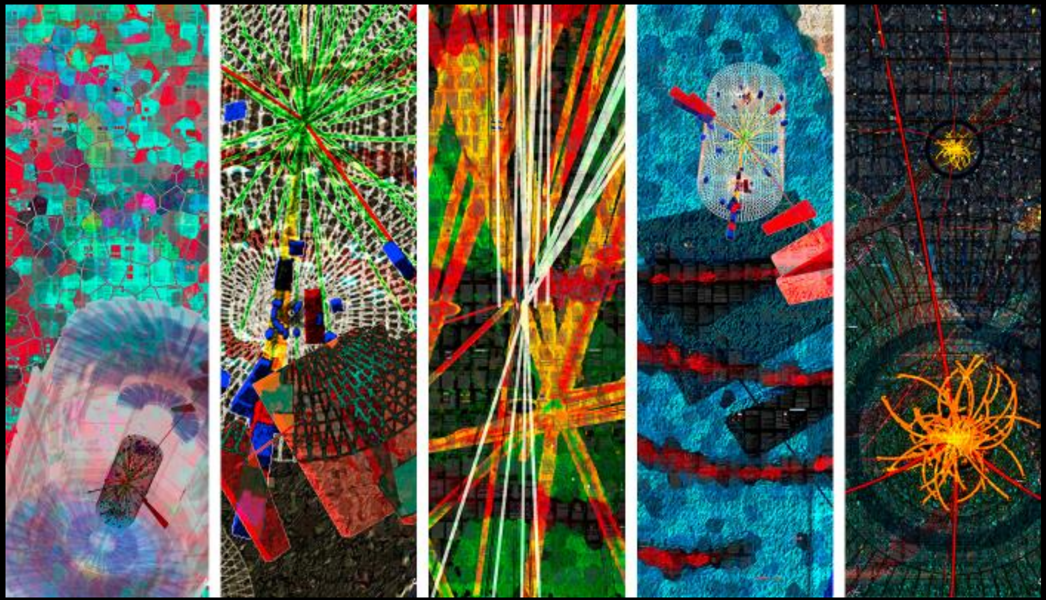
Higgs Results from LHC and future prospects

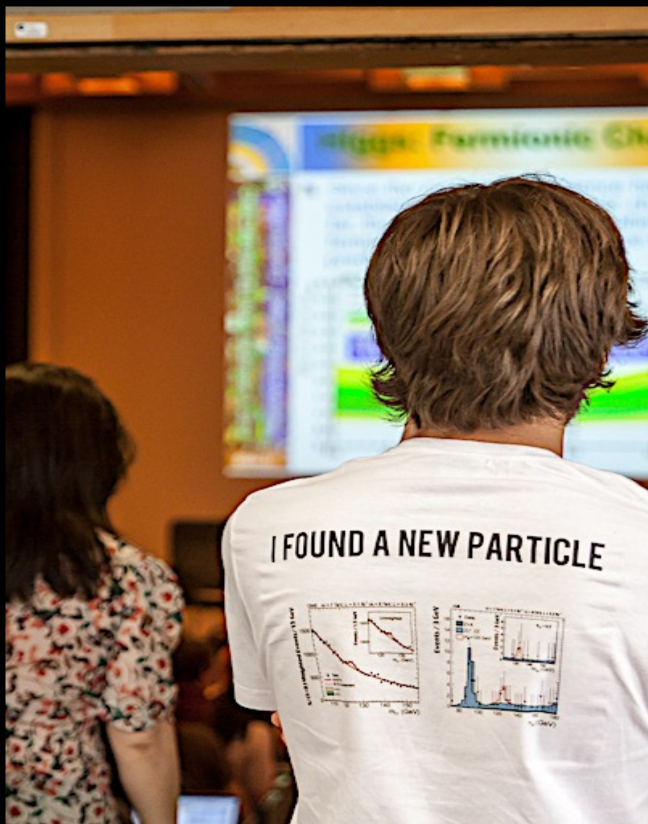


Meenakshi Narain
Brown University
on behalf of CMS and ATLAS

discovery

discovery … a year later.

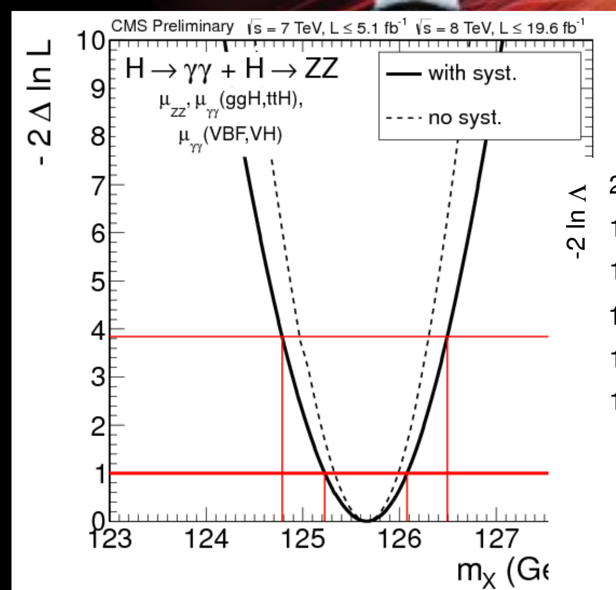
discovery ... a year later

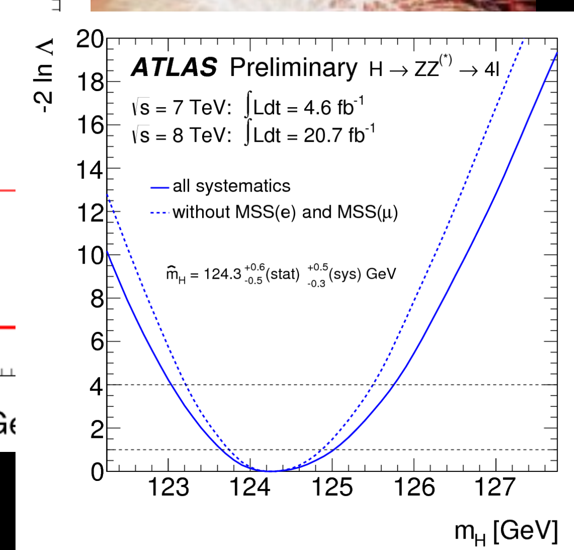


the most precisely measured particle

ATLAS: $125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV

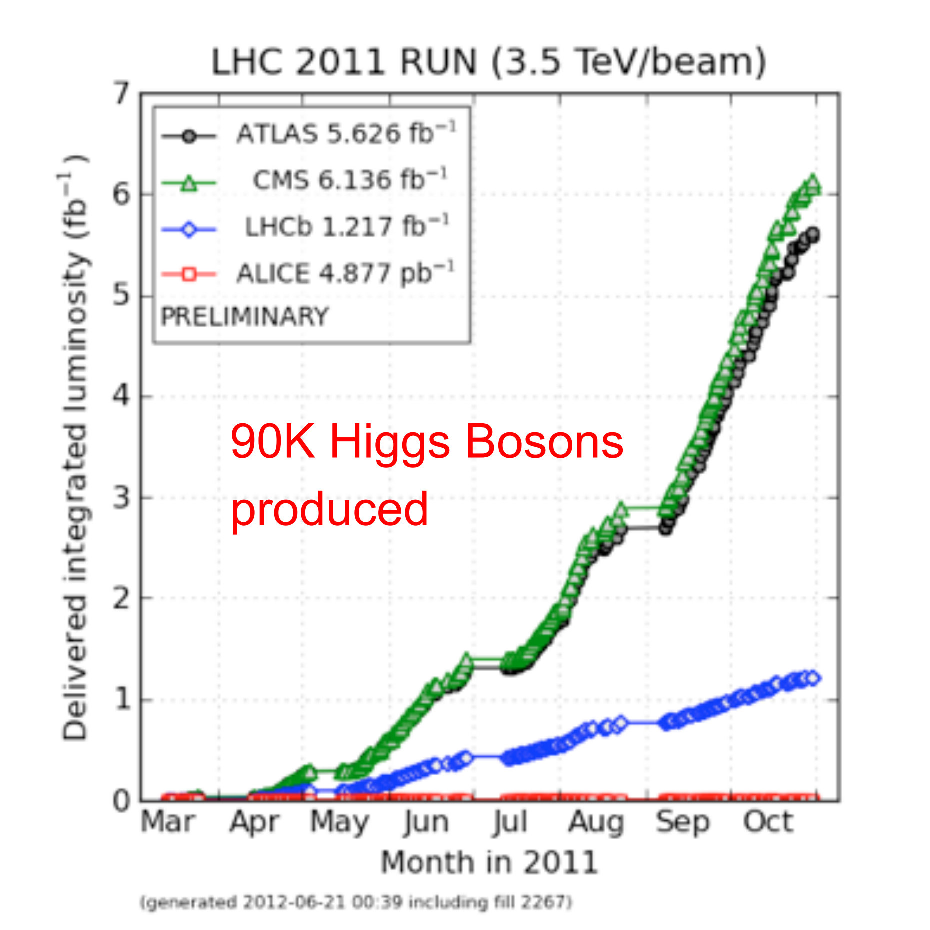
CMS: $125.7 \pm 0.3(\text{stat}) \pm 0.3$ (syst) GeV

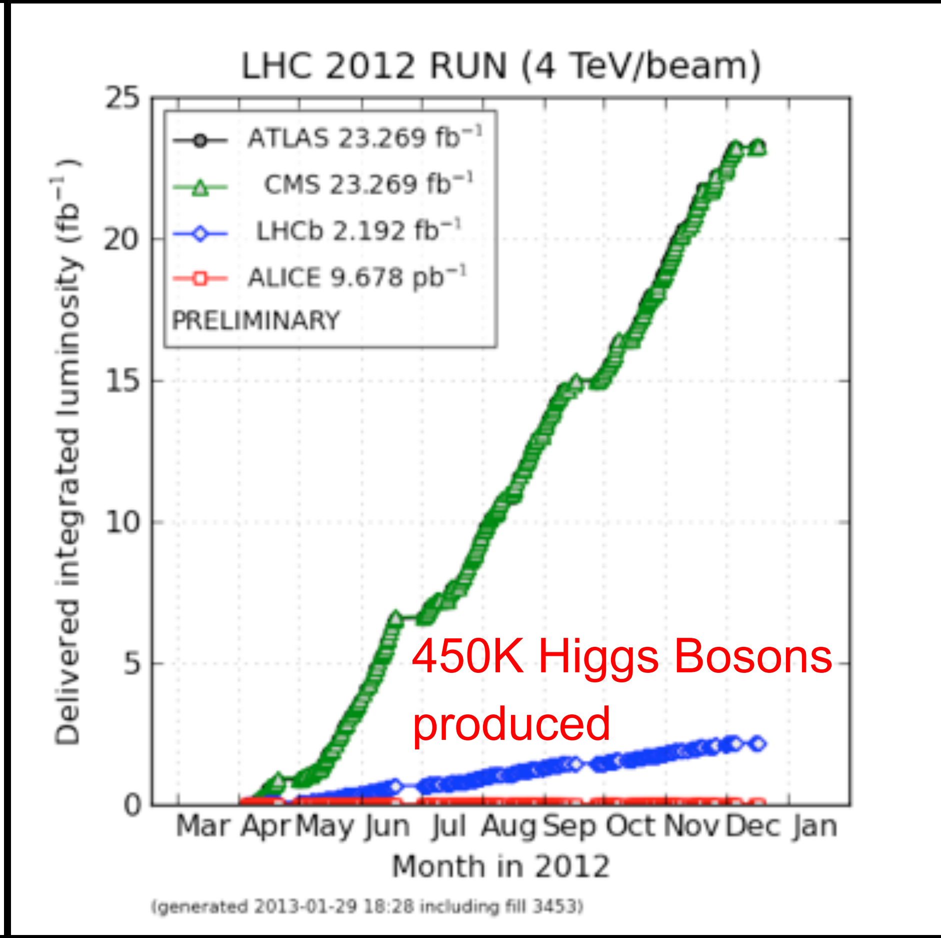




LHC Luminosity

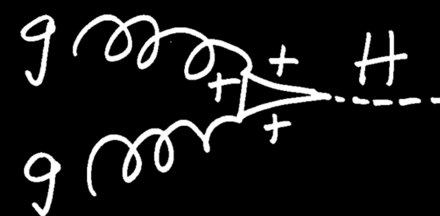
- spectacular 3 years of running and ~30/fb

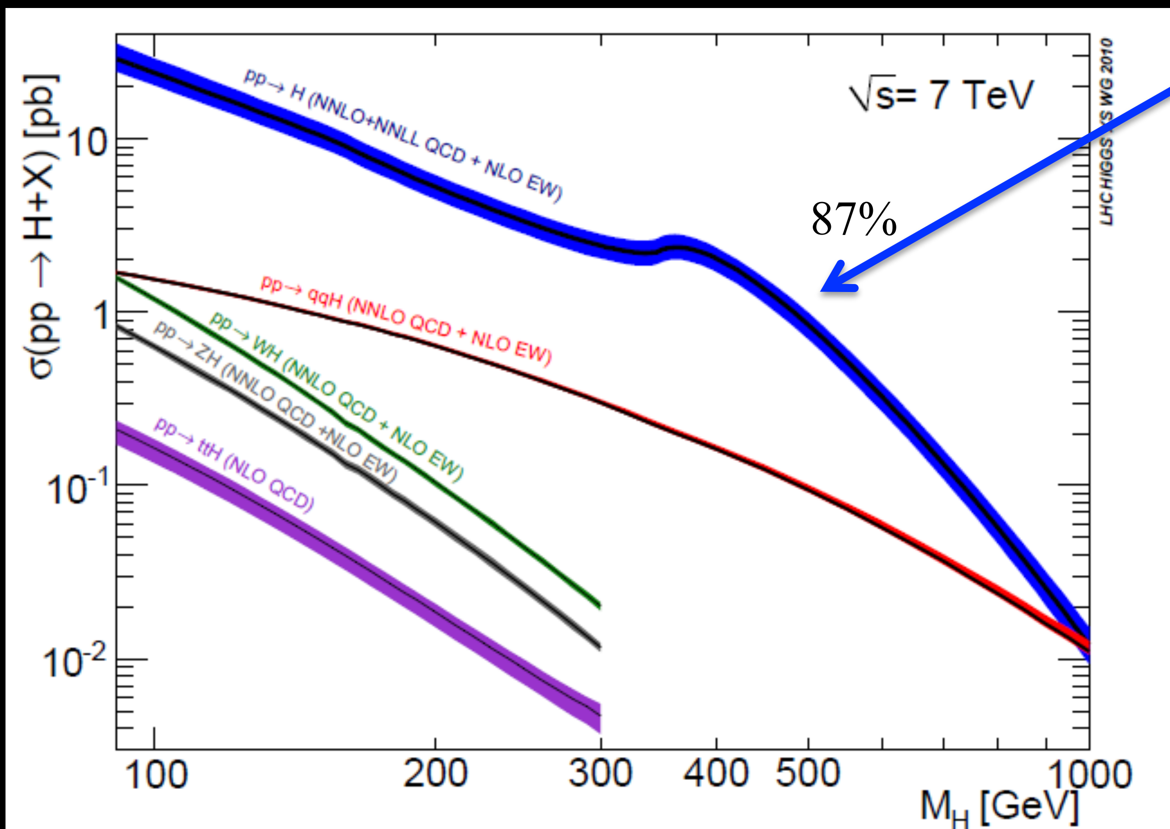




Higgs Production

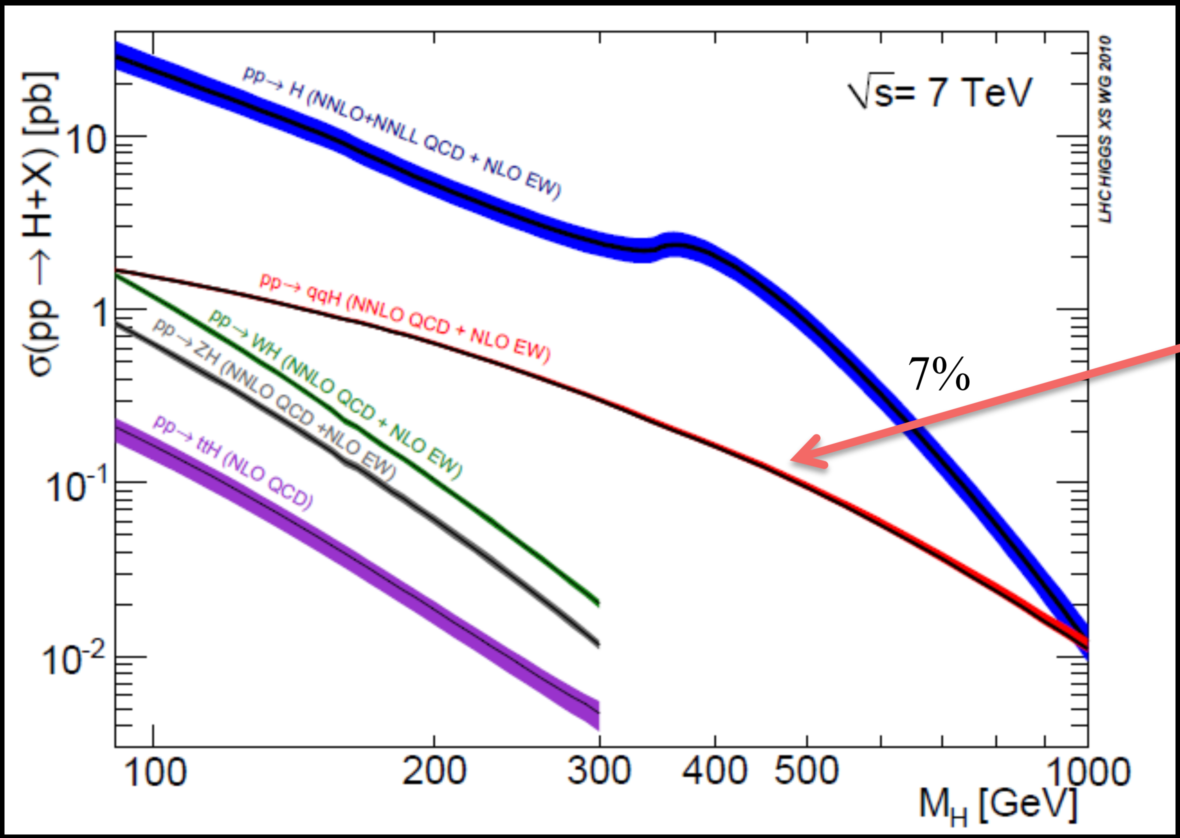
ggF



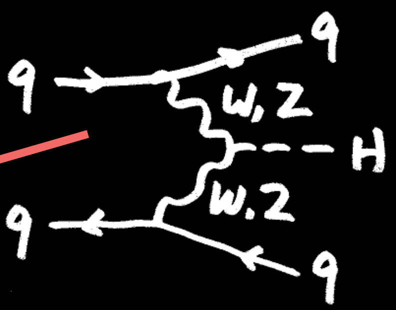


87%

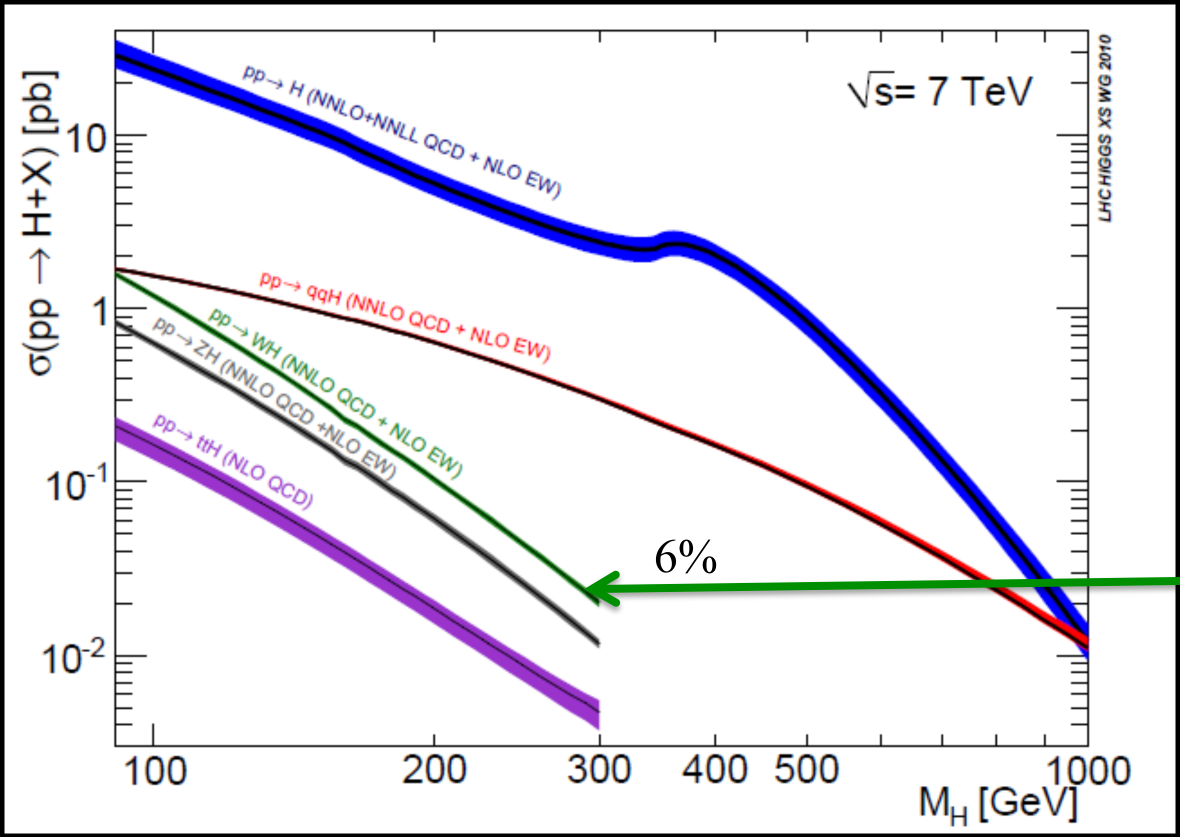
Higgs Production



VBF

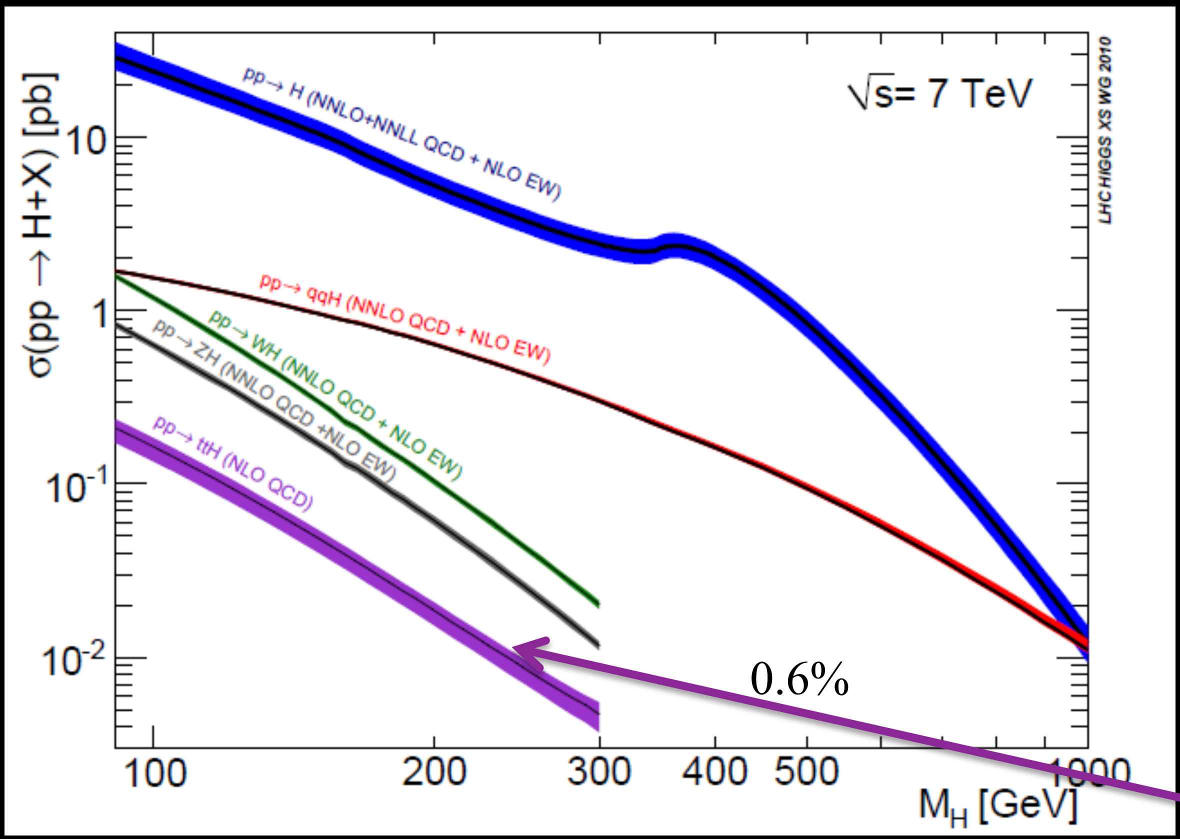


Higgs Production

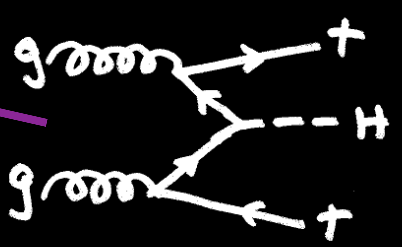


VH

Higgs Production

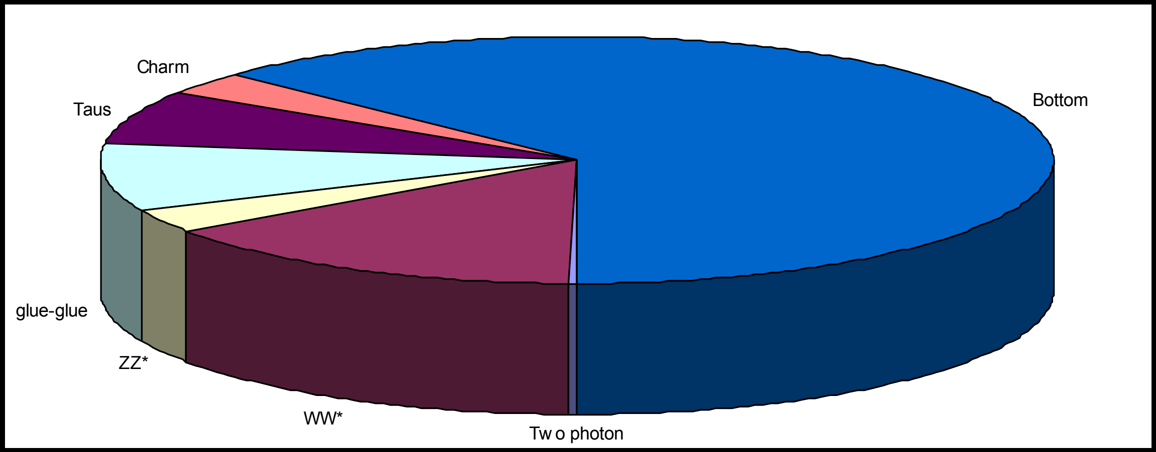


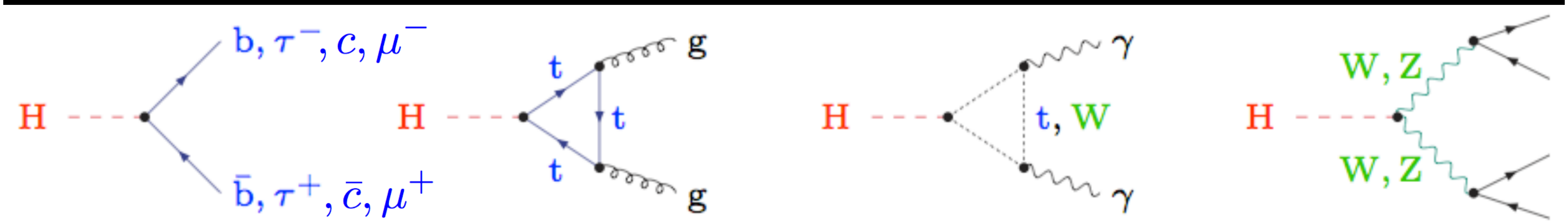
ttH



Higgs Decays

Relative decay rates for a ~125 GeV Higgs:





Higgs Decays

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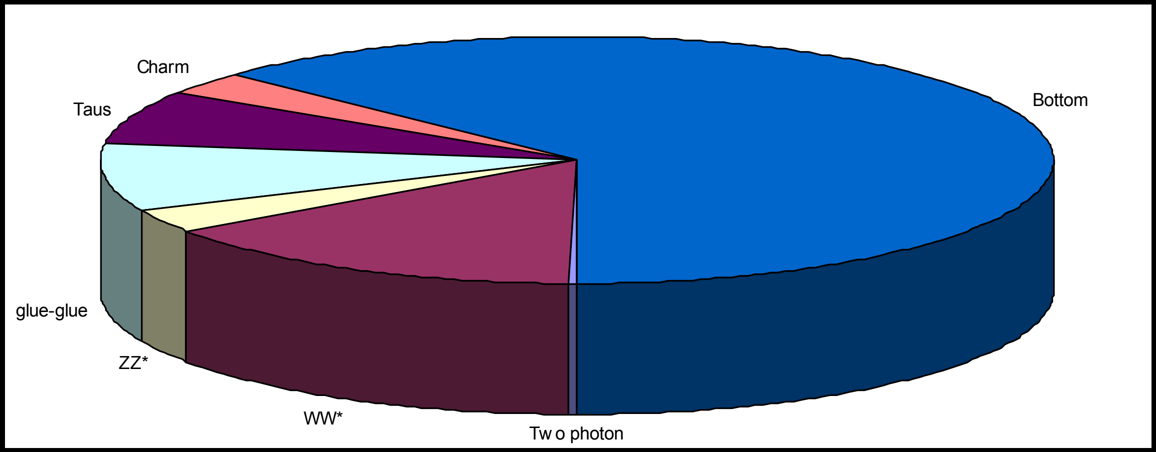
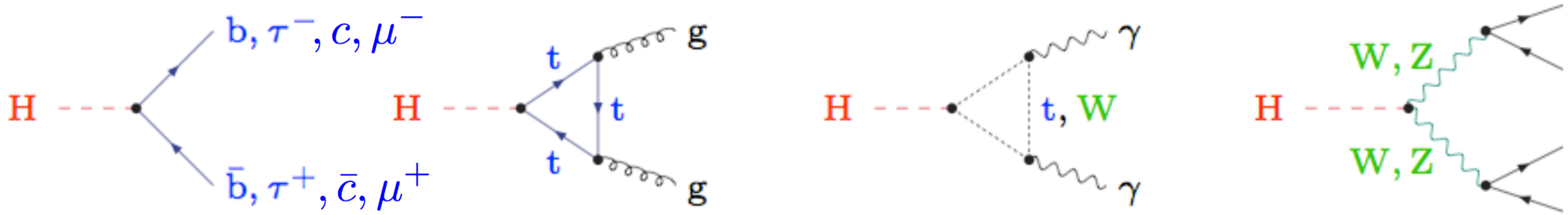


