Higgs at LHC

Discovery of a New Boson at LHC

Lecture 11

Dipartimento di Fisica

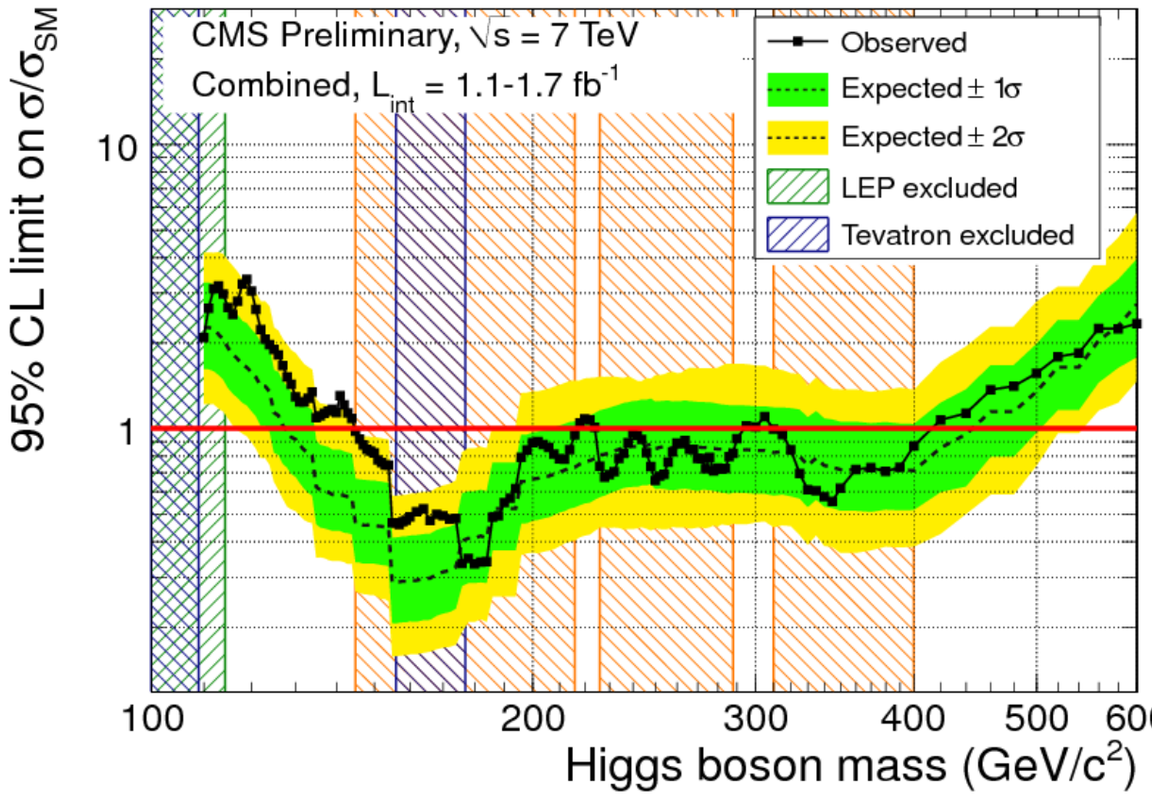
Sapienza
Università di Roma

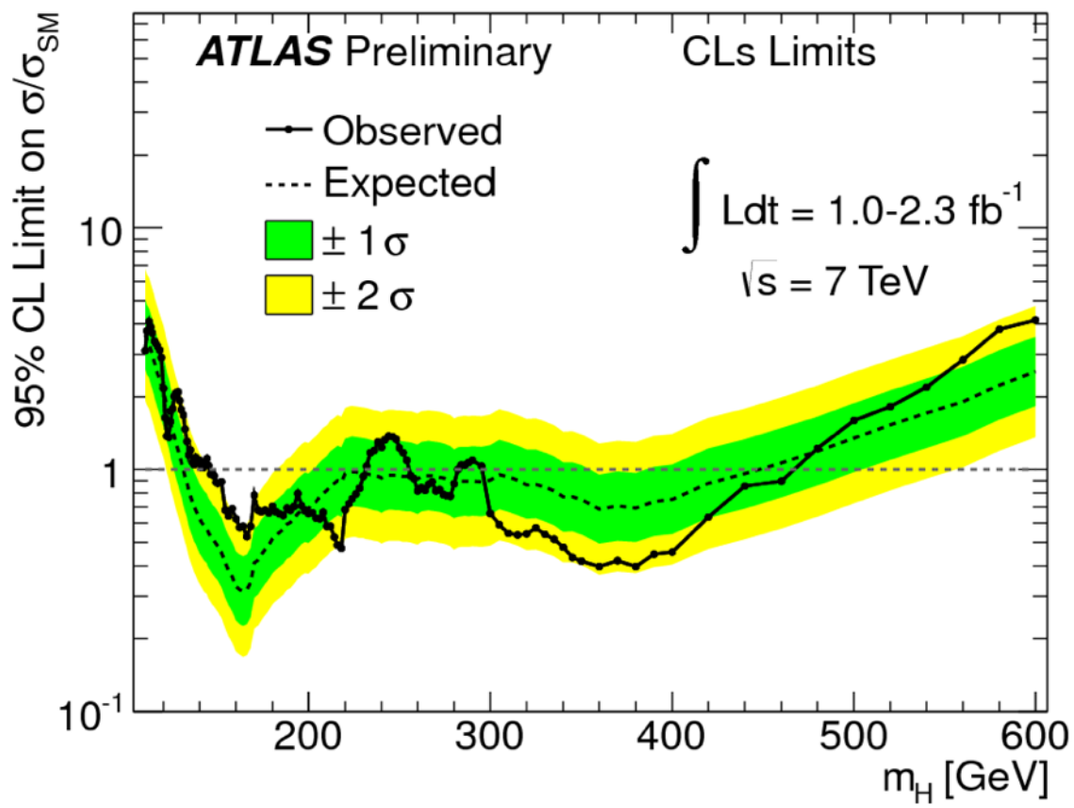
Shahram Rahatlou

Fisica delle Particelle Elementari, Anno Accademico 2015-16

http://www.roma1.infn.it/people/rahatlou/particelle/

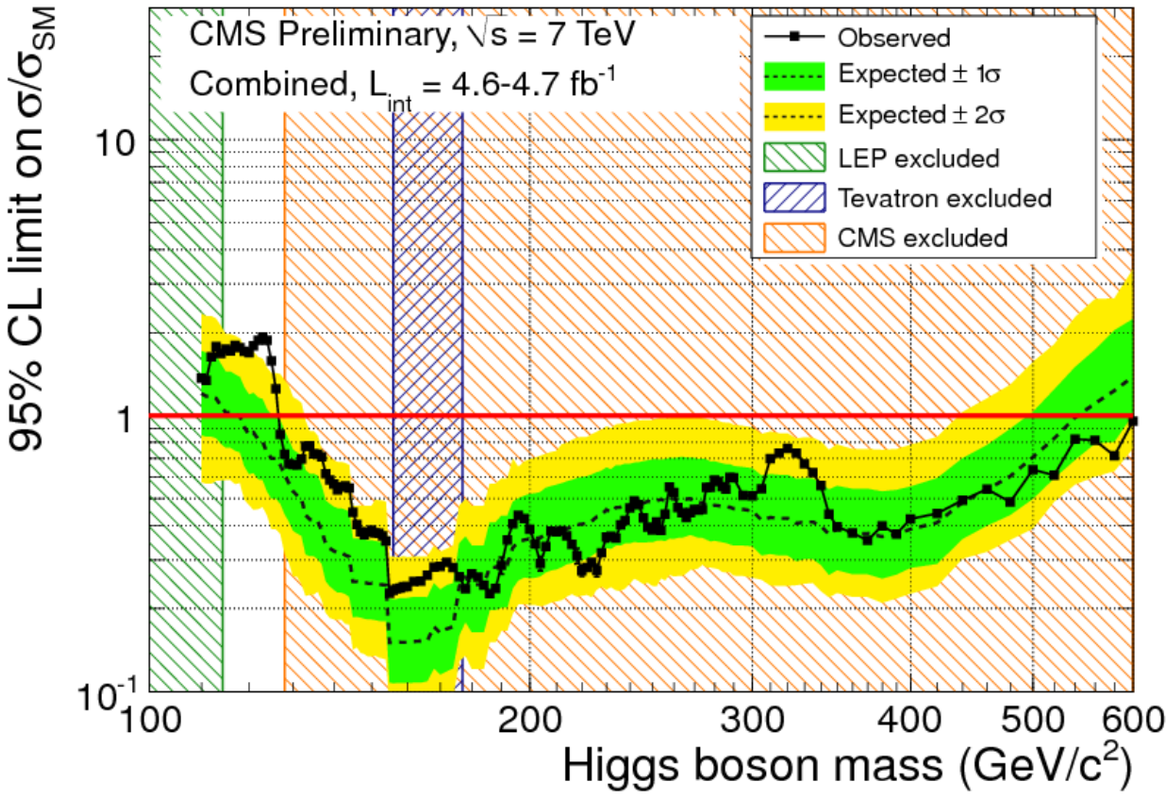
HIGGS SEARCHES, SUMMER 2011

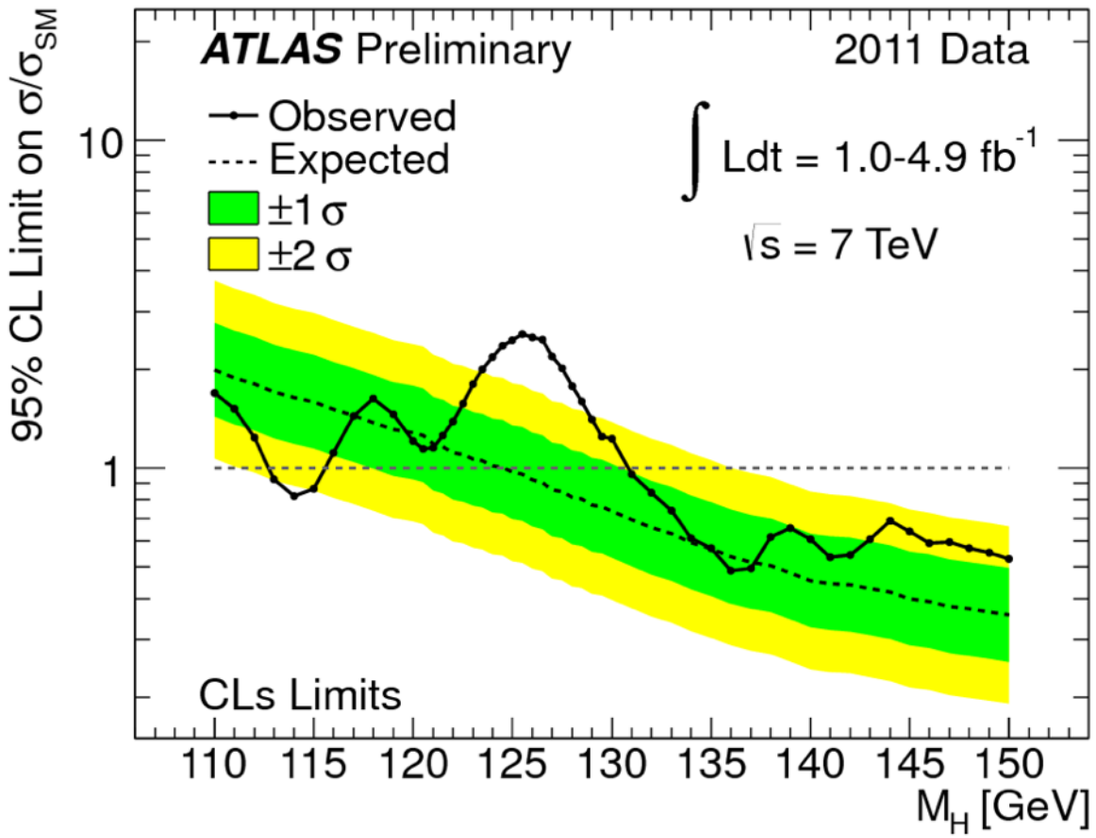




- 1/fb of data collected at LHC in 2011 at 7 TeV excluded very large mass regions

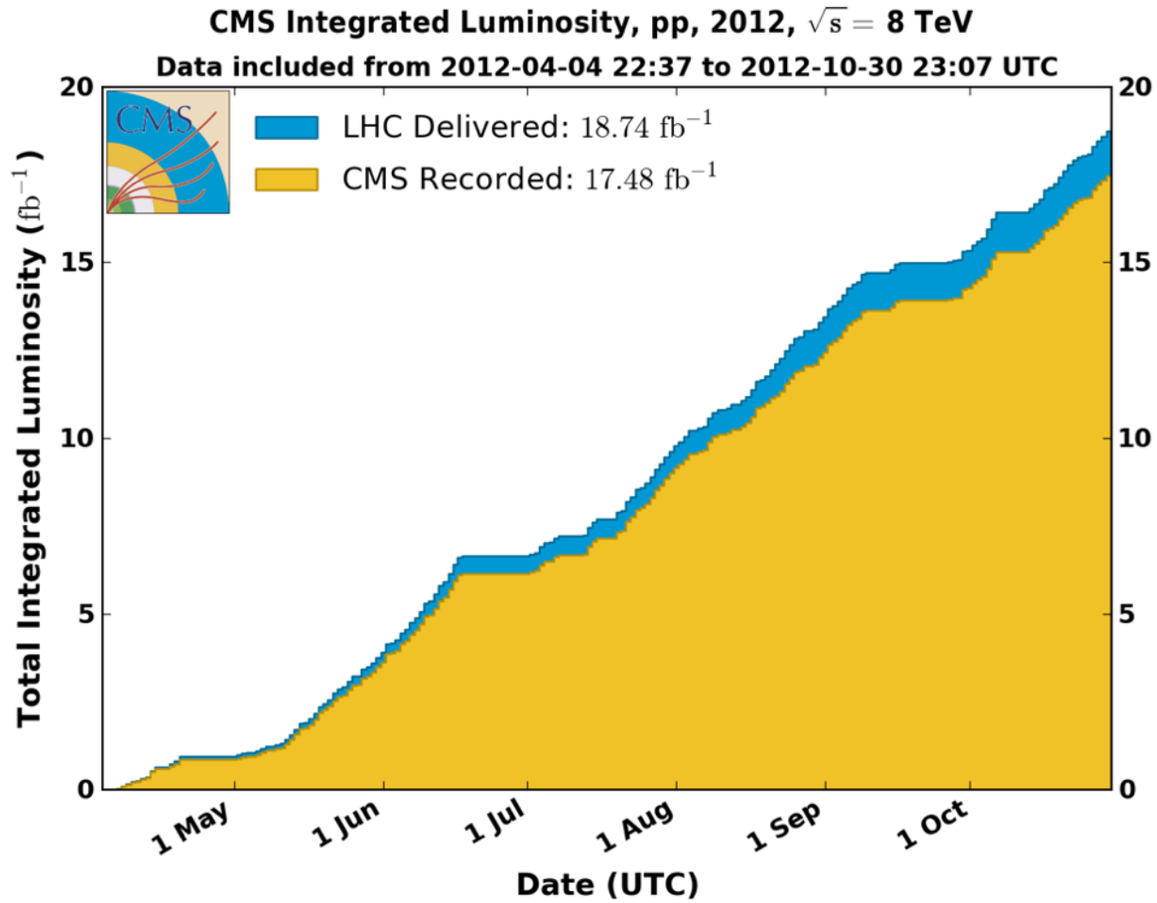
Higgs @ December 2011





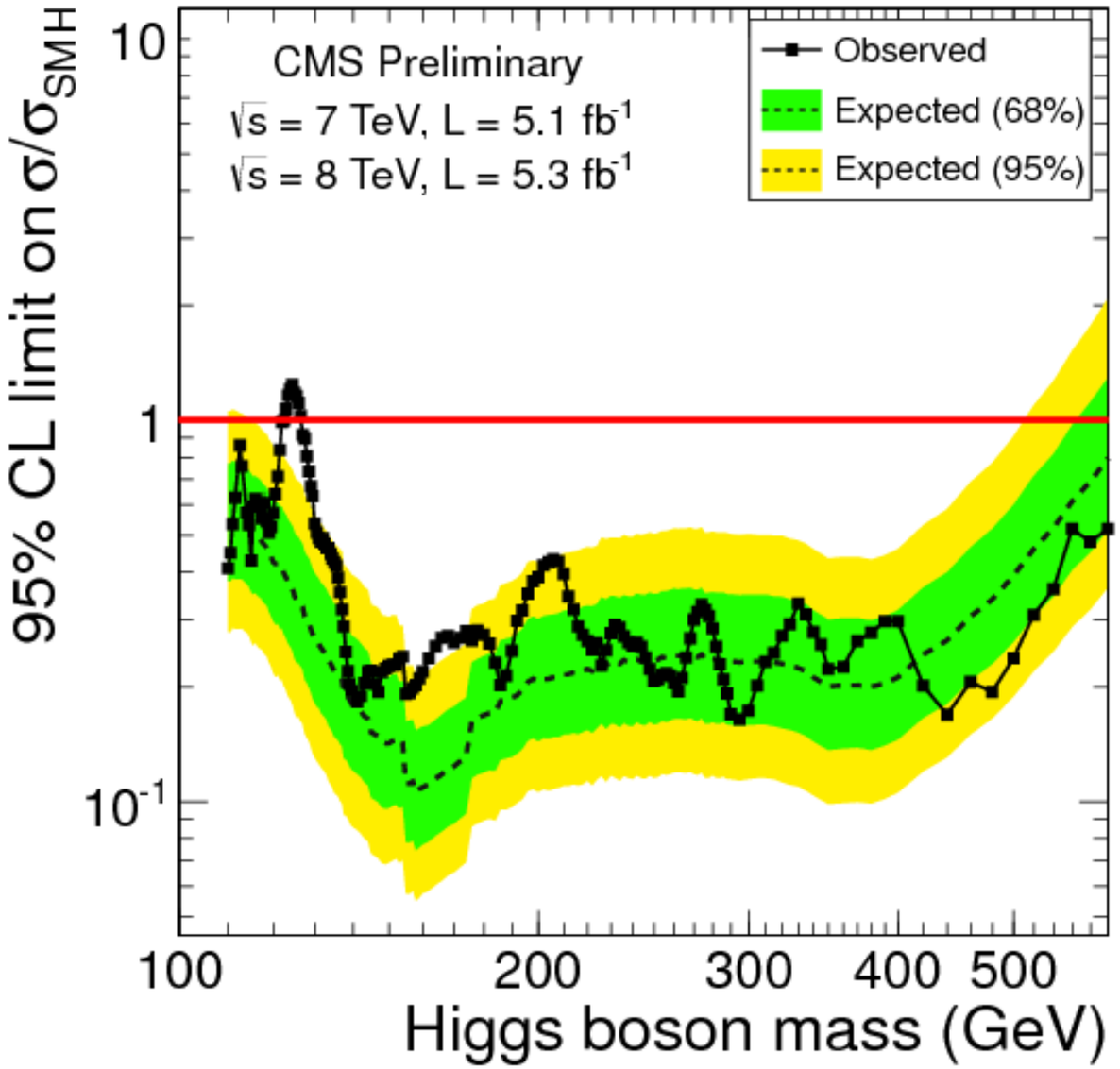
HIGGS HUNT@ SUMMER 2012

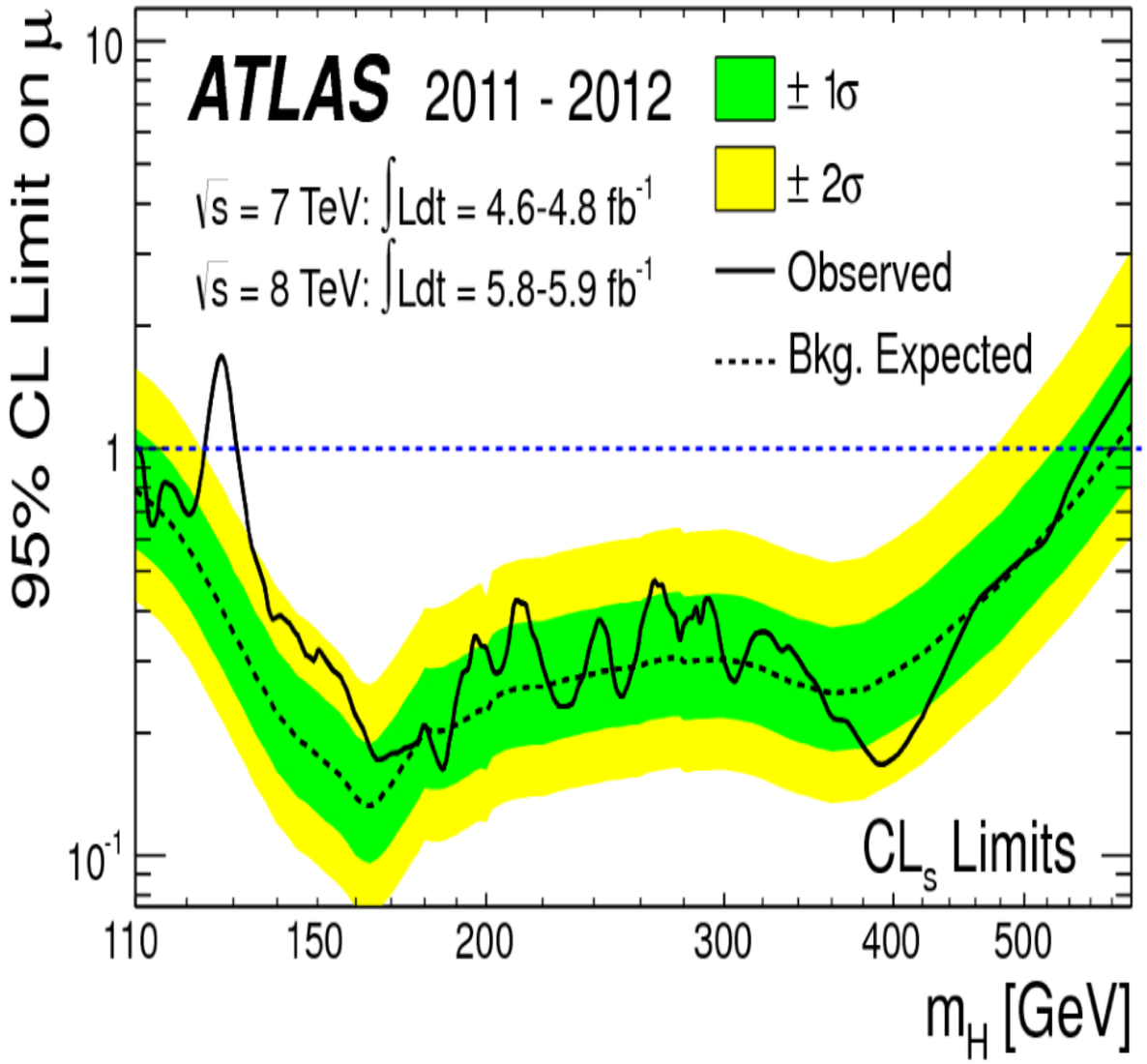
- additional 5/fb at 8 TeV in 2012
  - 25% higher cross section for higgs production



