Search for the Standard Model Higgs boson in H to $\tau\tau$ decays with the ATLAS detector

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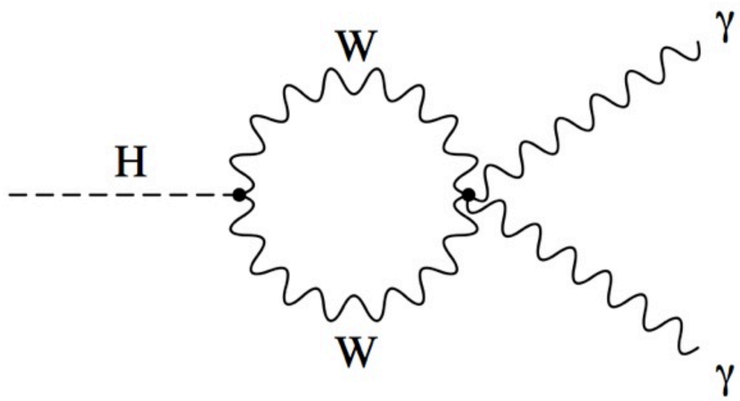
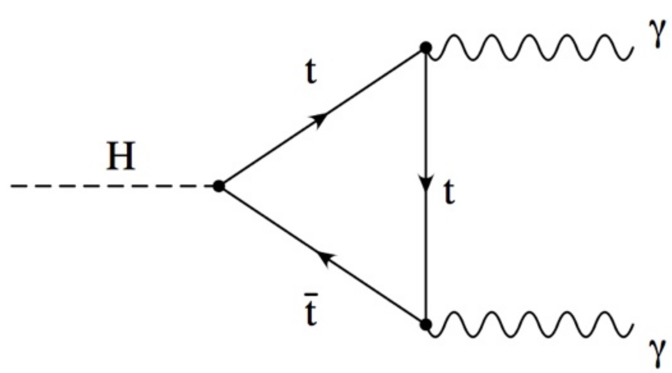
Beyond the initial observation...

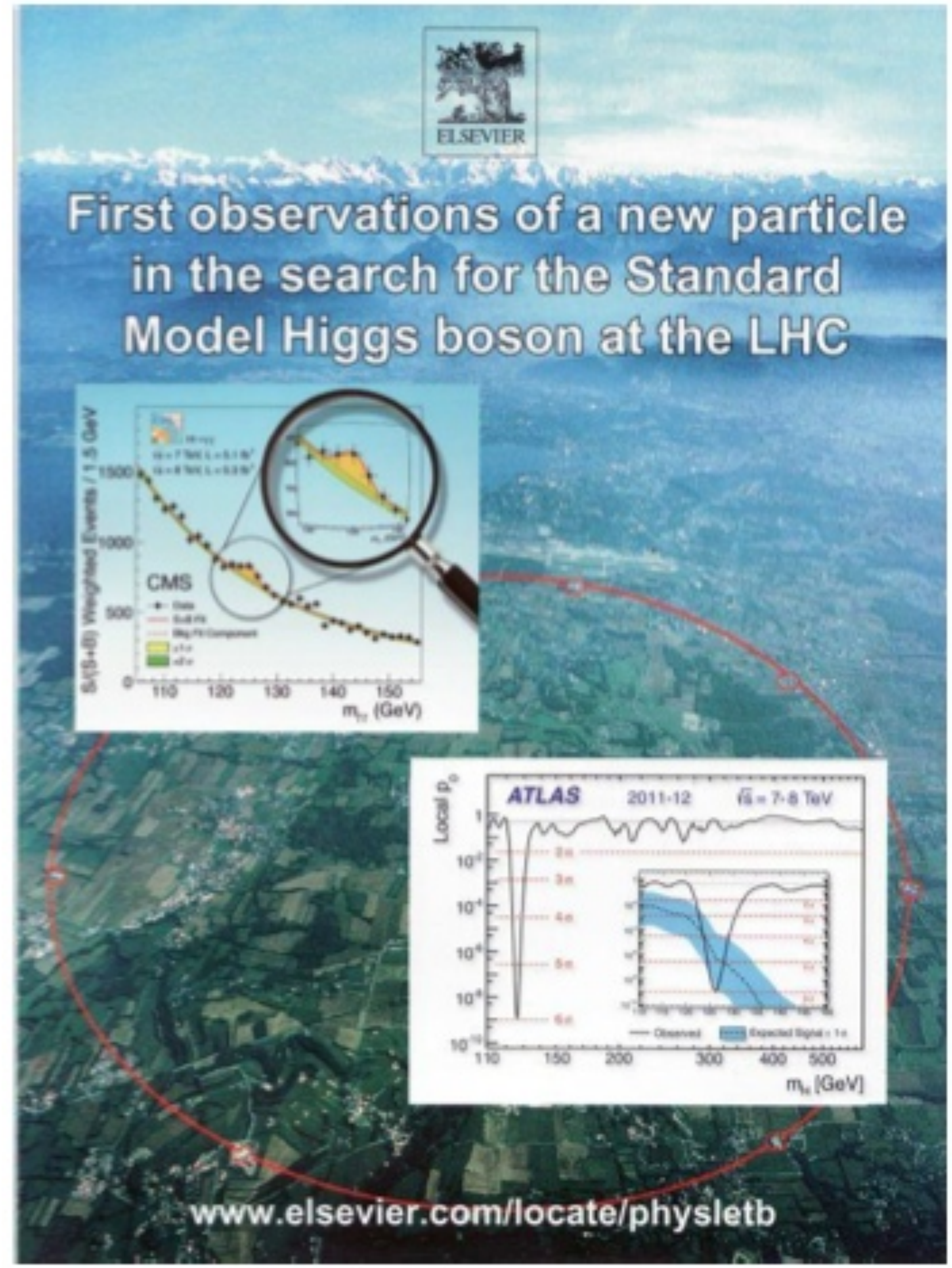
- New boson appears to couple directly with vector bosons (direct decay into ZZ, WW; decay to γγ through loops)



- Also appears to couple directly to fermions (quarks through ggF production and γγ through loops)



- Observation of direct decay into leptons is necessary to verify the lepton Yukawa coupling



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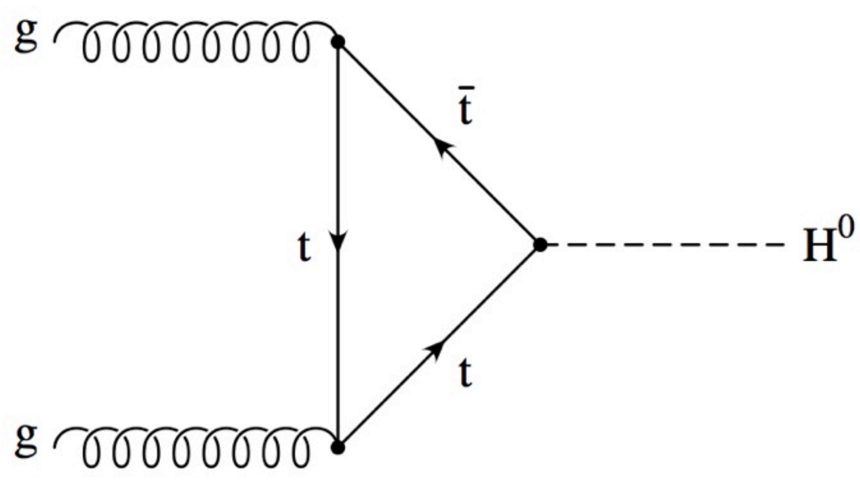
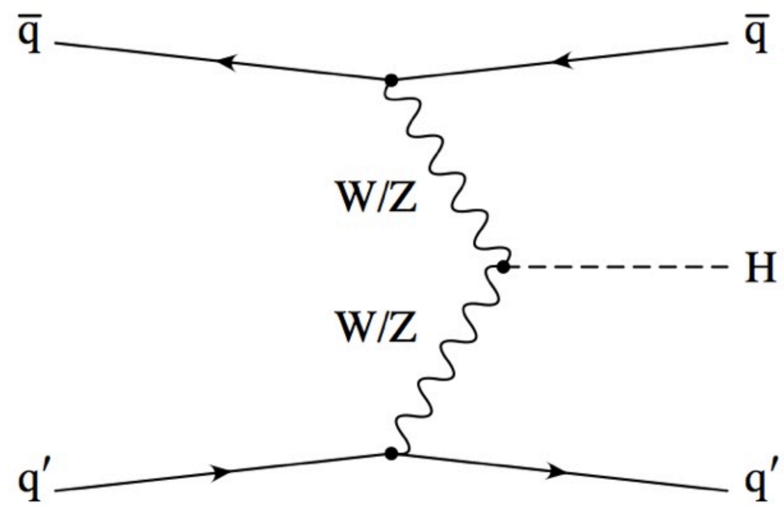
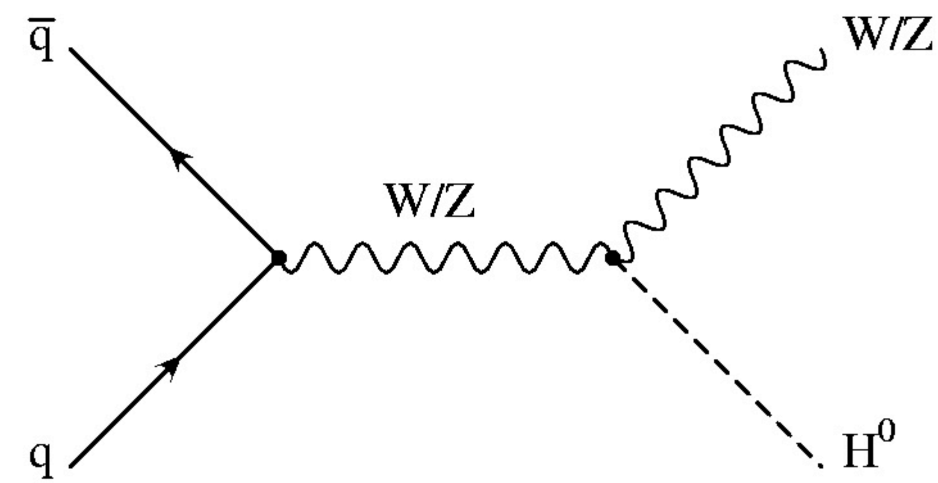
ATLAS Higgs to ττ analysis