	BR	b:s
bb	58%	10^4
WW	21.6%	10
ZZ	2.7%	10
gg	8.5%	10^6
$\tau\tau$	6.4%	10^5
cc	2.7%	10^4
$\gamma\gamma$	0.22%	10



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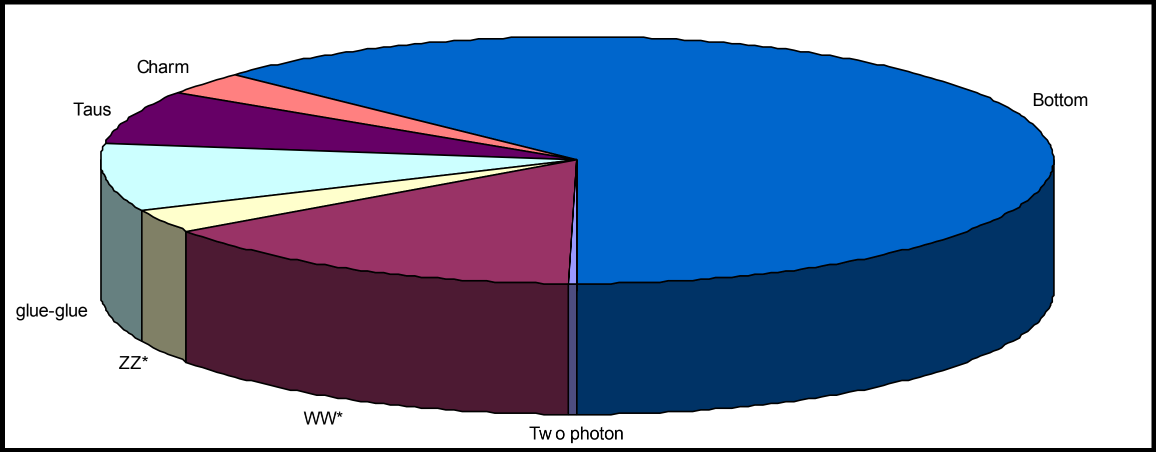

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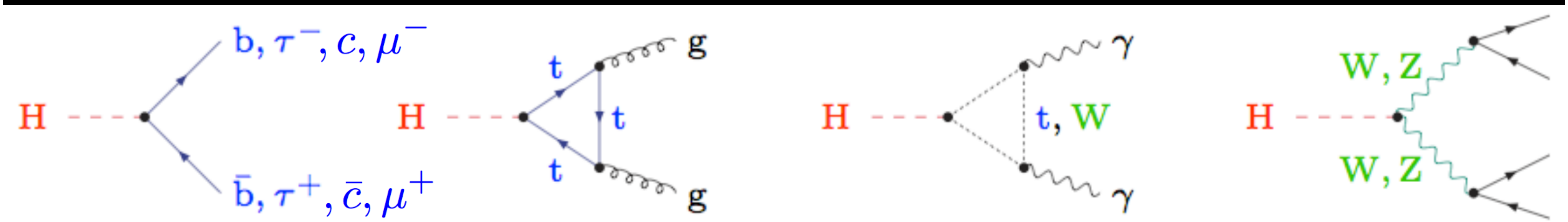

Signatures & Measurement Strategy

Defined by a combination of theoretical and experimental considerations:
e.g. expected signal rate, ability to trigger, signal-to-background ratio,…

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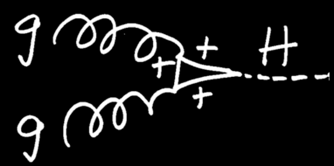

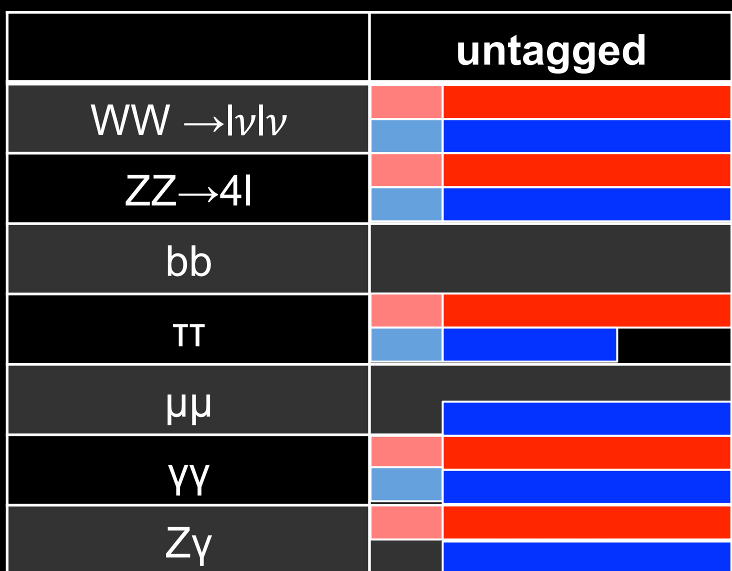

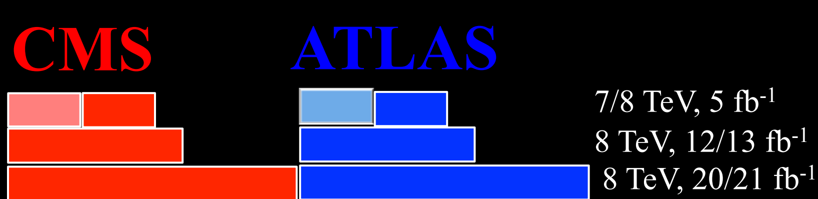

Note: Tags are never pure
e.g. VBF-tags have 20%-80% of ggF, depending on analysis

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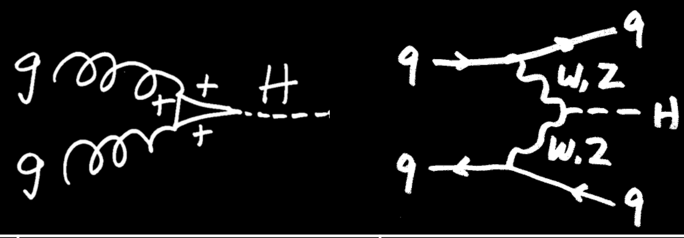

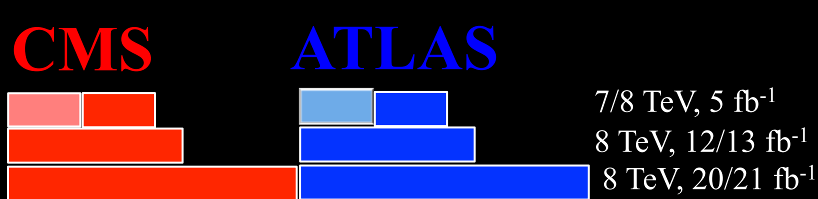

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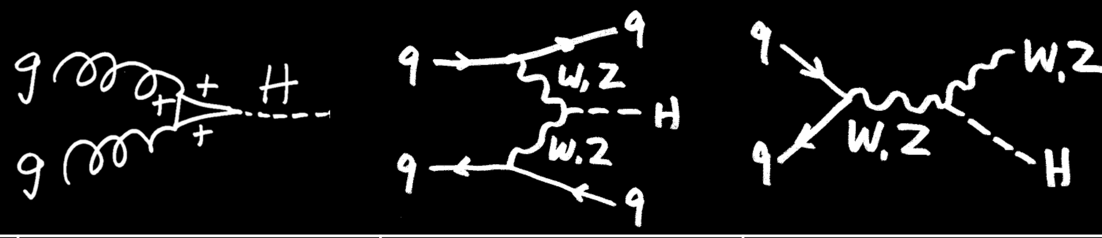

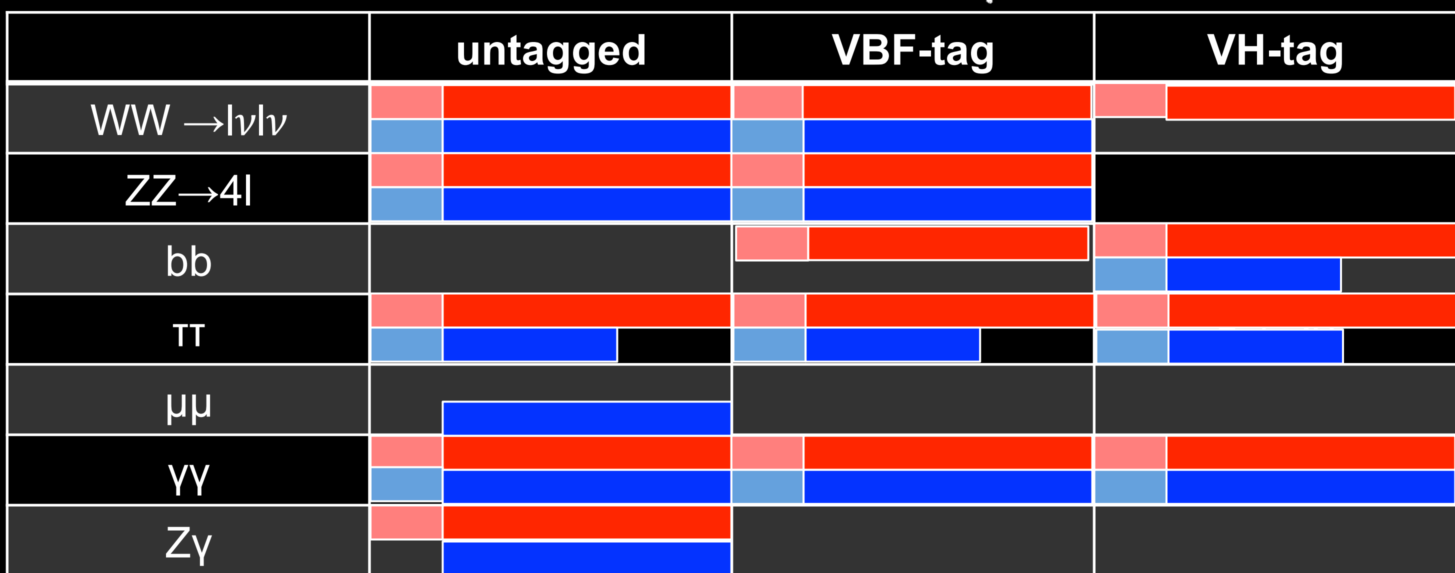

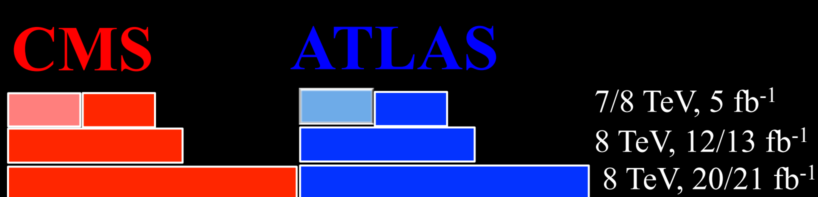

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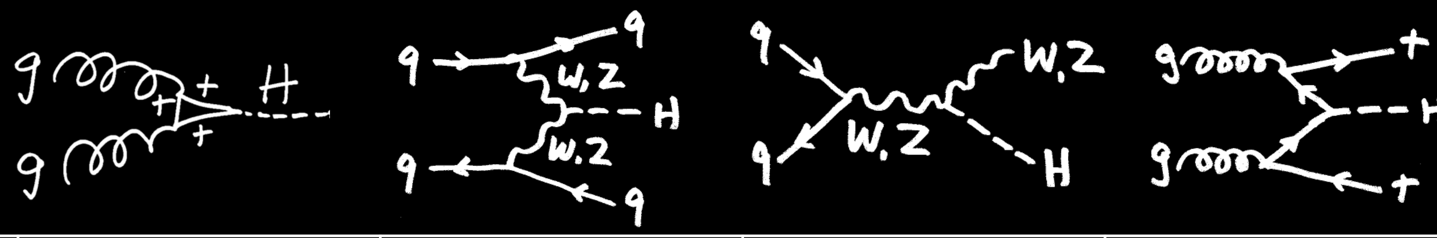

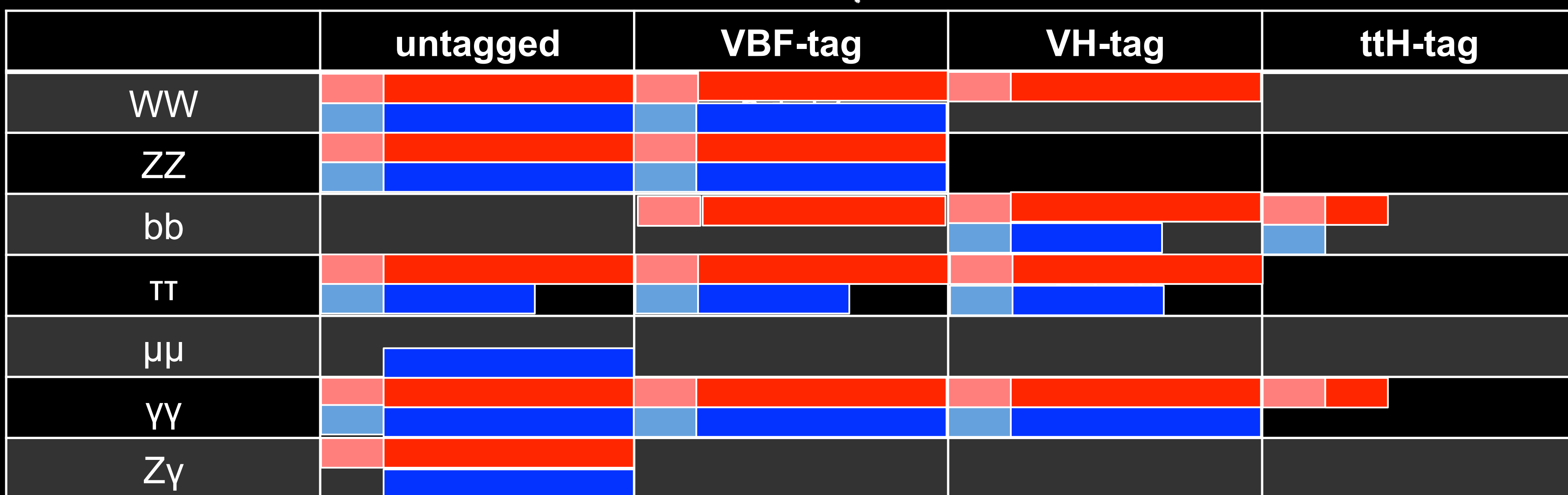

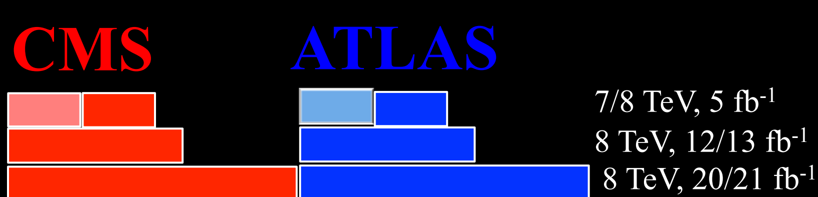

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Higgs Decays to Bosons

$H \rightarrow ZZ \rightarrow 4l$

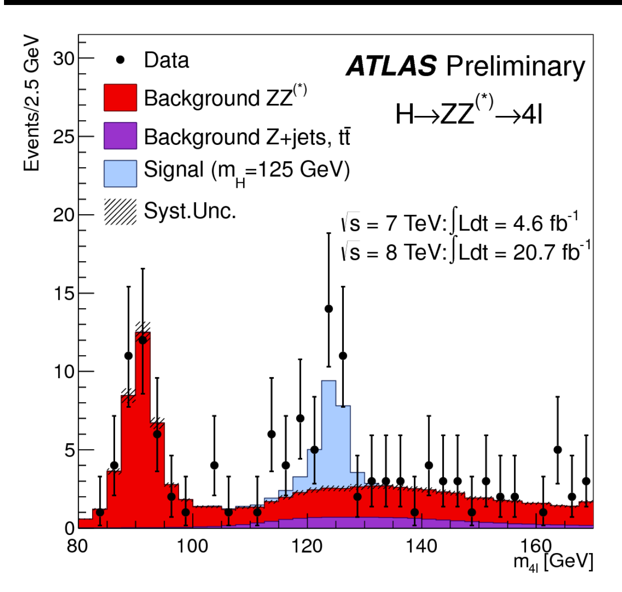
$H \rightarrow \gamma\gamma$

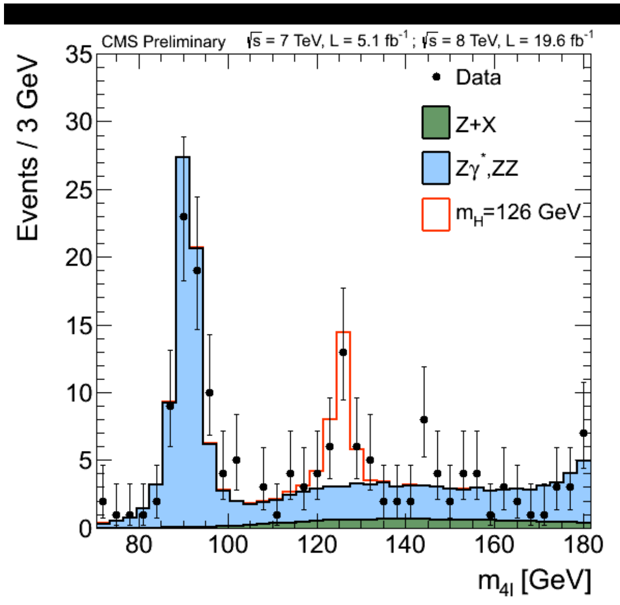
$H \rightarrow Z\gamma$

$H \rightarrow WW \rightarrow l\nu l\nu$

SIGNATURES OF THE HIGGS

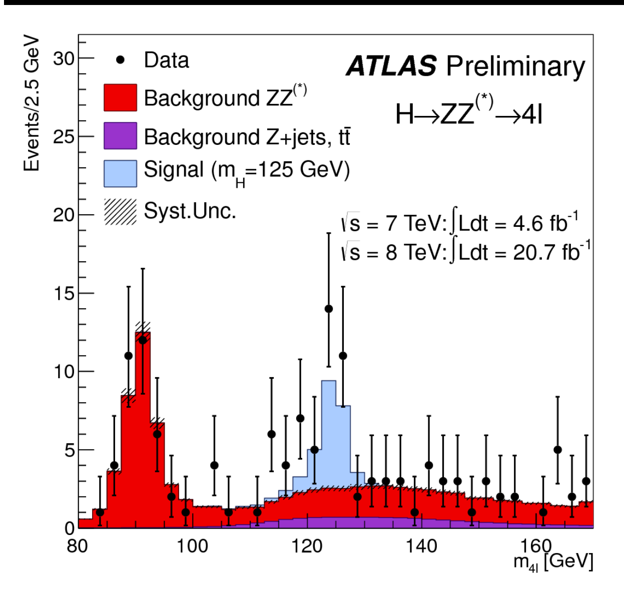
H→ZZ→4l: Golden mode





- Very small BR ~10^{-4} at m_H=125 GeV
- 4 isolated prompt leptons (low p_T)
- Reconstruct mass of the Higgs boson
- Good mass resolution ≈1-2.5%
- Backgrounds:
  - irreducible: ZZ (from MC)
  - reducible: Z+jets, Zbb, tt, WZ (from control samples)
- Checks in background control regions
  - SM Z→4l allows validation of the mass (and future width) measurements

$H \rightarrow ZZ \rightarrow 4l$: Golden mode



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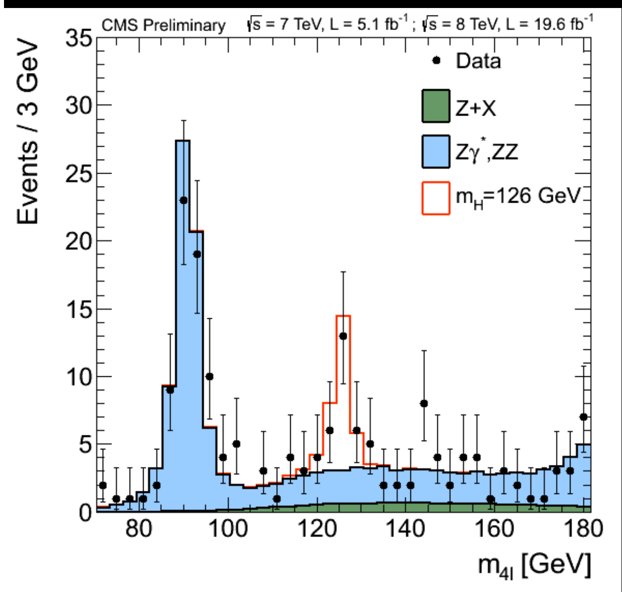
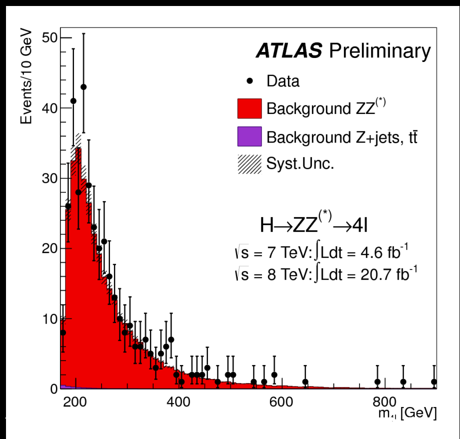
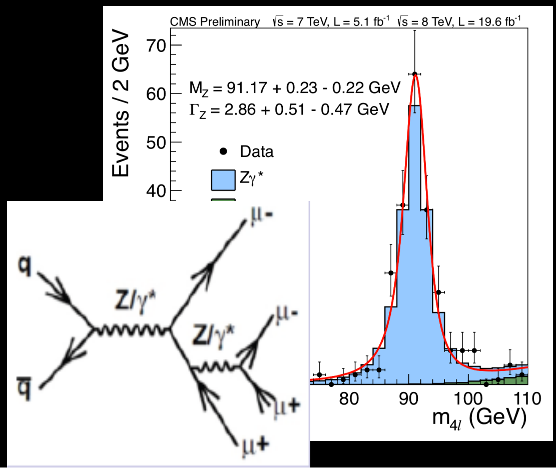


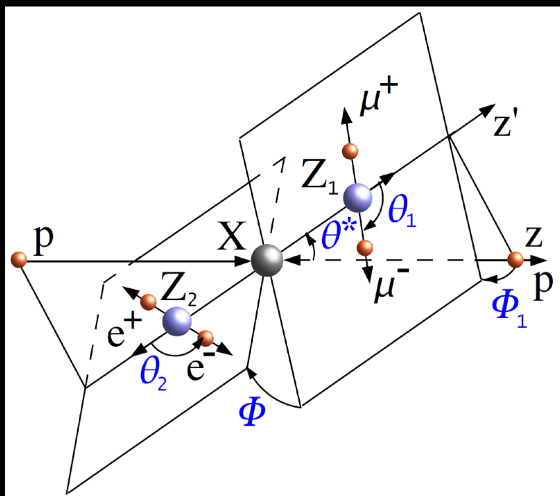
dominant ZZ bkg



$Z \rightarrow 4l$



Use of kinematical variables: K_D



K_D :**MELA: M**atrix **E**lement **L**ikelihood **A**nalysis:
use kinematic inputs for signal to ZZ discrimination: $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

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

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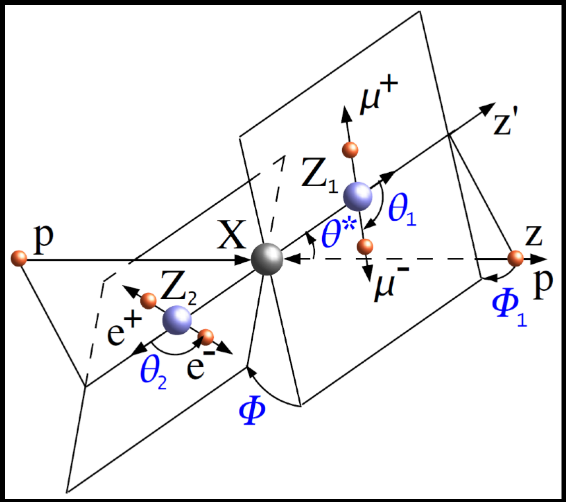

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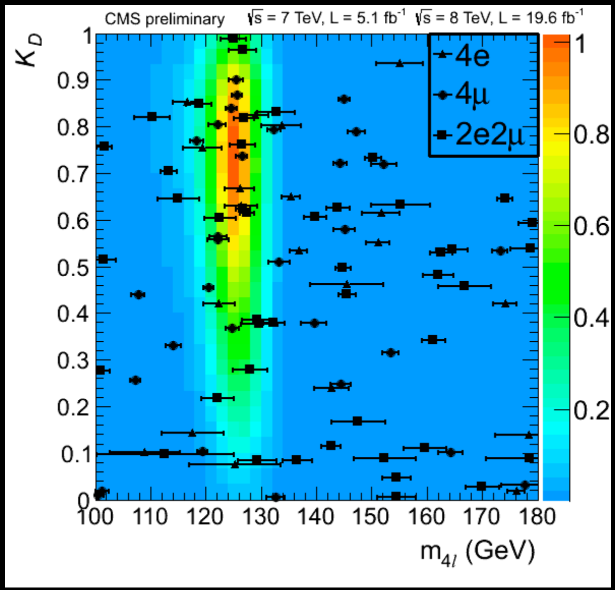
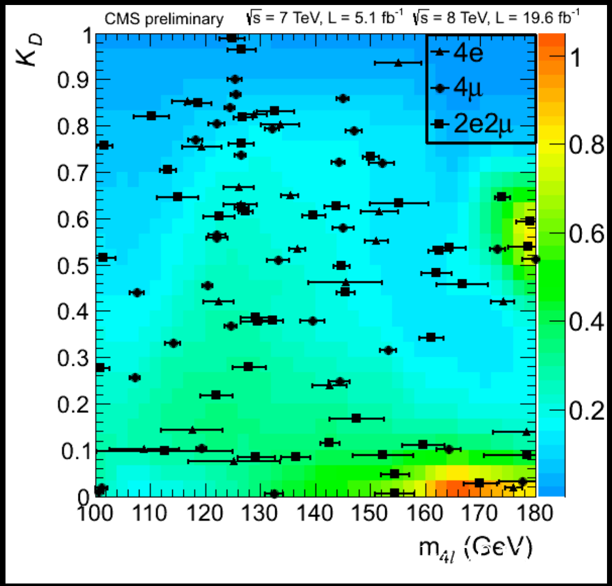
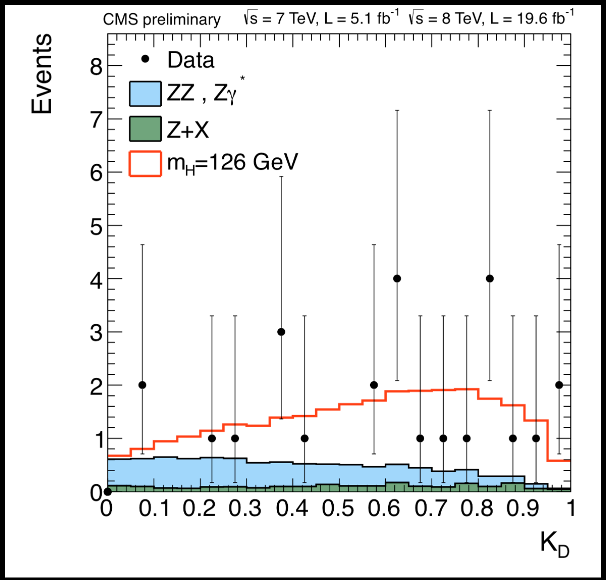
SIGNAL



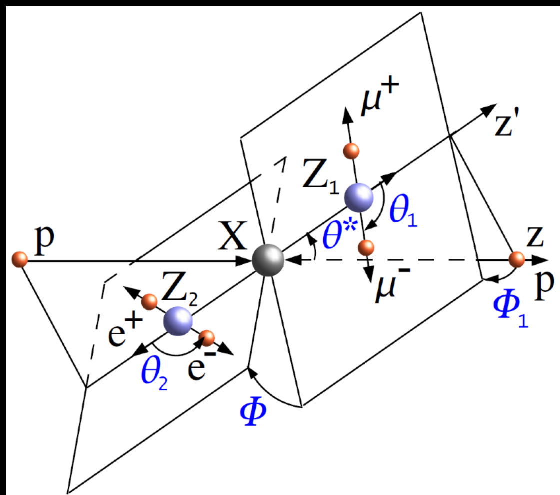
BACKGROUND



M_{4l} = 121.5 – 130.5 GeV



Use of kinematical variables: K_D



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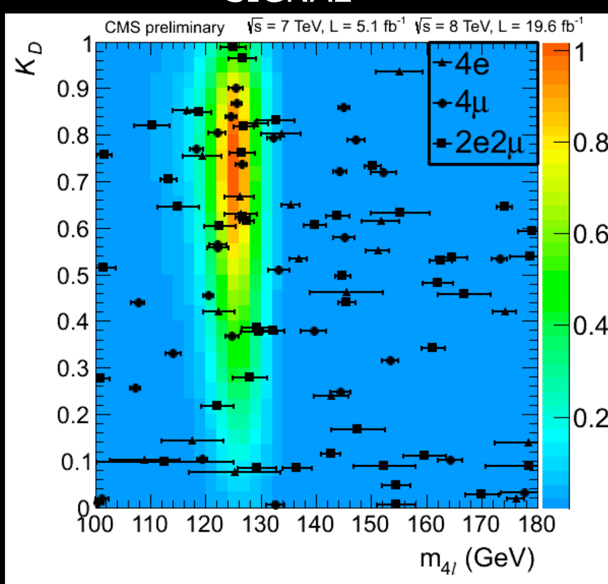
$$\mathbf{K_D} = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\rm sig}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

