Study of Higgs boson leptonic decay modes

Windows on the Universe
ICSE, Vietnam 11-17.08.2013

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CERN, 4 July 2012
Ladies and gentlemen, I think we've got it!
Discovery of a Higgs-like particle coupling to gauge bosons

Why do we care?

- The Yukawa interactions are not strictly needed for the Electroweak symmetry breaking via the Higgs mechanism.
- However, they give us a very appealing opportunity to dynamically introduce masses of otherwise massles fermion fields: $-L_{Yukawa} = Y_{ij}\left(\overline{\psi}_{Li}\,\phi\right)\psi_{Rj} + h.c.$

SU2 doublets ($\overline{\psi}_{Li}$, ϕ) — singlet (ψ_{Rj})

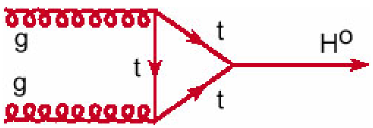
- If realized, couplings to all fermions in the SM are proportional to their masses.
- We nearly confirmed the Higgs E-W symmetry breaking mechanism.
- We only start gathering direct evidence for Yukawa couplings (indirect via ggF)
- So far, leptonic sector remains the least confirmed!

Hideki Yukawa

SM Higgs production @ LHC

in the context of its leptonic decays

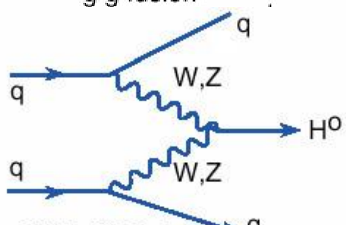
(~25 fb^{-1}/exp has been collected till LS1)



g g fusion

~19pb (0.95pb)

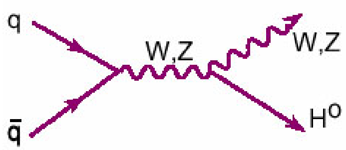
Dominant process. Can exploit high p_T of the Higgs due to associated jets.



WW, ZZ fusion

~1.5pb (0.07pb)

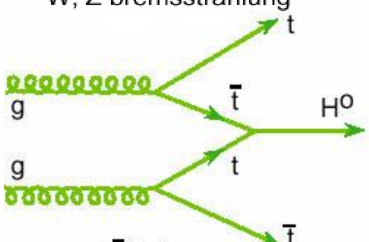
Clean signature with two forward jets and rapidity gap.



W, Z bremsstrahlung

~1.0pb (0.21pb)

Small contribution to significance. Consider W/Z->hadrons (ATLAS) and W/Z->leptons (CMS)



$t\bar{t}$ fusion

~0.1pb (0.004pb)

The smallest contribution Considered implicitly in H+jets.

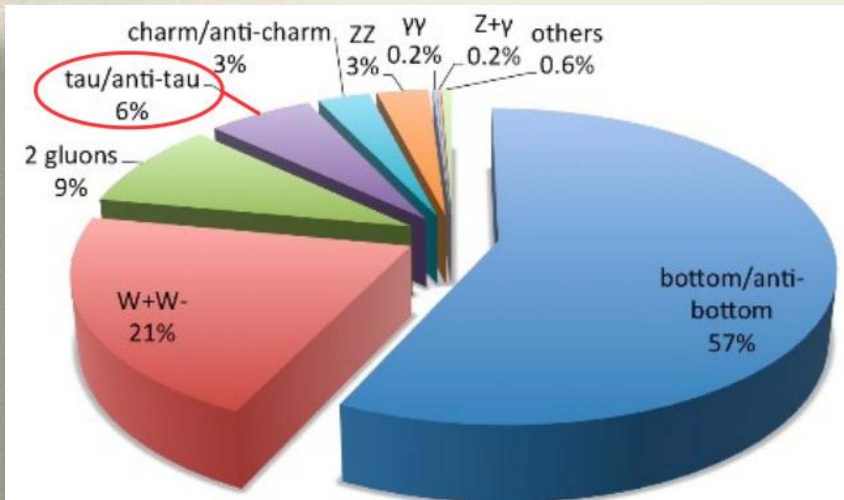
Tevatron

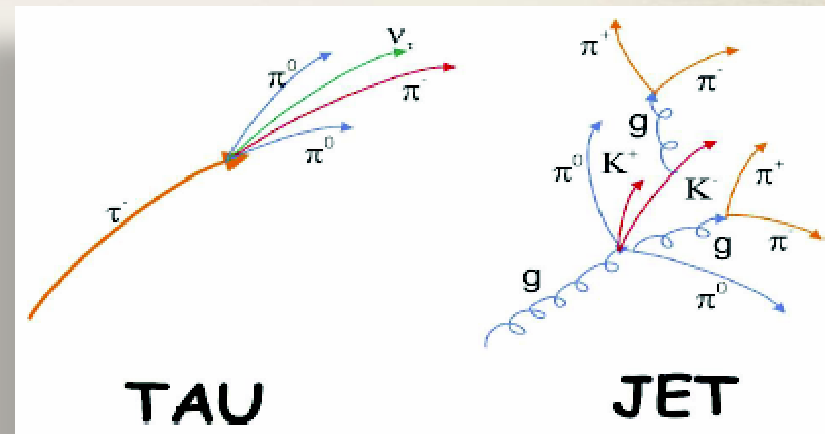
SM Higgs leptonic decays @ 125 GeV

- $H \to \tau\tau$ (6%)
- $H \to \mu\mu$ (0.02%)
- $H \to ee$ (5×10^{-9})

Higgs tauonic final states:

- (ll): $ee, e\mu, \mu\mu$ + 4ν (12%)
- ($l\tau_{had}$): $e\tau_{had}$, $\mu\tau_{had}$ + 3ν (46%)
- ($\tau_{had}\tau_{had}$): $\tau_{had}\tau_{had}$ + 2ν (42%)





Main challenges of the $H \to \tau\tau$ analyses:

- Identification of hadronic tau decays against QCD jets.
- Large irreducible background from $Z/\gamma^*\text{->}\tau\tau$
- Reconstruction of the invariant mass of the $\tau\tau$ system

Analysis strategy for $H\rightarrow\tau\tau$

(ATLAS: **ATLAS-CONF-2012-160**) and (CMS: **HIG-12-053, HIG-13-004**)

- Similar strategy adopted by the two experiments.

- Separate analyses in each decay mode allow optimization for different background compositions.

- Define mutually exclusive categories motivated by Higgs production modes and kinematics:
  - **VBF**: tagged by 2 forward jets in opposite hemispheres with large rapidity difference. Usually gives the highest significance
  - **Inclusive**: target ggF topology, further classified according to the apparent boost of the Higgs ($\tau\tau$ mass resolution).
  - **VH**: target H associated production with W/Z, tagged by either hadronic or leptonic W/Z decay. By far the least significant.

- $m_{\tau\tau}$ is the final discriminating variable

Analysis strategy for $H\to\tau\tau$

(ATLAS: **ATLAS-CONF-2012-160**) and (CMS: **HIG-12-053, HIG-13-004**)

ATLAS:

- **VBF**: two high p_T jets with high $\Delta\eta$ & high m_{jj}
- **Boosted**: high Higgs p_T (ll, $l\tau_{had}$) or high p_T jets ($\tau_{had}\tau_{had}$); (improve $\tau\tau$ mass resolution)
- No Boost (ll, $l\tau_{had}$):
  - **VH**: 2 jets with m_{jj}~$m_{Z/W}$, (ll mode only)
  - **1 jet**: target mostly ggF with a recoil against a jet
  - **0 jet**: ($e\mu$ only in 7TeV data)

CMS:

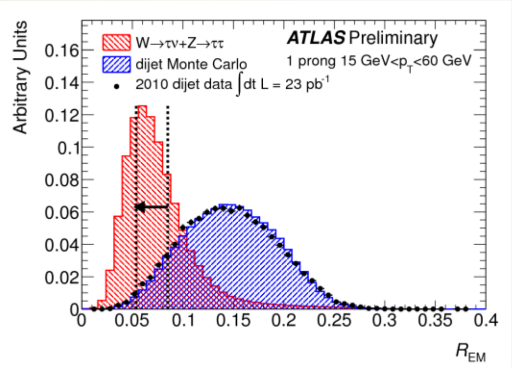
- **VBF**: two high p_T jets with high $\Delta\eta$ & high m_{jj} and a rapidity gap.
- **1-jet:** catch-all categories, mostly ggF with a recoil against a jet. Further split into "low-p_T" and "high-p_T" categories based on τ kinematics.
- **0-jet**: serves as a control region.
- **VH**: target VH with W/Z decaying leptonically. All tauonic Higgs decay modes considered.

Reconstruction of hadronic τ decays

(ATLAS: **ATLAS-CONF-2011-152**) and (CMS: JINST **7 (2012) P01001**)

ATLAS (top-down)

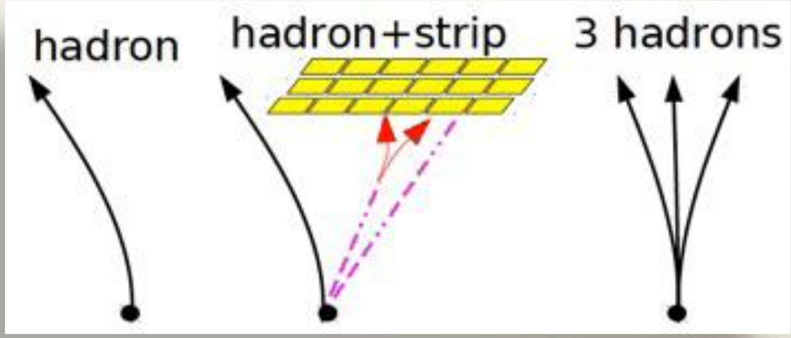
- ❖Start from the anti-k_T jets reconstructed from calorimeters.
- ❖Associate charged tracks.
- ❖Energy calibration based on MC.
- ❖Use MVA to discriminate against QCD jets and leptons.



BDT-based ID:
- ❖60%(40%) efficiency for medium (tight)
- ❖2-3% (0.5%) QCD jet acceptance.

CMS (bottom-up)

- ❖Start from particles reconstructed by the *Particle Flow* algorithm
- ❖Construct 1-prong, 1-prong+π0's, 3-prong τ candidates.