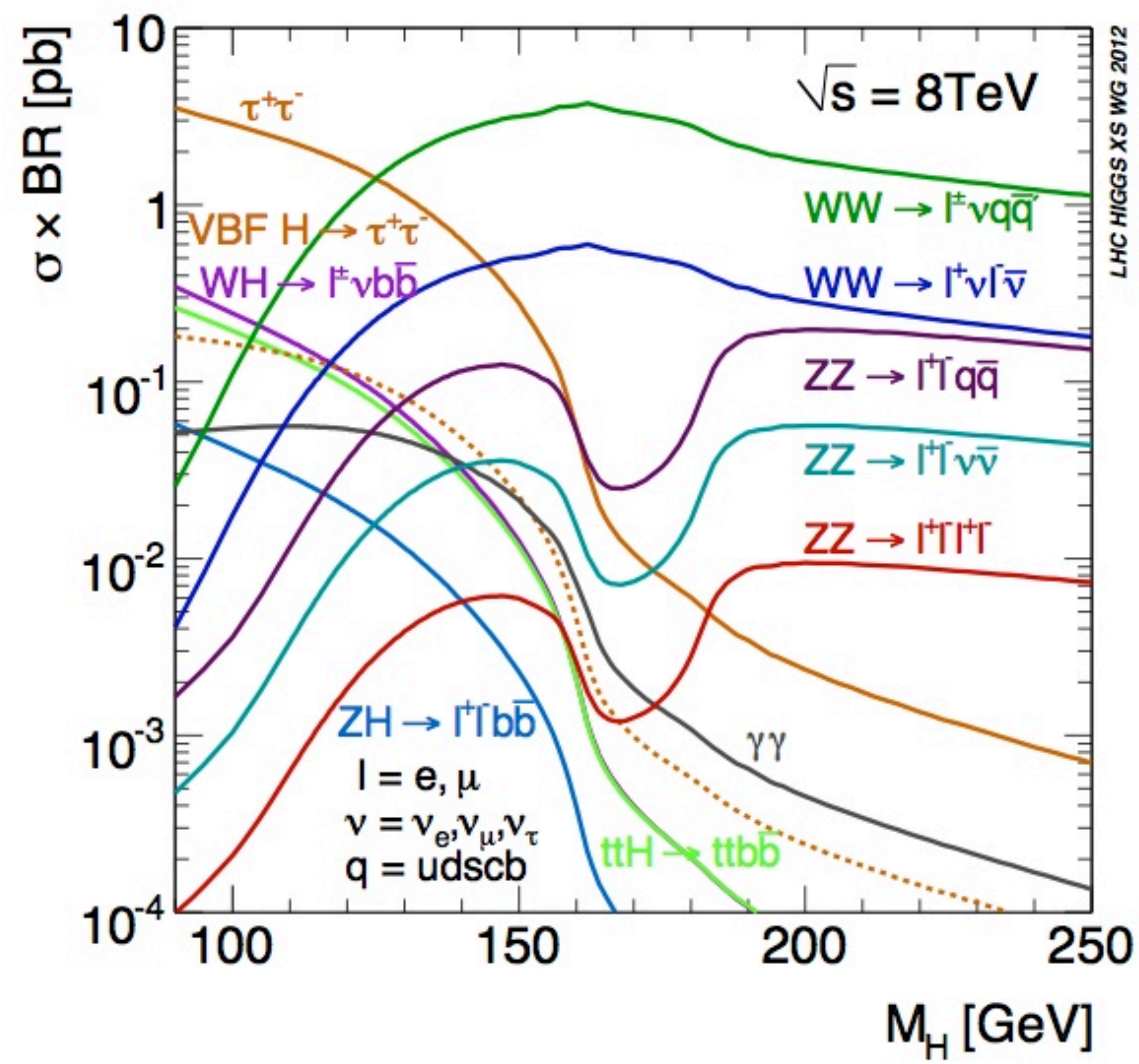
- The analysis targets three Higgs production processes:







- Use both leptonic and hadronic decays of τ leptons
- lepton-lepton, lepton-hadron, hadron-hadron
- All channels are combined for the ττ Higgs search
- The analysis presented here includes 4.6 fb^{-1} at 7 TeV and 13 fb^{-1} at 8 TeV



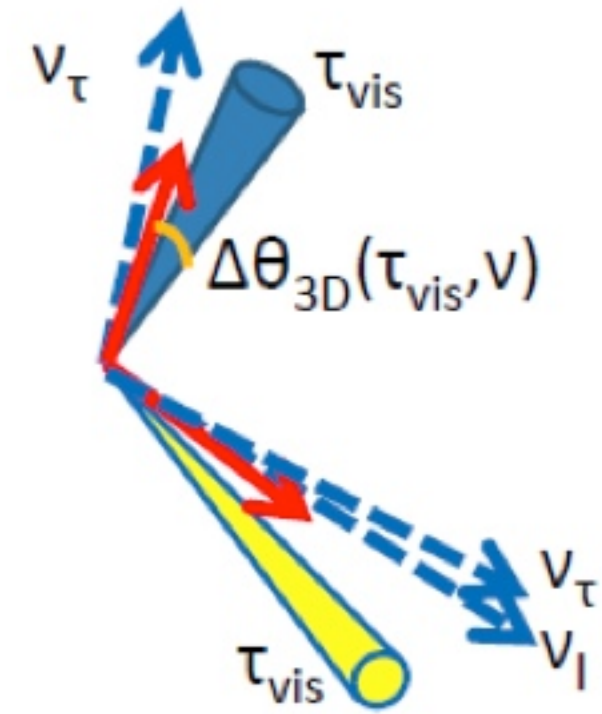
ATLAS-CONF-2012-160

Higgs to $\tau\tau$ challenges

- Working with τ leptons poses some unique challenges (see Ryan and Pavel's talks from yesterday)
- Triggering is challenging, in particular for final states with one more hadronic τ decays
- Identification of τ leptons relies on BDT using calorimeter and tracking variables. Hadronic τs are reconstructed as calorimeter jets using dedicated calibration
- For historic and technical reasons different selections / optimizations are used for the analyses performed on 7 and 8 TeV data (trigger, reconstruction, etc.)
- For all channels, a common discriminating variable, the missing mass calculator (MMC), is used to estimate $m_{\tau\tau}$ (broad Higgs signal due to neutrinos)
- The background in all channels is dominated by irreducible Z to $\tau\tau$

Mass reconstruction with τ leptons

- Missing Mass Calculator technique
  - A step beyond the "collinear mass"
  - Assume the angle between the neutrinos and the visible hadronic τs ($\Delta\theta_{3D}$) is non-zero
  - End up with more unknowns than equations



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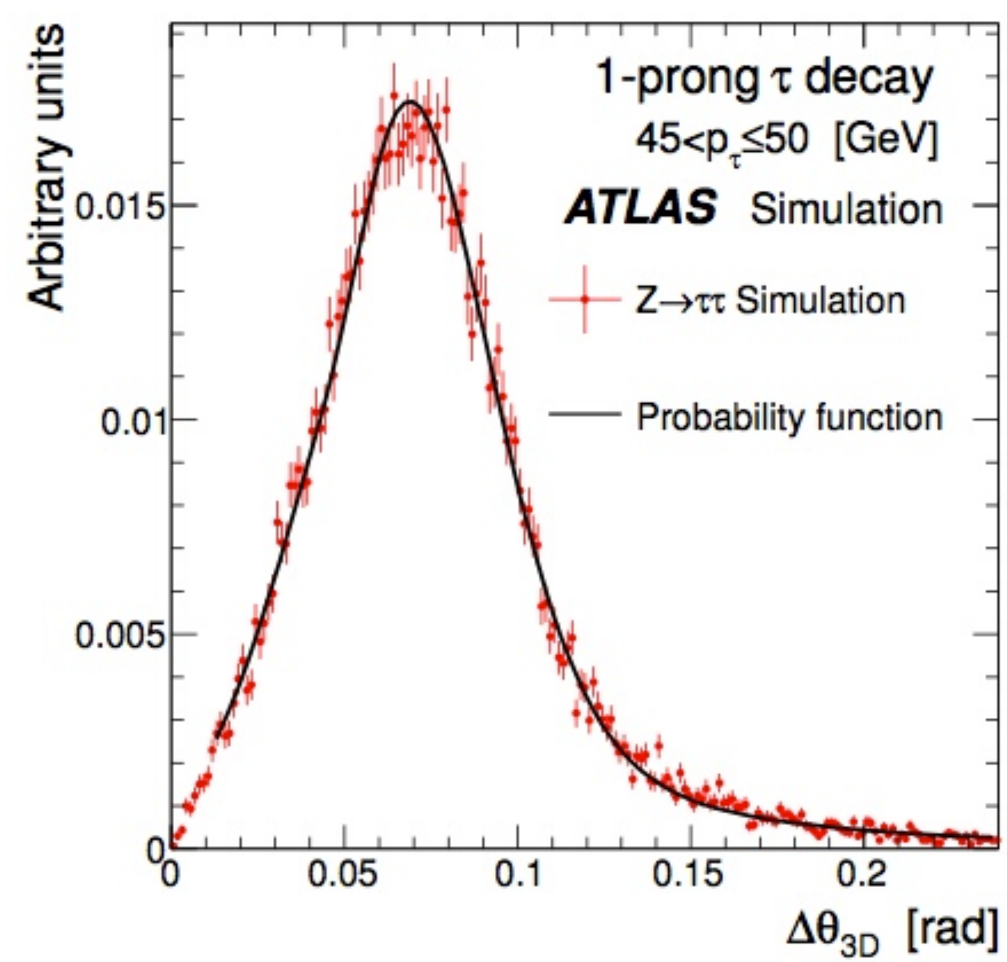
$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$

$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$

$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2 p_{\text{vis}_1} p_{\text{mis}_1} \cos\Delta\theta_{vm_1}$$

$$M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2 p_{\text{vis}_2} p_{\text{mis}_2} \cos\Delta\theta_{vm_2}$$

