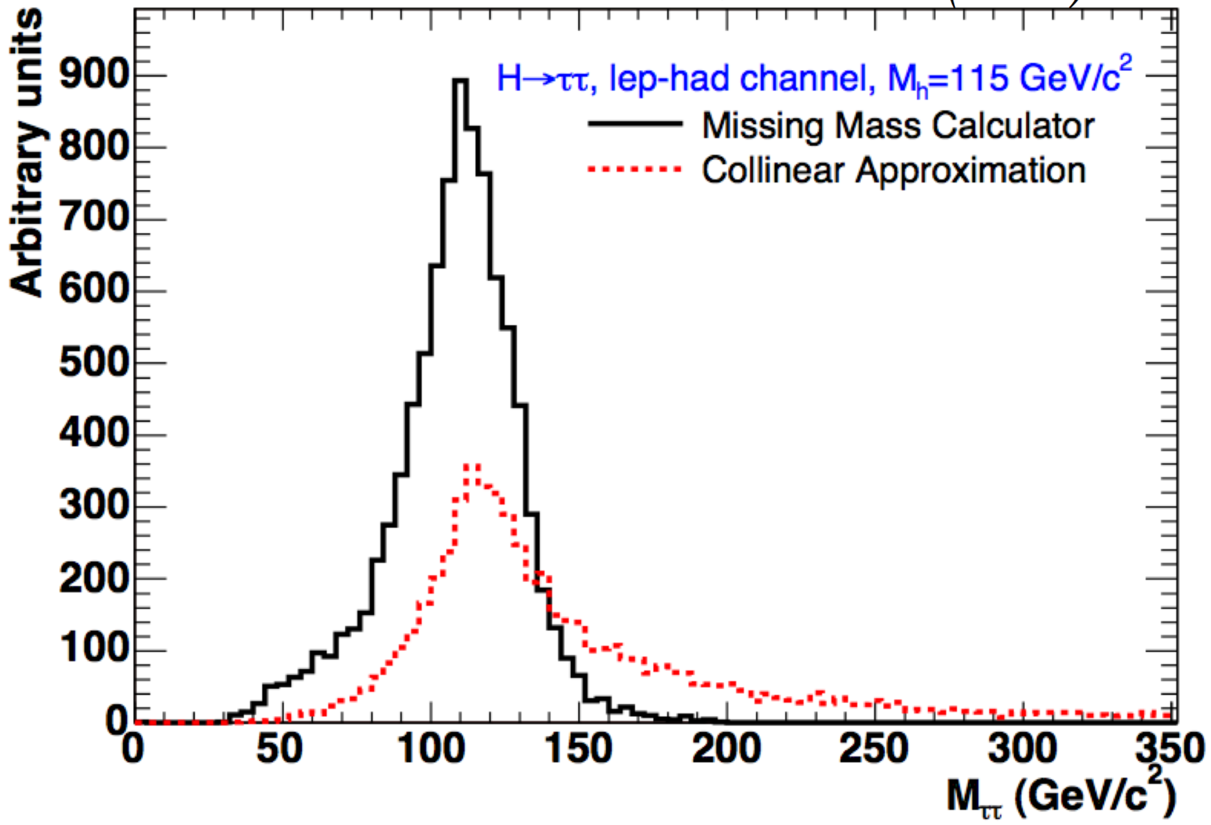
(3) Fill an histogram of m$_i$ **weighted by w$_i$=PDF(q$_i$)** , as a product each above PDF