- ❖MVA discriminant based on $\sum p_T$ of particles in rings around τ.

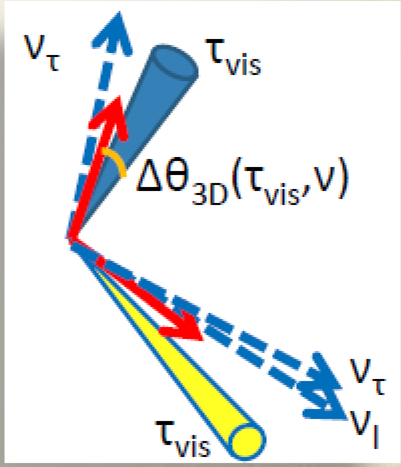
BDT-based ID:
- ❖50%(36%) efficiency for loose (medium)
- ❖1% (0.4%) QCD jet acceptance.

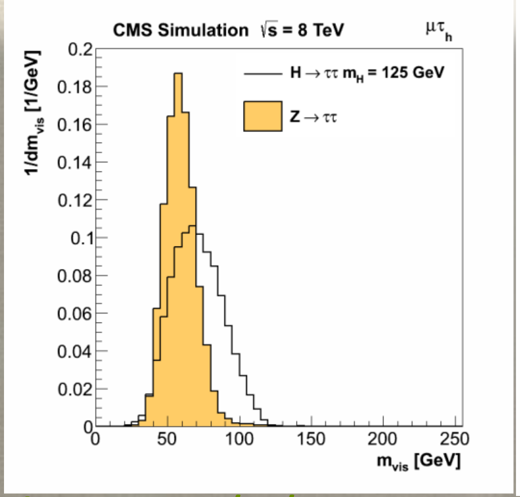
Invariant mass of the ττ system

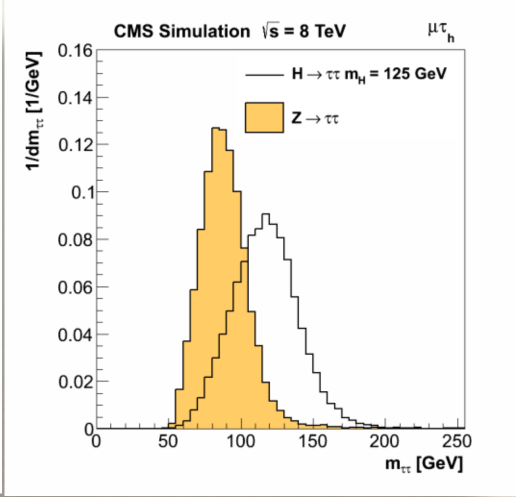
MMC (ATLAS: **NIM A 654 (2011)**) and SVFit (CMS: **HIG-13-004**)

- There are 6 to 8 parameters describing invisible neutrinos and 4 constraints ($2\times m_\tau$, $\not{E}_{Tx}$, $\not{E}_{Ty}$)
- Find max. likelihood solution accounting for the distributions of the ττ kinematics and $\not{E}_T$ resolution.

$$\mathcal{L} = -\log\left(\mathcal{P}(\Delta R_1, p_{\tau 1}) \times \mathcal{P}(\Delta R_2, p_{\tau 2}) \times \mathcal{P}(\Delta \not{E}_{T_x}) \times \mathcal{P}(\Delta \not{E}_{T_y})\right)$$





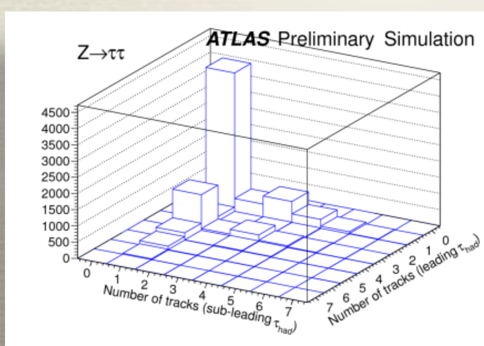


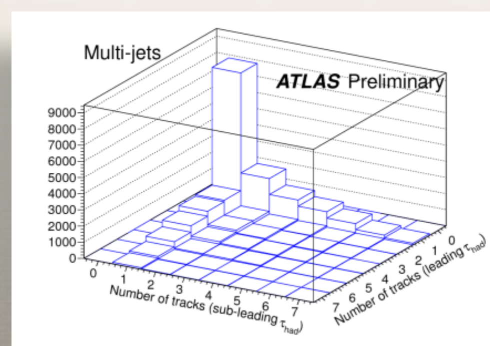
$\sigma(m_{\tau\tau}) \leq 20\%$ (depending on the channel and kinematics)

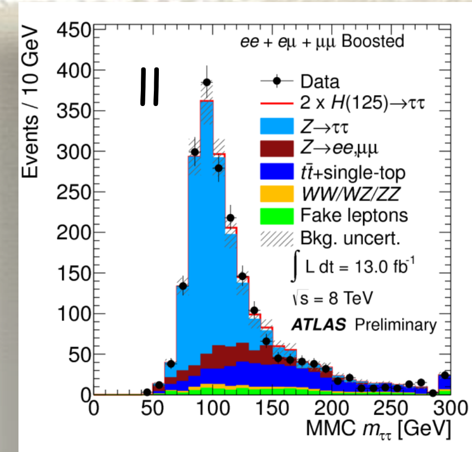
Main backgrounds

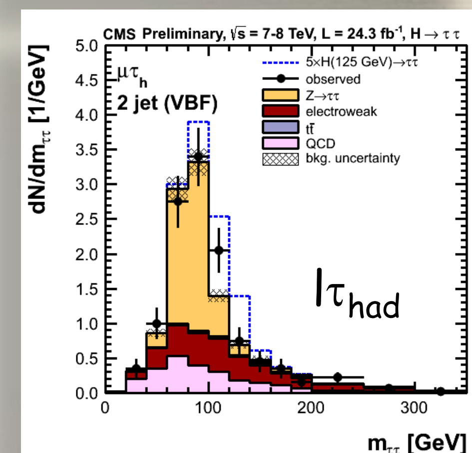
- Irreducible $Z/\gamma^*\to\tau\tau$: from „embedding", normalized using data-driven methods
- Others: (Electroweak, tt+single top): Simulation, normalized from data CR
- QCD: SS data, yield corrected from data CR

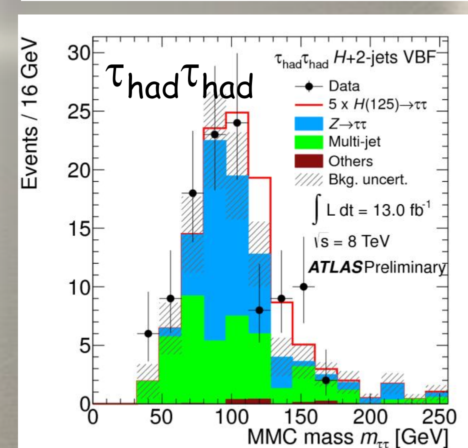
A: VBF $l\tau_{had}$ category uses MC and Fake Factor method $F=N_{id}/N_{anti\text{-}id}$ (W+jets, QCD)
A: 2D template fit to τ candidate track multiplicity for $Z/\gamma^*\to\tau\tau$ and QCD in $\tau_{had}\tau_{had}$ category:









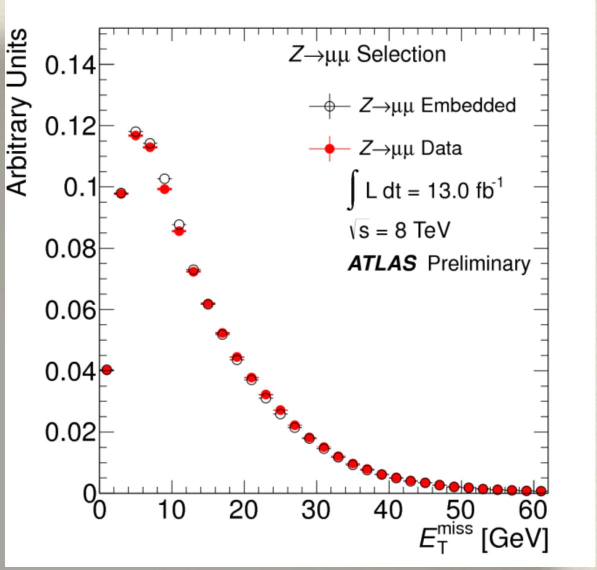


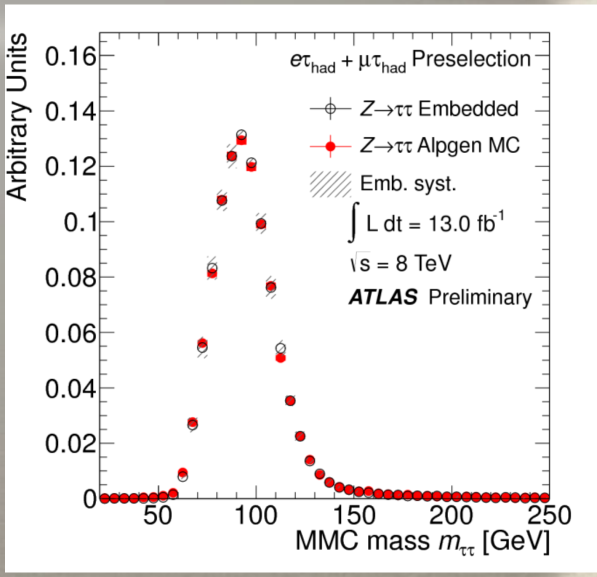
Background estimation: „embedding"

- Embedding in $Z/\gamma^* \to \mu\mu$ events: reconstructed muons are removed from data events and replaced by simulated τ decays with the same kinematics.

- Advantage: data-driven description of the entire event (except for lepton decays) leading to significantly reduced systematic uncertainties (jets, underlying event, luminosity, etc.) compared to the MC simulation.