- Average pile-up increased by factor x2 compared to 2011

Discovery of a New Boson

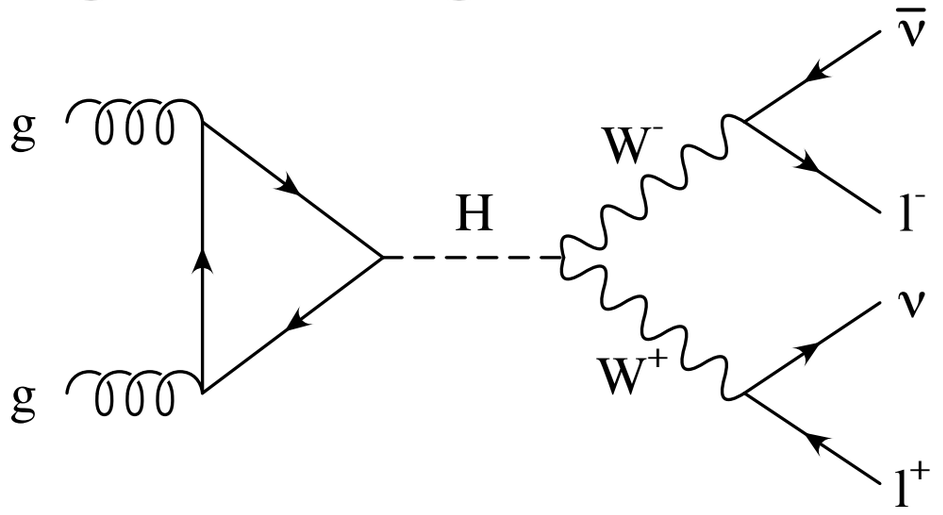




- Standard Model Higgs excluded everywhere except at low mass
- Combination of all decay modes

$H \rightarrow WW \rightarrow 2l\,2\nu$

- Most promising decay mode for mid-high mass region

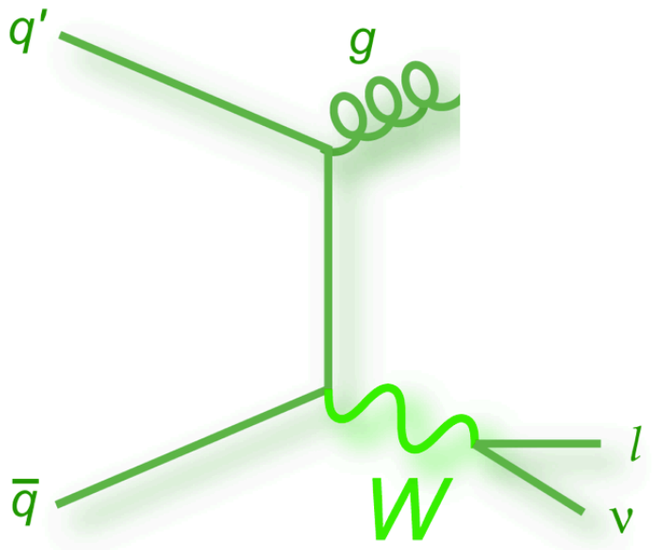


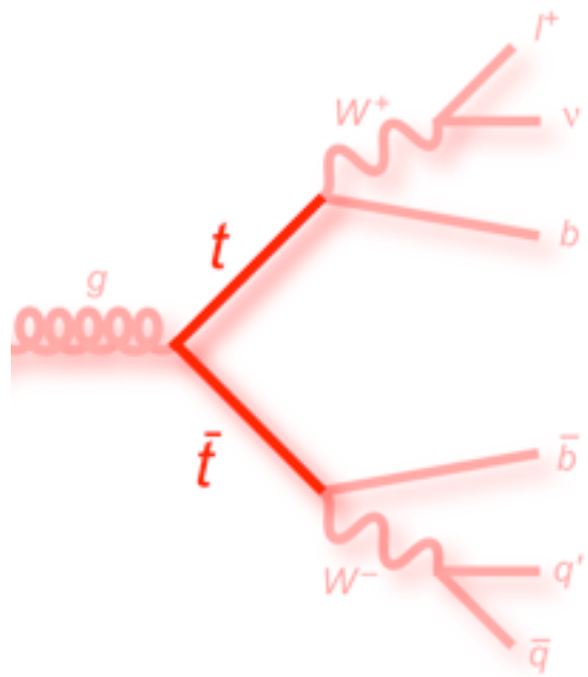
- De facto discovery channel for 160-170 GeV when ZZ is suppressed

$$\mathrm{BR}(H \rightarrow \nu\bar{\nu}\ell^+\ell^-) = 6\,\mathrm{BR}(H \rightarrow \ell^+\ell^-\ell^+\ell^-)$$

- Main disadvantage: no peak of invariant mass
  - only transverse mass of W
  - No Higgs peak
  - need very good missing transverse energy measurement
  - must determine very precisely background shape

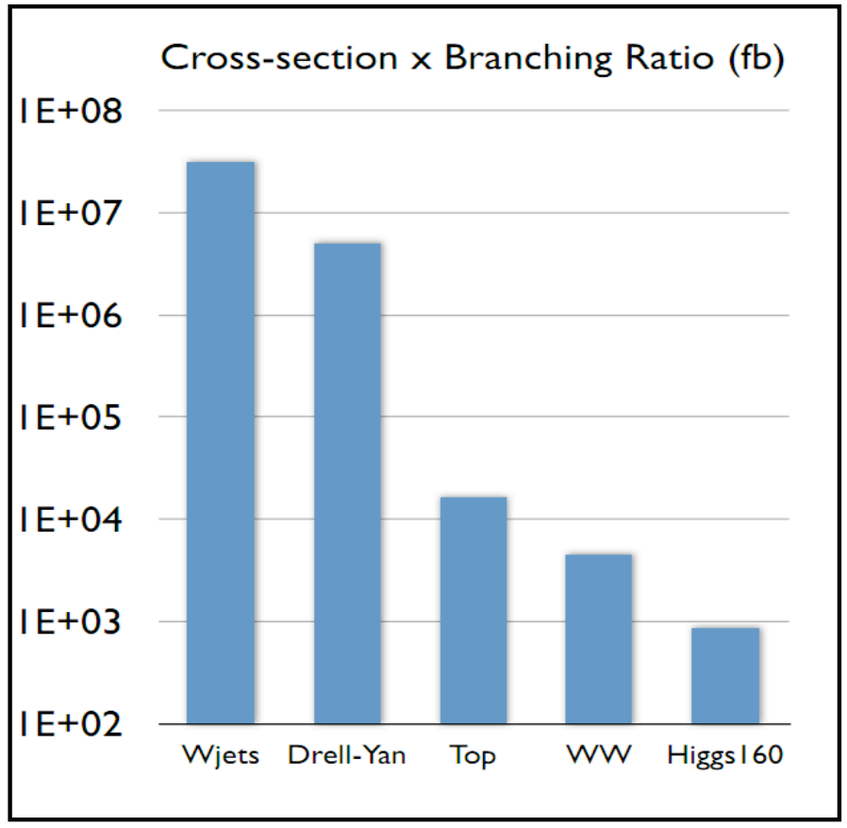
BACKGROUND FOR H→ WW→ 2l2ν





$qq/qg \rightarrow WW$
$gg \rightarrow WW$
$pp \rightarrow t\bar{t}$
$Z \rightarrow \tau\tau$+jets
W+iets

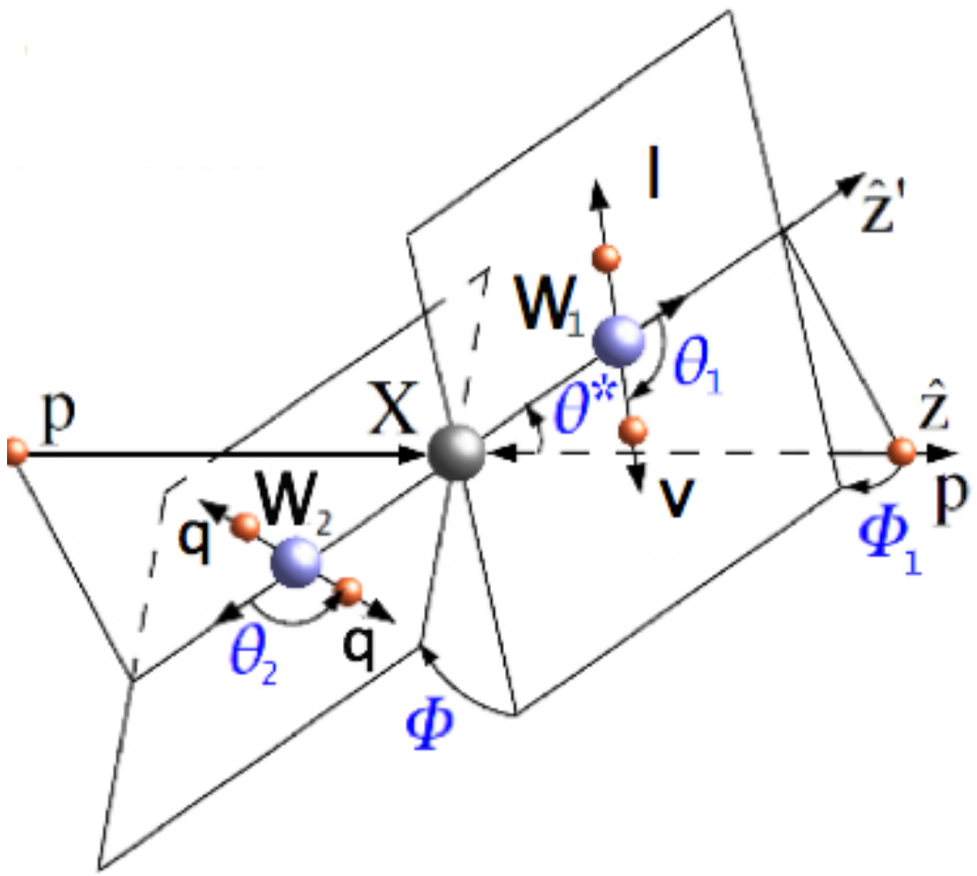
Processi	σ (pb)
Higgs m=300 GeV	0,482
Higgs m=400 GeV	0,341
Higgs m=500 GeV	0,134
W + jets	31314,0
ttbar	175,5



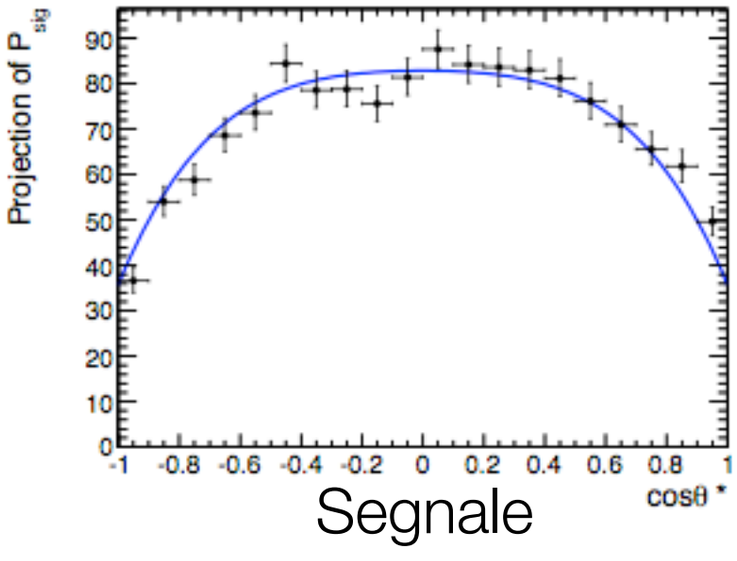
H→ WW→ 2l2ν

- Handles to remove background:
  - 2 opposite sign isolated leptons
    - Removes QCD & W+jets
  - large MET
    - Removes DY
  - classify events in #jets & b-jet veto
    - Remove top contamination
  - kinematics: low m_{ll} and small $\Delta\phi_{ll}$
    - To discriminate against WW

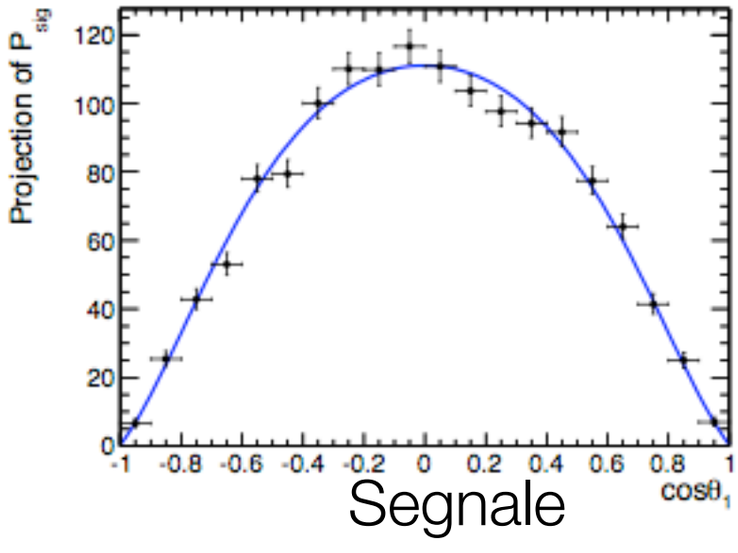
Angular Information in H→ WW→ 2l2ν



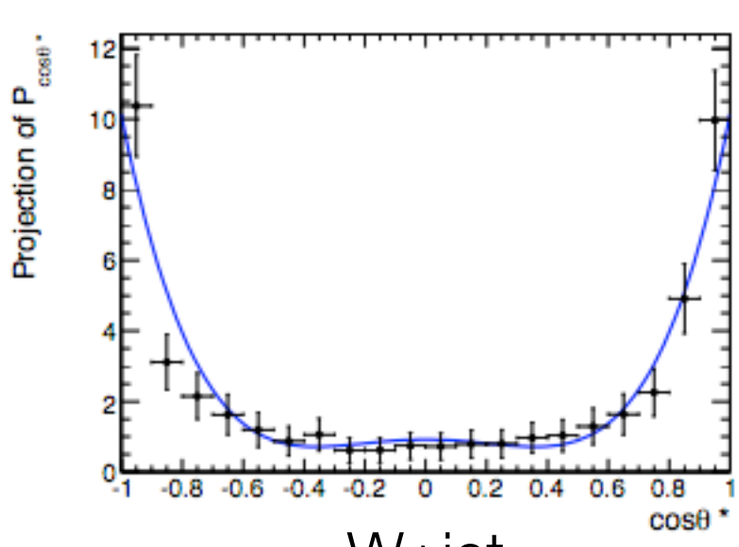
$\cos\vartheta^*$, $\cos\vartheta_1$, $\cos\vartheta_2$, Φ, Φ_1