(4) Final reconstructed mass, **MMC**, is given by the **max of this histogram**

MMC



NIM A 654 (2011) 481

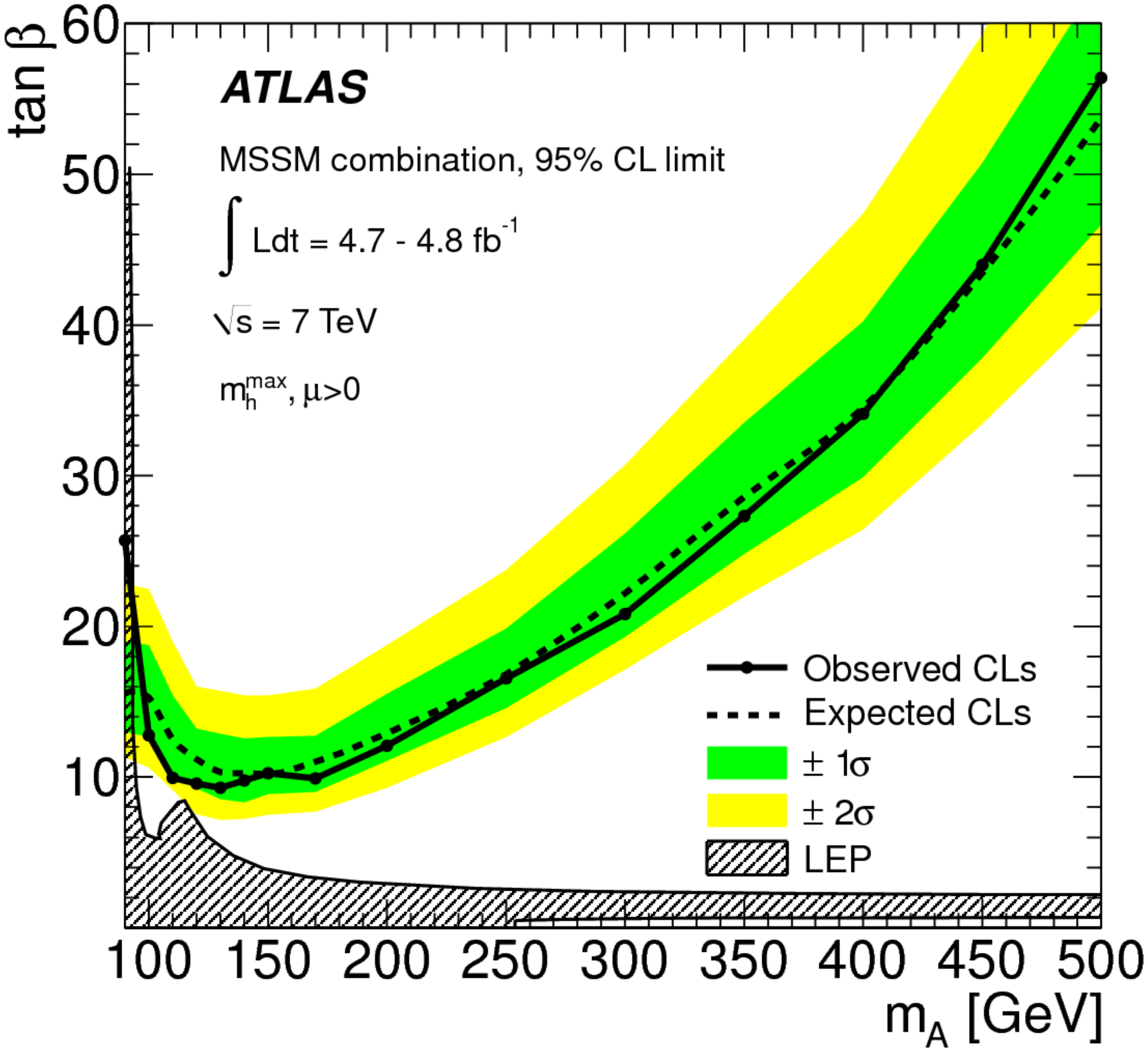


	Z→ττ
Lep-Lep	~21%
Lep-Had	~18%
Had-Had	~14%

Return

BSM Higgs

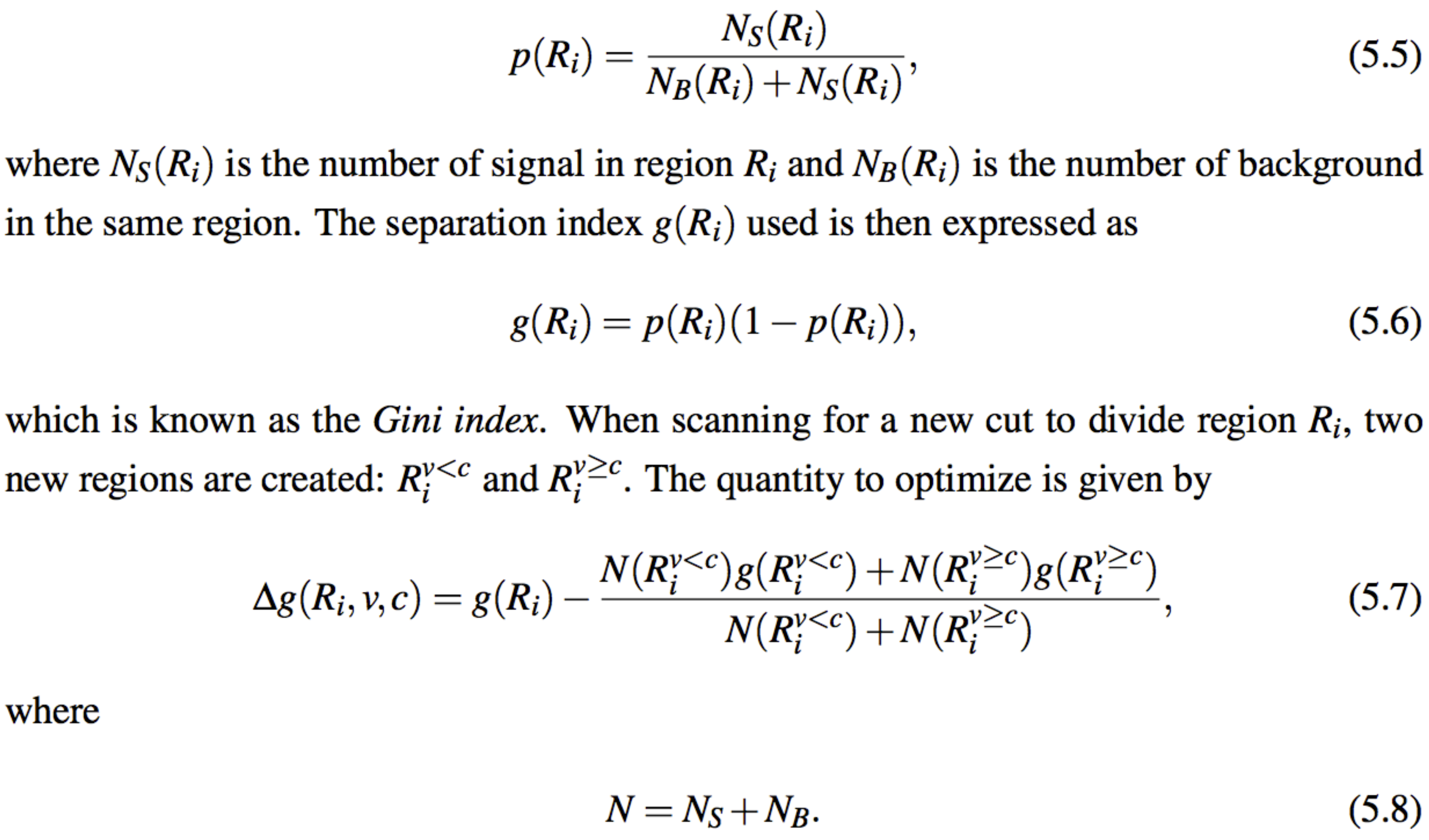
- Fermionic decays provide constraints on the MSSM in the context of 2 Higgs doublet models



Return

Decision Trees

- For each variable a range to scan defined by the spread of S and B in n steps
- Every such step is tested by evaluating a S Vs B separation index based on the proportions of S and B lying on each side of the cut



$$p(R_i) = \frac{N_S(R_i)}{N_B(R_i) + N_S(R_i)}, \tag{5.5}$$

where $N_S(R_i)$ is the number of signal in region R_i and $N_B(R_i)$ is the number of background in the same region. The separation index $g(R_i)$ used is then expressed as

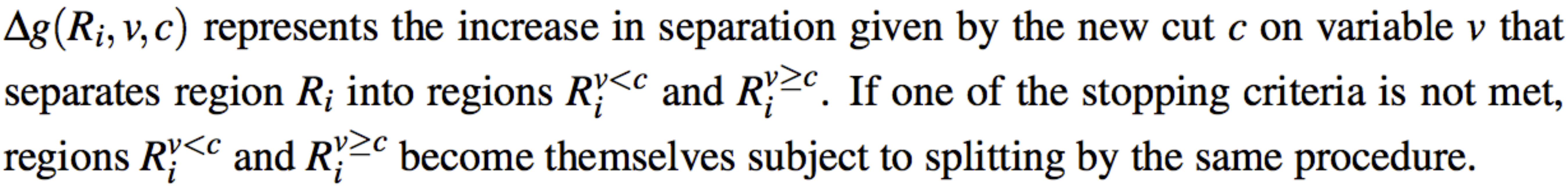
$$g(R_i) = p(R_i)(1 - p(R_i)), \tag{5.6}$$

which is known as the *Gini index*. When scanning for a new cut to divide region R_i, two new regions are created: $R_i^{v<c}$ and $R_i^{v\geq c}$. The quantity to optimize is given by

$$\Delta g(R_i, v, c) = g(R_i) - \frac{N(R_i^{v<c})g(R_i^{v<c}) + N(R_i^{v\geq c})g(R_i^{v\geq c})}{N(R_i^{v<c}) + N(R_i^{v\geq c})}, \tag{5.7}$$

where

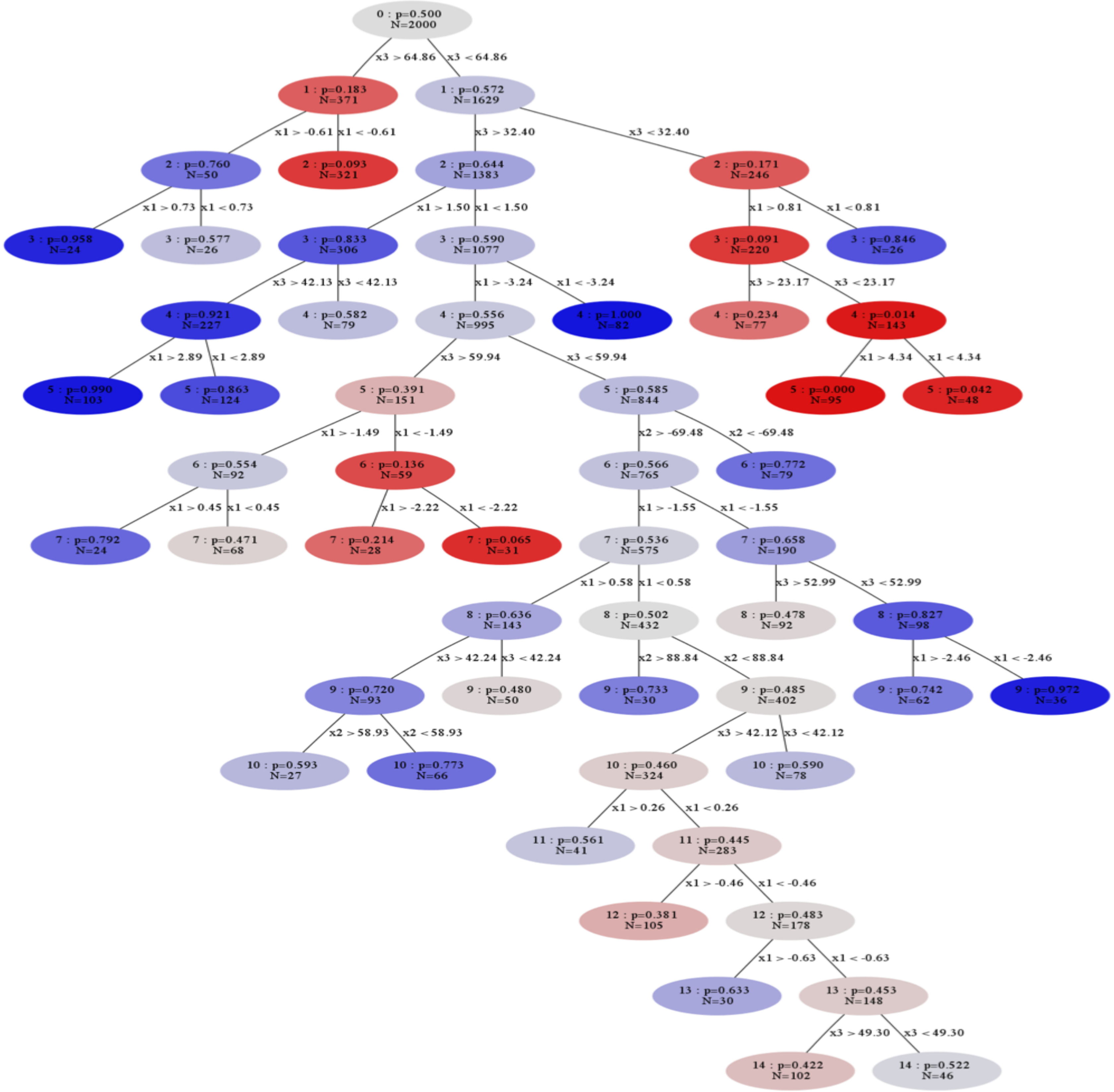
$$N = N_S + N_B. \tag{5.8}$$



$\Delta g(R_i, v, c)$ represents the increase in separation given by the new cut c on variable v that separates region R_i into regions $R_i^{v<c}$ and $R_i^{v\geq c}$. If one of the stopping criteria is not met, regions $R_i^{v<c}$ and $R_i^{v\geq c}$ become themselves subject to splitting by the same procedure.