- ll, $l\tau_{had}$, $\tau_{had}\tau_{had}$ (ATLAS & CMS)





Main sytematic uncertainties

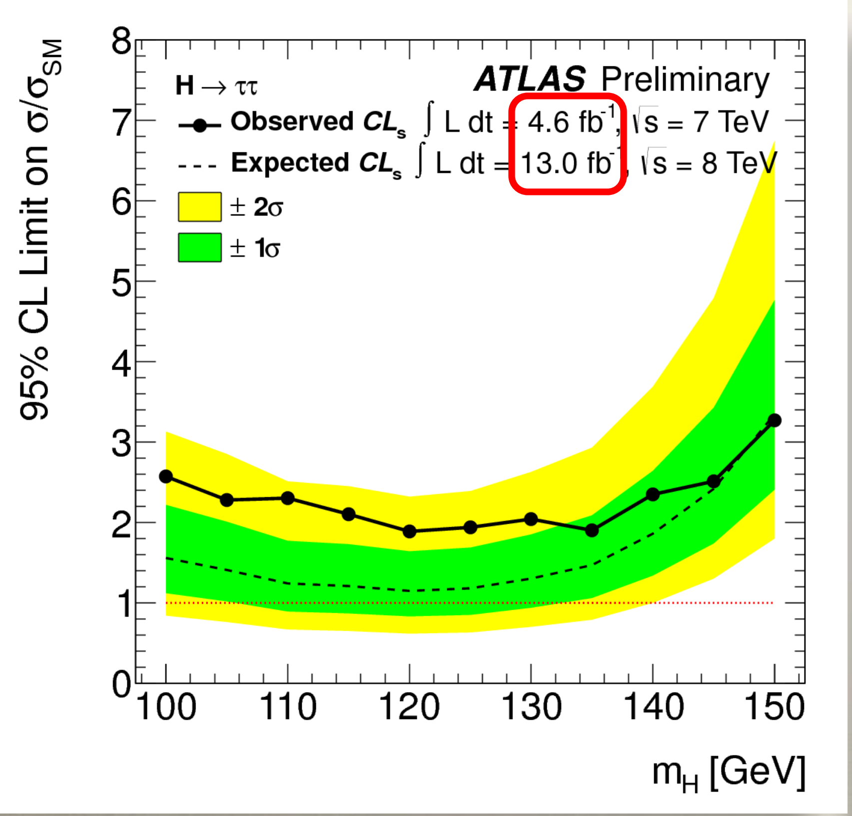
- Modeling and normalization of background processes:
  - Irreducible $Z/\gamma^*\text{->}\tau\tau$ is dominated by the data-driven normalization (5% to 10%).
  - Uncertainties on backgrounds with misidentified leptons and τ candidates (QCD, W+jets, etc.) can be as large as 50% ($l\tau_{had}$ VBF), but their contribution is much smaller.

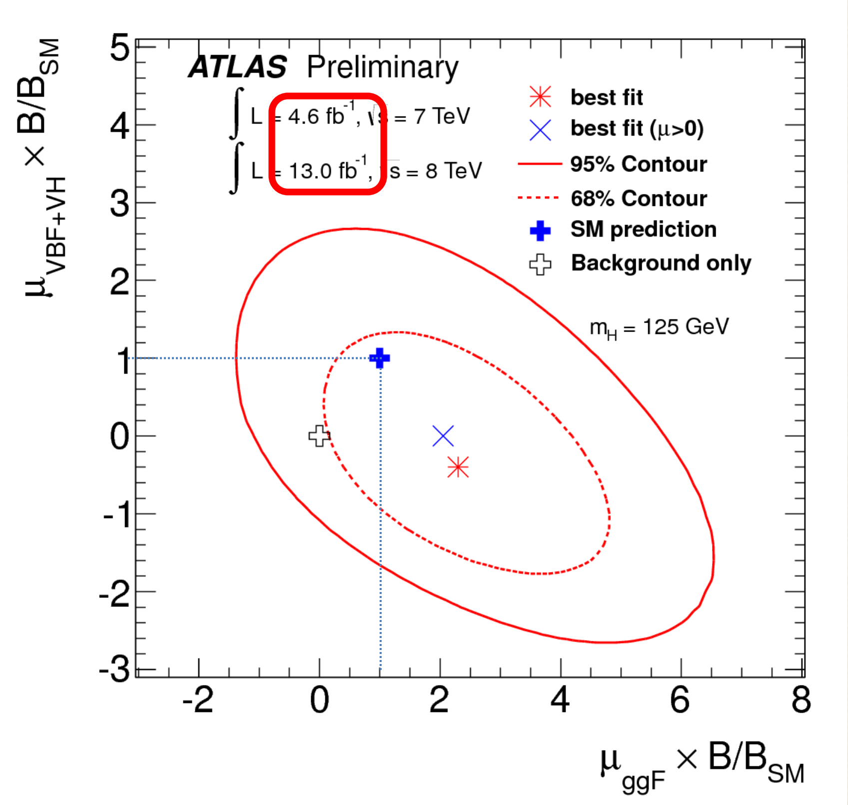
- Experimental uncertainties on the expected signal yield come from JES, τ energy scale and τ identification and add up to ~10%

- Theoretical uncertainty: $\sigma_H \times BR$ 3-28% (the largest for ggF)

ATLAS results (CONF-2012-160)

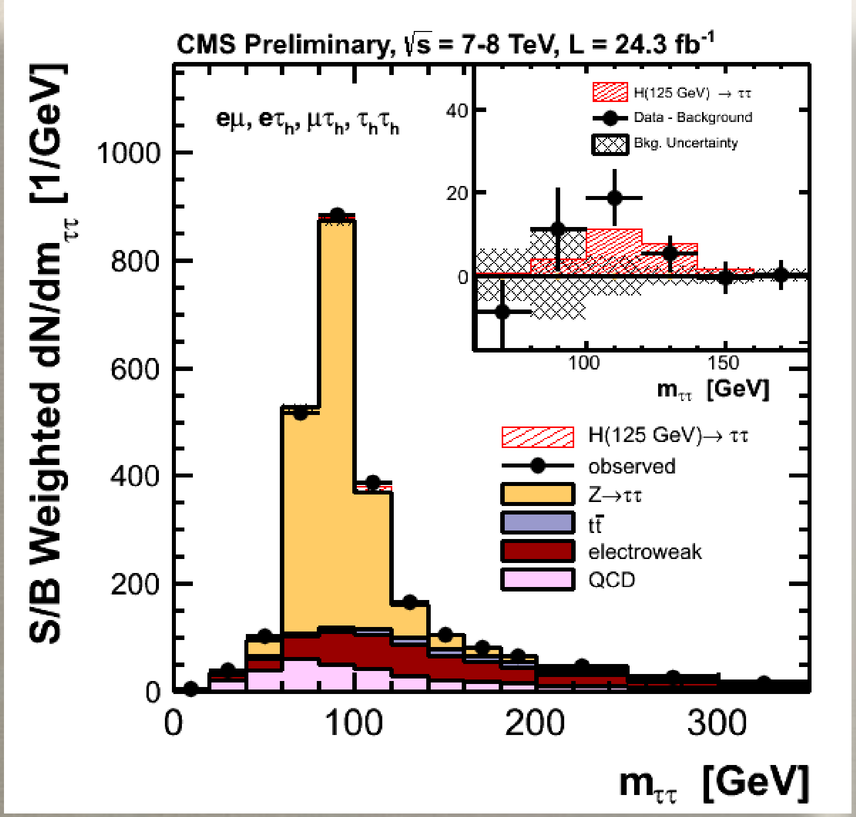
- $4.6\ fb^{-1}$ @ 7 TeV and $13.0\ fb^{-1}$ @ 8 TeV analysed.
- Update to full statistics imminent!
- μ=0.7 ± 0.7; significance 1.1σ (1.7 expected) @ 125 GeV

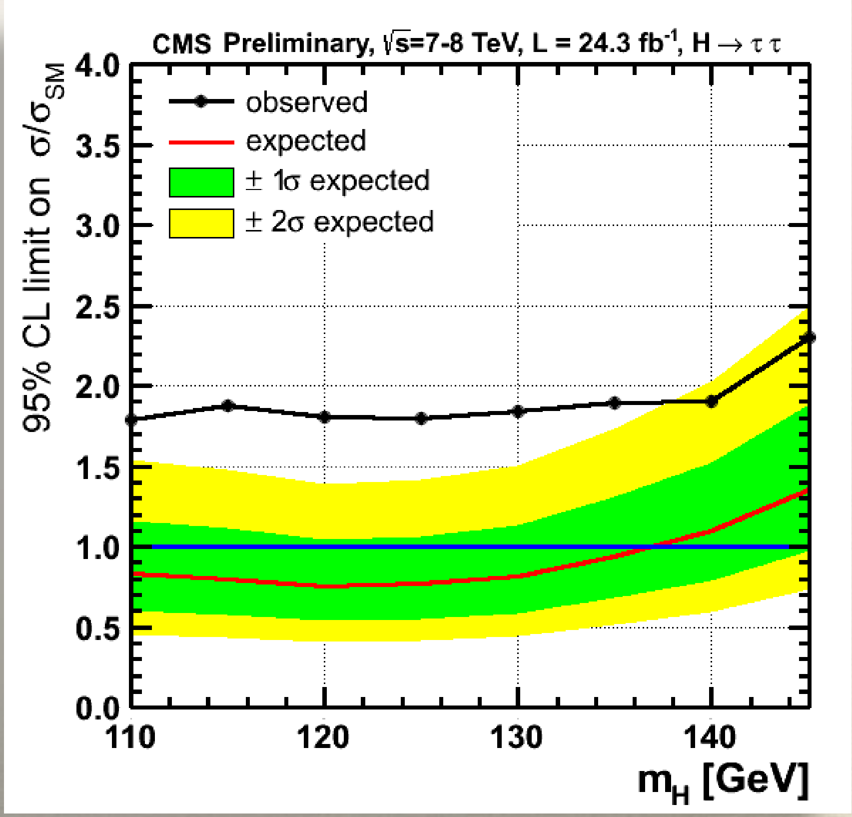




CMS results (HIG-13-004)

- All 24.3 fb^{-1} @ 7 & 8 TeV analyzed.
- μ=1.1 ± 0.4; significance 2.9σ (2.6 expected) @ 125 GeV
- Higgs mass has been estimated at $m_H=120^{+9}_{-7}$ GeV





$H \to \tau\tau$ at the Tevatron

- X-sections over an order of magnitude lower, half of the integrated luminosity – cannot expect sufficient sensitivity
- Both experiments searched for $H \to \tau\tau$ decays in three production channels (ggF, VBF, VH)

