ATLAS $H \to \tau\tau$ search results

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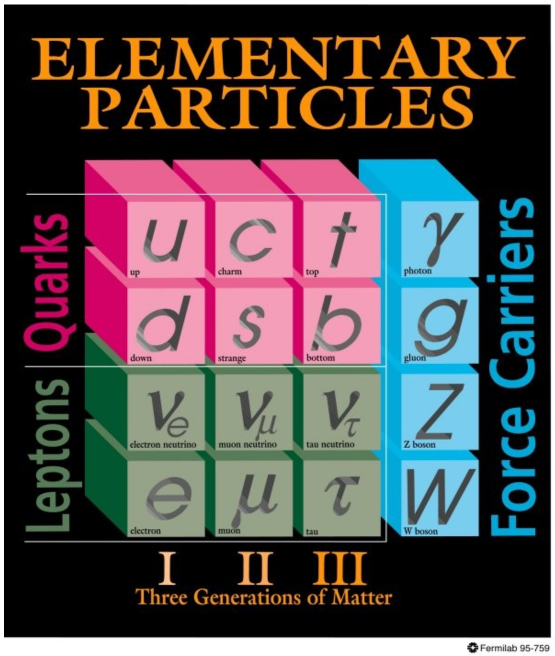
The Standard Model



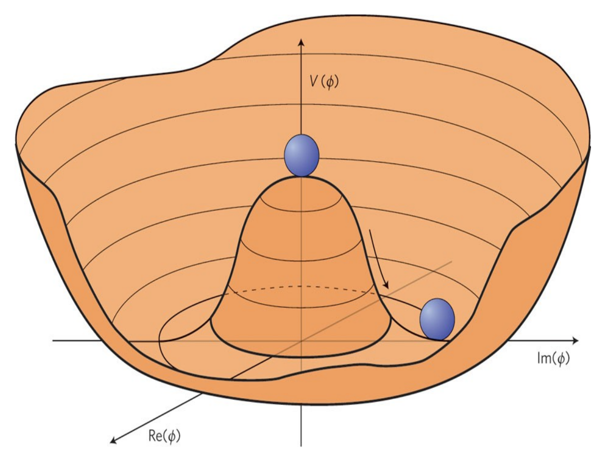
Force	Carrier
Strong	Gluons (g)
Electro-Weak	Electro-weak bosons (γ,W,Z)
Gravitation	?

- **Quarks and Leptons interact via the exchange of force carriers**

Interactions are controlled by symmetry:
$SU(3)\otimes SU(2)_L \otimes U(1)$

Gauge symmetry ⟺ **Particles massless**

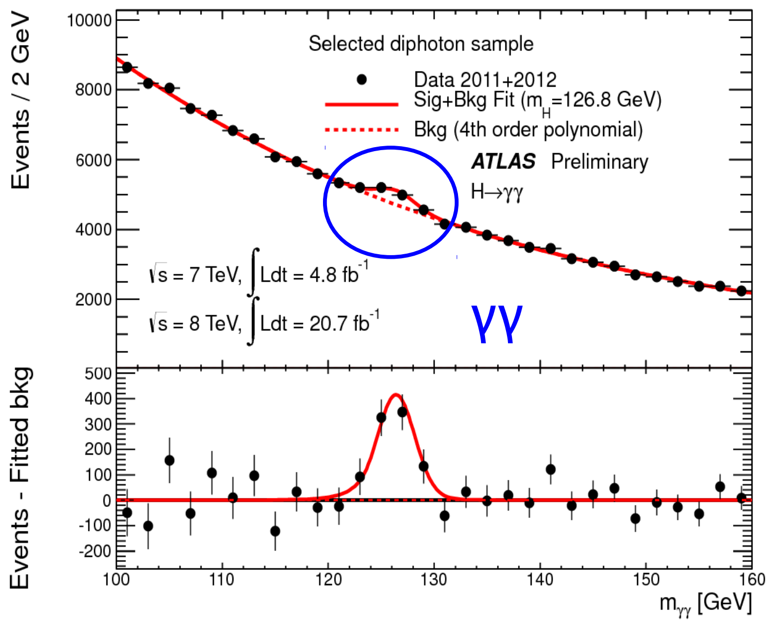
Gauge invariance is broken to generate particle mass – Higgs mechanism

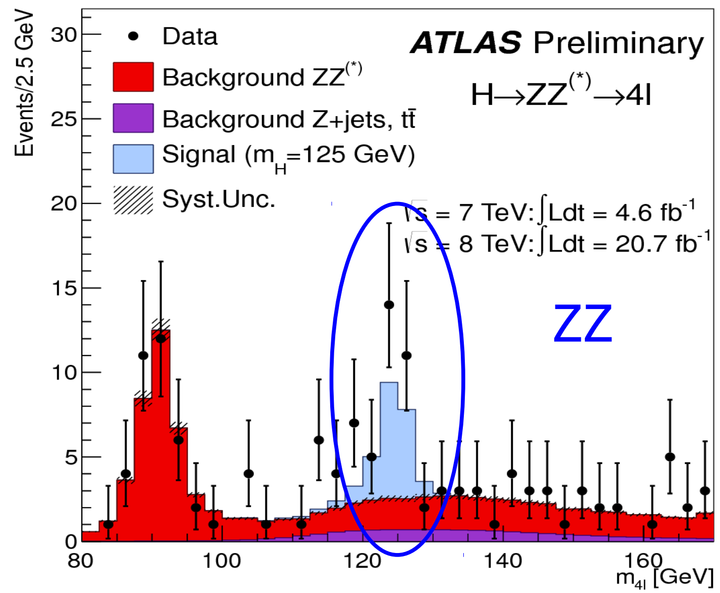


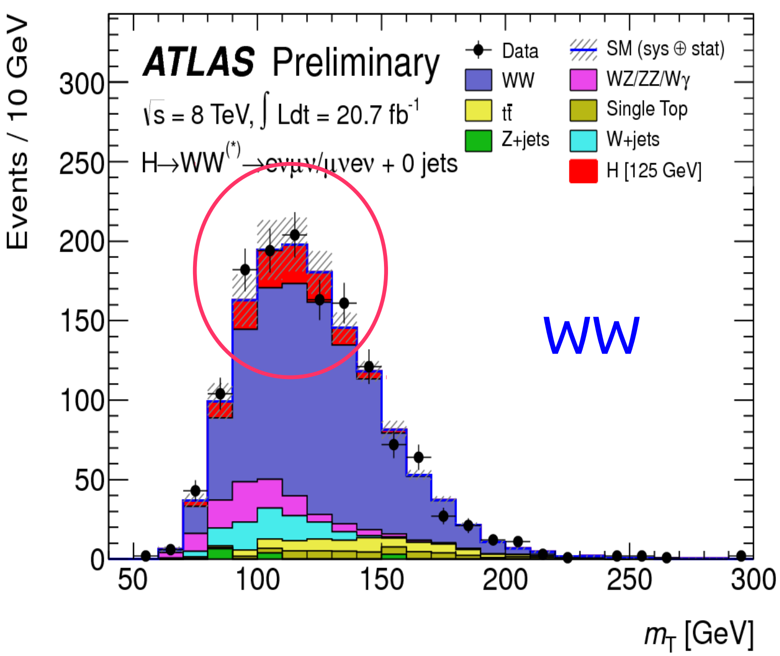
But the Higgs mass is not given by SM

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

The discovery of a Higgs-like particle



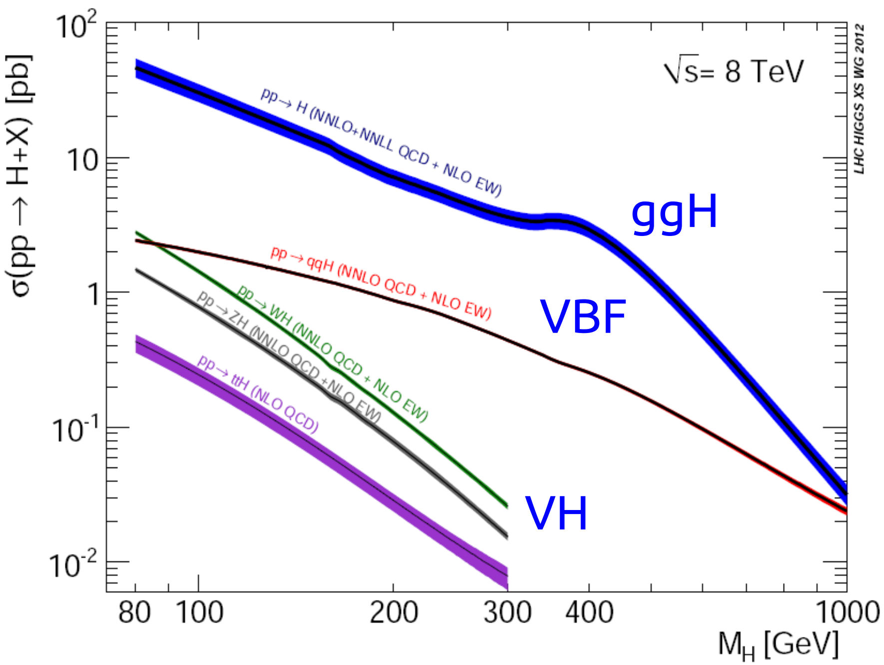


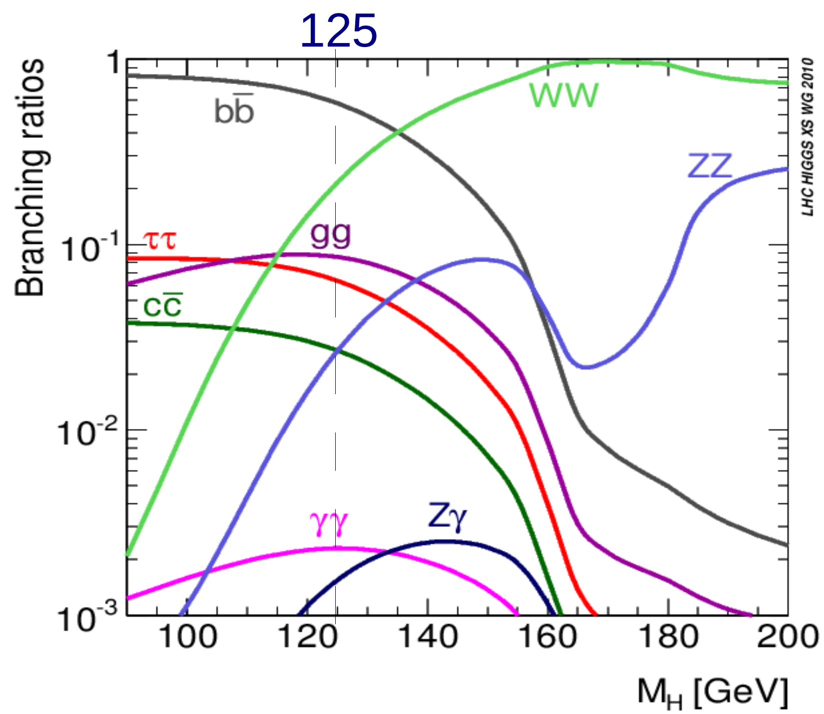


The Higgs-like particle was observed in γγ, ZZ → 4l and WW → 2l2ν decays

However, it has not been observed in fermion decays of bb and tautau yet. Need to see tautau to prove it is a SM Higgs!

Higgs production and decay





Higgs couplings to fermions and bosons:

$$g_{Hf\bar{f}} = \frac{g\, m_f}{2\, m_W}, \quad g_{HWW} = g\, m_W, \quad g_{HZZ} = \frac{g\, m_Z}{\cos\theta_W}$$

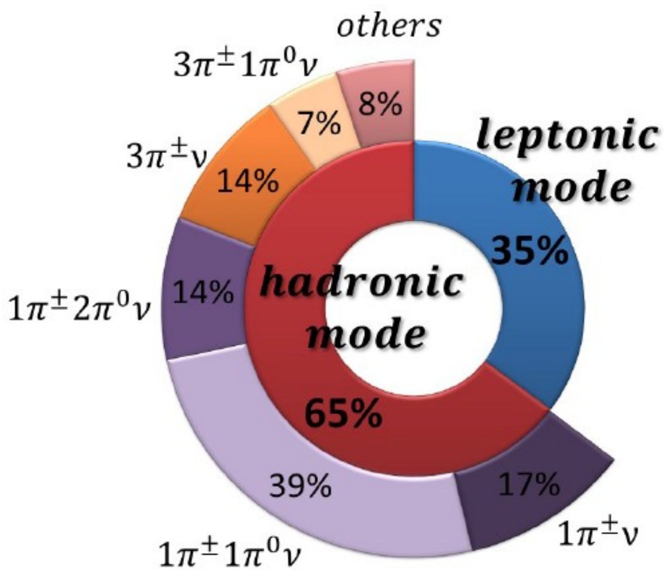
Yukawa Gauge Gauge

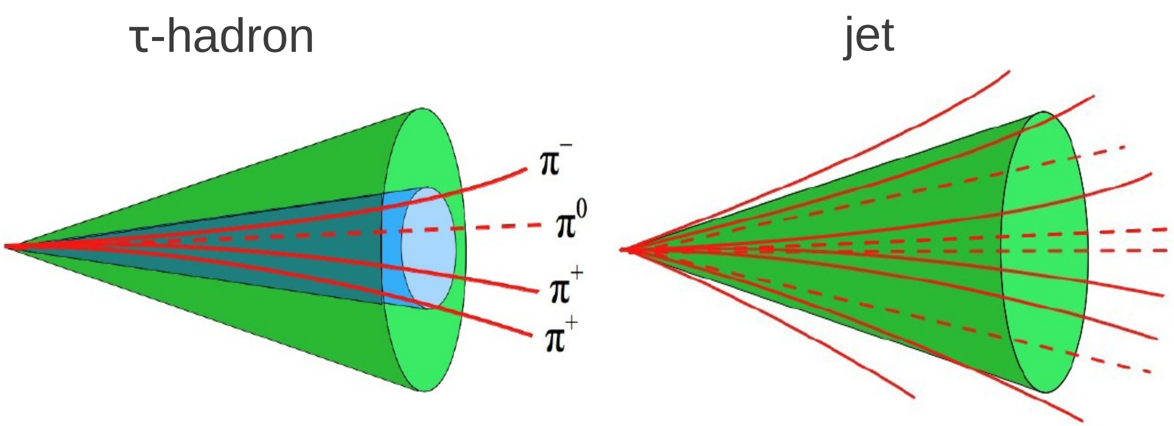
ττ channel: all final states can be reconstructed ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$). Relative high Branching Ratio. Direct measurement of Higgs Yukawa coupling, and prove it is a SM Higgs !