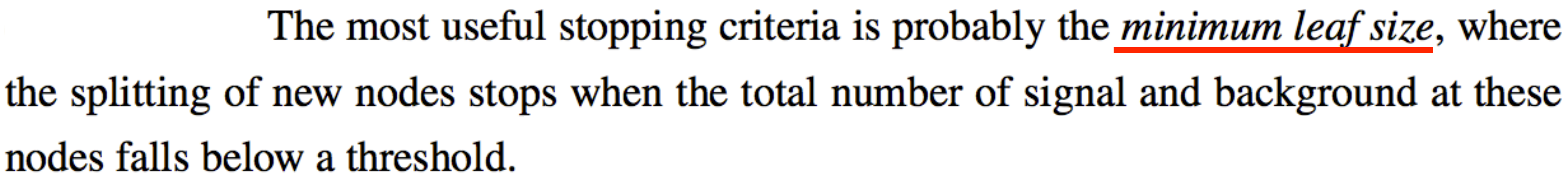
Return

Decision Trees

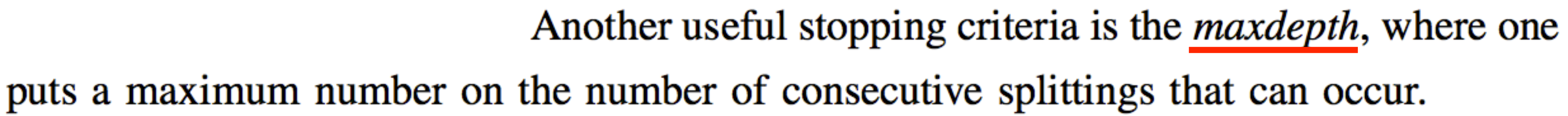


Return

Decision Trees stopping criteria



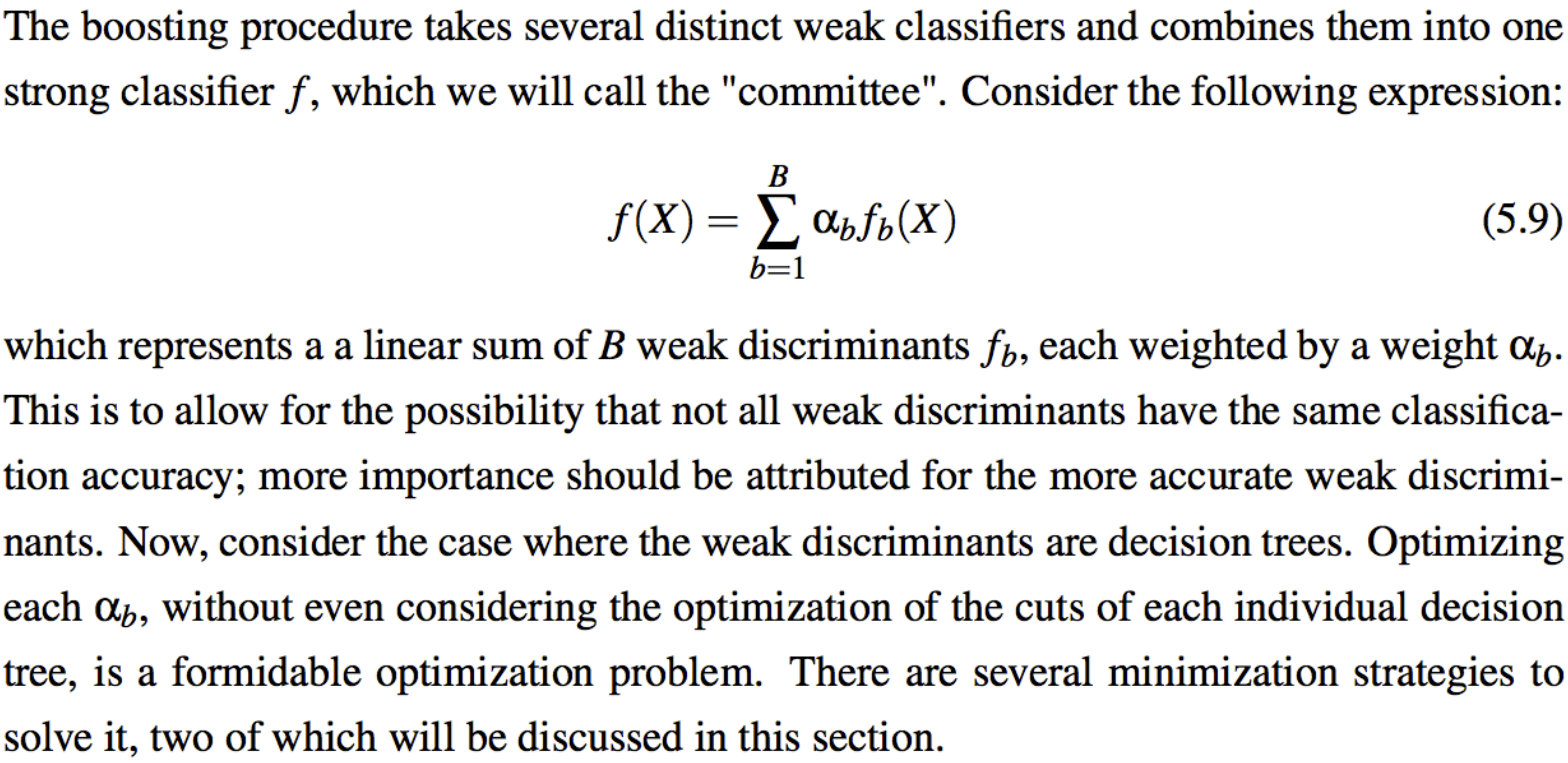
The most useful stopping criteria is probably the *minimum leaf size*, where the splitting of new nodes stops when the total number of signal and background at these nodes falls below a threshold.



Another useful stopping criteria is the *maxdepth*, where one puts a maximum number on the number of consecutive splittings that can occur.

Return

Boosting

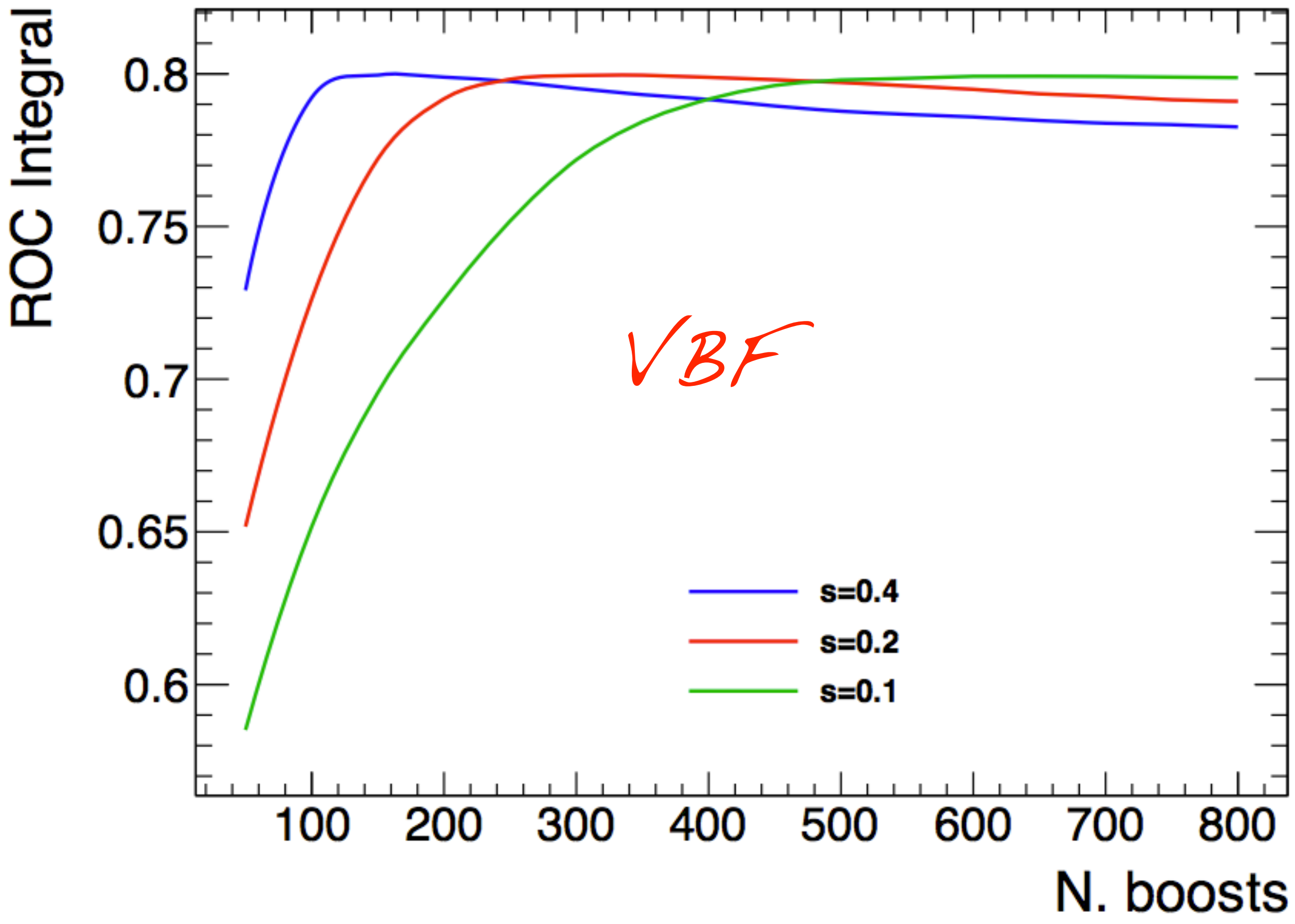


The boosting procedure takes several distinct weak classifiers and combines them into one strong classifier f, which we will call the "committee". Consider the following expression:

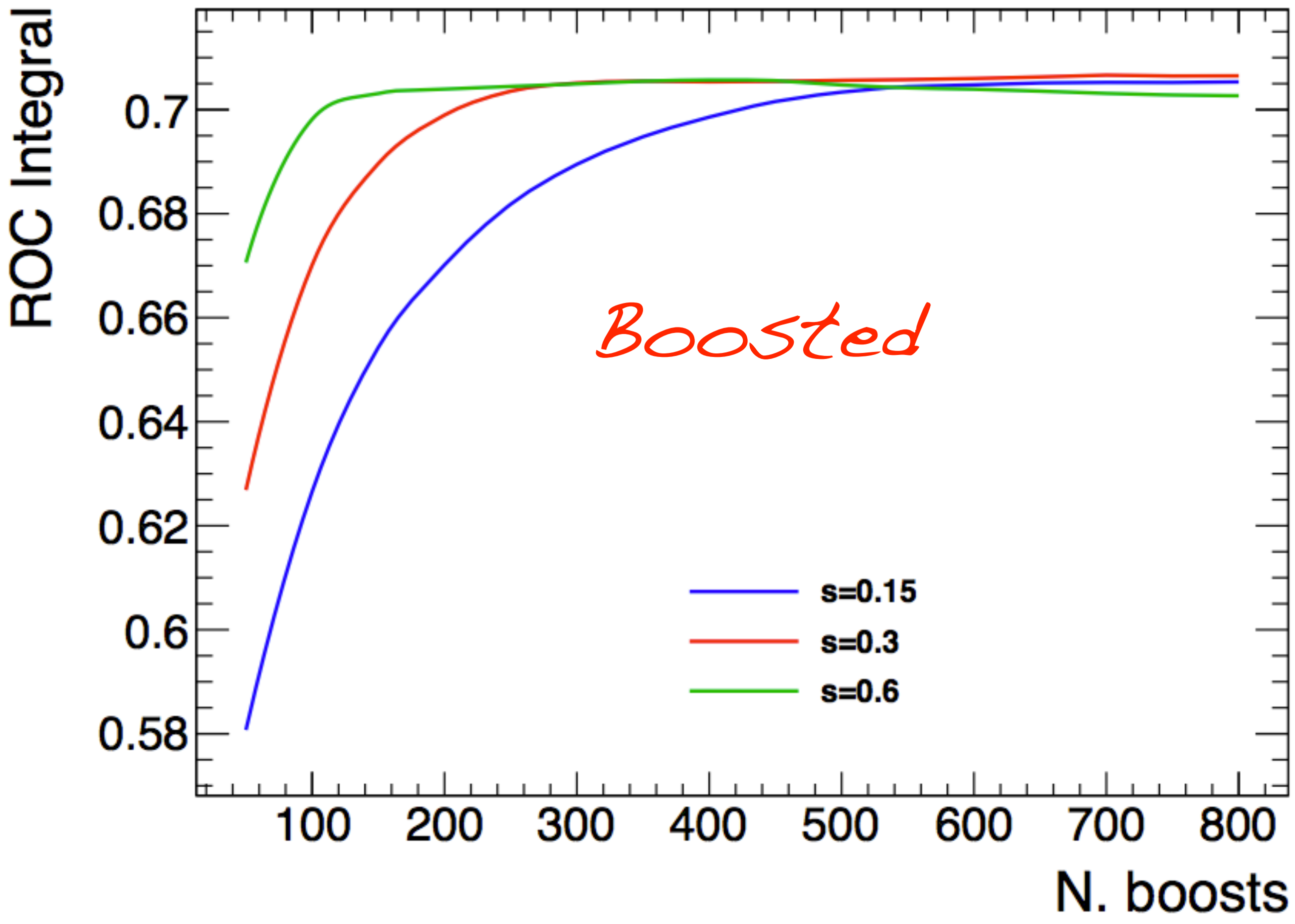
$$f(X) = \sum_{b=1}^{B} \alpha_b f_b(X) \tag{5.9}$$

which represents a a linear sum of B weak discriminants f_b, each weighted by a weight α_b. This is to allow for the possibility that not all weak discriminants have the same classification accuracy; more importance should be attributed for the more accurate weak discriminants. Now, consider the case where the weak discriminants are decision trees. Optimizing each α_b, without even considering the optimization of the cuts of each individual decision tree, is a formidable optimization problem. There are several minimization strategies to solve it, two of which will be discussed in this section.

BDT



VBF



Boosted

Table 8.2: Training parameters for the VBF category and Boosted category BDTs.

Parameter	VBF Category	Boosted Category
N. Boosts	400	600
Shrinkage	0.2	0.3
Tree Depth	4	4
Min. Leaf Size	150	150

