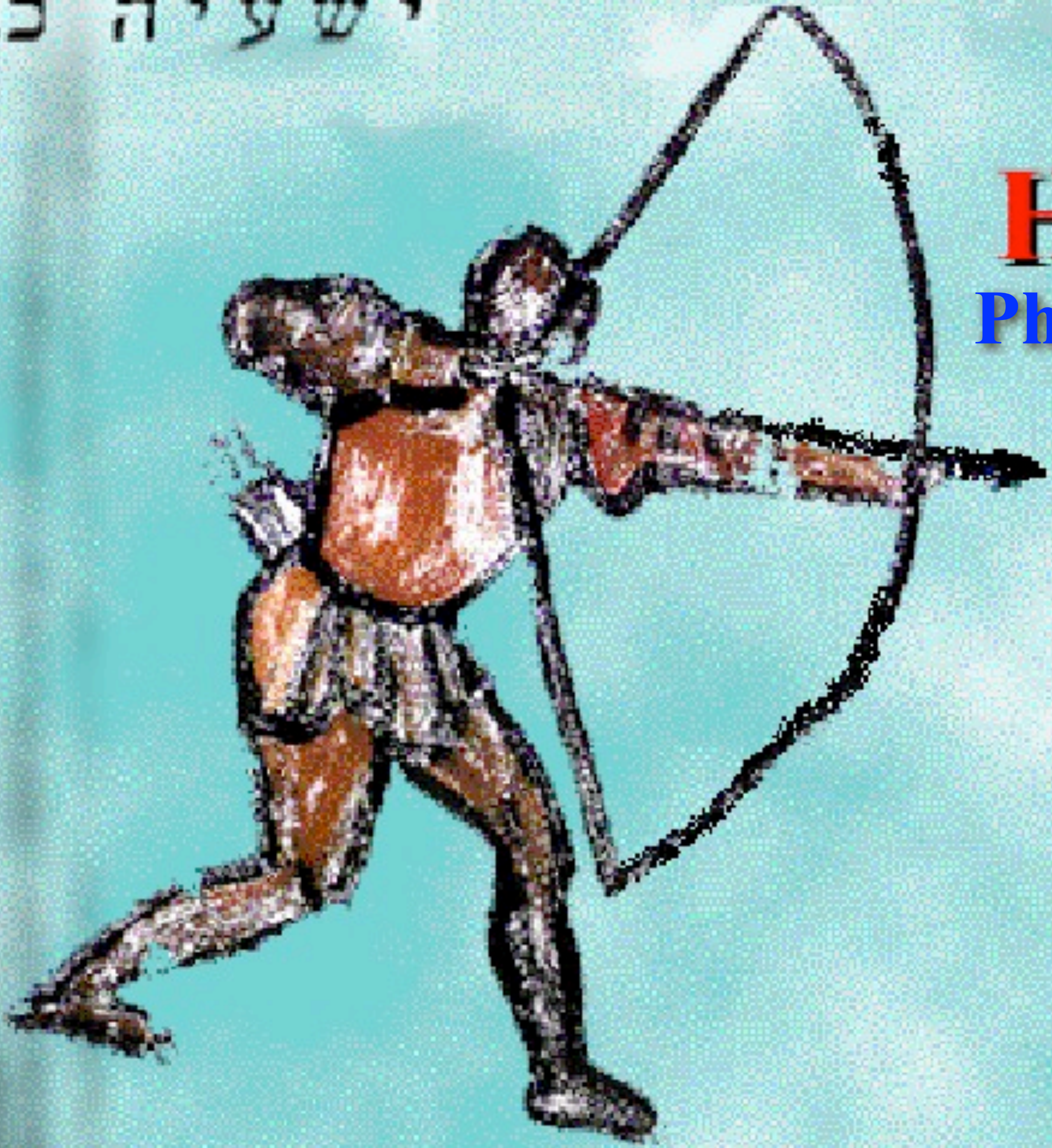
"וְעֵילָם נָשָׂא אַשְׁפָּה..."

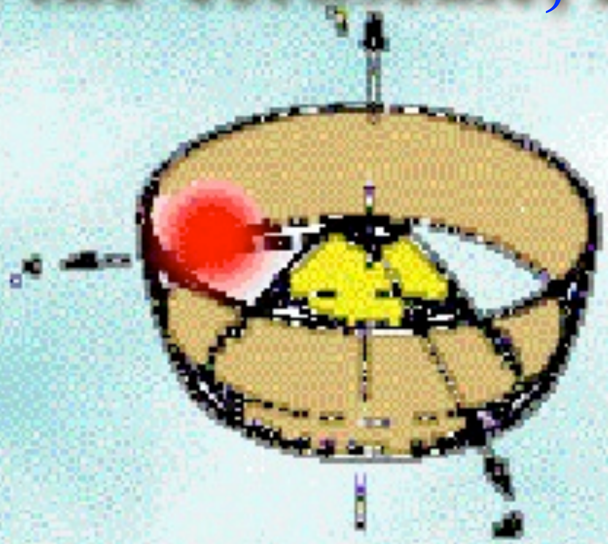
ישעיה כב

Eilam Gross

Hunting the Higgs

Physics at the Terascale, 2012



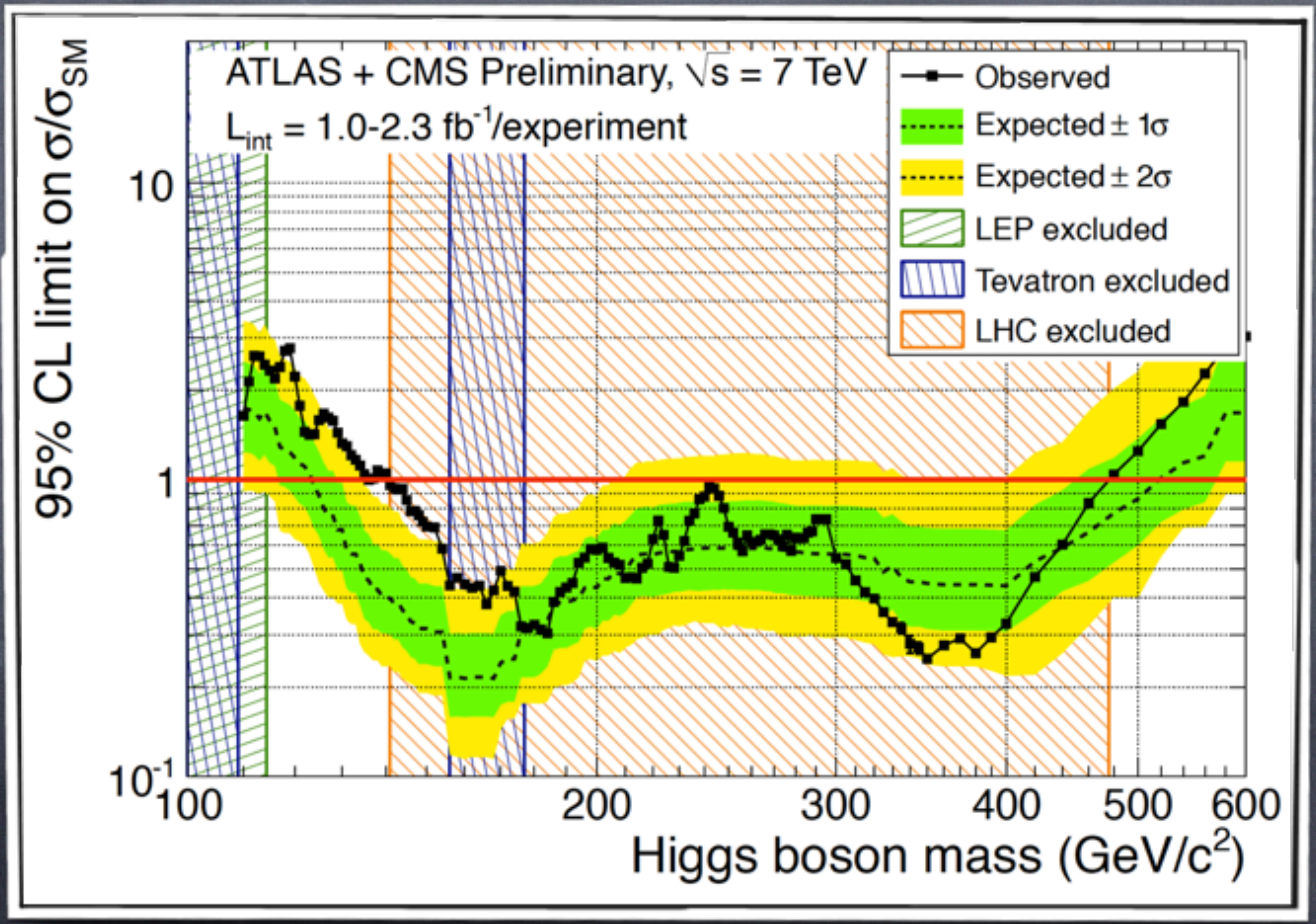


"And Eilam bare the quiver..."

Jesaia 22

Higgs- Nov 15th

Observed exclusion $141 < m_H < 476$ GeV @ the 95% Confidence Level



References

Combined Standard Model Higgs boson searches with up to 2.3 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV at the LHC

The ATLAS and CMS Collaborations

References

[1] F. Englert and R. Brout. Broken symmetry and the mass of gauge vector mesons. *Phys. Rev. Lett.*, 13:321–323, 1964.

[2] P.W. Higgs. Broken symmetries, massless particles and gauge fields. *Phys. Lett.*, 12:132–133, 1964.

[3] P.W. Higgs. Broken symmetries and the masses of gauge bosons. *Phys. Rev. Lett.*, 13:508–509, 1964.

[4] G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Global conservation laws and massless particles. *Phys. Rev. Lett.*, 13:585–587, 1964.

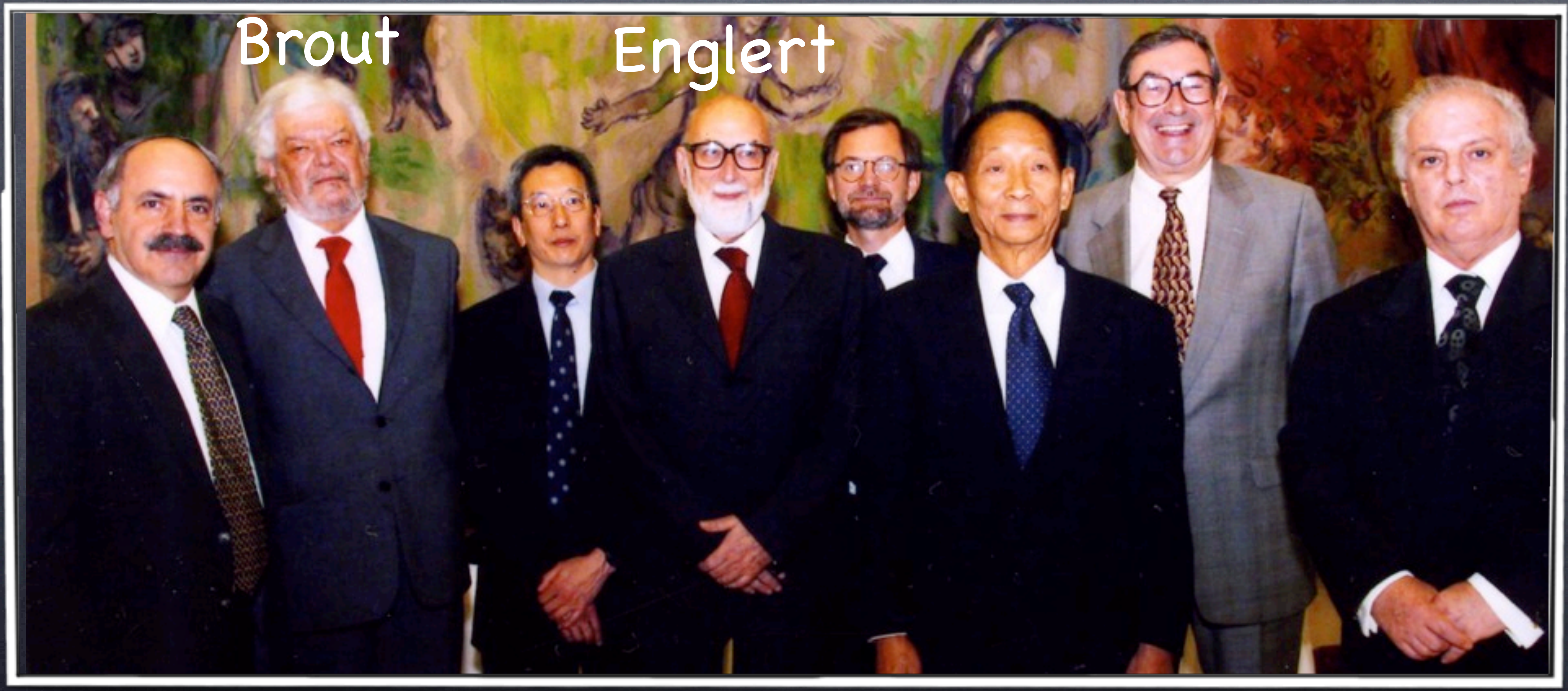
[5] P.W. Higgs. Spontaneous symmetry breakdown without massless bosons. *Phys. Rev.*, 145:1156–1163, 1966.

[6] T.W.B. Kibble. Symmetry breaking in non-Abelian gauge theories. *Phys. Rev.*, 155:1554–1561, 1967.

[7] LEP Working Group for Higgs boson searches. Search for the Standard Model Higgs boson at LEP. *Phys. Lett.*, B565:61–75, 2003.

Wolf Prize

- The 2004 Wolf prize, awarded by the Wolf Foundation, was given to Englert, Brout and Higgs




Air Mail
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2010
90P
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Higgs (in a snail mail to me):

History of SSB

(1) Order of contributions:–

1. Nambu (1960), Nambu & Jona-Lasinio (1961)
2. Goldstone (1961)
3. Goldstone, Salam & Weinberg (1962)
4. Anderson (1963)
5. Englert & Brout (Aug. 1964)
6. Higgs (Sep. & Oct 1964)
7. Guralnik, Hagen & Kibble (Nov. 1964)

See the enclosed reprint for my account of papers 1 to 6.

Guralnik, Hagen & Kibble (7) showed how the Goldstone theorem is evaded in a simple linear model. Note that all six of us were awarded the 2010 Sakurai Prize by the APS.

Higgs (in a snail mail to me):

Landau (1960)
Goldstone(1961)
Goldstone, Salam , Weiberg (1962)
Anderson (1963)
Englert & Brout (1964)
Higgs (1964)
Geralnik, Hagen & Kibble (1964)

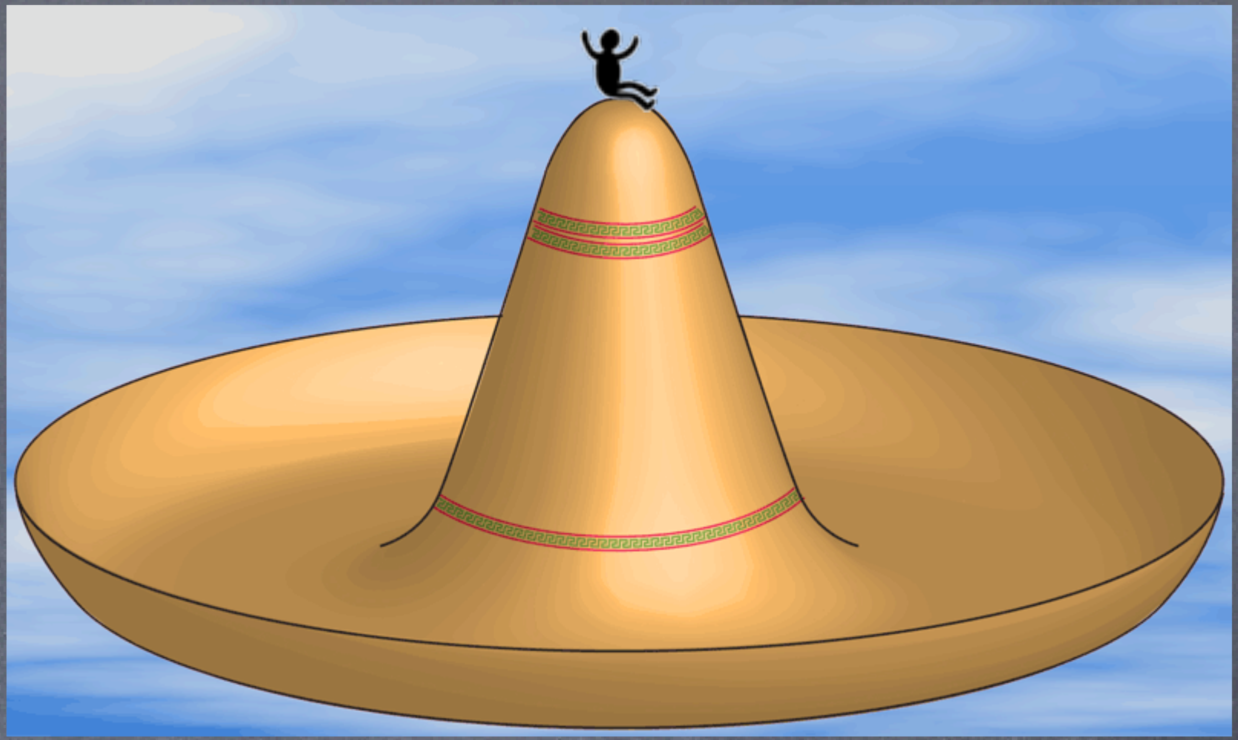
Note that all six of us
were awarded the 2010 Sakuarai Prize of the APS

A Prelude to the Nobel Prize

- **2010 Sakurai Prize awarded for 1964 Higgs Boson theory work to Hagen, Guralnik, Kibble, Brout, Englert & Higgs**

Spontaneous Symmetry Breaking

- Spontaneously Symmetry Breaking was first introduced by Ginzburg & Landau (1950,1957) (in an attempt to explain superconductivity)



- The physics of the system (Lagrangian) posses some exact symmetry, but the vacuum (ground state) breaks this symmetry

- Nambu (1960) proposed for the first time that SSB is the source of fermion masses in elementary particle physics: "the existence of such a condensate (scalar field) would break the symmetry of the model.... . In particle physics, that would be a non-Abelian group containing the U(1) group associated with electric charge conservation as a subgroup"

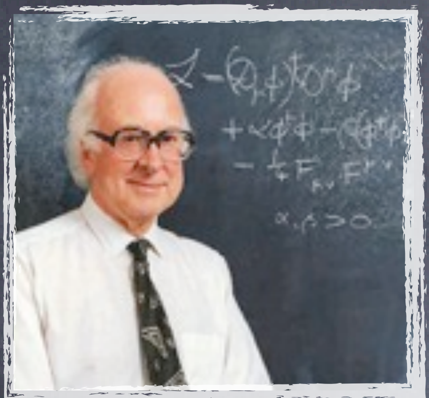
Spontaneous Symmetry Breaking

- Inspired by Nambu, Goldstone (1961) studies models featuring scalar fields and finds that all these models contains (under SSB) massless (Nambu-Goldstone) Bosons
- Goldstone, Salam and Weinberg (1962) prove formally that Goldstone Bosons must occur whenever a symmetry (*"like isospin or strangeness"*) is broken (Goldstone Theorem). But no such Bosons were observed experimentally.
- Weinberg recalls in his Nobel lecture (1979) that he was so disappointed that he added a quote to the paper from king Lear: *"Nothing will come out of nothing, speak again"*

- Is Quantum Field Theory a one trick pony? Can it explain only long range interactions?

Spontaneous Symmetry Breaking

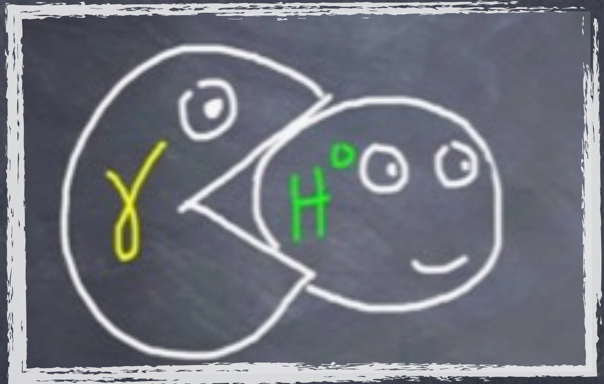
Philip Anderson (1963) points out that in a superconductor the Goldstone mode becomes a massive plasmon-mode, due to its electromagnetic interaction.



Peter Higgs (Phys. Lett. July 1964) shows that one can evade Goldstone theorem. He shows that if the broken symmetry is local gauge symmetry (like electromagnetic U(1) gauge invariance), then, although the Goldstone Bosons exist formally, and in some sense real, they can be eliminated by gauge transformation, so that they do not appear as physical particles. That explains why experiment fails to detect the massless Bosons.

- The missing Gloldstone boson appears instead as helicity zero state of the massless boson which thereby acquire a mass.

- The massless boson eats the Goldstone Boson and acquires mass.



The Higgs Mechanism

- Based on field theory (using a lagrangian formalism) Higgs develops the formalism of the mechanism by which the Goldstone Boson is "eaten" by the photon and the pohoton becomes massive -> short range interaction
- He sends the 3 pages paper to Physics Letter, the paper is rejected. Higgs: *"I was rather shocked. I did not see why they would accept a paper that said this is a possible way to evade the Goldstone theorem, and then reject a paper that showed how you actually do it."*
- Higgs adds an epilogue to the paper: *"it is worth noting that an essential feature of this type of theory is the prediction of incomplete multiplets of scalar and vector bosons"* and sends the revised version to PRL.

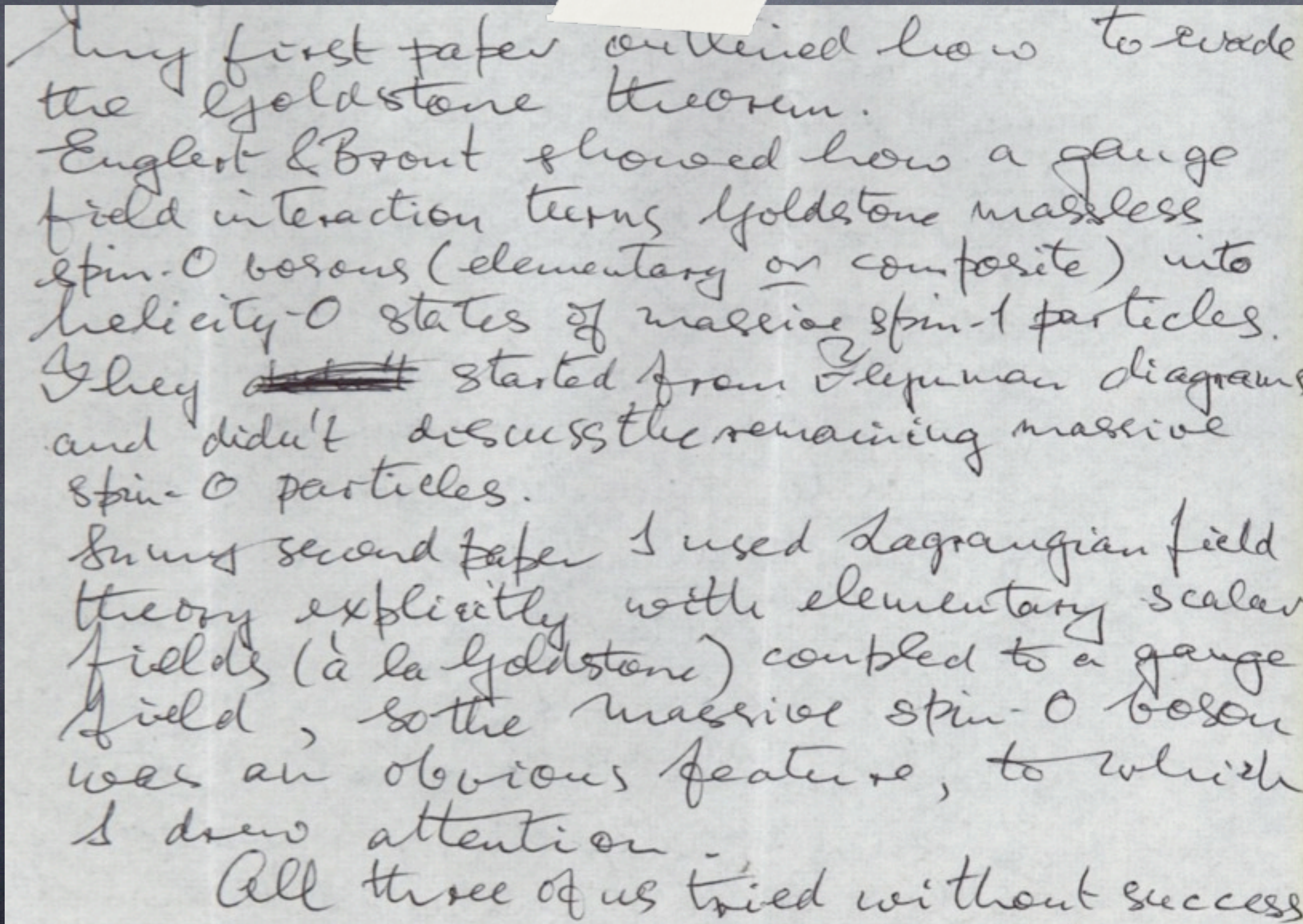
The Higgs Mechanism

- Higgs: "The referee who, I discovered later, was Nambu, drew my attention to a paper by Englert and Brout that they had just published in Physical Review Letters". Higgs is asked to cite Englert & Brout and the paper is accepted (August 1964)

- Guralnik, Hagen and Kibble (1964).
  Guralnik (2009): "As we were literally placing the manuscript in the envelope to be sent to PRL, Kibble came into the office bearing two papers by Higgs and the one by Englert and Brout. These had just arrived in the then very slow and unreliable... Imperial College mail. We were very surprised and even amazed."

The Higgs Mechanism

- Higgs (in a snail mail to me):



My first paper outlined how to evade
the Goldstone theorem.
Englert & Brout showed how a gauge
field interaction turns Goldstone massless
spin-0 bosons (elementary or composite) into
helicity-0 states of massive spin-1 particles.
They ~~[illegible]~~ started from Feynman diagrams
and didn't discuss the remaining massive
spin-0 particles.
In my second paper I used Lagrangian field
theory explicitly with elementary scalar
fields (à la Goldstone) coupled to a gauge
field, so the massive spin-0 boson
was an obvious feature, to which
I drew attention.
All three of us tried without success

The Higgs Mechanism

- Higgs (in a snail mail to me):

  In my first paper I outlined how to evade the Goldstone theorem.

  Englert & Brout showed how a gauge field interaction turns Goldstone massless bosons (elementary OR composite) into helicity-0 states of massive spin-1 particles. They started from Feynmann diagrams and didn't discuss the remaining massive spin-0 particles.

  In my second paper I used Lagarangian field theory explicitly with elementary scalar fields (a` la Goldstone) coupled to a gauge field, so the massive spin-0 boson was an obvious feature, to which I drew attention.

The Birth of the Standard Model

-  Glashow (1961) suggests that the symmetry of the Electro-Weak interaction is SU(2)xU(1) and is broken to U(1) em. But Glashow puts the masses of the force carriers by hand and his theory is therefore non-renormalizable
-  Weinberg (1967) implements Higgs mechanism to Glashow's SU(2)xU(1) and writes the most quoted paper in the history of particle phsyics

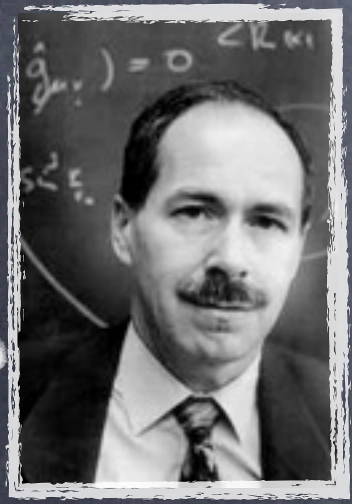
  (most quoted . .... >7500 citations).

- Weinberg predicts that the mass of the weak interaction force carriers is mW=80 GeV and mZ=90 GeV, but it took another 14 years to confirm it experimentally.

The Birth of the Standard Model

wrong.

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable, so the question is whether this renormalizability is lost in the reordering of the perturbation theory implied by our redefinition of the fields.



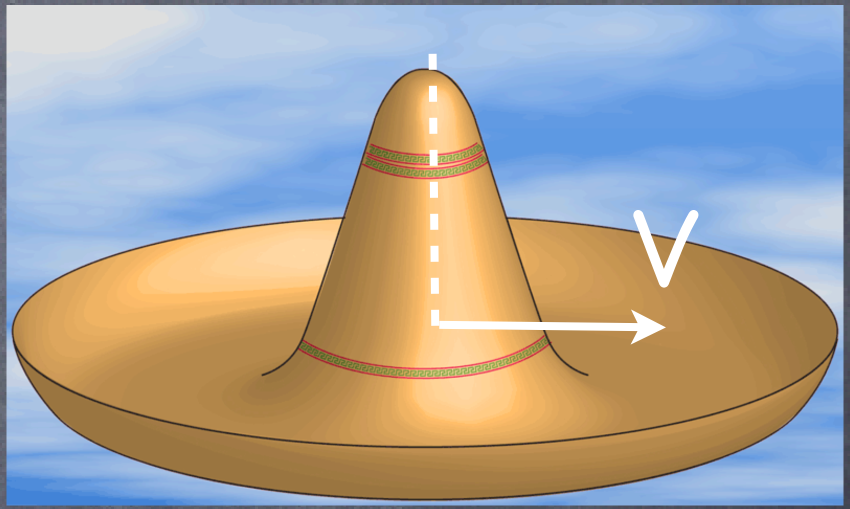
- The (theoretical) story was completed when `tHooft (& Veltman) proved the renormalizability of Yang-Mills theories with masses generated by spontaneous symmetry breaking in a scalar field system in 1971.
- All that is left is to find the mass generator, the Higgs Boson

How Elementary Particles Acquire Mass

- A mass term is given by $m\bar{\psi}_L \psi_R$
- Only left handed fields carry weak charge.
- Via SSB the Higgs field "charges" the vacuum with a weak charge and the symmetry is preserved ("hidden")

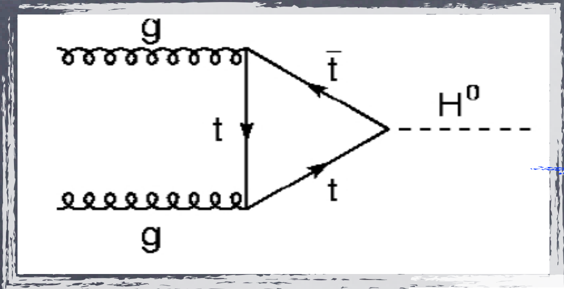
$$g_{H\psi} H_L \bar{\psi}_L \psi_R -> g_{H\psi} \langle H_L \rangle \bar{\psi}_L \psi_R = g_{H\psi} \mathrm{v} \bar{\psi}_L \psi_R$$

$$m_\psi = g_{H\psi} \mathrm{v}, \qquad g_{H\psi} = \frac{m_\psi}{\mathrm{v}}$$

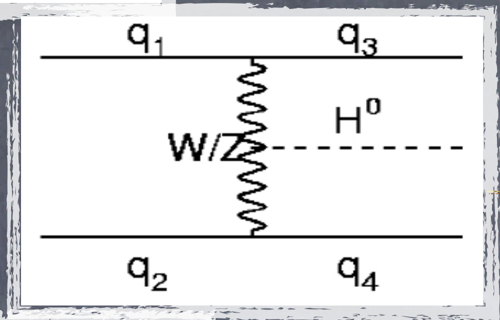


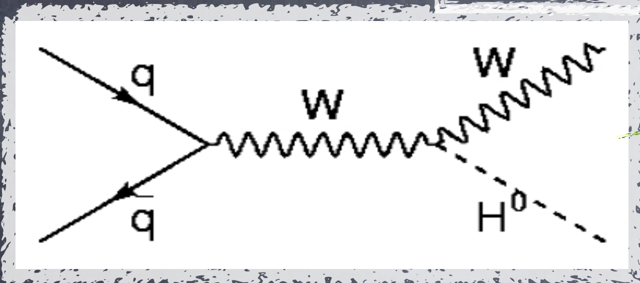
- The coupling of the Higgs to particles is proportional to the particles' mass
- The Higgs Boson will therefore decay with a higher probability to the heaviest particle kinematically available

Higgs Production

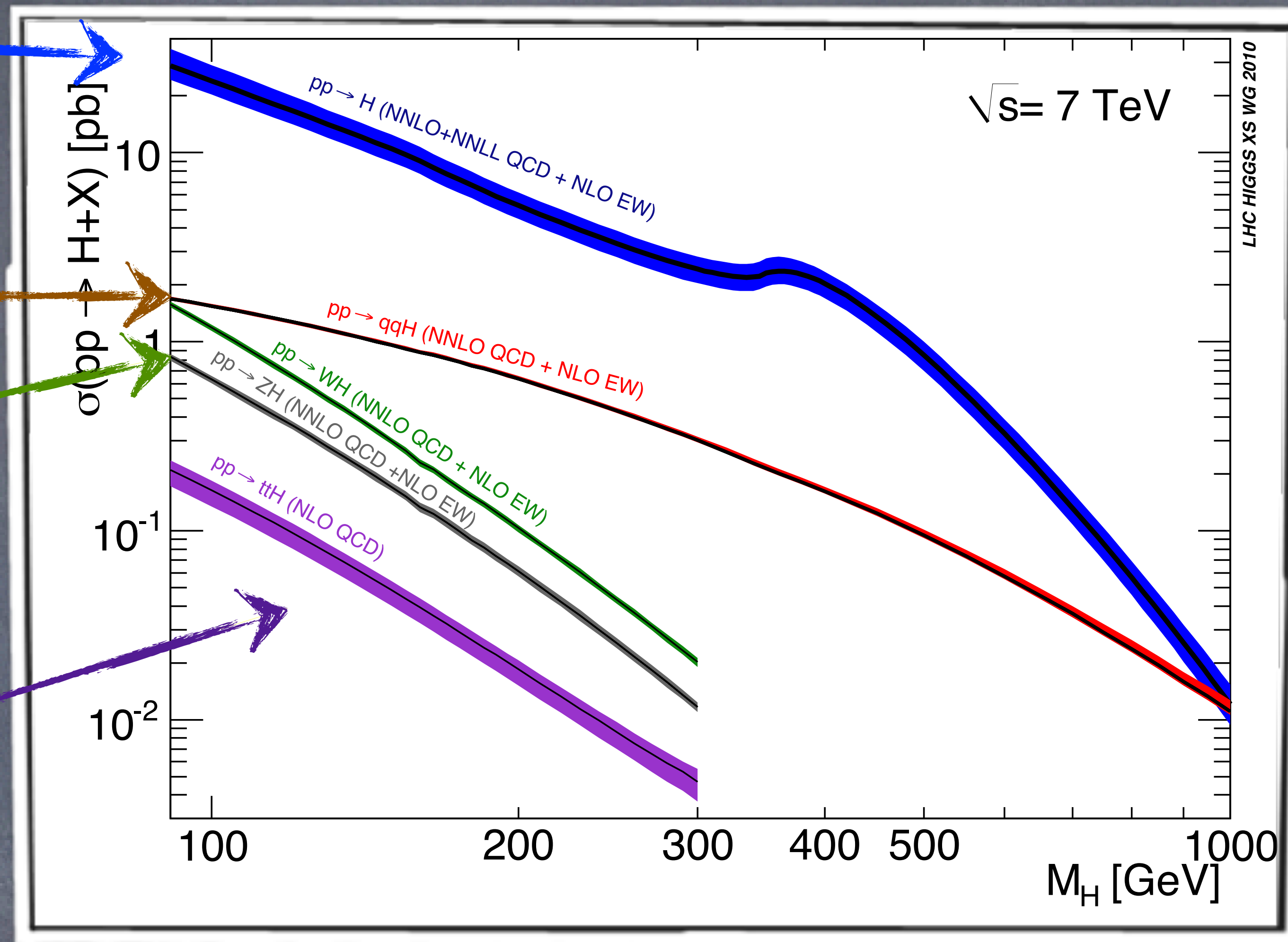


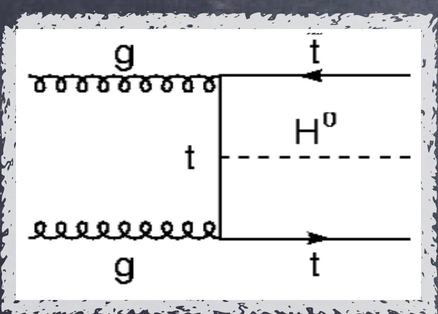
is x10 then





is even smaller, yet distinct

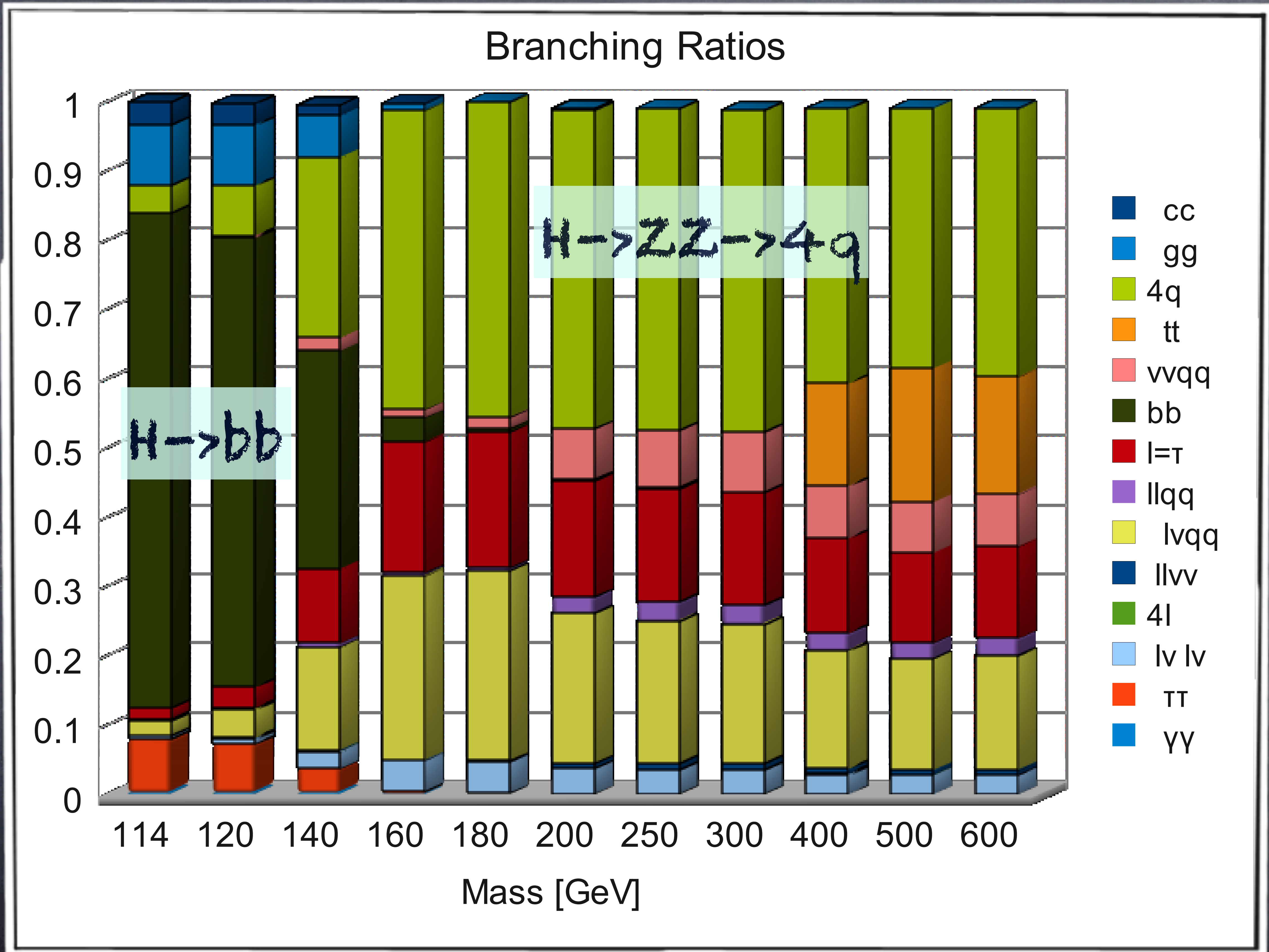




is the smallest and also difficult

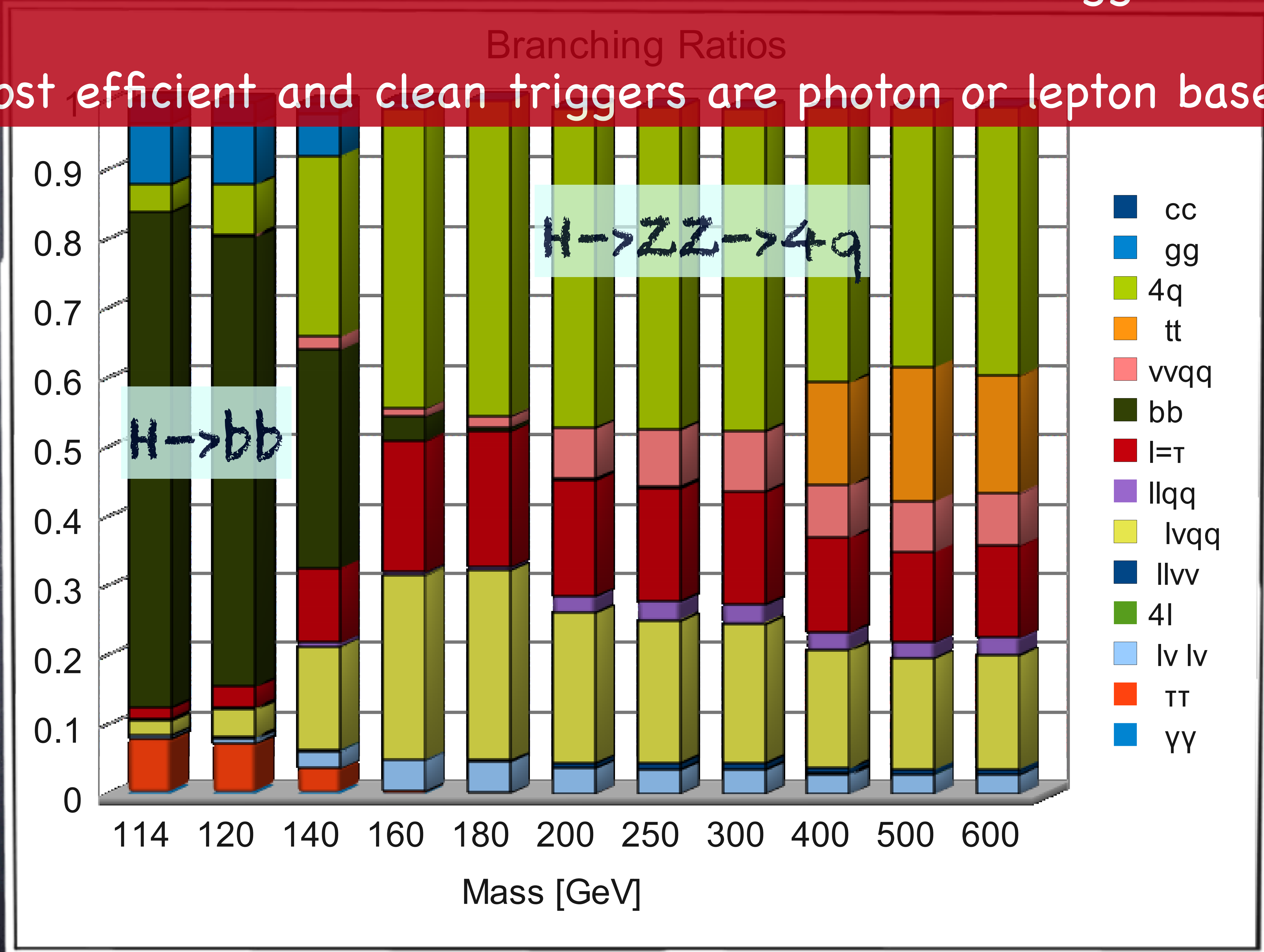
Typical size of uncertaint[illegible]alues depend on M_H):

	ggF	VBF	WH/ZH	$t\bar{t}H$
QCD scale:	$^{+12\%}_{-8\%}$	$\pm 1\%$	$\pm 1\%$	$^{+3\%}_{-9\%}$
PDF + α_s:	$\pm 8\%$	$\pm 4\%$	$\pm 4\%$	$\pm 8\%$
Mass line shape:	$(150\%) \times \left(\frac{M_H}{TeV}\right)^3$			

