Higgs and BSM searches at LHC: results and perspective

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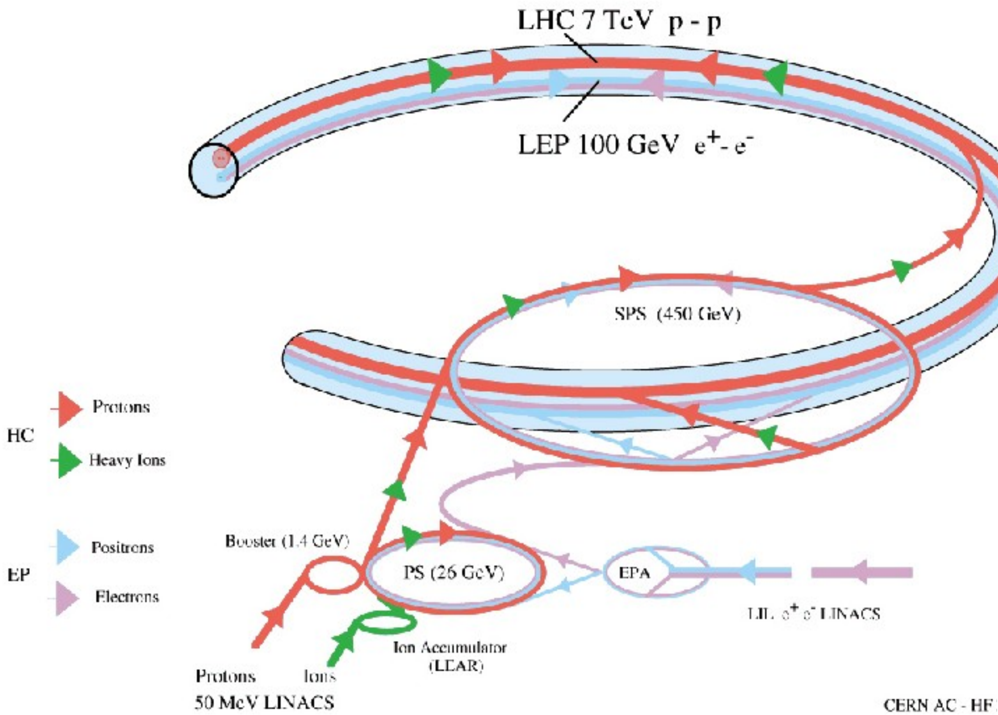
TeV Scale Physics workshop (7th)
Tsinghua University, Beijing
Nov. 12-15, 2012

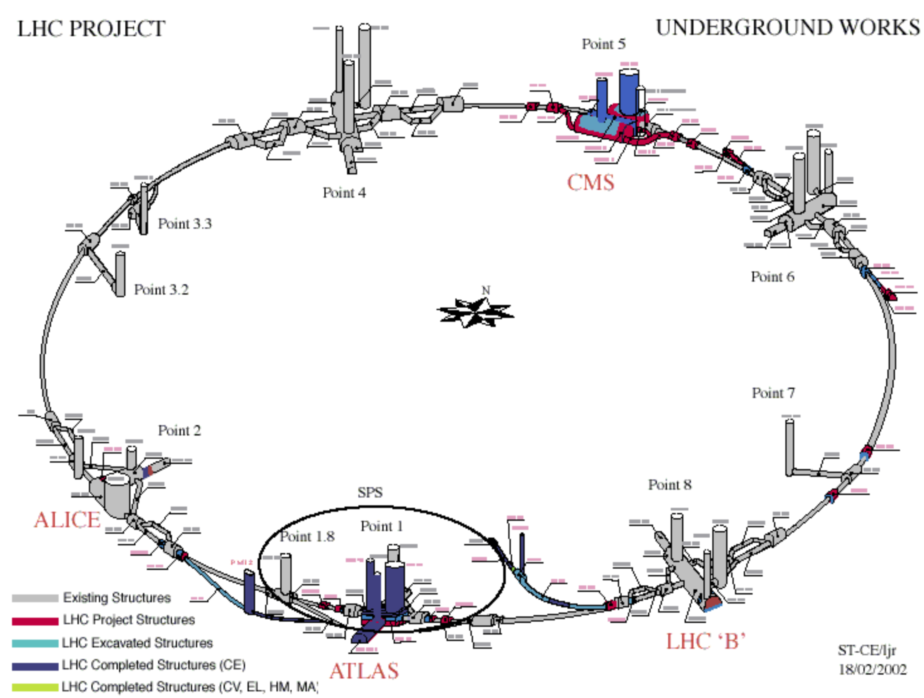
The Large Hadron Collider (LHC)



ATLAS and CMS: general purpose detectors

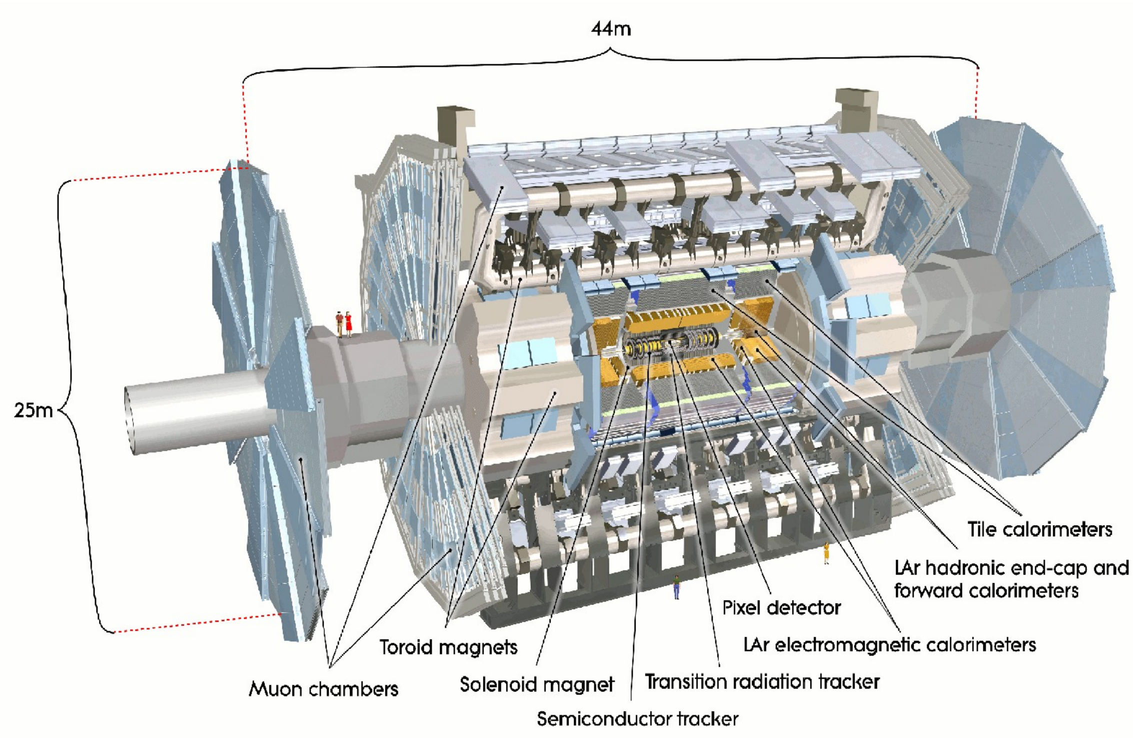
ALICE: heavy ions

LHC-B: b-physics

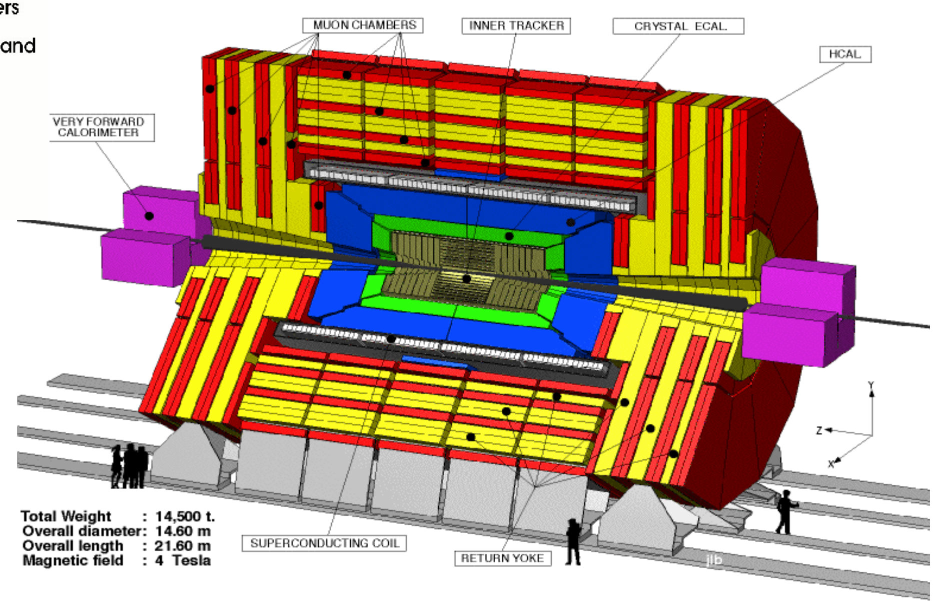


- 27 km circumference, 100 m underground
- Two proton beam in parallel pipes, rotating in opposite directions
- Dipole field increases from 0.54 T to 8.3 T in about 20 minitues. Protons are stored for 10 – 24 hours
- 25 ns bunch separation, 23 pp collisions per bunch crosing @ $10^{34} cm^{-2} s^{-1}$

ATLAS and CMS detector



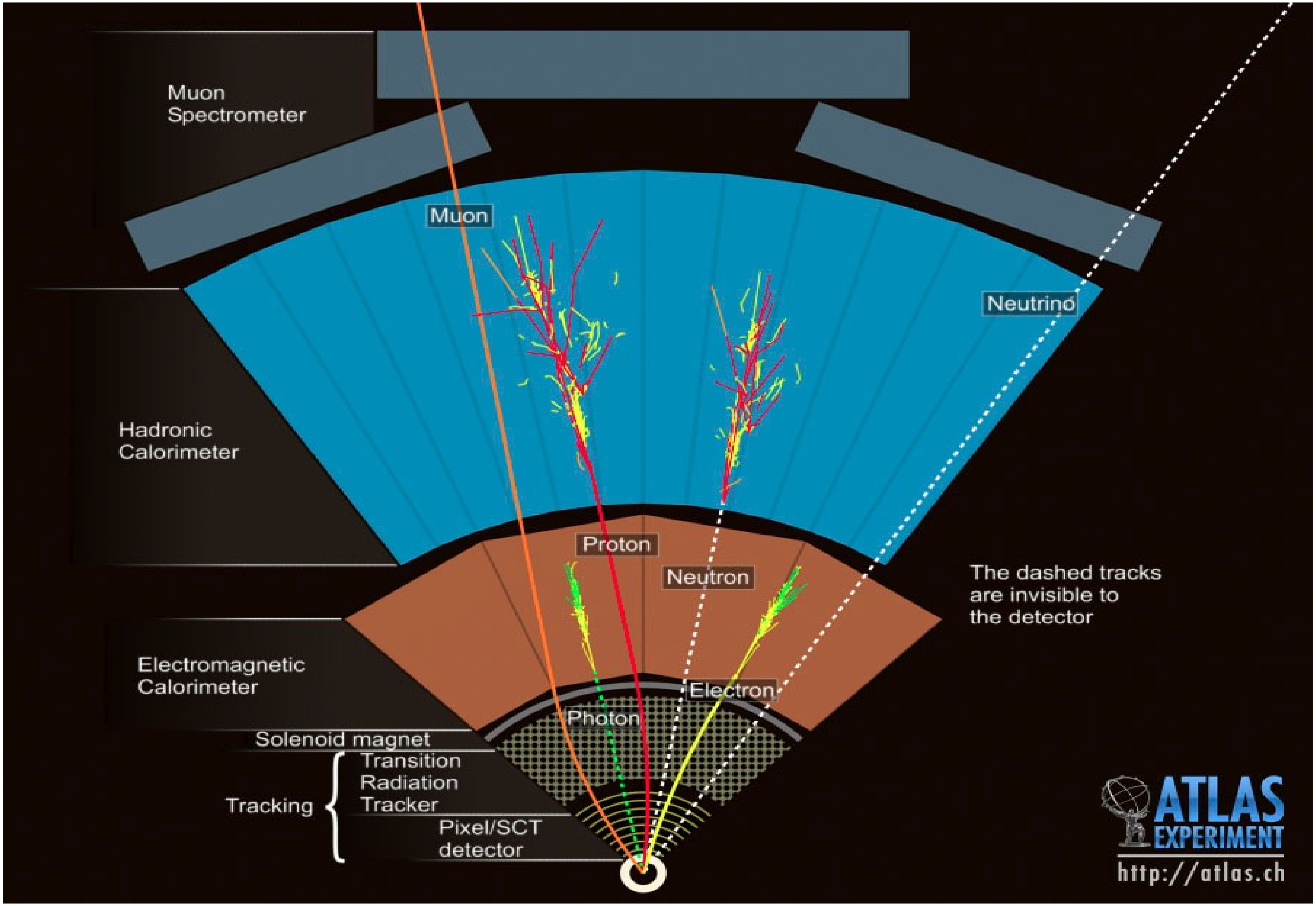
CMS
37 Countries
155 Institutions
2000+ Physicists



ATLAS
37 Countries
167 Institutions
2000+ Physicists

To claim a discovery, it is important to have 2 independent experiments giving consistent results !

Tracking and calorimetry

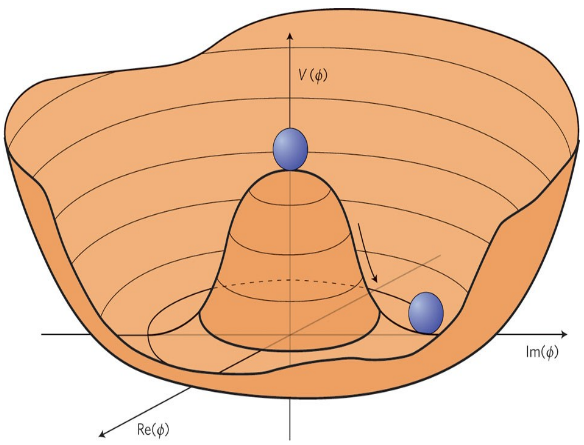


Missing transverse energy (**MET**), a 2D vector of:

sign-inversed vectorial sum of all visible objects on the transverse plane

Higgs mechanism in a nutshell

The local gauge invariant Higgs (ϕ) Lagrangian is



$$L_\phi = \left| \left(i\partial_\mu - g\frac{\vec{\tau}}{2}\cdot\vec{W}_\mu - g'\frac{Y}{2}B_\mu \right)\phi \right|^2 - V(\phi),$$

with the Higgs potential defined as

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2,$$

which has a minimum at $\phi = \upsilon/\sqrt{2} = \sqrt{\mu^2/2\lambda}$. Make the substitution:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad\rightarrow\quad \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \upsilon + h(x) \end{pmatrix},$$

ϕ_1, ϕ_2 and ϕ_4 become the Goldstone bosons in the Lorentz gauge – absorbed into the longitudinal polarizations of the three weak bosons in the Unitarity gauge. Electroweak gauge symmetry is broken, and Higgs field aquires a mass:

$$m_H = \sqrt{2\lambda}\,\upsilon, \quad \upsilon = (\sqrt{2}\,G_F)^{-1/2} = 246 \text{ GeV}$$

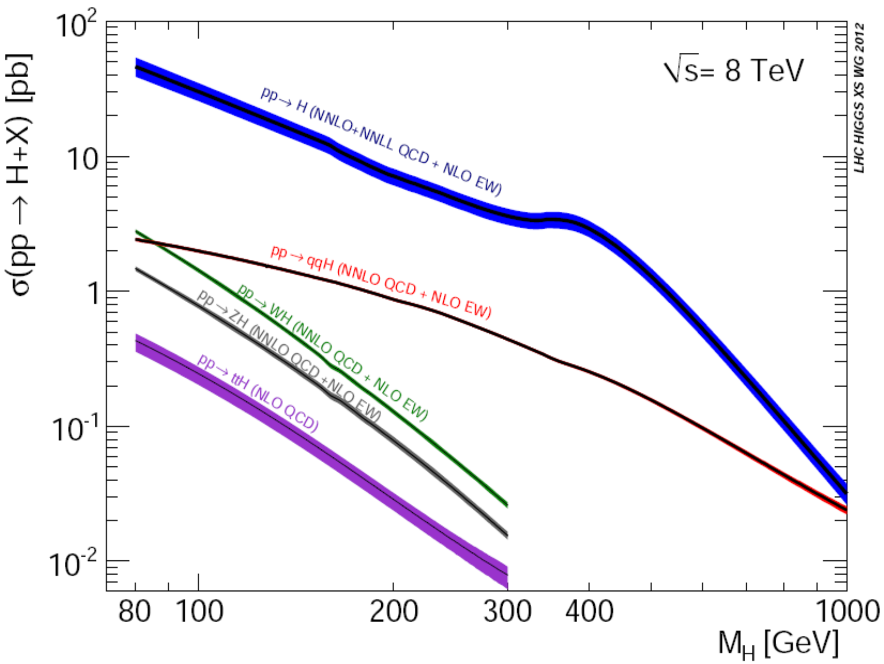
Thus, Higgs mass is not predicted in the Standard Model

Higgs production modes

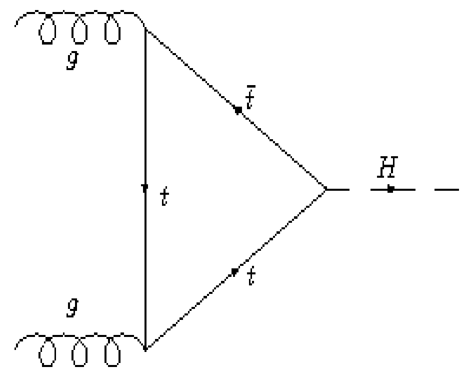
Higgs couplings to fermions and bosons:

$$g_{Hf\bar{f}}=\frac{g\,m_f}{2\,m_W},\quad g_{HWW}=g\,m_W,\quad g_{HZZ}=\frac{g\,m_Z}{\%cos\theta_W}$$

Yukawa Gauge Gauge

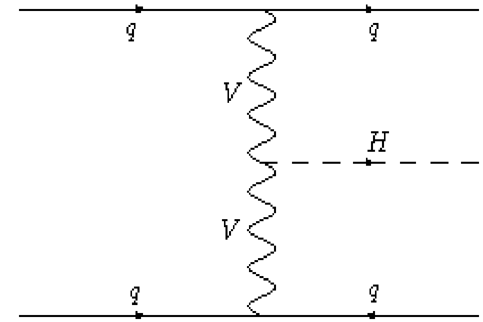


Higgs production channels at LHC:



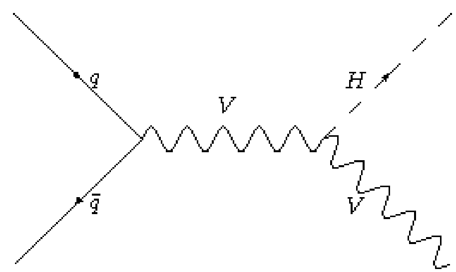
(1)

Gluon-gluon fusion



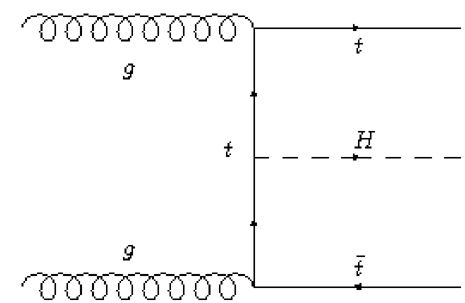
(2)

Vector-boson fusion



(3)

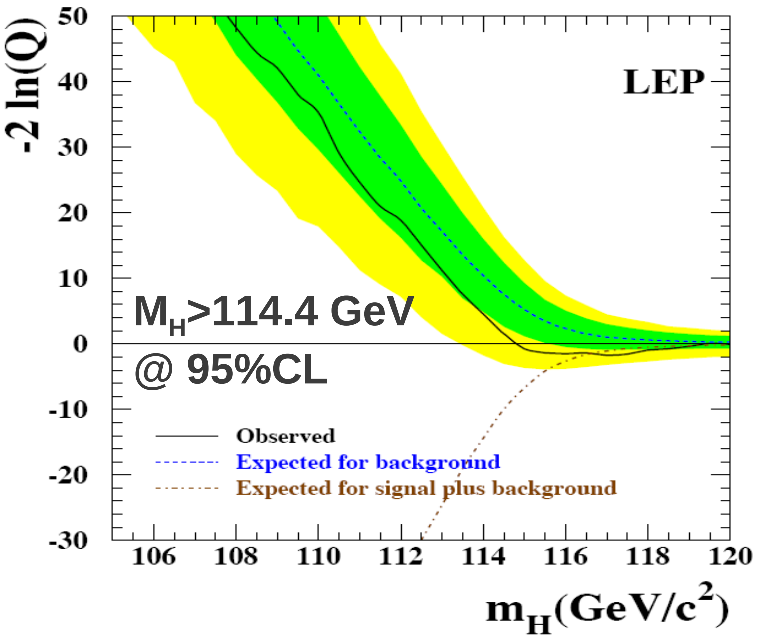
VH Associated



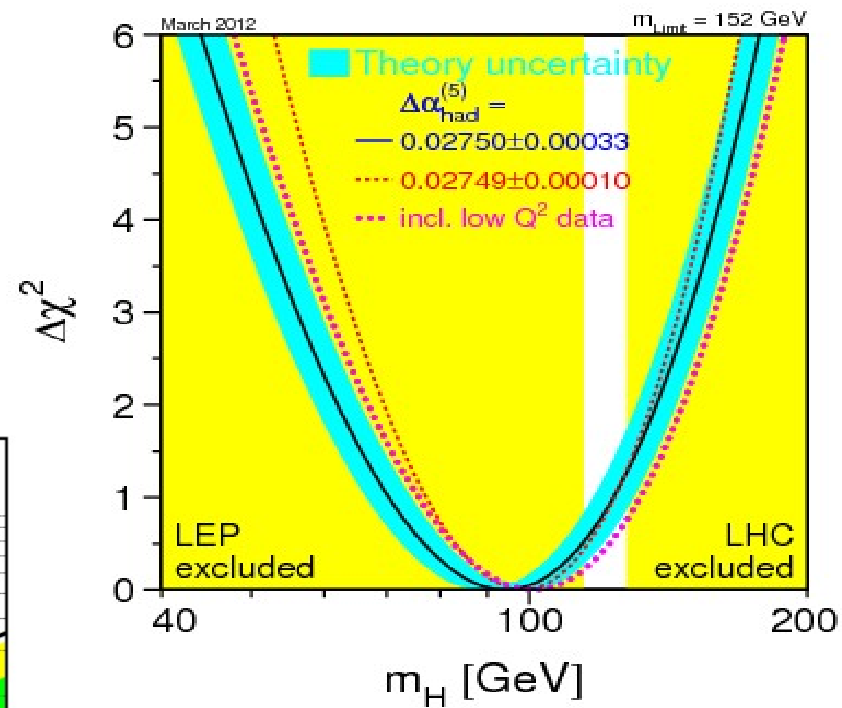
(4)

ttH

Bounds on the Higgs mass as of June 2012

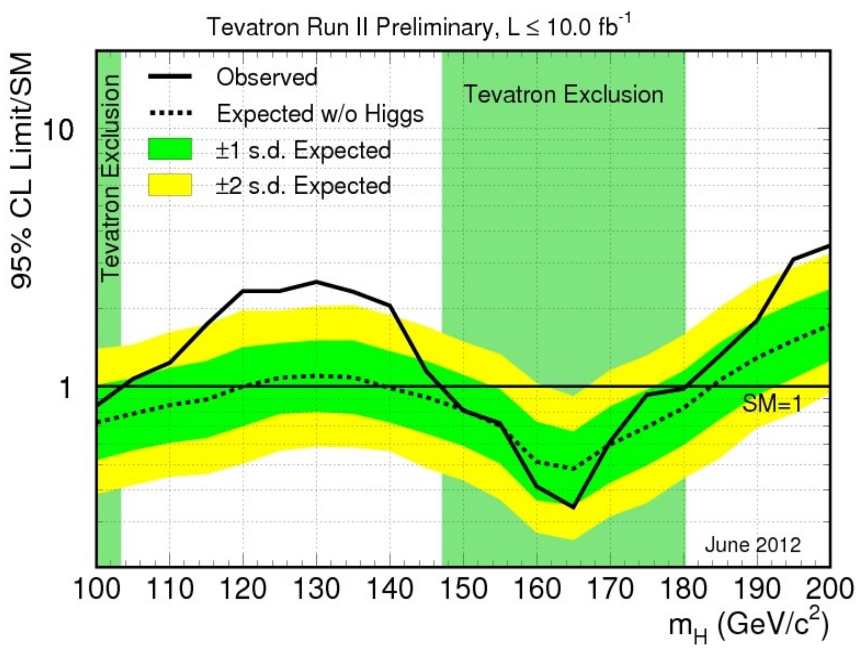


Electroweak precision measurements



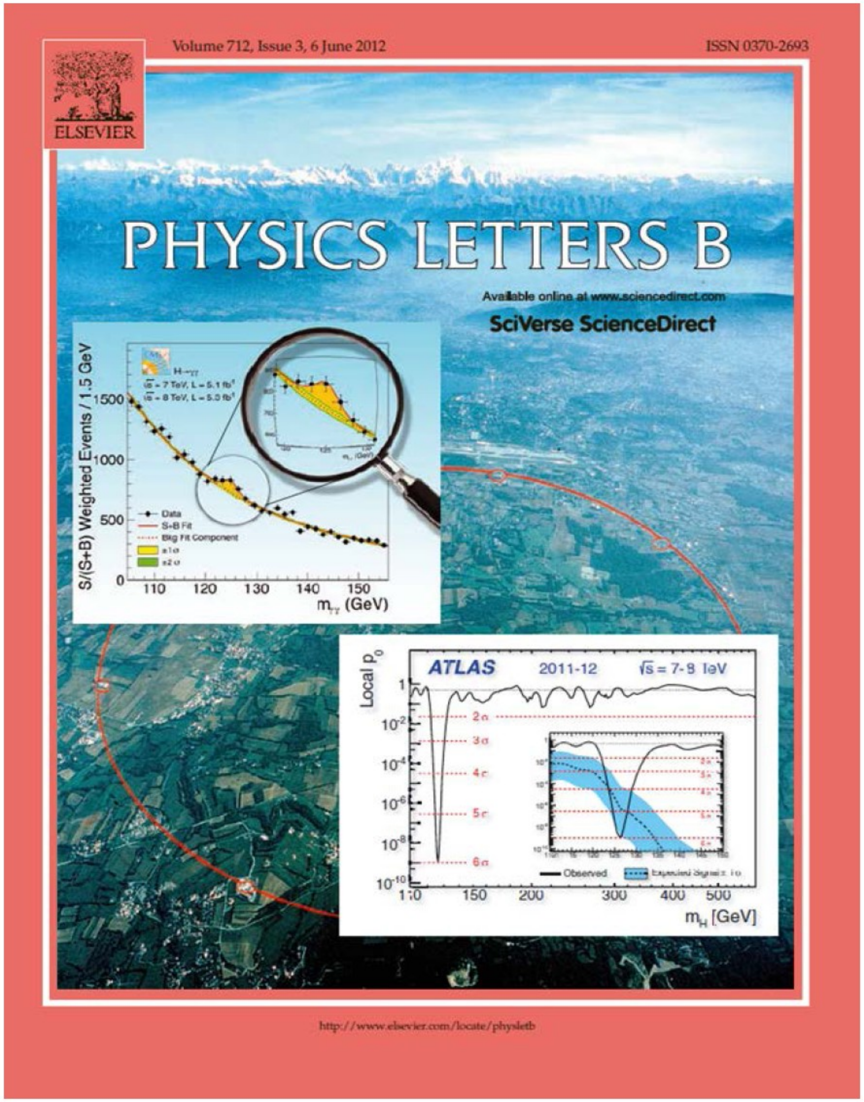
$m_H = 94^{+29}_{-24}$ GeV

$m_H < 152$ GeV, at 95% CL



Tevatron direct search limit as of June 2012

The paper for the discovery



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2012-218
Submitted to: Physics Letters B

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

Abstract

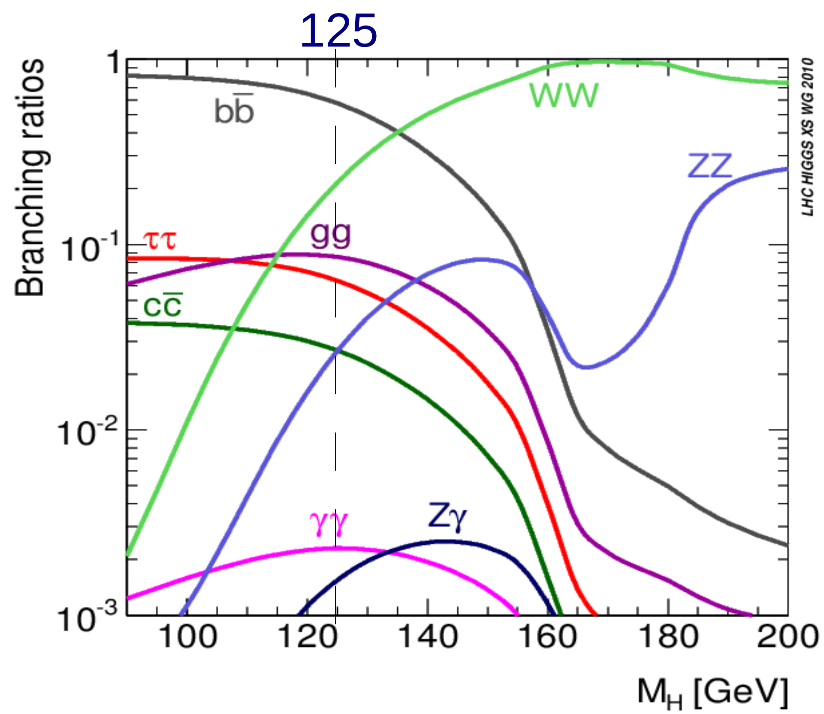
A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\,(\mathrm{stat}) \pm 0.4\,(\mathrm{sys})$ GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Both ATLAS and CMS submitted the discovery papers on July 31, 2012. ATLAS result is published in Phys. Lett. **B**176, 1 (2012)

Higgs decay channels

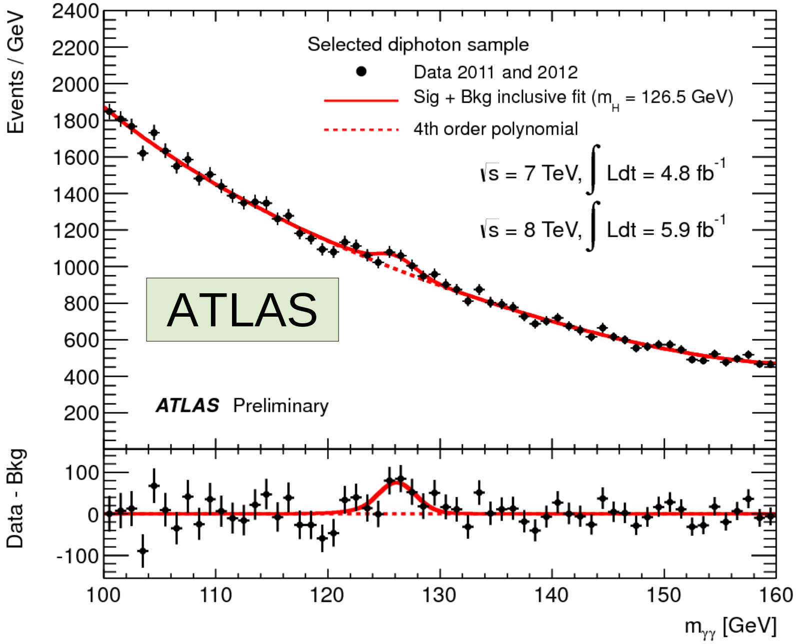
Braching ratios for a Higgs mass of 125 GeV:

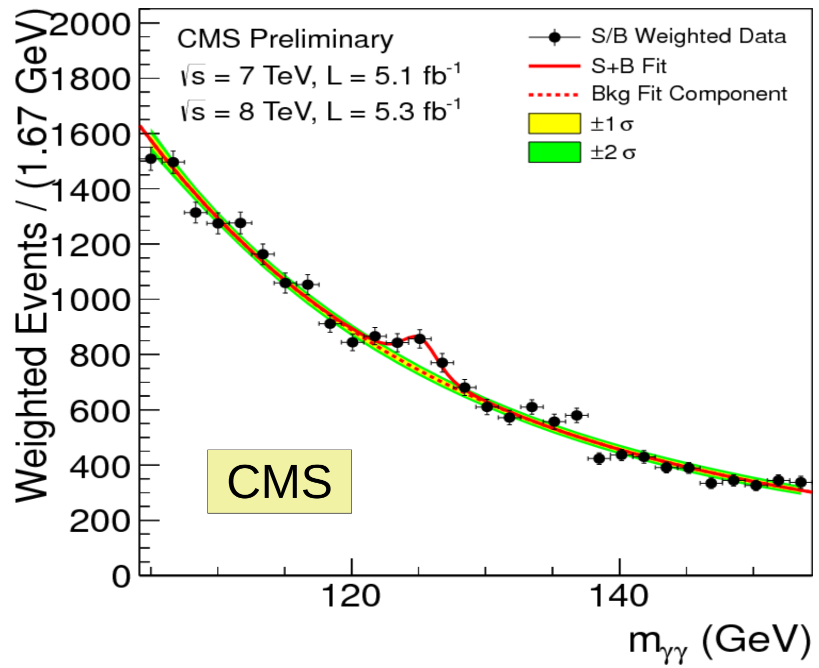
channel	BR
bbar	57.7%
WW	21.5%
ττ	6.3%
ZZ	2.6%
γγ	0.23%

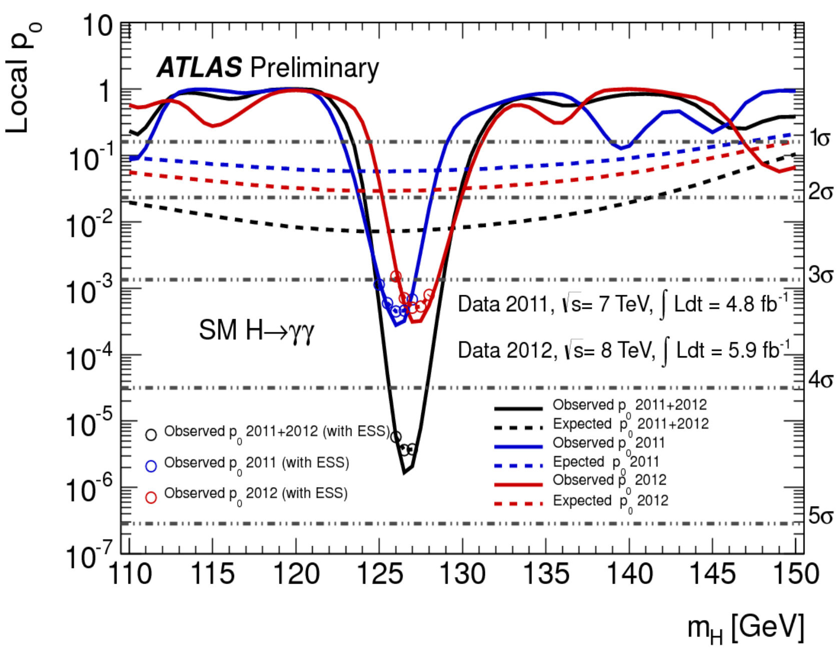


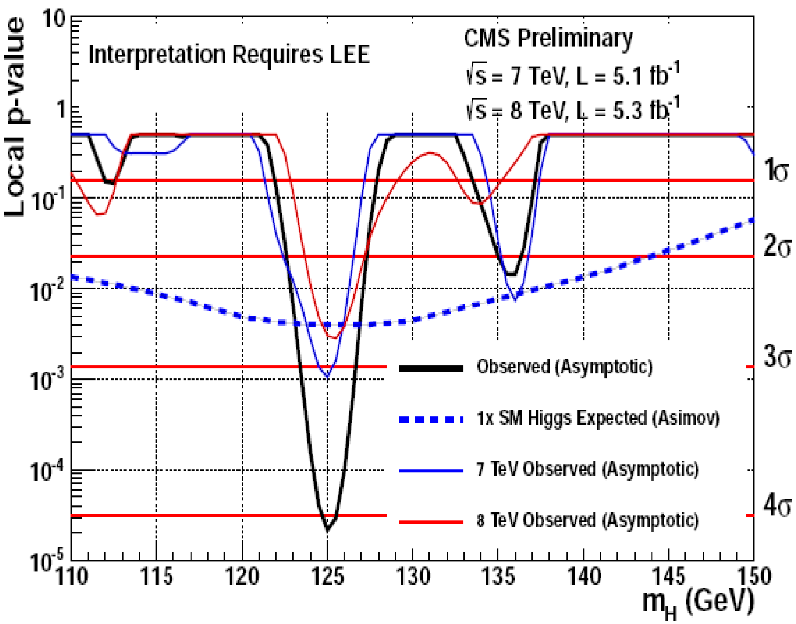
- bbar: highest BR, but suffers from bad mass resolution and large QCD background
- WW: only the dilepton decay modes are useful at low mass, and can not reconstruct the mass
- ττ: bad mass resolution (MET used), high signal efficiency (all final states are used: ll, lh, hh)
- ZZ and γγ: low BR, but good mass resuliton. Very low background for ZZ and powerful S/B shape separation for γγ

$H \rightarrow \gamma\gamma$

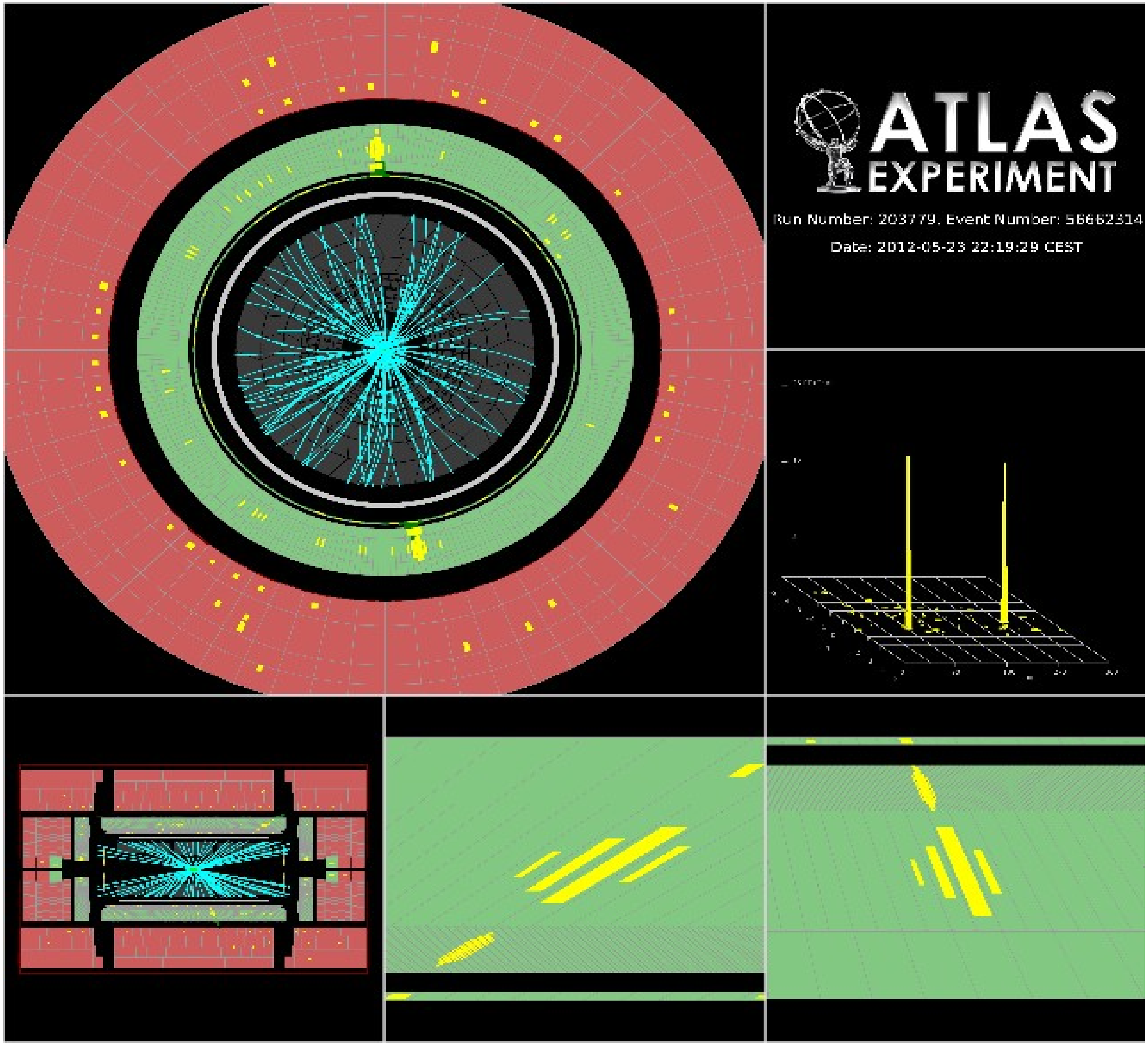




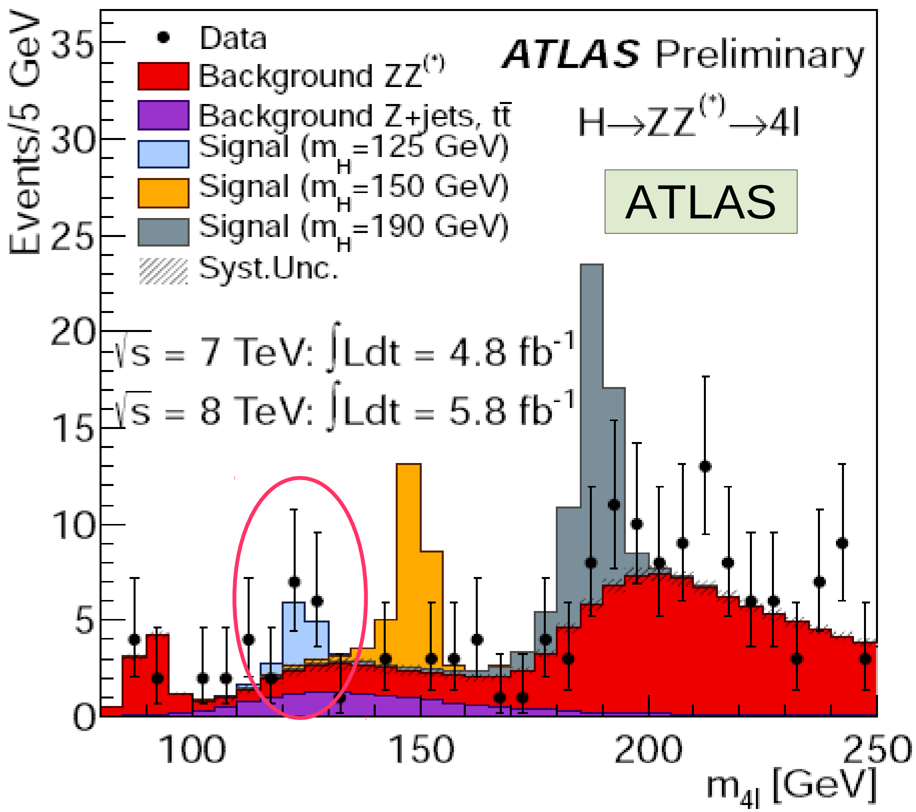


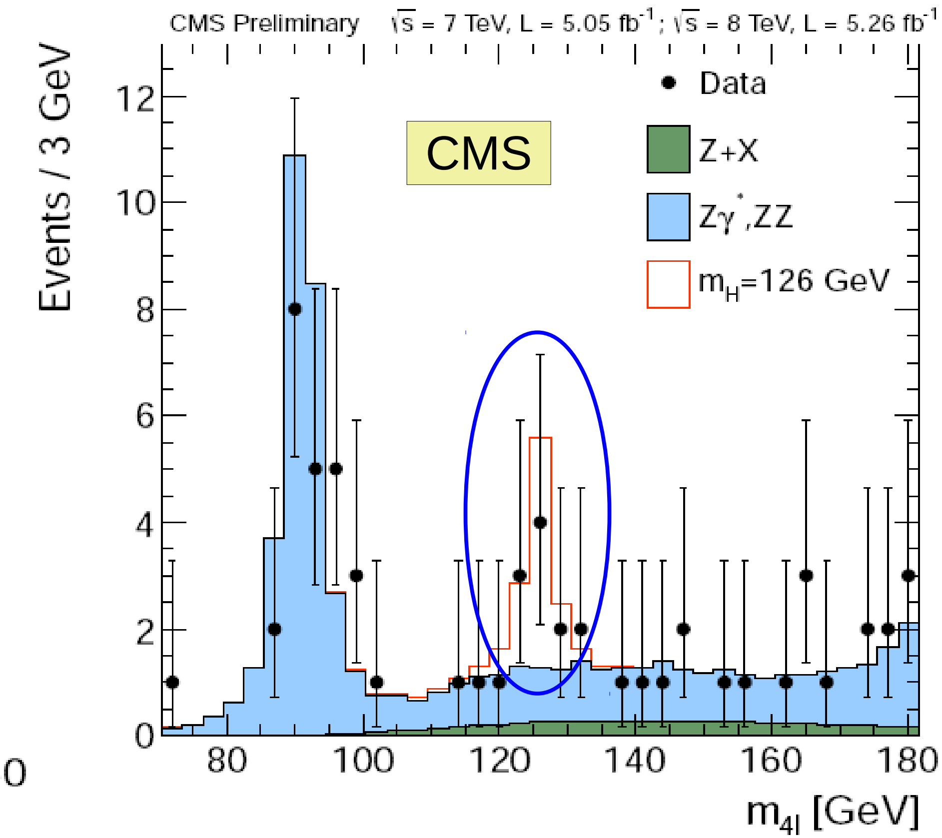


H→γγ candidate event (ATLAS)



$H \rightarrow ZZ \rightarrow 4l$

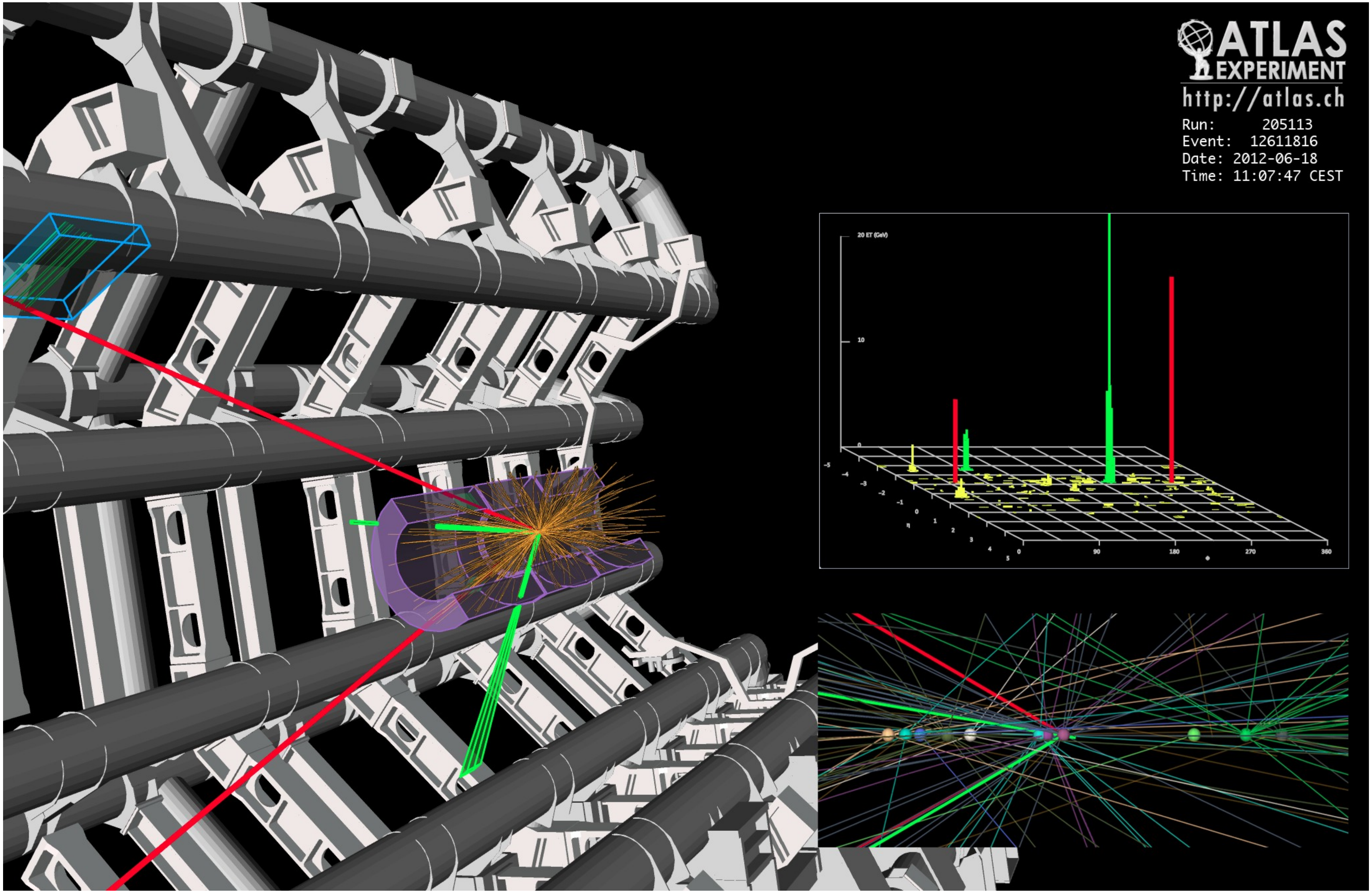




Both ATLAS and CMS have found a 4-lepton excess, and the mass is consistent with the one found in γγ channel !

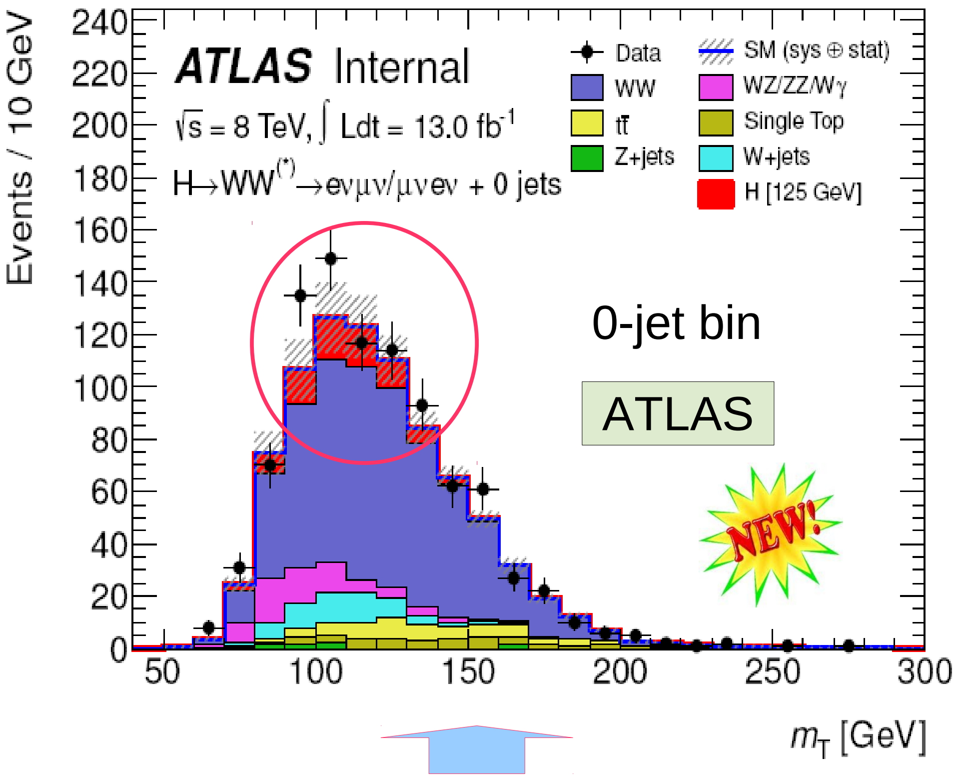
Maximum lcoal significance: 3.6σ (3.2σ) for ATLAS (CMS)

H → ZZ → 2e2μ candidate event

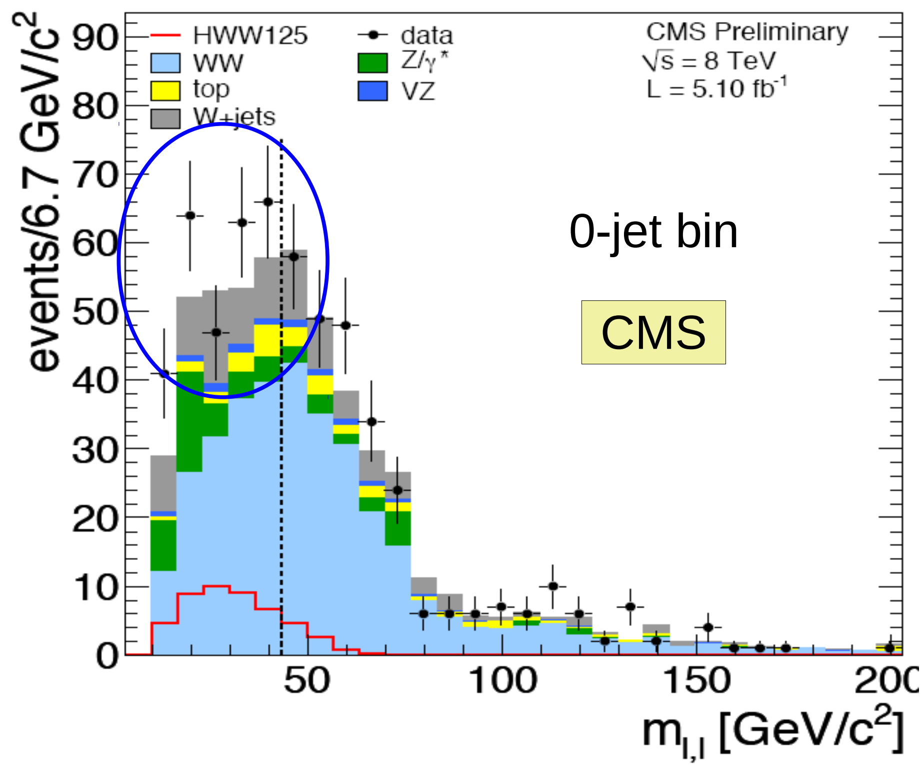


$H \rightarrow WW \rightarrow 2l2\nu$

- **The first proposal on WW at Tevatron by T. Han and R. Zhang in PRL 82, 1999**



Due to 2 neutrinos, it is difficult to Reconstruct the Higgs mass - ATLAS (CMS) uses m_T (m_{ll})

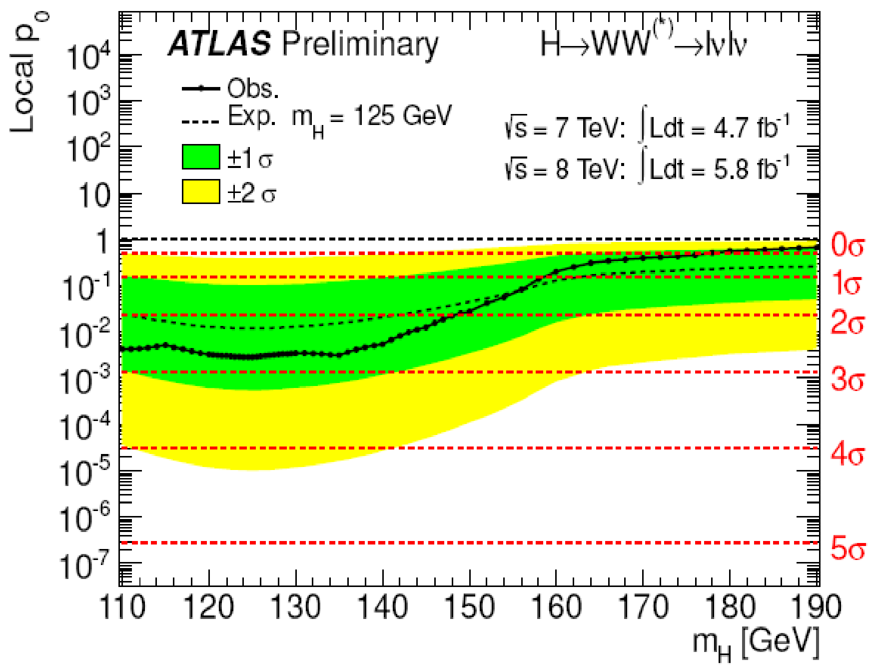


Results for ICHEP: 0/1/2- jet
Results for HCP: 0-jet and 1-jet
Main background: WW

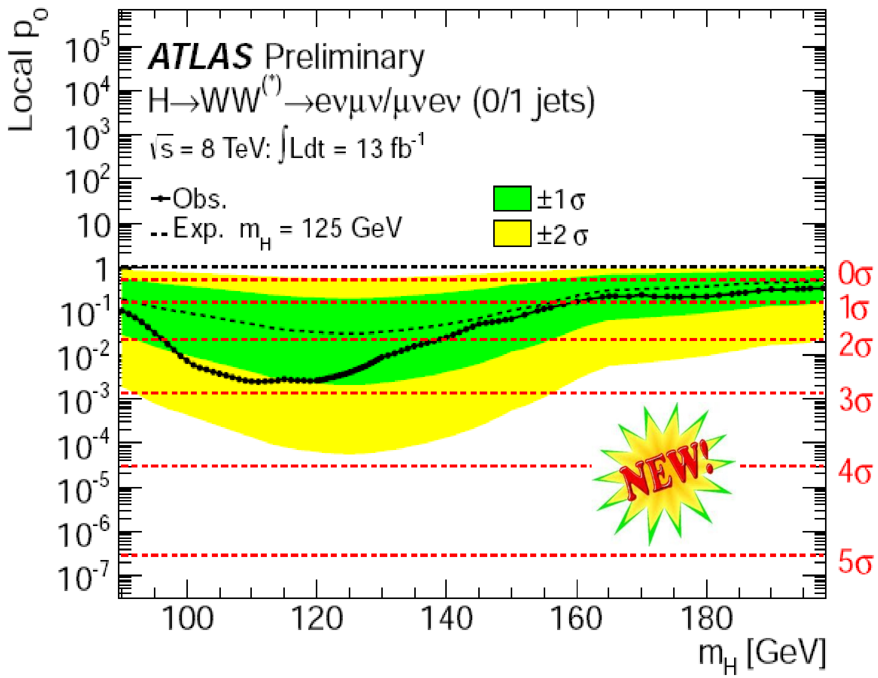
Due to spin correlation between the 2 Ws, the signal has the following properties:

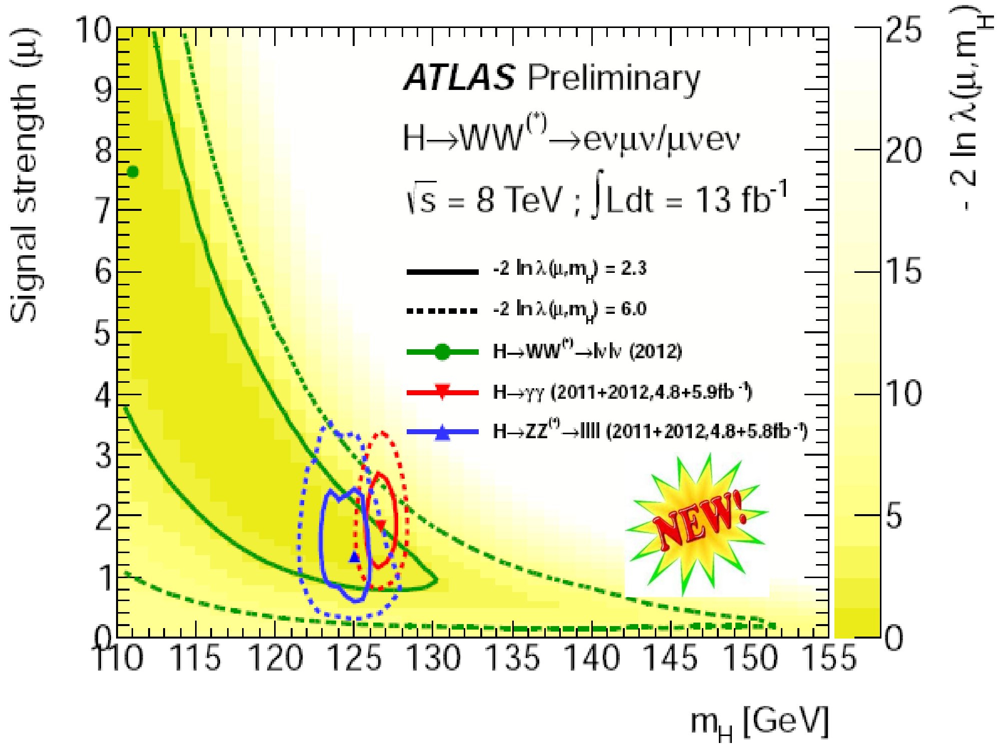
- Large $p_T(ll)$
- Small m_{ll}
- Small $\Delta\Phi(ll)$

$H \to WW \to 2l2\nu$

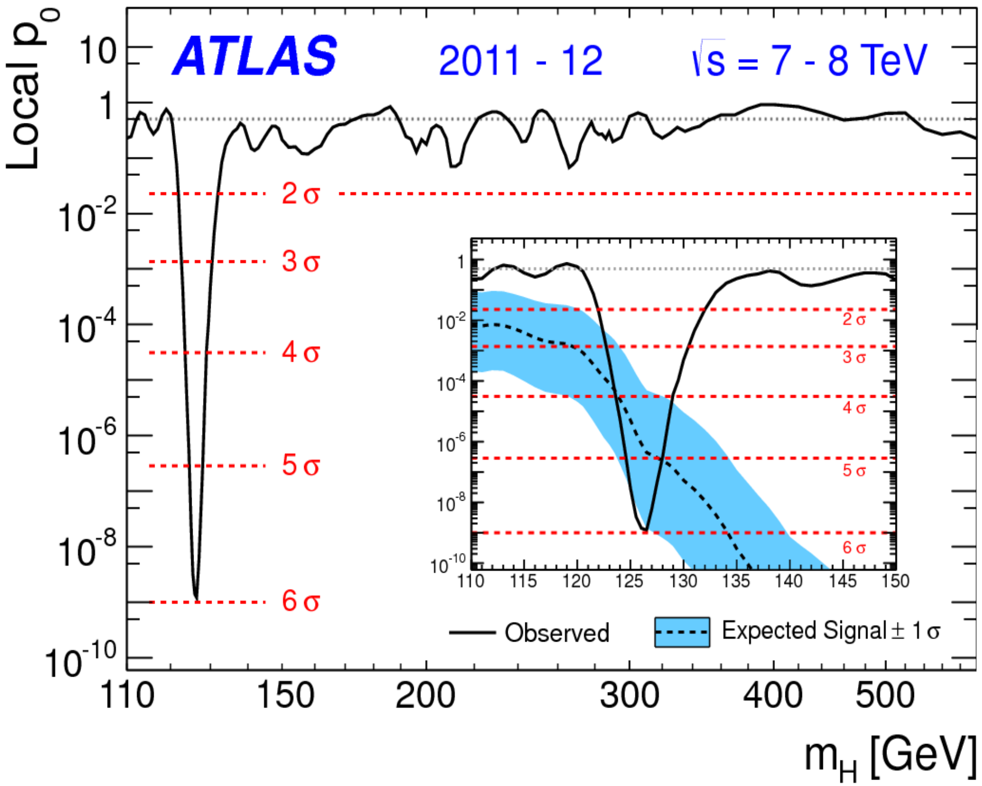


Fitted signal strength:
ICHEP($4.7fb^{-1}$+$5.8fb^{-1}$) : $\mu = 1.3 \pm 0.5$
2012 $13fb^{-1}$: $\mu = 1.5 \pm 0.6$



