$H \rightarrow ZZ$ and $H \rightarrow \tau\tau$

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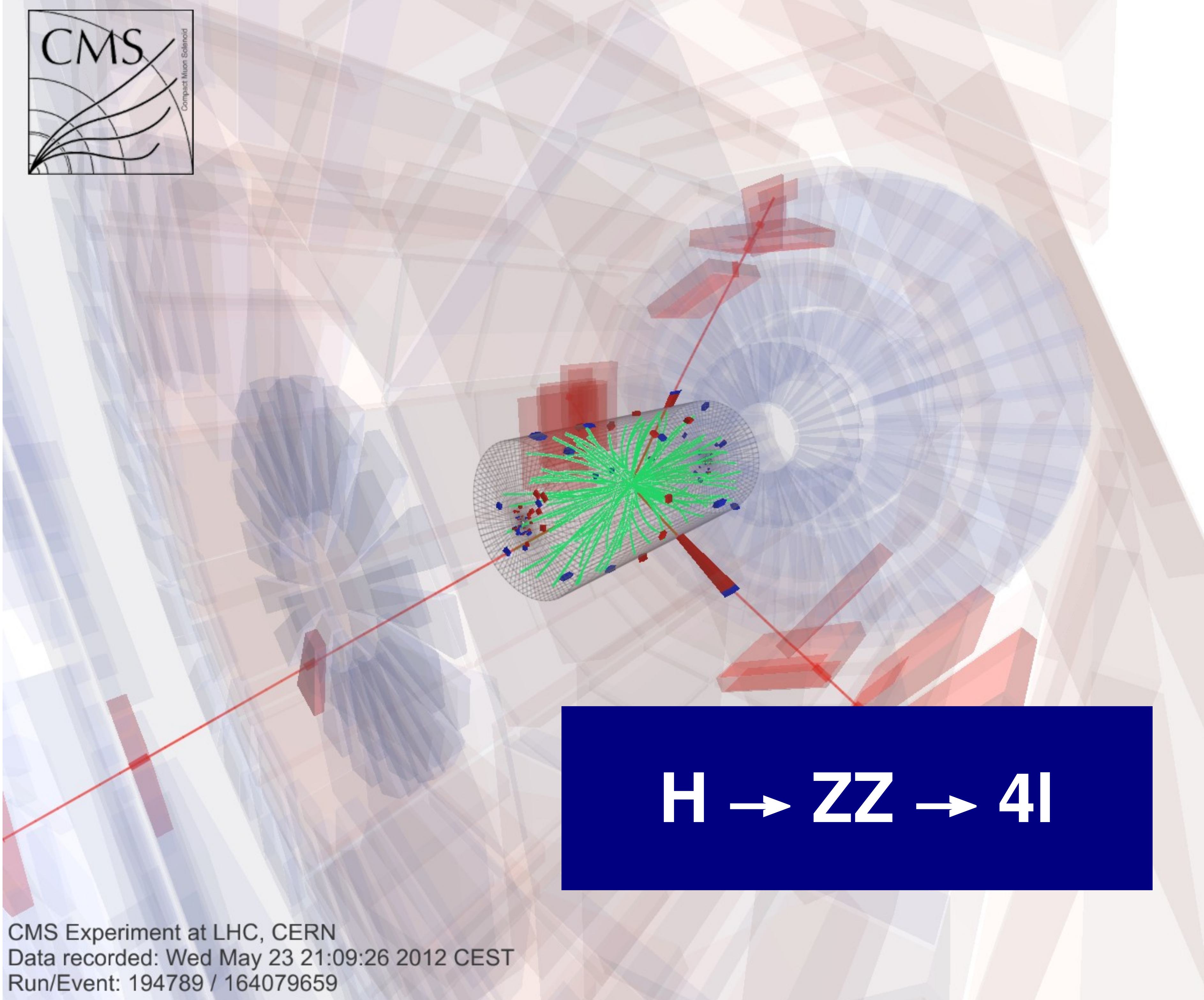
Introduction

- Today covering two final states that in first sight they have nothing in common
  - $H \to ZZ \to 4l$
    - High S/B
    - excellent mass resolution
    - Direct coupling of H to vector bosons → probes SSB
    - Excess at 125 GeV
  - $H \to \tau\tau$
    - Low S/B
    - Moderate mass resolution due to the neutrinos in tau decay
    - Only final state capable to study coupling to leptons
    - Signal not observed yet
- Both of them providing and expected to provide useful knowledge about the new h_{125} resonance

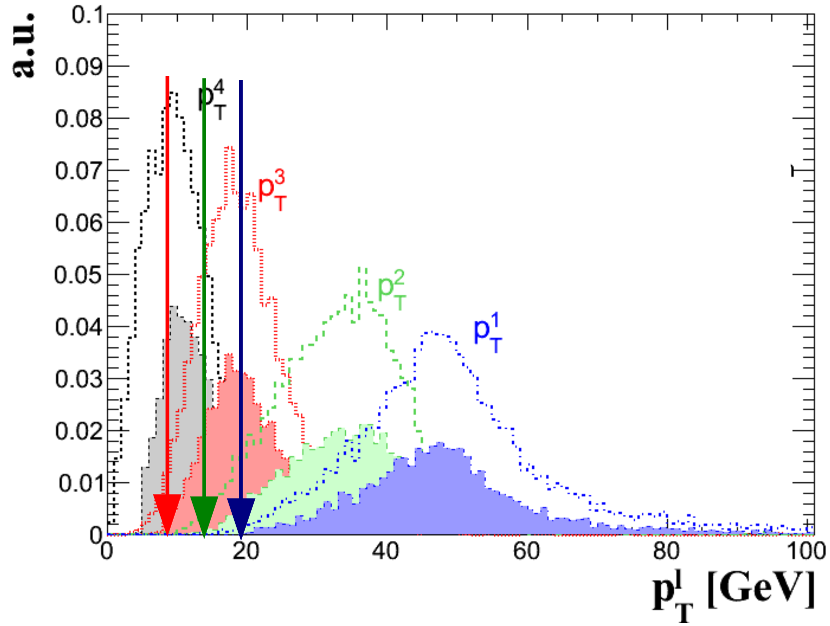

CMS
Compact Muon Solenoid
$H \rightarrow ZZ \rightarrow 4l$
CMS Experiment at LHC, CERN
Data recorded: Wed May 23 21:09:26 2012 CEST
Run/Event: 194789 / 164079659

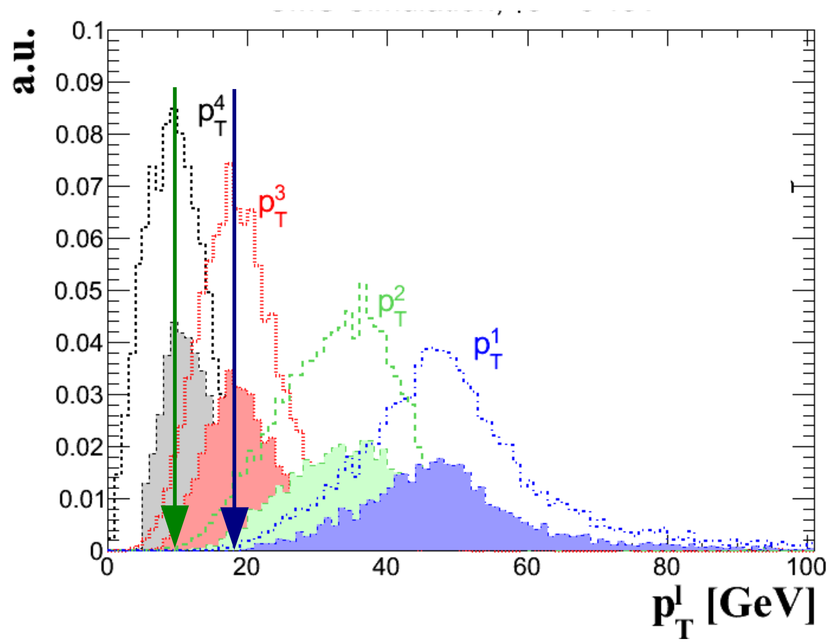
The H → ZZ* → 4l search

- Golden Channel
  - ATLAS and CMS experiments were designed based on it
  - Clean experimental signature
    - 4 isolated leptons (electrons or muons)
  - Benefit for high lepton reconstruction efficiency and excellent resolution
    - Narrow resonance on the four lepton mass spectrum
- Backgrounds
  - SM ZZ production (very small for $m_{4l}<2M_Z$)
  - Z + jets / Top pairs with fake leptons/leptons from HF decays
- Very low background contamination at low mass
- Current public results from ATLAS and CMS as of July 4th
- Both experiments performing inclusive search -not looking at specific production mechanisms (I.e VBF/VH) yet

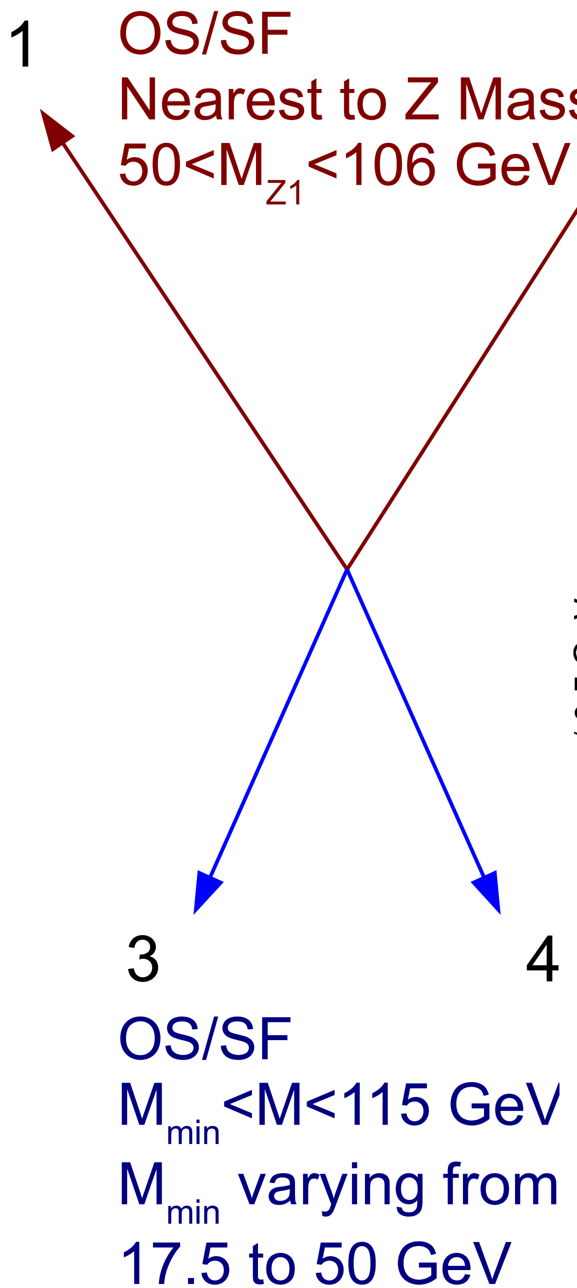
Trigger and Lepton selection

- ATLAS
  - Single and Double lepton triggers
  - Muon p_T> 6 GeV, η<2.7
  - Electron p_T>7 GeV, η<2.47
- CMS
  - Double Lepton triggers
  - Muon p_T > 5 GeV, η<2.4
  - Electron p_T >7 GeV, η<2.5

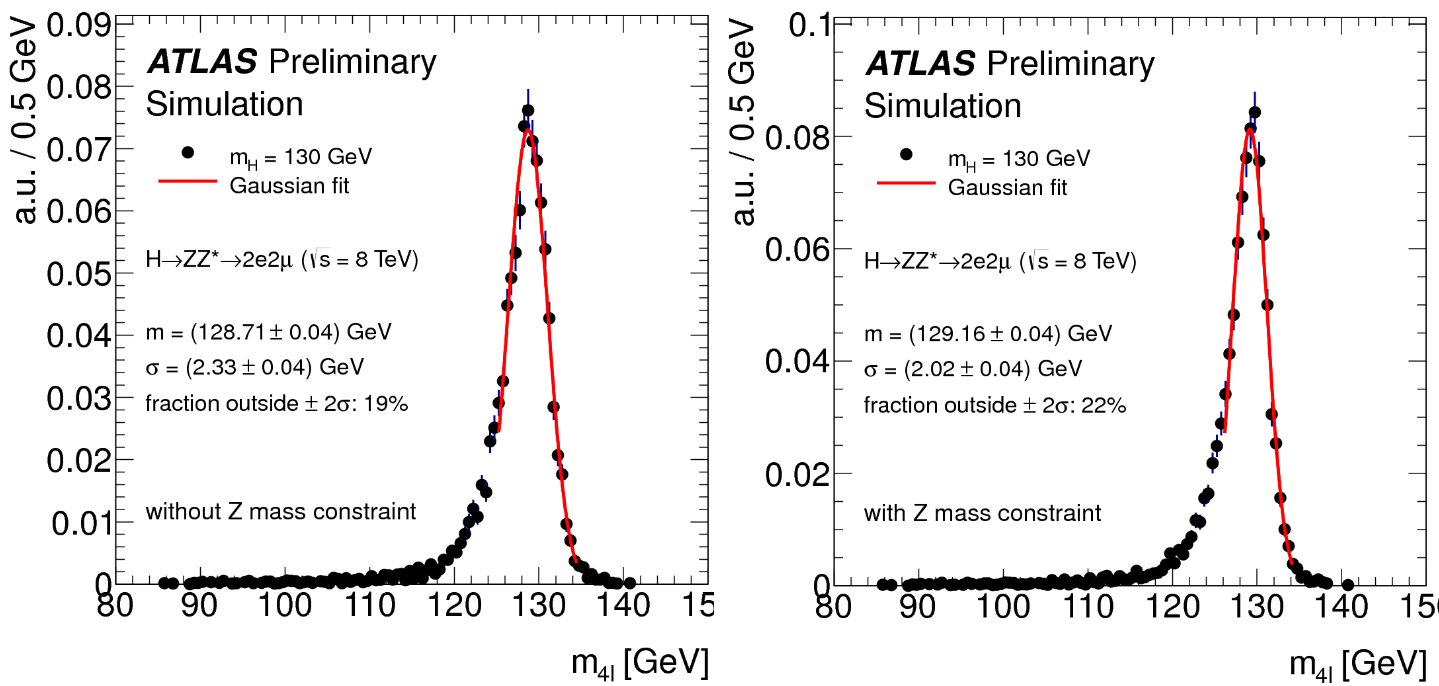




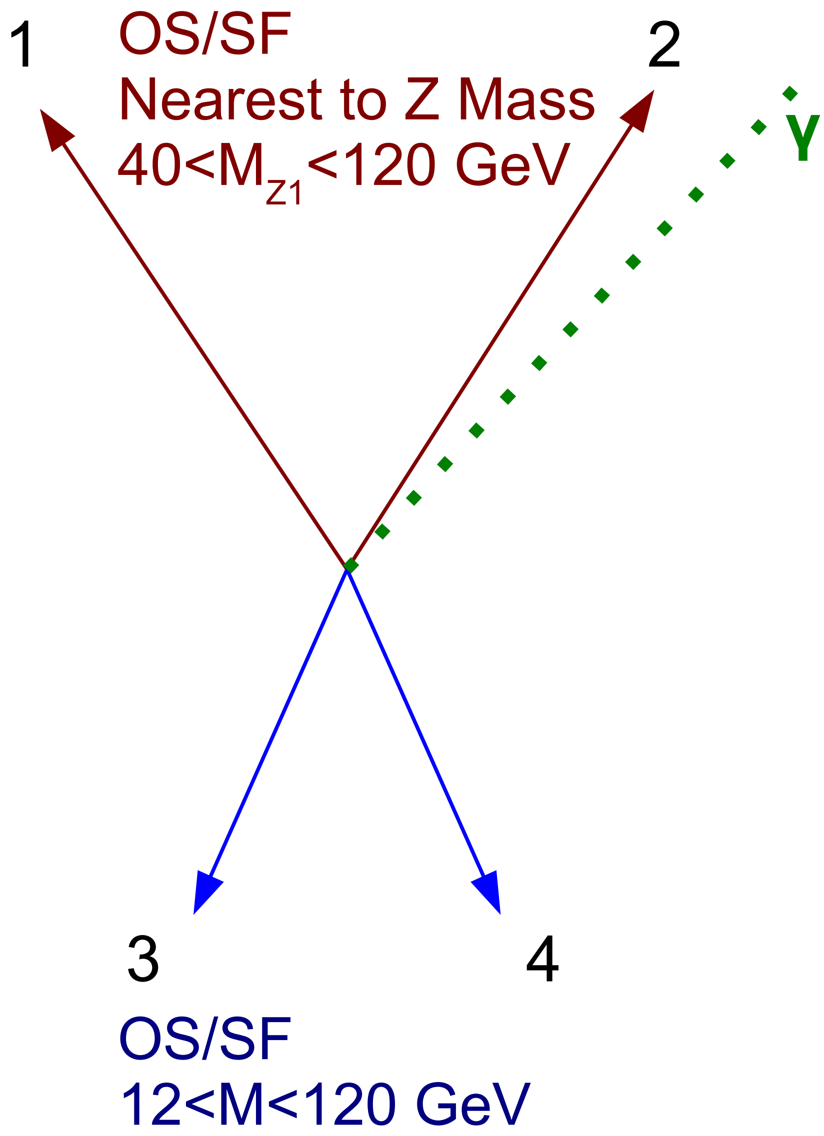
Construction of ZZ candidates(ATLAS)