SIGNAL



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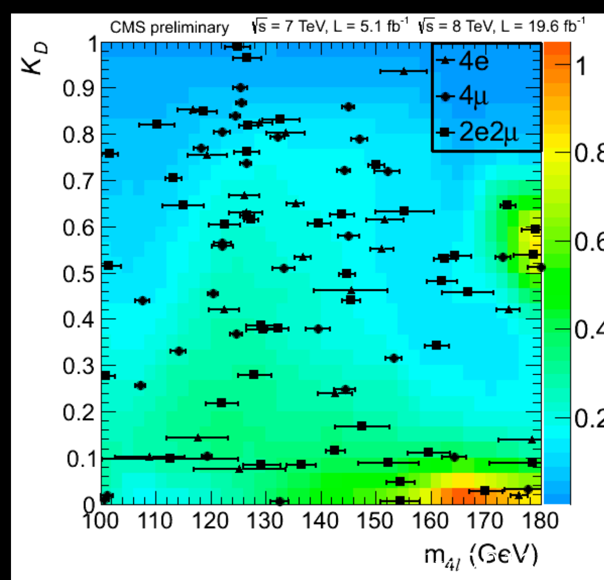
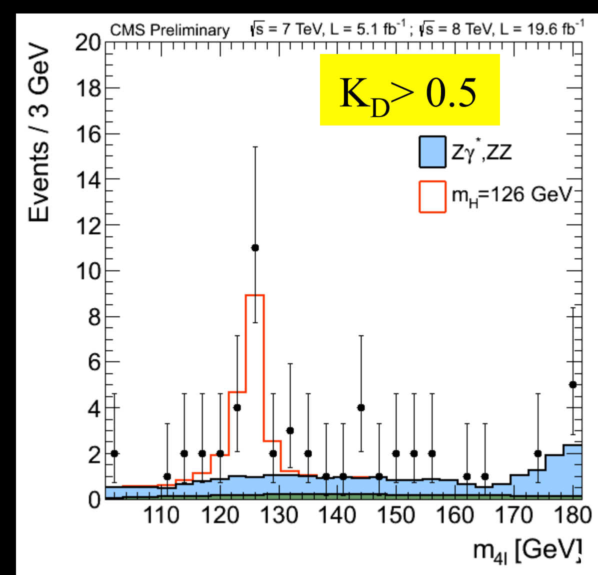
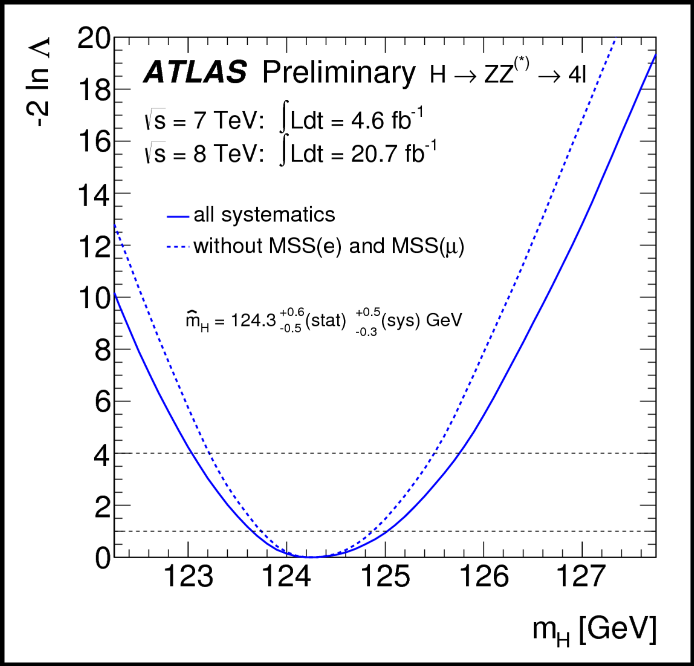
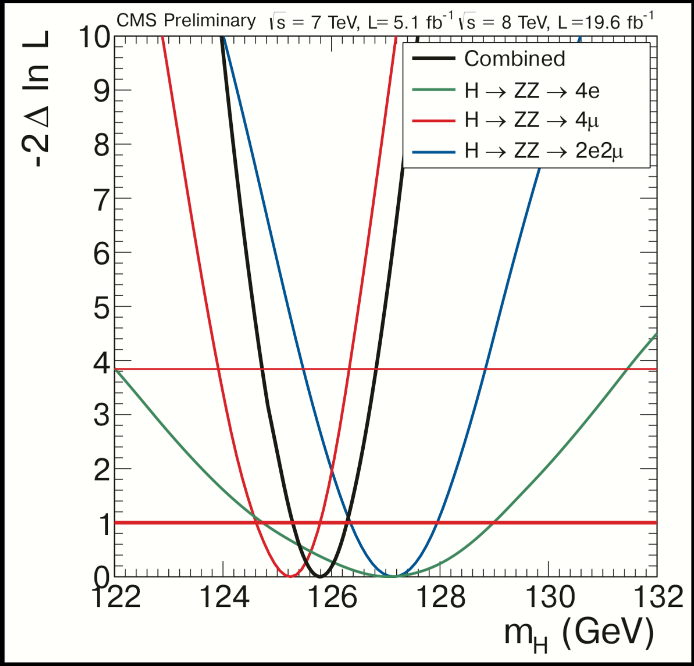




H→ZZ→4l : Mass Measurement

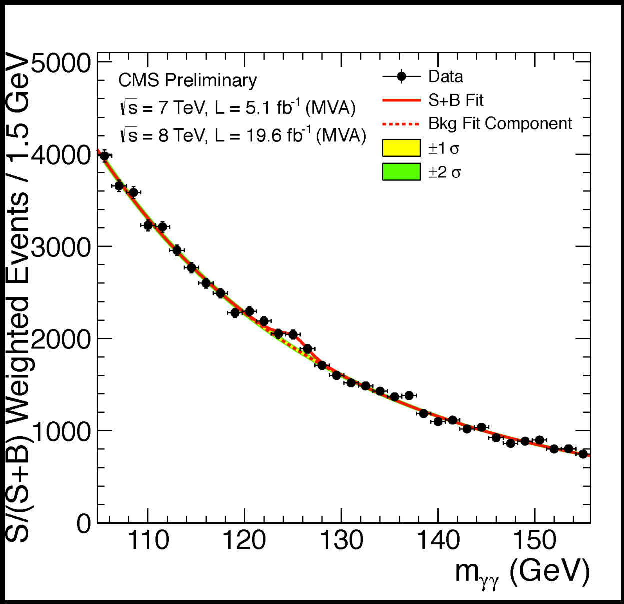


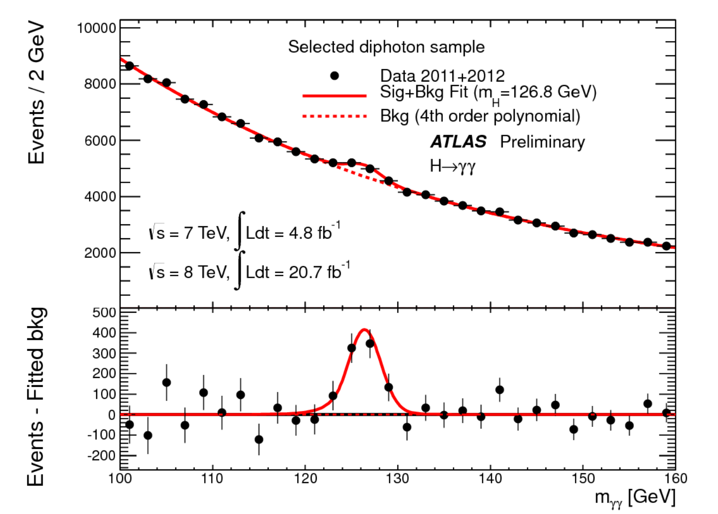


$M_H = 124.3\ ^{+0.6}_{-0.5}(\text{stat.})\ ^{+0.5}_{-0.3}(\text{syst.})$ GeV $M_H = 125.8 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.})$ GeV

- This channel provides the **most precise mass measurement**
- CMS: event-by-event mass uncertainties lead to an 8% improvement.

$H \rightarrow \gamma\gamma$





- Small BR ~2×10^{-3} at 125 GeV
- 2 isolated high p_T photons
- Primary vertex determination (pile-up!)
  - CMS: mainly from recoiling charged particles
  - ATLAS: also from photon pointing (longitudinal ECAL segmentation)
- Reconstruct mass of the Higgs boson
- Good mass resolution ≈1-2%
  - a narrow mass peak on top of a large steeply falling background
- Backgrounds:
  - Irreducible: 2γ QCD production
  - Reducible: γj and jj
- background: fit to $m_{\gamma\gamma}$-distribution

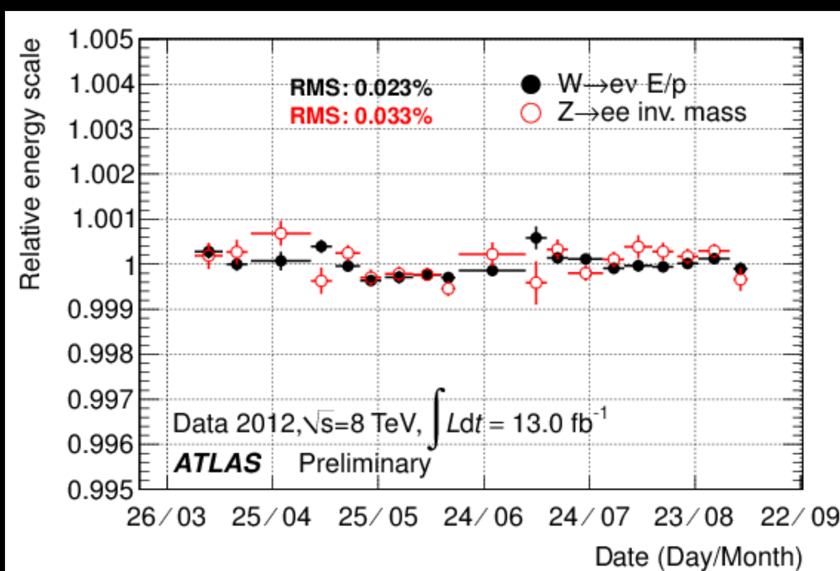
$H \rightarrow \gamma\gamma$

- Energy Scale Calibration, crucial for good mass measurement
- ECAL response calibrated with $\pi^0 \rightarrow \gamma\gamma$, $W \rightarrow e\nu$ (E/p), $Z \rightarrow ee$

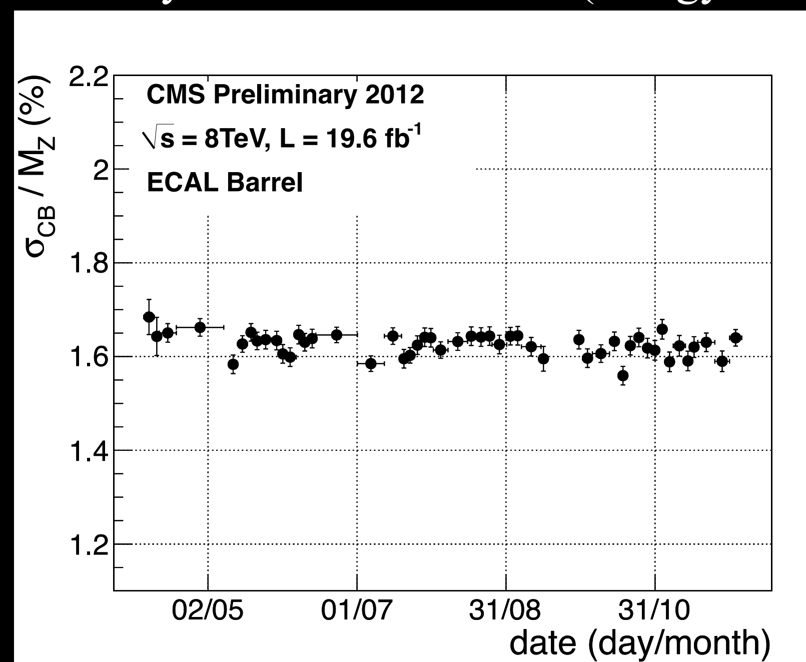
  CMS: Laser corrections measuring transparency loss are applied

  ATLAS: Calorimeter response stable at 0.1% level wrt. time/pile-up

Energy scale stable with pileup and time

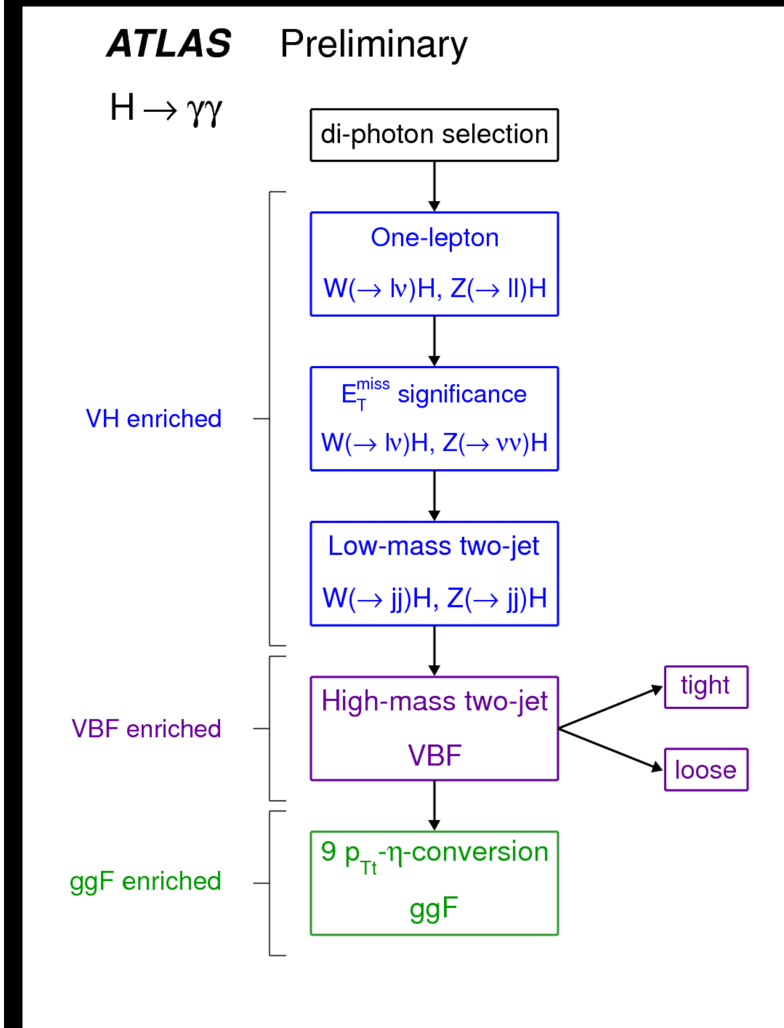


Z mass resolution as a function of time after application of analysis level corrections (energy scale)

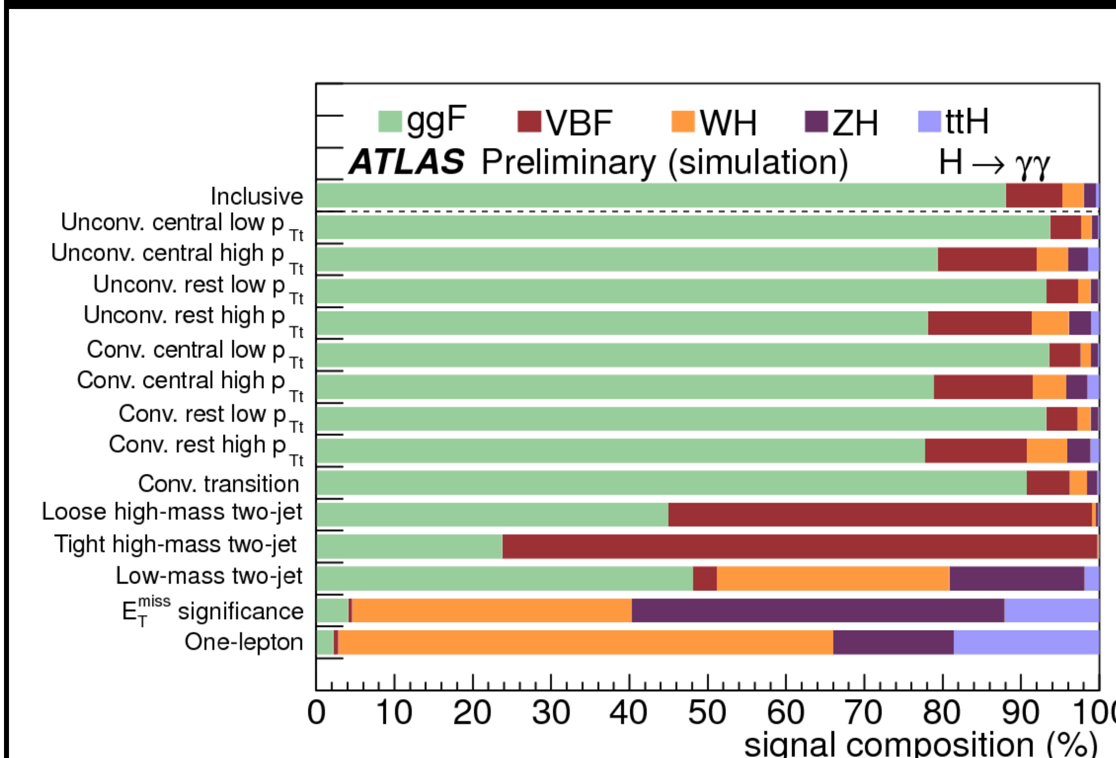


H → γγ: analysis strategy

exclusive event categories: to increase overall sensitivity and sensitivity to individual production modes (VH, VBF).

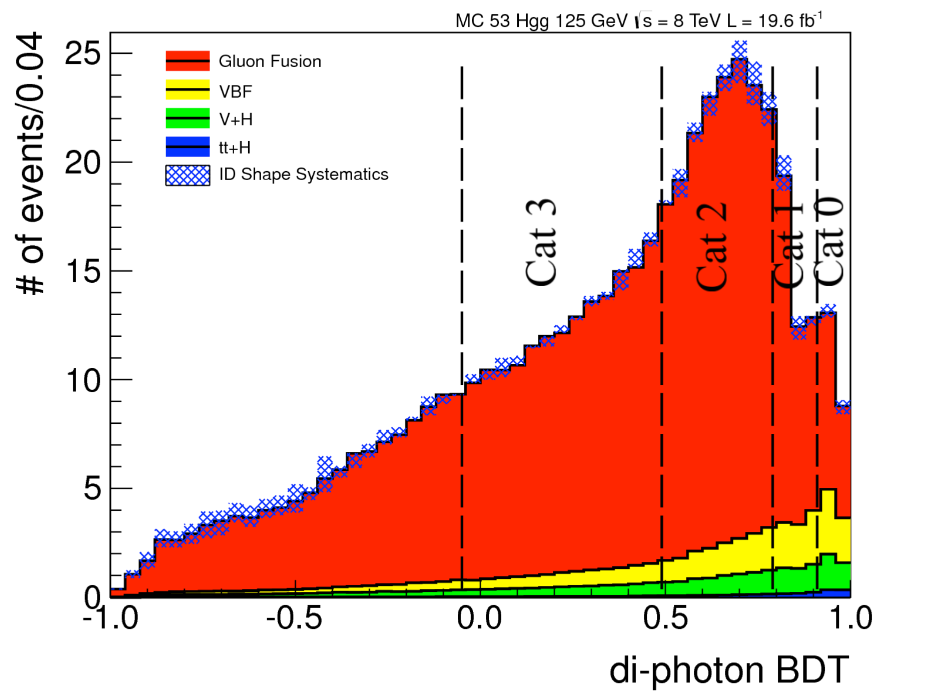


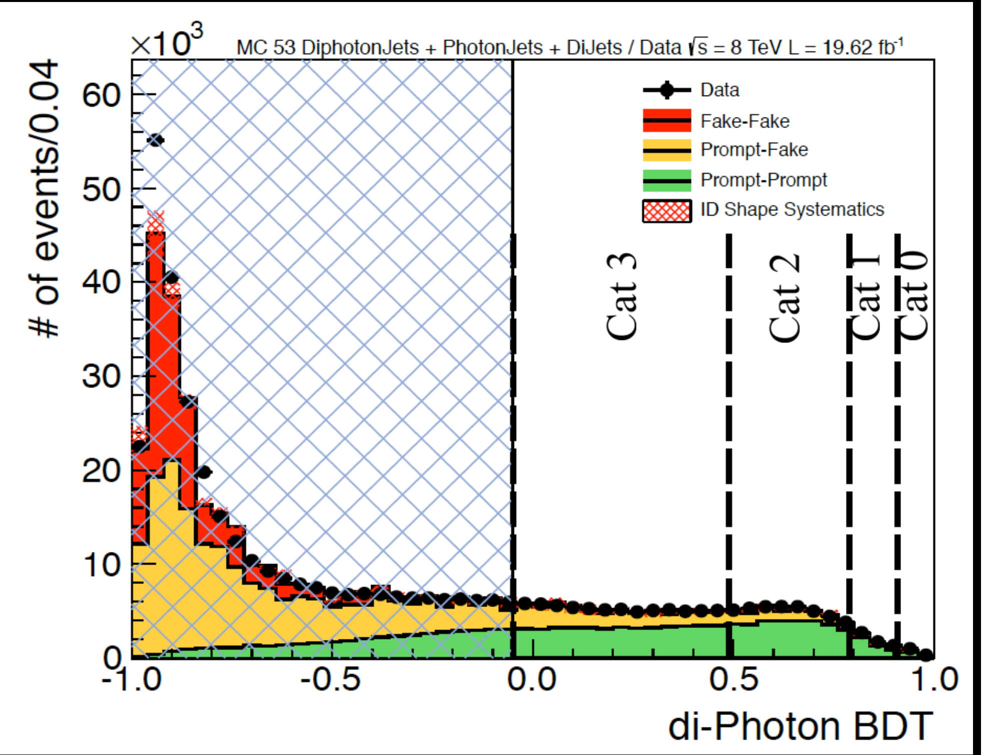
caution: purity of categories varies!



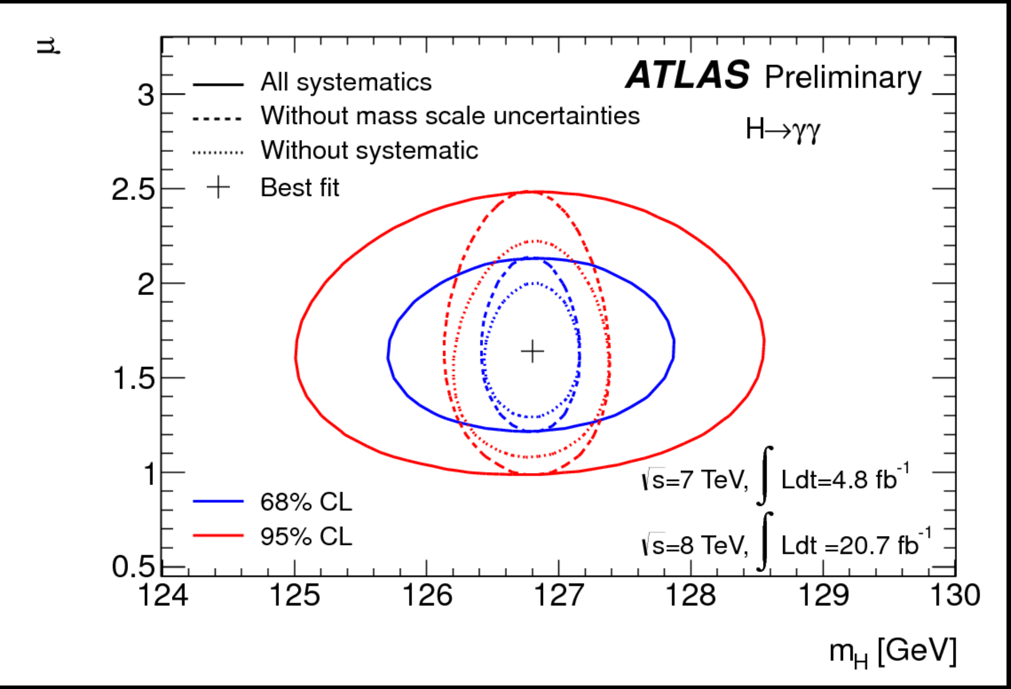
H → $\gamma\gamma$: analysis strategy

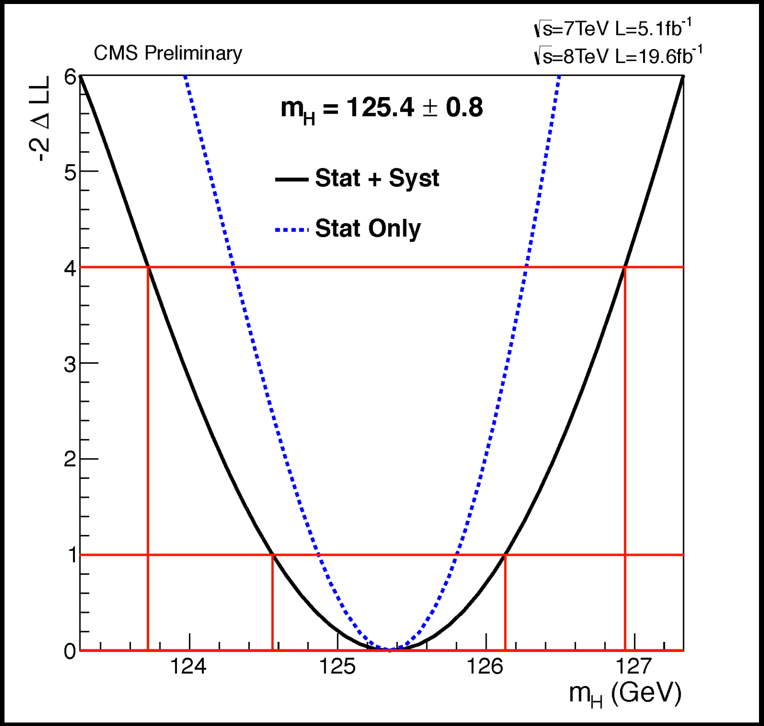
- 4 event classes based on a Boosted Decision Tree output
- BDT inputs:
  - Kinematic information, photon Id classifier, estimated mass resolution
- Additional exclusive classes for VBF and VH





H→γγ: Mass Measurement



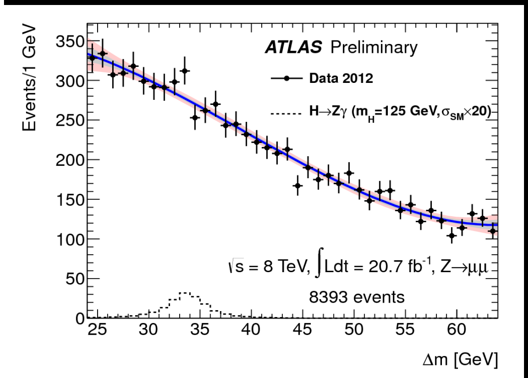


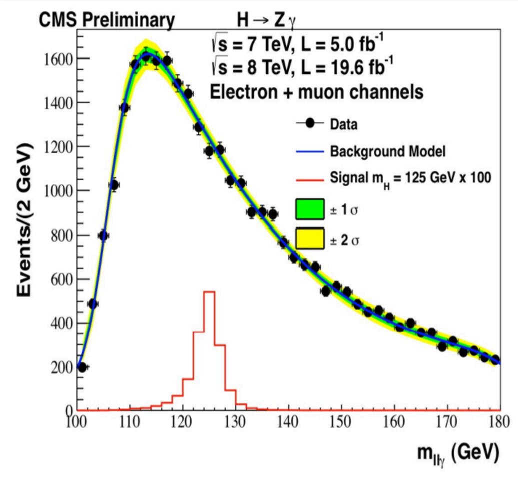
ATLAS: M_H= 126.8 ± 0.2(stat.) ± 0.7 (syst.) GeV

CMS: M_H= 125.4 ± 0.5(stat.) ± 0.6 (syst.) GeV

mass measurements limited by systematic uncertainties

$H \rightarrow Z\gamma \rightarrow ll\gamma$





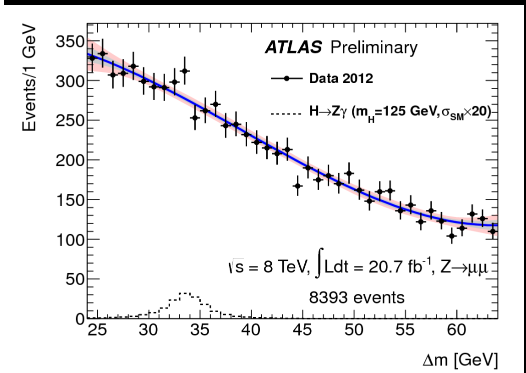
- A loop-mediated decay.
- In certain models this channel could be largely enhanced. Measurement/limit can constrain BSM models.
- Z decays into 2 charged leptons.

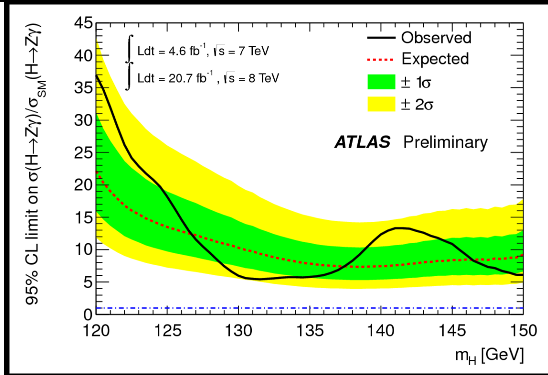
- BR ($H \rightarrow Z\gamma$) is comparable to BR($H \rightarrow \gamma\gamma$) , but BR ($Z \rightarrow ll$) reduces sensitivity (factor 15)

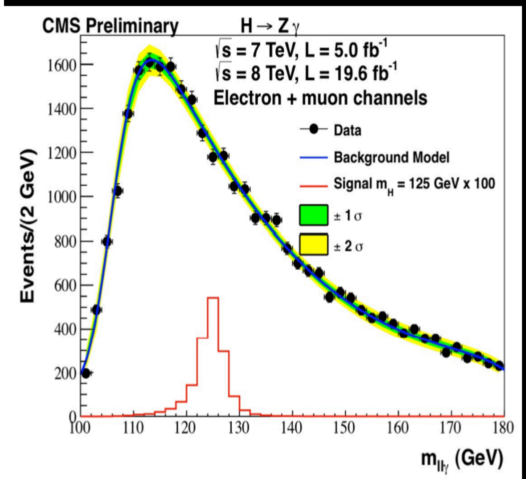
- mass reconstruction using dileptons and the photon.