CDF

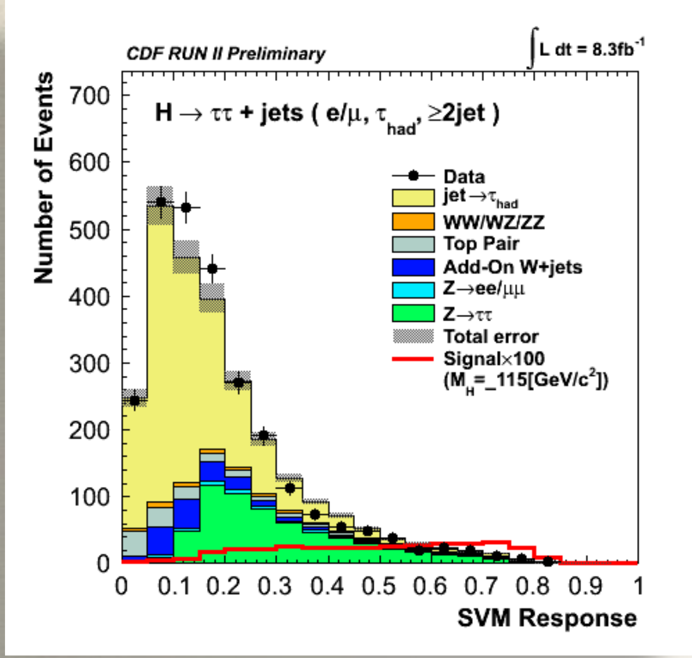
- Decay modes considered: ($e\mu$, $e\tau_{had}$, $\mu\tau_{had}$)
- 1-jet & ≥2jets categories
- Simulation and SS data samples are used to estimate main backgrounds.
- Main systematics: lumi, bkg normalization, JES

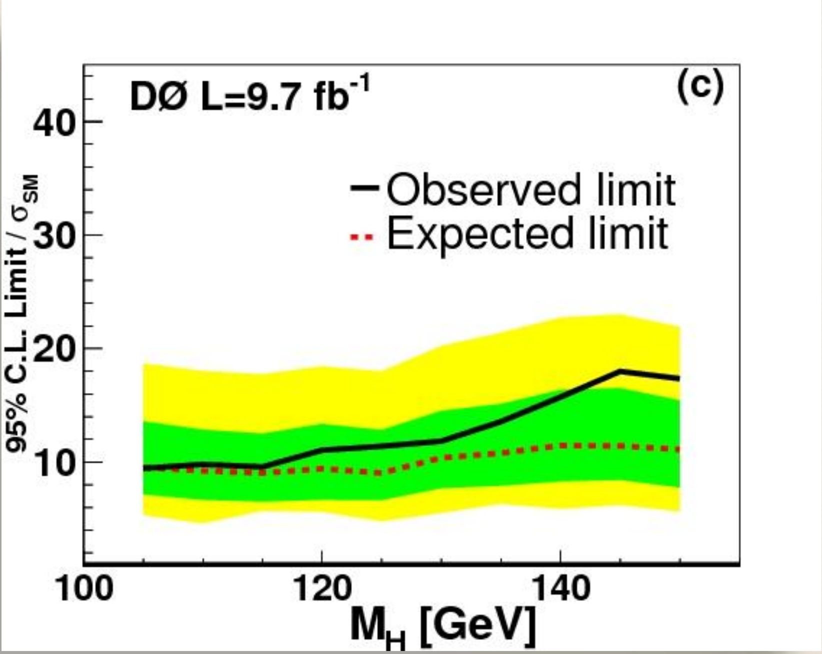
D0

- Decay modes considered: ($e\tau_{had}$, $\mu\tau_{had}$)
- ≥2jets required
- Simulation and SS (QCD) data samples are used to estimate main backgrounds.
- Main systematics: lumi, τ energy scale, QCD modeling.

H->ττ at the Tevatron

(PRL 108, 181804 (2012), arXiv:1211.6993v2)





CDF

- Int. Lumi: 8.3 fb^{-1}
- 95% CL @ m_H=125 GeV:
  - Limit obs.: 11.7 × σ_{SM}
  - Limit exp.: 14.8 × σ_{SM}

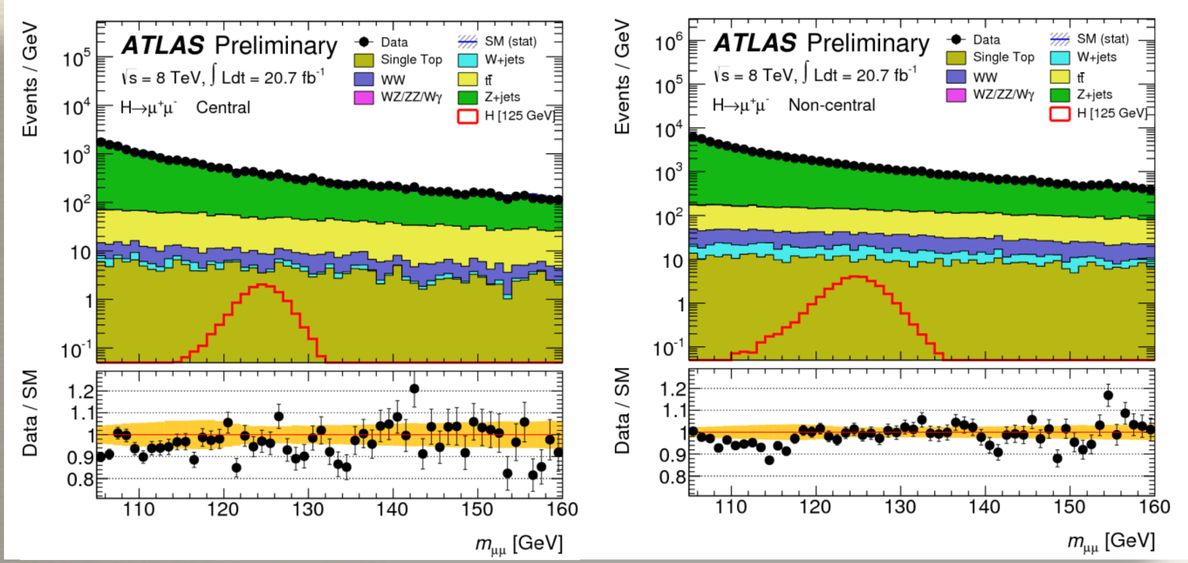
D0

- Int. Lumi: 9.7 fb^{-1}
- 95% CL @ m_H=125 GeV:
  - Limit obs.: 12.8 × σ_{SM}
  - Limit exp.: 10.4 × σ_{SM}

Search for H->μμ in ATLAS

Higgs coupling to second generation fermions: BR(H->μμ)=2×10^{-4} !

(ATLAS-CONF-2013-010)

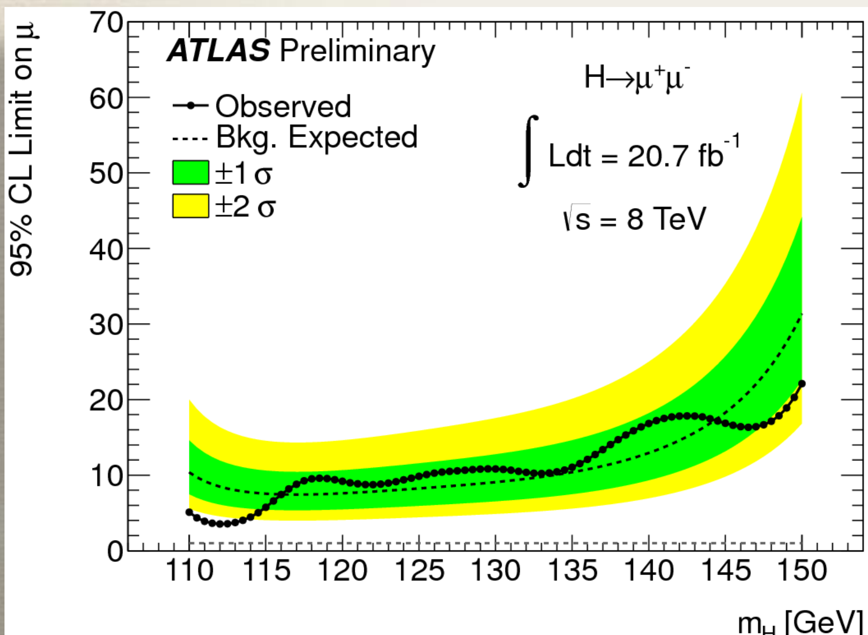


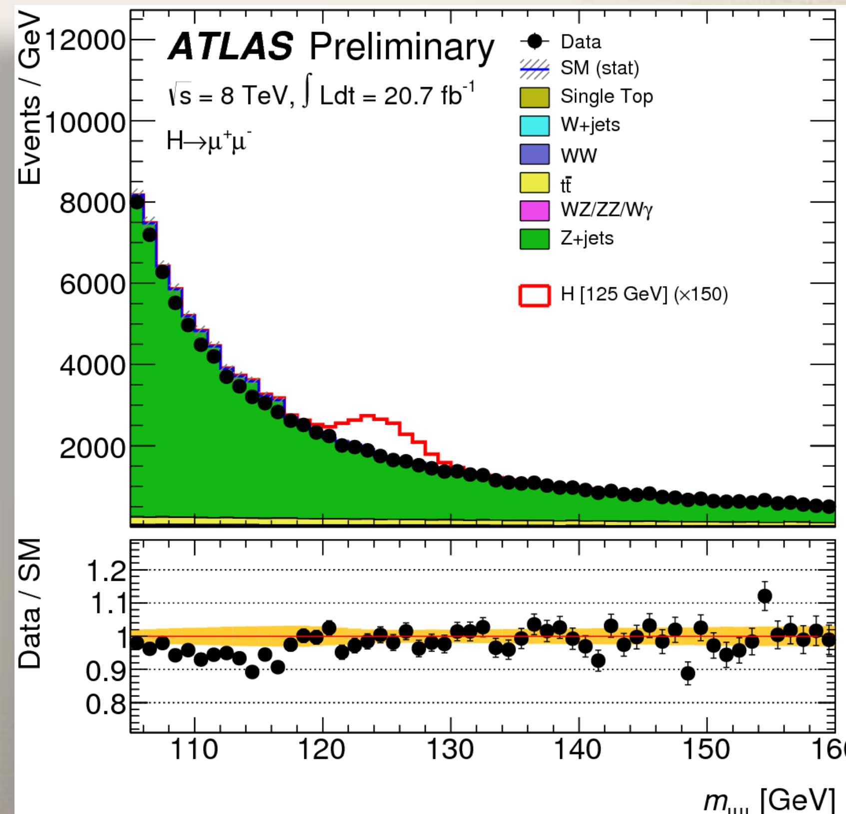
- ❖ Clean: only irreducible Z/γ*->μμ, but S/B=0.2% !!!.
- ❖ Very good mass resolution.
- ❖The search relies on a binned likelihood fit to background and signal (narrow resonance) PDF's in the range 110-150 GeV, separately for central and forward regions, due to different resolution.
- ❖ Systematic uncertainties are small, at a few percent level.