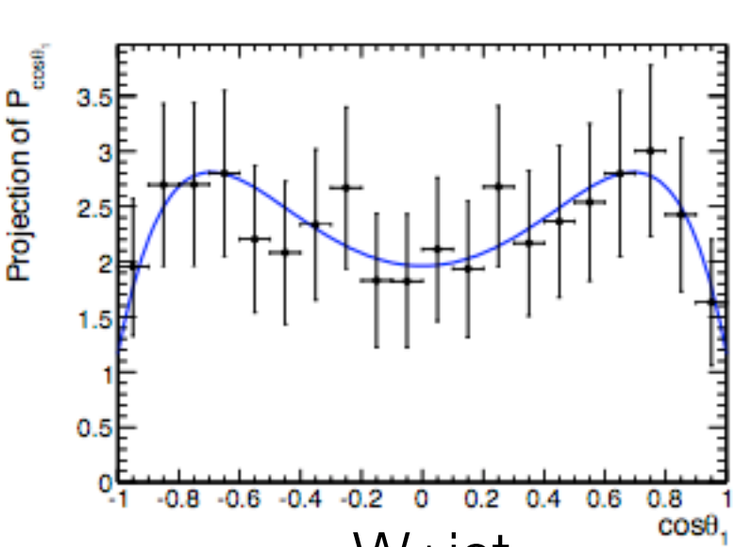
Segnale



Segnale



W+jet

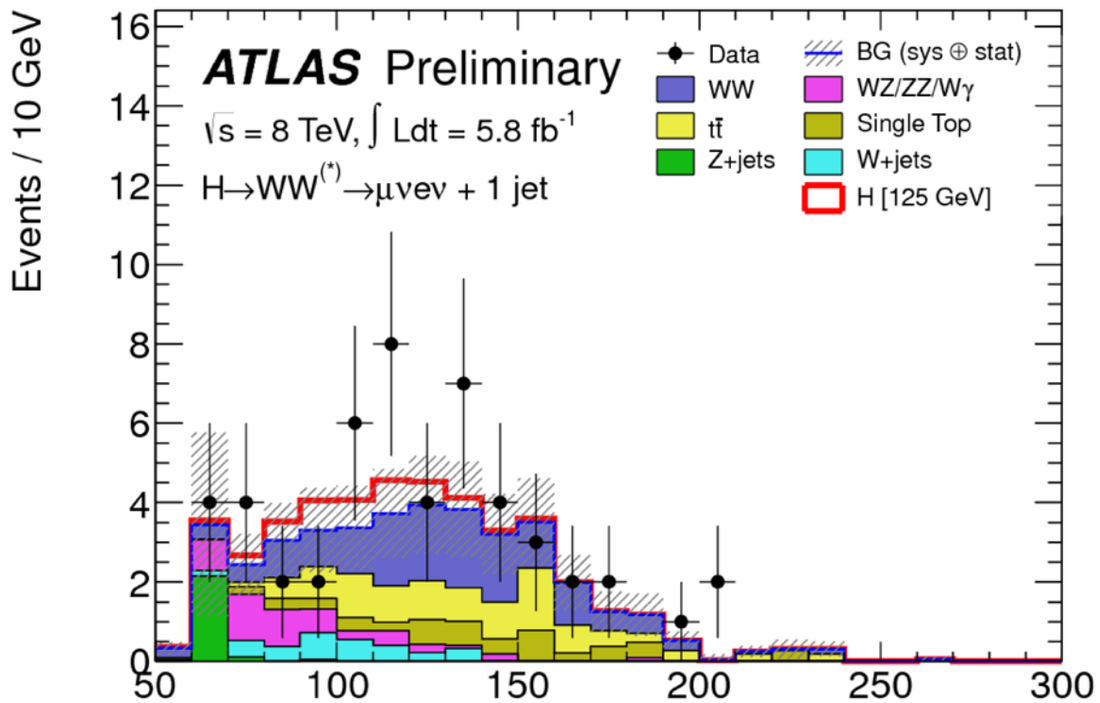


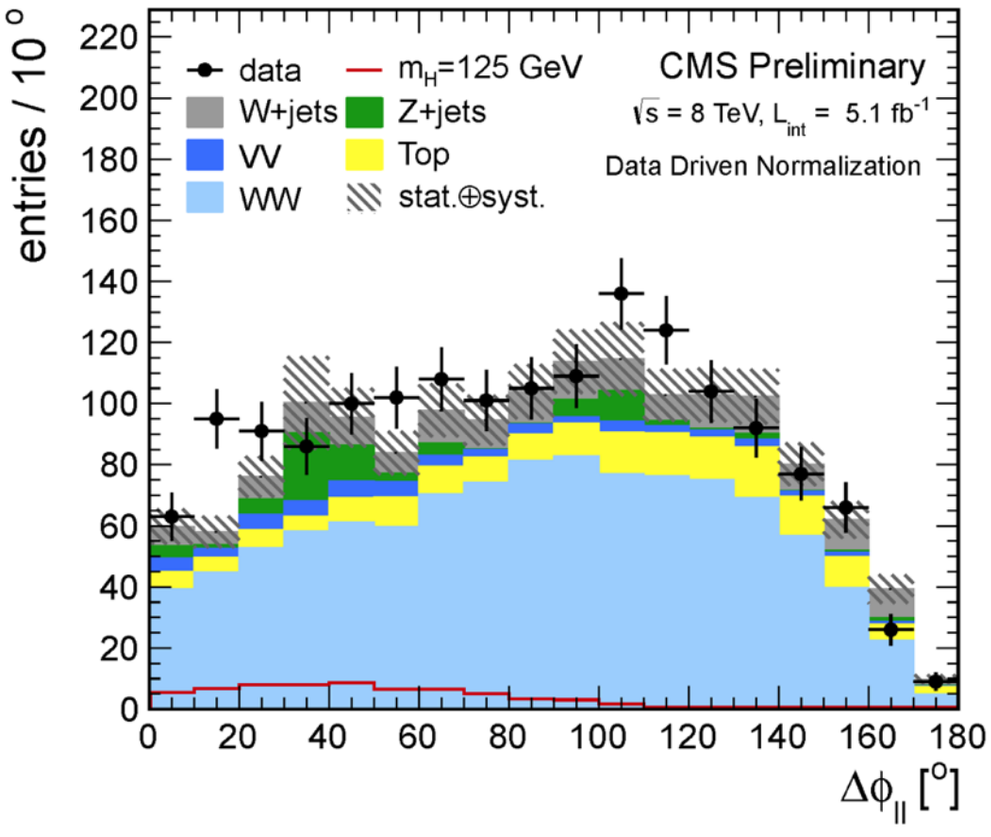
W+jet

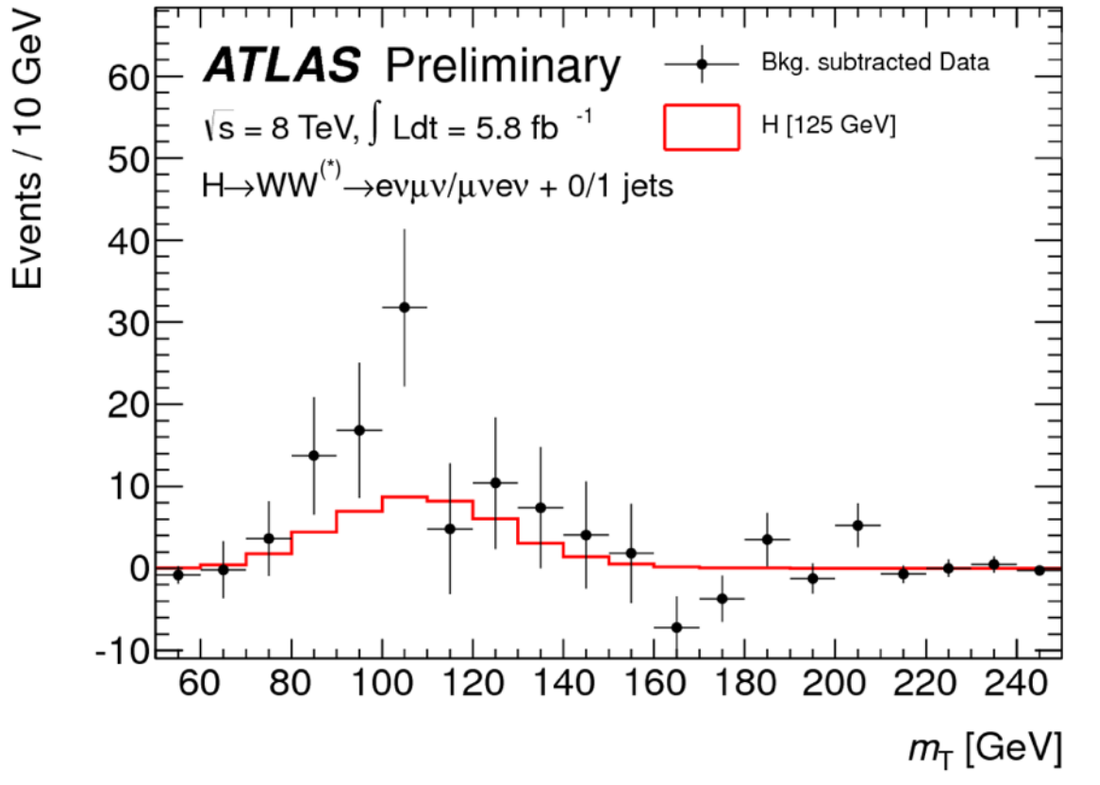
- Discrimination power using angular distributions

EVENTS IN H→ WW→ 2l2ν

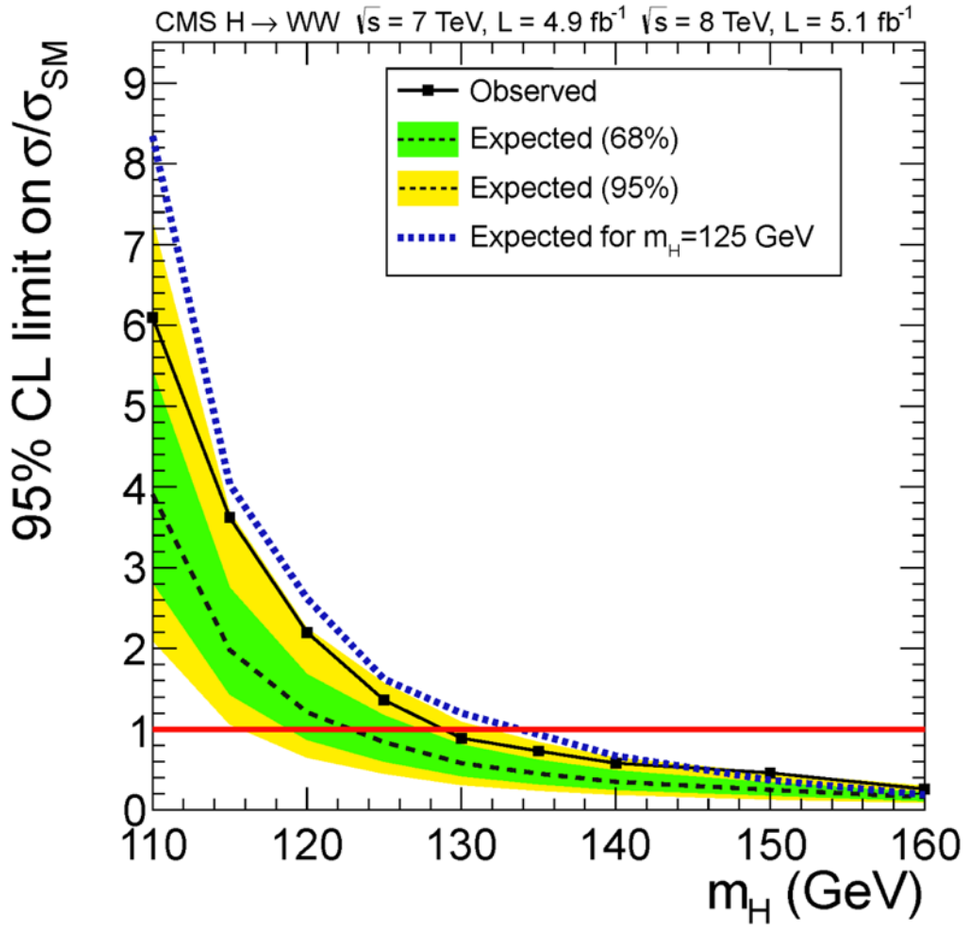
- After kinematical requirements sample dominated by W+W-, top and W+jets
- Further classify events by jet multiplicity and apply b-tag
  - b-tag veto to reduce top contribution
- 0 jet and 1 jet bin: apply topological cuts on mll,Δφll,mT

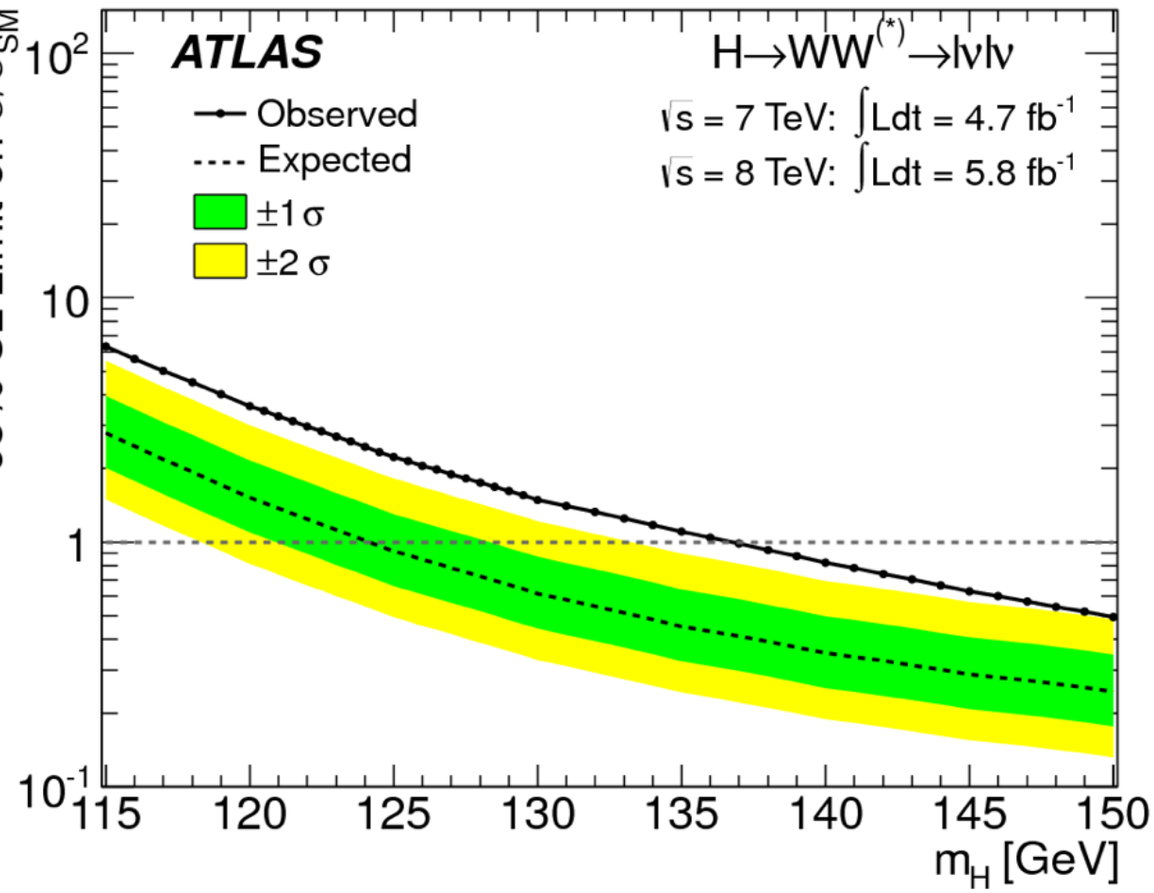






H→ WW

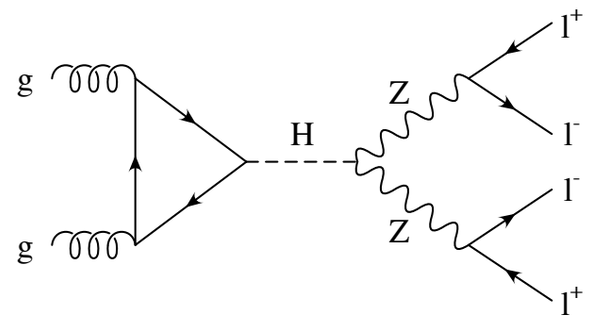




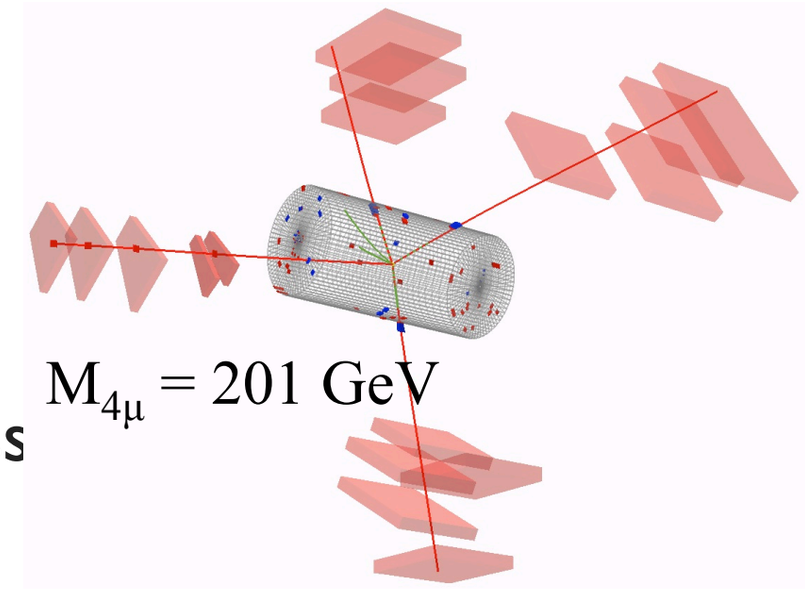
- No visible peak but broad excess compatible with a Standard Model signal

$H \rightarrow ZZ \rightarrow 4l$

- Potentially the cleanest mode for Higgs discovery
  - 2 Z invariant mass
    - very clean with little background from SM
  - narrow Higgs mass peak



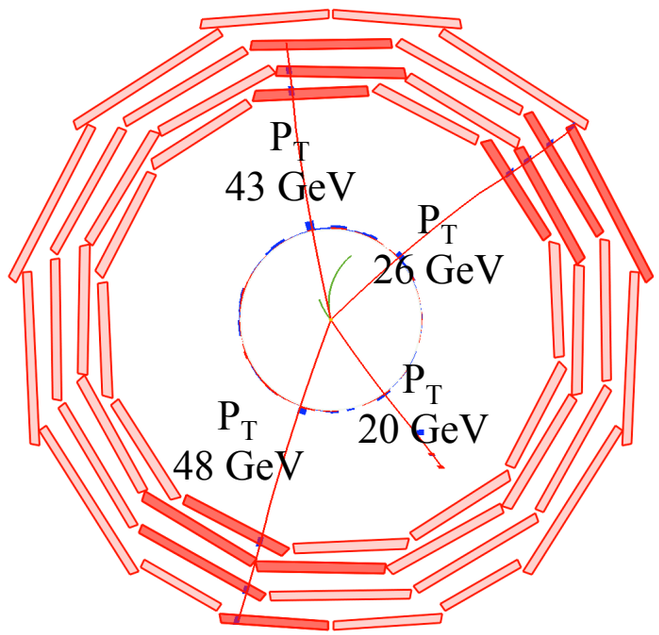
- Small branching fraction $\mathrm{BR}(H \rightarrow \ell^+\ell^-\ell^+\ell^-) \approx 0.15\%$
  - even worse below ZZ threshold $m_H < 2\,M_Z$



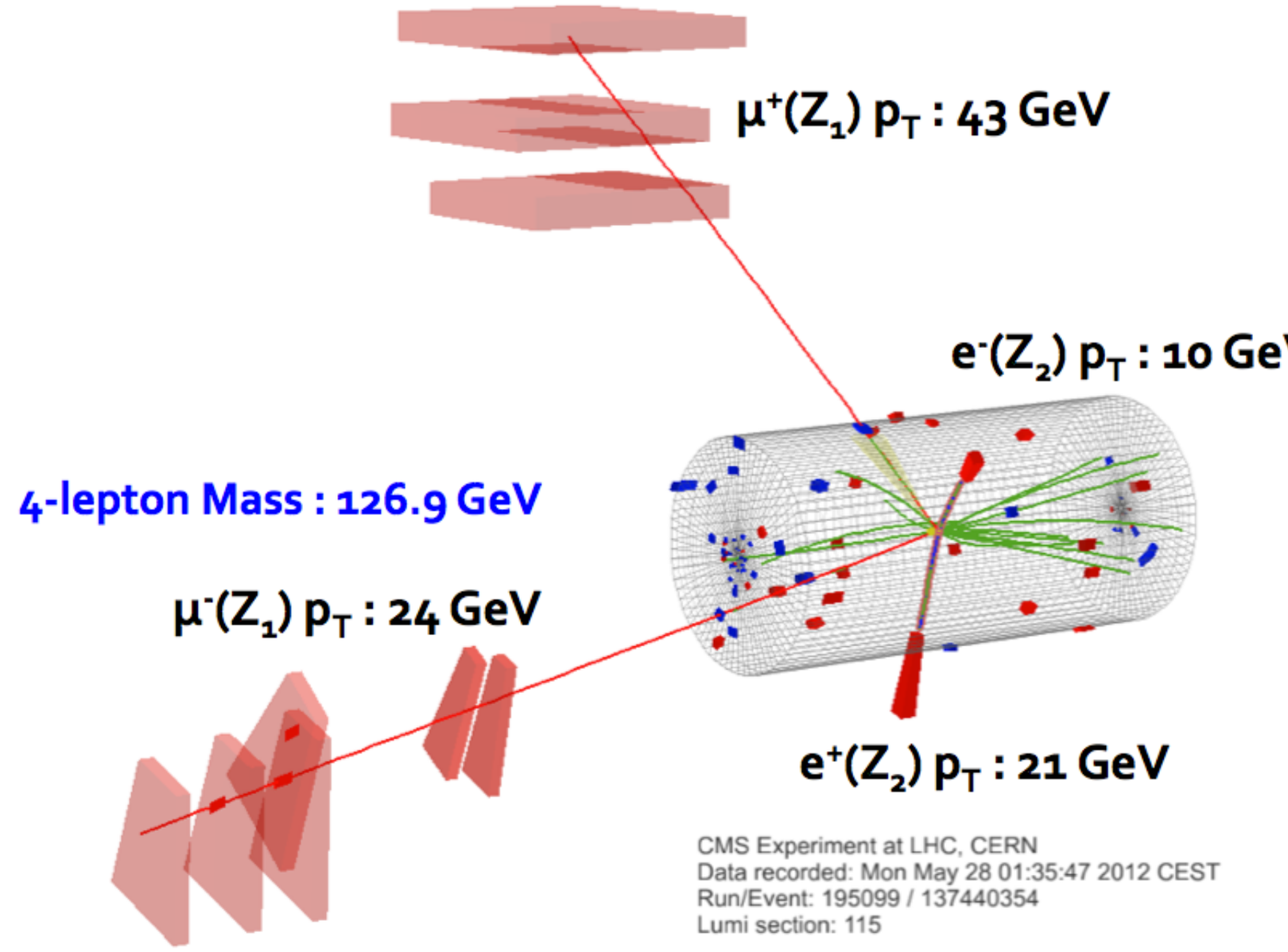
- Limited background mainly from continuum process
  - lepton identification and b-tagging very important

Irreducible

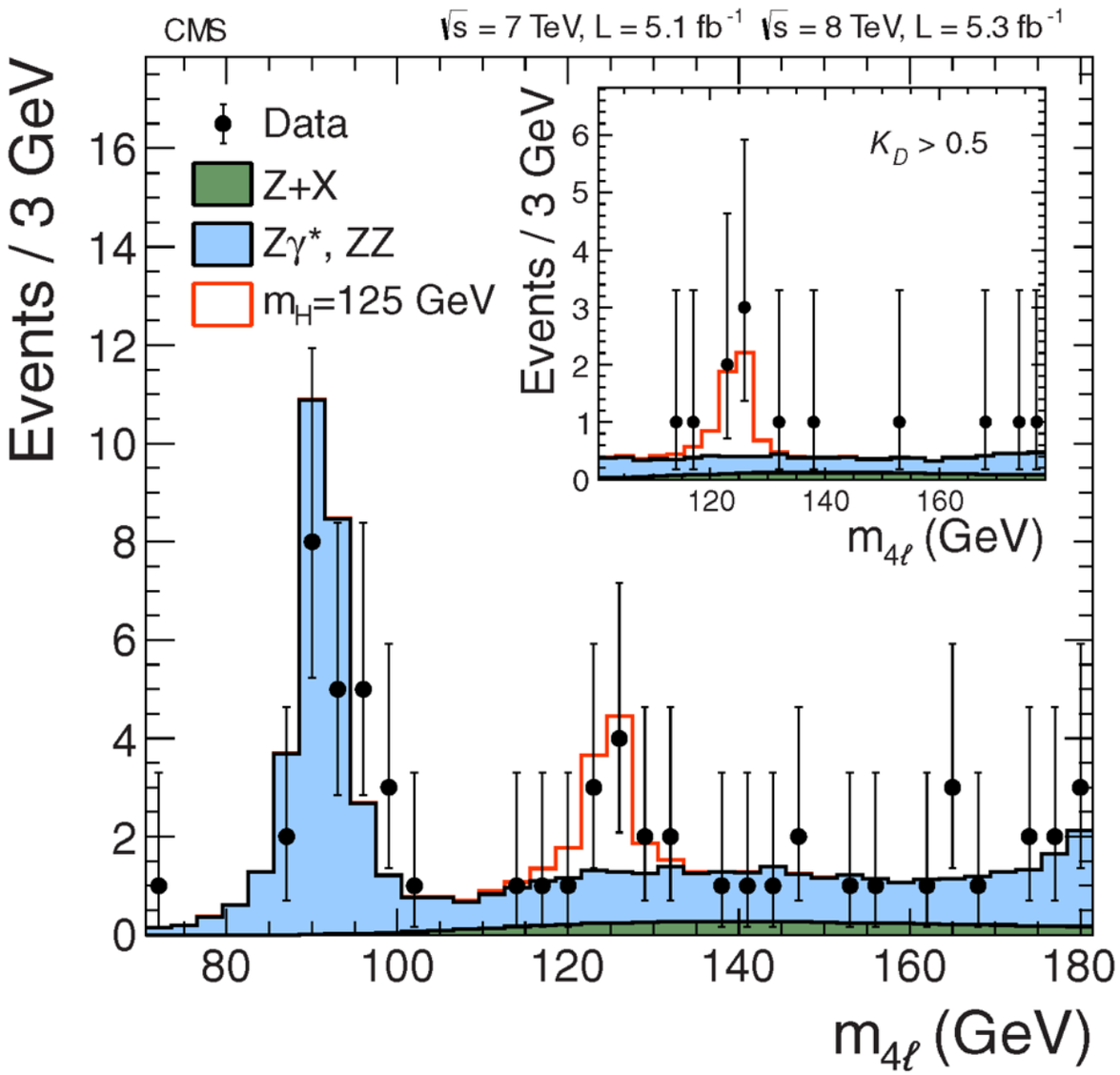
$$q\bar{q} \rightarrow ZZ \rightarrow 4\ell$$
$$gg \rightarrow Zb\bar{b} \rightarrow 2\ell b\bar{b}$$
$$gg \rightarrow Zb\bar{b} \rightarrow 2\ell b\bar{b}$$
$$gg, q\bar{q} \rightarrow t\bar{t}$$
$$q\bar{q} \rightarrow WZ$$
$$q\bar{q} \rightarrow Z \text{ inclusive}$$