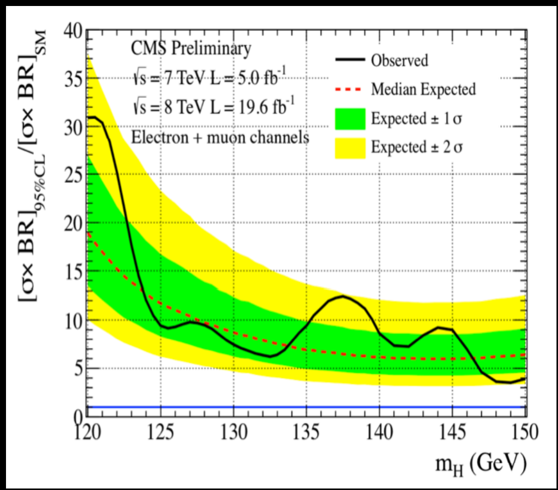
- Search for a narrow $ll\gamma$ peak on top of a falling background, similar to $H \rightarrow \gamma\gamma$

H→ Zγ→ llγ









- A loop-mediated decay.
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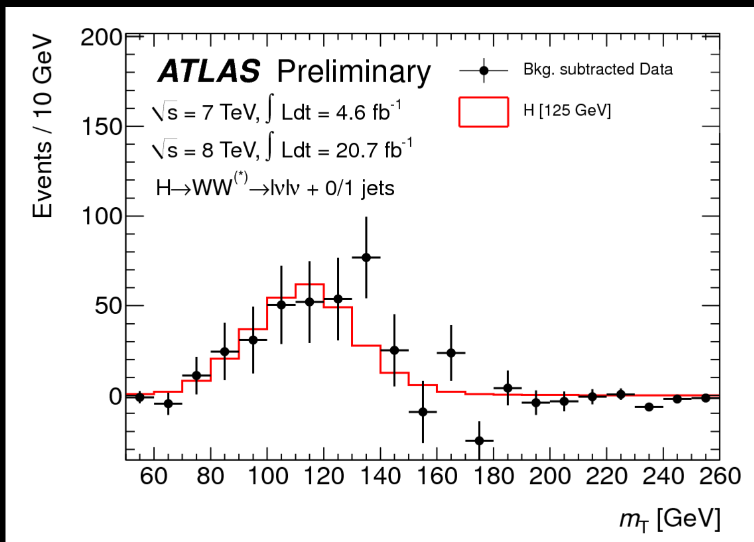
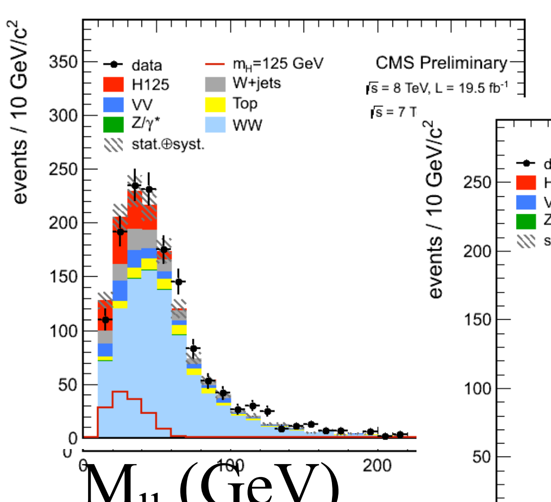
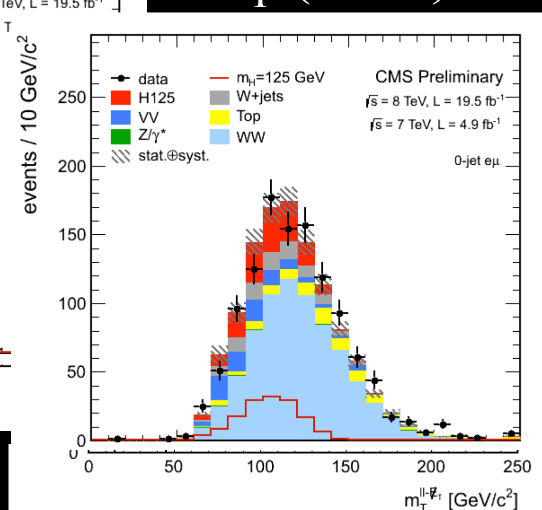
H→WW → lνlν





M_T (GeV)

M_{ll} (GeV)



A significant excess is observed…

- two high-pT leptons and Missing E_T
- Scalar Higgs boson + V-A structure of W decay favors small opening angle between the 2 charged leptons (tend to have small Δφ)
- Most sensitive channel around $2xM_W$
  - gives the smallest error on μ
- No narrow mass peak mass resolution ~20%
- Backgrounds
  - irreducible: WW
  - Z+jets, tt, W + jets, WZ
  - BG estimation is crucial and based on control regions from data for most processes.

Perform analysis in bins of jet multiplicity
- sensitivity to different S/B
- Sensitivity to VBF

ATLAS: m_T-distribution

CMS:

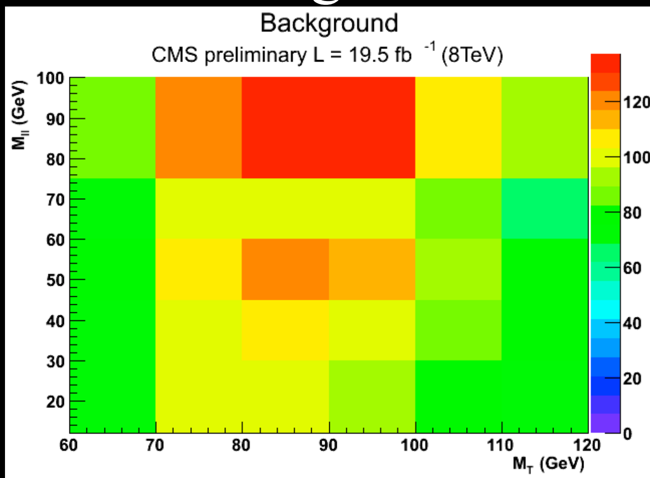
Different-flavor: 2D distribution $N(m_{ll},m_T)$

Same-flavor dileptons

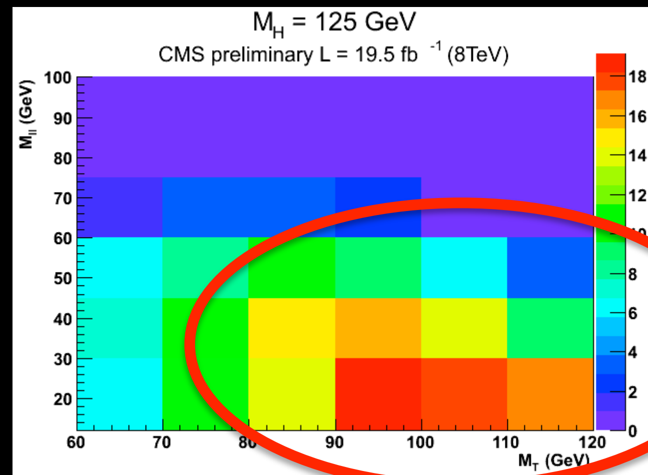
WW→lνlν

- CMS: 2D analysis (0 jet bin)

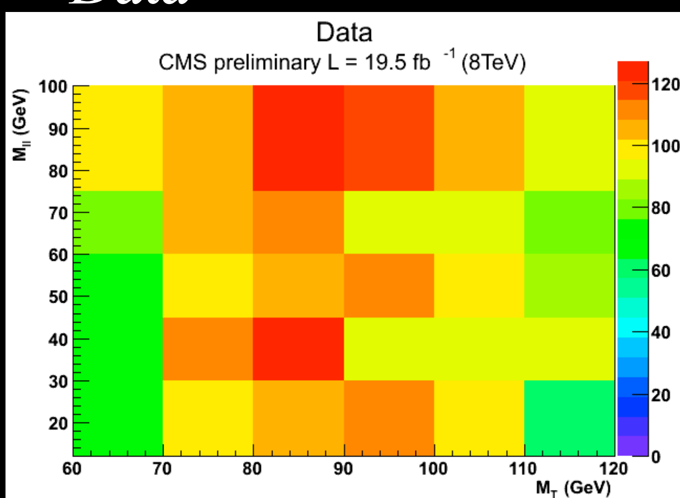
MC Background



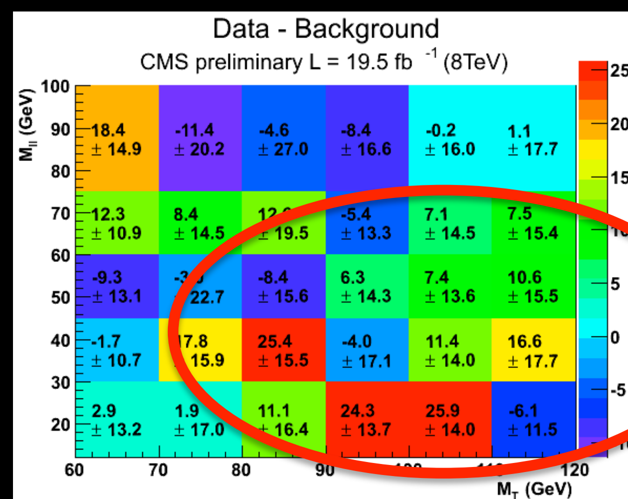
Higgs signal at 125 GeV



Data



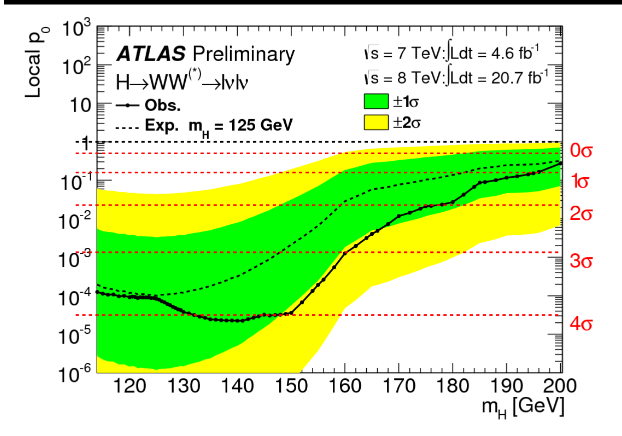
BG subtracted data



Signal region

H→WW→lνlν : results

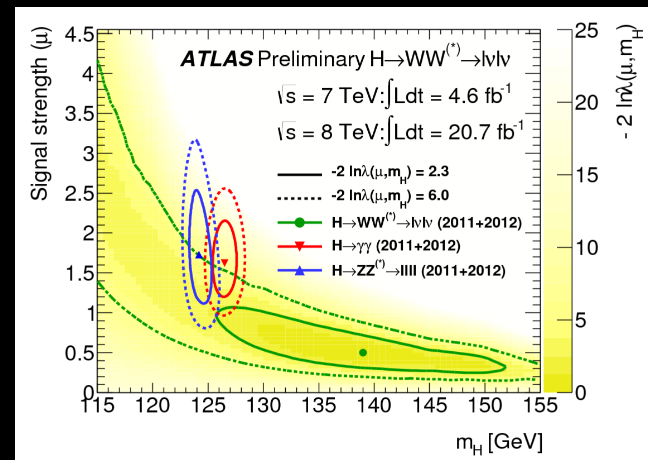
- Significance Signal Strength (μ)

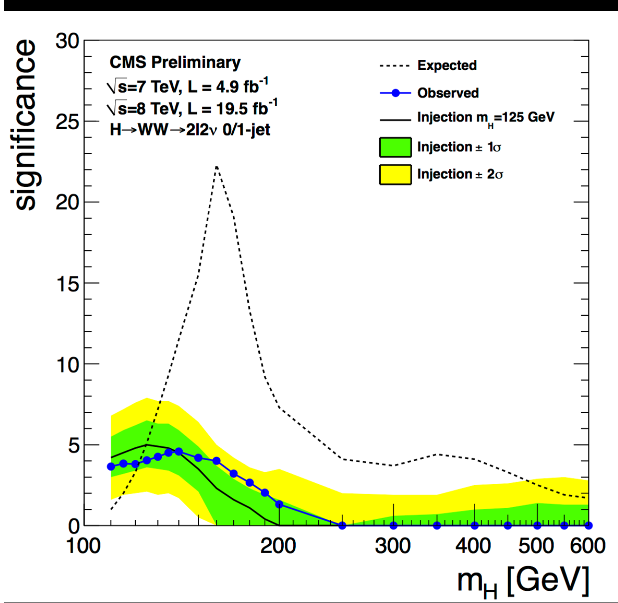


p-value:
Expected: 3.7σ
Observed: 3.8σ

$\mu = \sigma/\sigma_{SM} = 1.01 \pm 0.31$

@ m_H = 125 GeV

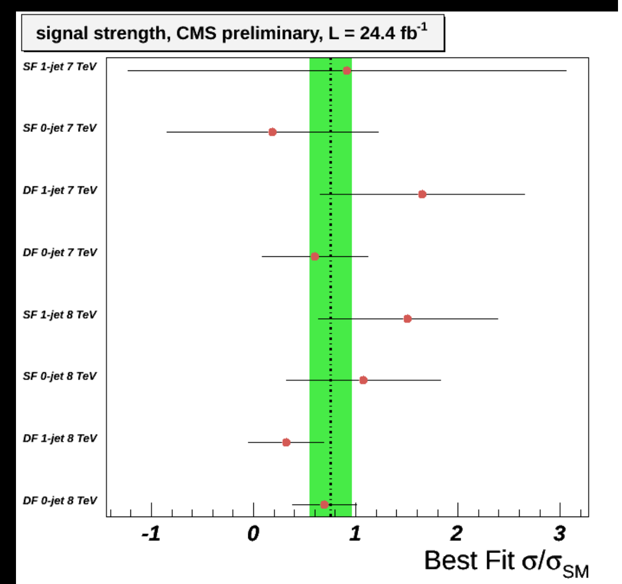




p-value:
Expected: 5.0σ
Observed: 4.0σ

$\mu = \sigma/\sigma_{SM} = 0.76 \pm 0.21$

@ m_H = 125 GeV



Higgs Decays to Fermions

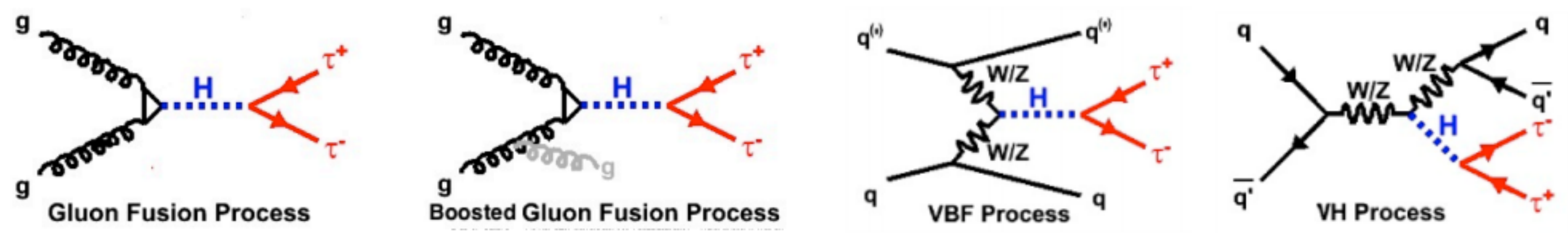
$H \rightarrow \tau\tau$

$H \rightarrow bb$

SIGNATURES OF THE HIGGS

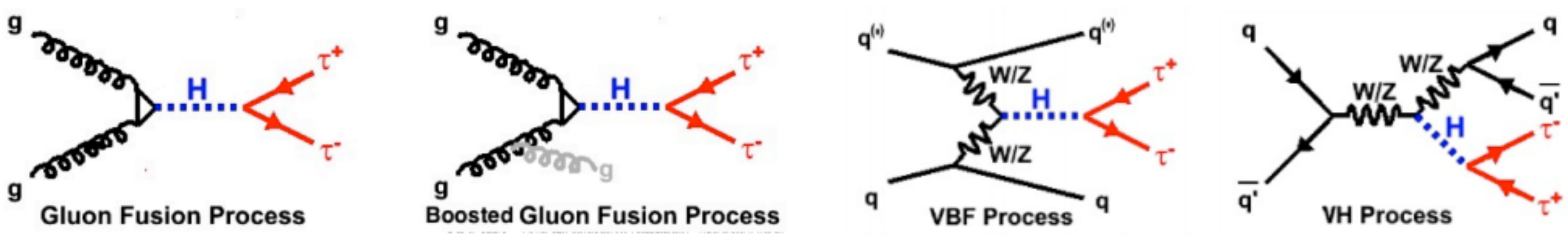
H→ττ

- multiple signatures



H→ττ

- multiple signatures



Decay

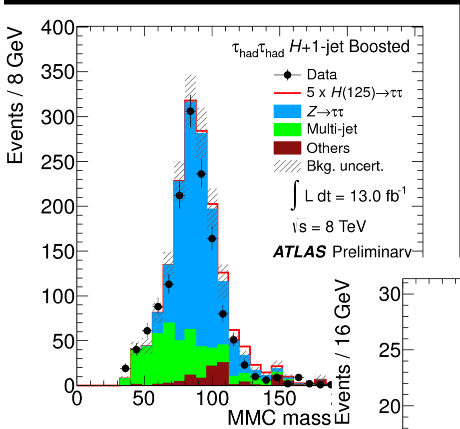
$$H \to \tau\tau \to \ell\ell + 4\nu \ (12\%)$$
$$H \to \tau\tau \to \ell\tau_h + 3\nu \ (46\%)$$
$$H \to \tau\tau \to \tau_h\tau_h + 2\nu \ (42\%)$$

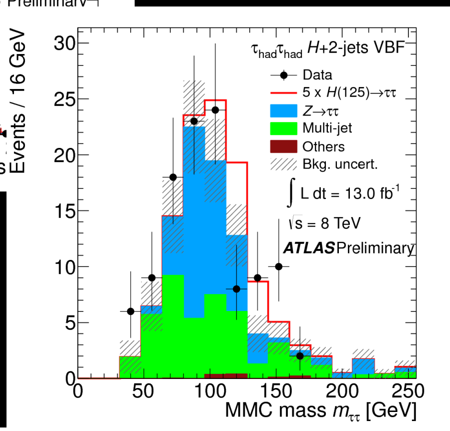
$\otimes$

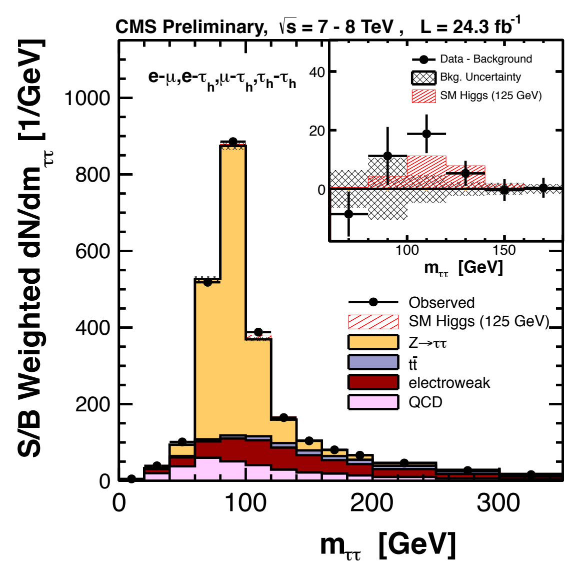
Production/signature

0-jet
1-jet boosted
2-jet VBF
VH (use leptonic decays of V)

H→ττ

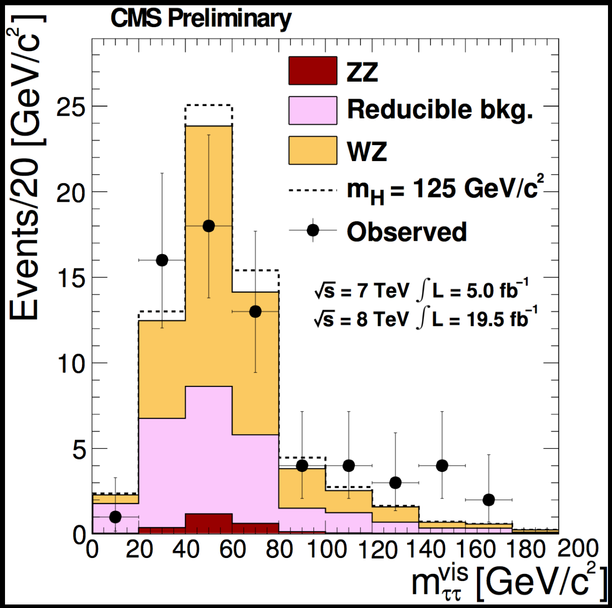






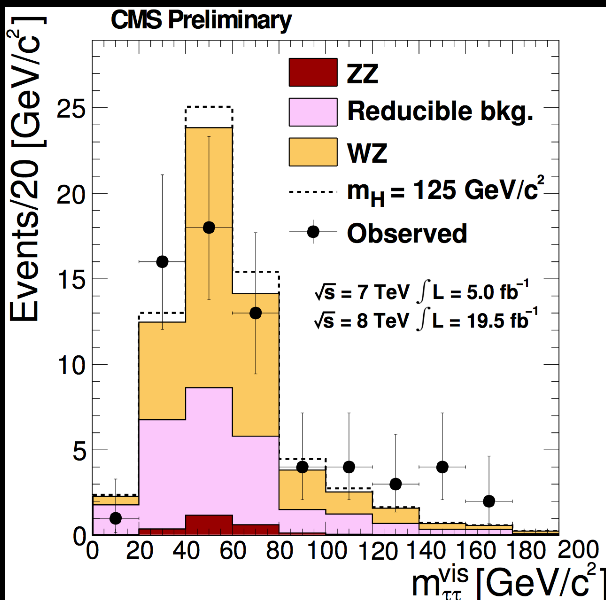
- di-tau candidates: $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
- reconstruct di-tau mass (including missing E_T)
- poor mass resolution ≈15%
- Higgs signal on a falling slope
- Backgrounds:
  - Z→ττ: use Z→μμ data, replace μ with simulated τ decay and use normalization from Z→μμ data
  - Z→ee, W+jets, ttbar: MC for shapes, data for normalization
  - QCD: from control regions

VH → $V\tau\tau$



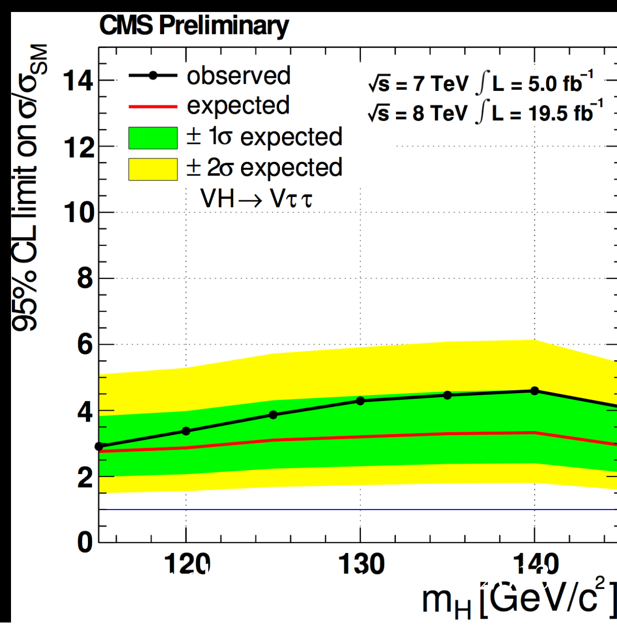
- Study topologies of 3 and 4 lepton final states
- Use tau decay channels into electrons muons and hadronic final states

VH → Vττ



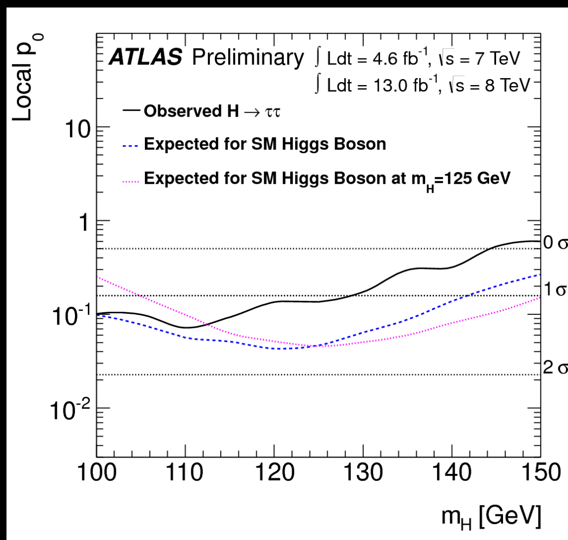
- Study topologies of 3 and 4 lepton final states
- Use tau decay channels into electrons muons and hadronic final states

- Upper limits of 2.9 to 4.6 times the predicted Standard Model value for σxBR at 95% CL.



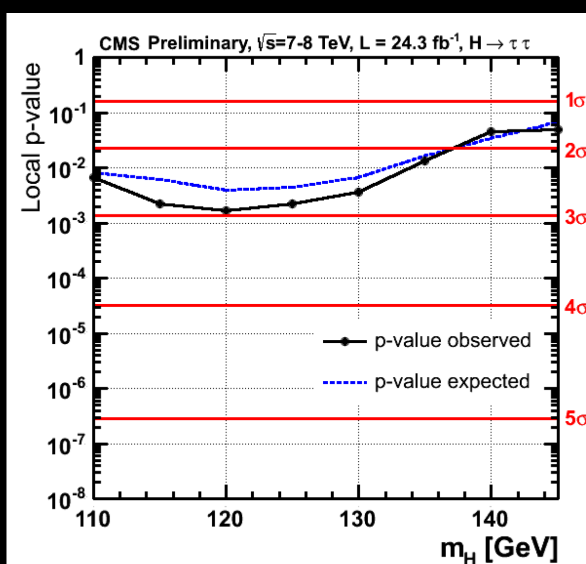
H→ττ : results

- Significance



p-value:
Expected: 1.7σ
Observed: 1.1σ

@ m_H = 125 GeV

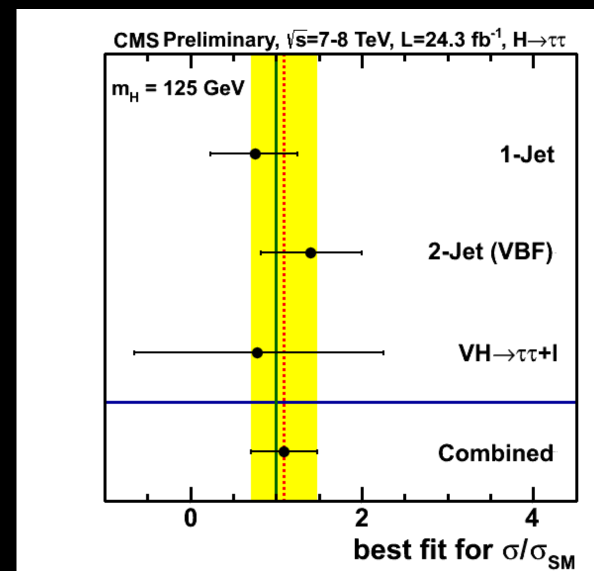


p-value:
Expected: 2.6σ
Observed: 2.9σ

$\mu=\sigma/\sigma_{SM}$ = 1.1 ±0.4

@ m_H = 125 GeV

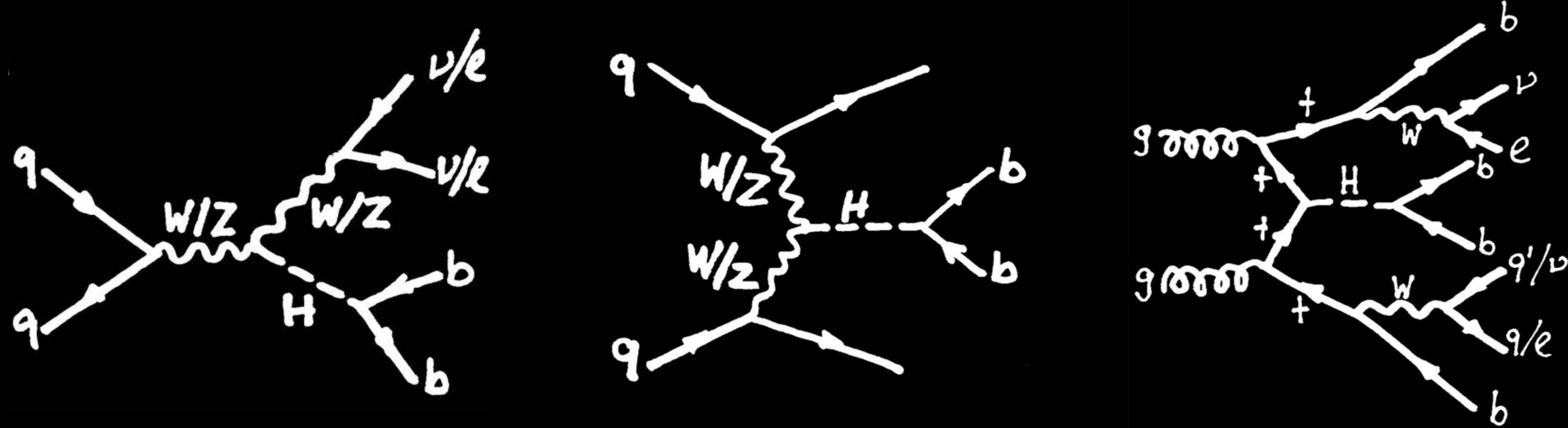
Signal Strength (μ)



include VH results

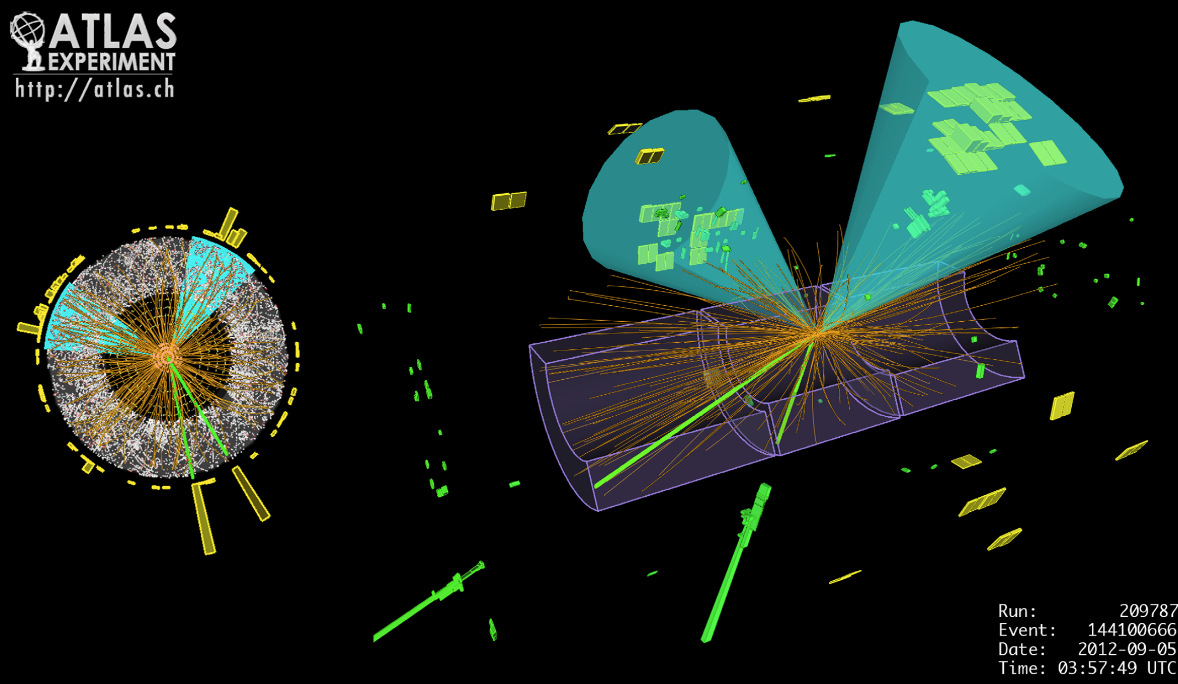
H→bb

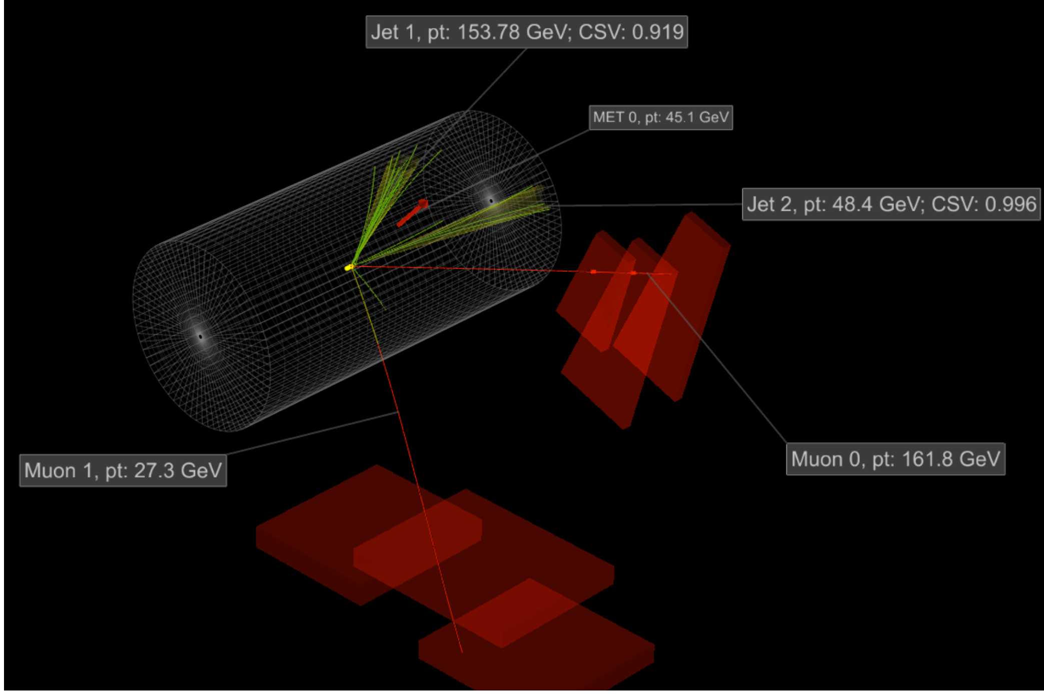
- process: VH, VBF and ttH



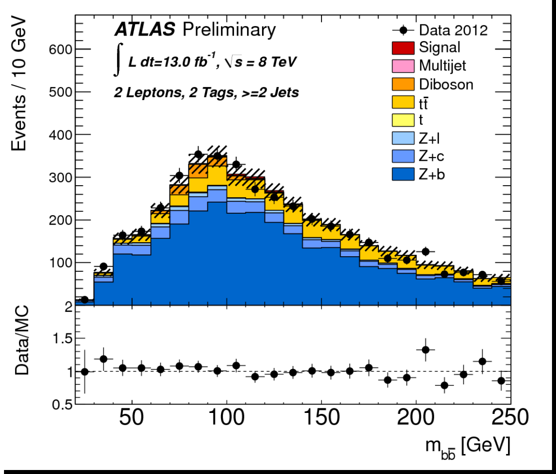
- Large rate BR(H→bb)~58% (mH=125 GeV)
- Provides direct constraint to Higgs couplings to fermions/ quarks
- Challenging due to high jet background