H->μμ search results

(ATLAS-CONF-2013-010)

- 20.7 fb^{-1} @ 8 TeV analysed.
- No evidence for signal seen.
- 95% CL @ m_H=125 GeV:
  - Limit obs.: 9.8 × σ_{SM}
  - Limit exp.: 8.2 × σ_{SM}
- Way more statistics needed!





CONCLUSIONS

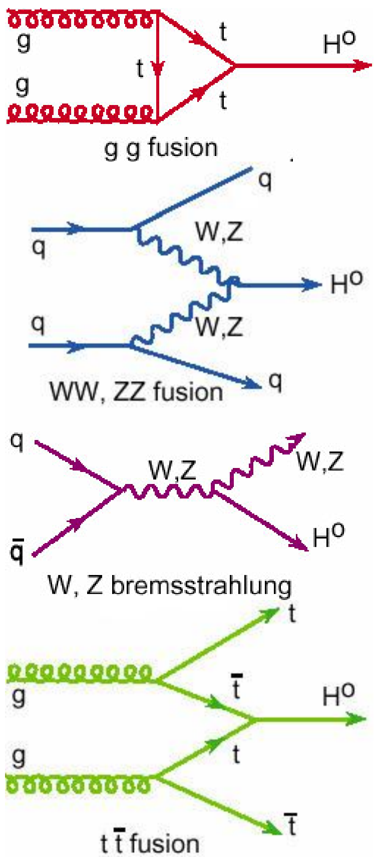
- Start exploring the Yukawa Higgs sector.
- Leptonic couplings particularly challenging.
- The least known. No indirect evidence.
- First direct evidence emerge (CMS: μ=1.1 $\pm$ 0.4).
- First attempt to tackle H->$\mu\mu$ (ATLAS: 95% CL 9.8 $\times$ σ_{SM}).
- With 3000 fb^{-1} @ 14 TeV, $\sigma(\mu_\tau)$~0.1, $\sigma(\mu_\mu)$<0.2.
- ATLAS update of H->$\tau\tau$ to full stats imminent.
- HL LHC will allow to explore leptonic Yukawa sector in much detail.

Stay tuned! **THANK YOU.**

BONUS MATERIAL

SM Higgs production @ LHC

(~25 fb^{-1}/exp has been collected till LS1)



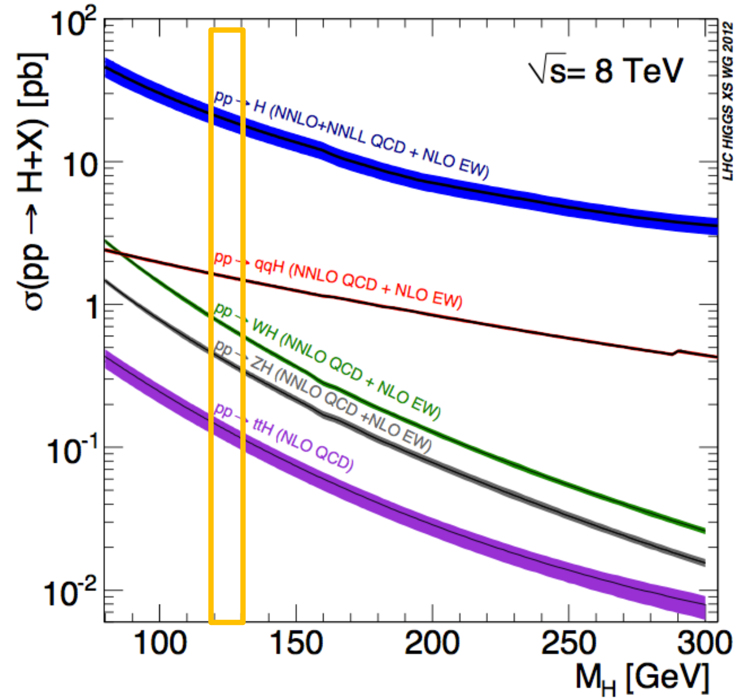
~19pb (0.95pb)

~1.5pb (0.07pb)

~1.0pb (0.21pb)

~0.1pb (0.004pb)

Tevatron



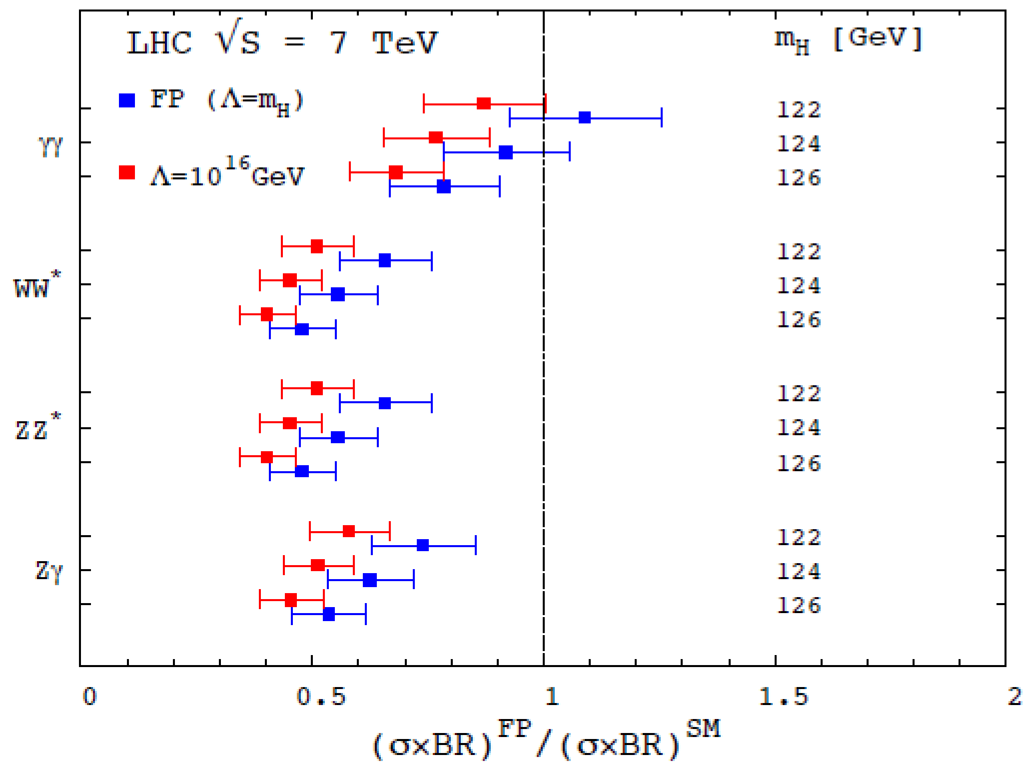
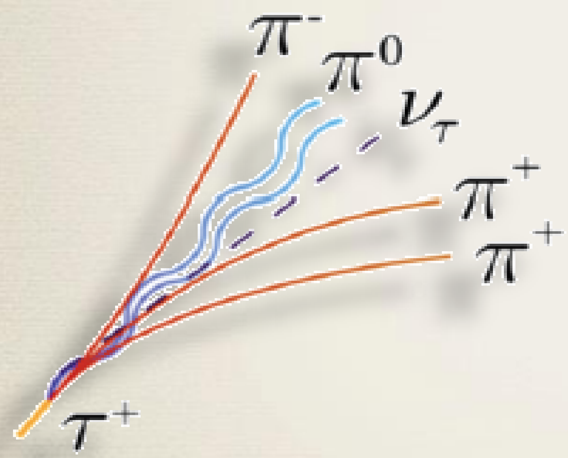


FIG. 2: Relative magnitudes of the FP Higgs prediction over a SM-like Higgs in different channels at the 7 TeV LHC for m_H = 122, 124, 126 GeV. The error bars correspond to the SM cross section uncertainties. The red (upper) and blue (lower) predictions show the theoretical errors associated with the new-physics scale Λ. For LHC at 8 TeV, the results are practically identical.