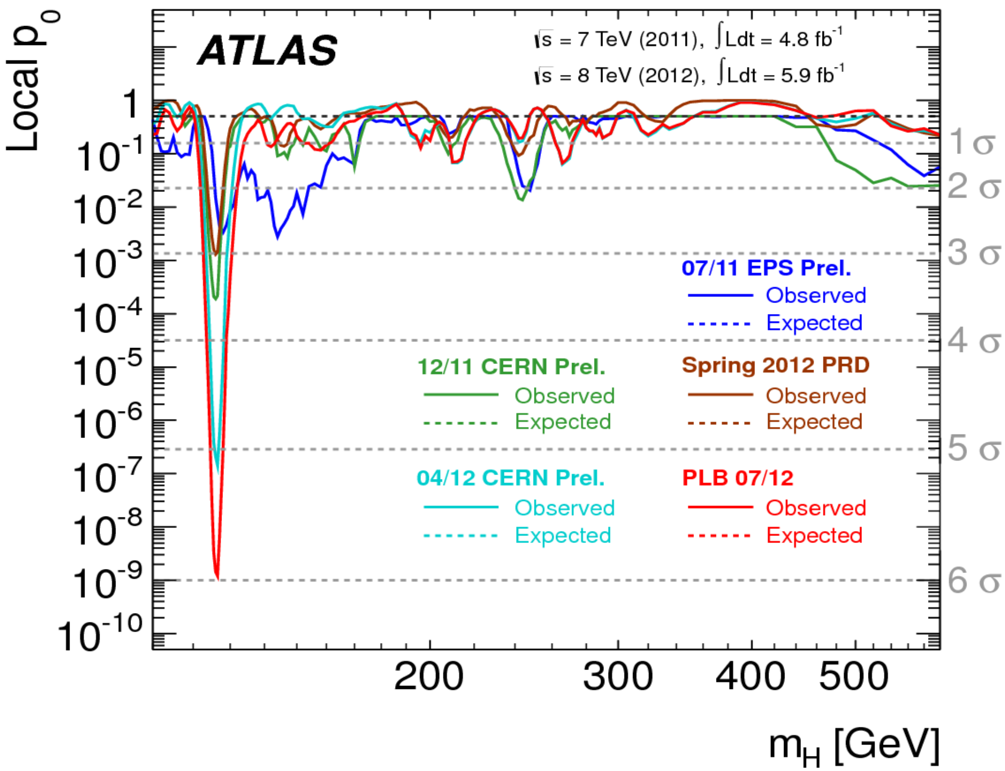


Combination of 3 channels at ATLAS

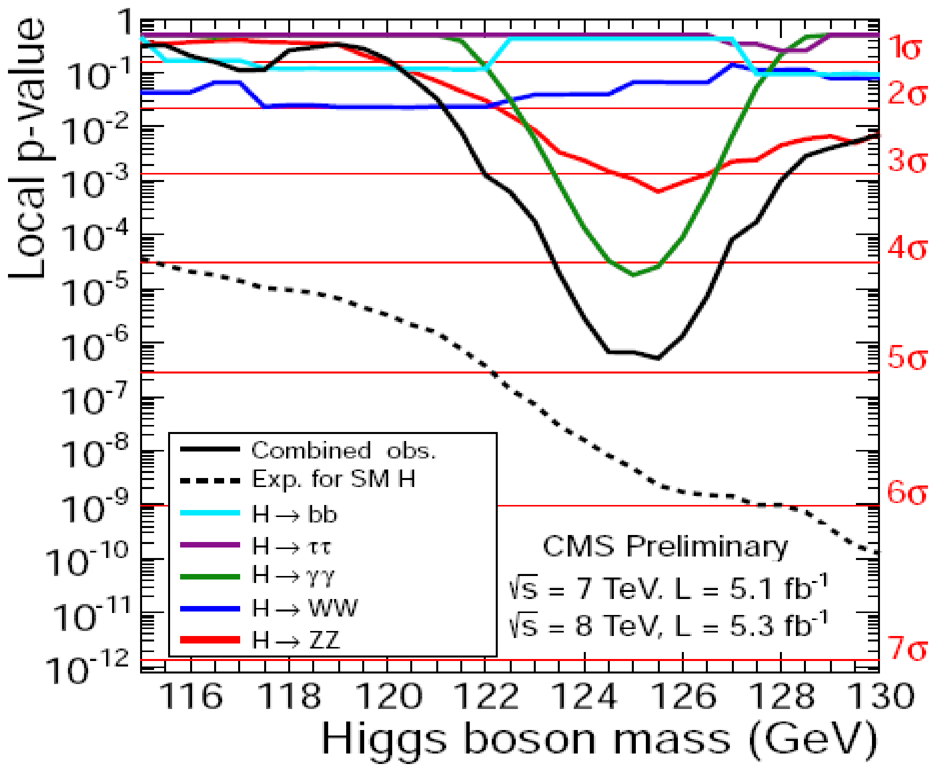


The combination at ATLAS alone yields >6σ discovery

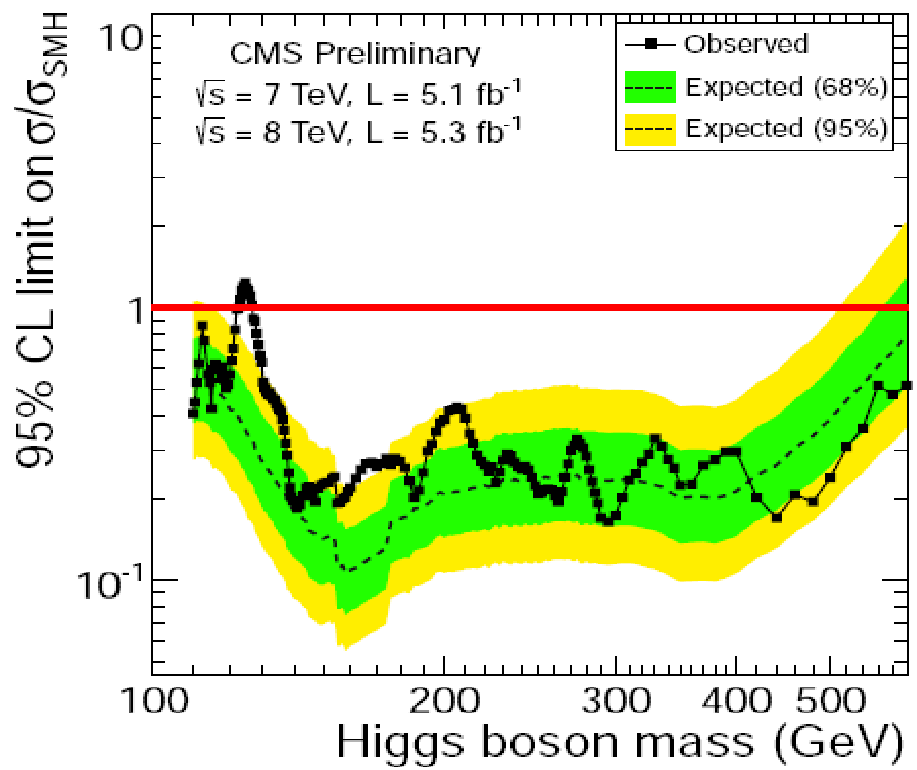
And the signal excess stays with time!



Combination of 5 channels at CMS



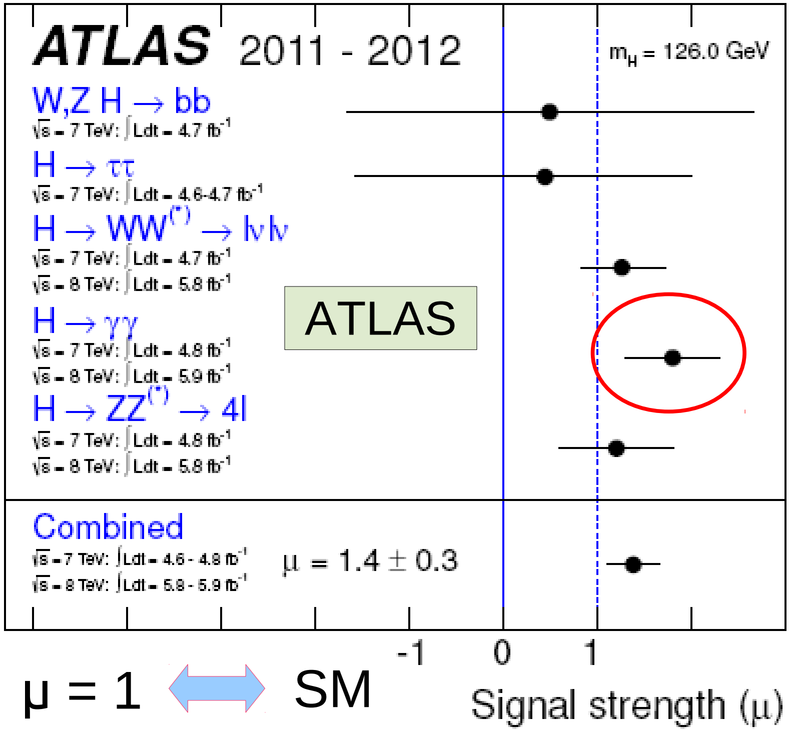
The discovery is reflected by the inability to exclude a Higgs at ~125 GeV in the mass landscape



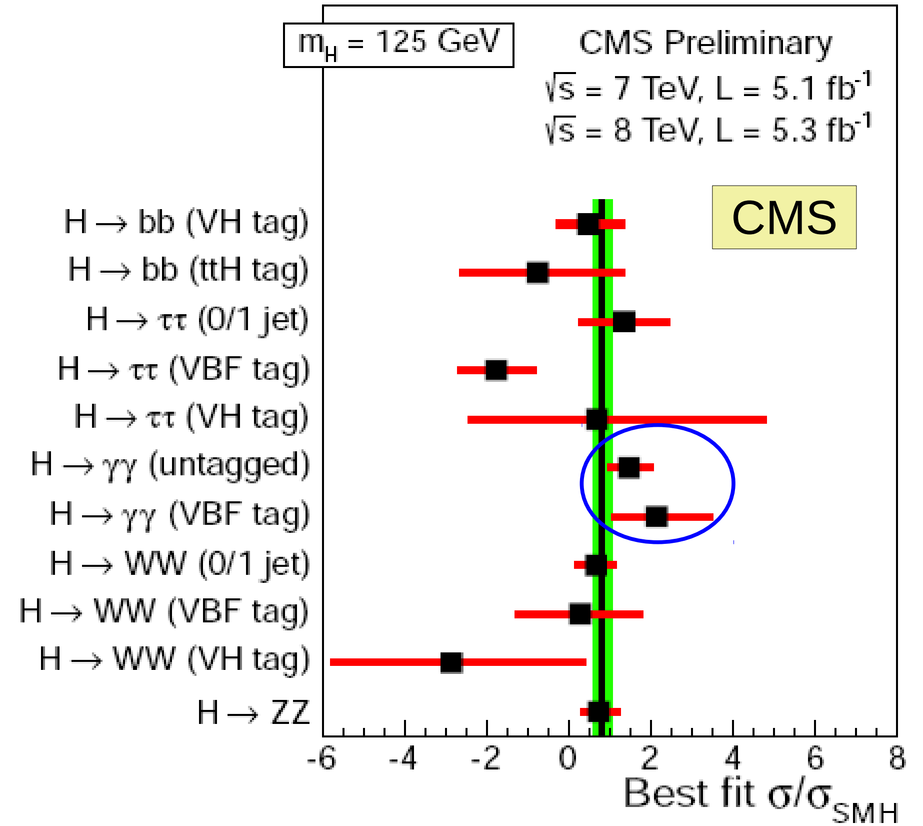
With a 5-channel combination, CMS reaches a local Significance of 4.9σ

The July 4th Higgs discovery

Higgs coupling strengths

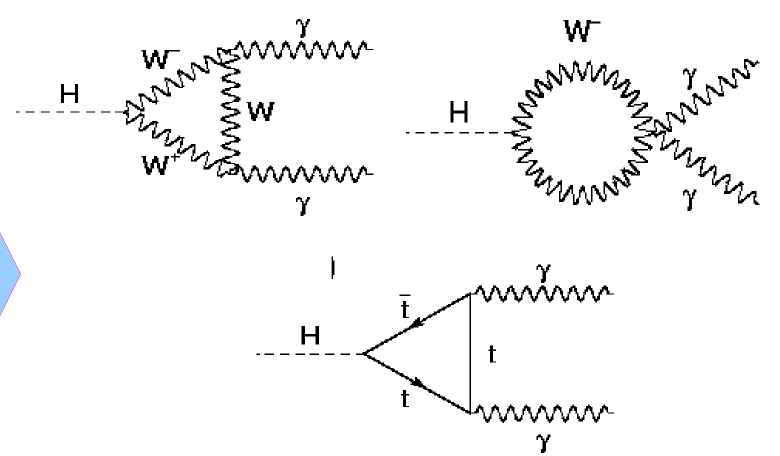


μ = 1 ⟺ SM

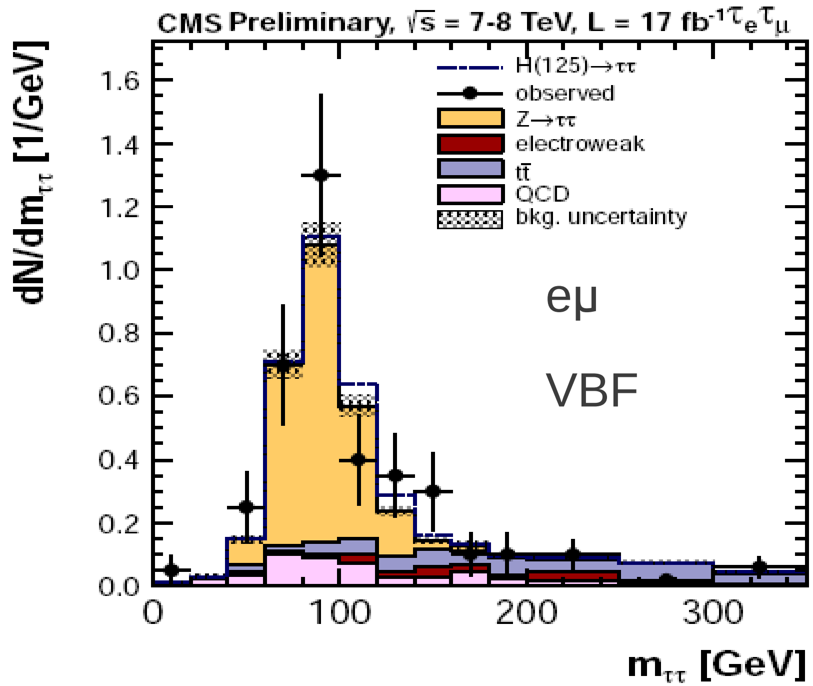


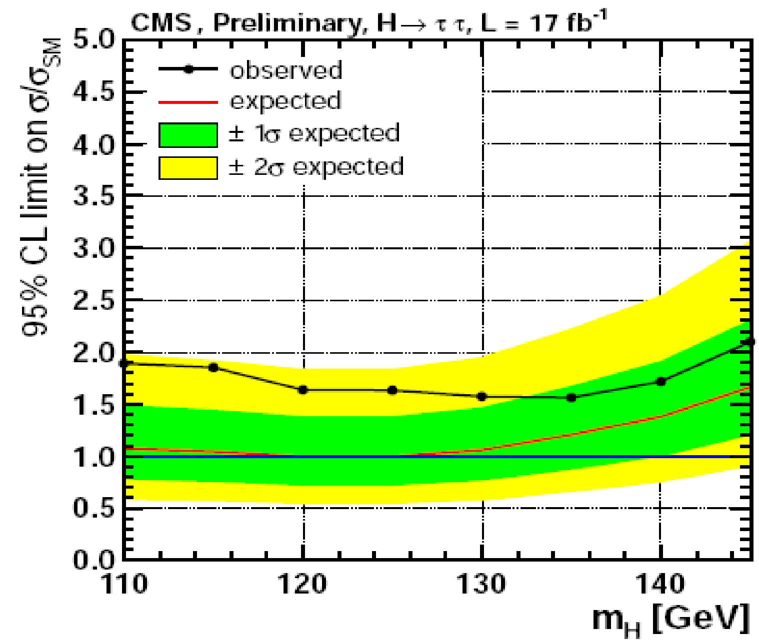
The overall fitted signal strength μ, in unit if SM, is 1.4±0.3 (0.80±0.22) for ATALS (CMS)

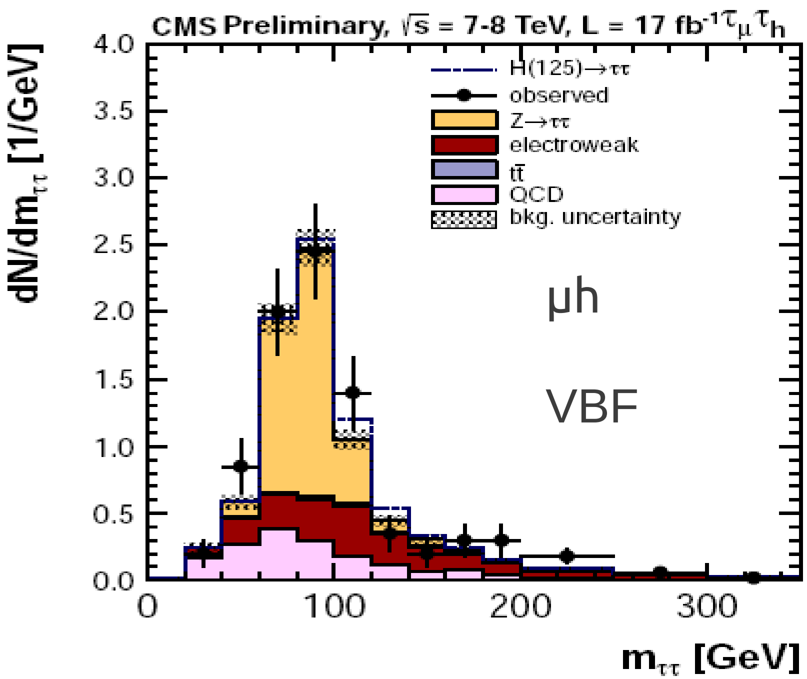
H → γγ rate is a bit higher than SM – new charged particle in the loop ?

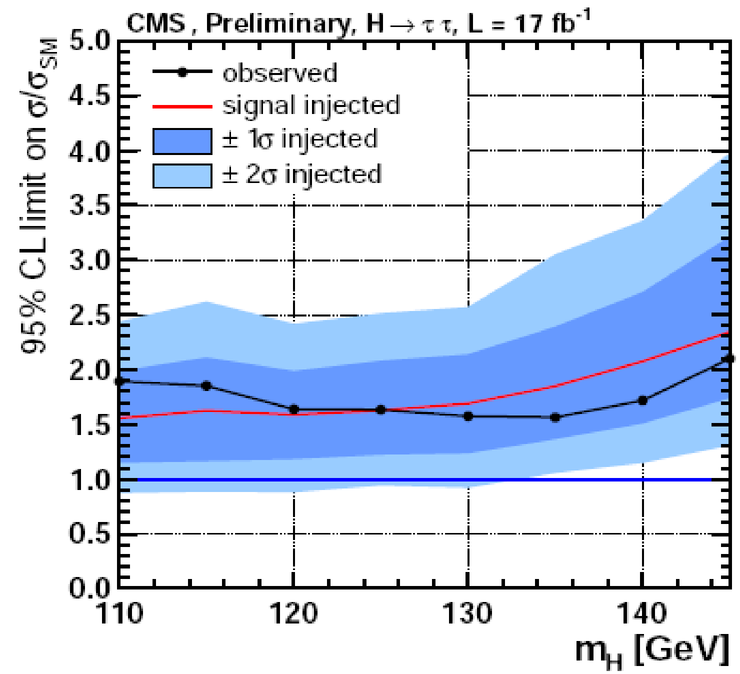


H → ττ result from CMS





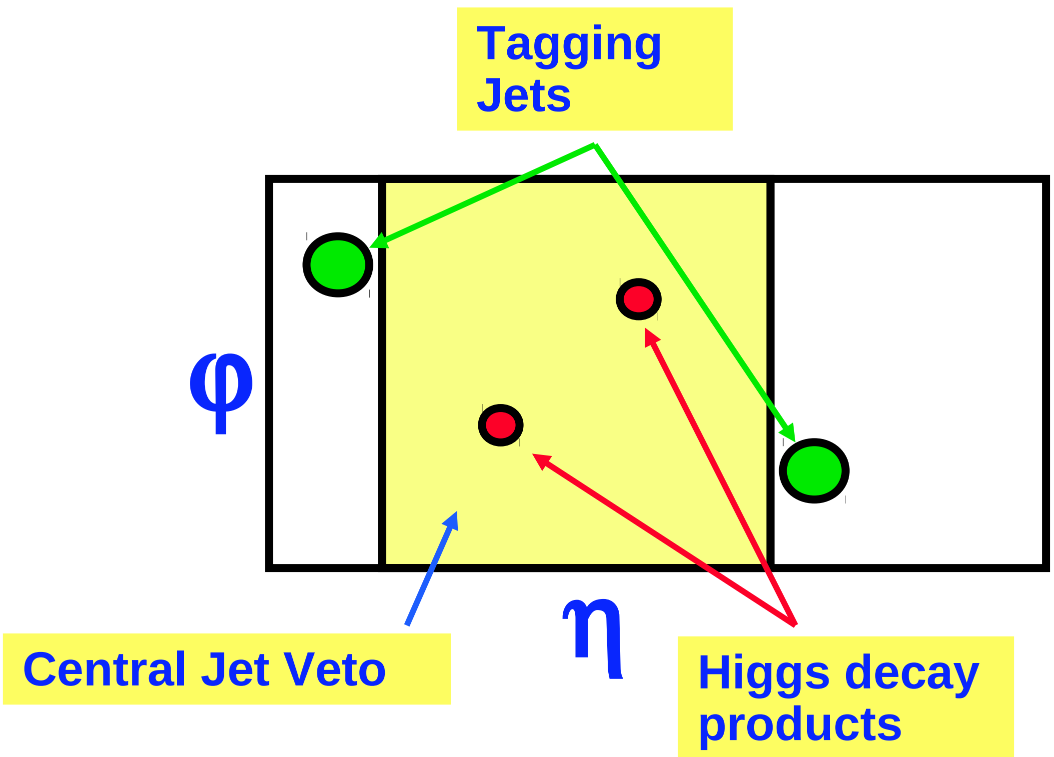


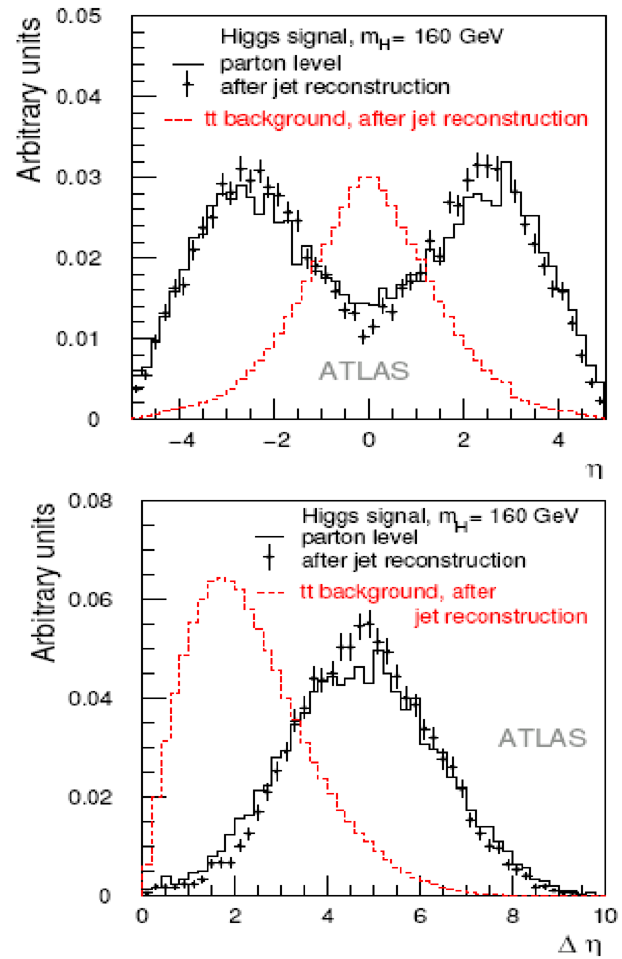


Low mass SM Higgs + 2jets

Wisconsin Pheno (D. Zeppenfeld, D. Rainwater, et al.) proposed searching for a low mass Higgs in association with 2 jets plus central jet veto

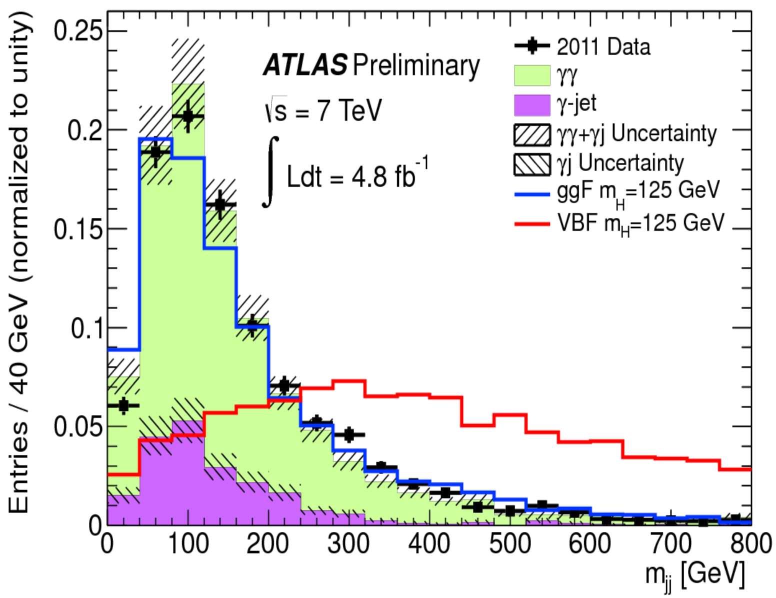
- **Central jet veto is initially suggested by V. Barger, K. Cheung and T. Han in PRD 42 3052 (1990)**

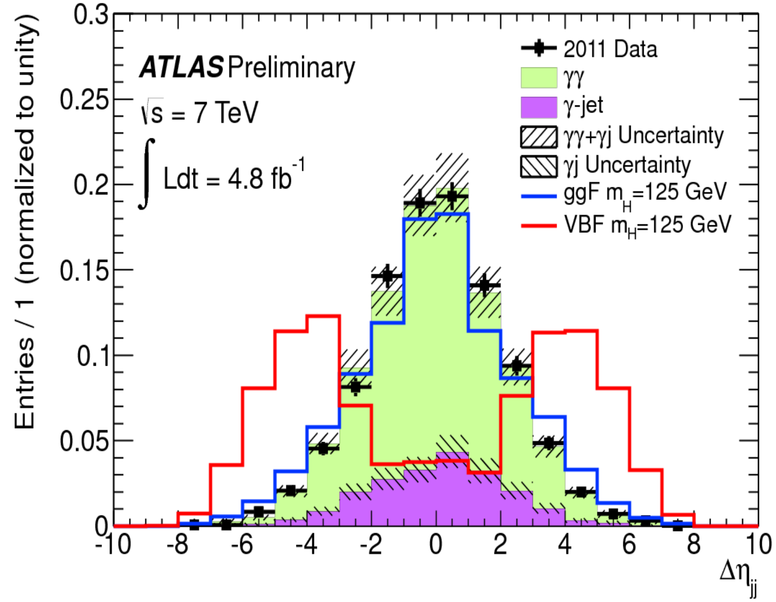


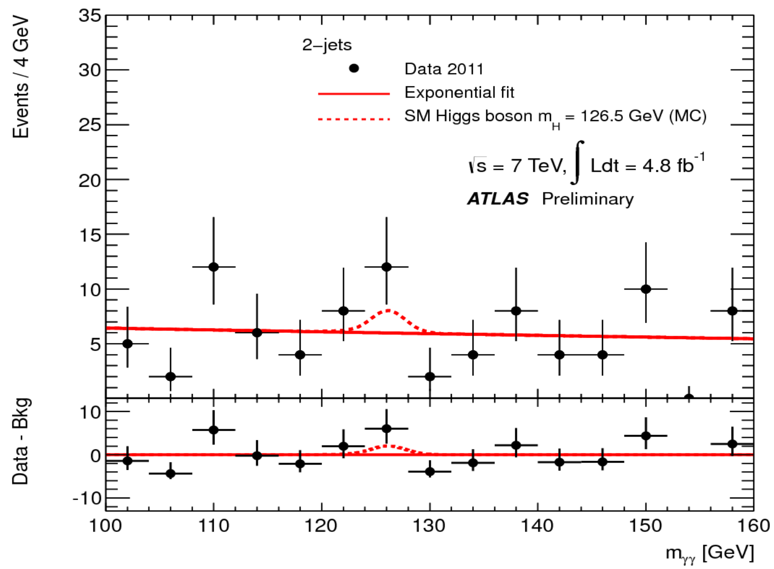


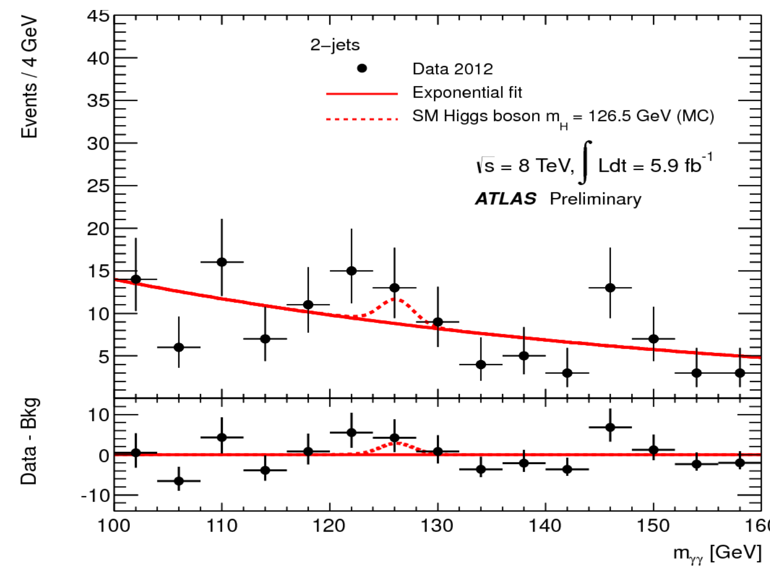
Very powerful to suppress the color-exchanging QCD backgrounds. Best suited for **$H \rightarrow \tau\tau$** and **$H \rightarrow \gamma\gamma$**

VBF category in the γγ channel







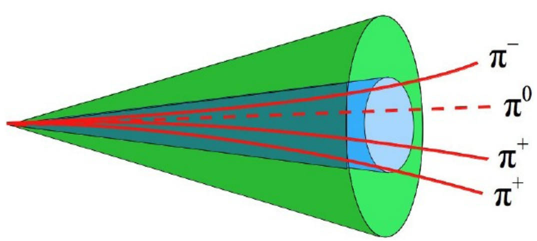


The S/B ratio is much improved w.r.t. inclusive search (see slide 10)

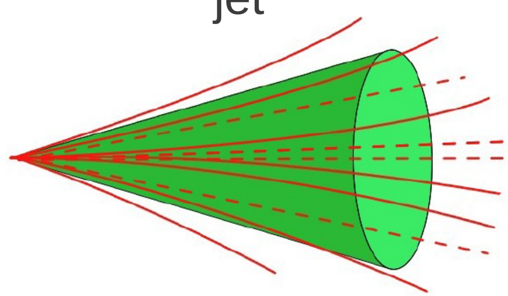
$H \rightarrow \tau\tau$ channels and objects

Pre-selection	
$ll+4\nu$	**Exactly 2 leptons with opposite** signs $30 < m_{LL} < 75$ (100) GeV for ee/μμ (eμ)
$lh+3\nu$	**Exactly 1 lepton and 1 hadronic τ** $p_T > 25$ (20) GeV for e (μ) **Di-lepton veto** $m_T < 30$ GeV
$hh+2\nu$	**Exactly 2 hadronic taus** $p_T > 35$ (25) GeV for the leading (subleading) tau **Single lepton veto**

τ-hadron



jet



Common object selection

Electron

$p_T > 15$ GeV, $|\eta| < 2.47$ with crack excluded
Calo and track isolation

Muon

$p_T > 10$ GeV, $|\eta| < 2.5$
Calo and track isoltion

Hadronic tau

$p_T > 20$ GeV, $|\eta| < 2.5$
1 or 3 tracks (prongs) in $\Delta R < 0.2$
Multivariate BDT for ID