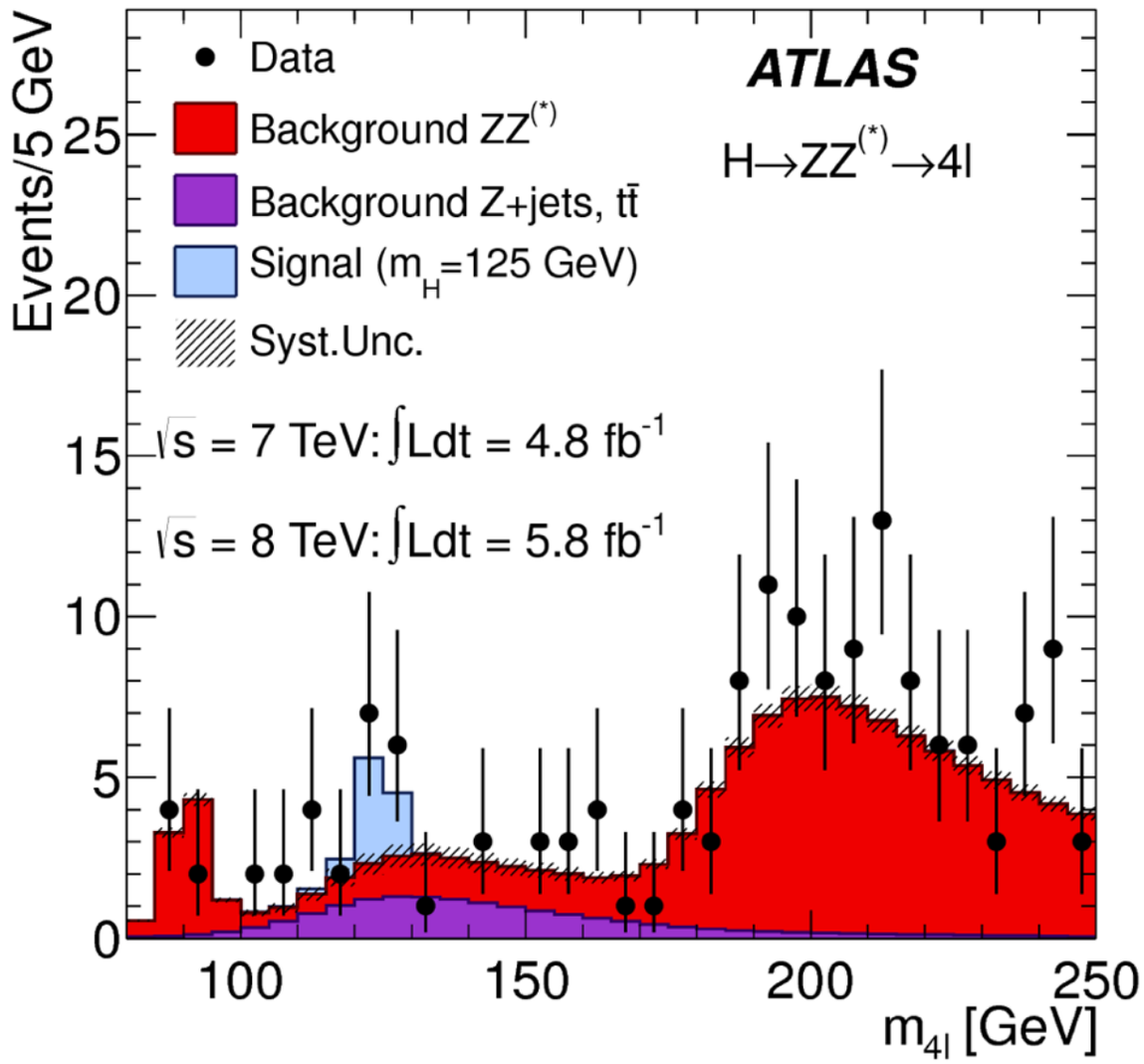


EXAMPLE OF ZZ EVENT



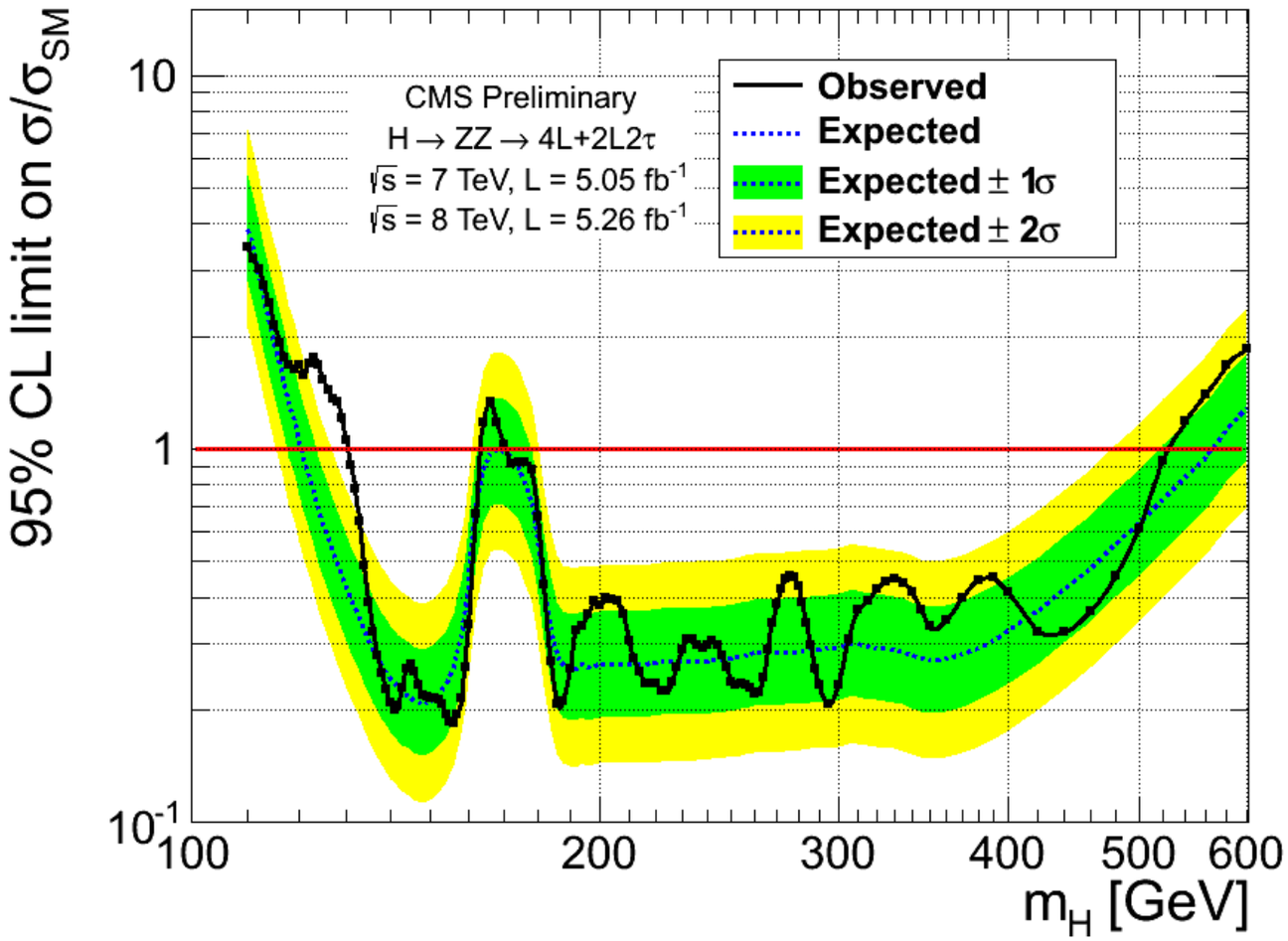
ZZ Mass Spectrum

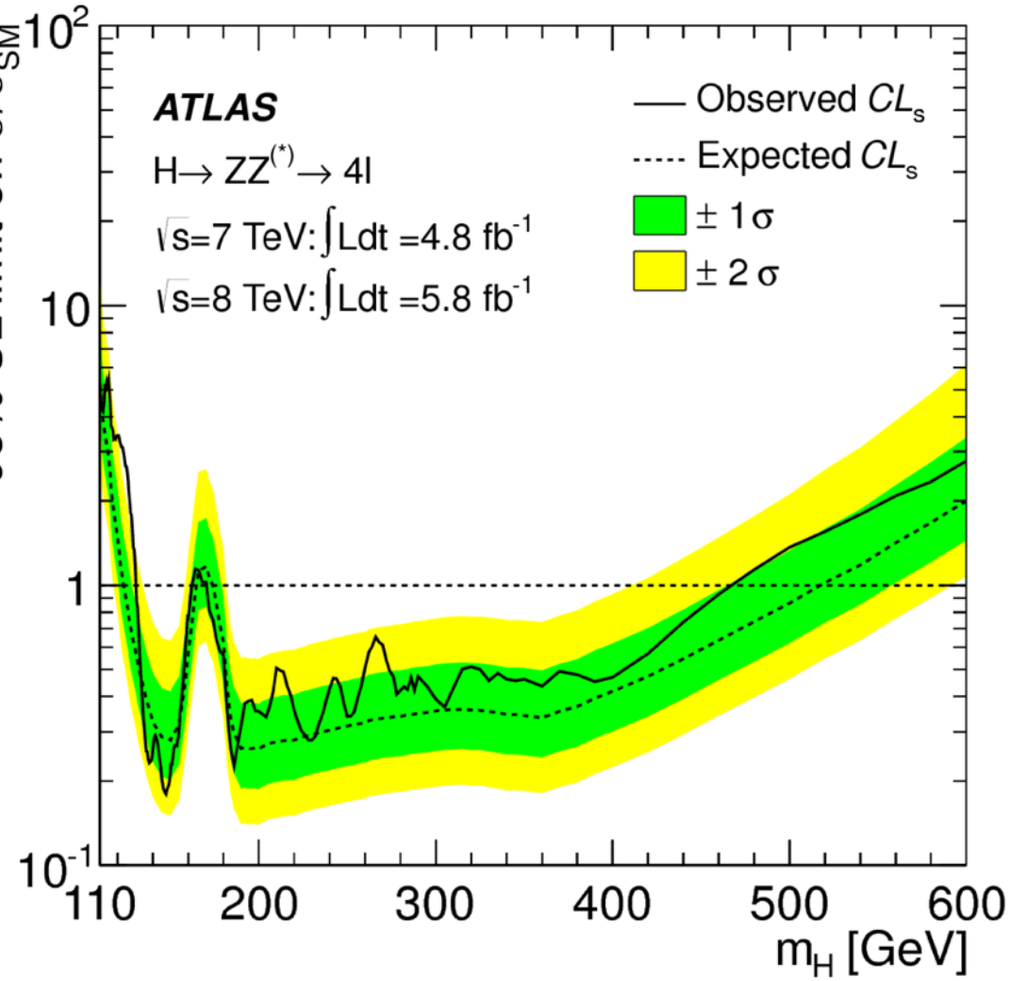




- Prominent excess observed at 125-126 GeV by both experiments

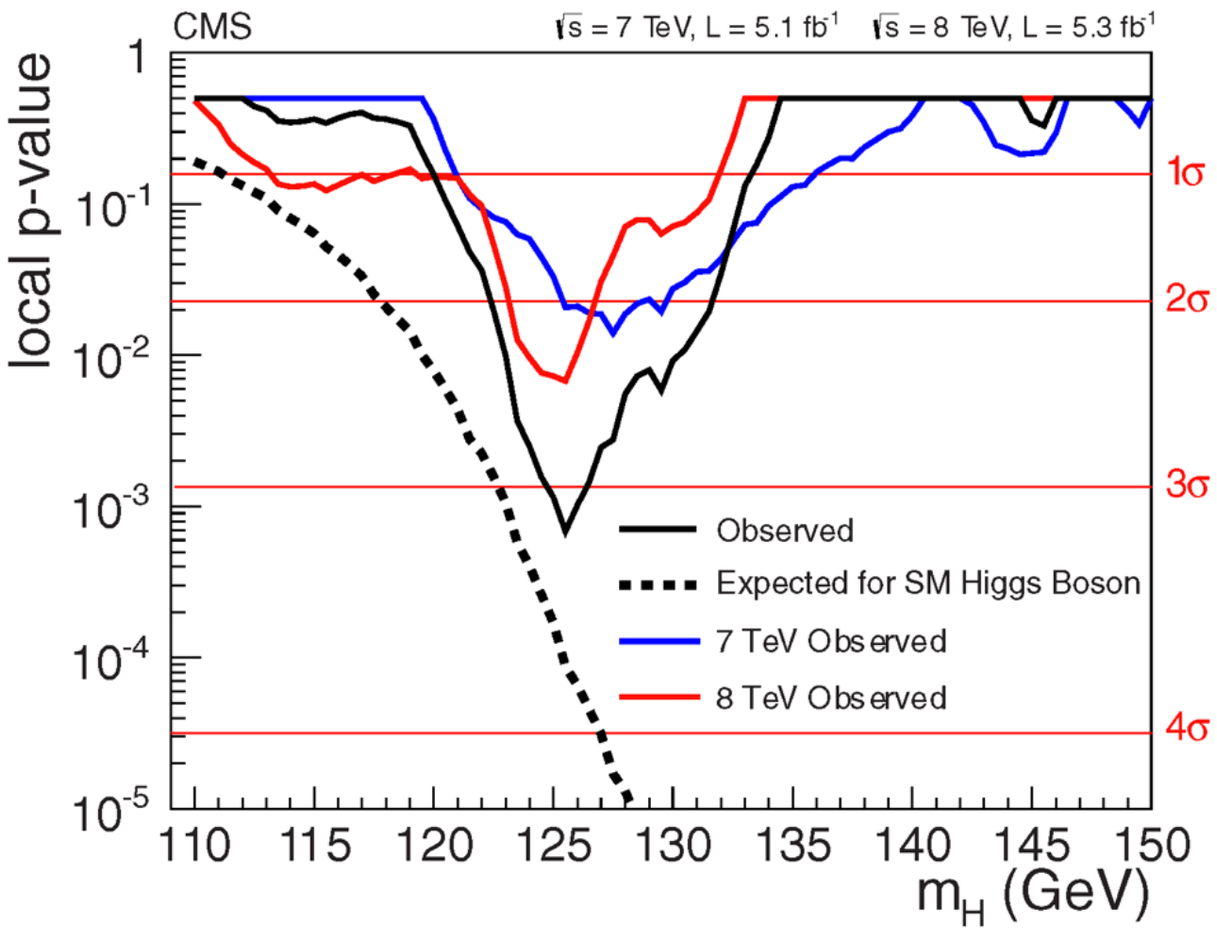
H→ ZZ→ 4L: EXCLUSION LIMITS

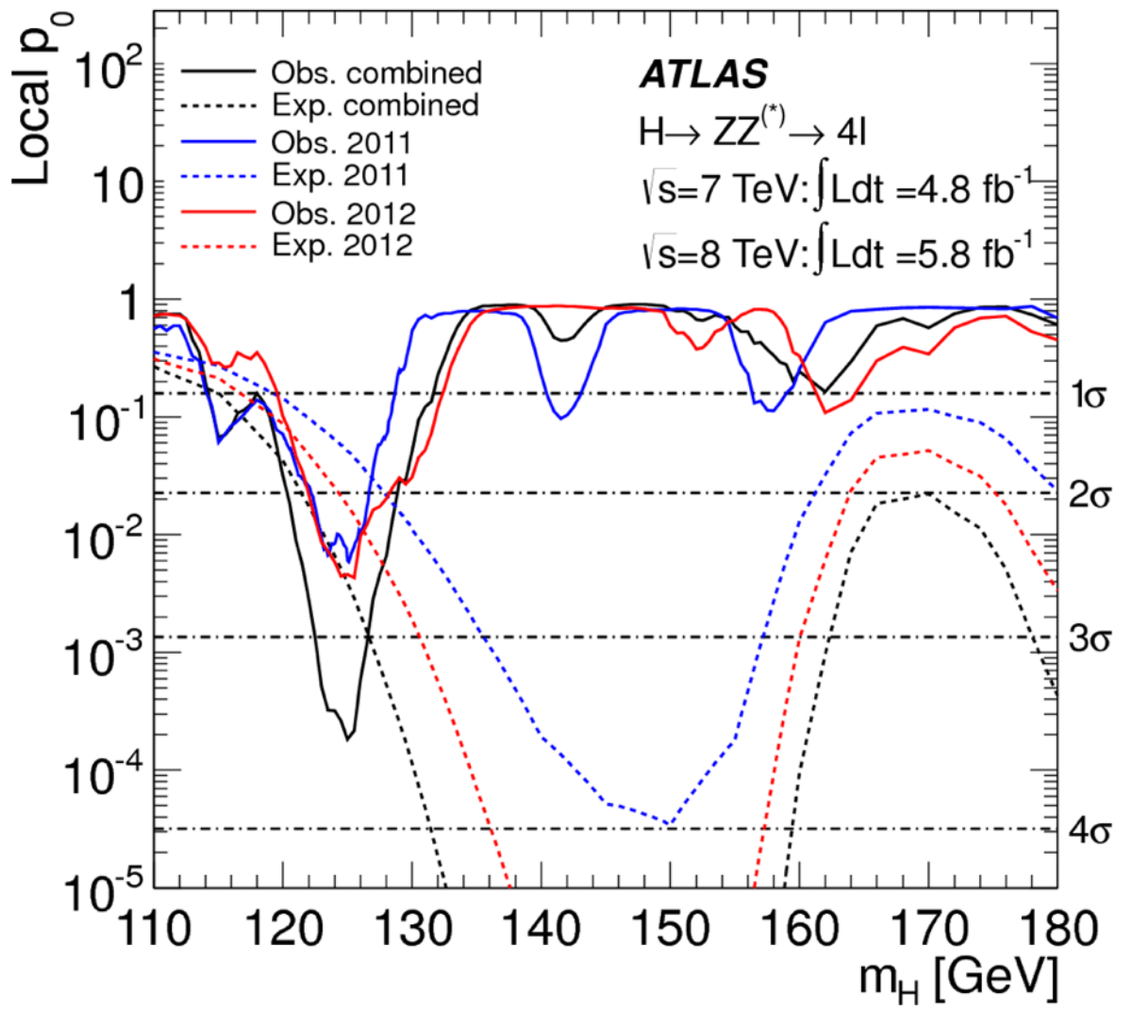




- Exclusion of almost all mass regions except where excess present

MAGNITUDE OF OBSERVED SIGNAL

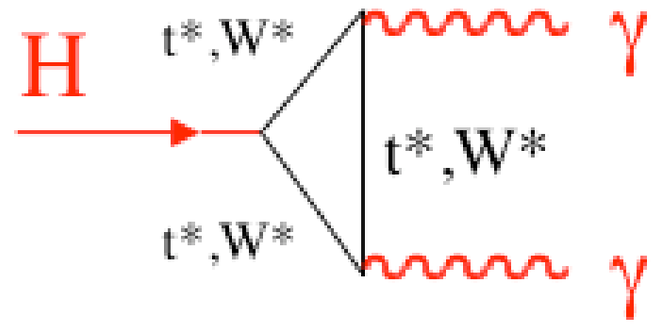




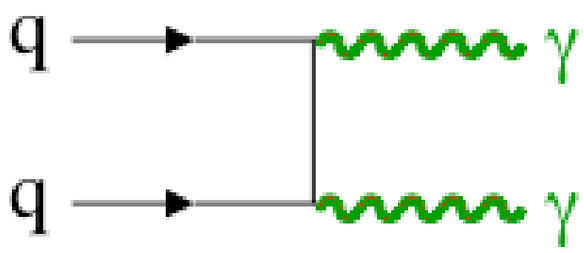
- CMS: strength at 125.5 GeV: $\mu = \sigma/\sigma_{SM} \sim 0.7$
- ATLAS: strength at 126 GeV: $\mu = \sigma/\sigma_{SM} \sim 1.2$