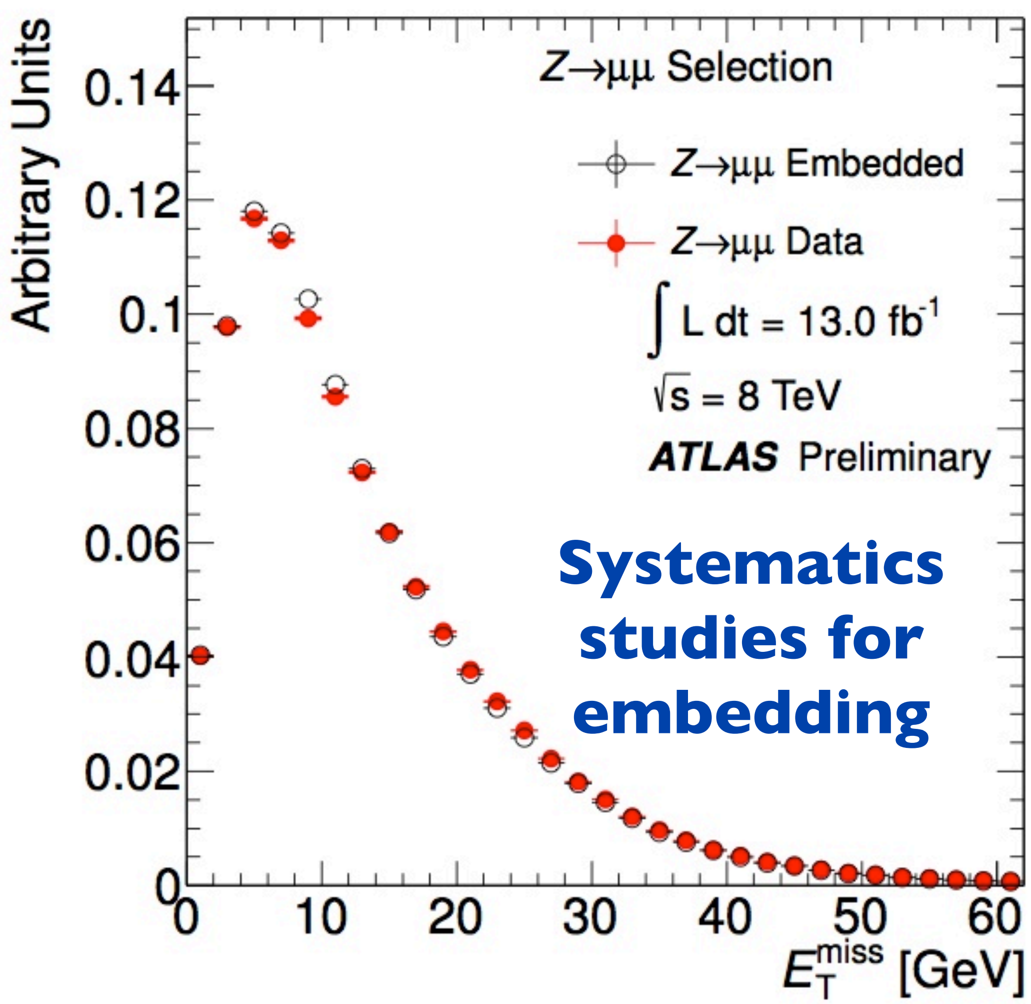


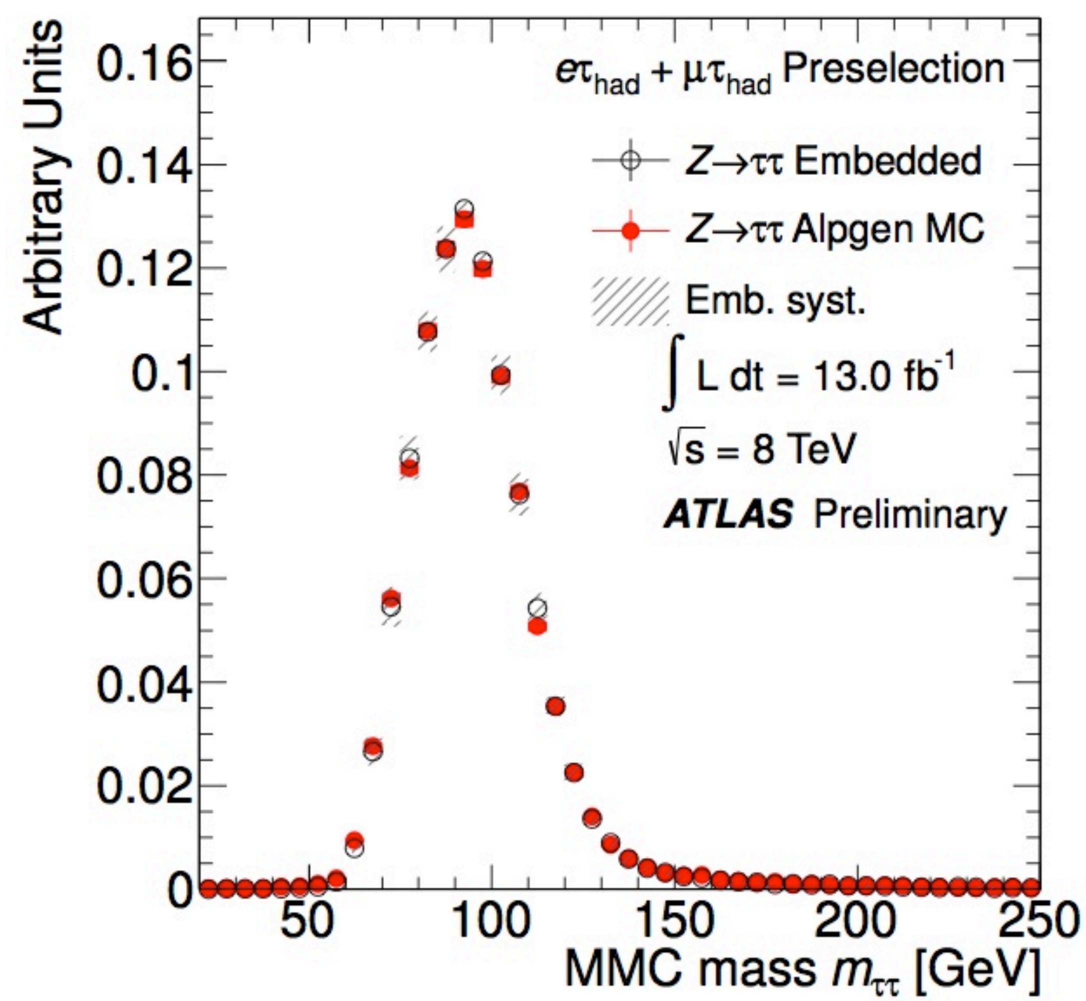
- Use a likelihood to solve an under-constrained set of equations
  - Solve the equations in a grid of angles $\Delta\theta_{3D}(\tau_{vis}, \boldsymbol{\nu})$ and choose the best one

Resolution 13-20%, depending on decay mode

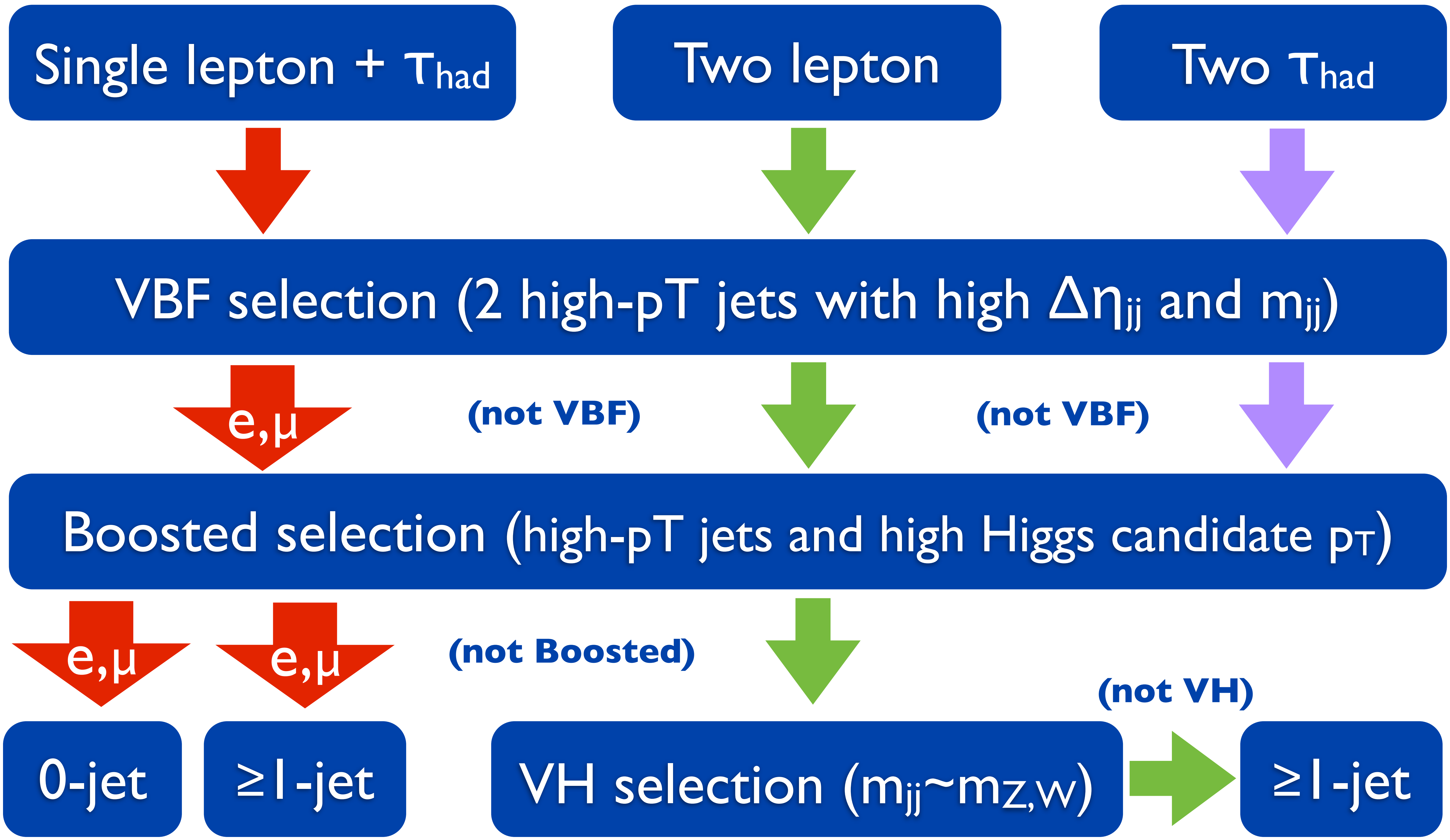
Special techniques used with τ leptons

- $Z \rightarrow \tau\tau$ is the most important (irreducible) background source for di-τ final states; need to model this as accurately as possible
- A semi-data-driven method: select an adequately pure $Z \rightarrow \mu\mu$ event sample from data and then replace the muons with simulated τs (aka "embedding"); correct polarization and spin correlation modeling
- Pile-up, underlying event, kinematics, etc. are all taken directly from the data
- Performance studied for all of the final states in this analysis