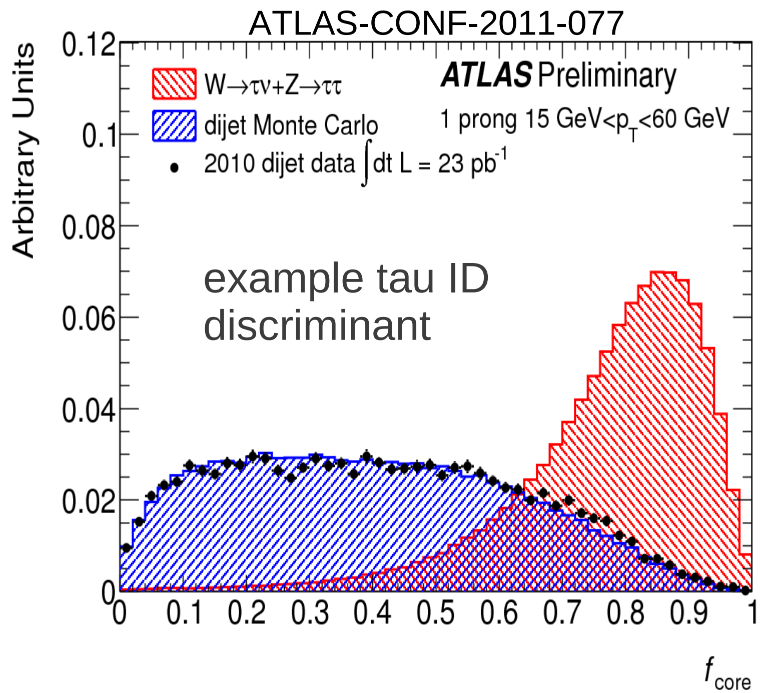
Braching ratios for a Higgs mass of 125 GeV:

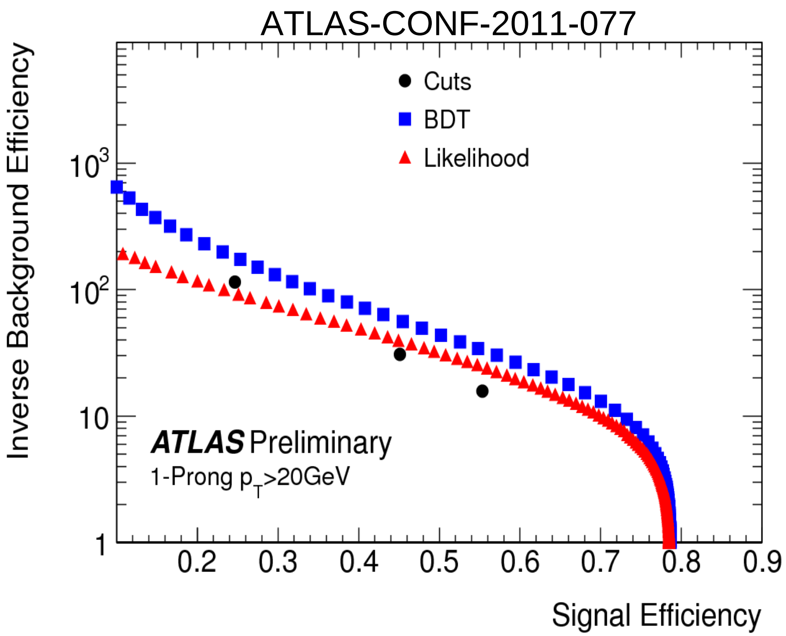
channel	BR
bb	57.7%
WW	21.5%
ττ	6.3%
ZZ	2.6%
γγ	0.23%

Tau ID and efficiency









For a typical working point around 60% efficiency, about 2% fake rate is expected

Channels and objects

Pre-selection	
$\tau_{lep}+\tau_{lep}+4\nu$	**Exactly 2 leptons with opposite** signs $30 < m_{LL} < 75$ (100) GeV for ee/μμ (eμ)
$\tau_{lep}+\tau_{had}+3\nu$	**Exactly 1 lepton and 1 hadronic τ** $p_T > 20$ (17) GeV for e (μ) **Di-lepton veto** $M_T < 50/30$ GeV
$\tau_{had}+\tau_{had}+2\nu$	**Exactly 2 hadronic taus** $p_T > 40$ (25) GeV for the leading (subleading) tau **Single lepton veto**

Three channels are mutually exclusive

Common object selection

Electron

$p_T > 15$ GeV, $|\eta| < 2.47$ with crack excluded
Calo and track isolation

Muon

$p_T > 10$ GeV, $|\eta| < 2.5$
Calo and track isoltion

Hadronic tau

$p_T > 20$ GeV, $|\eta| < 2.5$
1 or 3 tracks (prongs) in $\Delta R<0.2$
Multivariate BDT for ID

Jet

$p_T > 25$ GeV, $|\eta| < 4.5$
AntiKt4 jets, Jet Vertex Fraction cut

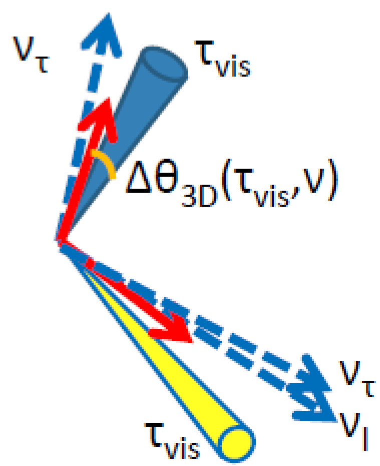
H → tautau mass reconstruction

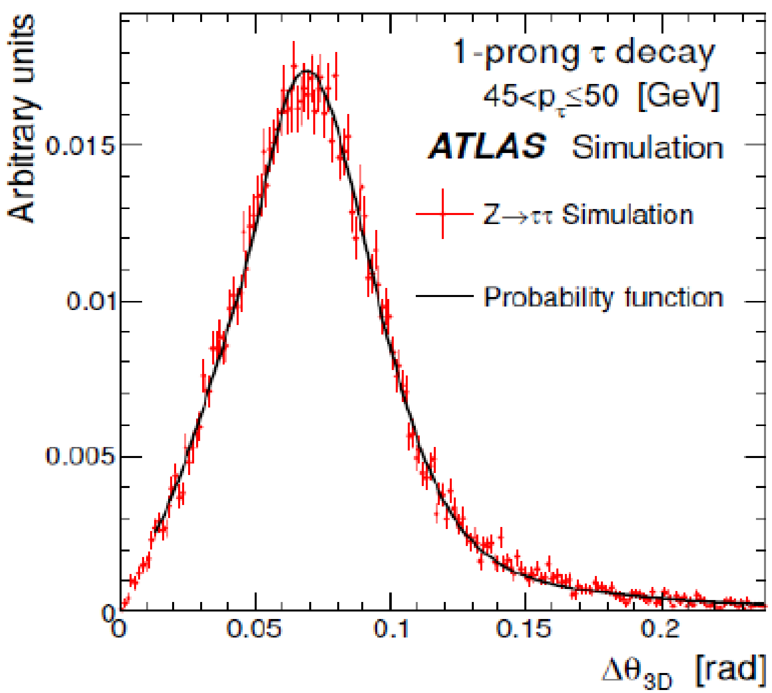
- Collinear mass reconstruction:
  - Assume neutrinos and visible decay products from the tau are collinear, then ditau mass can be calculated as

$$m_{\tau\tau} = \frac{m_{\ell\ell}}{\sqrt{x_1 \cdot x_2}}$$

$x_{1,2}$ are the fractions of momenta carried away by the visible decay products from the tau

- Missing Mass Calculator (MMC):
  - Does not assume neutrinos collinear with visible decay product. Taking into account the MET resolution, scan the $\Delta\theta_{3D}(\tau_{vis},\nu)$ space from simulation for the most likely solution consistent with tau decay kinematics





Categories, MET cut and mass calculator

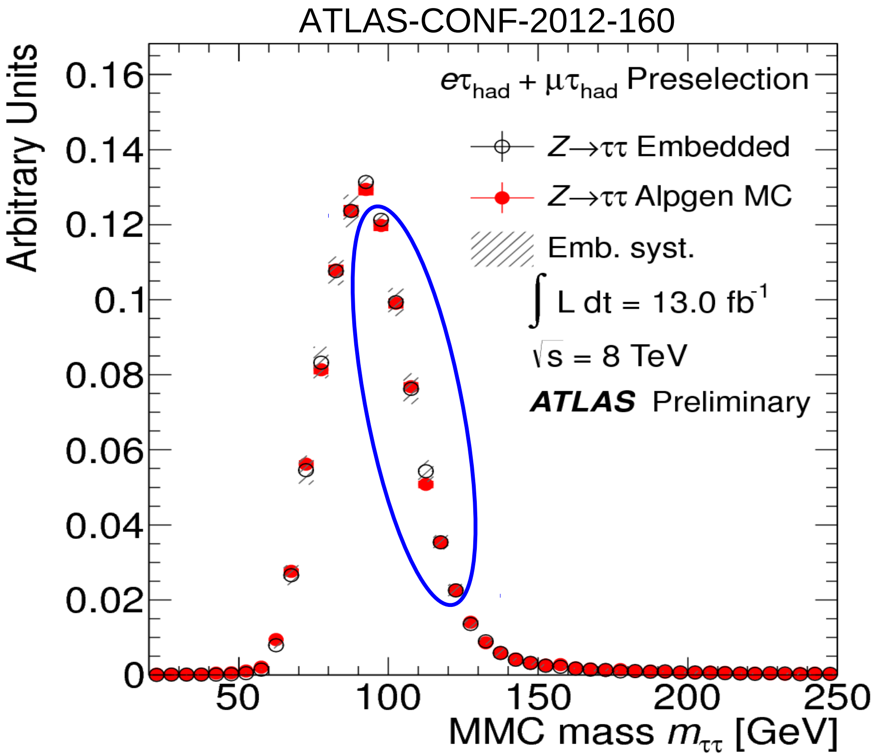
ll	lh	hh
2-jet VBF (p_T>40,25) 2-jet VH (p_T>40,25)	2-jet VBF (p_T>40,30)	2-jet VBF (p_T>50,30)
Boosted: $p_{T,H}$>100	Boosted: $p_{T,H}$>100	1-jet inclusive (p_T>70)
1-jet inclusive (p_T>40)	1-jet inclusive (p_T>30)	
0-jet inclusive in eμ channel	0-jet exclusive (p_T<30)	
MET>40 for SF MET>20 for DF	MET>20	MET>20
MMC mass	MMC mass	MMC mass

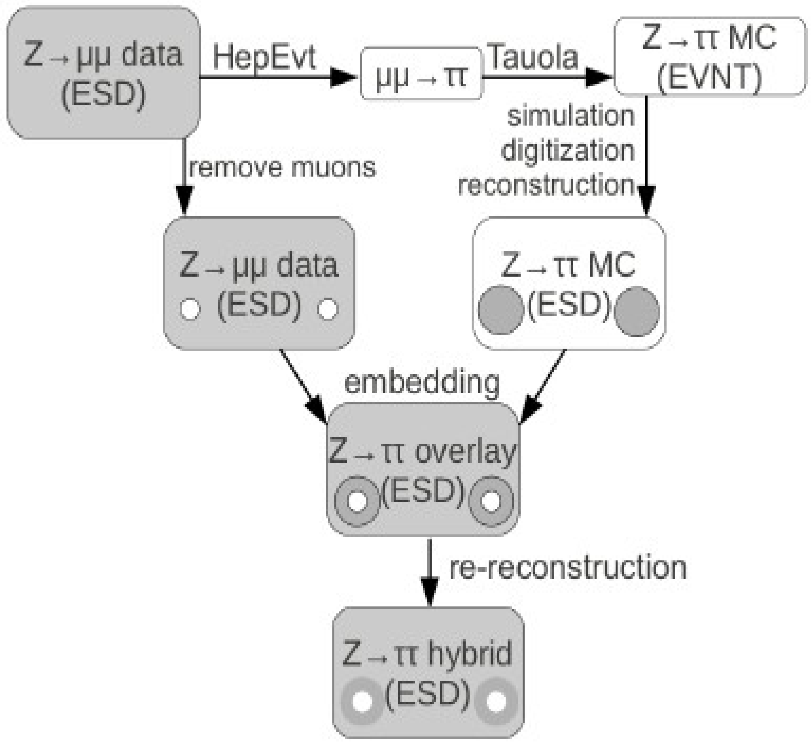
All units are in GeV

Most sensitive categories: VBF and Boosted

Z → ττ background

- Z → ττ (dominant background) is estimated from data using embedding:





The Higgs signal is sitting on the right shoulder of the Z → ττ peak. It is very important to use embedding to model this background well

1) Replace muons from Z → μμ data by taus and decay the taus

2) Embed the simulated tau decay products into the original event

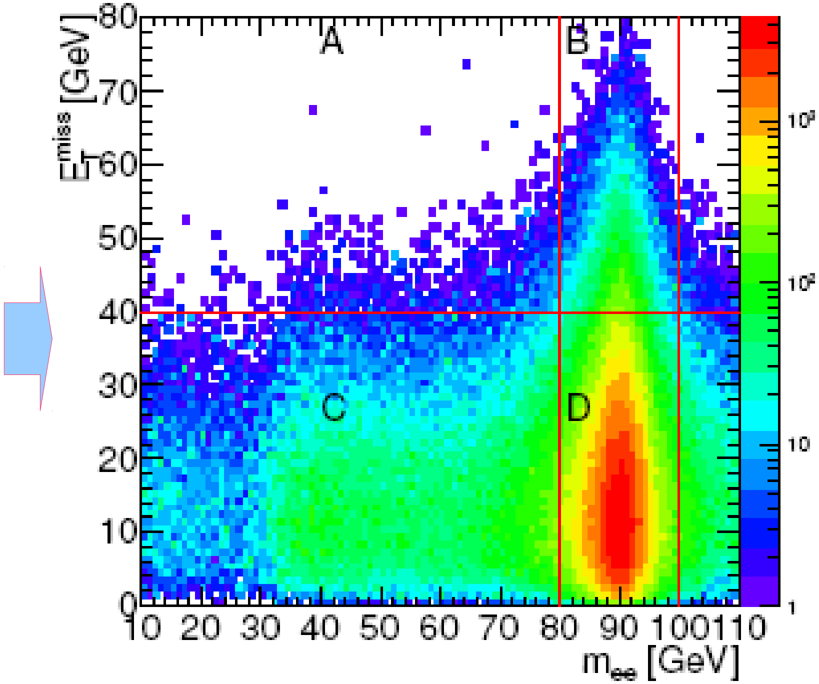
ll-channel background estimation

- Fake lepton backgrounds: QCD, W+jets and semi-leptonic ttbar. At least one lepton is misidentified or coming from jet fragmentation and secondary decays

  — We reverse the lepton isolation to get a control sample, and fit it to the subleading lepton p_T spectra to normalize it