Jet

$p_T > 25$ GeV, $|\eta| < 4.5$
AntiKt4 jets, $|JVF| > 0.75$ if $|\eta| < 2.4$

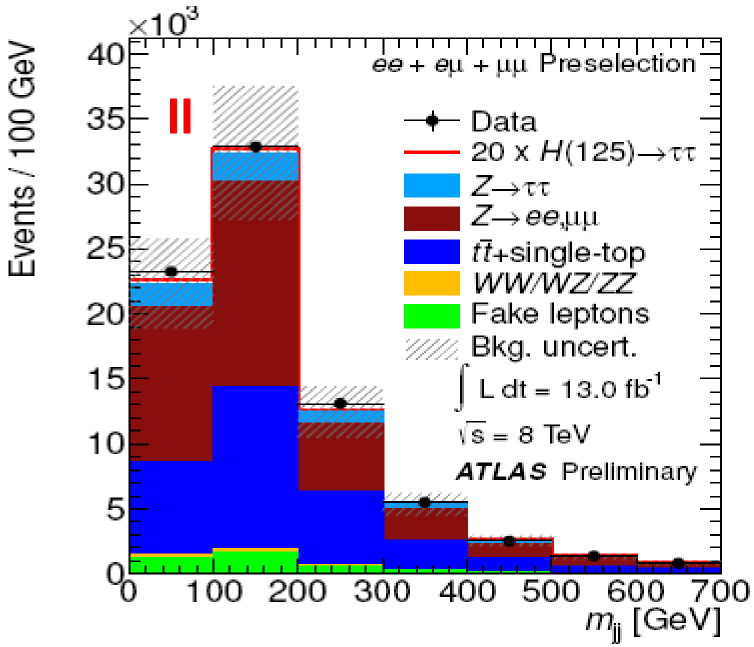
Categories, MET cut and mass

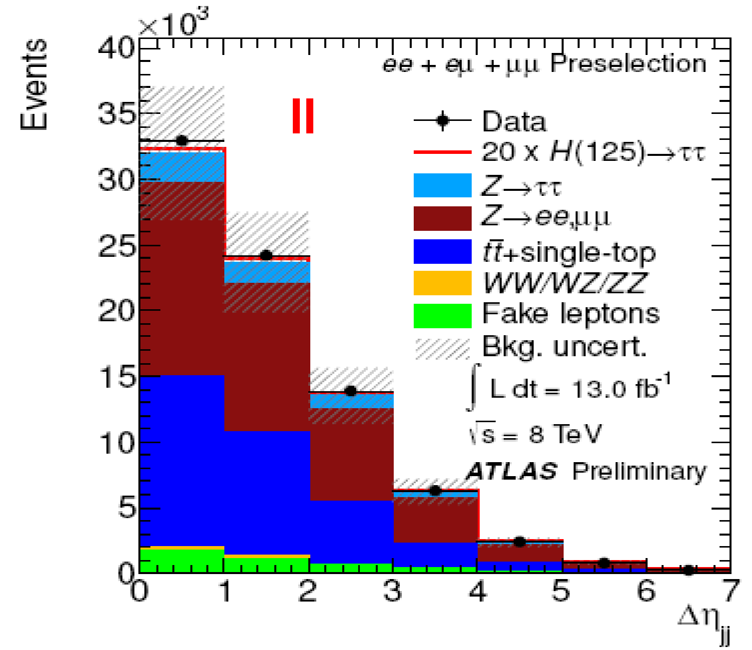
ll	lh	hh
2-jet VBF (p_T>40,25) 2-jet VH (p_T>40,25)	2-jet VBF (p_T>40,30)	2-jet VBF (p_T>50,30)
Boosted: $p_{T,H}$>100	Boosted: $p_{T,H}$>100	1-jet inclusive (p_T>70)
1-jet inclusive (p_T>40)	1-jet inclusive (p_T>30)	
0-jet inclusive in eμ channel	0-jet exclusive (p_T<30)	
MET>40 for SF MET>20 for DF	MET>20	MET>20
MMC	MMC	MMC

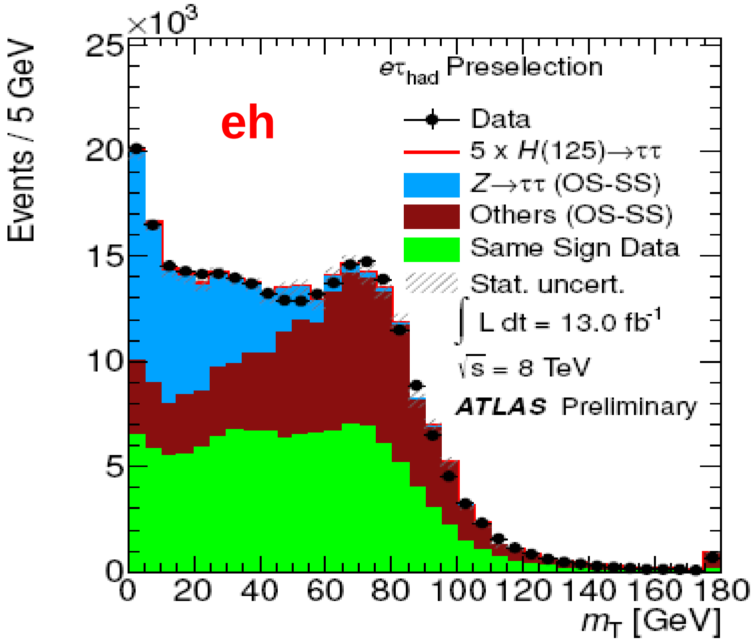
All categories are mutually exclusive

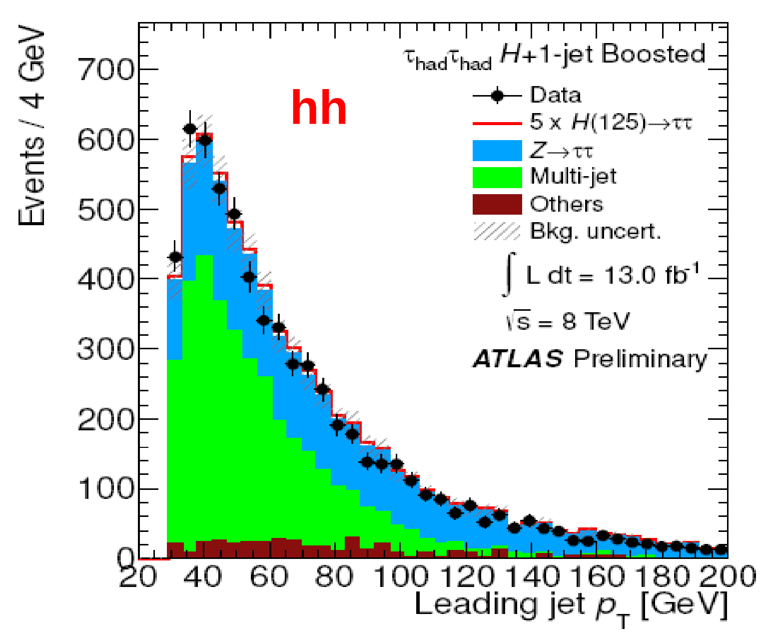
All 3 channels: use $Z\rightarrow\mu\mu$ data to simulate $Z\rightarrow\tau\tau$ background

Control plots



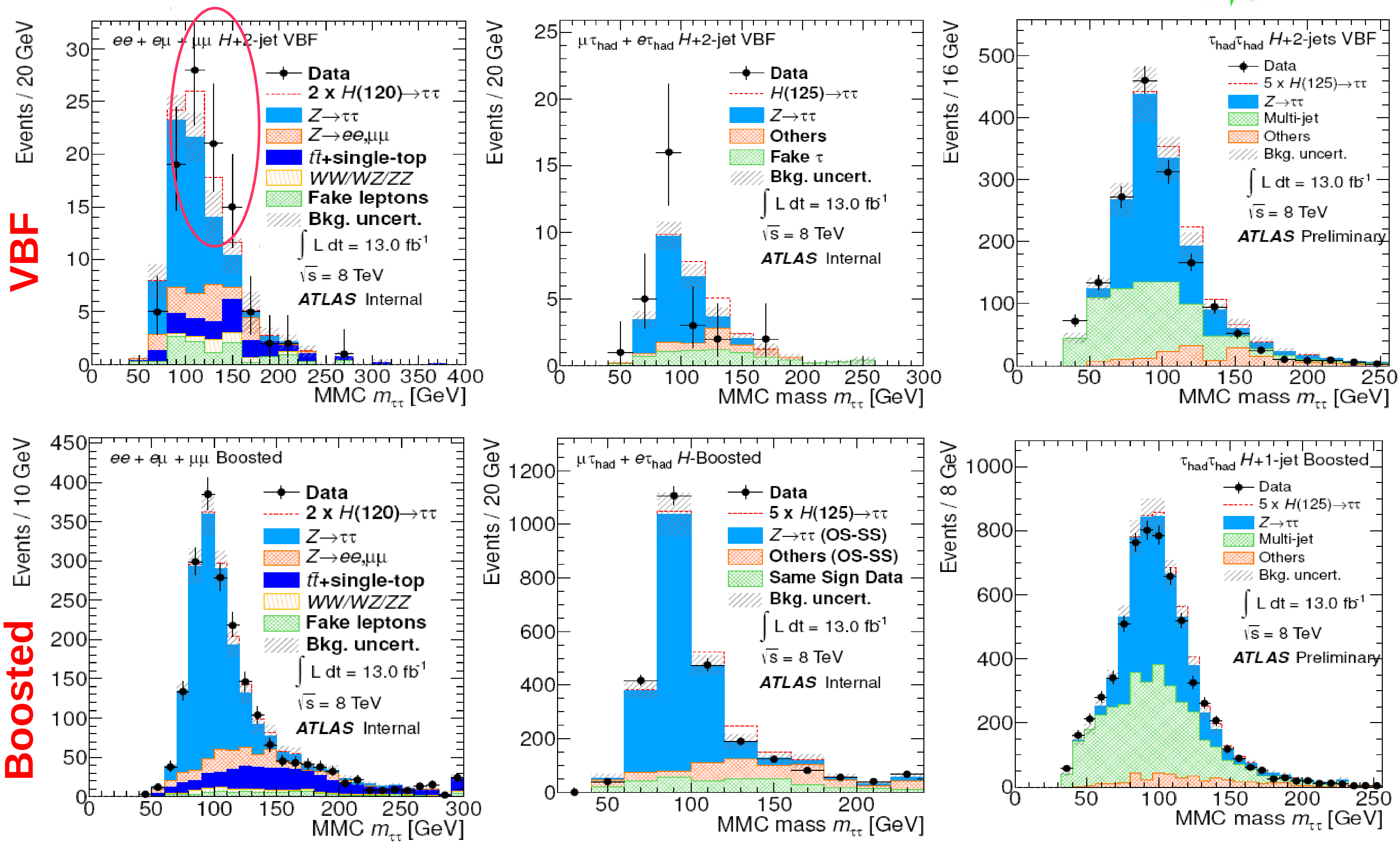






Final mass distributions (VBF and boosted)

NEW!

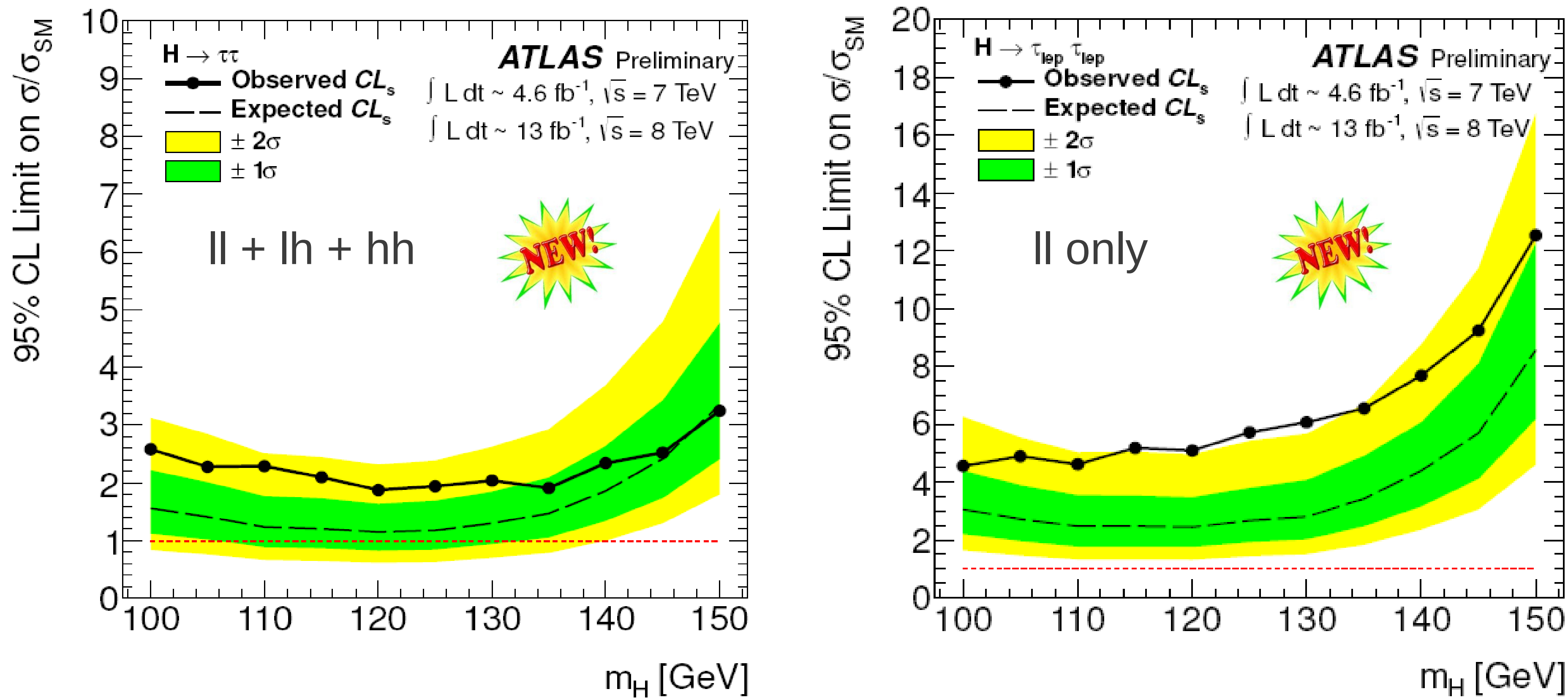


leplep **lephad** **hadhad**

ATLAS

VBF and boosted categories are most sensitive

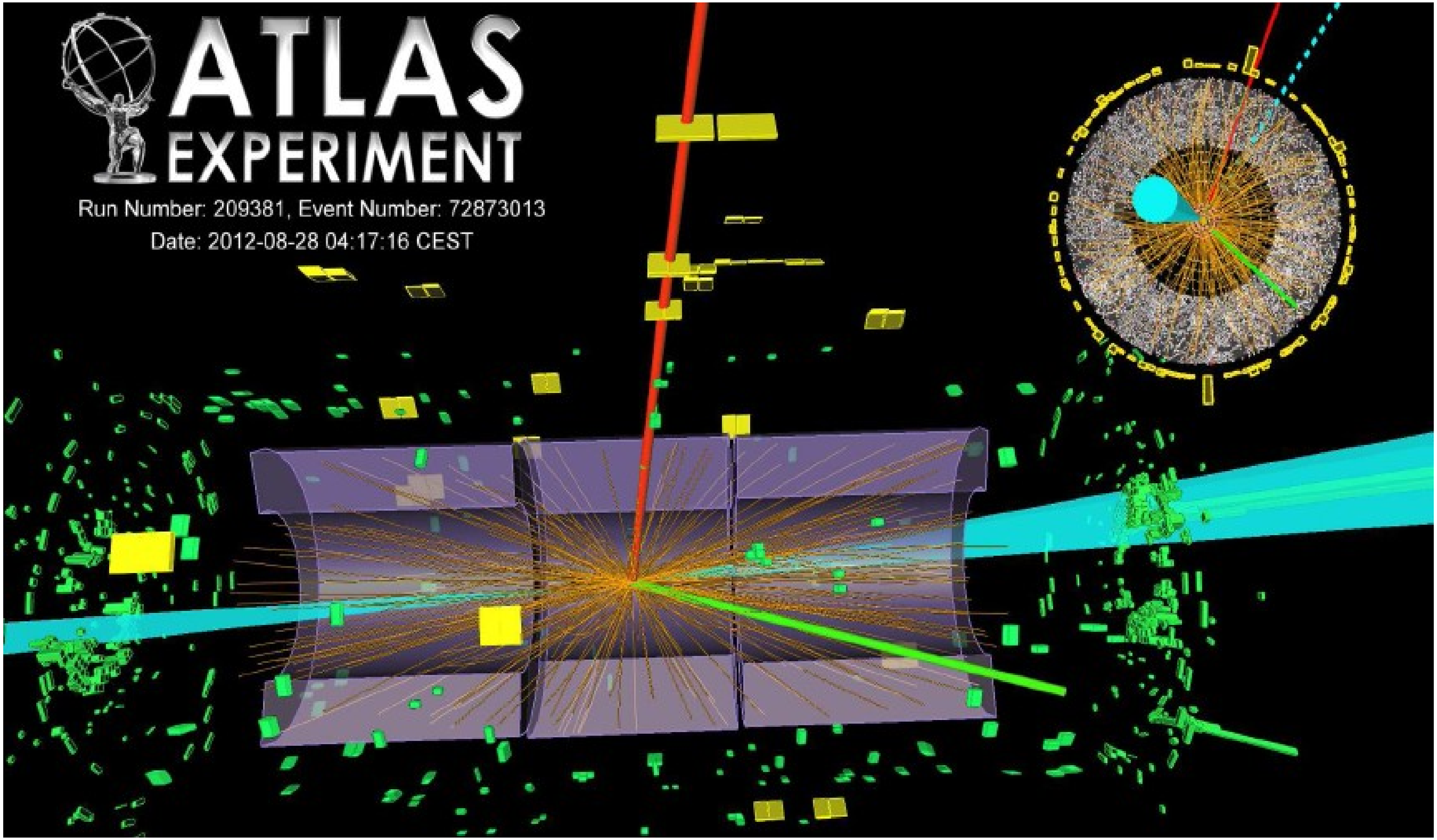
Statistical limits



The largst deviation of observed from expected limit is in the 2lep channel
The best fitted signal strength @ 125 GeV: $\mu = 0.7 \pm 0.7$

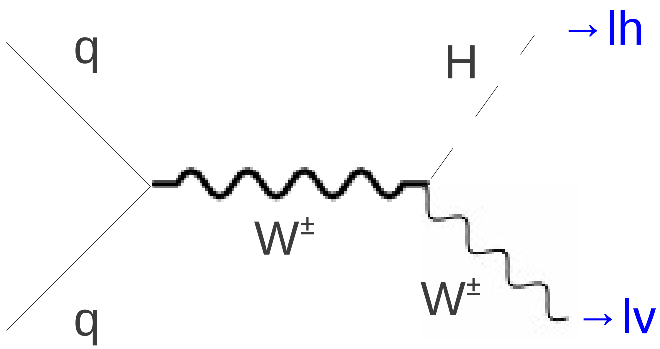
The lower combined H→ττ rate is consistent with CMS

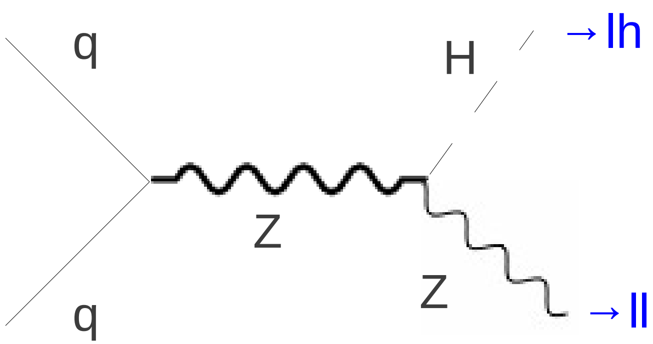
H→ττ→eμ+4ν candidate event NEW!



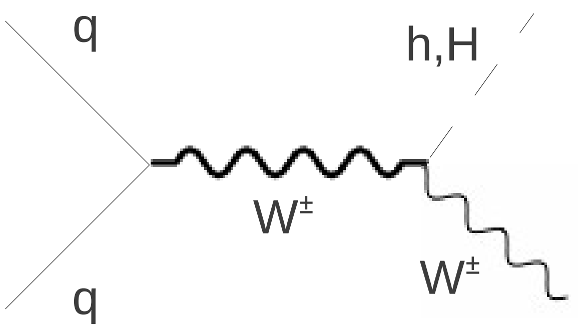
The channels we are adding: 2l+h and 3l+h

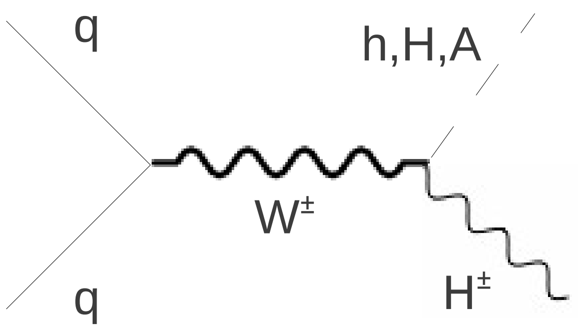
- Adding the 2l+h and 3l+h channels for the VH production of Higgs:





- These channels can be even more interesting in the context of MSSM or 2HDM, with possible double Higgs production modes and sensitivity to new physics:

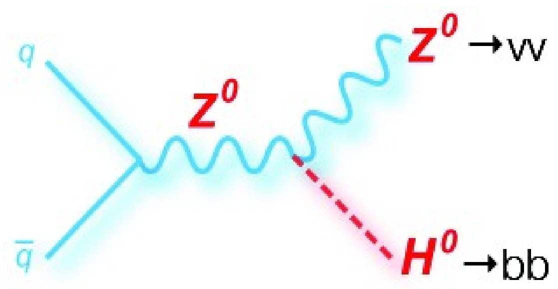


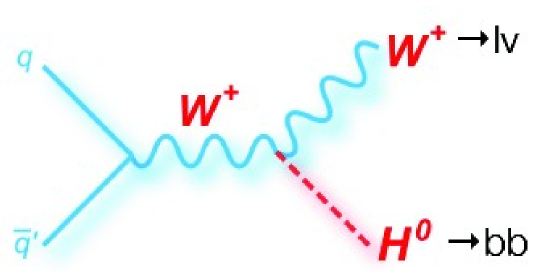


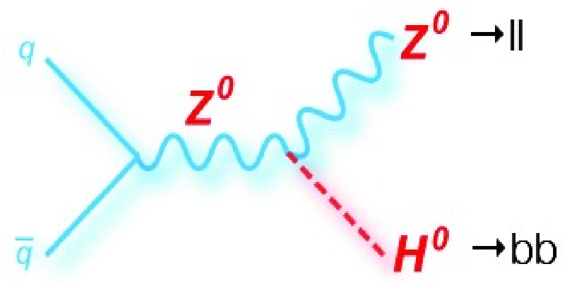
An exclusion limit of ~10xSM has been reported by CMS with the 2l+h channel

$H \to$ bbar

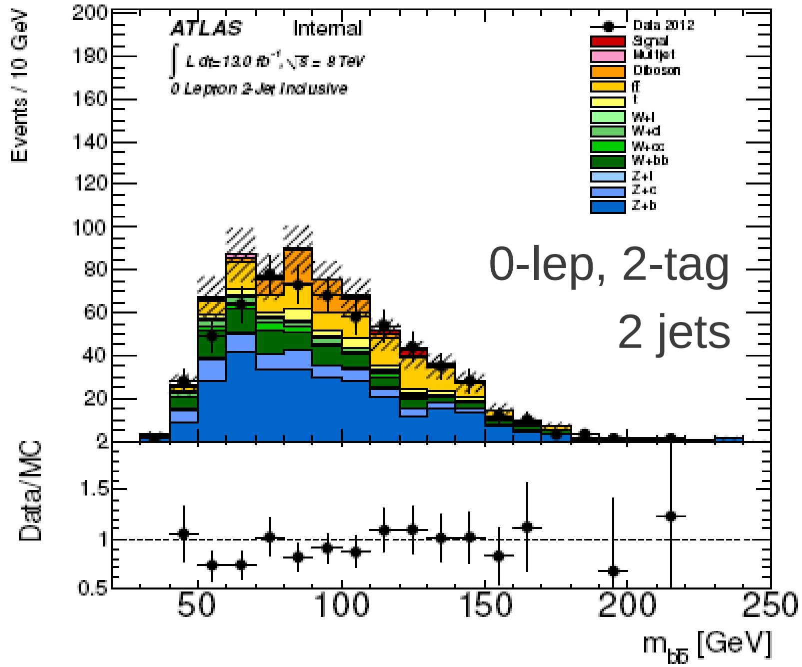
$ZH \to \nu\bar{\nu}b\bar{b}$	$WH \to \ell\nu b\bar{b}$	$ZH \to \ell^+\ell^- b\bar{b}$
0 lepton	1 lepton	2 leptons
2 b-jets	2 b-jets	2 b-jets
2 or 3 jets	2 jets	no N_{jet} requirement
MET > 120	MET > 25-50	MET < 60
	$40 < m_T < 120$	$83 < m_{LL} < 99$
3 bins in $p_T(Z)$	5 bins in $p_T(W)$	5 bins in $p_T(Z)$

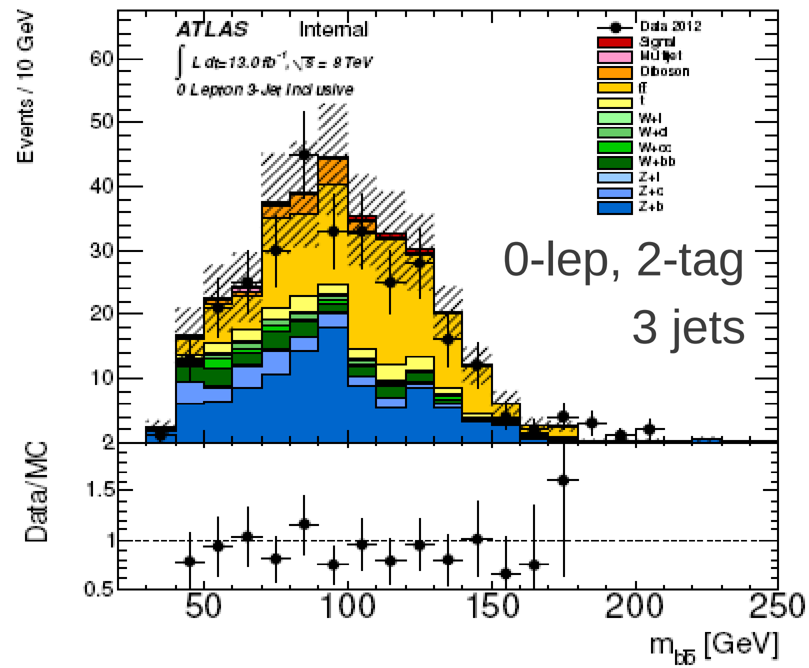


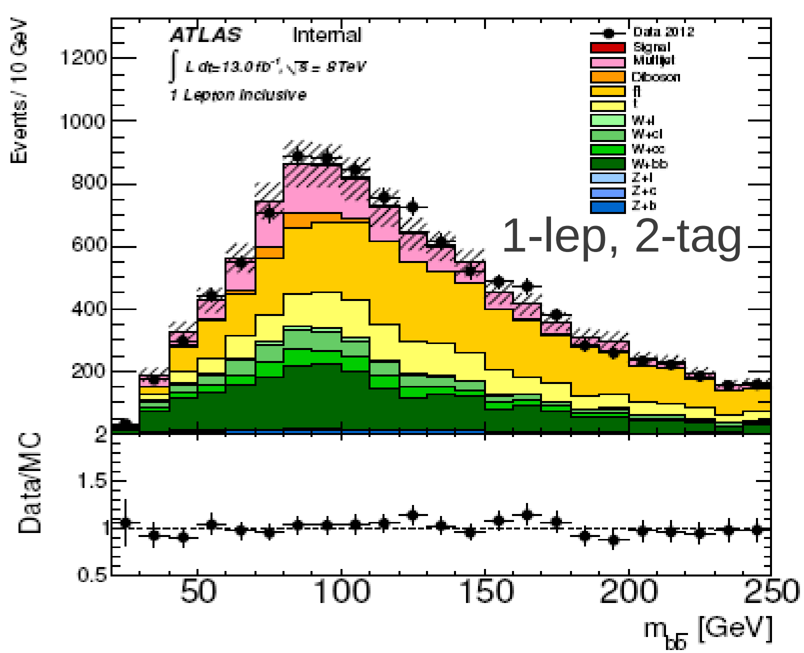


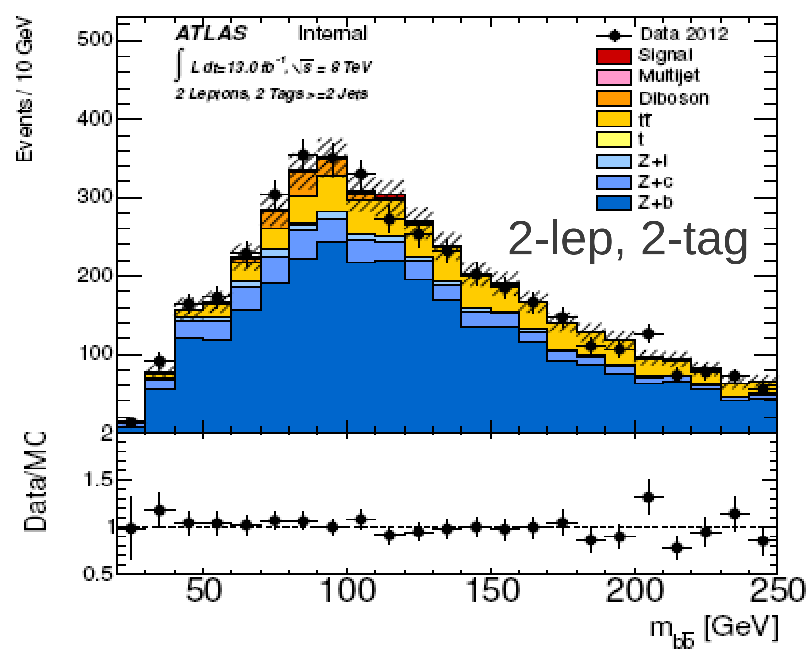


Signal regions bbar mass spectra

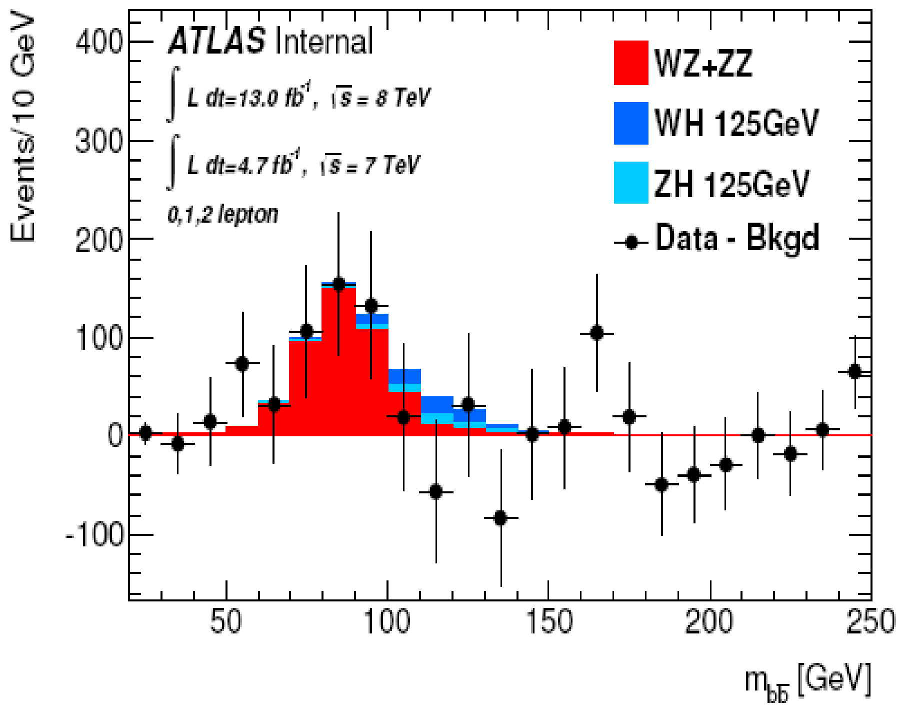








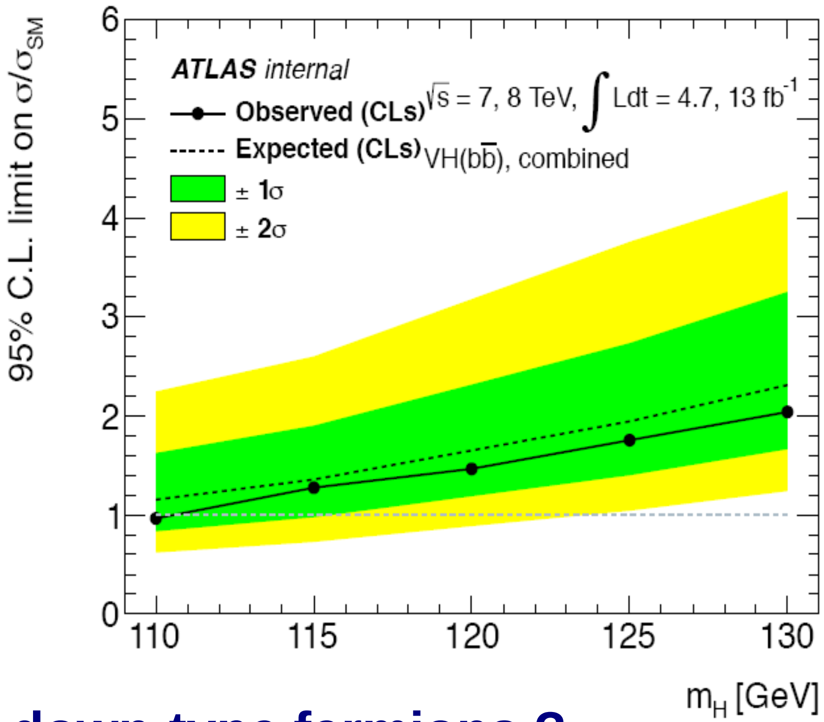
Statistical results



A SM Higgs in bbar decay is excluded for 1-2xSM rate.