Higgs to ττ analysis strategy (8 TeV)

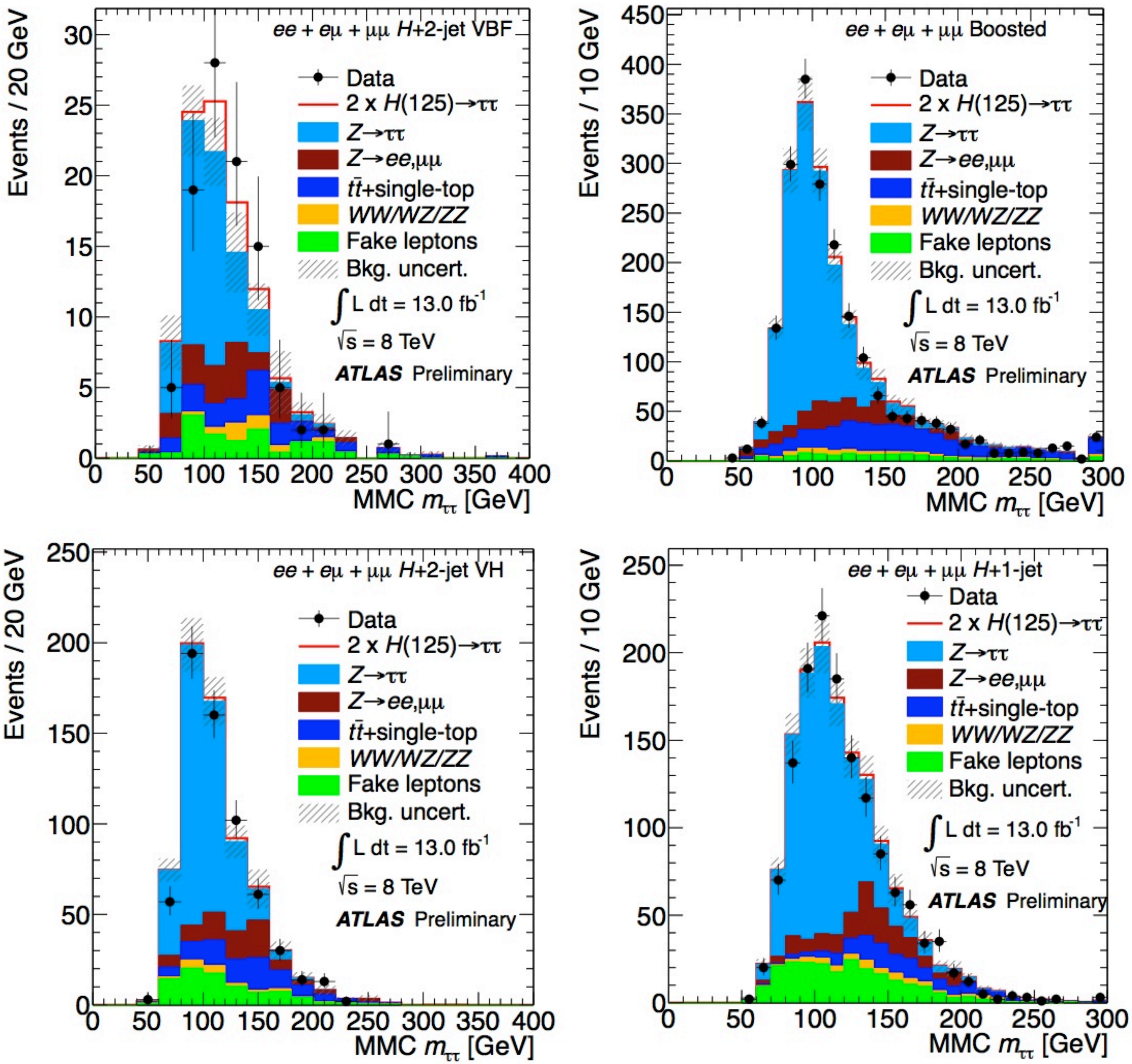


7 single-lepton categories   4 two-lepton categories   2 hadronic-τ categories

Higgs to ττ lepton-lepton channel

- H to ττ to lepton-lepton is 12.4% of the total ττ rate
- In order to improve efficiency, both single lepton and di-lepton triggers are used
- For the 8 TeV analysis, 4 mutually exclusive categories are used (all include a b-jet veto):
  - 2-jet VBF: with P_T(jet) > 25 GeV, $\Delta\eta$(jj) > 3.0, m(jj) > 400 GeV
  - Boosted: not 2-jet VBF, $P_T(\tau\tau)$ > 100 GeV
  - 2-jet VH: not boosted, $\Delta\eta$(jj) < 2.0, 30 GeV < m(jj) < 160 GeV
  - 1-jet: not 2-jet VBF, boosted, or 2-jet VH, m(ττj) > 225 GeV
- Embedding sample used for estimating the dominant Z to ττ background; Z to ee and μμ determined using simulation normalized to control regions
- Top and di-boson backgrounds are estimated from simulation; top backgrounds are normalized using data in control regions
- Backgrounds due to fake leptons are determined from data using templates fitted to regions with relaxed identification criteria

Higgs to ττ lepton-lepton channel



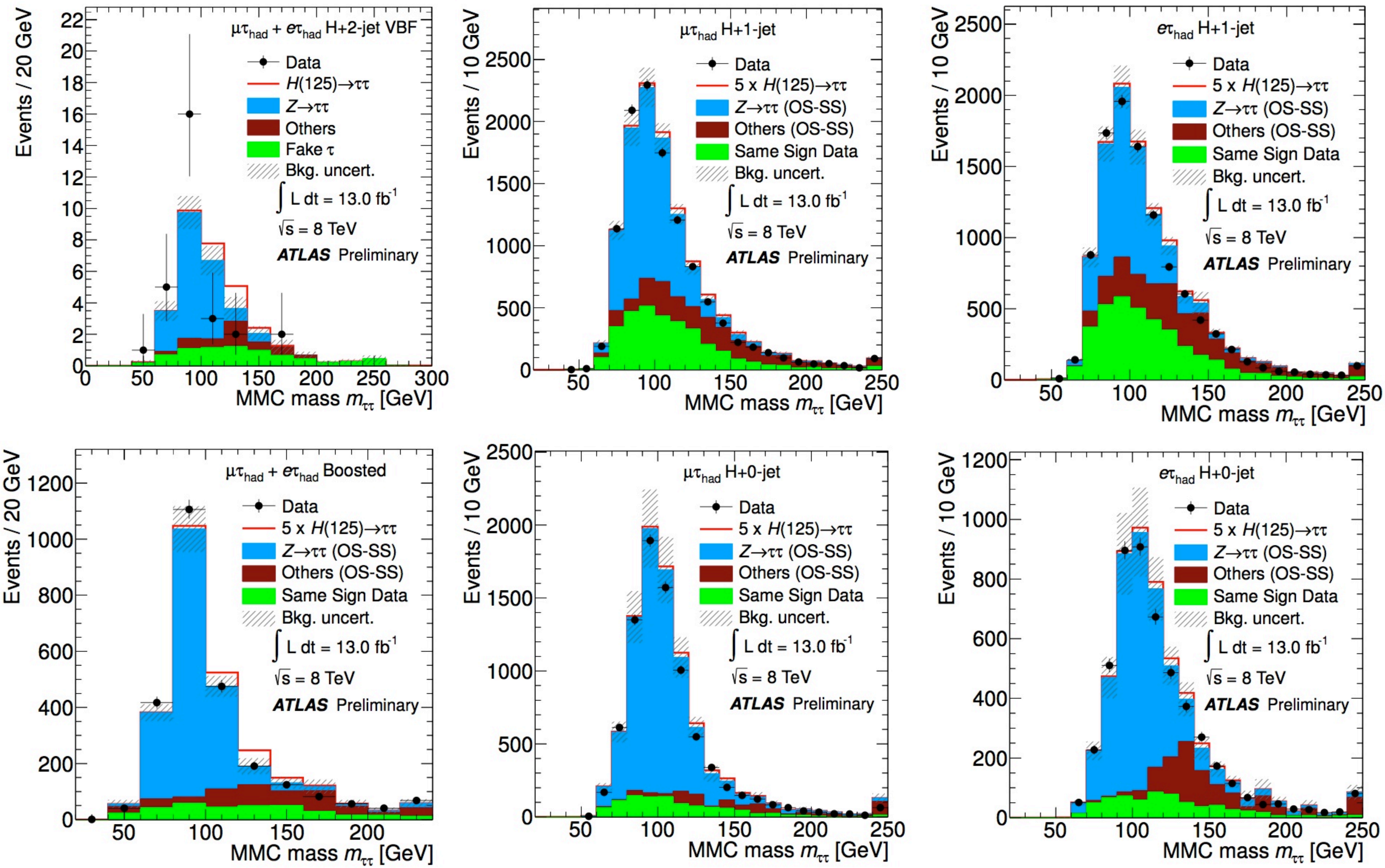
- Results shown for each of the 4 lep-lep categories used in the 2012 analysis
- In general the agreement is quite good

SM Higgs signal x2

Higgs to ττ lepton-hadron channel

- H to ττ to lepton-hadron is 45.6% of the total ττ rate; combined e,mu + tau trigger used to increase signal yield (due to lower threshold for the combined trigger)
- For the 8 TeV analysis, 4 mutually exclusive categories are used (all include a b-jet veto):
  - 2-jet VBF: with P_T(jet) > 40/30 GeV, $\Delta\eta$(jj) > 3.0, m(jj) > 500 GeV, m_T<50 GeV
  - Boosted: not 2-jet VBF, $P_T(\tau\tau)$ > 100 GeV, m_T<50 GeV
  - 1-jet: not 2-jet VBF, boosted, P_T(jet) > 30 GeV, m_T<50 GeV
  - 0-jet: no jets with P_T(jet) > 30 GeV
- Additional kinematic requirements...
- Background estimation for non-VBF categories:
  - Multijet background estimated from same-sign events, re-scaled by correction factor for differences in flavor composition between SS and OS. This is referred to as "Same Sign Data" in following figures.
  - Dominant Z to ττ backgrounds are estimated using embedding technique.
  - Z to ee/μμ backgrounds where a lepton is mis-identified as a hadronic tau, plus other backgrounds such as W+jets, top, and di-bosons, are added to the same-sign data, and called "Other (OS-SS)". W +jets and Top use data-driven normalization in CRs, di-bosons use MC normalization.
- Background estimation for VBF category:
  - Use special VBF-filtered MC samples for Z to ττ and ll, and normalize them using real Z to ee/μμ events with VBF-like jet requirements.
  - For multi-jet and W+jet backgrounds, use enriched CRs by defining relaxed lepton ID criteria, and scale to SR.