- Drell-Yan $Z \rightarrow ee, \mu\mu$ background: normalize it with the control events in the Z mass window

$$A_{MC}^{corrected} = A_{MC} \times \frac{B_{data}}{B_{data} + D_{data}} \times \frac{B_{MC} + D_{MC}}{B_{MC}}$$



- Top background (ttbar and single top): controlled by the events in the b-tagged region (signal regions have b-veto cut applied)

lh-channel background estimation

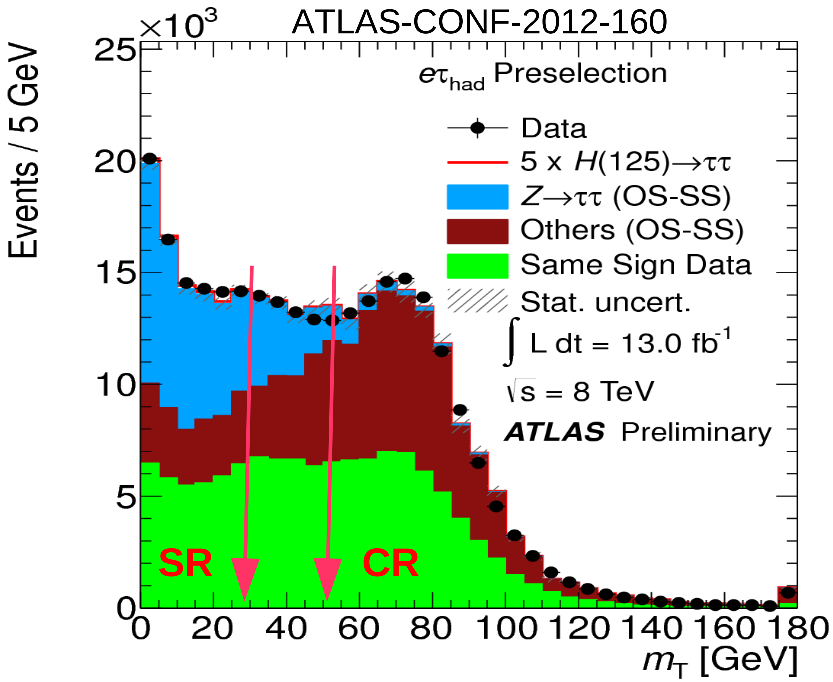
- Basic idea is that the background in signal region (OS) is equal to the background in SS signal region, plus the "add-on" (OS - SS) terms

$$n_{\rm OS}^{\rm bkg} = n_{\rm SS}^{\rm all} + \underbrace{n_{\rm OS-SS}^{QCD} + n_{\rm OS-SS}^{W+\rm jets} + n_{\rm OS-SS}^{Z\to\tau\tau} + n_{\rm OS-SS}^{\rm other}}_{\text{Add-on terms}}$$

- QCD add-on is expected to be zero – checked in a control region with MET<15 GeV:

$$n_{OS-SS}^{QCD} \to 0$$

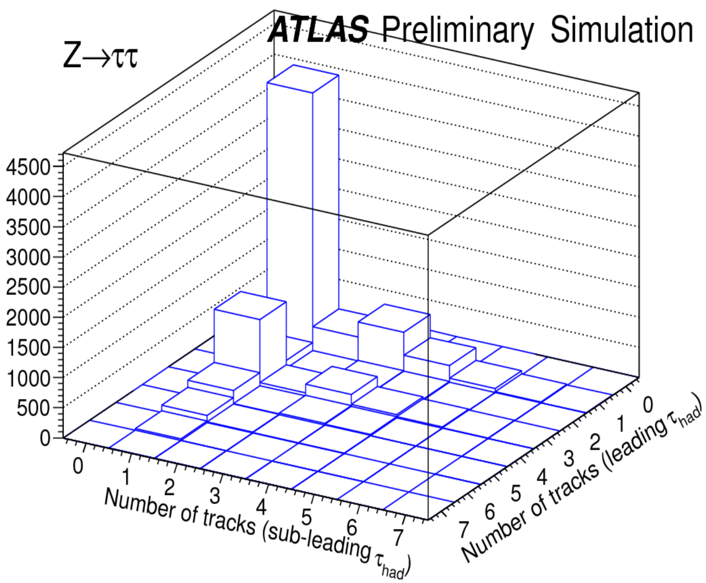
- W+jet add-on is estimated from a control region with m_T>50 GeV
- $Z\to\tau\tau$ add-on is estimated from the embedding sample
- ”other” add-on is estimated from MC simulation, and contains $Z\to ee,\mu\mu$, top and diboson



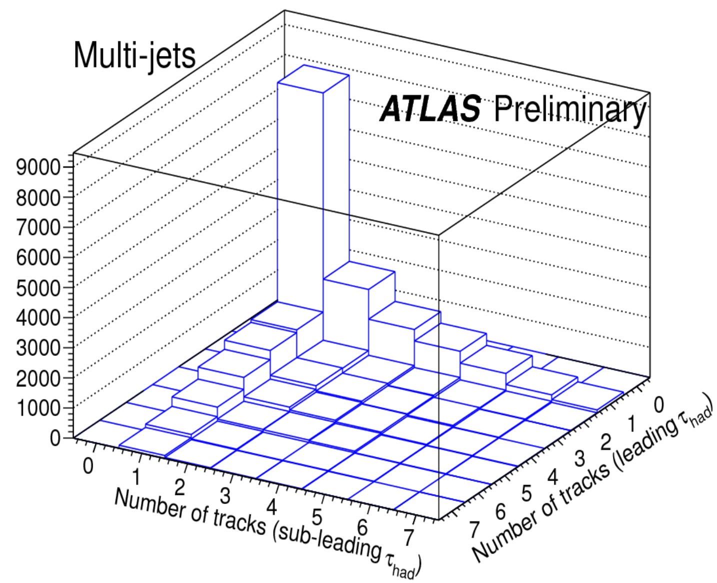
hh-channel background estimation

- To separate real tau from fake tau events, count the number of tracks around the hadronic tau objects

- Perform 2-D fit to the track multiplicity distributions of the 2 taus



Z→ττ

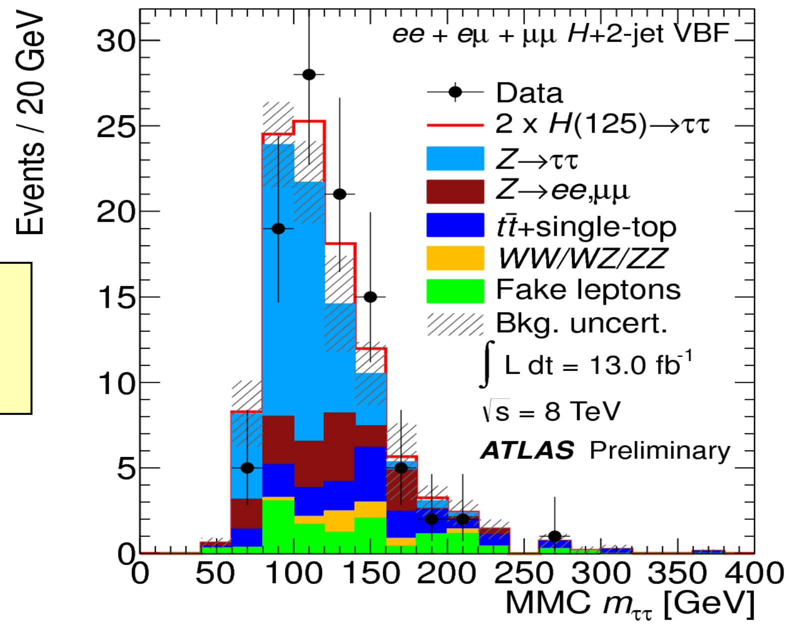


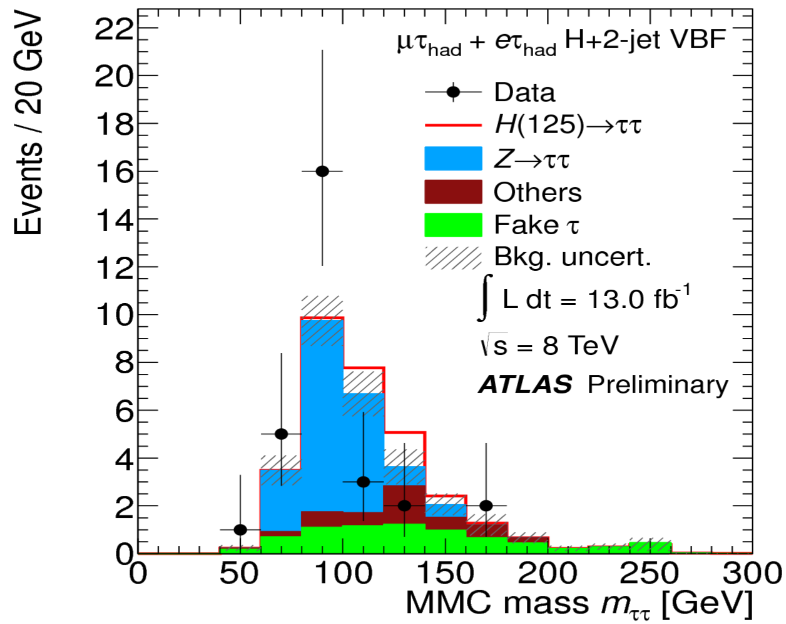
QCD

- Embedding sample is used for Z→ττ, whose normalization is determined in a low $m_{\tau\tau}$ region