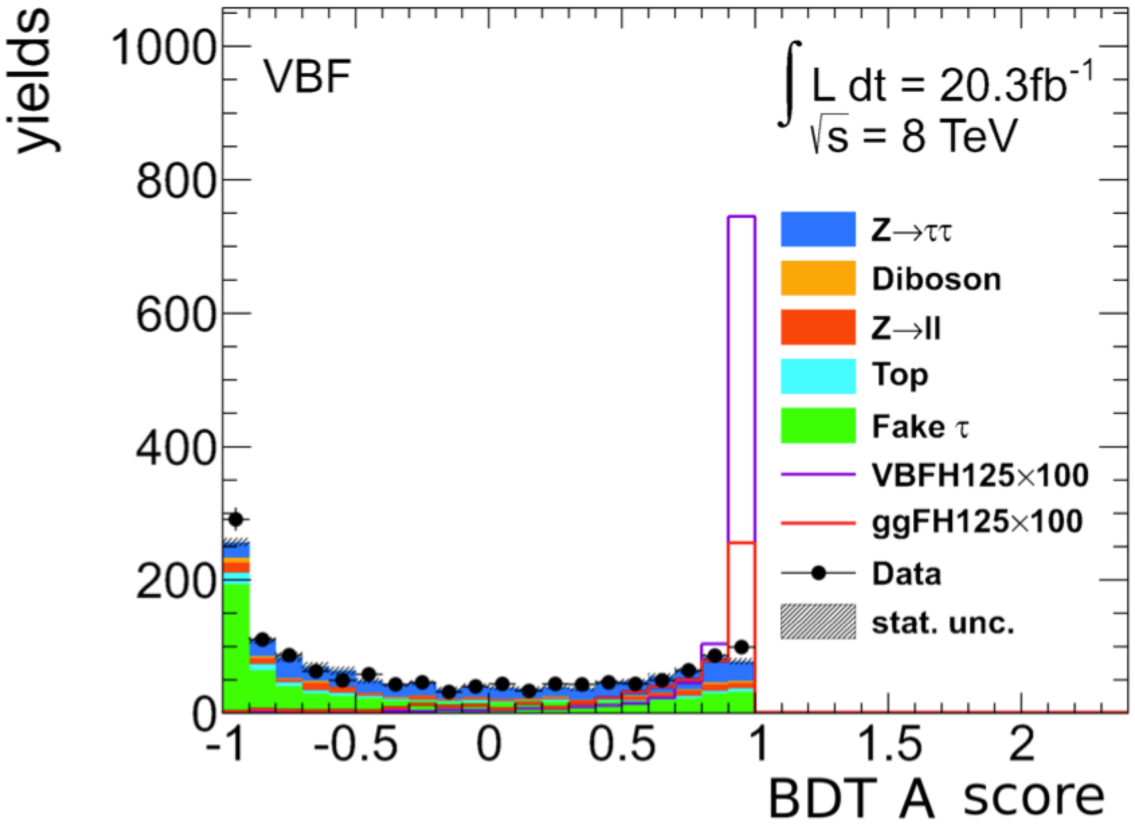
Return

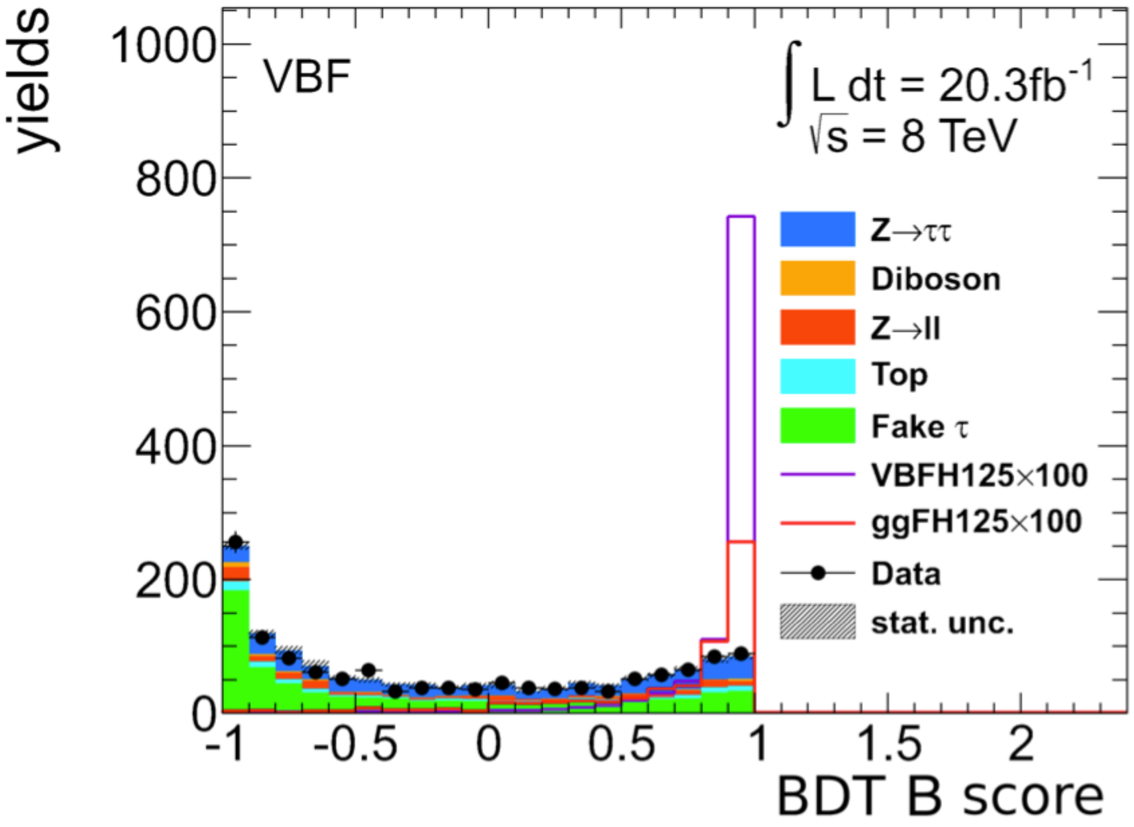
How we use BDT’s

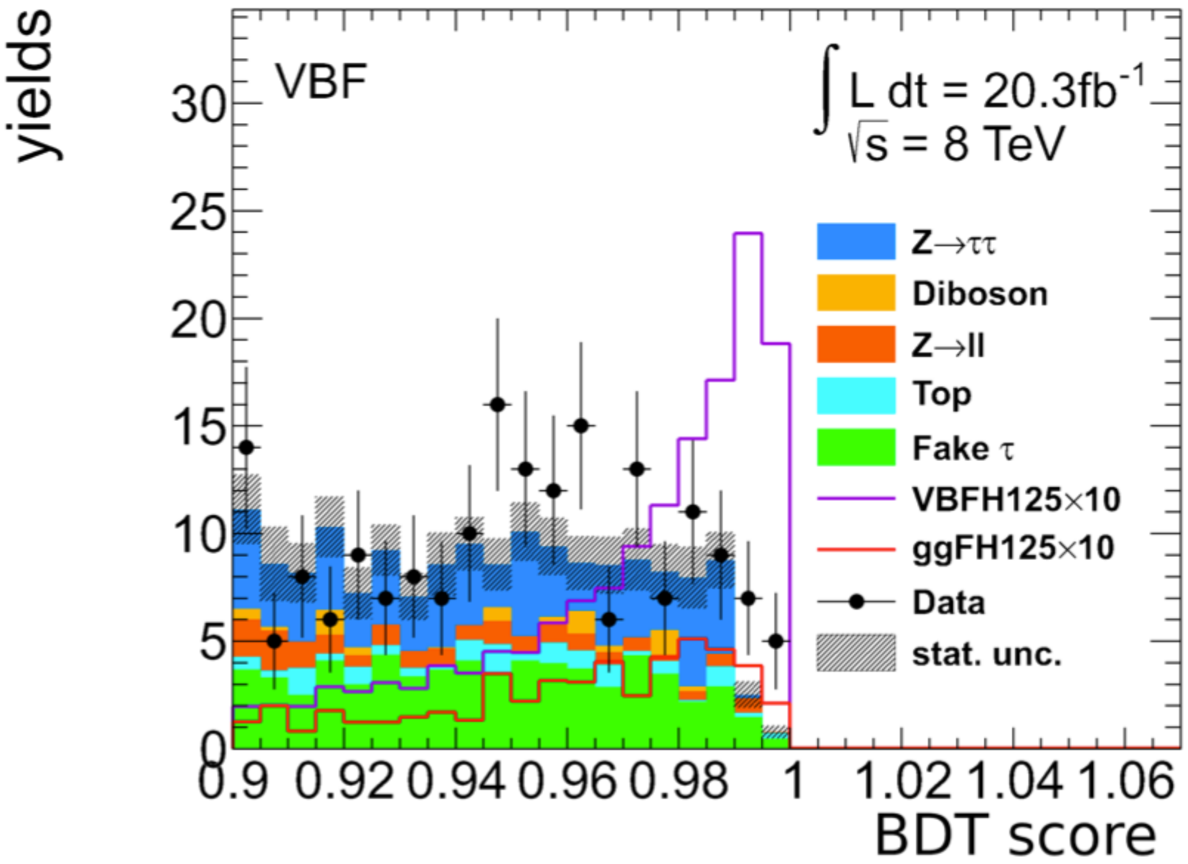
- We train separate BDTs in each channel and category (see following pages).
- The BDT is trained against a mix of all backgrounds in nature’s proportions. Signal is VBF-only in the VBF category and a mix elsewhere.
- Training is performed on each half of the events and applied to the other half (cross-evaluation) such that all events appear in the final plots.
- The BDT score is used as the final discriminant in the fit model.