Higgs to ττ lepton-hadron channel

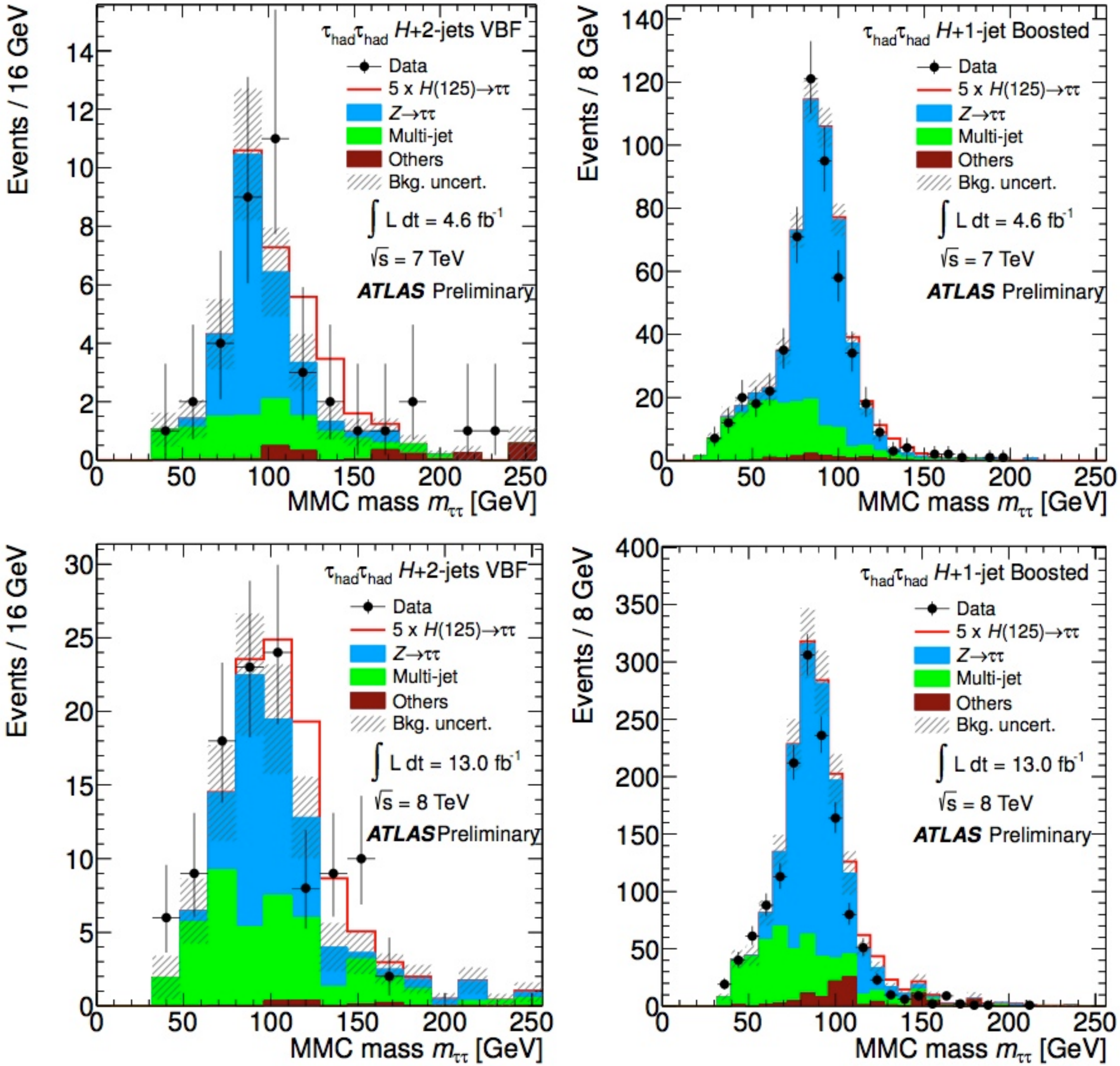


SM Higgs signal x5 (except VBF)

Higgs to ττ hadron-hadron channel

- H to ττ to hadron-hadron is 42% of the total ττ rate
- Triggers requiring two hadronic tau decays are used
- Define 2 mutually exclusive categories:
  - 2-jet VBF: with P_T(jet) > 50/30 GeV, $\Delta\eta$(jj) > 2.6, m(jj) > 350 GeV, τ between "tagging" jets in η
  - Boosted: not 2-jet VBF, $P_T(\tau)$ > 70 (50) GeV for 2012 (2011), $\Delta R(\tau_1, \tau_2) < 1.9$
- Additional kinematic requirements...
- Multijet background estimated from same-sign events, using 2D templates to fit track multiplicity (multijet background has broad track multiplicity).
- Dominant Z -> ττ backgrounds are estimated using embedding technique and a 2D template fit to track multiplicity for the two hadronic taus. Normalize in region $60 < m_{\tau\tau} < 108$ GeV to exclude any possible Higgs signal.
- Other EWK backgrounds are taken directly from simulation, but are very small

Higgs to ττ hadron-hadron channel

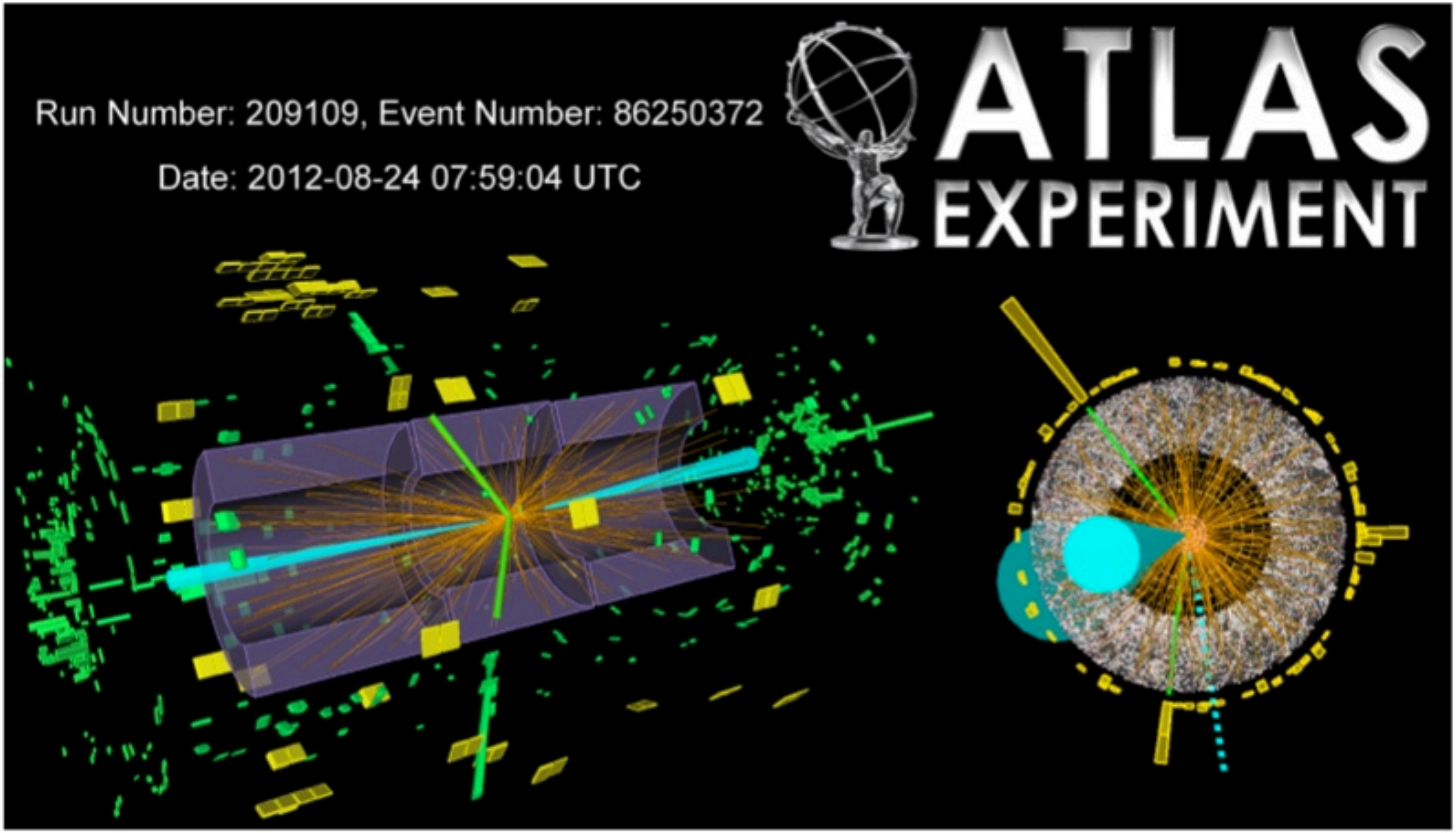


Results shown for each of the 2 had-had categories used in both the 2011 and 2012 analyses