Invariant mass of ττ

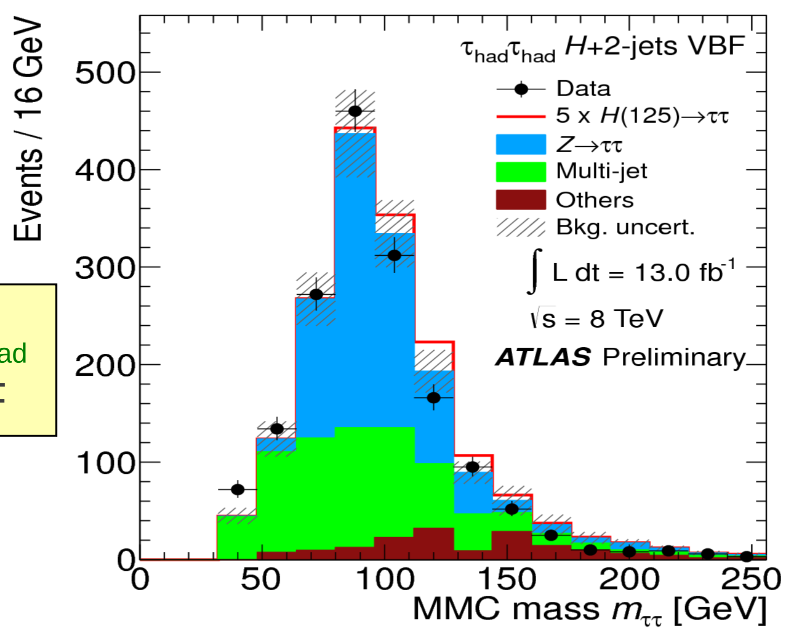
$\tau_{lep}\tau_{lep}$
VBF

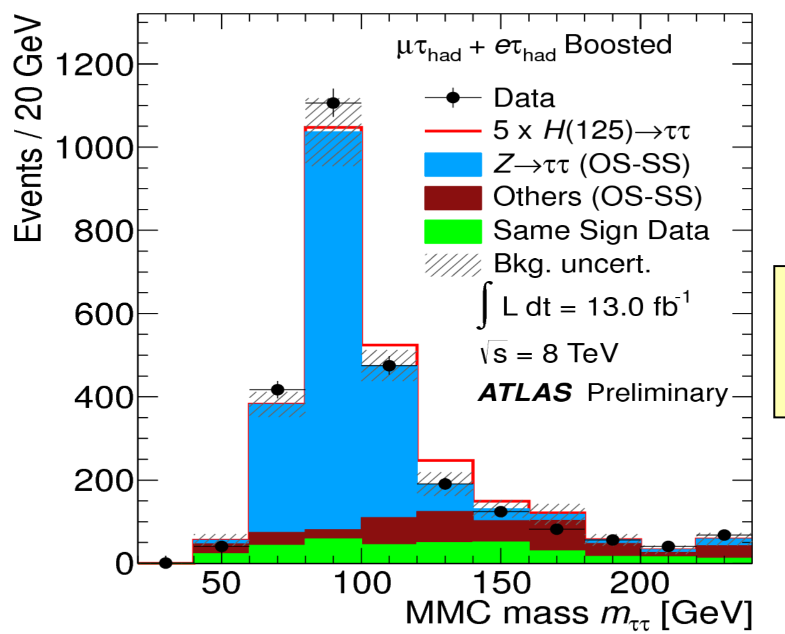




$\tau_{lep}\tau_{had}$
VBF

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





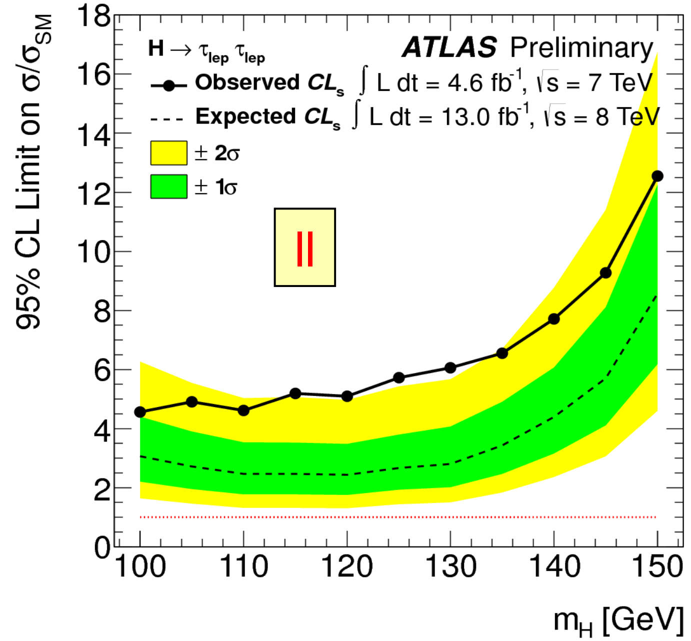
$\tau_{lep}\tau_{had}$
Boosted

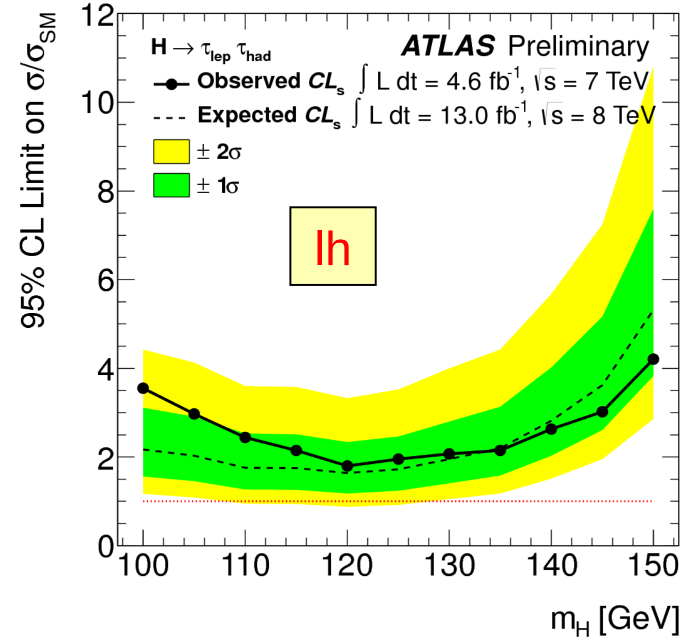
Systematics

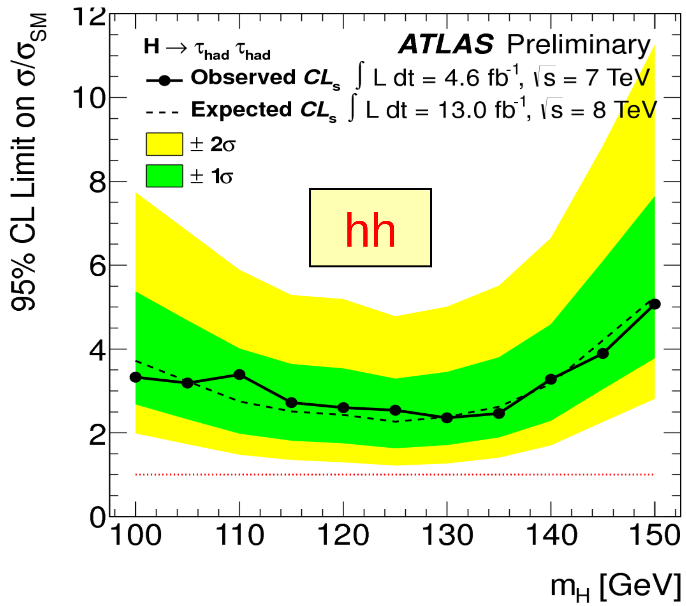
Uncertainty	$H \to \tau_{lep}\tau_{lep}$	$H \to \tau_{lep}\tau_{had}$	$H \to \tau_{had}\tau_{had}$
		$Z \to \tau^+\tau^-$	
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	2–4%	2–5%	2–4%
Normalisation	5%	4% (non-VBF), 16% (VBF)	9–10%
		Signal	
Jet Energy Scale	1–5% (S)	3–9% (S)	2–4% (S)
Tau Energy Scale	–	2–9% (S)	4–6% (S)
Tau Identification	–	4–5%	10%
Theory	8–28%	18–23%	3–20%
Trigger Efficiency	small	small	5%

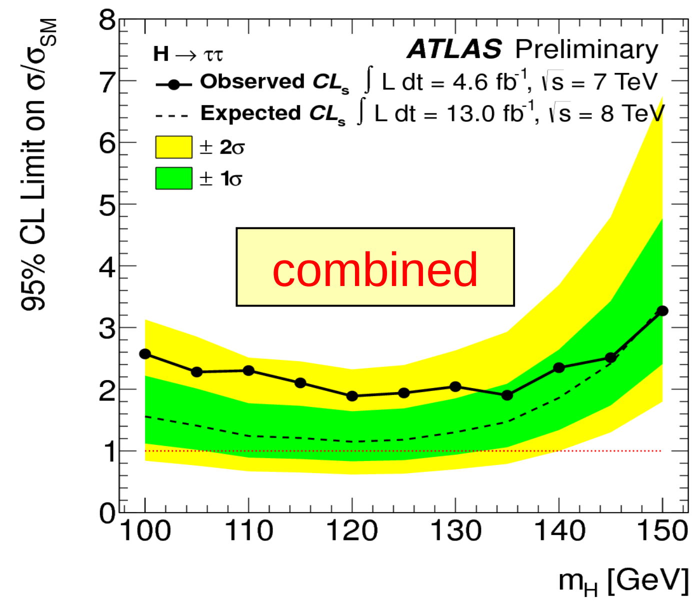
- Dominant systematics for signal are JES, TES and theory (25% for ggH in in the VBF category being the largest)
- No JES uncertainty for Ztautau – good and expected!
- Systematics of data-driven methods. For example:
  - QCD and W+jets: 20-25% in ll amd ~50% in lh

The limits on signal cross sections



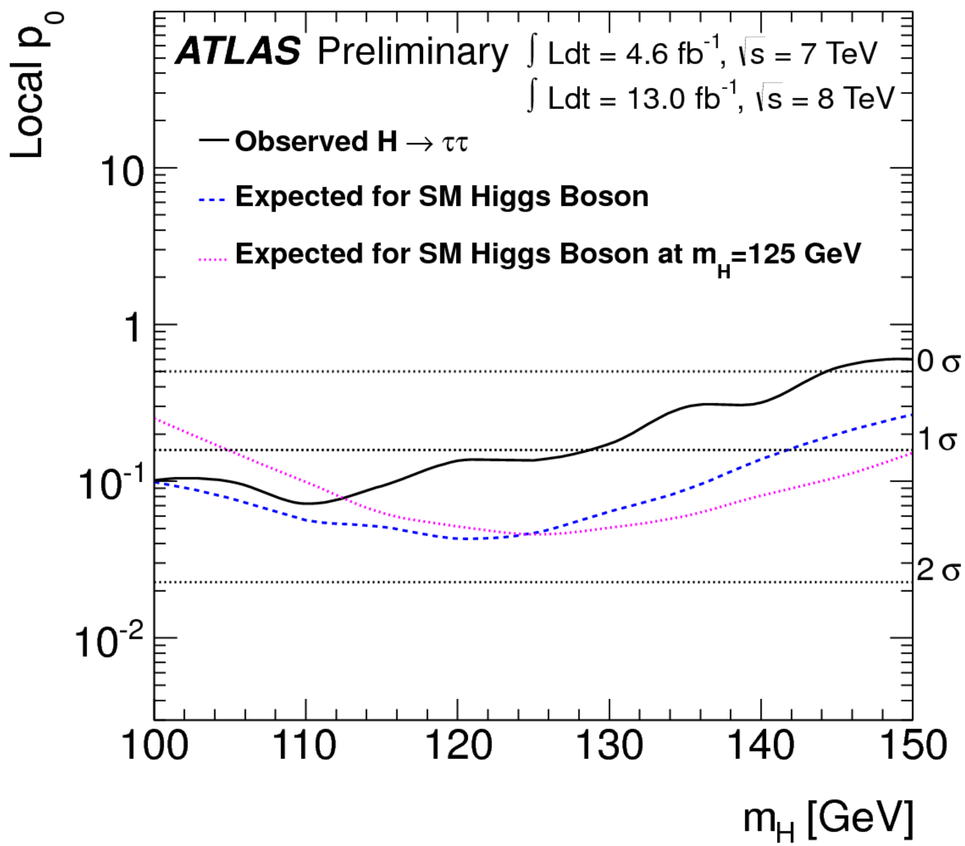


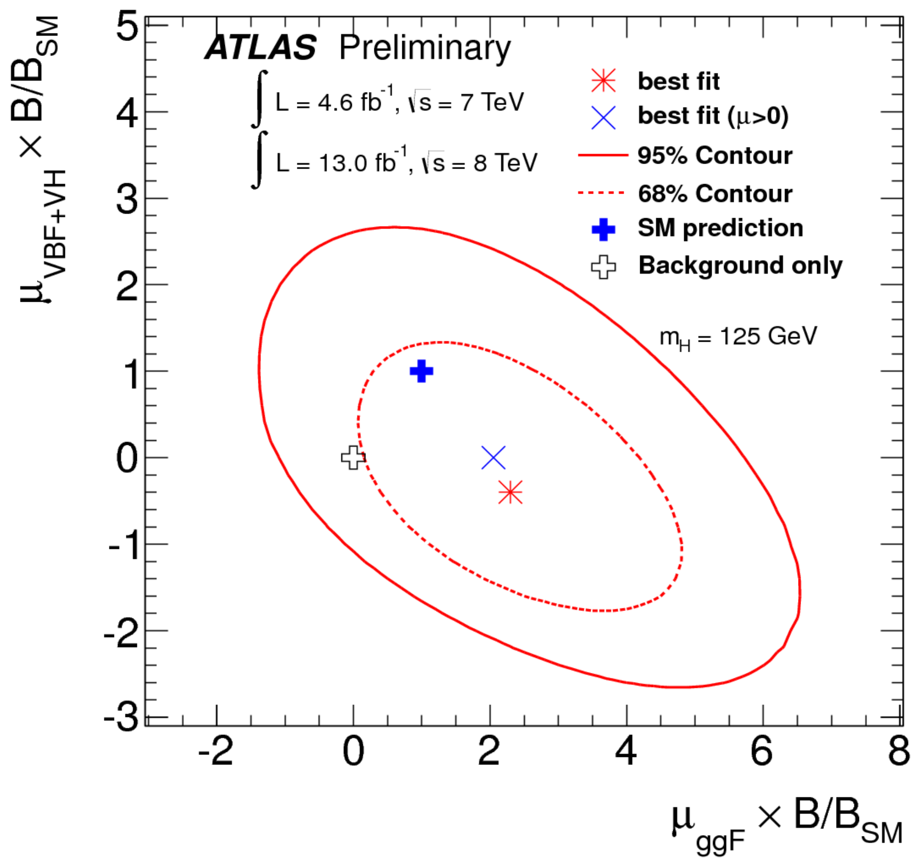




For mass at 125 GeV, expected limit is 1.2xSM, observed is 1.9xSM

The signal strength





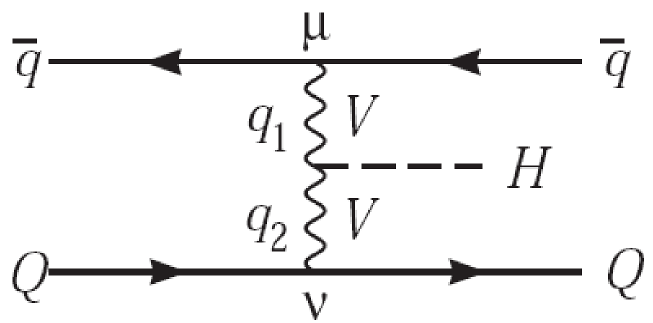
Best-fit $\mu = 0.7 \pm 0.7$ at $m_H = 125$ GeV

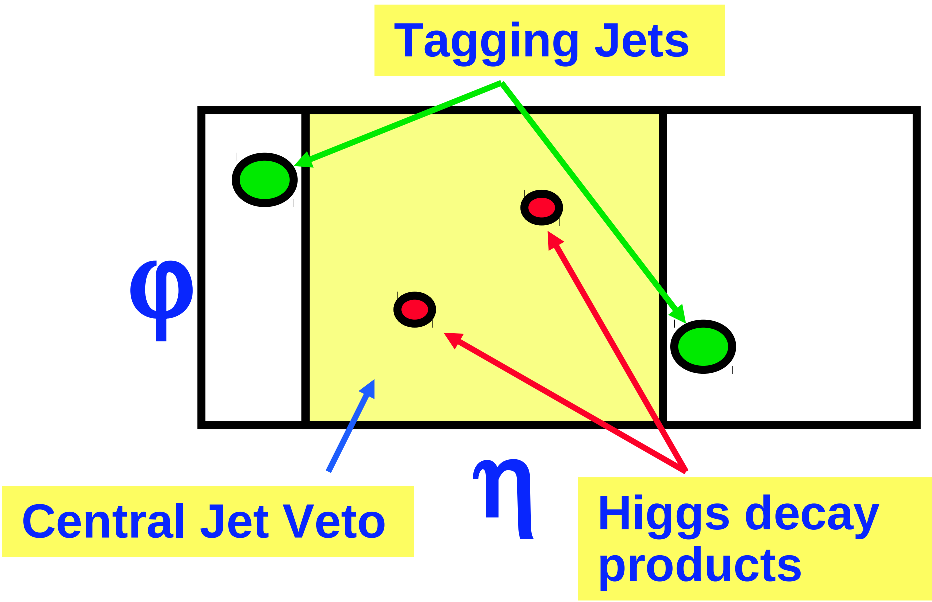
The best-fit stengths are still compatible with both bg-only and sig+bg hypothethis

Probing the HVV structure in VBF

The VBF channel is very powerful in revealing the HVV vertex structure:

$$T^{\mu\nu}(q_1, q_2) = \underbrace{a_1(q_1, q_2)\ g^{\mu\nu}}_{\text{SM}} + \underbrace{a_2(q_1, q_2)\ [q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu]}_{\text{CP-even}} + \underbrace{a_3(q_1, q_2)\ \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}}_{\text{CP-odd}}$$