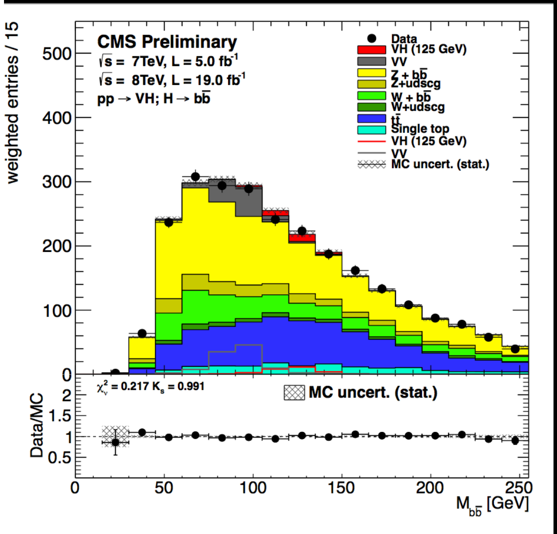
VH→bb candidate





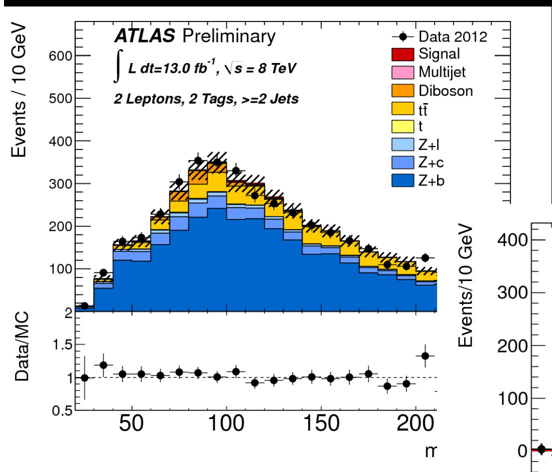
VH→bb

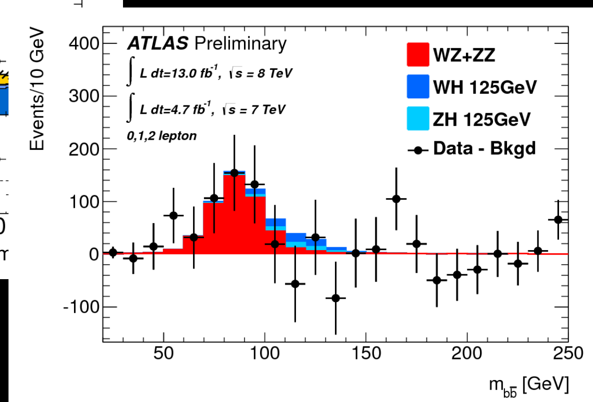


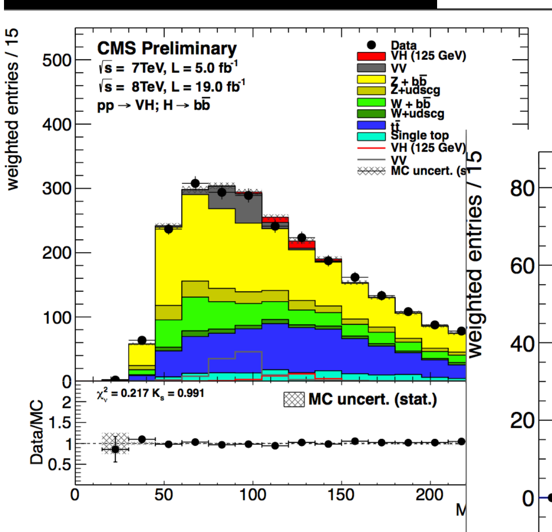


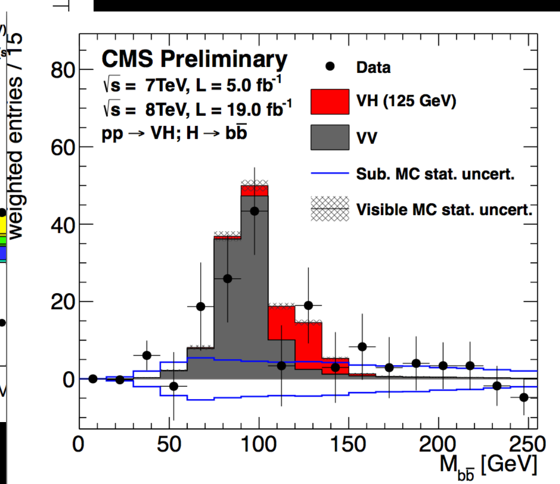
- event selection:
  - eν, μν, ee, μμ, νν
  - 2 b-tagged jets (70% efficiency)
  - split analysis in 0, 1, and 2-lepton categories
- reconstruct mass using b-jets
- use BDT regression (σM/M = 8-9%)
- backgrounds
  - W/Z bb, W+jets, tt
- maximize sensitivity
  - s/b better for boosted Higgs boson
  - split analysis in bins of $p_T(V)$
  - 15 categories (0,1,2 jets x p_T bins)

VH→bb









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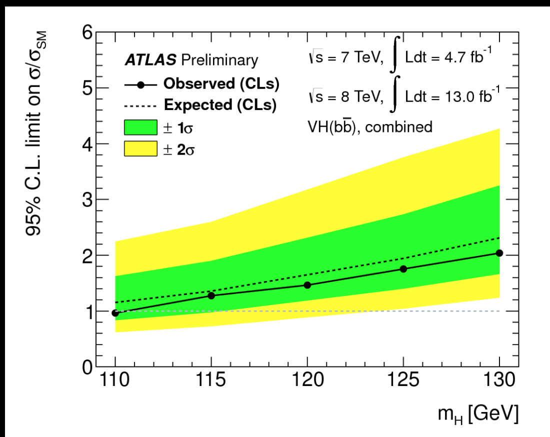
reconstruct mass using b-jets

use BDT regression ($\sigma M/M$ = 8-9%)

- backgrounds
  - W/Z bb, W+jets, tt

maximize sensitivity
  - s/b better for boosted Higgs boson
  - split analysis in bins of $p_T(V)$
  - 15 categories (0,1,2 jets x p_T bins)

VH→bb: results



95% C.L.:

Expected: 1.9 x σ_{SM}

Observed: 1.8 x σ_{SM}

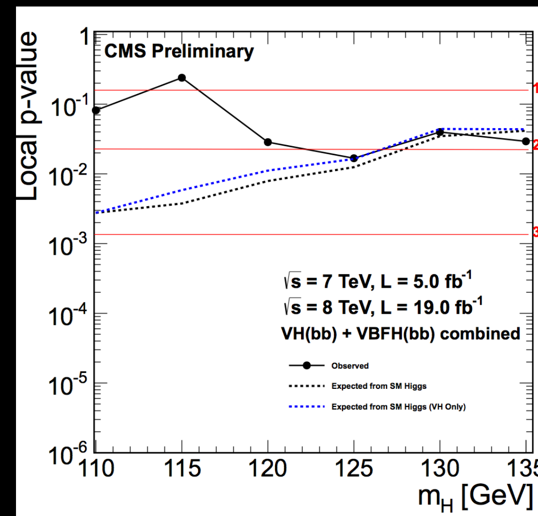
WW+WZ:

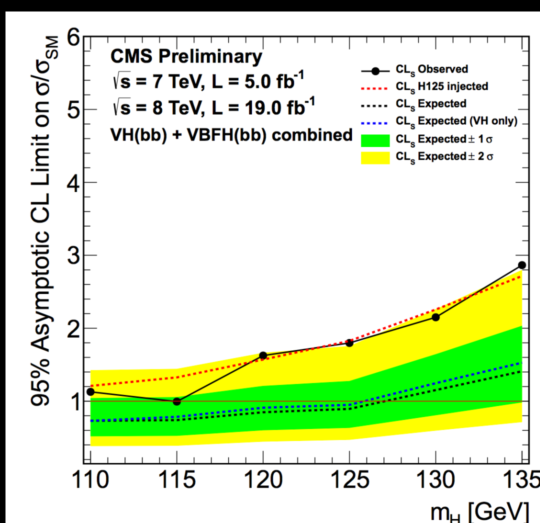
μ=1.09 ±0.22

@ m_H = 125 GeV

$\mu=\sigma/\sigma_{SM}$ =-0.4 ±0.8

Significance





Combined VH/VBF

p-value:

Expected: 2.1σ

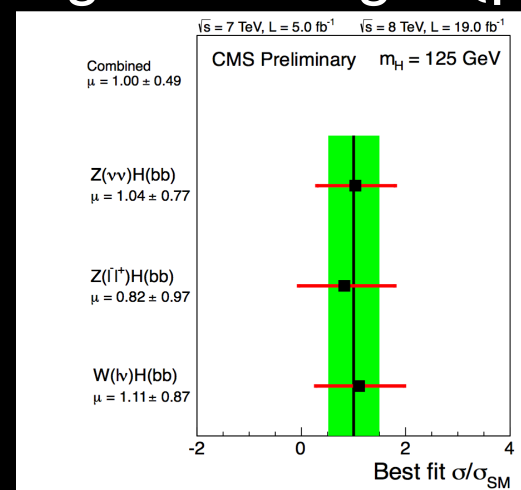
Observed: 2.2σ

$\mu=\sigma/\sigma_{SM}$ = 0.97 ±0.5

@ m_H = 125 GeV

Combined with H->ττ significance 3.4 σ

Signal Strength (μ)

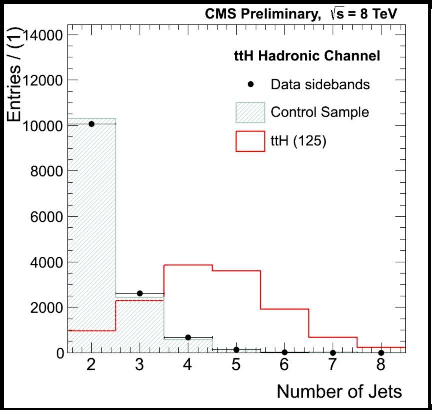


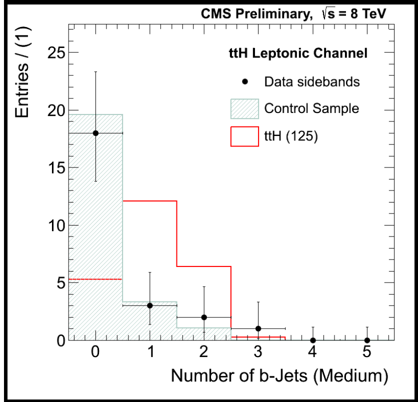
ttH w/ H→bb & H→$\gamma\gamma$

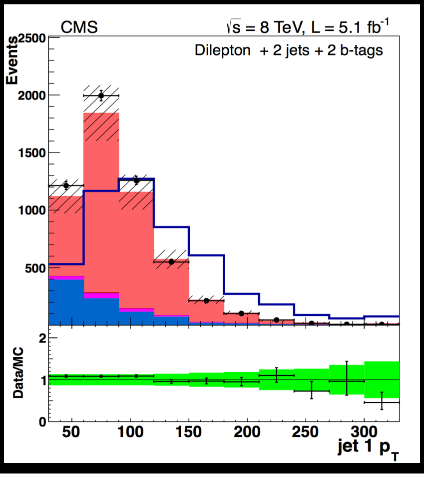
H→bb: shape analysis of NN output

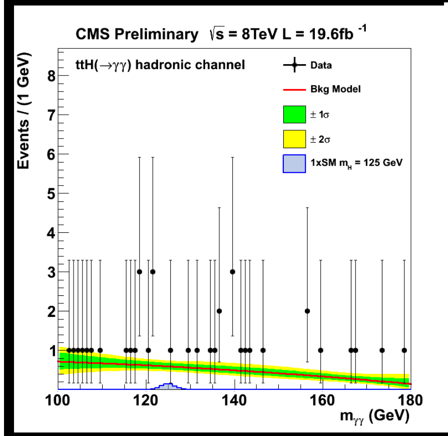
B-tagging of jets, Kinematic of jets, M_{bb}

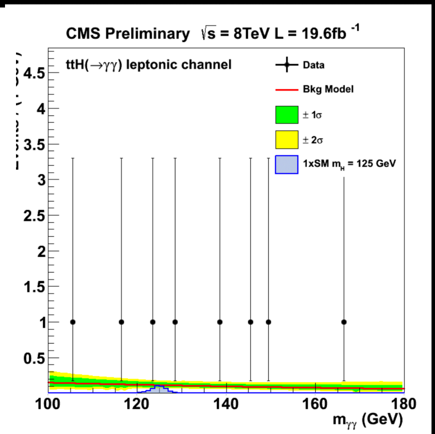
H→$\gamma\gamma$: select leptonic and hadronic ttbar events with btags and photons











ttH w/ H→bb & H→$\gamma\gamma$

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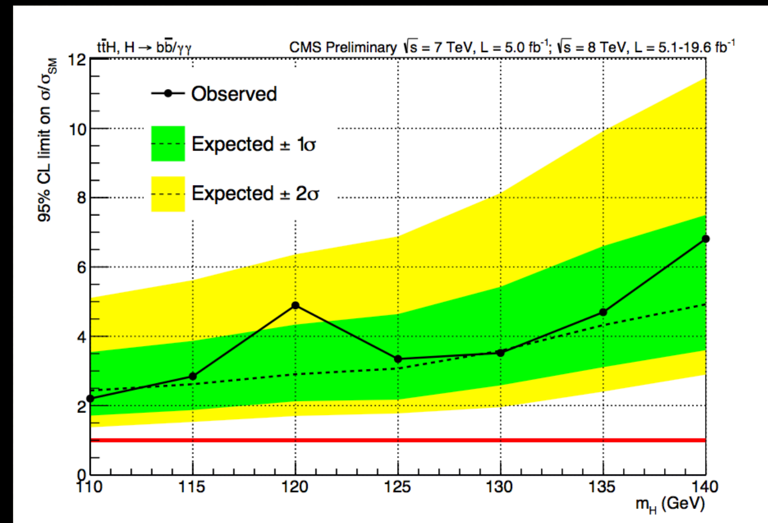
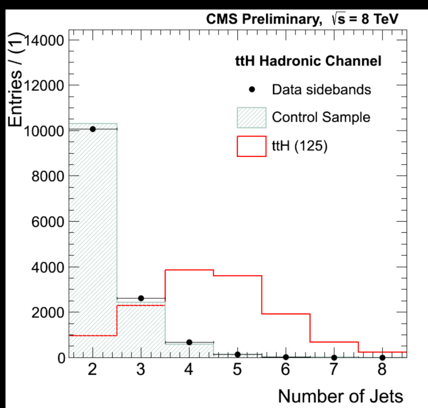
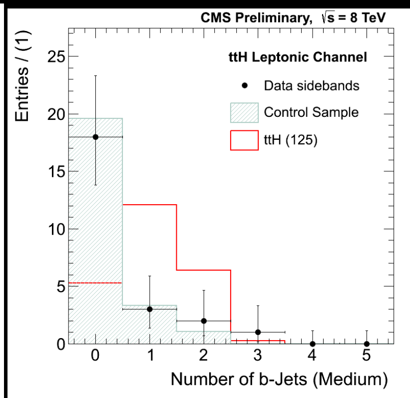
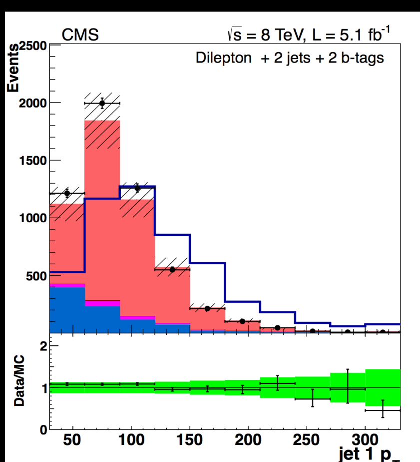


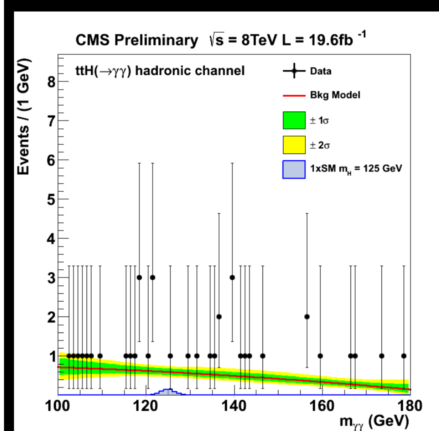
95% C.L. Limit:
Expected: 3.1 xSM
Observed: 3.3 xSM

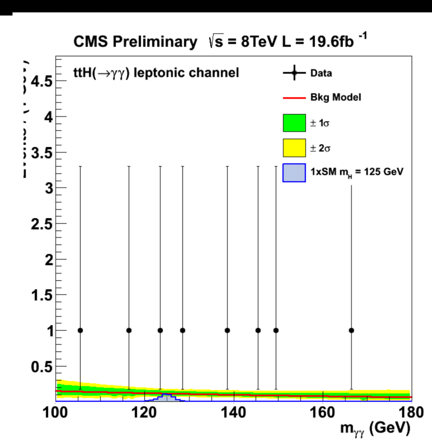
Sensitivity to 1-2 xSM within reach with full data set/all channels!



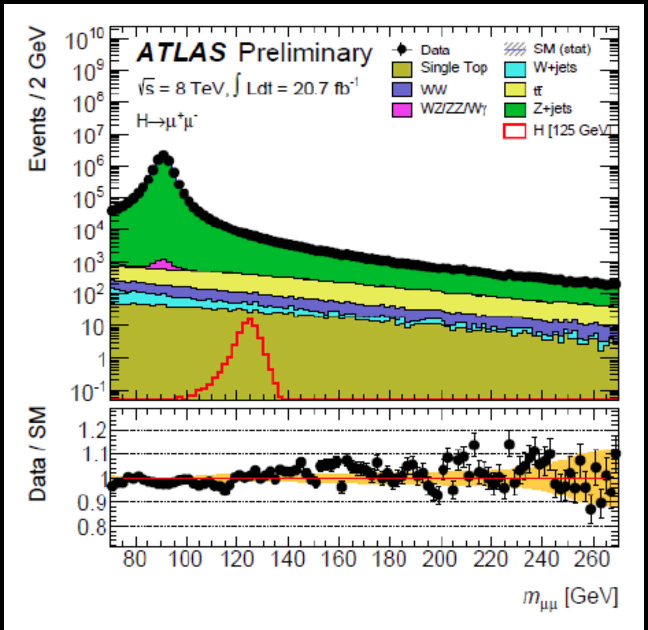








H → μμ



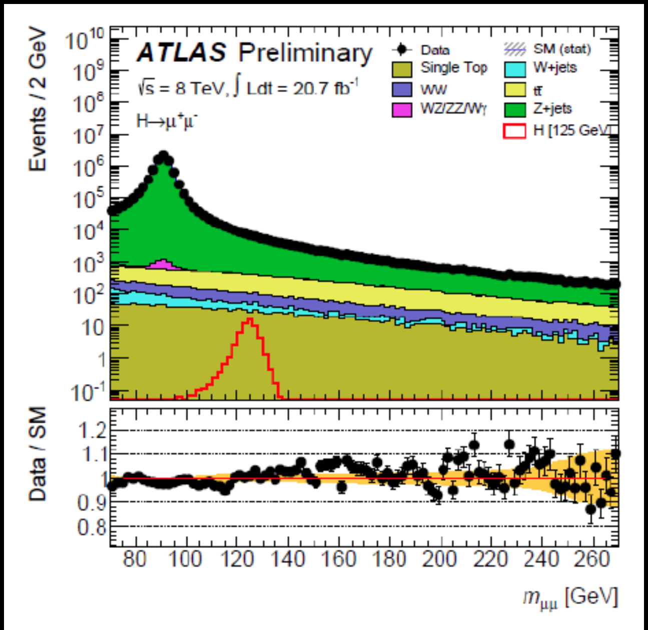
- Extremely low rate process

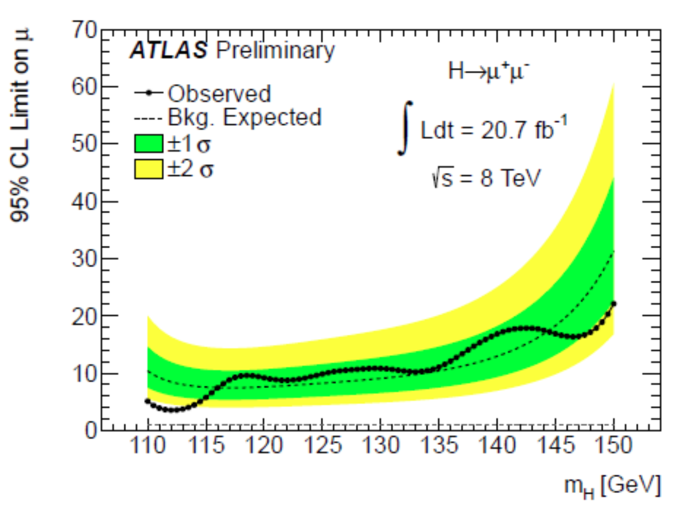
BR(H→μμ)~2.2x10^{-4} @m_H=125 GeV

- two prompt muons
- reconstruct mass using dimuons
- mass resolution = 2%

- Background: fit using sidebands

H → μμ





- Extremely low rate process

BR(H→μμ)~2.2x10^{-4} @m_H=125 GeV

- two prompt muons
- reconstruct mass using dimuons
- mass resolution = 2%

- Background: fit using sidebands

- Results (ATLAS):

μ>10 is excluded at 95% CL

(@mH=125 GeV)

Significance of the Excess

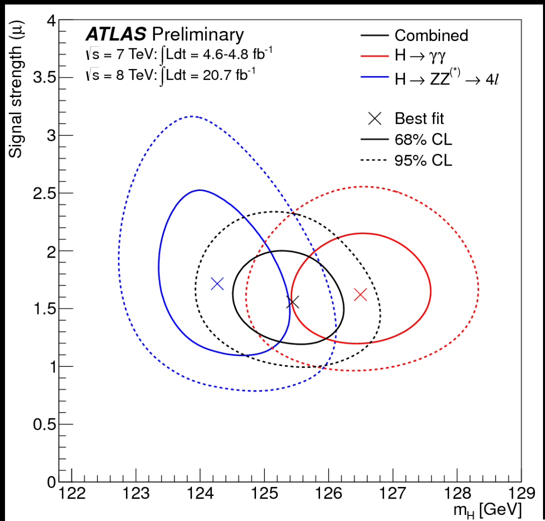
	ATLAS		CMS		
	expected	**observed**	expected	**observed**	observed
H→ZZ	4.4	**6.6**	7.1	**6.7**	
H→γγ	4.1	**7.4**	4.2	**3.2**	
H→WW	3.7	**3.8**	5.6	**3.9**	
H→ττ	1.6	**1.1**	2.6	**2.9**	3.4
H→bb	1.0	**0**	2.1	**2.1**	
combined	7.3	**10**	stopped computing		

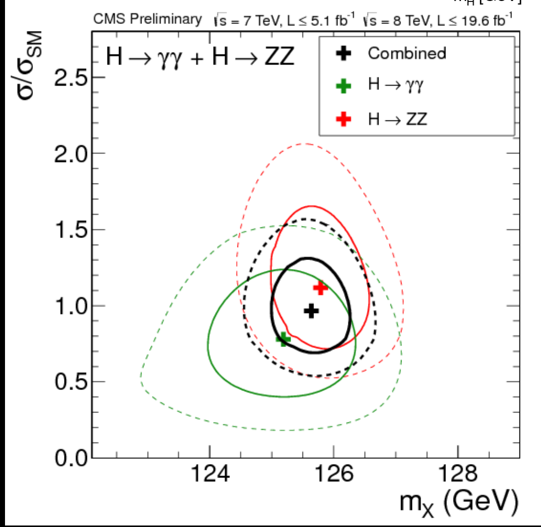
CMS mH=125.7 GeV
ATLAS mH=124.3 GeV
Higgs-like signal ? beyond any doubt !!