Return

BDT cross-evaluation



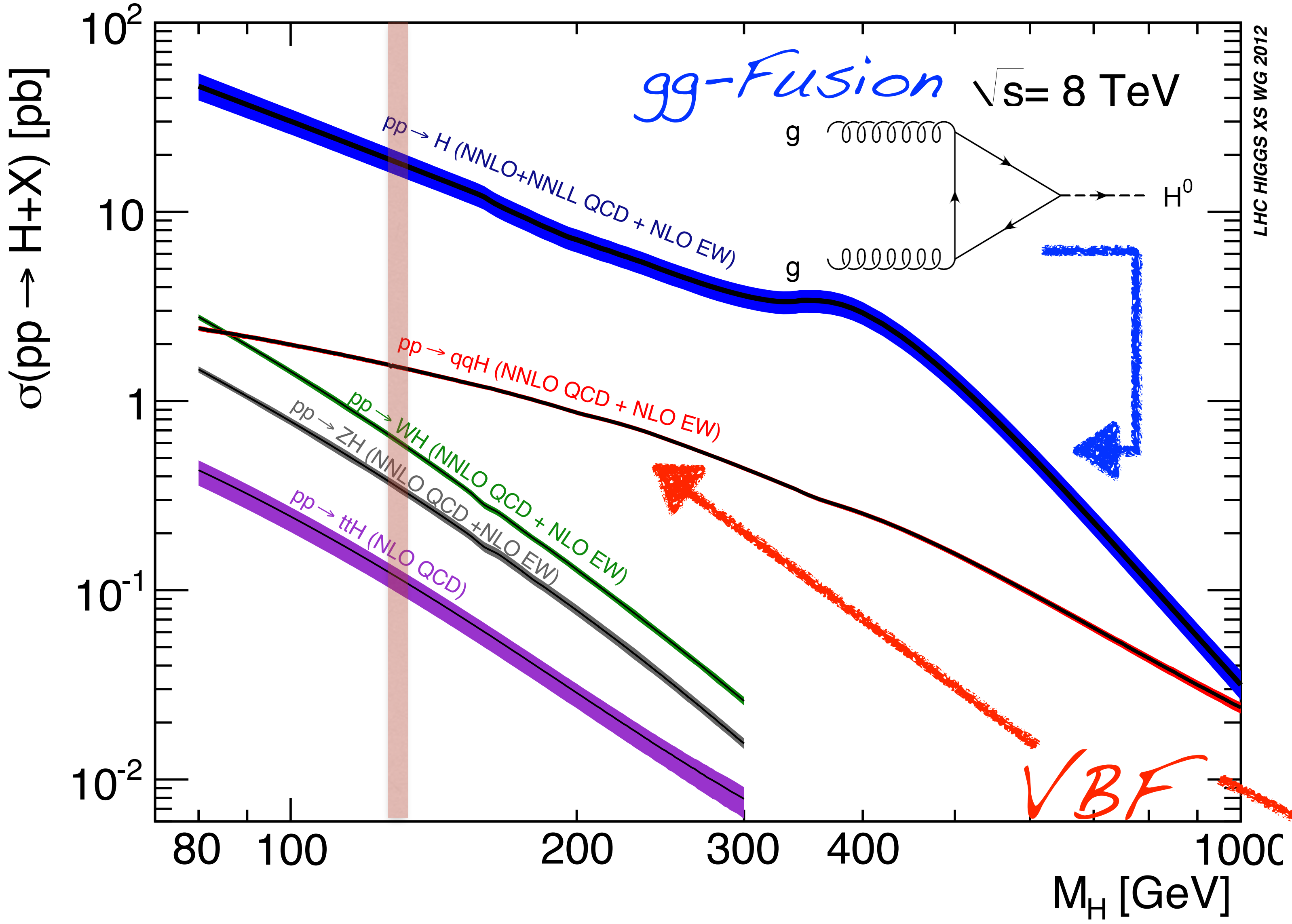


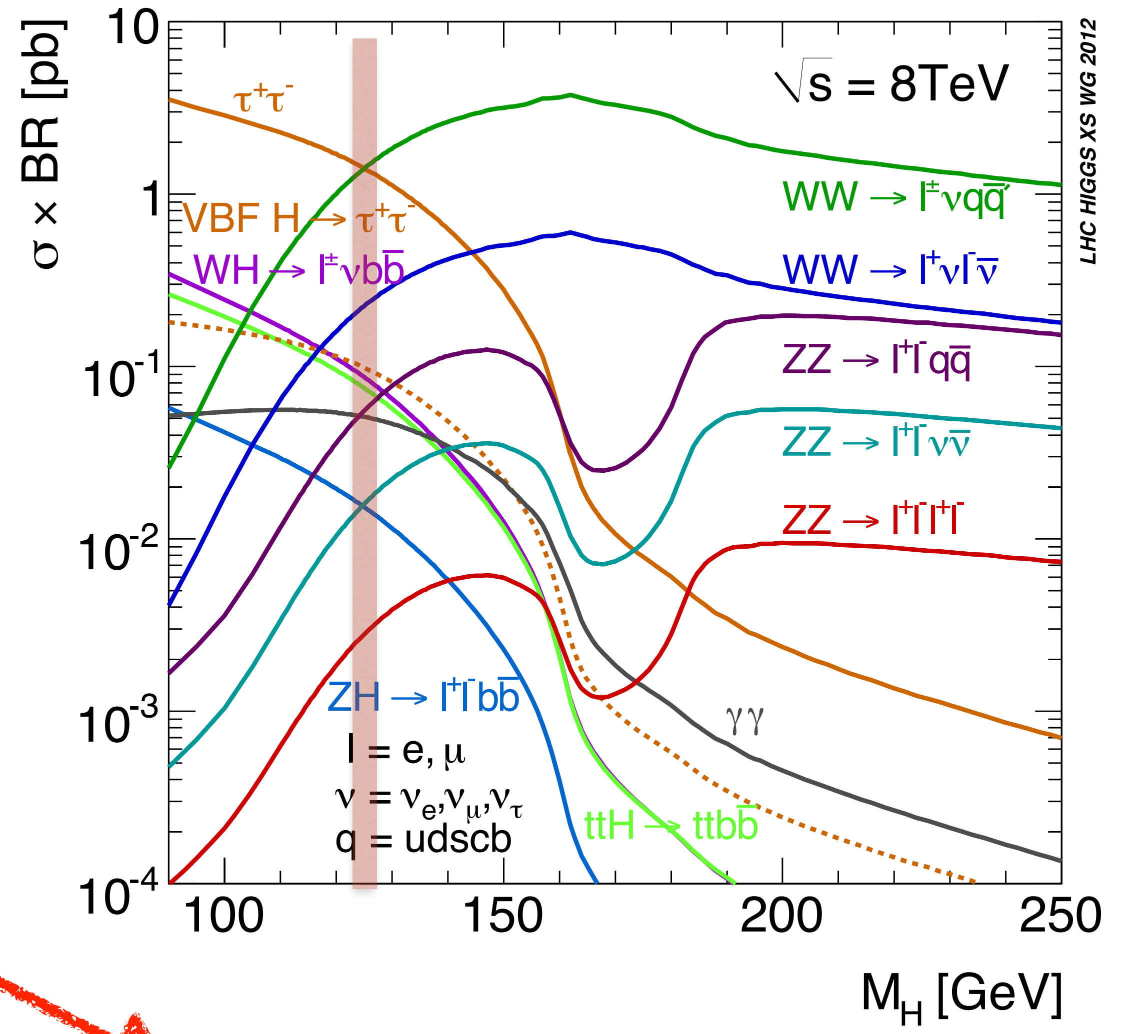


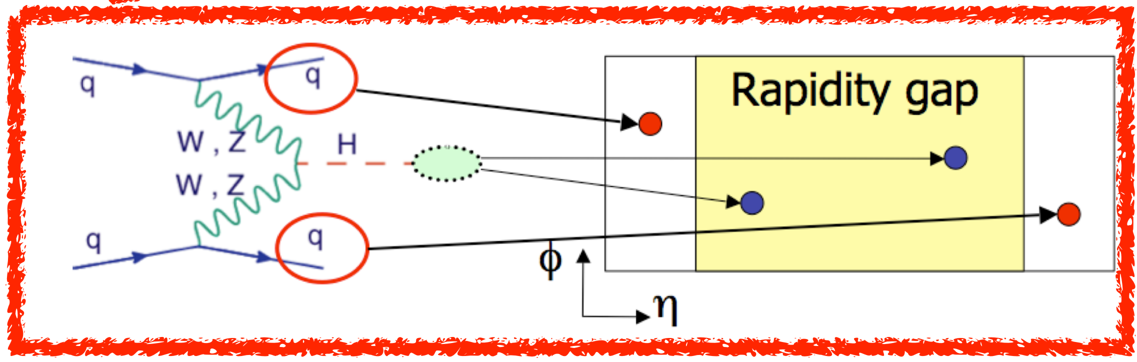
Return

Higgs phenomenology in LHC

focusing on fermions







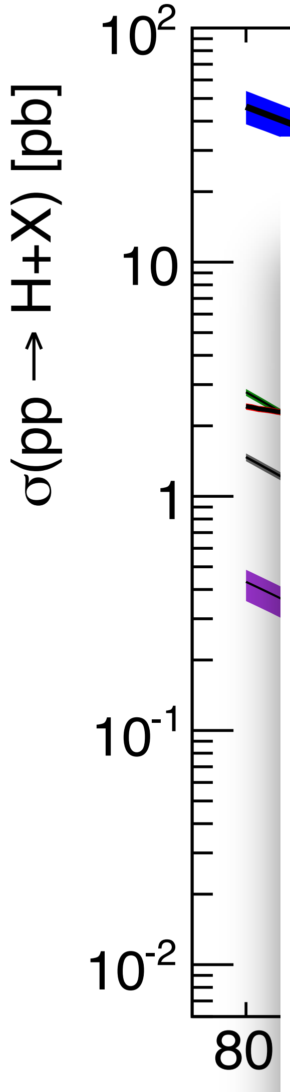
- **gg-Fusion,** dominant production mode
- **VBF** offers interesting topology for **ττ** with two forward jets
- **V(W,Z)H** smaller production rate but the most powerful channel to search for decays to b-quarks

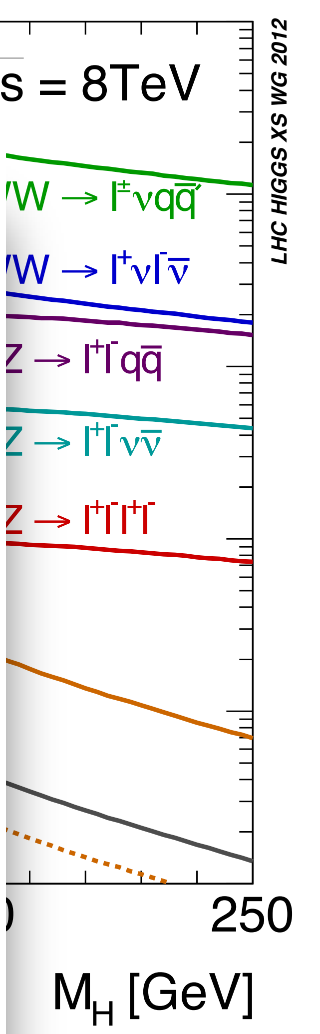
m	ττ	VH(bb)	μμ
σ×BR [pb]	~1.4	~0.08	~0.0002