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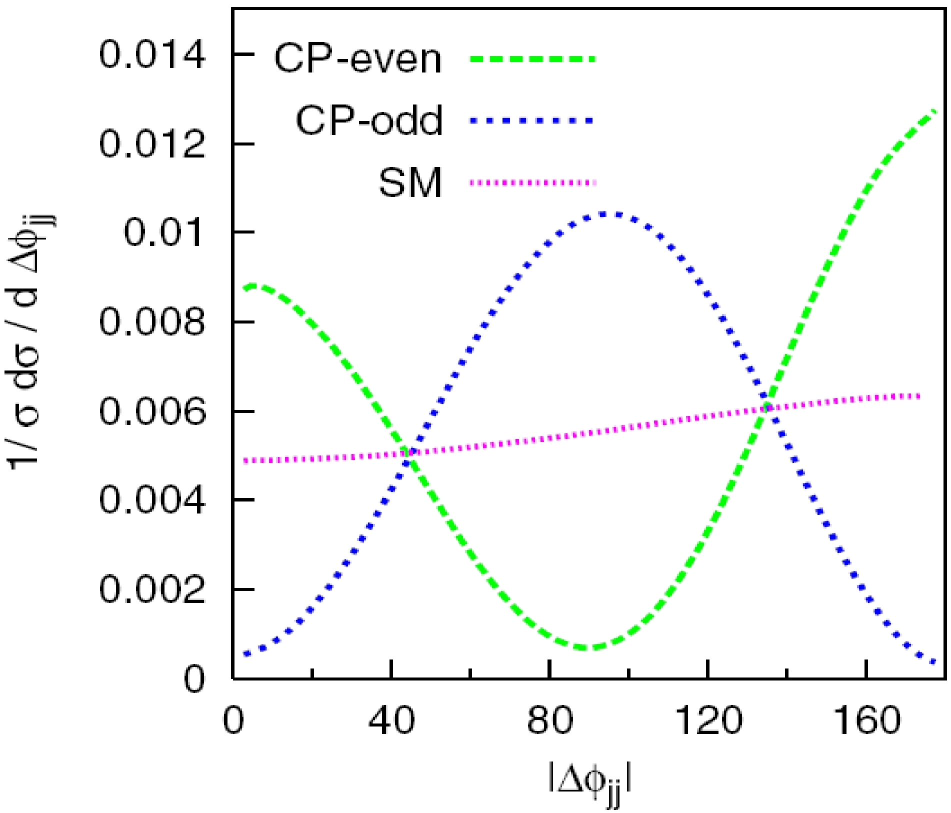
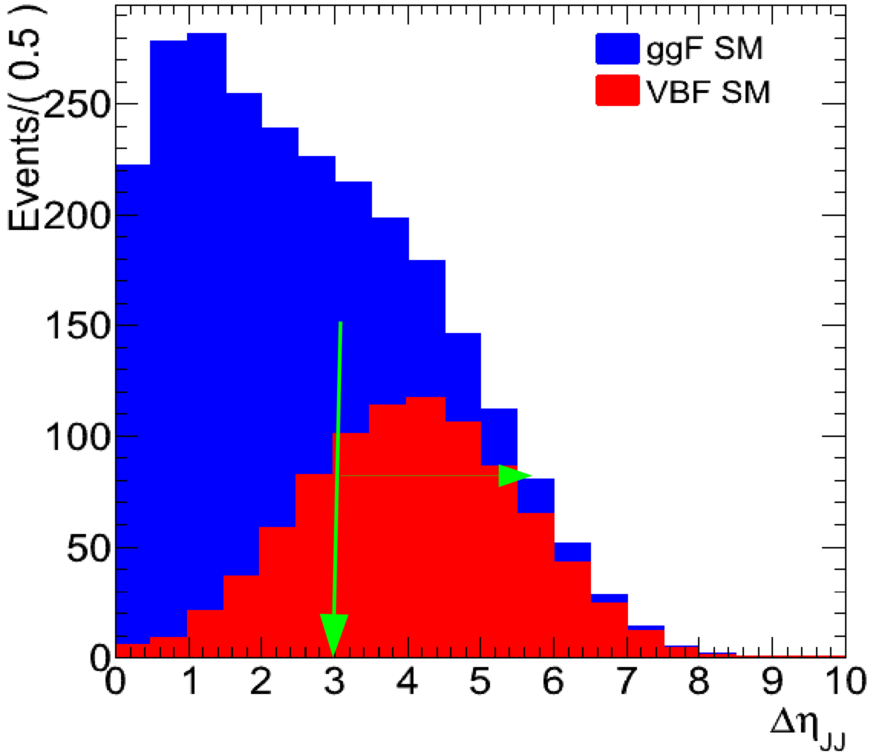
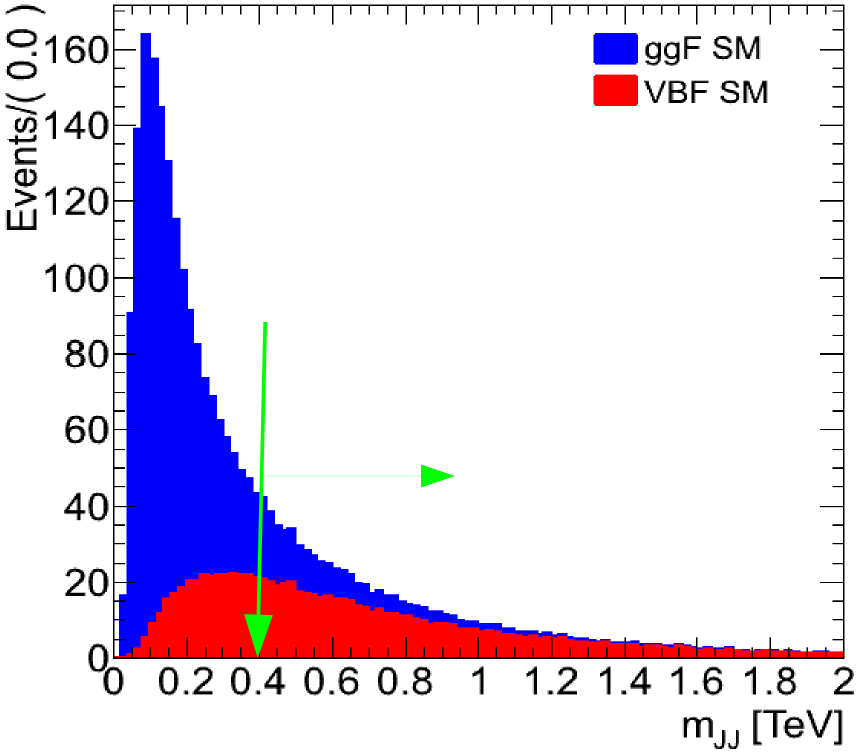


$\Delta\eta_{JJ}$ and m_{JJ} for the ggH and VBF signals

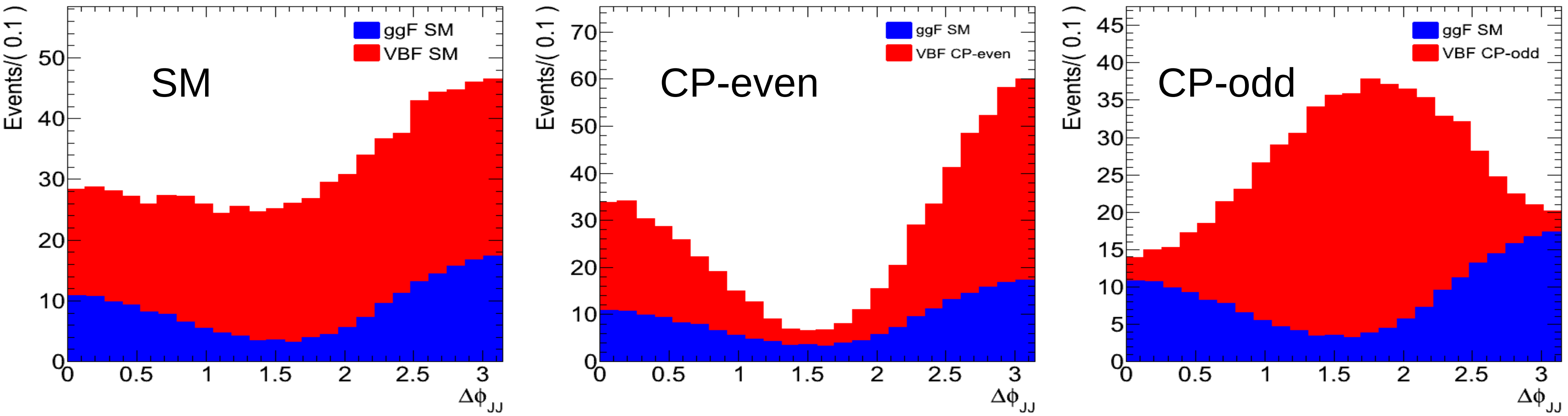




- SM gg-fusion and VBF signals are generated with **VBFNLO-2.6.2** at parton level: http://www.itp.kit.edu/~vbfnloweb/wiki/doku.php?id=overview

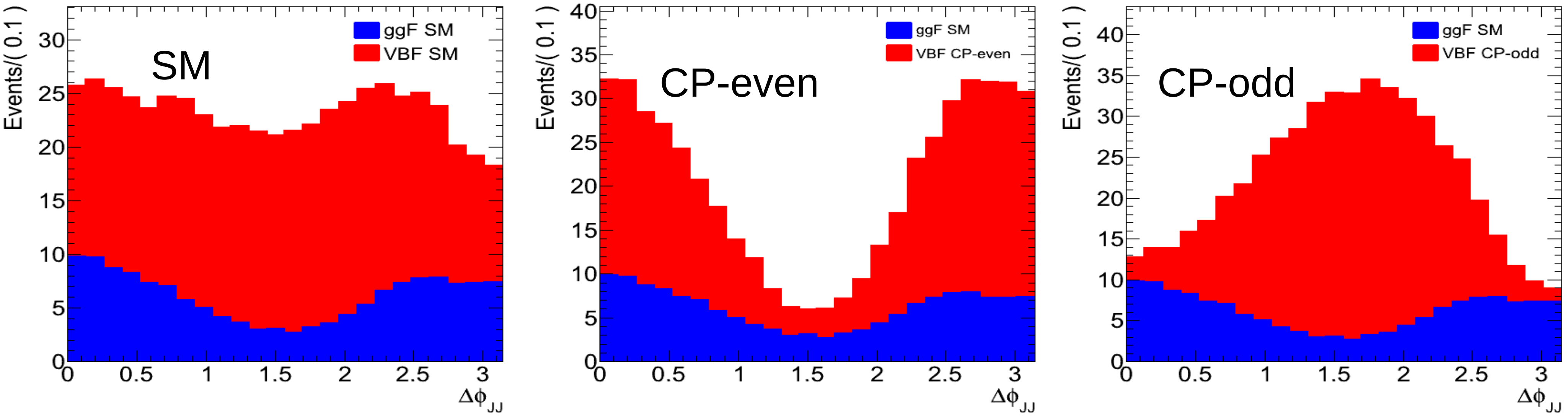
- Both VBF H+2jets and ggH+2jets are generated at LO

$\Delta\phi_{JJ}$ between the tagging jets



- Distinct $\Delta\phi_{JJ}$ distributions for the SM, pure CP-even and CP-odd couplings (after cuts $\Delta\eta_{JJ}>3.0$ and $m_{JJ}>400$ GeV)
- The effect SM ggH coupling (via top loop) is CP-even (V-shaped $\Delta\phi_{JJ}$)
- The ggH rate is about 27% of the combined VBF+ggH rate

$\Delta\phi_{JJ}$ between the tagging jets



- In the $H \rightarrow \tau\tau$ VBF categories, the Higgs is usually required to be somewhat boosted in p_T (via the cuts such as $\Delta\phi_{LL}$, MET, MET centrality, ΔR_{LL})
- The effect of these cuts is shown above: the $\Delta\phi_{JJ}$ distributions are more symmetric (and flat in the case of SM). The SM, CP-even and CP-odd distributions are distinct: BSM coupling, CP-violation via mixing of CP

Summary/Outlook

- A Higgs-like boson has been observed in the bosonic decay modes. Its fermionic decays such as tautau need to be observed to measure the Yukawa coupling and prove it is a SM Higgs

- With 4.6 fb^{-1} 7 TeV and 13.0 fb^{-1} 8 TeV collision data, ATLAS is able to reach a sensitivity very close to $\mu=1$

- A first measurement of the couling strength has been performed in the tautau channel, but more data are needed to make precise tests of the Higgs

- As an improvement of current results, the complete 20.3 fb^{-1} 8 TeV data will be shown for the next public results

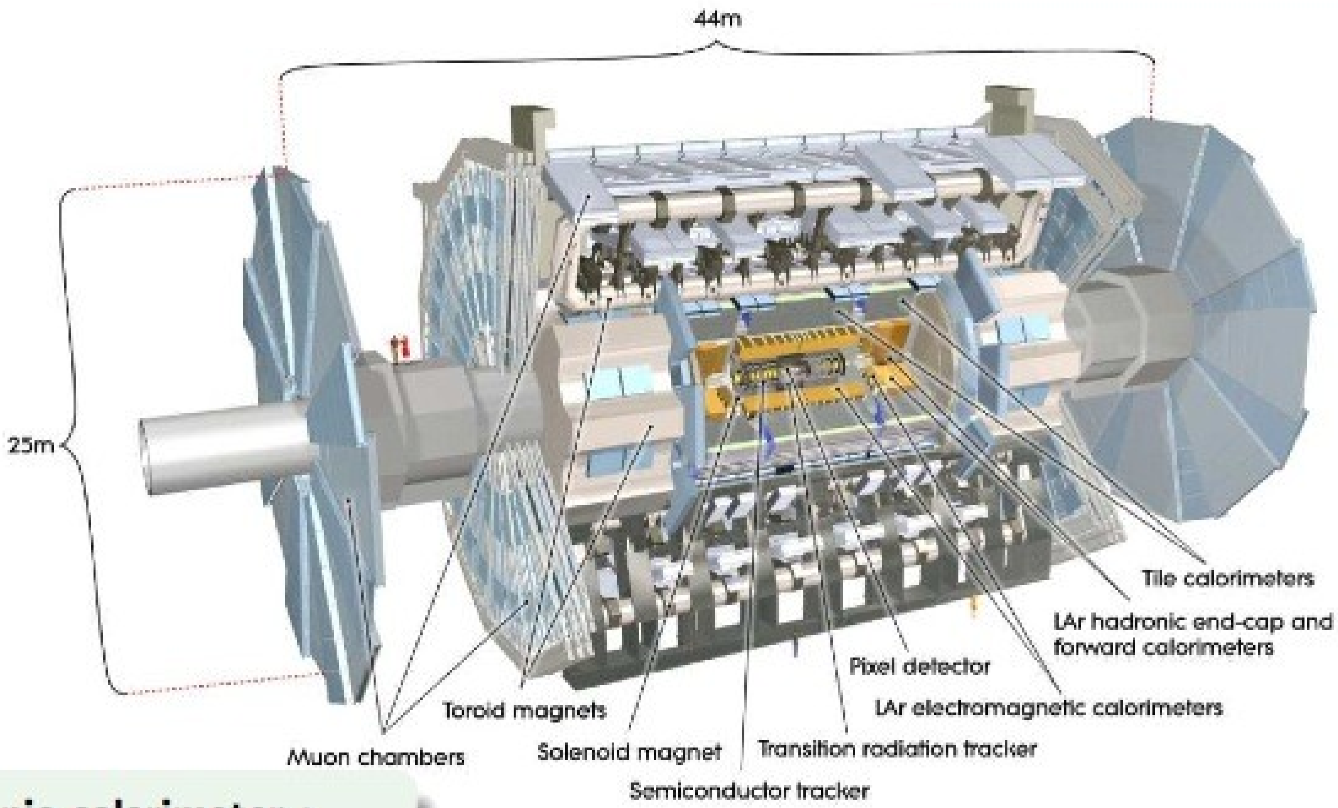
- Once an $H\rightarrow\tau\tau$ excess is seen in currently available or future data collected, the HVV structure can be probed by looking at the tagging jets in the VBF category for signs of BSM physics and CP-violation in the Higgs sector (can be combined with $H\rightarrow\gamma\gamma$)

Backup

The ATLAS detector

Inner detector :
Pixel detector + SCT + TRT
$$\frac{\sigma_{p_T}}{p_T} \approx 0.05\% p_T \oplus 1\% \,,\ |\eta| < 2.5$$

EM calorimeter :
Lead-LAr sampling calo. with accordion geometry
$$\frac{\sigma_E}{E} \approx \frac{10\%}{\sqrt{E}} \oplus 0.7\% \,,\ |\eta| < 3.2$$