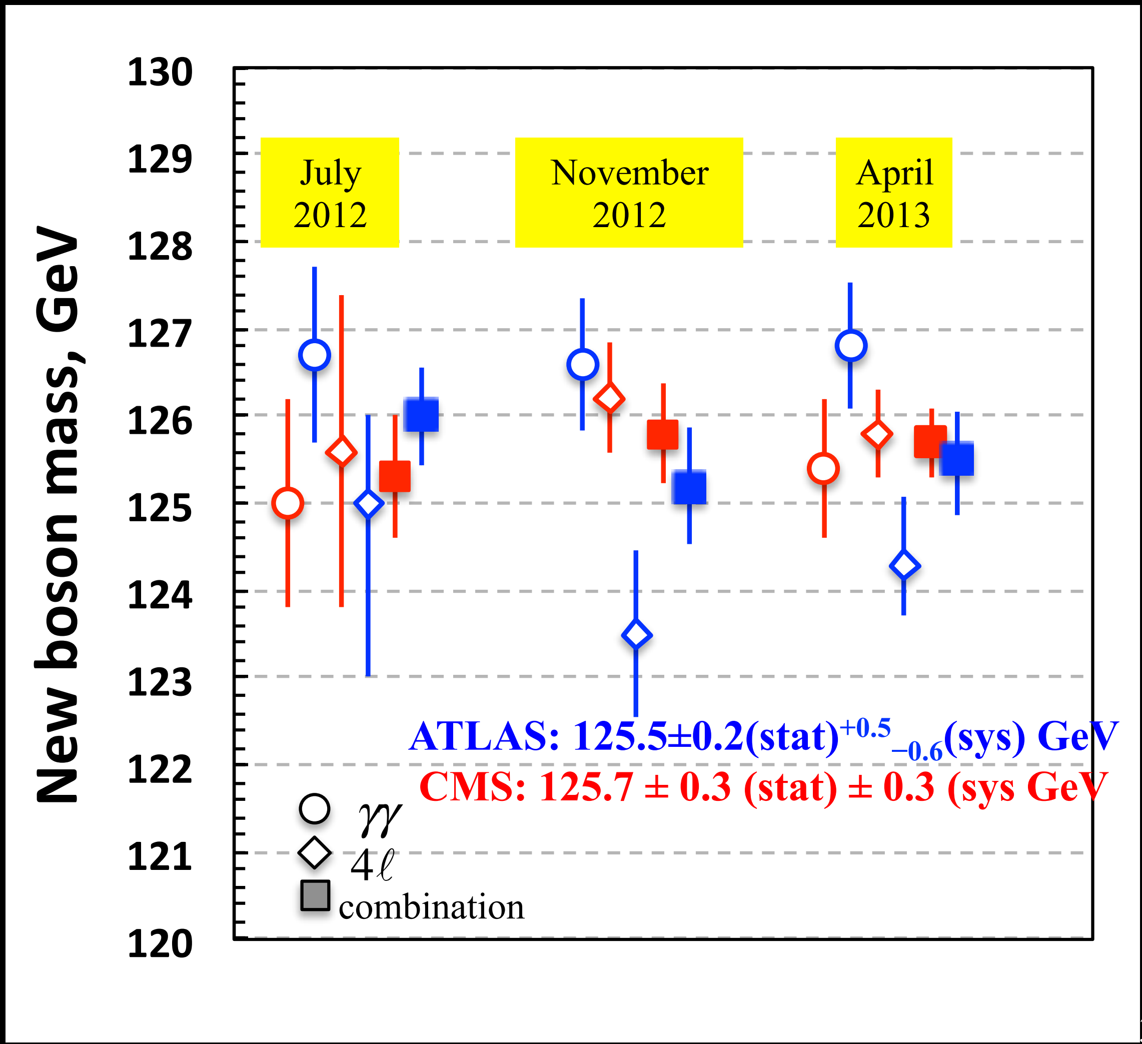
HIGGS PROPERTIES

Mass measurement

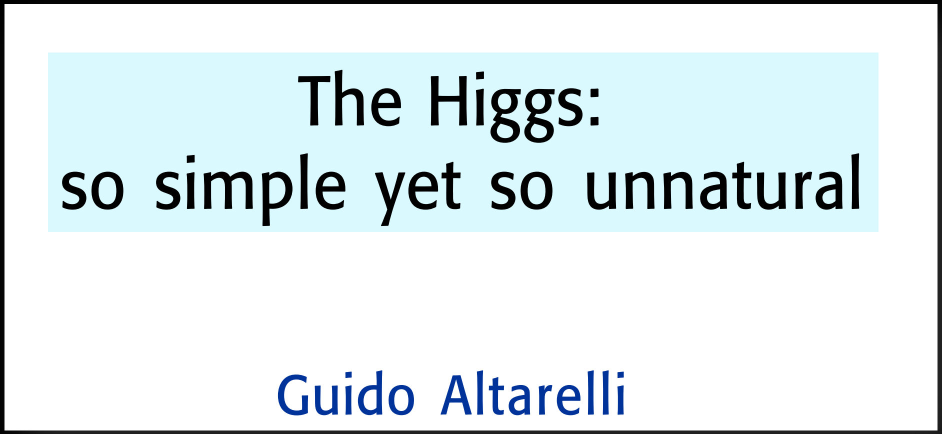
- Combine H→ZZ, H→$\gamma\gamma$ events



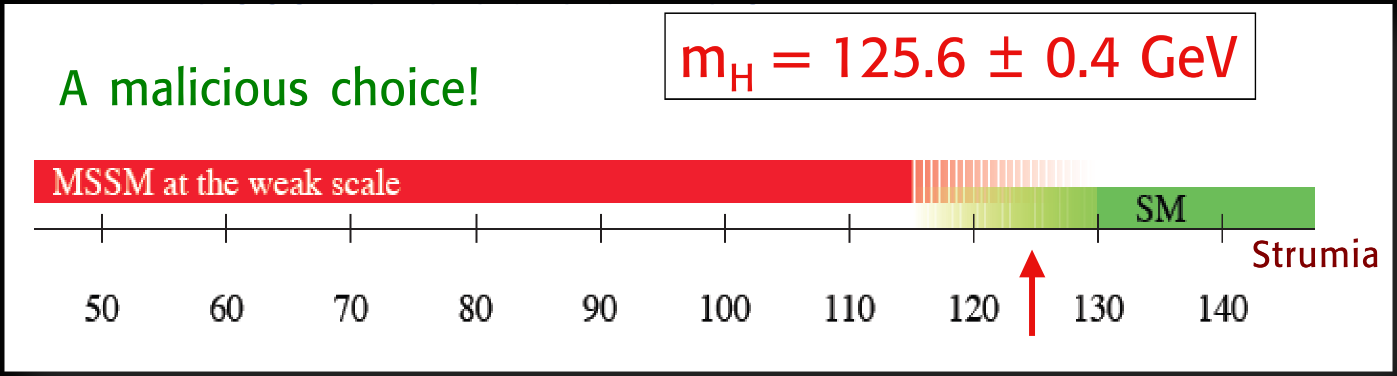




Implications of the mass msm’t



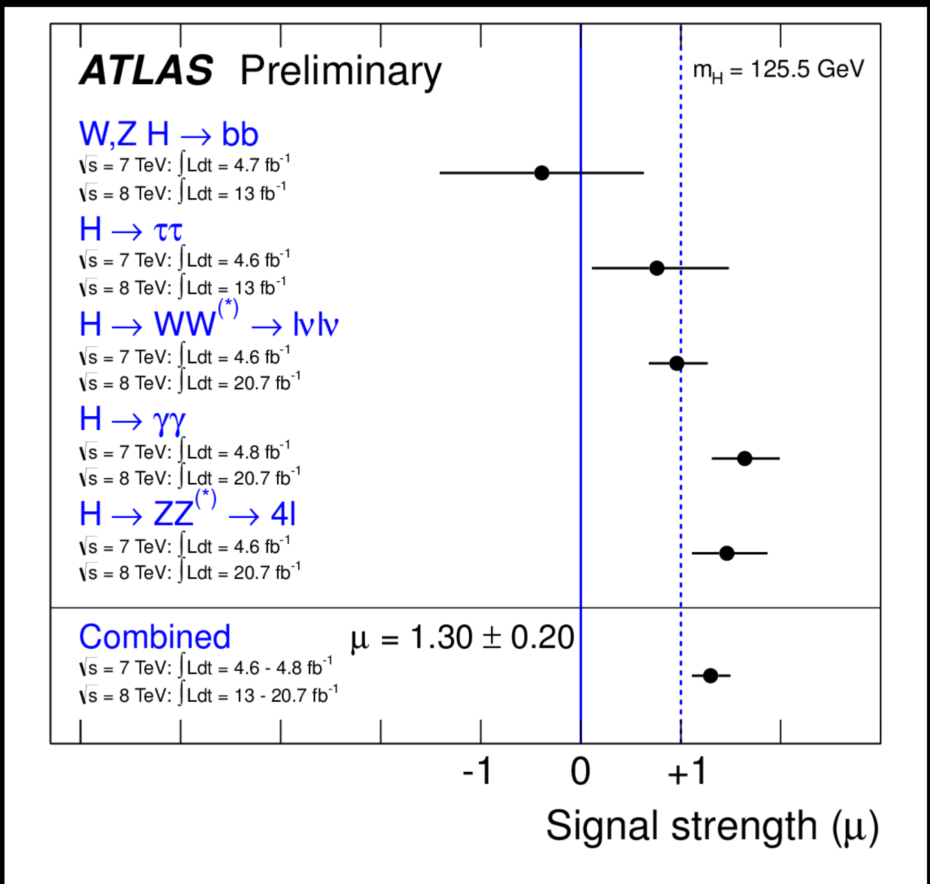
Presentations/ discussions *(Nobel Symposium, May 12-17 Uppsala)*

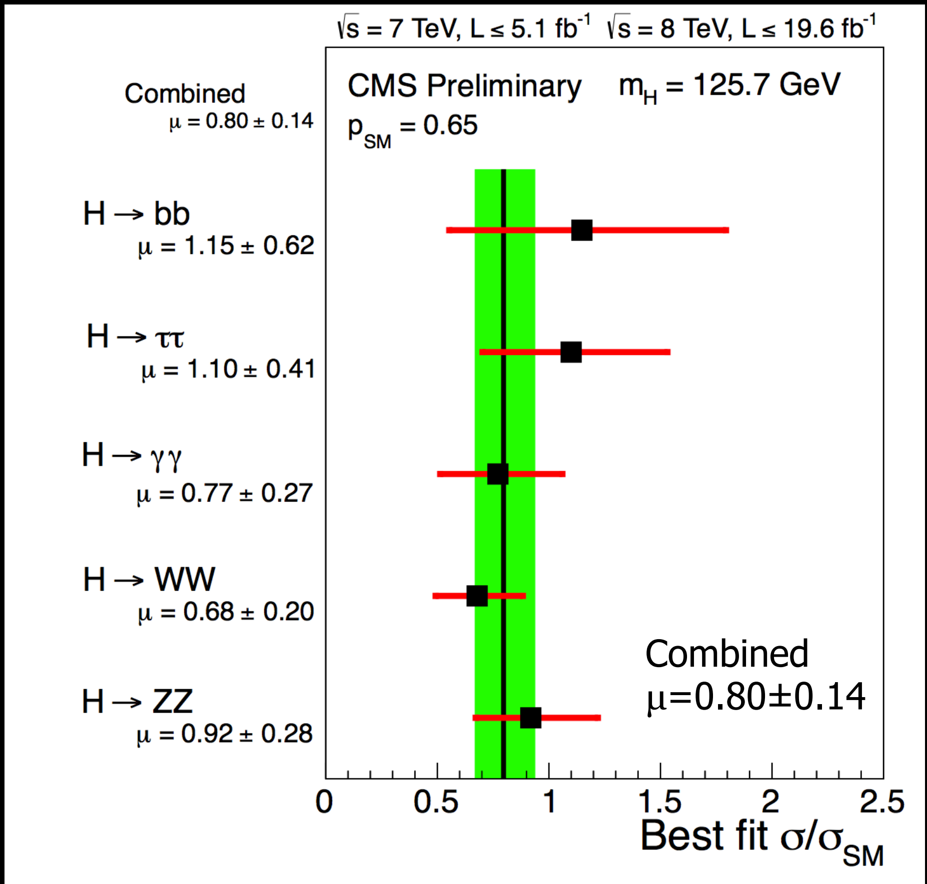


**G. Altarelli: https://indico.cern.ch/conferenceDisplay.py?confId=239571*

Consistency with SM Hypothesis

- Signal Strength: Maximum likelihood fit to data with signal rate scaling factor (**μ**) as free parameter.
- Ratios of production cross sections for the various processes (ggF, VBF,..) fixed to SM values.



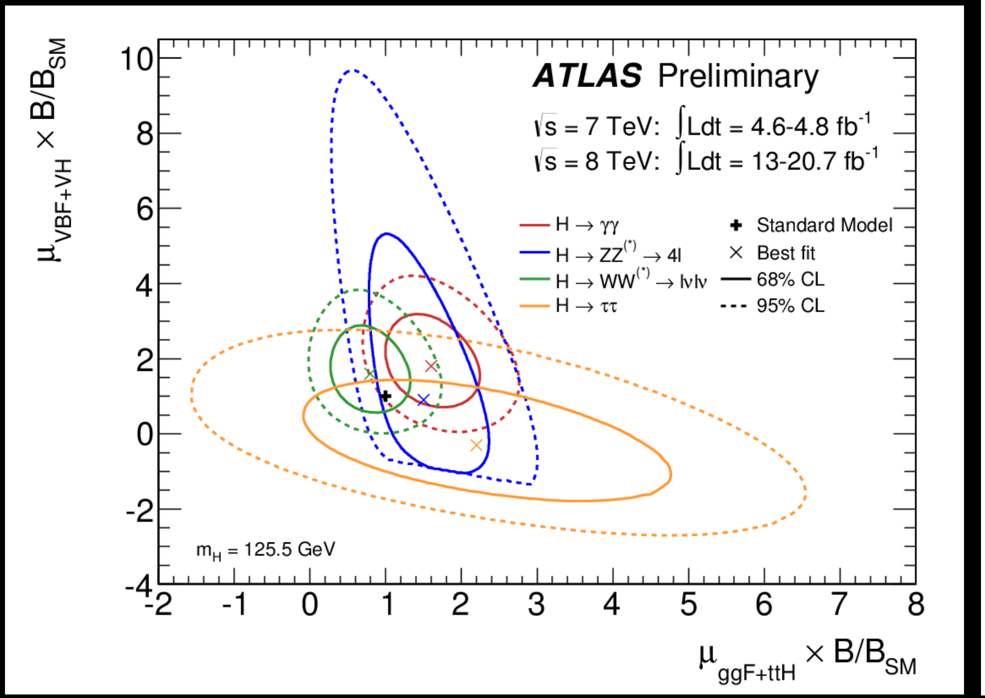


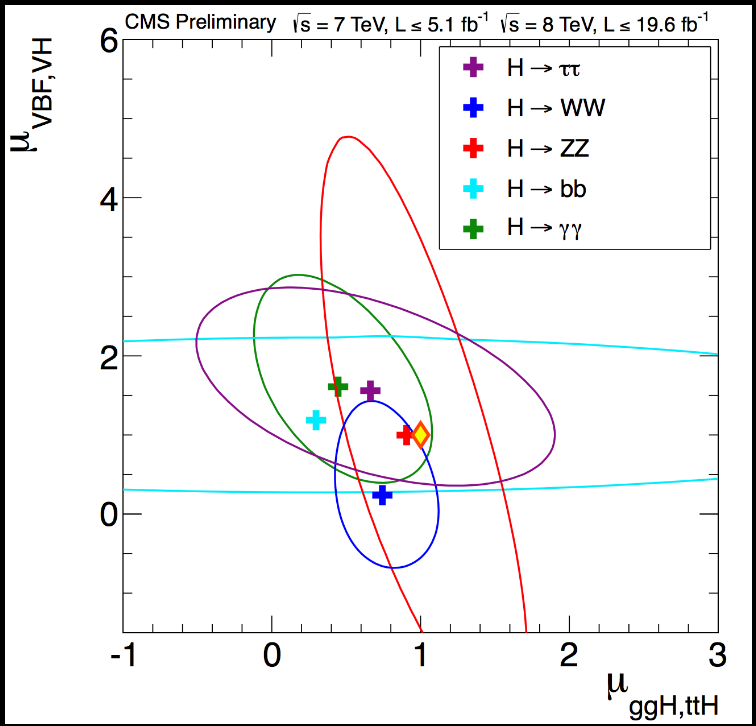
Signal strengths in fermionic decay modes have large uncertainties, but compatible with SM.

Gluon fusion vs vector boson fusion

- Sensitivity to (ggF + ttH) and (VBF+VH) production fractions, modulo branching ratio factors B/B_{SM}

Vector Boson Couplings

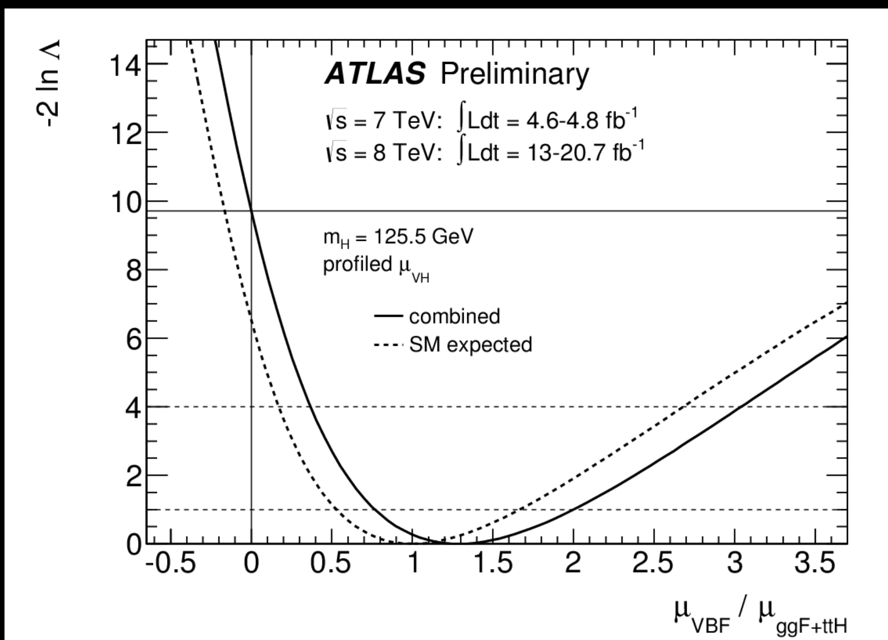


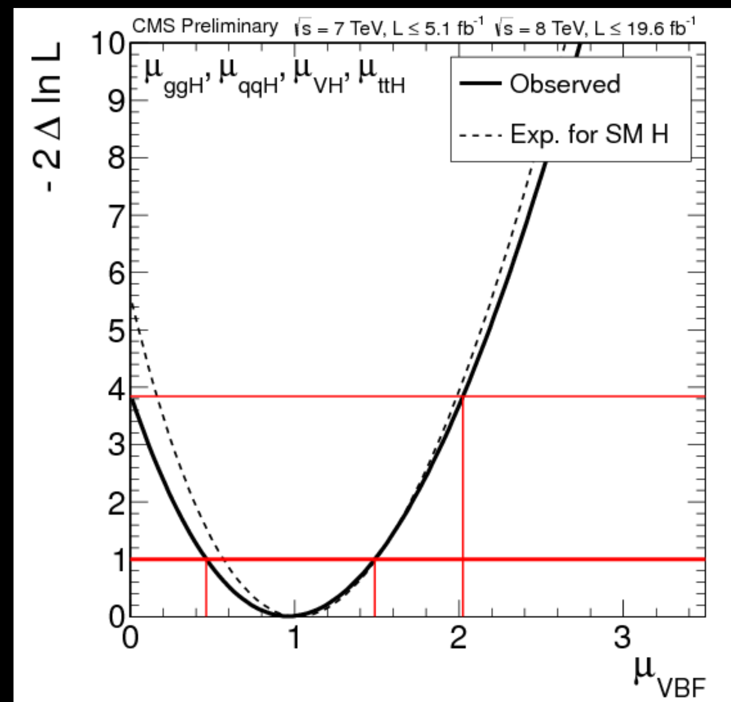


Fermion Couplings

Evidence for production via VBF

- Fit for the ratio of $\mu_{VBF+VH} / \mu_{ggF+ttH}$ for the individual channels (model independent)





$\mu_{VBF} / \mu_{ggF+ttH} = 1.4_{-0.3}^{+0.4}$ (stat) $_{-0.4}^{+0.6}$ (syst)
3.3σ evidence for VBF production

2σ significance for VBF

Higgs boson Couplings

Recast the event yields into "measurements" of couplings

8 independent parameters to describe all currently relevant decays and production mechanisms:

$$\sigma(xx \to H) \cdot BR(H \to yy) \;\; \propto \;\; \frac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{TOT}}$$

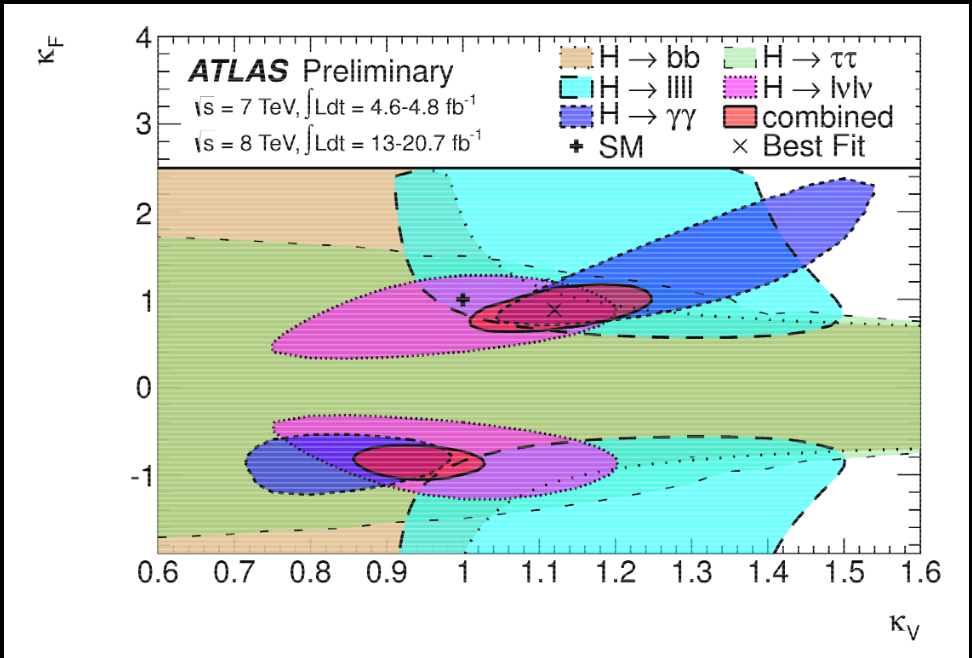
- Γ_{WW}
- Γ_{ZZ}
- Γ_{bb}
- $\Gamma_{\tau\tau}$
- $\Gamma_{\gamma\gamma}$ (loop induced)
- Γ_{gg} (loop induced)
- Γ_{tt}
- Γ_{TOT} (including H → "invisible")
- **Zγ** and **μμ** still have too little sensitivity to affect anything in the combination

	untagged	**VBF-tag**	**VH-tag**	**ttH-tag**
WW	✔	✔	✔	
ZZ	✔	✔		
bb			✔	✔
ττ	✔	✔	✔	✔
γγ	✔	✔	✔	✔

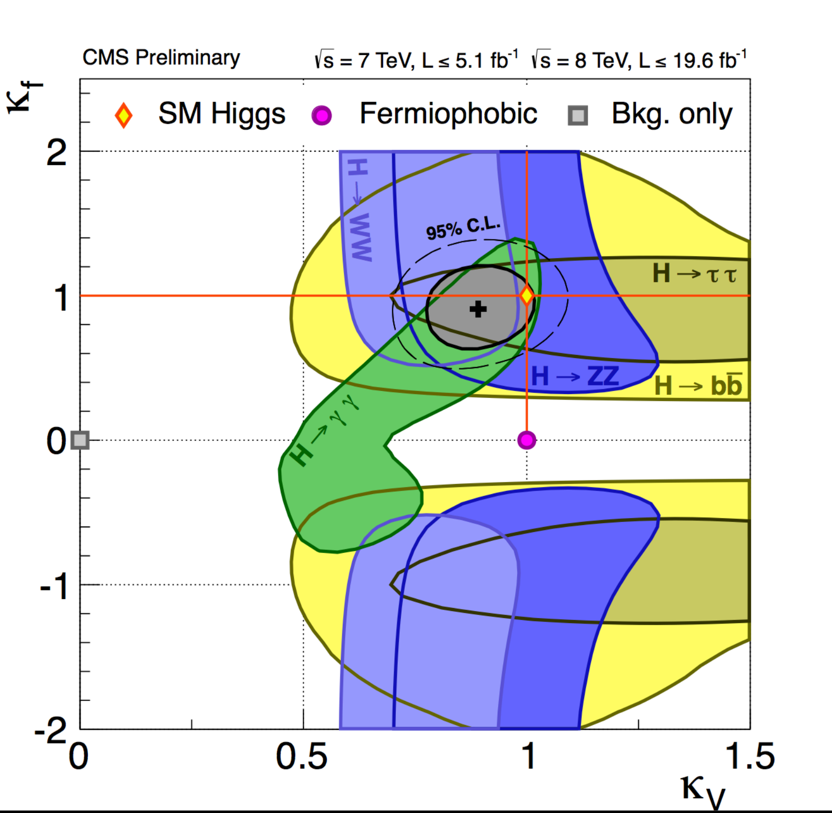
- introduce scaling factors ***κ*** w.r.t. the SM Higgs couplings

Couplings to fermions and bosons

- Assume one scale factor for fermion and vector couplings $\kappa_V=\kappa_W=\kappa_Z$ & $\kappa_F=\kappa_t=\kappa_b=\kappa_\tau$
- Assume $H\rightarrow\gamma\gamma$, $gg\rightarrow H$ and total width of the Higgs depends only on κ_V and κ_F (asume no BSM physics)

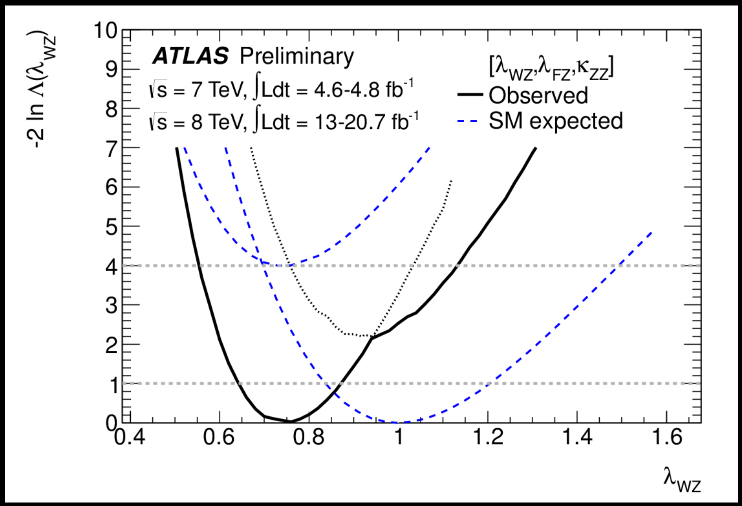


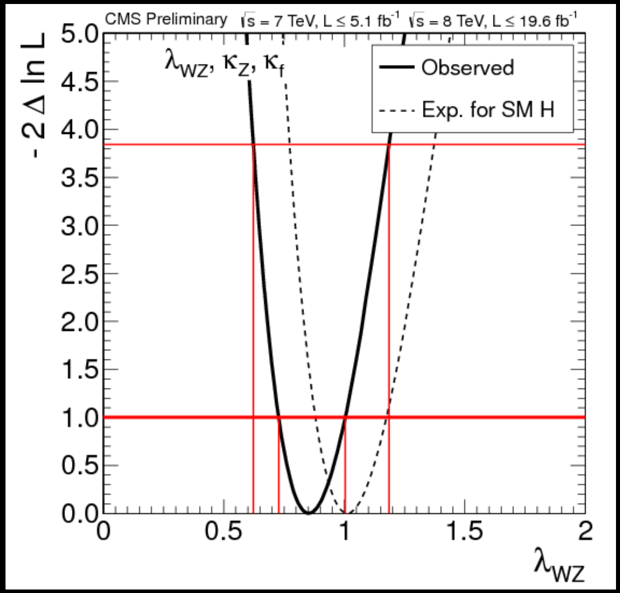
68% CL intervals:
$\kappa_F \in [0.76, 1.18]$ $\kappa_V \in [1.05, 1.22]$



Custodial symmetry: λ_{WZ}, κ_Z, κ_F

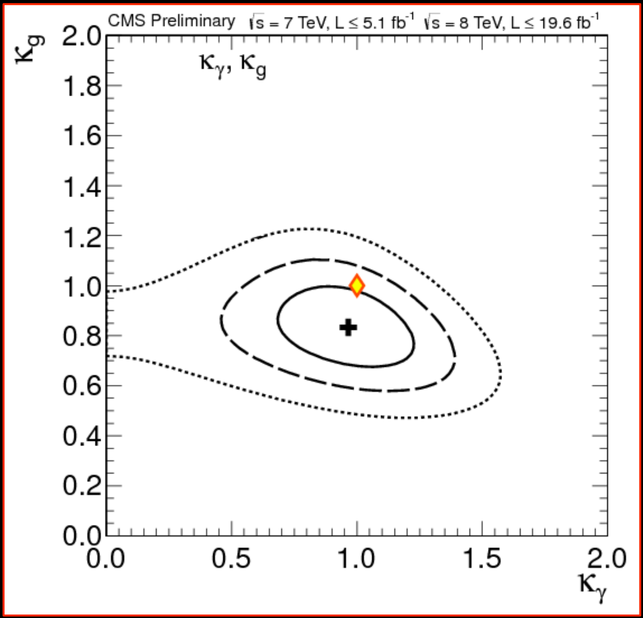
- Custodial symmetry requires $\lambda_{WZ} = \kappa_Z/\kappa_W = 1$
  - in SM, the ratio of couplings to W and Z bosons is almost not affected by loop corrections
  - Assume a common scaling factor κ_F for all fermionic couplings
  - Fit for: λ_{WZ}, κ_Z, κ_F

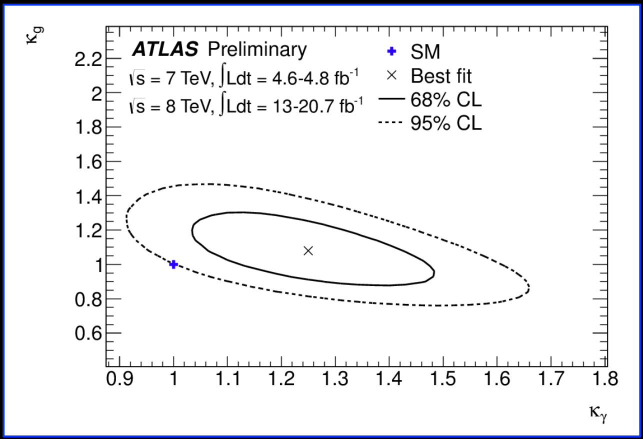




Data are consistent with the custodial symmetry

new physics in loops: κ_g and κ_γ





- Test for contributions from other particles contributing to loop-induced processes
- Assume nominal couplings for all SM particles κ_i = 1 and that the new particles do not contribute to the Higgs boson width
- Introduce effective scale factors κ_g and κ_γ
- BR(BSM)=0
  – Fit for: κ_g and κ_γ

Data are consistent with (κ_γ; κ_g)=(1; 1)

Spin/Parity: J^P : 0^+ vs 0^-

- SM Higgs boson: $J^P=0^+$
- Strategy is to falsify other hypotheses (JP=0^-, $1^{\pm}$, 2±) and to demonstrate consistency with JP=0+. J=1 strongly disfavored by observation of $H \rightarrow \gamma\gamma$ (Landau-Yan theorem)

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- $H \to ZZ \to 4l$ channel : sensitive to 0^+ vs 0^-
- Kinematic discriminant built to describe the kinematics of production and decay of different J^P state of a "Higgs"

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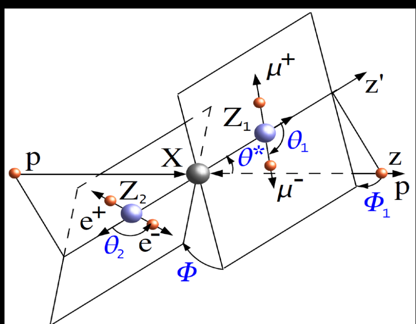
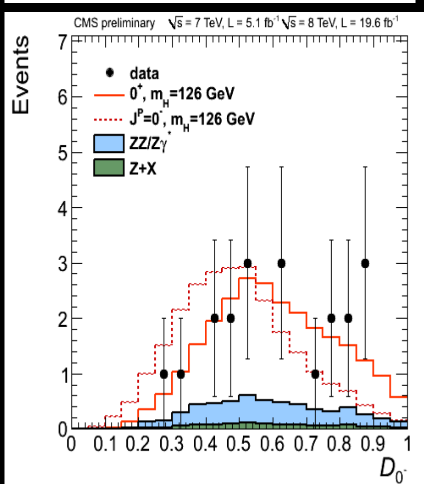
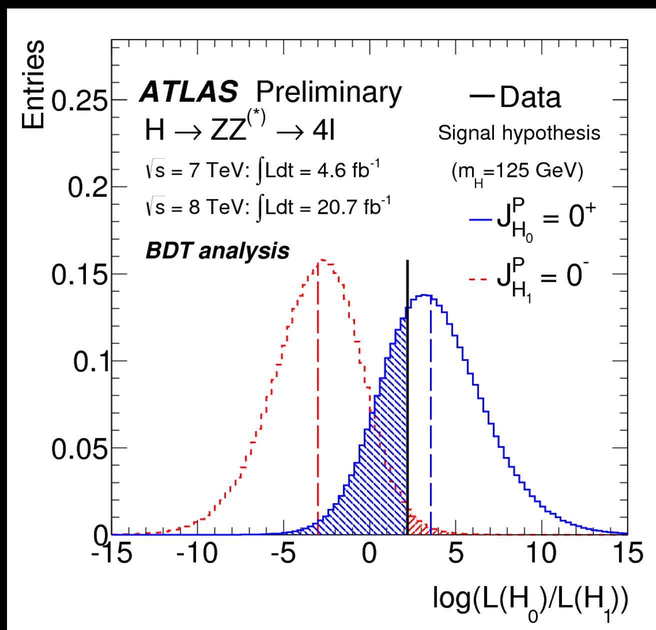
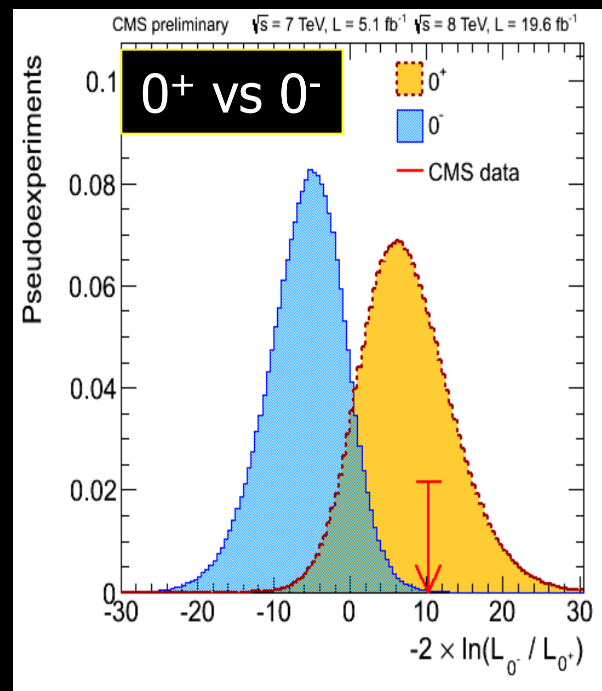