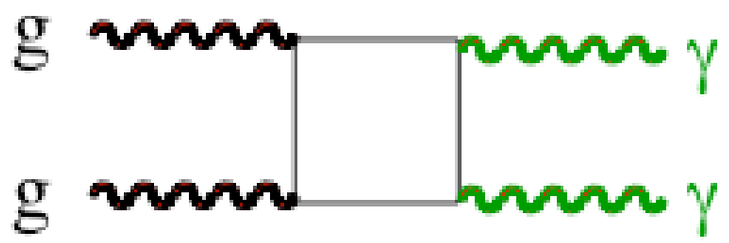
$H \rightarrow \gamma\gamma$

- Signal
  - nice mass peak
  - energy and angular resolution are critical ingredients
  - Selection: isolated high p_T photons

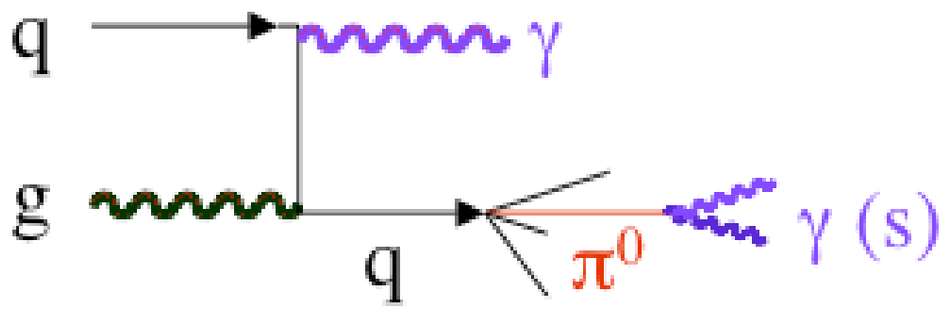


- Irreducible background: direct production of di-photon events in Standard Model
  - Any signal selection selects also these events
  - no peak in invariant mass but lots and lots of then

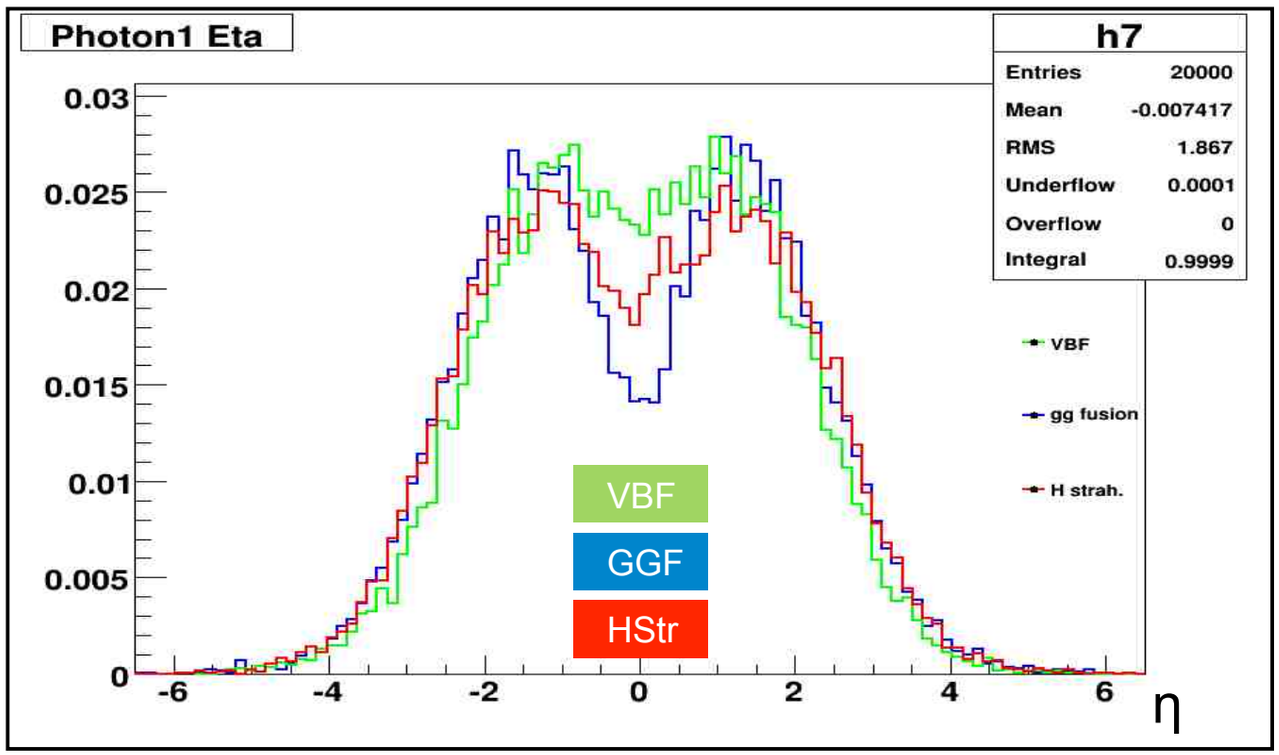


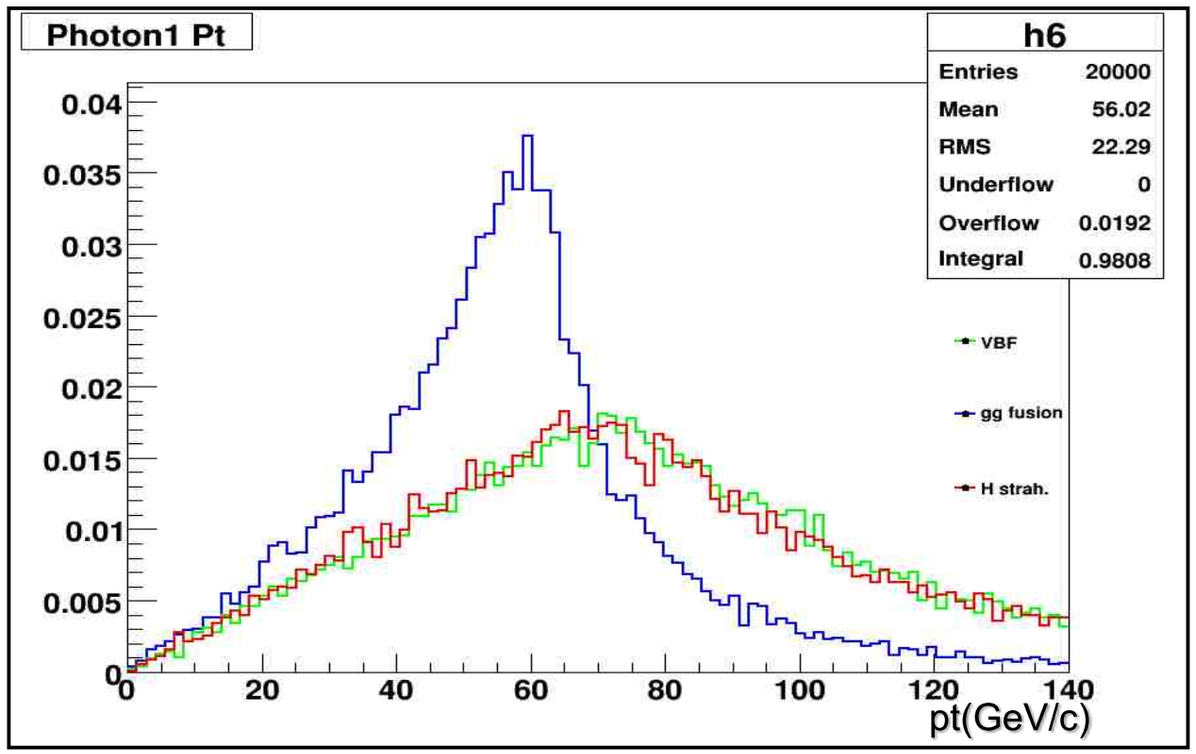


- Reducible background
  - gamma + jet: jet mis-identified as photon
  - di-jet: two jets with misidentified photons



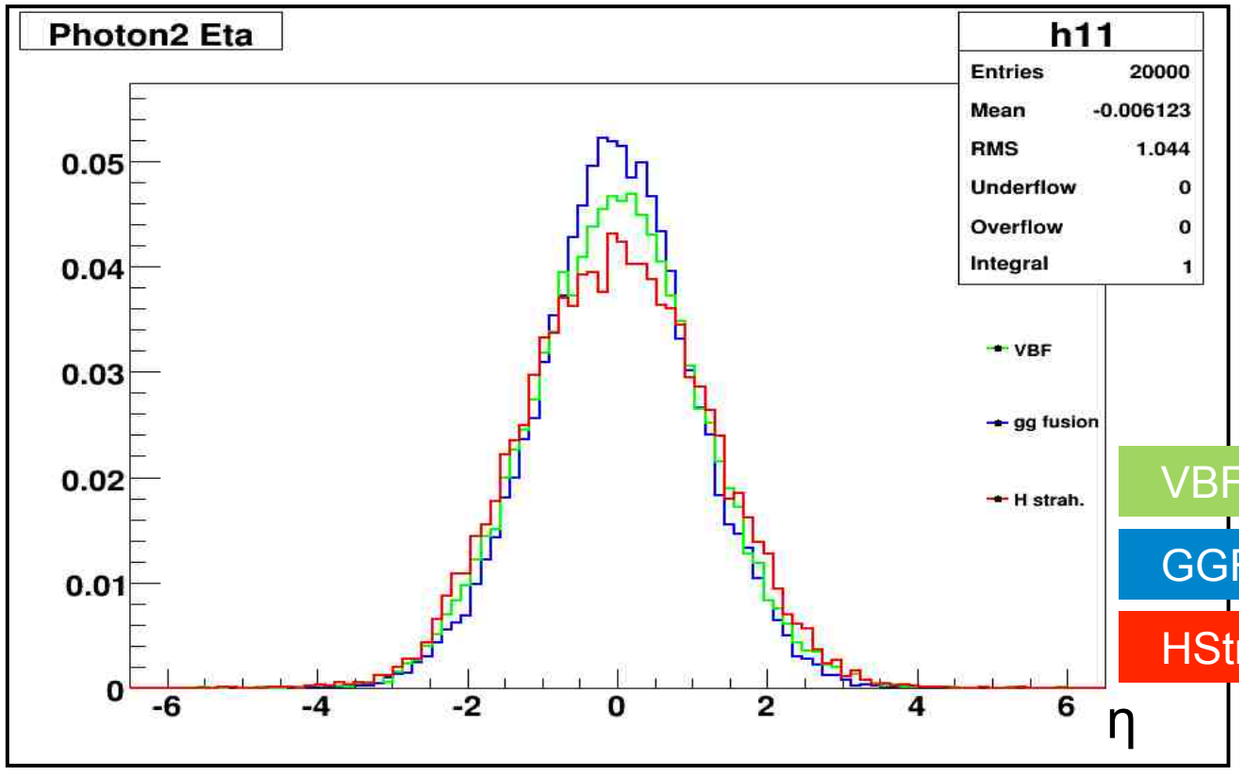
HIGGS DAUGHTER WITH HIGHER PT





- Higher p_T for VBF and Higgs-strahlung
  - less background from standard model: not many SM particles decaying in high pt photons!
- Unfortunately these are also the modes much smaller than gluon-gluon fusion

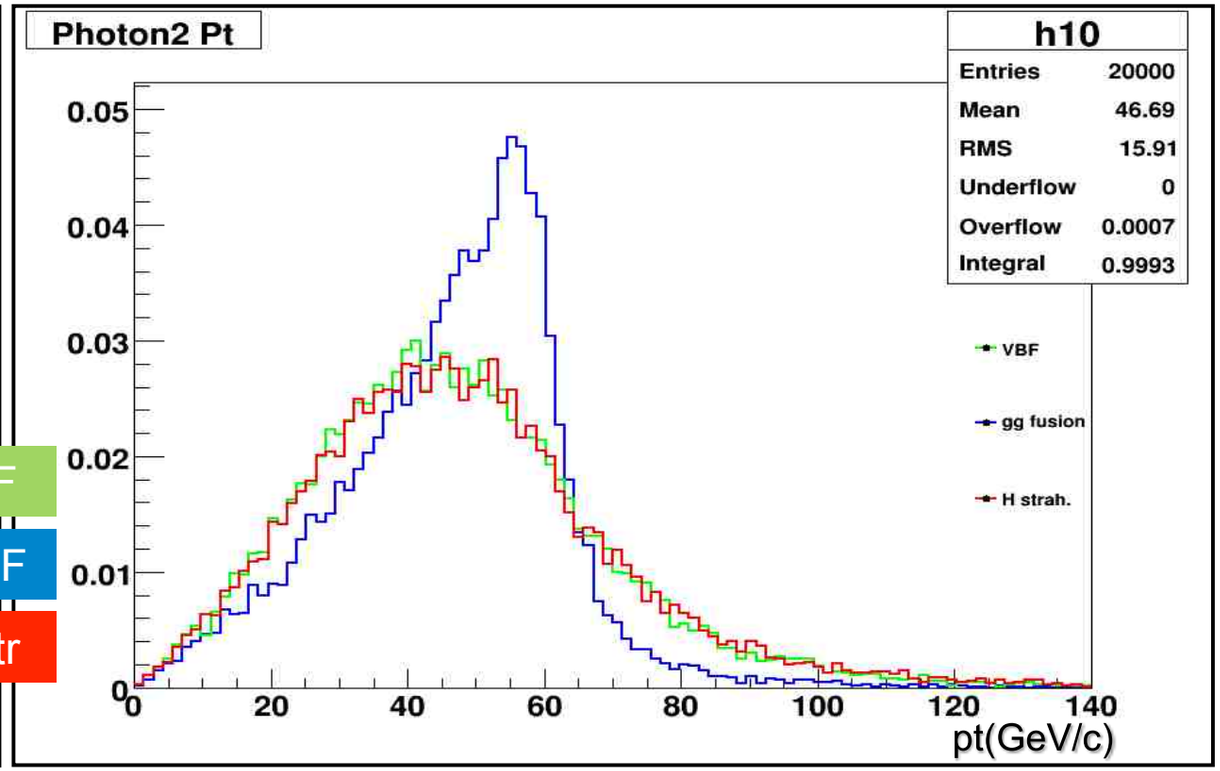
HIGGS DAUGHTER WITH LOWER PT



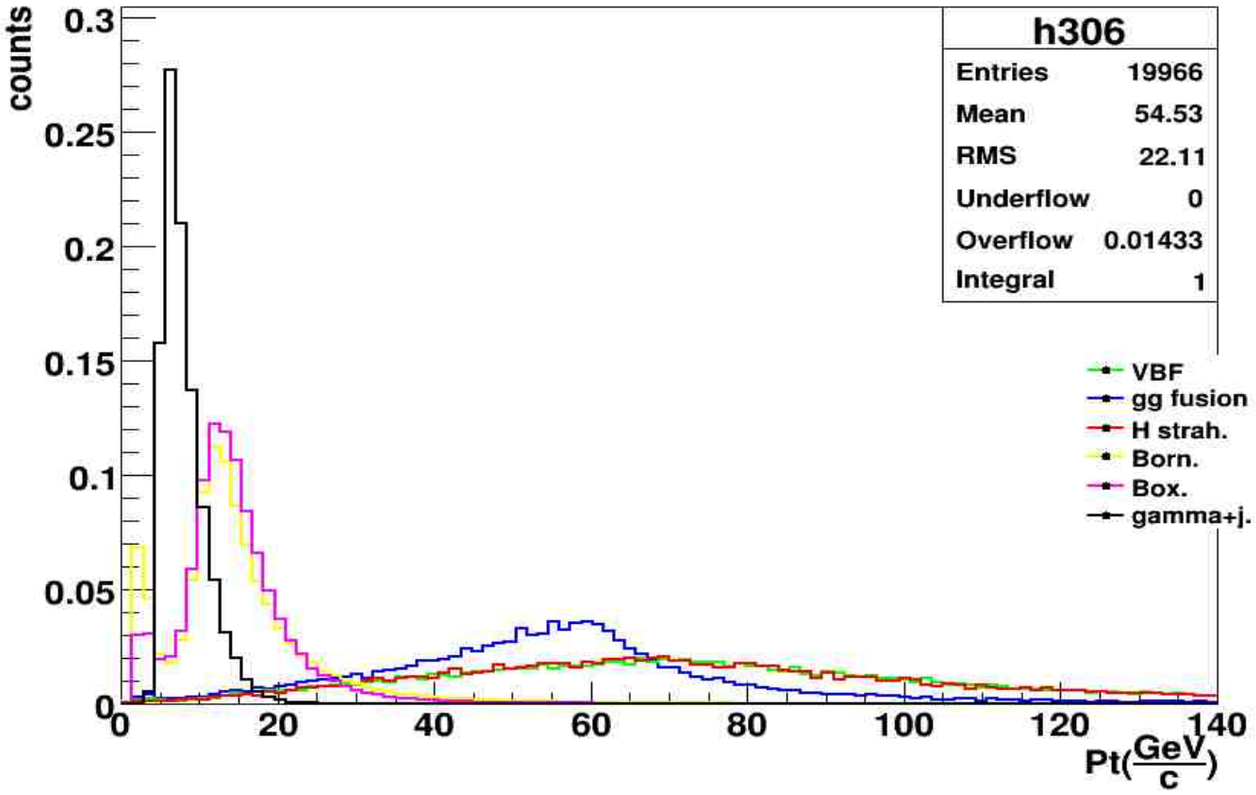
VBF

GGF

HStr

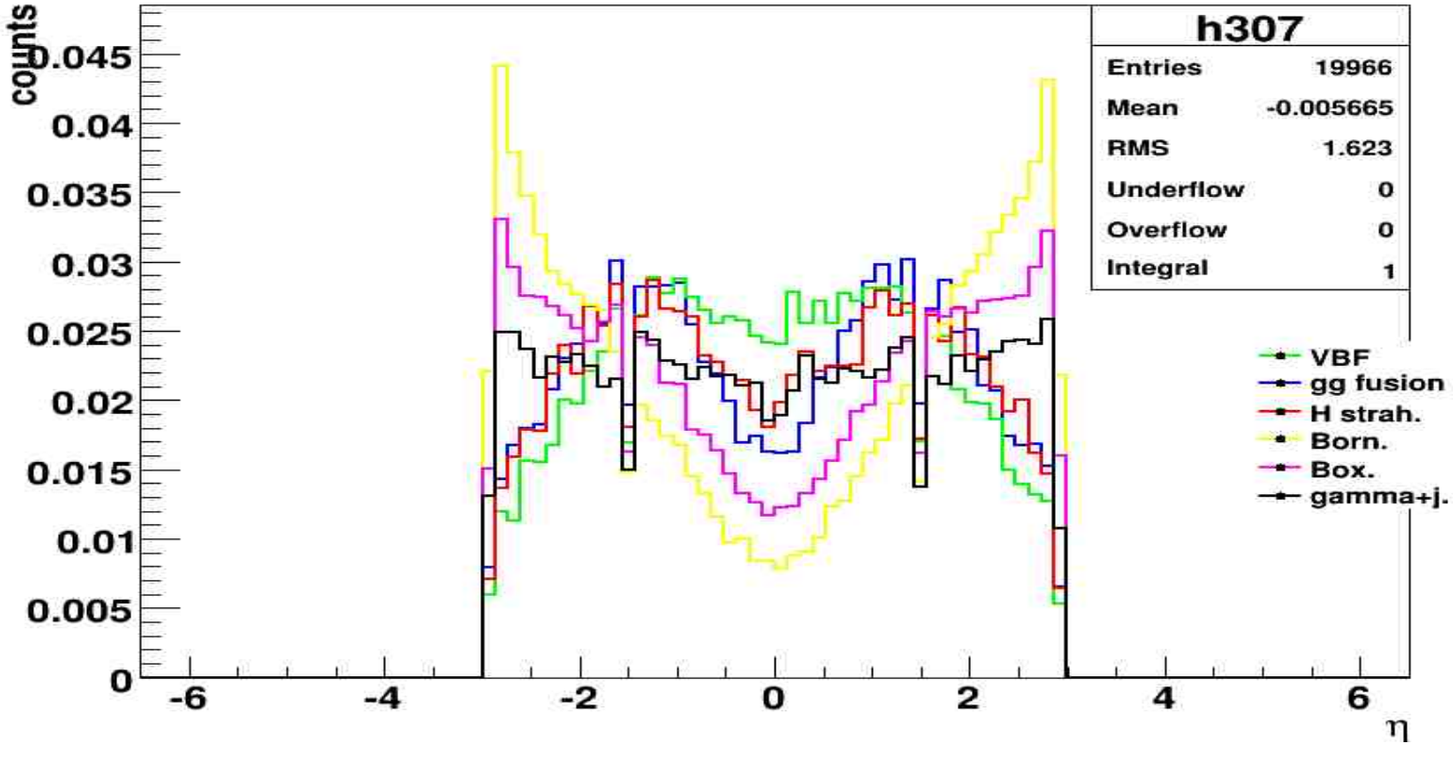


IRREDUCIBLE BACKGROUND



VBF
GGF
HStr
Born
Box
γ+j

- background processes have spectrum more similar to photons from gluon-gluon fusion
  - irreducible background