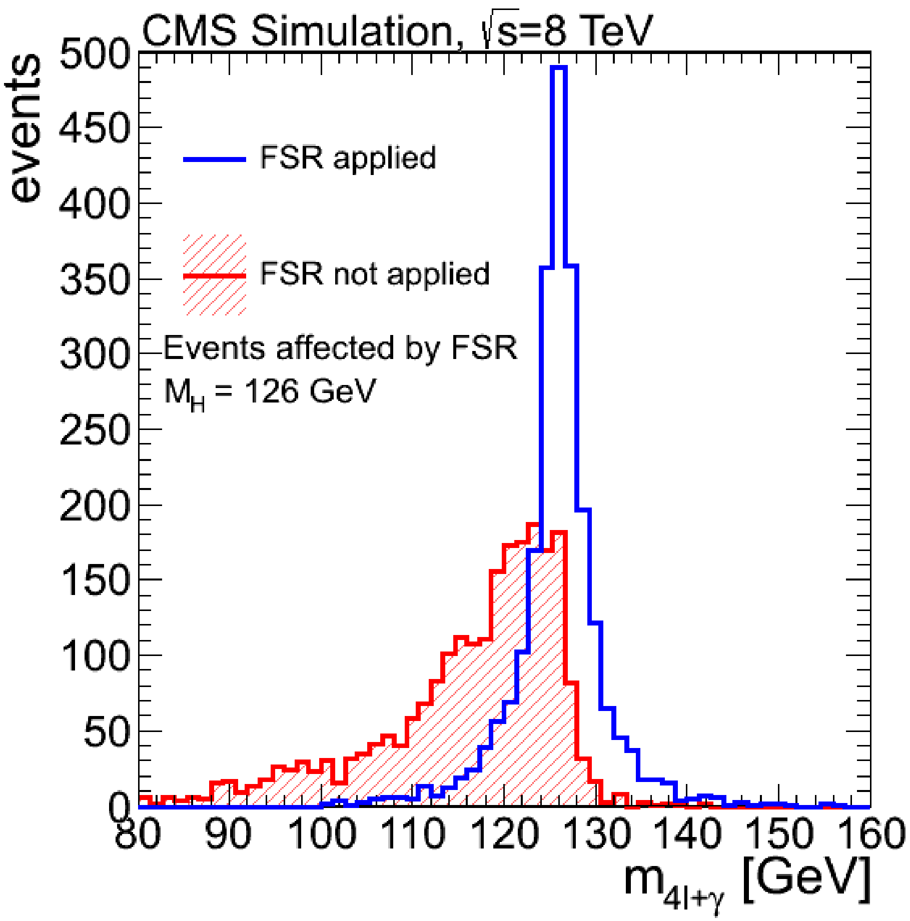
- Any OS/SF lepton pair must have M_{ll}>5 GeV
  - To suppress QCD
- Z_1 Mass constraint
  - Z_1 constrained to the Z mass to calculate the four lepton four vector



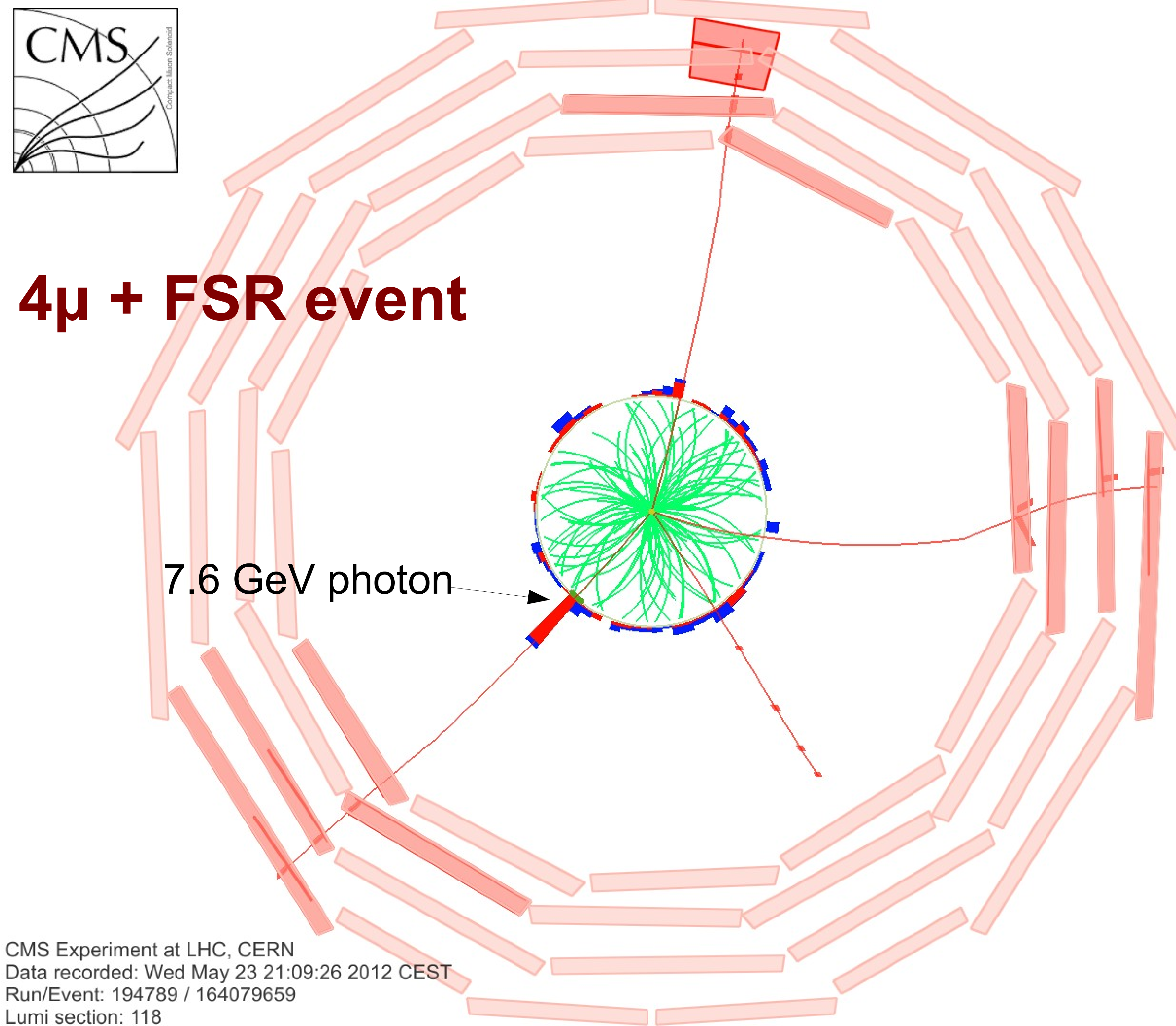
Construction of ZZ candidates(CMS)



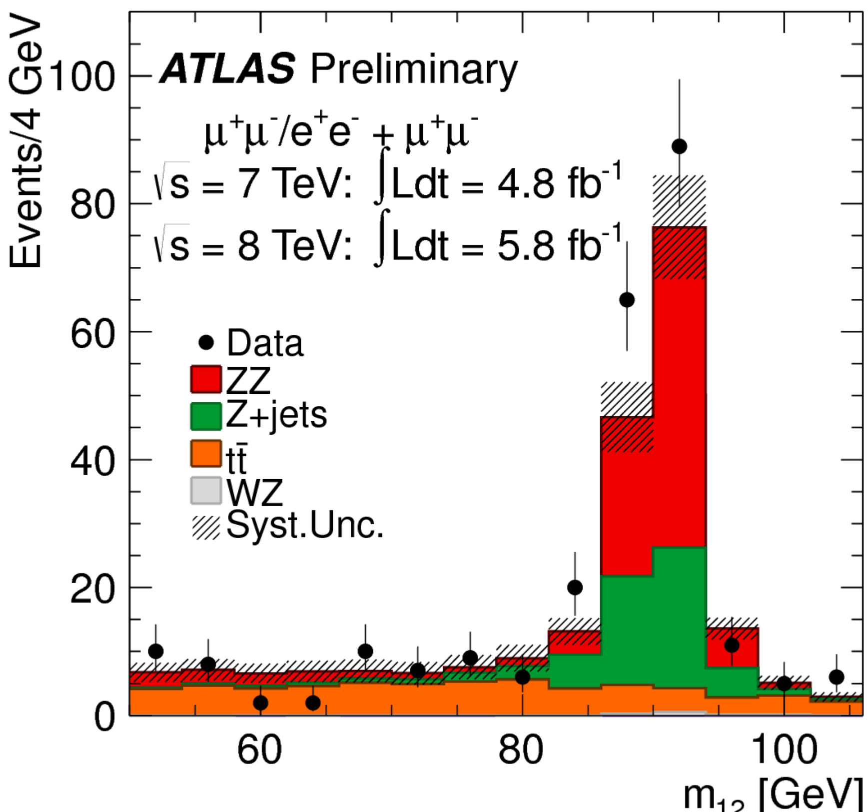
- Any OS/SF lepton pair must have M_{ll}>4 GeV
  - To suppress QCD
- FSR recovery
  - Photons added to the Z candidates before cuts

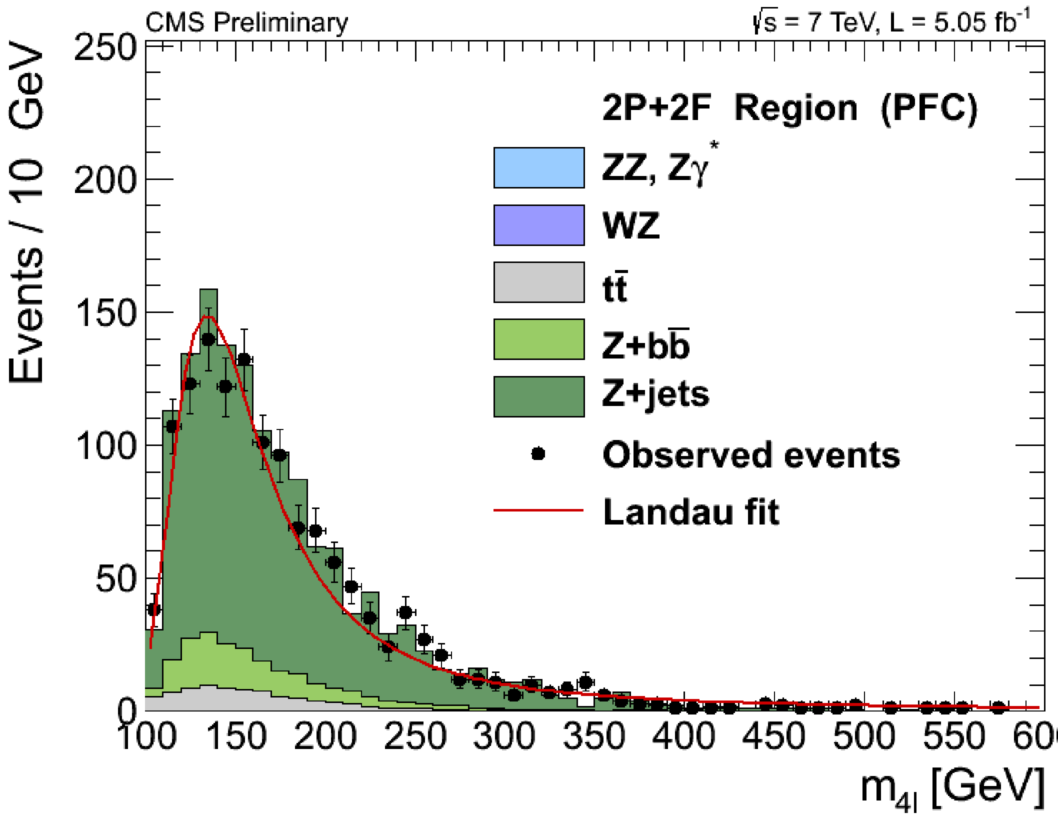


4μ + FSR event


7.6 GeV photon
CMS Experiment at LHC, CERN
Data recorded: Wed May 23 21:09:26 2012 CEST
Run/Event: 194789 / 164079659
Lumi section: 118

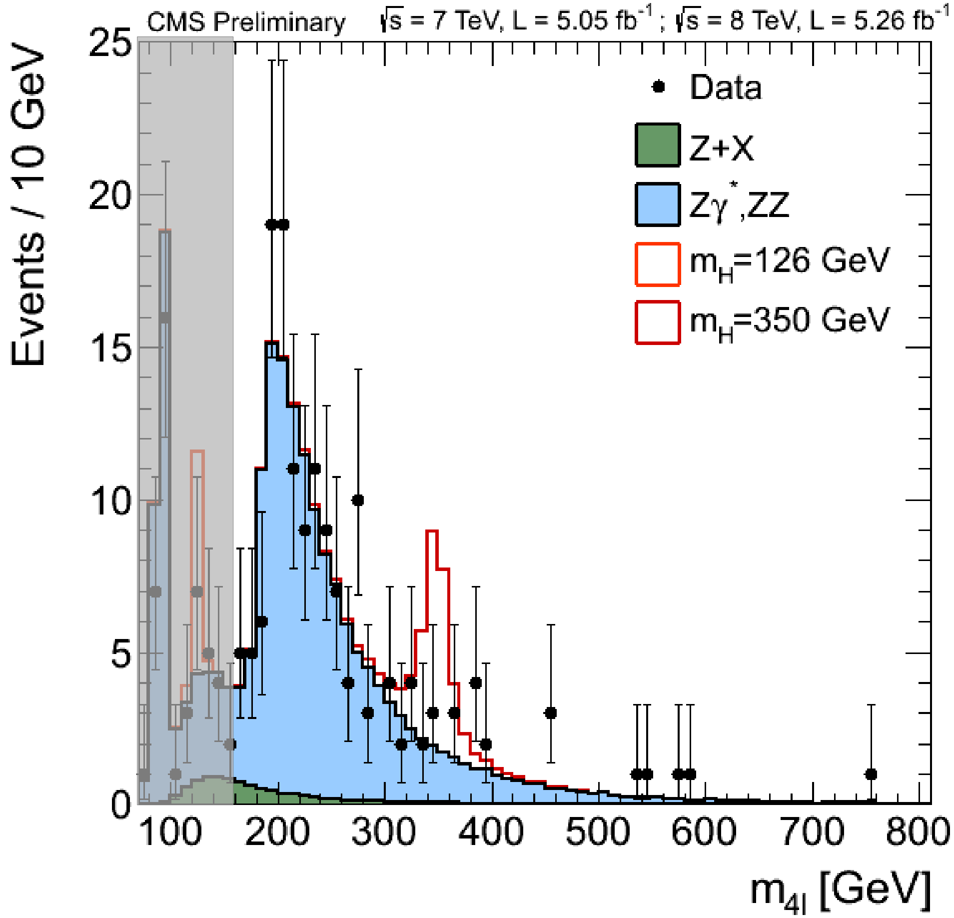
Estimation of the backgrounds

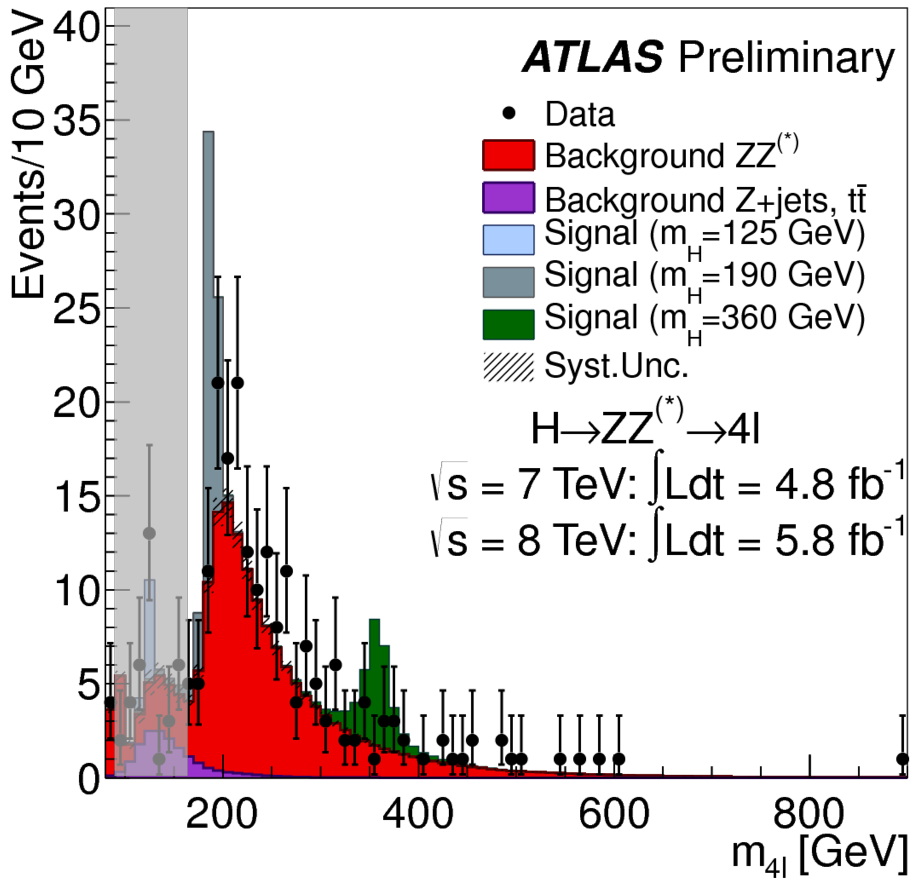




- The irreducible background (qq → ZZ, gg → ZZ) is estimated using the theoretical cross section
- Reducible backgrounds from data
  - Dominated by a real lepton pair + 1 or 2 fake leptons (or leptons from HF decays)
  - Similar estimation methods
    - Exploiting fake rate measurement in tri-lepton sample
    - Using several control regions (I.e SS or Non isolated OS)