In general the agreement is quite good

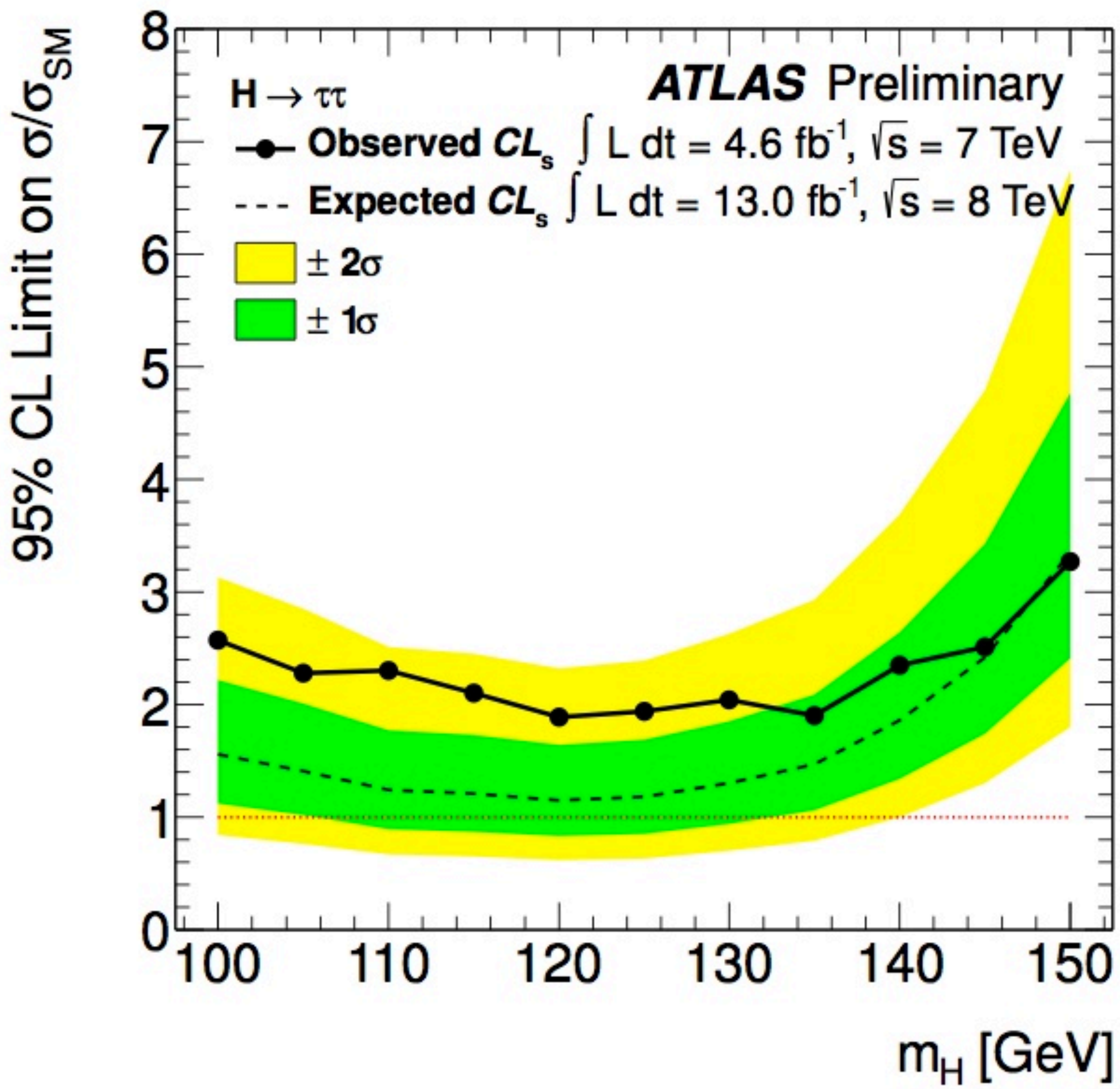
SM Higgs signal x5

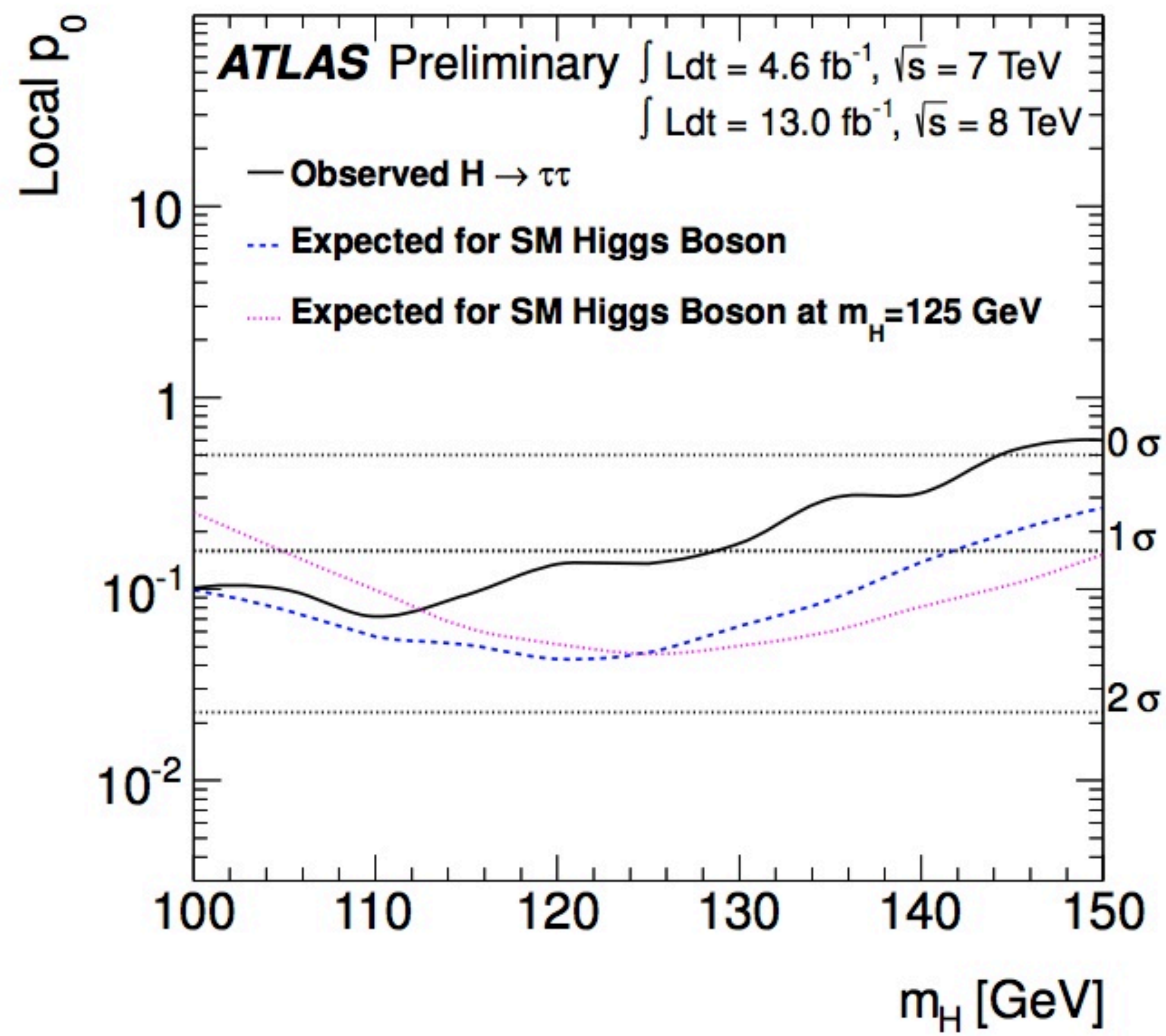
A VBF H to τ(had)τ(had) candidate event



Higgs to ττ results: Combined limit and p_0

- Using the MMC distribution as the discriminant, the limit and significance were calculated
- A profile likelihood method was used to extract a possible signal