Exclude $J^P=0^-$ (vs. 0^+) with 97.8% CL

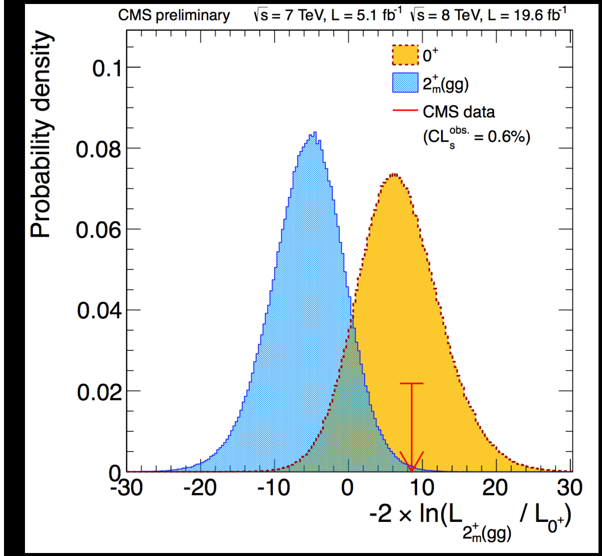


CL_s=0.16%

Spin/Parity J^P : 0^+ vs 2^+

- $H \rightarrow WW$ and ZZ channel
- Spin 2: consider graviton-like tensor, equivalent to a Kaluza-Klein graviton
- Production via gluon fusion and qq annihilation
- test J^P hypothesis as a function of the qq annihilation fraction (fqq)

Combined WW and ZZ channel



Expected results with m=1

ZZ	WW	Comb
6.8%	1.4%	0.2%

Observed results at measured m

ZZ	WW	Comb
1.4%	14%	0.6%

Observation compatible with SM Higgs expectations of 0^+. The current data cannot exclude this particular model of spin-2

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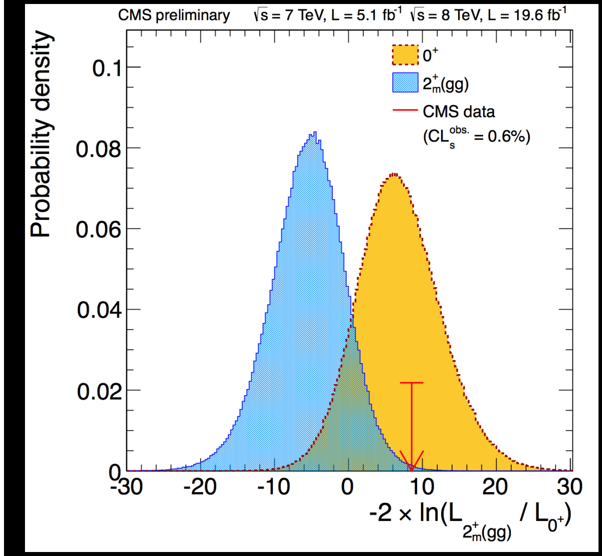

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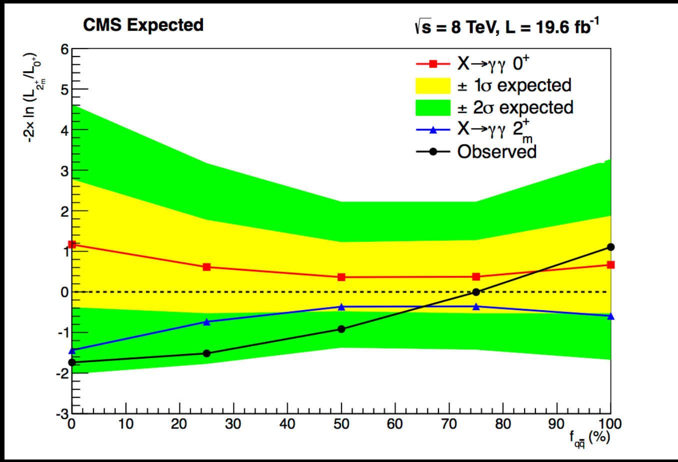
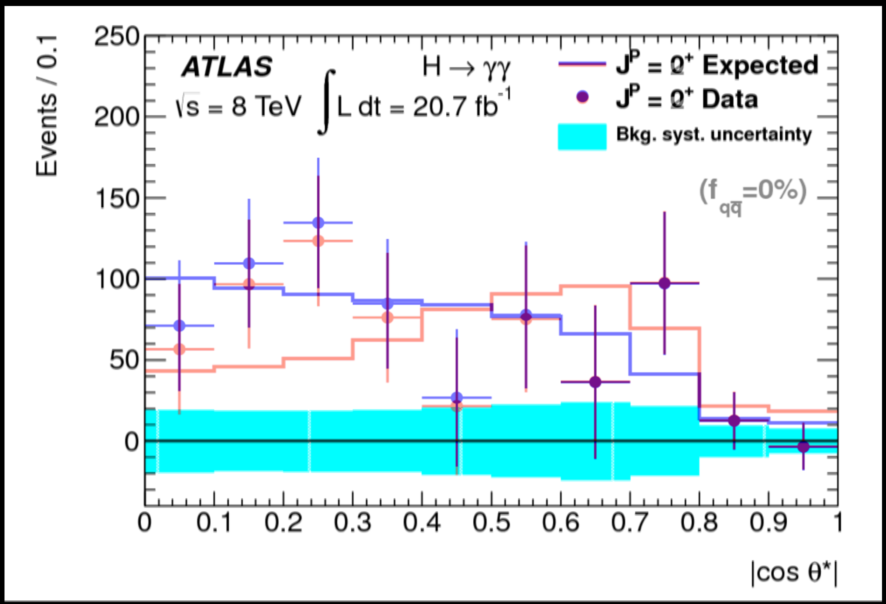


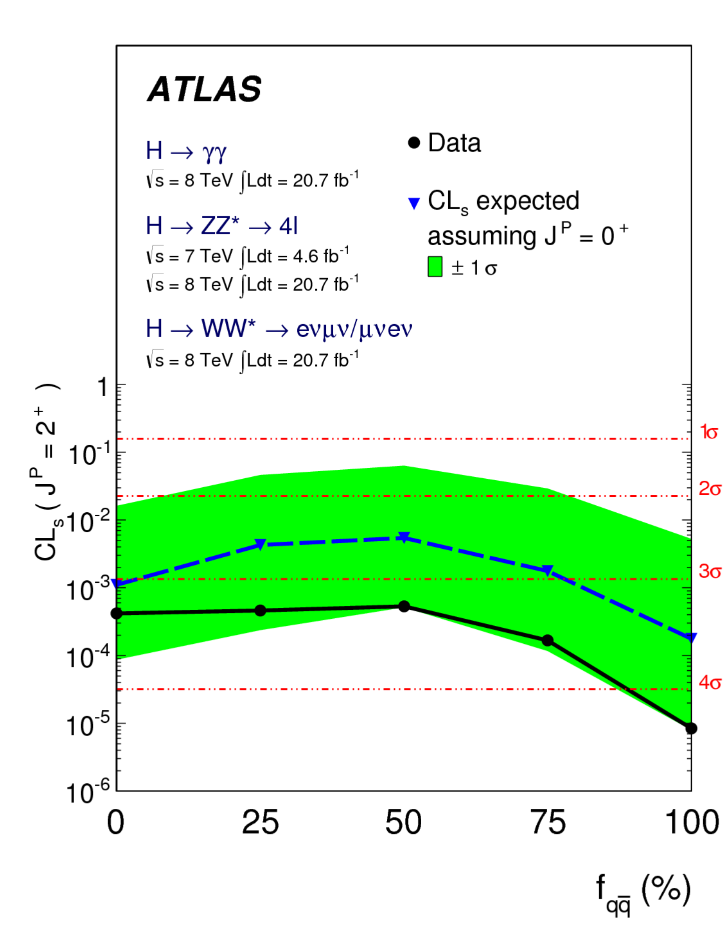
Observation compatible with SM Higgs expectations of 0^+. The current data cannot exclude this particular model of spin-2

Use γγ events to distinguish $0^+/2^+_m$(gg). Present γγ data does not have the power for a significant hypothesis test

Spin/Parity J^P : 0^+ vs 2^+

- H → WW and ZZ channel
- Spin 2: consider graviton-like tensor, equivalent to a Kaluza-Klein graviton
- Production via gluon fusion and qq annihilation
- test J^P hypothesis as a function of the qq annihilation fraction (fqq)





H→ZZ→4l, H→WW→lνlν, and H→γγ.

Exclude $J^P=2^+_m$ (vs. 0^+) w/ >99.9% CL

Spin-parity (J^P)

CL_s values for testing J^{CP} state hypotheses vs SM-like Higgs boson (0^+_m)

$CL_s < 0.05$
$CL_s < 0.01$

	CMS				ATLAS			
	γγ	ZZ	WW	ZZ+WW	γγ	ZZ	WW	comb
0^-		0.0016				0.022		
0^+_h		0.081						
1^-	excluded	<0.001			excluded	0.060	0.017	0.0027
1^+	excluded	<0.001			excluded	0.002	0.08	0.0003
$gg \to 2^+_m$	<0.006	0.015	0.14	0.006	0.007	0.169	0.05	0.0004
$qq \to 2^+_m$		<0.001			0.12	0.026	0.0004	<0.0001
$gg \to 2^-$						0.116		

Example:
Spin-0 Lagrangian
(lowest dimension)

$$\mathcal{L} = X\left[\kappa_1 \frac{m_Z^2}{v} Z_\mu Z^\mu + \frac{\kappa_2}{2v} F_{\mu\nu} F^{\mu\nu} + \frac{\kappa_3}{2v} F_{\mu\nu} \tilde{F}^{\mu\nu}\right] + \ldots$$

Higgs 0^+_h 0^-

Some issues to consider…

Is this the only Higgs Boson?

is this Higgs elementary or composite?

what else is out there?

- models: SUSY, technicolor, Little Higgs?
- other new particles?

is it the only Higgs boson?

- the SM Higgs boson is the minimal solution
- there could be more than one Higgs field
  - more than one physical Higgs particle
  - often one of them is similar to the SM Higgs boson
- two different approaches:
  - look for deviations of Higgs properties from SM predictions
    - requires precision measurements, lots of data
  - discover the other types of Higgs particles
    - maybe heavy and couple weakly to SM particles

other implications

measure properties precisely

- Higgs couplings are predicted by SM

  $hWW \sim gM_W$

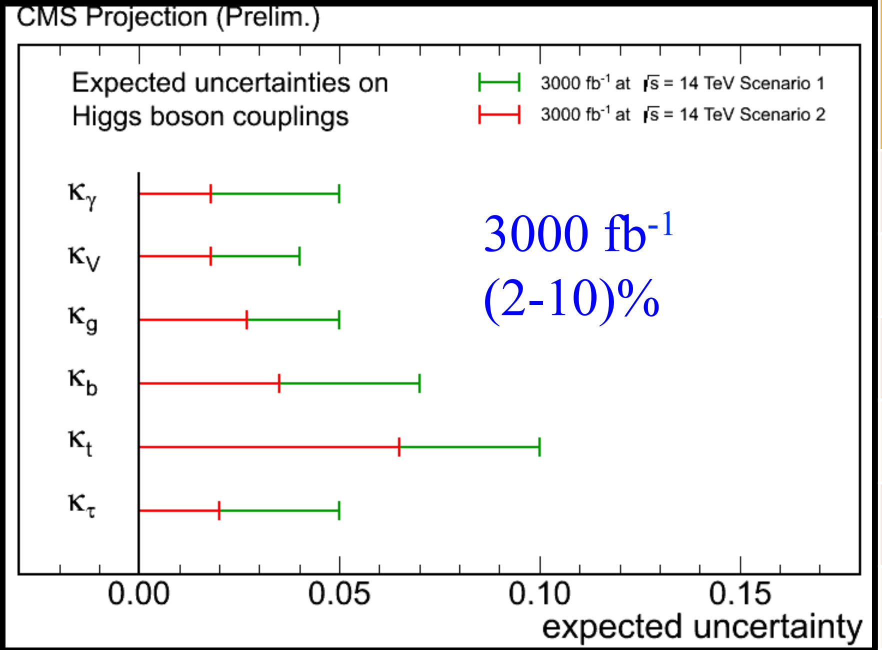
  $hZZ \sim gM_Z/\cos(\vartheta_W)$

  $hff \sim gm_f/2M_W$

- must have exactly these values in order to regularize WW scattering.
- A topic which requires a tremendous amount of careful analysis and a large dataset!
  - program extends over the next decade.

measure properties precisely

- Higgs couplings with 300 fb^{-1} @14 TeV
  ⇒2015 onwards
- Higgs couplings with 3000 fb^{-1} at HL-LHC
  ⇒2020 onwards

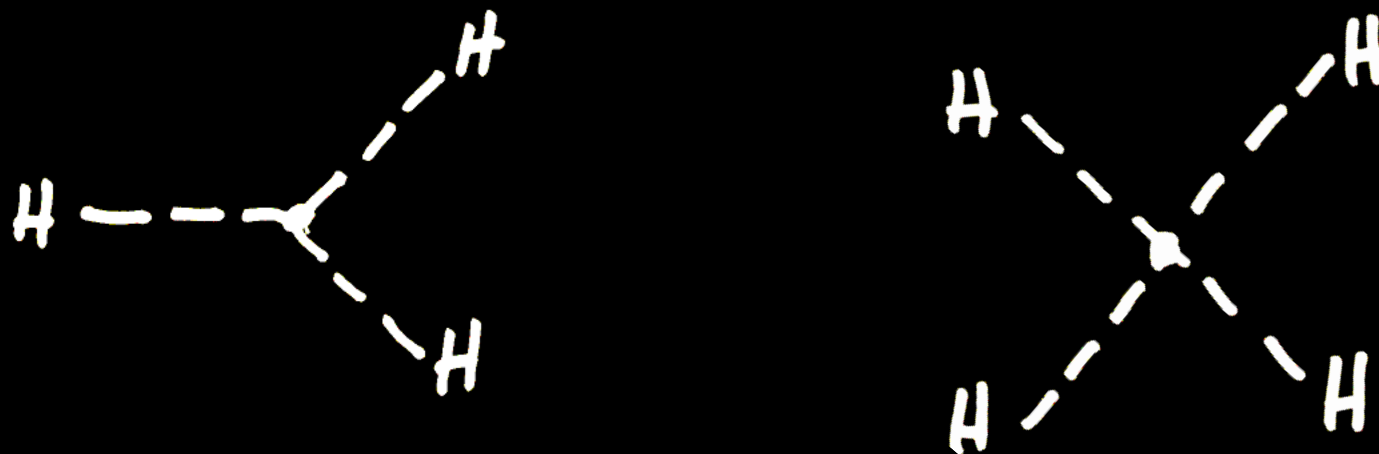


coupling	fractional uncertainty
κ_γ	[2-5]%
κ_V	[2-3]%
κ_g	[3,5]%
κ_b	[4,7]%
κ_t	[7,10]%
κ_τ	[2,5]%

- Goal: ultimate precision of ~5% or better
- observe H→μμ with significance of 5 sigma
  – Measure κ_μ to ≈10%.

measure properties precisely

- Higgs self couplings



- Search for Higgs pair production
- cross section rather low and needs HL-LHC for a measurement at the level of 30%.

Higgs factories: near and far future

- The fun is just beginning!
- LHC as a Higgs factory:
  - premium in increasing $\sqrt{s}$ close to 14 TeV
  - High-Luminosity LHC with a factor of 200 more data
    - Good prospects for precision measurements, discovering additional Higgs, and other new particles needed
- Future plans beyond the LHC:

Higgs Factory proposals include

  - Linear Collider start @ 250 GeV
  - LEP3: e+e- ring in the LHC tunnel @240 GeV
  - TLEP: a new 80 km ring @350 GeV

conclusion

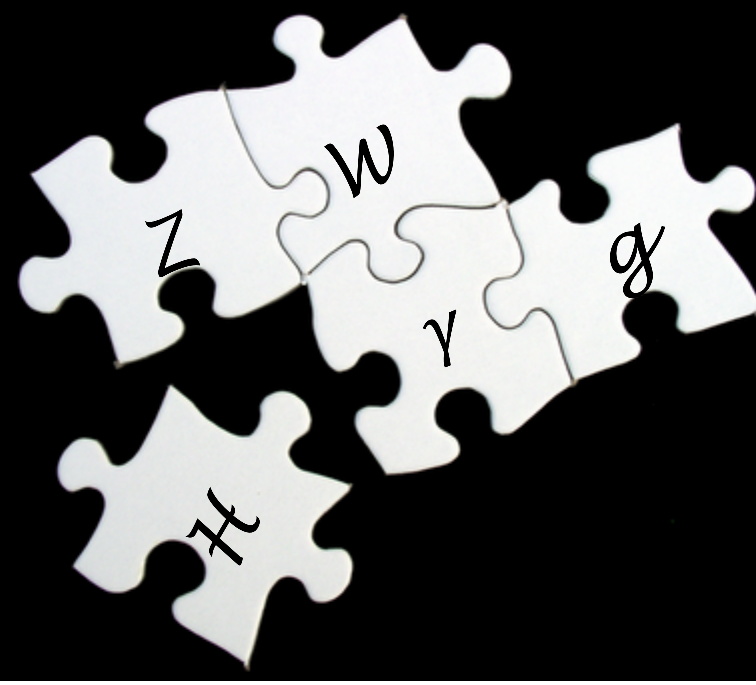
- this discovery has changed particle physics
- it has taught us something new: the Higgs mechanism appears to be the correct theory

- Based on the analysis of the full 7 and 8 TeV datasets, the discovered particle appears consistent (within the current precision) with the SM Higgs boson:
  - CP-even scalar
  - Couplings proportional to mass
- Precision is still limited and there is room for surprises
  - deviations in couplings, non-standard production/ decay modes, additional Higgs bosons,…

conclusion

- it has given us a signal to scrutinize for hints of what the physics beyond the SM could be
- We are just at the beginning of a 20-year program!
- Exciting times ahead!

is it the missing piece that completes the puzzle or is it a connecting piece to a whole new part of the puzzle?



thanks to

LHC, CMS and ATLAS collaborators for the spectacular results

and…

for allowing me to borrow generously from your presentations and notes

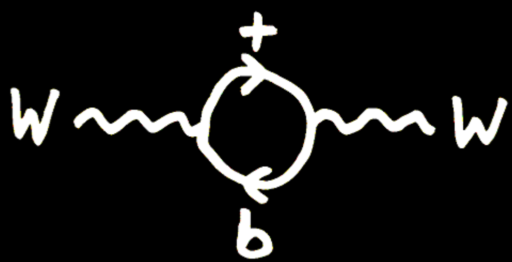
References

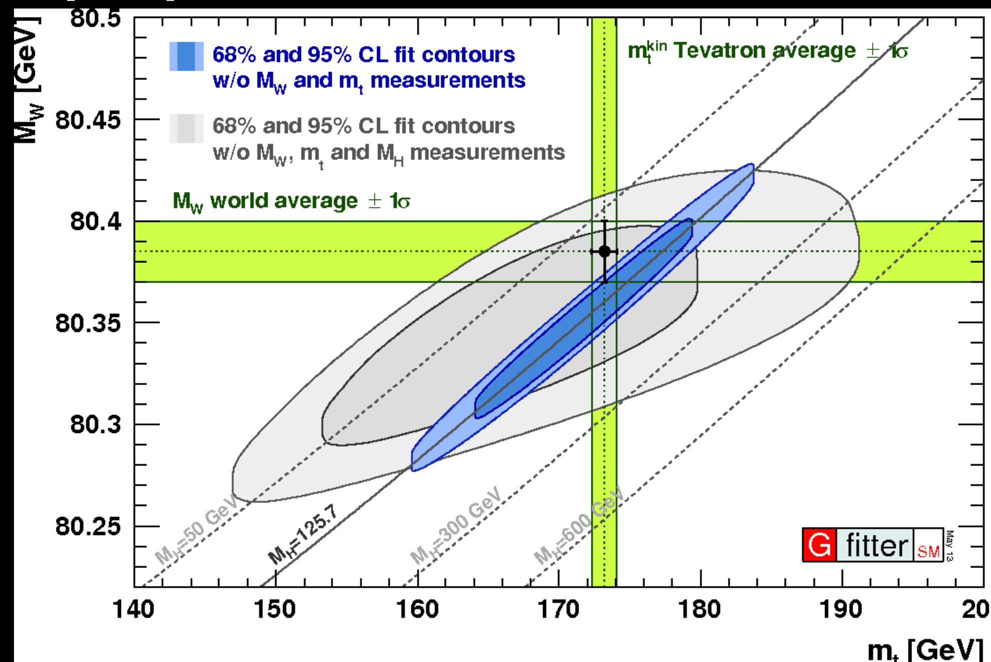
- CMS and ATLAS notes
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

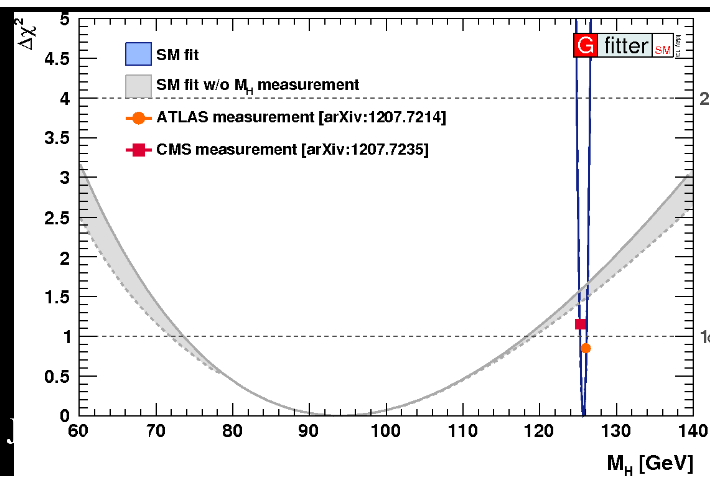
backup

is it the (minimal SM) Higgs?

- W boson mass and top quark mass





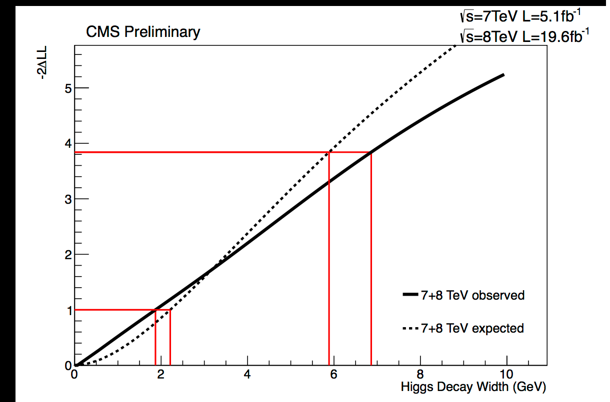


from gfitter.desy.de

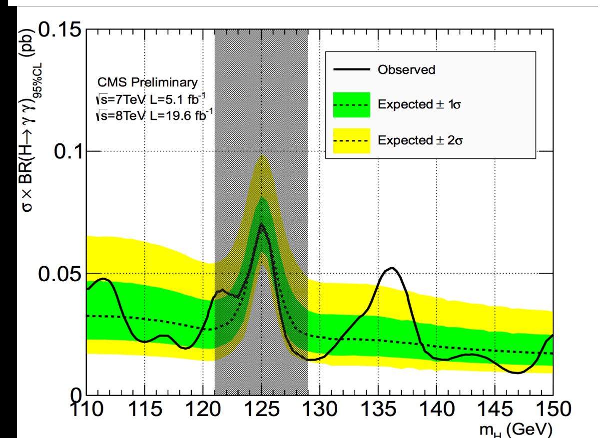
Higgs Properties from H→γγ

CMS-PAS-HIG-13-016

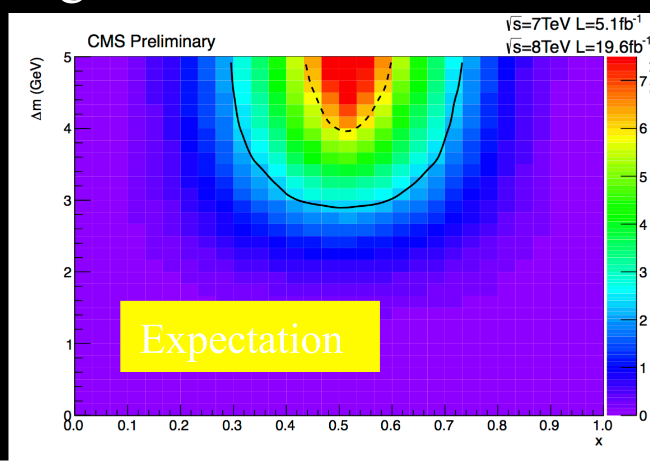
Upper limit on the Higgs width
- Dominated by experimental resolution
- Breit-Wigner + Gaussian fit
- Observed (exp) upper limit = 6.9 (5.9) GeV 95% CL

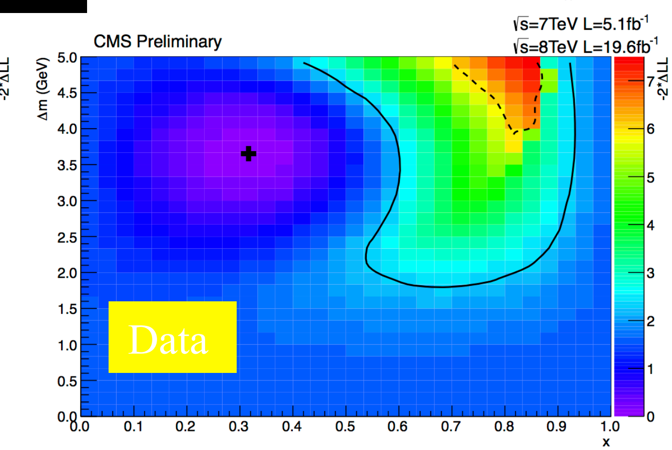


Additional Higgs-like states:
- Take SM 125 GeV as part of the background
- Search for additional Higgses
- Largest excess: 136.5 GeV with 2.9σ(<2σ after LEE)



Search for near mass degenerate states
- Two signals with relative strength x mass difference Δm
- Perform a 2D scan
- No signal at 95% CL for Δm> 4 GeV





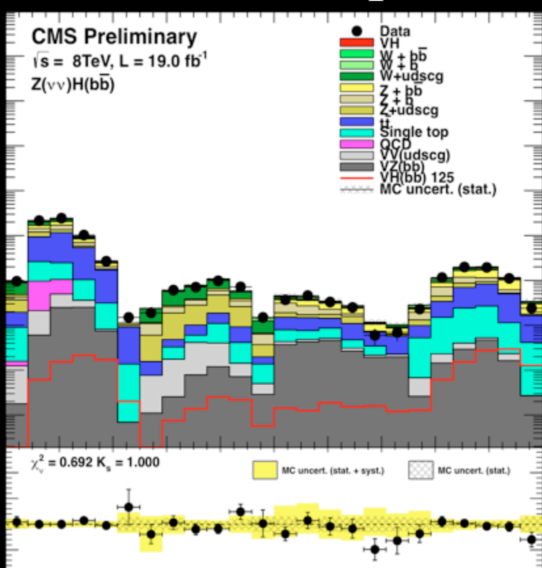
When word spread in early July that scientists at CERN had discovered the Higgs Boson, many Americans we're left scratching their heads, asking, what is it? …
It's simultaneously the most profound and most perplexing discovery of the year. ..