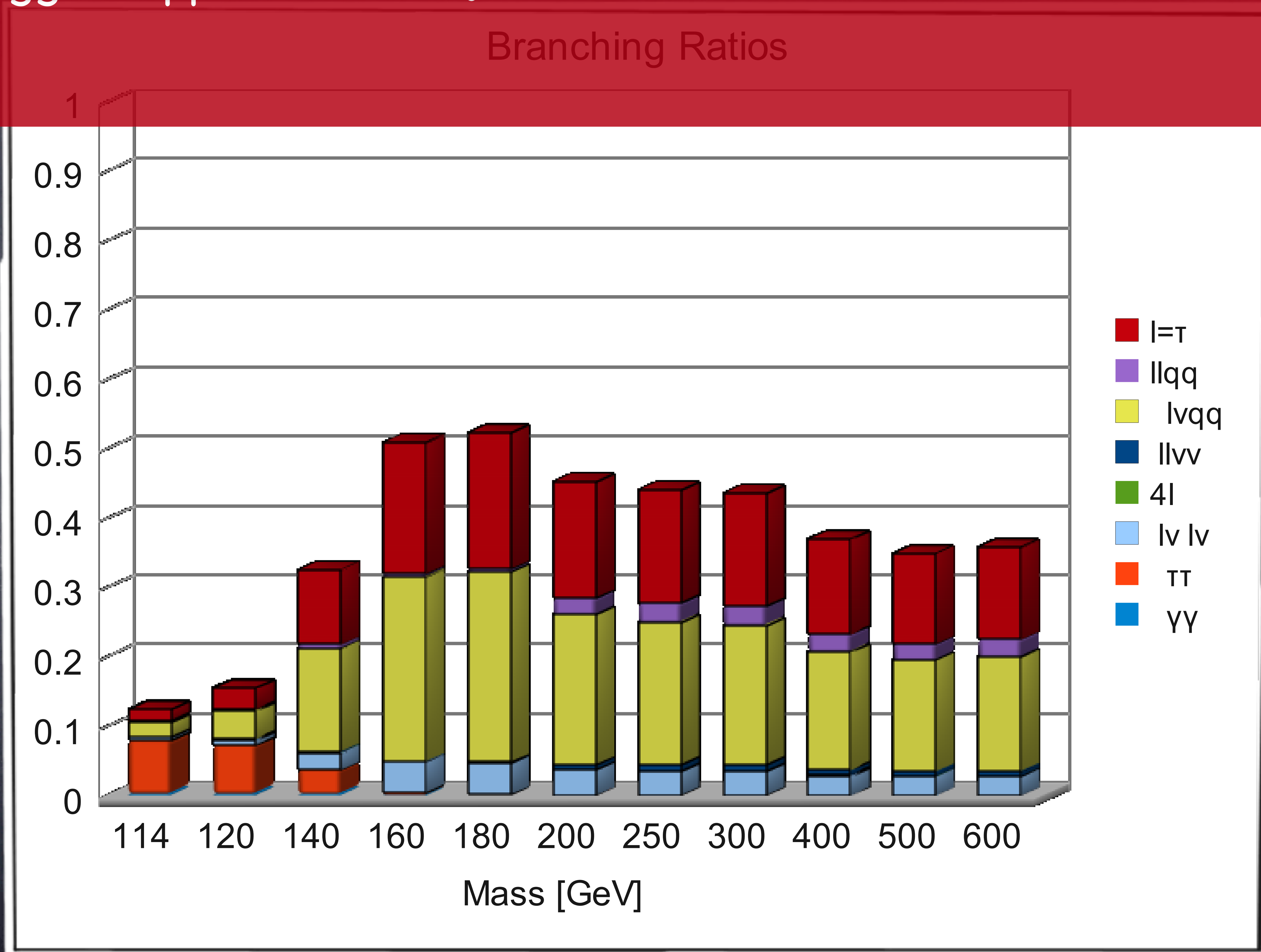


Branching Ratios
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
H->bb
H->ZZ->4q
114
120
140
160
180
200
250
300
400
500
600
Mass [GeV]
cc
gg
4q
tt
vvqq
bb
l=τ
llqq
lvqq
llvv
4l
lv lv
ττ
γγ

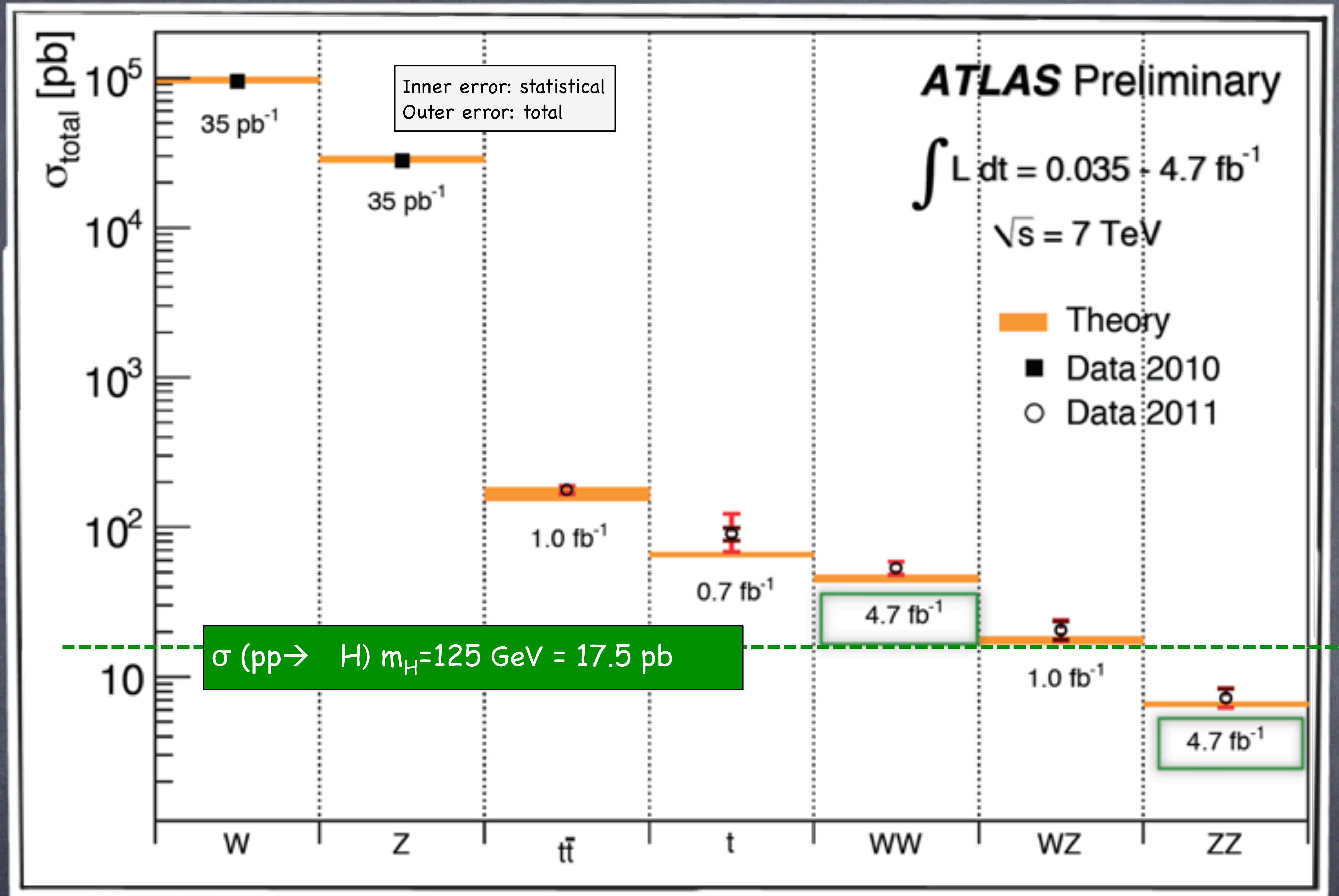
- For a channel to be usable, we must be able to trigger it
- Most efficient and clean triggers are photon or lepton based



Trigger ripped off the jet channels

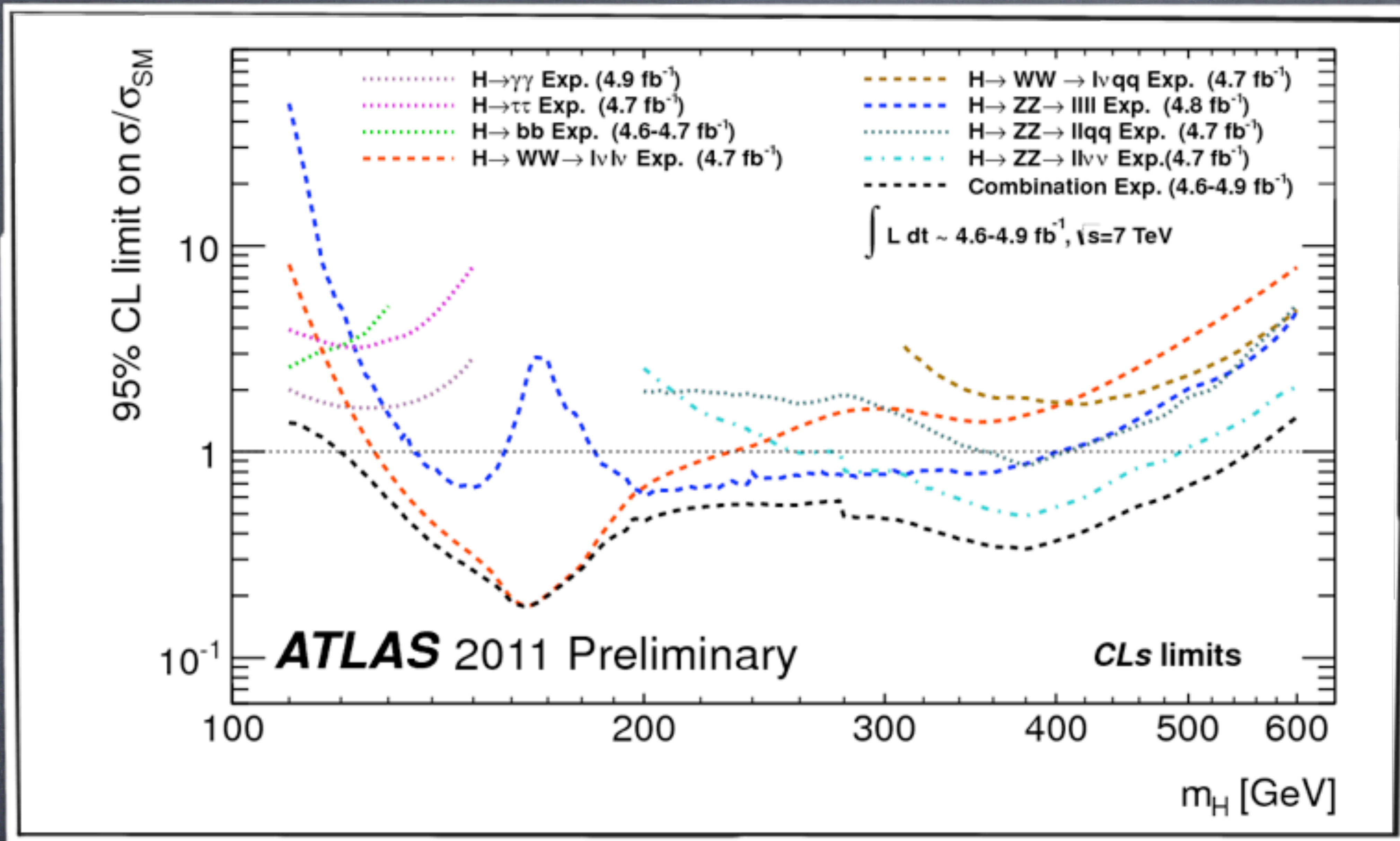


Elecroweak measurements are Higgs backgrounds



- Good agreement with theory , W, Z, tt become a challenge for theory
- Systematics dominate
- Higgs cross section same order of magnitude as Di-Boson production (WW,WZ,ZZ)

Combined Limit



- Low mass is completely dominated by γγ, then bb, ττ and a bit of WW
- High mass completely dominated by llνν

Channels Weight

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

- Asymptotically *Cowan et. al. , EPJC 71 (2011) 1-19.*

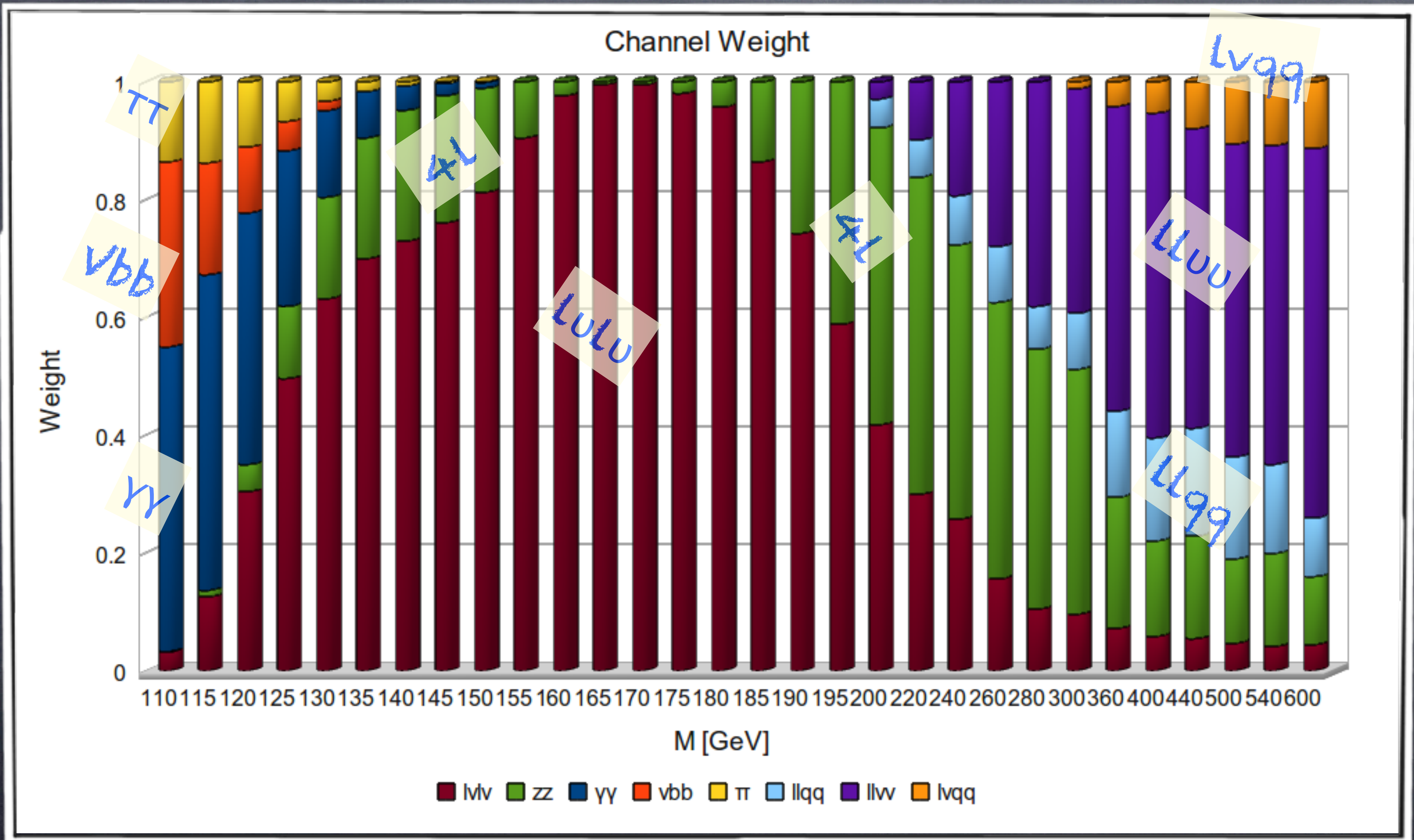
$$\mu_{up,\exp,i}(\mathcal{L}_i) \rightarrow \mu_{up,\exp,i}(\mathcal{L}_0) = \mu_{up,\exp,i}(\mathcal{L}_i)\sqrt{\frac{\mathcal{L}_i}{\mathcal{L}_0}}$$

Luminosity normalized:

$$\mathrm{w}_i = \left(\frac{\mu_{up,\exp,C}}{\mu_{up,\exp,i}}\right)^2 = \left(\frac{\dfrac{1}{\mu_{up,\exp,i}}}{\sqrt{\sum\left(\dfrac{1}{\mu_{up,\exp,i}}\right)^2}}\right)^2 \rightarrow \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

If we normalize individual channels to the same luminosity, the weight, w_i is independent of the luminosity

Channels Weight



A nano statistical interlude I

Understanding The Yellow and Green Bands

Exclusion with Pofile Likelihood

Define a test statistic to probe the compatibility of the data with the Signal Hypothesis

$$\mu = \frac{\sigma}{\sigma_{SM}(m_H)} \qquad <n> = \mu \cdot s(m_H) + b \qquad \mu = 1 \text{ is SM Higgs}$$

$$\tilde{q}_\mu = -2\log\frac{max_{\{b\}} L(\mu s(m_H)+b)}{max_{\{\mu,b\}} L(\mu s(m_H)+b)} = -2\log\frac{L(\mu s(m_H)+\hat{b}_\mu)}{L(\hat{\mu} s(m_H)+\hat{b})}$$

Cowan, Cranmer, E.G. and Vitells, EPJC 71 (2011) 1-19.

Reject the signal hypothesis (at the 95% CL) if the compatibility of the data with the signal model at μ=1, is less than 5%

Exclusion: Profile Likelihood "vs" CLs

$$\mu = \frac{\sigma}{\sigma_{SM}(m_H)}$$

->CLs measures the compatibility of the data with the signal hypothesis.

->If CLs<5% the signal hypothesis is excluded at the 95% CL

->μ_{up} is the signal strength for which CLs=5%

-> If $\mu_{up}<1 \Rightarrow \sigma(m_H)/\sigma_{SM}<1 \Rightarrow \sigma(m_H)<\sigma_{SM}$
$\Rightarrow m_H$ is excluded at the 95% Confidence Level

Understanding The Yellow and Green Bands

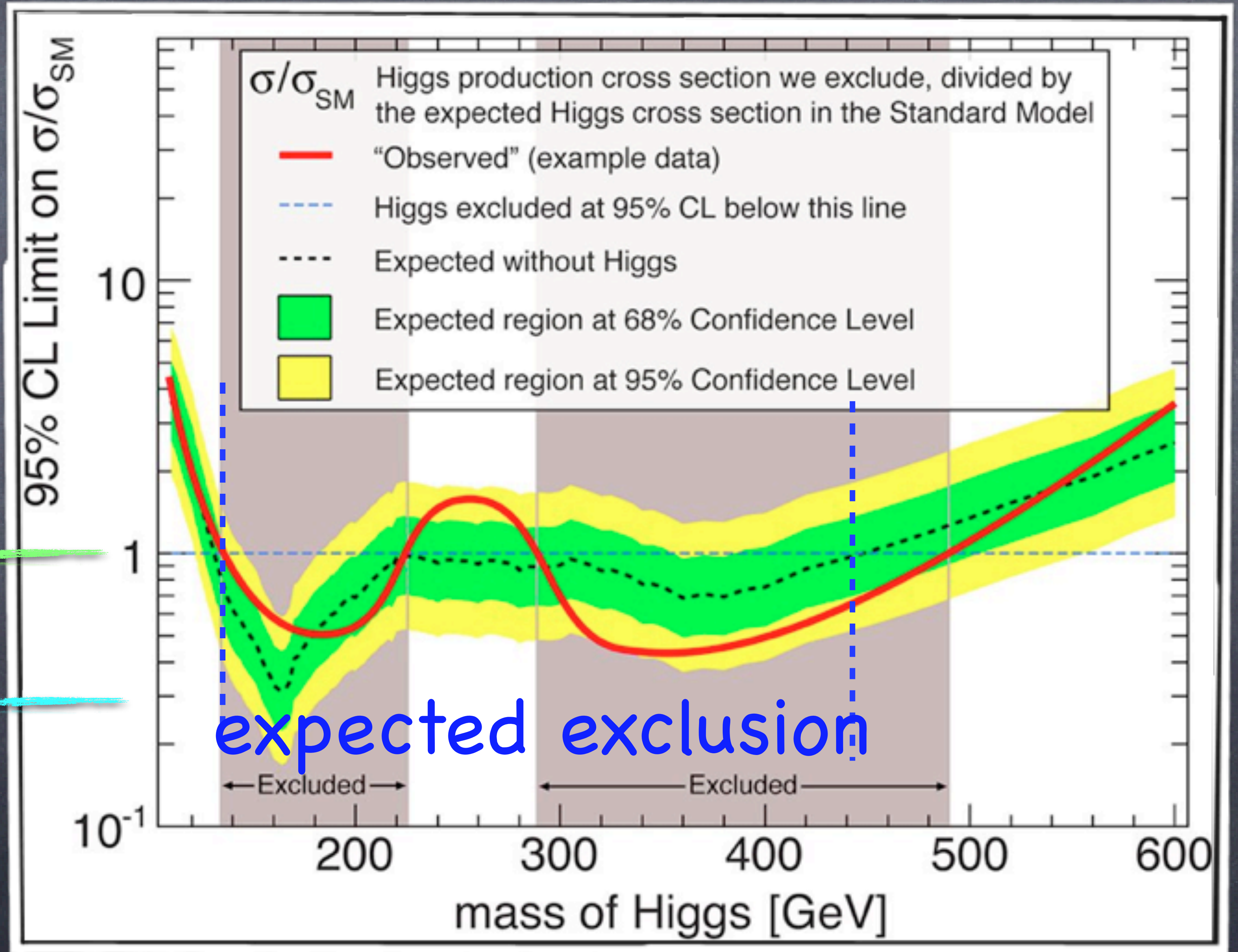
The idea behind CLs:
If the expected number of signal events is tiny then $s(m_H)+b \sim b$, this signal cannot be excluded

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

$$CLs = 1 - CL$$

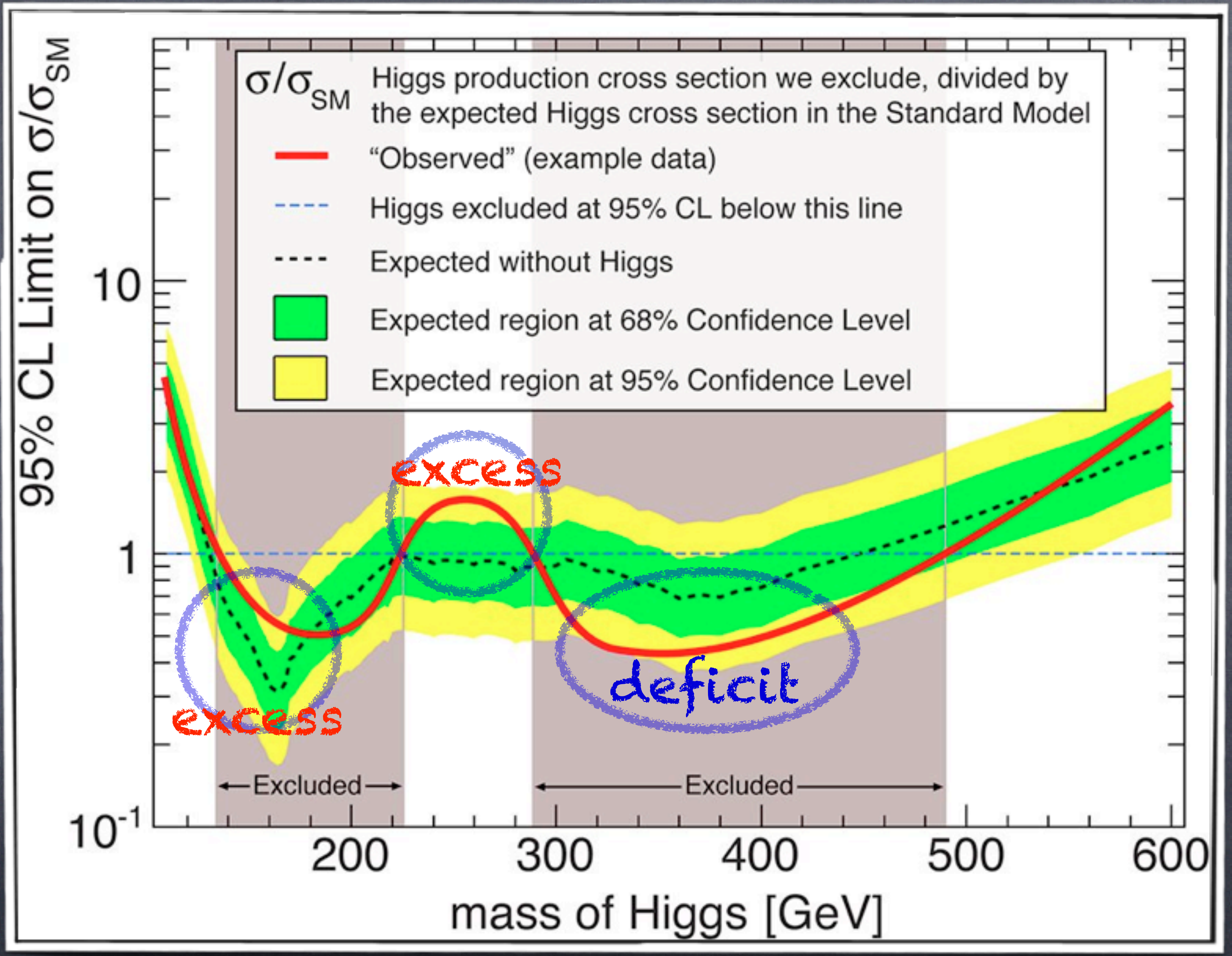
$$CLs = 95\%$$

$$CLs < 95\%$$

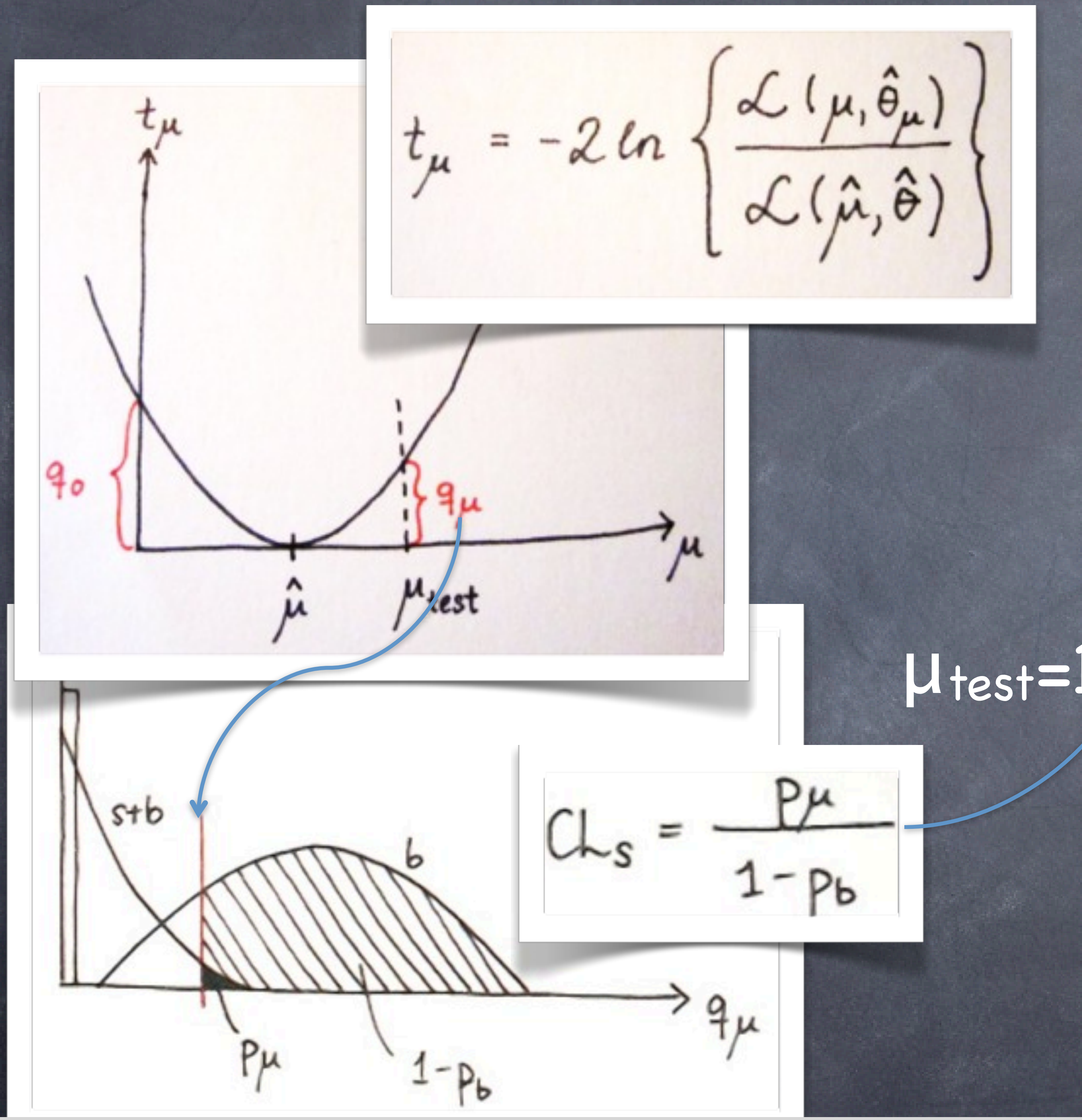


Understanding The Yellow and Green Bands

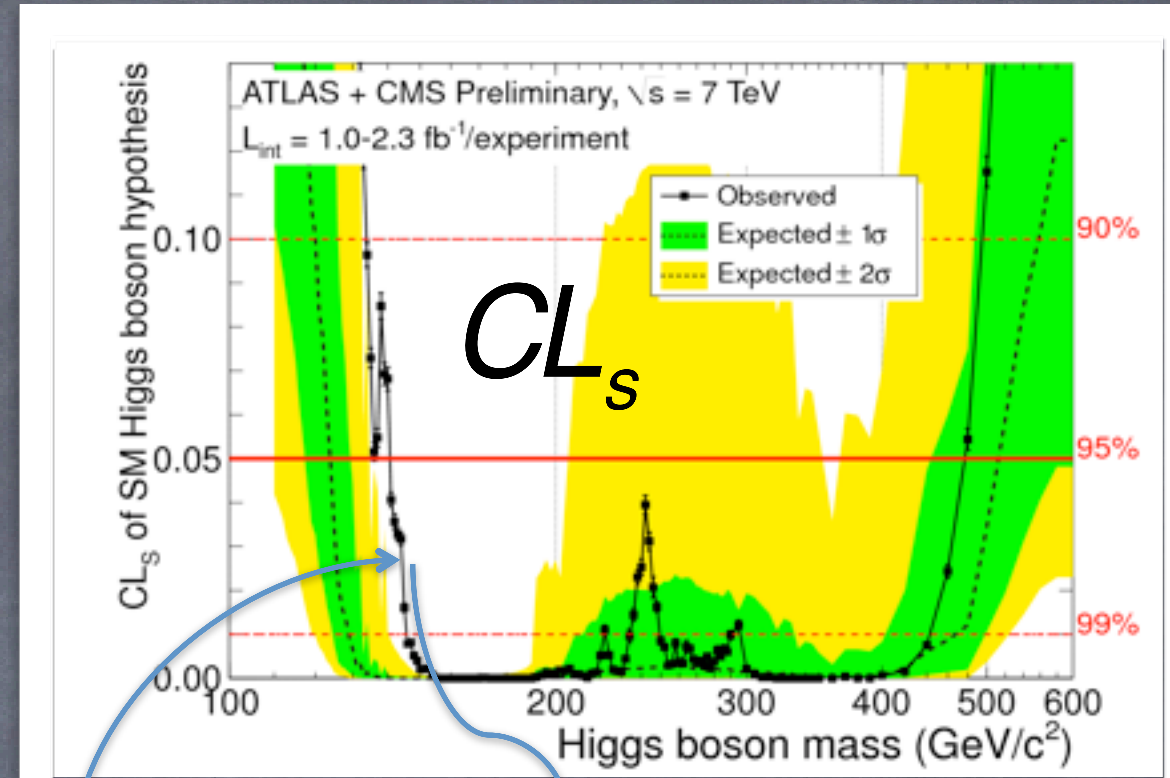
$$\mu = \frac{\sigma}{\sigma_{SM}}$$



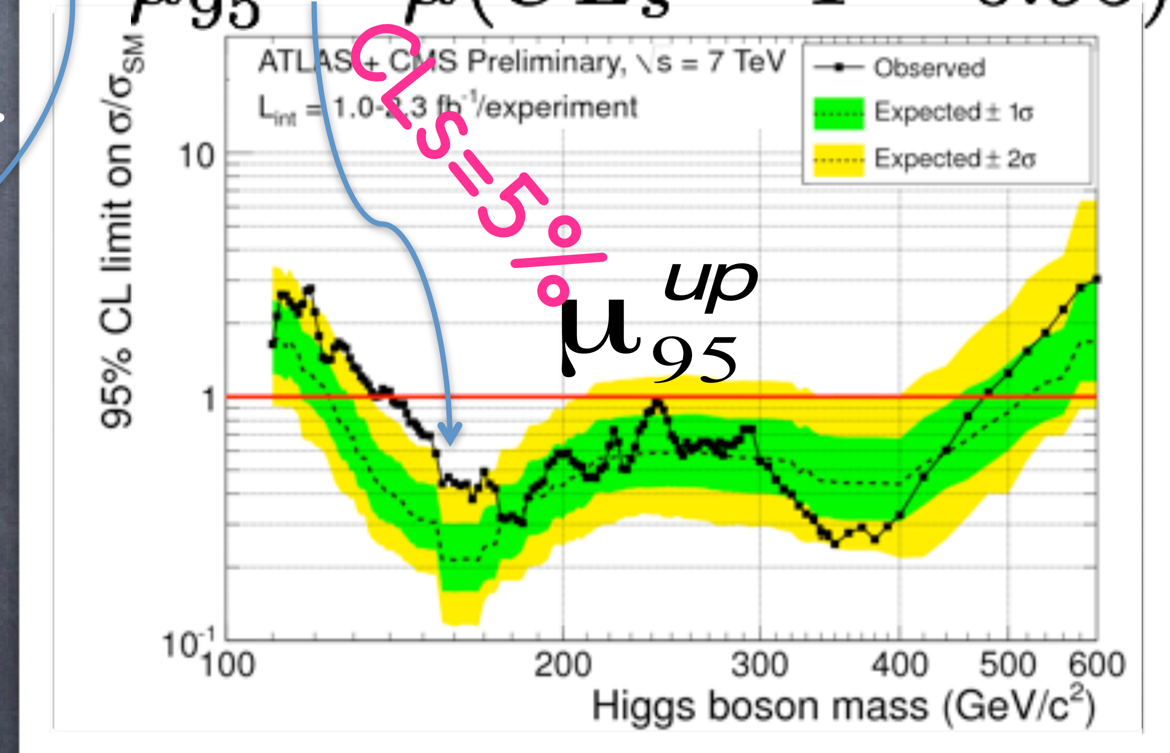
Profile likelihood ratio: CL_s and μ^{up}_{95}



$\mu_{test}=1$



$$\mu^{up}_{95} = \mu(CL_s = 1 - 0.95)$$

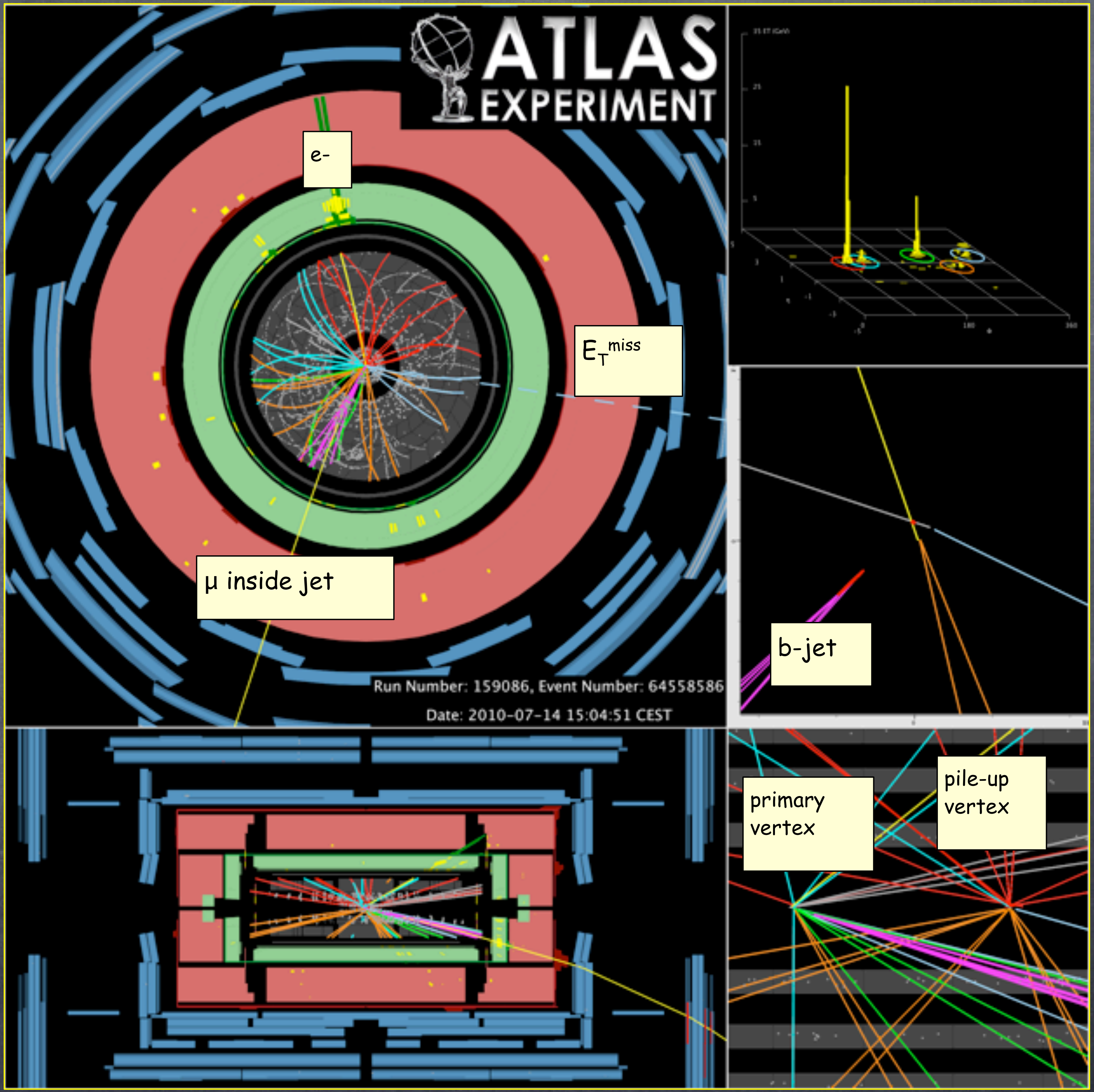


p_μ : test signal+background → CL_s : ~test signal


SUX 1

Physics Analysis Objects

- Higgs searches require detailed understanding of all of the Physics objects:
  - electrons,
  - muons,
  - light-quarks (jets),
  - heavy flavours (charm, bottom-jets),
  - missing energy (E_T^{miss})



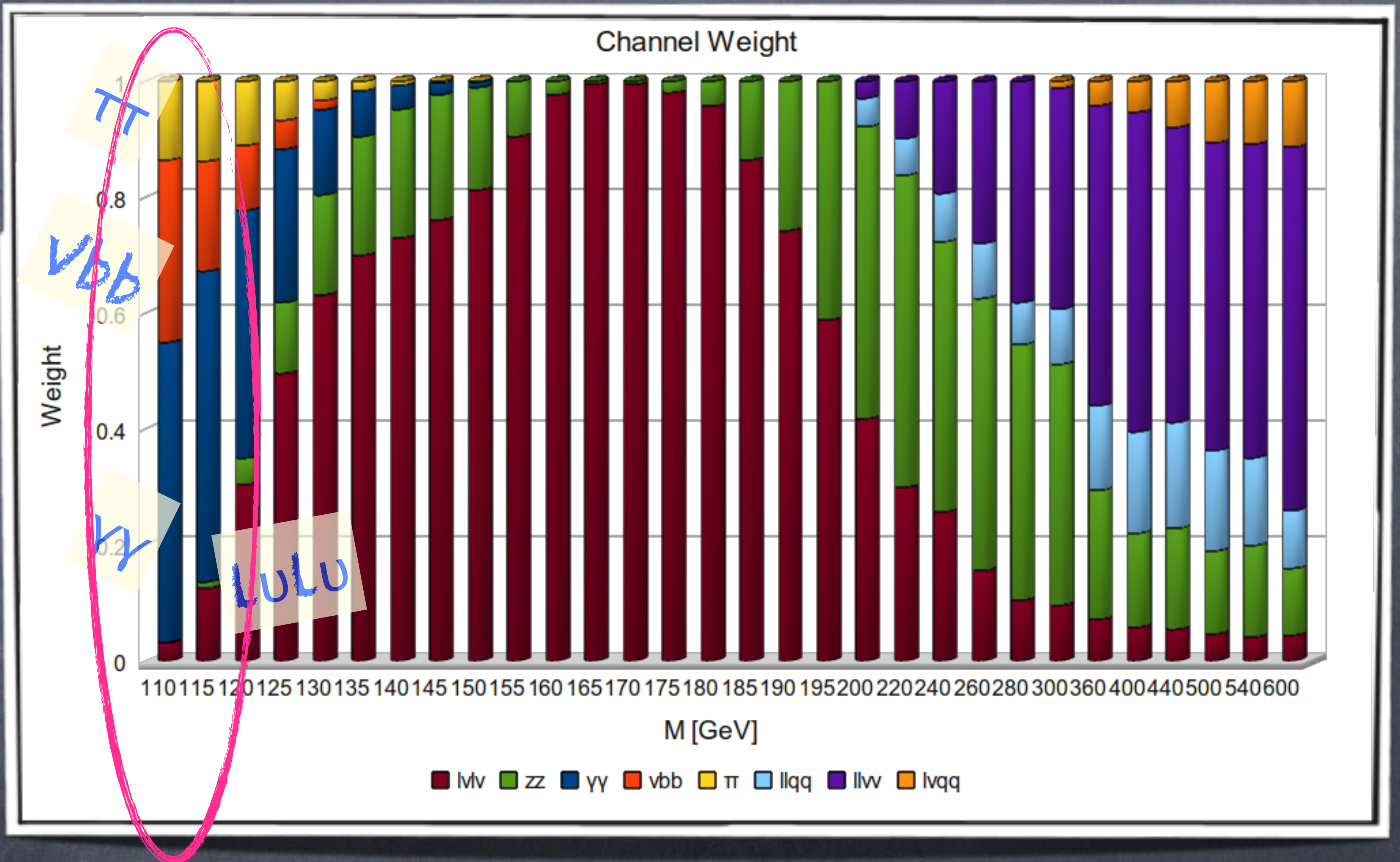
Probing low mass & the LEP Edge

- Probing 114-140 GeV
- Probing channels:

H->γγ

VH-> Vbb,

H-> ττ



H->$\gamma\gamma$ Probing LEP 114 GeV

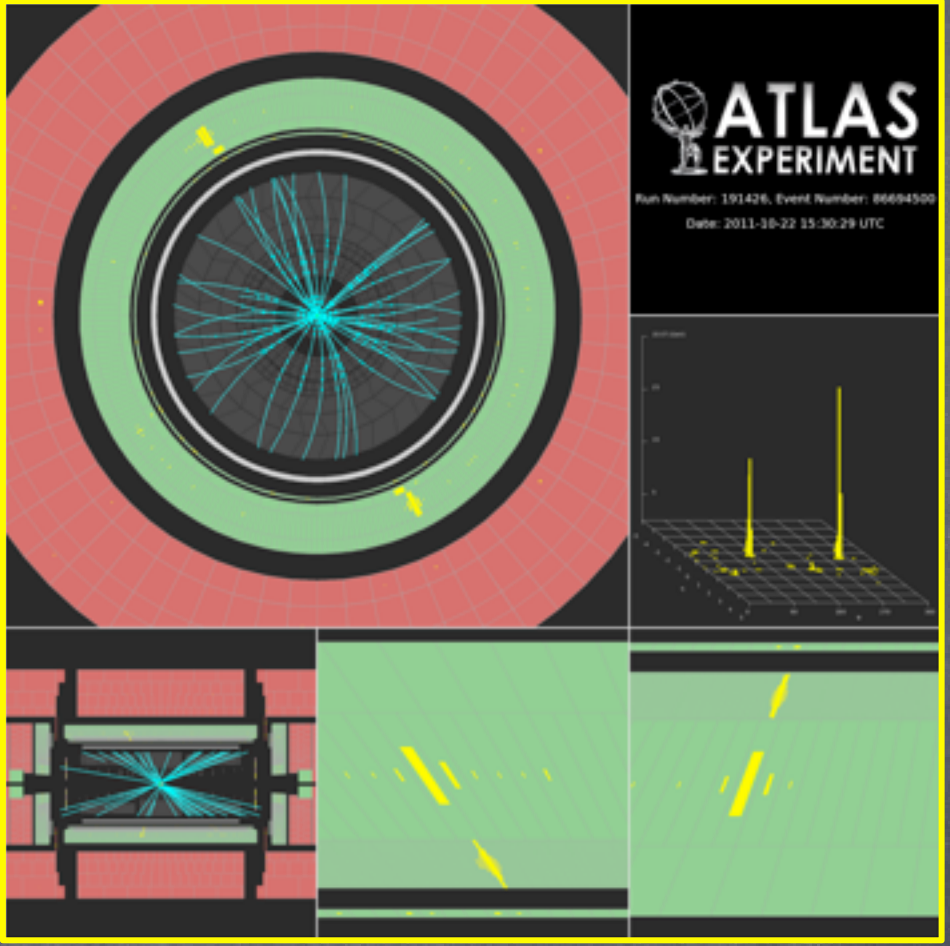
Clean signature: 2 energetic isolated photons->narrow mass peak

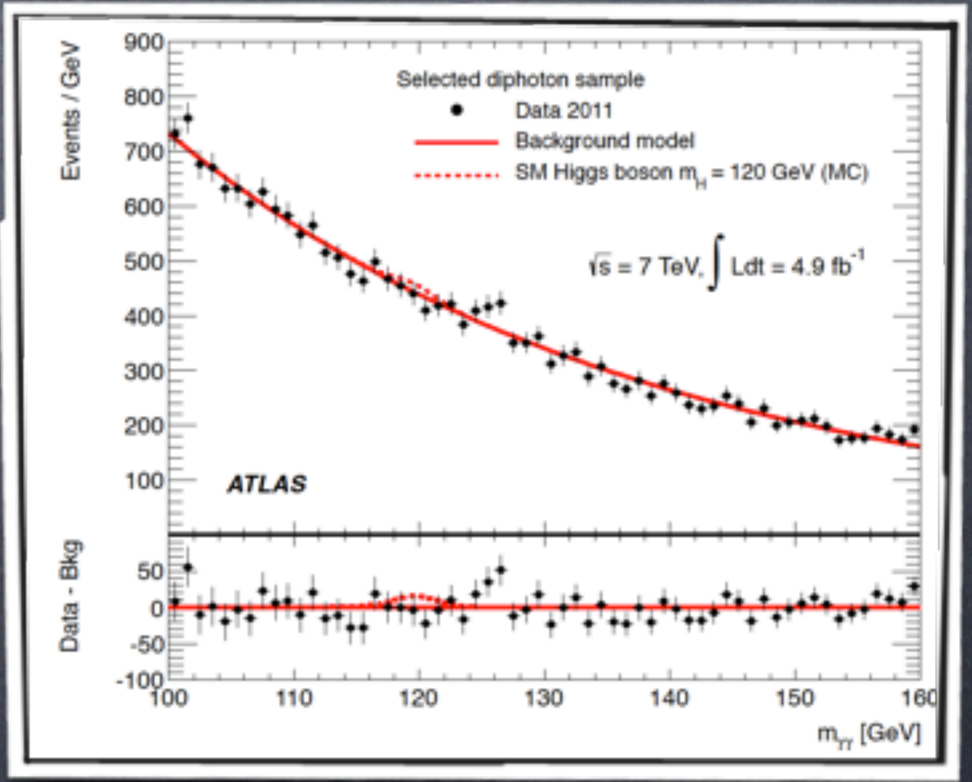
E^T (γ1, γ2) > 40, 25 GeV

A narrow peak is searched for over a large, smooth background.