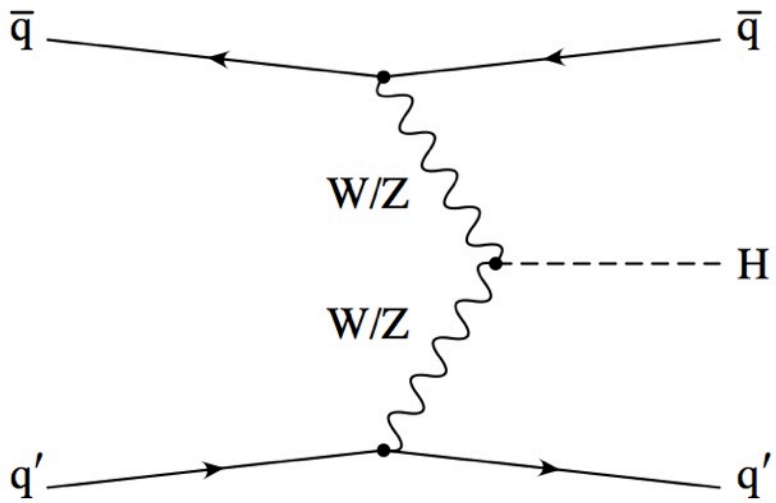


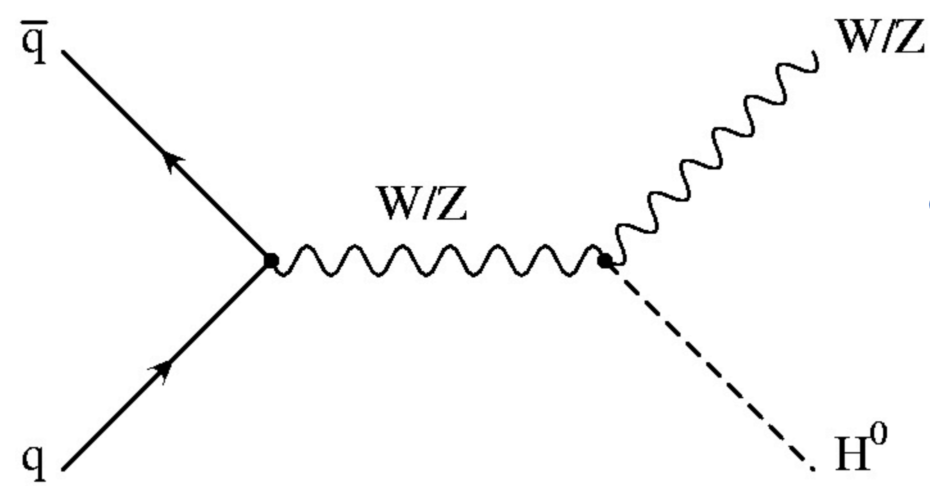


For μ=0:
Expected: 1.2 x SM
Observed: 1.9 x SM

For μ=1 (at m_H=125 GeV):
Expected: 1.7 σ
Observed: 1.1 σ

Higgs to ττ results: Production dependence



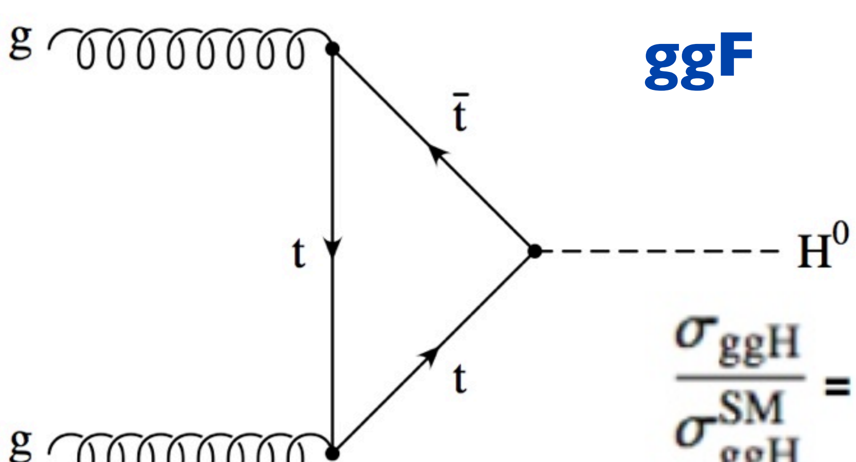


With μ_{ggF} and μ_{VBF+VH} constrained to be positive:

$\mu_{ggF} \times B/B_{SM} = 2.1$
$\mu_{VBF+VH} \times B/B_{SM} = 0$

VBF **VH**

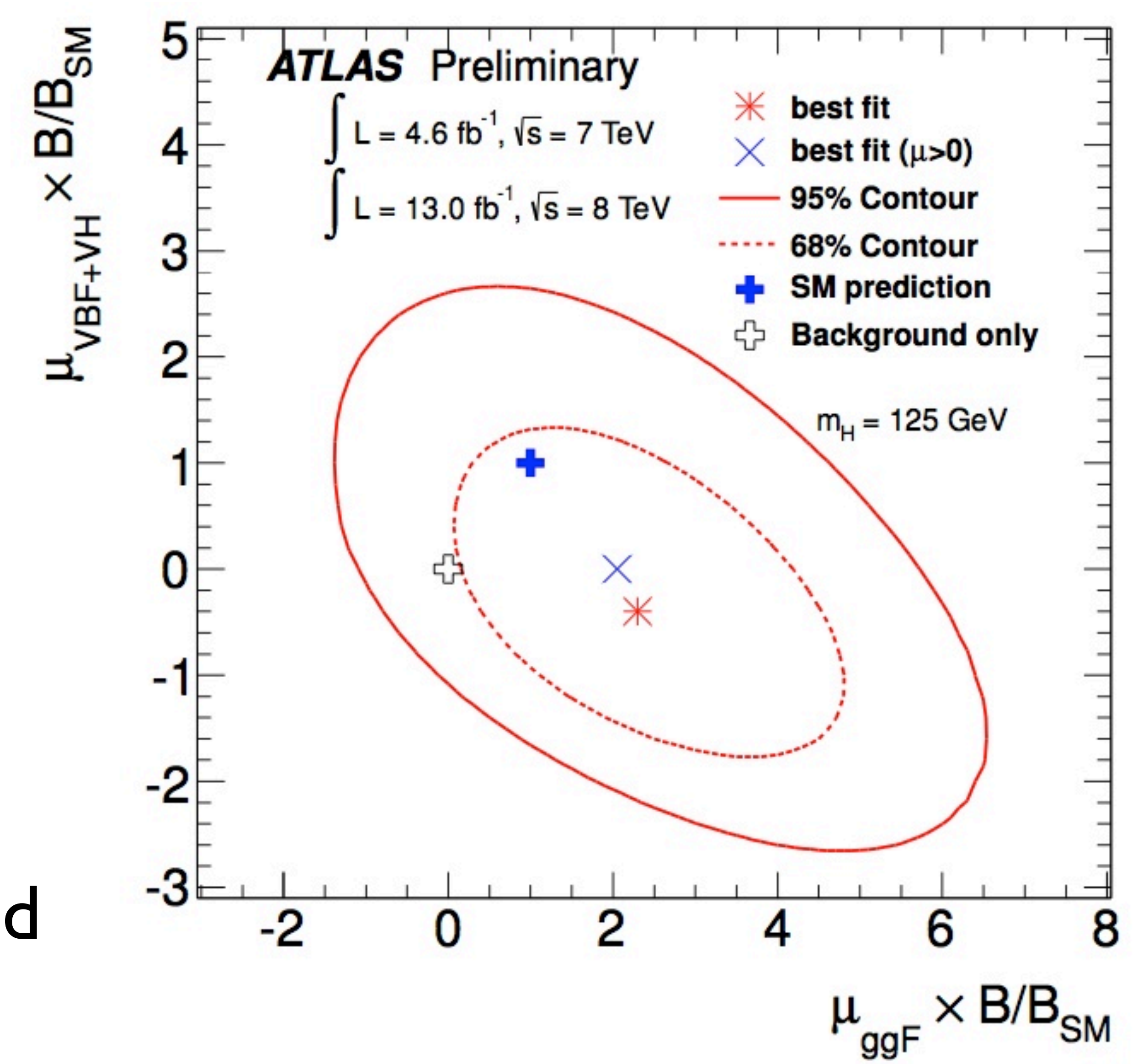
$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \mu_{VBF+VH}$$



ggF

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \mu_{ggF}$$

- Result consistent with both the SM and background-only hypotheses, within a large error