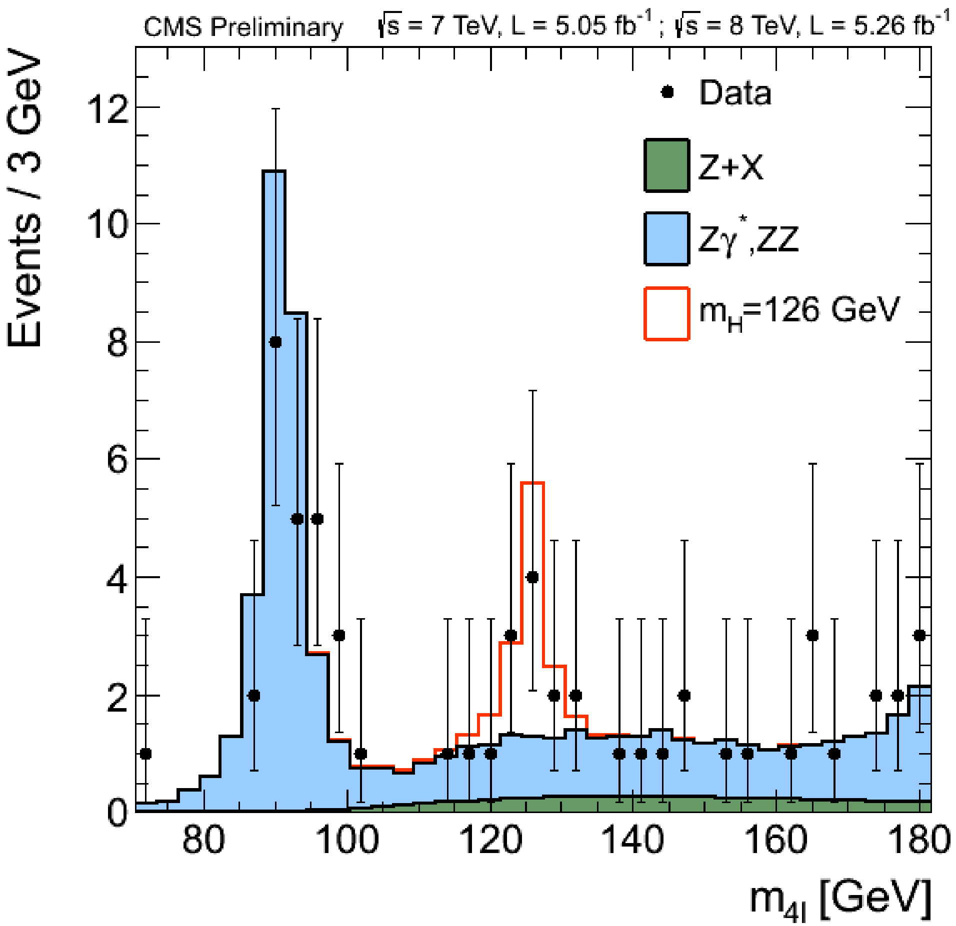
4 lepton mass spectra

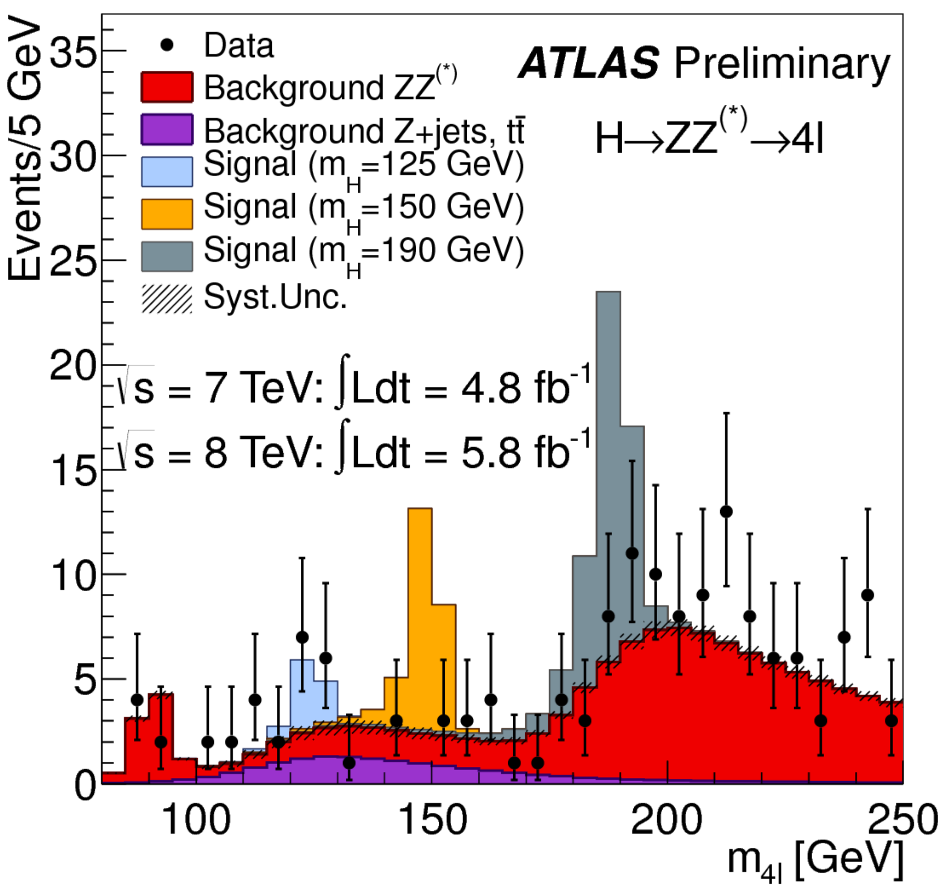




- First looking at ZZ continuum
  - ATLAS ZZ cross section: 1.25 ± 0.15 x σ(theory)
  - CMS ZZ cross section: 1.10 ± 0.16 x σ(theory)

Low mass spectra





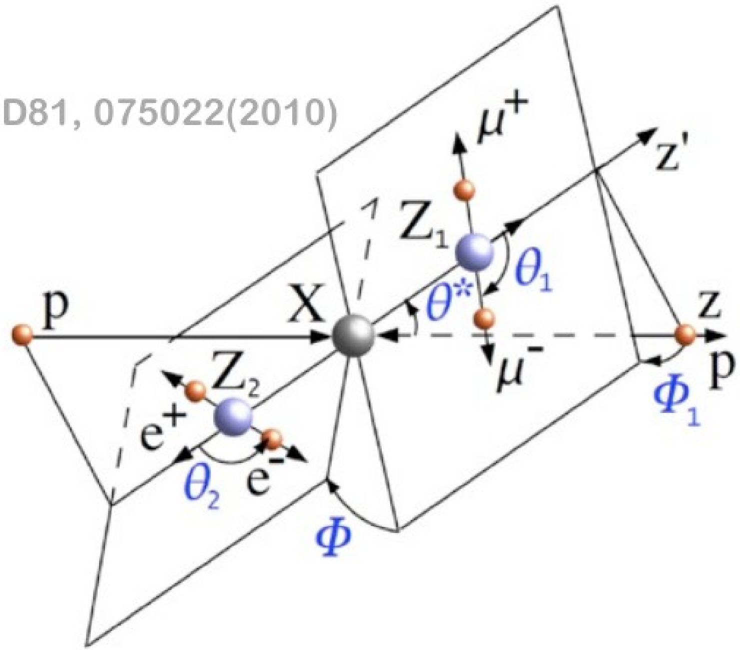
- $Z \to 4l$ resonance
  - Suppressed more in ATLAS selection
- Well known h_{125} bump

	ATLAS (120-130)	CMS (121.5-130.5)
Background	4.9	3.8
Signal	5.3	7.5
Observed	13	9

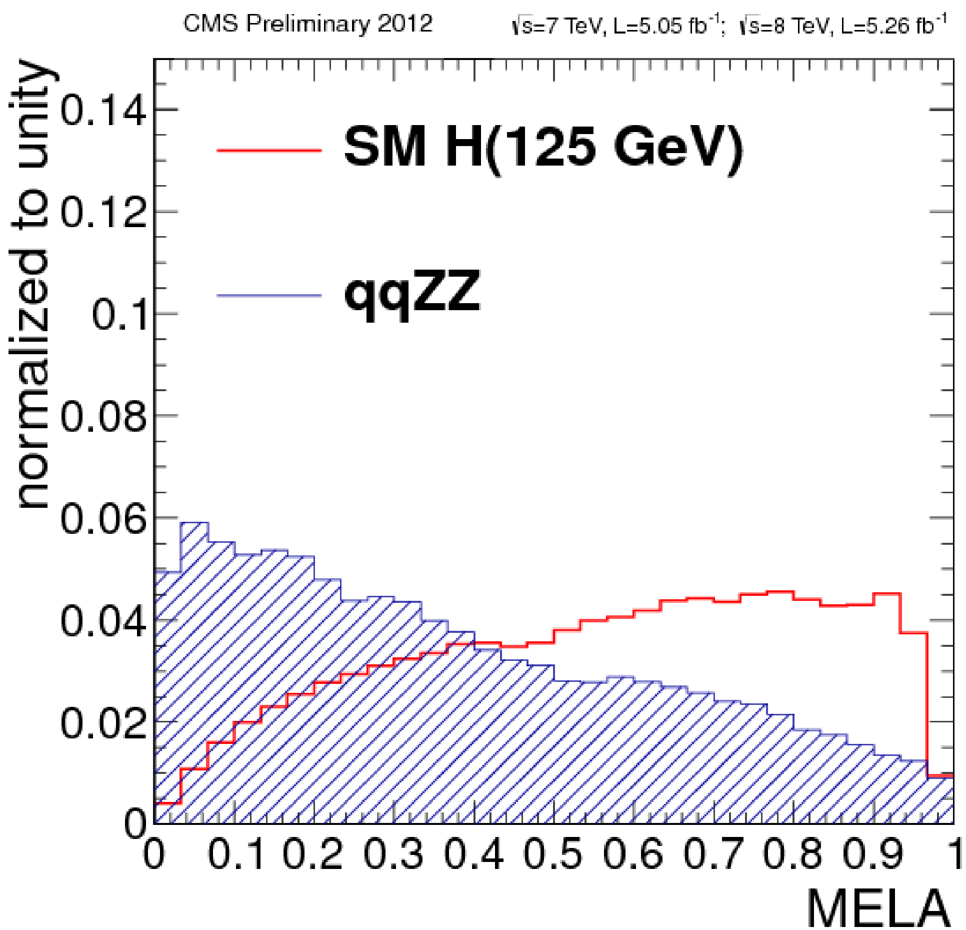
ATLAS over-fluctates, CMS unde-rfluctuates within statistics

Matrix element approach (CMS)

PRD81, 075022(2010)



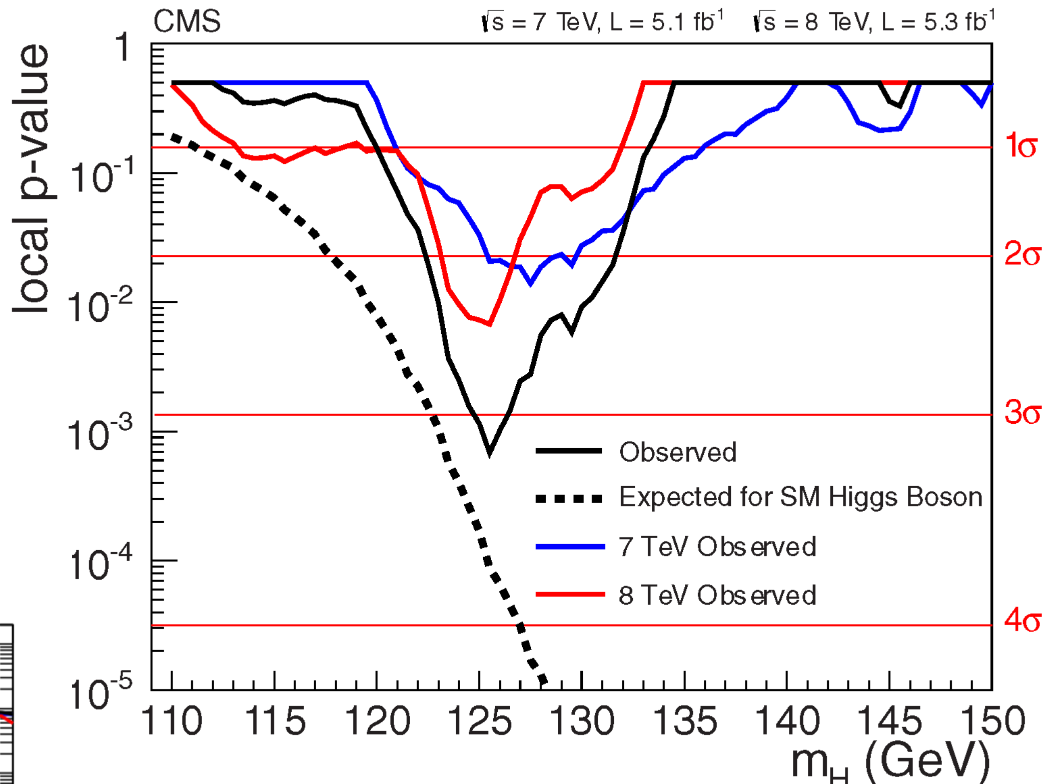
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

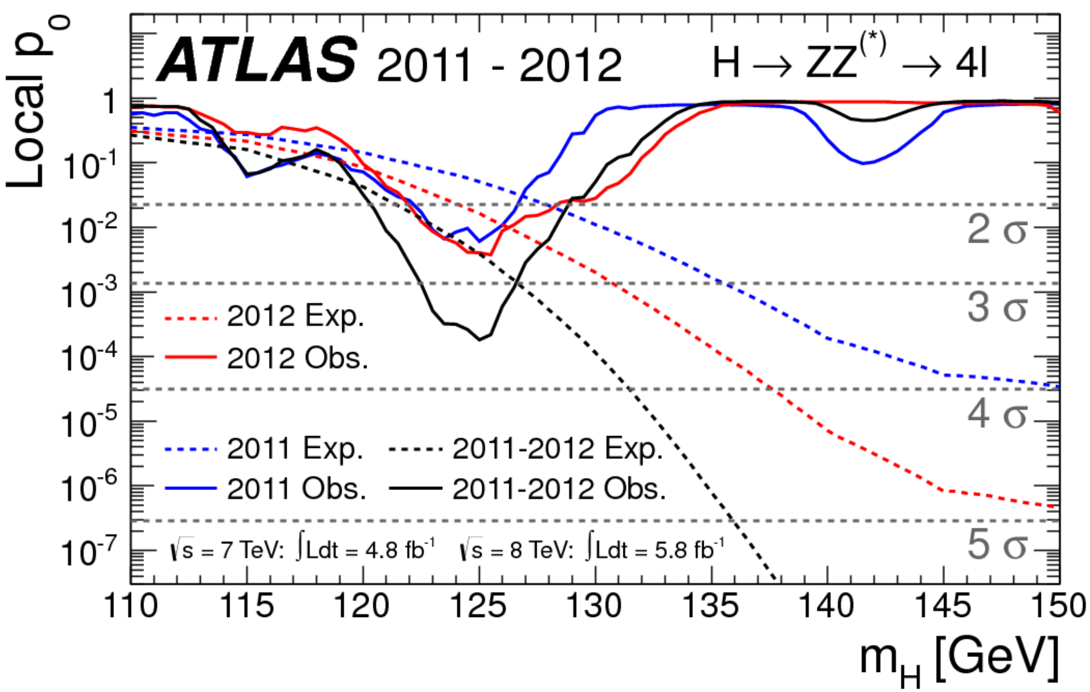


- **M**atrix **E**lement **L**ikelihood **A**pproach
- Uses 5 angles and 2 masses
  - To discriminate spin 0 signal from background

Significance of the excess

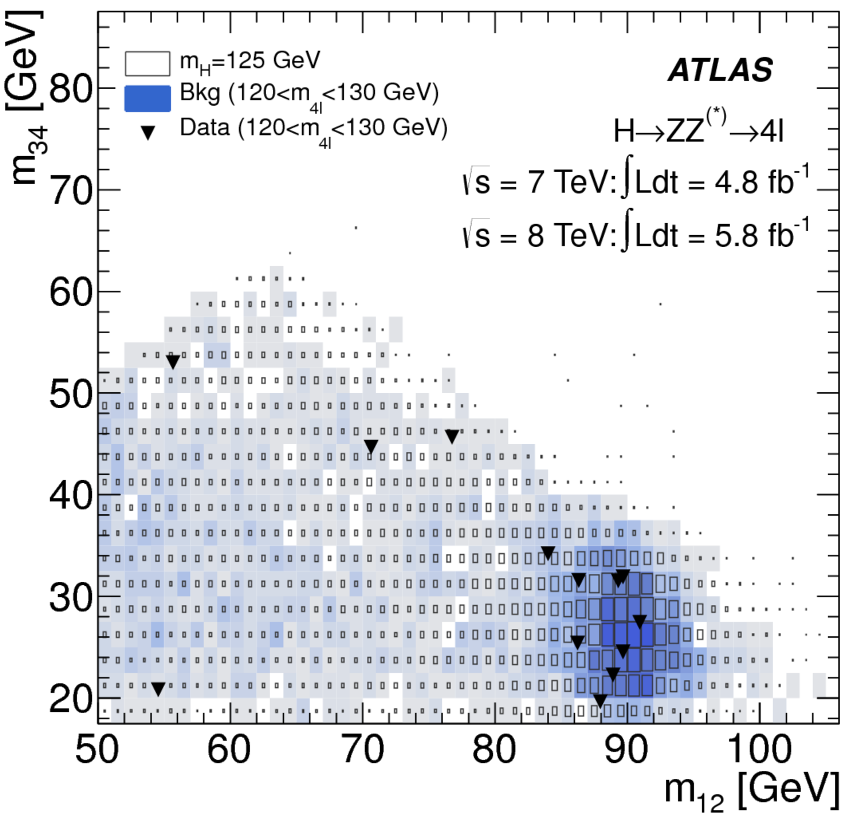
- CMS
  - Expected 3.8σ
  - Observed 3.2σ

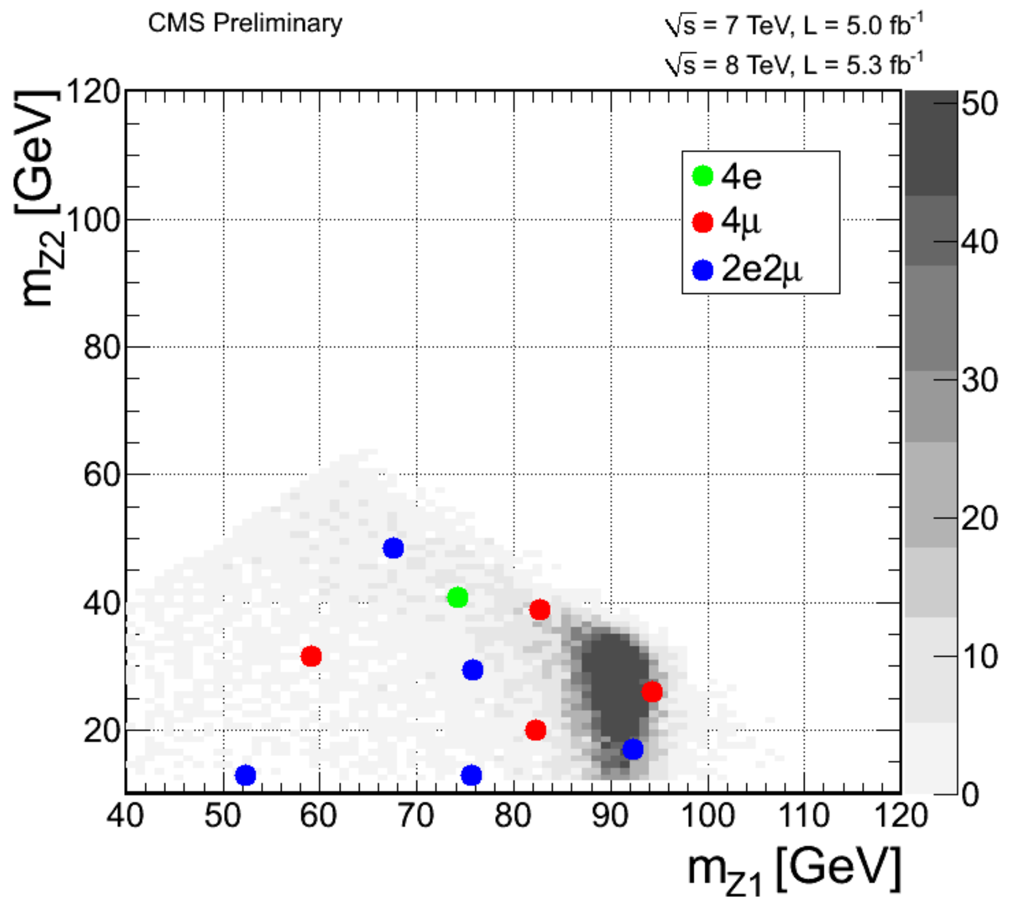




- ATLAS
  - Expected 2.6σ
  - Observed 3.4σ

Anatomy of the excess (M_{Z1} vs M_{Z2})