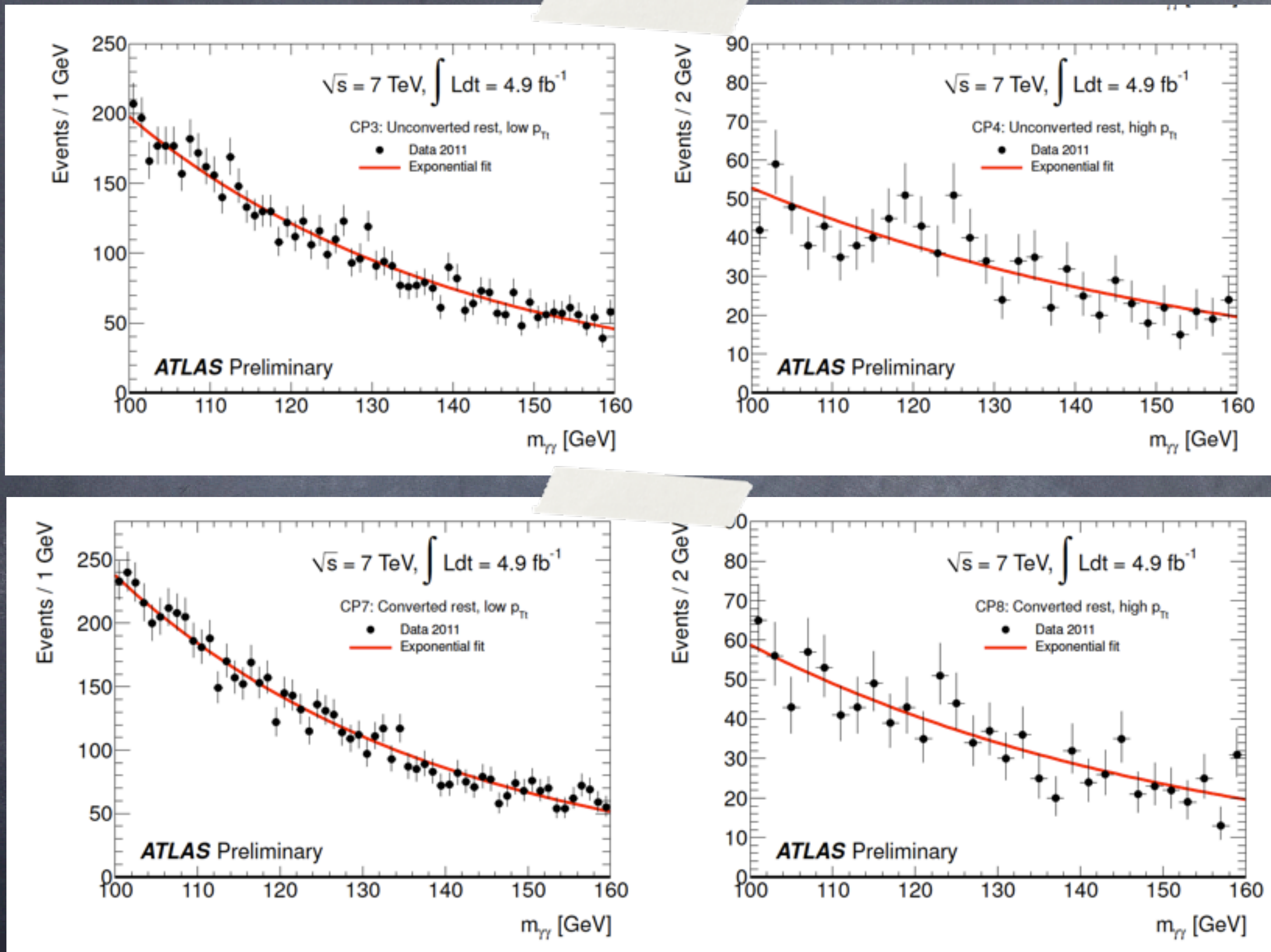
Data are split into categories based on direction of photons (detector region) , conversion mode (which affect $\gamma\gamma$ mass resolution, which is excellent) and $p^T_{\gamma\gamma}$ perpendicular to $\gamma\gamma$ thrust axis

A fit is performed to the background side band under the BG only hypothesis (an exponential in EACH category) (only data is considered)





H->γγ Results

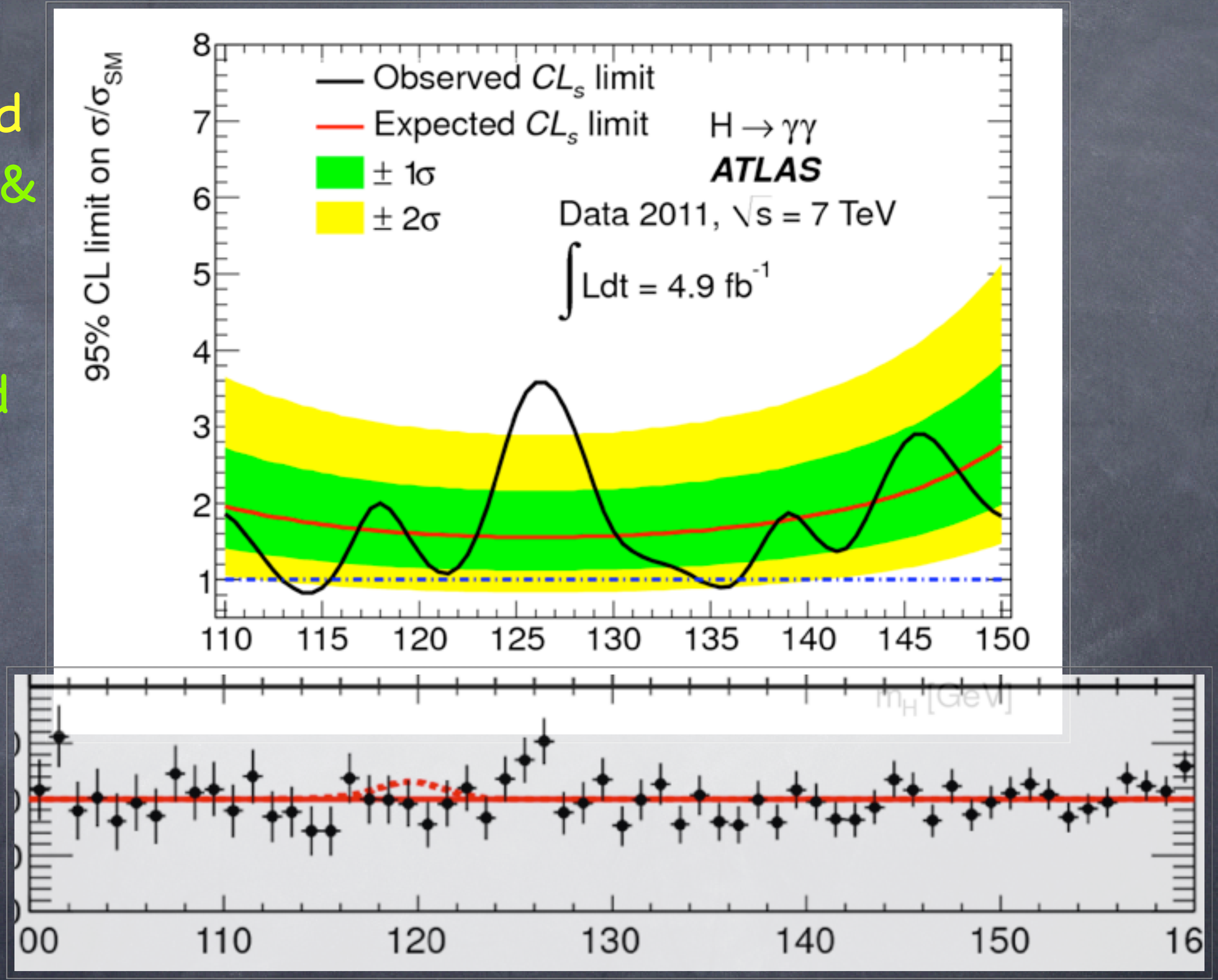


$\sqrt{s}$ = 7 TeV, ∫ Ldt = 4.9 fb^{-1}
CP3: Unconverted rest, low p_{Tt}
Data 2011
Exponential fit
ATLAS Preliminary
Events / 1 GeV
$m_{\gamma\gamma}$ [GeV]
$\sqrt{s}$ = 7 TeV, ∫ Ldt = 4.9 fb^{-1}
CP4: Unconverted rest, high p_{Tt}
Data 2011
Exponential fit
ATLAS Preliminary
Events / 2 GeV
$m_{\gamma\gamma}$ [GeV]
$\sqrt{s}$ = 7 TeV, ∫ Ldt = 4.9 fb^{-1}
CP7: Converted rest, low p_{Tt}
Data 2011
Exponential fit
ATLAS Preliminary
Events / 1 GeV
$m_{\gamma\gamma}$ [GeV]
$\sqrt{s}$ = 7 TeV, ∫ Ldt = 4.9 fb^{-1}
CP8: Converted rest, high p_{Tt}
Data 2011
Exponential fit
ATLAS Preliminary
Events / 2 GeV
$m_{\gamma\gamma}$ [GeV]

H->γγ ATLAS Results

A SM Higgs Boson is excludd @ 113-115 GeV & 134.5-136 GeV due to a large downward fluctuation

Unable to exclude a Higgs Boson all over, in particular around 122-130 GeV



A nano statistical interlude II

Understanding p0 and the LEE (Look Elsewhere Effect)

Discovery: p_0

$$\mu = \frac{\sigma}{\sigma_{SM}(m_H)}$$

$$q_0 = -2\log\frac{max_{\{b\}}L(b)}{max_{\{\mu,b\}}L(\mu s(m_H)+b)} = -2\log\frac{L(\hat{b}_0)}{L(\hat{\mu}s(m_H)+\hat{b})}$$

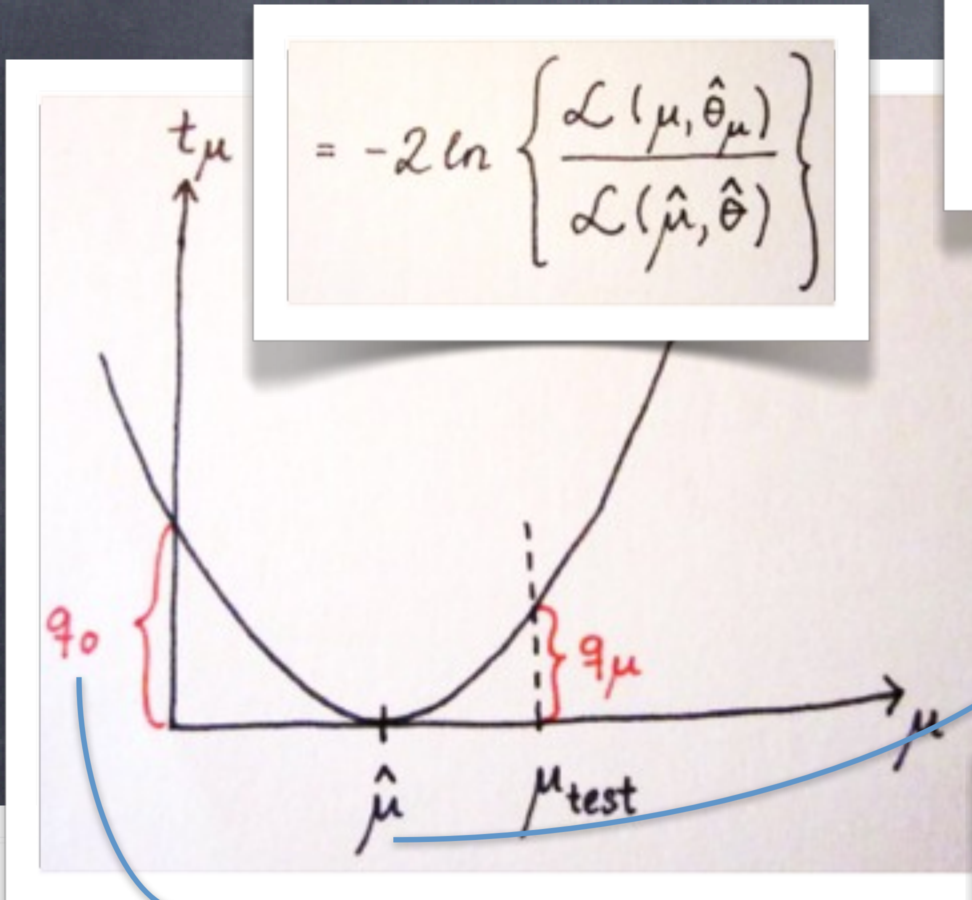
->p_0 measures the compatibility of the data with the NO-HIGGS hypothesis.

->If p_0=0.025 the NO-HIGGS hypothesis is rejected at the 2σ level

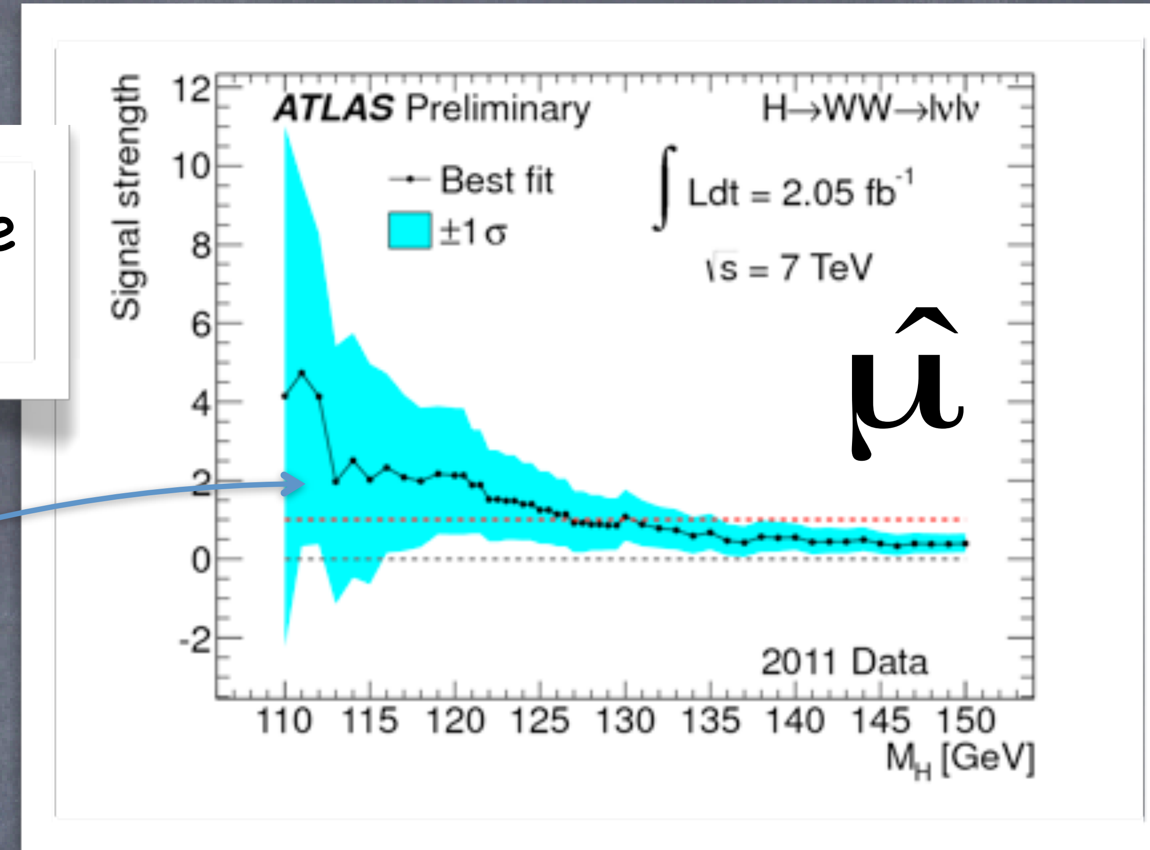
$$p_0 = Prob(q_0 > q_0^{obs} \mid H_0)$$

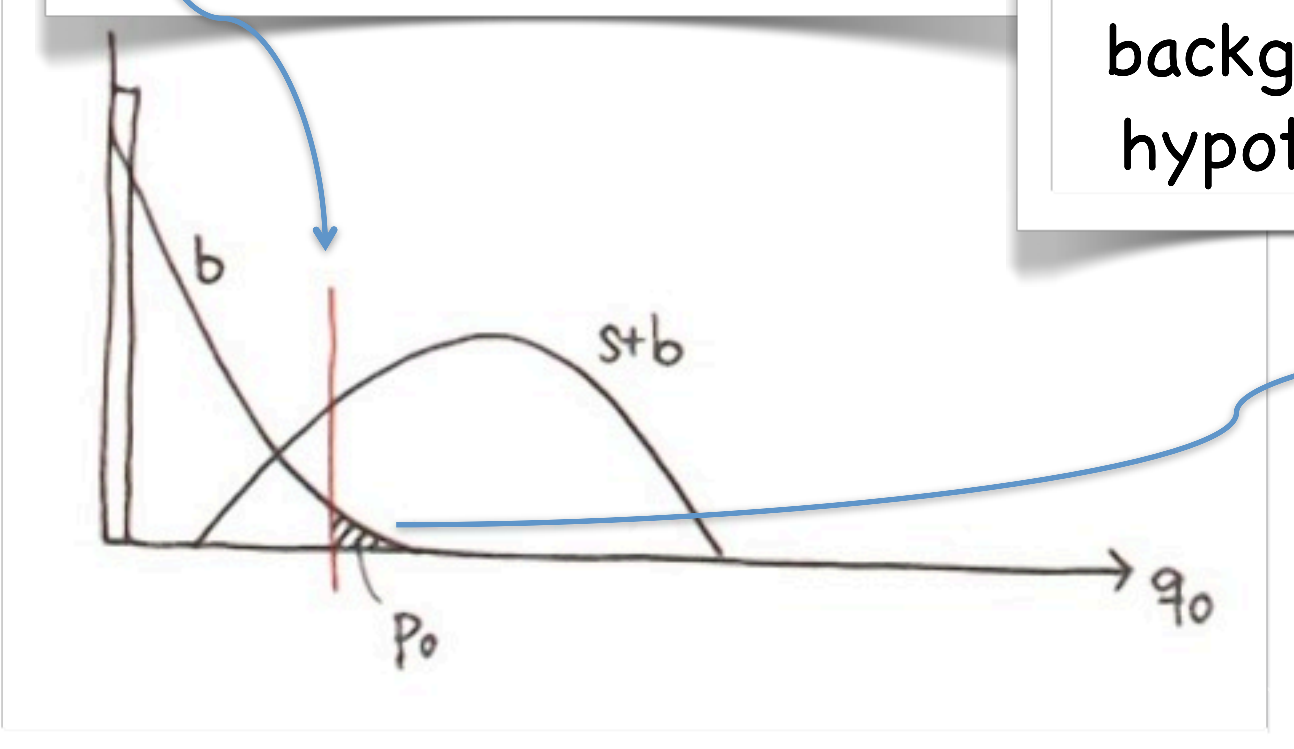
Profile likelihood ratio: p_0 and $\hat{\mu}$

LHCHCG Combination Procedures

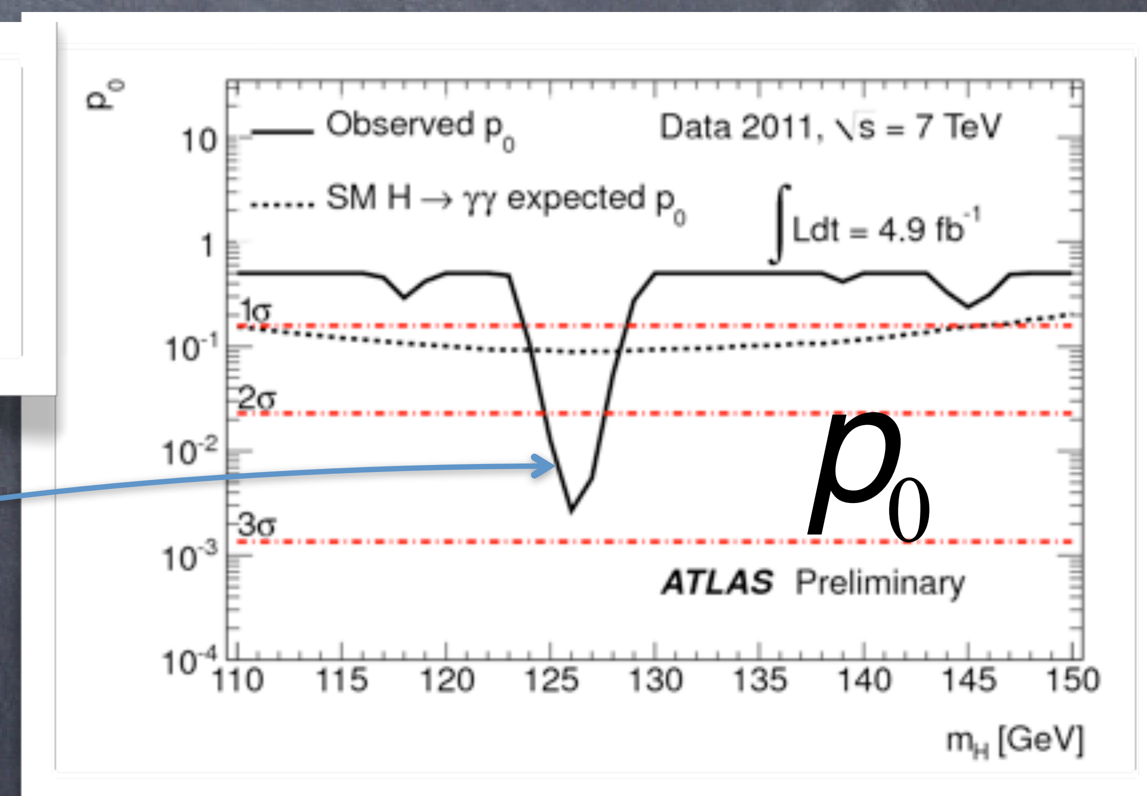


$\hat{\mu}$ to estimate signal strength





p_0 to test background hypothesis



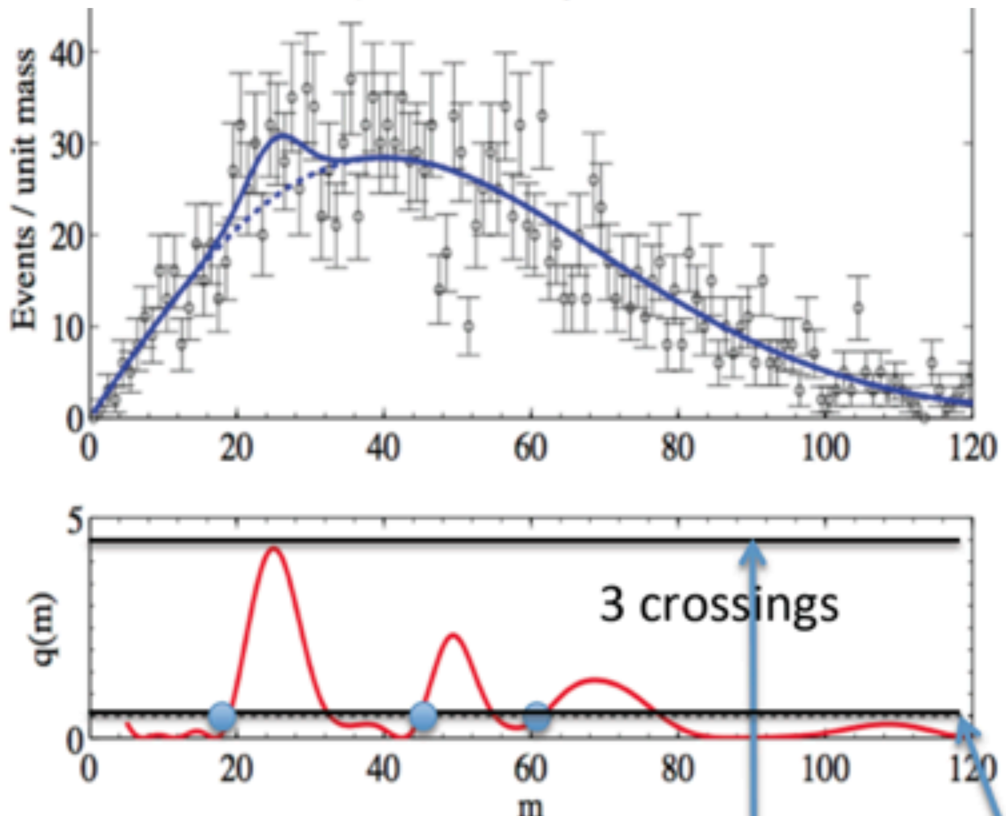
Discovery: Look Elsewhere Effect

- What is the probability to see such an excess (or more) ANYWHERE in the search mass range

$$p_{global} = p_{local} + N_0 e^{-Z_{max}^2/2}$$

- arXiv 1005.1892

E. Gross and O. Vitells, "Trial factors for the look elsewhere effect in high energy physics", *The European Physical Journal C - Particles and Fields* **70** (2010) 525–530.



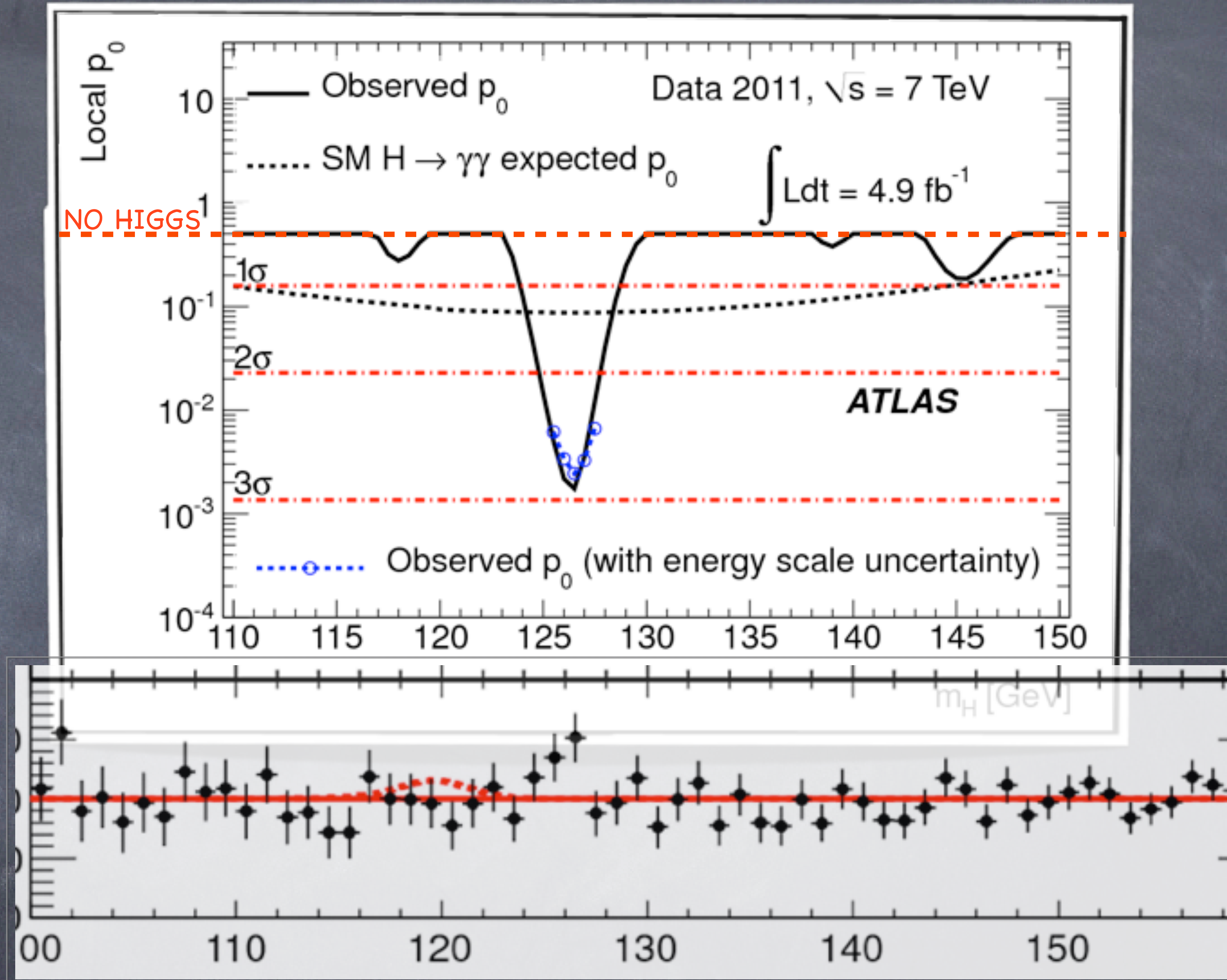
- Example:
  - q_{test} = 4.5 (2.1σ)
  - 3 crossings at 0.5σ
  - significance reduced to about 0.3σ
  - trials factor about 22

Local σ	Crossings	σ ref.	Trials factor	Global σ
3.5	3	1.0	47	2.3
5.0	3	2.0	290	3.8
7.0	3	2.0	400	6.1

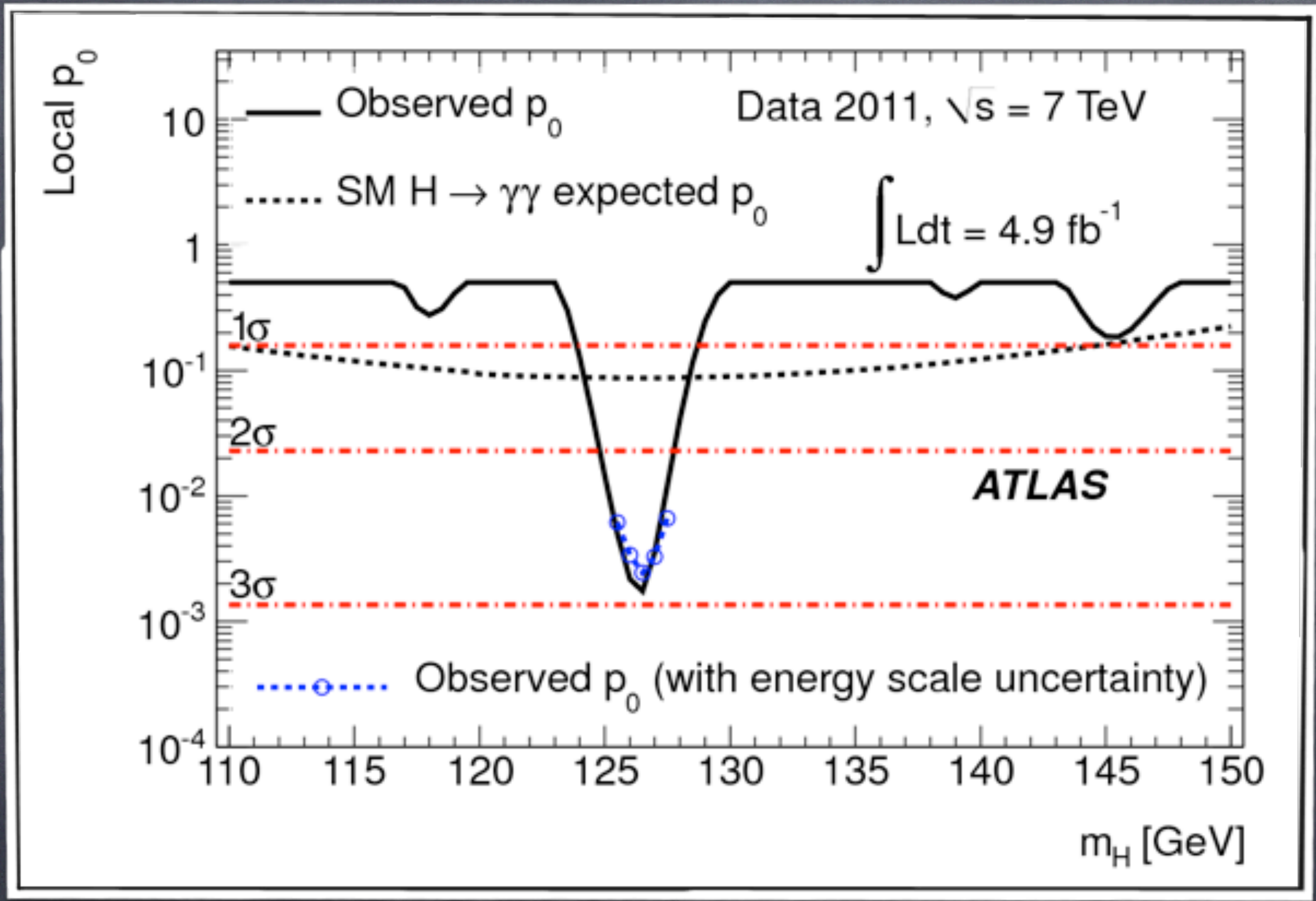
$$p_0^{global} \cong p_0^{local} + \langle N(q_{ref}) \rangle \, e^{-(q_{test}-q_{ref})/2}$$

$H\rightarrow\gamma\gamma$ ATLAS p_0 results

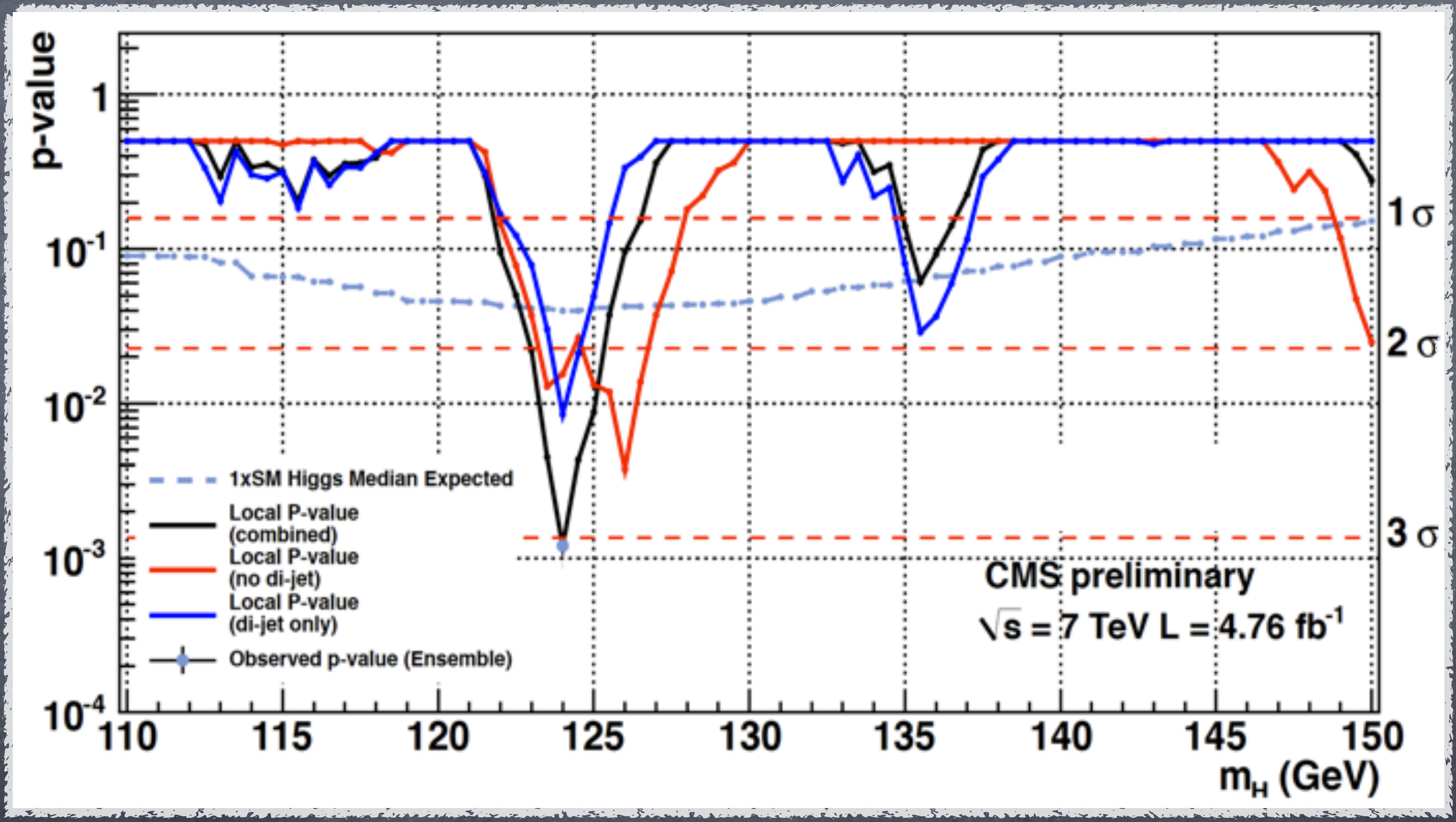
- ATLAS observes an excess of events with a maximum deviation from the background only expectation at 126.5 GeV.
- The significance of this excess is 2.8σ
- The significance to observe such an excess anywhere in the search mass range is reduced to 1.5σ



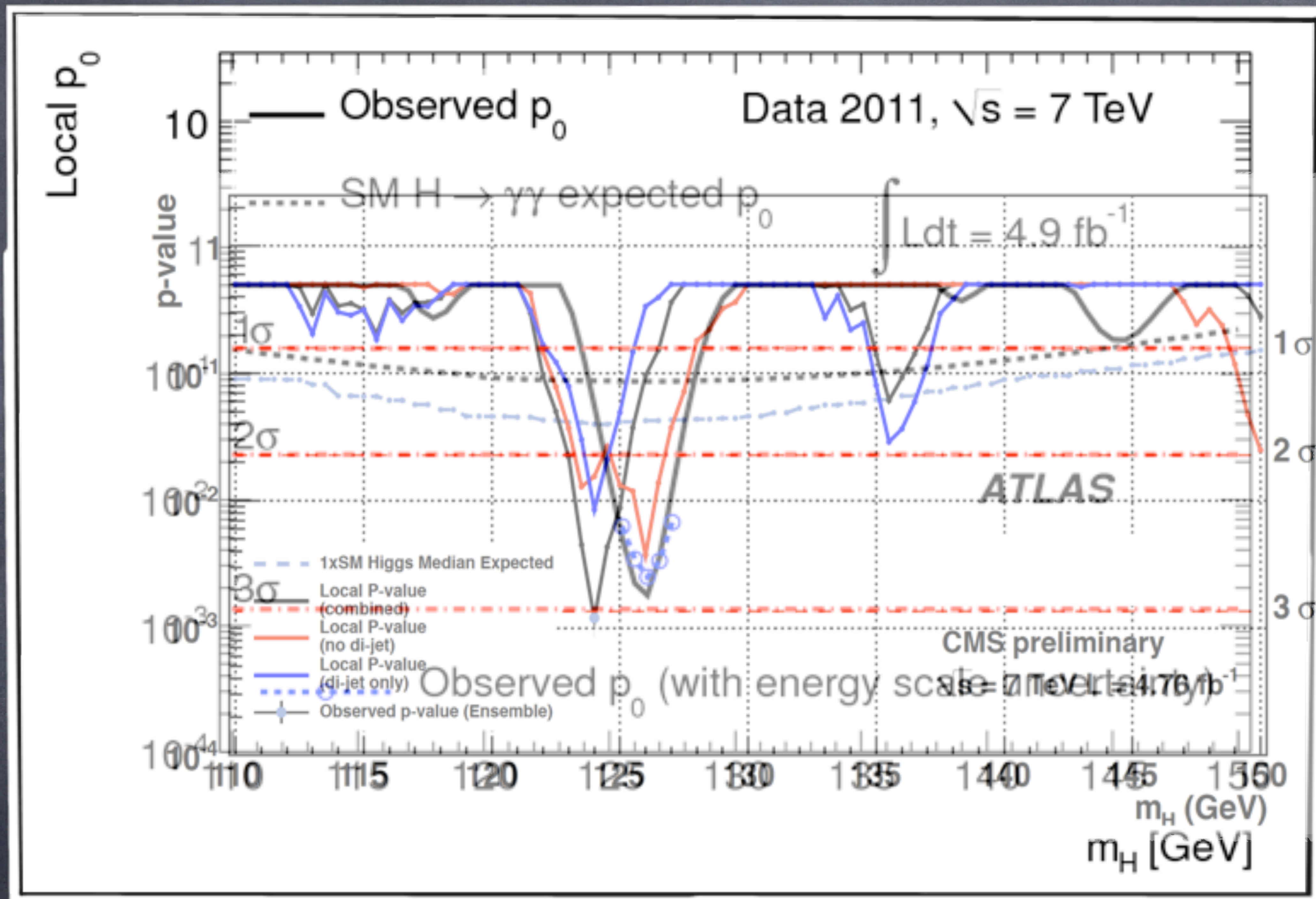
H->γγ ATLAS vs CMS p_0 results



H->γγ ATLAS vs CMS p_0 results



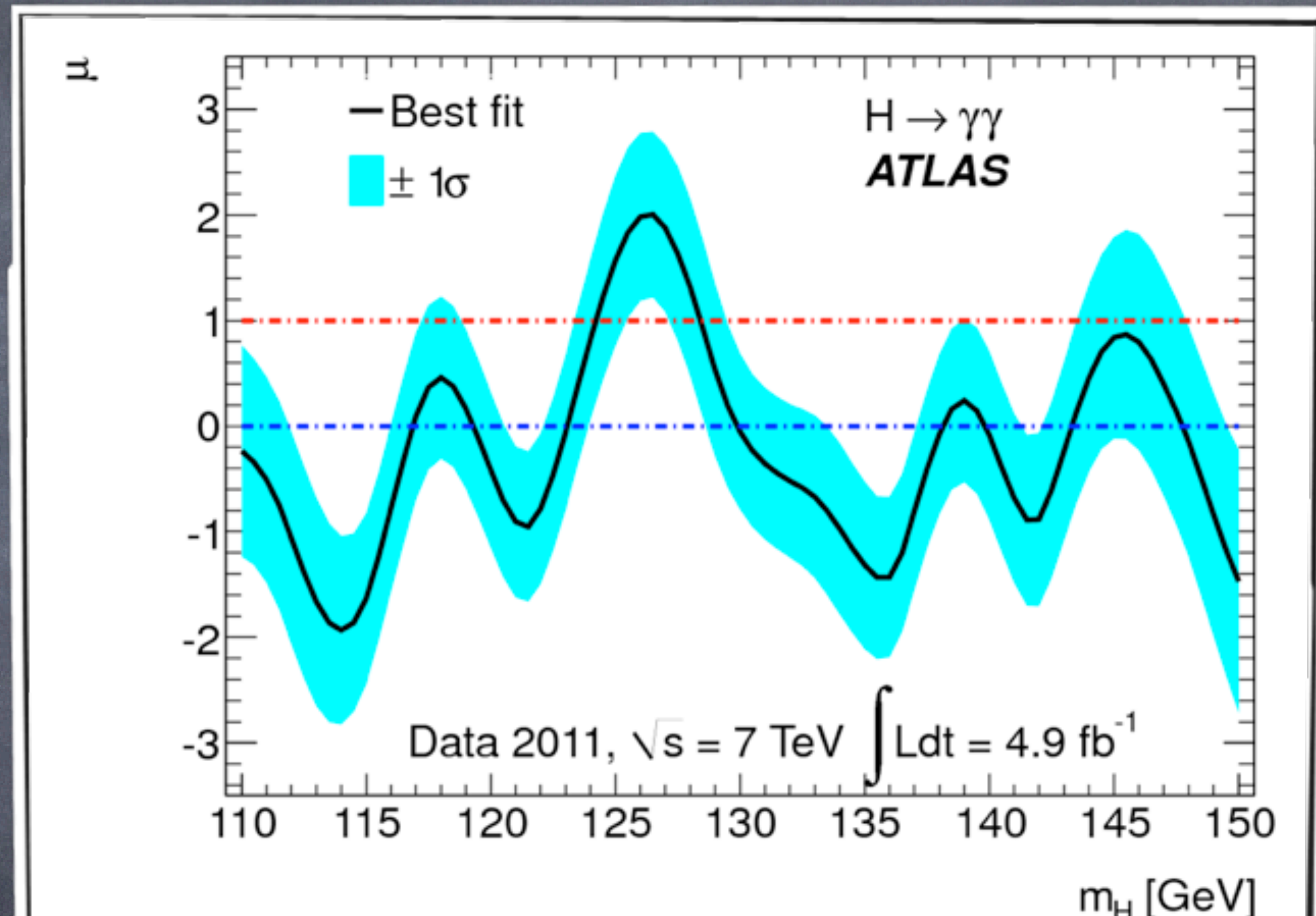
H->γγ ATLAS vs CMS p_0 results



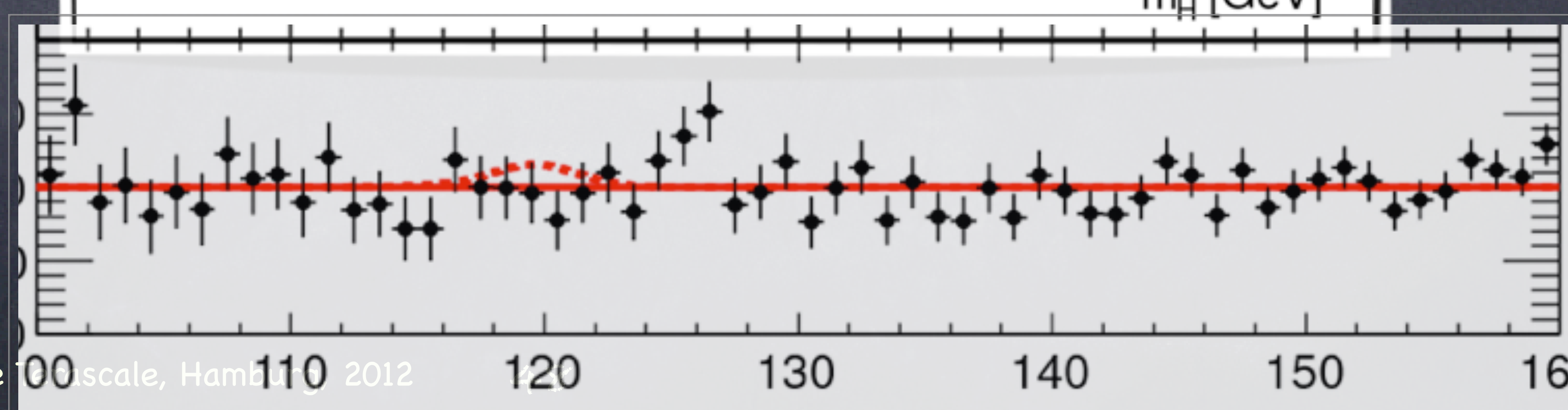
$\mu = \sigma / \sigma SM$

Signal Strength Fit

$$\hat{\mu} = \left\{ \mu \middle| L\left(\mu s(m_H) + b\right) = \max L(\mu, b) \right\}$$