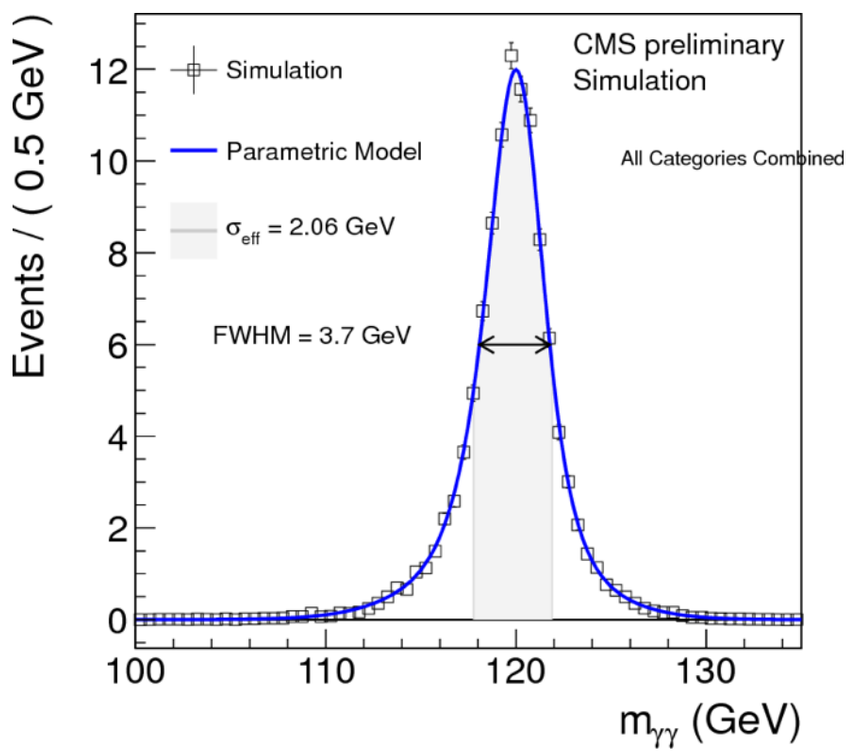
ANALYSIS STRATEGY

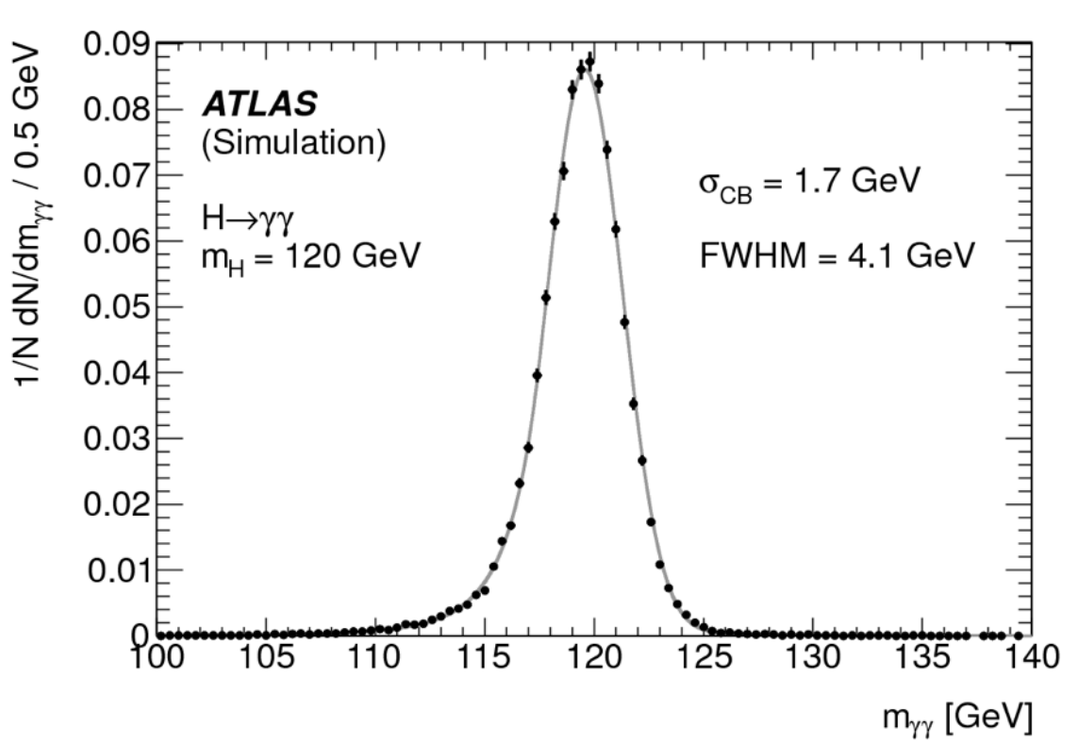
STEP	CRITICAL ISSUES
1) two isolated photons with large transverse momentum	• isolation to reject γ+jet and QCD background • determine efficiency from data
2) di-photon mass reconstruction $m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{\gamma\gamma})}$ $\frac{\sigma_m}{m} = \frac{1}{2}\sqrt{\left(\frac{\sigma_1}{E_1}\right)^2 + \left(\frac{\sigma_2}{E_2}\right)^2 + \left(\frac{\sigma_\theta}{\tan\theta/2}\right)^2}$	• vertex determination in presence of multiple interactions pile-up (PU) • energy scale and resolution • At θ=90° 15 mrad of angular resolution equivalent to 1% of energy resolution!
3) signal extraction	• event categories to maximize sensitivity • background shape

Mass Resolution

- In both detectors m(γγ) resolution depends on photon kinematics, conversion probability, and pseudorapidity
- CMS performs better in central region, ATLAS in forward
- Overall performance for Higgs signal quite similar

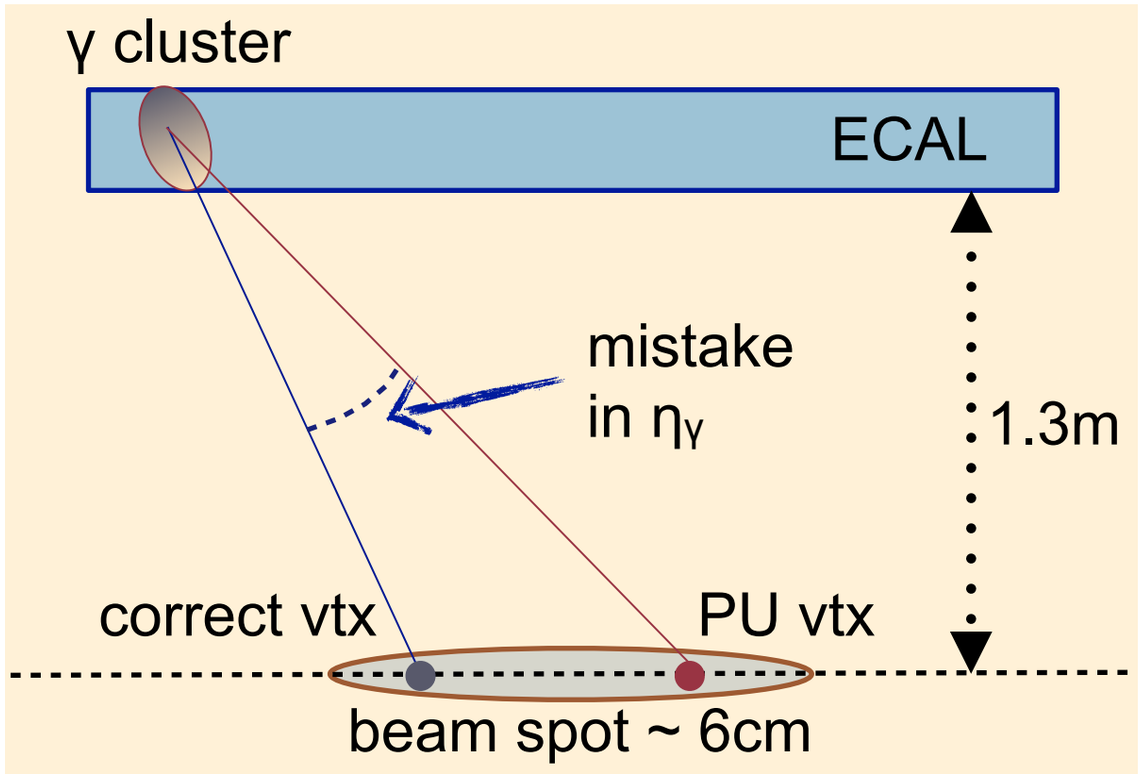
CMS (after cut on MVA)		ATLAS (2011 analysis)	
best resolution cat.	worst resolution cat.	best resolution cat.	worst resolution cat.
FWMH ~ 2.5GeV	FWMH ~ 5.5GeV	FWMH~3.3GeV	FWMH~5.9GeV

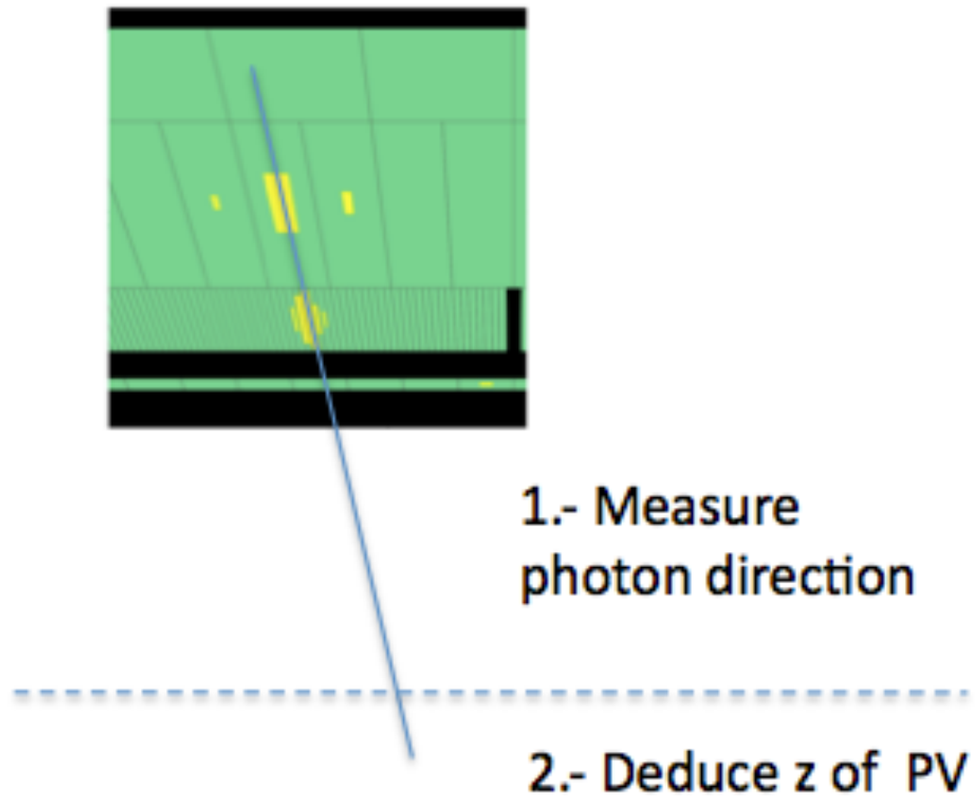




VERTEX DETERMINATION

- large pile-up conditions
  - <NPU>~20
- di-photon invariant mass resolution affected by vertex choice
- vertex determination based on
  - CMS: tracks belonging to vertex combined with di-photon kinematics and conversion-track finding
    - performance cross-checked using $Z \rightarrow \mu^+\mu^-$ after removing muon tracks
  - ATLAS: direction from calorimeter segmentation. Also use of conversions
    - monitored with electrons and events with two gammas



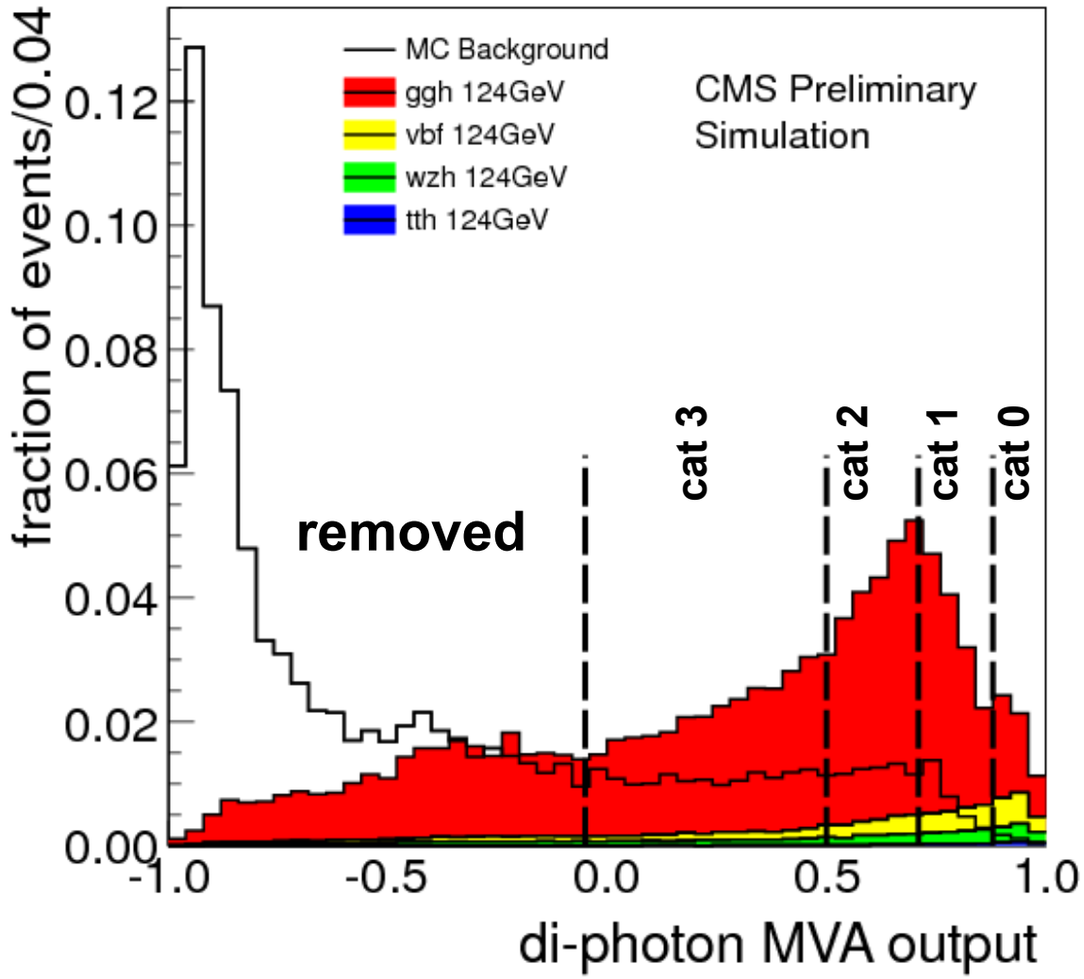


CATEGORIES OF EVENTS

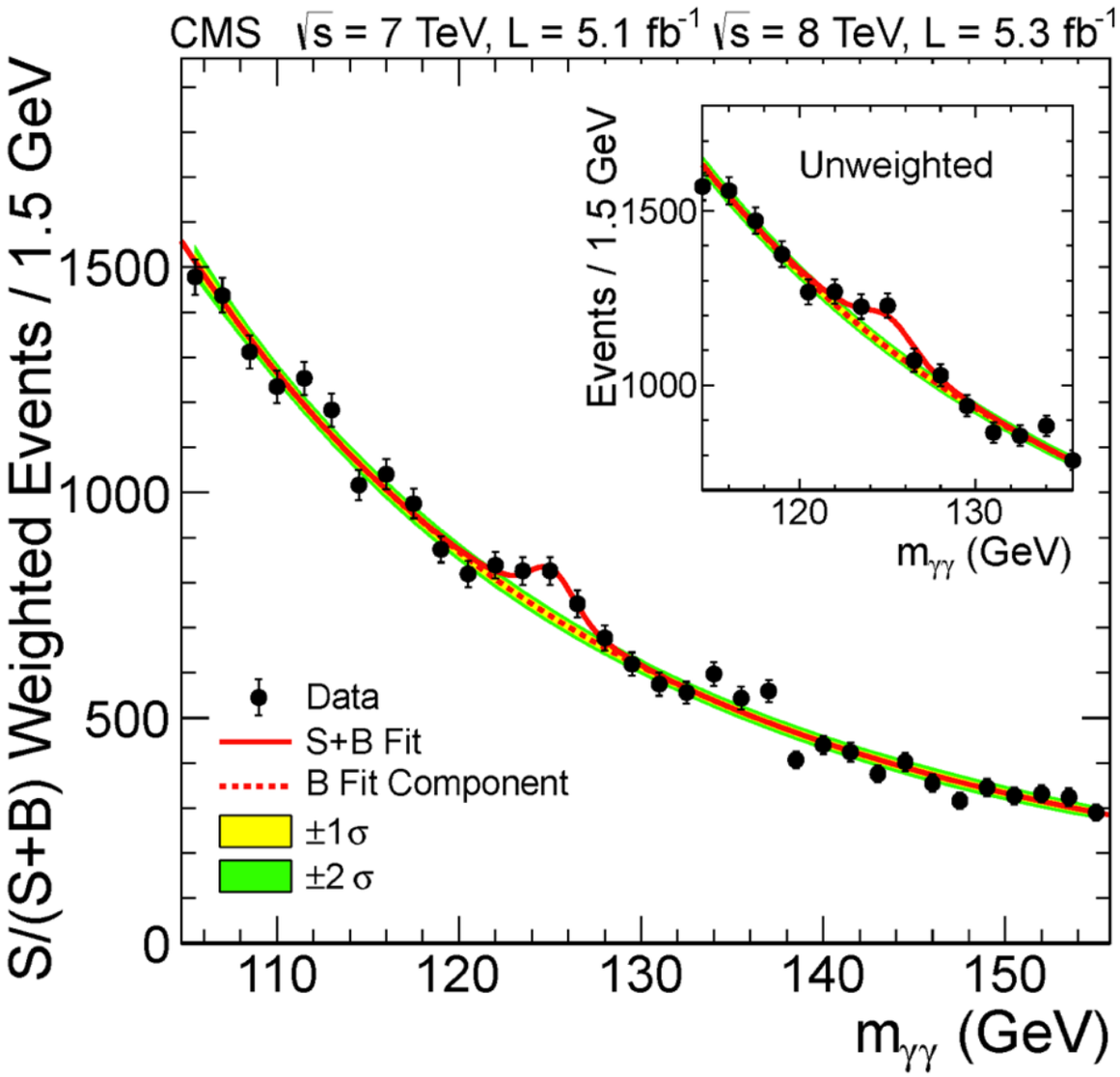
- Event categories to
  - maximize statistical power
  - exploit differences in kinematics between signal and backgrounds

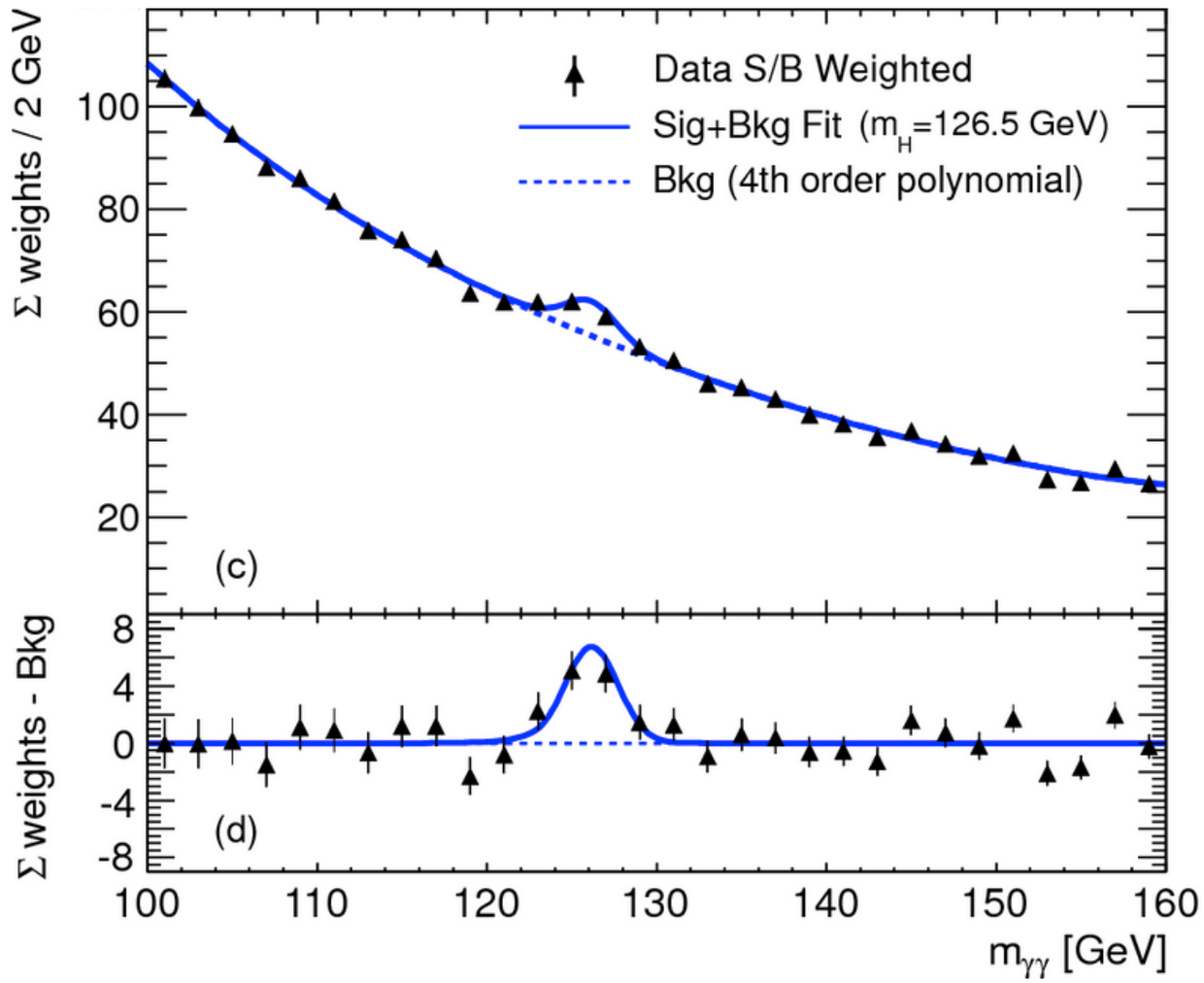
- CMS: 4 categories based on diphoton MVA (multi variate analysis) output based on
  - diphoton mass resolution
  - photon ID (γ shape, isolation)
  - kinematics
- ATLAS: 9 categories based on
  - kinematics and conversions