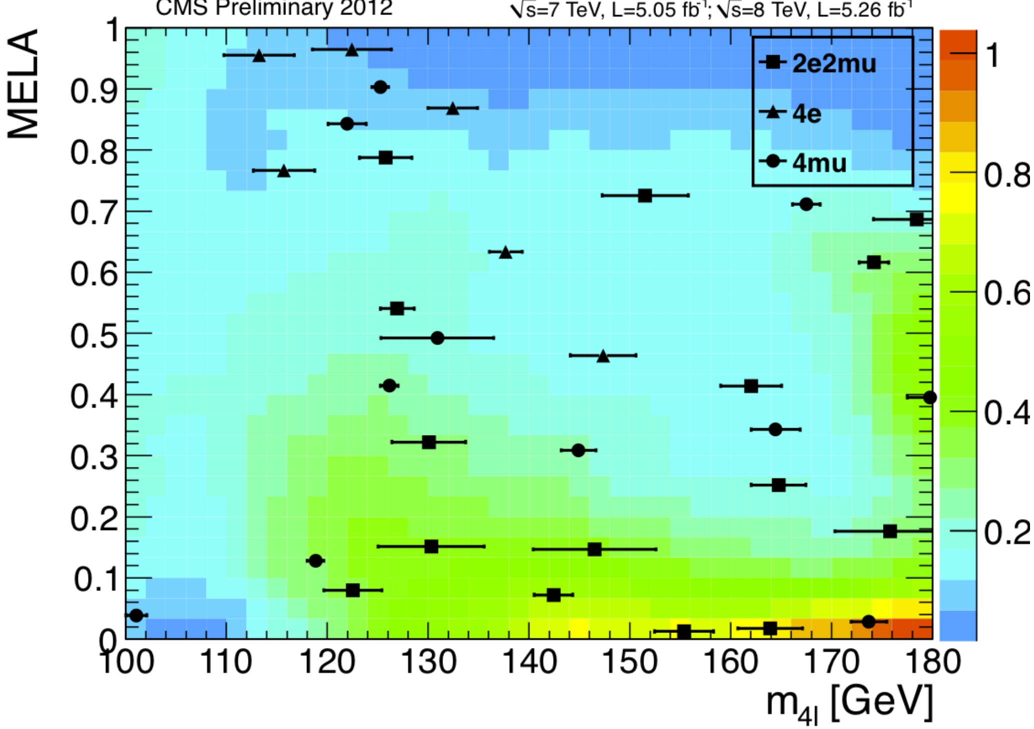




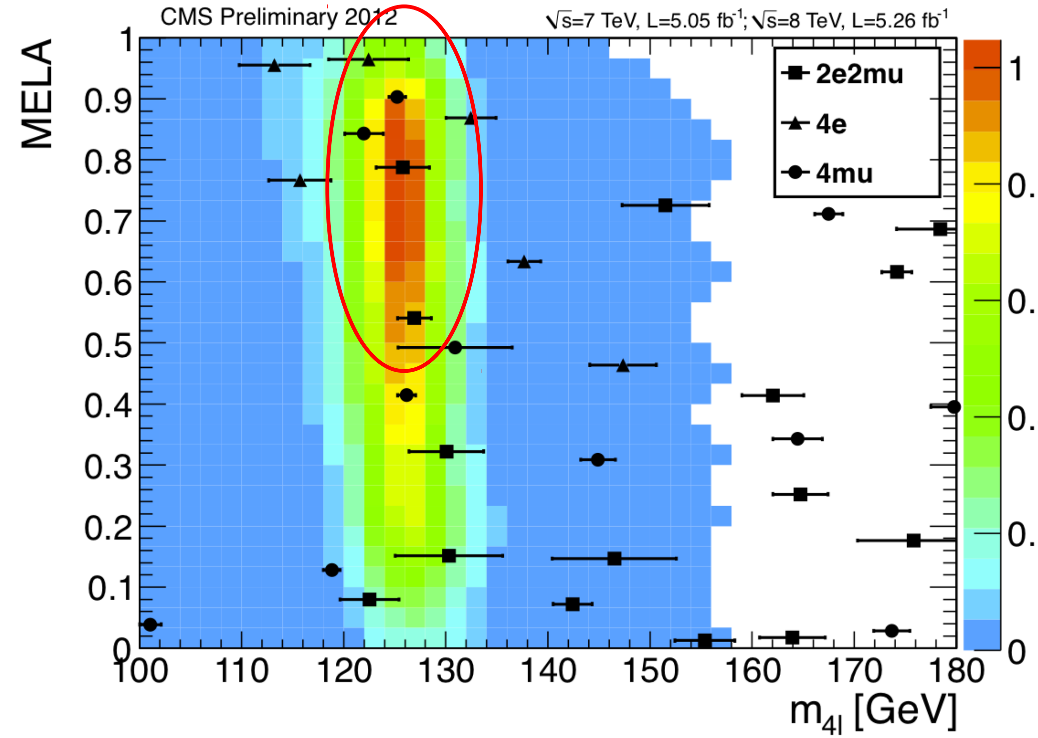
- CMS shows most of events off-shell on Z_1
- ATLAS shows consistency with the expectation
- Considering expected S+B yields the results can still be consistent

Anatomy of the excess(CMS MELA)

Data vs Background Model

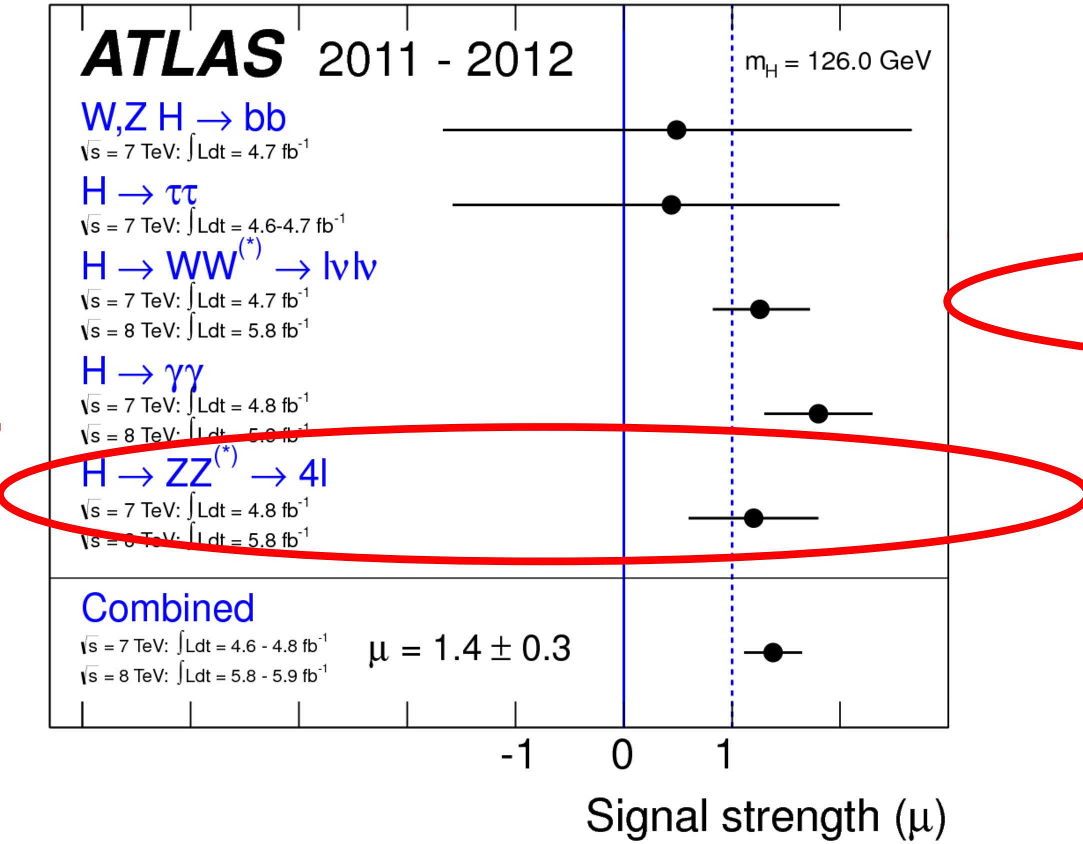


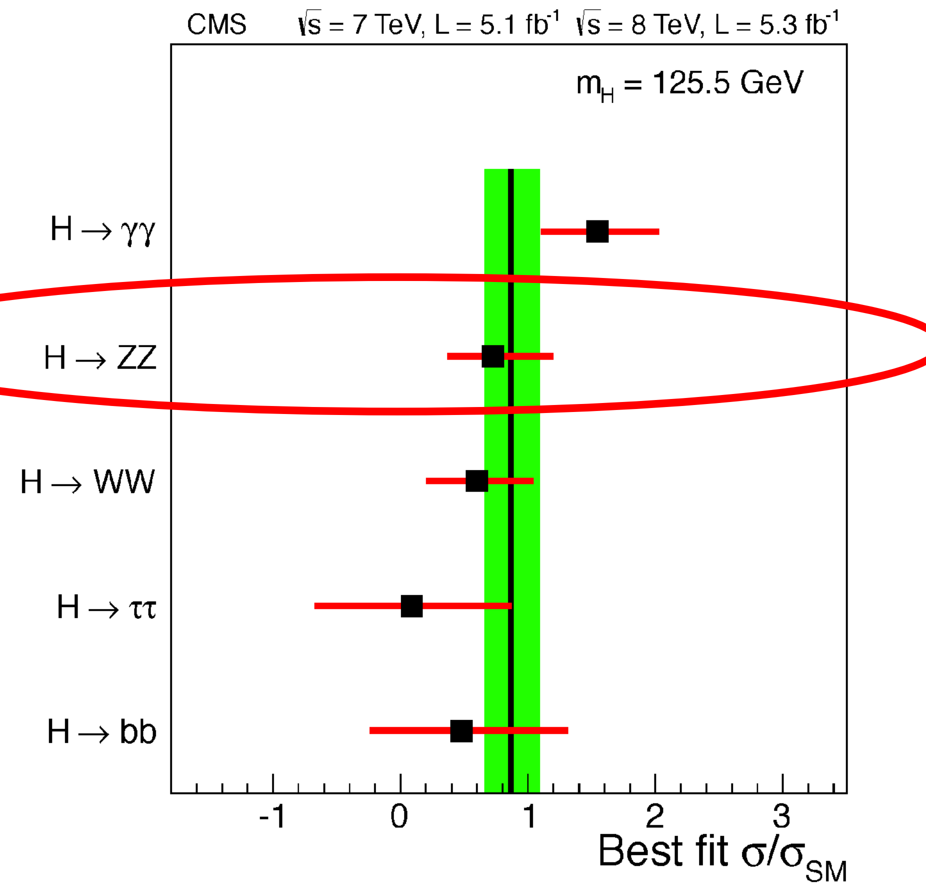
Data vs Signal Model



- Large fraction of events appear with high MELA
  - Very signal like
- Those events tend to have high M_{Z2} and small M_{Z1}

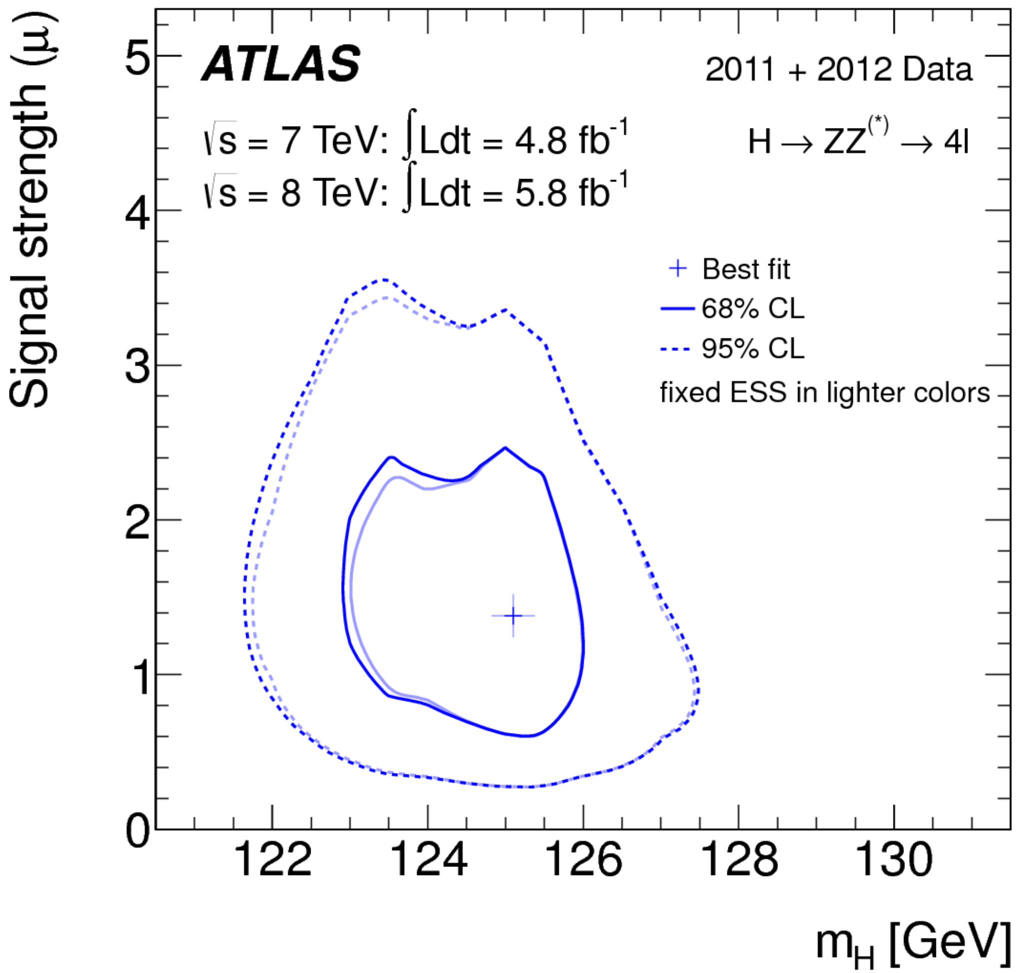
Consistency with the SM

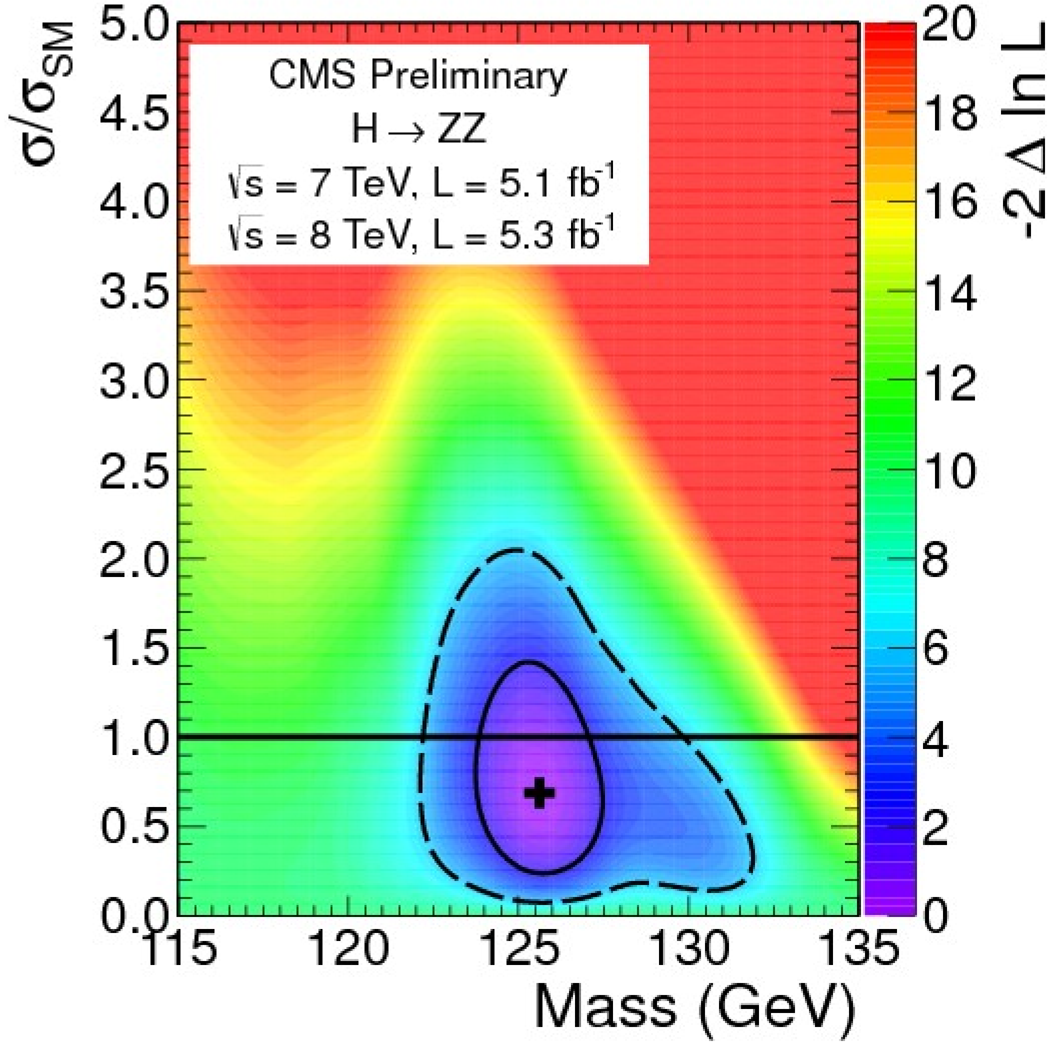




- ATLAS and CMS results consistent with SM, other channels and between them

Mass of the new resonance

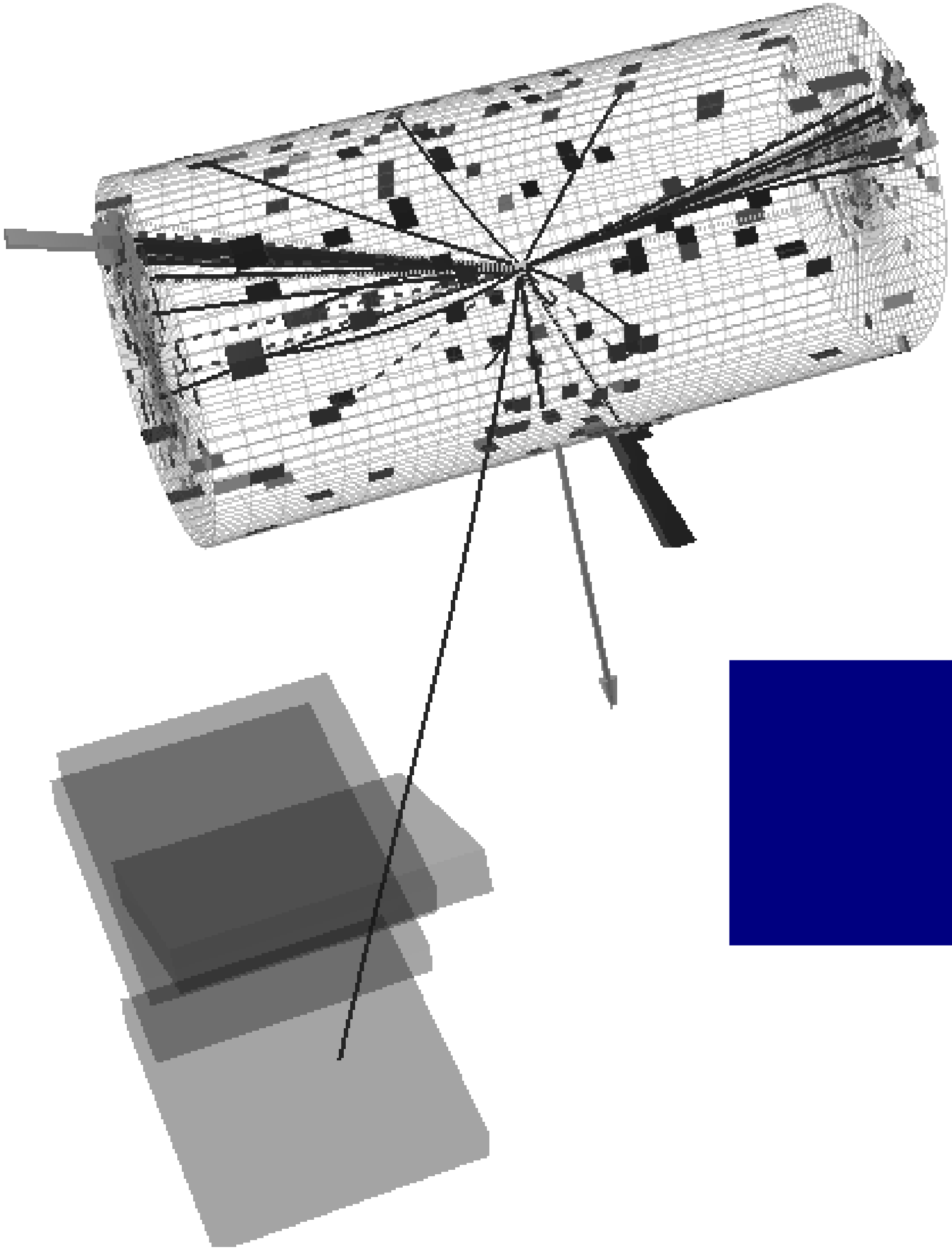




- ZZ is currently the second more sensitive final state to measure the mass affter γγ
- Consistent results between the experiments