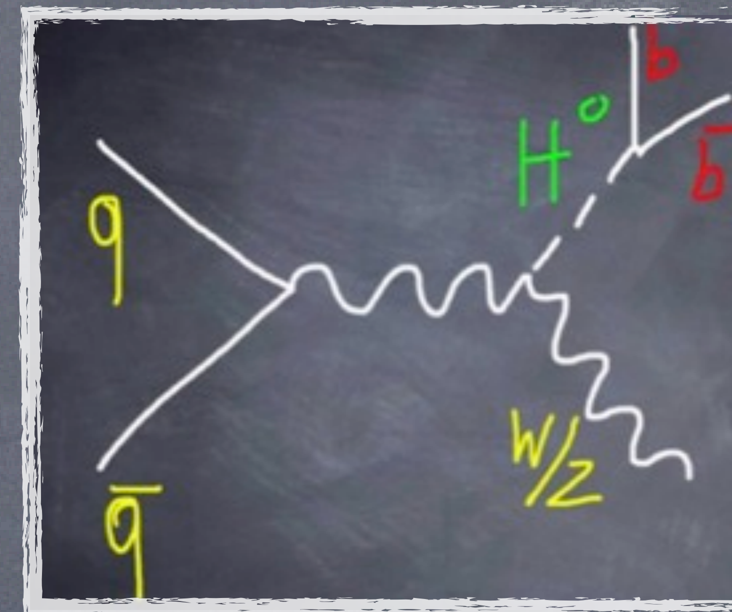


- For a SM Higgs ATLAS sees an excess of ~1.5σ

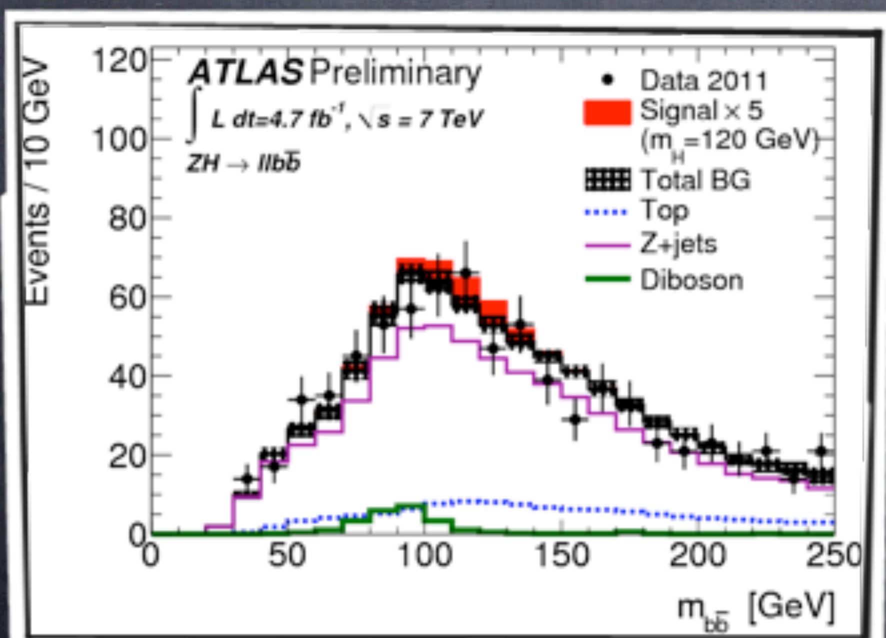


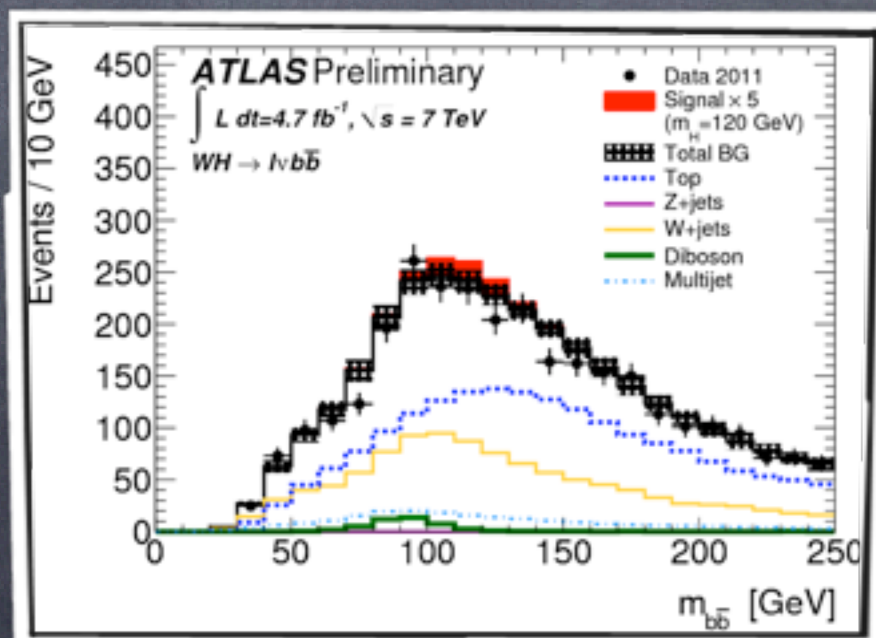
Probing Deeper: W/ZH->W/Zbb

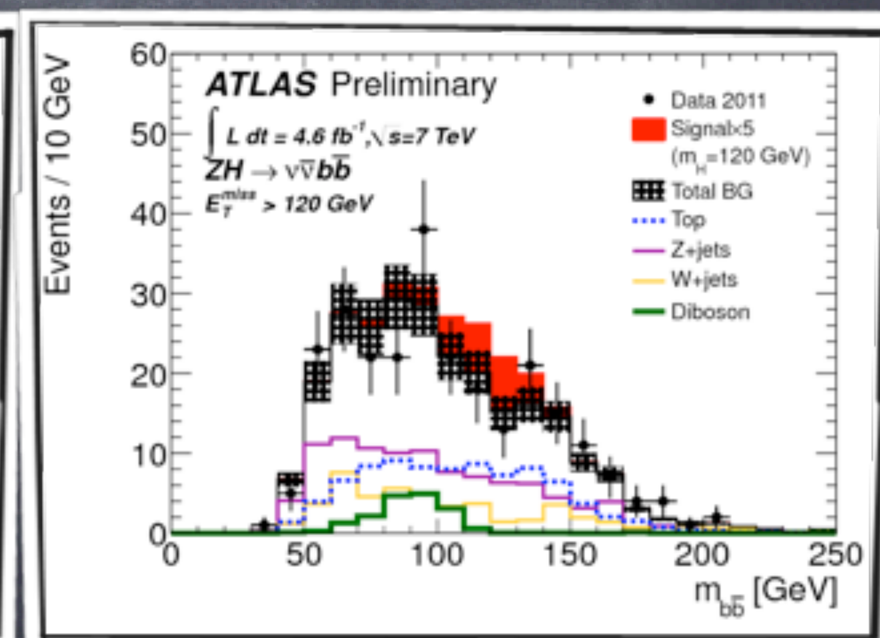
- H->bb is the dominant decay of a low mass Higgs.
  It also extremely important to measure Higgs couplings.
- Multi-jet background kills its inclusive production (though there are hopes with boosted Higgs and jets substructure)
- W/ZH is feasible for low Higgs mass channels: lυbb,llbb and υυbb



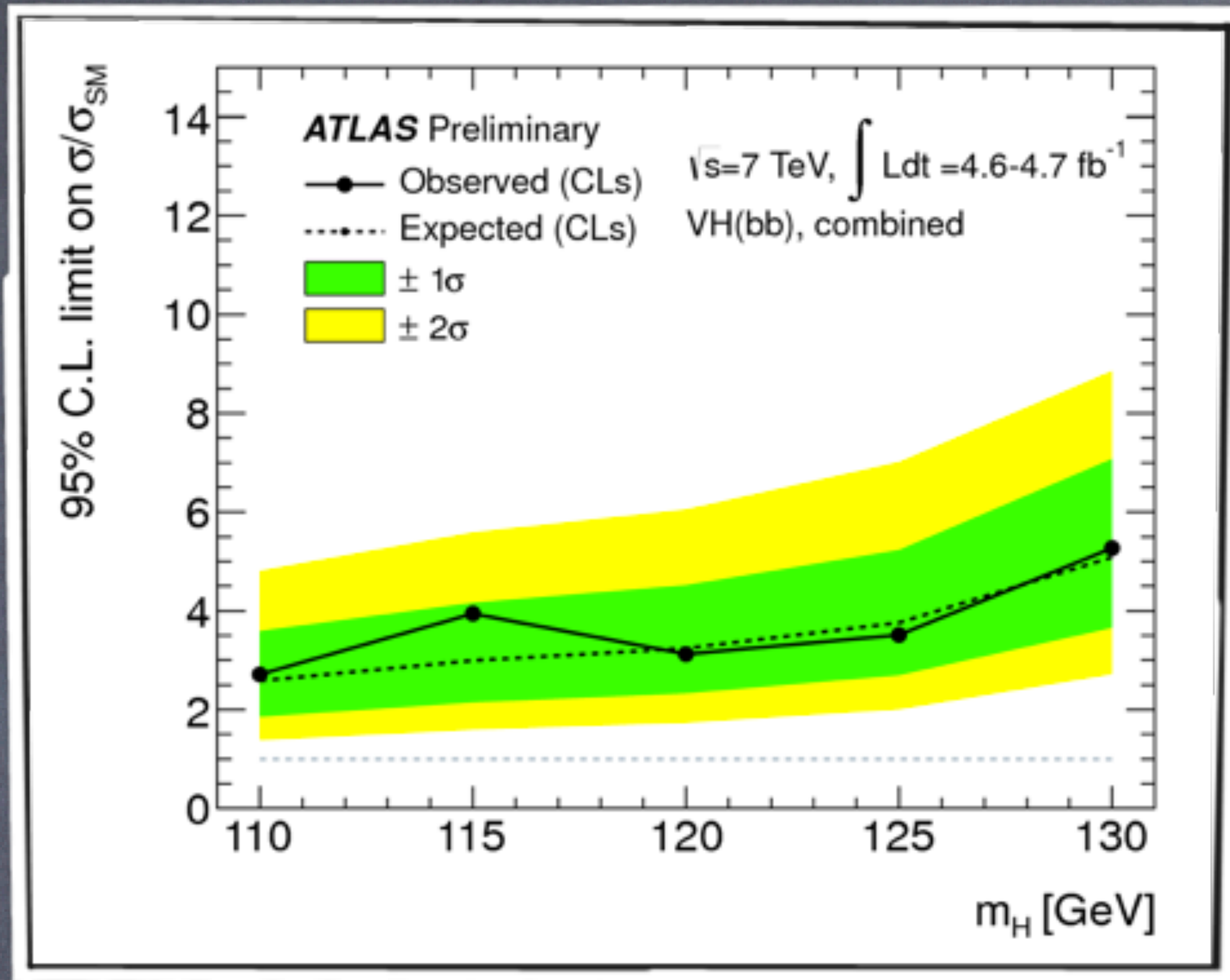
- Signature : lepton,MET and b-tag
  (exactly two b-tag jets with E_Tb>45,25 GeV)
- Analysis is performed in p_{TW} (lvH), p_{TZ} (llH) and E_T^{miss} (vvH) , total of 4+4+3 bins
- m_{bb} as a discriminator, dominant Bacgrounds:
  Z+jets for ZH->llbb W+jets and tt for WH->lvbb Z+jets and tt for ZH->vvbb

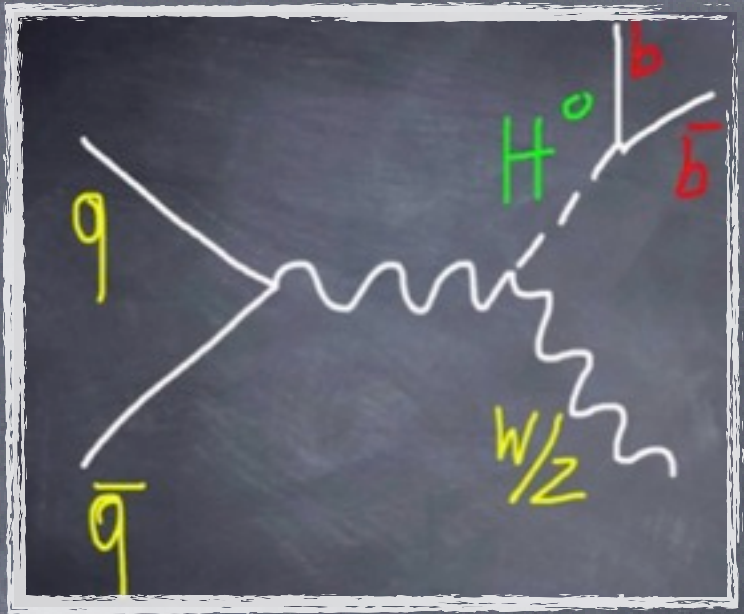






Probing Deeper: W/ZH->W/Zbb





Mass	ZH->llbb		WH->lvbb		ZH->vvbb		Combined	
	obs	exp	obs	exp	obs	exp	obs	exp
125	10.4	8.2	8.0	7.5	5.9	5.6	3.5	3.8

$H\to\tau\tau$

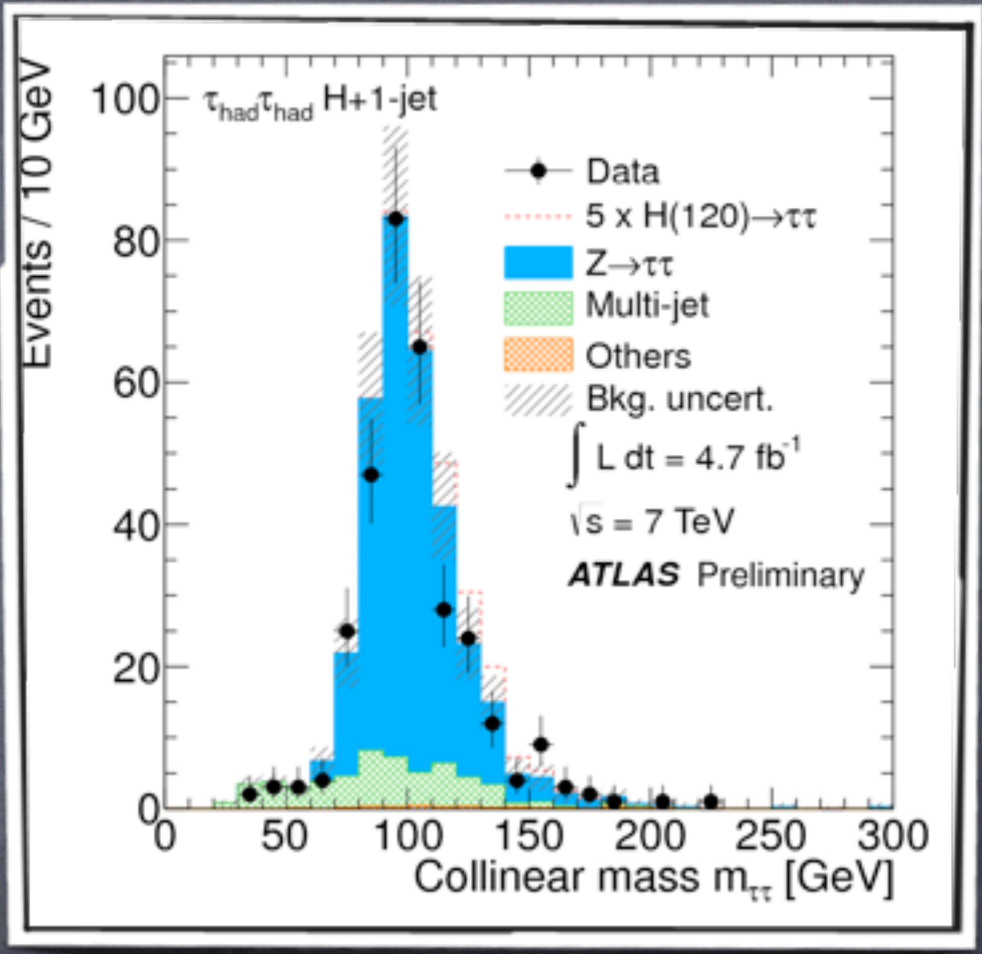
- 3 channels in 12 bins
  (0 jets, 1 jet, 2 jets VBF & VH)

  $H\to\tau_l\tau_l+E_T^{miss}$ in 0 jets (eμ),1 jet, 2jets (VH,VBF)
  $H\to\tau_l\tau_h+E_T^{miss}$ in (l=e,μ)⊗(0 jets (2 E_T^{miss} bins),1-jet)⊕VBF
  $H\to\tau_h\tau_h+E_T^{miss}$ with ≥1 jet

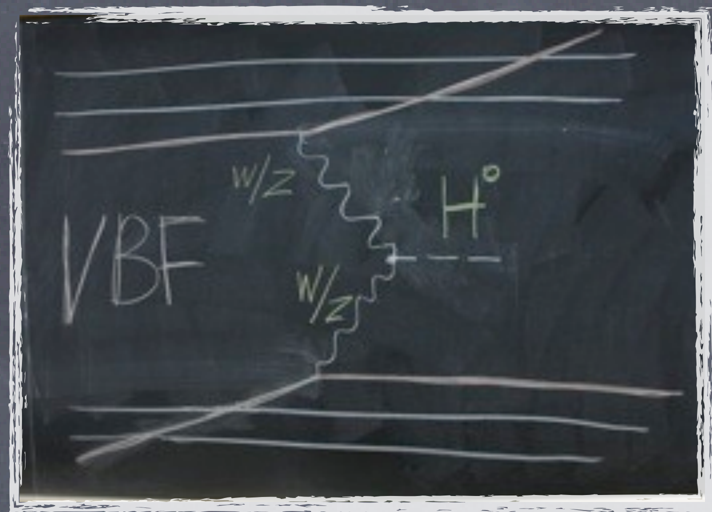
- Discriminator $m_{\tau\tau}$
  (m_{eff}, colinear or MissingMassCalculator)
  Elagin et. al. NIM A654(2011)481

- Main background from $Z\to\tau\tau$, shape via embedding
  ($Z\to\mu\mu$ replacing μ with a τ)

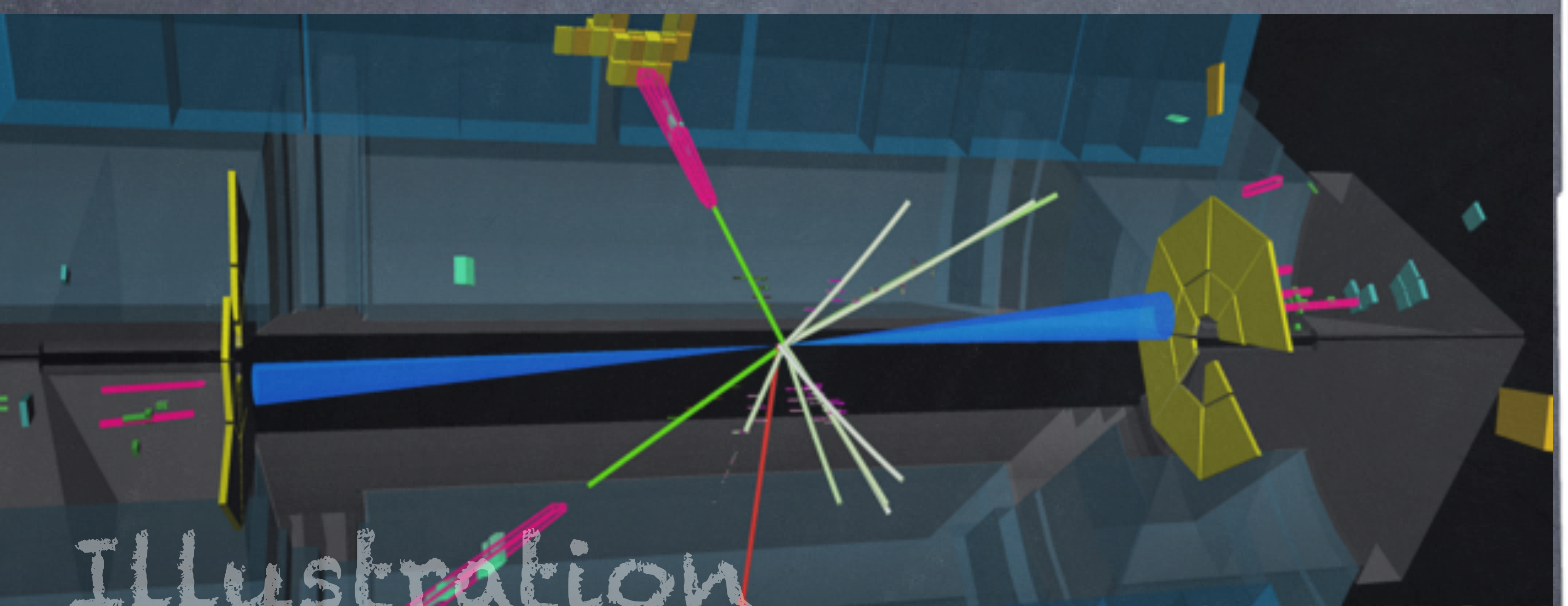
- Fake leptons and τ jets from data with an uncertainty of up to 40%

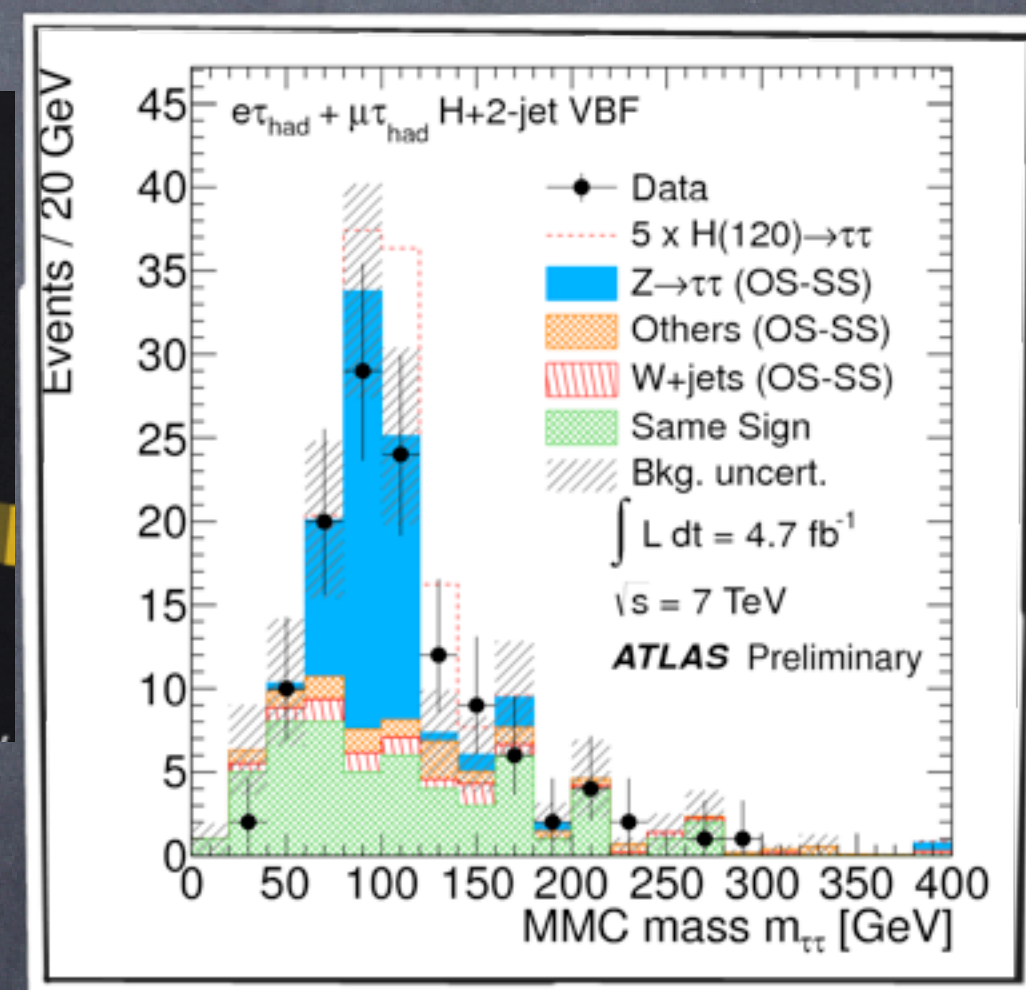


H->ττ



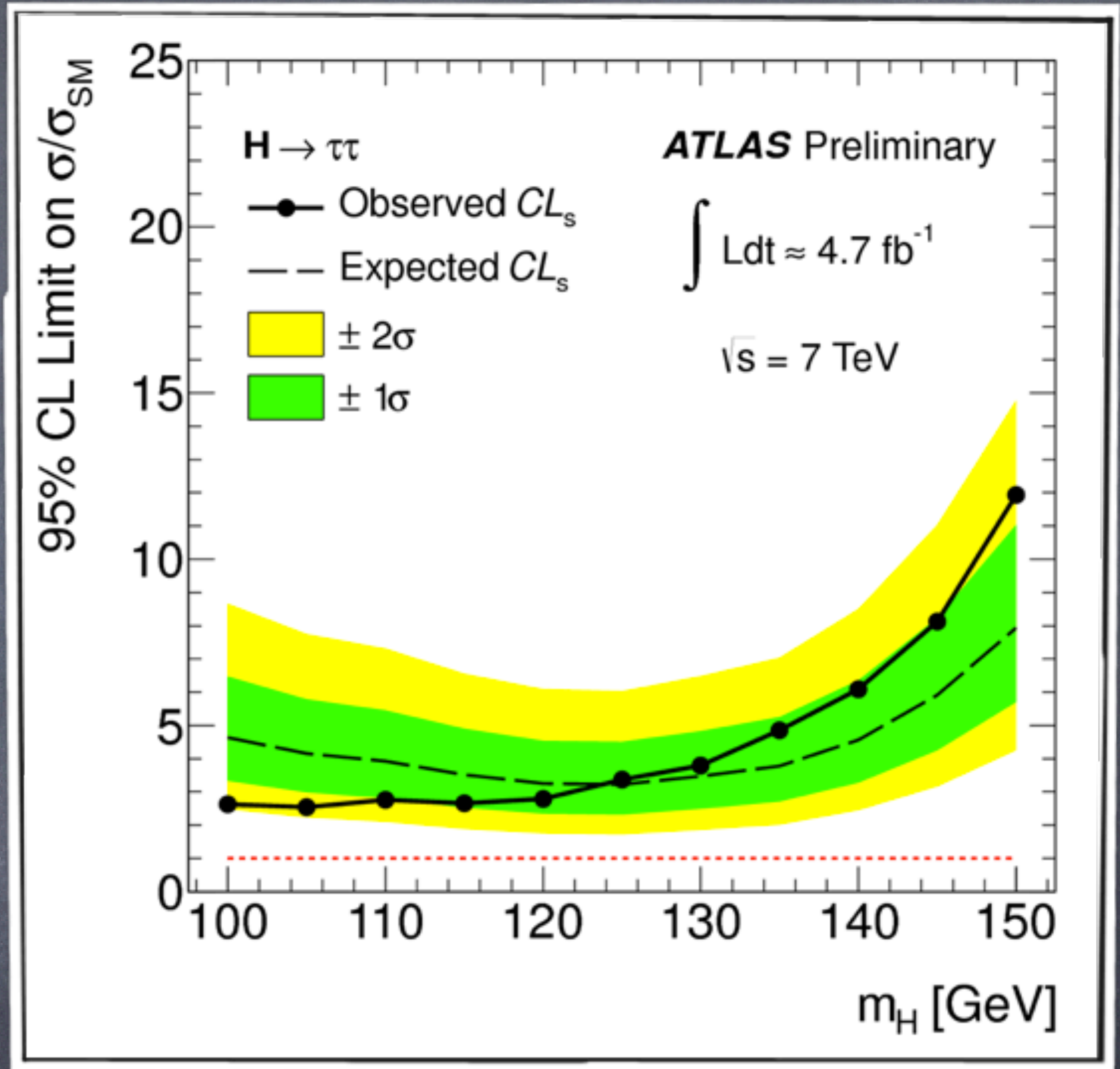
- VBF
  clean and sensitive
- 2 tagged back to back forward jets and two tagged taus





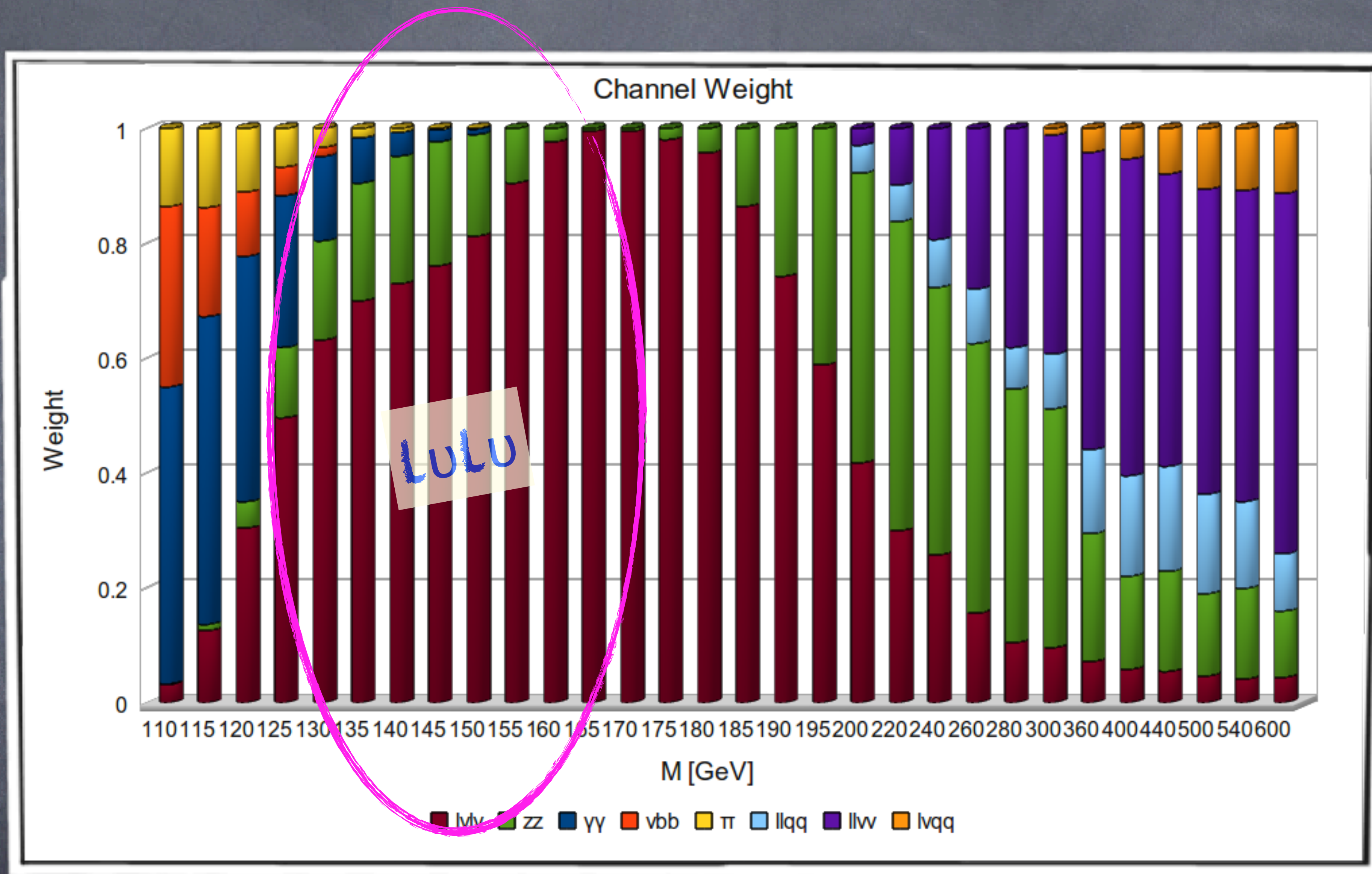
$H \to \tau\tau$

- Expected limit between $\sigma < (3.2\text{–}7.9) \times \sigma_{SM}$
- Most sensitive categories
  H+1j in $\tau_{had}\tau_{had}$,
  and
  2-jet VBF in $\tau_l\tau_l$ and $\tau_l\tau_{had}$
- Observed limit $\sigma < (2.5\text{–}11.9) \times \sigma_{SM}$



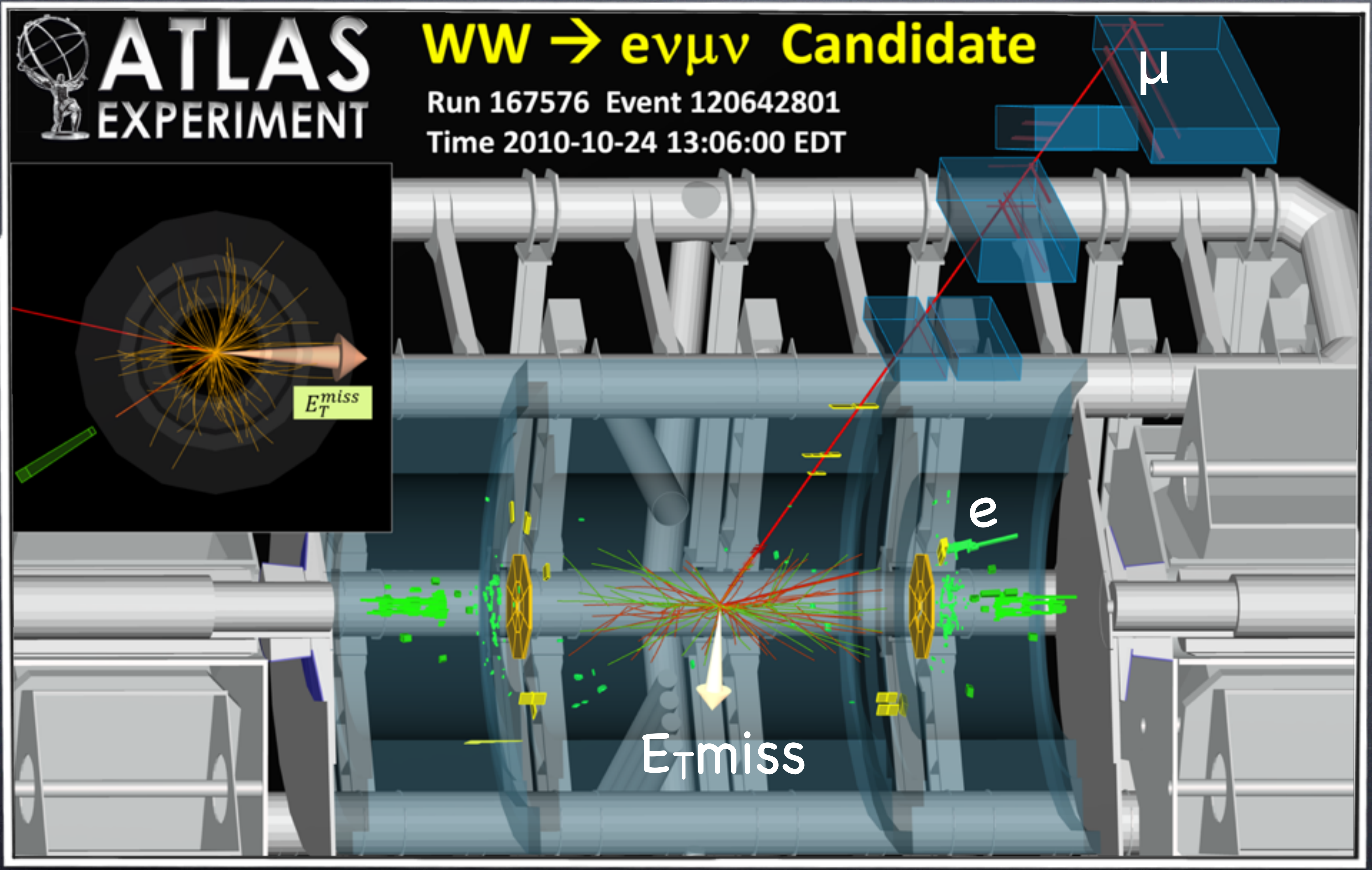
"TEVATRON++" mass region

- "TEVATRON++" mass region 140-200 GeV
- Probing channel: H->WW->lulu



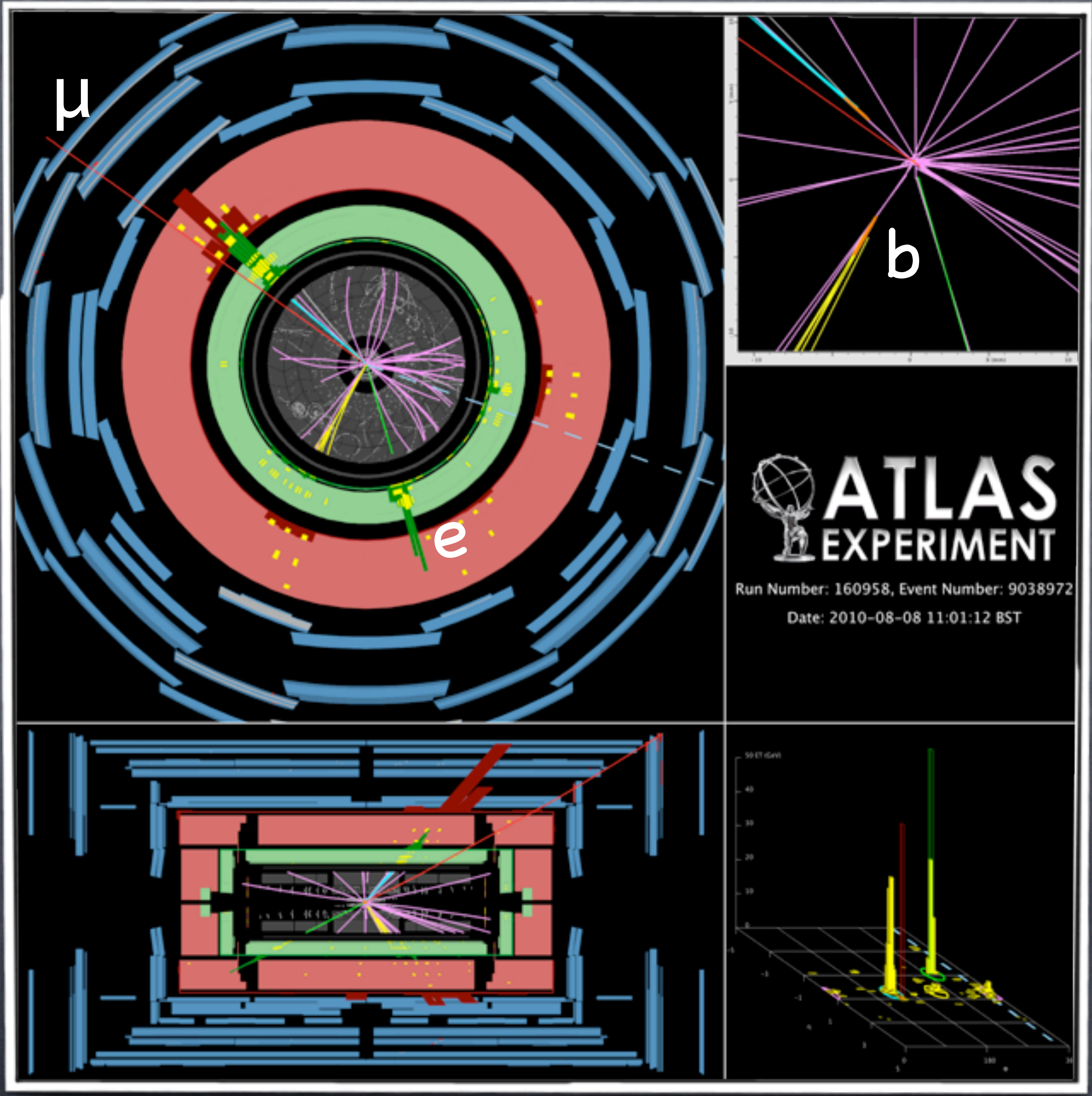
H->WW->lνlν: WW->eμ "Irreducible" BG

- WW can be reduced by exploiting the Higgs spin, require small $\Delta\Phi_{ll}$



H->WW->lνlν: tt->eμ background

Event display of a top pair e-mu dilepton candidate with two b-tagged jets.
The electron is shown by the green track pointing to a calorimeter cluster,
 the muon by the long red track intersecting the muon chambers, and the
missing ET direction by the dotted line on the XY view. The secondary vertices
 of the two b-tagged jets are indicated by the orange ellipses on the zoomed
 vertex region view.