[Abby Haglage Dec 19, 2012]

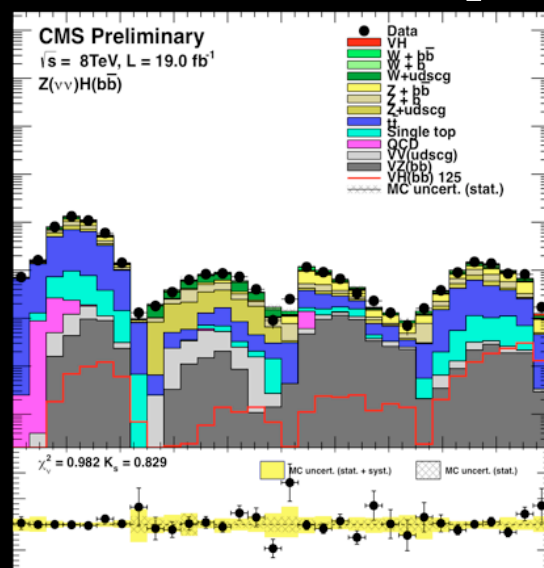
H→bb: MVA shape analysis

- Use shape analysis with MVA discriminator with input variables: jet kinematic variables, b-tag variables, …
- Also split according to MVAs trained to select different bkg
- Cout simultaneous fit to all channels

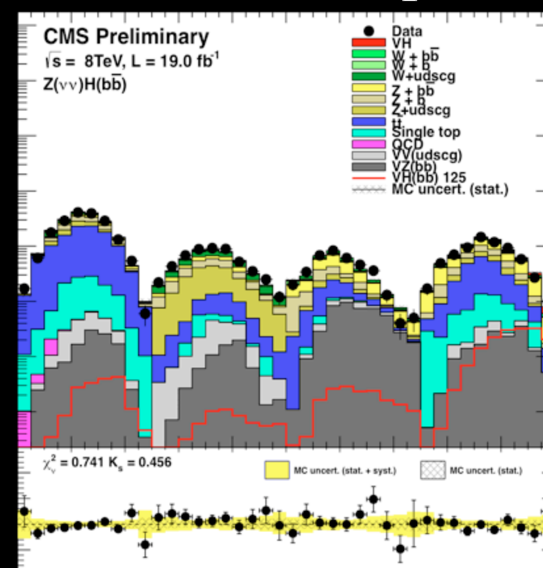
Z->νν, low p_T^{bb}



Z->νν, medium p_T^{bb}

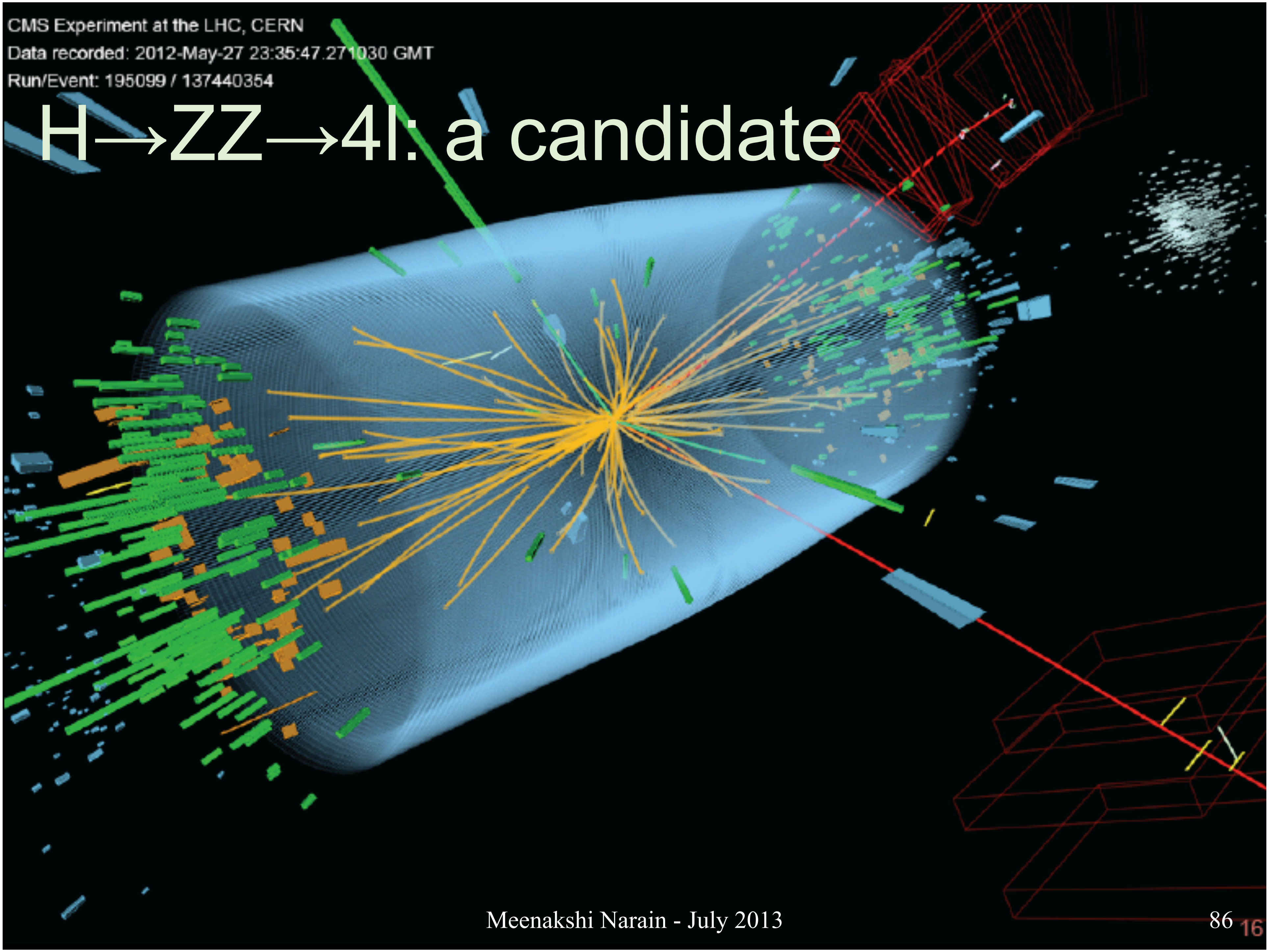


Z->νν, high p_T^{bb}

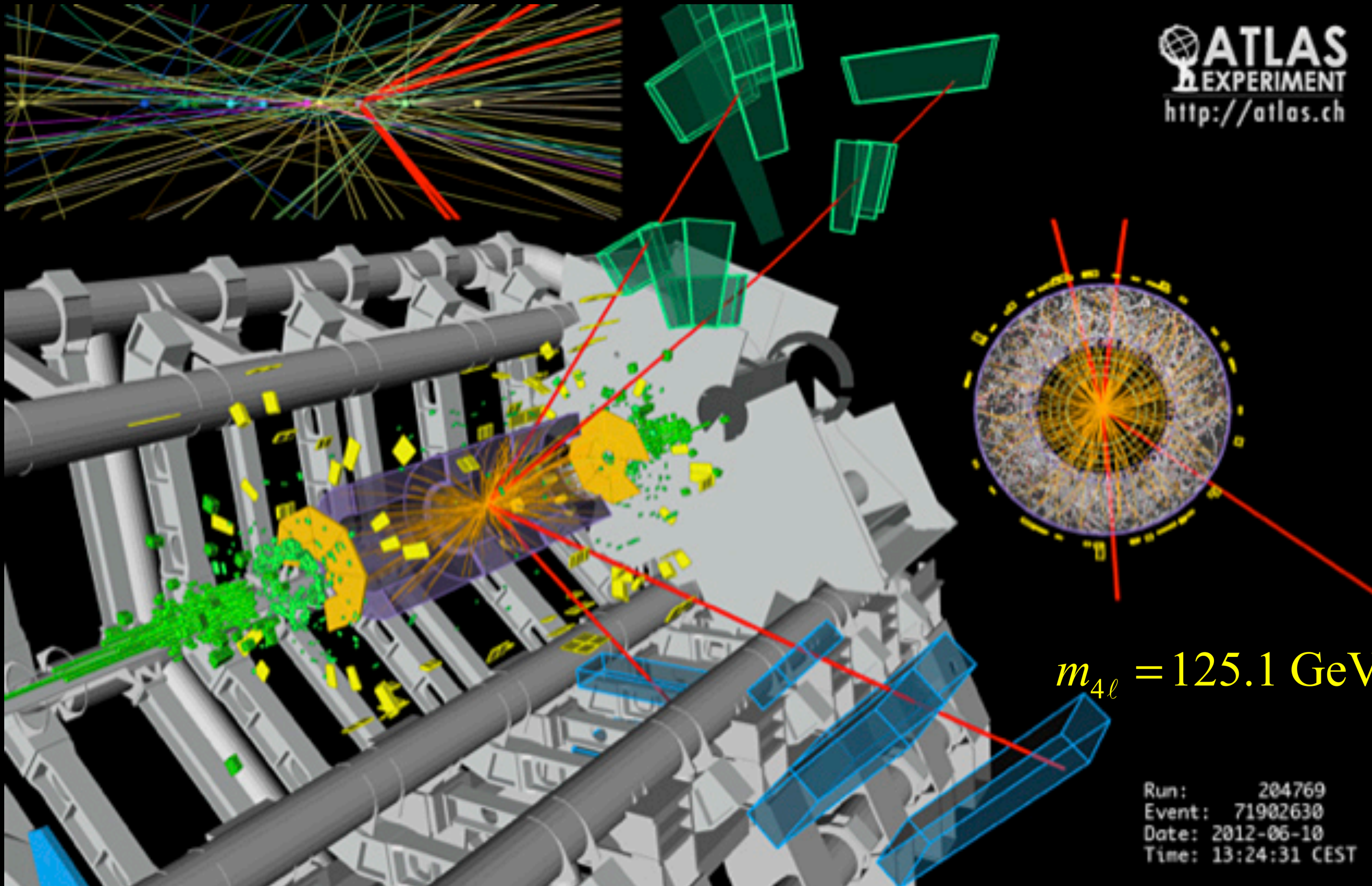


4 sub-regions are enriched in: tt V + jets VV VH

H→ZZ→4l: a candidate

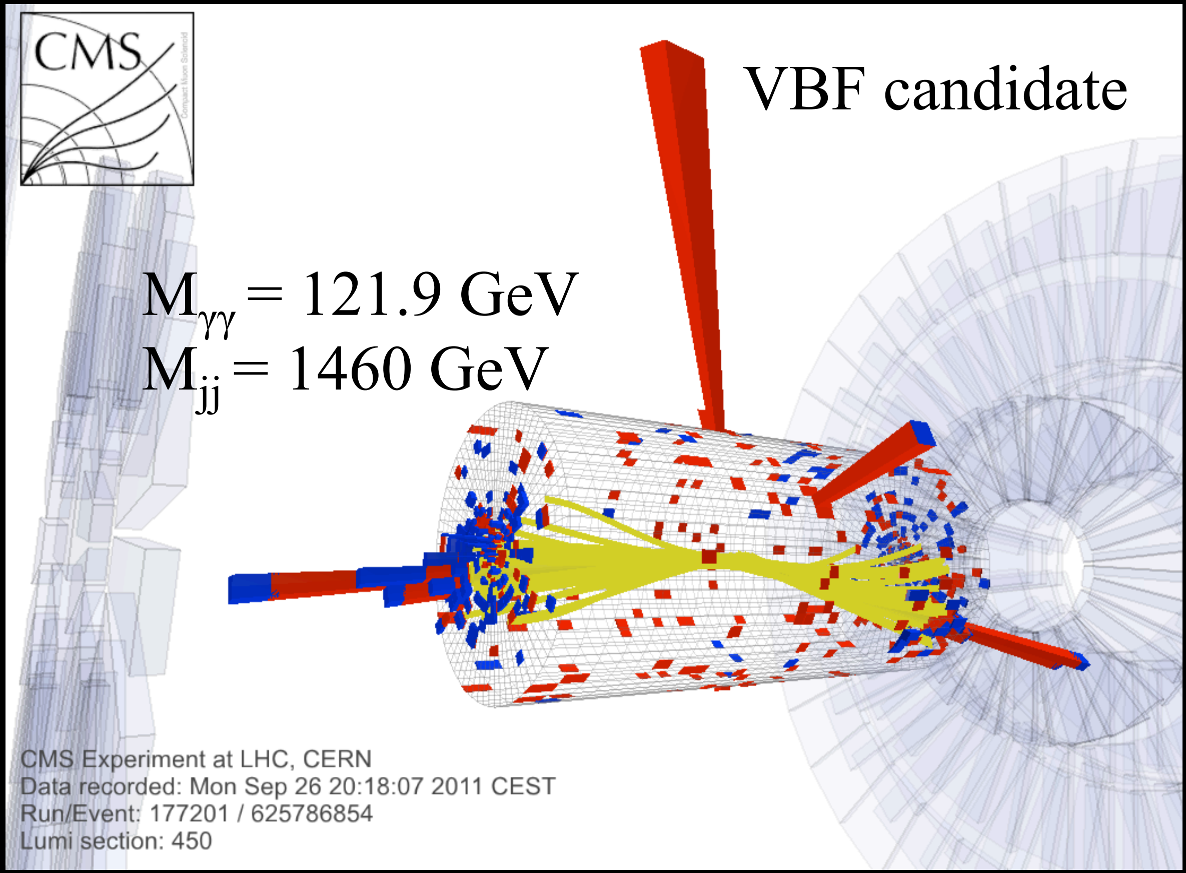


H→ZZ→4l: a candidate



H → $\gamma\gamma$: exclusive channels

- Add exclusive categories to address specific production processes:
  - VBF: dijet selection (dijet BDT)

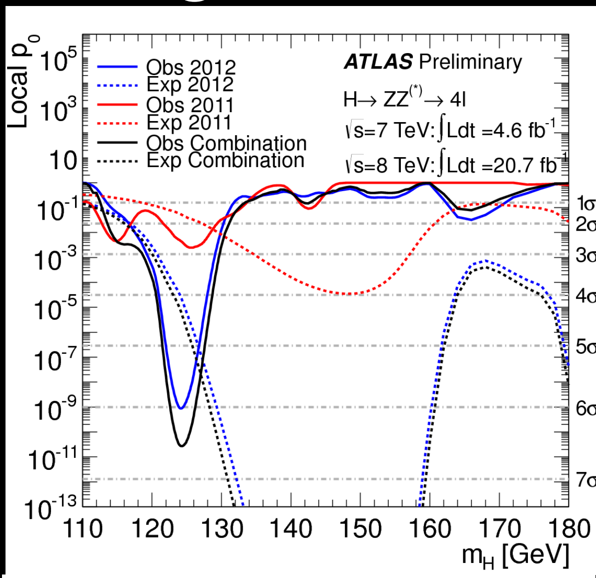


  - VH: lepton and MET tag to address W->lv, Z->ll and Z->vv decays

H→ZZ→4l : results

- Significance

Signal Strength (μ)



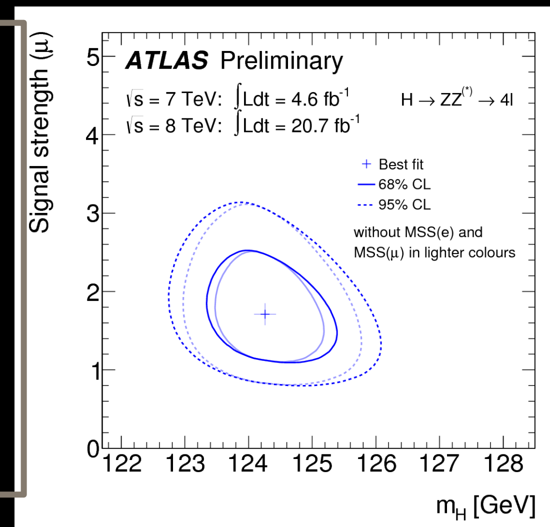
p-value:

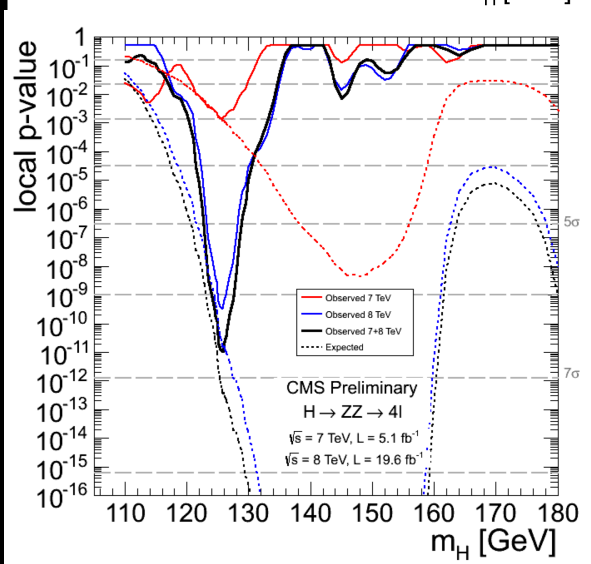
Expected: 4.4σ

Observed: 6.6σ

$\mu = \sigma/\sigma_{SM} = 1.75 \pm 0.05$

@ m_H = 124.3 GeV





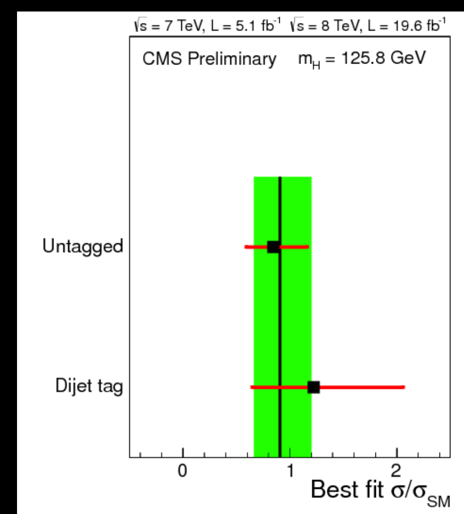
p-value:

Expected: 7.1σ

Observed: 6.7σ

$\mu = \sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$

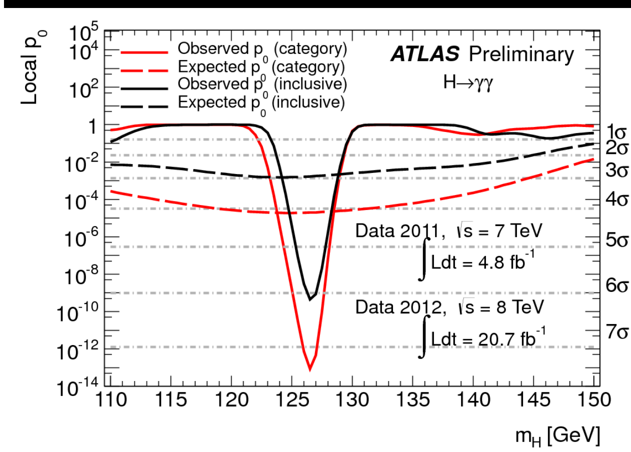
@ m_H = 125.8 GeV



H→γγ: results

- Significance

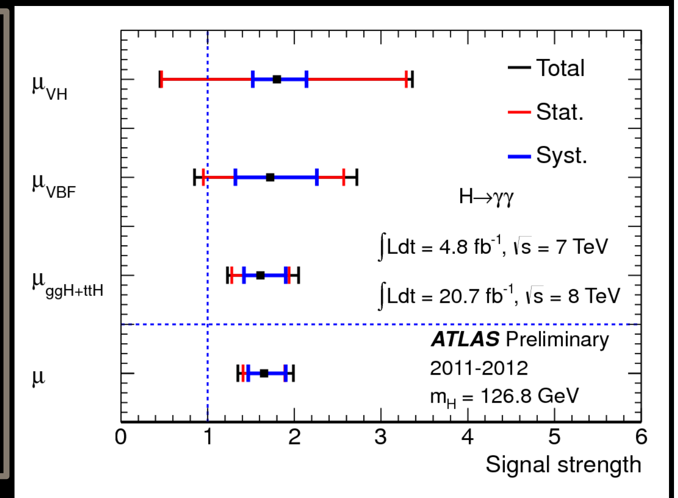
Signal Strength (μ)

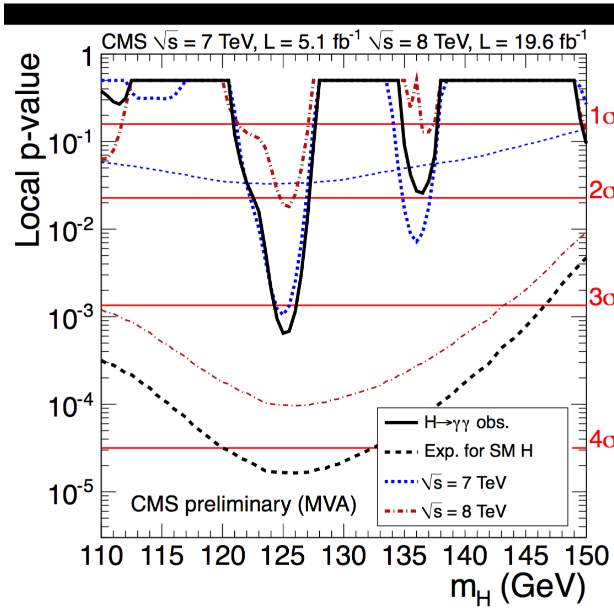


p-value:
Expected: 4.1σ
Observed: 7.4σ

$\mu = \sigma/\sigma_{SM} = 1.57 \pm 0.22$

@ m_H = 126.8 GeV

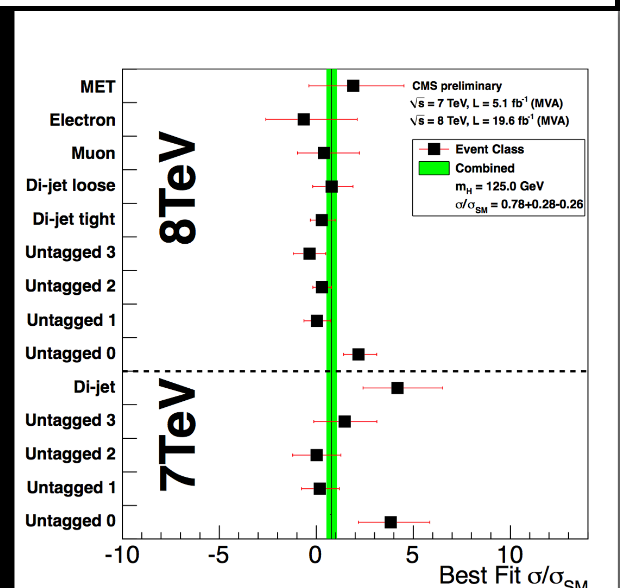




p-value:
Expected: 4.2σ
Observed: 3.2σ

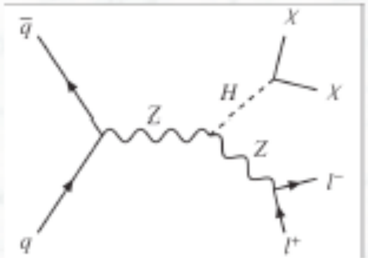
$\mu = \sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$

@ m_H = 125 GeV



Search for invisible Higgs boson decays

- Some extensions of the Standard Model allow a Higgs boson to decay to stable or long-lived particles
- Search for excess in ZH associated production



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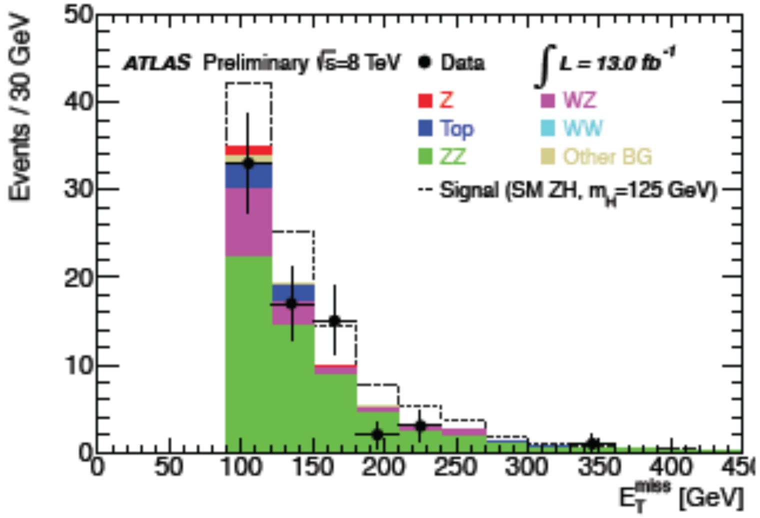
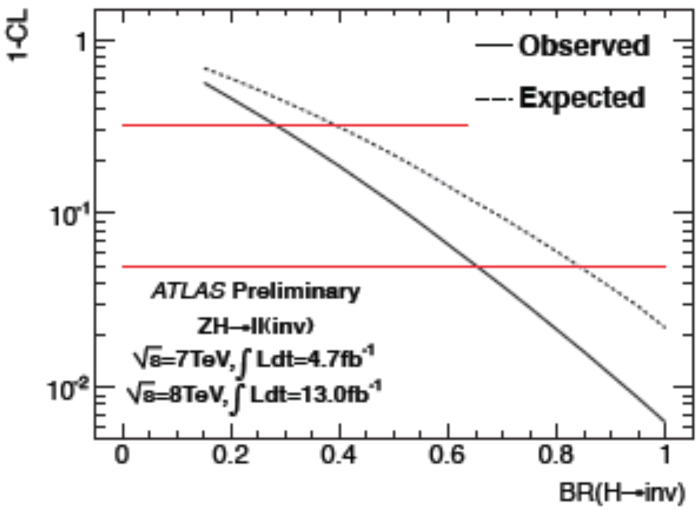
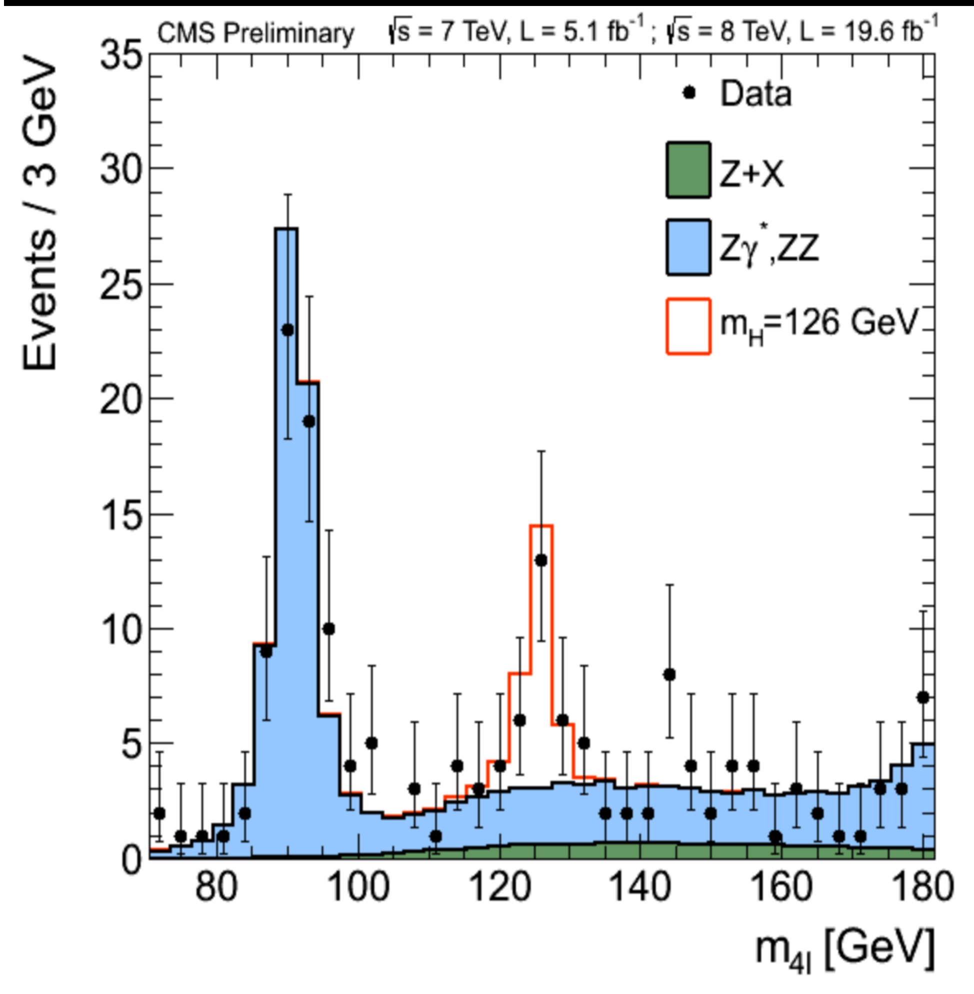
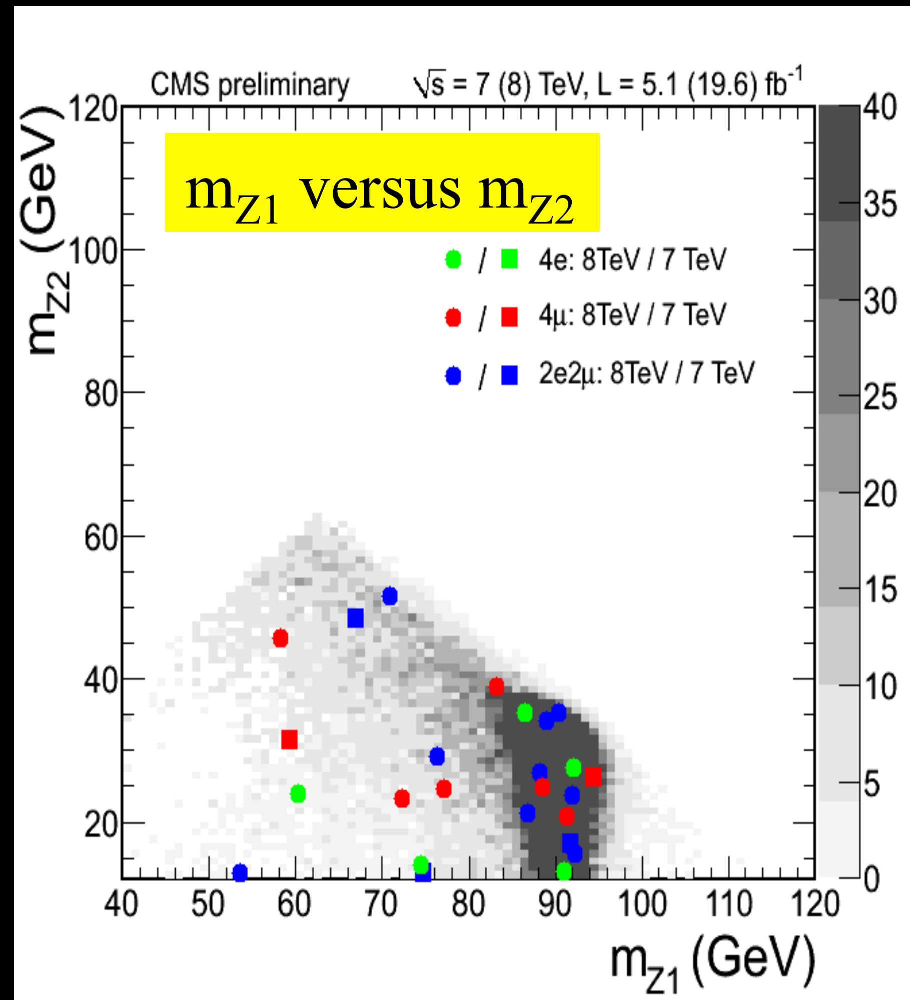




Assuming the ZH production rate for m_H = 125 GeV:

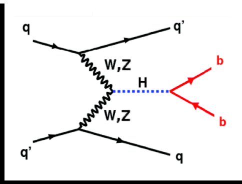
The Decay H → ZZ → 4l

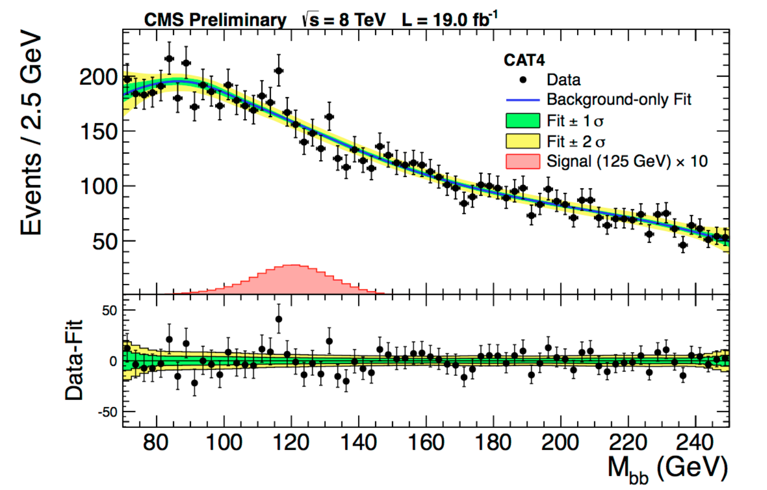




121.5 < M(4l) < 130.5 GeV

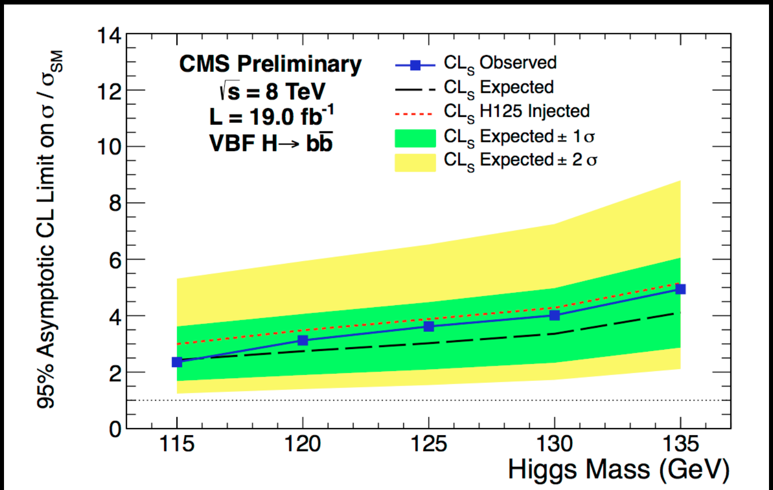
VBF H→bb: results





bb event + >= 2 non-b jets at large Δη

Selection based on MVA



@mH=125 GeV

95%C.L. UL σxBR =3.6xSM (3.0 exp.)