H → ZZ summary

- Both experiments have observed a new resonance in the ZZ final state
- The results are consistent within statistics between the two experiments and between each experiment and the SM
- The excellent performance of ZZ analysis will provide in the future interesting information about
  - spin-CP
  - Couplings
  - Mass
- Possible discrepancies in some distributions will be reled-out/confirmed by the end of the year



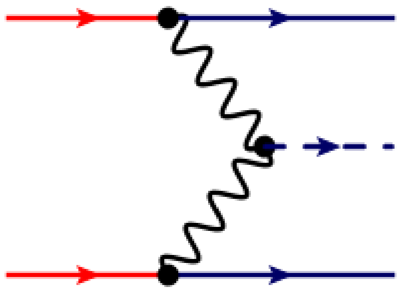
$H \rightarrow \tau\tau$

The H $\rightarrow$ ττ search

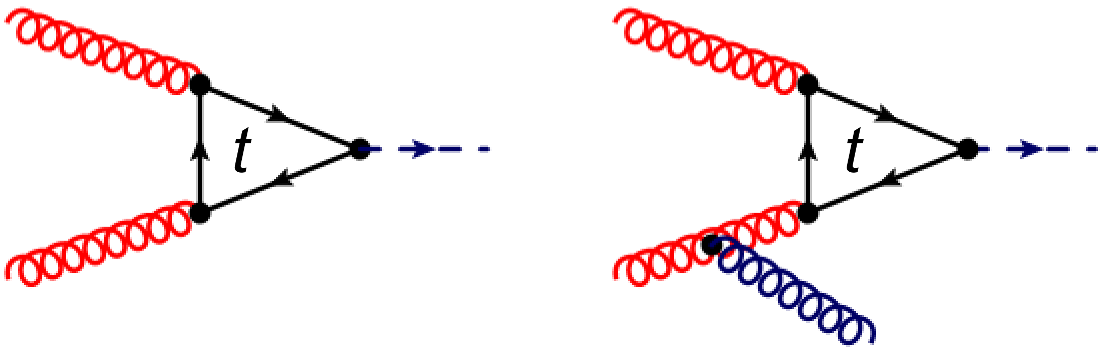
- H $\rightarrow$ ττ is the only handle we have to study Higgs couplings to leptons at the LHC
- Dominated by Z $\rightarrow$ ττ background
- Taus decay hadronically 64% of the time
  - Hadronic tau identification is an experimental challenge
- There are 2-4 neutrinos present in the tau decays
  - Degrades mass resolution. New techniques are need to improve this
- There have been huge improvements in H $\rightarrow$ ττ since the LHC startup in both experiments
  - The sensitivity was proven to be much better than initially projected

Relevant production mechanisms

Vector boson fusion(qqH)



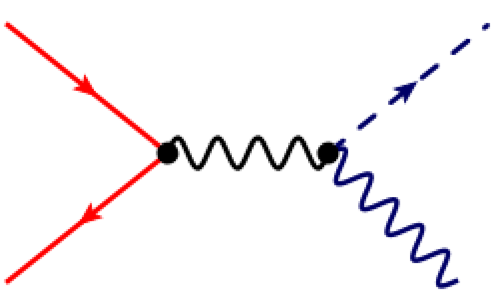
gluon fusion(ggH)



- Golden mode
  - Cross section ~ 1/10 ggH
  - Di-jet signature suppresses Z → ττ

- Largest cross section
  - Dominated by Z → ττ background
  - Z+1 jet experimentally more promising

Associated production(VH)



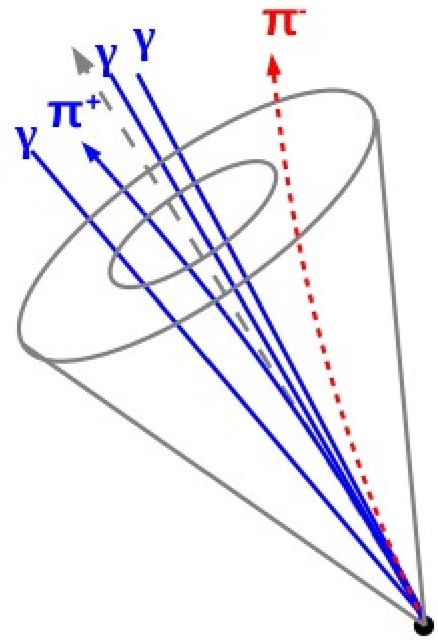
- Additional boson suppresses Z → ττ
  - Dominant background: dibosons
  - Very small cross section

Current H → ττ public results

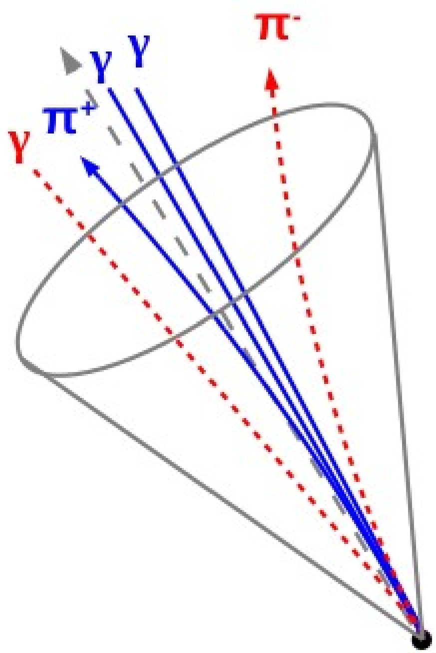
- Moriond 2012
  - 4.7 fb^{-1} @ 7 TeV
- Covered
  - gluon fusion
  - vector boson fusion
  - associated production

- ICHEP 2012
  - 4.7 fb^{-1} @ 7TeV
  - 5.0 fb^{-1} @ 8 TeV
- Covered
  - gluon fusion
  - Vector boson fusion
  - associated production

Hadronic tau identification

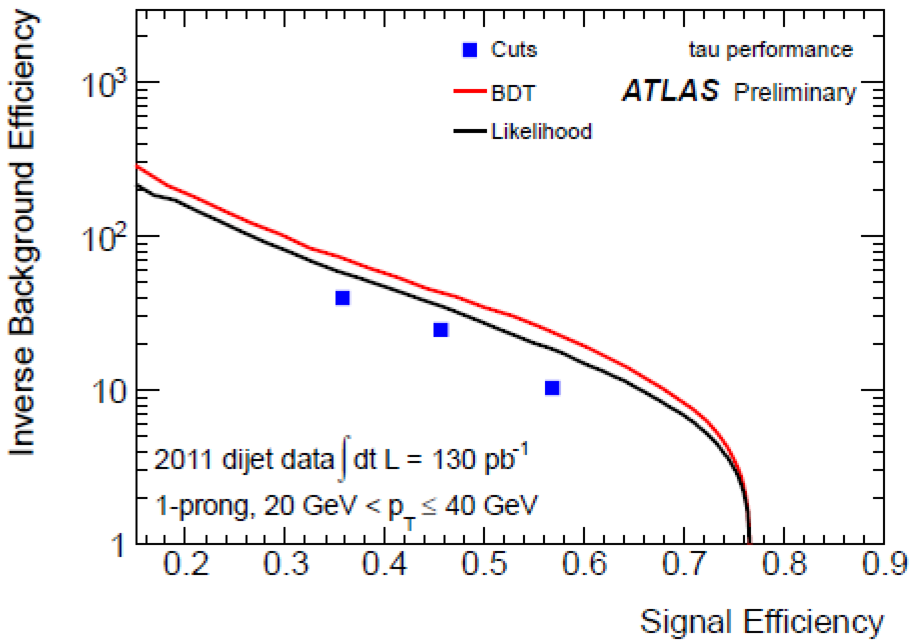


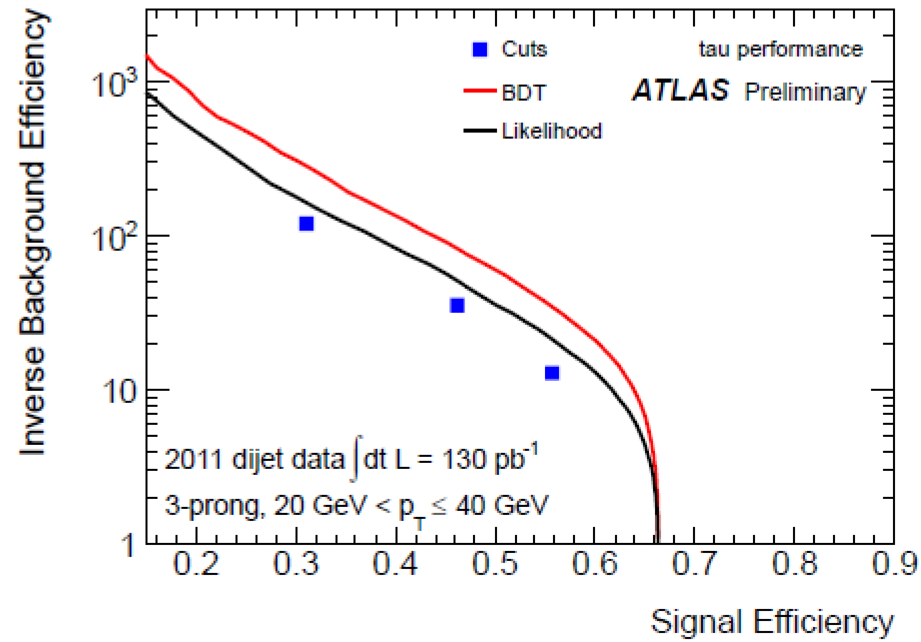
- Cone based approach
  - Starting from jet define signal cone
  - Define discrimination variables based on cone contents
  - Define isolation annulus between signal and isolation cone



- Combinatorial approach
  - Starting from jet make combinations of decay modes
    - π/K, $\rho \rightarrow \pi^+\pi^0$s, $\alpha_1 \rightarrow \pi^+\pi^-\pi^+$
  - Apply mass and narrowness criteria
  - Define isolation cone excluding decay mode constituents

Tau Identification (ATLAS)

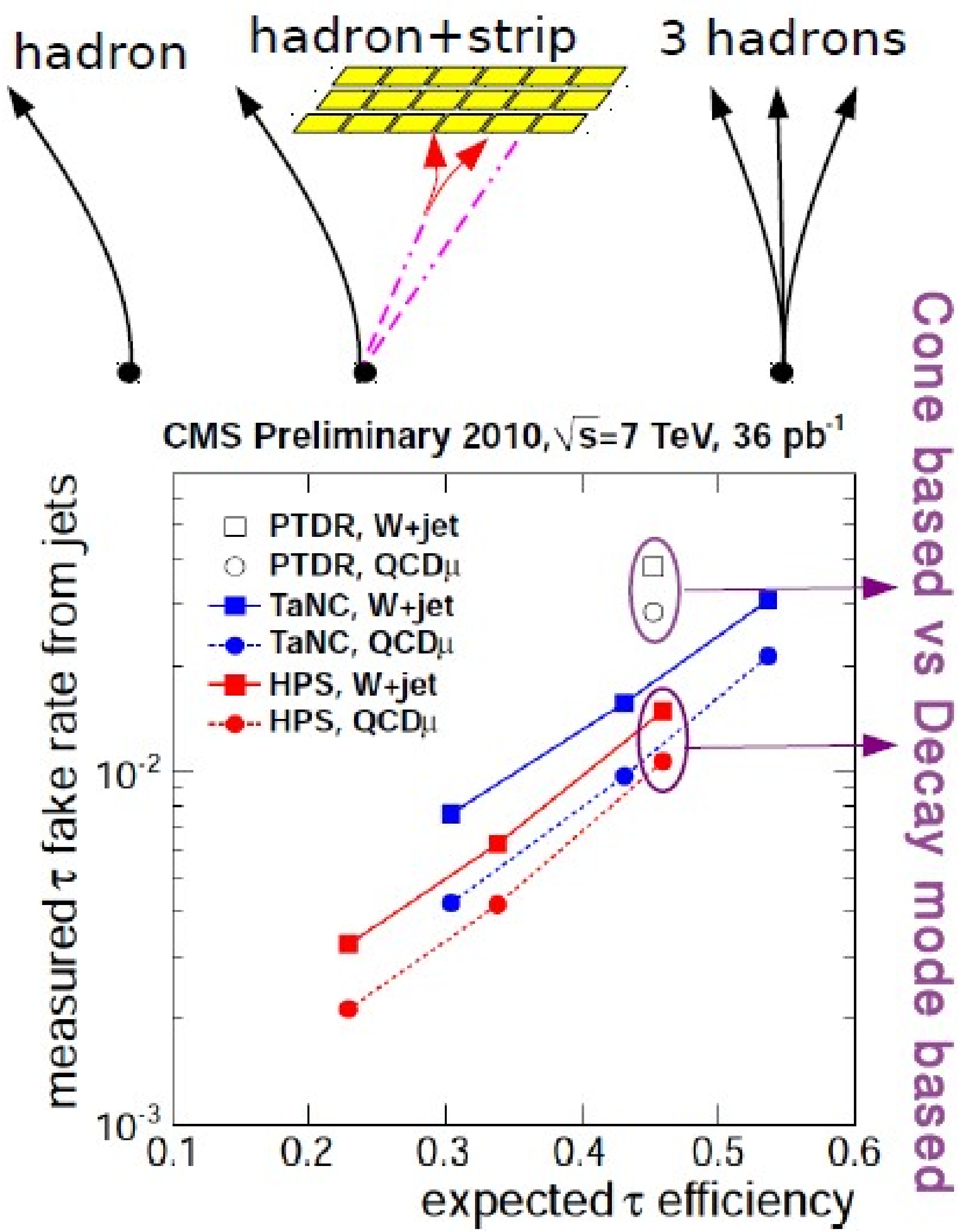




- Cone based approach
  - Define discrimination variables and combine in a multivariate discriminant (BDT)
- Tau energy measured with Calorimeter
  - Specific tau corrections applied

Tau Identification (CMS)

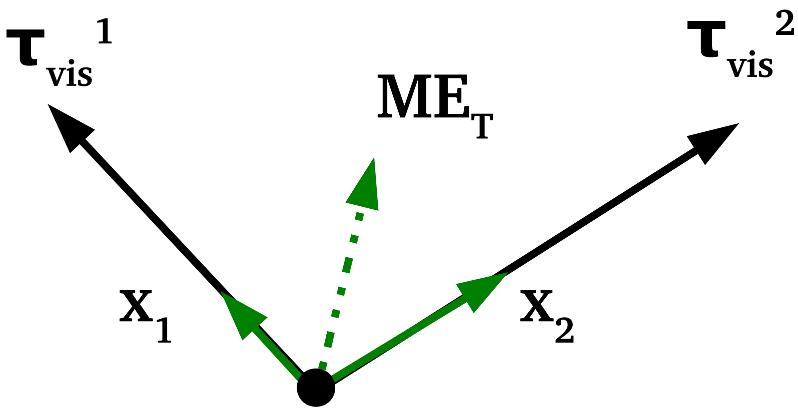
- Combinatorial approach
  - Uses reconstructed particles from Particle Flow Algorithm
- Reconstructs individual decay modes
  - Using particles from Particle Flow event description)
- Energy of the tau measured using only associated decay mode PF constituents
  - Dominated by Tracker+ECAL
  - Pileup effect in energy scale minimal



Reconstructing the tau mass

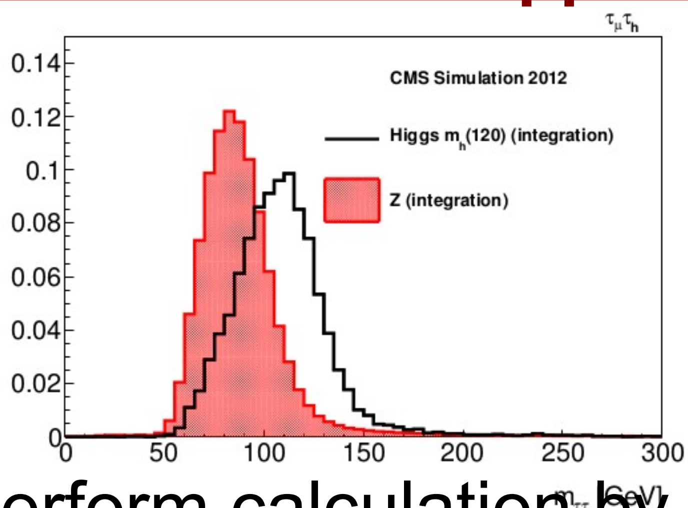
- Crucial to separate $Z \rightarrow \tau\tau$ from Higgs $\rightarrow \tau\tau$
- A semi-leptonic $\tau\tau$ final state has three neutrinos
  - Corresponding to 7 unknown variables
  - Missing ET and tau mass constraint reduces them to 3