The fitted signal strength
μ = -0.4±1.1

To validate the bbar decays of diboson background, subtract all other background from data except diboson – we have confidence in signal modeling



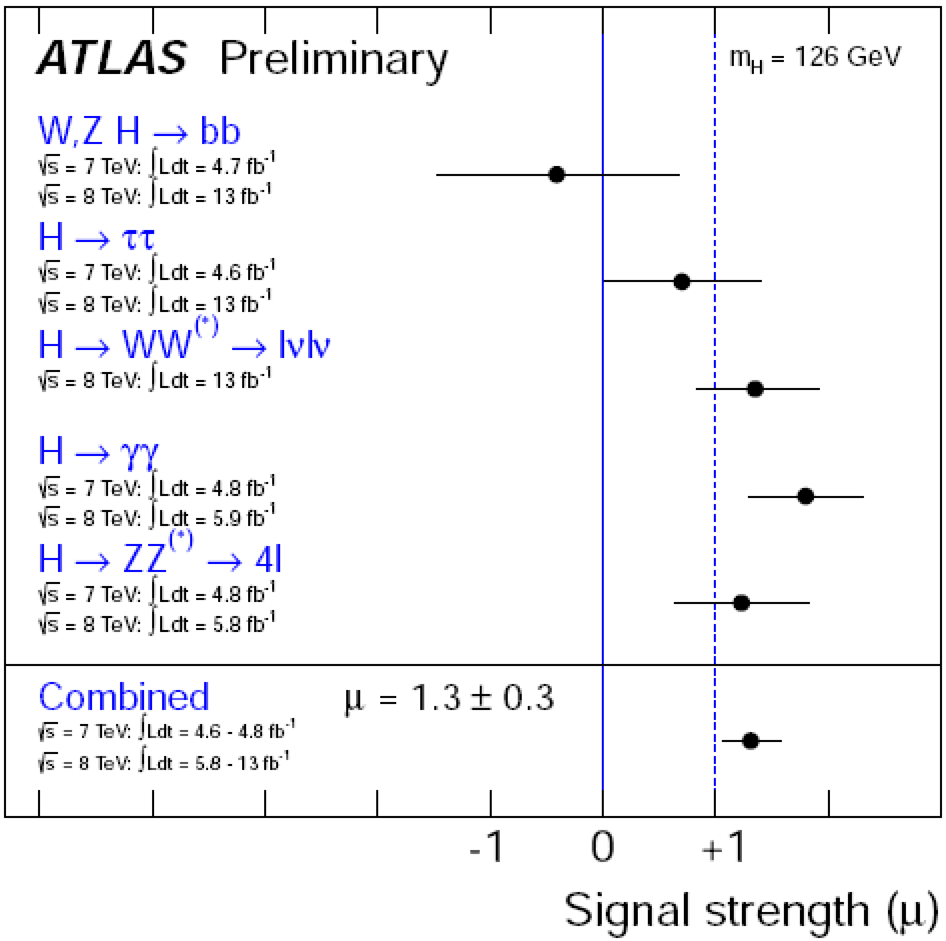
Does Higgs couple less to down-type fermions ?

Updated ATLAS Higgs signal strengths (1)

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	4.8	[1]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	4.8	[1]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet, } p_{\mathrm{T},\tau\tau} > 100\text{ GeV}, VH\}$	4.6	[4]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e,\mu\} \otimes \{\text{0-jet, 1-jet, } p_{\mathrm{T},\tau\tau} > 100\text{ GeV, 2-jet}\}$	4.6	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet, 2-jet}\}$	4.6	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	4.6	[5]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	5.8	[1]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	5.9	[1]
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet}\}$	13	[6]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{\text{1-jet, 2-jet, } p_{\mathrm{T},\tau\tau} > 100\text{ GeV}, VH\}$	13	[4]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e,\mu\} \otimes \{\text{0-jet, 1-jet, } p_{\mathrm{T},\tau\tau} > 100\text{ GeV, 2-jet}\}$	13	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet, 2-jet}\}$	13	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	13	[5]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$	13	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$	13	

Updates since ICHEP 2012 for HCP

Updated ATLAS Higgs signal strengths (2)



Higgs Boson Decay	μ (m_H=126 GeV)
$H \to ZZ^{(*)}$	1.2 ± 0.6
$H \to \gamma\gamma$	1.8 ± 0.5
$H \to WW^{(*)}$	1.4 ± 0.6
$H \to \tau\tau$	0.7 ± 0.7
$VH \to Vbb$	-0.4 ± 1.1

The signal strengths are not commensurate among different channels

Combined fitted strength is μ = 1.3 ± 0.3

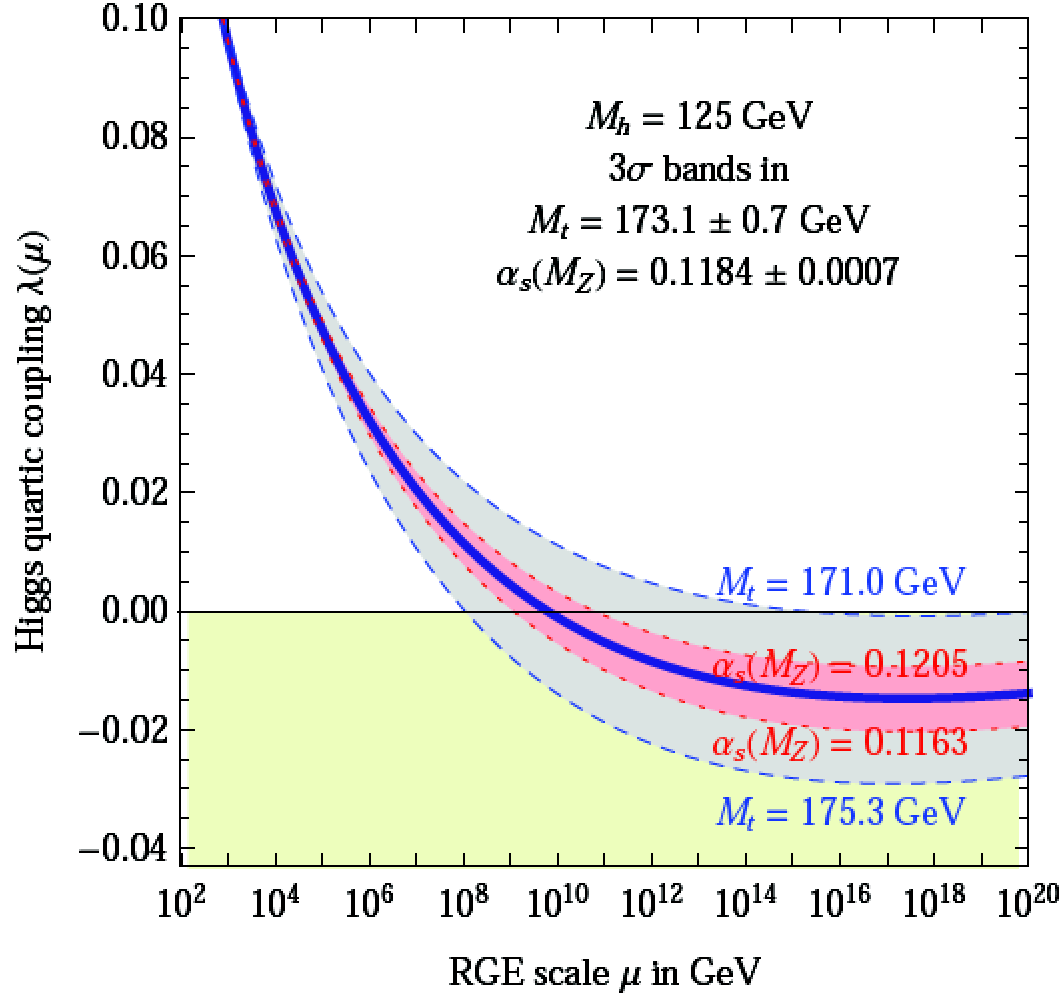
Implication of a light Higgs

The running of Higgs quartic coupling λ

Higgs potential positive – vacuum stability

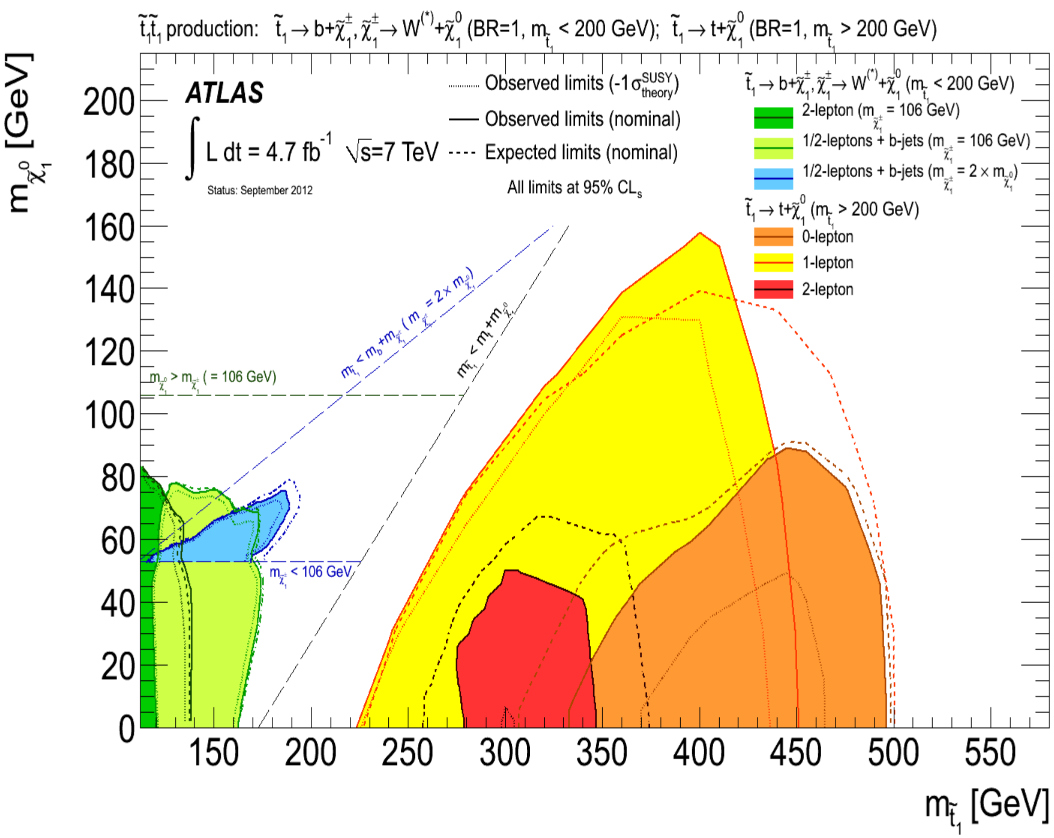
Expect new physics at high energy scales – is it SUSY ?

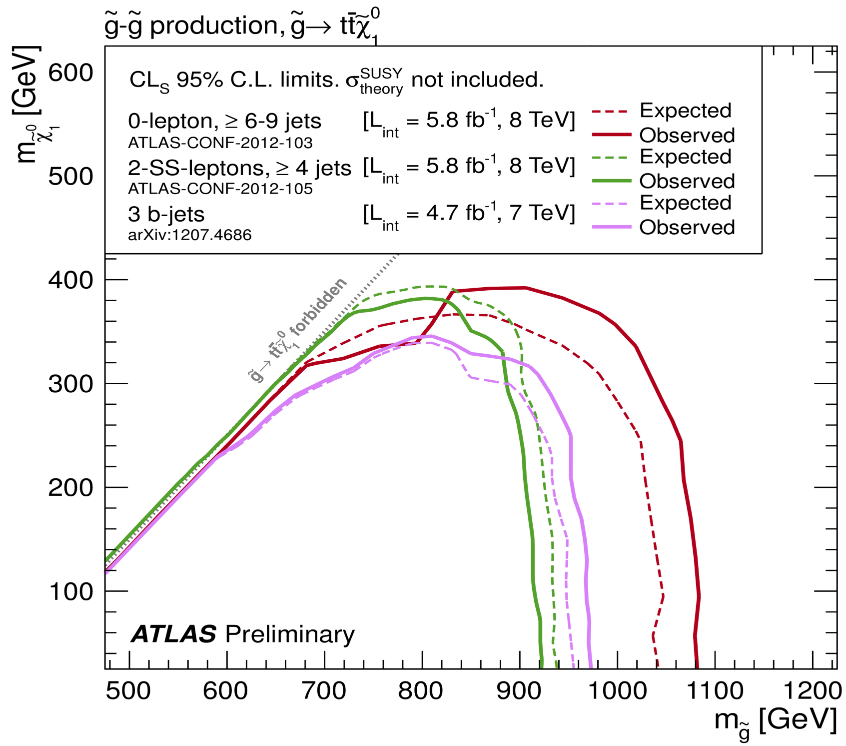
arXiv:1205.6497



The top channels

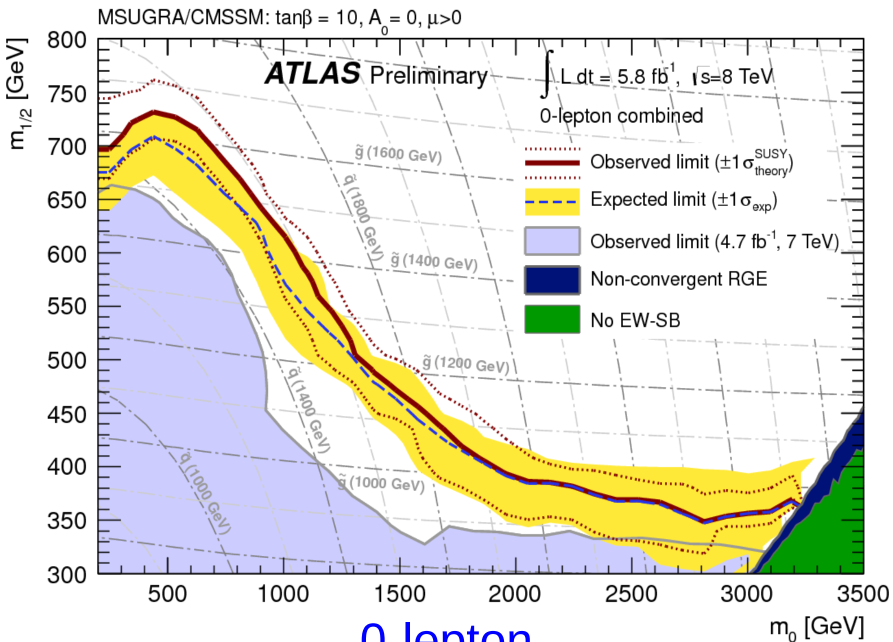
Direct stop pair production.
Assuming 100% BR of stop → top+LSP for heavy stop (>200 GeV), and 100% BR of stop → $b\chi_1$ → b+W+LSP for light stop (<200 GeV)



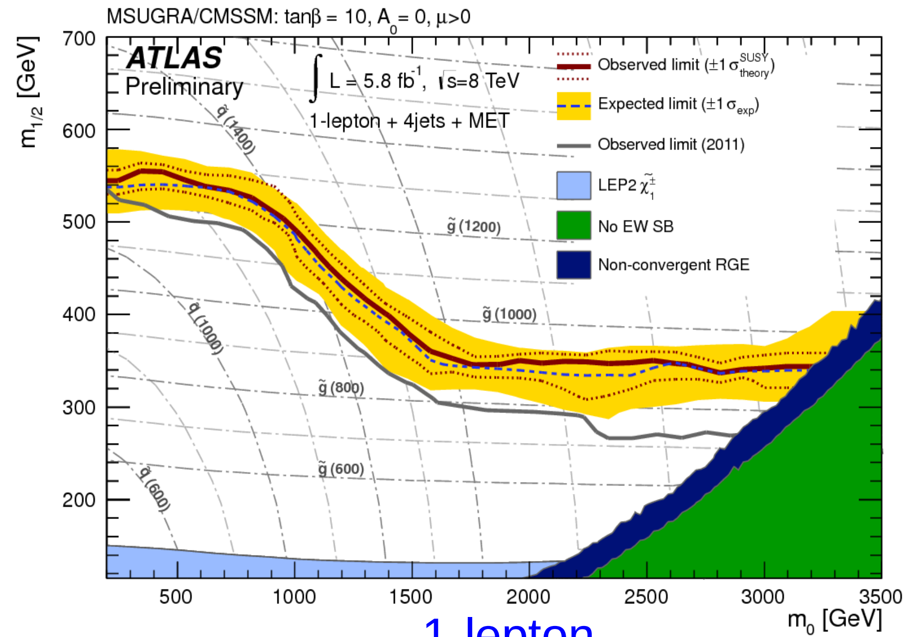


Gluino pair production with gluino → ttbar+LSP:
4 tops + 2 LSPs in the final state

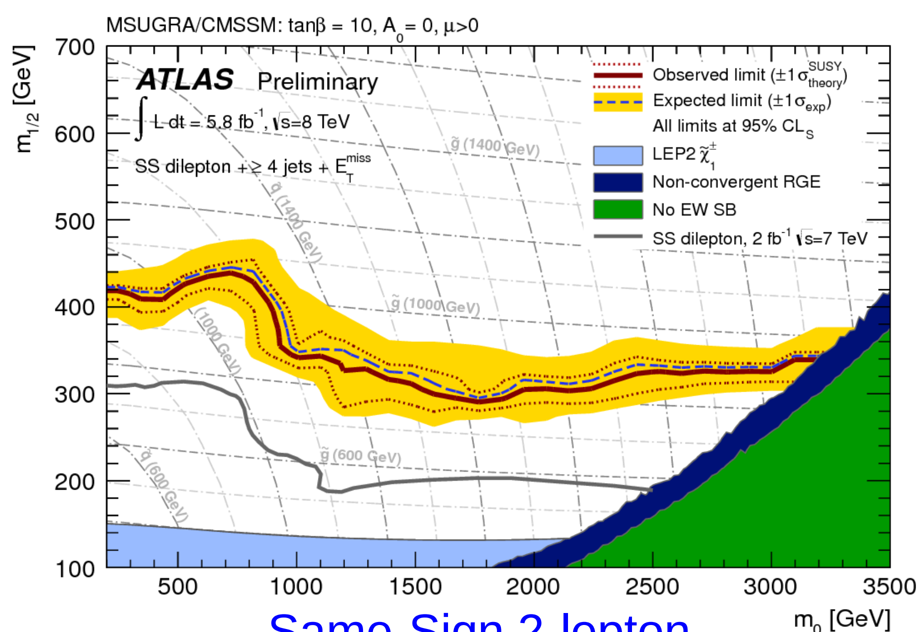
The generic modes



0-lepton

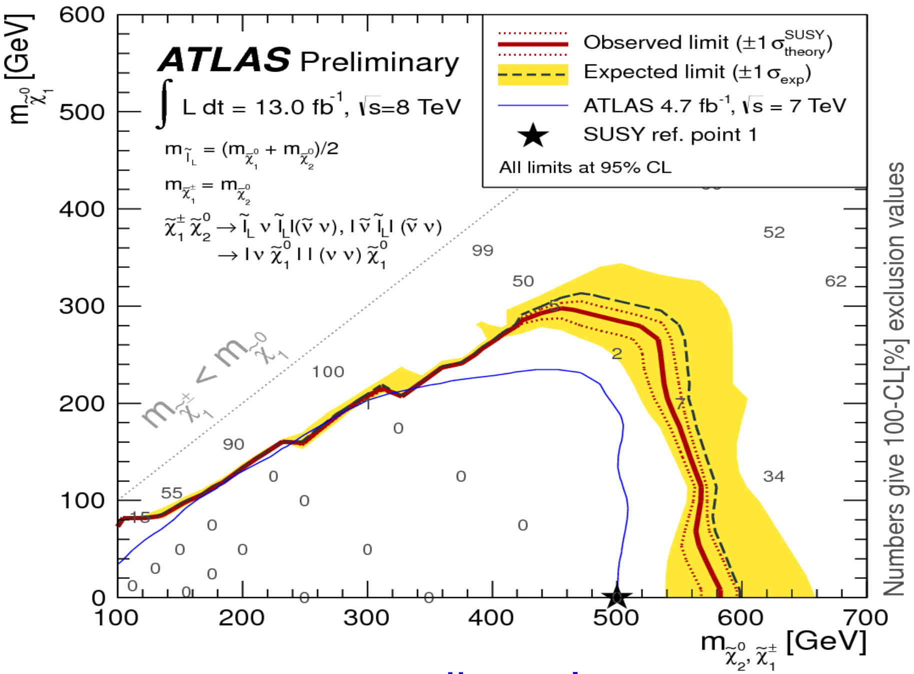


1-lepton

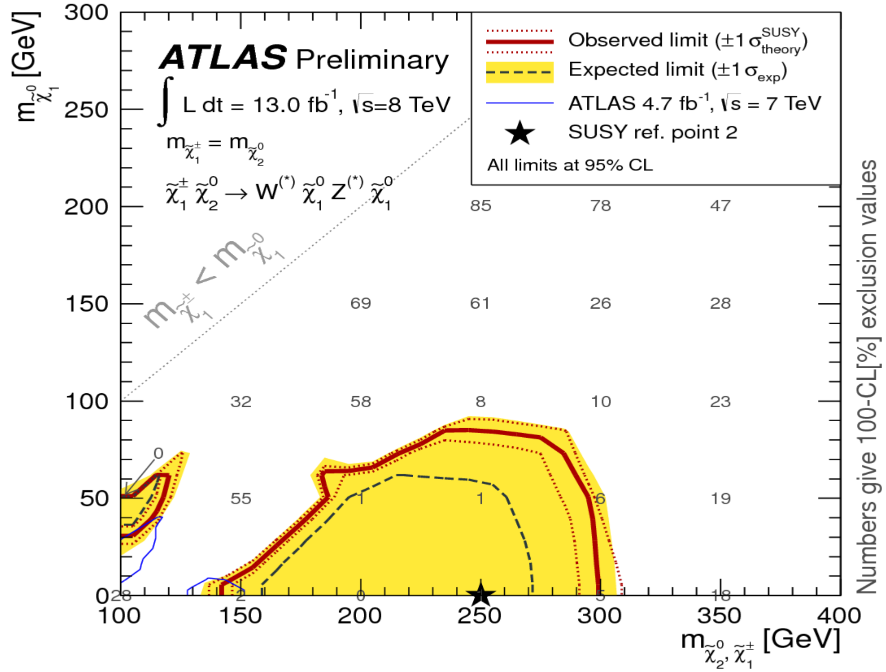


Same-Sign 2-lepton

The electroweak modes



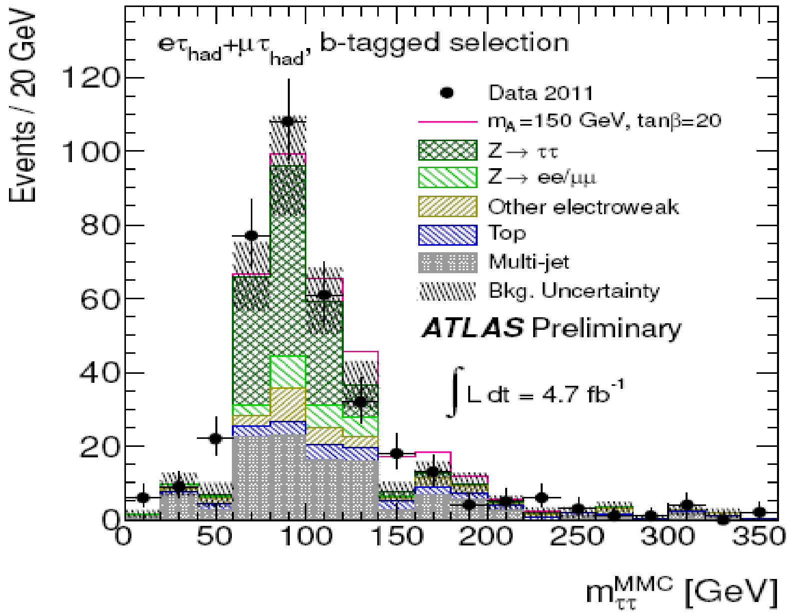
Intermediate sleptons

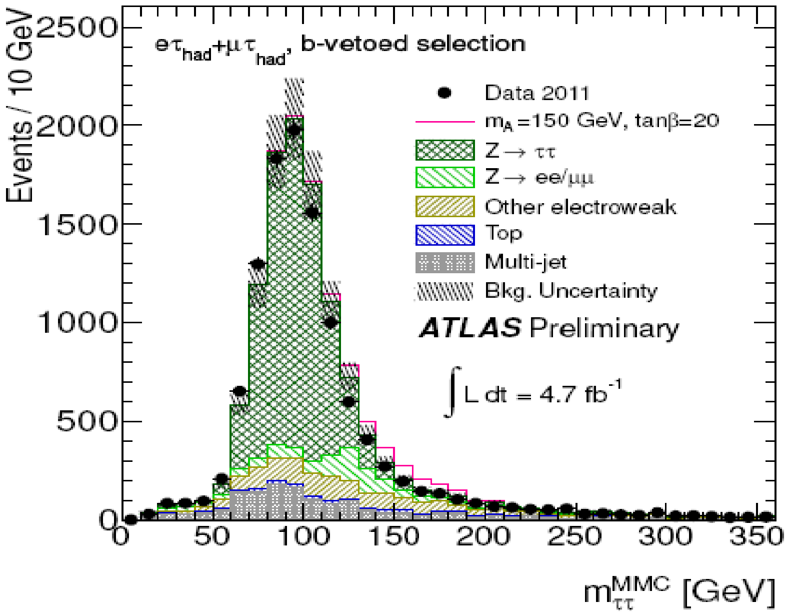


Intermediate gauge bosons

- The electroweak modes becomes important if the gluino and squark masses are very high
- Final state is 3 leptons + large MET with very few jets
- Dominant background is WZ. The top is the sub-dominant background – require b-jet veto or on-shell $Z \rightarrow ll$ to suppress top

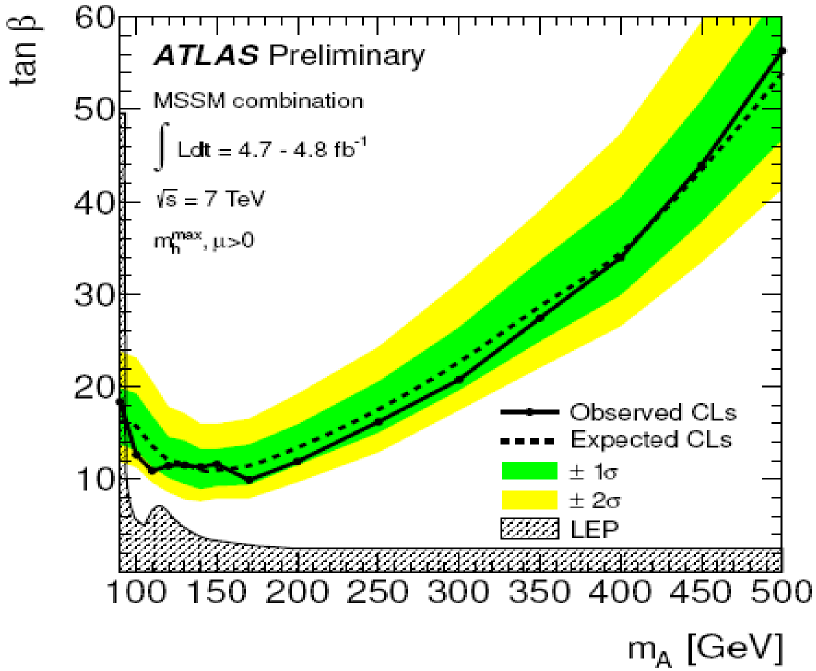
MSSM neutral Higgs





The neutral MSSM Higgs is carried out in 4 search channels:

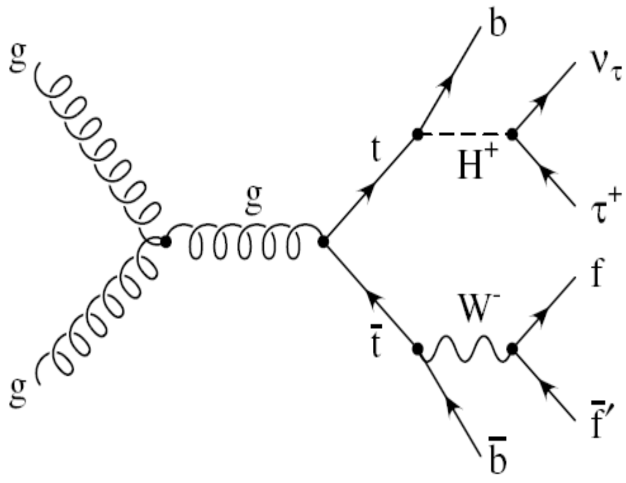
μμ, **eμ**, **lh** and **hh**

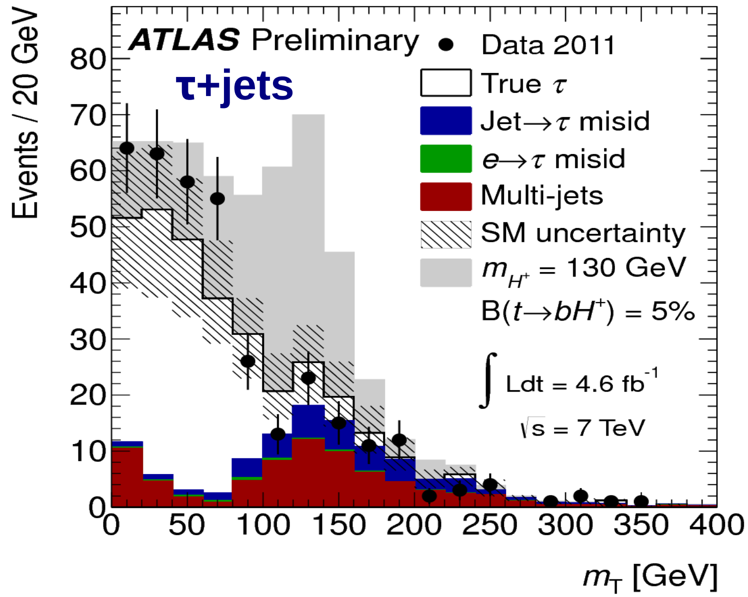


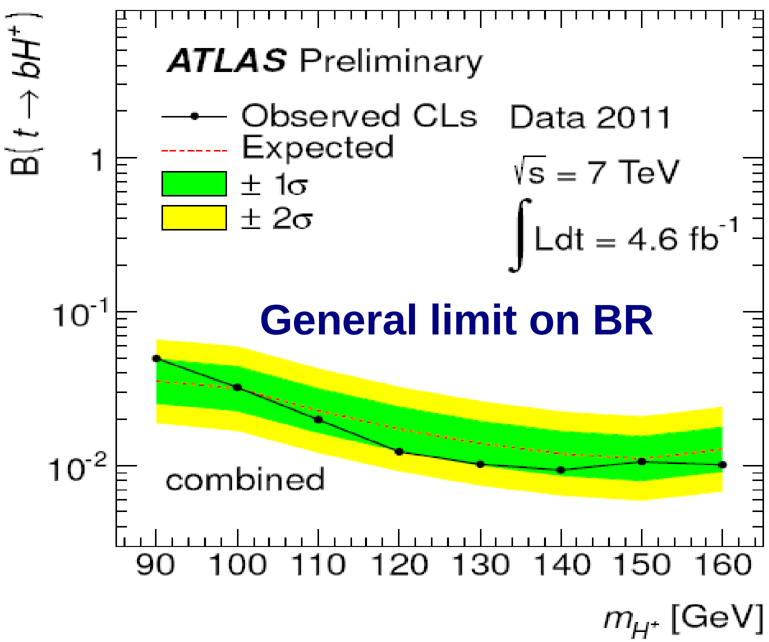
Explored 2 important regions

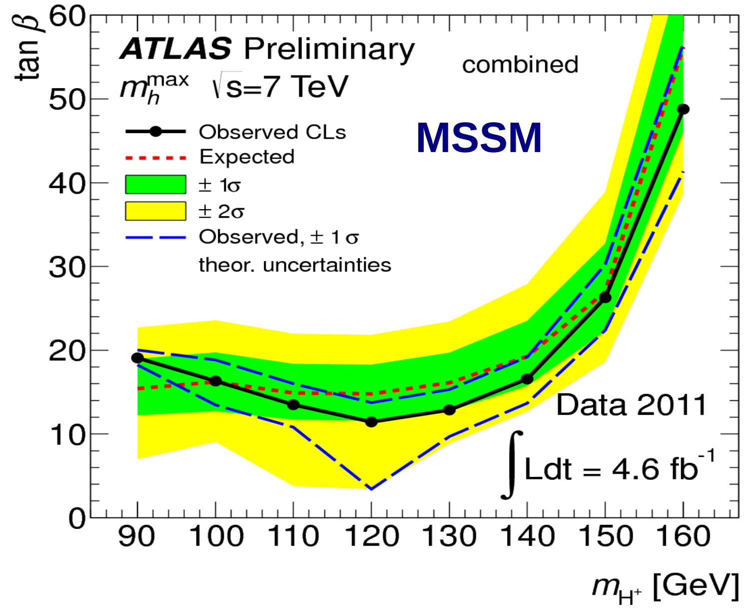
- b-tag vetoed region ⟶ gg fusion
- b-tagged region ⟶ bbar associated

Charged Higgs



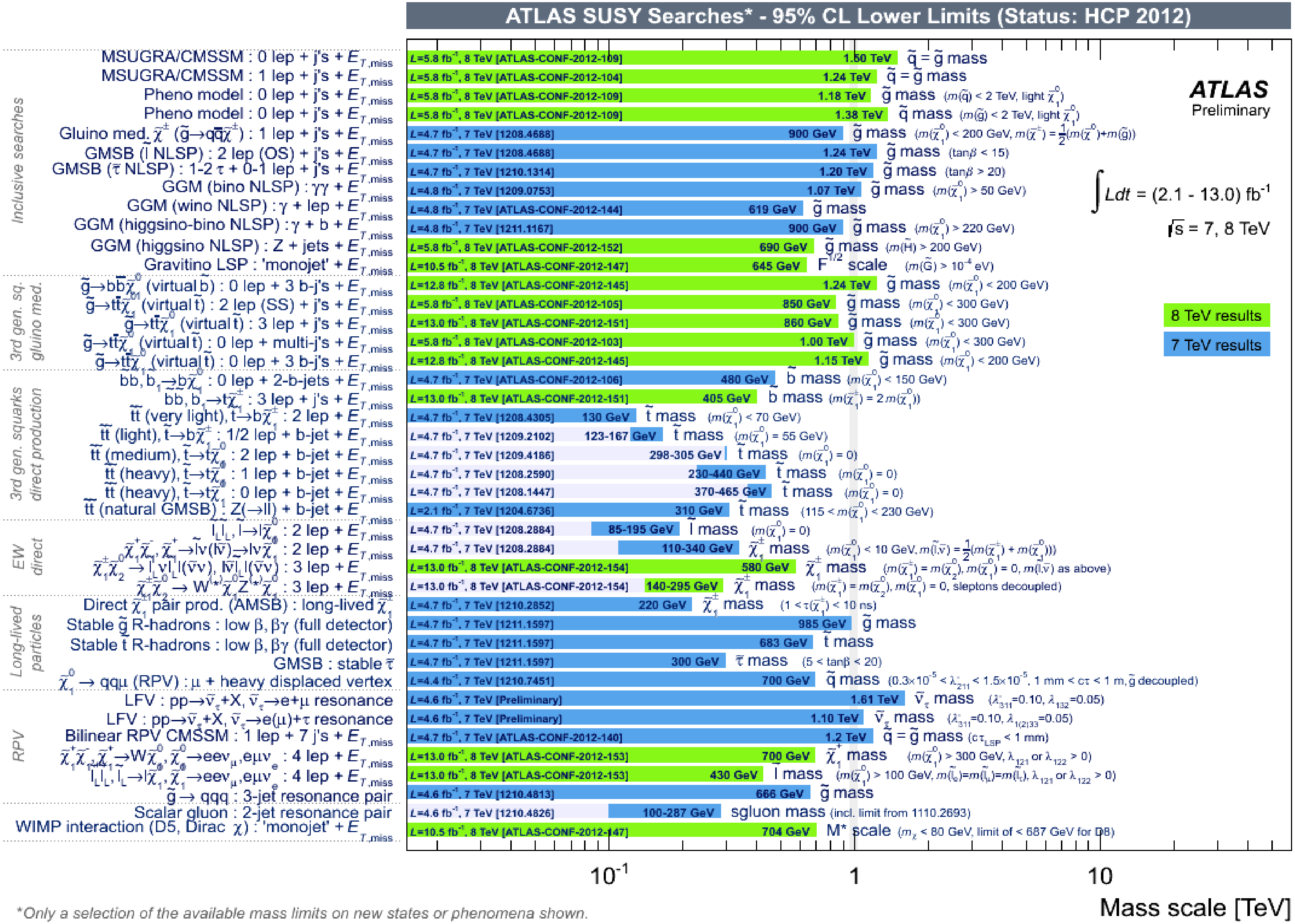






Summary for SUSY

NEW!



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

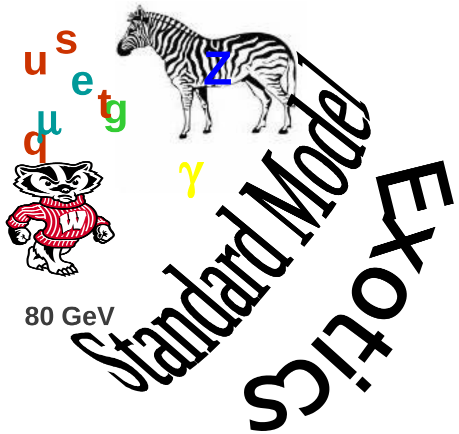
The “prospect” for SUSY

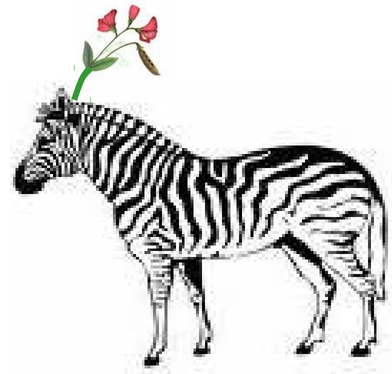
- So far, no evidence from direct SUSY search channels. Gluino/squark mass of ~1 TeV, stop mass of ~400 GeV, and chargino mass of ~250 GeV are excluded

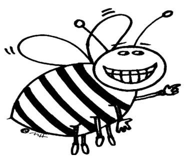
- The non-standard SUSY scenarios (”hidden modes”) are also possible:
  - R-parity vialating SUSY → lead to low MET
  - GMSB scenarios → long-lived charged sleptons or R-hadrons
  - Compressed scenariso → sparticle masses are highly degenerate. Use ISR jet to trigger the event. For example, soft leptons + mono-jet
  - Lower cross section → Dirac gluino
  - Sparticle mass > 10 TeV ?

- However, care should be taken as many of the results have assumptions (e.g., branching ratios, particular mass hierarchy). Search should continue in all aspects, including the ”hidden modes”

Exotics: fun in the wild



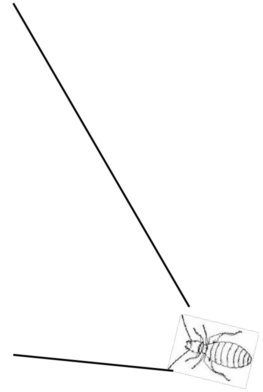




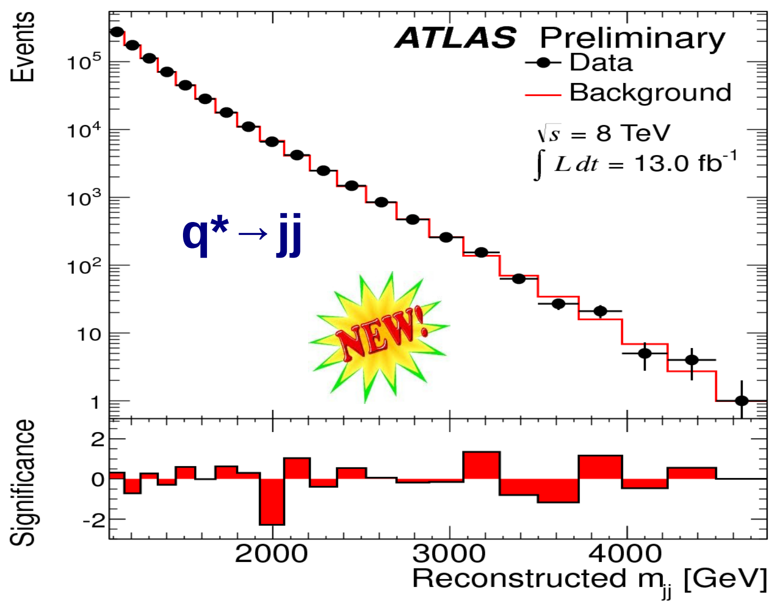
LQ

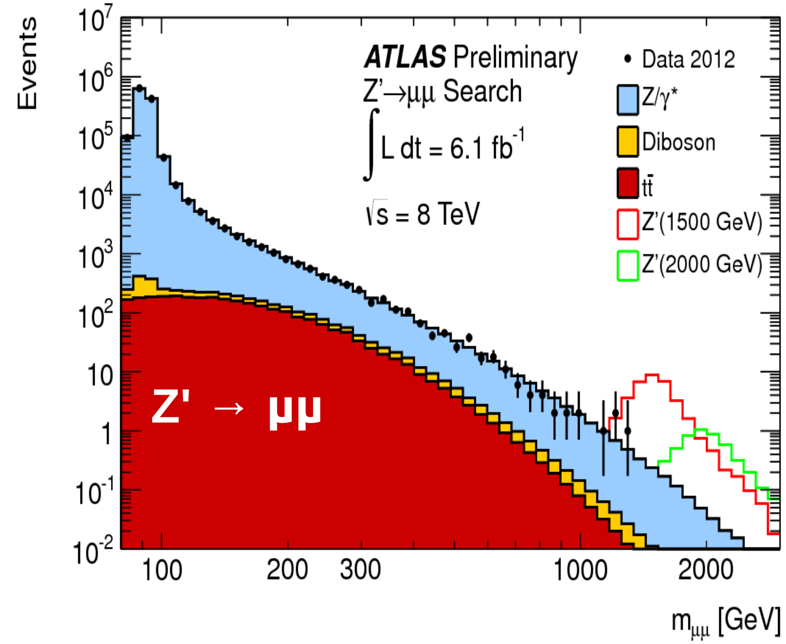
Black Holes

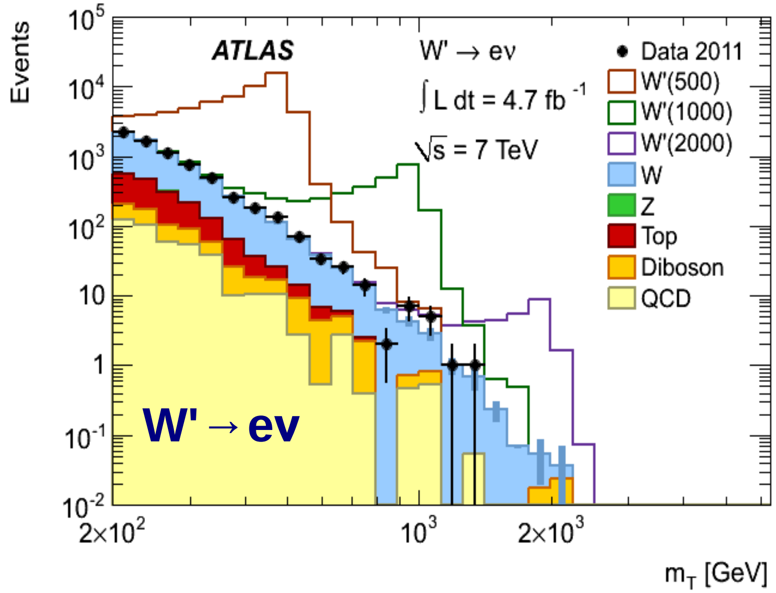
Extra Dimensions

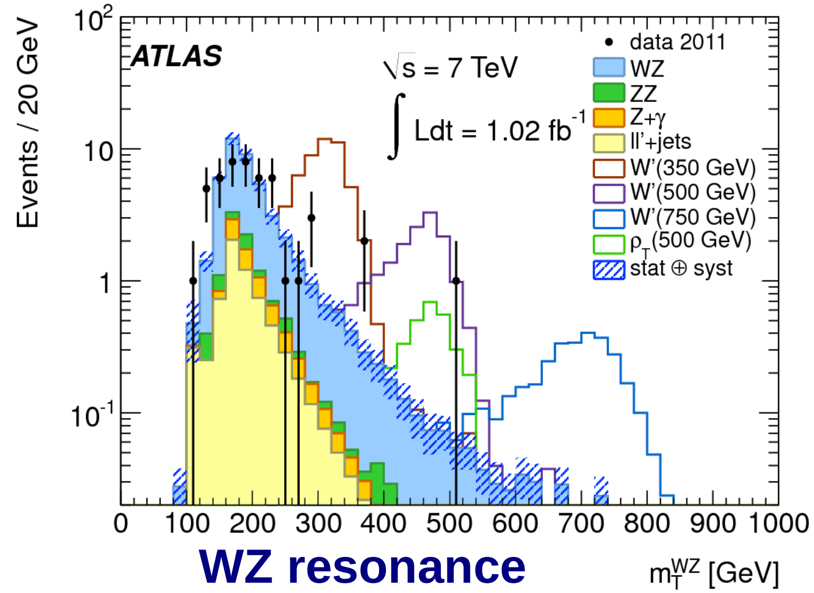


Q*, W', Z' ...

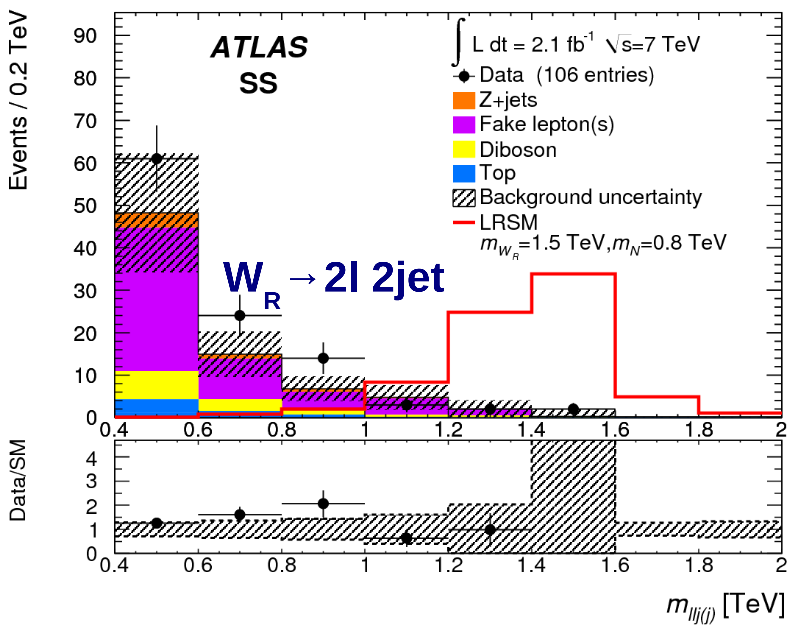

ATLAS Preliminary
Data
Background
$\sqrt{s}$ = 8 TeV
$\int L\,dt$ = 13.0 fb^{-1}
q* → jj
NEW!
Events
Significance
Reconstructed m_{jj} [GeV]

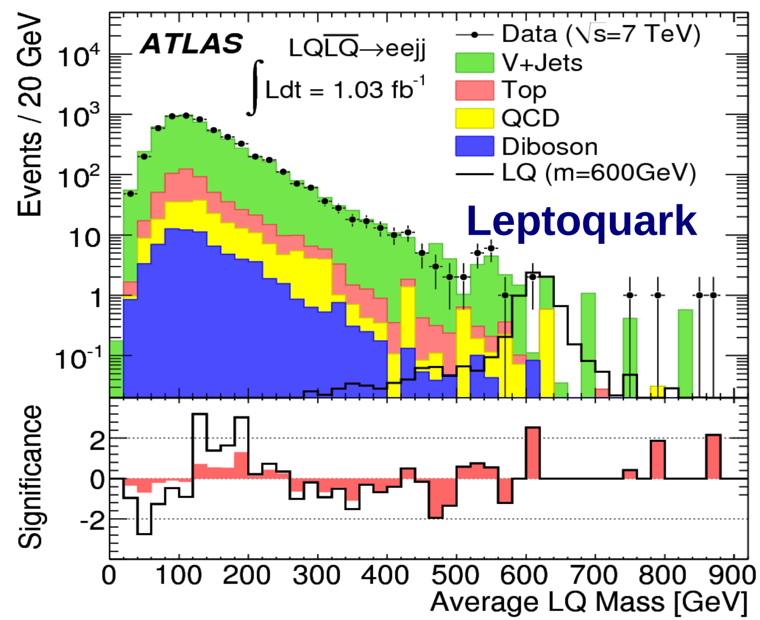

ATLAS Preliminary
Z'→μμ Search
$\int L\,dt$ = 6.1 fb^{-1}
$\sqrt{s}$ = 8 TeV
Data 2012
Z/γ*
Diboson
$t\bar{t}$
Z'(1500 GeV)
Z'(2000 GeV)
Z' → μμ
Events
$m_{\mu\mu}$ [GeV]

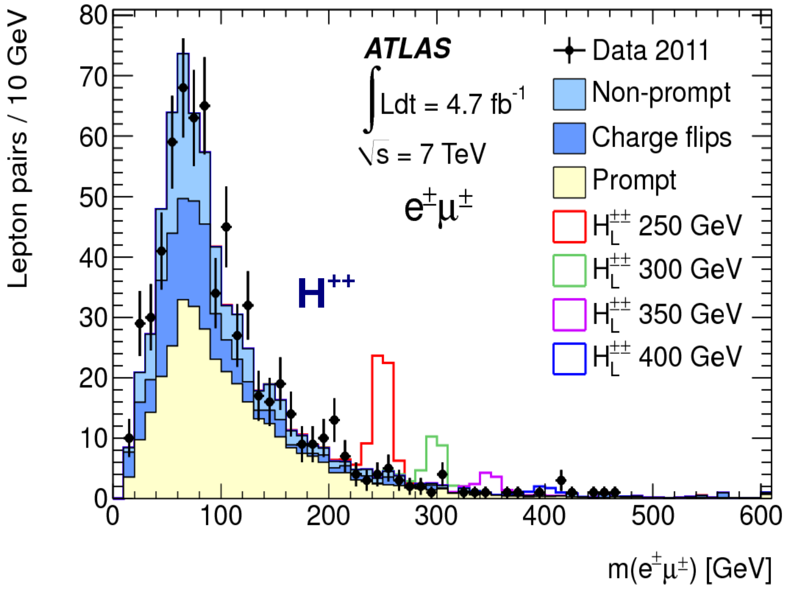

ATLAS
W' → eν
$\int L\,dt$ = 4.7 fb^{-1}
$\sqrt{s}$ = 7 TeV
Data 2011
W'(500)
W'(1000)
W'(2000)
W
Z
Top
Diboson
QCD
W' → eν
Events
m_T [GeV]

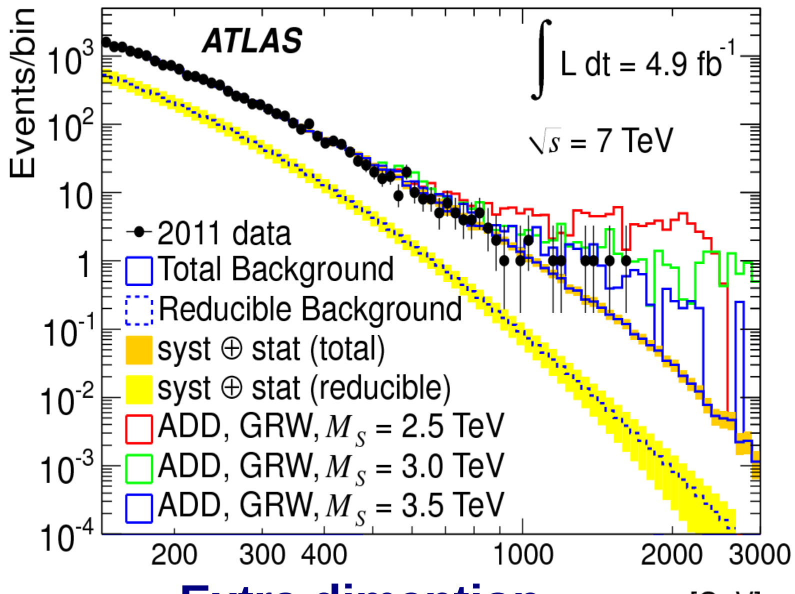

ATLAS
$\sqrt{s}$ = 7 TeV
$\int Ldt$ = 1.02 fb^{-1}
data 2011
WZ
ZZ
Z+γ
ll'+jets
W'(350 GeV)
W'(500 GeV)
W'(750 GeV)
ρ_T(500 GeV)
stat ⊕ syst
Events / 20 GeV
m_T^{WZ} [GeV]
WZ resonance

W_R, leptoquark, extra dimention, H^{++} ...



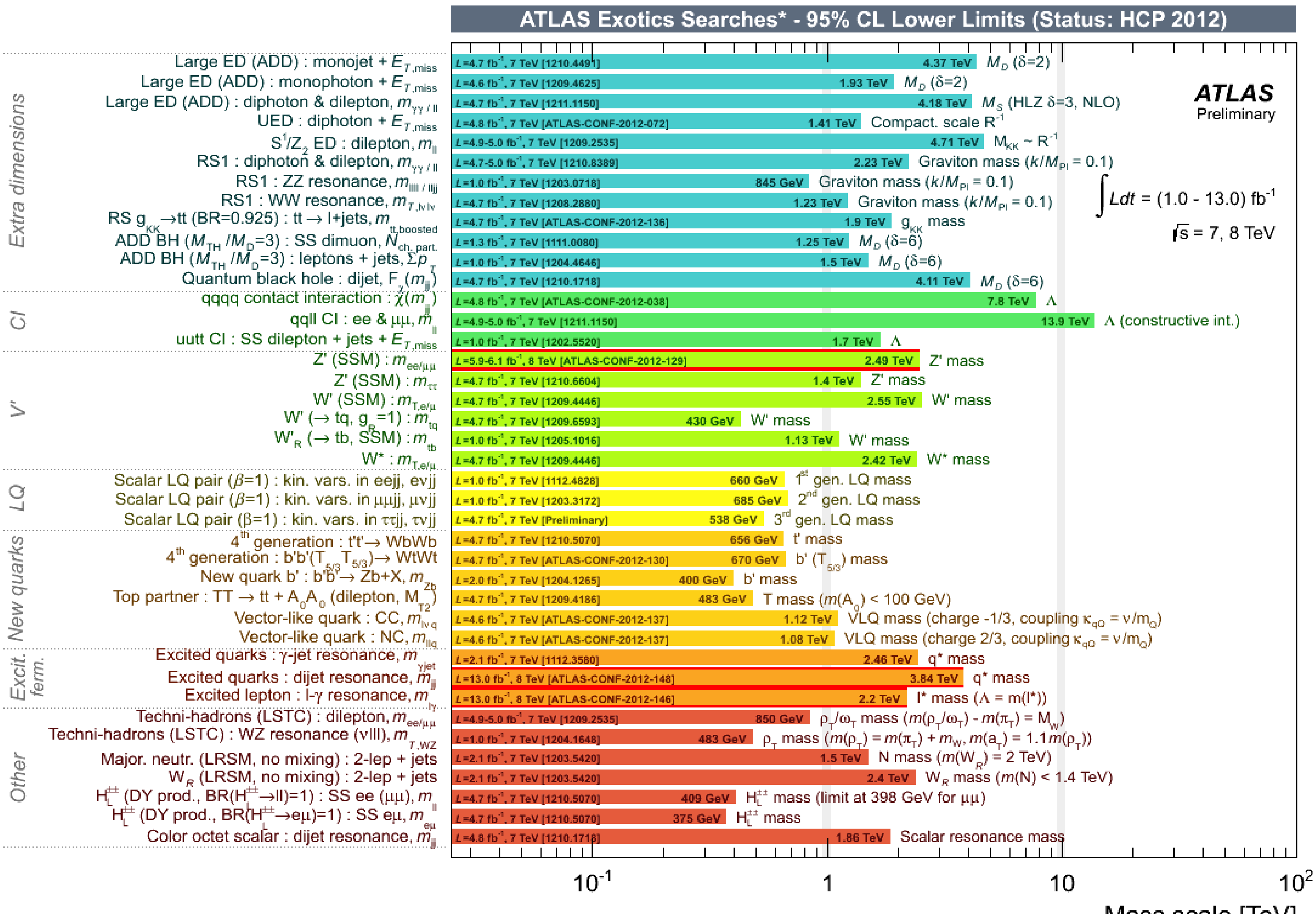






Extra dimention

Summary for Exotics



*Only a selection of the available mass limits on new states or phenomena shown

Summary and outlook

- We have found a new Higgs-like particle with mass around 125 GeV
- The properties if the particle are not fully known
  - All Higgs decay channels seems to agree with SM so far
  - There is a tendencay that γγ is a bit high, and ττ and bbbar are a bit low. We need to analyze more data to shrink the error bars
  - The decay width, spin and CP are not determined yet
- Searches for SUSY, including MSSM Higgs, are null
- Searches for Exotics (q*, Z'/W', leptoquark, W_R, extra dimentions, ...) are null

For experimentalists: more data and higher energy (14 TeV 2014)

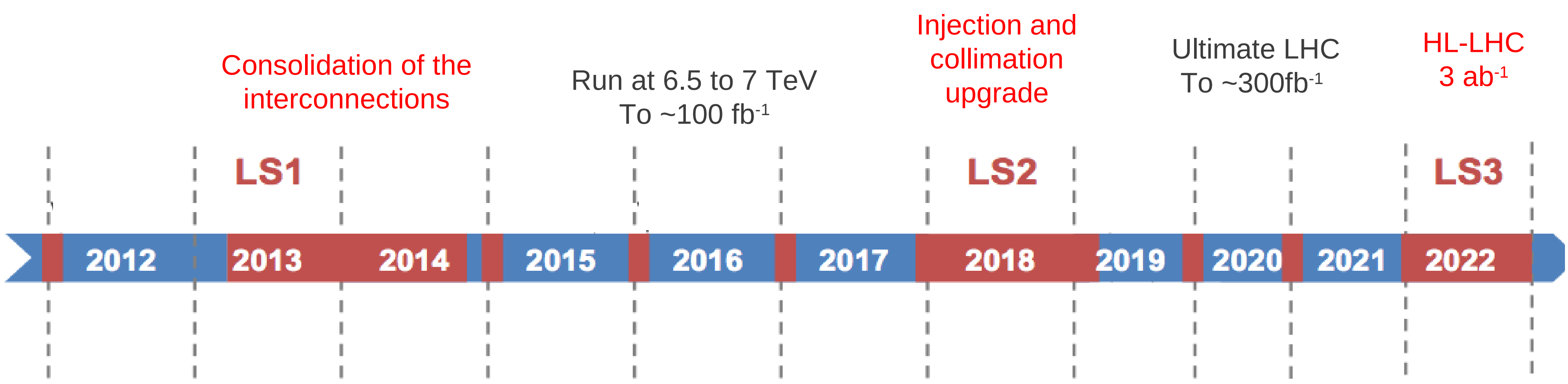
For theorists: constraints and new models based on the current results

stay tuned for more exciting news from LHC !