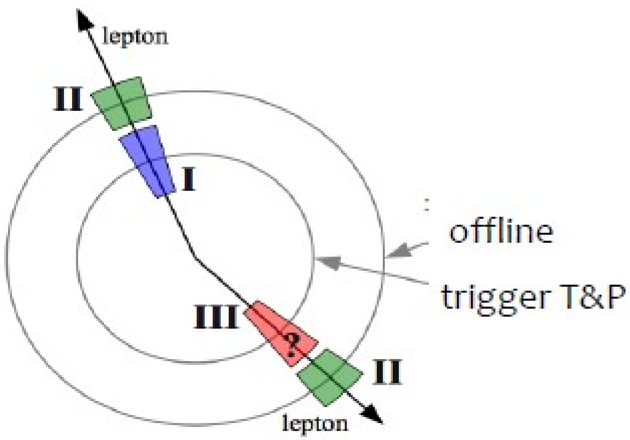


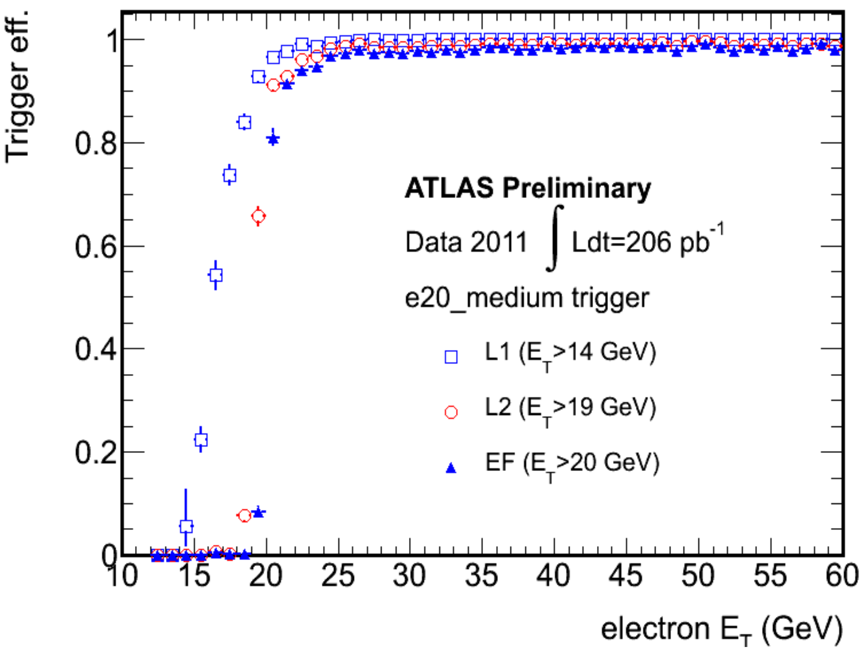
Hadronic calorimeter :
Steel and scintillating tiles in the barrel, copper and liquid argon in end-caps
$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%,\ |\eta| < 3.2$$
$$\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%,\ 3.1 < |\eta| < 4.9$$

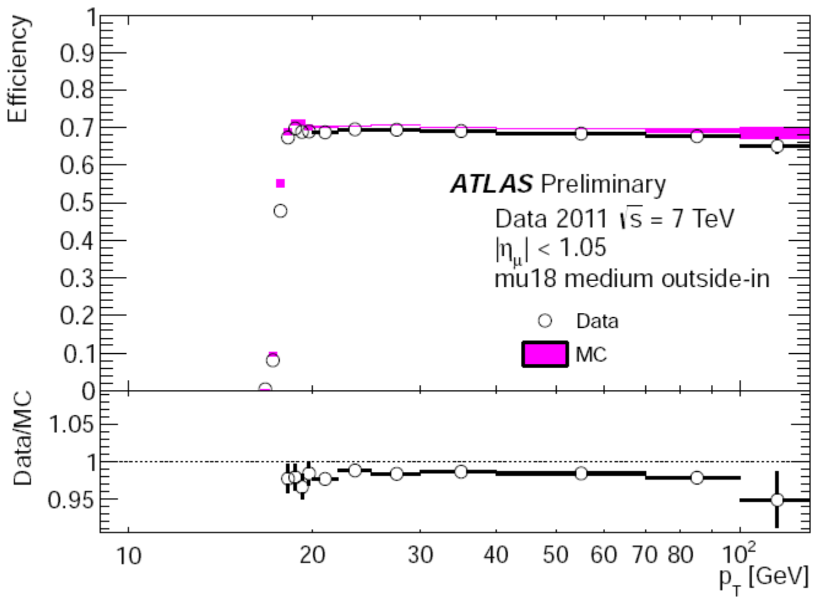
Muon spectrometer :
superconducting air-core toroid magnets, gaz based muon chambers
$$\frac{\sigma_{p_T}}{p_T} \approx 2\% \text{ at 50GeV to } 10\% \text{ at 1TeV},\ |\eta| < 2.7$$

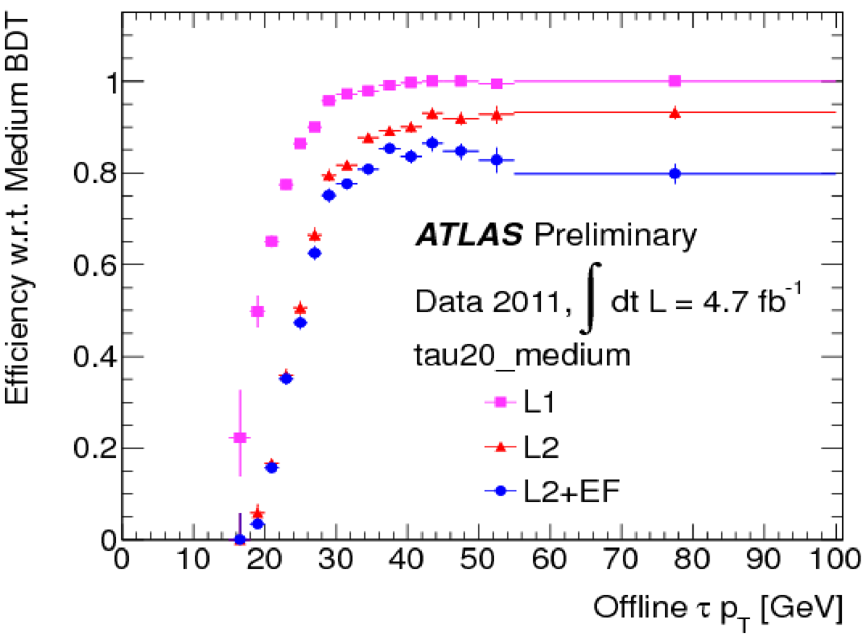
Trigger efficiency and scale factors

✯ Trigger efficiency and scale factors obtained by Tag&Probe method, using Z→ee, μμ, μτ events:









Triggers and datasets

- Triggers used for different channels:
  - ll: logical ”OR” of single and dilepton triggers (trigger thresholds vary in different periods/years):

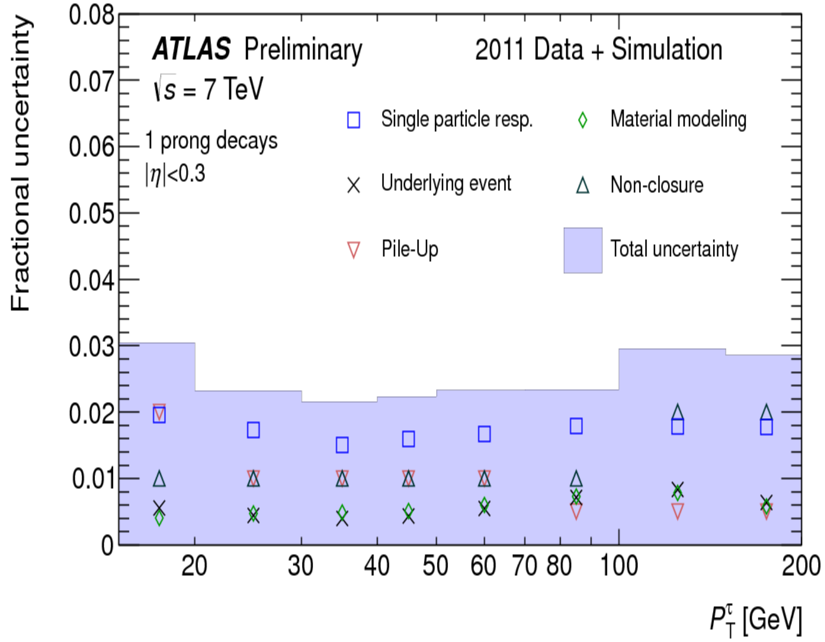
    ee: dielectron trigger 2e12

    eμ: single e or μ trighers, and combined eμ trigger

    μμ: single and dimuon triggers
  - lh: single electron (e24) or muon (mu24) triggers, and eτ and μτ combined triggers to cover low p_T leptons
  - hh: ditau trigger (tau29_tau20)
- MC generators:
  - Signal: PowHeg for ggH and VBF, Pythia for WH/ZH
  - W/Z+jets: Alpgen+Jimmy
  - ttbar: MC@NLO
  - Single top: AcerMC
  - diboson: MC@NLO or Herwig

Tau reconstruction

- Seeded from AntiKt4 Local Hadron Calibration (LC) jets in |η|<2.5 (1/3-prongs). Ininial tau 4-vector defined by LC clusters within ΔR=0.2 of the jet barycenter
- The final tau energy scale is obtained by apply to the raw LC energy 1) a pileup offset subtraction, and 2) a response correction as a function of raw energy, η and number of primary vertices – final reconstruction is 1% within the true energy
- Tau energy scale (TES) uncertainty:
  - Low p and |η|<2.5: in-situ E/P measurements
  - High p and |η|<0.8: combined test beam (CBT) measurements
  - High p and |η|>0.8: MC simulation, but confirmed with the Z→ττ data analysis
  - Neutral pions: EM response from Z→ee and muons in Tile
  - Shower shape models, dead material, underlying event and pileup



- Final TES uncertainty of ~3% is provided by the Tau Working Group

ll-channel: categorization and signal regions

1) Preselection, and exactly 2 leptons with opposite charge

2) $30<m_{LL}<75$ GeV ($30<m_{LL}<100$ GeV) for SF (DF), and $p_{T,lep1}+p_{T,lep2}>35$ GeV

3) At least 1 jet with $p_T>40$ GeV ($|JVF|>0.5$ if $|\eta|<2.4$)

4) MET>40 GeV (MET>20 GeV) for SF (DF)

5) $0.1<x_{1,2}<1$

6) $0.5<\Delta\Phi_{LL}<2.5$

0-jet:

2d) DF leptons with $30<m_{LL}<100$ GeV, and $p_{T,lep1}+p_{T,lep2}>35$ GeV

3d) $\Delta\Phi_{LL}>2.5$

4d) b-tag veto

2-jet VBF:

7) $p_T(j2)>25$ GeV

8a) $\Delta\eta_{JJ}>3.0$

9a) $m_{JJ}>400$ GeV

10a) b-tag veto

11a) CJV and lepton centrality

Boosted:

7c) exclusing VBF events

8c) $p_{T,H}>100$ GeV

9c) b-tag veto

2-jet VH:

7b) excluding VBF and boosted

8b) $p_T(j2)>25$ GeV

9b) $\Delta\eta_{JJ}<2.0$

10b) $30<m_{JJ}<160$ GeV

11b) b-tag veto

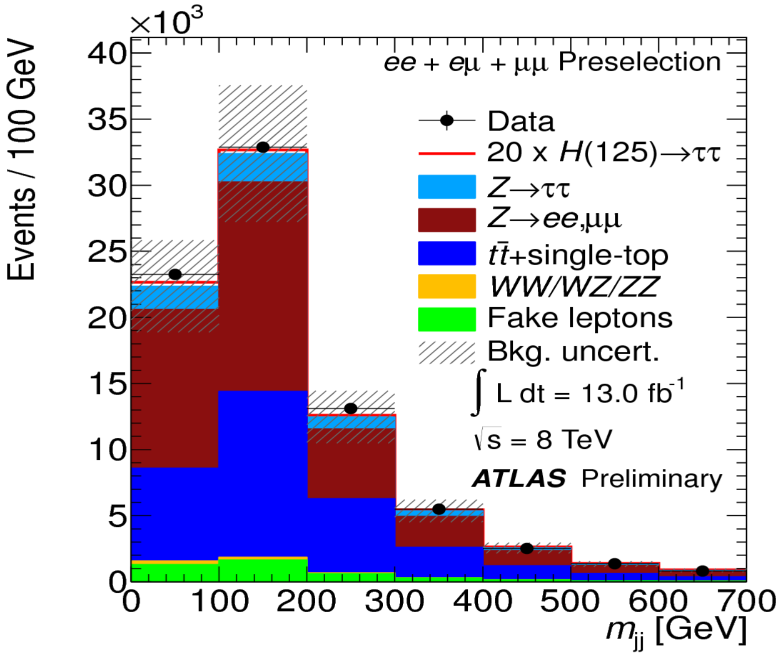
1-jet:

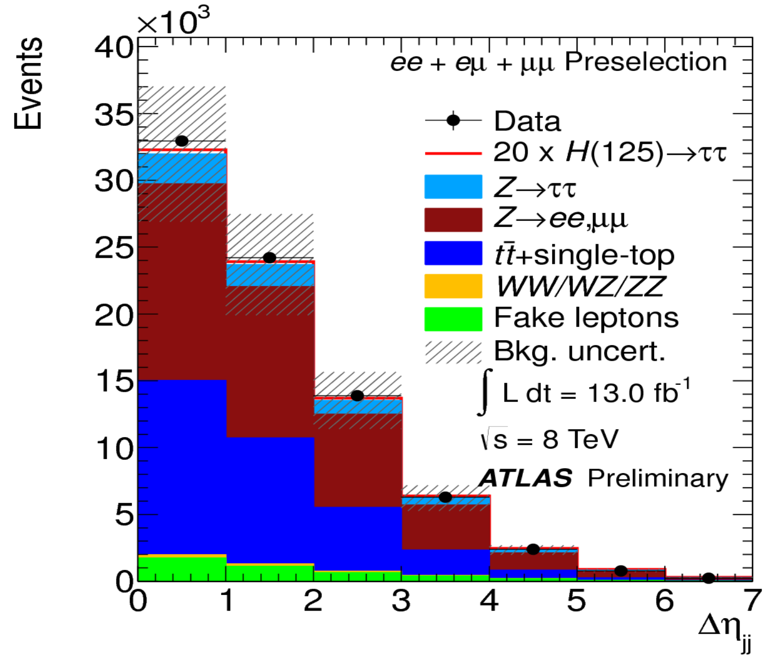
7e) excluding VBF, boosted and VH

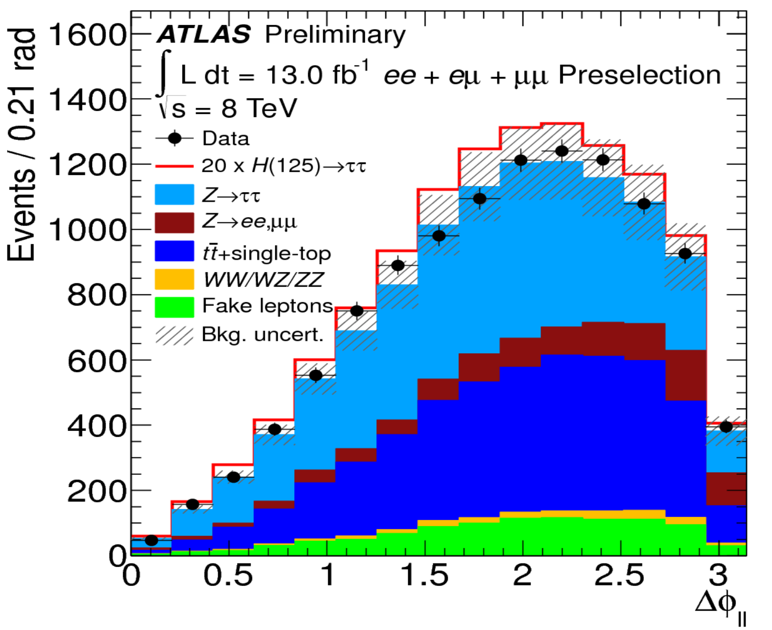
8e) $m_{HJ}>225$ GeV

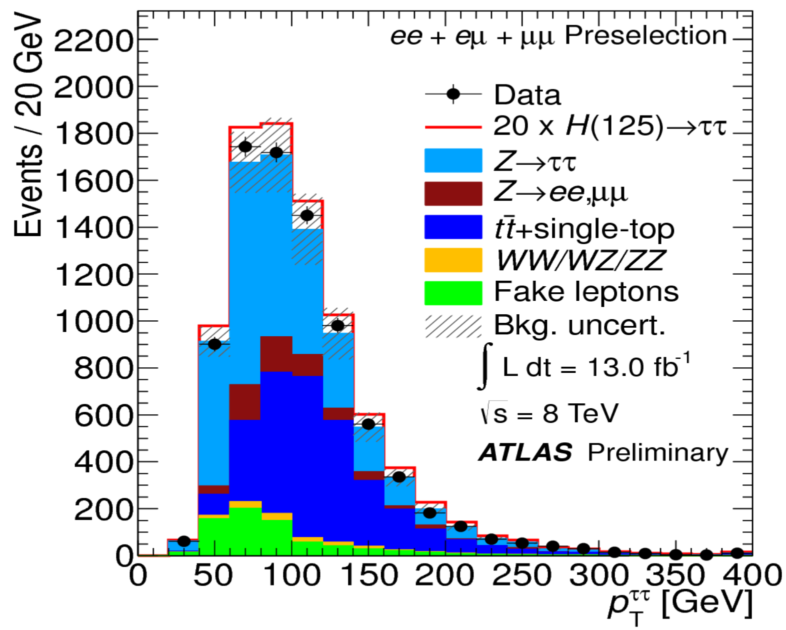
9e) b-tag veto

ll-channel: control plots

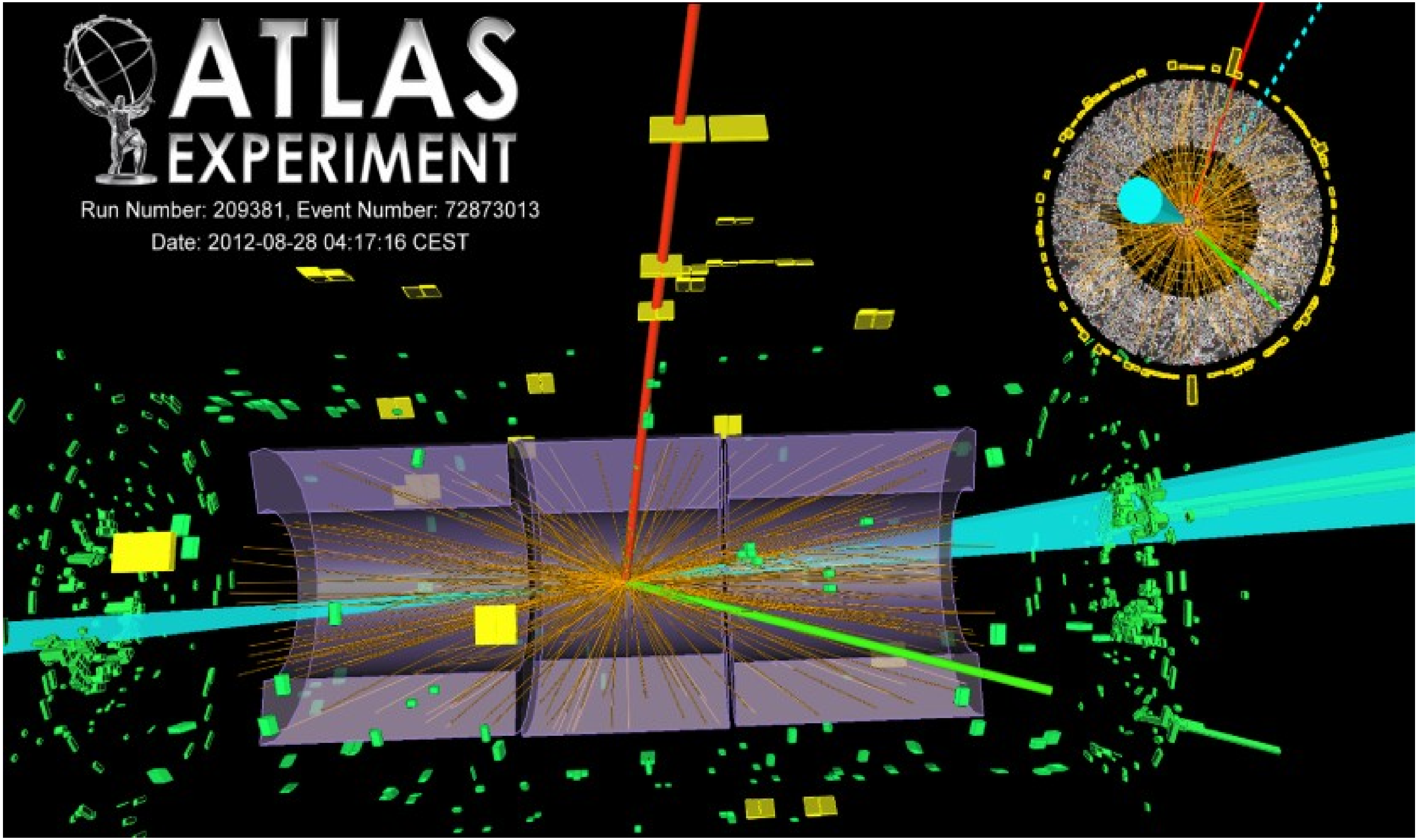








Event display of a candidate VBF $\tau\tau \rightarrow e\mu$ event



lh-channel: categorization and cuts

- Four main categories: 2-jet VBF, Boosted, 1-jet and 0-jet

  1) Exactly 1 lepton and 1 hadronic tau with opposite sign (OS)

  2) MET > 20 GeV

  3) m_T<50 (30) GeV for VBF, Boosted and 1-jet (0-jet)

  4) $\Delta(\Delta R)$, $\Sigma\Delta\Phi$ cuts

  5) b-tag veto for VBF and Boosted

2-jet VBF cuts:

- 2 jets with p_T>40,30
- $\eta_{J1}*\eta_{J2}<0$, $\Delta\eta_{JJ}>3.0$
- m_{JJ}>500 GeV
- l,h centrality

Boosted:

- $p_{T,H}$ > 100 GeV
- $x_{1,2}$ cuts

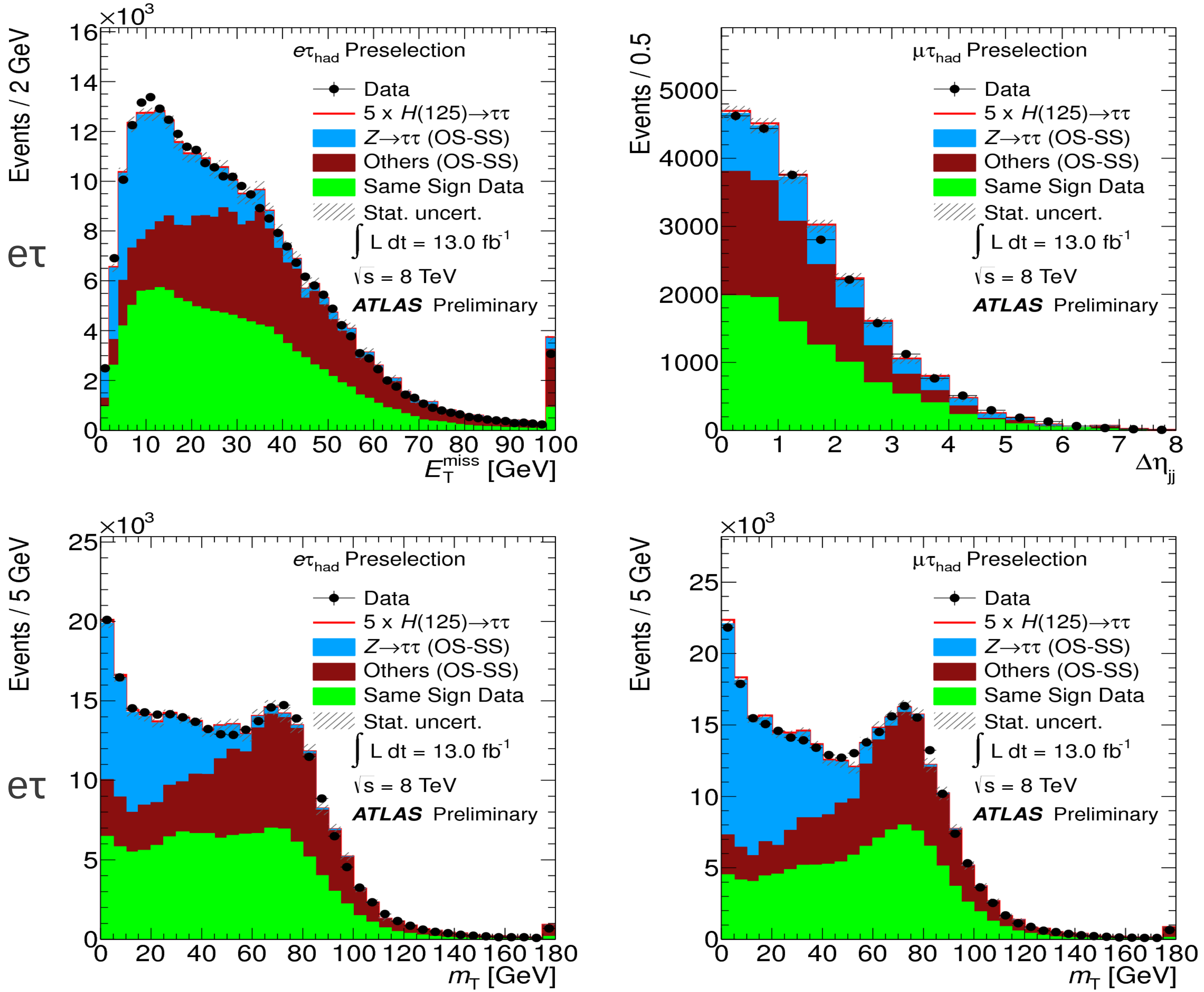
1-jet cuts:

- Excluding VBF and Boosted
- ≥1 jet with p_T>30 GeV

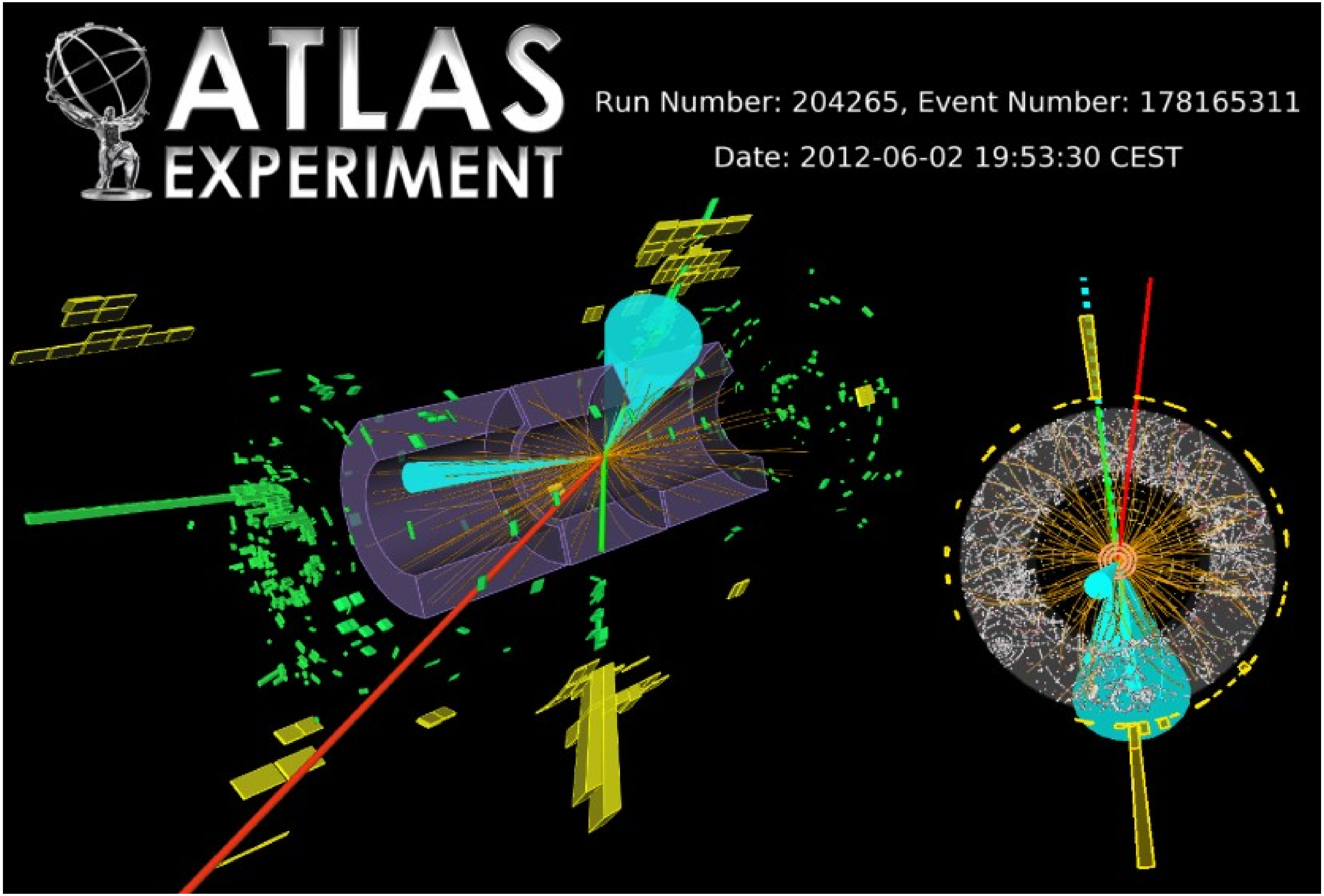
0-jet cuts:

- Excluding Boosted
- Require no jet with p_T > 30 GeV
- Lepton p_T < tau p_T

lh-channel: control plots



Event display of a candidate VBF $\tau\tau \rightarrow \mu\tau_{had}$ event



hh-channel: categorization and cuts

- Two categories: VBF, Boosted

1) Preselection: veto electrons and muons, Medium+Tight tau ID with p_T > 40,25 GeV, $\Delta R_{\tau\tau}$ and $\Delta\eta_{\tau\tau}$ cuts, MET centrality

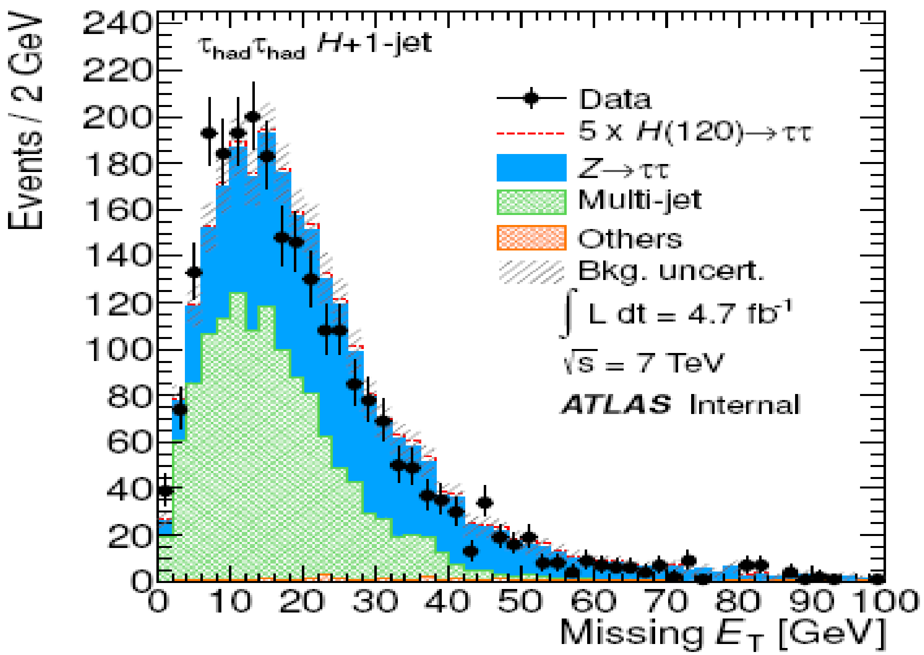
2) MET > 20 GeV

2-jet VBF cuts:

- 2 jets with p_T>50,30
- $\eta_{J1}*\eta_{J2}$<0, $\Delta\eta_{JJ}$> 2.6
- m_{JJ}>350 GeV
- hadron centrality

Boosted:

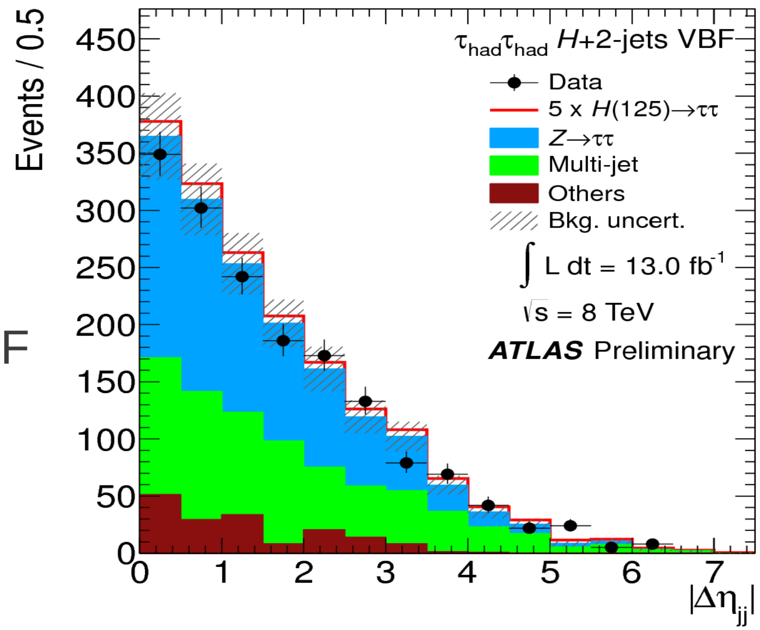
- $p_{T,J}$ > 70 GeV
- Tighter $\Delta R_{\tau\tau}$ cut
- Tighter MET centrality

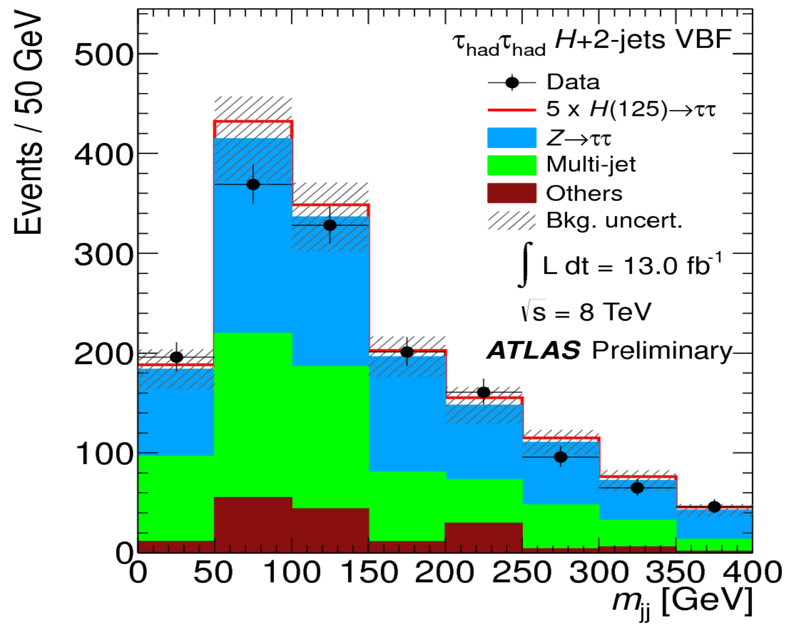


The main backgrounds are Z→ττ and QCD multijets

hh-channel: control plots

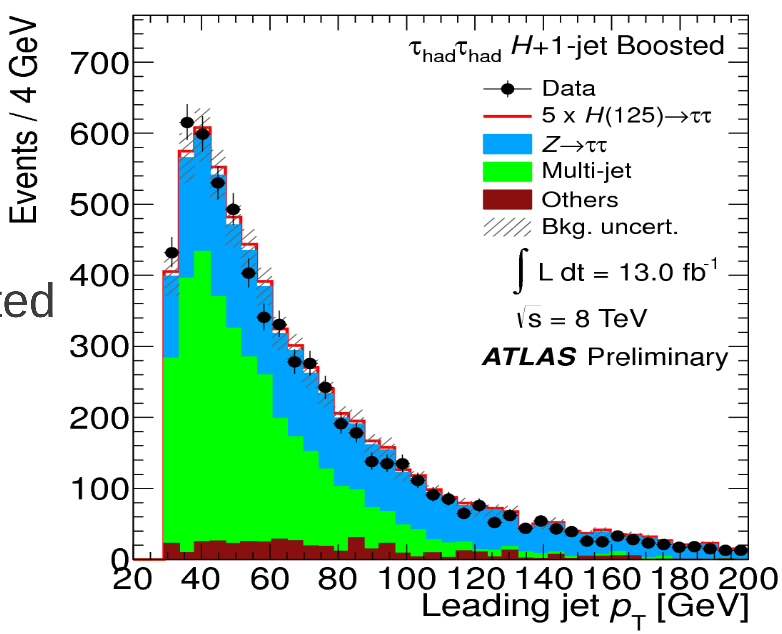
VBF

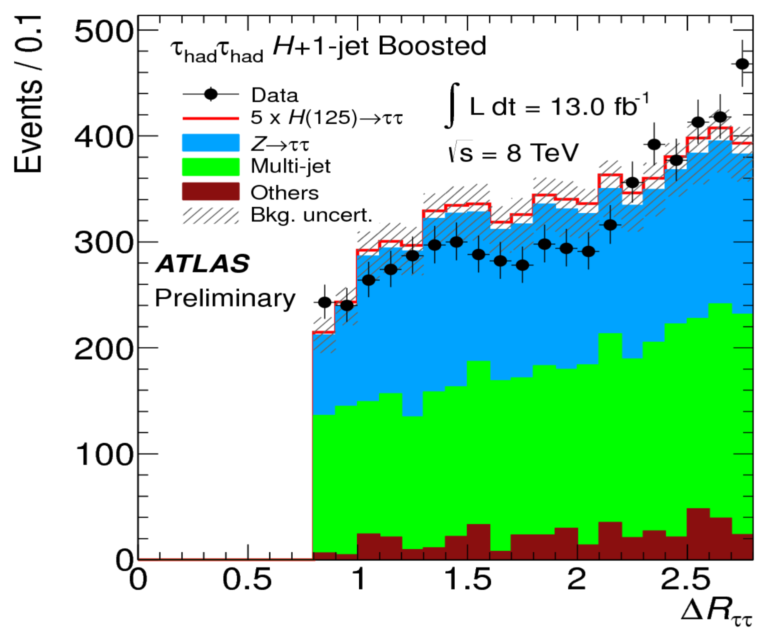




VBF

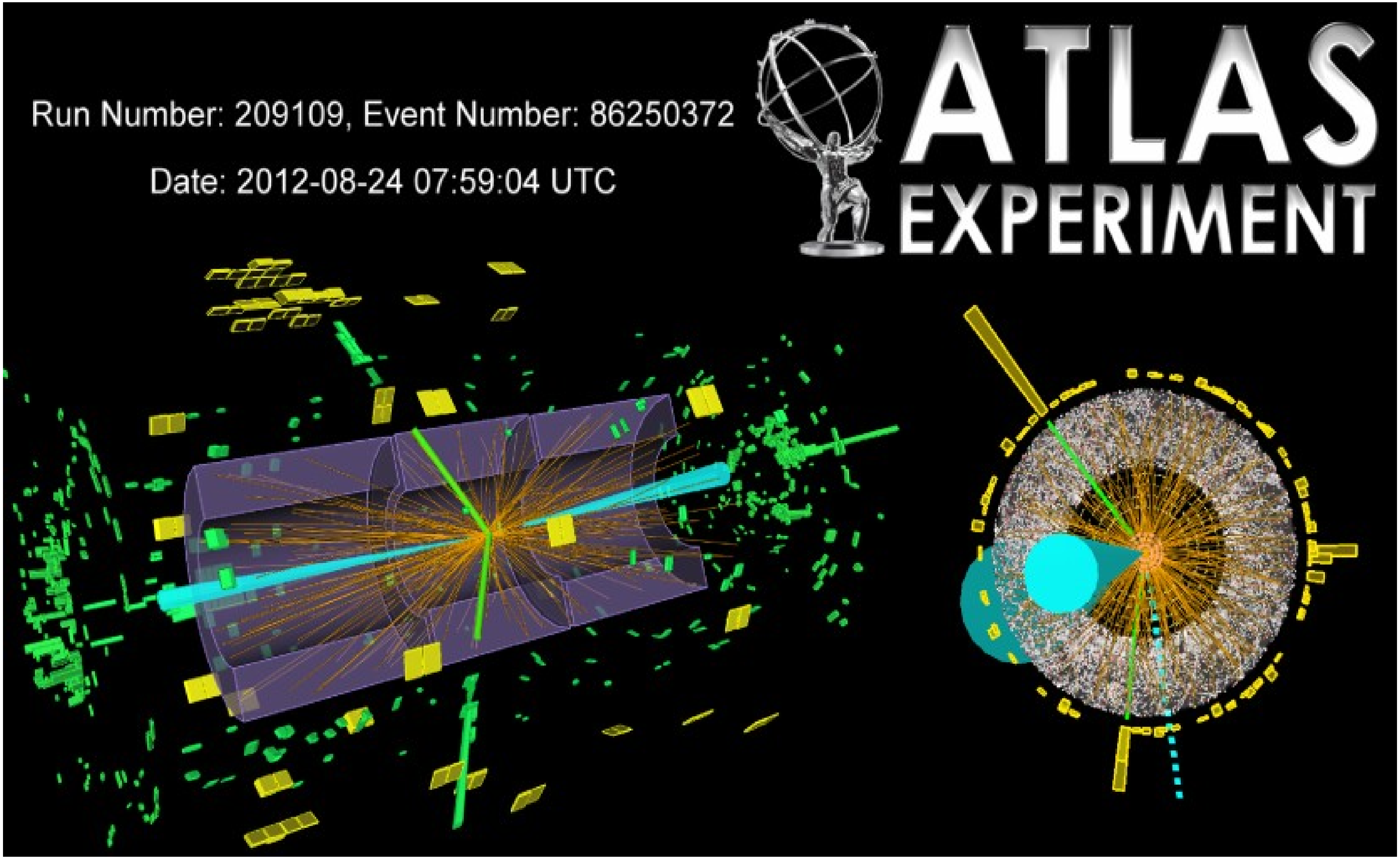
Boosted





Boosted

Event display of a candidate VBF $\tau\tau \rightarrow \tau_{had}\tau_{had}$ event



Statistical formulation

- A binned likelihood function constructed as the product of individual likelihood terms from each category (12 total categories in 3 channels):

$$\mathcal{L}(\mu, \theta) = \prod_{j=\text{bin}} \text{Poisson}(N_j | \mu(s_j) + b_j) \prod_{\theta} \text{Gaussian}(\theta | 0, 1)$$

- μ is the ”signal strength” parameter multiplied to the SM prediction. μ=0 (μ=1) corresponds to background-only (signal+background) hypothesis

- Expected signal (s) and background (b) depends on systematic uncertainties which are parametrized by the nuisance parameters θ

- The nuisance parameters are constrained by Gaussian functions, and their correlations are taken into account in the technical implementation

- The test statistic used to calculate the modified frequentist limit CL_s:

$$q_\mu = -2 \ln \left(\mathcal{L}(\mu, \hat{\theta}_\mu) / \mathcal{L}(\hat{\mu}, \hat{\theta}) \right)$$

- Limits are calculated with asymptotic formulas which are validated by pseudo-experiment ensembles

Jet Vertex Fraction (JVF)