Collinear approximation



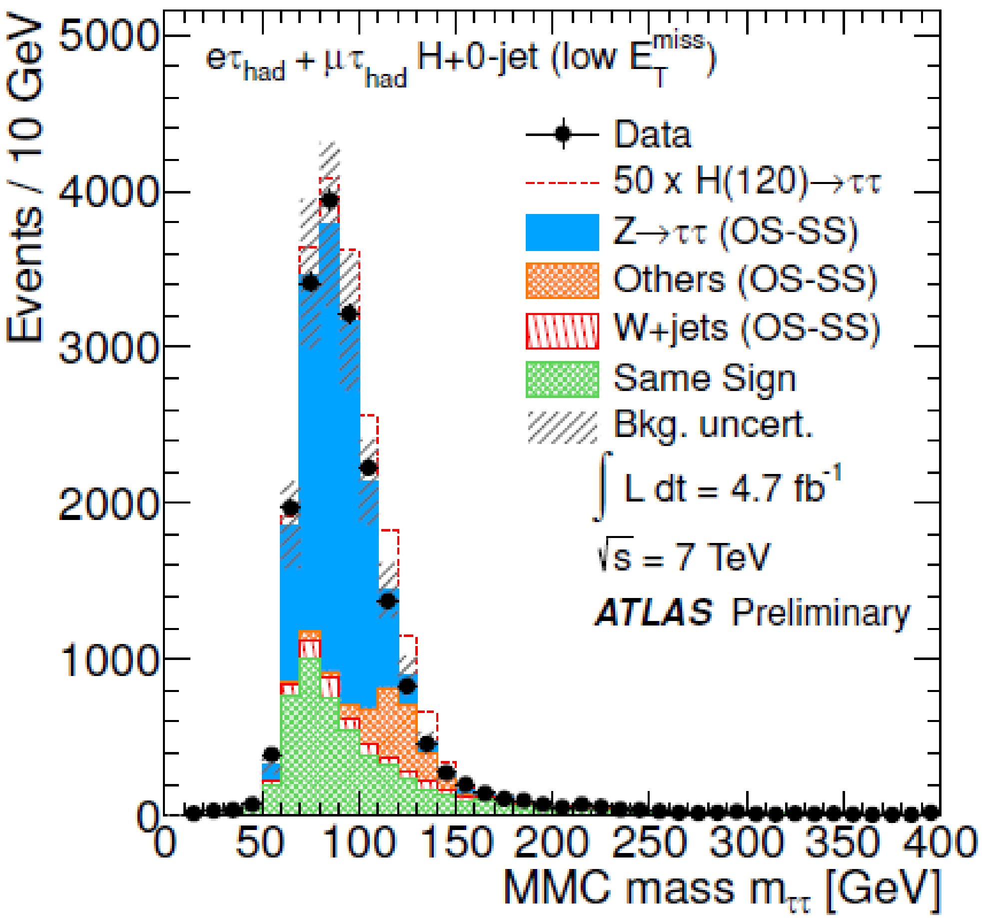
- Project the MET in the direction of the visible products
  - Often no solution → events discarded

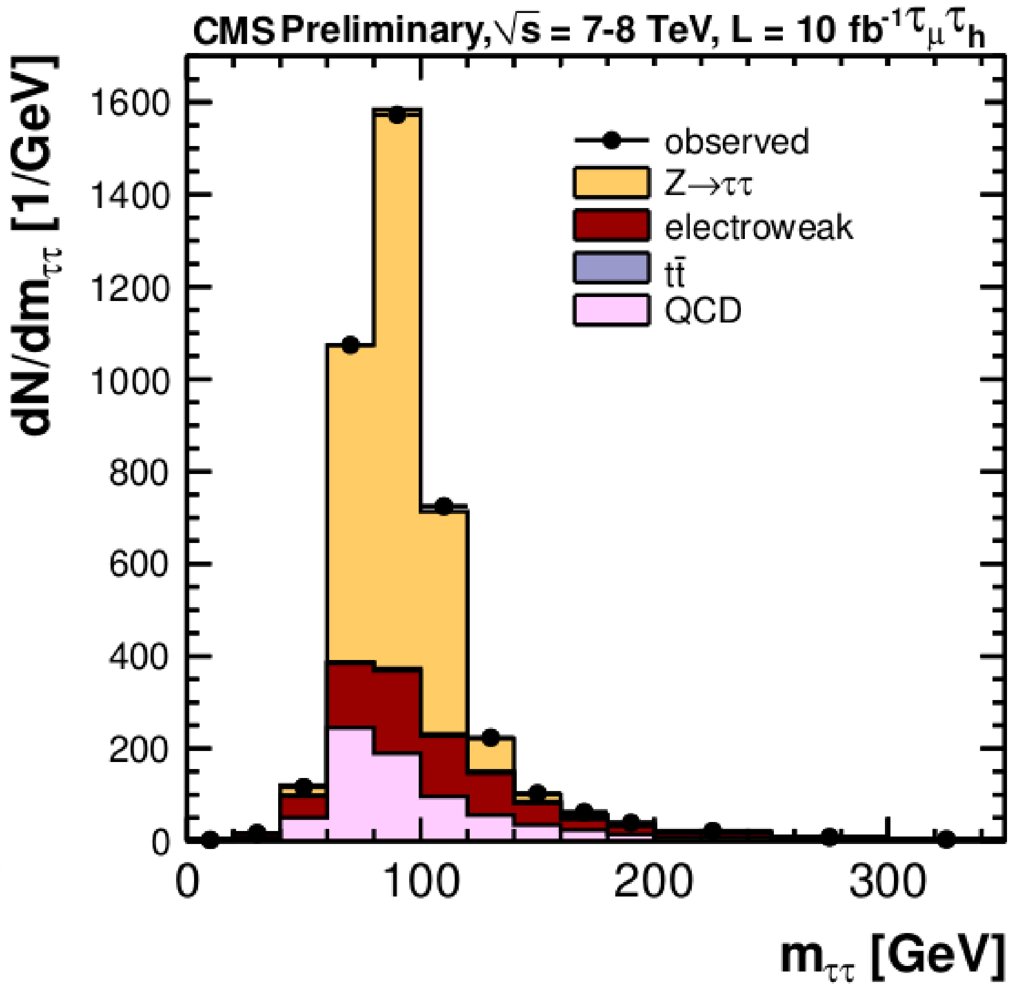
Likelihood based approximation



- Perform calculation by minimizing an event likelihood
  - Using visible decay kinematics and MET

Methods used

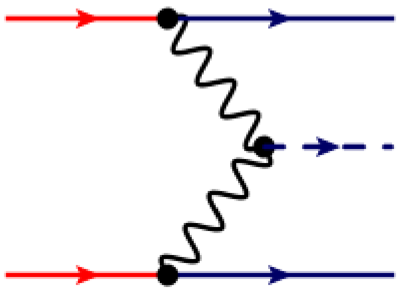




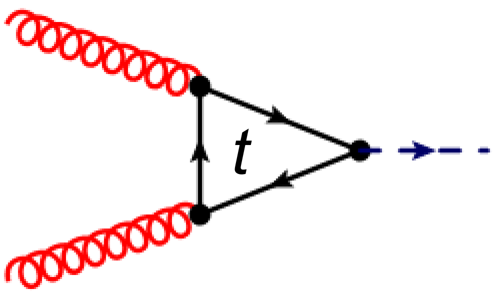
- Likelihood approach(MMC)
  - For μτ,eτ,ττ
- Collinear approximation
  - For ee,μμ,eμ
- Likelihood approach(SVfit)
  - For all final states

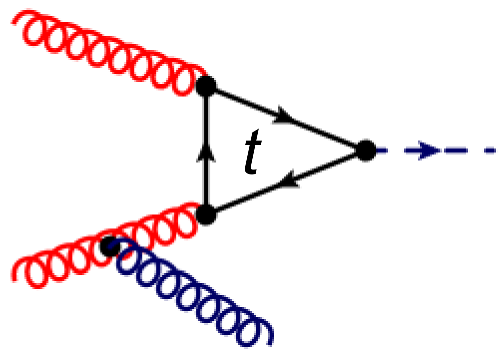
Analysis strategy

- Exploit best the properties of each event



- Exploit VBF by applying di-jet tagging (Δη,Mjj)
  - Use multivariate approaches to improve sensitivity



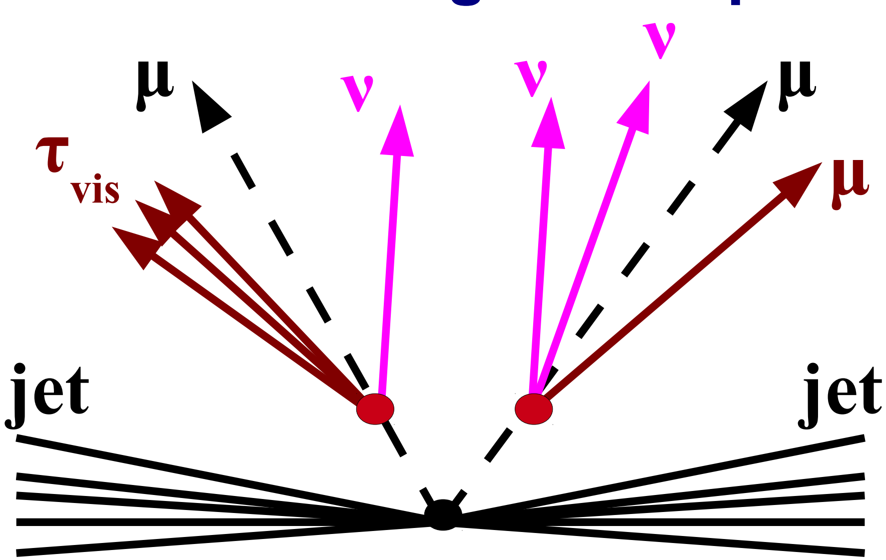


- Exploit gluon fusion + 1 jet
  - Boost from the jet improves mass resolution
- All other events are collected in a 0-jet category

Background estimation techniques

- Well established and similar techniques in both experiments

Embedding Technique



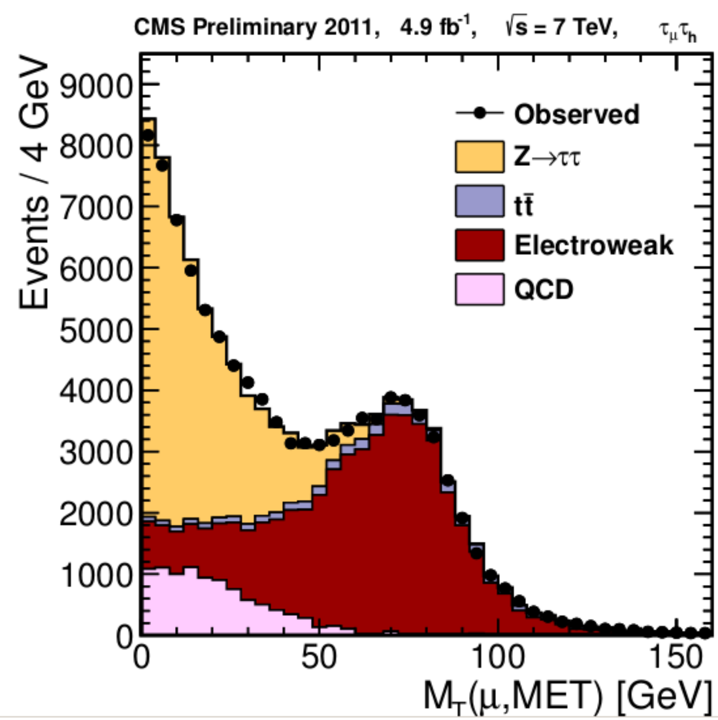
- Reconstruct Z → μμ events in data
- Replace μ with decay the event
- Mix the simulated tau pair event with the initial events without the muon
- PU/UE and jets from data