LHC timeline

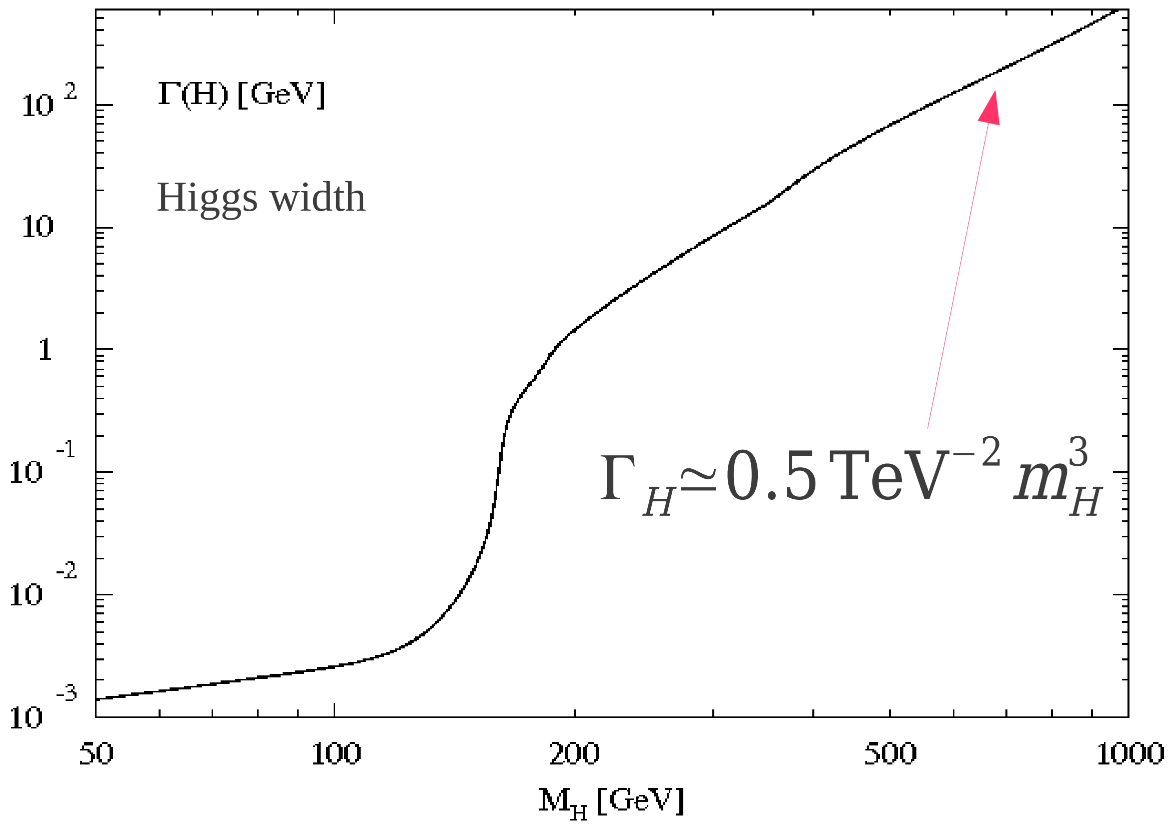
-2012 End of December : Reach 20-25 fb^{-1}/experiment

-2013-2014 : LS1



Backup Slides

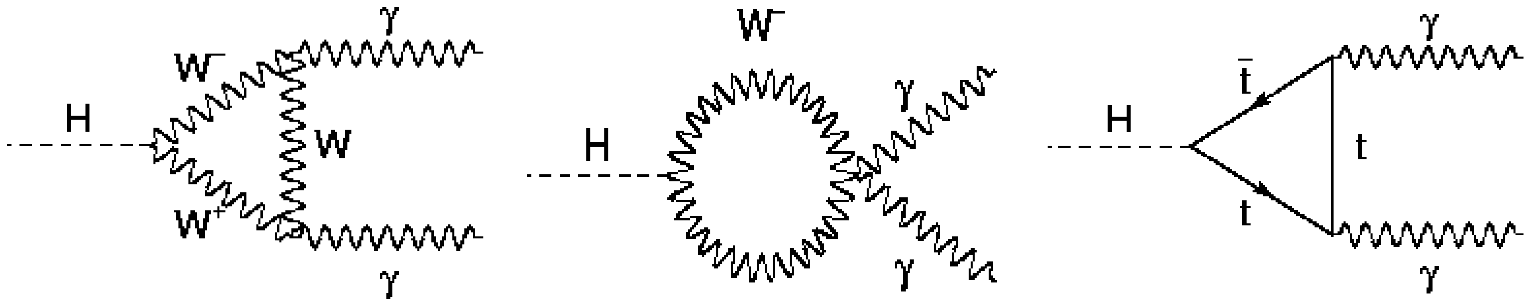
Higgs decay width



The Higgs decay width increases dramatically when above 200 GeV, and its interference with SM processes becomes sizable – tough for heavy SM-like Higgs search

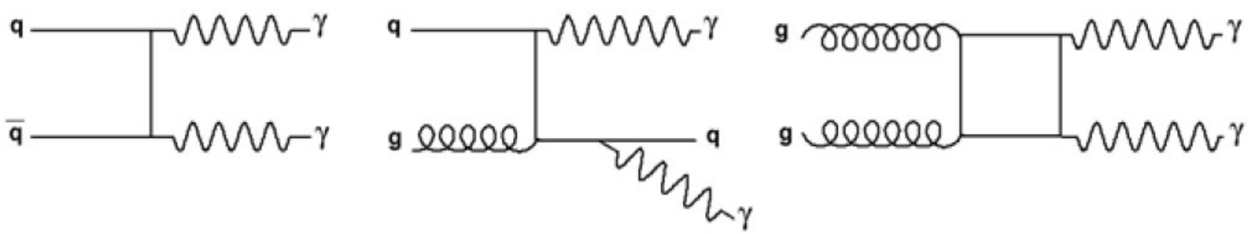
$H \rightarrow \gamma\gamma$

- $H \rightarrow \gamma\gamma$ proceeds via W and top loops (σxBR≈50 fb @125 GeV)



New charged particle in the loop : enhanced $H \rightarrow \gamma\gamma$ rate

- Irreducible $\gamma\gamma$ background (σ≈40 pb, theoretical error ~20%)



- Reducible background: γ+jet (σ≈μb), and jet+jet (σ≈mb)

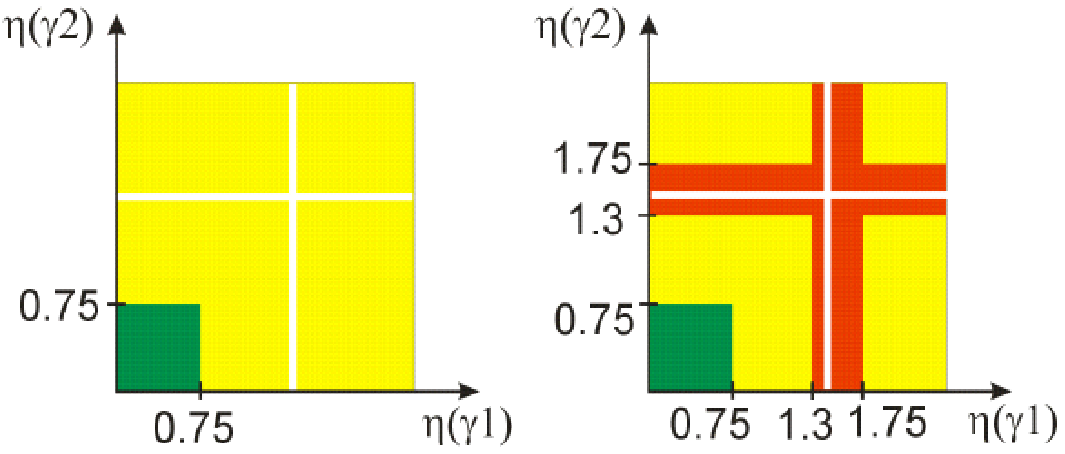
  One or more photons are fake photon from jets (mainly $\pi^0 \rightarrow \gamma$). The fake rate to hard to model with simulation

  Have to rely on data to normalize the diphoton backgriunds

Categorization of events

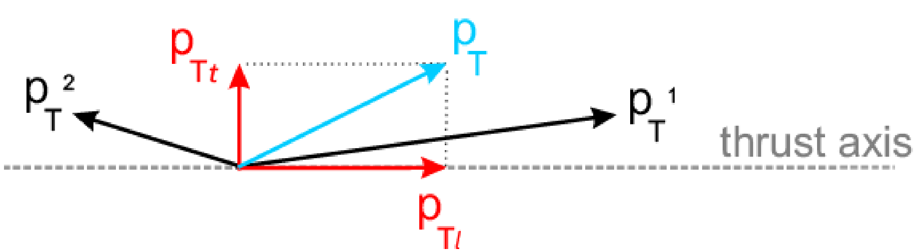
Category	σ_{CB} [GeV]	FWHM [GeV]
Inclusive	1.63	3.87
Unconverted central, low p_{Tt}	1.45	3.42
Unconverted central, high p_{Tt}	1.37	3.23
Unconverted rest, low p_{Tt}	1.57	3.72
Unconverted rest, high p_{Tt}	1.51	3.55
Converted central, low p_{Tt}	1.67	3.94
Converted central, high p_{Tt}	1.50	3.54
Converted rest, low p_{Tt}	1.93	4.54
Converted rest, high p_{Tt}	1.68	3.96
Converted transition	2.65	6.24
2-jets	1.57	3.70

2 converted: ≥1 converted:



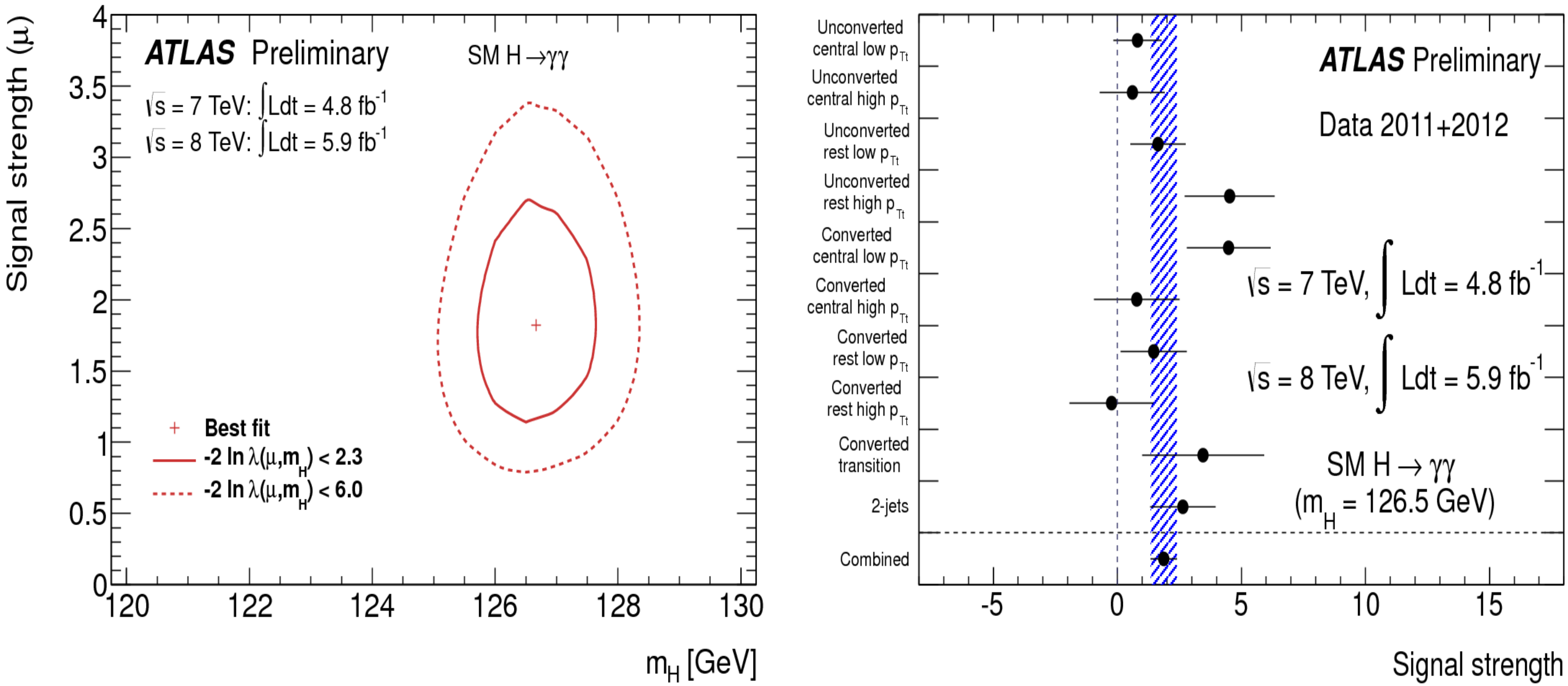
- Central
- Rest

- Central
- Transition
- Rest



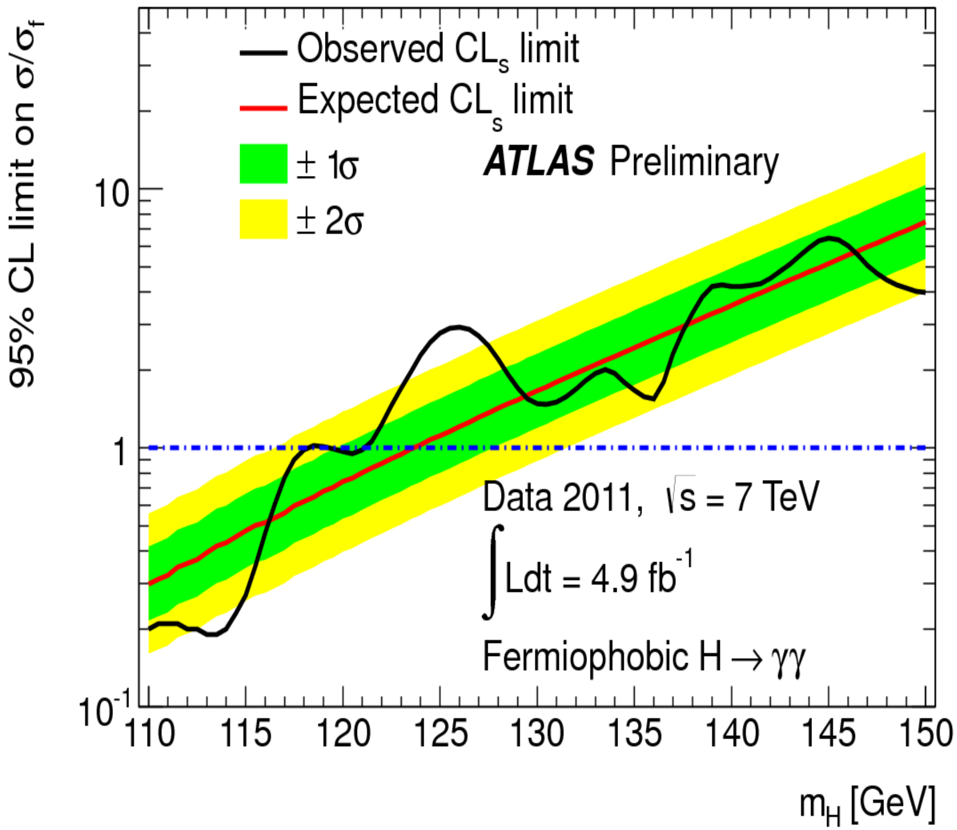
- Classify events with different mass resolution:
  - High p_{Tt} is better than low pTt
  - Unconverted is better than converted
  - Central is better than rest, and rest better than transition
- There is a special 2-jet category for VBF. There are 10 categories in total

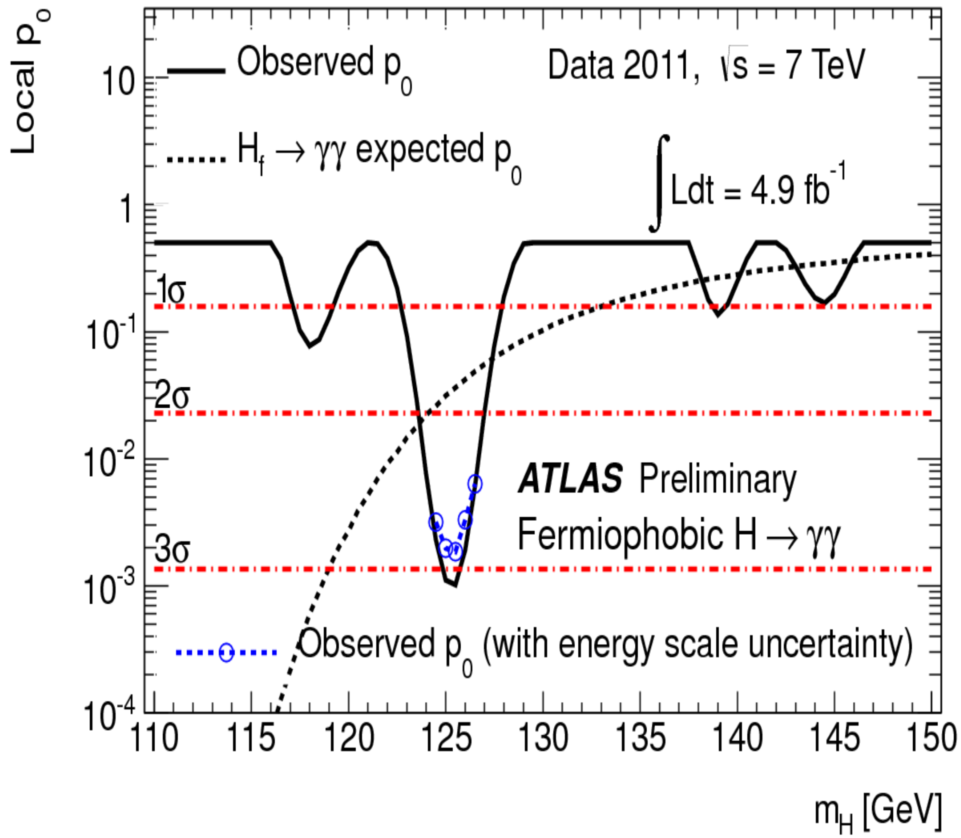
Mass and signal strength



- Left: likelihood of the fit floating both the mass and signal strength parameter μ
- Right: Fitted signal strength for 126.5 GeV: μ = 1.9 ± 0.5

Fermiophobic limits





- For a fermiophobic Higgs, since only VBF and VH diagrams contribute, the Higgs p_T is expected – better S/B separation
- Higher (lower) σxBR in low (high) mass region compared to SM. Expect to exclude m_H<123.5 GeV (2011)

$H \to ZZ \to 4l$

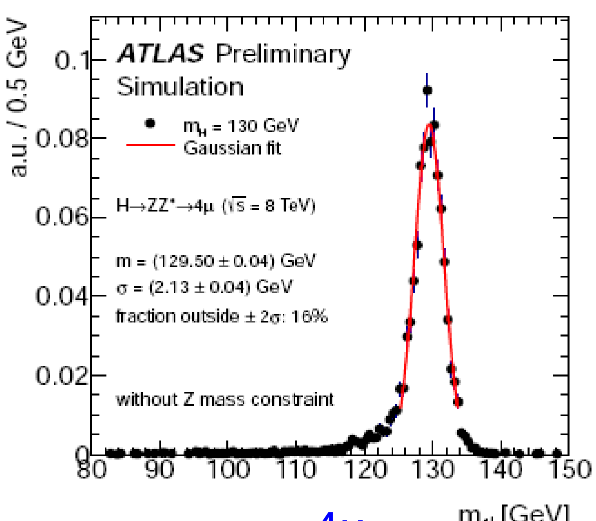
- $H \to ZZ \to 4l$ is the gold-plated channel – good mass resolution, powerful rejection of SM background due to 4-lepton requirement

- Suffers from low rate and total lepton acceptance loss

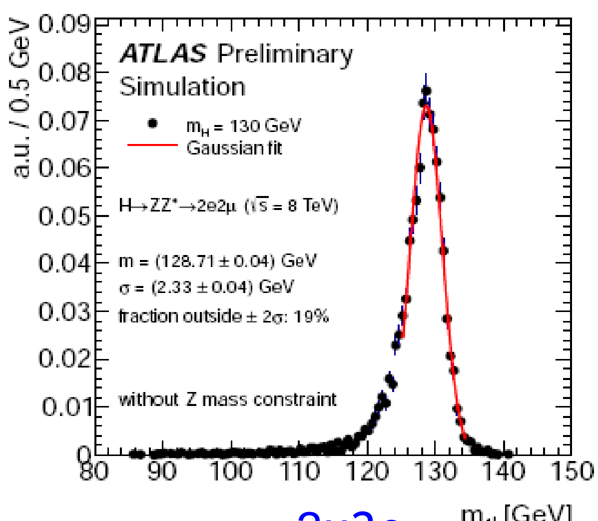
  $BR(ZZ \to 4l) = 0.45\%$ ⇨ $\sigma \times BR(H \to ZZ \to 4l) = 2.6$ fb

  Single lepton acceptance (tracking volume, trigger and reconstruction) is high (≈80%), but the total acceptance is low ($0.8^4 = 0.4$)

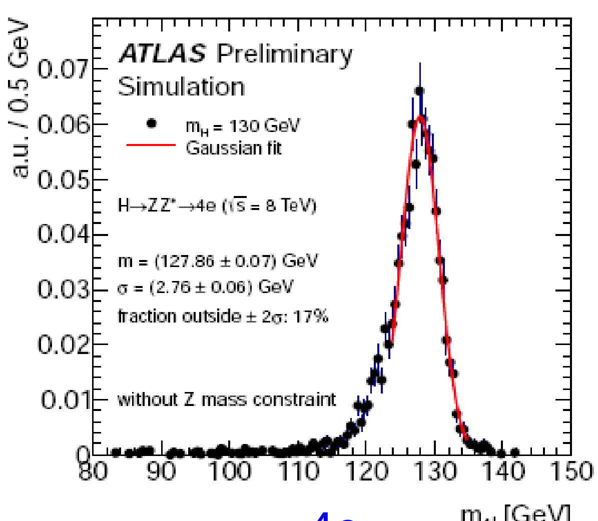
- Higgs mass resolutions – 1.8 to 2.5 GeV:



4μ



2μ2e



4e

Selection cuts and mass spectrum

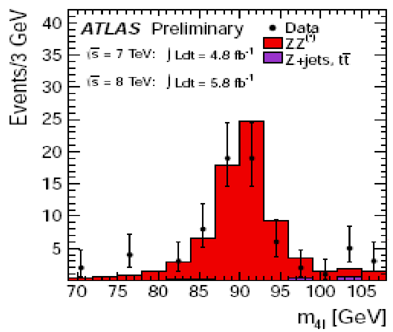
- Require 2 pairs of same-flavor opposite-sign leptons

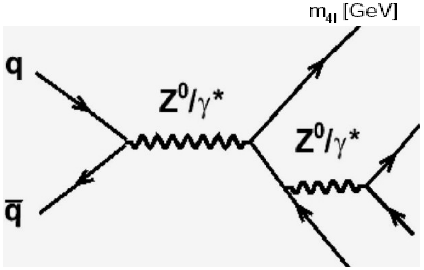
4 leptons with p_T > 20, 15, 10, 7 (6 for muon) GeV (lep1, 2, 3, 4)

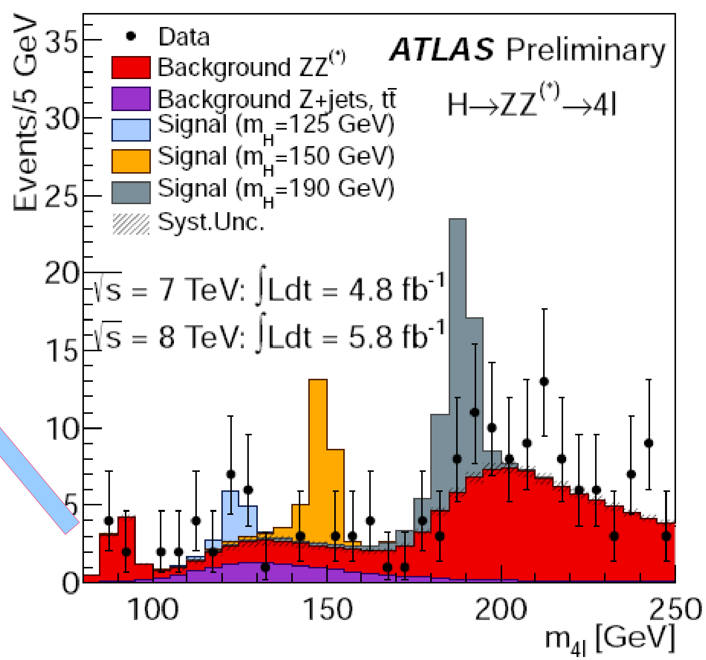
50 GeV < m_{12} < 106 GeV, and m_{min} < m_{34} < 115 GeV. m_{min} depends on the 4l mass

m_{LL} > 5 GeV for all same-flavor opposite-sign pair – J/ψ rejection

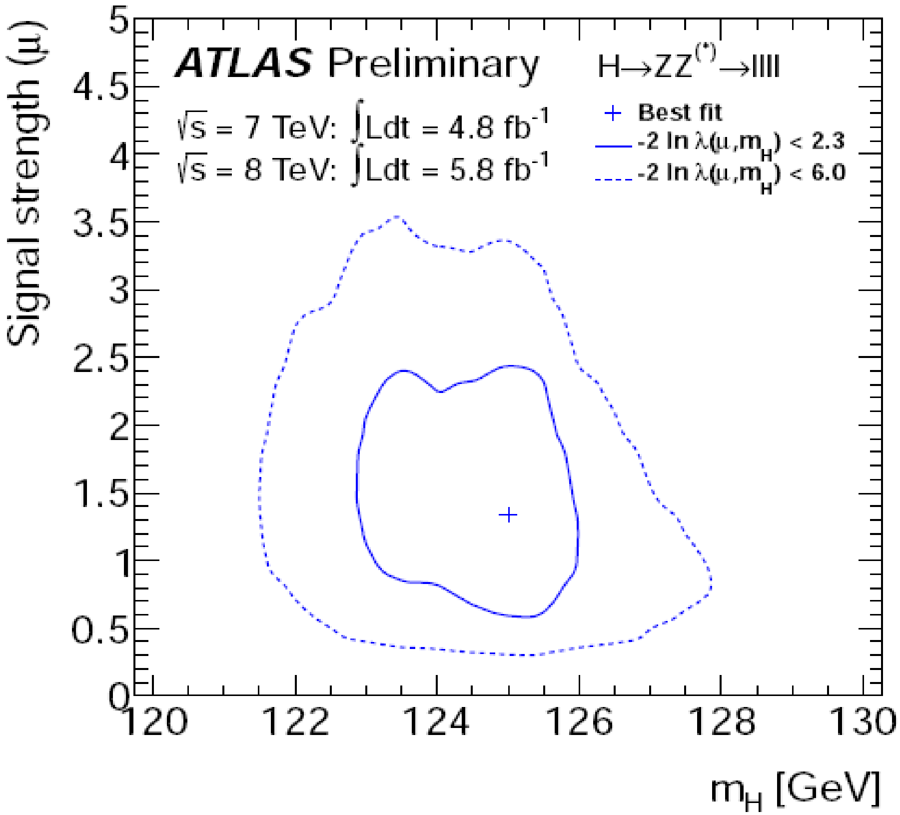
Lepton isolation (calo-energy and tracks around real leptons should be small) and track d0 cut (should come from hard IP)







Mass and signal strength



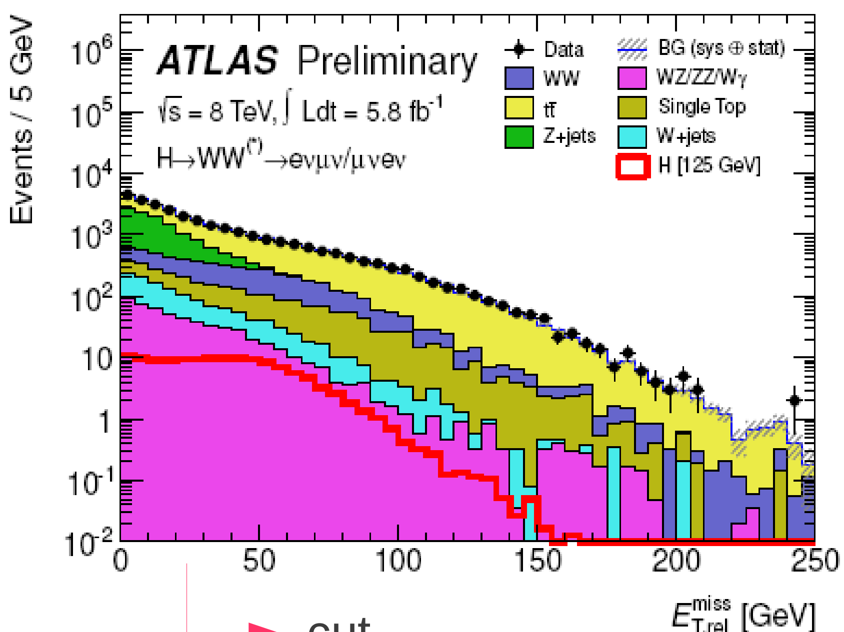
- Left: likelihood of the fit floating both the mass and signal strength parameter μ. Fitted signal strength: μ = 1.4 ± 0.6
- Right: scan of discovery p-value abd significance: 3.6σ

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

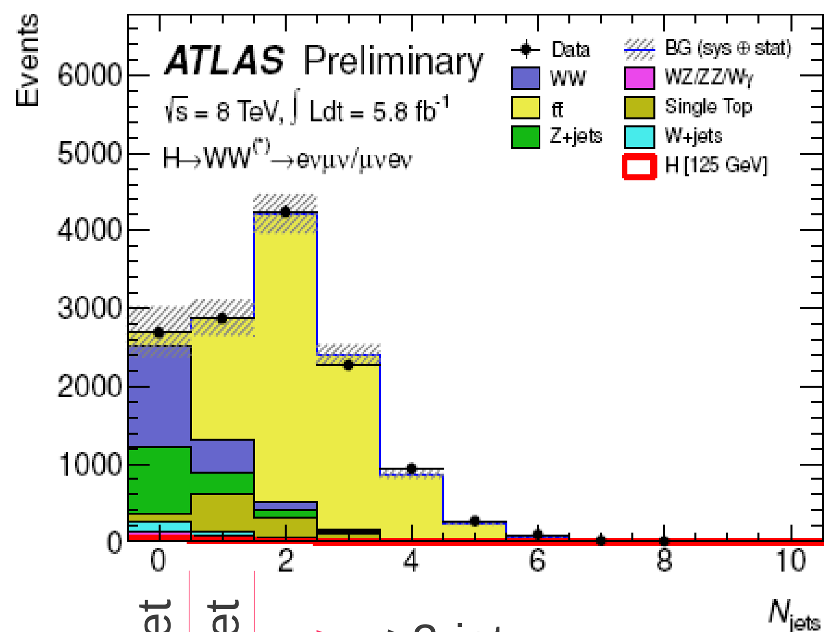
Can not reconstruct the Higgs mass – background rates estimation is crucial in this channel

Devide analysis into 6 categories: (eμ, μe) x (0-jet, 1-jet, ≥2-jet)

Preselection
- Lepton p_T > 25, 15 GeV, m_{LL}>10 GeV
- $E_{T,rel}^{miss}$ > 25 GeV. $E_{T,rel}^{miss}$ is the MET component perpendicular to the closest object (lepton or jets). $E_{T,rel}^{miss} = E_{T}^{miss}$ if ΔΦ > π/2
- anti-kt jet p_T>25 GeV (>30 GeV if |η|>2.5)



cut

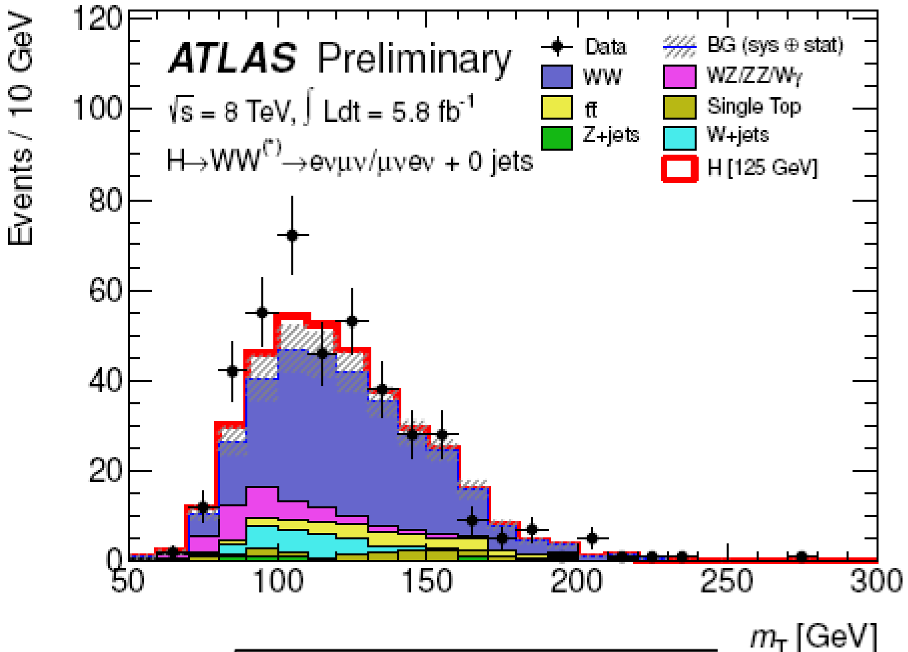


0-jet 1-jet ≥2-jet

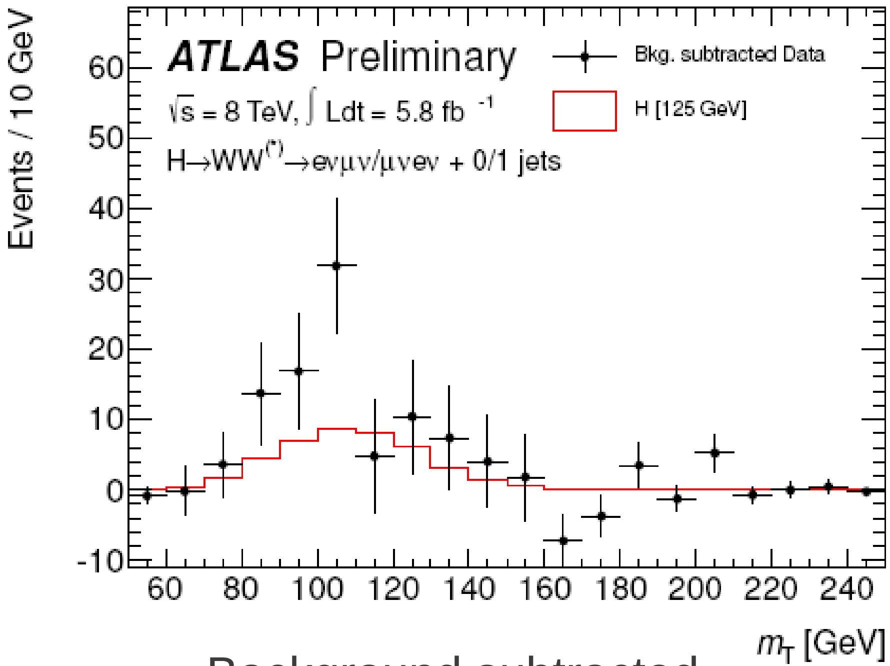
Final yields and distribution

Yields for 2012 5.8 fb^{-1} (94 GeV < m_T < 125 GeV):

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + jets	W + jets	Total Bkg.	Obs.
$H+$ 0-jet	20 ± 4	101 ± 13	12 ± 3	8 ± 2	3.4 ± 1.5	1.9 ± 1.3	15 ± 7	142 ± 16	185
$H+$ 1-jet	5 ± 2	12 ± 5	1.9 ± 1.1	6 ± 2	3.7 ± 1.6	0.1 ± 0.1	2 ± 1	26 ± 6	38
$H+$ 2-jet	0.34 ± 0.07	0.10 ± 0.14	0.10 ± 0.10	0.15 ± 0.10	-	-	-	0.35 ± 0.18	0



$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}|^2}$$



Background subtracted

Higgs mass reconstruction

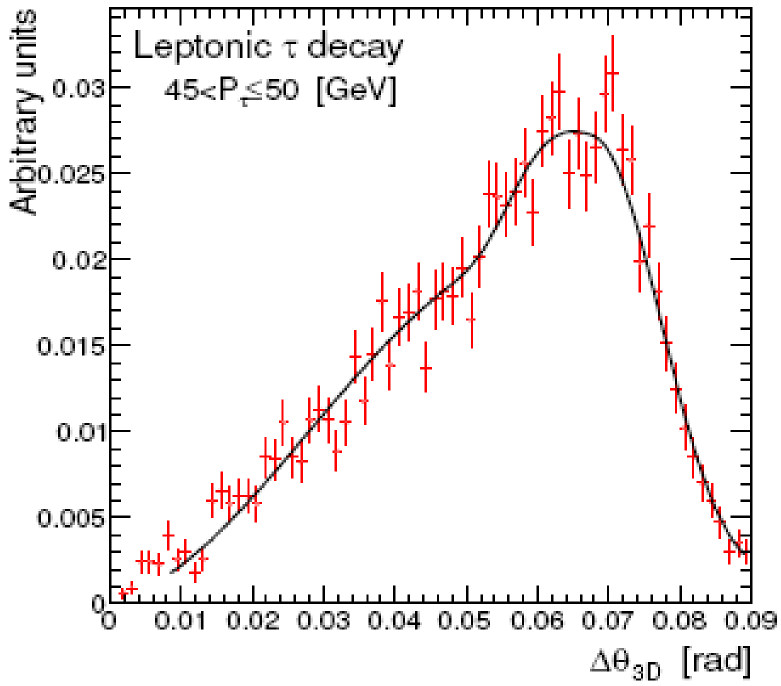
- Effective mass: invariant mass of the visible tau decay products and MET

- Collinear mass:
  - Assume neutrinos and visible decay products from the tau are collinear, then ditau mass can be calculated as

$$m_{\tau\tau} = \frac{m_{\ell\ell}}{\sqrt{x_1 \cdot x_2}}$$

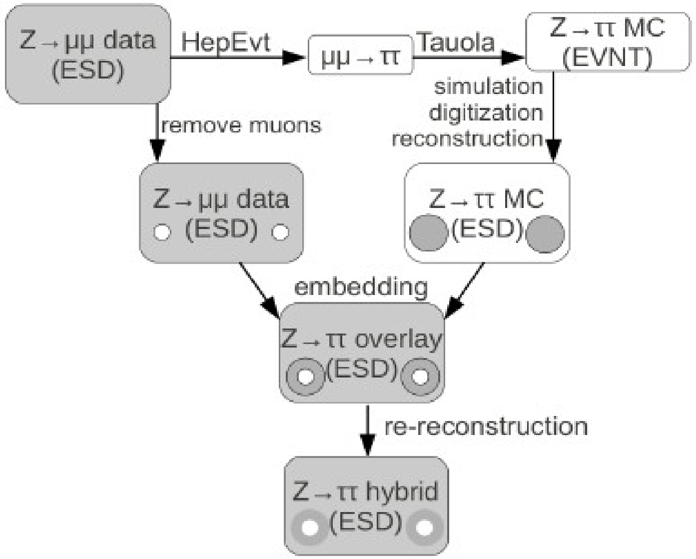
  - $x_{1,2}$ are the fractions of momenta carried away by the visible decay products from the tau

- Missing Mass Calculator (MMC):
  - Mass estimation by requiring the mutual orientations between neutrinos and other tau decay products are consistent with the mass and decay kinematics of a tau
  - Scan in the allowed phase space region (including MET variables) for the most likely solutions



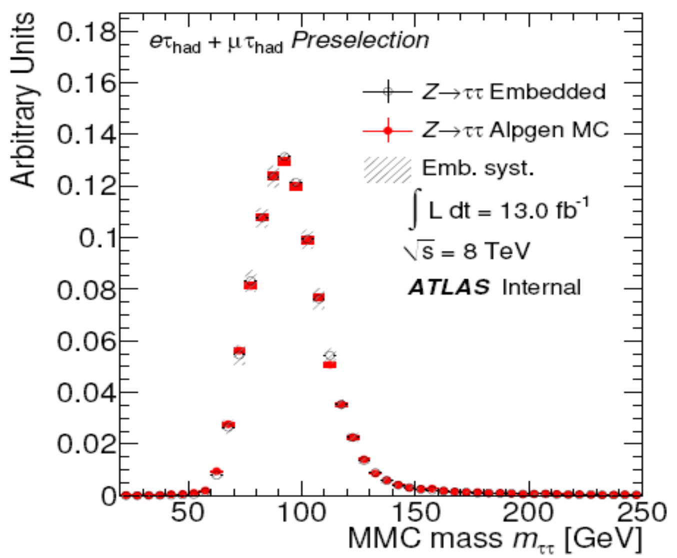
Embedding sample for Z → ττ background

- Z → ττ is the dominant background for all 3 sub-channels. To estimate this background from data, an embedding method is used:
  - Select Z → μμ events from data, replace the two muons by taus, and remove muons and calorimeter cells passed in the original event
  - Pass the taus through Tauola decay, and fully simulate the tau decay products
  - Embed the simulated tau decay products into the original event



- The embedding procedure is validated by replacing the muons in data by muons from full simulation (mu-embedding)

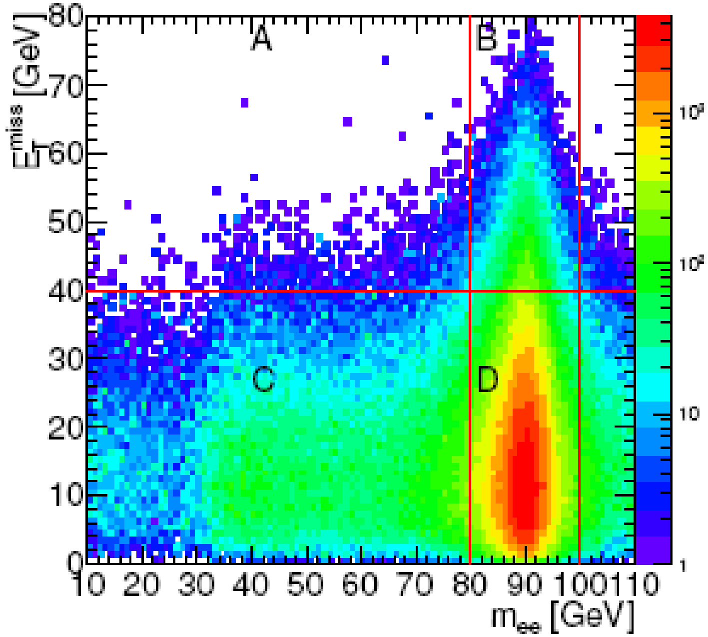
- Only shapes and relative efficiencies are provided by the embedding sample. The absolute normalization comes from MC predictions after lepton/tau selections or from control regions



ll-channel: Drell-Yan and top background

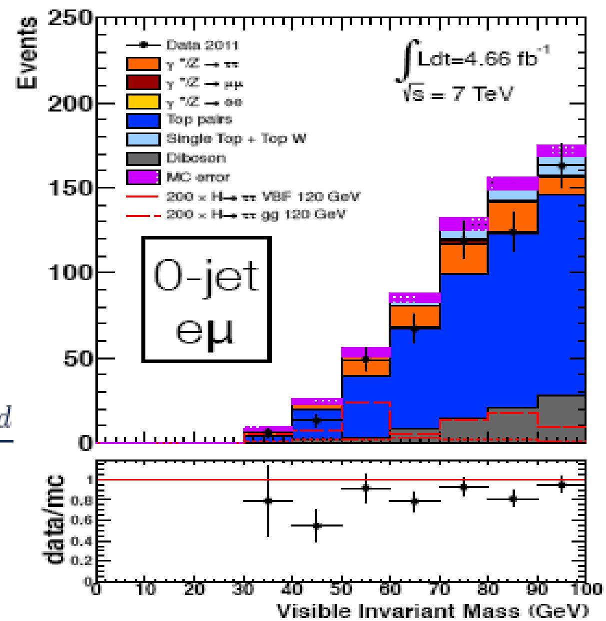
- $Z \rightarrow ee,\mu\mu$ Drell-Yan is controlled by the MET distribution in events under the Z peak:

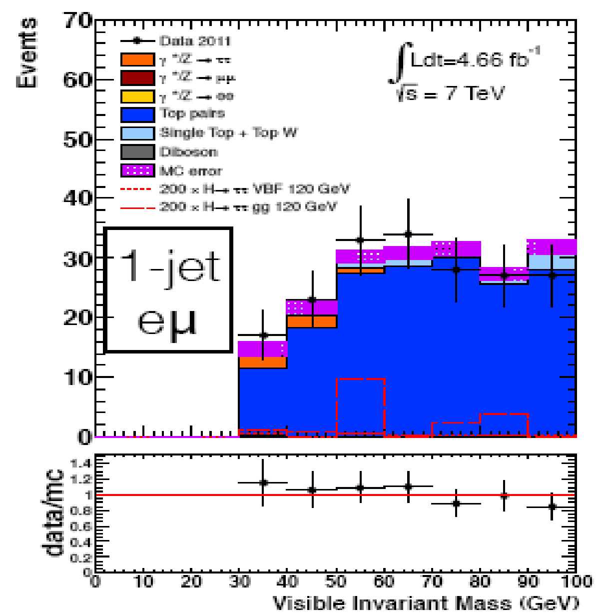
$$A_{\mathrm{MC}}^{\mathrm{corrected}} = A_{\mathrm{MC}} \times \frac{B_{\mathrm{data}}}{B_{\mathrm{data}} + D_{\mathrm{data}}} \frac{B_{\mathrm{MC}} + D_{\mathrm{MC}}}{B_{\mathrm{MC}}}$$



- Top background: estimated from MC, and validated in top control regions:
  - Require b-tag to obtain the top control sample
  - Correct the top normalization in the control sample:

$$\frac{N_{top}^{CR,Data}}{N_{top}^{CR,MC}} = \frac{N^{CR,Data} - N_{otherbkgd}^{CR,MC}}{N_{top}^{CR,MC}}$$





lh-channel: background estimation – Same Sign sample

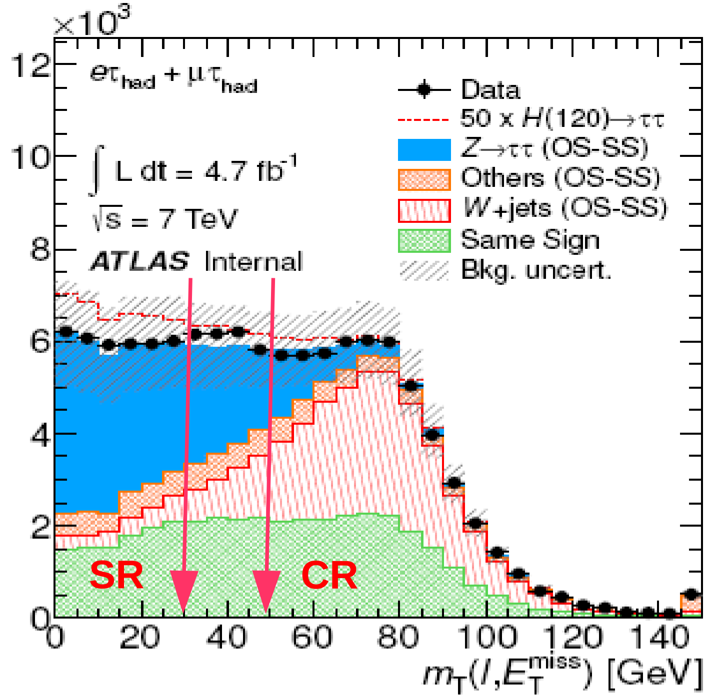
- Basic idea is that the background in OS signal region is equal to the background in SS signal region, plus any excess expected from OS than SS:

$$n_{\mathrm{OS}}^{\mathrm{bkg}} = n_{\mathrm{SS}}^{\mathrm{all}} + n_{\mathrm{OS-SS}}^{QCD} + n_{\mathrm{OS-SS}}^{W+\mathrm{jets}} + n_{\mathrm{OS-SS}}^{Z\to\tau\tau} + n_{\mathrm{OS-SS}}^{\mathrm{other}}$$

  - ”other” contains $Z\to ee,\mu\mu$, top (ttbar and single top) and diboson
  - QCD excess (OS than SS) is expected to be zero – checked in a control region with MET<15 GeV:

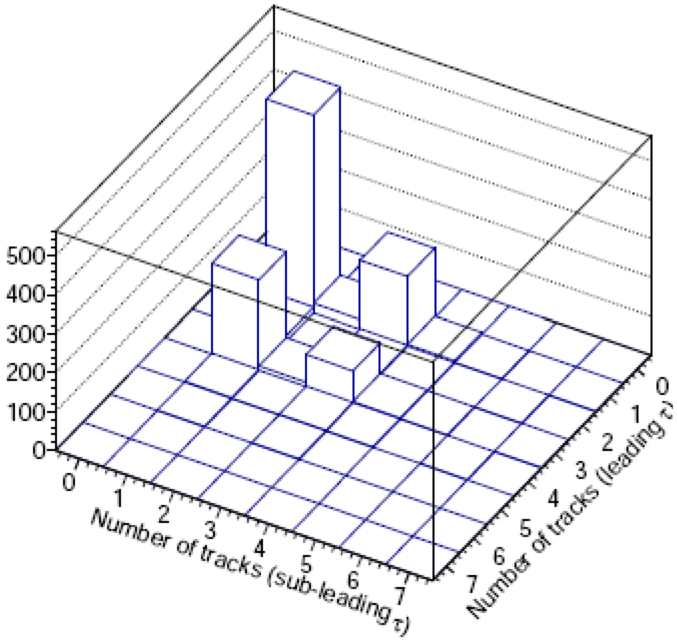
$$r_{OS/SS}^{QCD} = 1.10 \pm 0.01(\mathrm{stat.}) \pm 0.09(\mathrm{syst.}) \to n_{\text{OS-SS}}^{\text{QCD}} = 0$$

  - W+jet excess is estimated from a control region with m_T>50 GeV
  - $Z\to\tau\tau$ excess is estimated from the embedding sample
  - ”other” excess is estimated from MC simulation

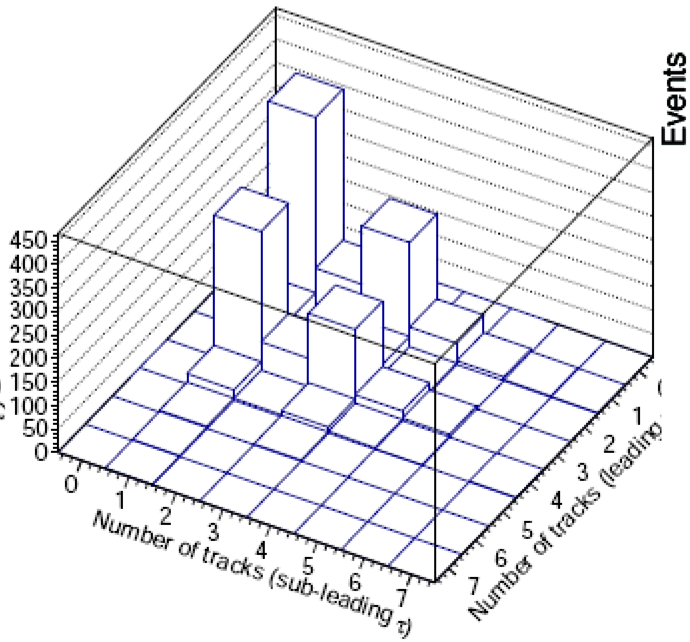


hh-channel: background estimation – track fitting

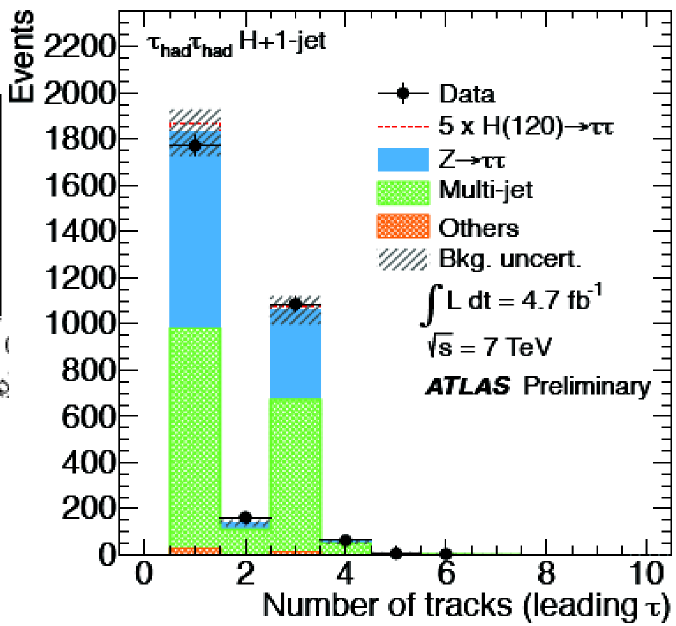
- Anti-K_T style track counting in a cone of $\Delta R<0.6$ around the tau
- 2-D fit to the track multiplicity distributions of the 2 taus
- Signal tau ($Z\rightarrow\tau\tau$) template is taken from MC, fake tau (QCD) template is from SS taus in data
- Fractions of QCD background can be obtained from the fits in both control sample and signal region



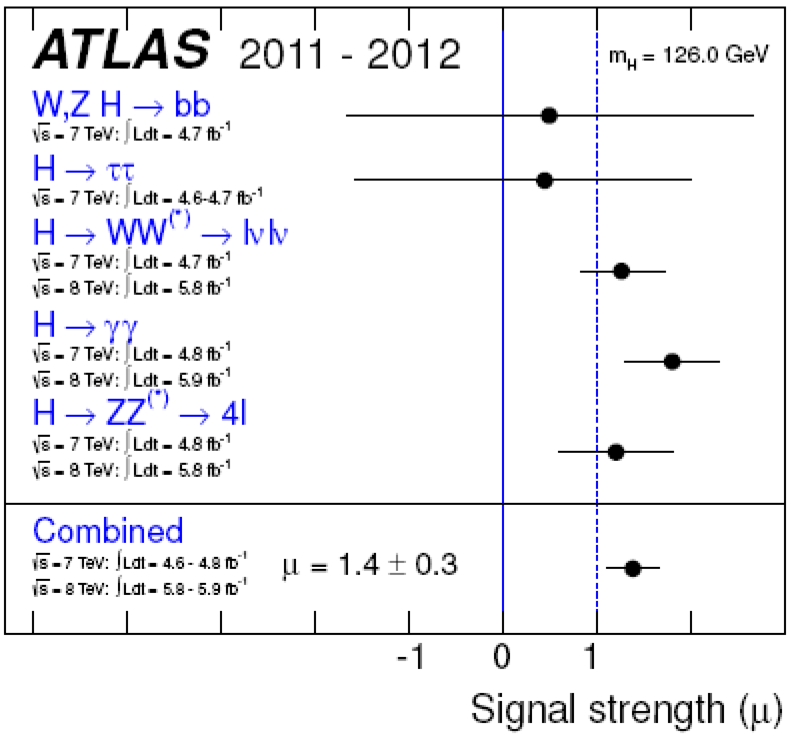
Z→ττ



QCD



Pinning down the Higgs couplings



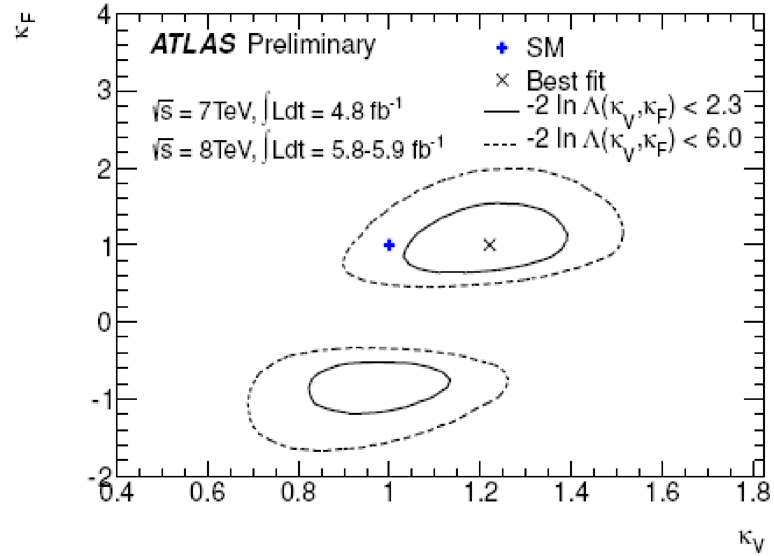
Global signal strength:

$\mu = 1.4 \pm 0.3$

Equivalent to a global coupling ratio

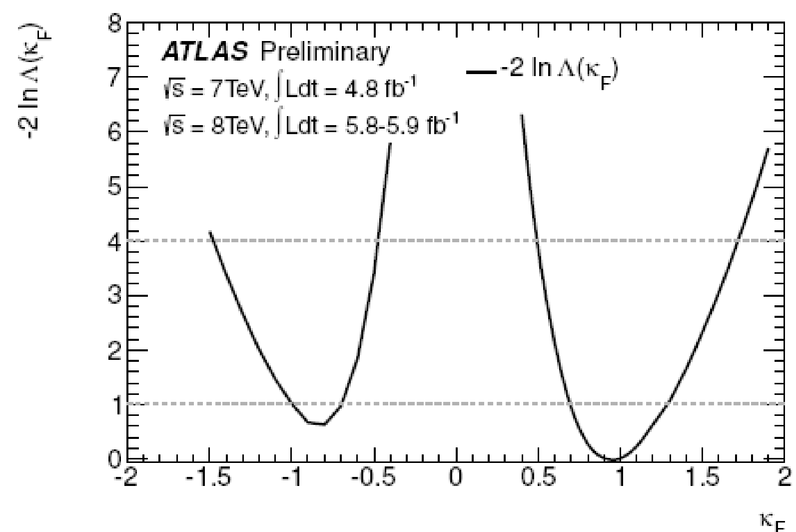
$k = g/g_{SM} = \mathrm{sqrt}(\mu) = 1.19 \pm 0.13$

Boson vs. fermion coupling

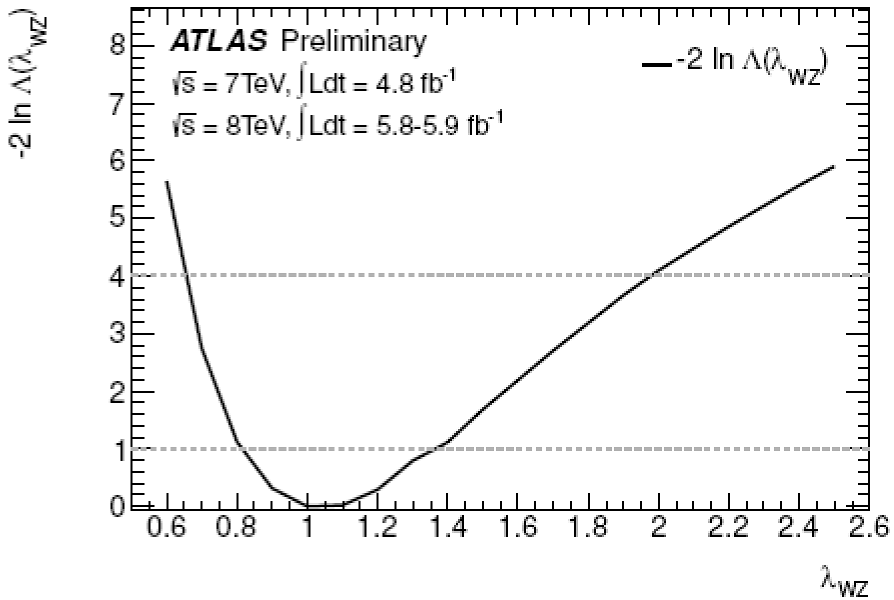


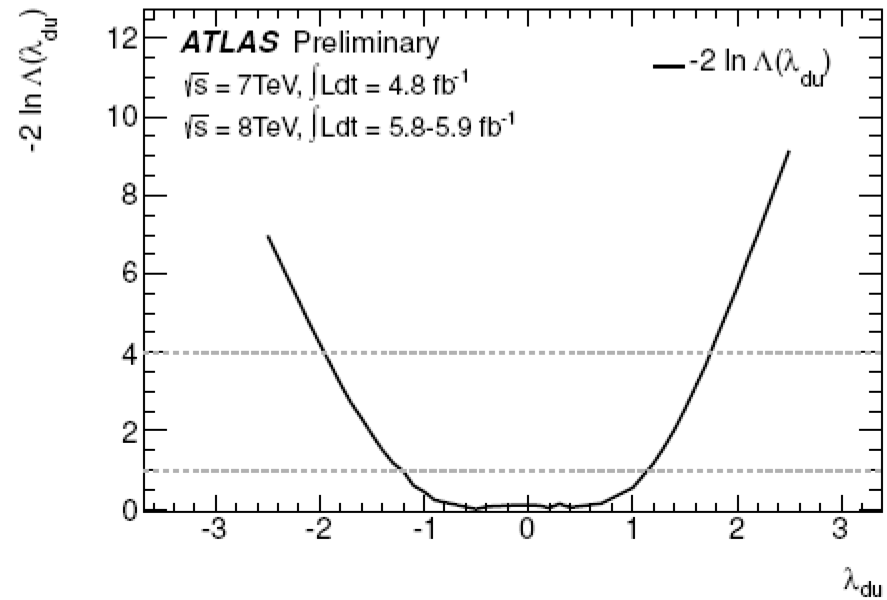
Double minima because of the H→γγ loop:

$$\sim \kappa_\gamma^{\ 2} = |1.28\ \kappa_W - 0.28\ \kappa_t|^2$$

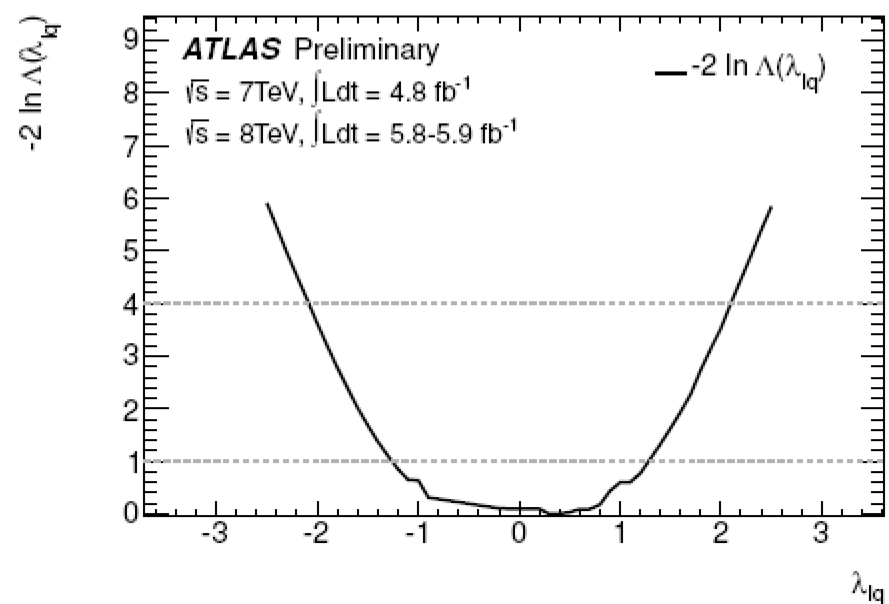


Pinning down the Higgs couplings

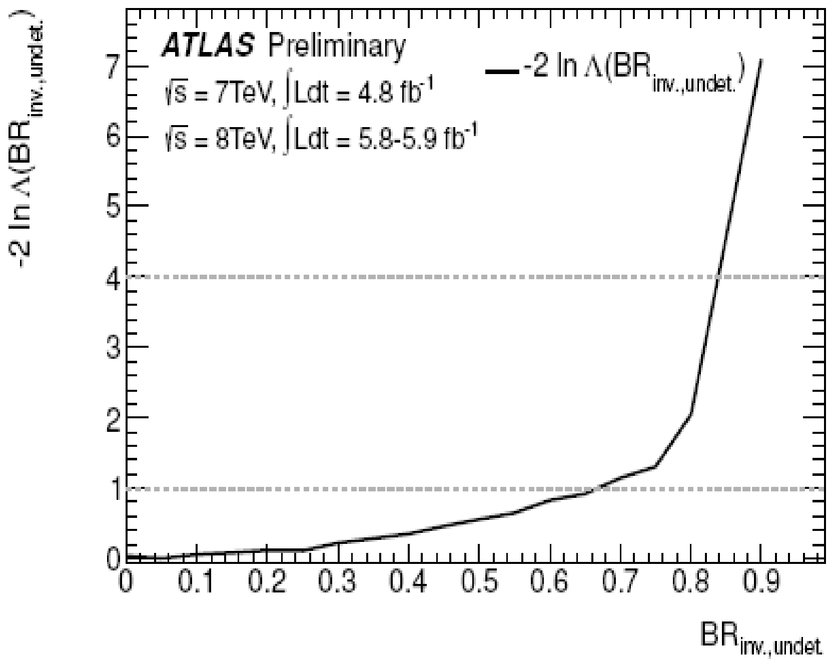




- W and Z couplings are consistent
- Not enough data from H→ττ and H →bbar to determine the up/down coupling ratios
- Not enough data from H→ττ to determine the lepton/quark coupling ratios



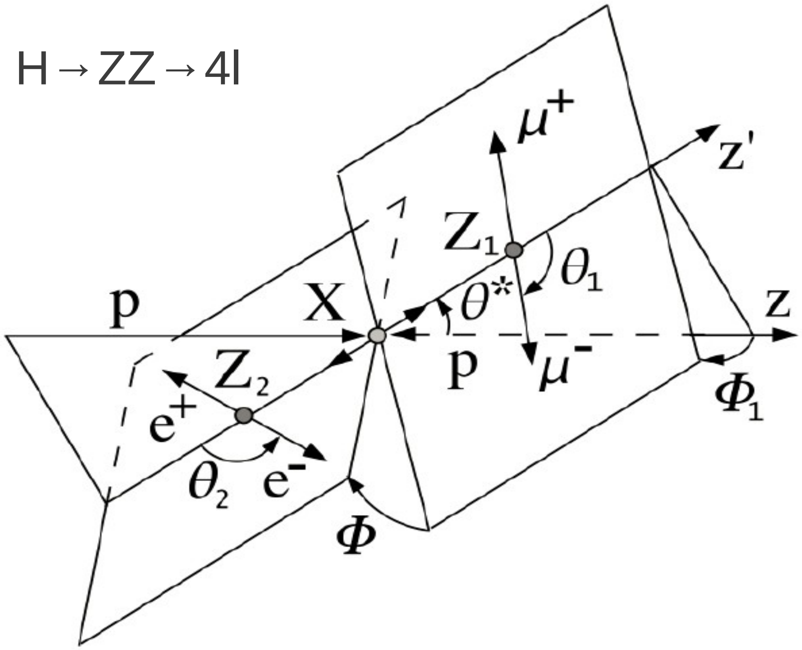
Higgs decay width, spin and CP



$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})}\Gamma_H^{SM}$$

BR(H→invisible/undetected)
< 0.65 @ 68% CL

H→ZZ→4l



H→γγ