Return

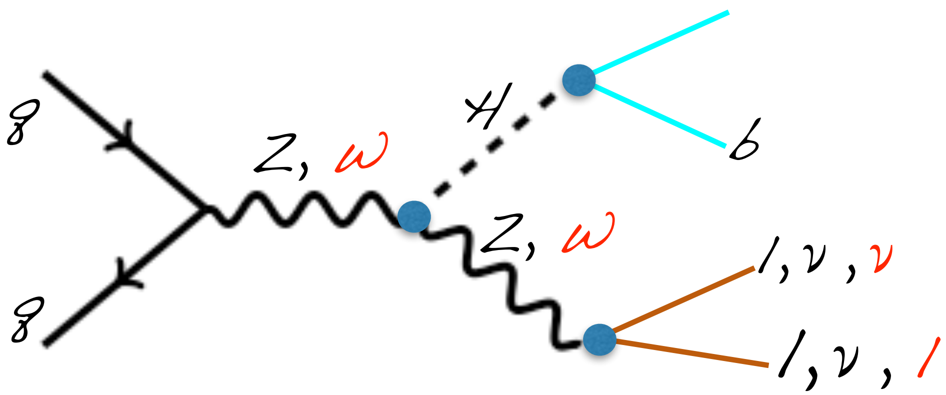
Higgs phenomenology in LHC

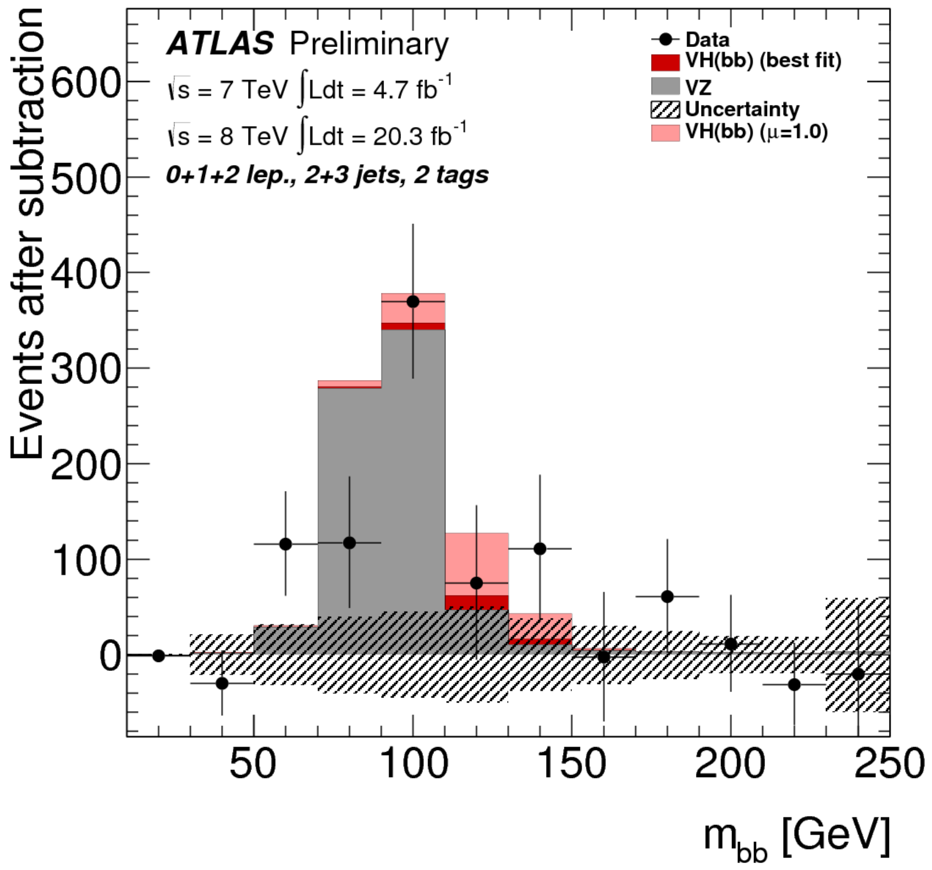
focusing on fermions





H→bb in VH channel



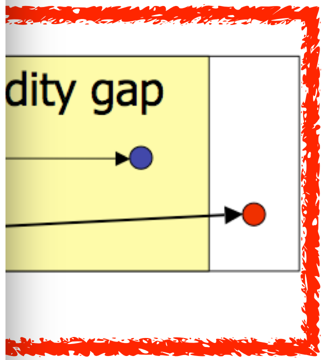


- No signal excess observed

$$\mu = \frac{\sigma^{VH\to b\bar{b}}_{measured}}{\sigma_{SM}} = 0.2^{+0.7}_{-0.6}$$

- Result consistent with **both S+B** and **B-only** hypotheses within 1σ
- **Observed**(**expected**) upper limit at 95% CL: **1.4**(**1.3**) x σ_{SM}

ATLAS-CONF-2013-079



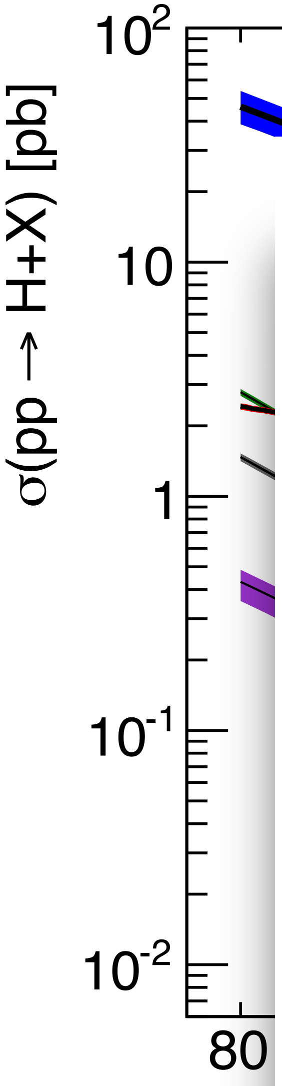
- **gg-Fu**
- **VBF** c
  with t
- **V**(**W,Z**)**H** smaller production rate
  the most powerful channel to search for decays to b-quarks

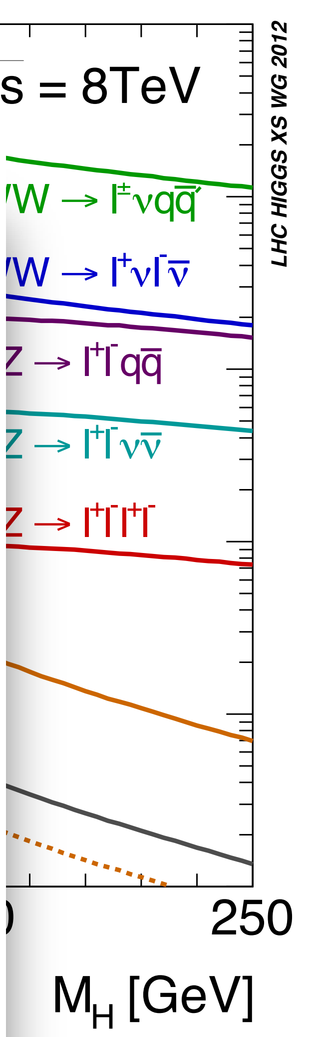
		VH(bb)	μμ
σ×BR [pb]	~1.4	~0.08	~0.0002

Return

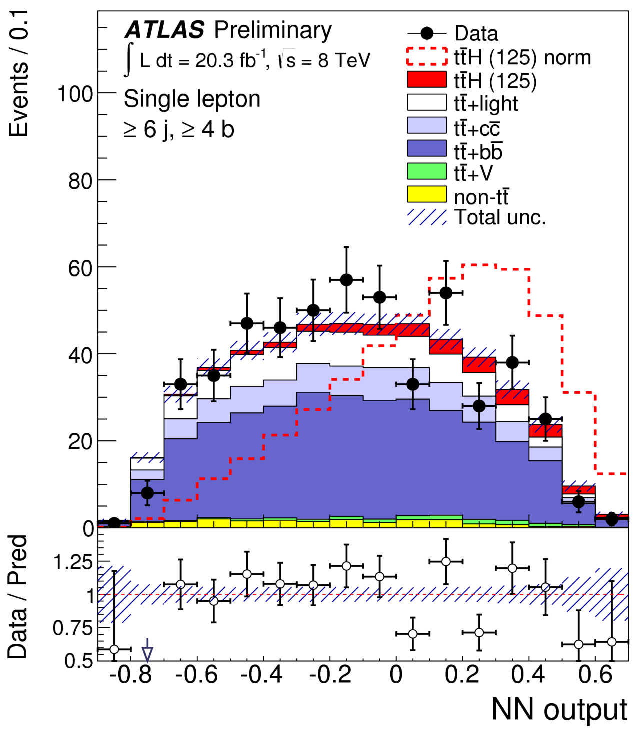
Higgs phenomenology in LHC

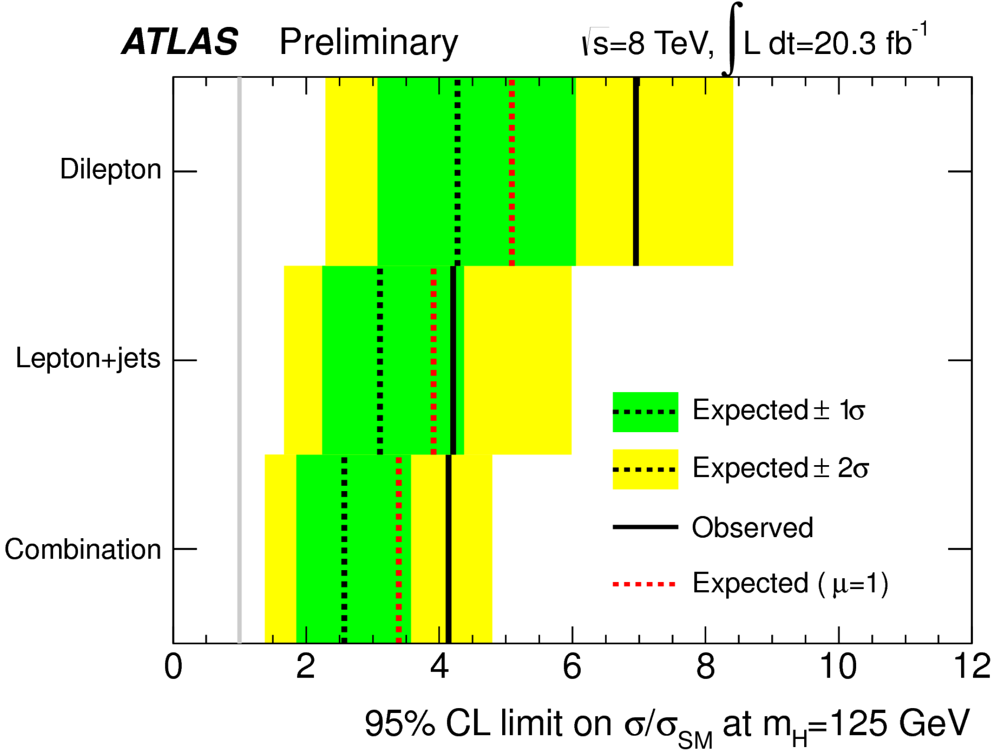
focusing on fermions





ttH→bb

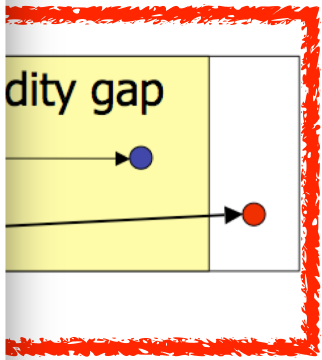




- **Direct** measurement of the **top**-Higgs **Yukawa coupling**
- Perform **MVA** in single **lepton** and **dilepton** channels
- **Observed** (**expected**) upper limit at 95% CL: **4.1** (**2.6**) x σ_{SM}
- Most sensitive ttH→bb result at LHC