τ lepton basics

- Mass: 1.777 GeV/c2
  the heaviest lepton
- cτ: ~87μm
  short lifetime
- decays via weak interactions



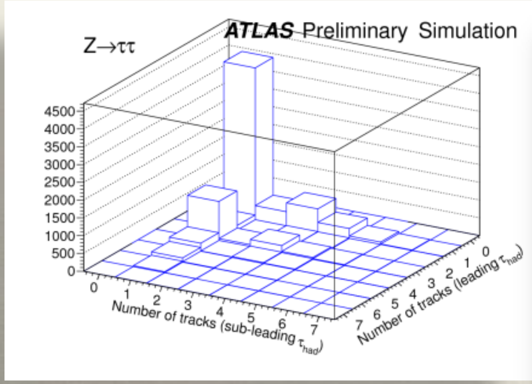
First observed in 1977 by Martin Perl et al. (SLAC-LBL)

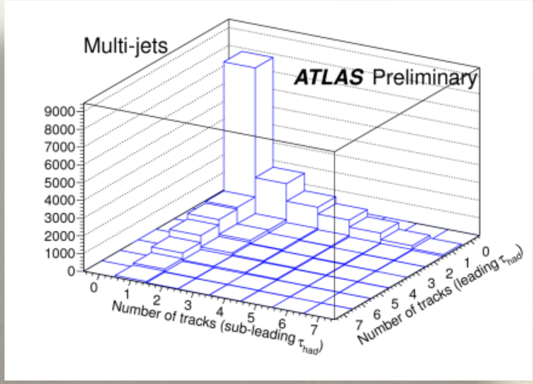
Most important decay modes

Decay Mode	Branching Fraction
Leptonic modes	**~35%**
$\tau^{\pm} \to e^{\pm} \nu_e \nu_\tau$	18%
$\tau^{\pm} \to \mu^{\pm} \nu_\mu \nu_\tau$	17%
Hadronic modes	**~65%**
1 prong (1 charged particle)	**46%**
$\tau^{\pm} \to \pi^{\pm} \nu_\tau$	11%
$\tau^{\pm} \to \pi^{\pm} \pi^0 \nu_\tau$	26%
$\tau^{\pm} \to \pi^{\pm} \pi^0 \pi^0 \nu_\tau$	9%
3 prong (3 charged particles)	**14%**
$\tau^{\pm} \to \pi^{\pm} \pi^{\pm} \pi^{\mp} \nu_\tau$	9%
$\tau^{\pm} \to \pi^{\pm} \pi^{\pm} \pi^{\mp} \pi^0 \nu_\tau$	5%

Background estimation

- From MC with normalisation correction from control regions:
ATLAS: $Z/\gamma^*\to ll$ ttbar (ll); W+jets tt ($l\tau_{had}$);
$Z/\gamma^*\to ll$, $Z/\gamma^*\to\tau\tau$ ($l\tau_{had}$ VBF);
CMS: ttbar (ll); W+jets ($l\tau_{had}$);
- From data CR with normalisation from the 2-D track multiplicity template fit:
ATLAS: $Z/\gamma^*\to\tau\tau$, QCD ($\tau_{had}\tau_{had}$);





Background estimation

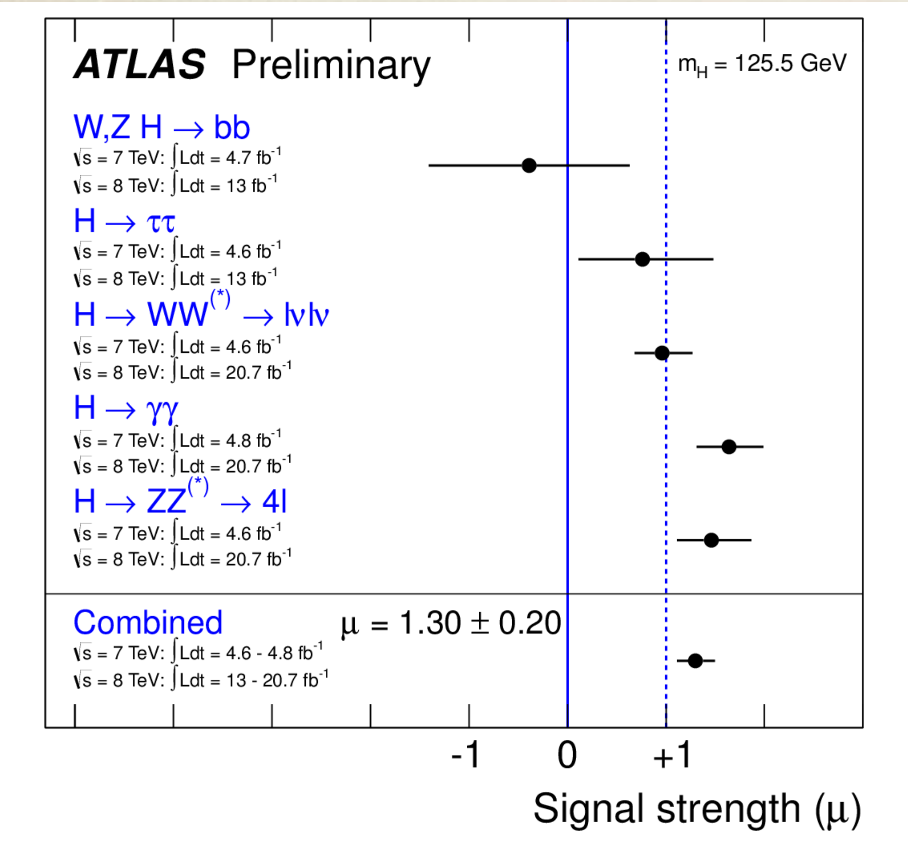
- SS corrected for the rate in the QCD control region. Other backgrounds taken as OS-SS.
ATLAS: ($l\tau_{had}$, not VBF, QCD $\tau_{had}\tau_{had}$);
CMS: QCD ($l\tau_{had}$, $\tau_{had}\tau_{had}$);

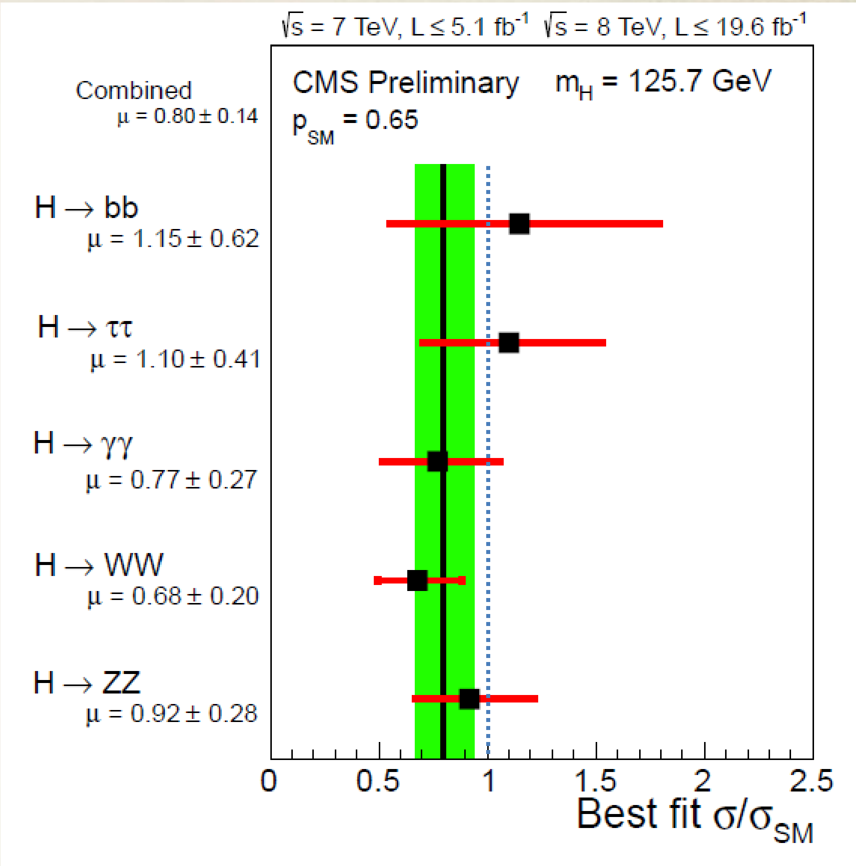
- Fake Fraction method to estimate fake τ contribution
ATLAS: QCD, W+jets ($l\tau_{had}$ VBF);
CMS: QCD, W/Z+jets ($l\tau_{had}$ VBF, all VH);

$$N_m^T = \frac{p_m}{(p_r - p_m)}(p_r * N^L - N^T)$$

- OTHER: Directly from MC or templates in CR.

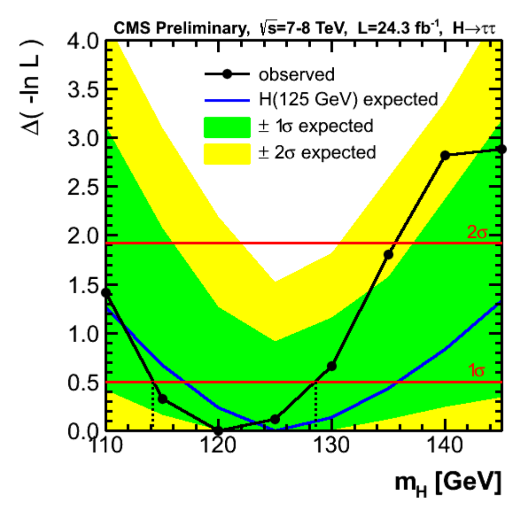
Summary of LHC Higgs results
(signal strength)