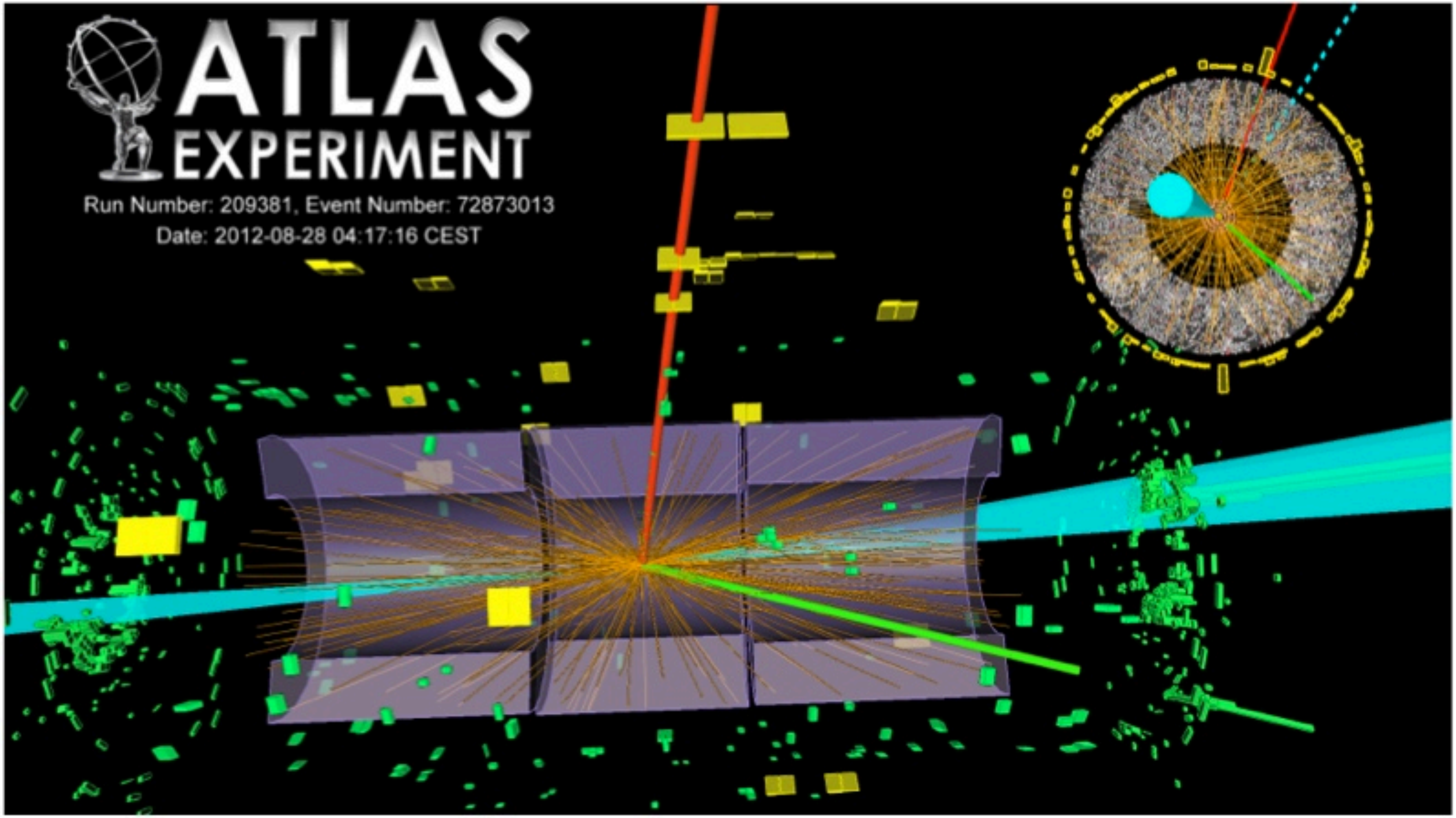


Conclusions and Outlook

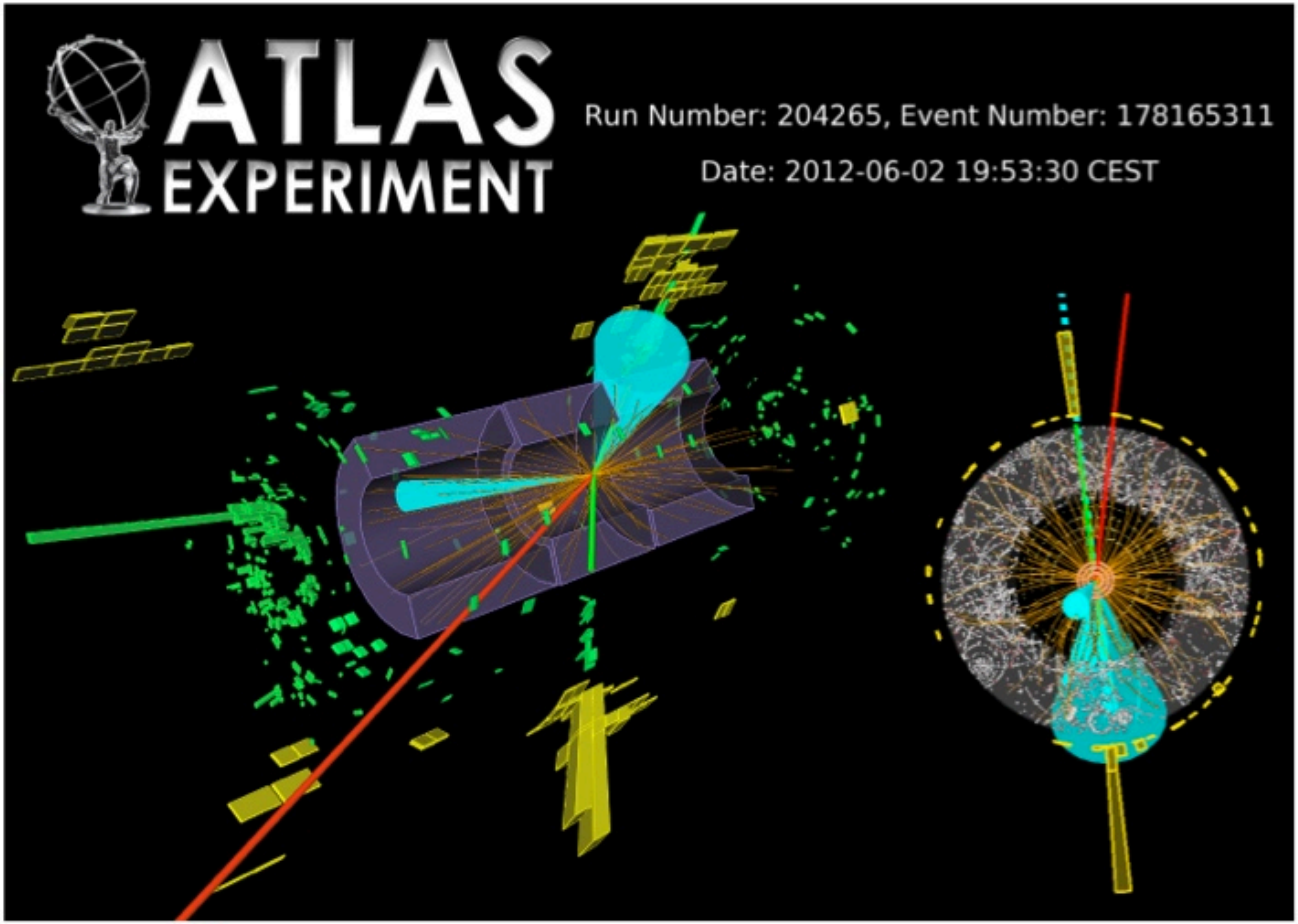
- A new Higgs to $\tau\tau$ analysis using 13 fb^{-1} of the 2012 data sample has been presented
- The 4.6 fb^{-1} 2011 dataset has been examined again using a re-optimized version of the analysis (giving significant improvements on our previously-published 2011 result)
- The sensitivity of the analysis approaches μ=1, however the results of this Higgs to $\tau\tau$ analysis are compatible with either the background-only hypothesis or the SM Higgs hypothesis: expected (μ=0) 1.2 x SM; observed 1.9 x SM at m_H=125 GeV
- The best-fit signal strength is: $\mu_{best\text{-}fit} = 0.7 \pm 0.7$ at m_H=125 GeV
- Additional improvements are currently being implemented and aimed at the full 2012 data sample
- These are very exciting times!

Back-up Slides

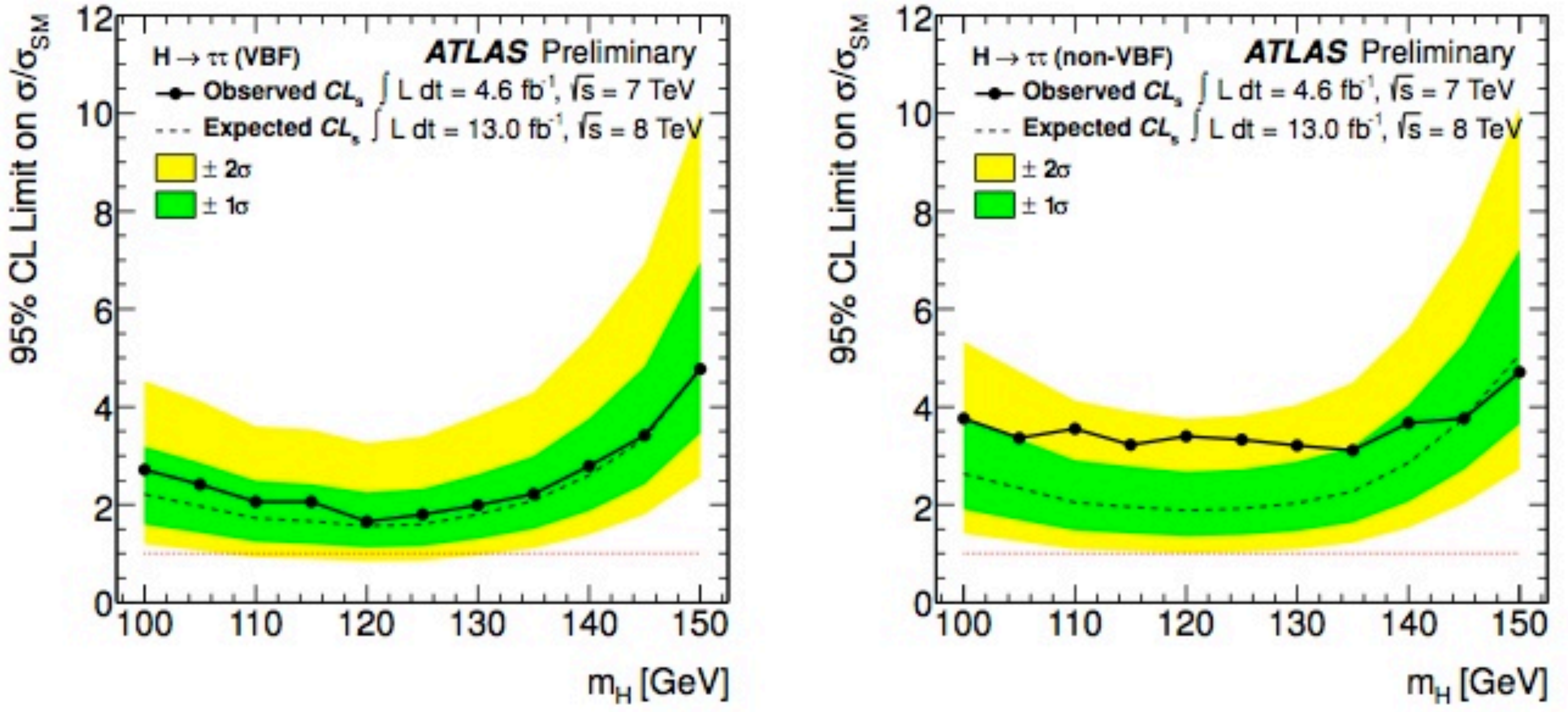
A VBF H to τ(e)τ(μ) candidate event



A VBF H to τ(μ)τ(had) candidate event



VBF and non-VBF limits



(a) VBF categories

(b) Non-VBF categories

Figure 18: Observed (solid) and expected (dashed) 95% confidence level upper limits on the Higgs boson cross-section times branching ratio, normalised to the SM expectation, as a function of the Higgs boson mass. Expected limits are given for the scenario with no signal. The bands around the dashed line indicate the $\pm1\sigma$ and $\pm2\sigma$ uncertainties of the expected limit. Combined 2011 plus 2012 results for all channels are presented for the VBF (a) and non-VBF (b) categories.

Systematics

Table 14: Summary of $Z \to \tau^+\tau^-$ background and signal systematic uncertainties by channel. The quoted ranges refer specifically to the 8 TeV dataset, but they are similar for the 7 TeV dataset. Uncertainties indicated with (S) are also applied bin-by-bin, and therefore affect the shape of the final distributions. Signal systematic uncertainties are derived from the sum of all signal production modes.

Uncertainty	$H \to \tau_{\text{lep}}\tau_{\text{lep}}$	$H \to \tau_{\text{lep}}\tau_{\text{had}}$	$H \to \tau_{\text{had}}\tau_{\text{had}}$
	$Z \to \tau^+\tau^-$		
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%

Mass Reconstruction with τ leptons

- Visible mass:
  - Invariant mass of the visible τ decay products

- Effective mass
  - Invariant mass of the visible τ decay products + MET

- Collinear mass:
  - Assume that neutrinos are emitted parallel to the visible τ decay products' direction ⇒ 2 equations and 2 unknowns

$$\not{E}_X = P_{\nu 1}\cdot\cos(\theta_1)\cdot\cos(\varphi_1) + P_{\nu 2}\cdot\cos(\theta_2)\cdot\cos(\varphi_2)$$

$$\not{E}_Y = P_{\nu 1}\cdot\cos(\theta_1)\cdot\sin(\varphi_1) + P_{\nu 2}\cdot\cos(\theta_2)\cdot\sin(\varphi_2)$$

$$m_{collinear} = \frac{m_{vis}}{x_1 x_2}$$

$x_{1,2}$ are the momentum fractions carried away by the visible τ products