Reject by b-tag veto

H->WW->lνlν

- The cannel is challenging
  2 neutrinos- no mass reconstruction ->mT

- Signature: 2 high p_T opposite sign isolated leptons with large E_T^{miss}->Understanding of E_T^{miss} is crucial

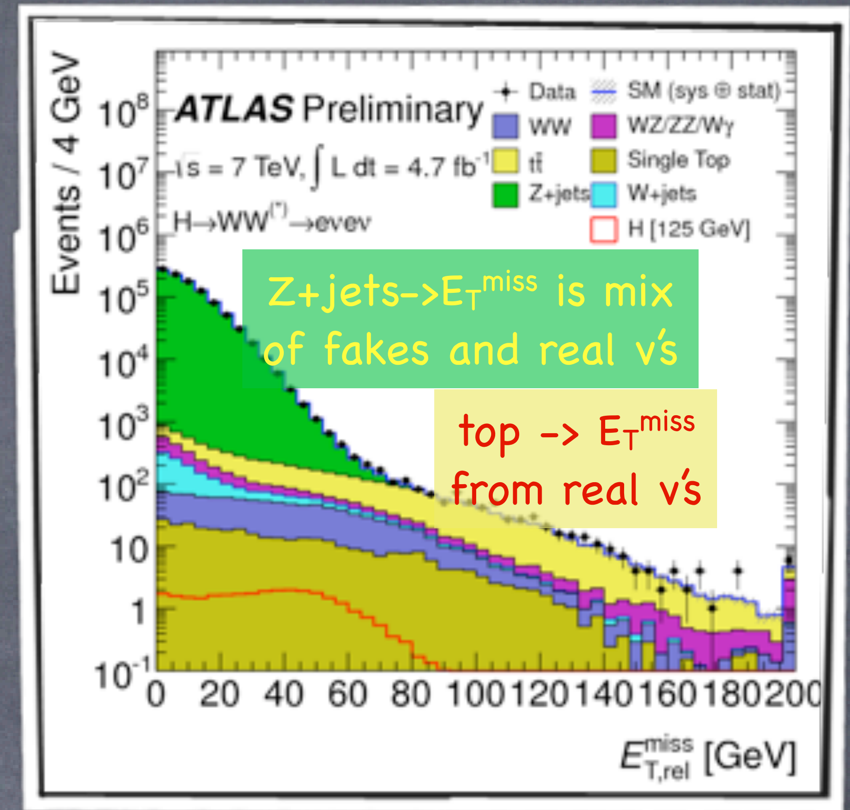
- Main background from WW, top,
  Z+jets, W+jets ->Use of control regions to estimate fakes

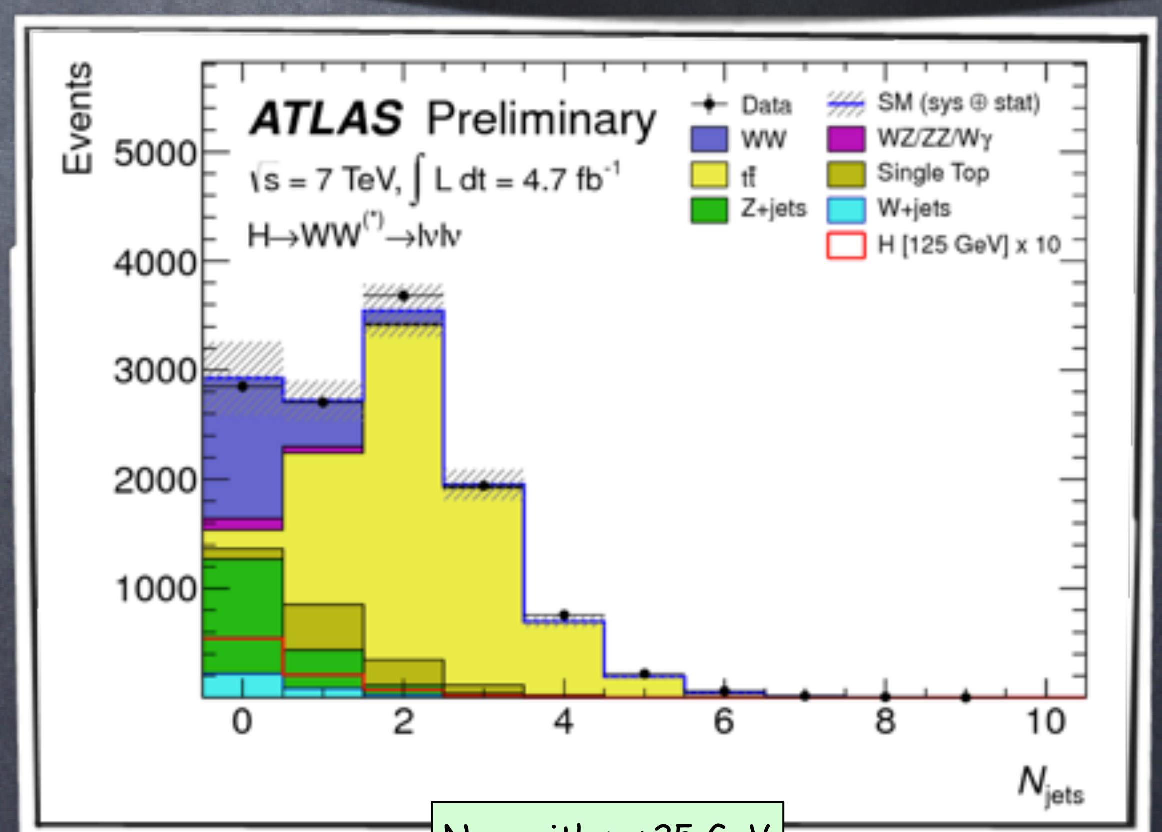
- A control region is defined rich in the measured BG (e.g. WW or top), contaminations are being subtracted and then the BG is extrapolated to the signal region (mostly using MC)
  Example: b-tag is inverted to estimate Top BG

- -> large E_T^{miss}, m_{ll} incompatible with m_Z (DY),
  -> b jet veto (tt),
  ->Topological cuts against irreducible WW ($\Delta\Phi_{ll}$)

- Jet bins: +0j, +1, +2jet (VBF)

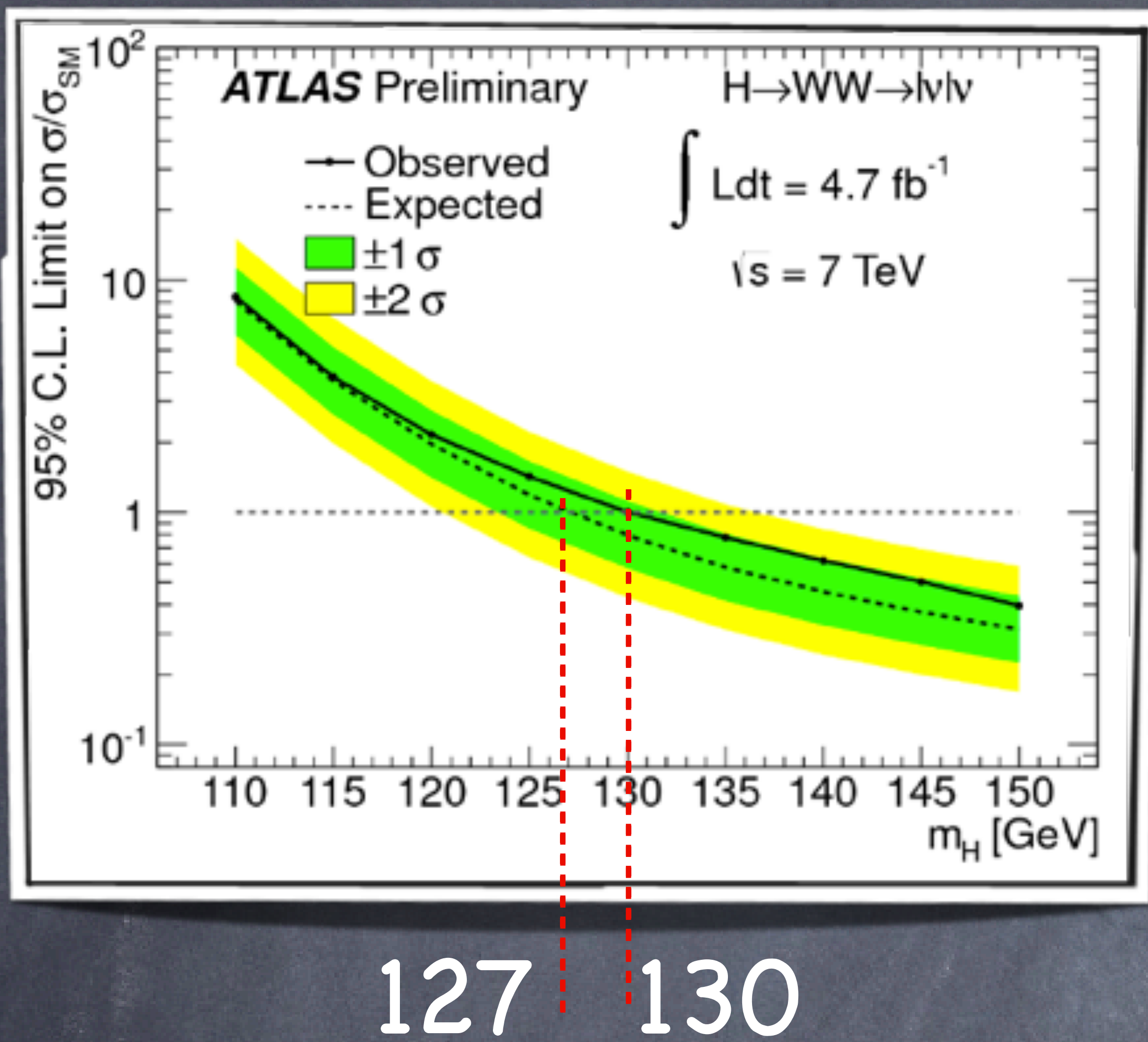
- Discriminating variable $m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 + (p_T^{ll} + p_T^{miss})^2}$

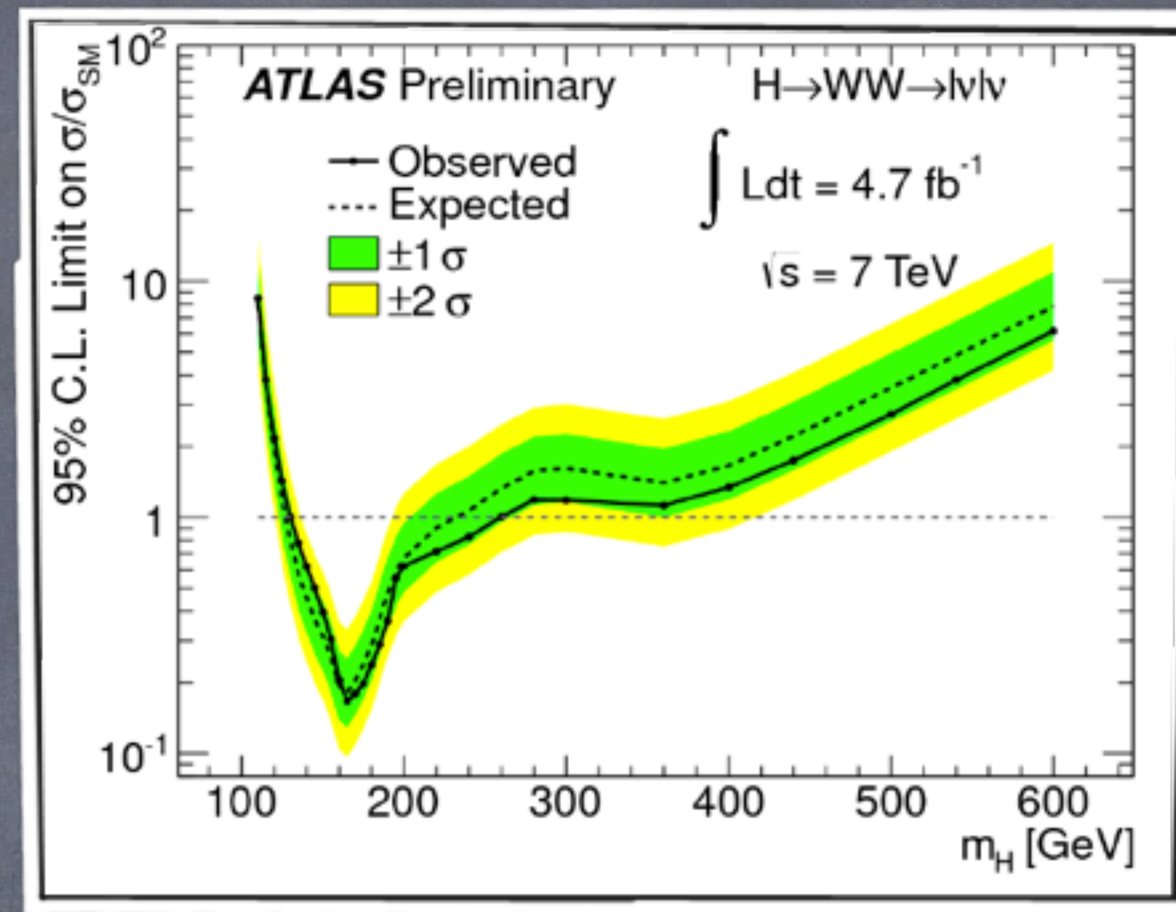




N_{jets} with p_T>25 GeV

H->WW->lνlν (2.1 fb^{-1} ATLAS)

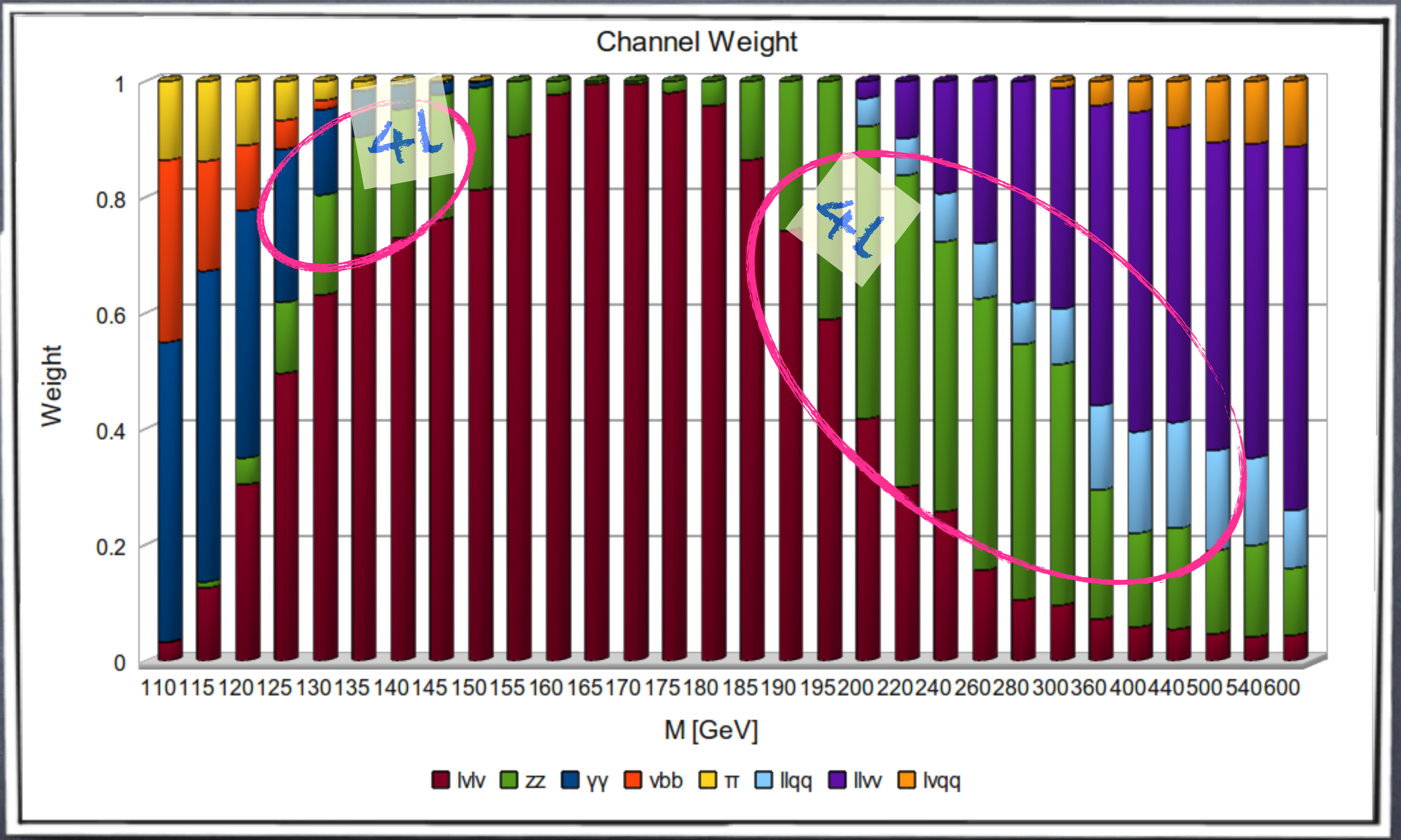




- ATLAS excludes (4.7 fb^{-1}) $130<m_H<260$ GeV
  (exp 127-234 GeV)

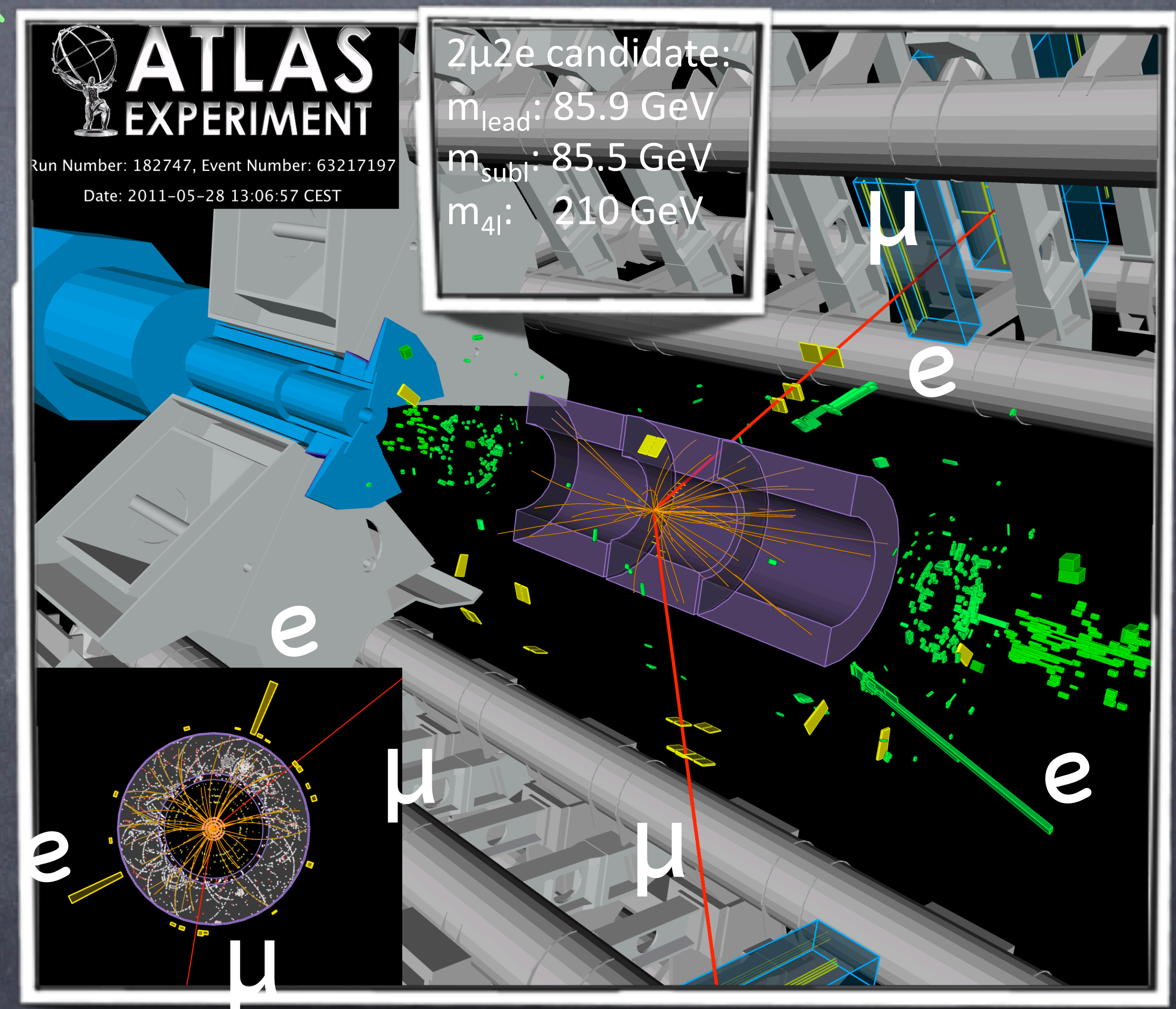
The Golden Channel - H->ZZ->4l

- Around 140 and above 200 GeV
- Probing channel: H->ZZ->4l



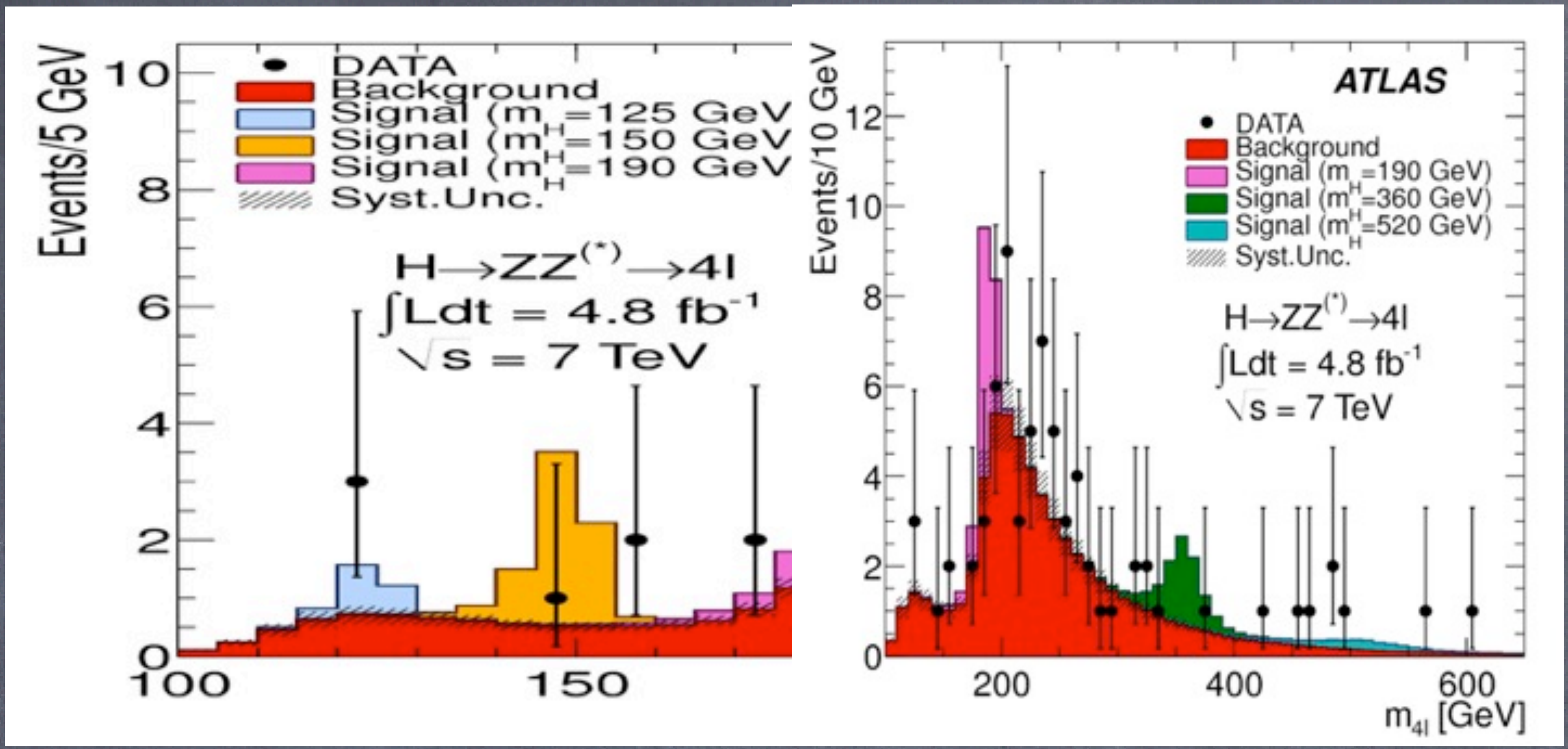
The Golden Channel: H->ZZ->4l

- CLEAN but very low rate (σ~2-5fb), yet probably most trustable
- All information is available, one can fully reconstruct the kinematics and the masses (m_{2l}, m_{4l})
- Signature: Two pairs of same flavor high pT opposite charged isolated leptons, one or both compatible with Z ->narrow peak
- Main backgrounds:
  - ZZ* (irreducible)
  - for $m_H<2m_Z$, Zbb, Z+jets, tt
- Suppress backgrounds with isolation and impact parameters cuts on two softest leptons



H->ZZ->4l Results I

Low mass range (<180): Observed: 8 events,
3 4μ+
3 2e2μ+2 4e
Expected 9.3+-1.5

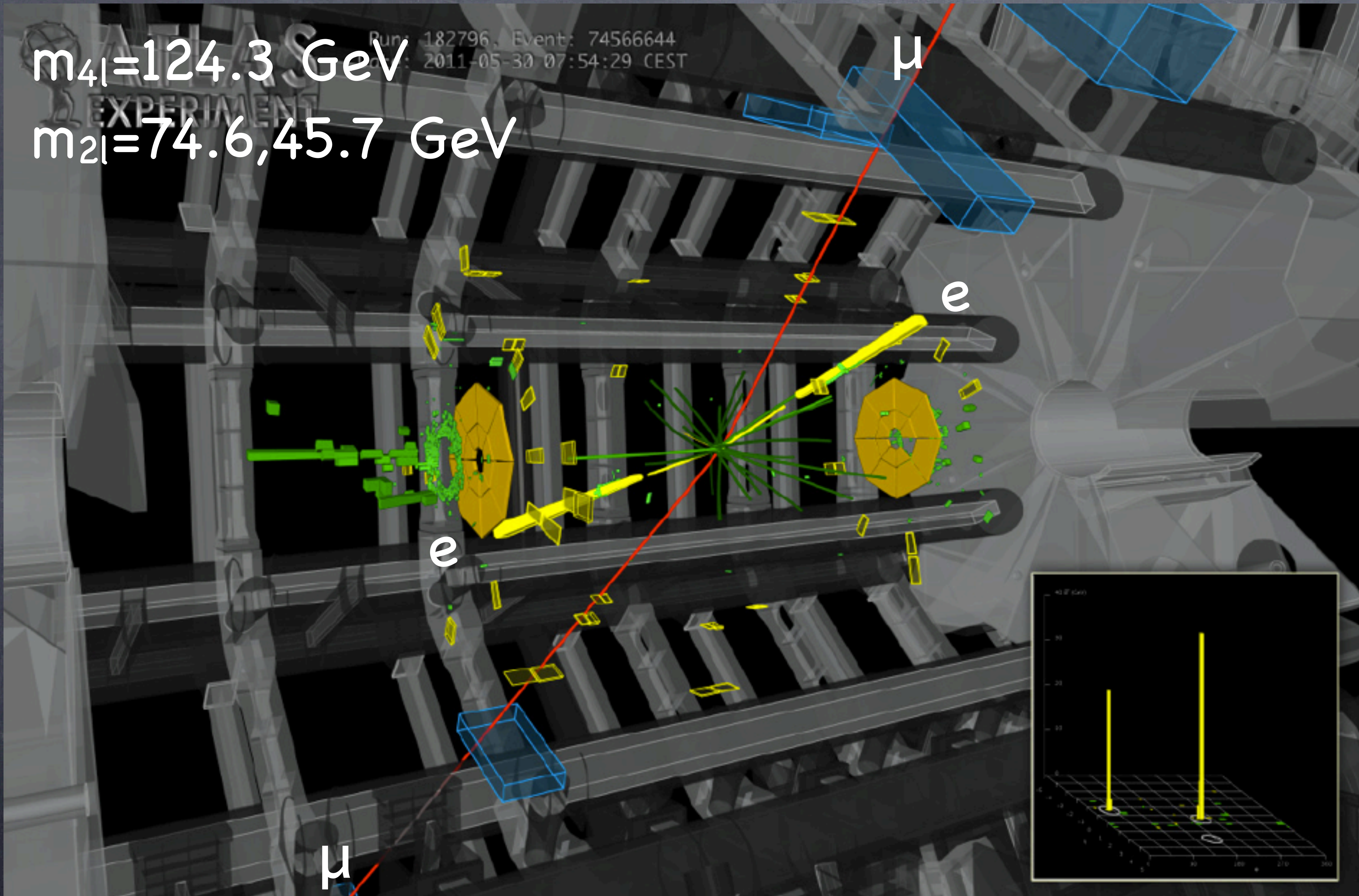


Full mass range: Observed: 71 events,
24 4μ+
30 2e2μ+
17 4e
Expected 62+-9

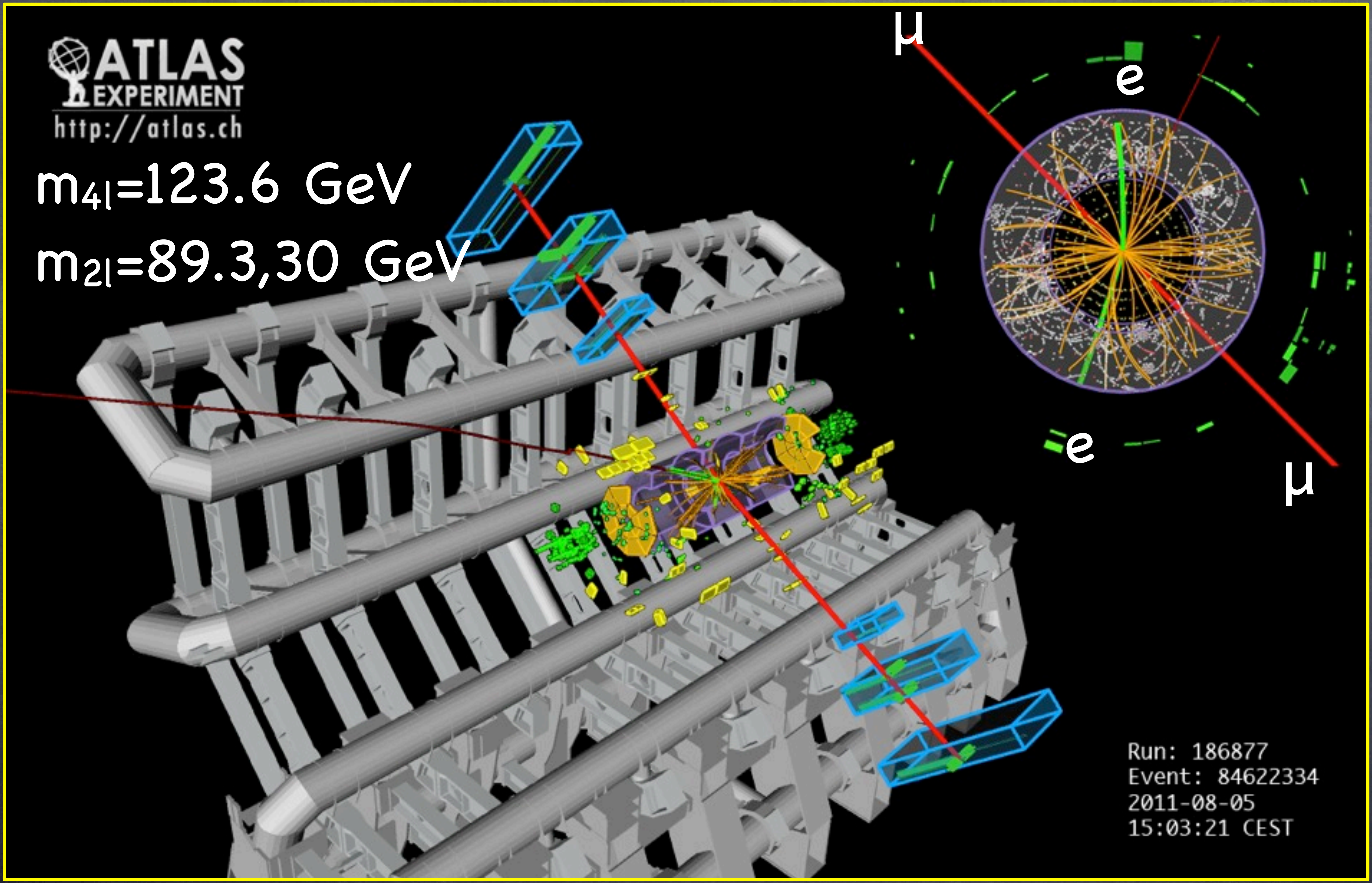
- In the interesting low mass region ATLAS observe 3 events, two 2e2μ (m=123.6,124.3 GeV) and one 4μ (m=124.6)
- In the region around 125 GeV (+-2σ) expect 1.5 BG evens from ZZ* (4μ,4e and 2e2μ) and Z+jets (4e)
- Expected m_H=125 GeV signal is 1.5 events with S/B~2(4μ),1(2e2μ) and 0.3(4e)

Main Systematic Uncertainties	
Higgs cross section	<2%
Zbb,Z+jets BG	40-45%
ZZ* BG	14%
E-efficiency	2-8%

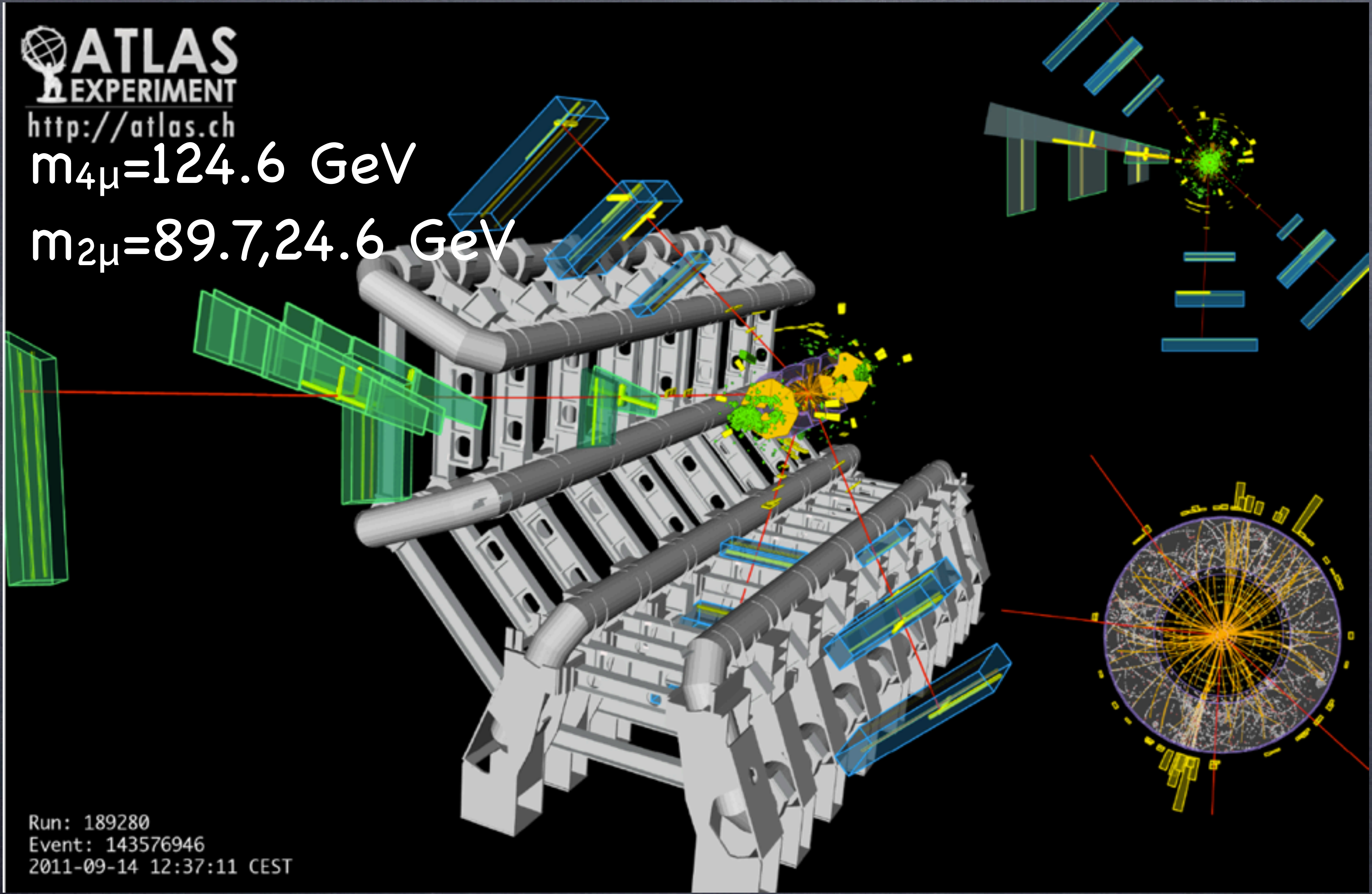
The Golden Channel: H->ZZ->4l



The Golden Channel: H->ZZ->4l



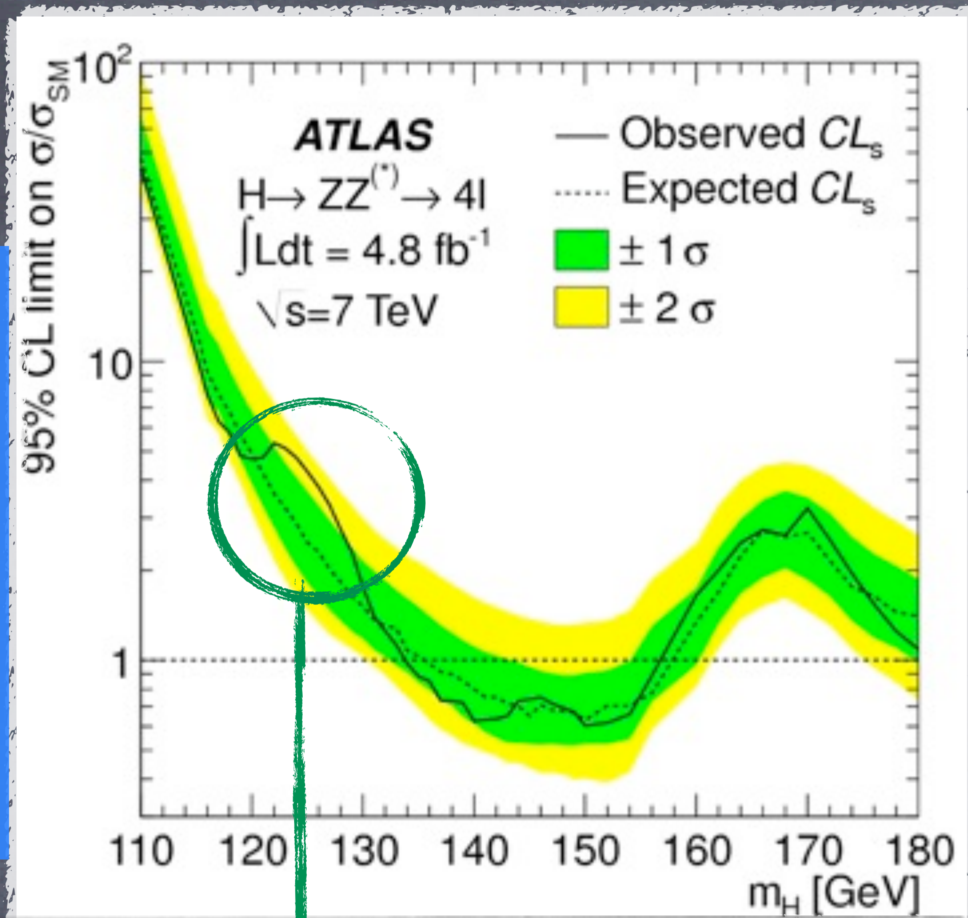
The Golden Channel: H->ZZ->4μ

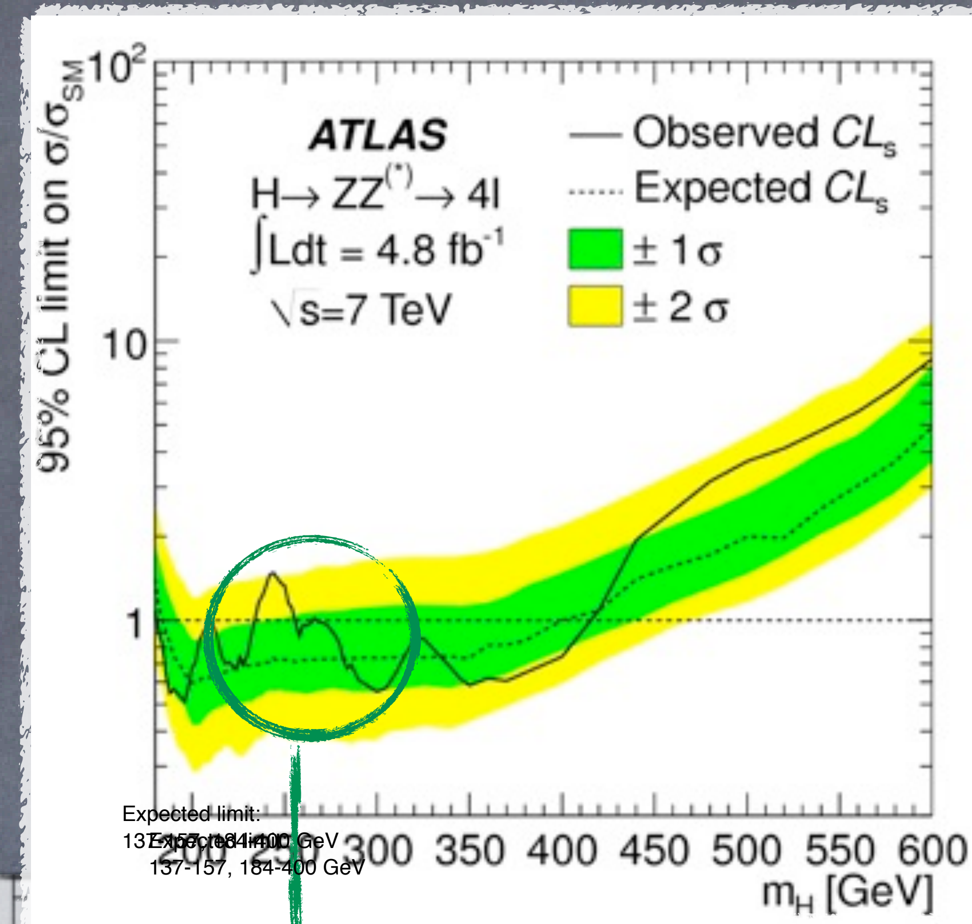


$m_{4\mu}$=124.6 GeV

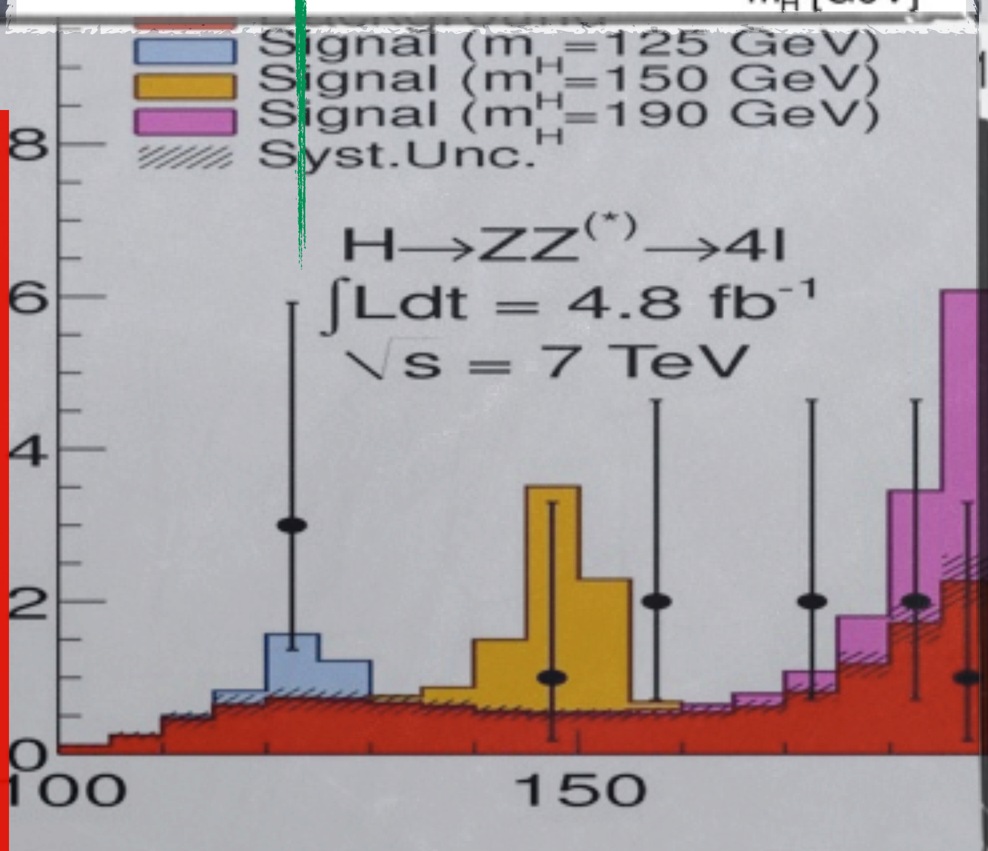
$m_{2\mu}$=89.7,24.6 GeV

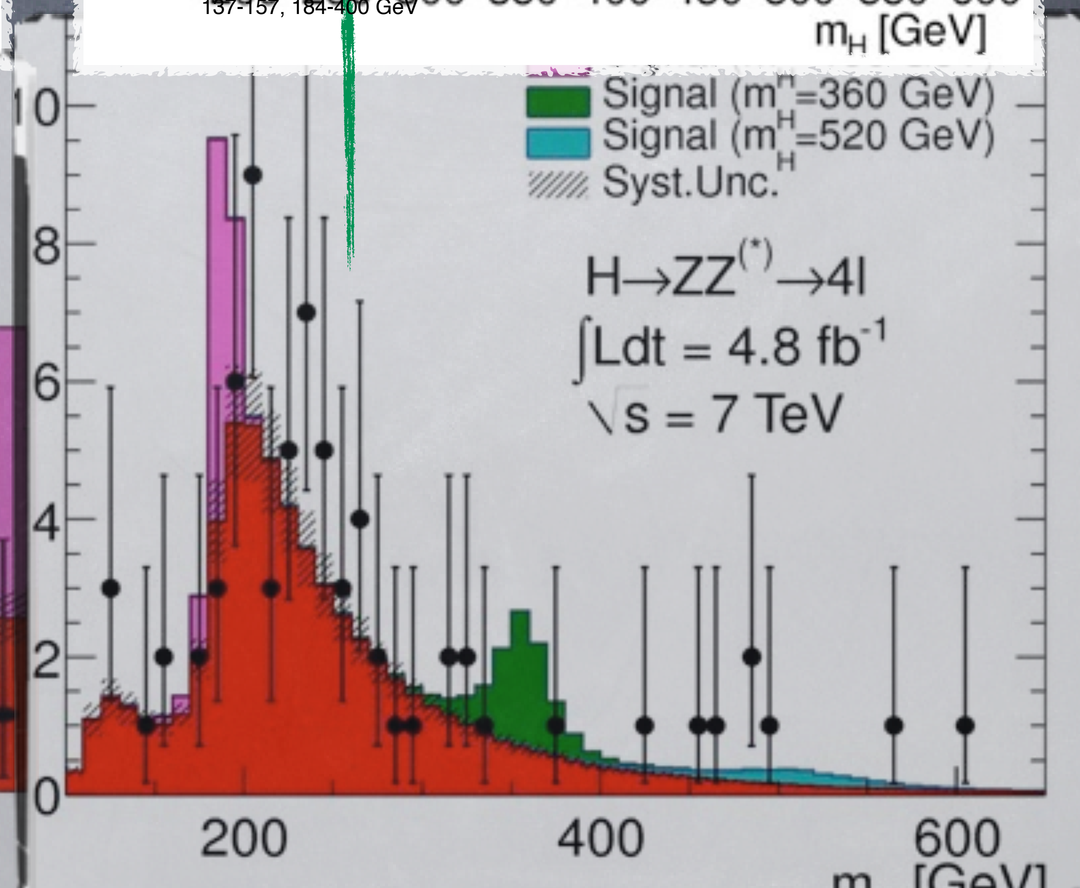
H->ZZ->4l Limits





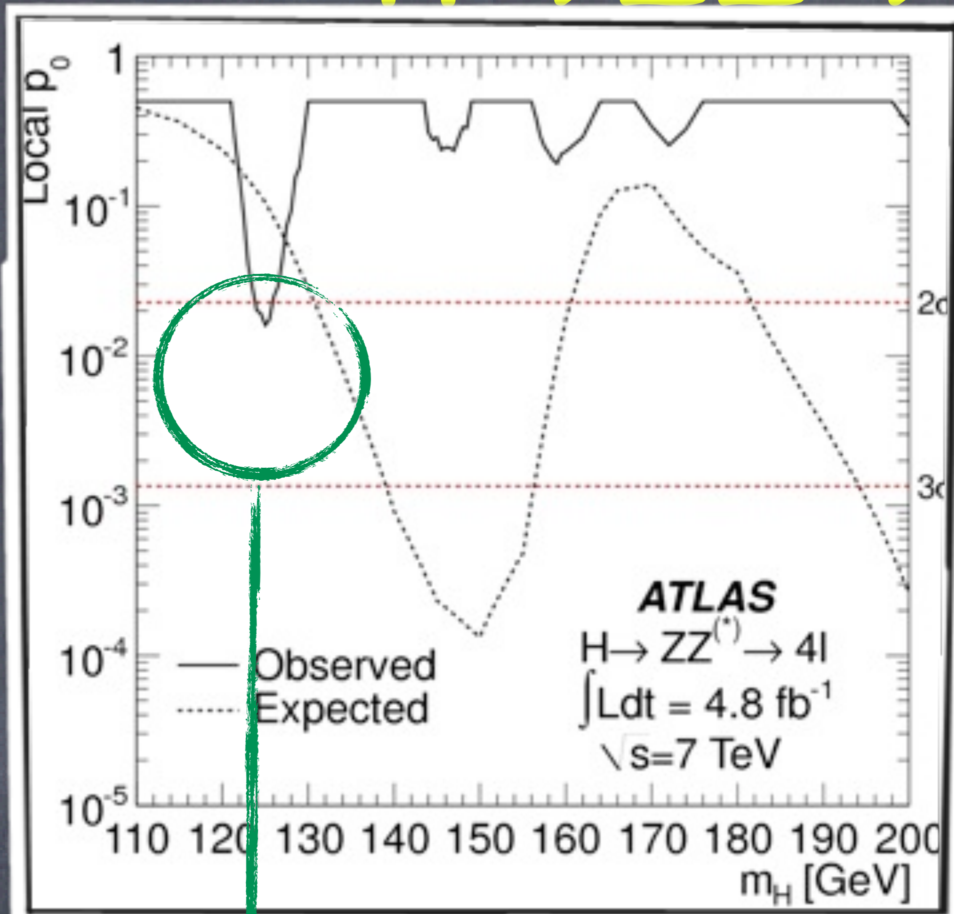
Expected Exclusion
m_H=
137-157
184-400
GeV