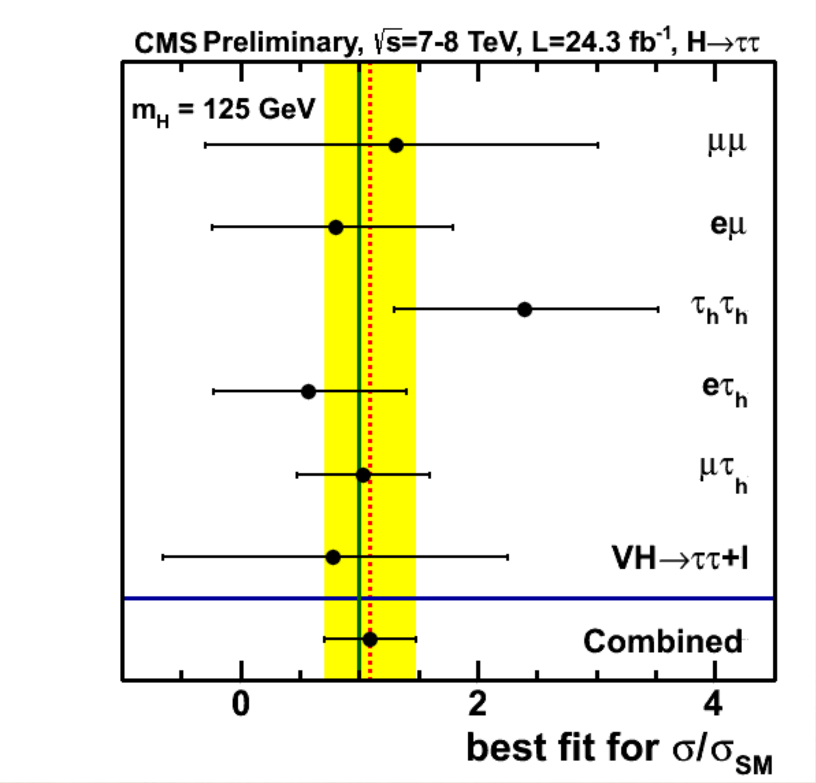


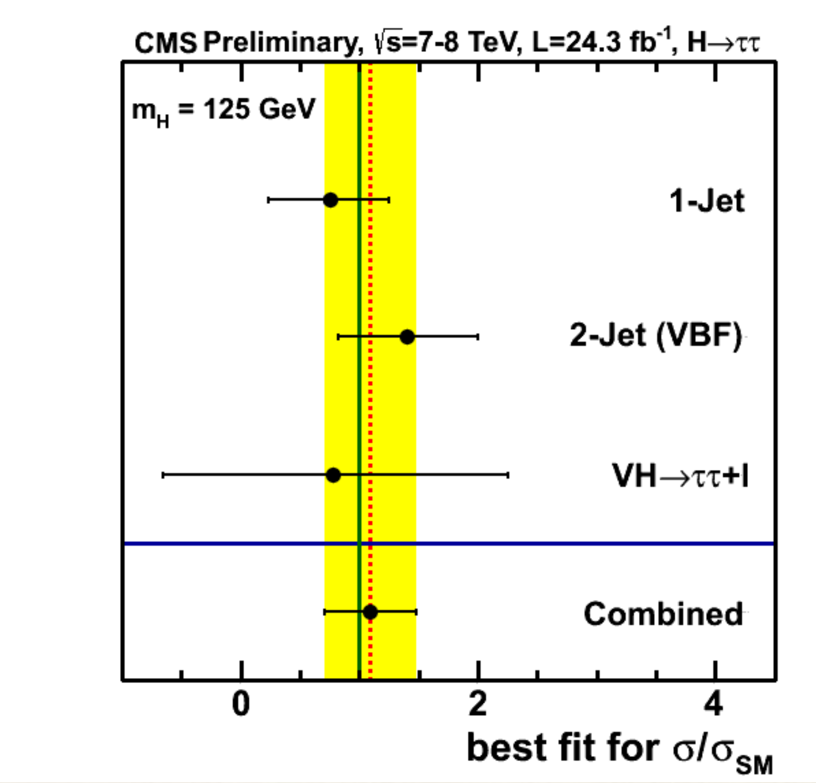


$$(\sigma \cdot \mathrm{BR})\,(x \to \mathrm{H} \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{tot}}$$

CMS H->ττ results
(production, decay, fitted mass)

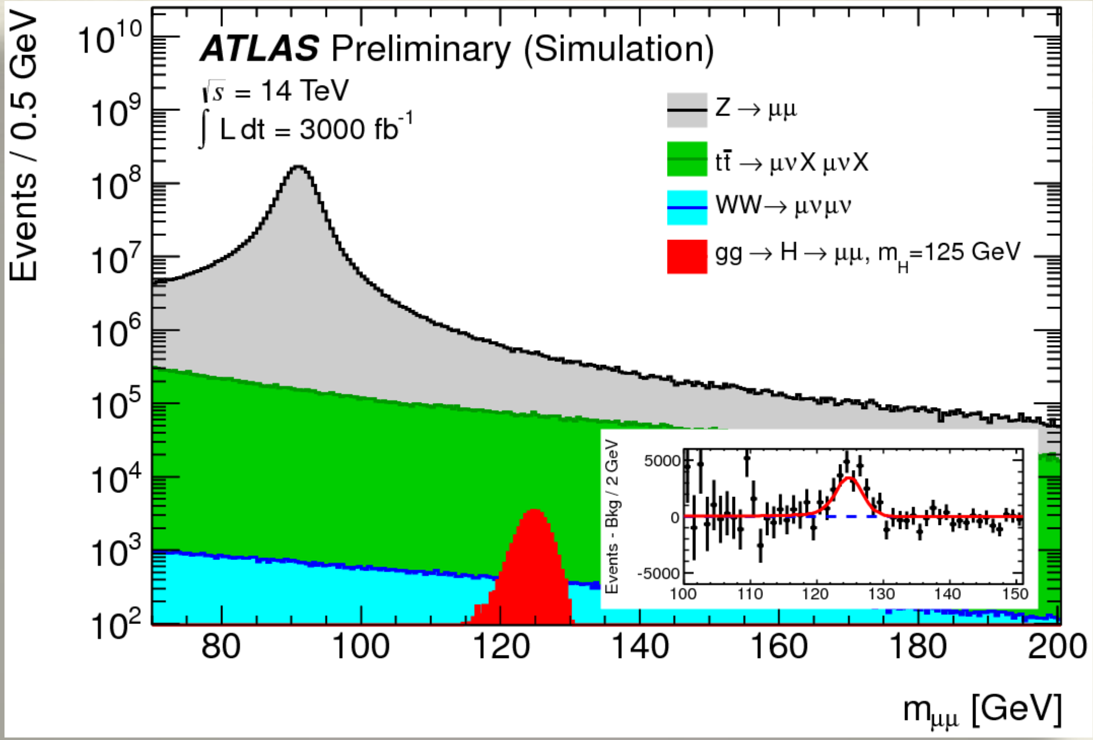






H->μμ search: outlook

(ATL-PHYS-PUB-2012-004)



- Are Higgs couplings ~m_F, i.e. nonuniversal?
- >6σ significance expected @3000 fb^{-1}
- Signal strength μ with σ<0.2
- Strong case for HL LHC!

Main backgrounds and sytematics (II)

- Irreducible $Z/\gamma^*\to\tau\tau$

Estimated from „embedding" σ_{sys} ~8%

- $Z/\gamma^*\to ll$

MC normalized from CR σ_{sys} =10-30%

- tt+single top

MC normalized from CR σ_{sys} =3-10%

- WW/WZ/ZZ

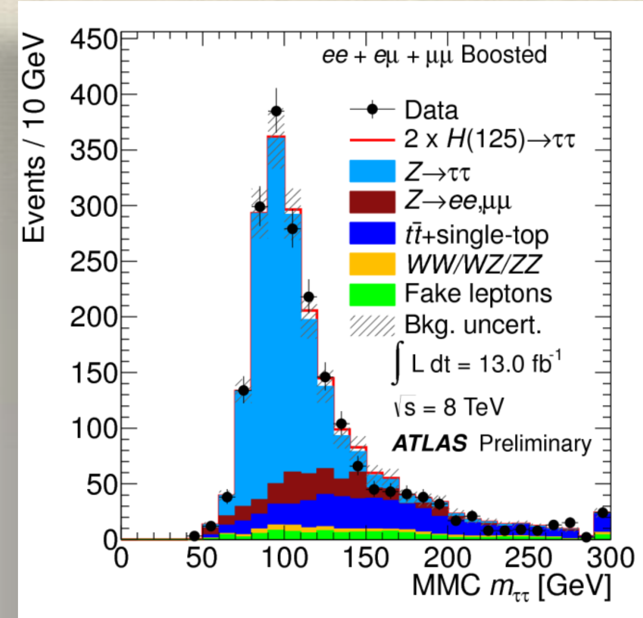
MC normalized from CR σ_{sys} ~10%

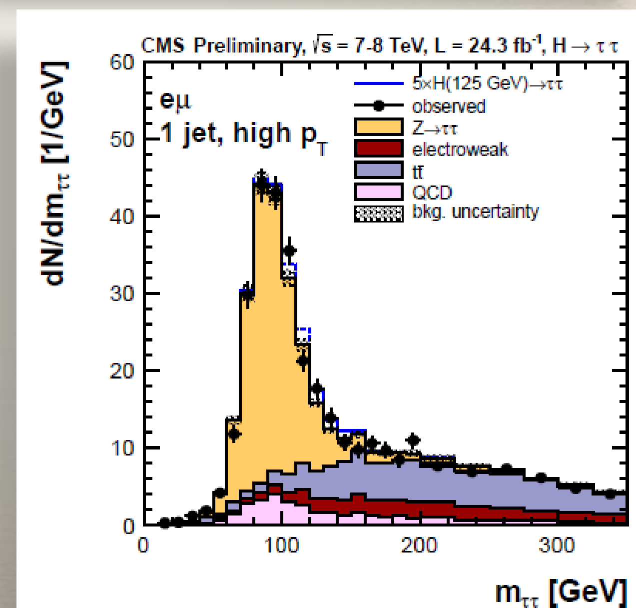
- Fake leptons (QCD)

A: Template method

C: Fake Factor method σ_{sys} =10-25%

- Theoretical uncertainty: $\sigma_H \times BR$ 8-28% (ggF largest by far)





Main backgrounds and sytematics ($l\tau_{had}$)

- Irreducible $Z/\gamma^*\to\tau\tau$

Estimated from „embedding" σ_{sys} =6-20%

- Others (Electroweak)

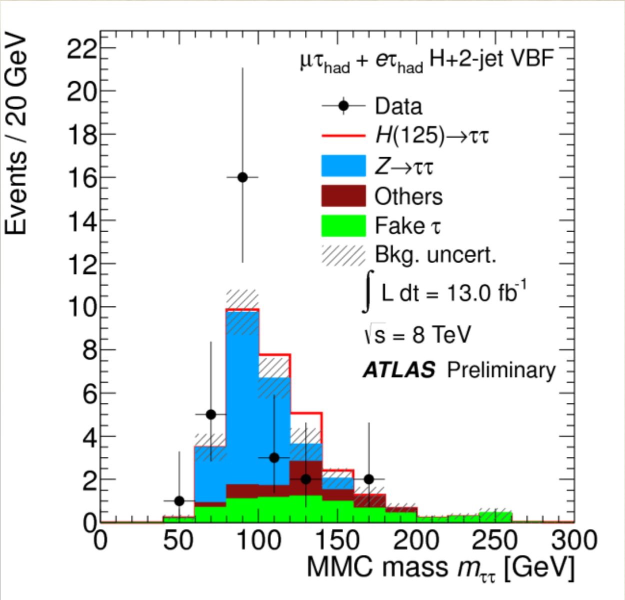
A: SS data corrected in the CR

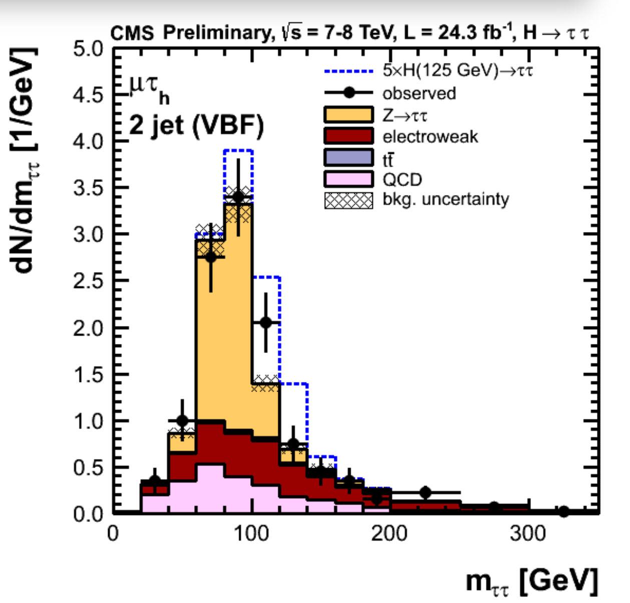
C: simulation, yield from CR σ_{sys} ~20%