ATLAS-CONF-2014-011

- **gg-Fu**
- **VBF** c
  with t
- **V**(**W**,**Z**)H smaller production rate
  the most powerful channel to search for decays to b-quarks

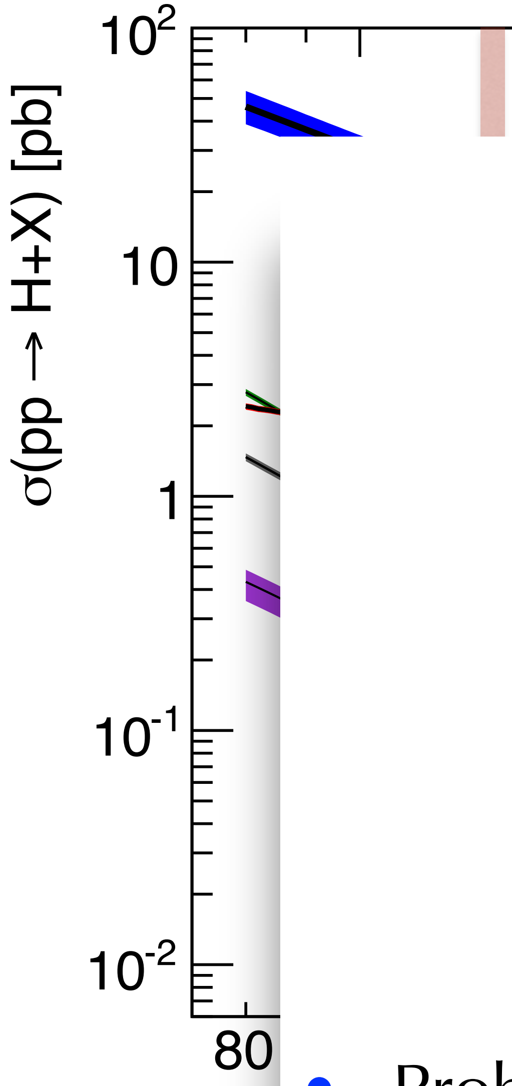


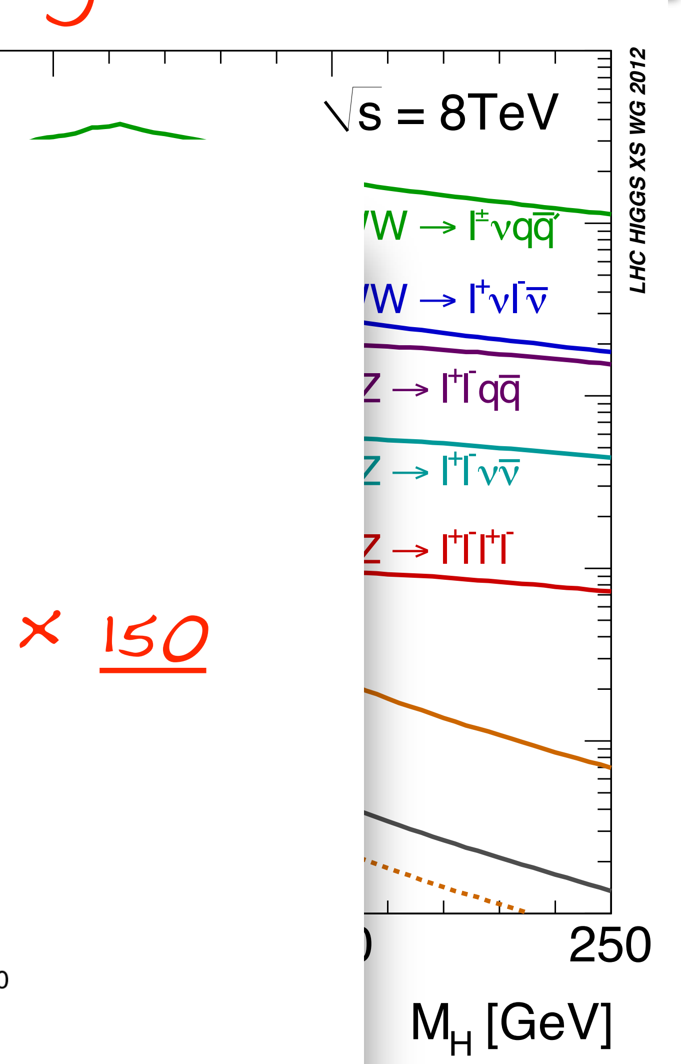
		VH(bb)	μμ
σxBR [pb]	~1.4	~0.08	~0.0002

Return

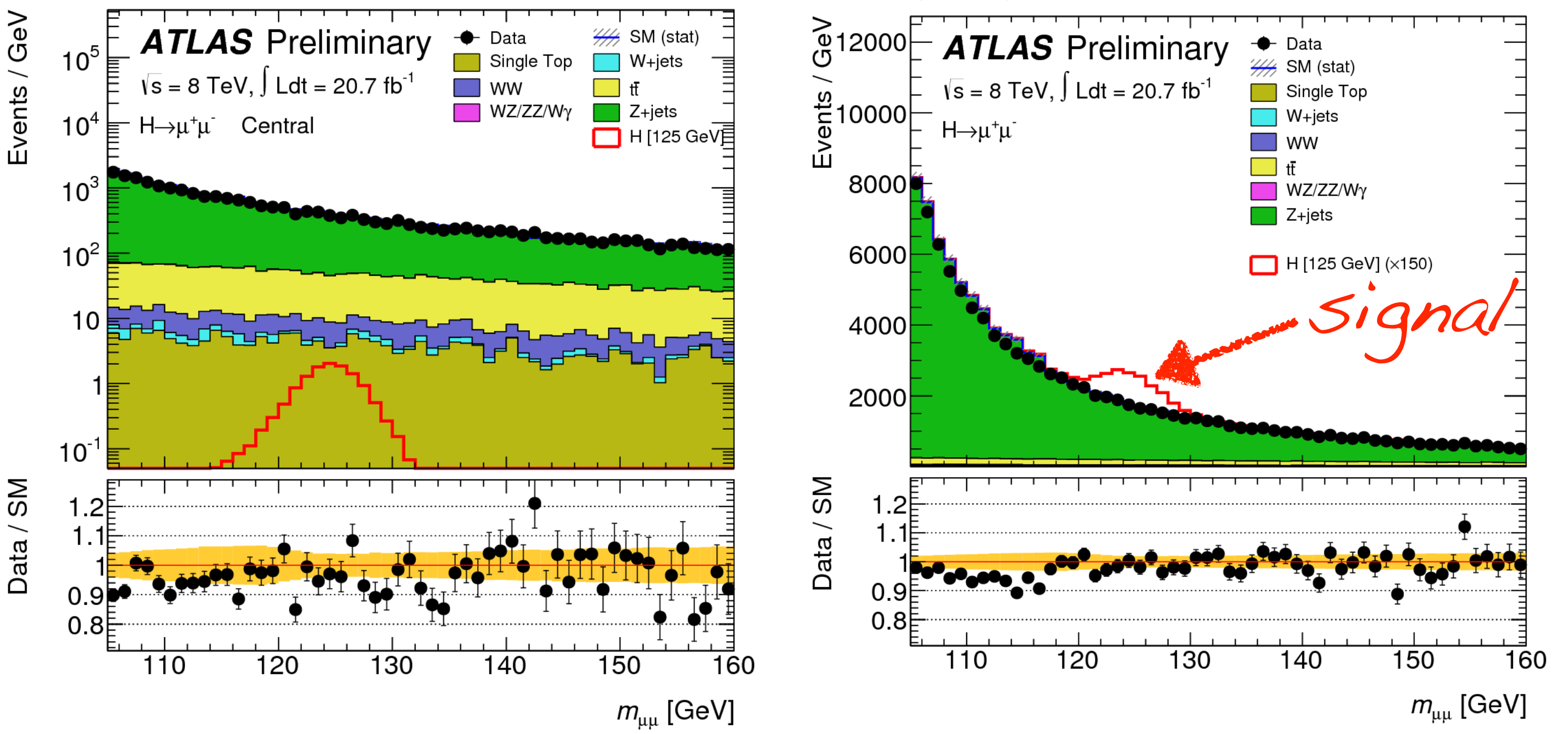
Higgs phenomenology in LHC

focusing on fermions





$H \rightarrow \mu\mu$

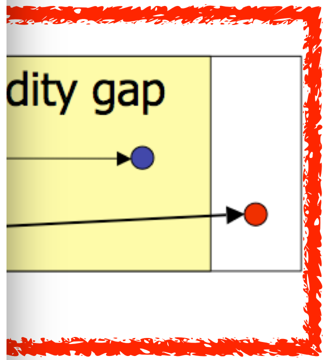


signal × 150

- Probe Higgs coupling to 2nd generation leptons
- **Clean signature** with two isolated opposite sign **muons**
- LHC current statistics **not sufficient** for **conclusive statement**
- **Observed**(**expected**) upper limit at 95% CL: **9.8**(**8.2**) x σ_{SM}

ATLAS-CONF-2013-010

- **gg-Fu**
- **VBF** c with t
- **V(W,Z)H** smaller production rate b the most powerful channel to search for decays to b-quarks



		VH(bb)	μμ
σ×BR [pb]	~1.4	~0.08	~0.0002

Return