QCD from Same Sign Events

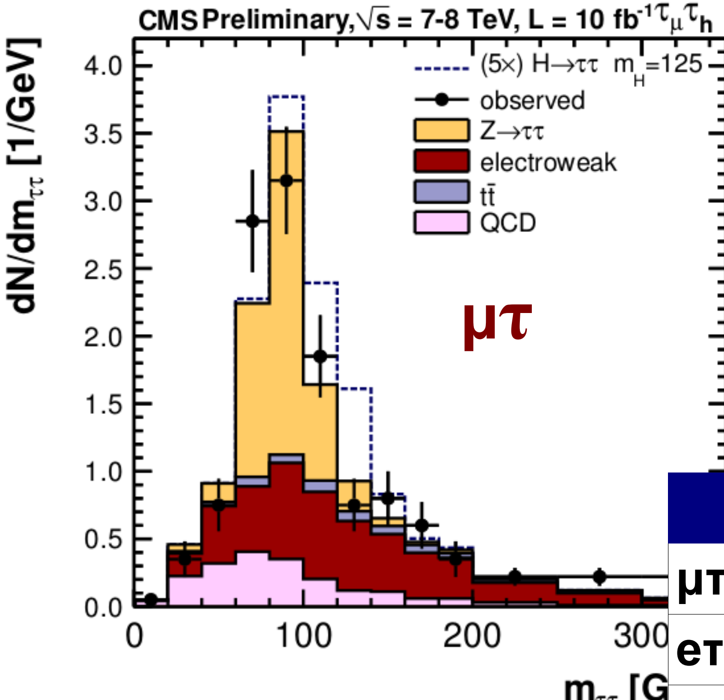
ATLAS : QCD(OS/SS)=1.10 ± 0.09

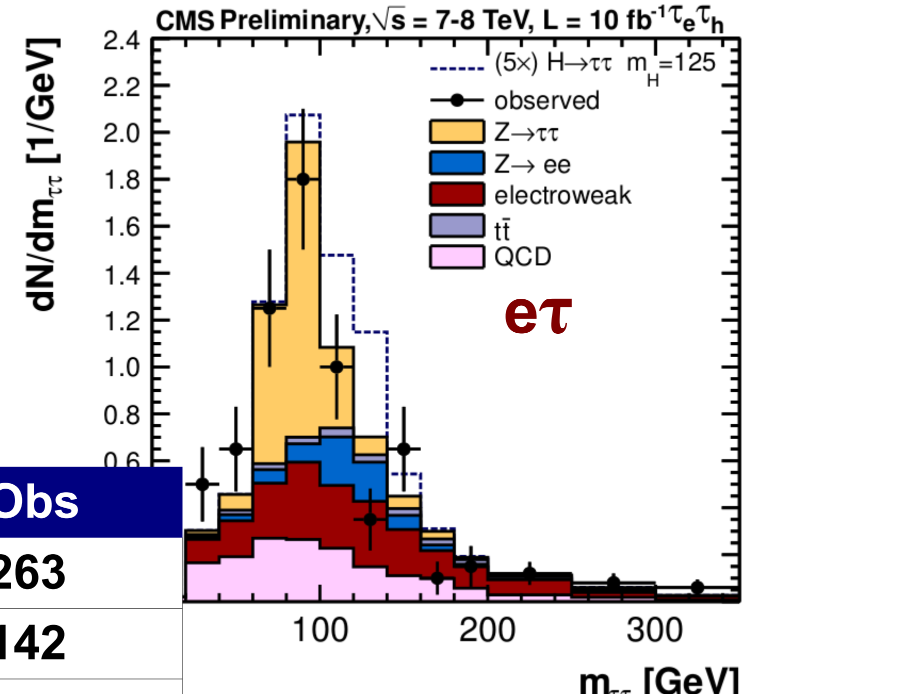
CMS : QCD(OS/SS)=1.10 ± 0.10

W from sidebands

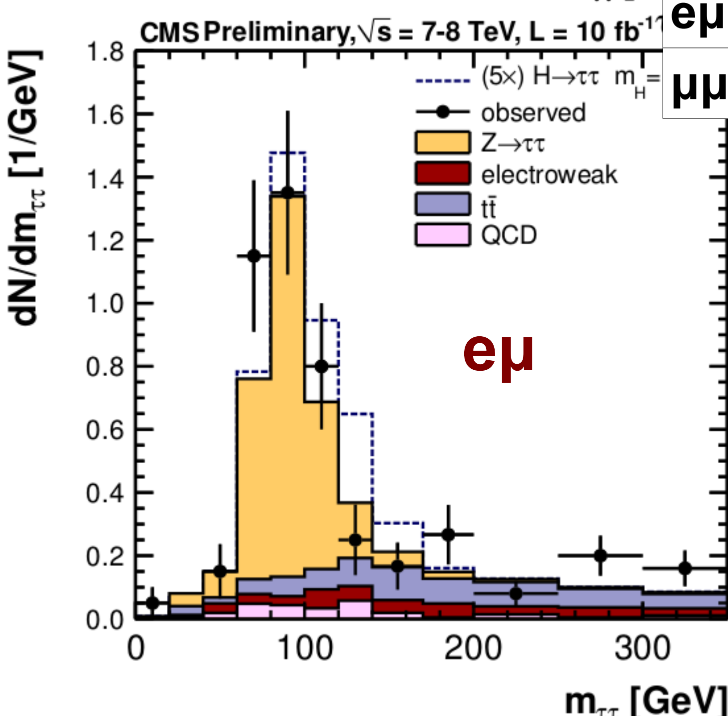


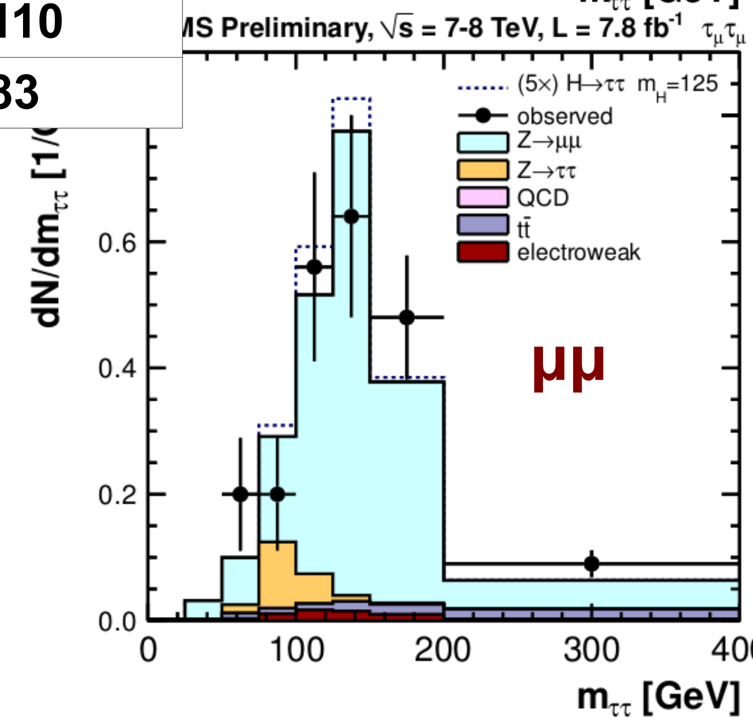
VBF category



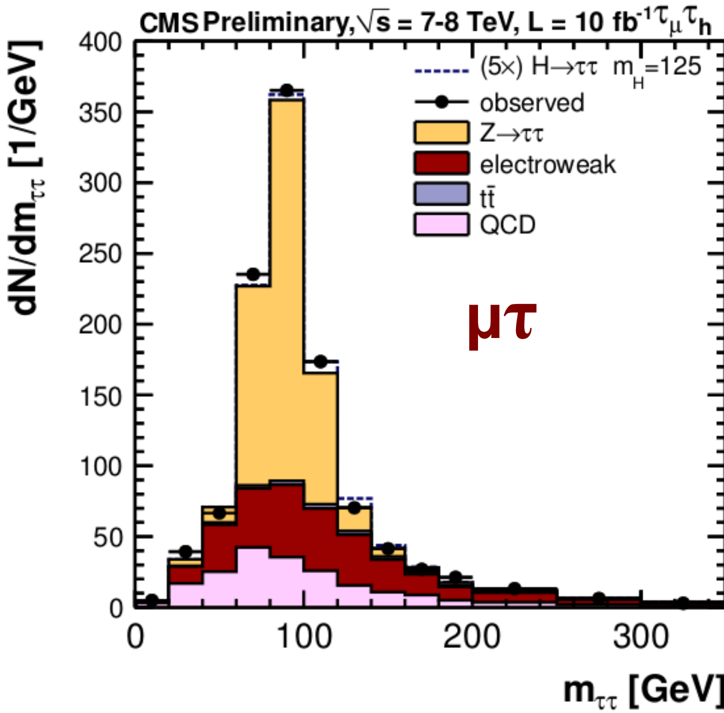


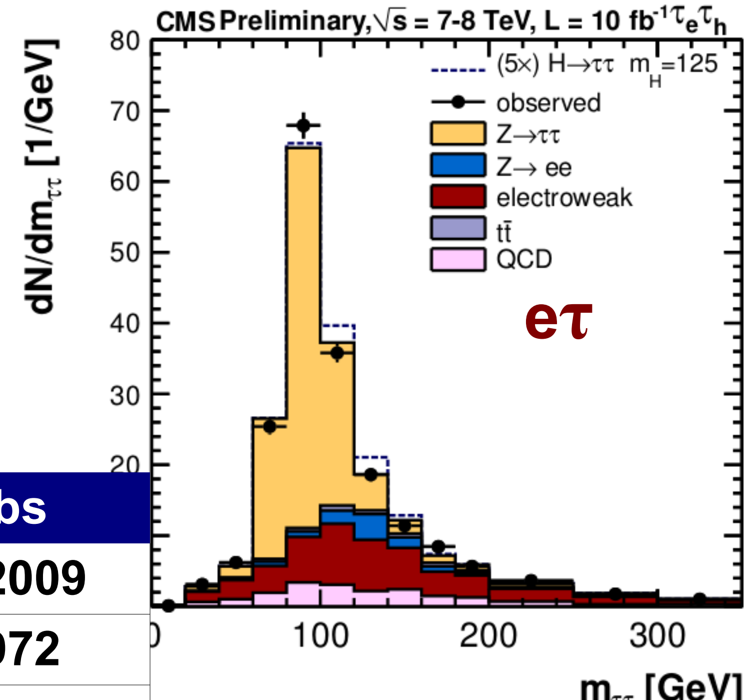
	Expected	Obs
μτ	233 ± 20	263
eτ	156 ±13	142
eμ	99 ± 13	110
μμ	85 ± 9	83



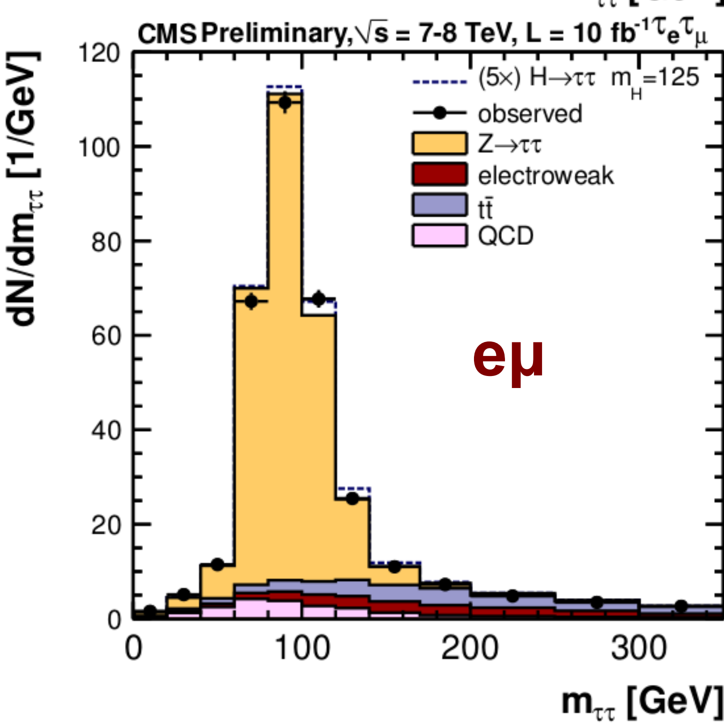


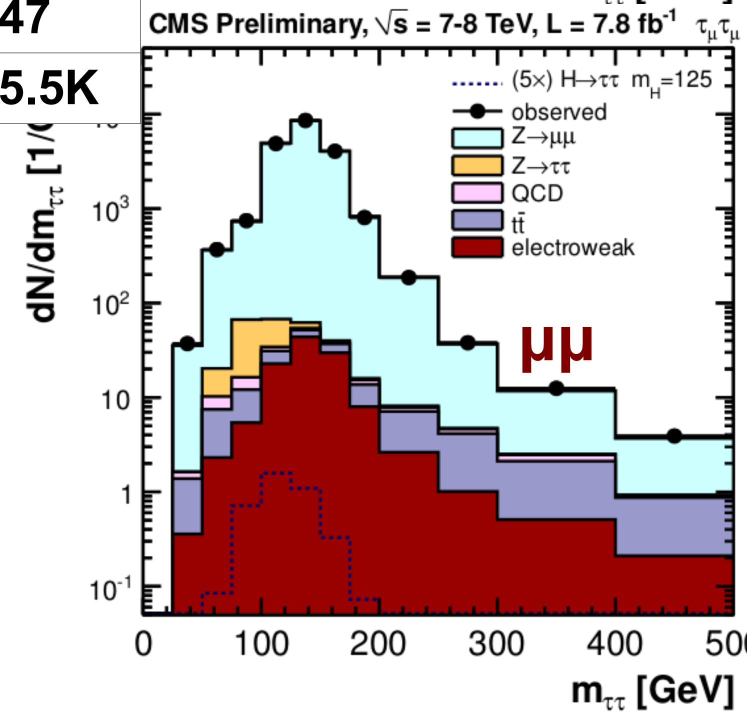
H+1 jet category



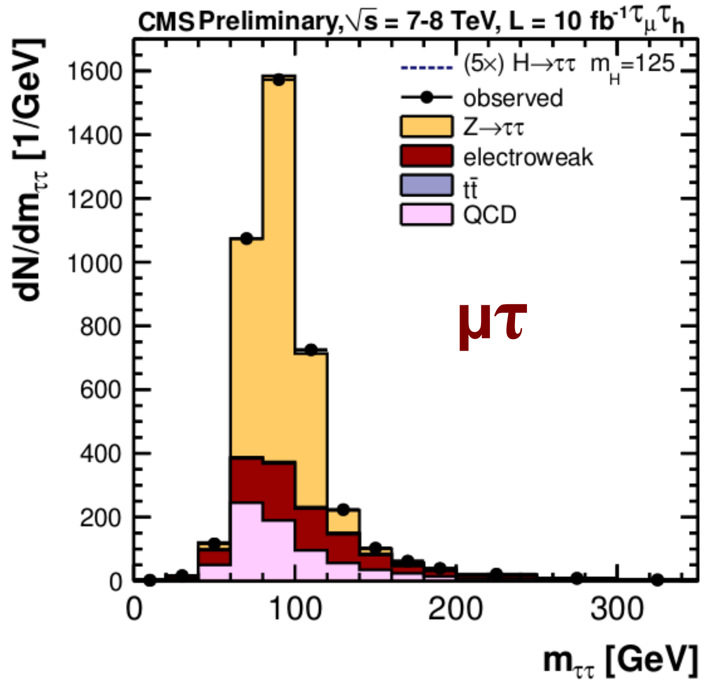


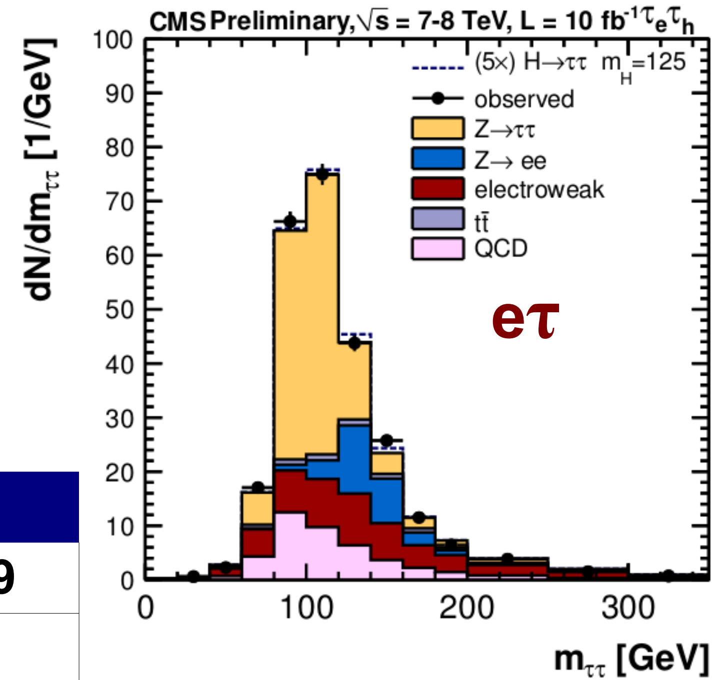
	Expected	Obs
μτ	21544 ± 865	22009
eτ	4017 ±133	3972
eμ	6958 ± 913	6847
μμ	385.5 ± 21 K	385.5K



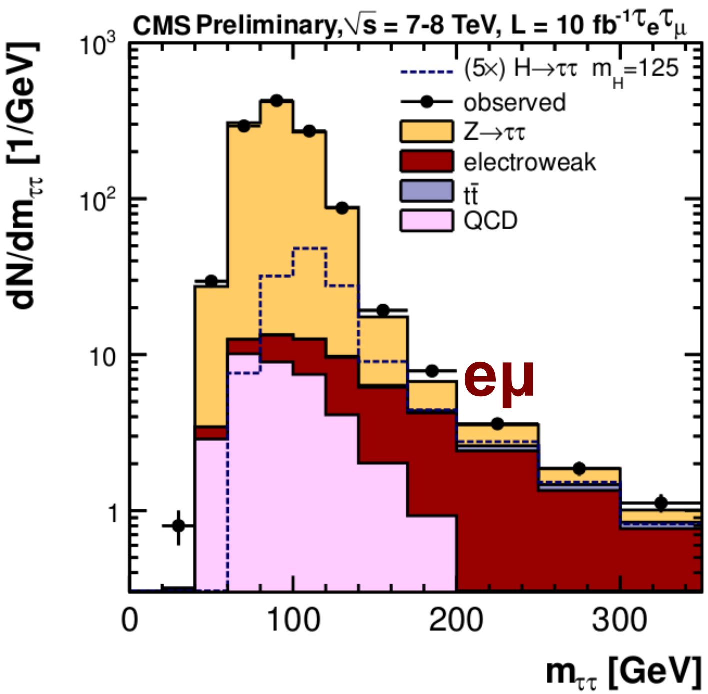


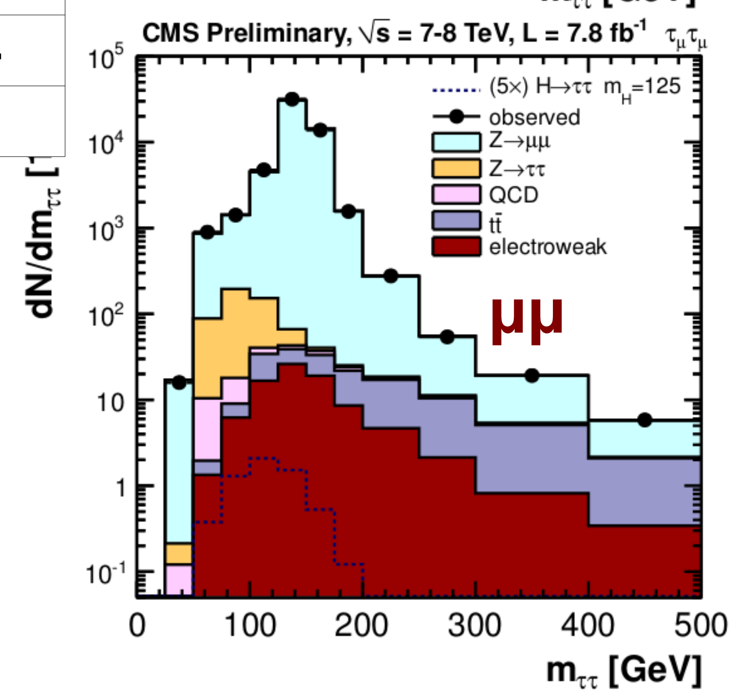
H+0 jet category



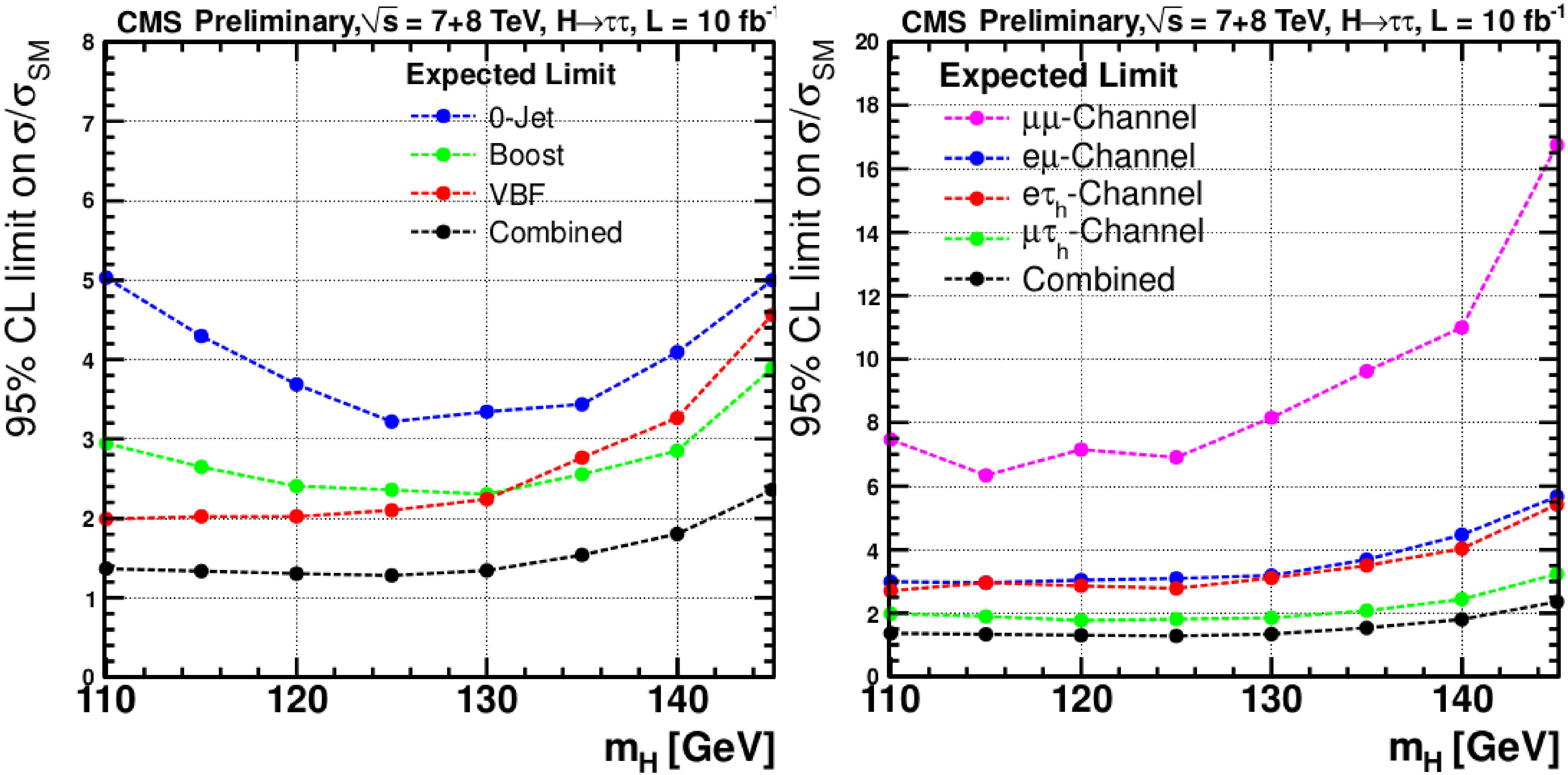


	Expected	Obs
μτ	80448±3569	80229
eτ	5411 ±168	5273
eμ	23799±4285	23274
μμ	1.28 ±0.06 M	1.29M