- Background from data
  - fit to the γγ invariant mass
  - use of polynomials (3rd-5th order)



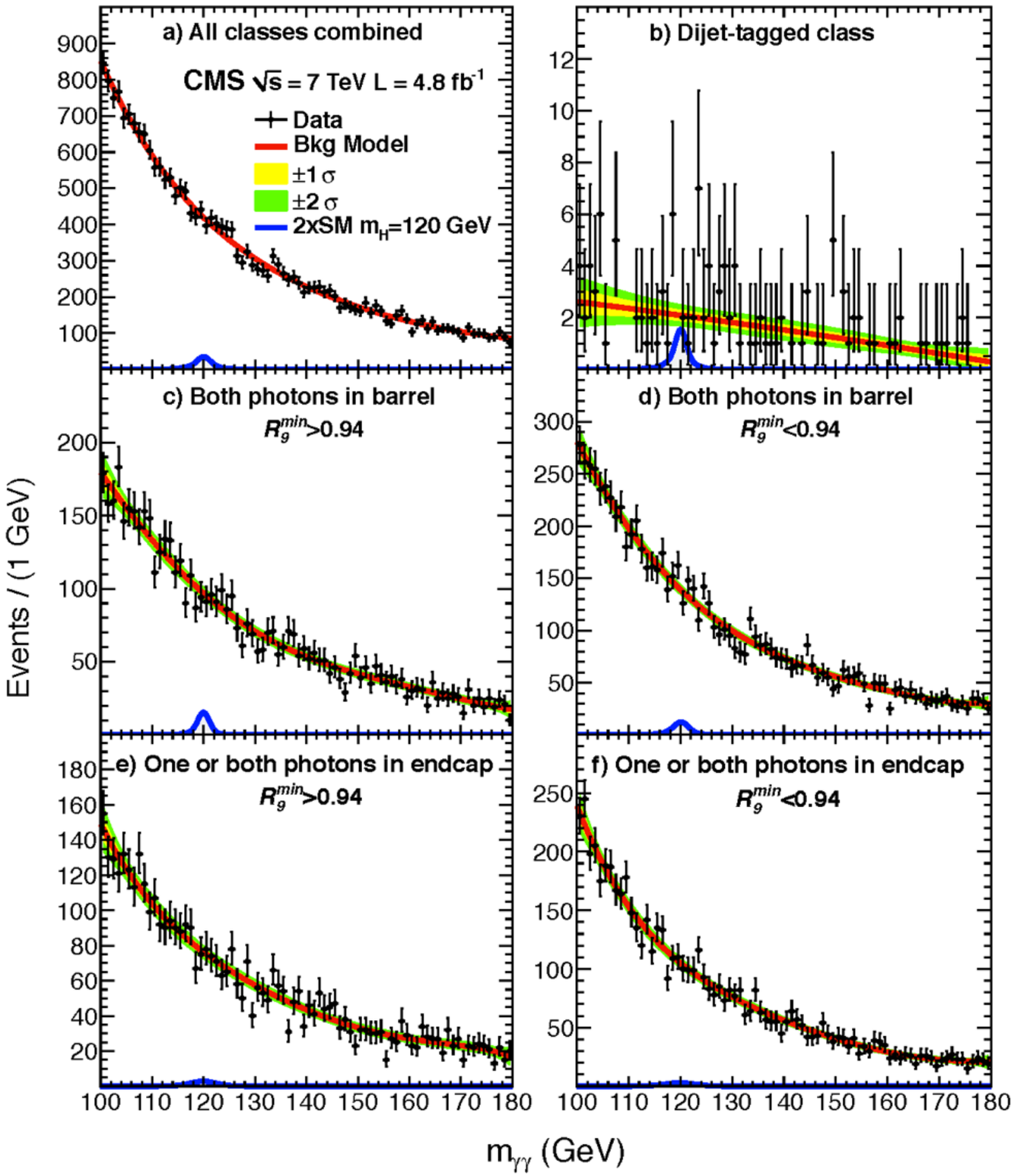
H → γγ: Mass Spectra



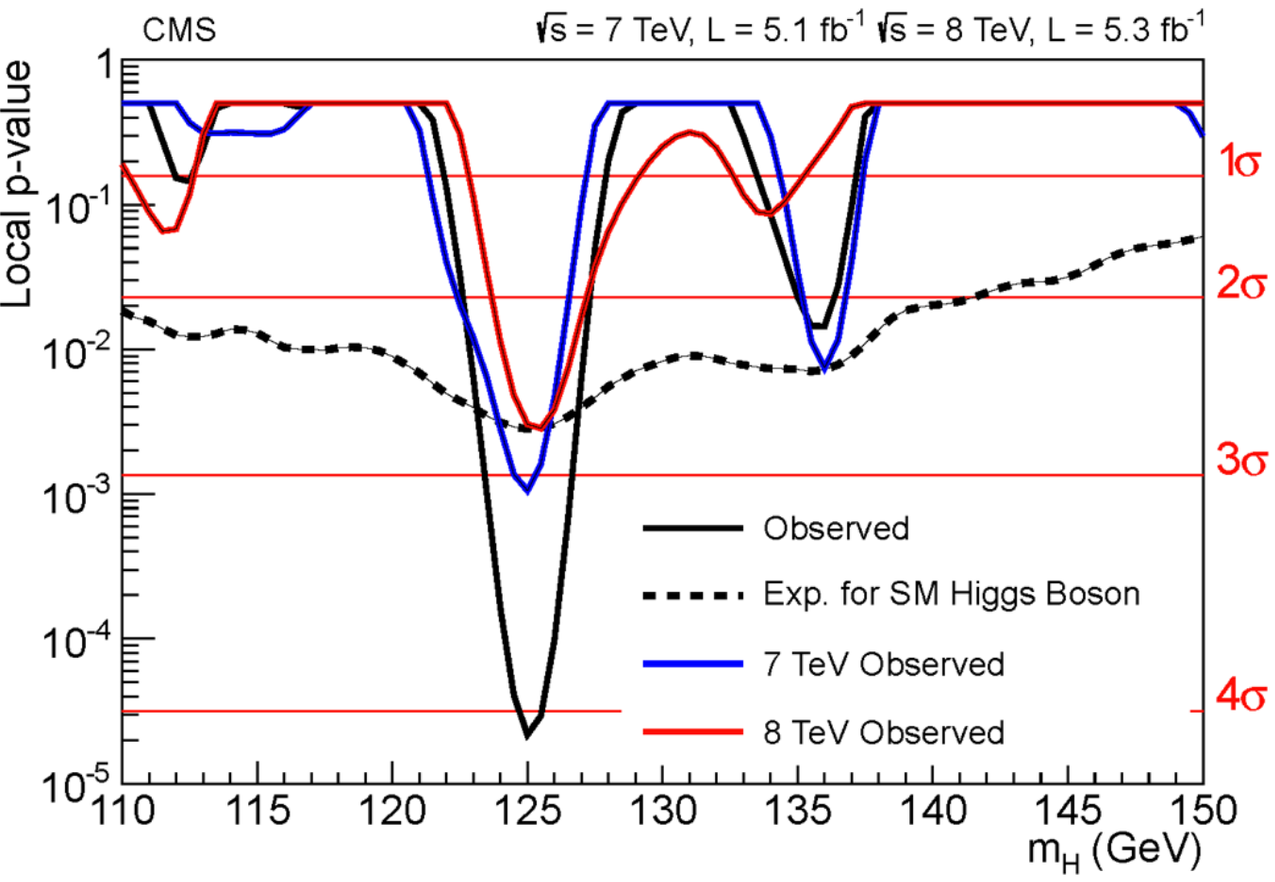


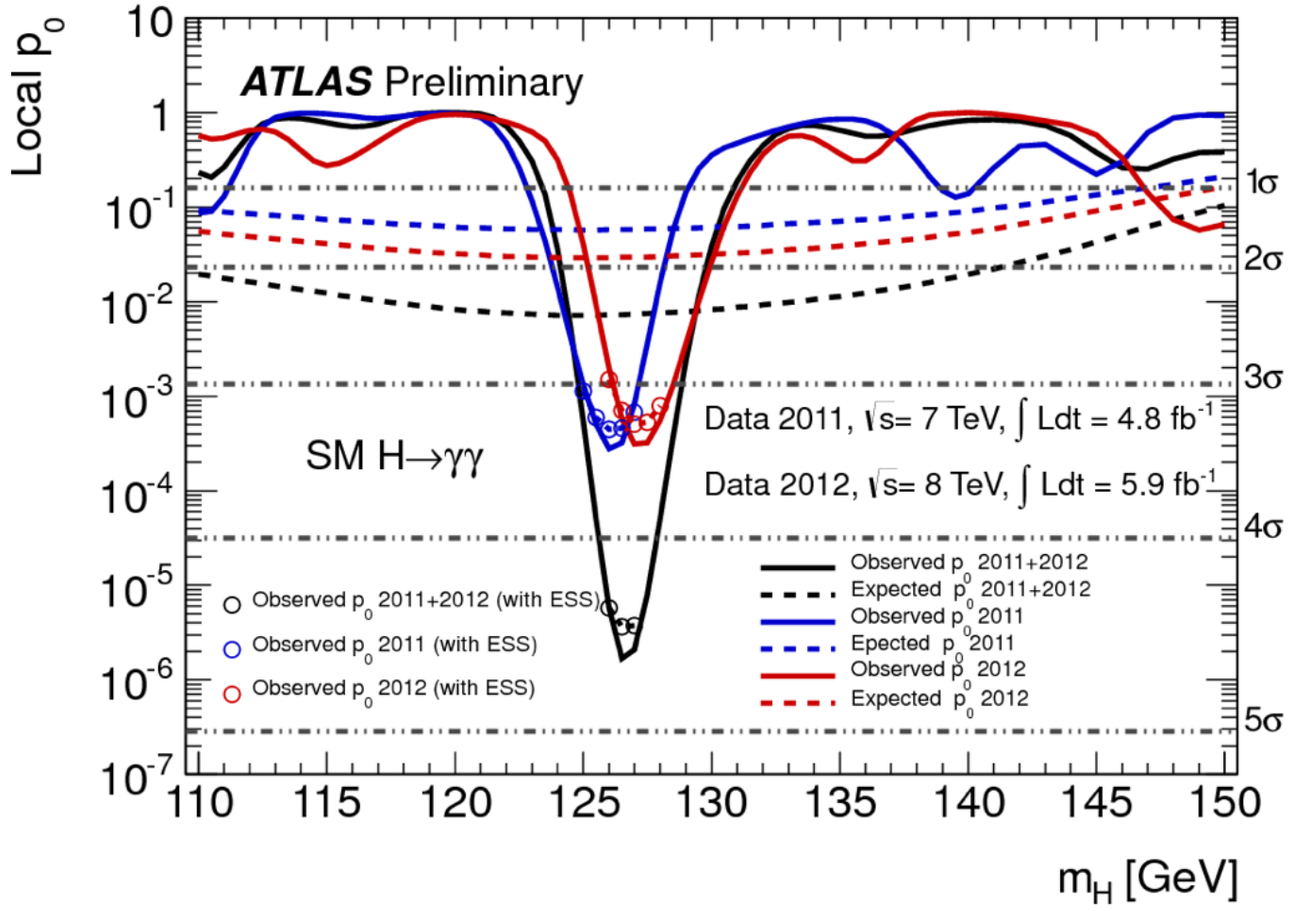
- Improved visualization of events by weighting events from each category
  - CMS: weight S/(S+B)
  - ATLAS: S/B
- Same events by cleaner categories provide larger weight in the histogram