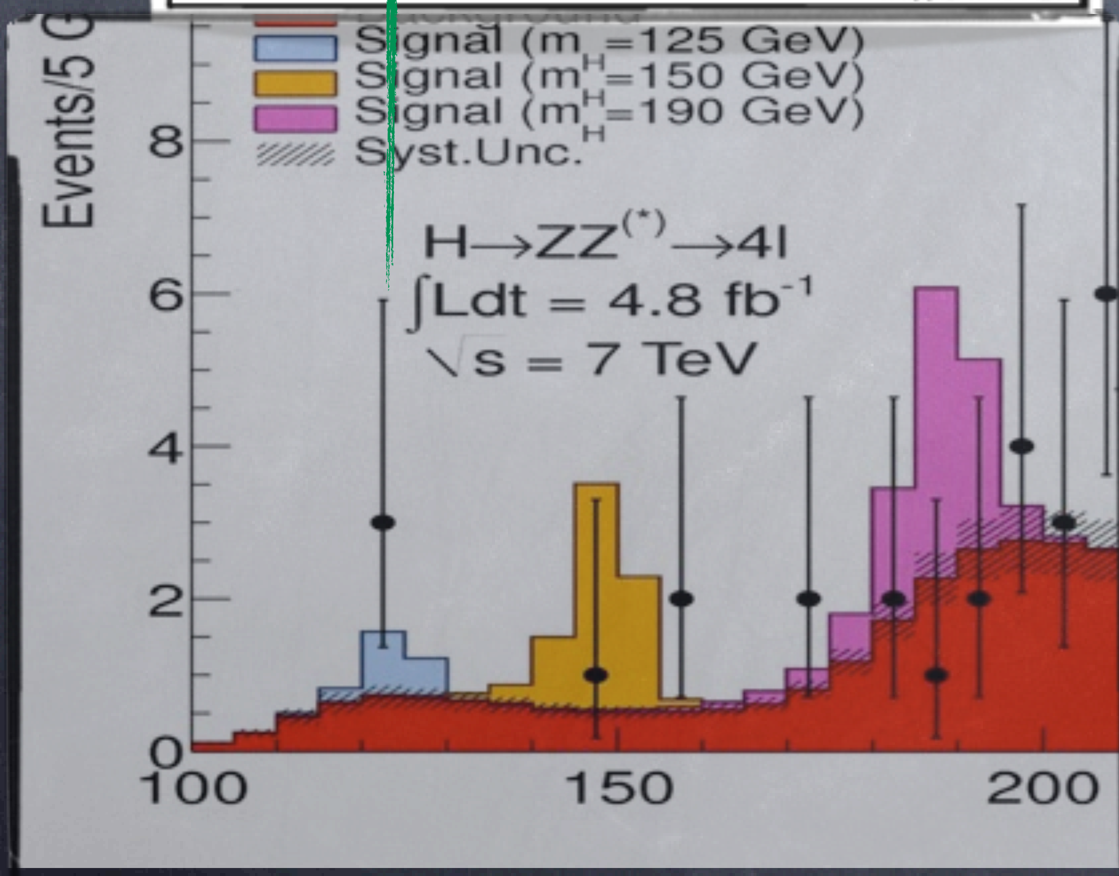


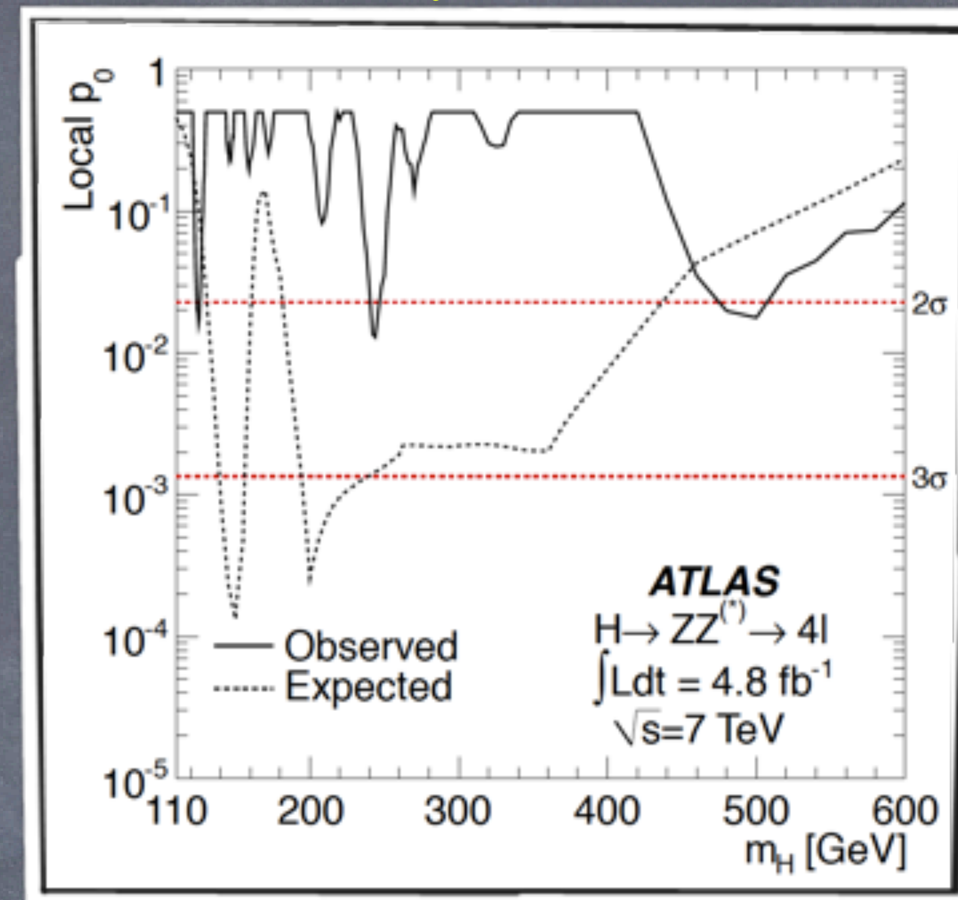


Observed Exclusion
m_H=
134-156
182-233,
256-265
268-415
GeV

H->ZZ->4l ATLAS p0



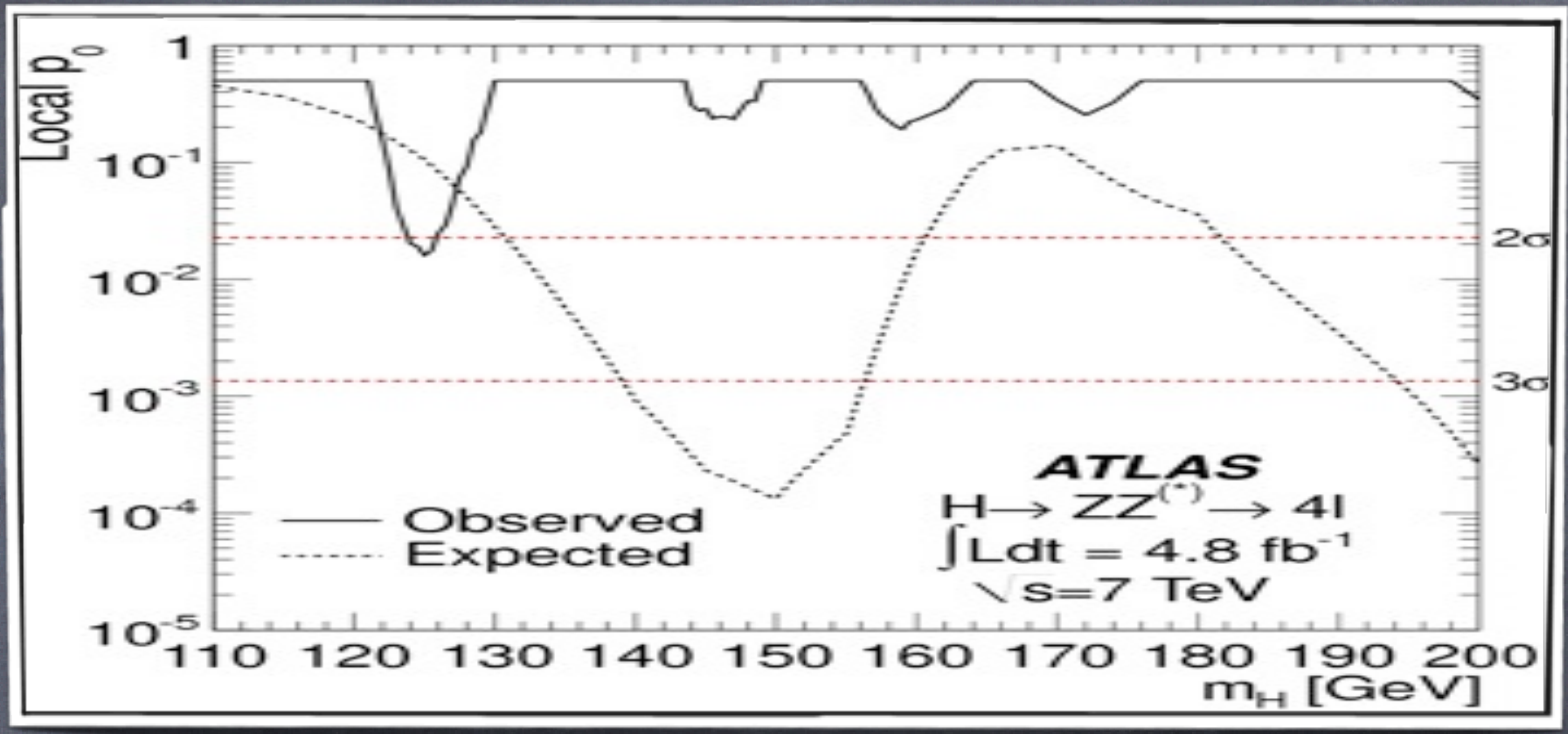




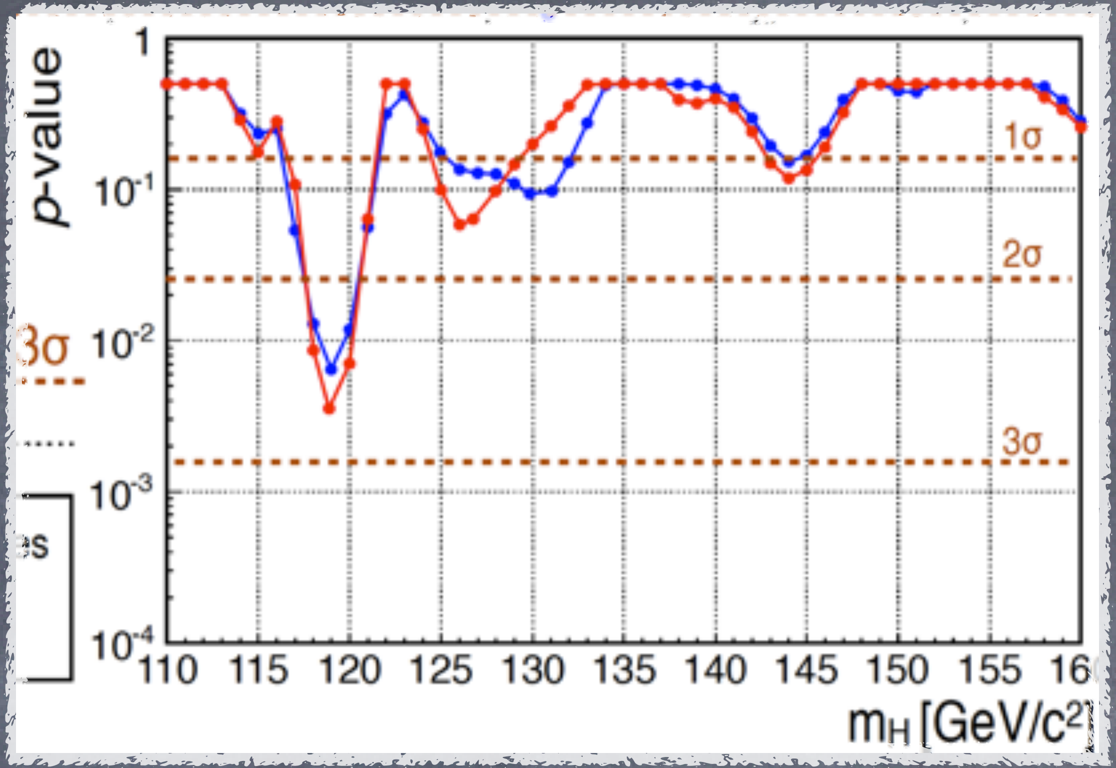
$m_{4\ell}$	125 GeV	244 GeV	500 GeV
Exp. w. signal	1.3σ	3.0σ	1.5σ
Observed	2.1σ	2.2σ	2.1σ

Look Elsewhere Effect is estimated over the full mass range to be O(50%)

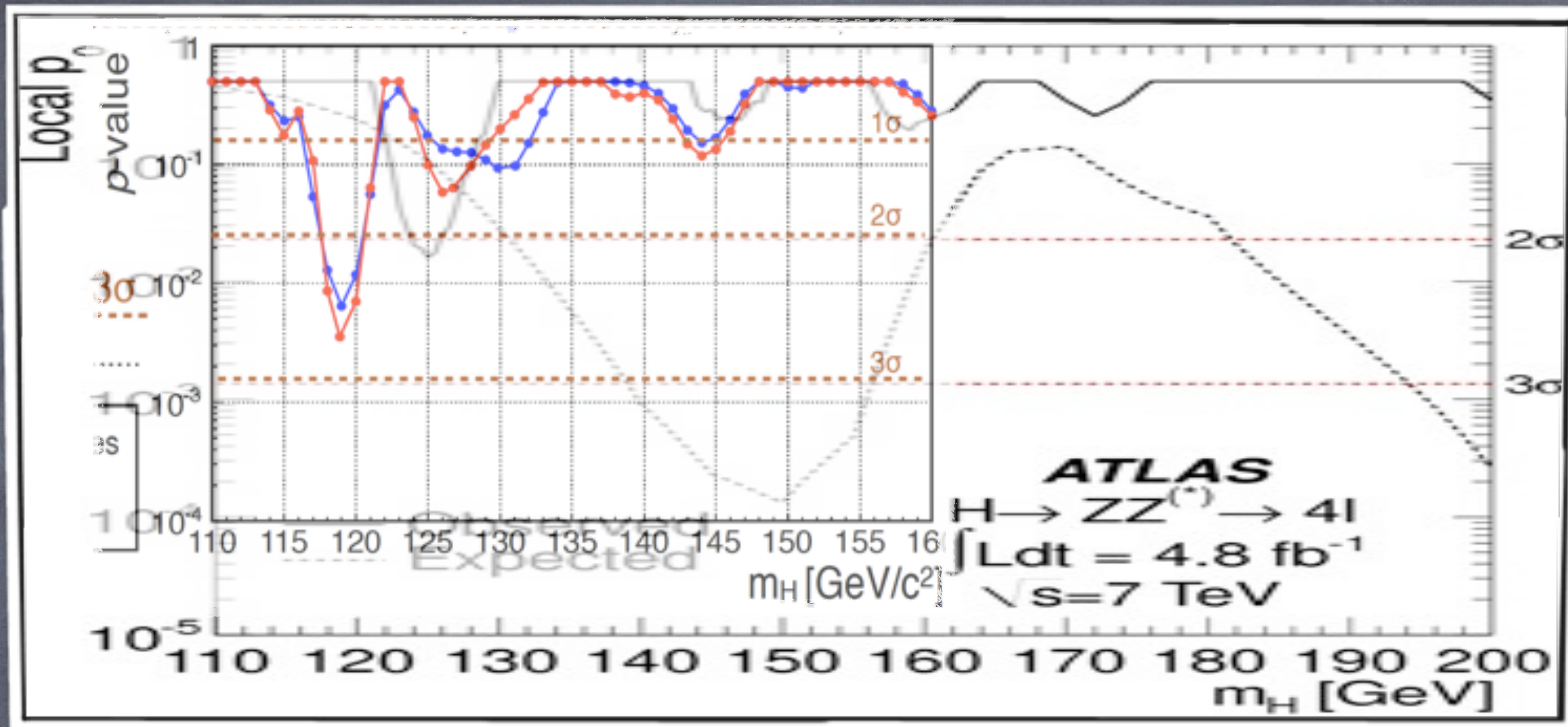
H->ZZ->4l p0 ATLAS vs CMS



H->ZZ->4l p0 ATLAS vs CMS

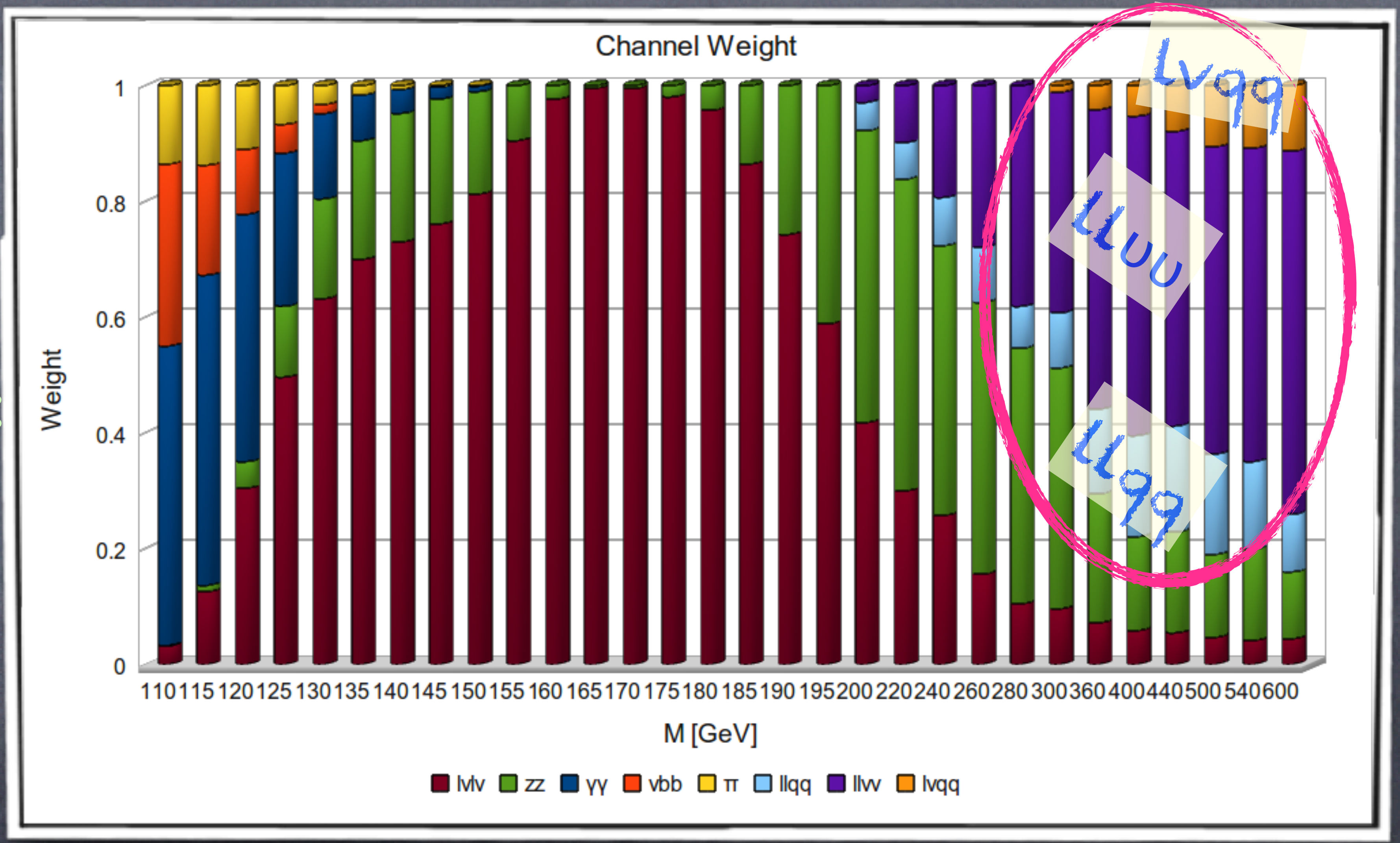


H->ZZ->4l p0 ATLAS vs CMS



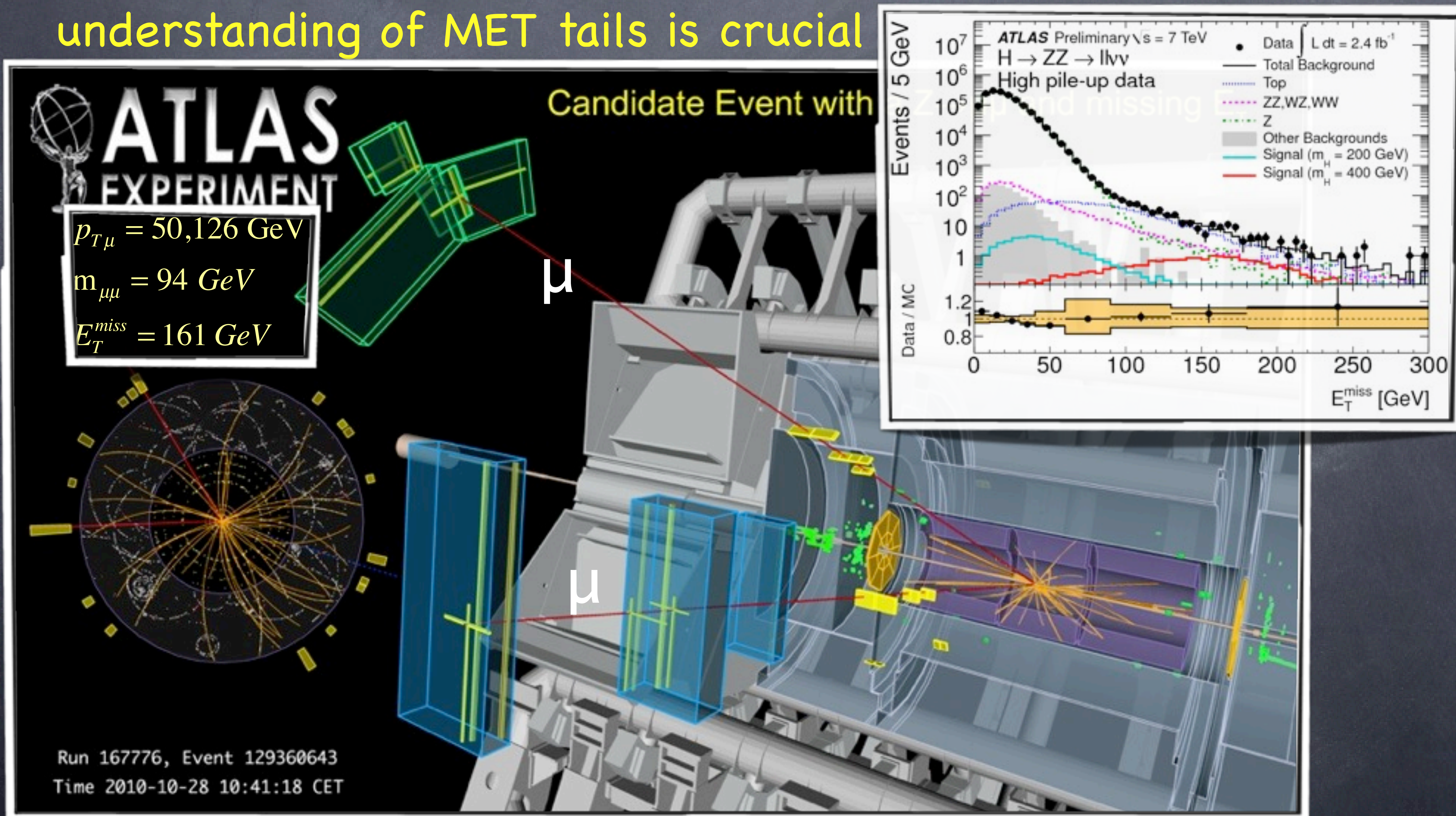
Heavy Higgses

- mH>300
- Probing channels:
  H->ZZ->llvv
  H->ZZ->llqq
  H->WW->lvqq



Heavier Higgs: H->llνν

- Signature: two high p_T opposite charged isolated leptons (with $m_{ll} \sim m_Z$) with high MET (both Z's are boosted for high m_H), understanding of MET tails is crucial

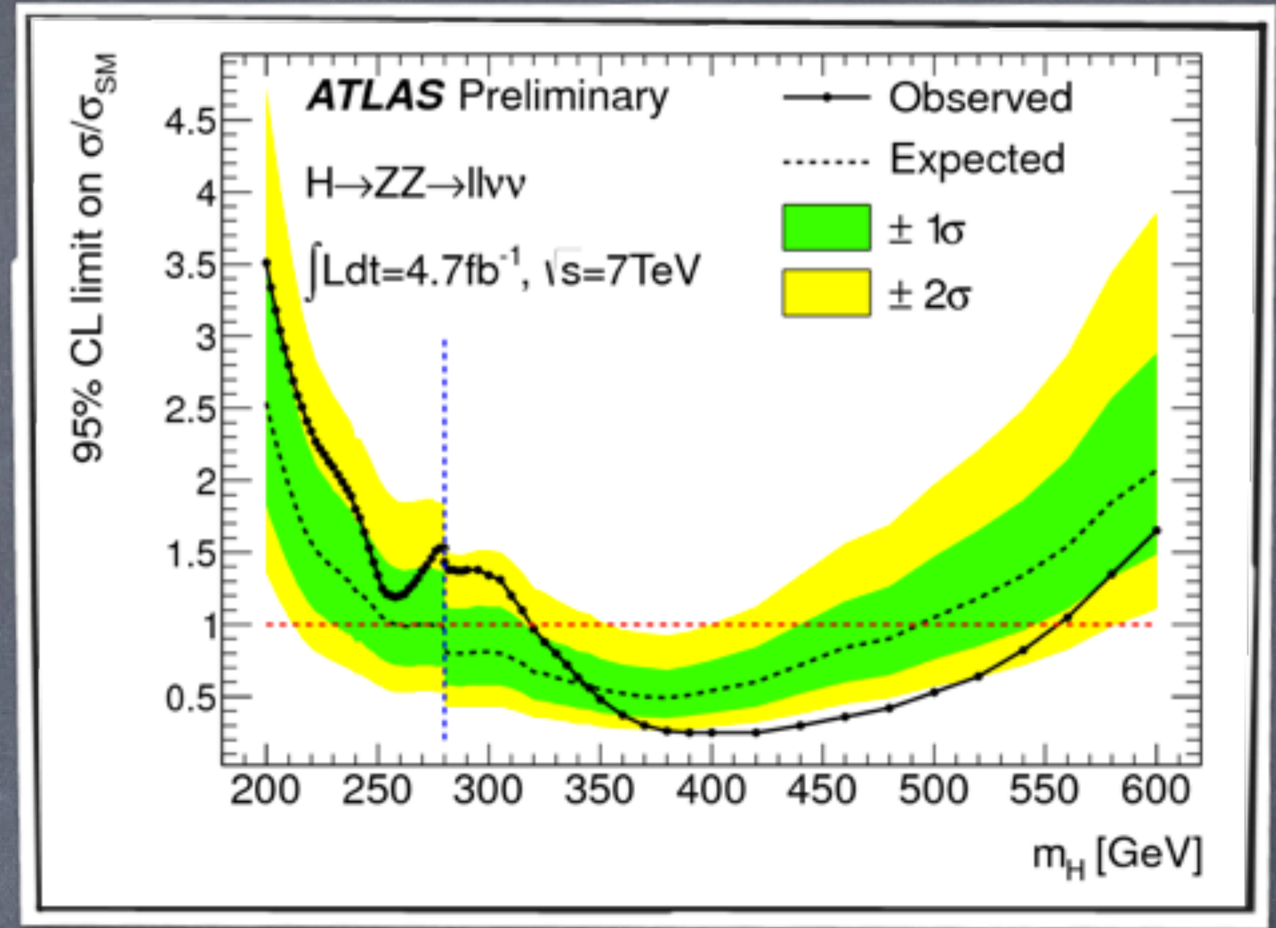


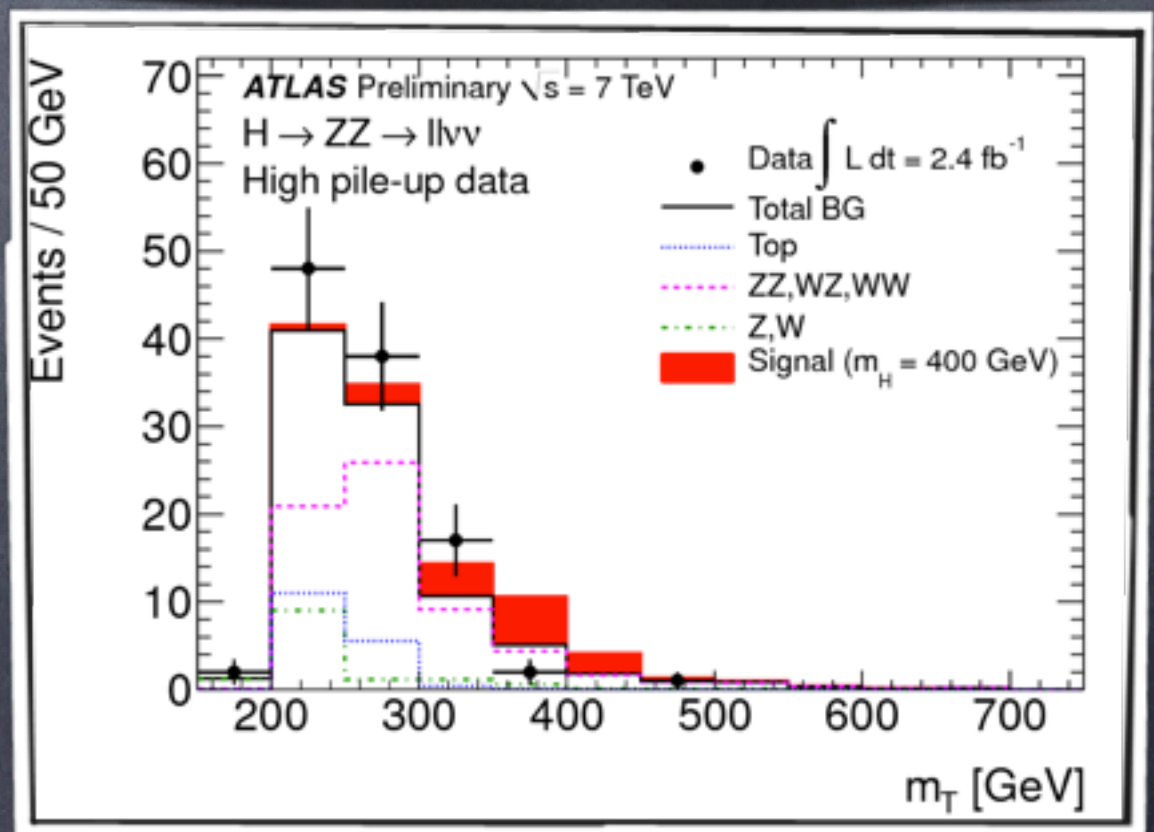
Heavier Higgs: H->llνν

- Transverse mass
  (two mass bins [≶280 GeV])

$$m_T^2 \equiv \left(\sqrt{\vec{p}_{TZ}^{\,2} + m_Z^2} + \sqrt{|\vec{p}_T^{\,miss}|^2 + m_Z^2}\right)^2 - (\vec{p}_{TZ} + \vec{p}_T^{\,miss})^2$$

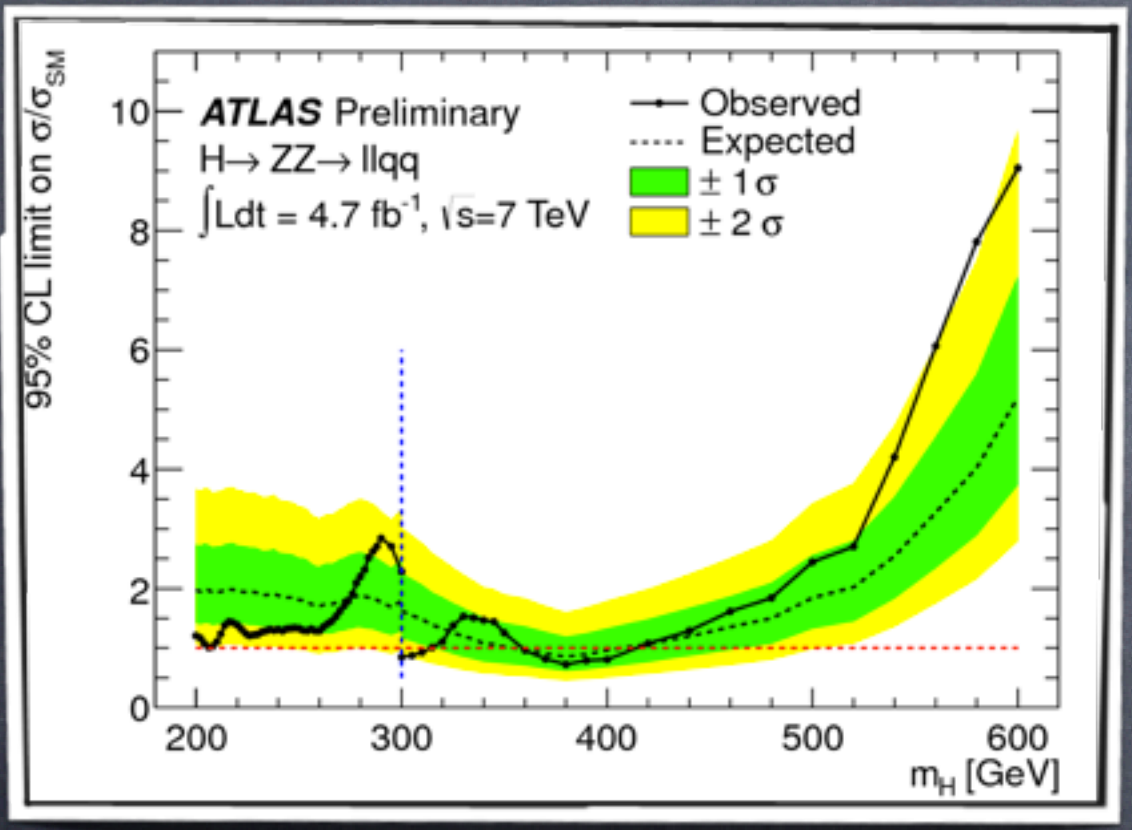
Obs: excl 350<mH<450
Exp: excl 260<mH<490

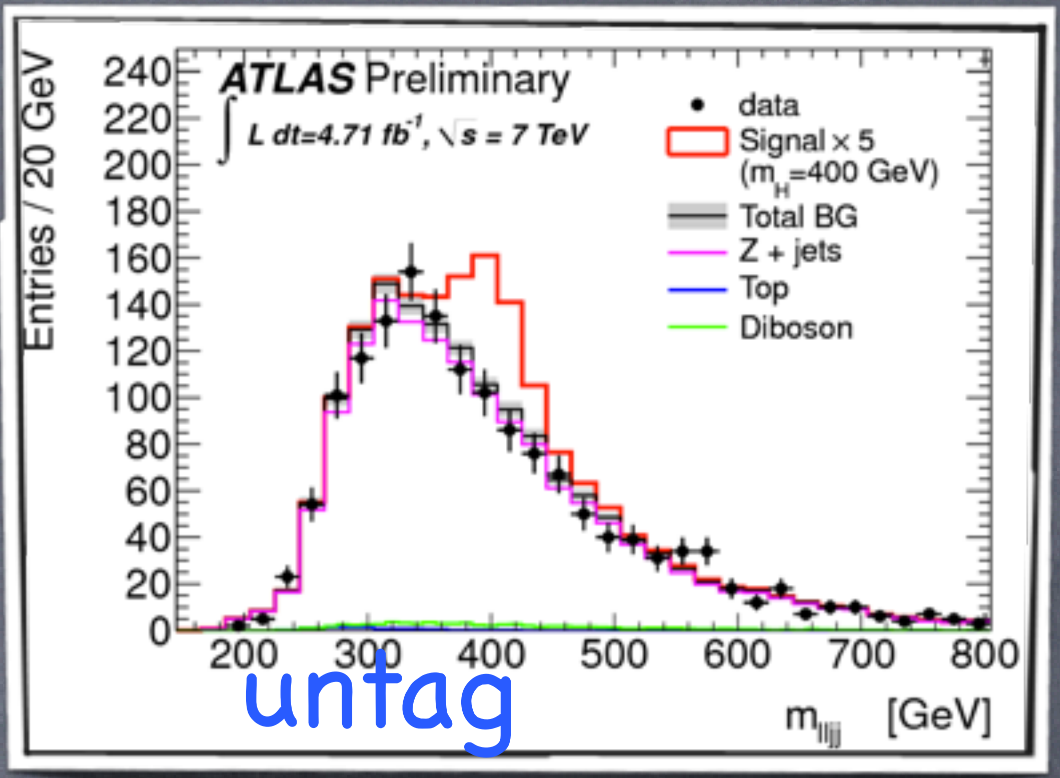


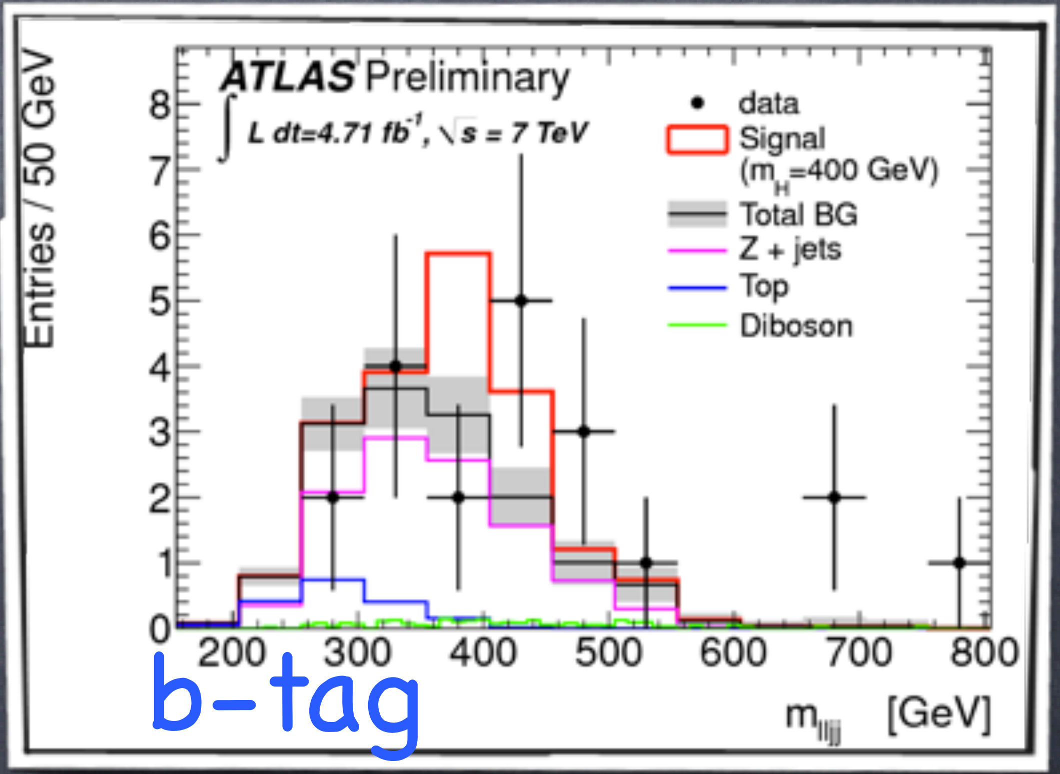


Heavier Higgs: H->llqq,llbb

- Highest rate, yet high Z+jets BG
- Clear signature:
  Exactly one pair of oppositely charged same flavor leptons and a pair of jets.
  both pairs compatible with a Z boson. Low MET
- Discriminating variable m_{lljj}



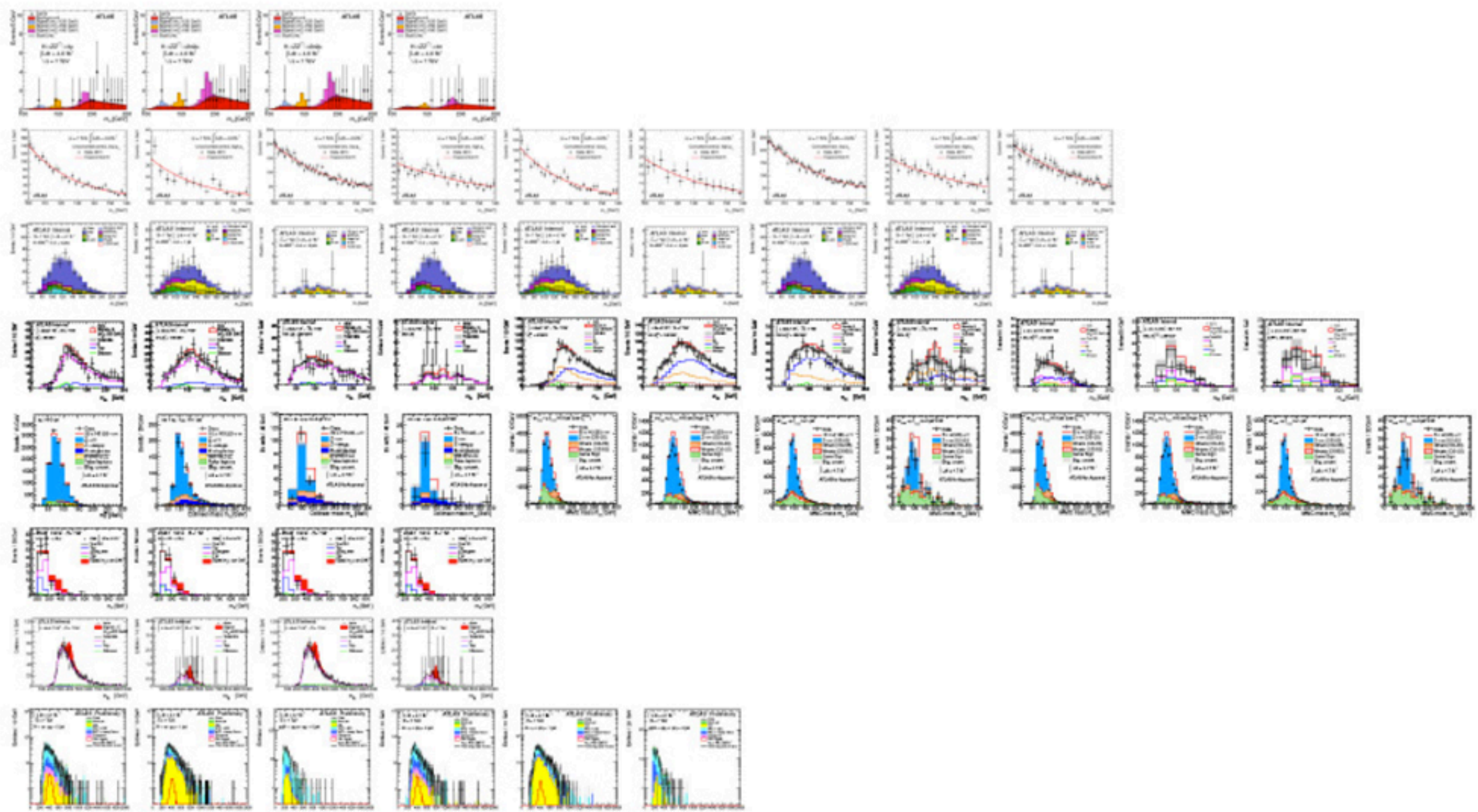




Obs: excl 300<mH<310,
360<mH<400

Exp: excl 360<mH<400

All for one - Combine forces

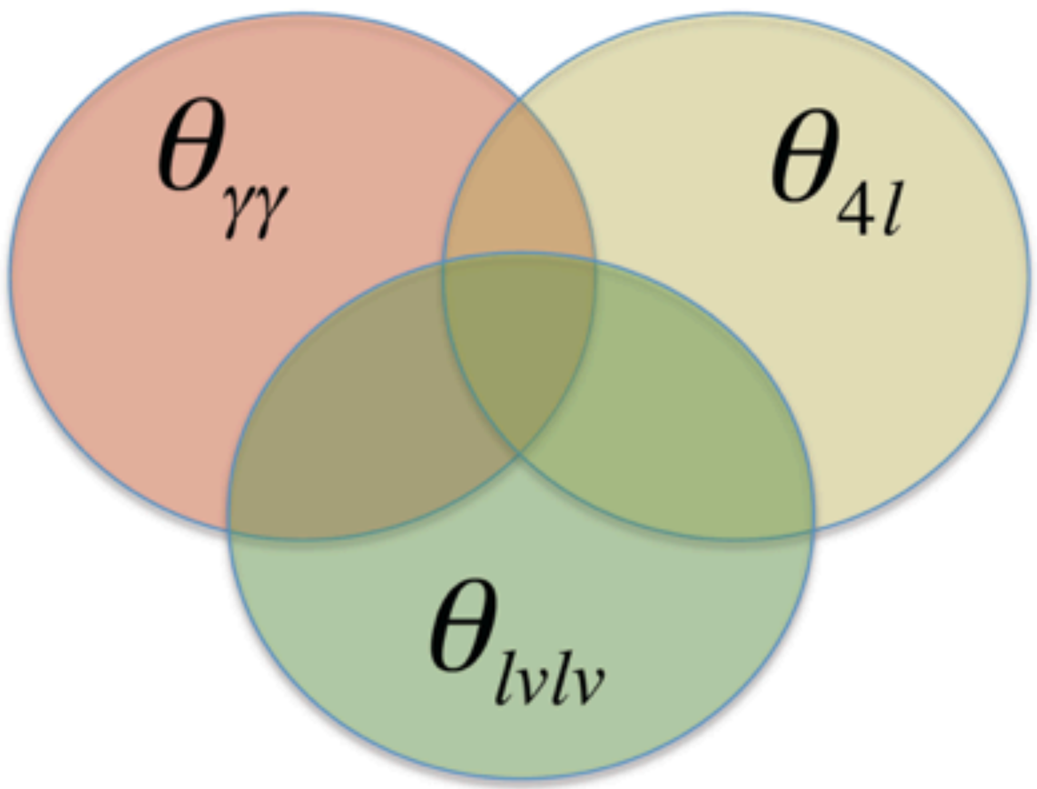


Disclaimer

- Correlated uncertainties (Jet energy scales, Luminosity etc… taken into account)
- When data driven methods are used, systematics are not correlated
- Theory uncertaintes are carefully taken into account across channels using the recommendation of the LHC cross section group

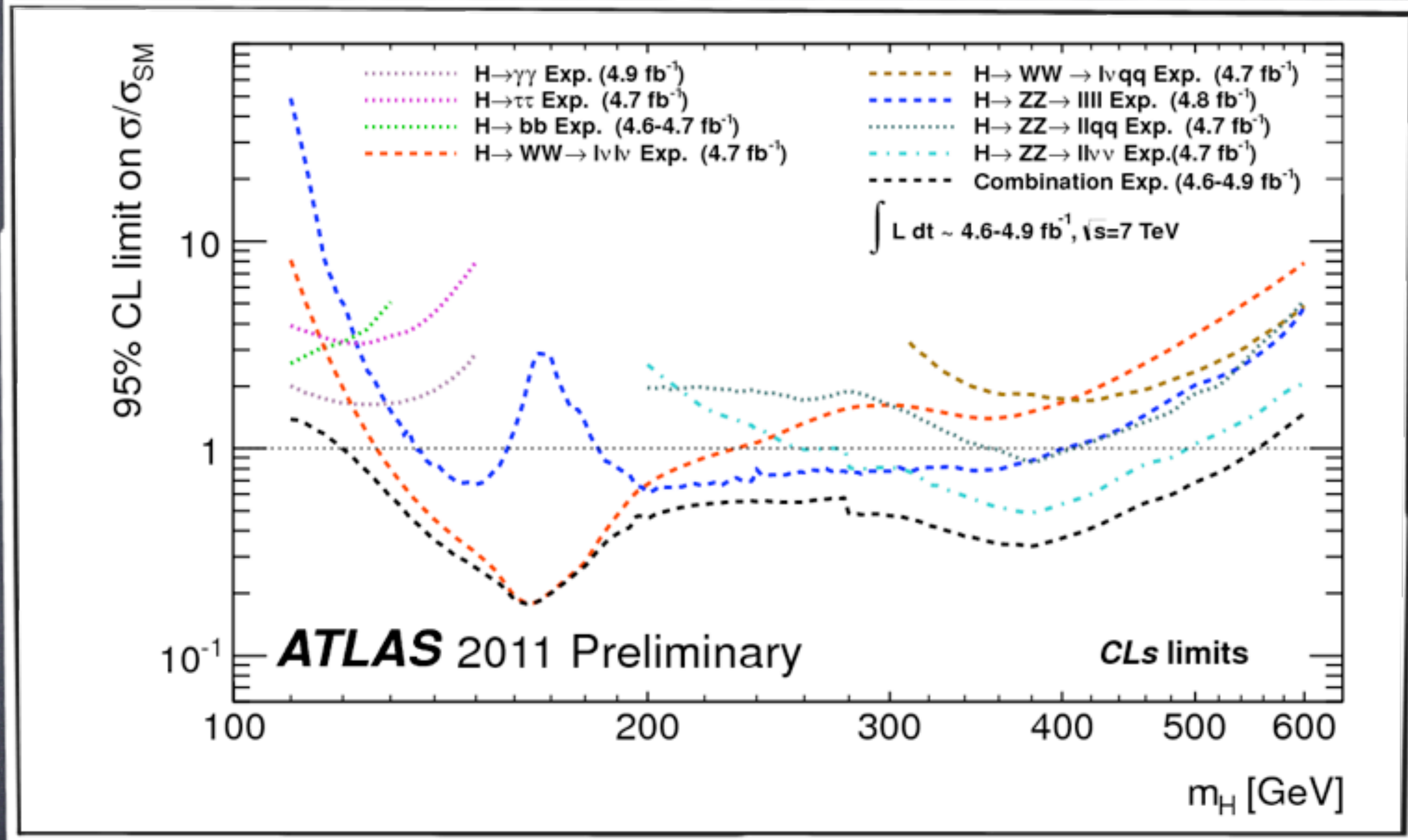
Combination : Use Correlations with Caution

$$L_{Combined}(\mu,\theta) = L_{\gamma\gamma}(\mu,\theta_{\gamma\gamma}) \times L_{4l}(\mu,\theta_{4l}) \times L_{l\nu l\nu}(\mu,\theta_{l\nu l\nu}) \times L_{\tau\tau}(\mu,\theta_{\tau\tau})$$



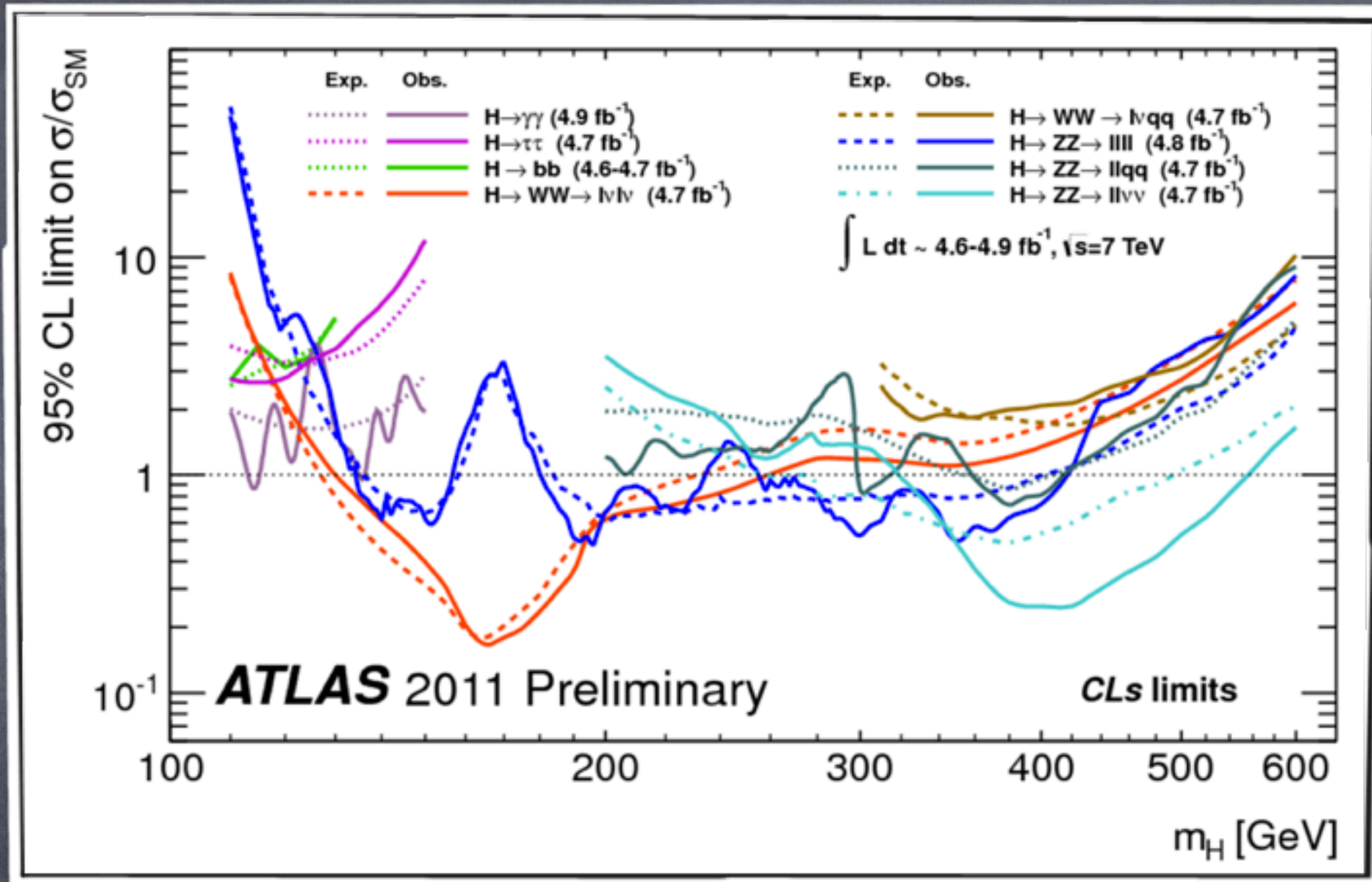
Need to very carefully check the interplay between correlated systematics...

Combined Limit



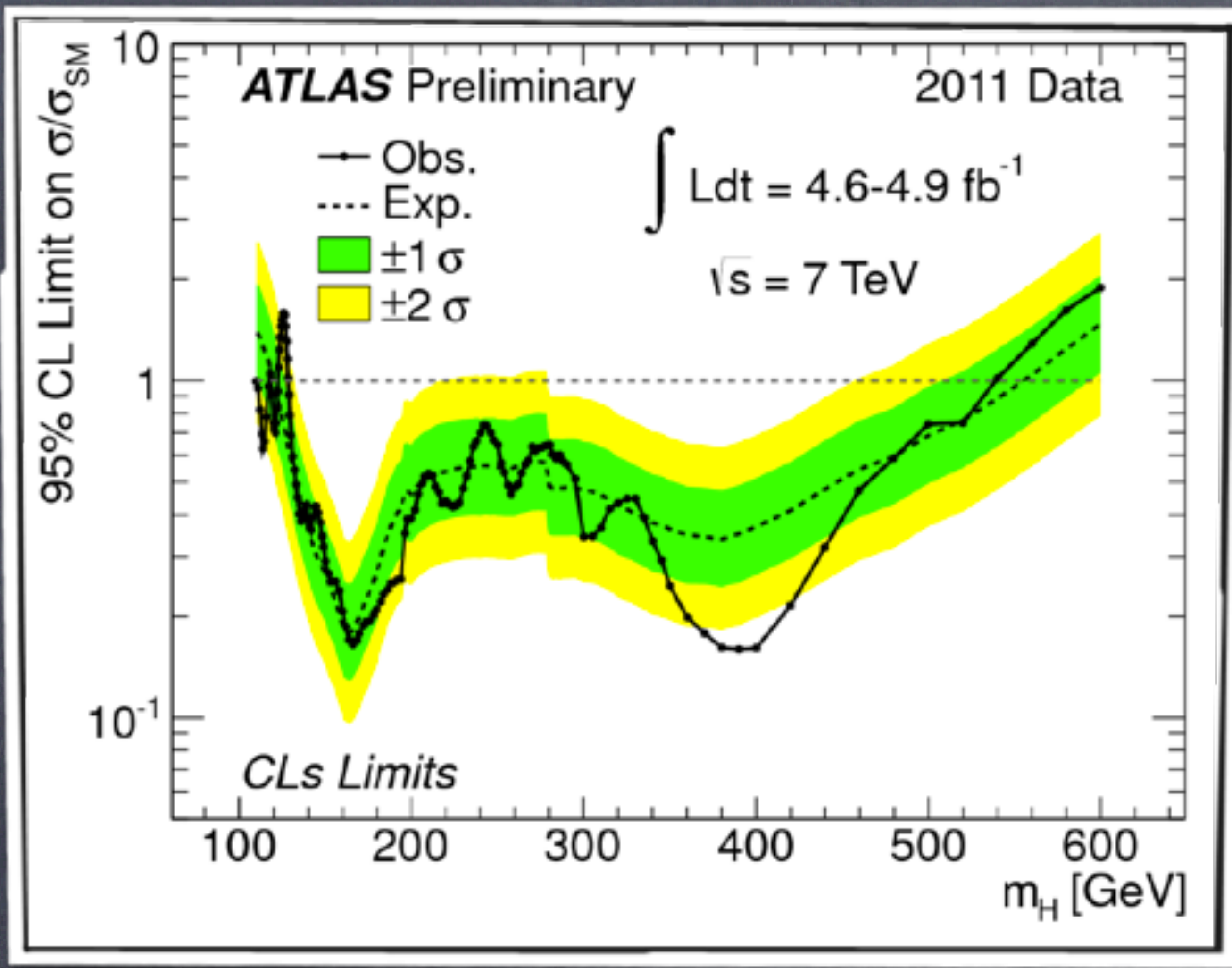
- Low mass is completely dominated by γγ, then ττ, bb and WW
- High mass completely dominated by llνν

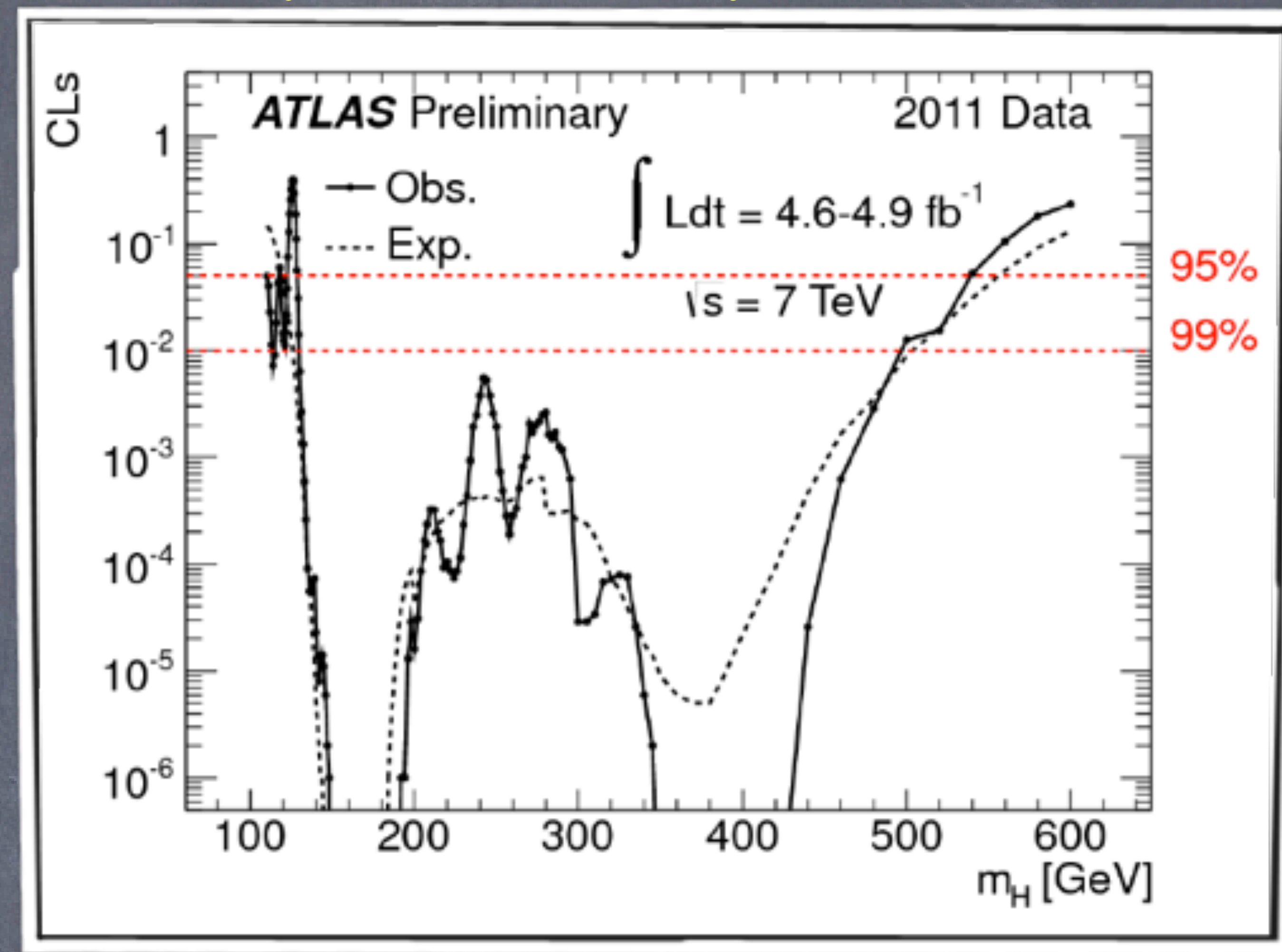
Combined Limit



- Low mass is completely dominated by γγ, then bb, ττ and WW
- High mass completely dominated by llνν

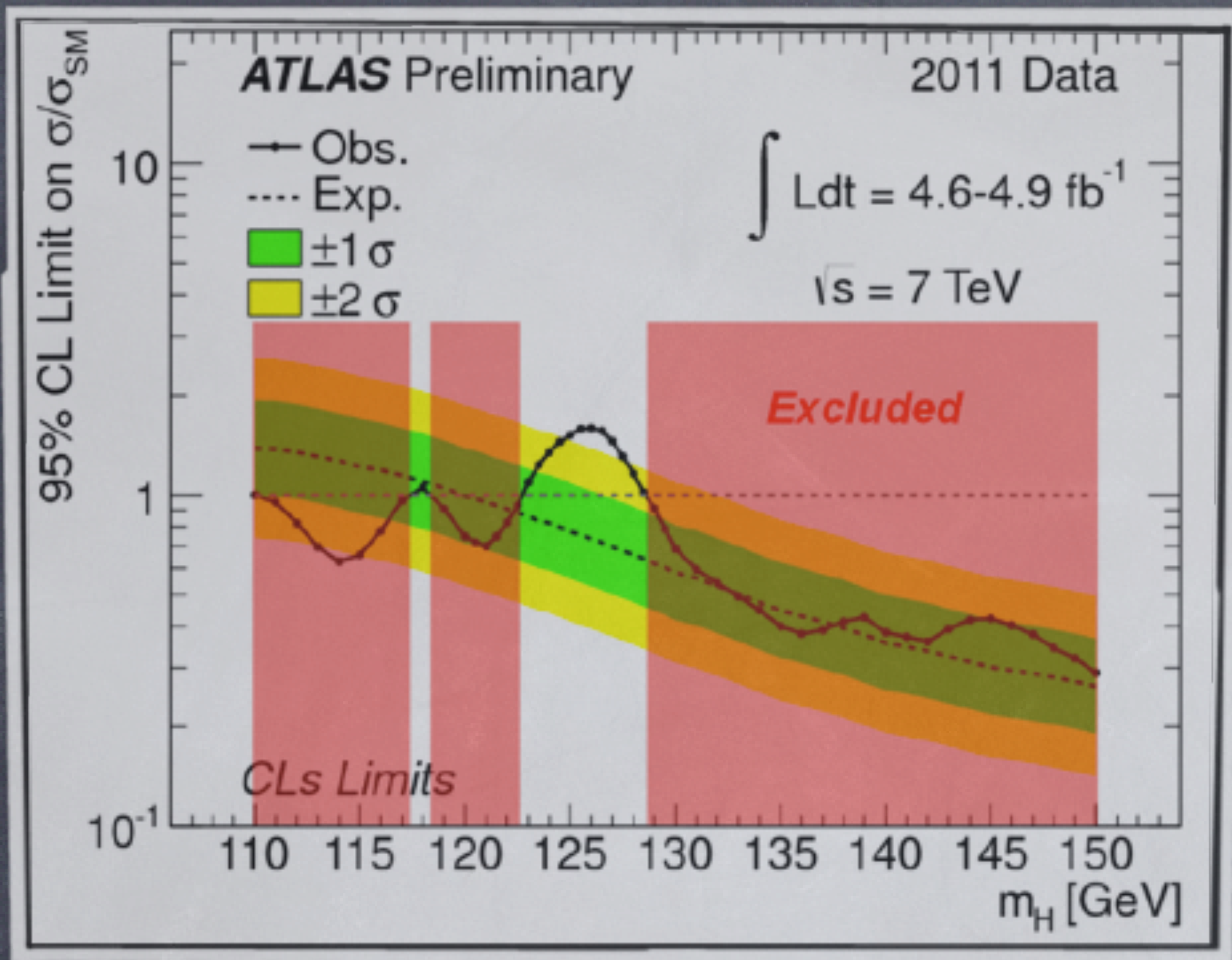
Combined Limit (ATLAS)

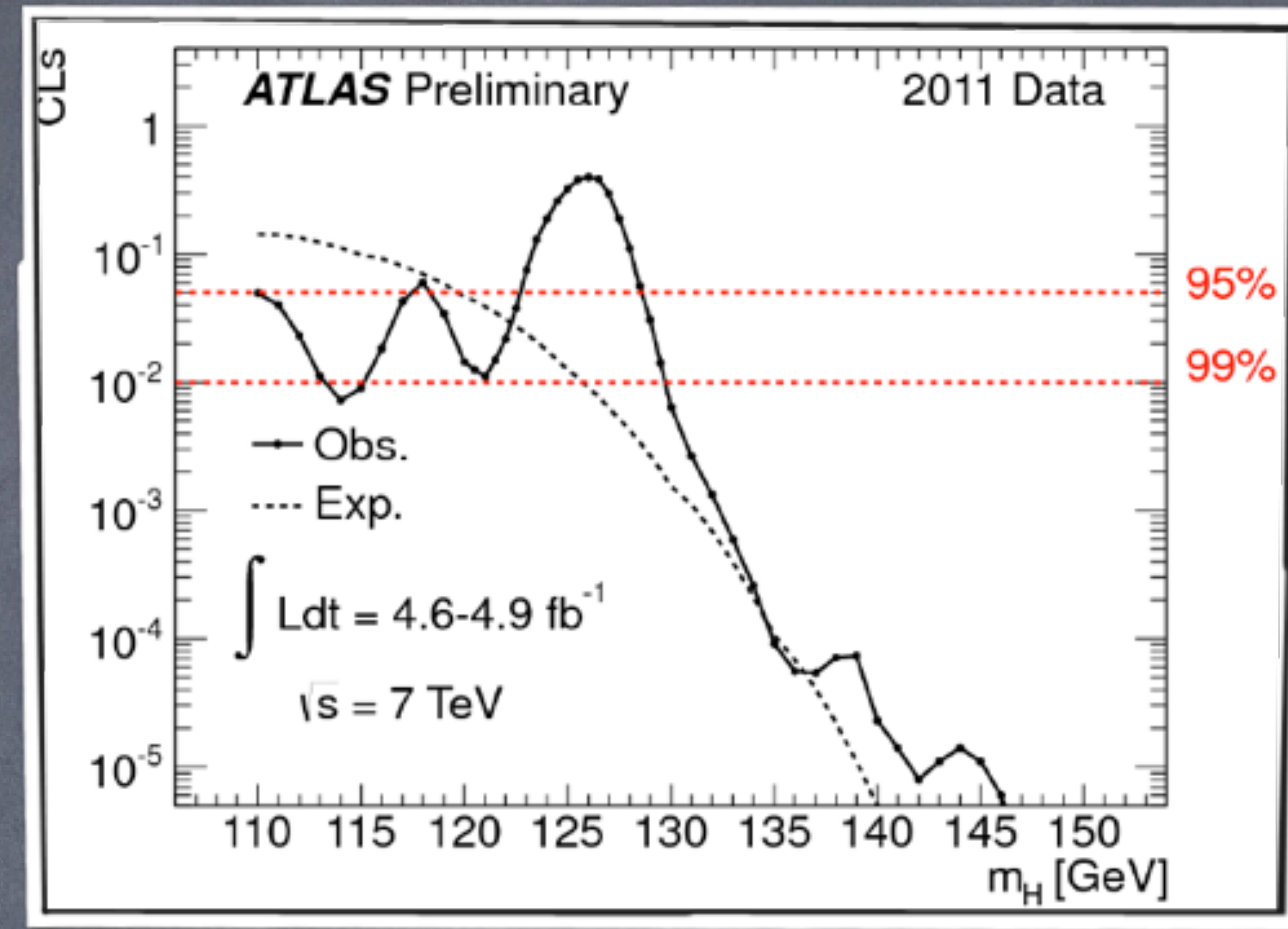




- ATLAS expected @ 95% Confidence Level 120<mH<555 GeV
- ATLAS excluded 95% Confidence Level $110<m_H<117.5$
  $118.5<m_H<122.5$
  $129<m_H<539$ GeV
- ATLAS excluded 99% Confidence Level $130<m_H<486$

Combined Limit





- ATLAS expected @ 95% Confidence Level 120<mH<555 GeV
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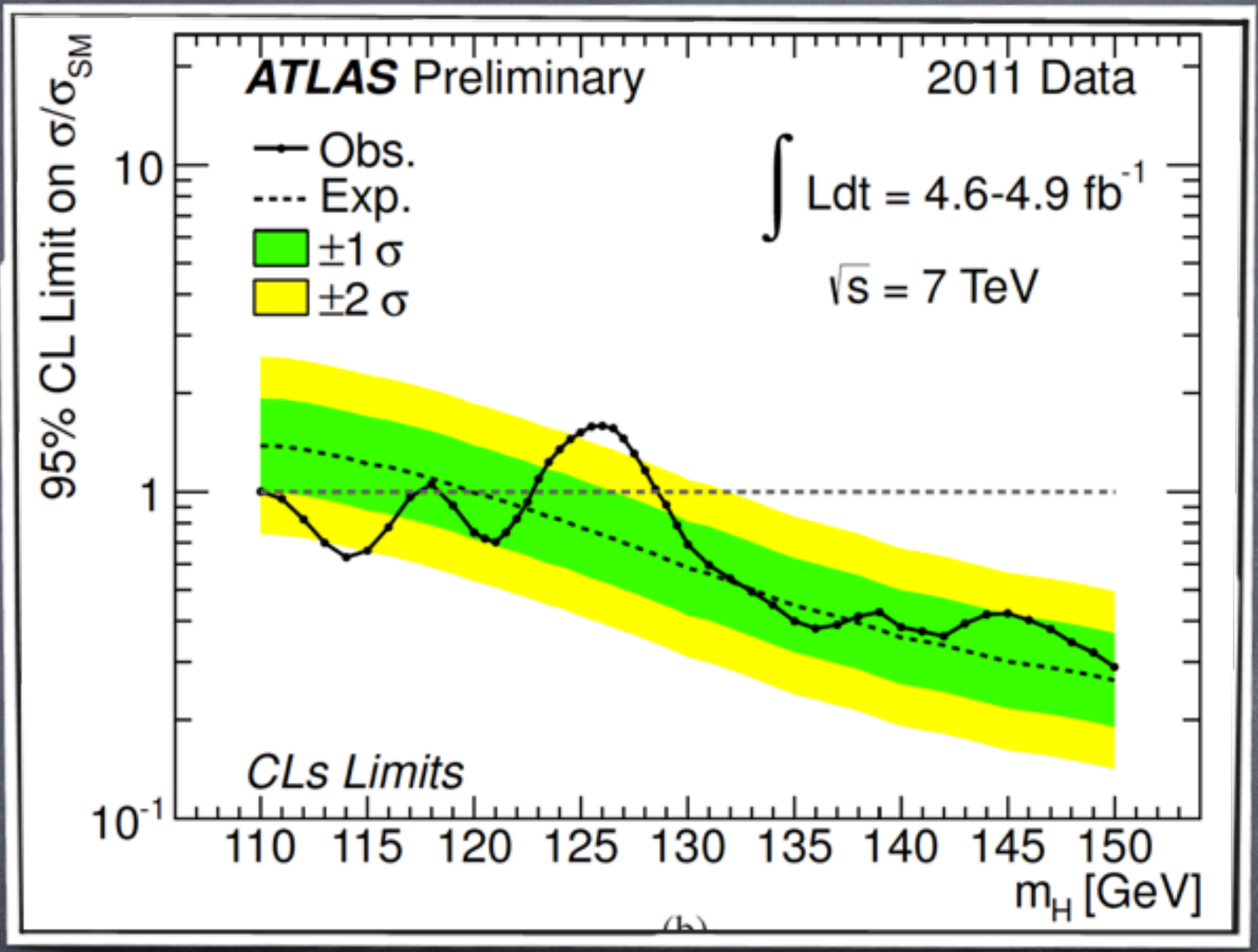
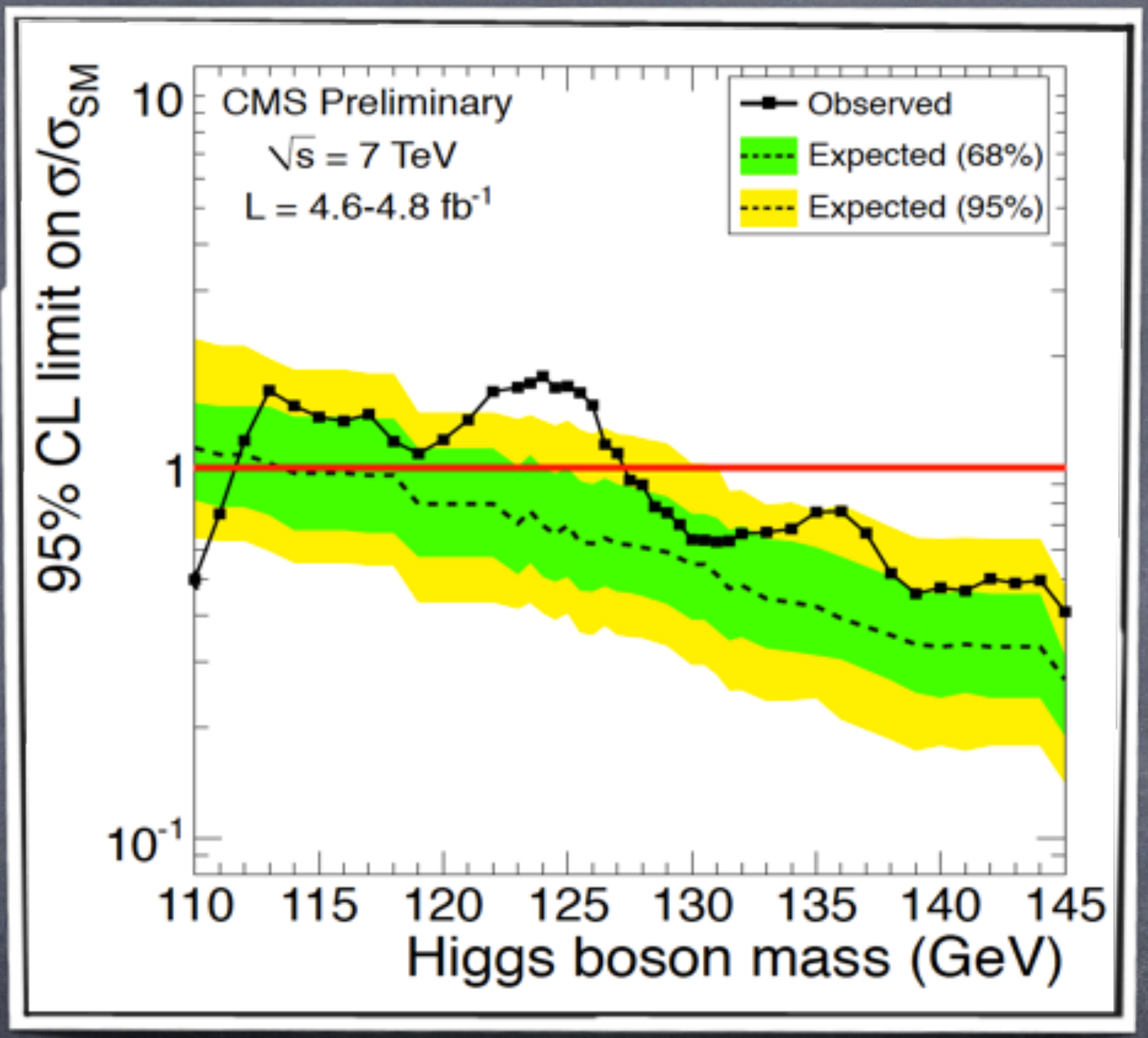
Cmbined Limit CMS vs ATLAS

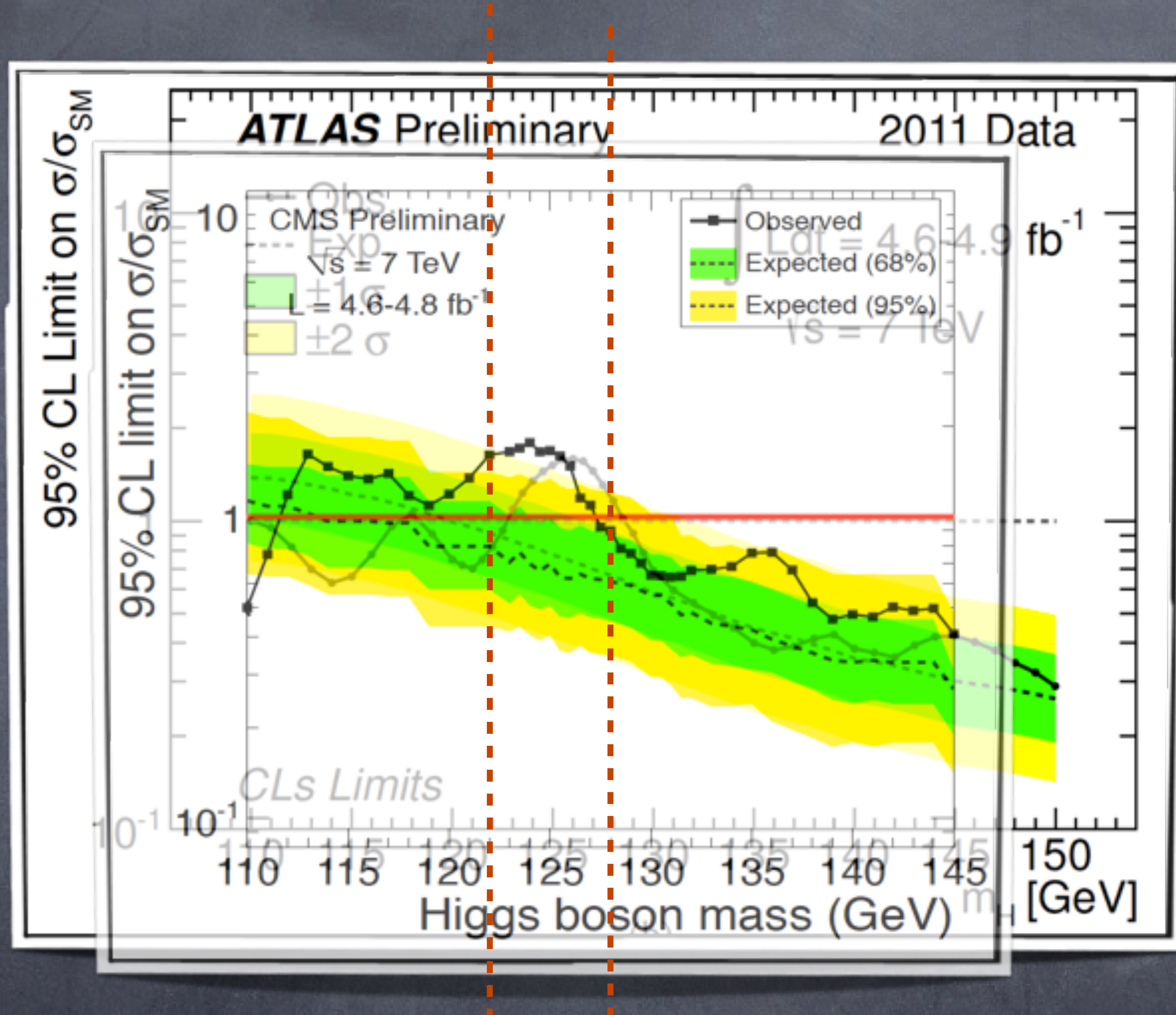


Combined Limit CMS vs ATLAS



- CMS ex[ected exclusion 114.5-543 GeV
- CMS observed exclusion 127.5-600 GeV

Combined Limit CMS vs ATLAS

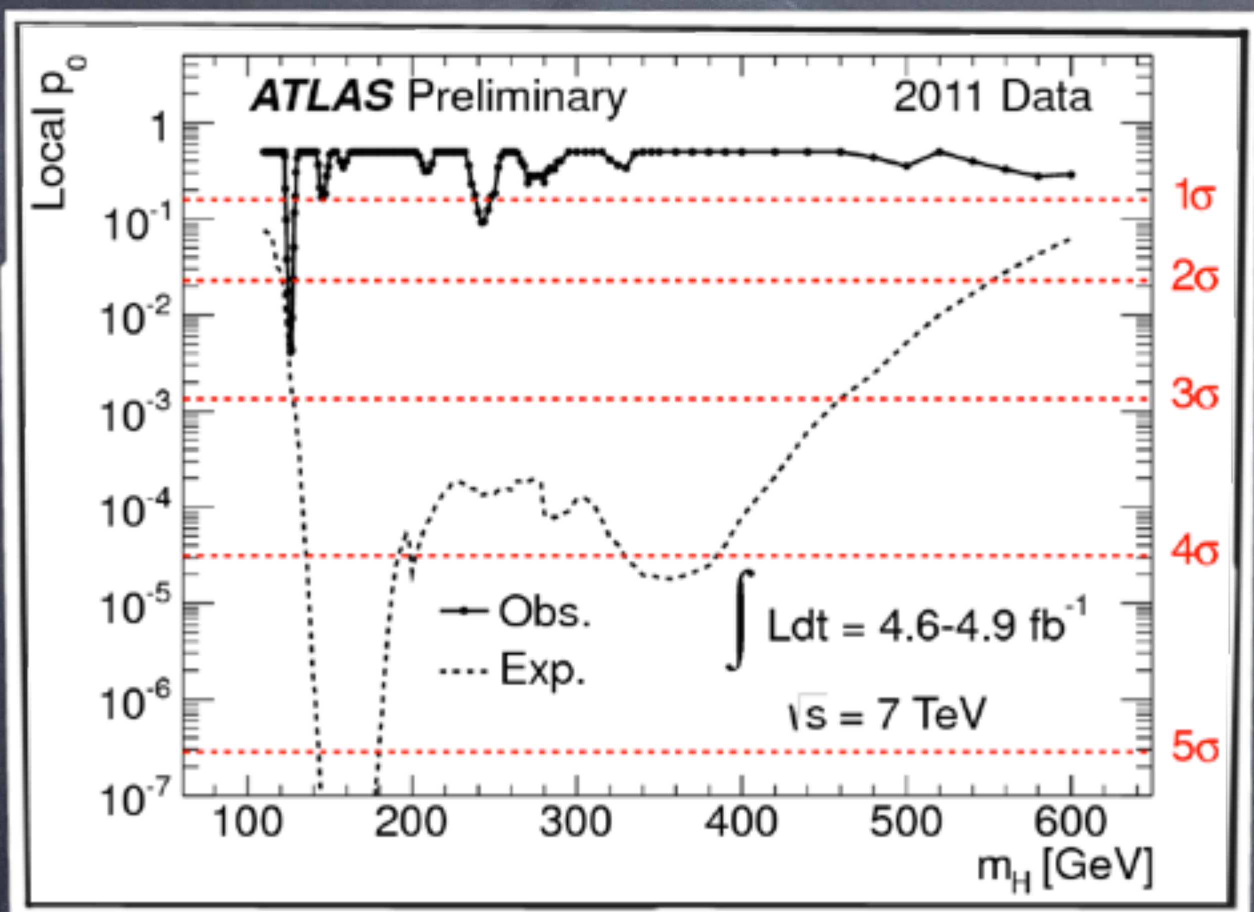


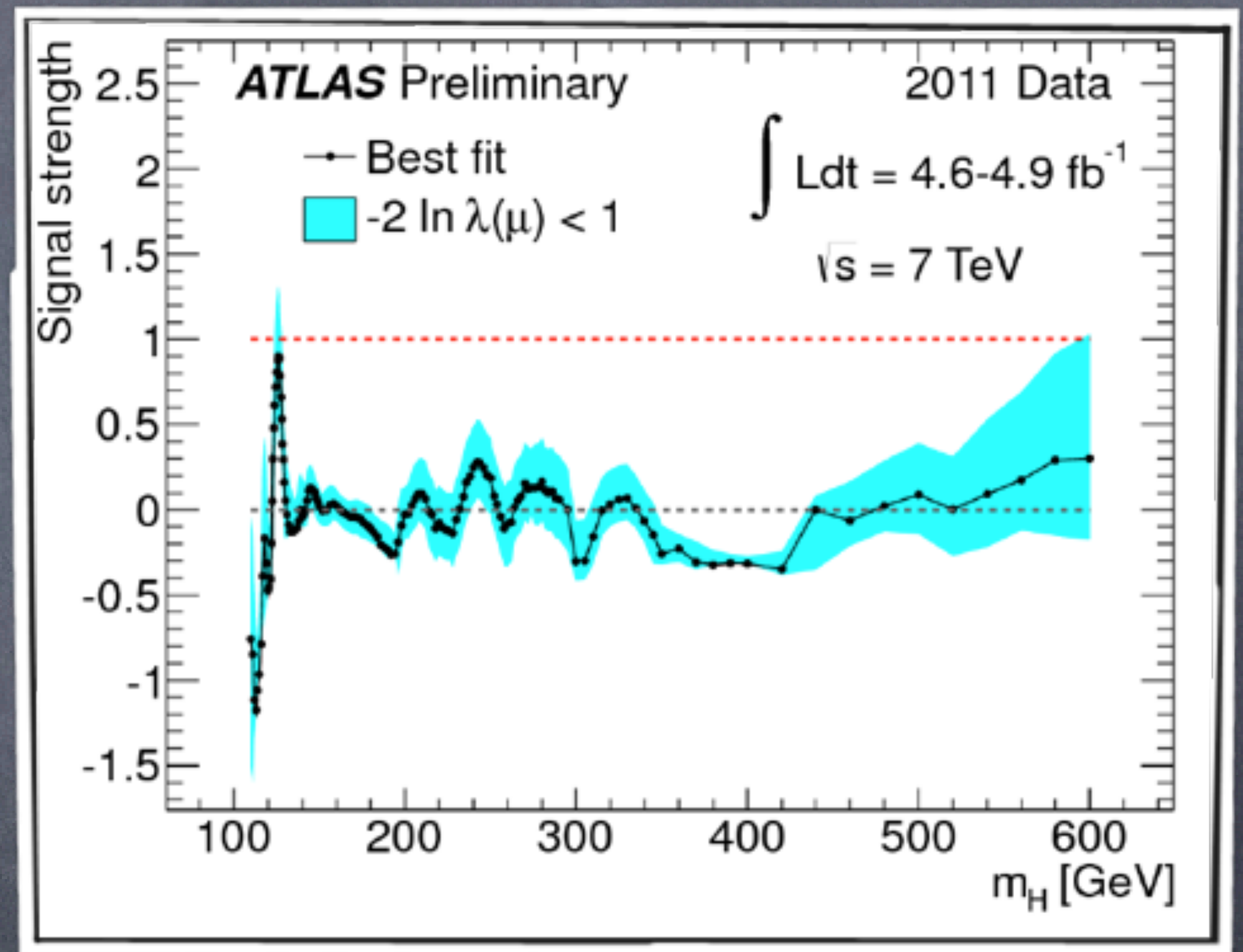
- Not much living space for the Higgs to be, around 122-128 GeV

ATLAS combined p_0 and $\hat{\mu}$

$$\mu = \sigma / \sigma SM$$

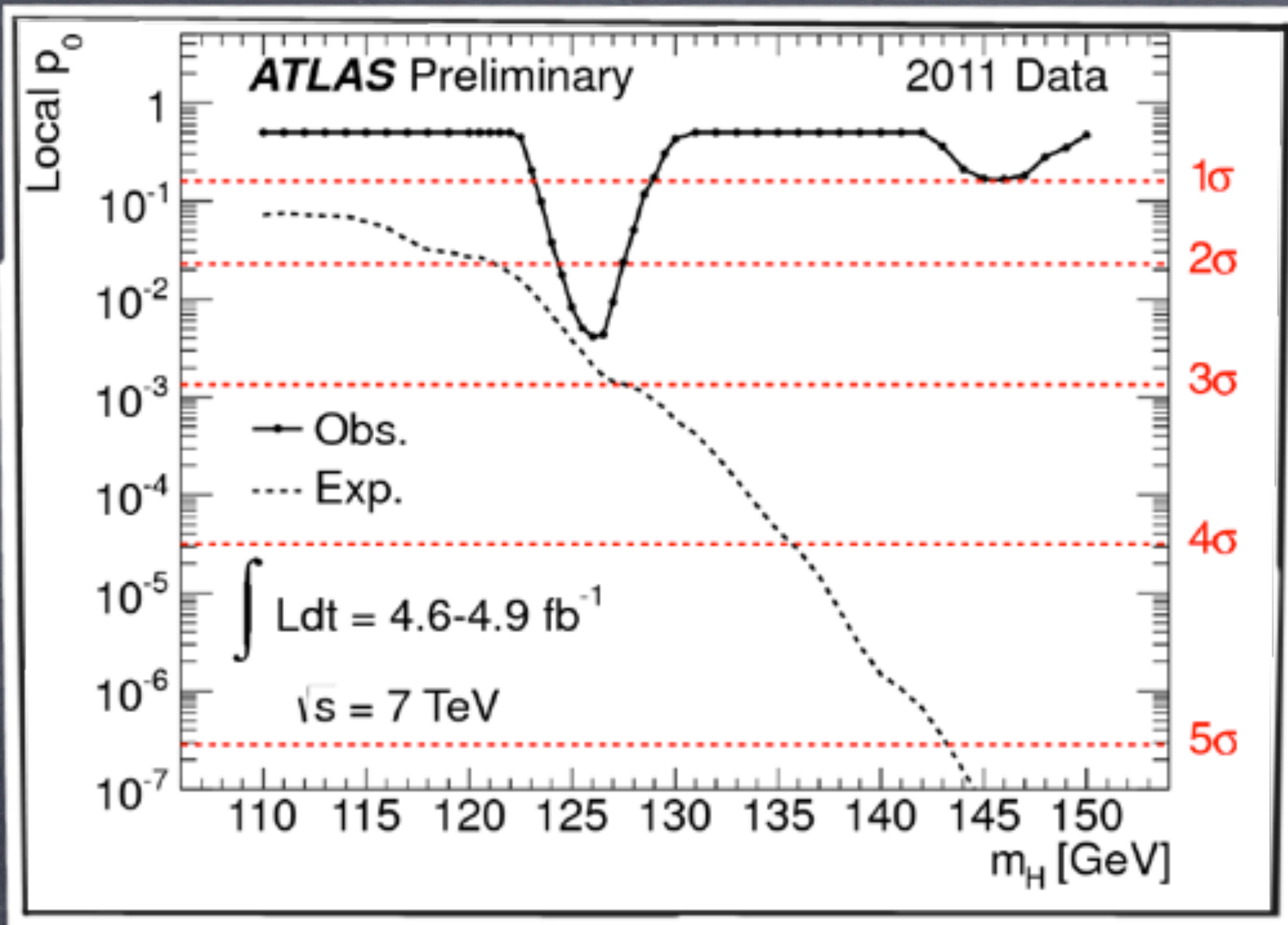
$$\hat{\mu} = \left\{ \mu \middle| L(\mu s(m_H) + b) = \max L(\mu, b) \right\}$$

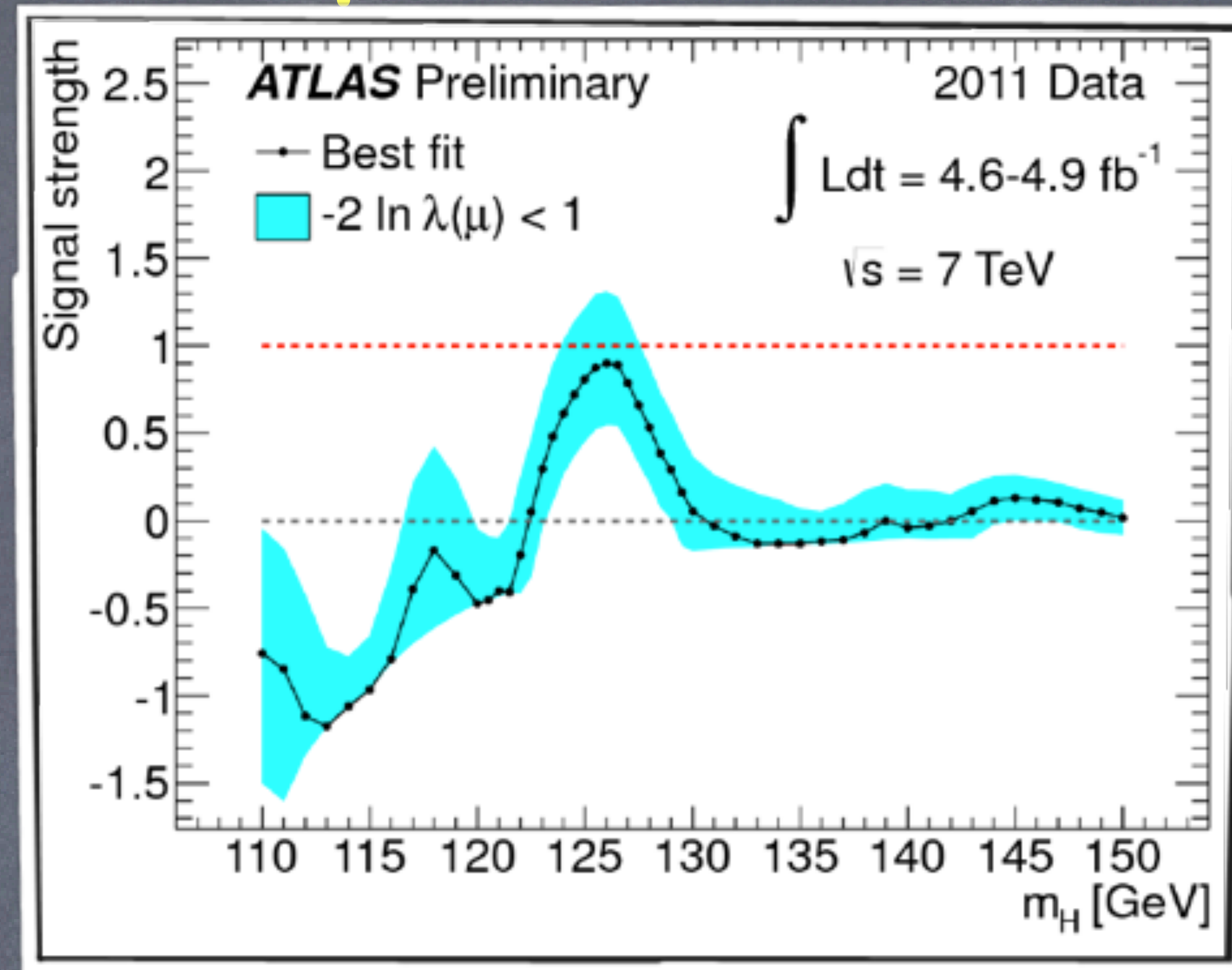




- There is an excess at the low mass that could be compatible with a SM light Higgs

ATLAS combined p_0 and $\hat{\mu}$



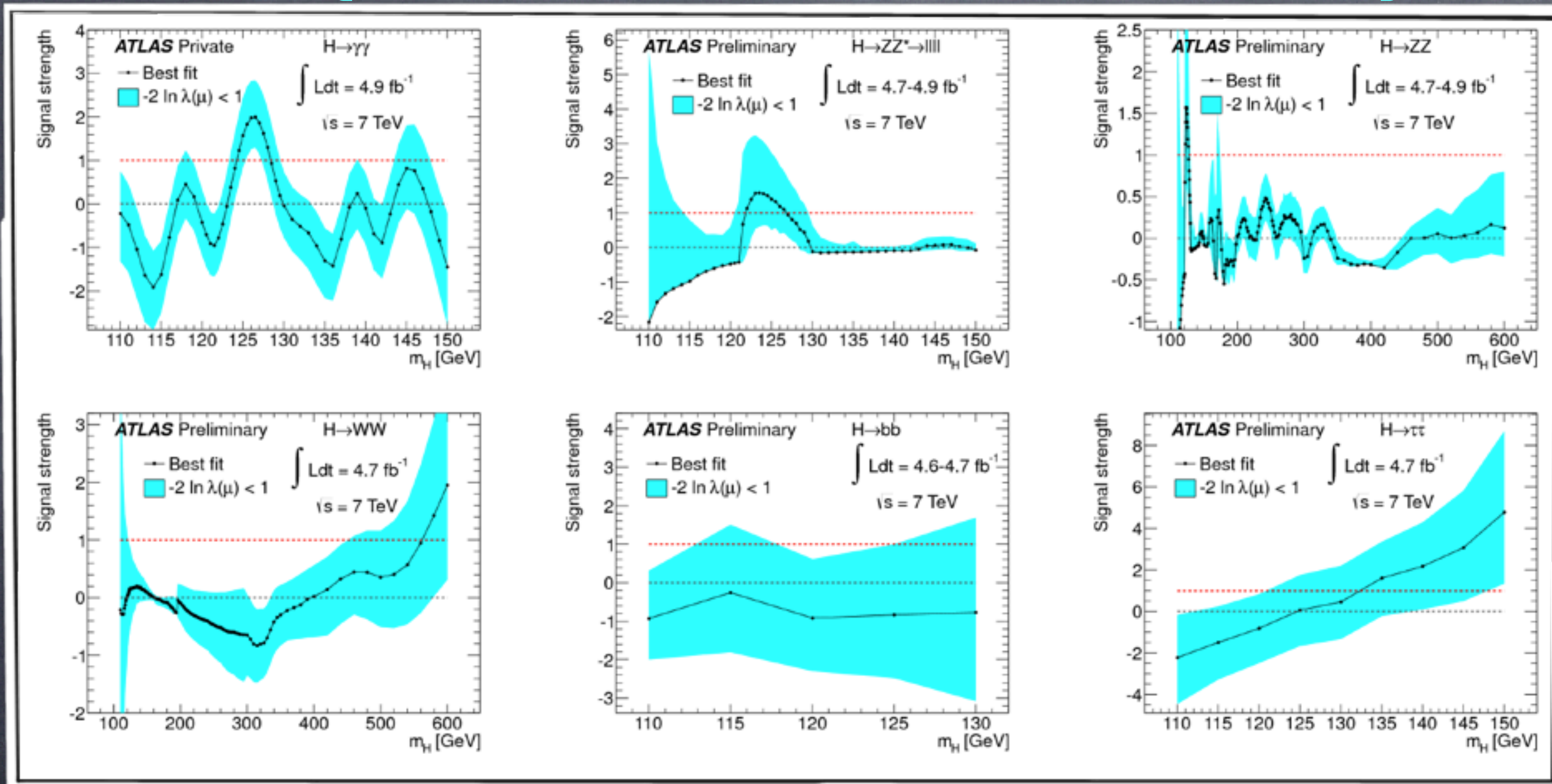


- There is an observed fluctuation at the level of 2.5σ (expected 2.9σ) at m_H=126 GeV with a best fit signal strength of $\hat{\mu} = 0.9^{+0.4}_{-0.3}$

- Global p_0: 10% with LEE over 110-146 GeV
  30% with LEE over 110-600 GeV

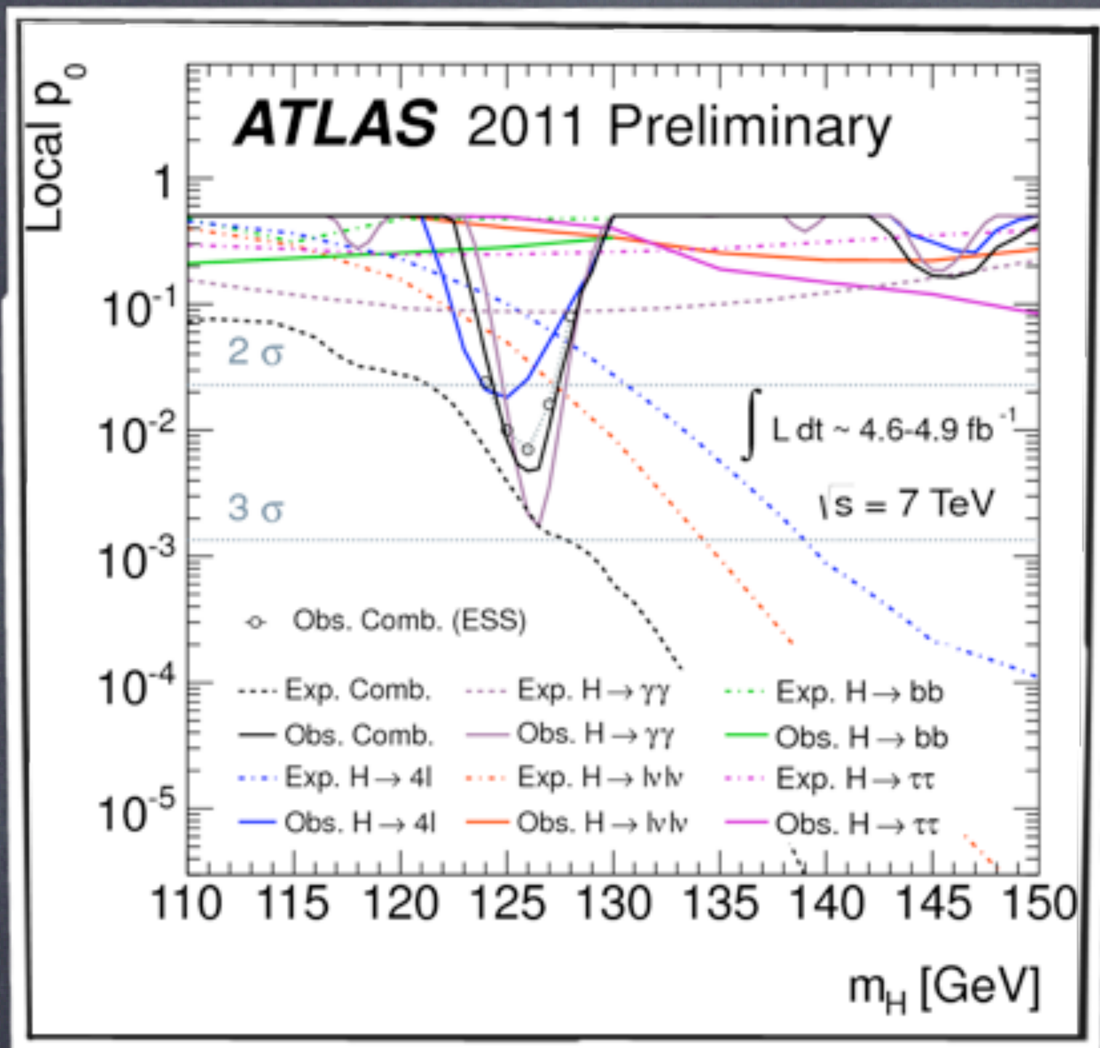
Combined ATLAS signal strength

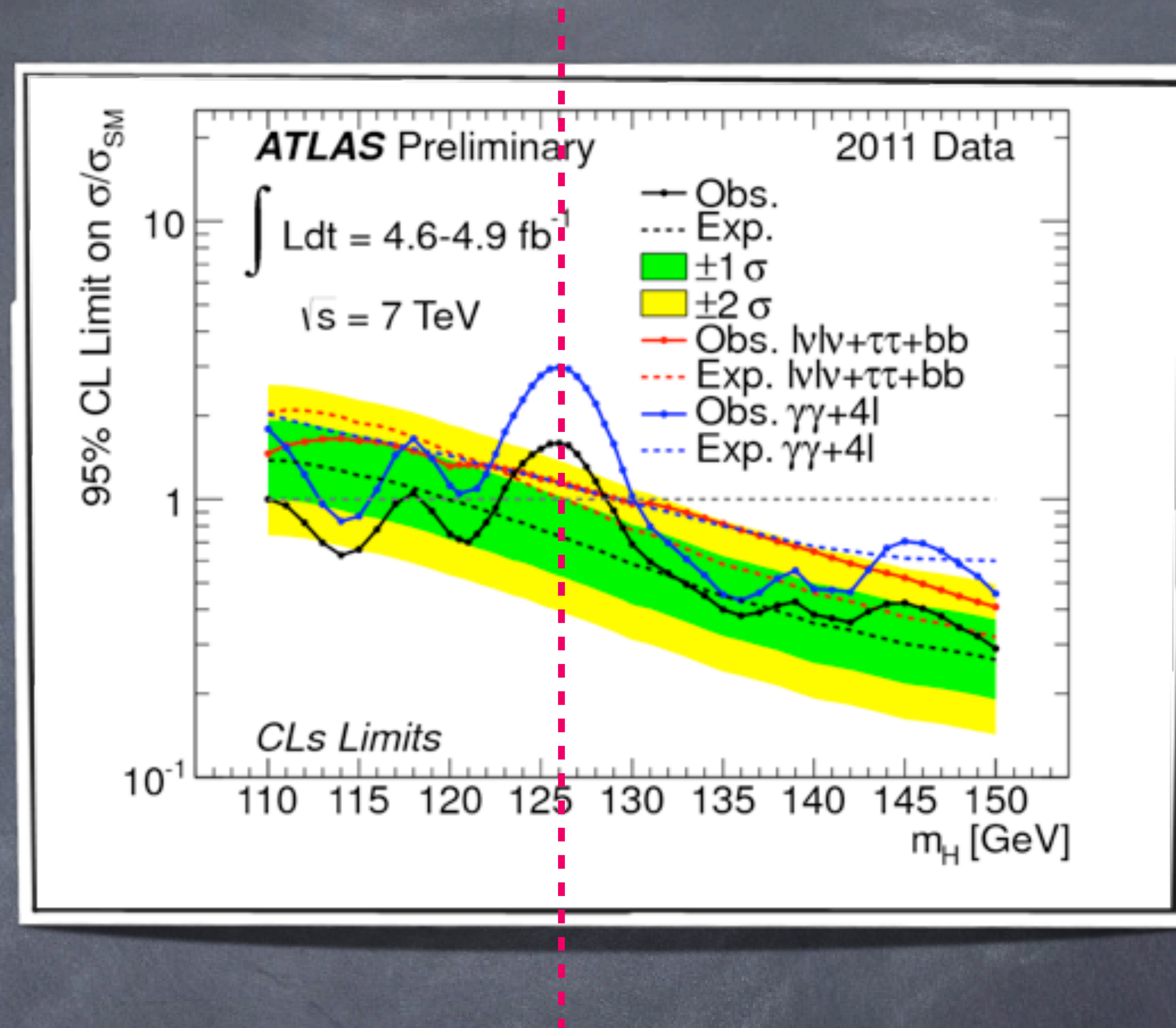
$$\hat{\mu} = \left\{ \mu \middle| L(\mu s(m_H) + b) = \max L(\mu, b) \right\}$$



The observed excess is driven by γγ at 126 GeV, it is larger than 1σ (γγ) from the SM value ($\hat{\mu}_{SM} = 1$) and within 1σ when combined $\hat{\mu} = 0.9^{+0.4}_{-0.3}$

Composition of Excess



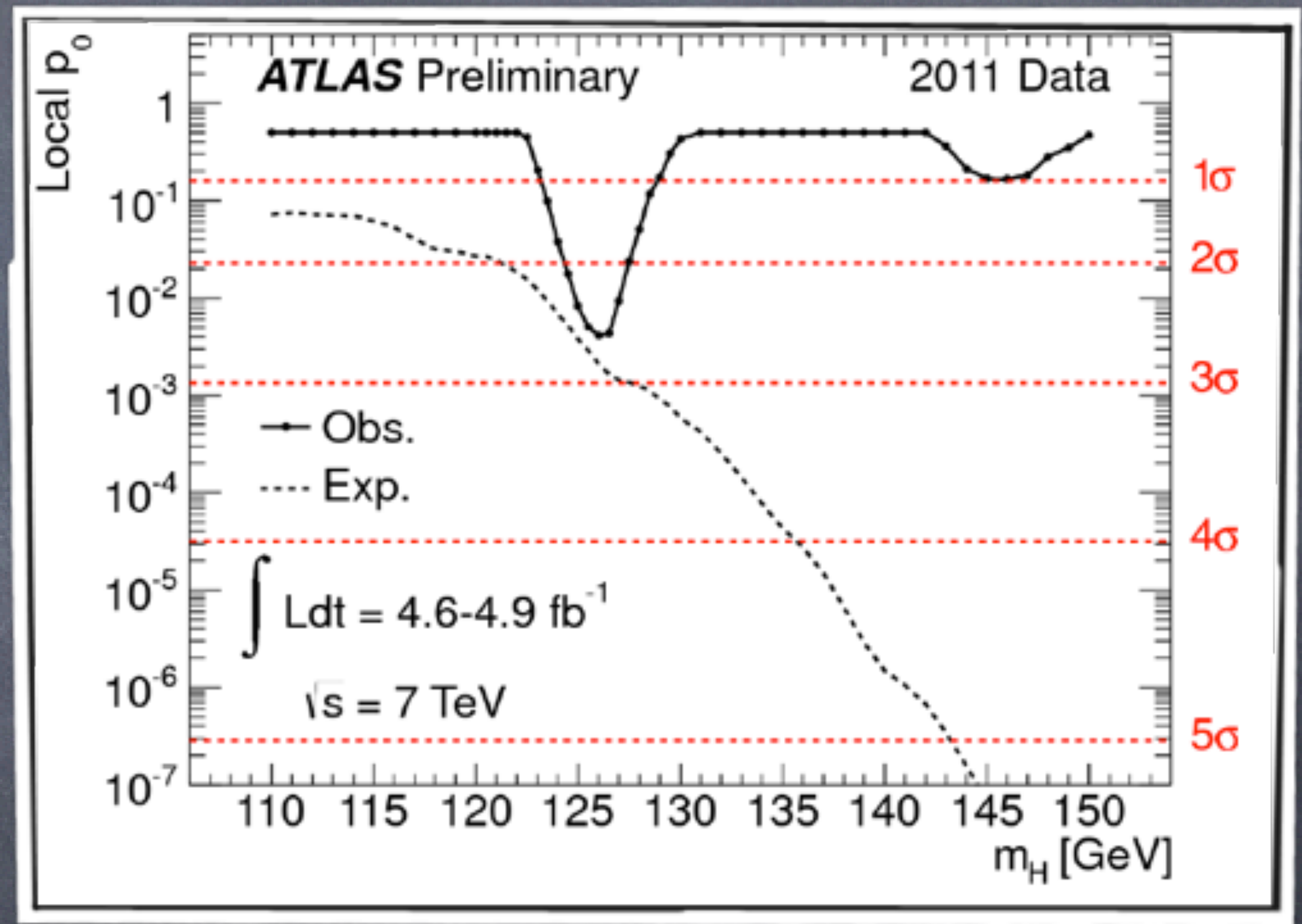


- Excess is mainly composed of the high resolution channels,
  γγ (obs 2.8σ exp 1.4σ) and 4l (obs 2.1σ, exp 1.4σ)
- Excess is not seen in the low resolution channels WW->lvlv (obs 0.2σ, exp 1.6σ), bb and ττ.
- Combined local significance of 2.5σ (taking Energy Scale Systematics into account)

- The low resolution channels do not exclude 126 GeV Higgs

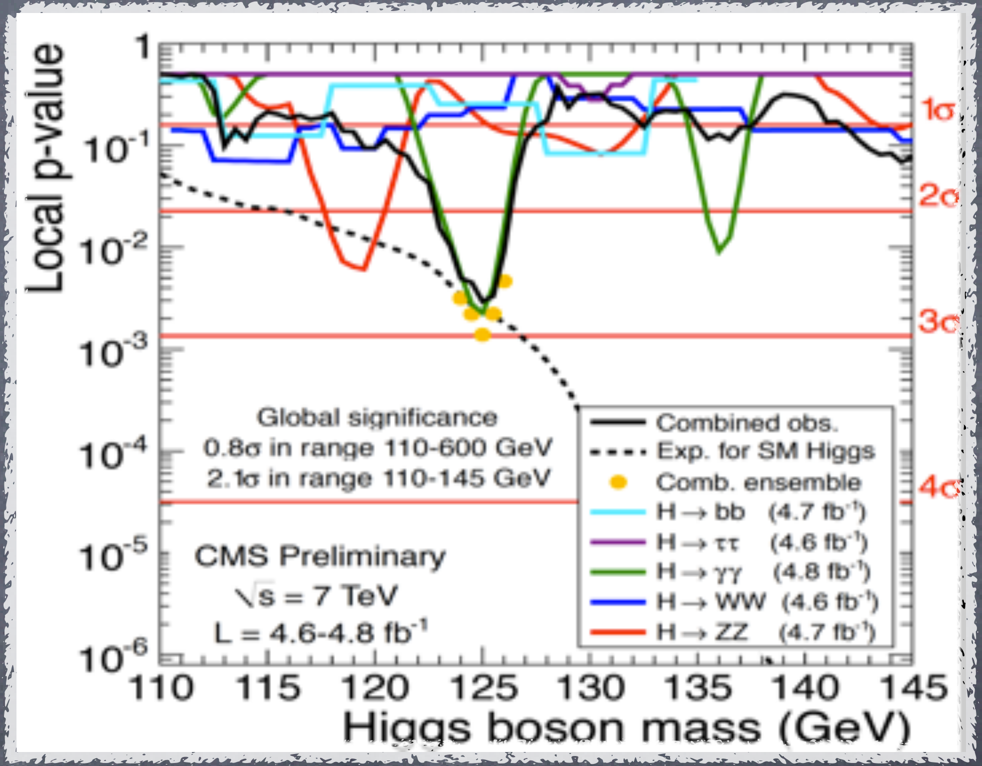
ATLAS vs CMS combined p_0

- ATLAS: local excess of 2.5σ at mH=126 GeV
-



ATLAS vs CMS combined p_0

- ATLAS: local excess of 2.5σ at mH=126 GeV
- CMS: local excess of 2.9σ at mH=125 GeV



ATLAS vs CMS combined p_0

- ATLAS: local excess of 2.5σ at mH=126 GeV
- CMS: local excess of 2.9σ at mH=125 GeV

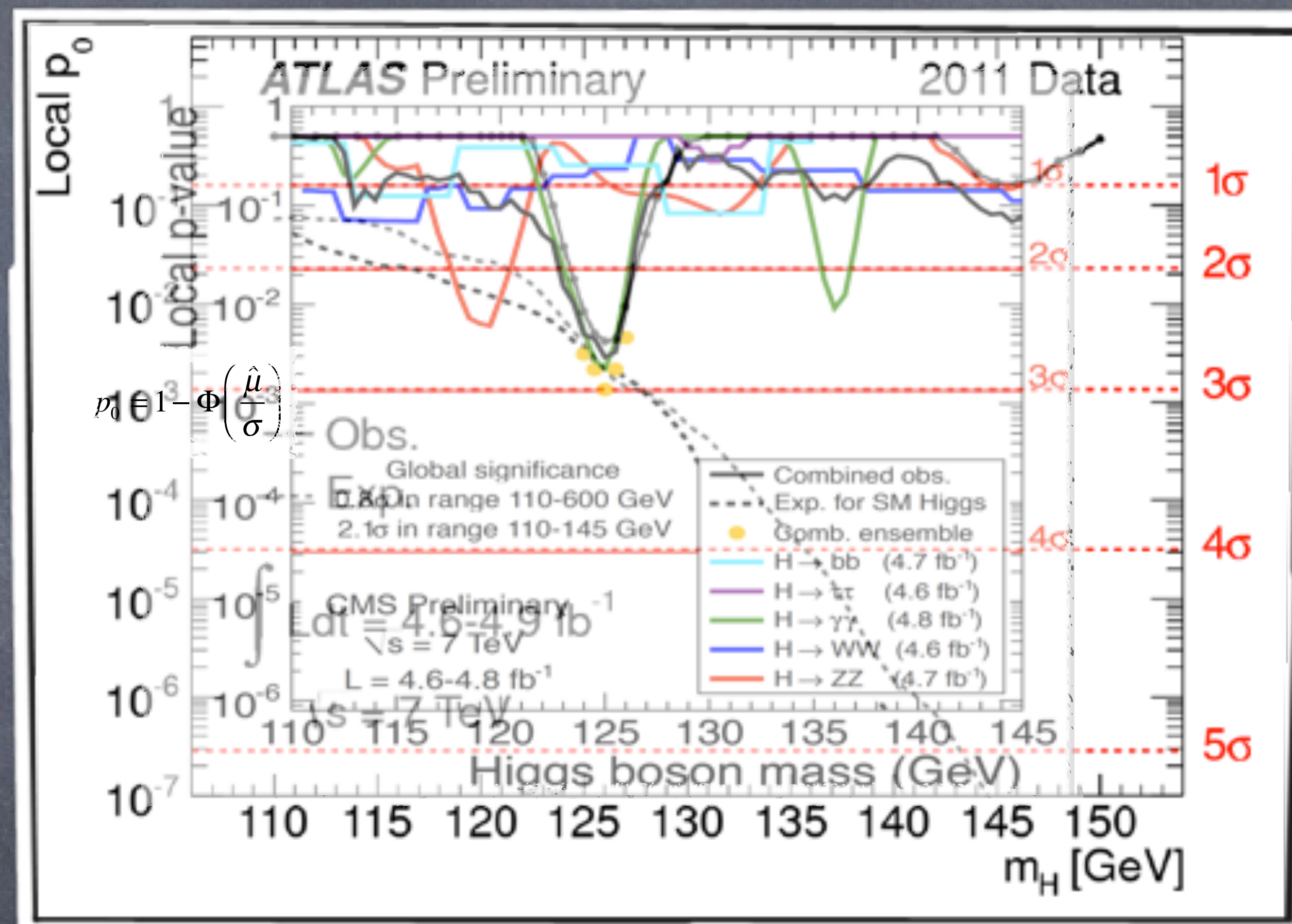
Cowan et. al. , EPJC 71 (2011) 1-19.

$$\mu_{up} = \hat{\mu} + \sigma\Phi^{-1}\left(1 - \alpha\Phi\left(\frac{\hat{\mu}}{\sigma}\right)\right)$$

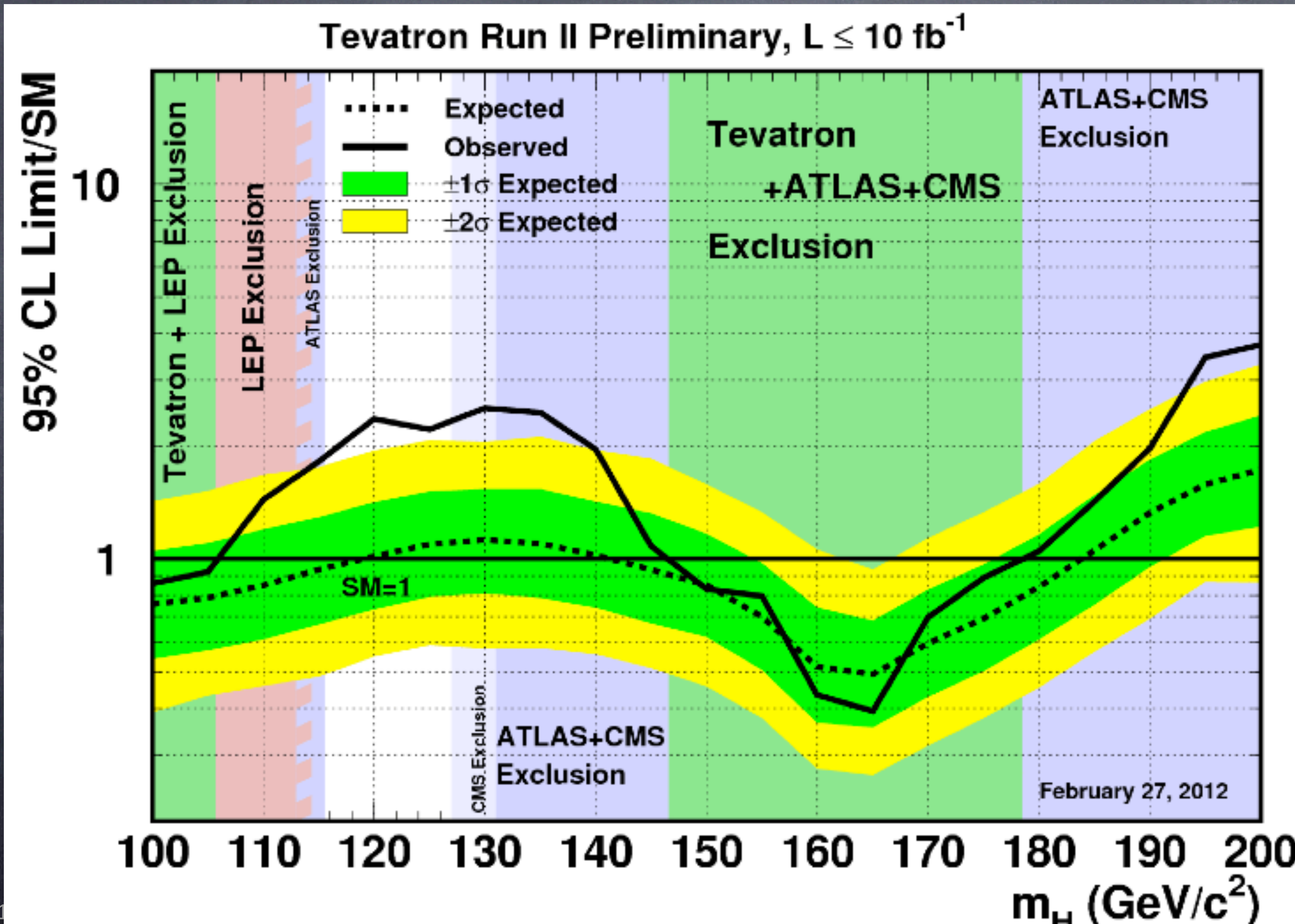
$$\hat{\mu} = \frac{\hat{\mu}_1\sigma_1^{-2} + \hat{\mu}_2\sigma_2^{-2}}{\sigma_1^{-2} + \sigma_2^{-2}}$$

$$\sigma^{-2} = \sigma_1^{-2} + \sigma_2^{-2}$$

$$p_0 = 1 - \Phi\left(\frac{\hat{\mu}}{\sigma}\right)$$

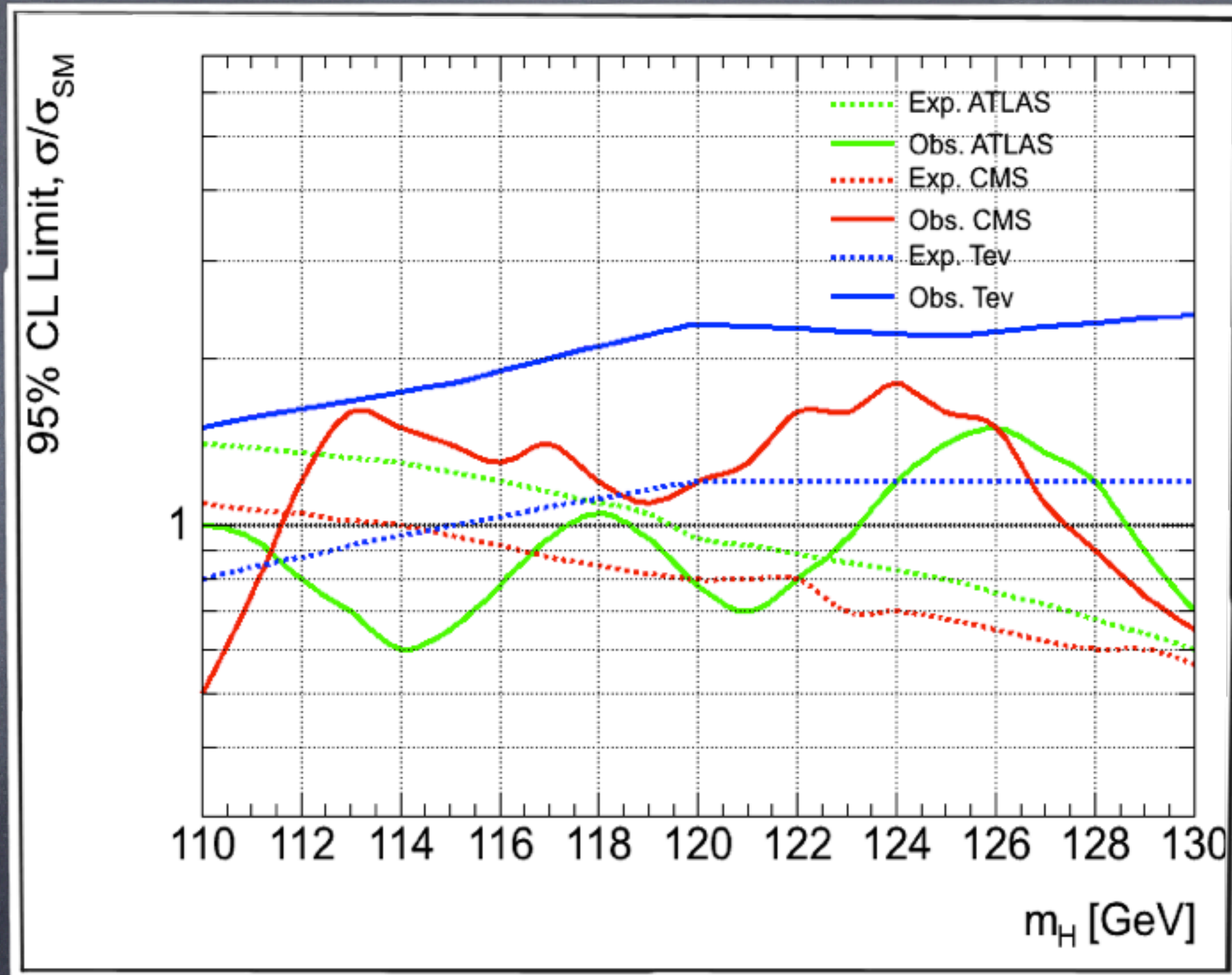


Tevatron results March 2012



ATLAS+CMS+TEVATRON

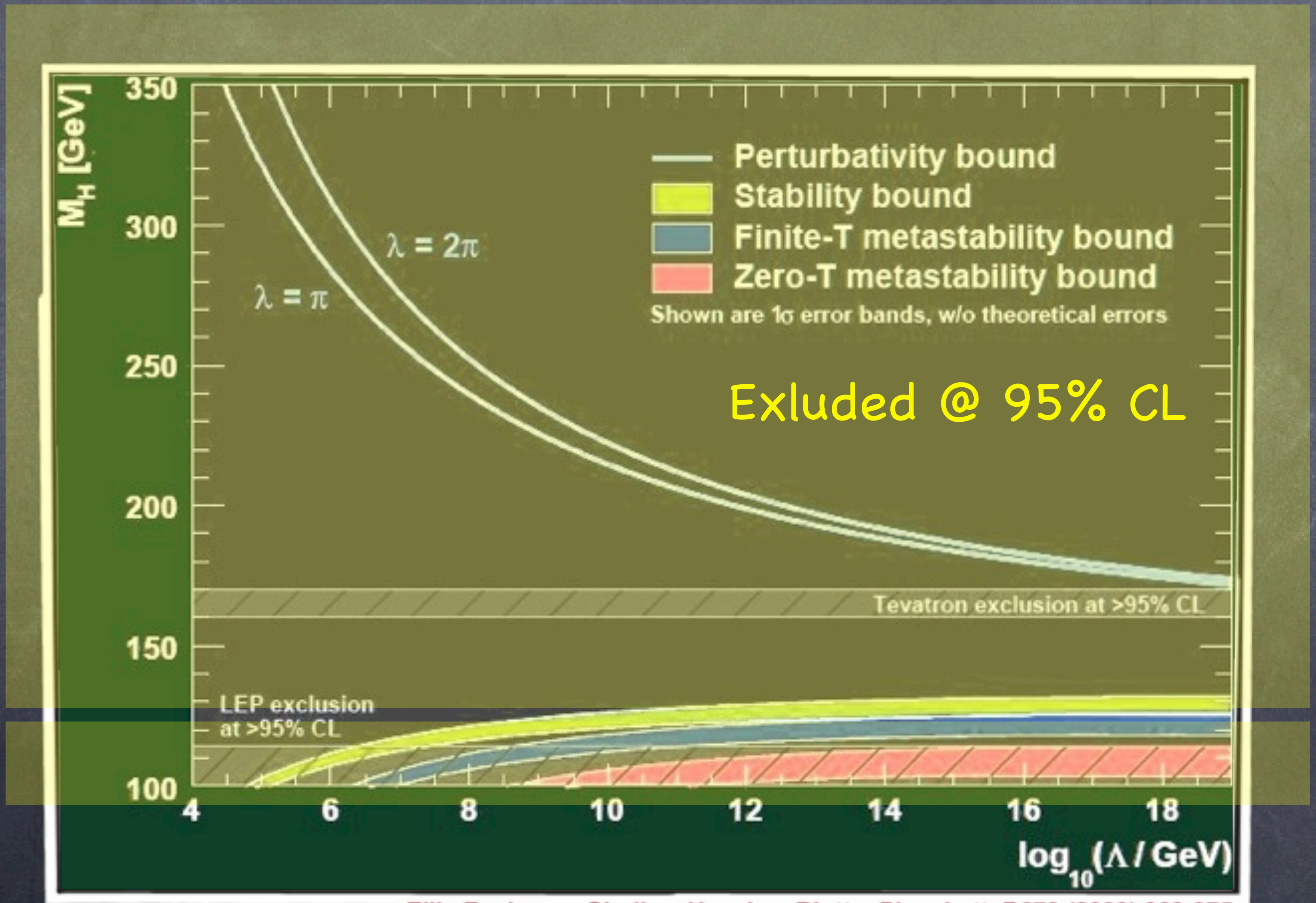
- ATLAS and CMS compensate each other except ~125 GeV
- TEVATRON pulls the combination a bit up
- The observed TEVATRON is too high to affect the combination, yet the expected is low, will reduce the 1σ band size and increase the exclusion significance



from B Murray

Nightmare Scenario I: SM Higgs, period.

- Not much living space is left for the Higgs boson
- Looks like if there is a SM Higgs, it is either not Standard (i.e. not alone) or our vacuum is metastable



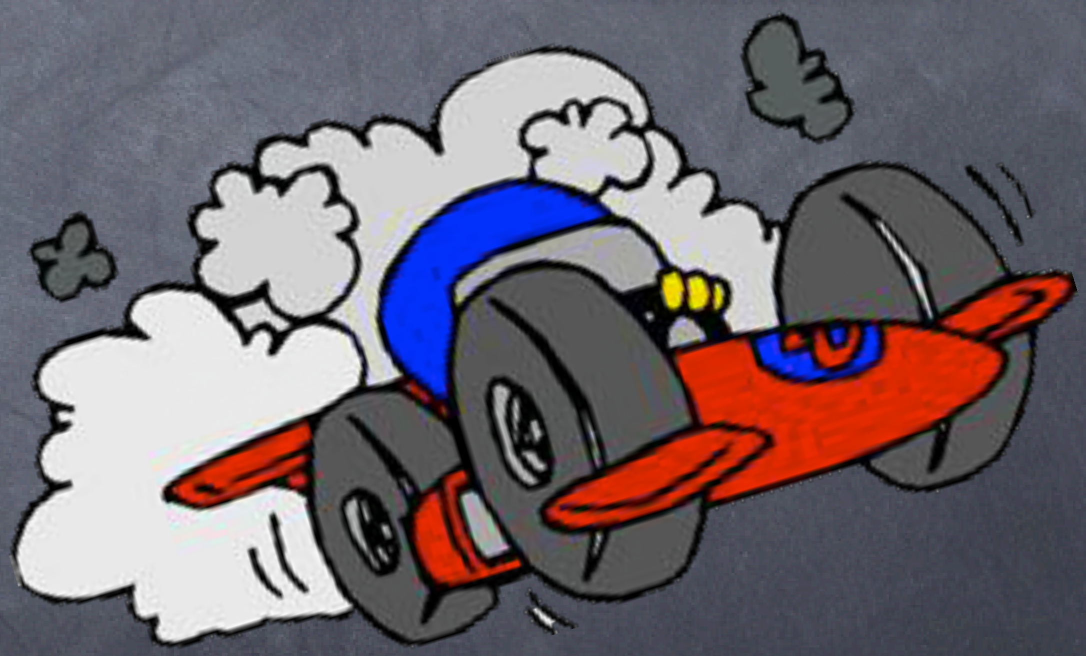
Deserted Higgs space

Ellis,Espinosa, Giudice, Hoecker, Riotto Phys.Lett. B679 (2009) 369-375

M. Lindner, Z. Phys. C 31, 295 (1986); M. Lindner, M. Sher and H. W. Zaglauer, Phys. Lett. B 228, 139 (1989);

Nightmare Scenario II: No Higgs

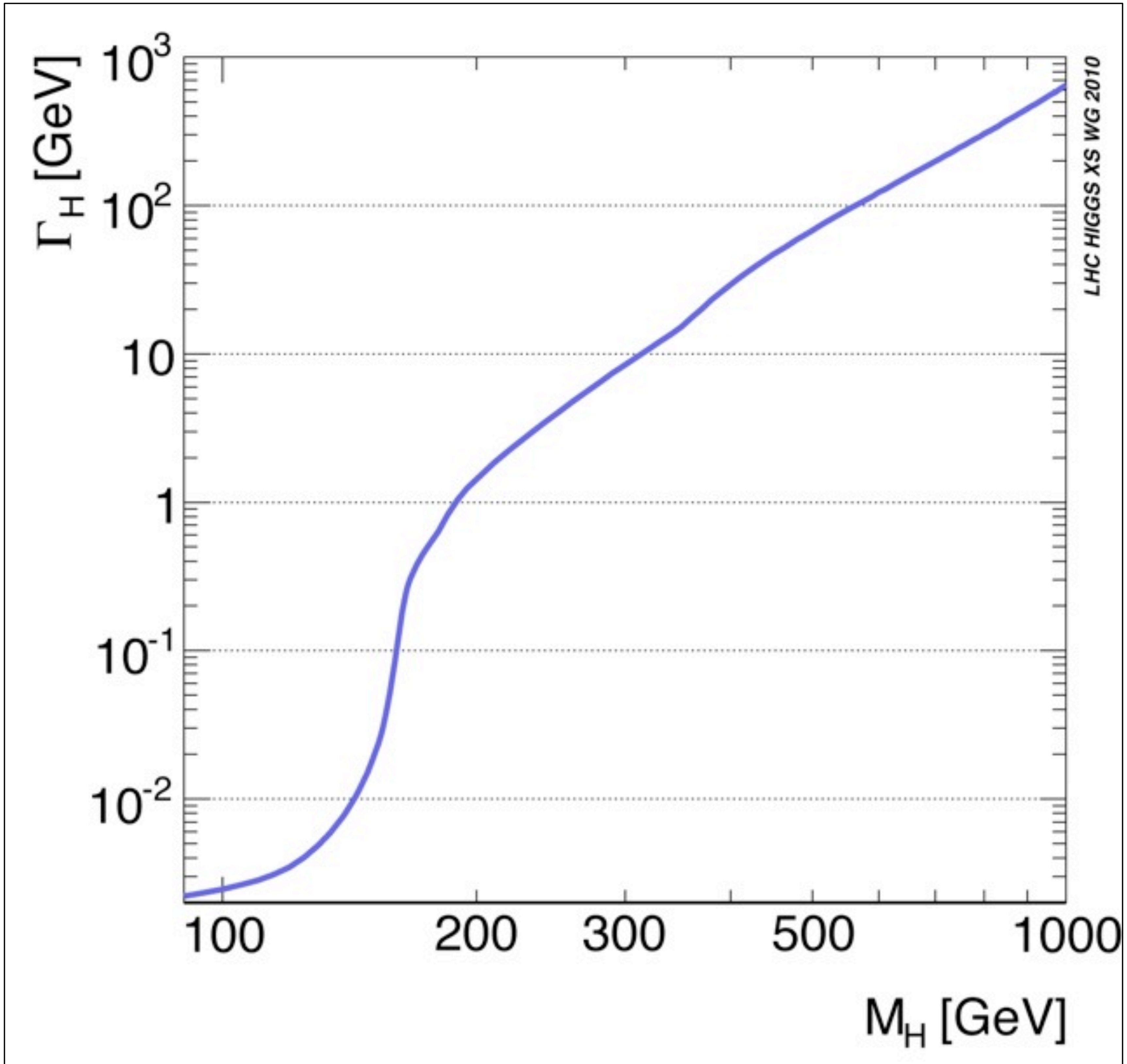
- Not much living space is left for the Higgs boson
- If there is no engine, how does the SM car drives so smooth and fast?



(No) Conclusion

- 2011-2012 are the Higgs & LHC Miraculous Years
- The SM Higgs (if there) is probably light m_H~122-127 GeV ☺
- I think from any point of view (SM, Exotic, SUSY, Higgs ......) this is the prime time for any High Energy Physicist
- 2012 run as of April
  Over 12 fb-1/experiment of delivered luminosity is needed for: 5σ discovery of a 125 GeV Higgs Boson (ATLAS or CMS alone) @E_{CM}=8 TeV OR 7-8 fb-1/experiment taking the 7 TeV results into account

Backup



Γ_H [GeV]
10^3
10^2
10
1
10^{-1}
10^{-2}
100
200
300
500
1000
M_H [GeV]
LHC HIGGS XS WG 2010