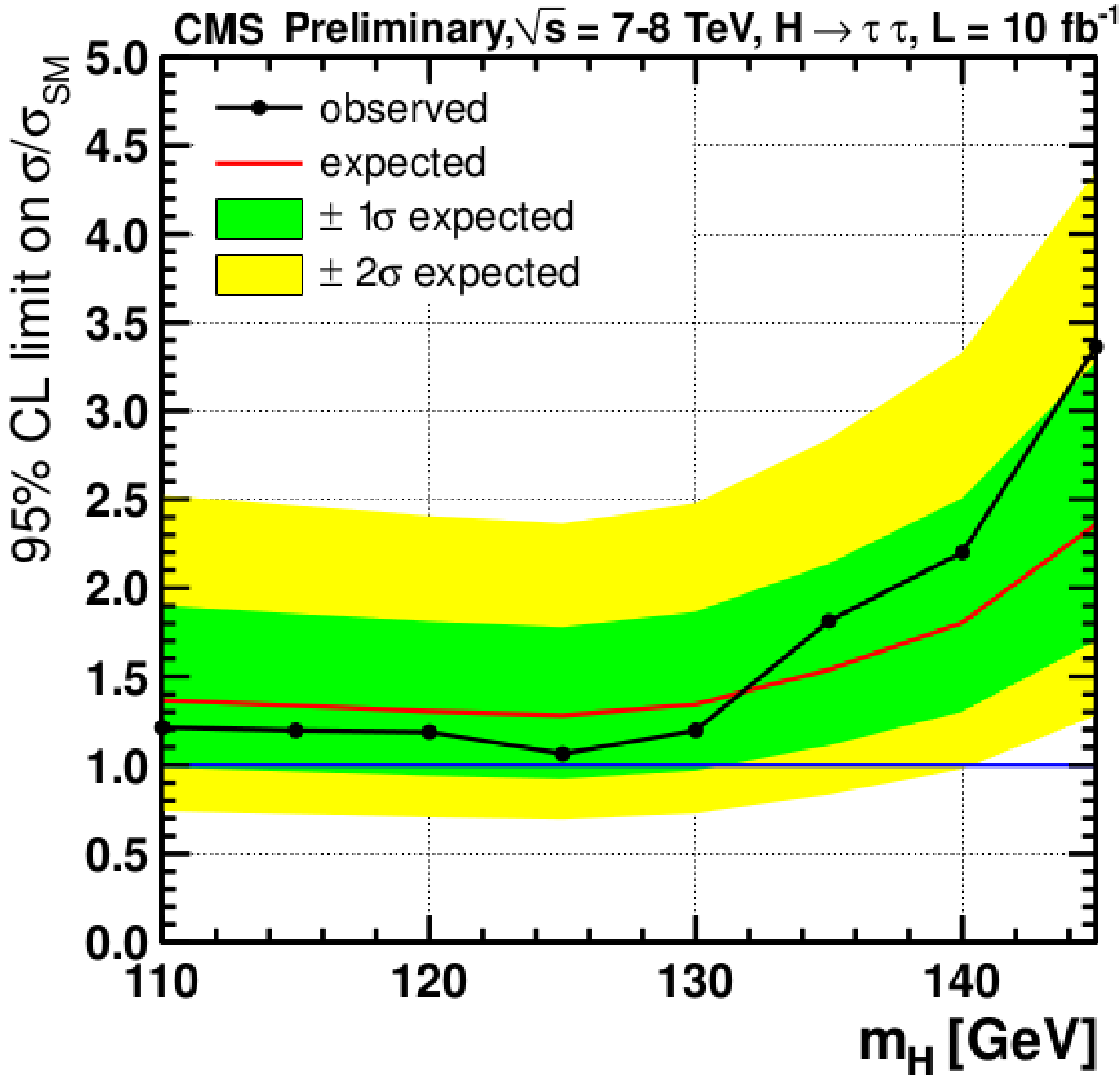
Expected Sensitivity



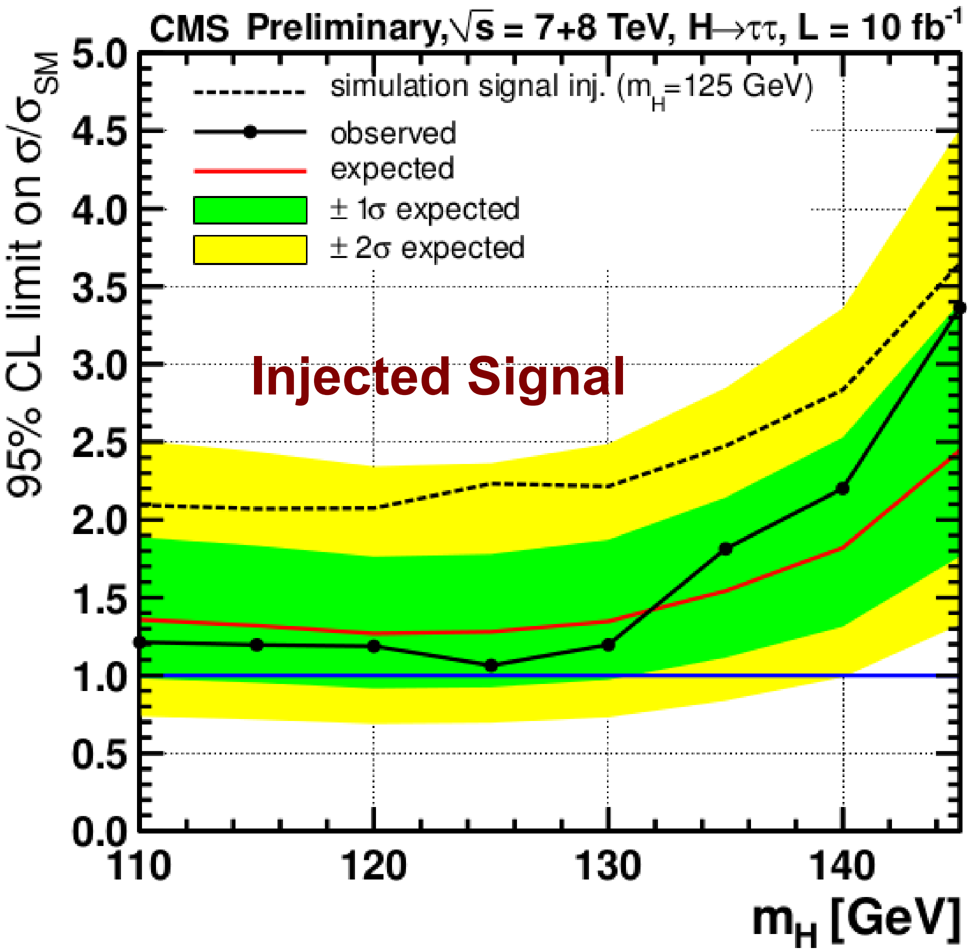
- Sensitivity dominated by VBF +1 jet(Boosted) category
- Most sensitive final state is μτ

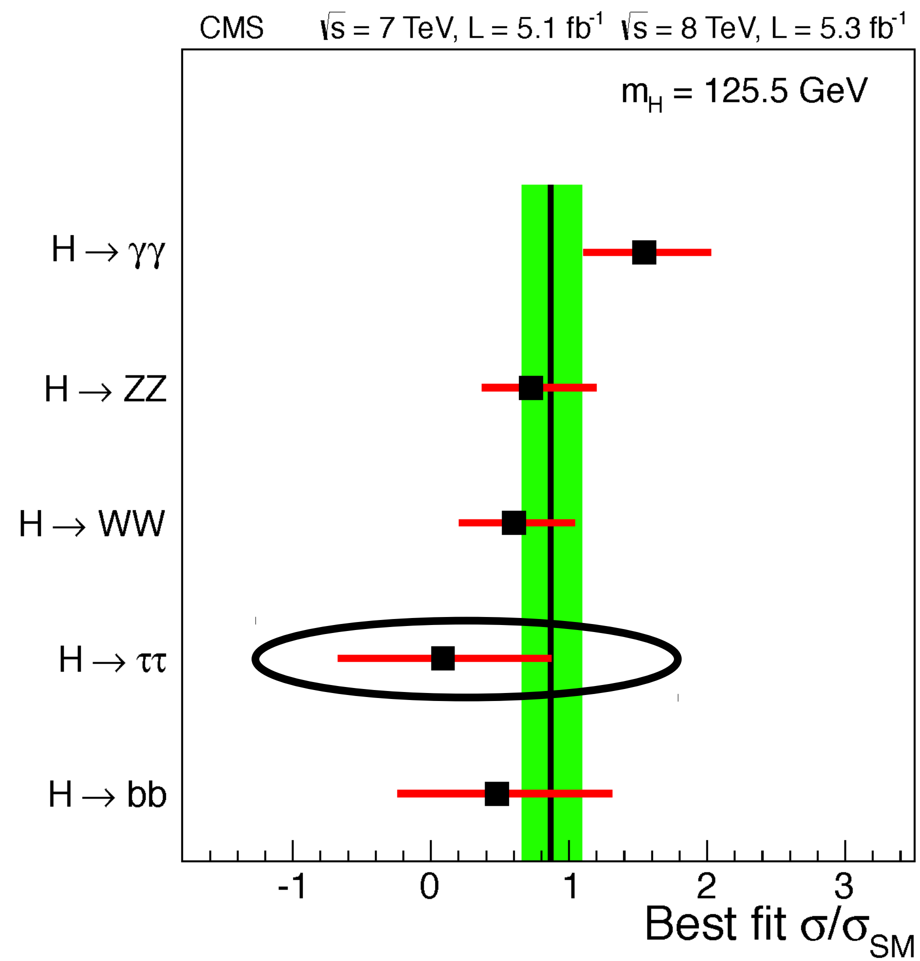
CMS Results with $10fb^{-1}$

- Expected sensitivity
  - 1.3 x SM @ 125 GeV
- Observed
  - 1.06 x SM
- Good agreement with background only hypothesis



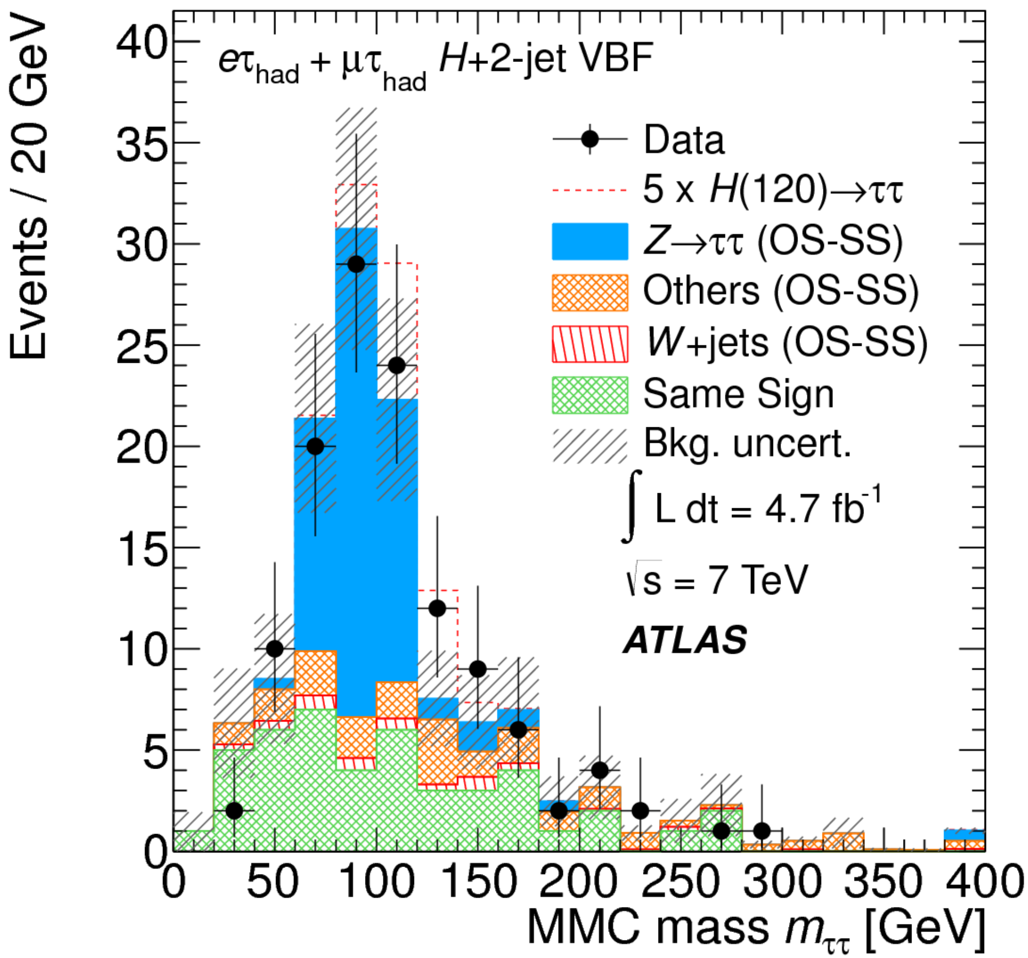
Consistency with the SM

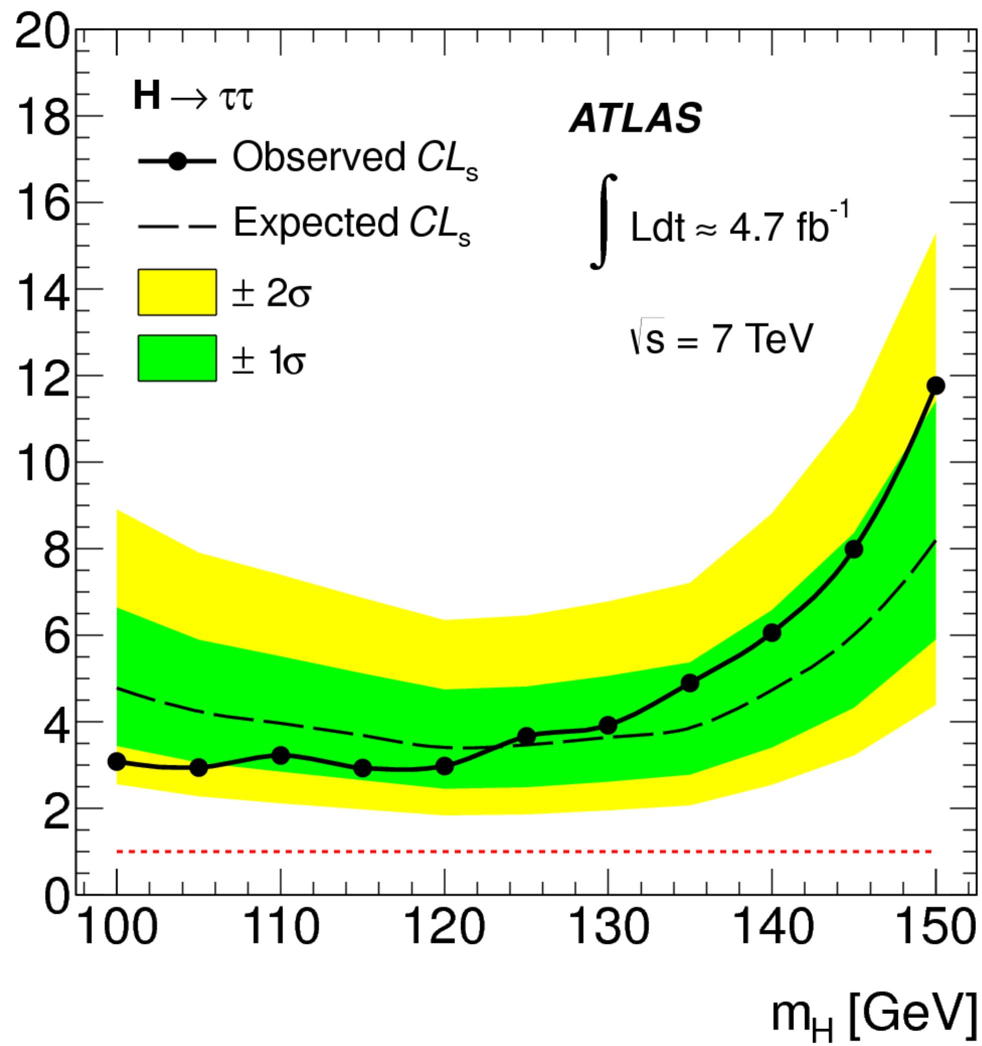




- Injected test shows broad excess as expected from resolution
- Best fit value still compatible with the SM and the other CMS channels
- With the current dataset an under-fluctuation could still be possible
  - By the end of the year we will have a better picture(exp ~ 0.8xSM sensitivity)

ATLAS results at 4.7 fb^{-1}



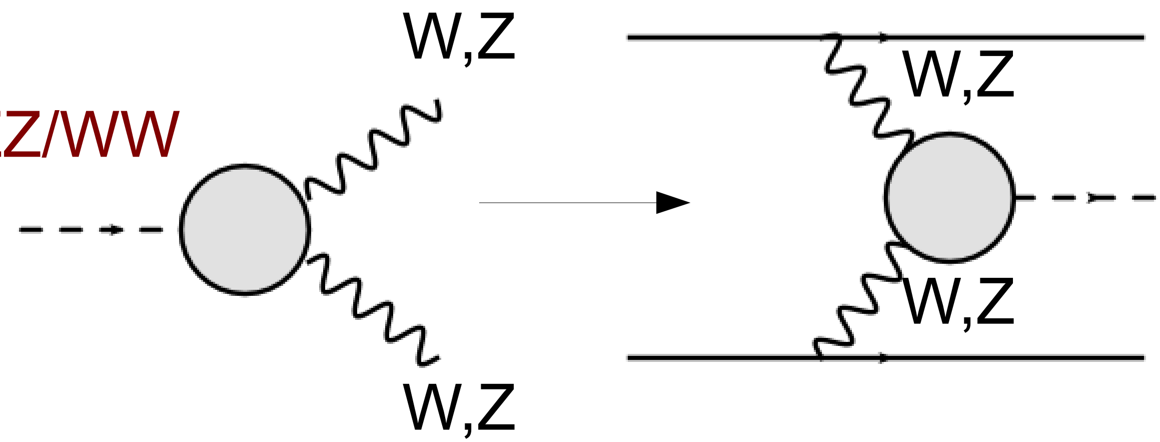


- Sensitivity of 3.5x SM
  - Good agreement with background only hypothesis
- Update expected soon with the 2012 dataset

What if we don't see $H \rightarrow \tau\tau$?

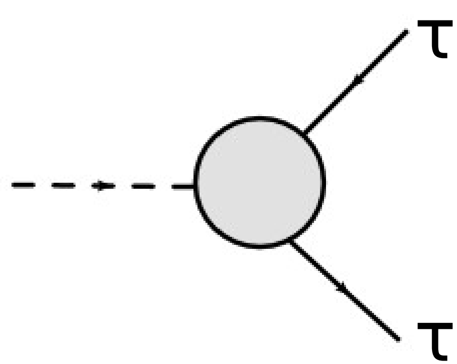
We know we can produce it also in the most sensitive VBF mode

We have observed ZZ/WW



So VBF must exist

Lower or zero cross section implies smaller coupling



- Can measure/set limits to the BR($H \rightarrow \tau\tau$)
- Limited precision with 2011+2012 dataset
  - Promising for LHC restart

Conclusions

- $H \rightarrow \tau\tau$ final state has surpassed all expectations in sensitivity
- Will reach 0.8 x SM by the end of the year with one experiment
  - ~0.5 for ATLAS/CMS combination
- Up to now no signal observed but consistent with the SM
- By the end of the year we will have first evidence if the coupling of the new boson to tau is SM like
- In parallel, a lot of studies ongoing on the context of 2HDM