- Fake taus (QCD)

SS data corrected in the CR σ_{sys} <50%

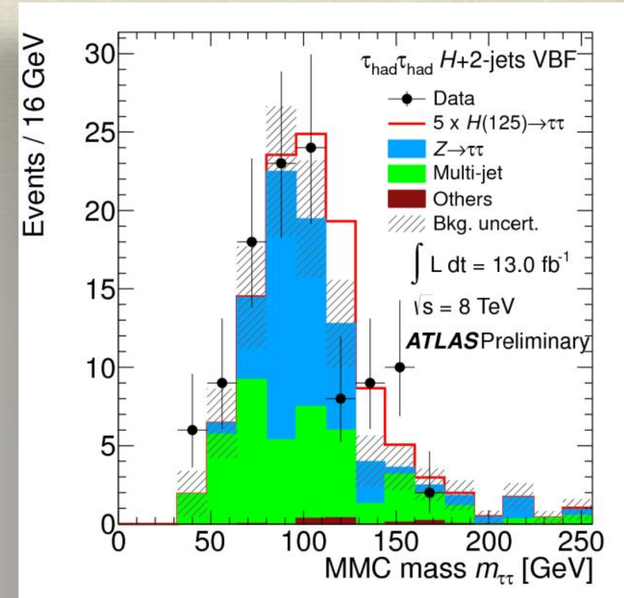
A: VBF category uses MC and Fake Factor method (W+jets, QCD)





- Theoretical uncertainty: $\sigma_H\times$BR 18-23% (ggF largest by far)

Main backgrounds and sytematics ($\tau_{had}\tau_{had}$)



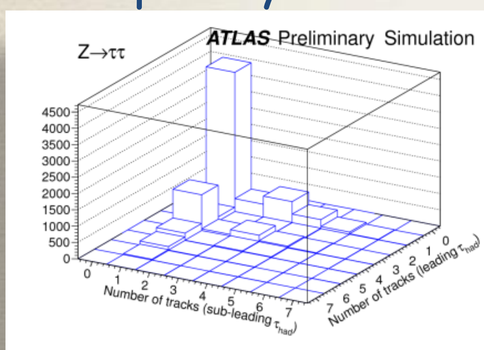
- ❑ Irreducible $Z/\gamma^{*}\text{->}\tau\tau$

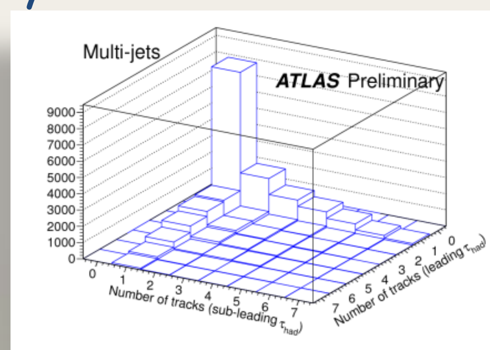
Estimated from „embedding" σ_{sys} =10-13%

- ❑ Multi-jet (QCD)

SS data selection σ_{sys} ~10%

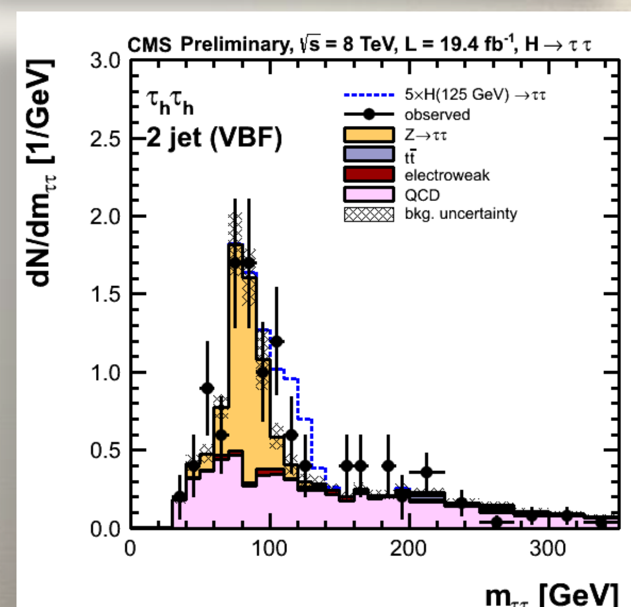
A: a 2D template fit to the candidate multiplicity used for yield estimation:





C: Yield corrected from CR

- ❑ Theoretical uncertainty: $\sigma_H \times BR$ 3-20% (ggF largest by far)



Brout-Englert-Higgs-Hagen-Guralnik-Kibble field and… the Higgs boson (1964)

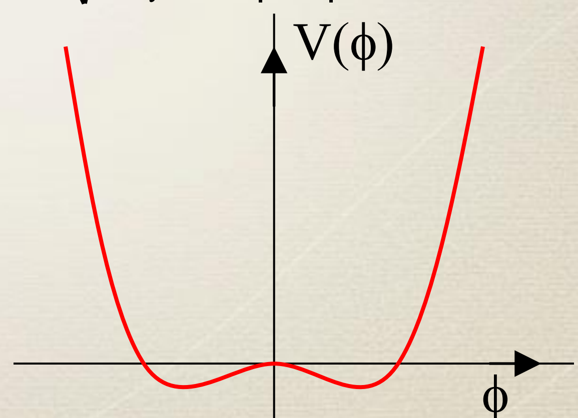
T.Kibble G.Guralnik R.C.Hagen F.Englert R.Brout & P.Higgs

$$L_{Higgs} = D_\mu \phi^\dagger D^\mu \phi - V_{Higgs}$$

$$V_{Higgs} = \frac{1}{2}\mu^2\left(\phi^\dagger\phi\right) + |\lambda|\left(\phi^\dagger\phi\right)^2$$

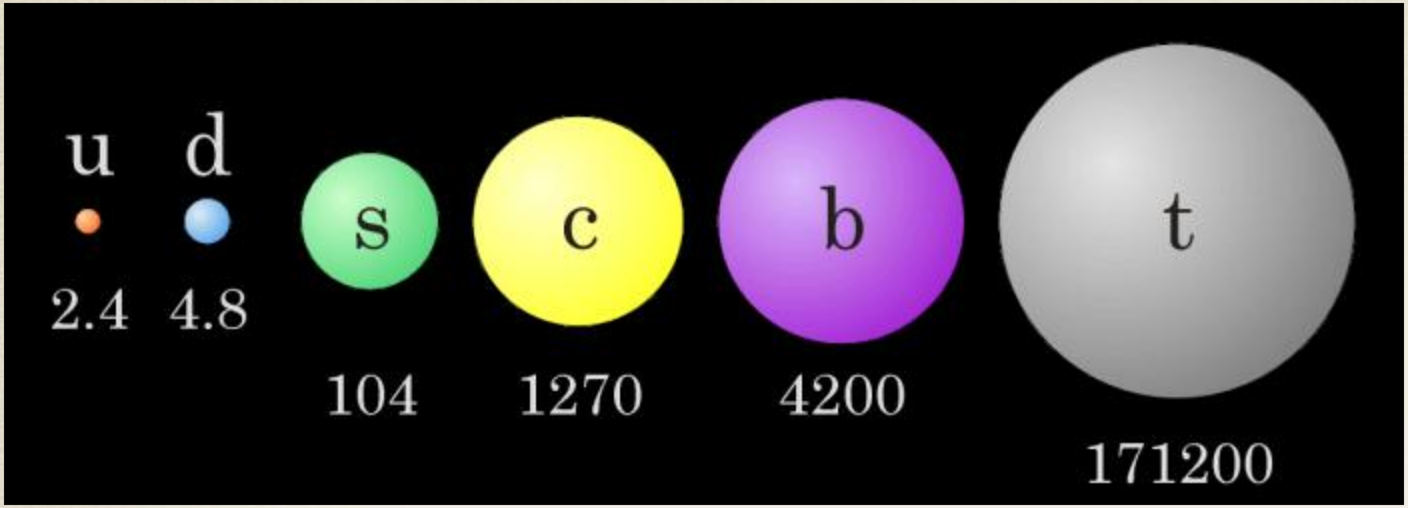
$$\boldsymbol{\Phi} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \boldsymbol{\Phi}_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \upsilon + h(x) \end{pmatrix}$$

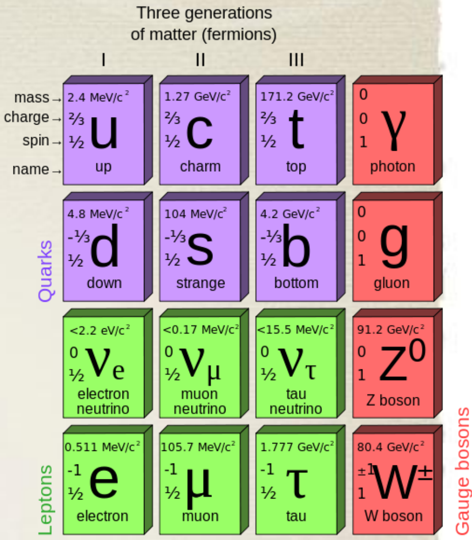
$$v = \sqrt{-\mu^2 / |\lambda|} \sim 246 \text{ GeV}$$



Vacuum state (174 GeV) physical Higgs particle

This is not the end of the story…





- Do you want to be famous?
- Do you want to be a king?
- Do you want more than the Nobel Prize?

- Then solve the mass problem -

R.P. Feynman