IMPORTANCE OF INDIVIDUAL CATEGORIES

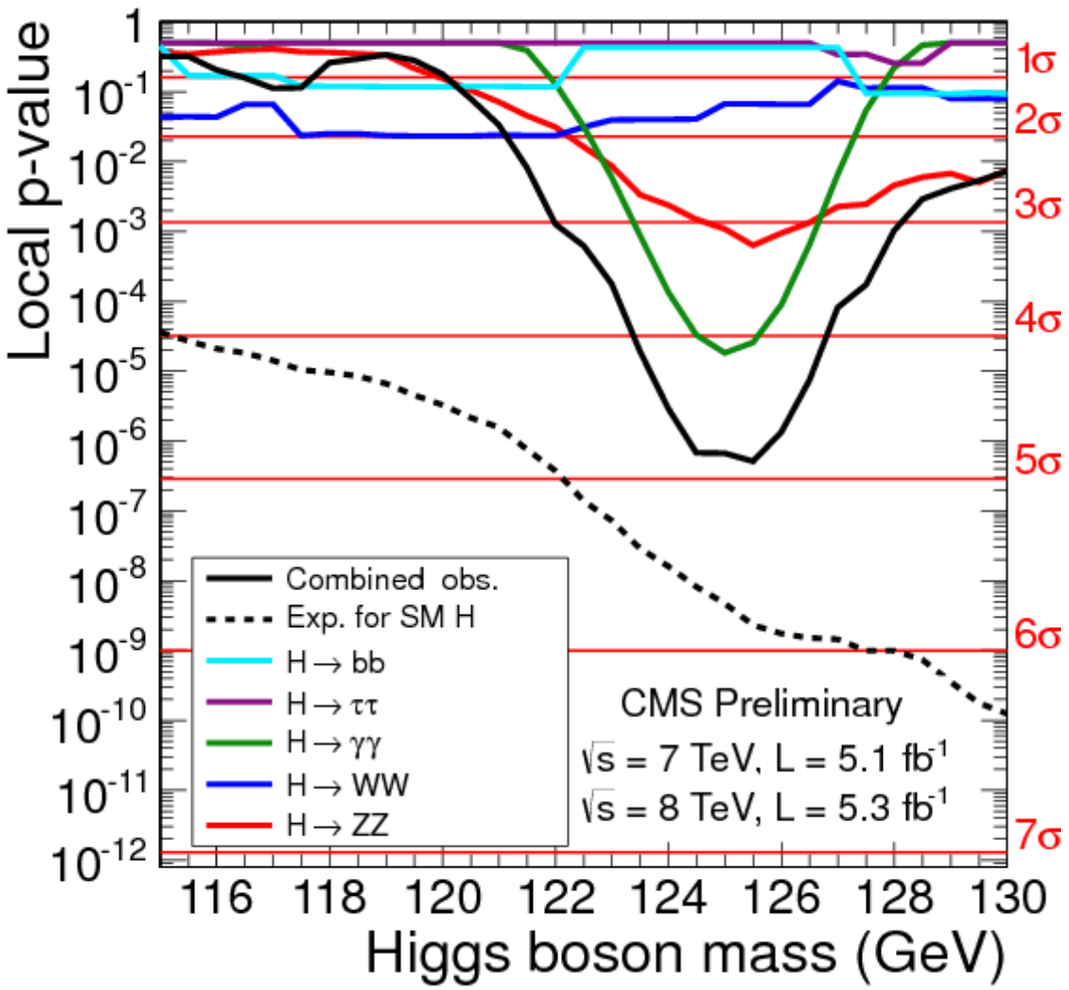


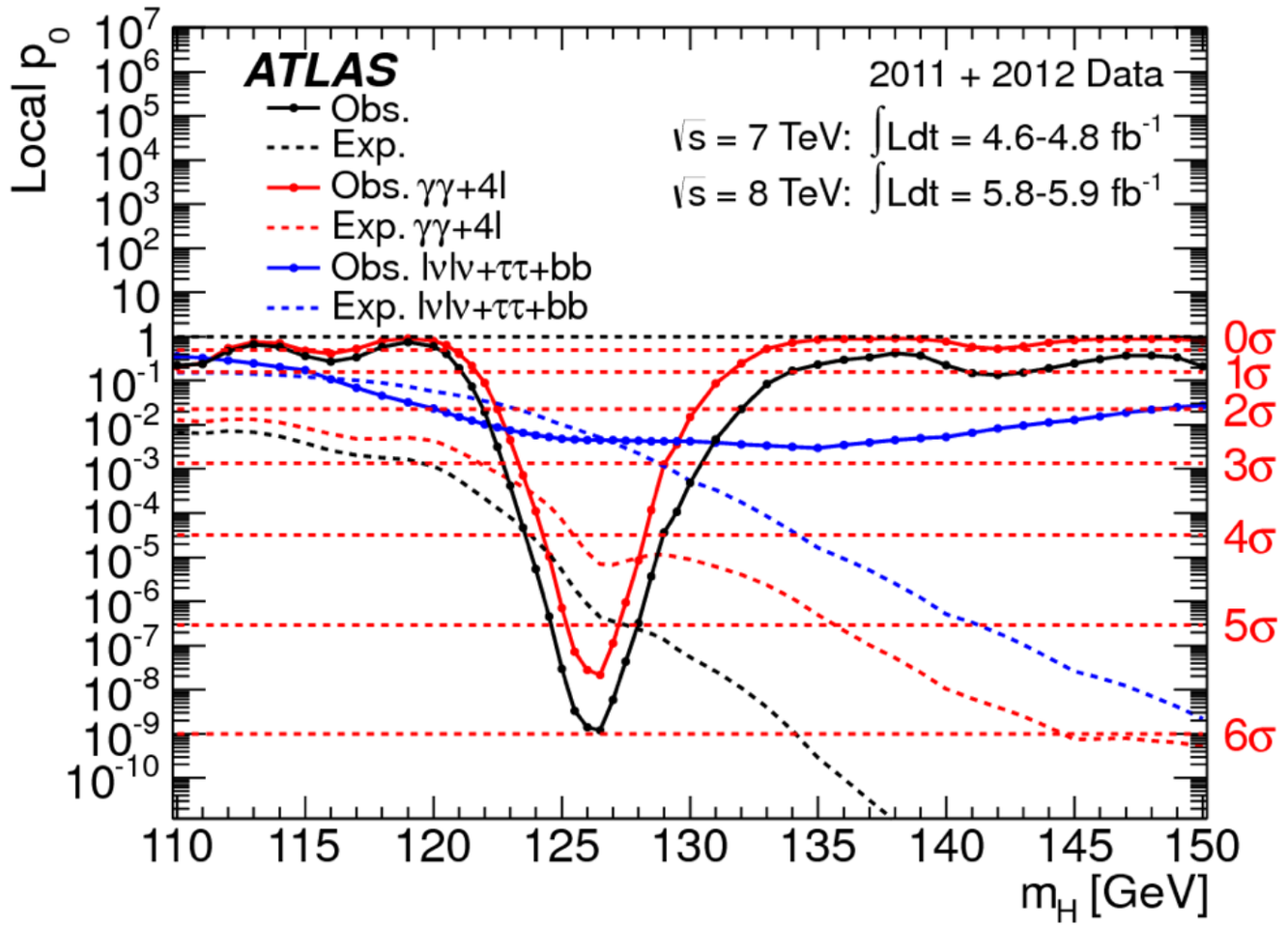
SIGNIFICANCE OF EXCESS



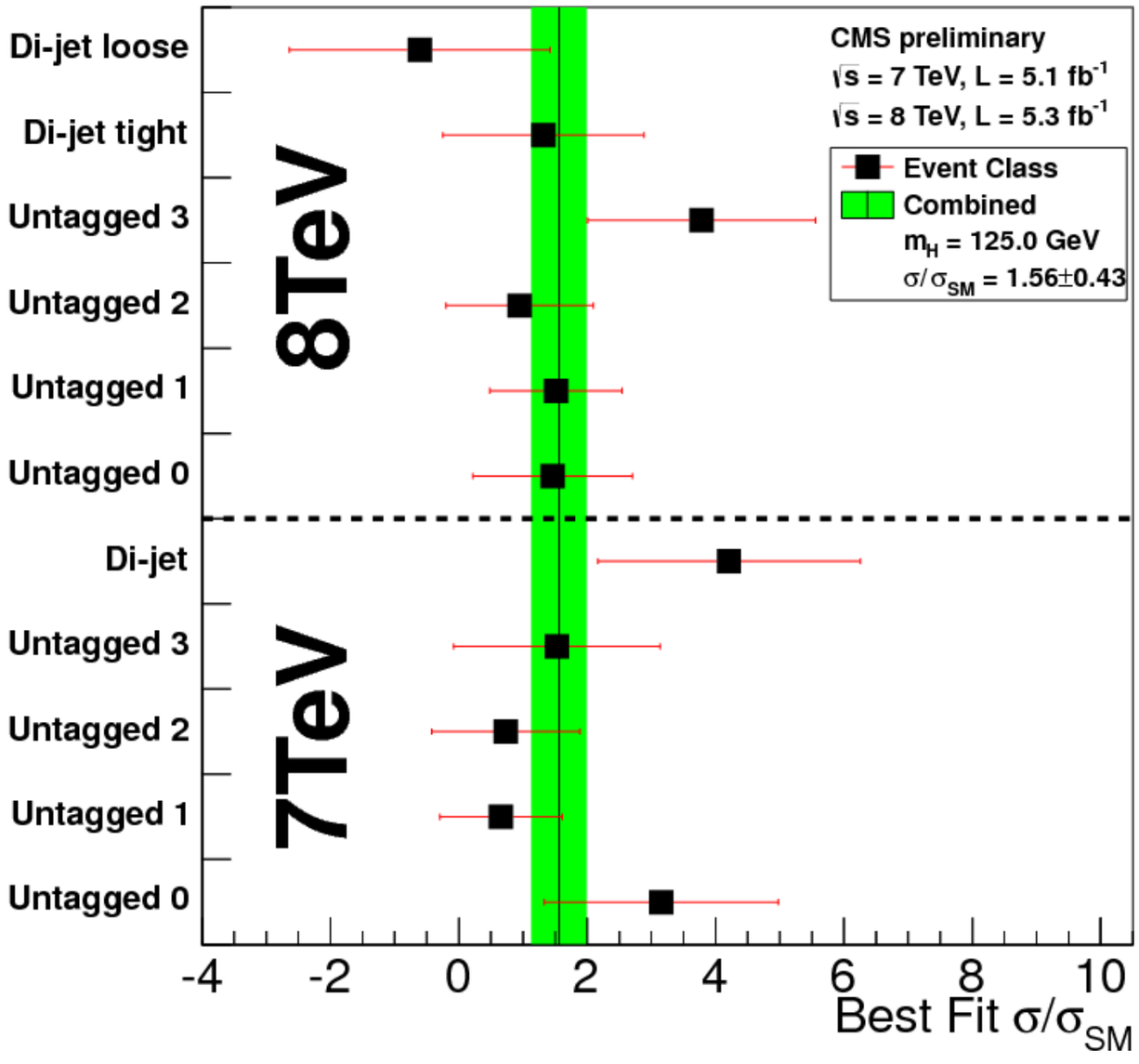


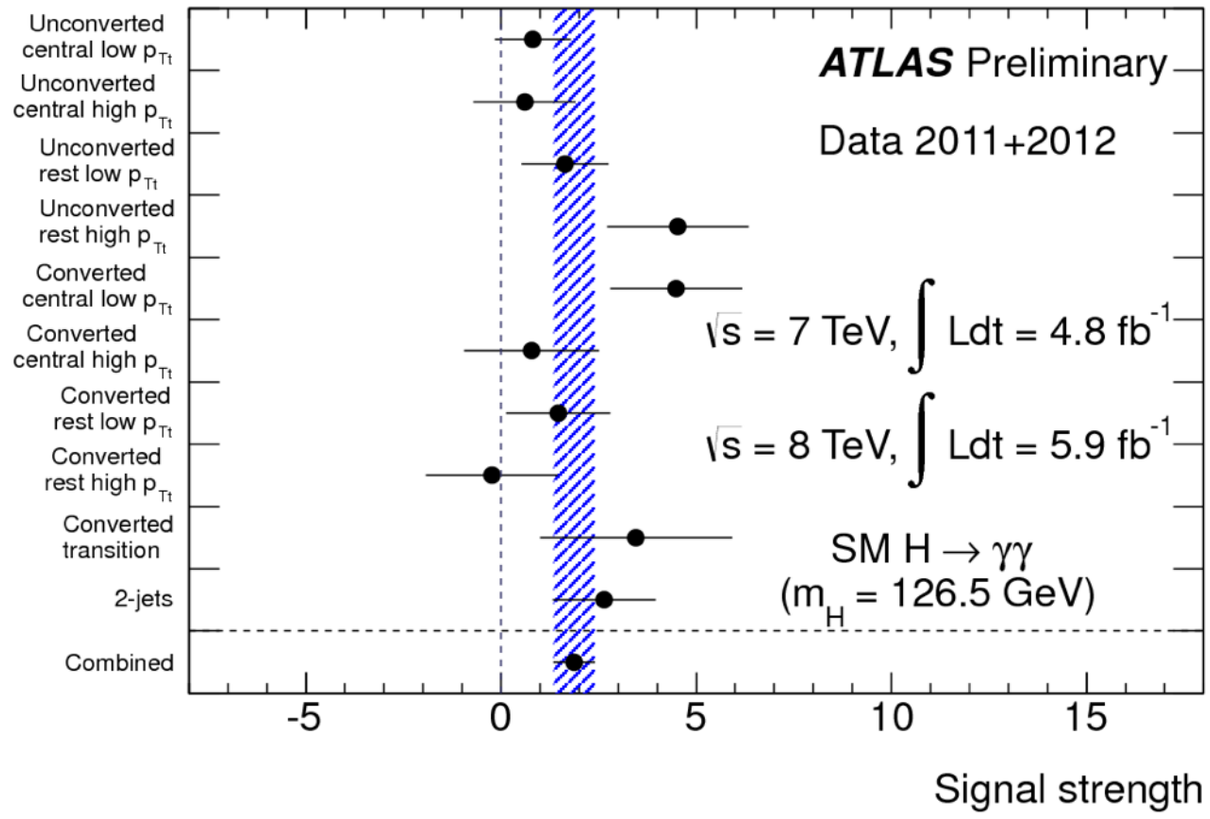
Contribution of Each Decay Mode





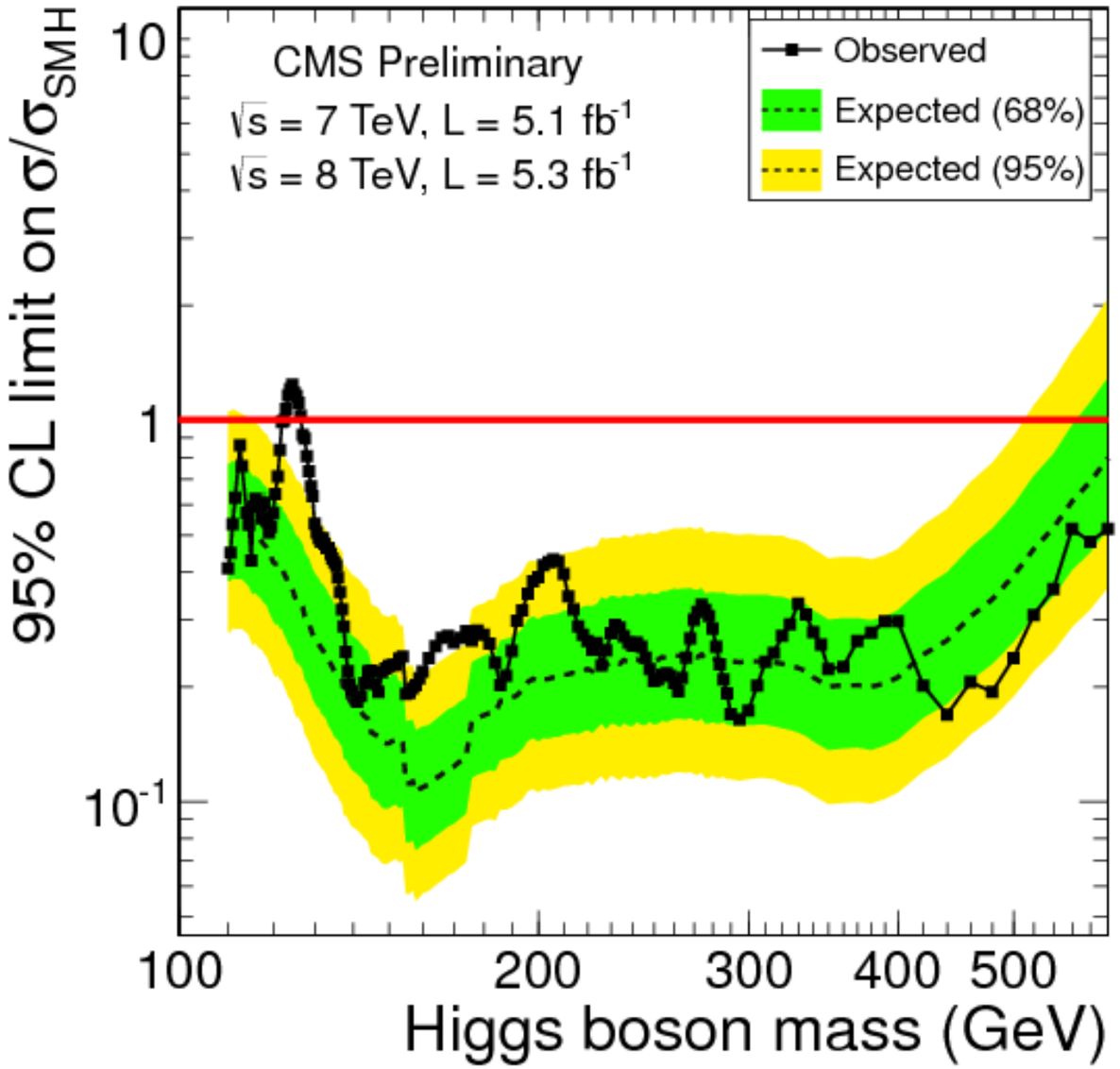
COMPATIBILITY OF CATEGORIES

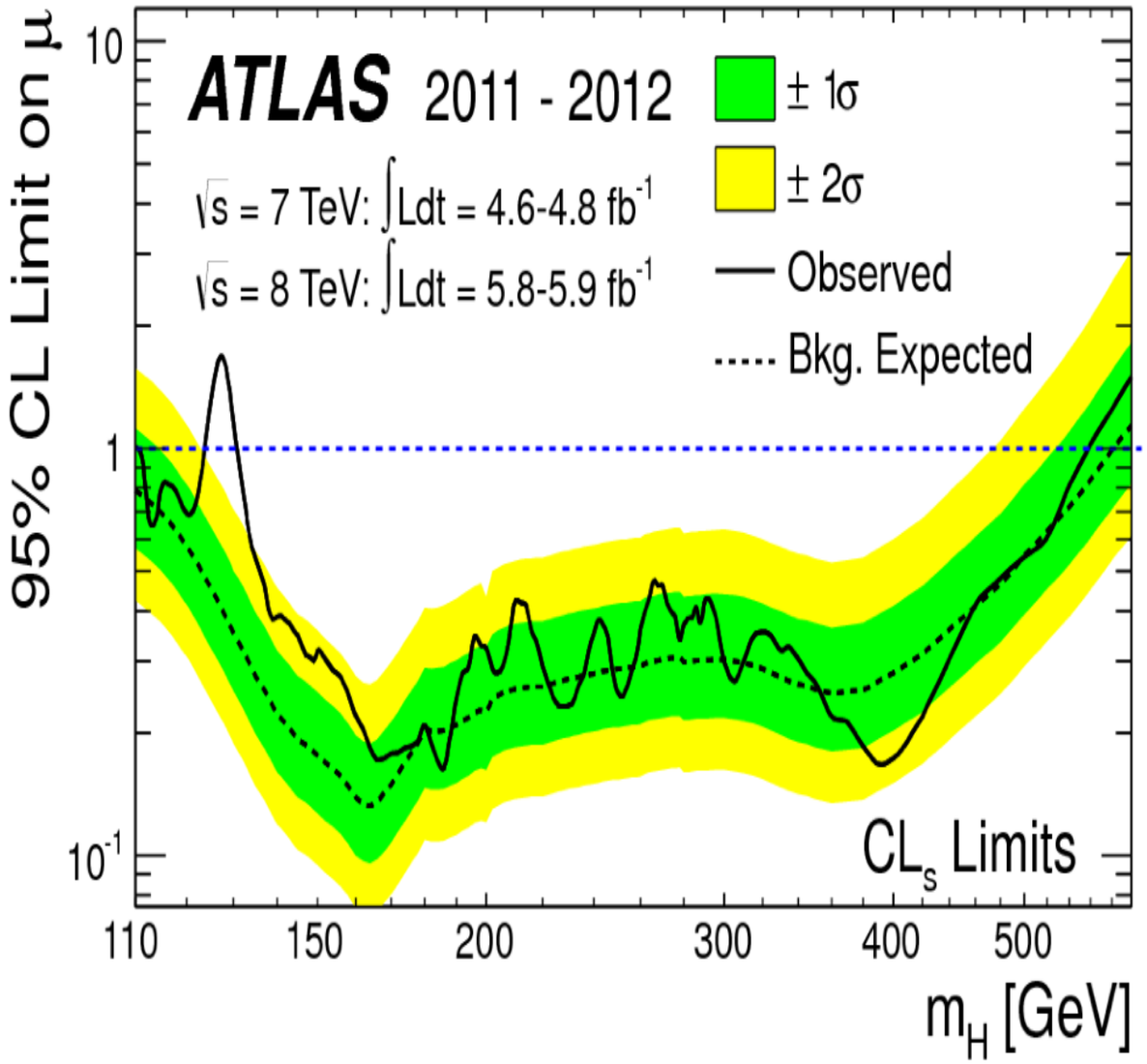




- Measured strength
  - CMS at 125 GeV μ = σ/σSM = 1.56 ± 0.43
  - ATLAS at 126.5 GeV μ = σ/σSM = 1.9 ± 0.5

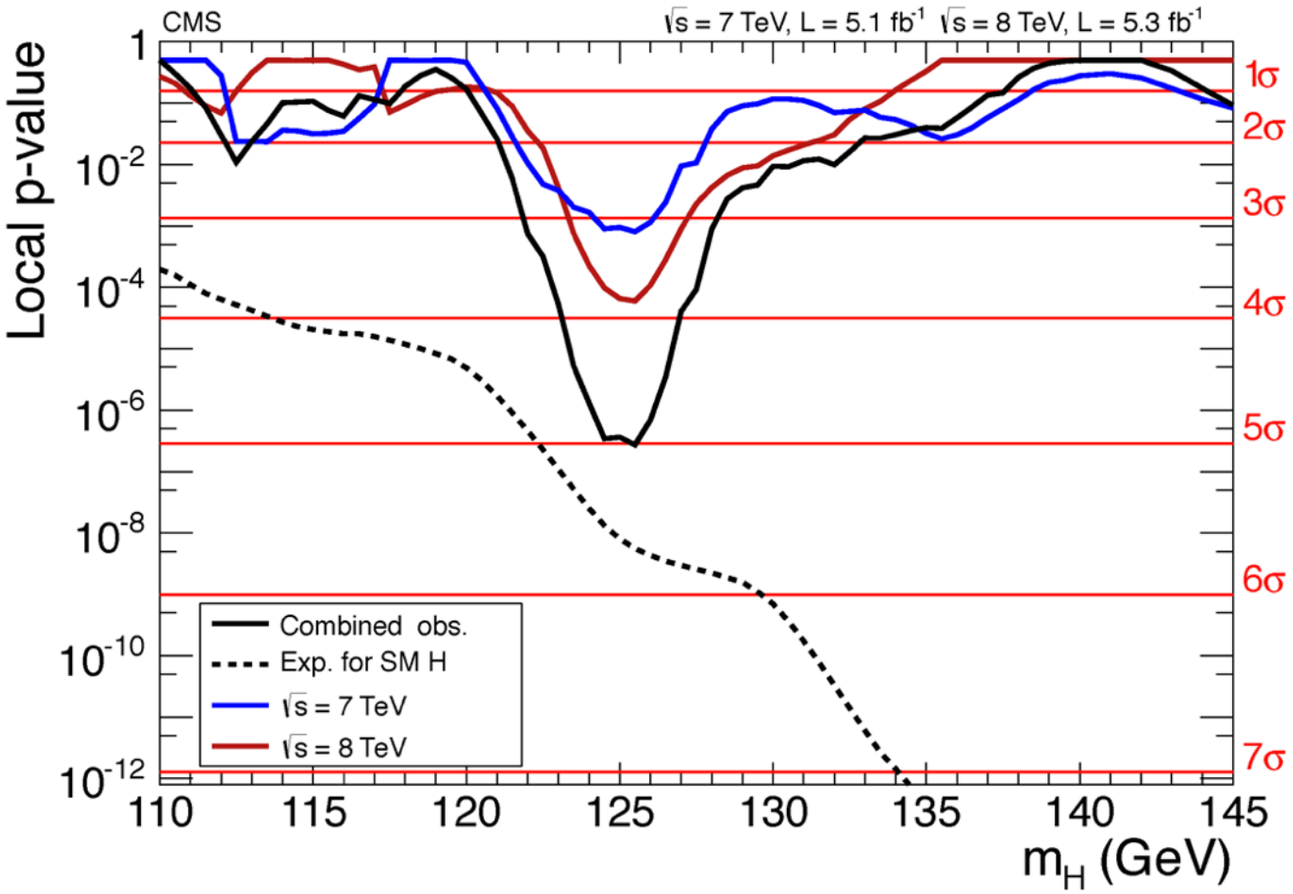
Discovery of a New Boson

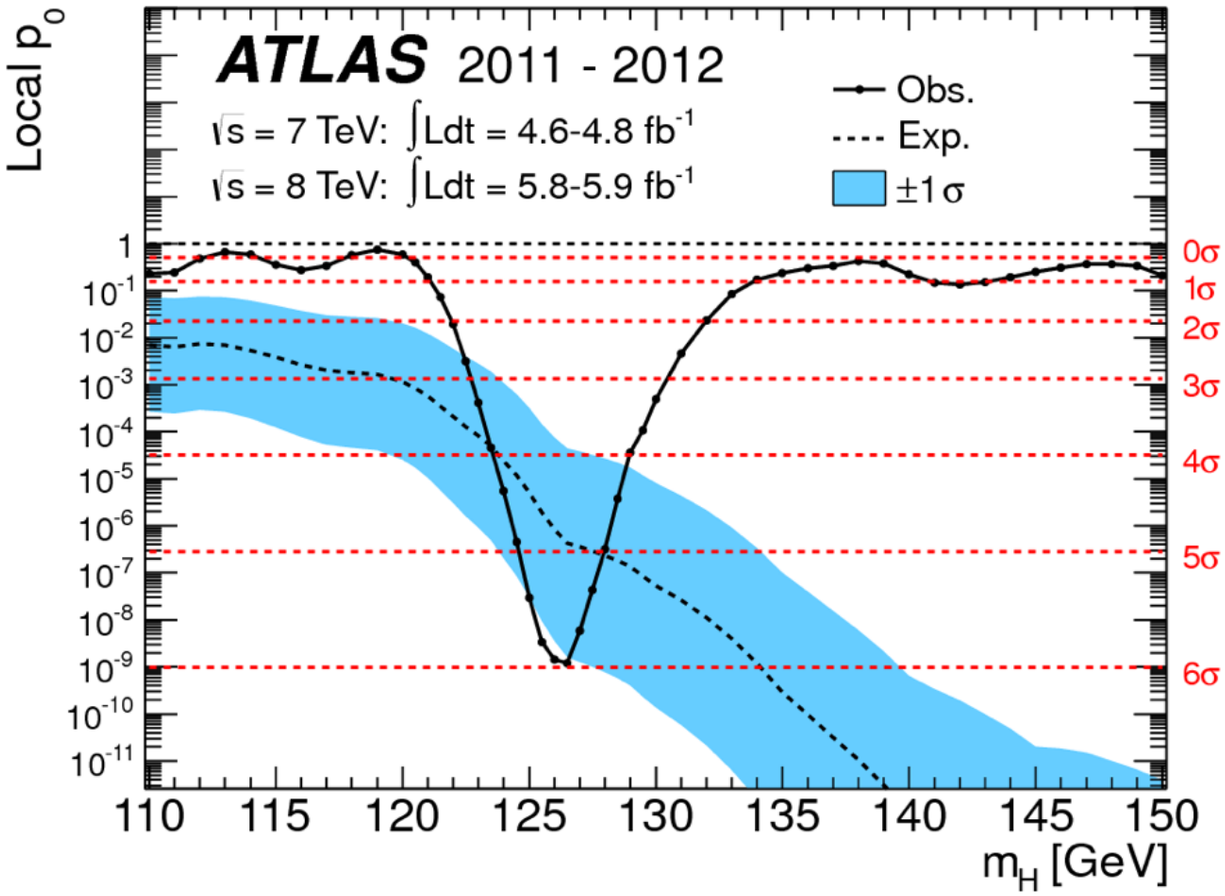




- Standard Model Higgs excluded everywhere except at low mass
- Combination of all decay modes

SIGNIFICANCE OF DISCOVERY





CMS
expected at 5.8
observed at 5.0

ATLAS
expected at 4.9
observed at 6.0

Mass of the New Boson

CMS: m = 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV

ATLAS: m = 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV