Second Lecture: Higgs Boson Search and Discovery

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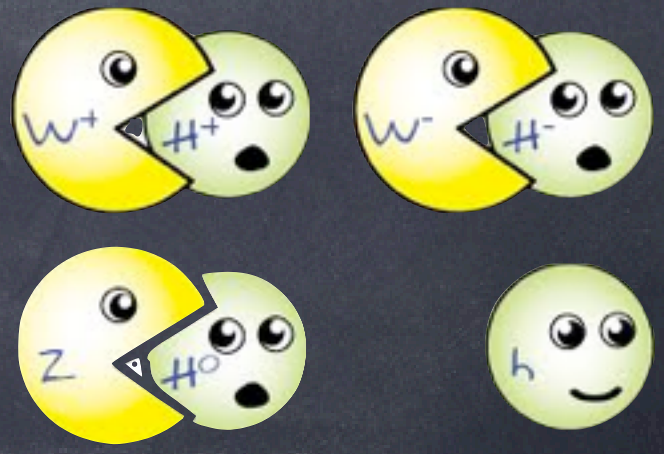
Summary of Lecture 1: SM

- Standard Model of Electroweak interactions has SU(2)XU(1) symmetry
- The symmetry requires that the Electroweak force carriers: Photon, W and Z be massless.
- The photon is massless —>EM interaction has an infinite range
- The range of the weak interaction is short and requires massive force carriers

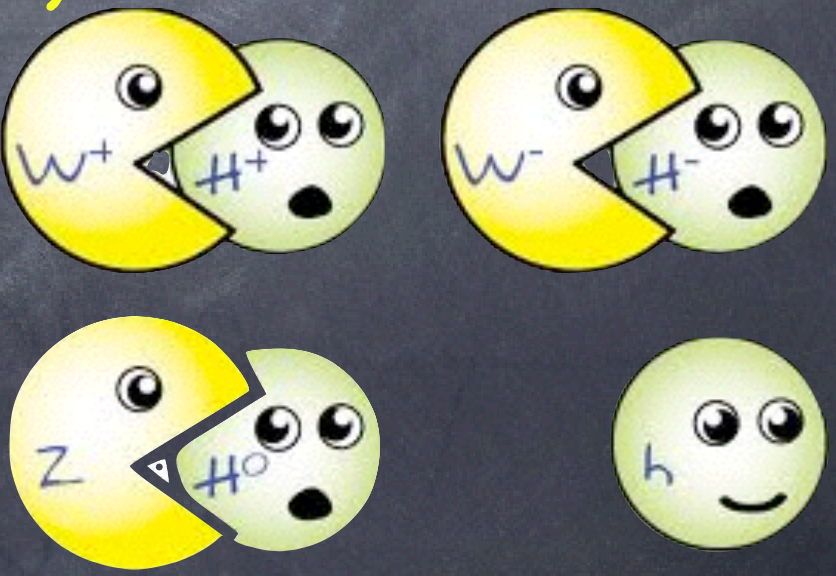


Summary of Lecture 1: SSB

- We introduce to the model additional complex doublet (4 degrees of freedom)

$$\begin{pmatrix} \phi^+ = \phi_1 + i\phi_2 \\ \phi^0 = \phi_3 + i\phi_4 \end{pmatrix}$$

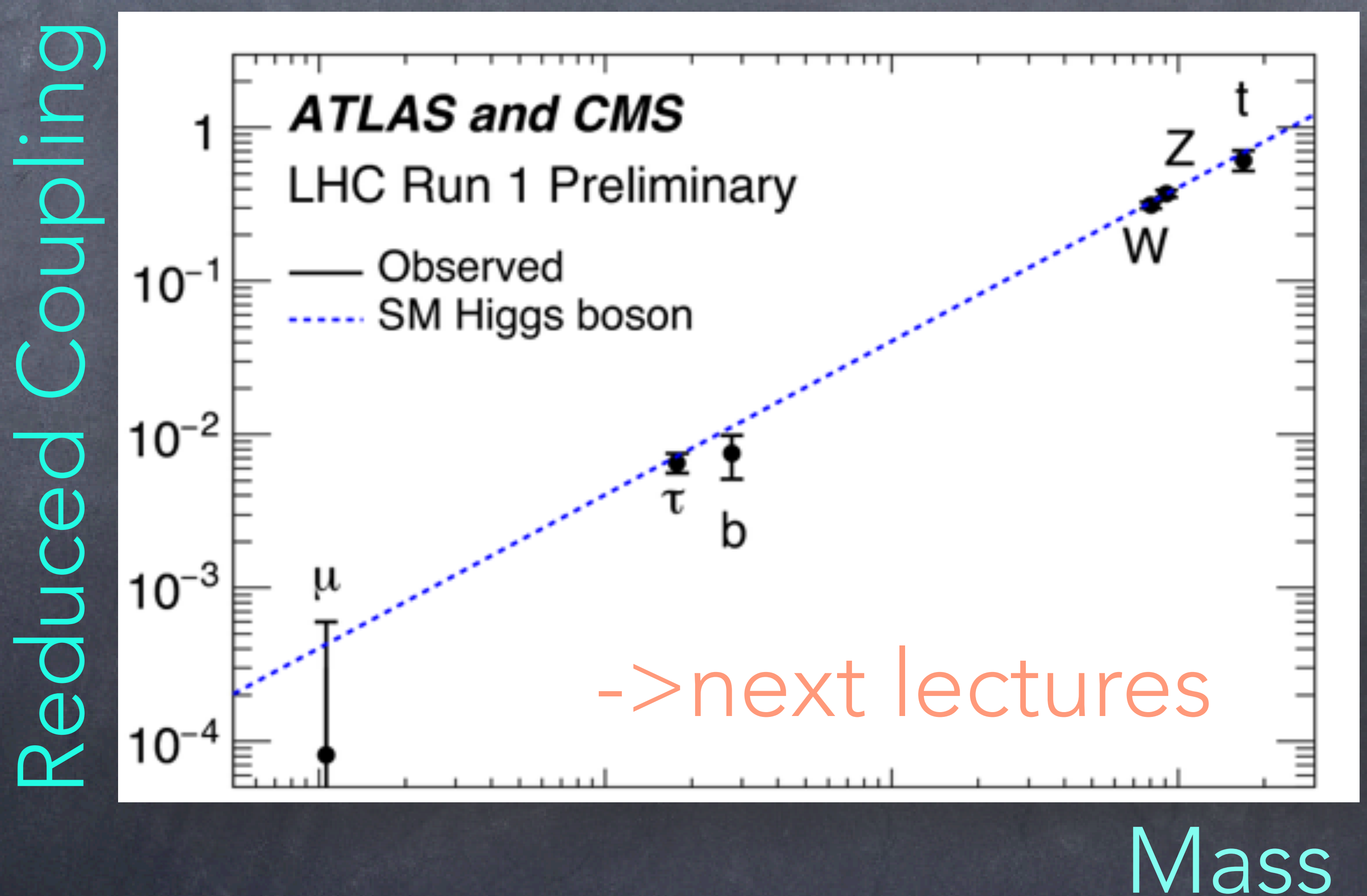
- The W and Z acquire mass WITHOUT explicitly breaking the SU(2)XU(1) symmetry by Spontaneous Symmetry Breaking (SSB).
- The massless W^+,W^- and Z (2x3=6 d.o.f) "eat" the 3 of the 4 doublet d.o.f. and acquire mass
- The leftover d.o.f. is the higgs Boson



Summary of Lecture 1: Higgs Couplings

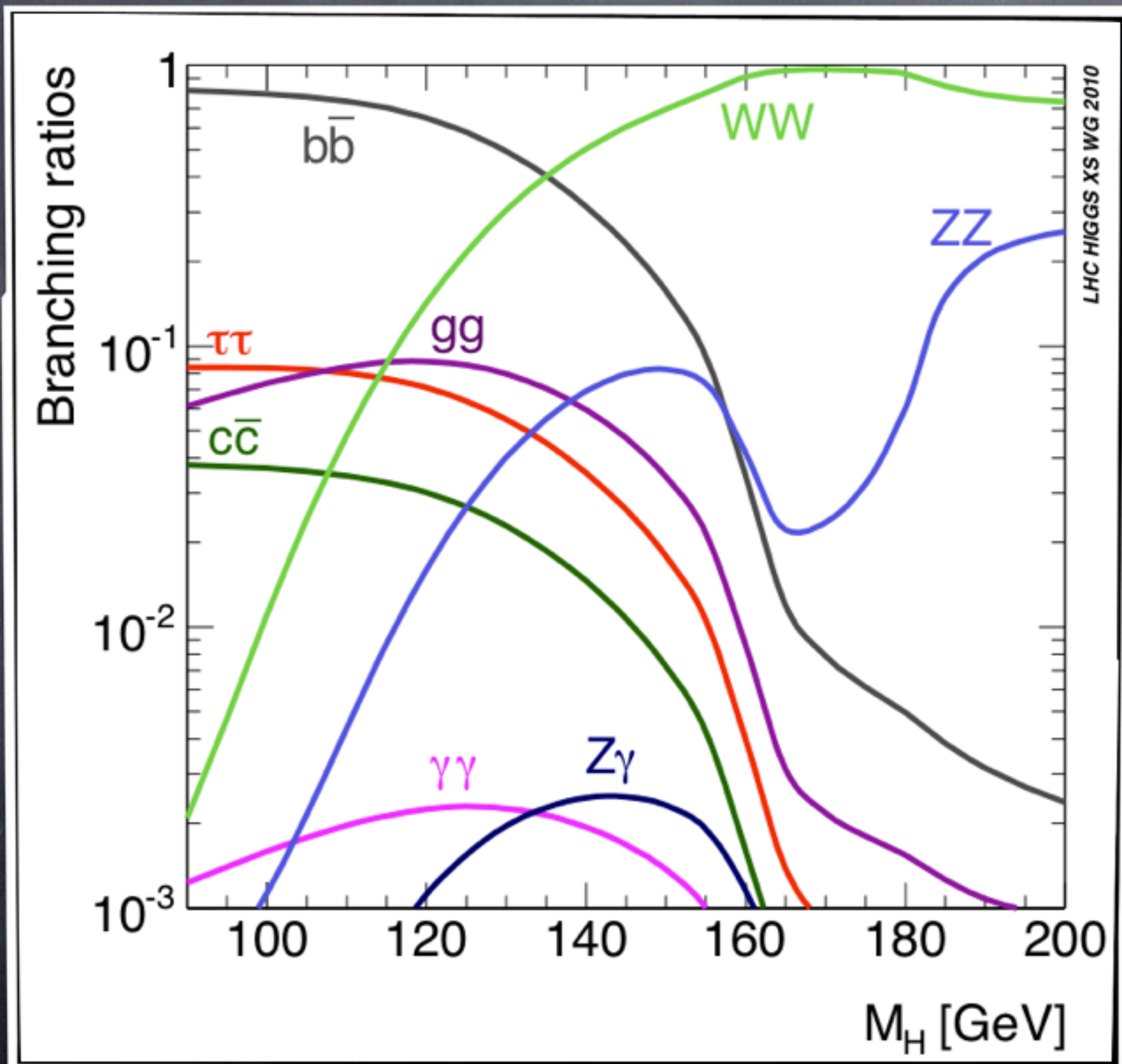
- Te Higgs coupling to particles is proportional to their mass

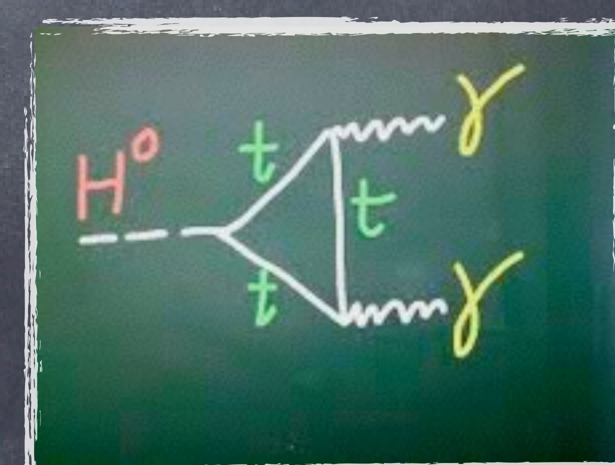
$$g_{Hff} = \frac{m_f}{v} \quad v \approx 240 GeV \qquad g_{HVV} \sim m_V^2$$



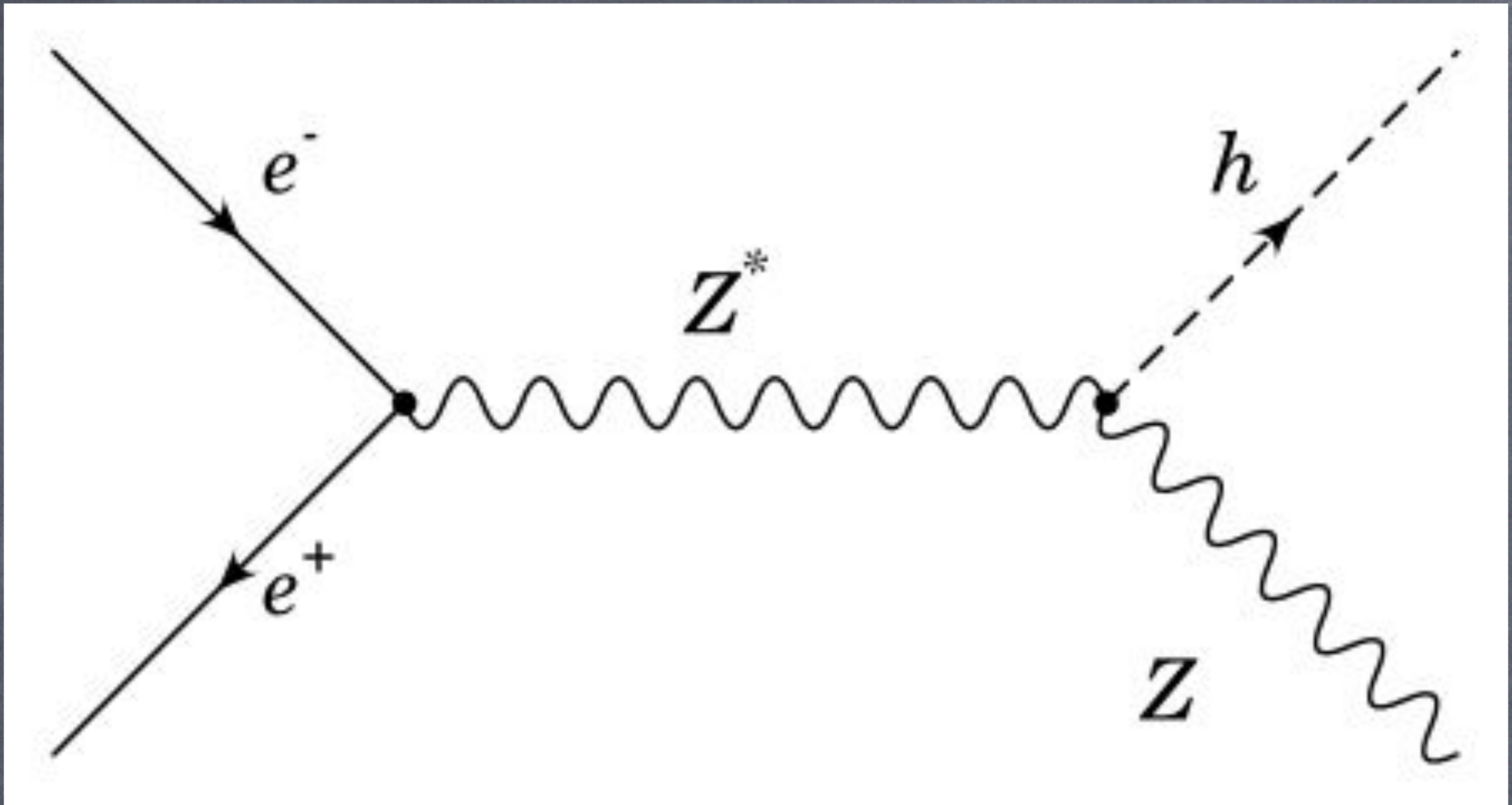
Branching Ratios

$$BR(H \to \bar{f}f) = Prob(H \to \bar{f}f) \sim m_f^2$$



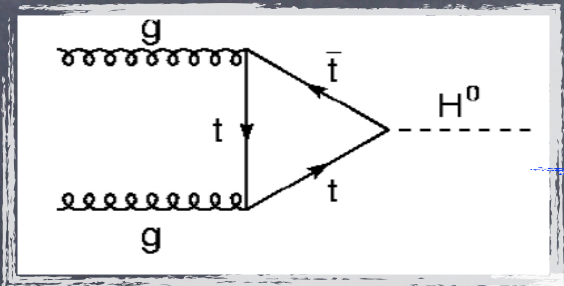


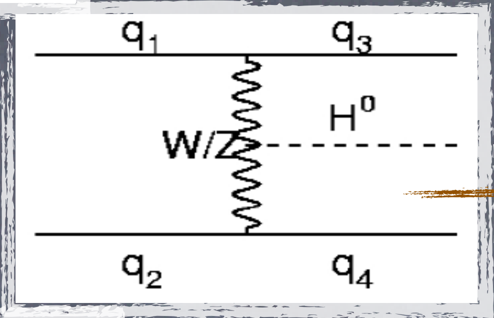
Higgs at LEP



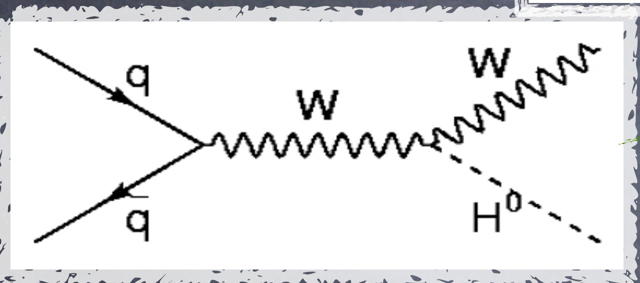
- LEP legacy: mH>114 GeV

Higgs Production @ LHC

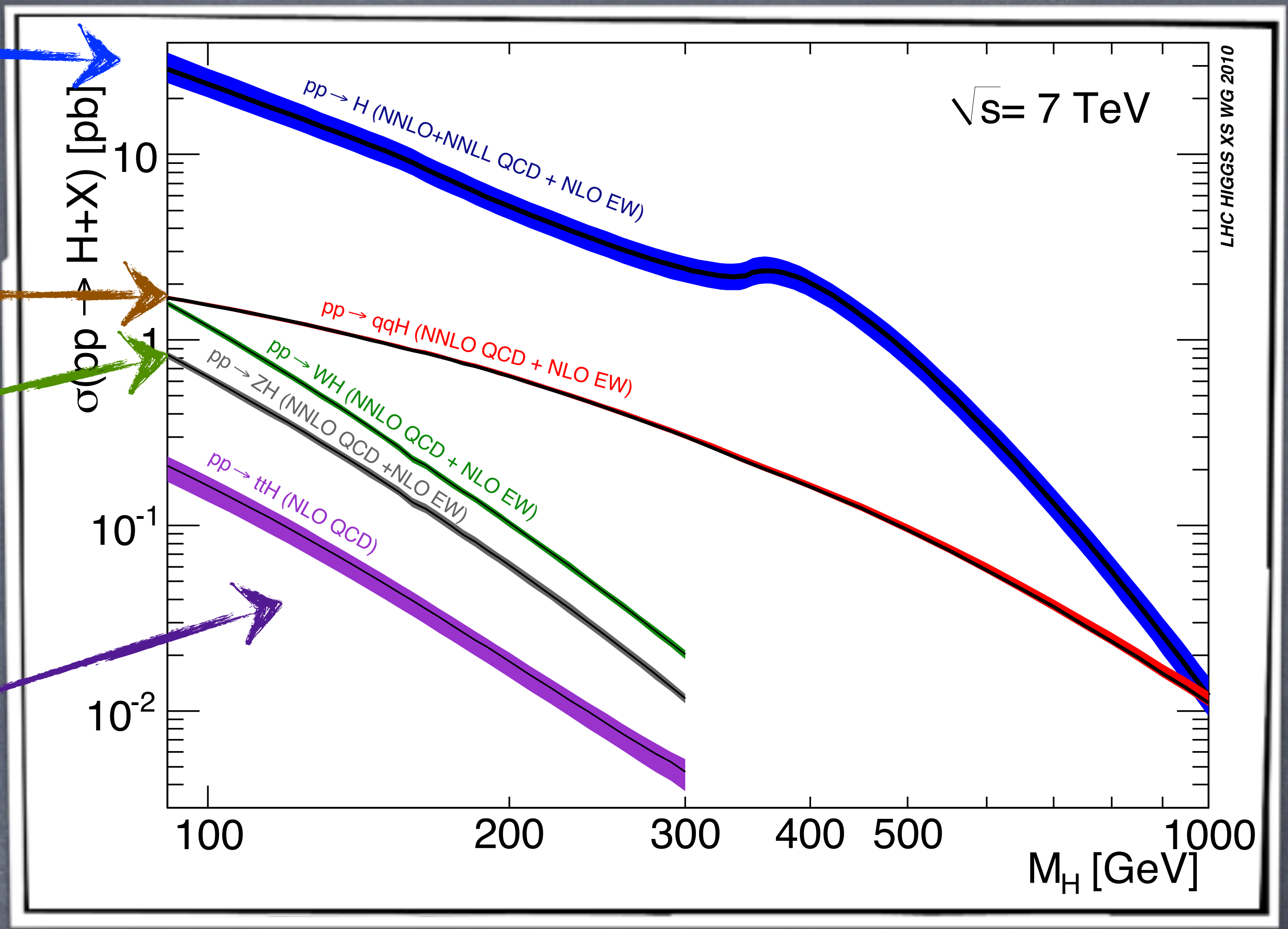


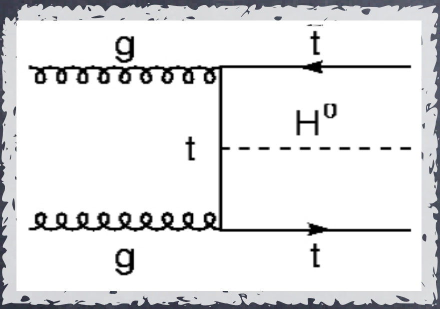


is x10 then



is even smaller, yet distinct





is the smallest and also difficult

Unit	Symbol	m^2	cm^2
megabarn	Mb	10^{-22}	10^{-18}
kilobarn	kb	10^{-25}	10^{-21}
barn	b	10^{-28}	10^{-24}
millibarn	mb	10^{-31}	10^{-27}
microbarn	µb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb	10^{-52}	10^{-48}

$$1\,fb = 10^{-3}\,pb$$

$$1\,fb^{-1} = 1000\,pb^{-1}$$

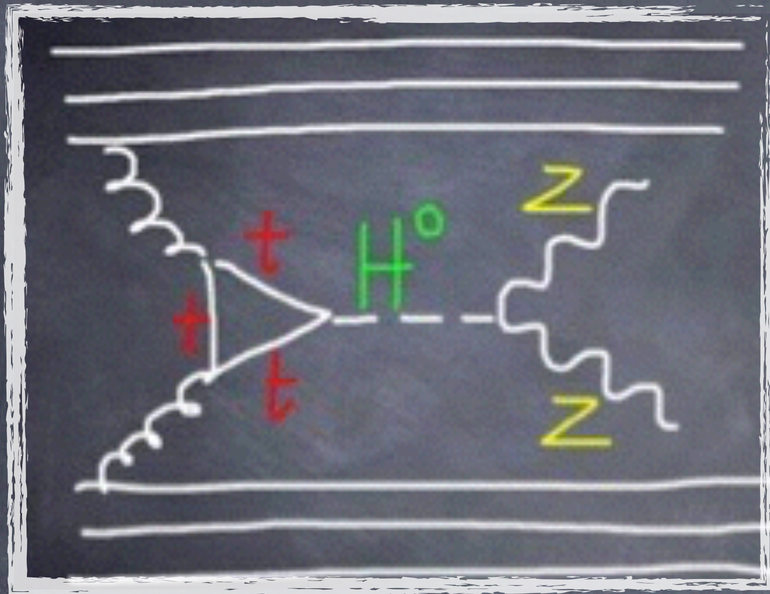
$$L = 3\times 10^{32}\,collisions/(cm^2\,\text{sec})$$

$$in\ 8\ hours = 28800\,sec$$

$$\int Ldt = 8.64\ collisions/pb =$$

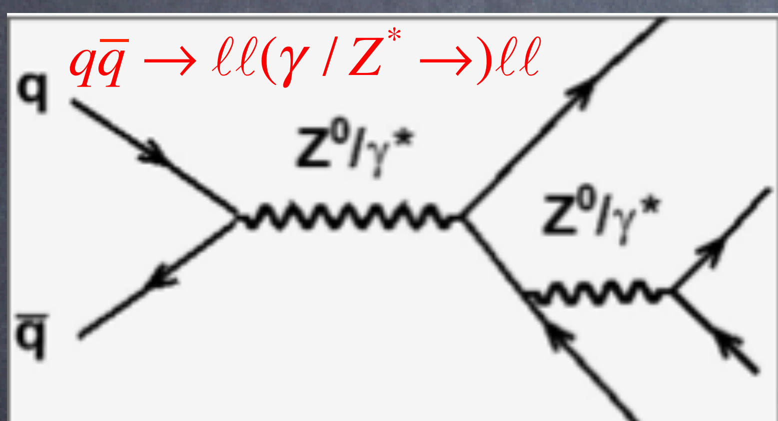
$$\sigma_x = 10\ pb ==> N_x = \sigma\int Ldt = 864$$

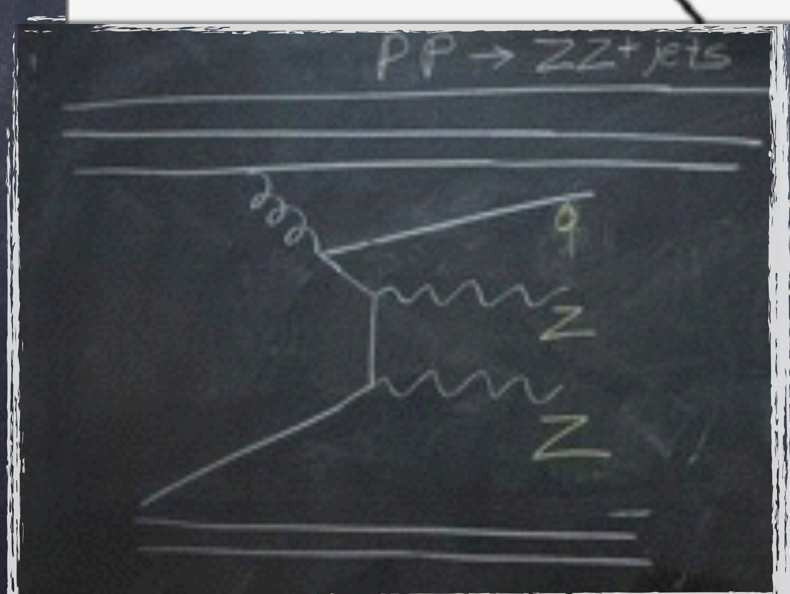
Signal and Background

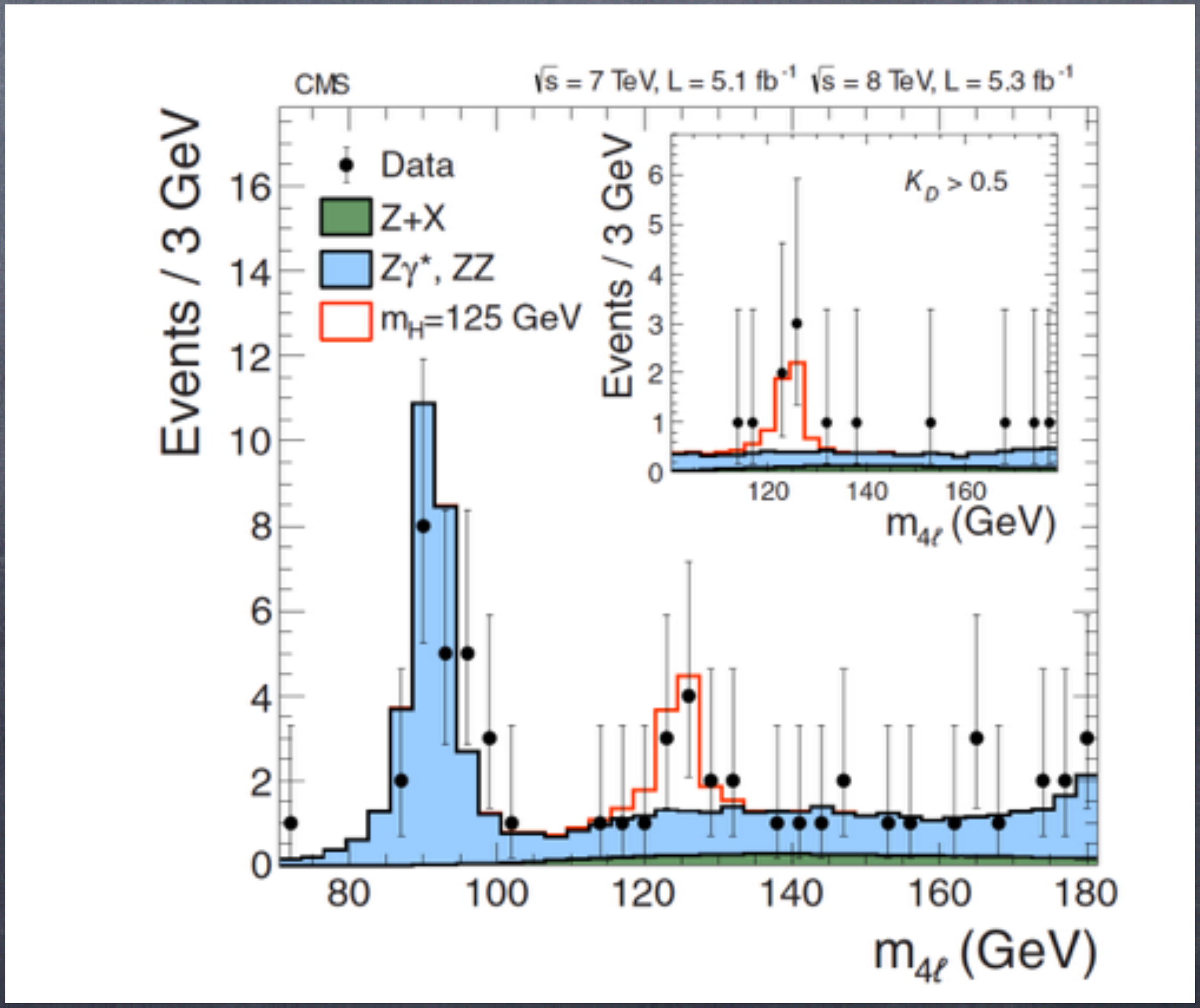


An example of H->ZZ and possible background gq->ZZq

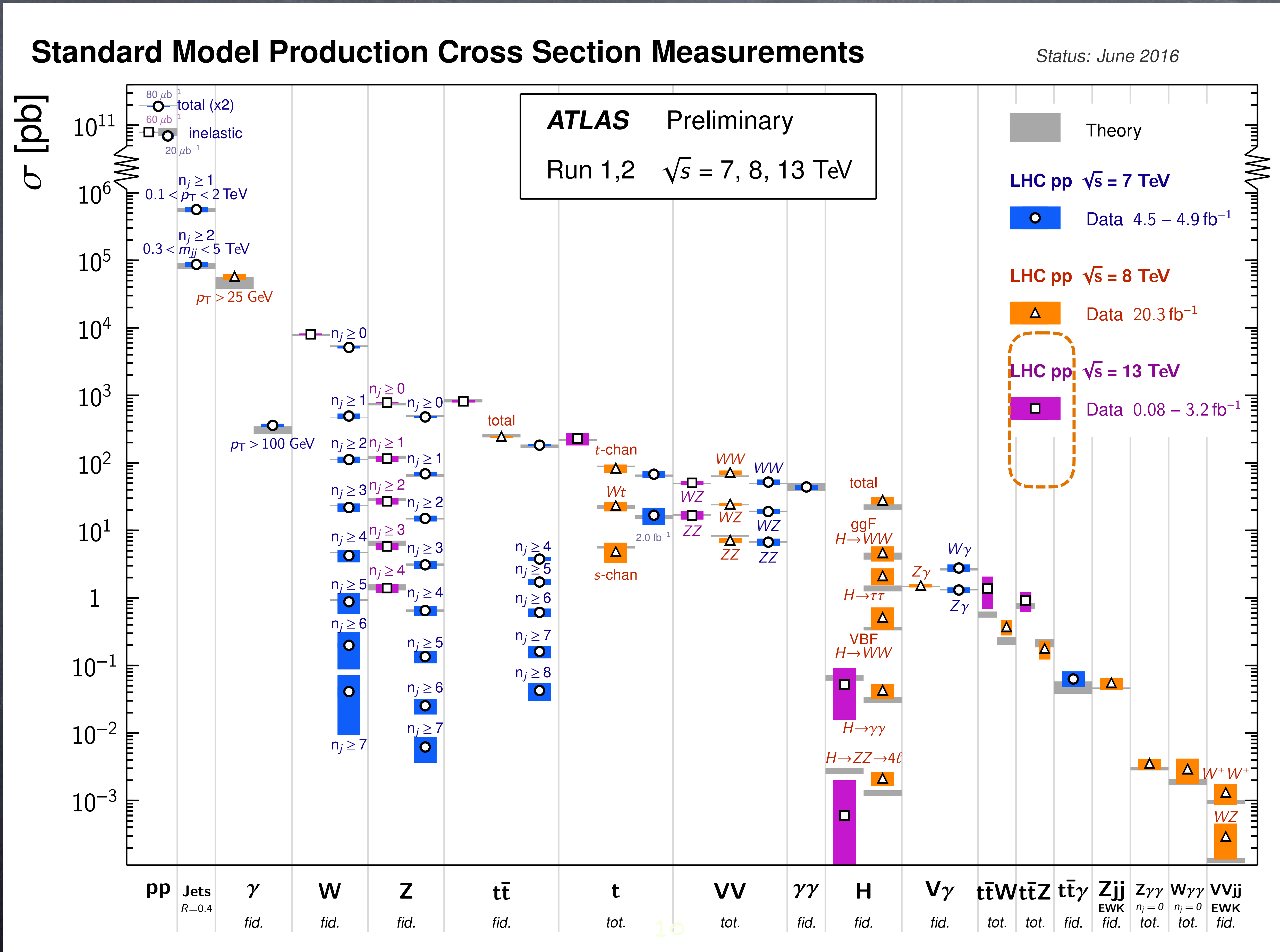
The experimentalist job is to identify efficient discriminators between Signal and Background and use them to extract the signal (if it exist)







Elecroweak measurements are Higgs backgrounds



A nano statistical interlude

Understanding The Yellow and Green Bands

The Model

- The Higgs hypothesis is that of signal $s(m_H)$

$$s(m_H) = L \cdot \sigma_{SM}(m_H) \cdot A \cdot eff$$

For simplicity unless otherwise noted $s(m_H) = L \cdot \sigma_{SM}(m_H)$

- In a counting experiment

$$n = \mu \cdot s(m_H) + b$$

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

- μ is the strength of the signal (with respect to the expected Standard Model one
- The hypotheses are therefore denoted by H_μ
- H_1 is the SM with a Higgs, H_0 is the background only model

Hypothesis Inference in a Nut Shell

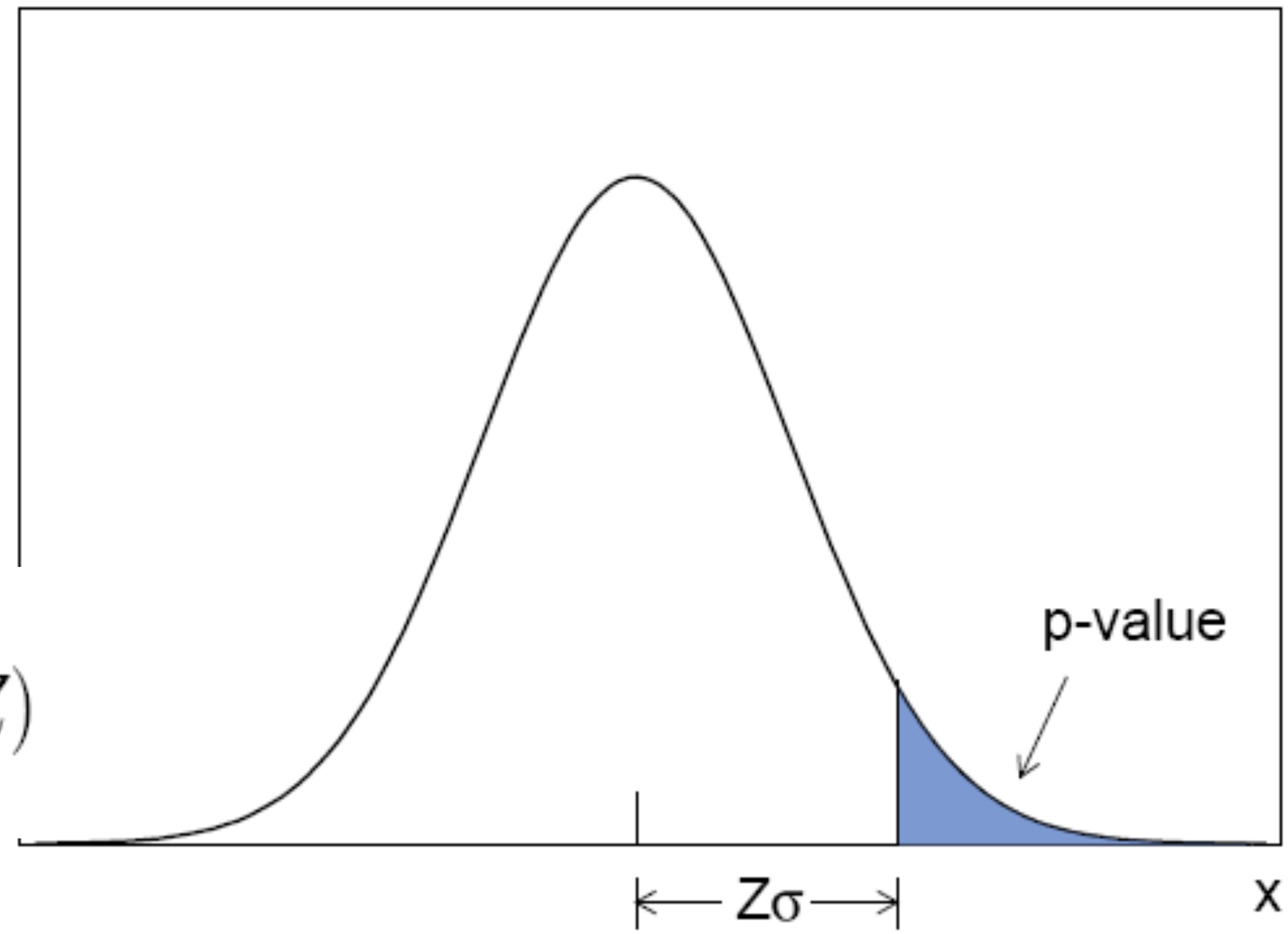
- Normally you test the null hypothesis and try to reject it
- You define a test statistics q (usually a Likelihood Ratio). The distribution of the test statistics is known (or can be cross checked with toys)
- We use the test statistic to find the p-value which is a measure of the compatibility of the data with null hypothesis
- If the p-value is small, we reject the null hypothesis in favour of the alternative hypothesis.
- It is a custom in High Energy Physics to use

$$H_{null} = BG \quad p_{bg} = 2.9 \cdot 10^{-7} \sim 5\sigma$$

$$H_{null} = s + b \quad p_s = 0.05 = 5\% \sim 2\sigma$$

From p-values to Gaussian significance

It is a custom to express the p-value as the significance associated to it, had the pdf were Gaussians



$$p = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx = 1 - \Phi(Z)$$

$$Z = \Phi^{-1}(1-p)$$

A significance of $Z = 5$ corresponds to $p = 2.87 \times 10^{-7}$.

Beware of 1 vs 2-sided definitions!

WILKS THEOREM

$$q(\alpha_i) \equiv -2\ln\frac{L(\alpha_i,\hat{\hat{\theta}}_j)}{L(\widehat{\alpha}_i,\hat{\theta}_j)} = -2\ln\frac{\max_\theta L(\alpha_i,\theta_j)}{\max_{\alpha,\theta} L(\alpha_i,\theta_j)}$$

$$q(\alpha_i) \equiv -2\log\frac{L(\alpha_i,\hat{\hat{\theta}}_j)}{L(\widehat{\alpha}_i,\hat{\theta}_j)} \sim \chi_n^2$$

Test Statistics	Purpose	Experession	LR
q_0	discovery of positive signal	$q_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$	$\lambda(0) = \dfrac{L(0,\hat{\hat{\theta}}_0)}{L(\hat{\mu},\hat{\theta})}$
t_μ	2-sided measurement	$t_\mu = -2\ln\lambda(\mu)$	$\lambda(\mu) = \dfrac{L(\mu,\hat{\hat{\theta}}_\mu)}{L(\hat{\mu},\hat{\theta})}$
$\tilde{t}_\mu$	avoid negative signal (FC)	$\tilde{t}_\mu = -2\ln\tilde{\lambda}(\mu)$	$\tilde{\lambda}(\mu) = \begin{cases} \dfrac{L(\mu,\hat{\hat{\theta}}_\mu)}{L(\hat{\mu},\hat{\theta})} & \hat{\mu} \geq 0 \\ \dfrac{L(\mu,\hat{\hat{\theta}}_\mu)}{L(0,\hat{\hat{\theta}}_0)} & \hat{\mu} < 0 \end{cases}$
q_μ	exclusion	$q_\mu = \begin{cases} -2\ln\lambda(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$	
$\tilde{q}_\mu$	exclusion of positive signal	$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$	

q_{null}

$f(q_{null} \mid H_{null})$

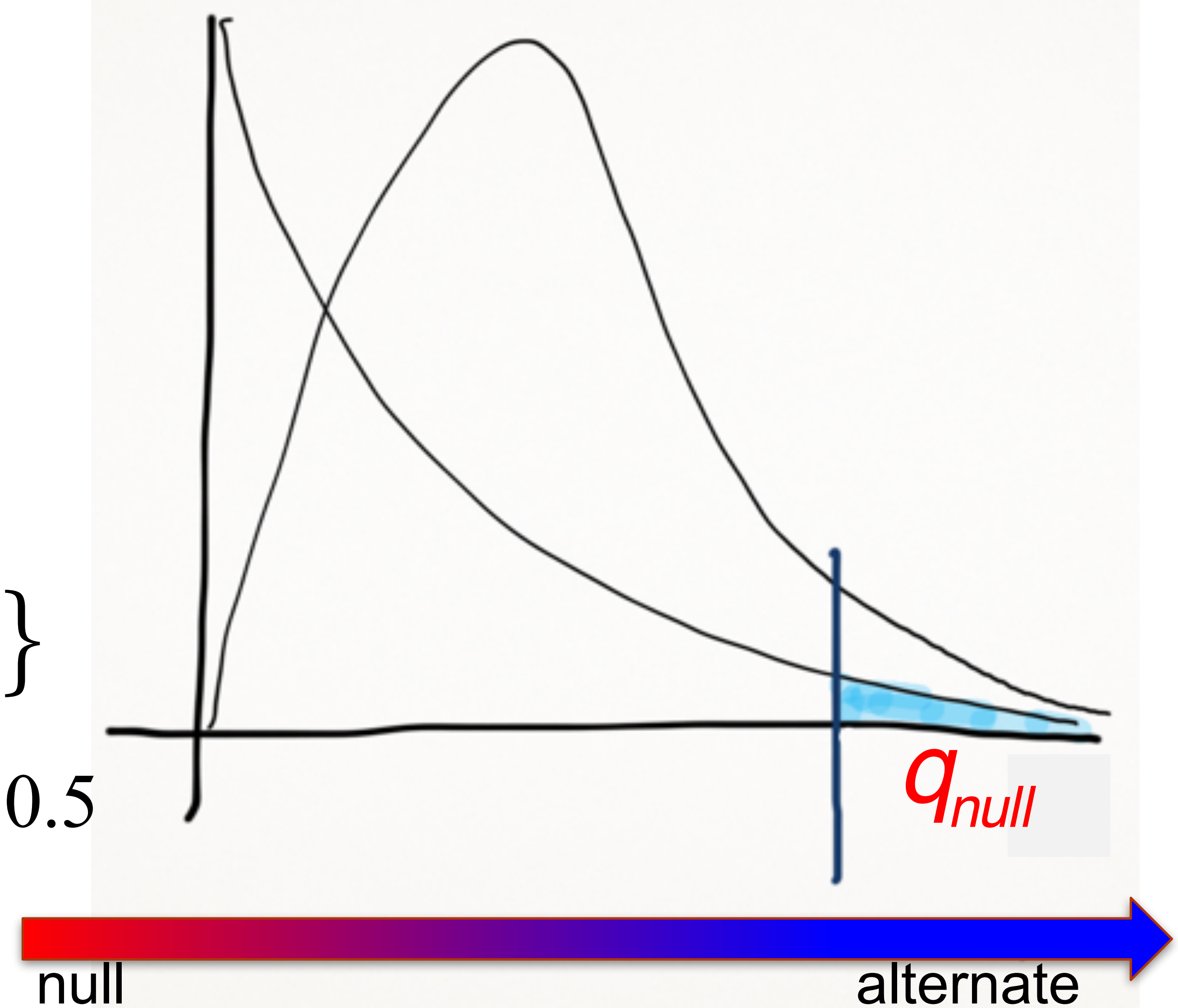
$q_{obs} \equiv q_{null,obs}$

$$p = \int_{q_{obs}}^{\infty} f(q_{null} \mid H_{null}) dq_{null}$$

$f(q_{null} \mid H_{alt})$

$$q_A \equiv q_{null,A} = \left\{ q \mid med\{ f(q_{null} \mid H_{alt}) \} \right\}$$

$$\int_{q_{null,A}}^{\infty} f(q_{null} \mid H_{null}) dq_{null} = 0.5$$



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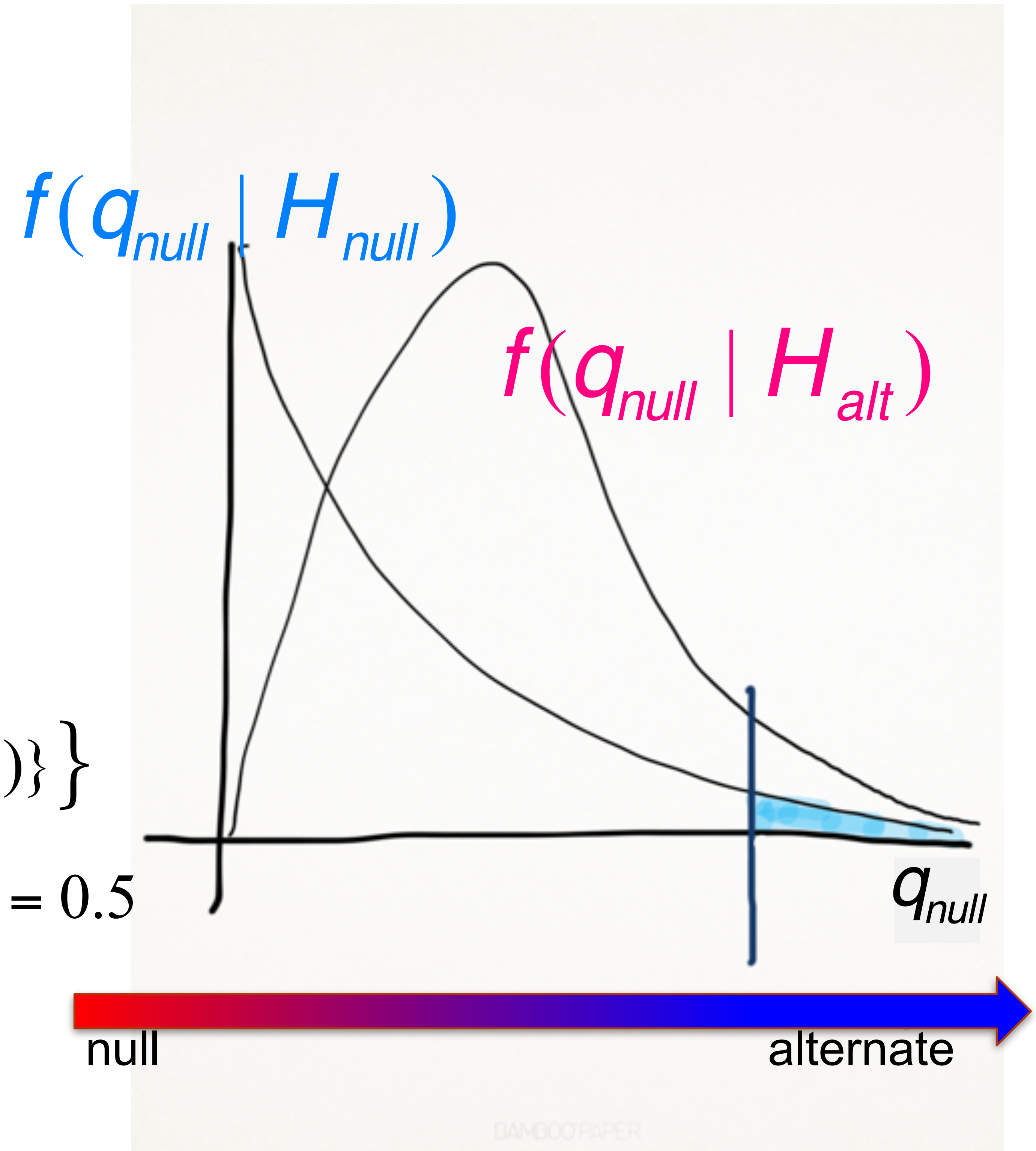
$f(q_{null} \mid H_{alt})$

$$q_A \equiv q_{null,A} = \begin{matrix} \{q \mid med\{ f(q_{null} \mid H_{alt})\}\} \\ \int_{q_{null,A}}^{\infty} f(q_{null} \mid H_{null}) dq_{null} = 0.5 \end{matrix}$$



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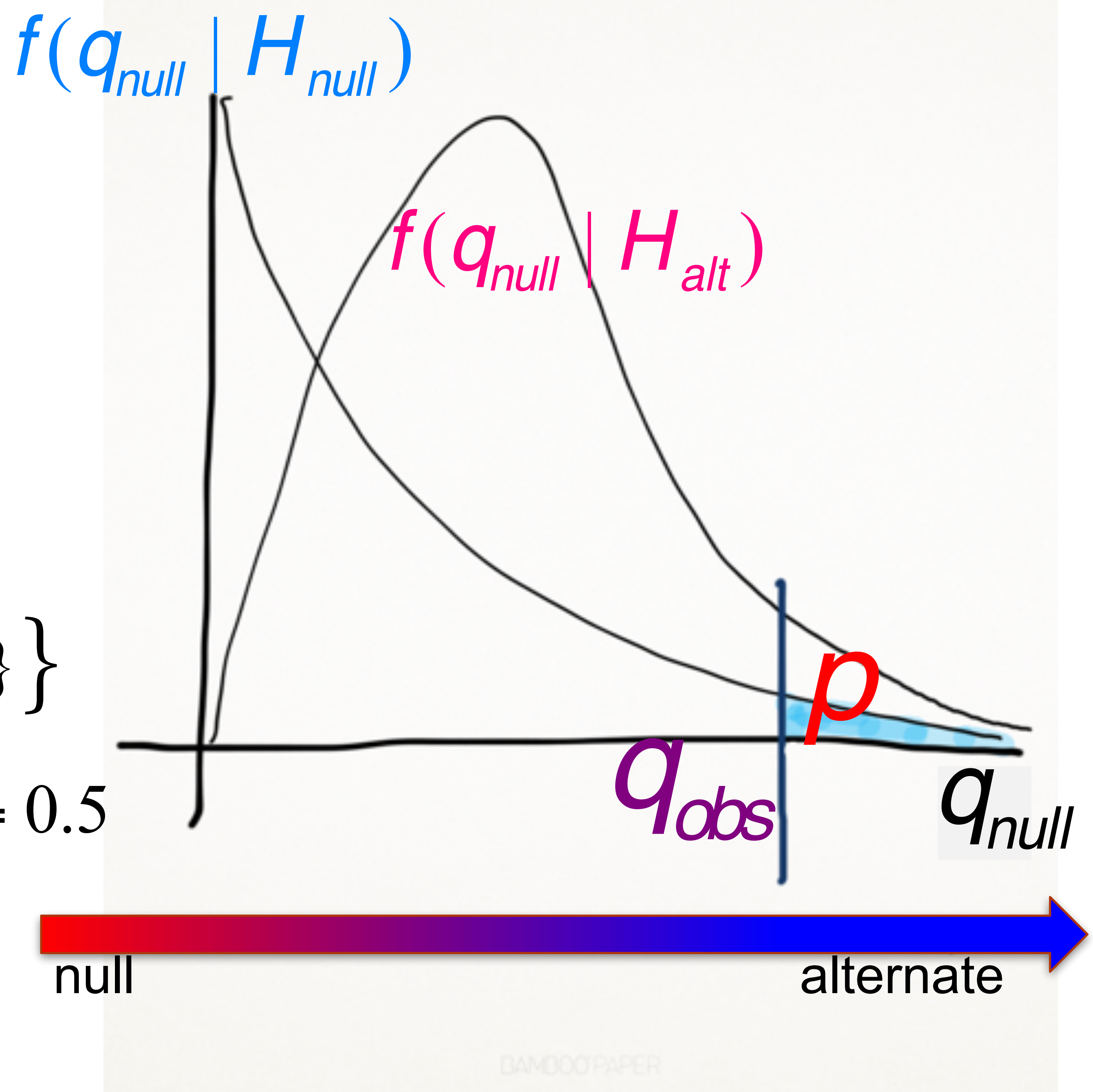


q_{null}

$f(q_{null} \mid H_{null}) \sim \chi^2$

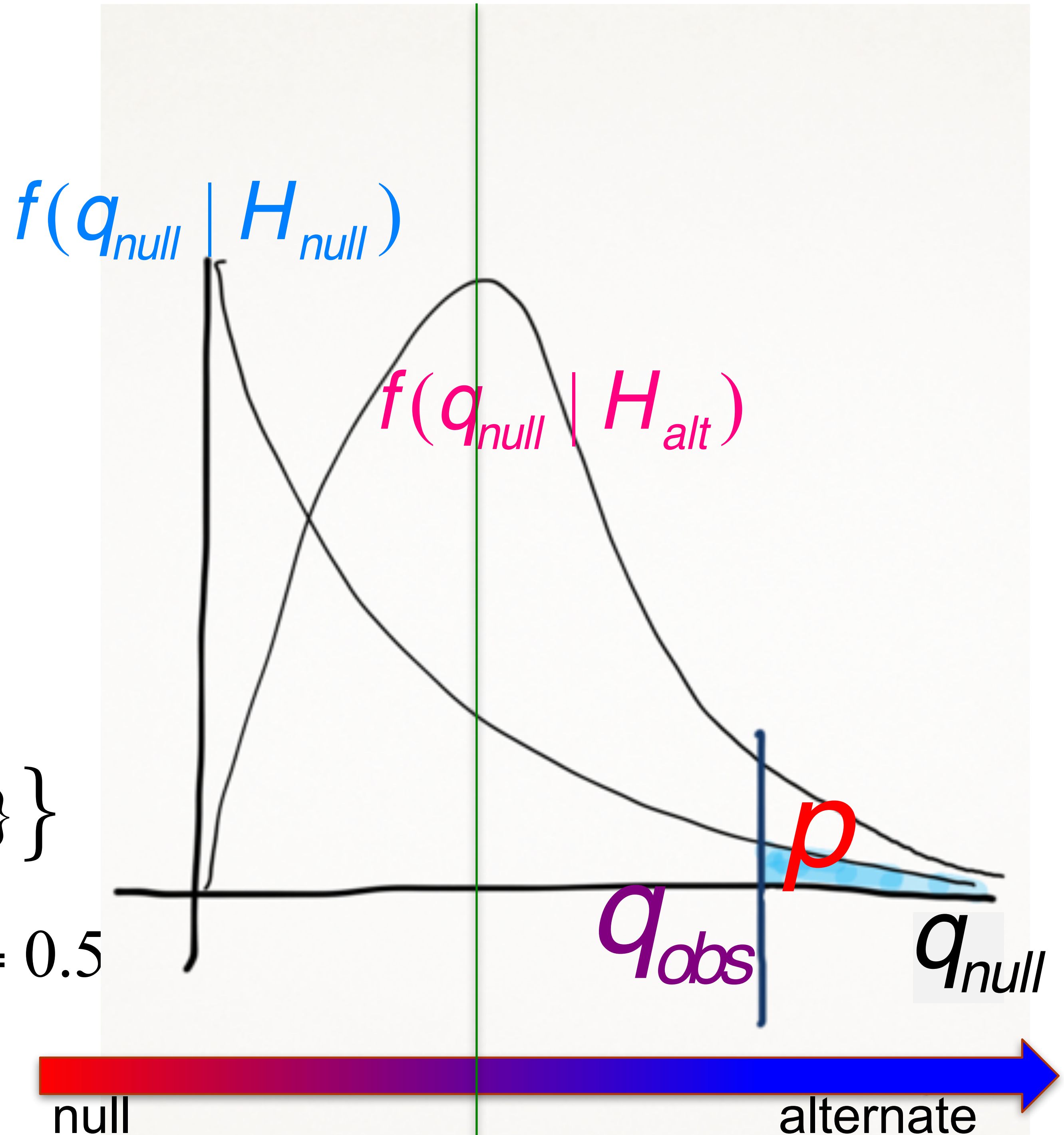
$q_{obs} \equiv q_{null,obs}$

$$p = \int_{q_{obs}}^{\infty} f(q_{null} \mid H_{null})\, dq_{null}$$

$f(q_{null} \mid H_{alt})$

$$q_A \equiv q_{null,A} = \{q \mid med\{f(q_{null} \mid H_{alt})\}\}$$

$$\int_{q_{null,A}}^{\infty} f(q_{null} \mid H_{null})\, dq_{null} = 0.5$$



$$Z_{expected} = \sqrt{q_{null,A}}$$

$q_A \equiv q_{null,A}$

Profile Likelihood "vs" CLs

- Exclusion a mass range is a statement about the Higgs cross section.

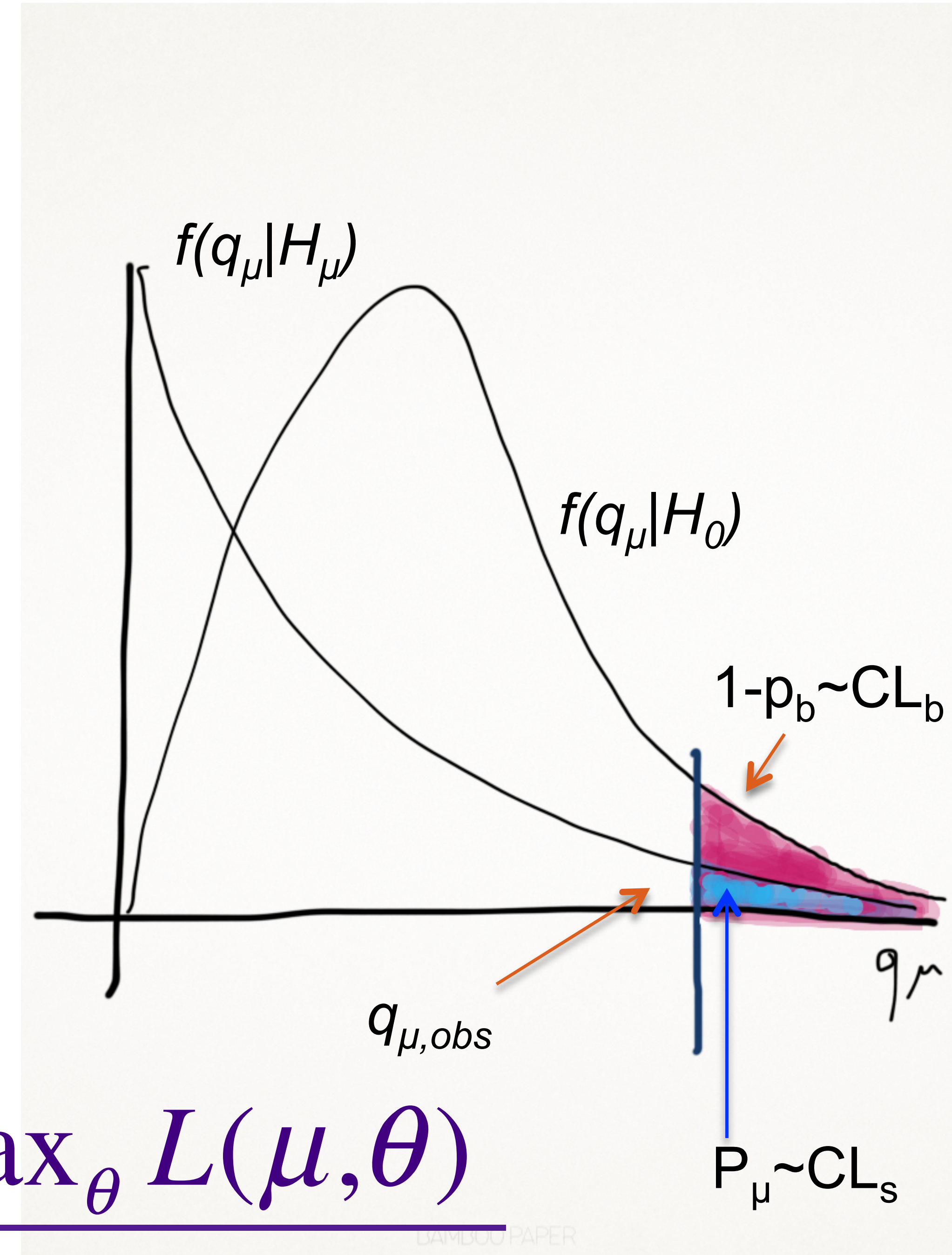
$$\mu(m_H) = \frac{\sigma(m_H)}{\sigma_{SM}(m_H)} < 1 --> \sigma(m_H) < \sigma_{SM}(m_H)$$

- m_H=125 GeV, yet had we repeated the LHC experiment an infinite amount of times, less than 5% of these experiments will make a false statement. i.e.
it could be that we failed to observe it

- As we collect more data, and still fail to observe the Higgs, the exclusion Confidence Level increases
(the failure probability decreases)

- Any discovery of the Higgs will start by failing to exclude it

- The CLs method modifies the p-value to prevent rejecting the s+b hypothesis due to downward fluctuations of the background (which prevents the exclusion of a signal, to which you might not be sensitive)



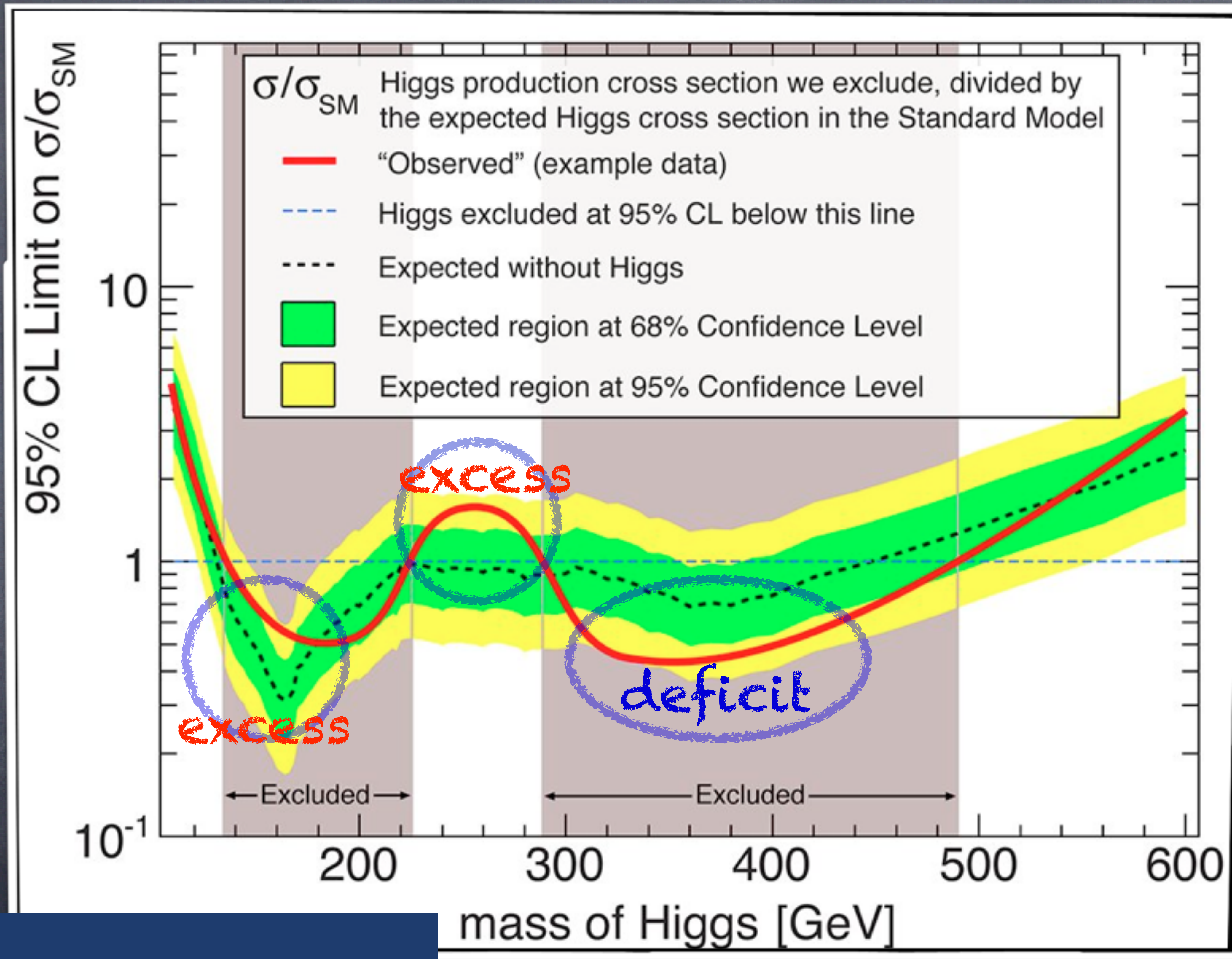
$$p'_\mu(m_H) = \frac{p_\mu}{1-p_b}$$

$$q_\mu \equiv -2\ln\frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})} = -2\ln\frac{\max_\theta L(\mu,\theta)}{\max_{\mu,\theta} L(\mu,\theta)}$$

Scan μ until you find $\mu_{up}(m_H) = \left\{ \mu \middle| p'_\mu(m_H) = 5\% \right\}$

Understanding The Yellow and Green Bands

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



L=L(Data)
Expected is with the alternative Asimov Data
i.e. find μ_{up} with the expected BG data set

Channels Weight

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

- Asymptotically

CCGV, EPJC 71 (2011) 1-19.

$$\mu_{up,obs} = \hat{\mu} + \sigma_{\mu_{up}} \cdot 1.64,$$

$$\mu_{up,exp} = \hat{\mu}_A + \sigma_{\mu_{up}} \cdot 1.64 = \sigma_{\mu_{up}} \cdot 1.64$$

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

Luminosity normalized:

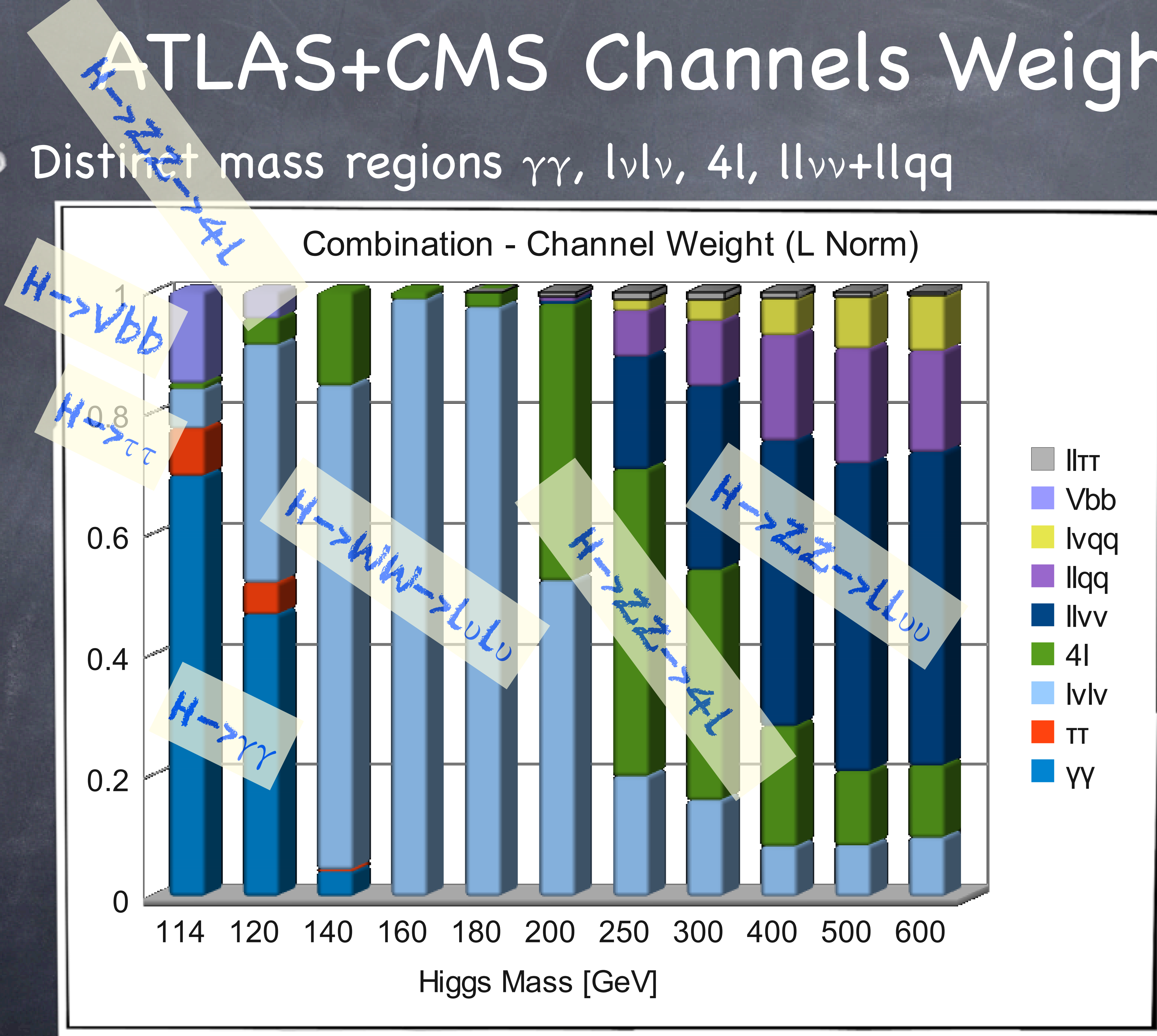
$$\mu_{up,\exp,i}\left(\mathcal{L}_i\right) \to \mu_{up,\exp,i}\left(\mathcal{L}_0\right) = \mu_{up,\exp,i}\left(\mathcal{L}_i\right)\sqrt{\frac{\mathcal{L}_i}{\mathcal{L}_0}}$$

If we normalize individual channels to the same luminosity,

the weight, w_i is independent of the luminosity

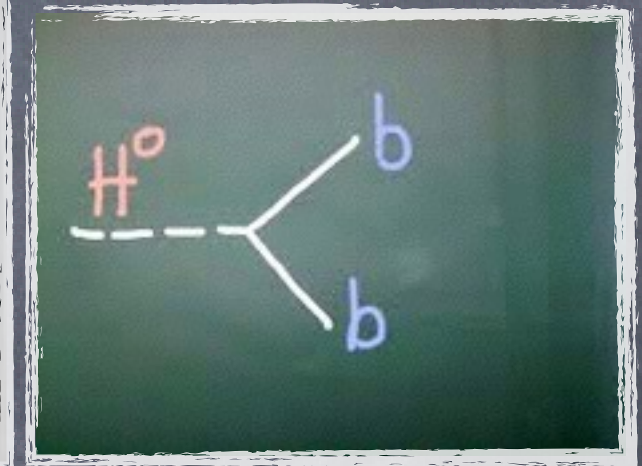
ATLAS+CMS Channels Weight

- Distinct mass regions $\gamma\gamma$, $l\nu l\nu$, 4l, $ll\nu\nu$+llqq

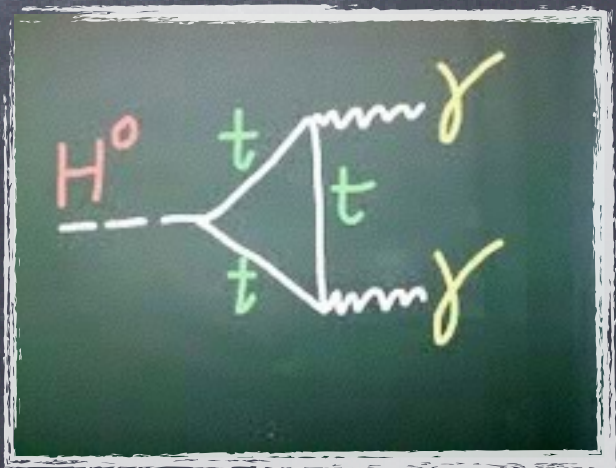


Higgs Decay Modes

- The Higgs Boson decays to the heaviest kinematically available particles pair
- A light Higgs (mH<130) decays to tau tau and mainly to bb
- But H->bb is hard to detect or trigger on, unless produced in assosiation with a W or a Z



- Leptons (electrons or muons) and photons are easy to trigger on and detect.
  Though BR(H->gamma gamma)~10^{-3}, H->gamma gamma is a favorite channel for a Higgs with mH~110-120



Higgs Decay Modes

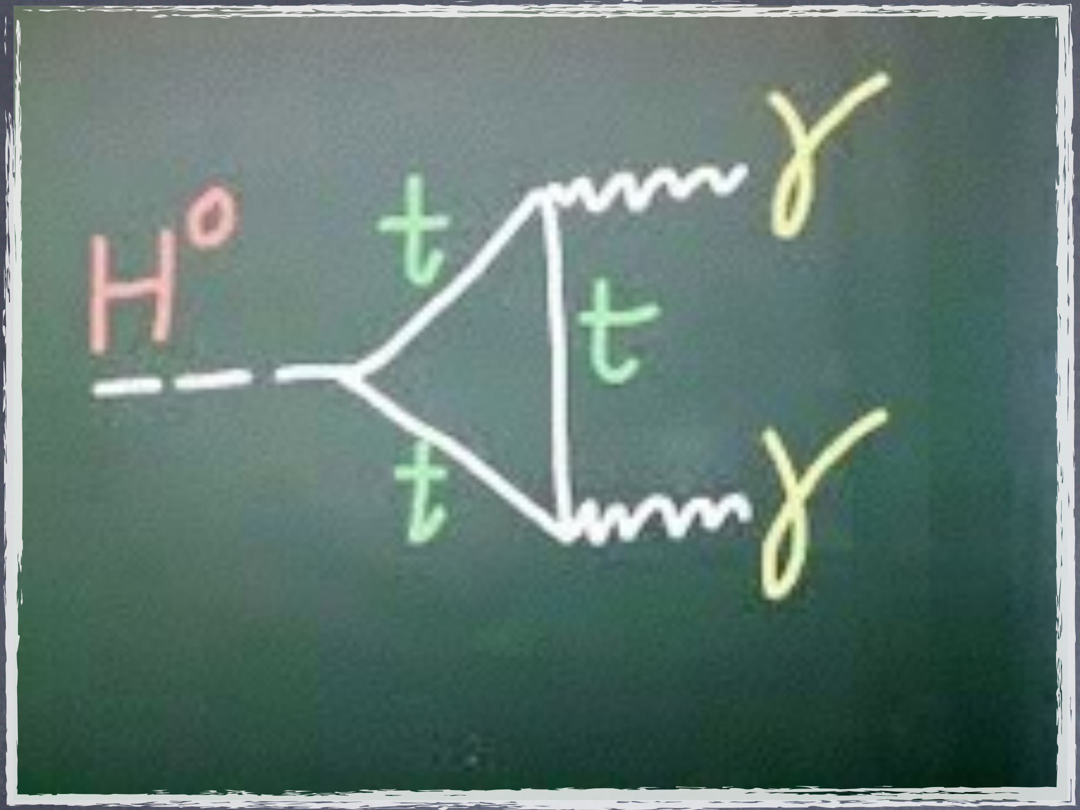
- Once the Z and W channels are open (mH>140) it decays to ZZ* and WW*

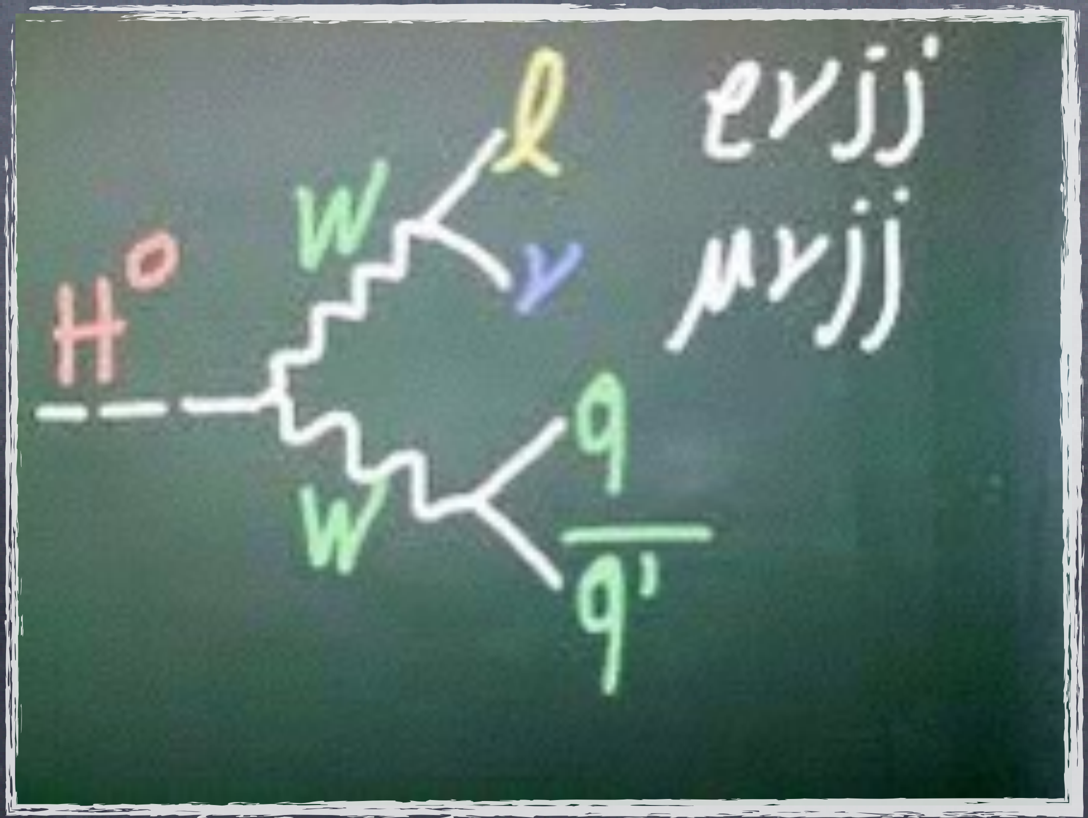
- The Higgs decay modes are classified according to the decays of the daughter bosons, thus the main decay modes are

- the golden channel 4l=4 leptons

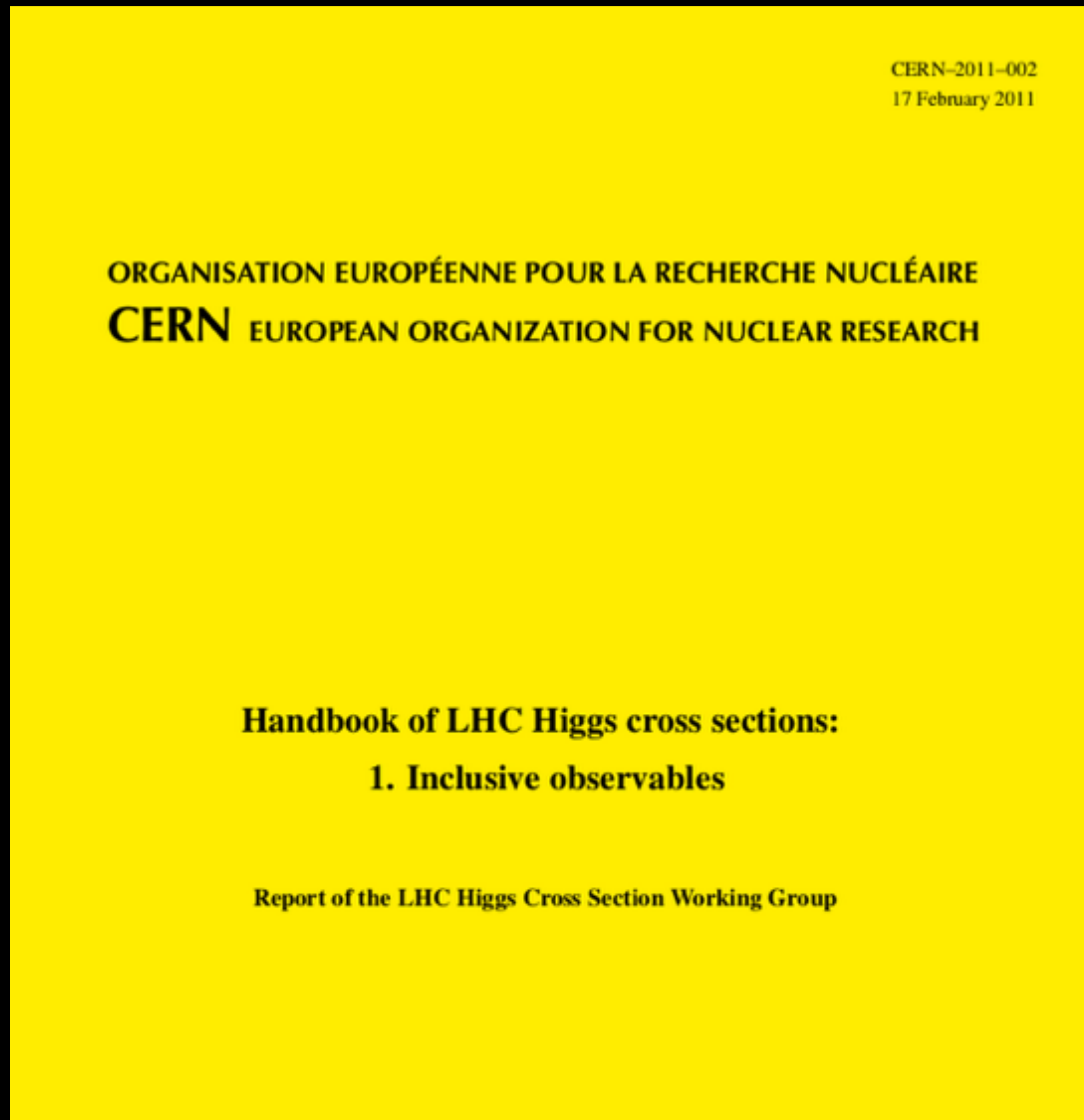
- and other WW or ZZ channels

Higgs Discovery Decay Modes





THE "BIBLE" - THE YELLOW BOOKS
COMMUNICATION CHANNEL OF THEORY & EXPERIMENT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Handbook of LHC Higgs cross sections:
1. Inclusive observables

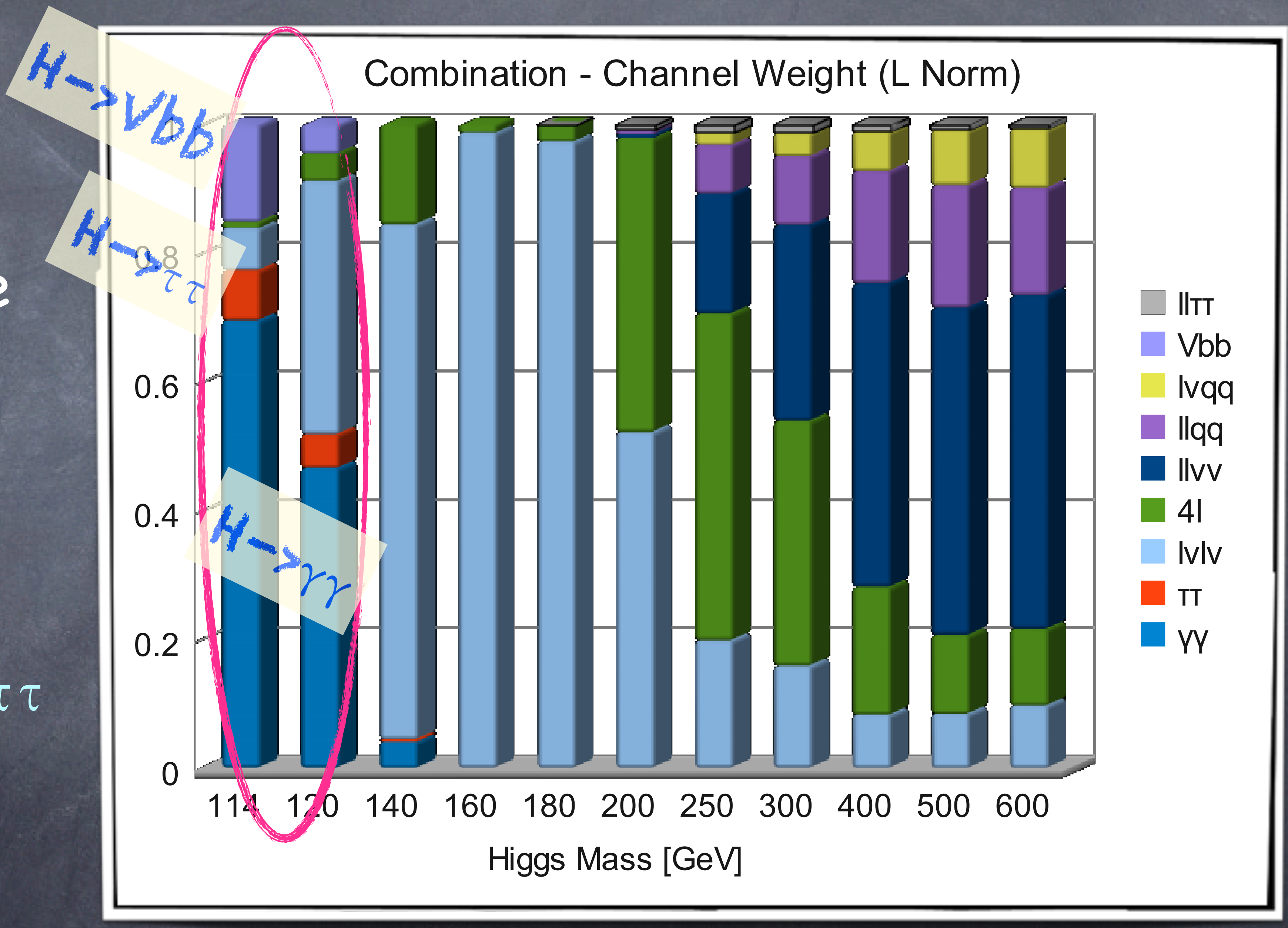
Report of the LHC Higgs Cross Section Working Group

History of Exclusions

- Until 2011 the Higgs search was a story of exclusions
- Any discovery starts with the inability to exclude.

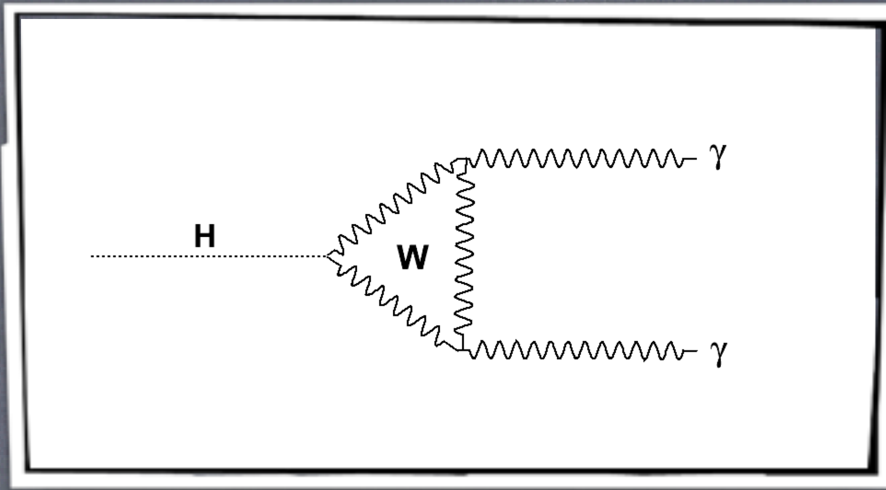
Probing the LEP Edge

- The LEP edge 114-140 GeV
- Probing channels:
  H->$\gamma\gamma$, Vbb, $\tau\tau$

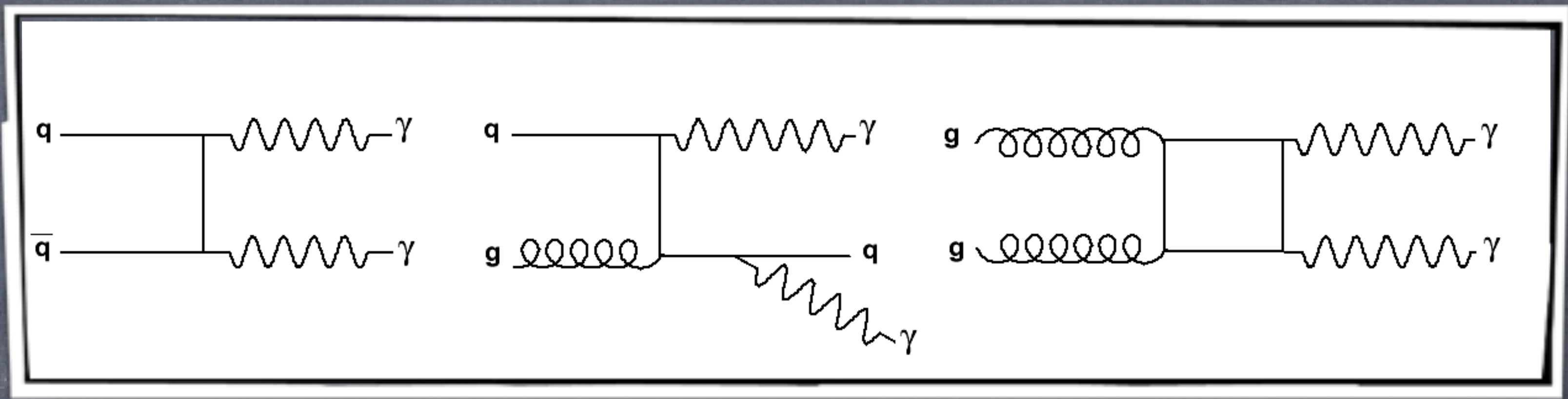


H->γγ   Probing LEP 114 GeV

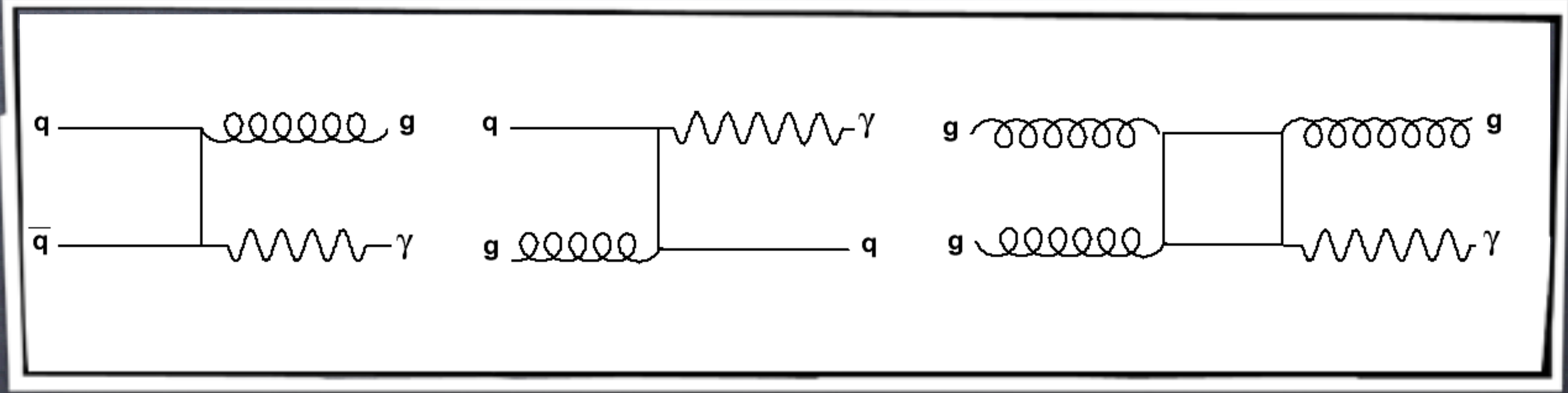
- Though its the most important channel for very low mass Higgs, σ×BR=0.04pb



- Large irreducible BG from pp->γγ+X (continuum)

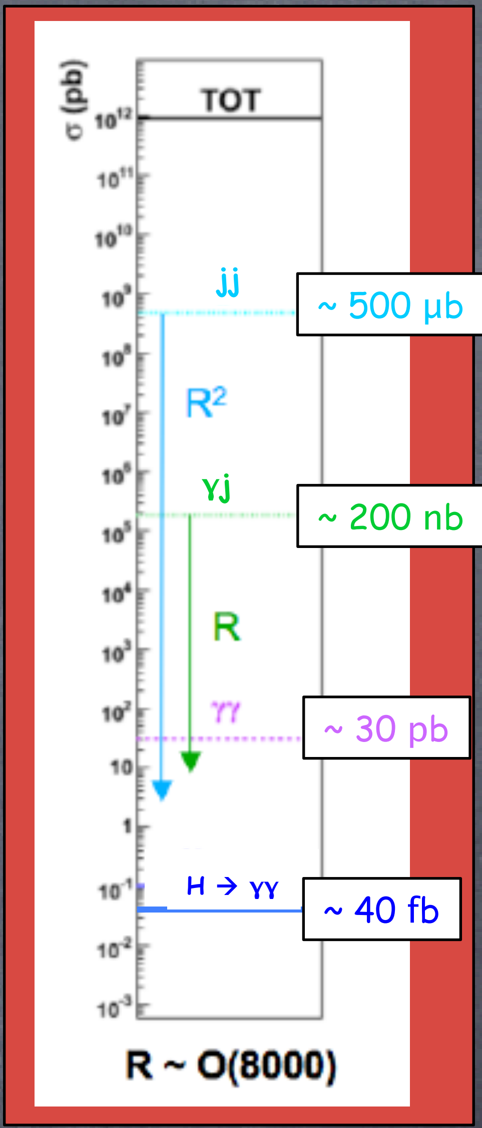


- Large BG from fakes pp->γj, jj+X



H->γγ Experimental Aspects

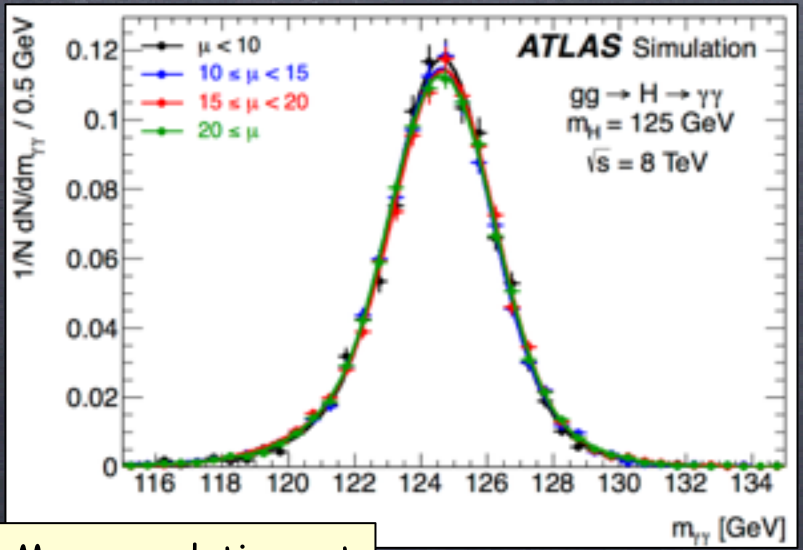
Needs a powerful γ/jet separation to suppress γj and jj background
with jet -> π^0 faking single γ



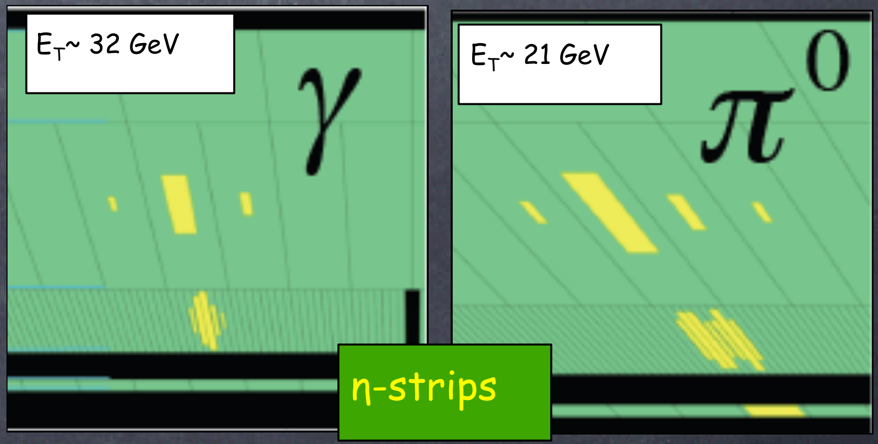
$$m^2_{\gamma_1\gamma_2} = 2E_{\gamma_1}E_{\gamma_2}\left(1 - cos\measuredangle(\gamma_1,\gamma_2)\right)$$

The longitudinal and lateral segmentation and pointing geometry of the ATLAS EM calorimeter enable good γγ angular separation and better Z-vertex determination.
This is crucial in high pile up environment and in identifying fake photons from pions

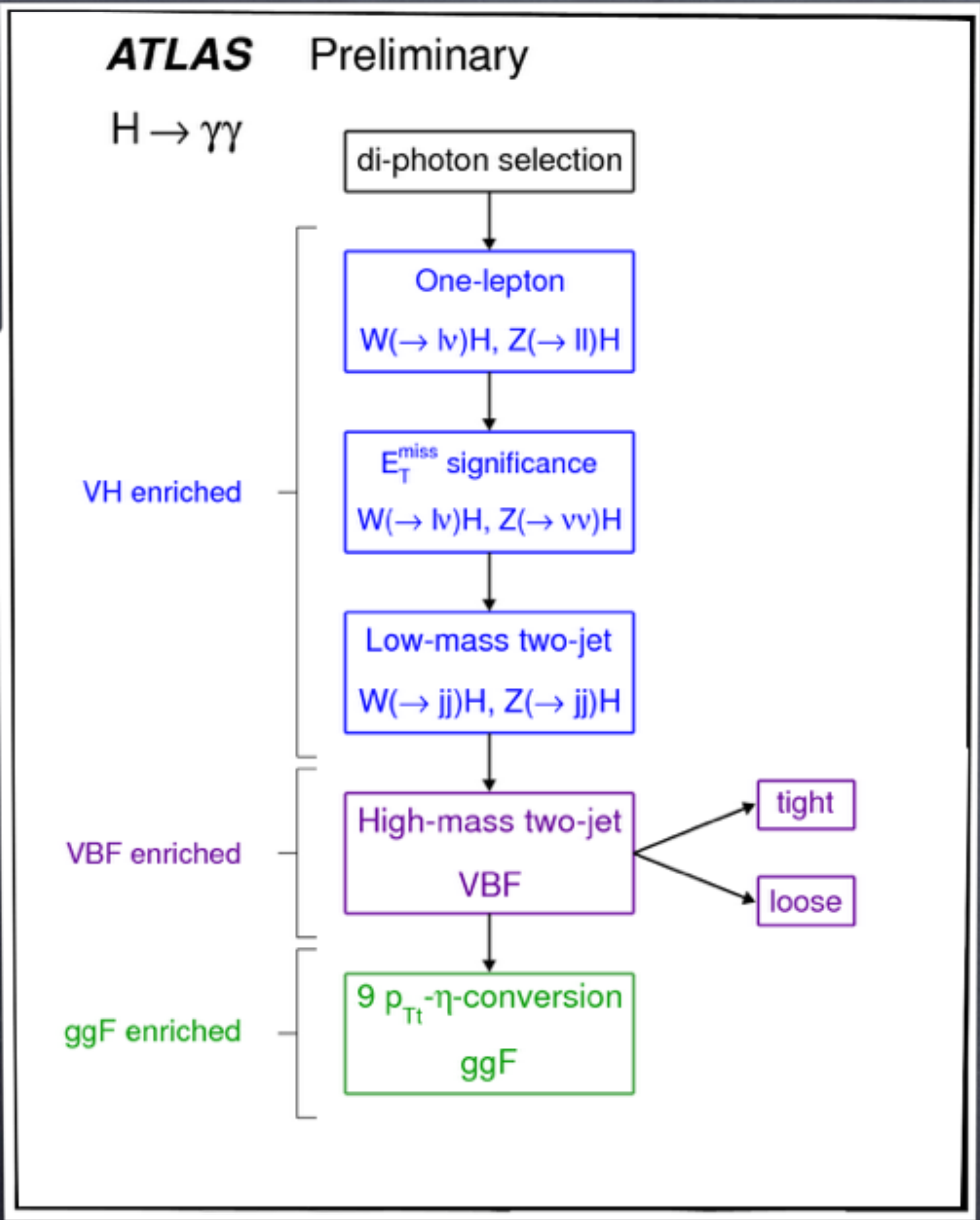
Present understanding of calorimeter
E response (from tag&probe Z->ee, J/ψ ->ee, W->eν data and MC)->
Excellent mass resolution

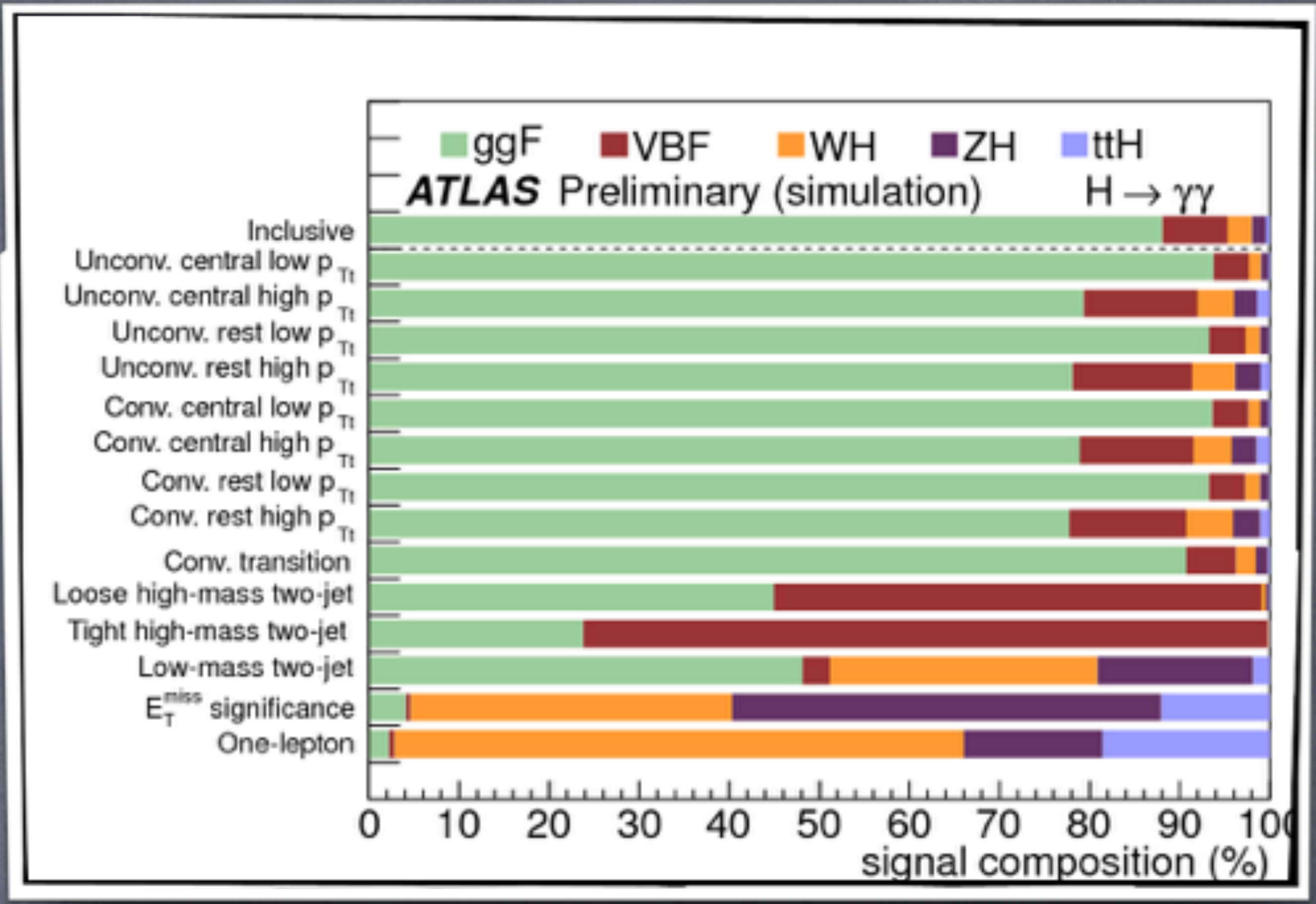


Mass resolution not affected by pile-up



H->γγ Categories



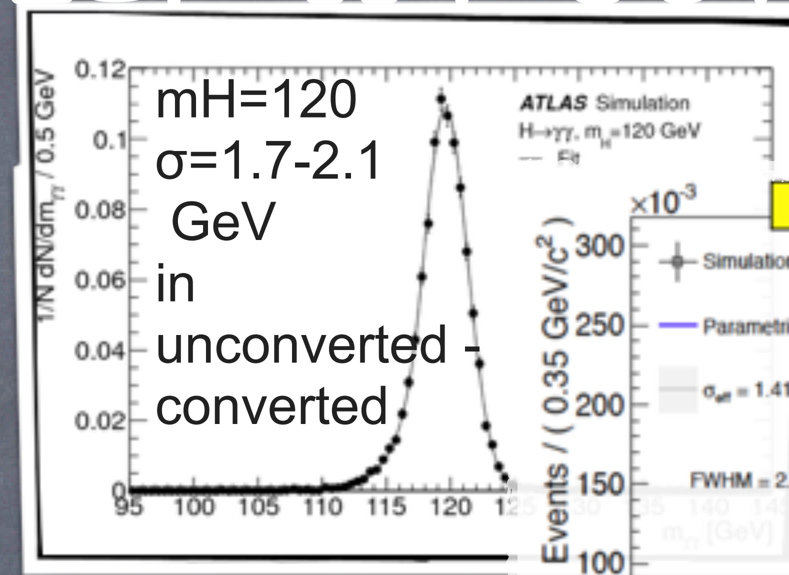


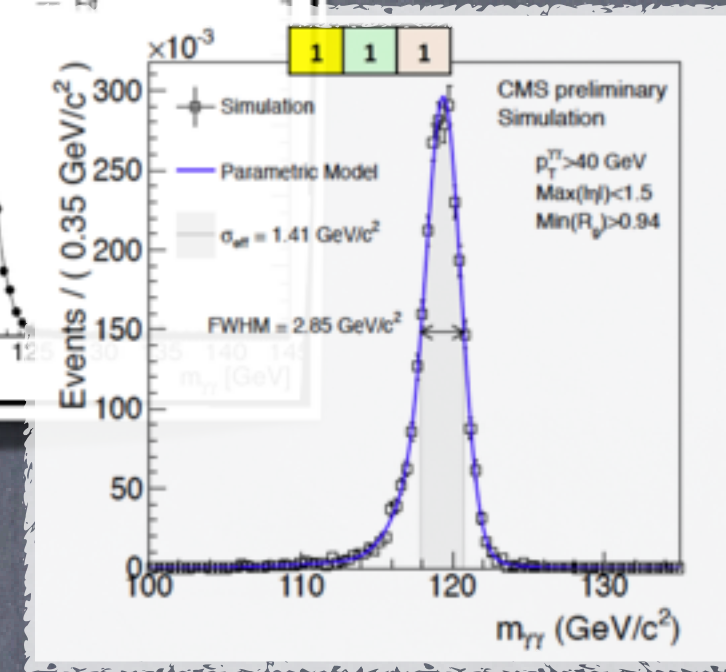
Tight BDT ≥ 0.74

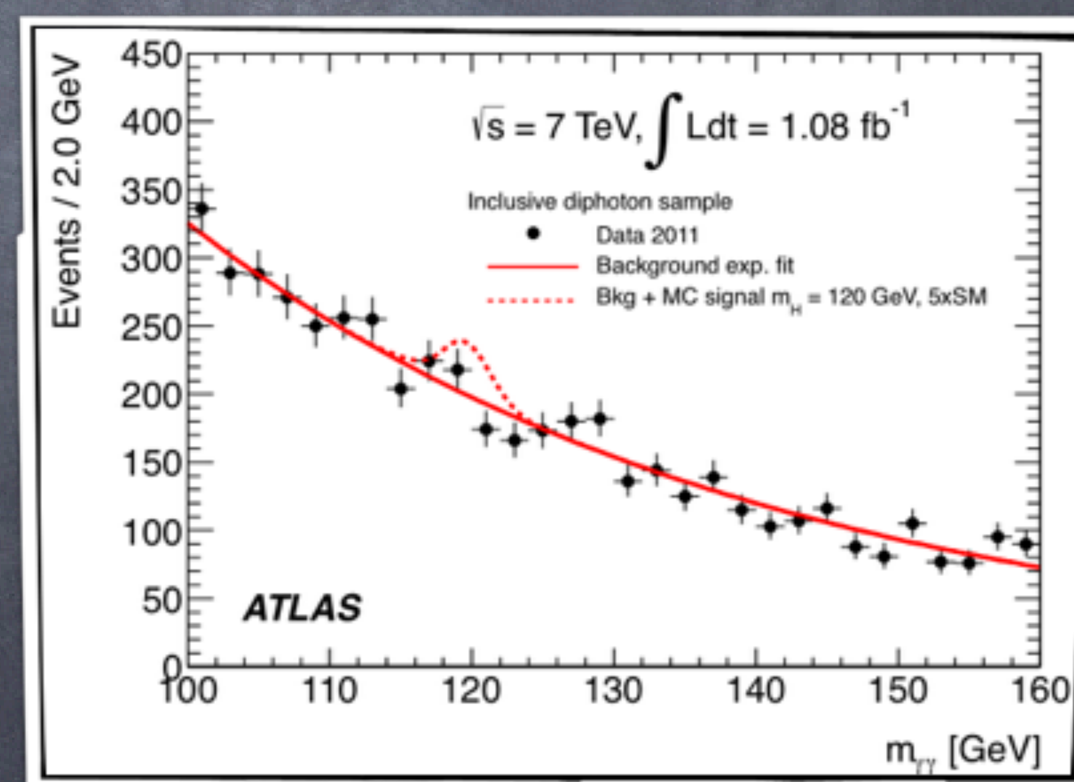
Loose 0.44 < BDT < 0.74

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

- Clean signature: 2 energetic isolated photons->narrow mass peak
- A narrow peak is searched for over a large, smooth background.
- Data are split into categories based on direction of photons (detector region) and conversion mode (which affect $\gamma\gamma$ mass resolution, which is excellent)
- A fit is performed to the background side band under the BG only hypothesis
  (only data is considered)
- A fit of s+b on the background (MC) is used to estimate the spurious signal demanding it to be small

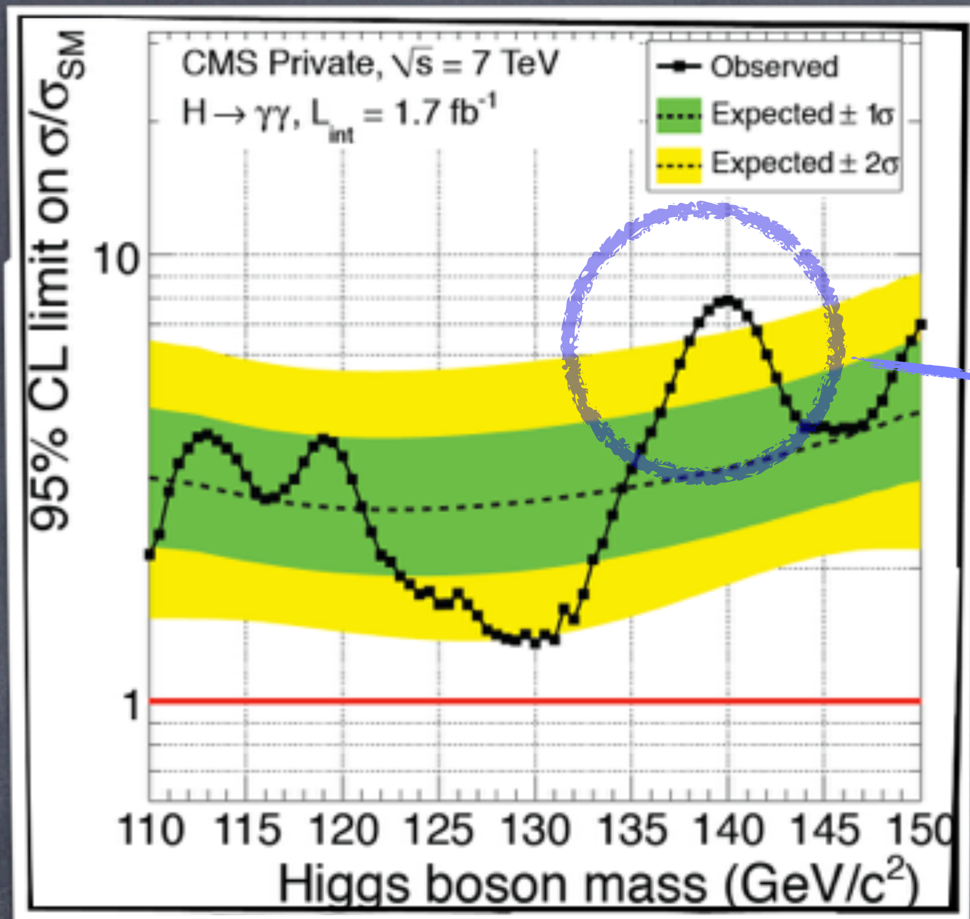


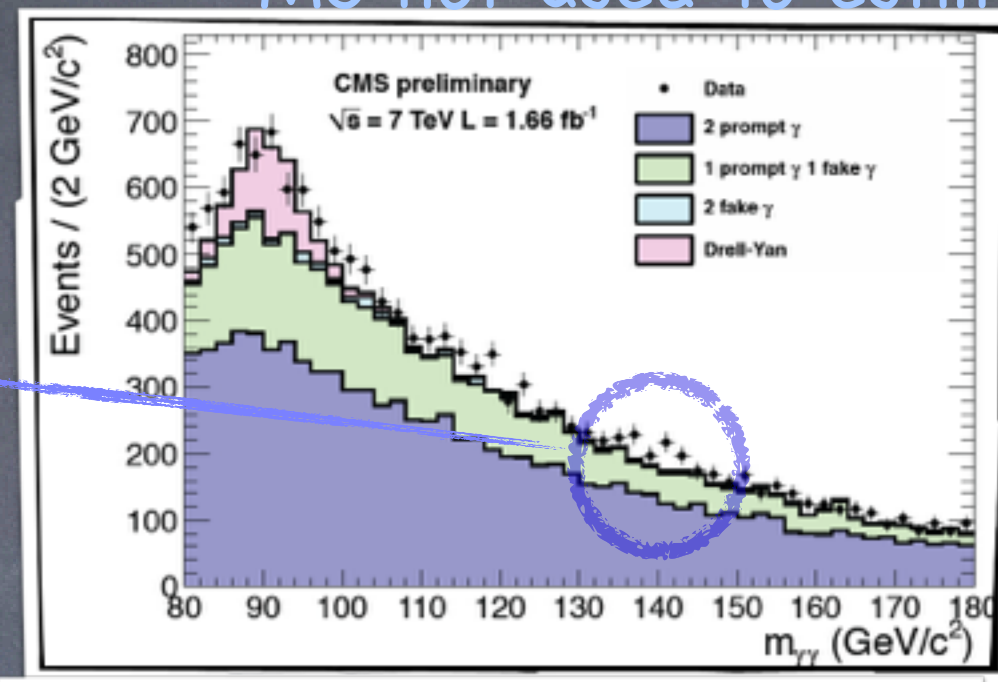


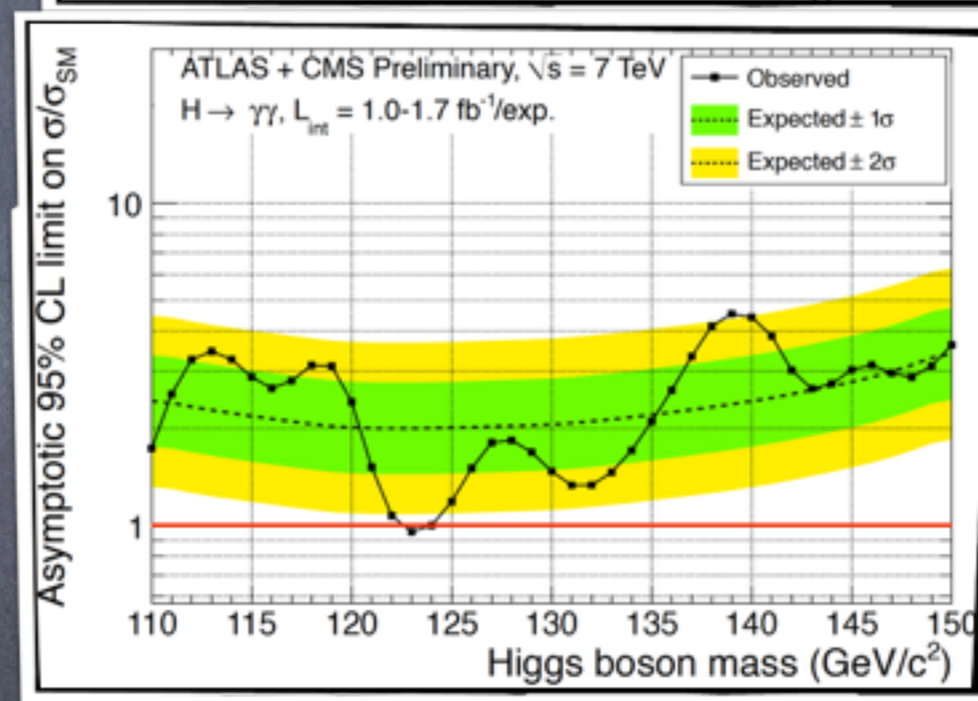


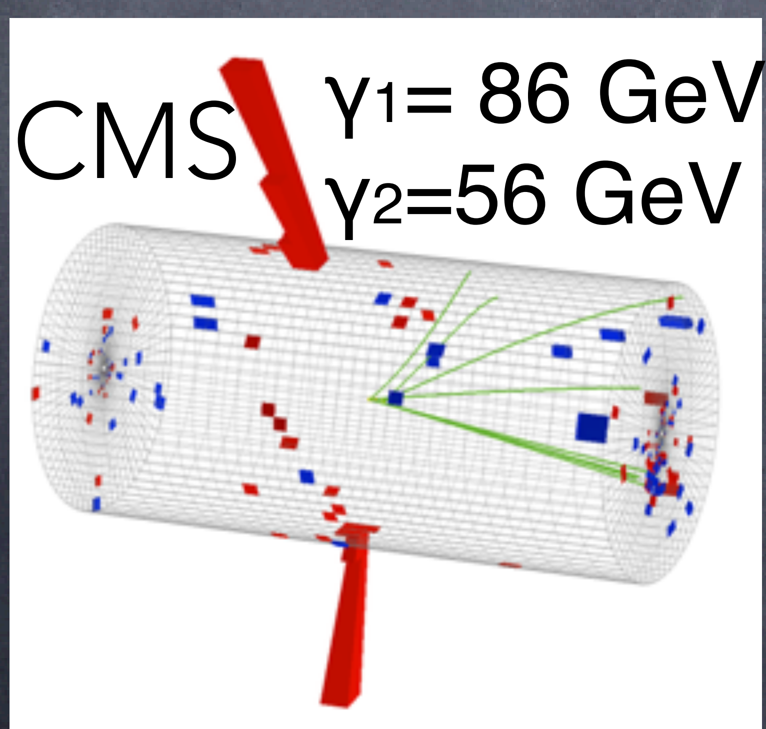
H->γγ Probing LEP 114 GeV

MC not used to estimate BG





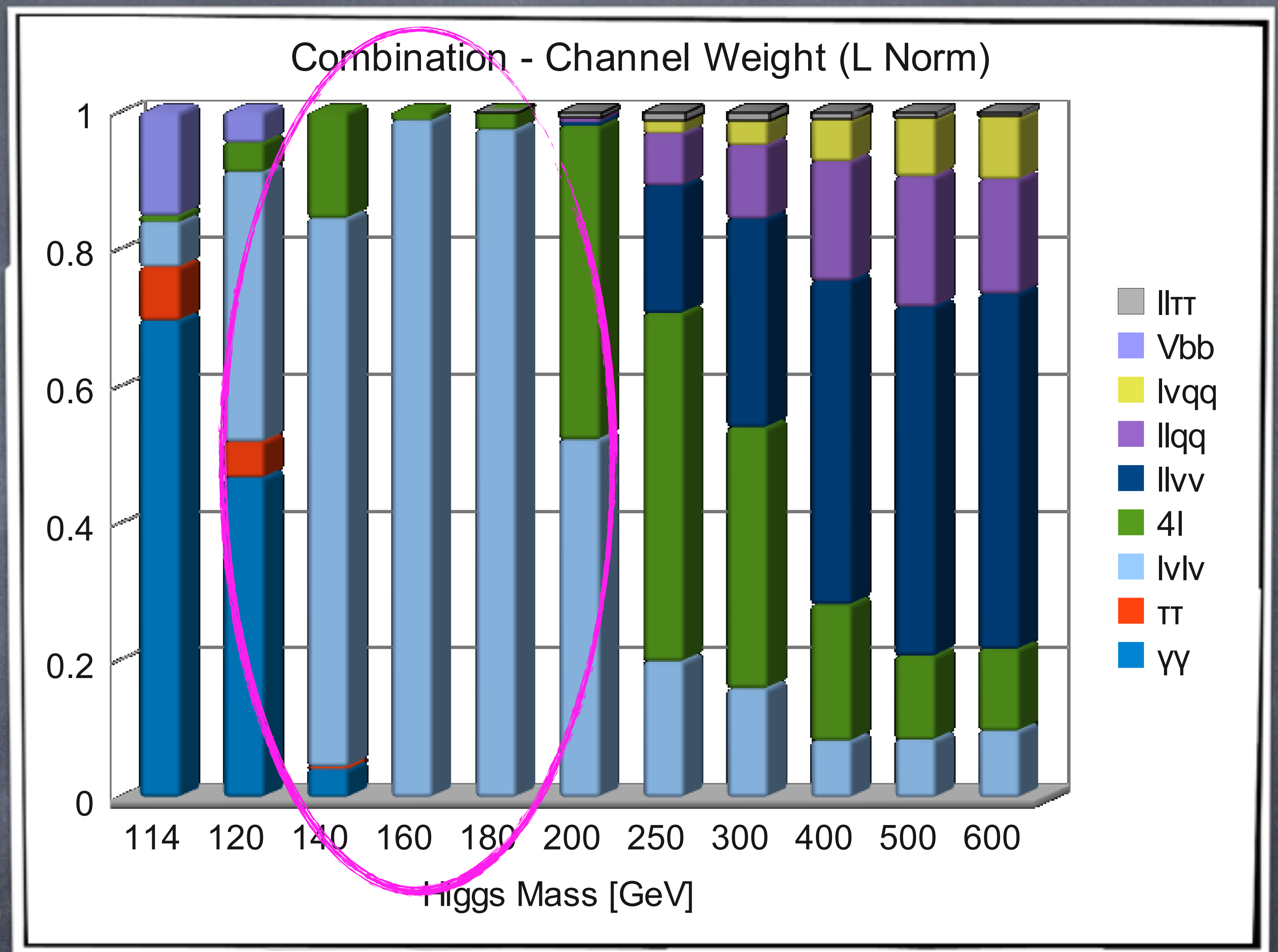




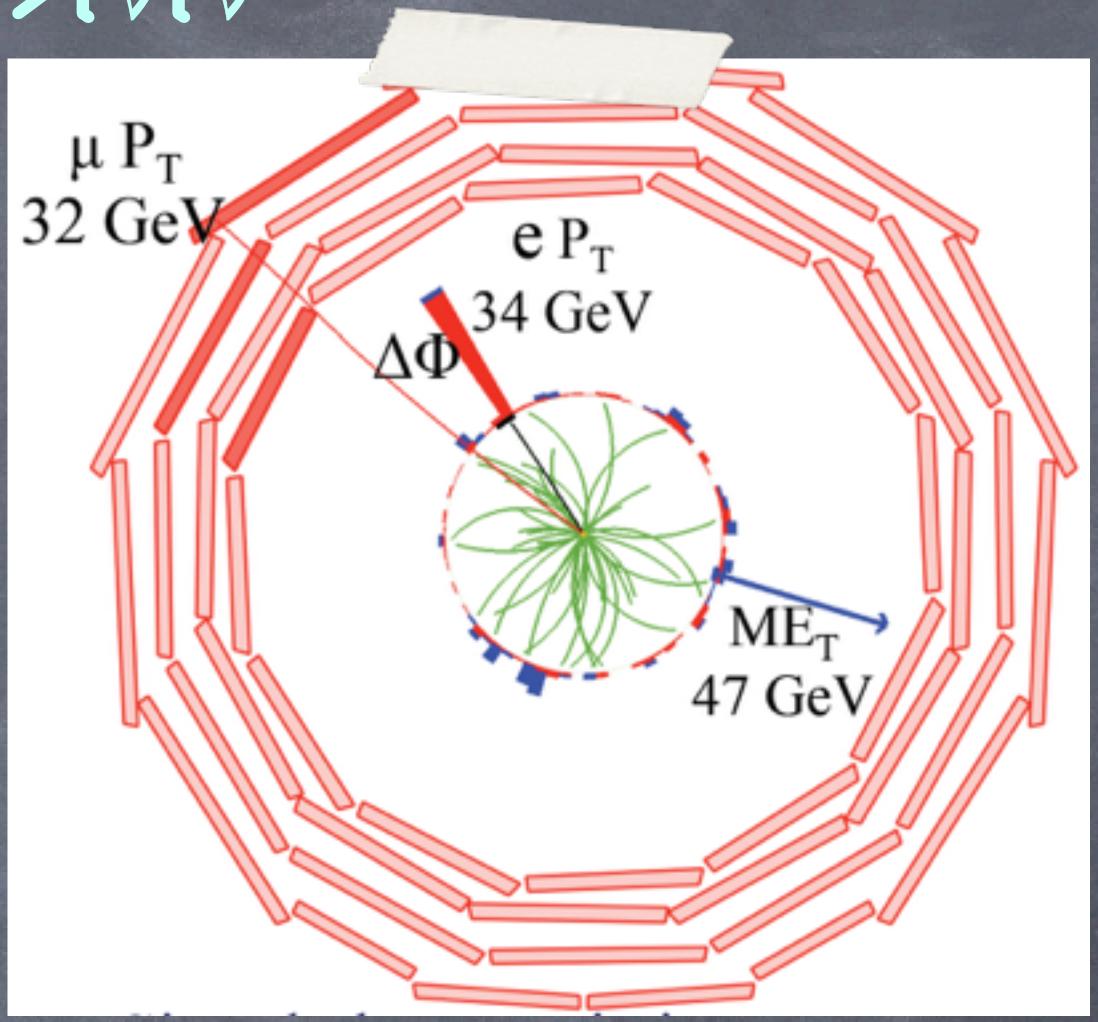
- 114 GeV combined expected sensitivity ~2xSM
- γγ alone excludes the SM @ mH=123 GeV due to a strong downward fluctuation of the data
- Need a few more fb^{-1}/experiment to close the 114 GeV gap

“TEVATRON++” mass region

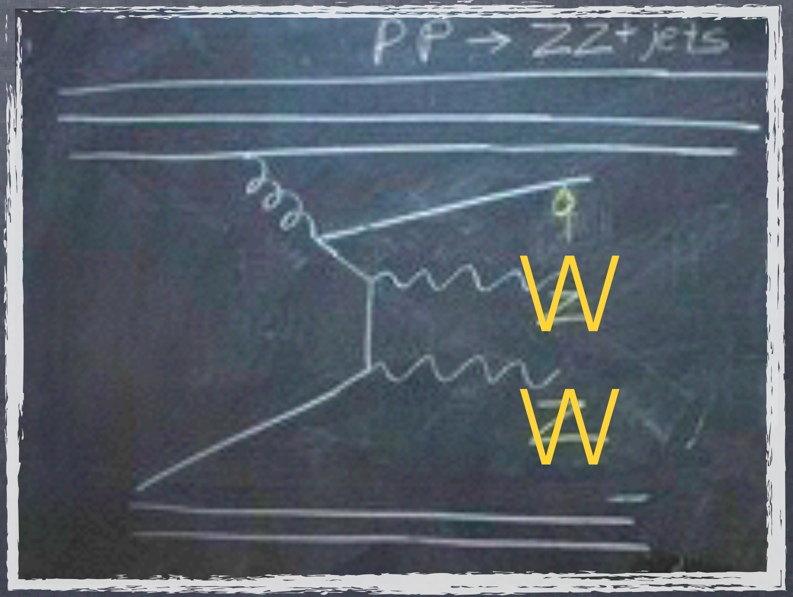
- “TEVATRON++” mass region 140-200 GeV
- Probing channel: H->WW->lυlυ



H->WW->lνlν

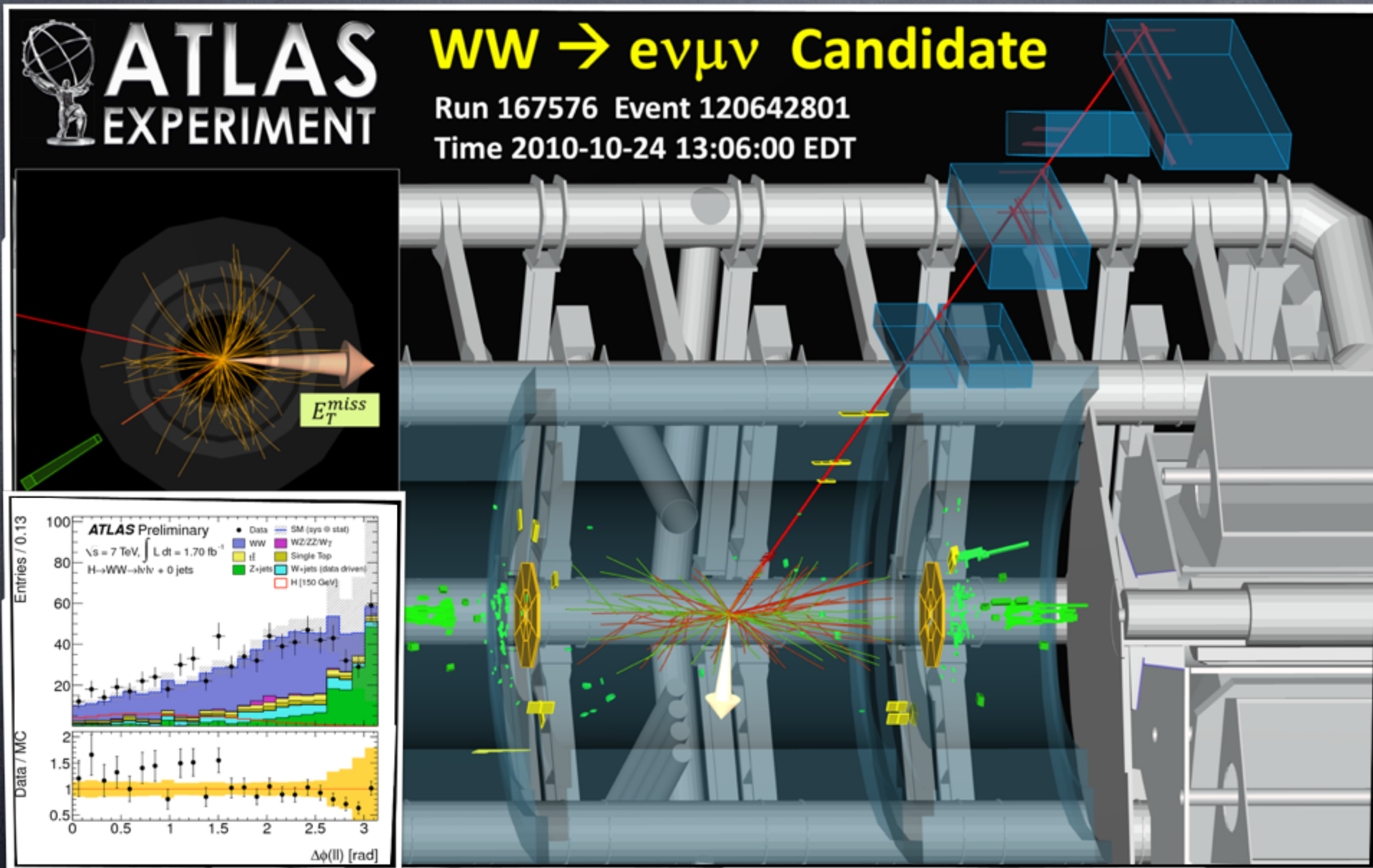


- The cannel is challenging (2 neutrinos- no mass reconstruction)
- Signature: 2 high pT opposite sign isolated leptons with large MET
- 3 bins: +0,1 and 2 jets (VBF)



WW->eμ Irreducible BG

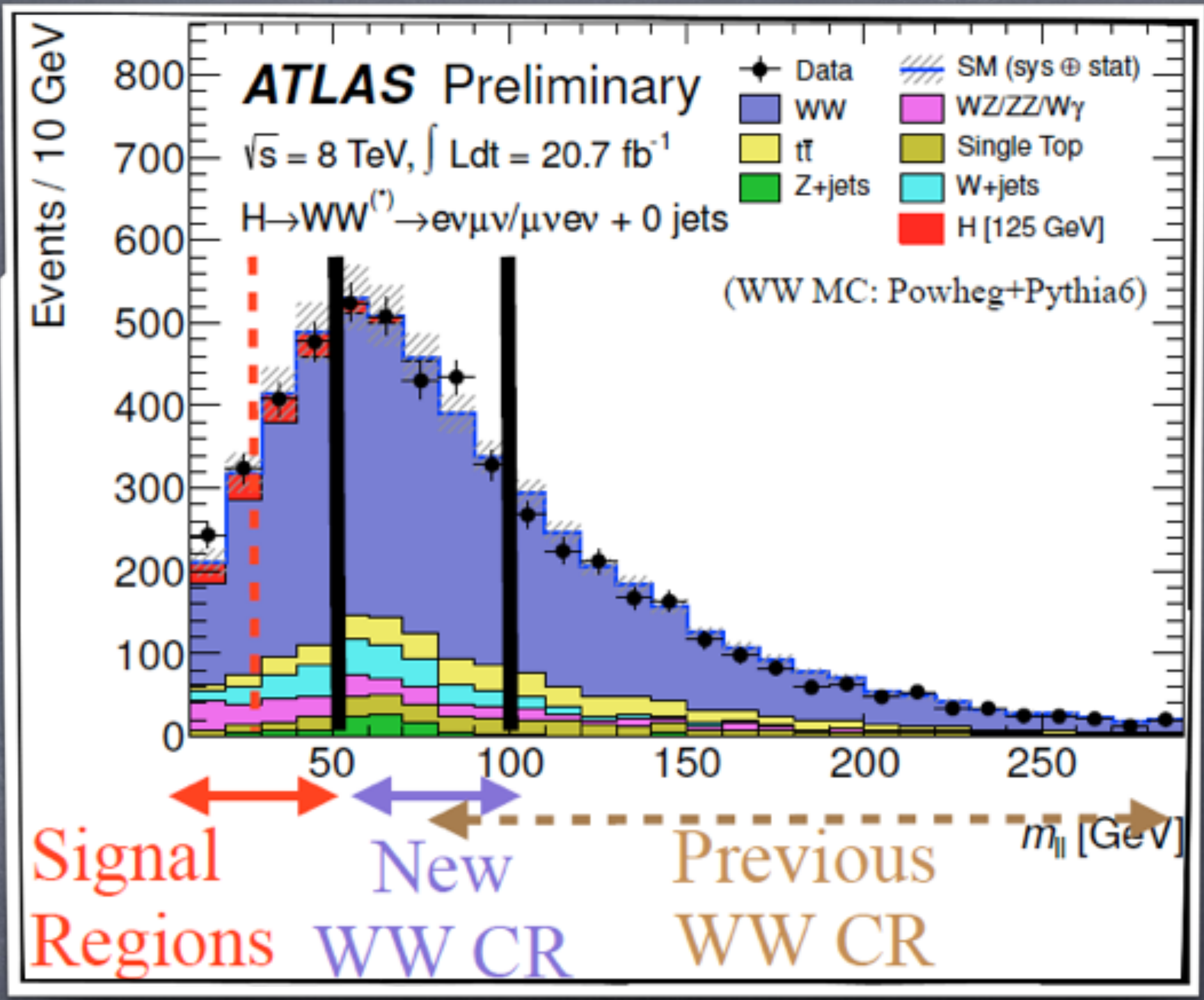
- WW can be reduced by exploiting the Higgs spin, require small $\Delta \Phi_{ll}$



H->WW->lνlν

- 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

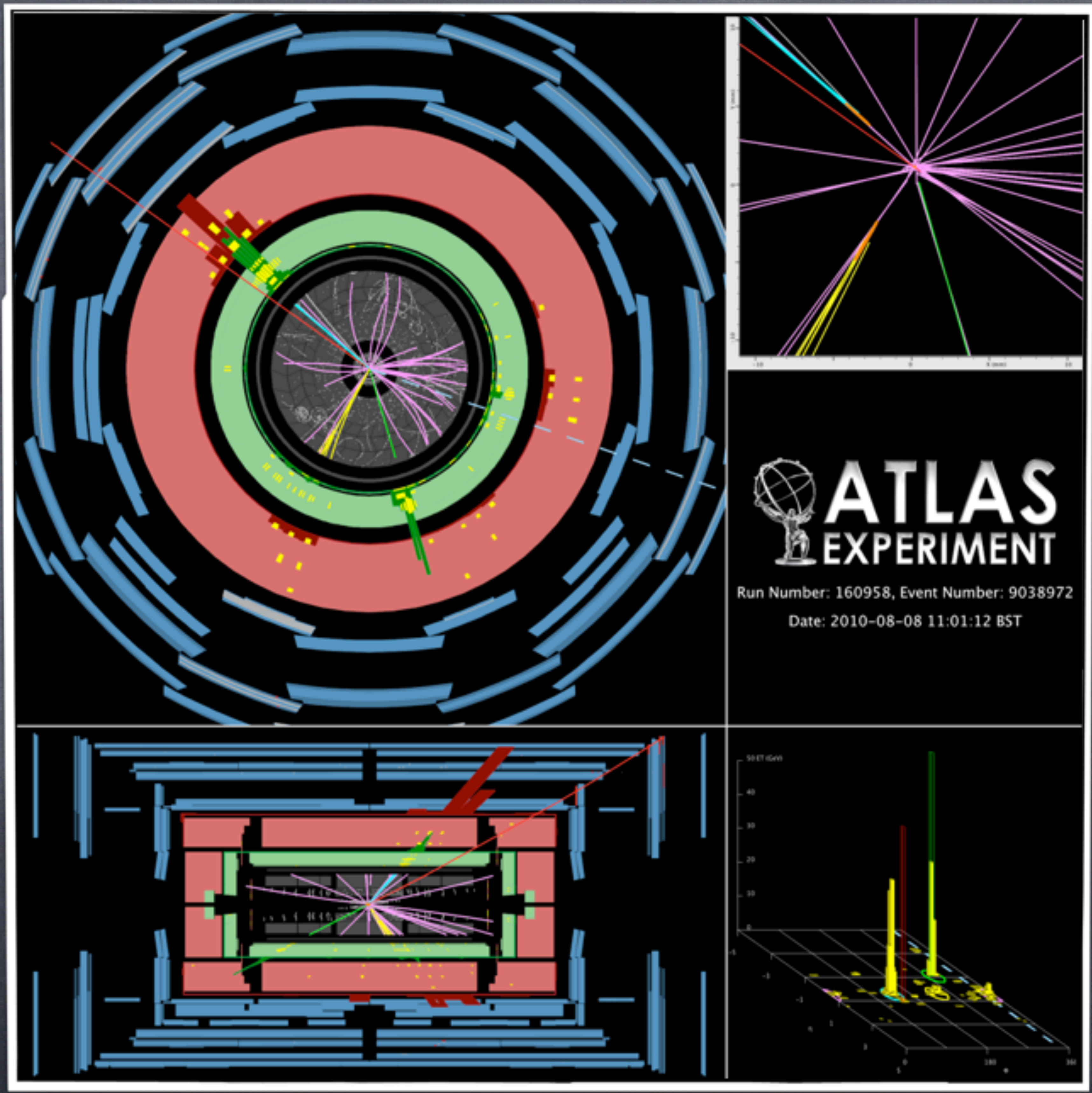
WW 0j control region



mll<50 -> 50<m_{ll}<100
validate with mll>100

ATLAS WW->eμ background: tt->eμ

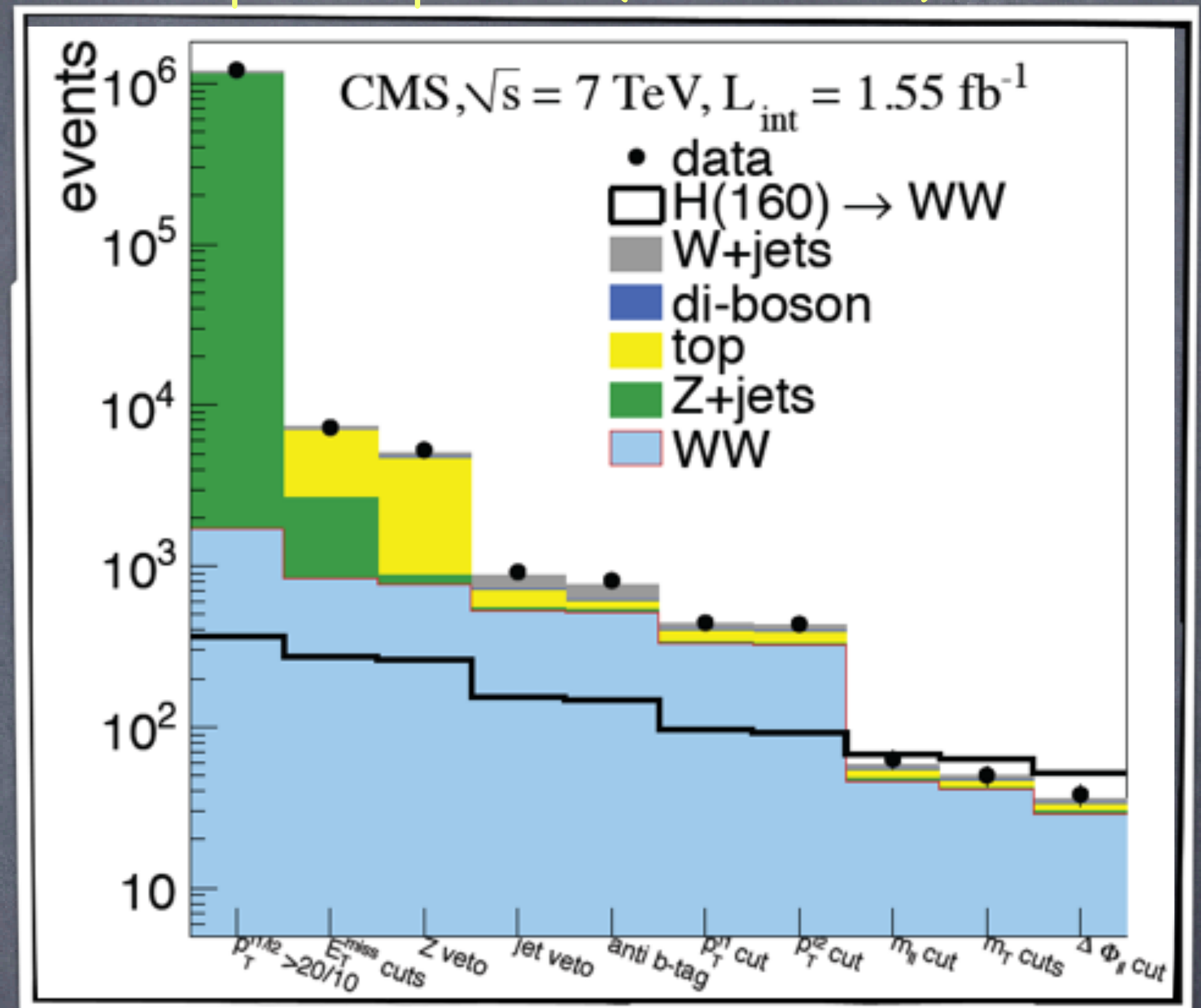
Event display of a top pair e-mu dilepton candidate with two b-tagged jets.
The electron is shown by the green track pointing to a calorimeter cluster, the muon by the long red track intersecting the muon chambers, and the missing ET direction by the dotted line on the XY view. The secondary vertices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

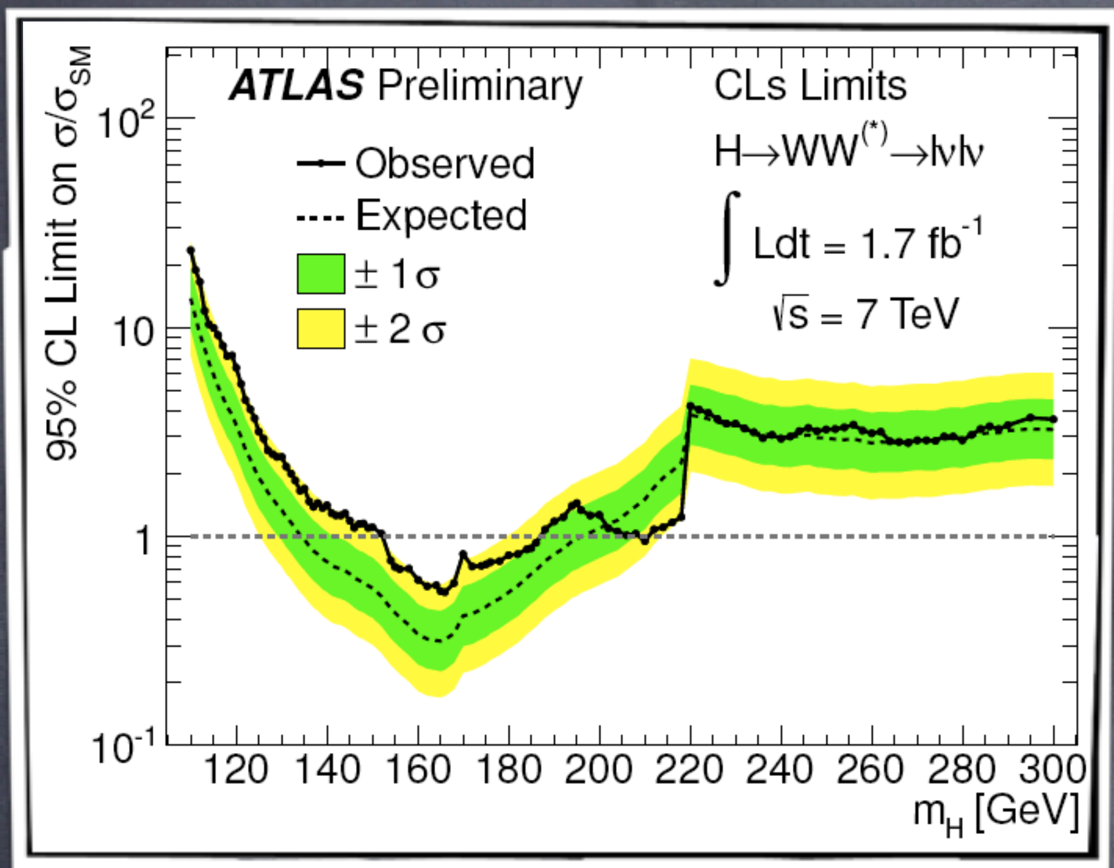
in this plot expected (data driven) vs data

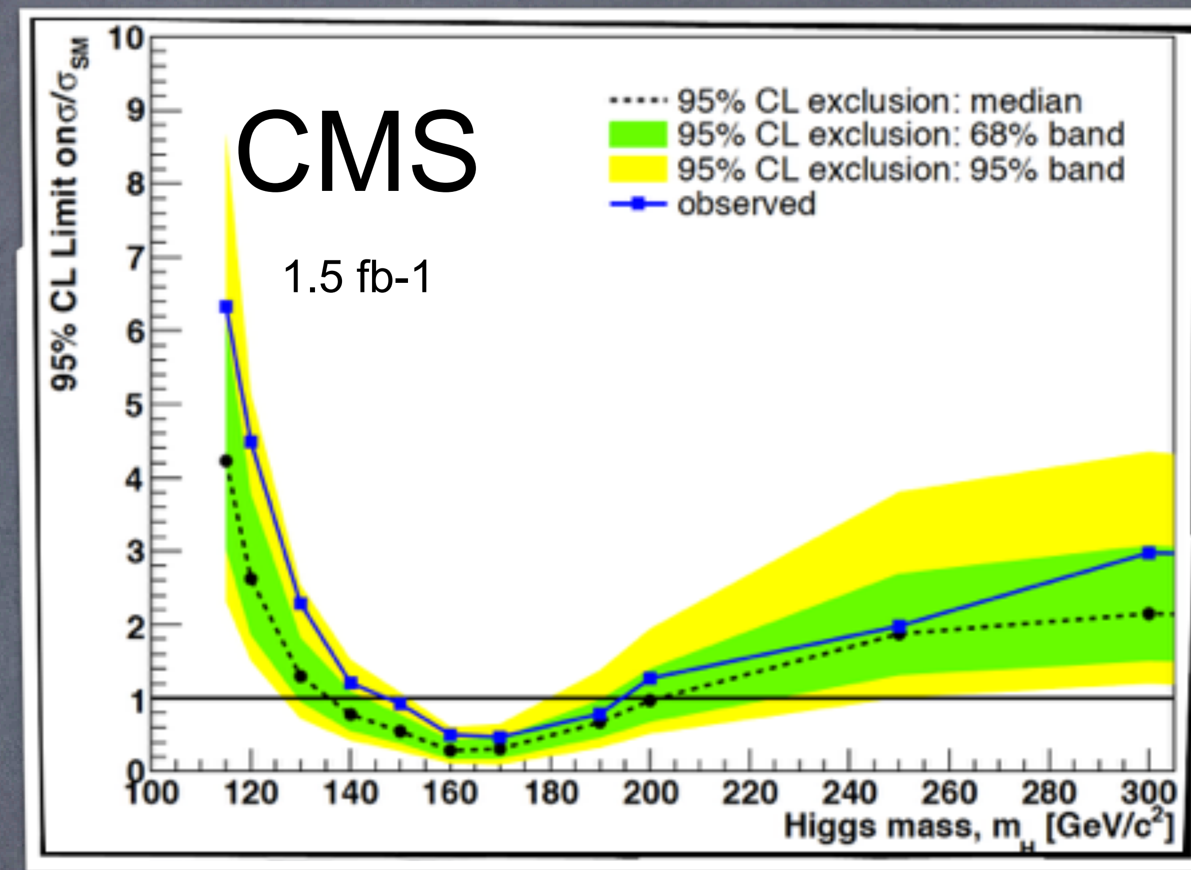


- BG: WW, W+jets, DY (Z+jets), top
- Irreducible WW BG can be slightly reduced requiring small $\Delta\Phi_{ll}$
- Large MET and Z Veto against DY
- b-tag veto to remove top contamination
- Finally mass dependent cuts are applied (e.g. ATLAS $0.75m_H<m_T<m_H$)

H->WW->lνlν Limits

- Results are counting based





Obs: 154<mH<186 Obs: 147<mH<194

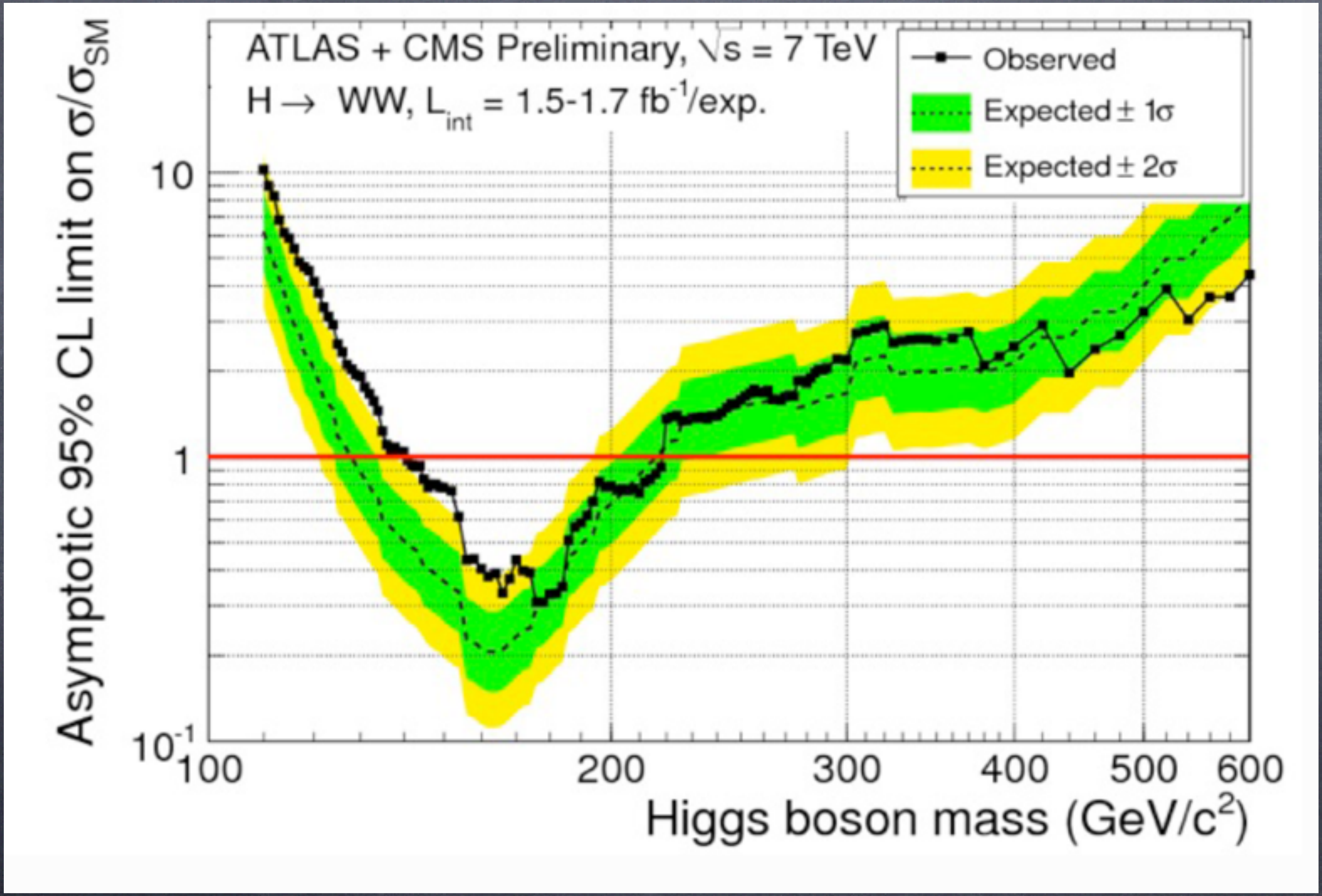
Exp: 135<mH<196 Exp: 136<mH<200

Both cut based

ATLAS: only +0,1 jets

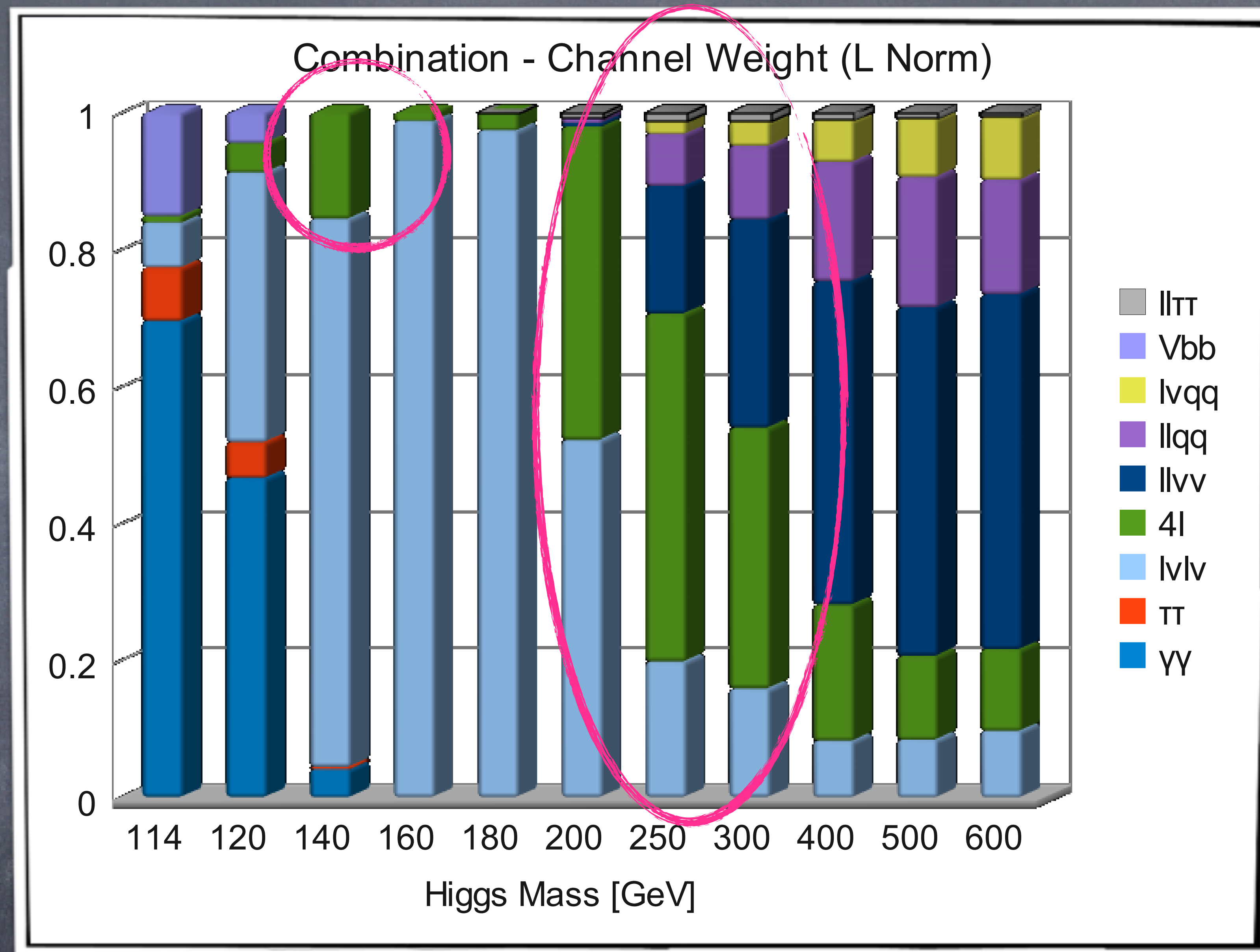
H->WW->lνlν Limits

- ATLAS+CMS first official Combination



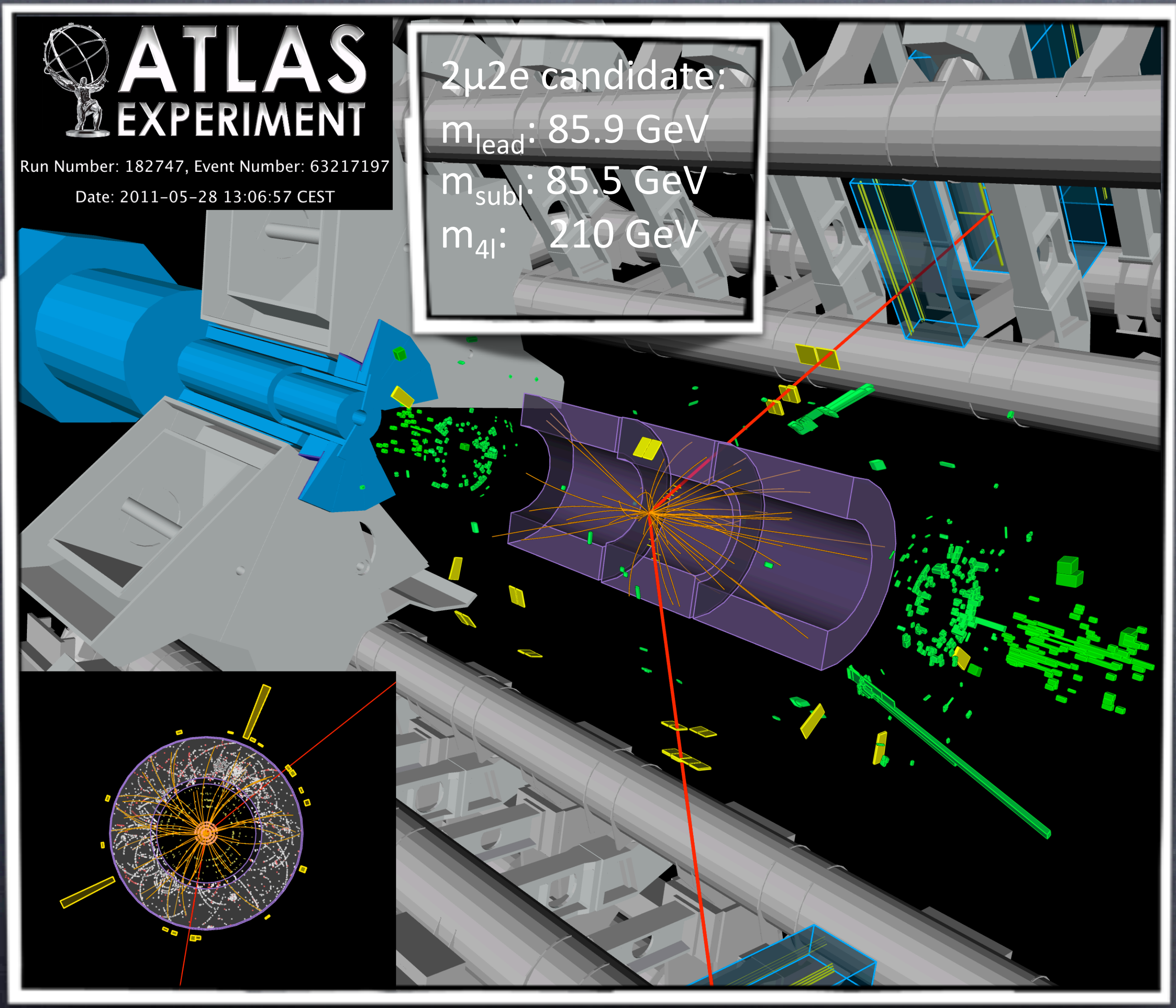
The Golden Channel - H->ZZ->4l

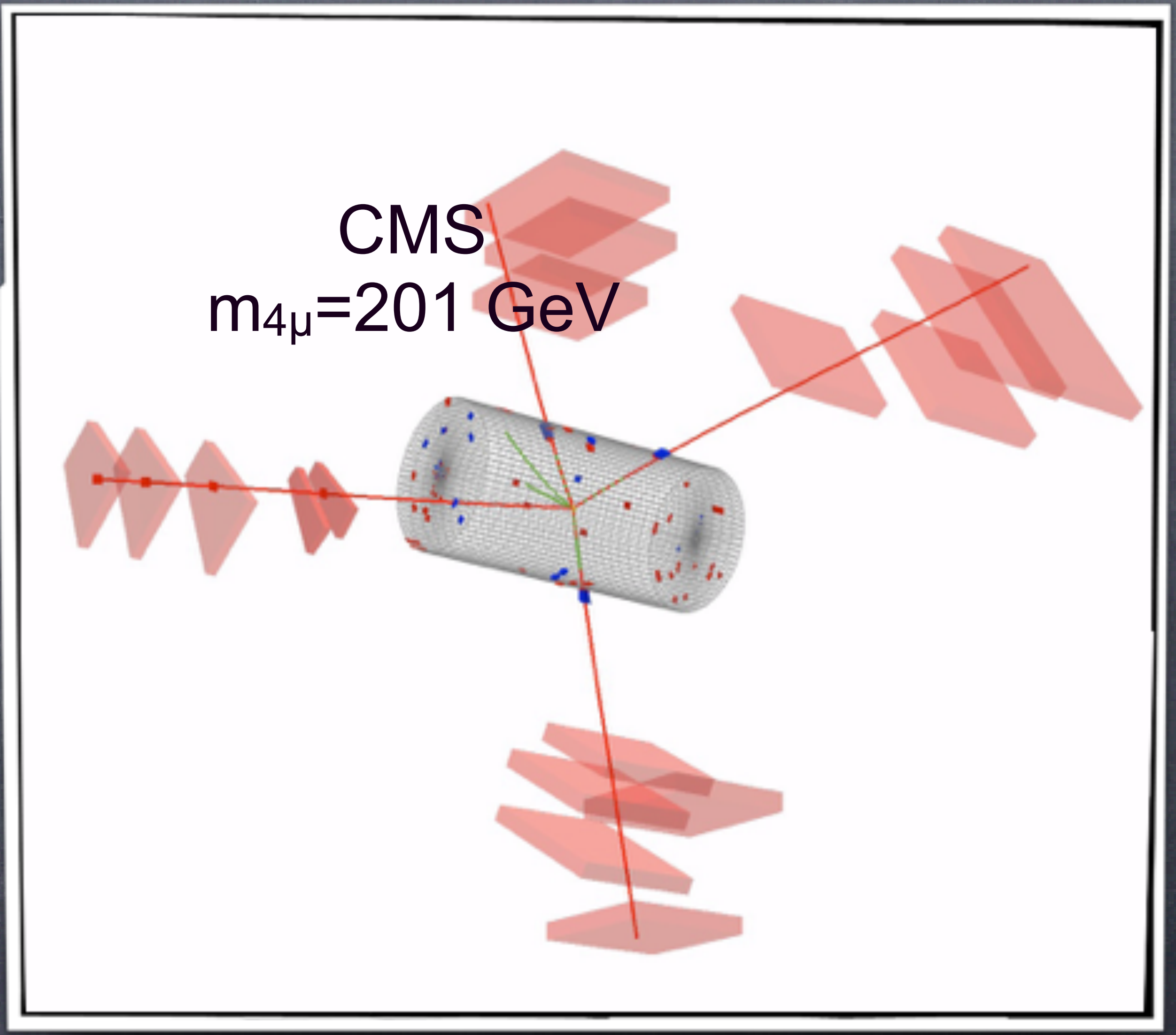
- Around 140 and above 200 GeV
- Probing channel: H->ZZ->4l



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

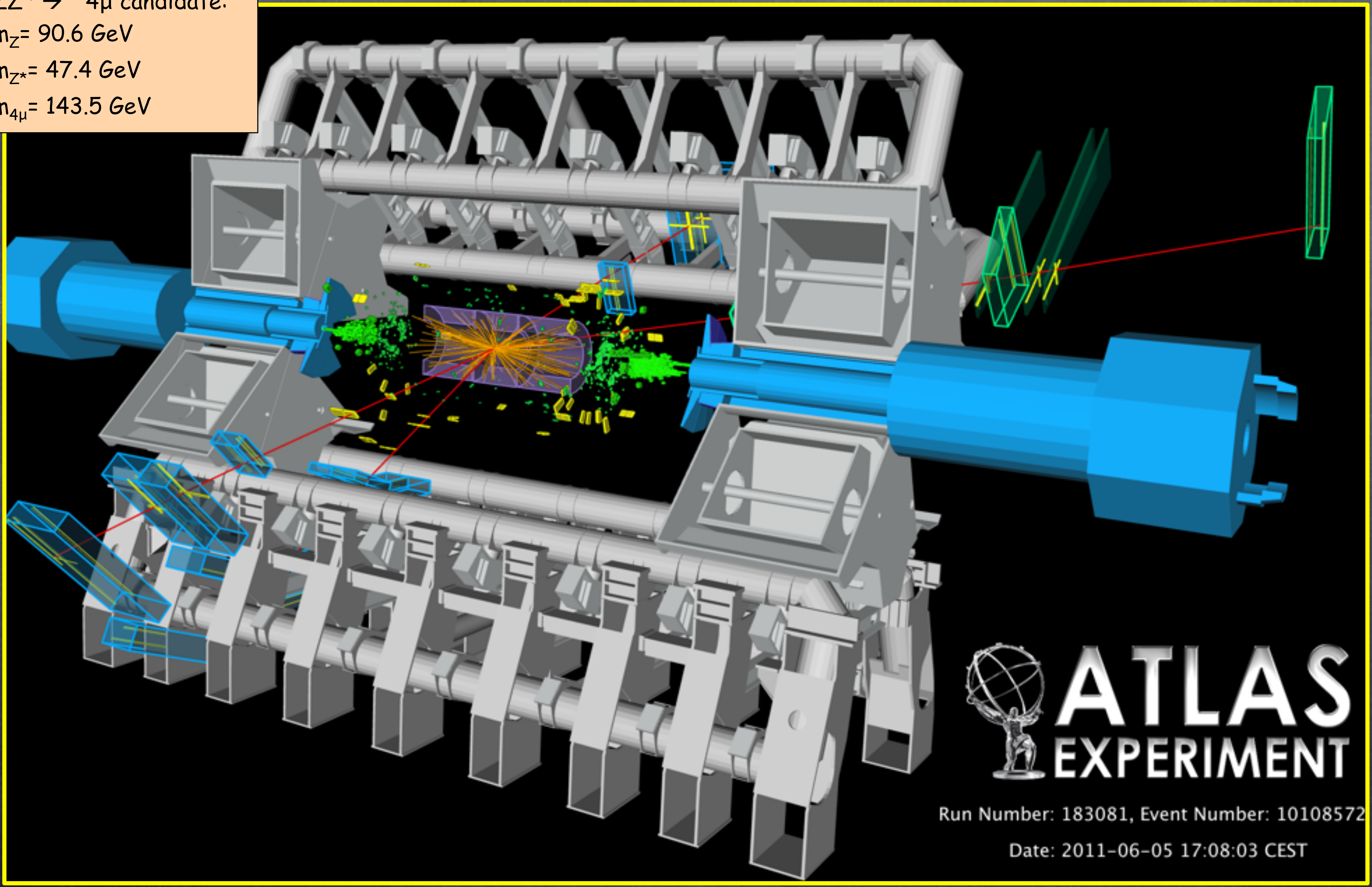
- CLEAN but very low rate, yet probably most trustable
- All information is available, one can fully reconstruct the kinematics and the masses (m_{2l}, m_{4l})
- Signature: Two pairs of same flavor high pT opposite charged isolated leptons, one or both compatible with Z

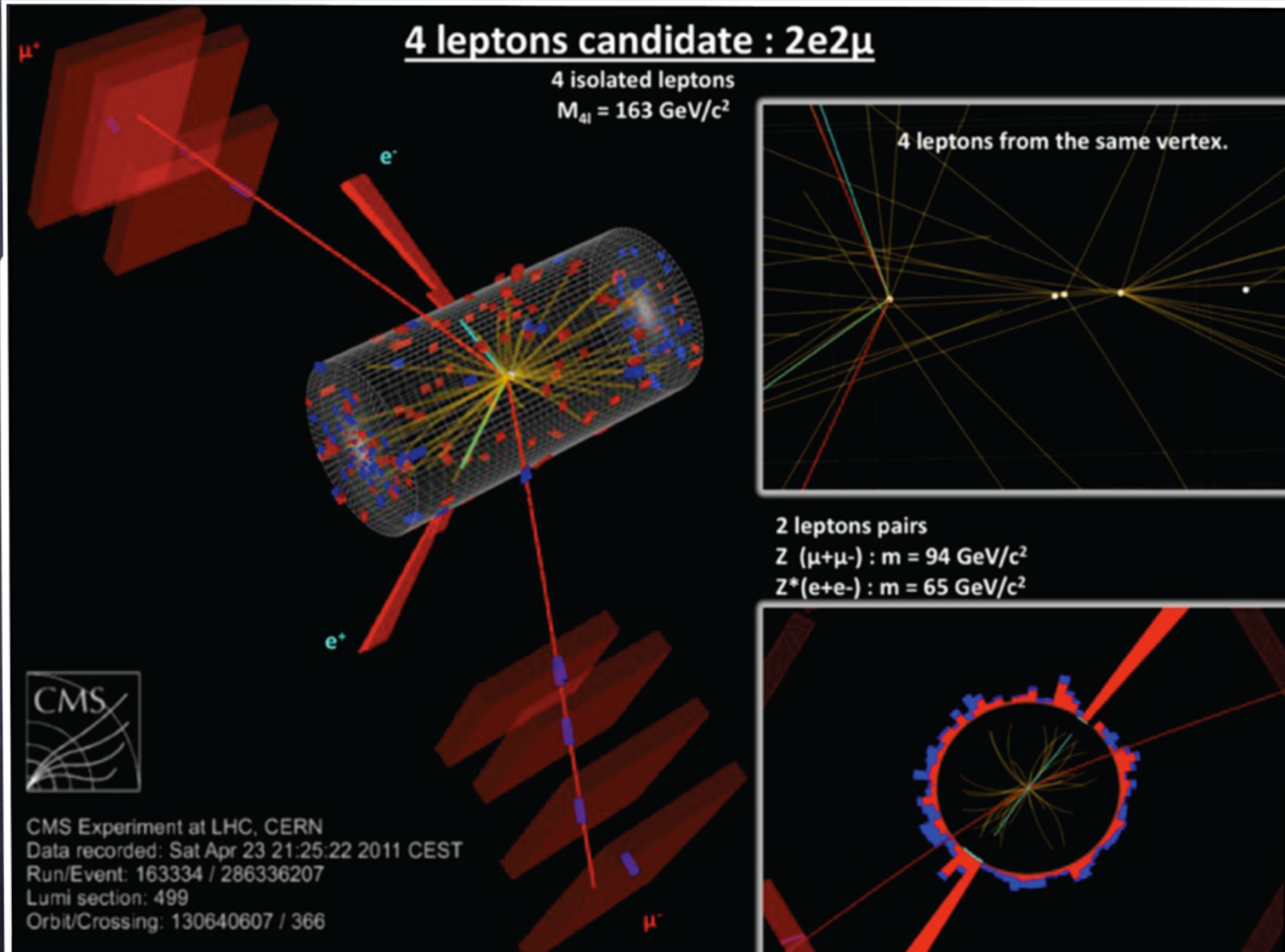




The Golden Channel: H->ZZ->4l

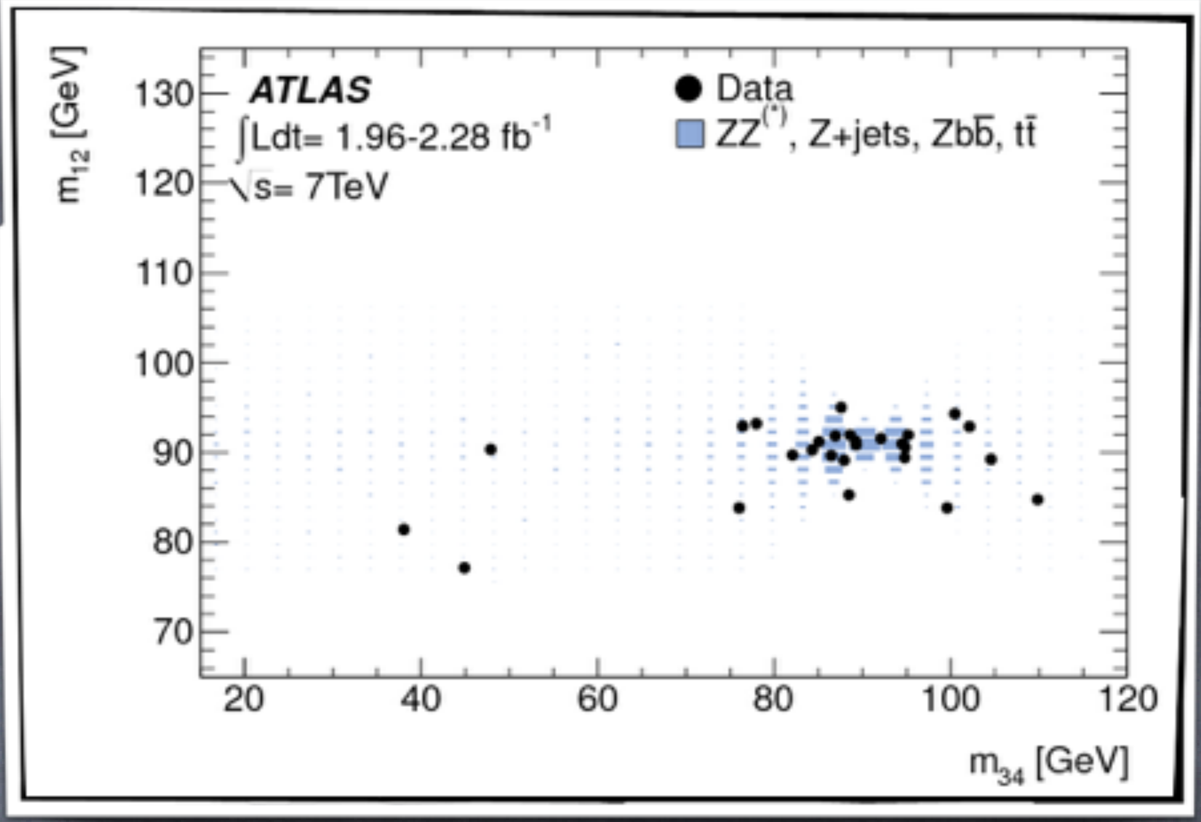
ZZ* → 4μ candidate:
m_Z= 90.6 GeV
m_{Z^*}= 47.4 GeV
$m_{4\mu}$= 143.5 GeV

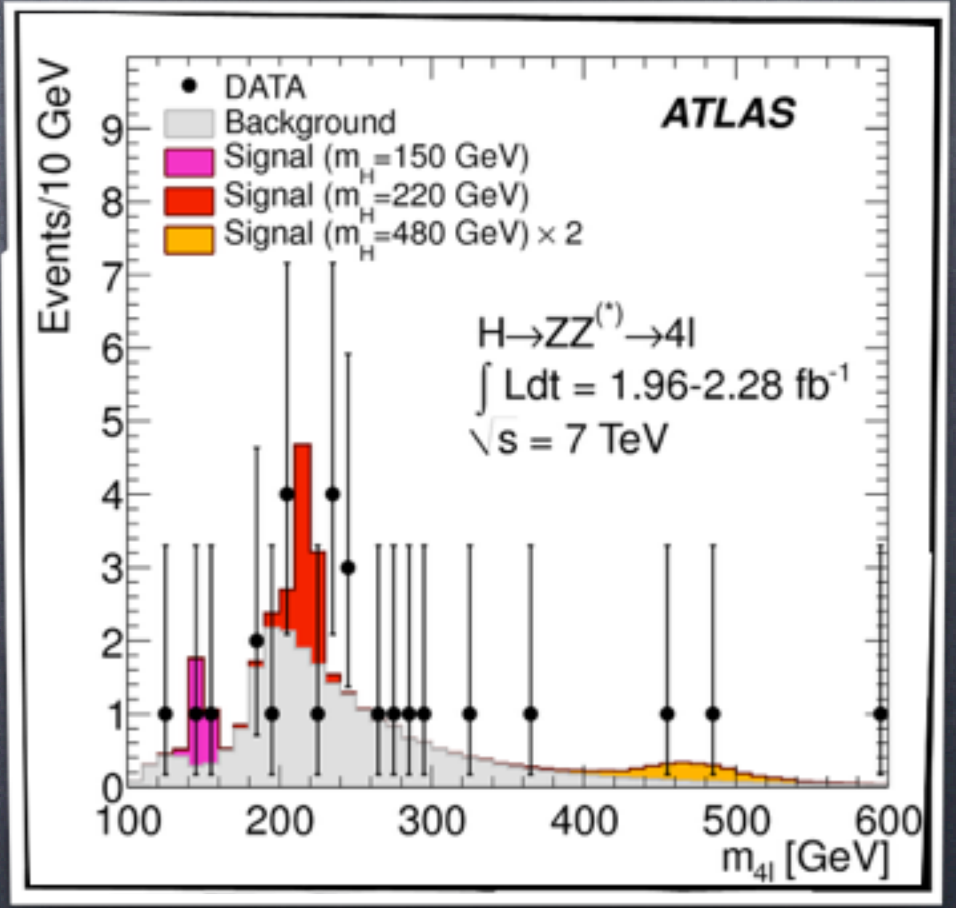



4 leptons candidate : 2e2μ
4 isolated leptons
M4l = 163 GeV/c2
4 leptons from the same vertex.
2 leptons pairs
Z (μ+μ-) : m = 94 GeV/c2
Z*(e+e-) : m = 65 GeV/c2
μ+
e-
e+
μ-
CMS
CMS Experiment at LHC, CERN
Data recorded: Sat Apr 23 21:25:22 2011 CEST
Run/Event: 163334 / 286336207
Lumi section: 499
Orbit/Crossing: 130640607 / 366

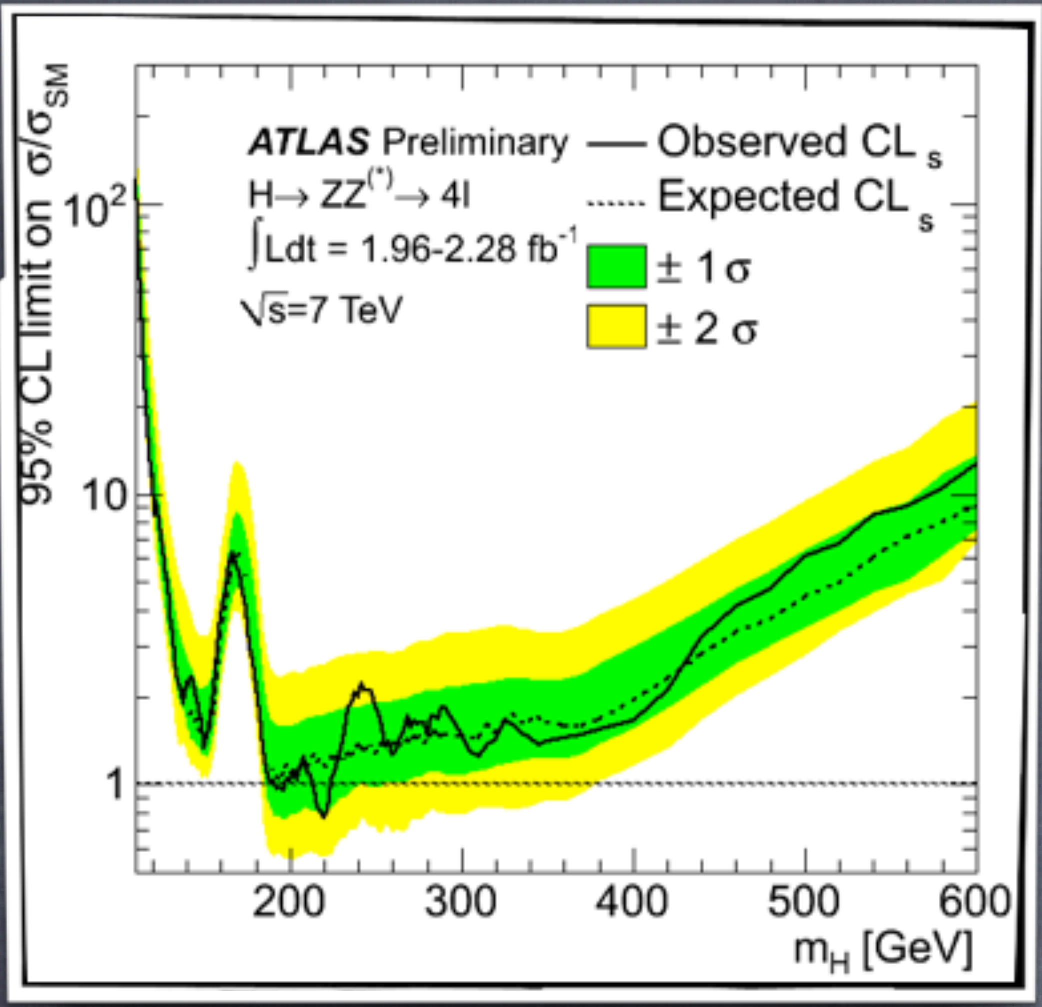
The Golden Channel: H->ZZ->4l

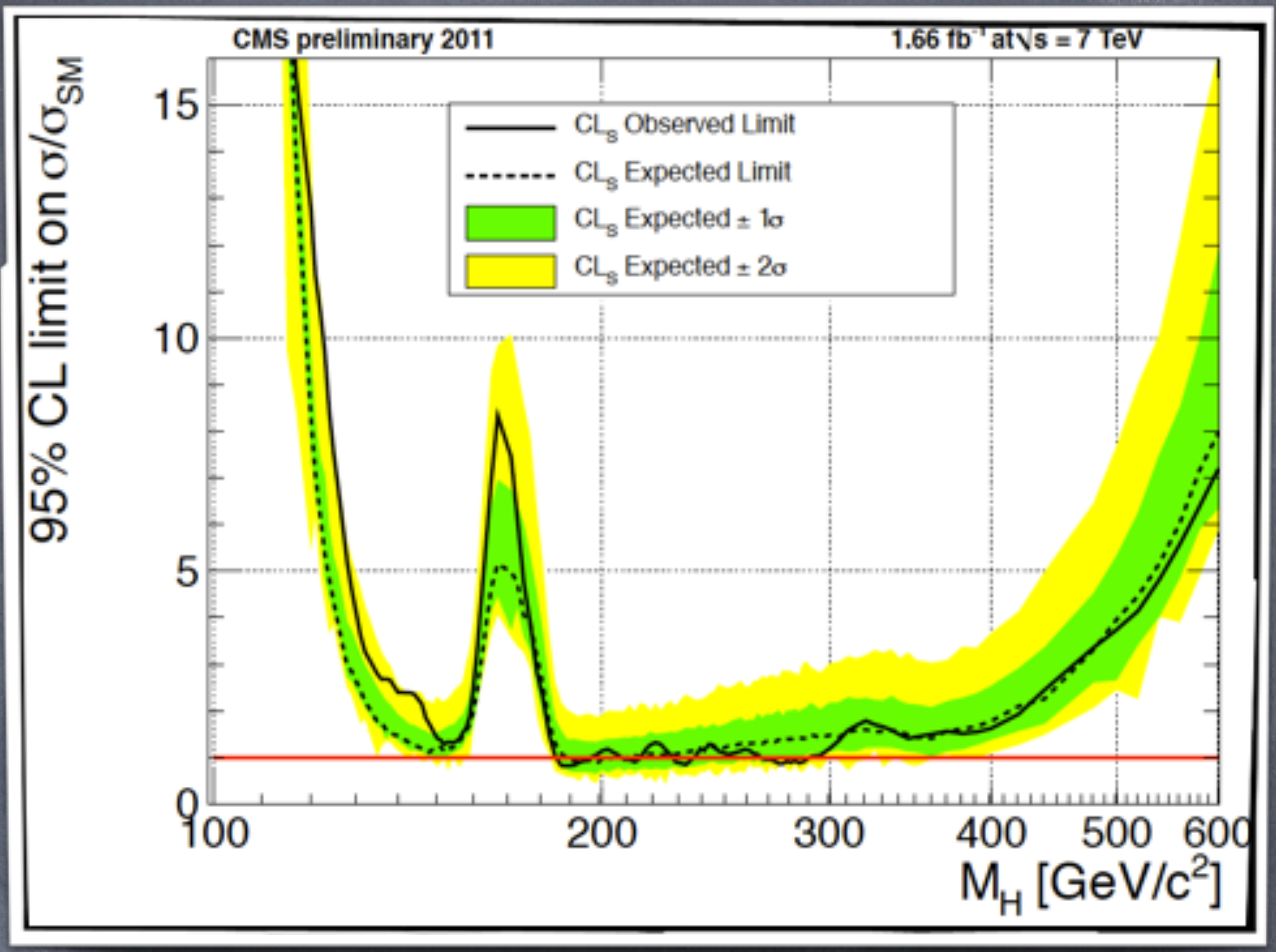
- A distinct signature due to the excellent mass resolution
- Irreducible BG from ZZ
- Highly sensitive to lepton ID performance (electron efficiency from J/Ψ->ee, W->eυ, Z->ee data)
- Z+jets (Z+bb) BG estimated from data
- Reducible BG: tt, Zbb removed by isolation and small impact parameter (for $m_{4l}<2m_Z$) requirements





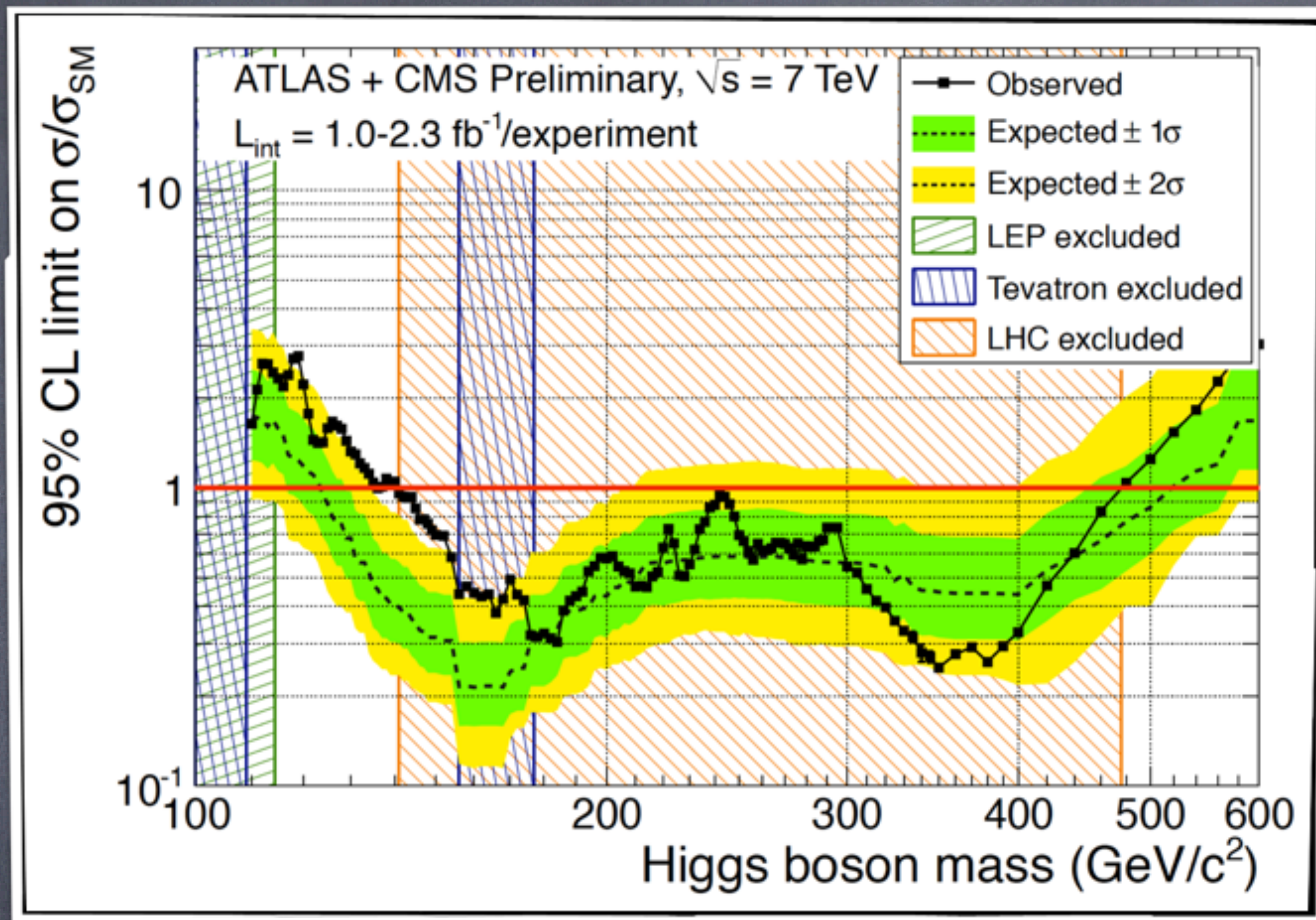
The Golden Channel: H->ZZ->4l





- Both experiments are getting closer to exclude
- There is no real excess anywhere

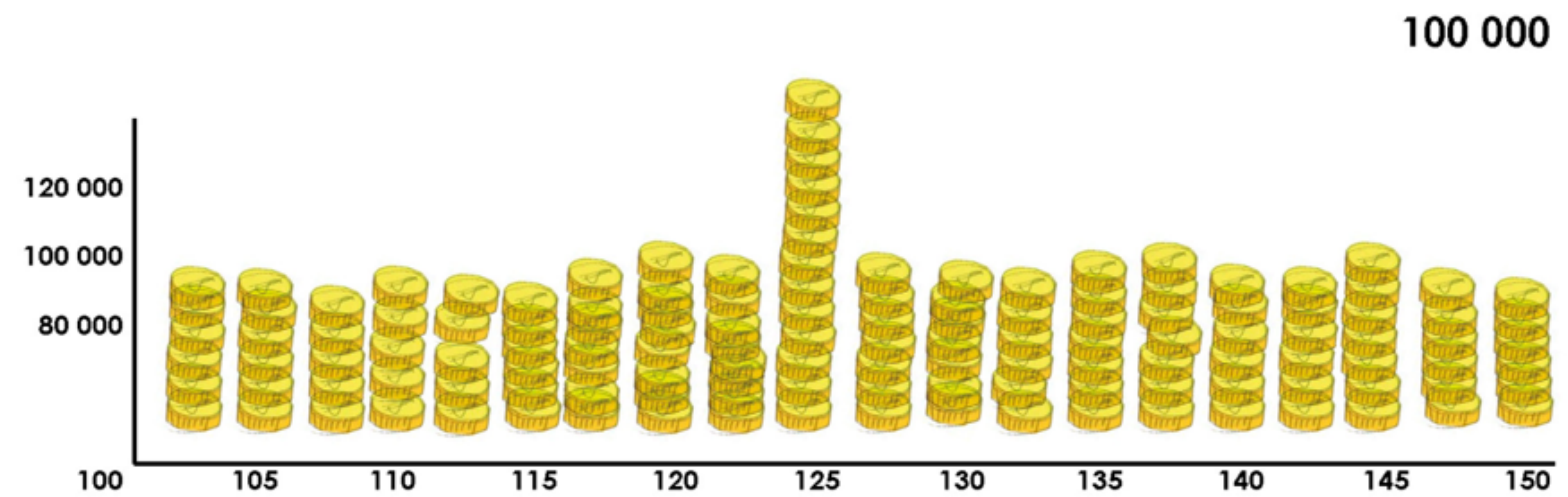
Higgs- The Story So Far



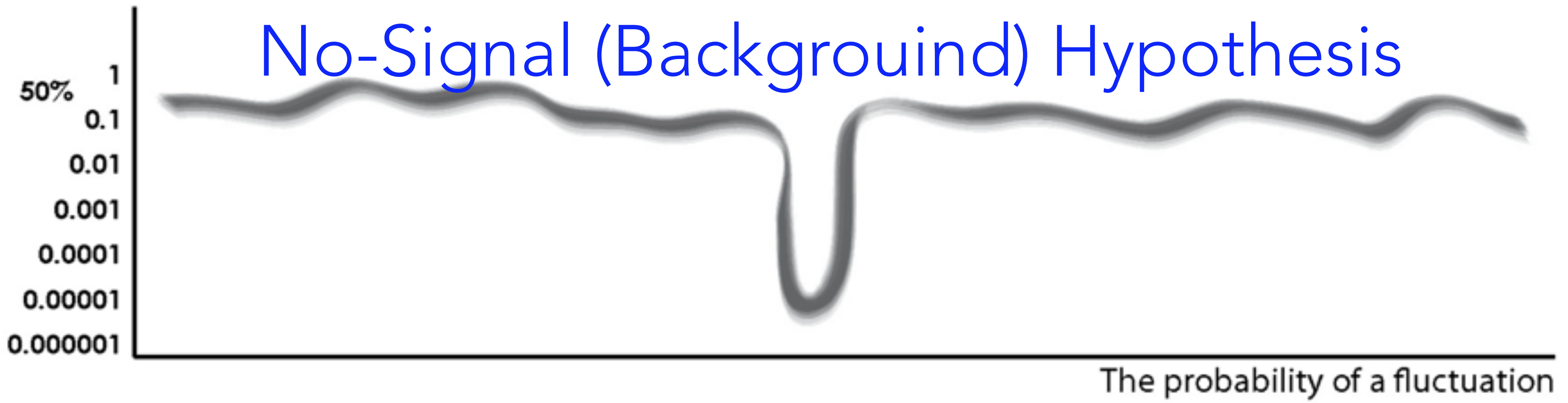
- Sensitivity (Expected exclusion) 124-520 GeV @ the 95% Confidence Level
- Observed exclusion 141-476 GeV @ the 95% Confidence Level
- Interesting regions are very low mass 114<mH<130 and mH>470

THE HIGGS DISCOVERY

DISCOVERY - A GAME OF BUMPS



Compatibility of Data with
No-Signal (Backgrouind) Hypothesis



p-value

$$2\sigma \sim 5\% \sim 1:20$$

$$3\sigma \sim 0.003 \sim 1:330$$

There is a chance of 1:330 that the observed particle is a mere fluctuation

The Magic Number

$$5\sigma \sim 3 \times 10^{-7} \sim 1:3.3\ \text{M}$$

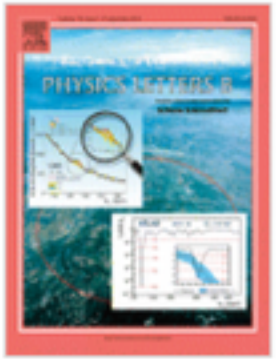
Discovery

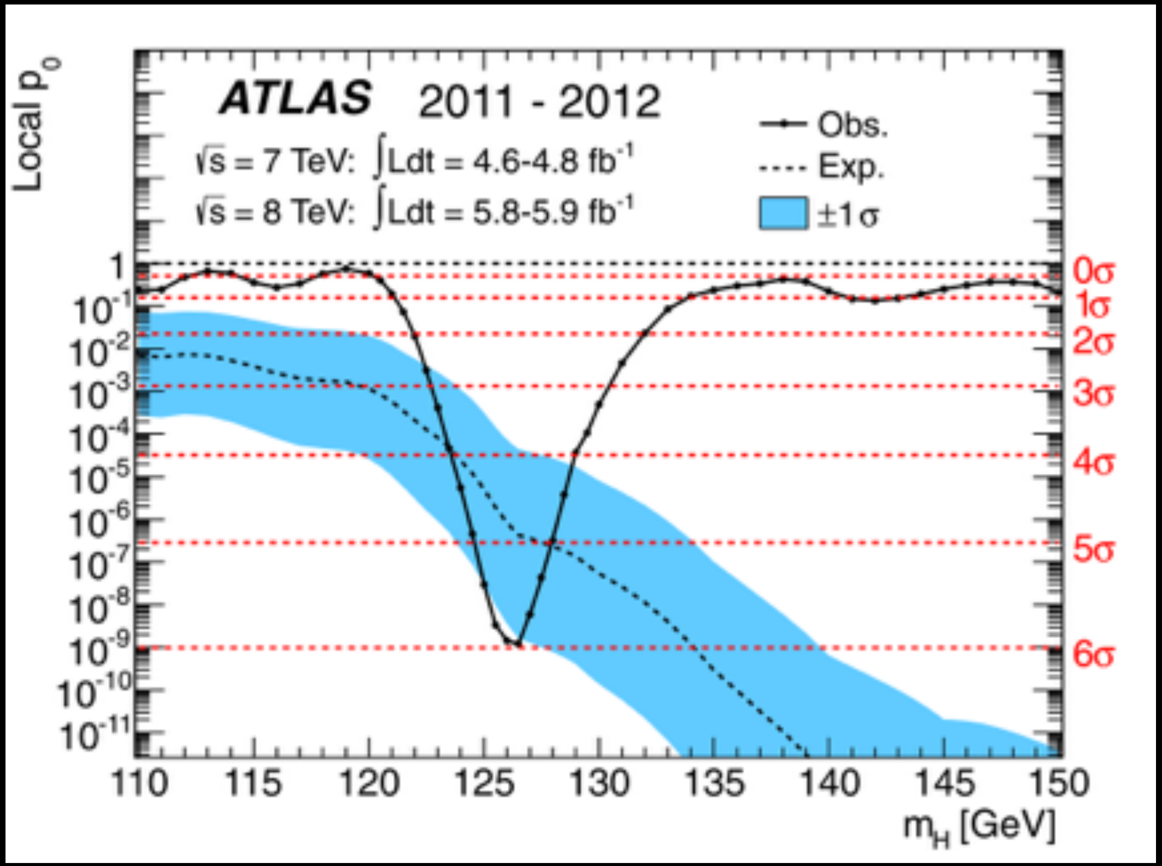
THE PUBLICATION

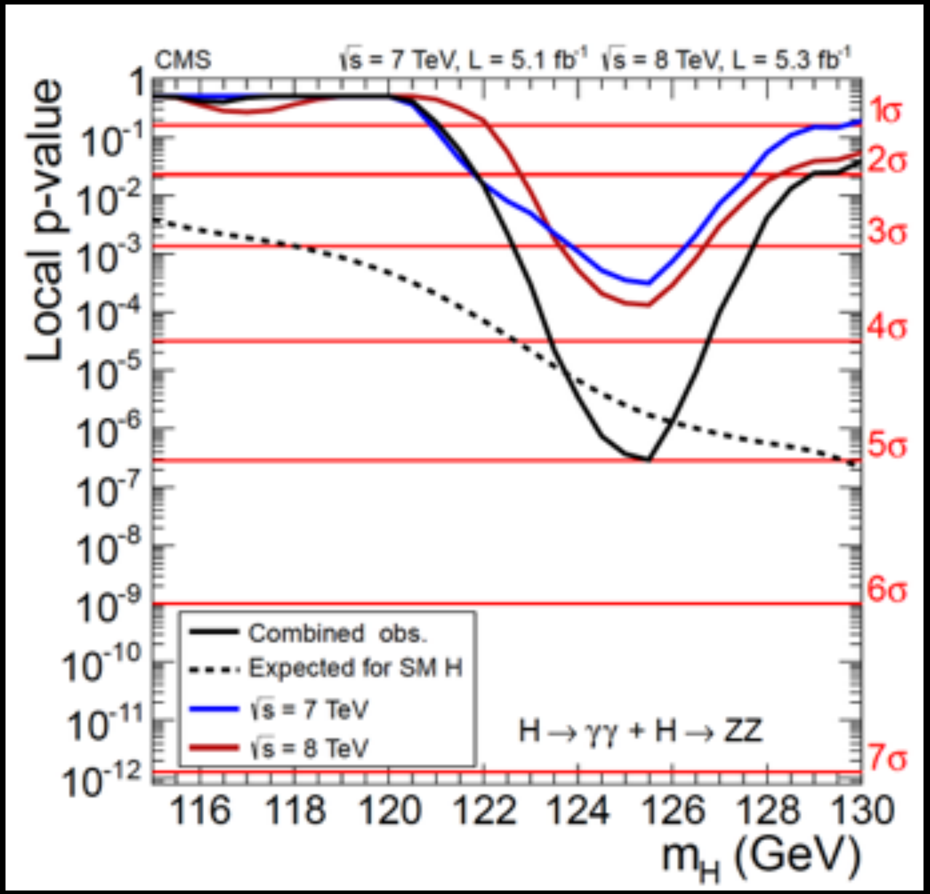
ELSEVIER

Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 1–29





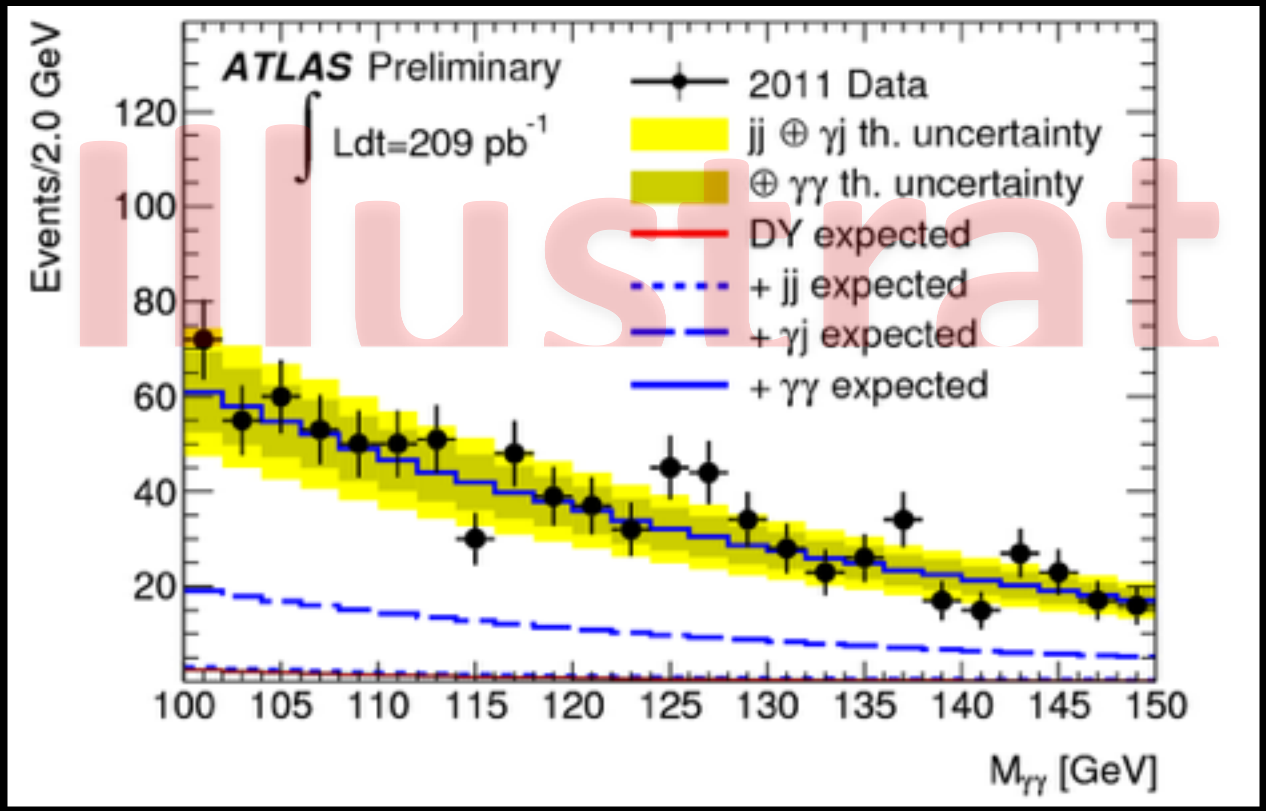


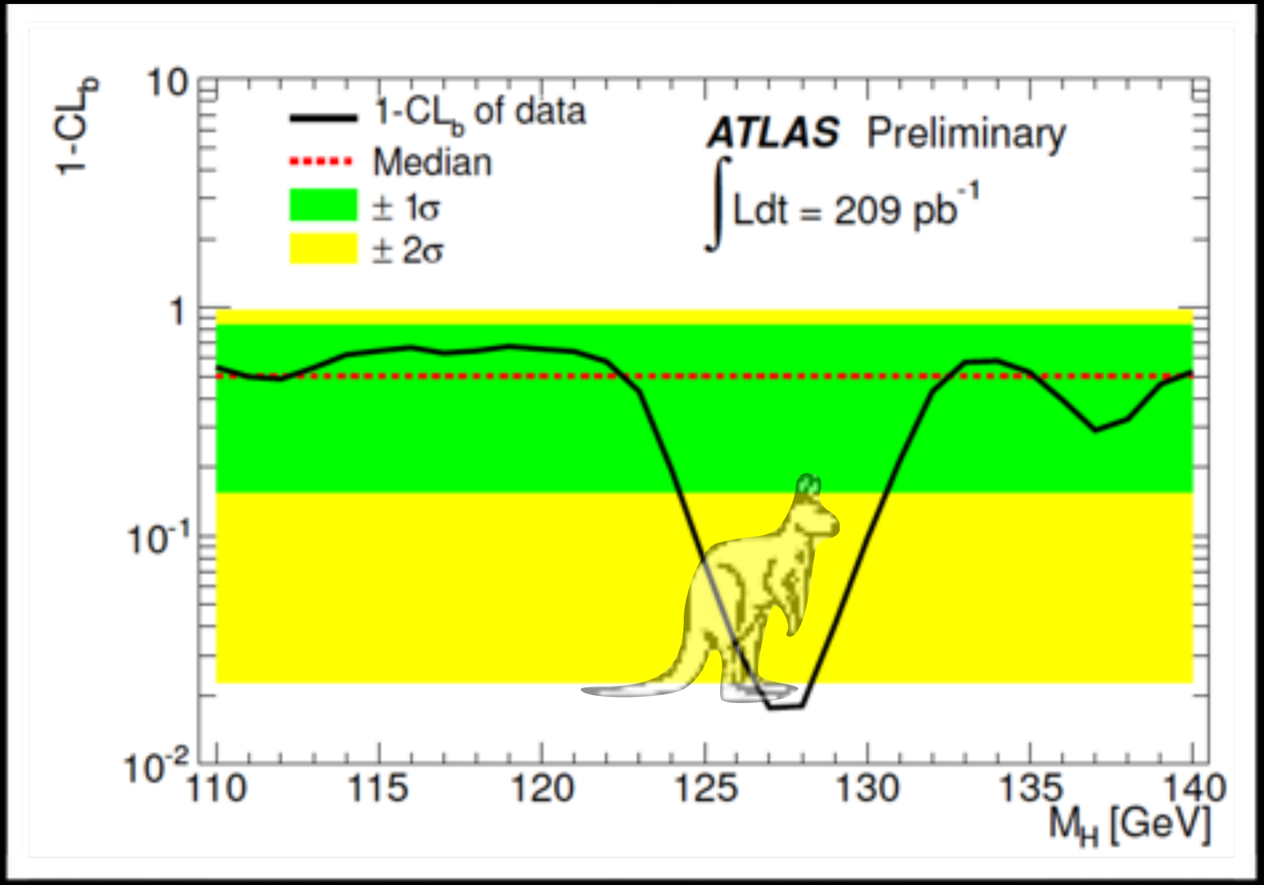
THE HIGGS DISCOVERY DIARY

EASY TO BE WISE AFTER THE EVENT
WE HAD IT SINCE THE BEGINNING.....

$H \rightarrow \gamma\gamma$

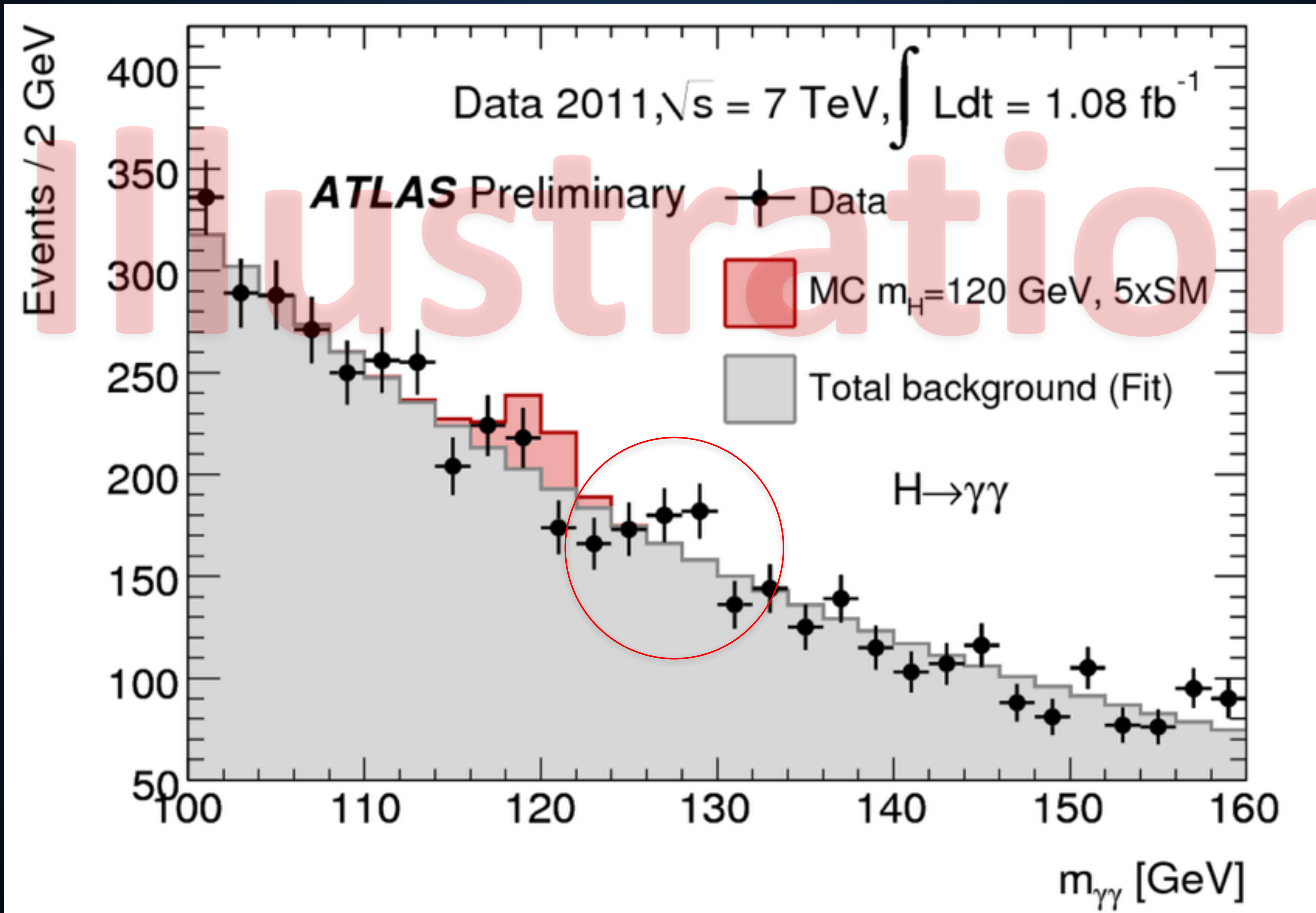
ATLAS-CONF-2011-085 06 June 2011





- EPS July 2011 : All the attention was on the 145 GeV Peak but...

Excess at 127 GeV ~2.7 sigma see:



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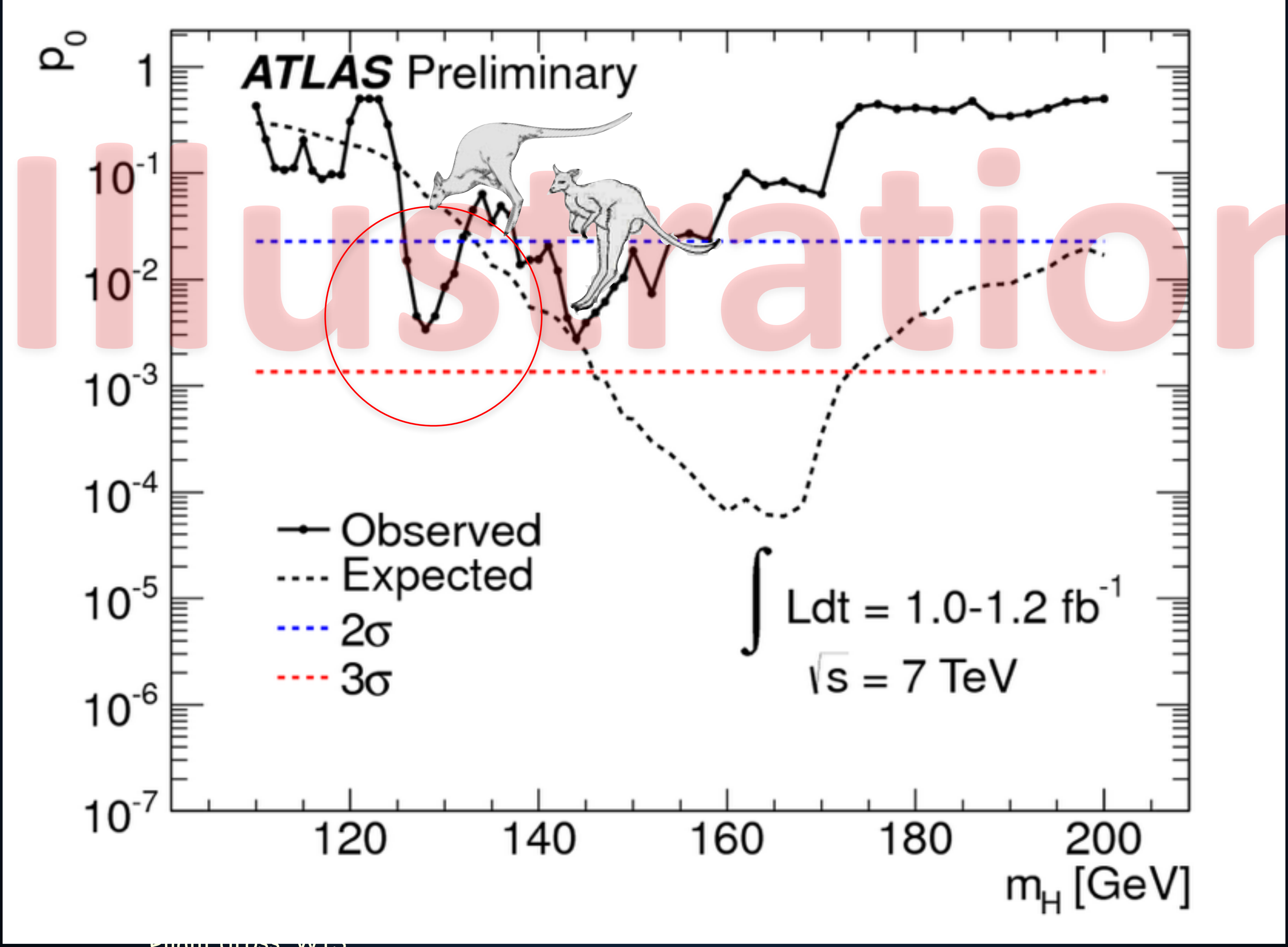


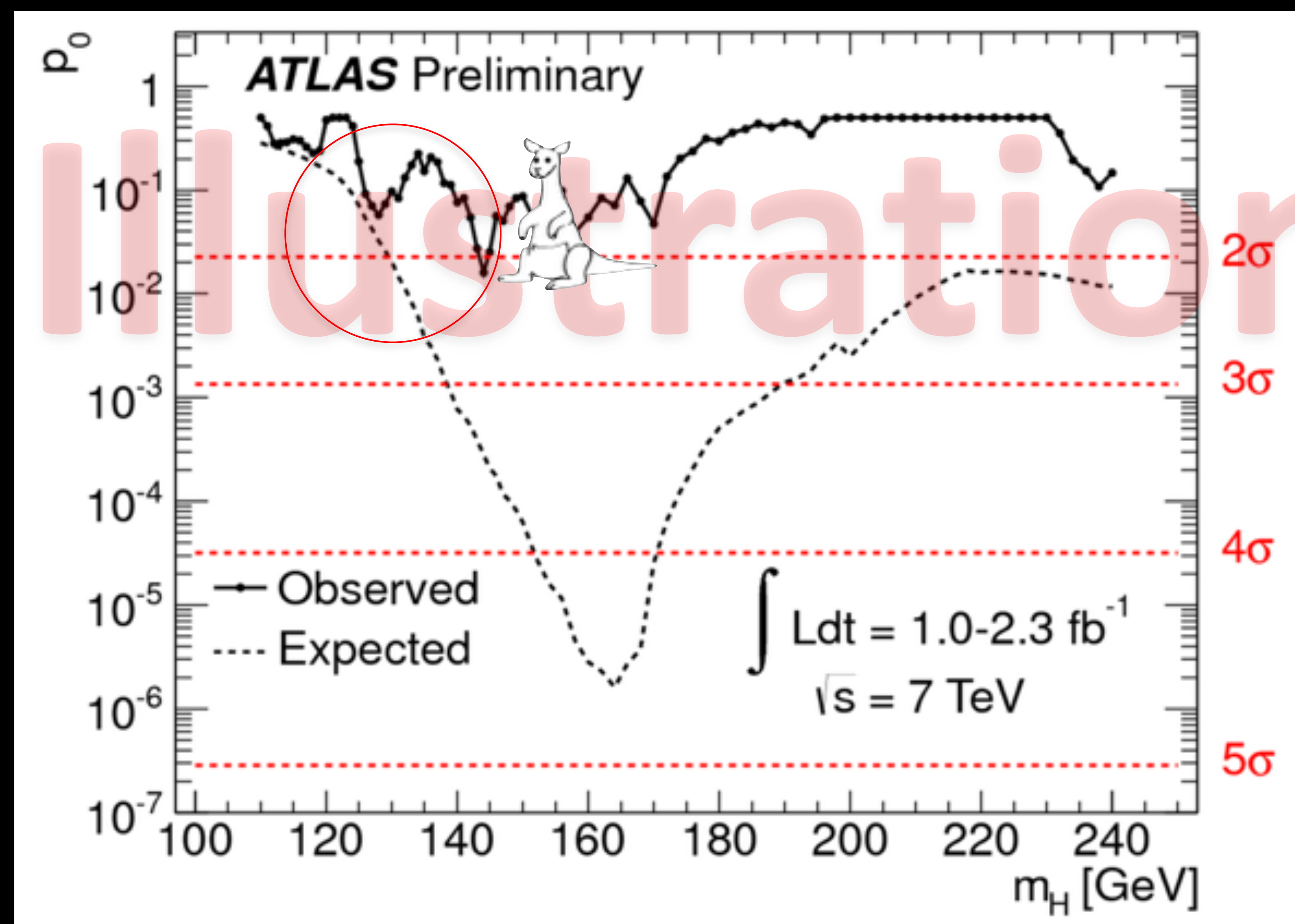
LP 2011 MUMBAI 27 AUGUST 2011

ATLAS-CONF-2011-135

- The noticeable excesses at 127 GeV,144 GeV and 245 GeV reported in Ref. [7], are less significant but still present.

- LP 2011 (August 2011) : Everything went down...

Excess at 127 GeV ~1.6 sigma see:

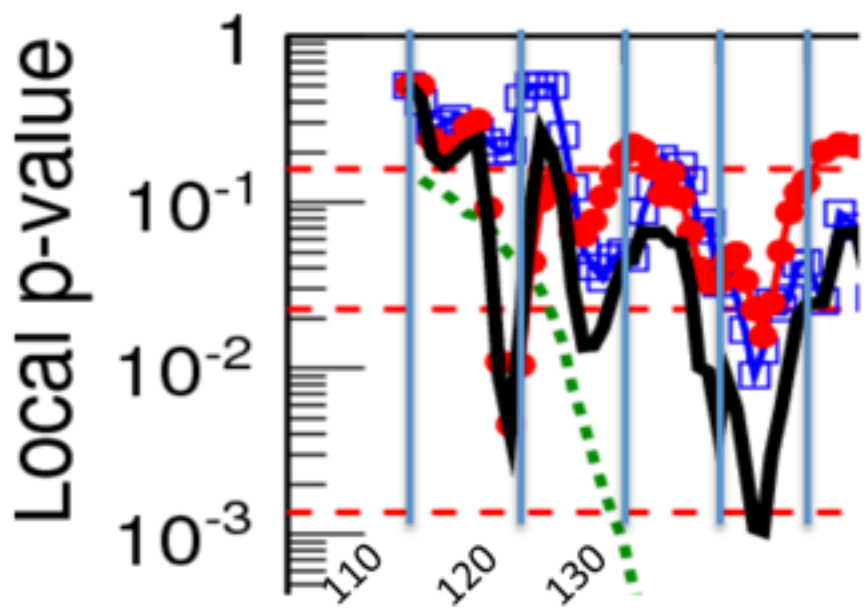


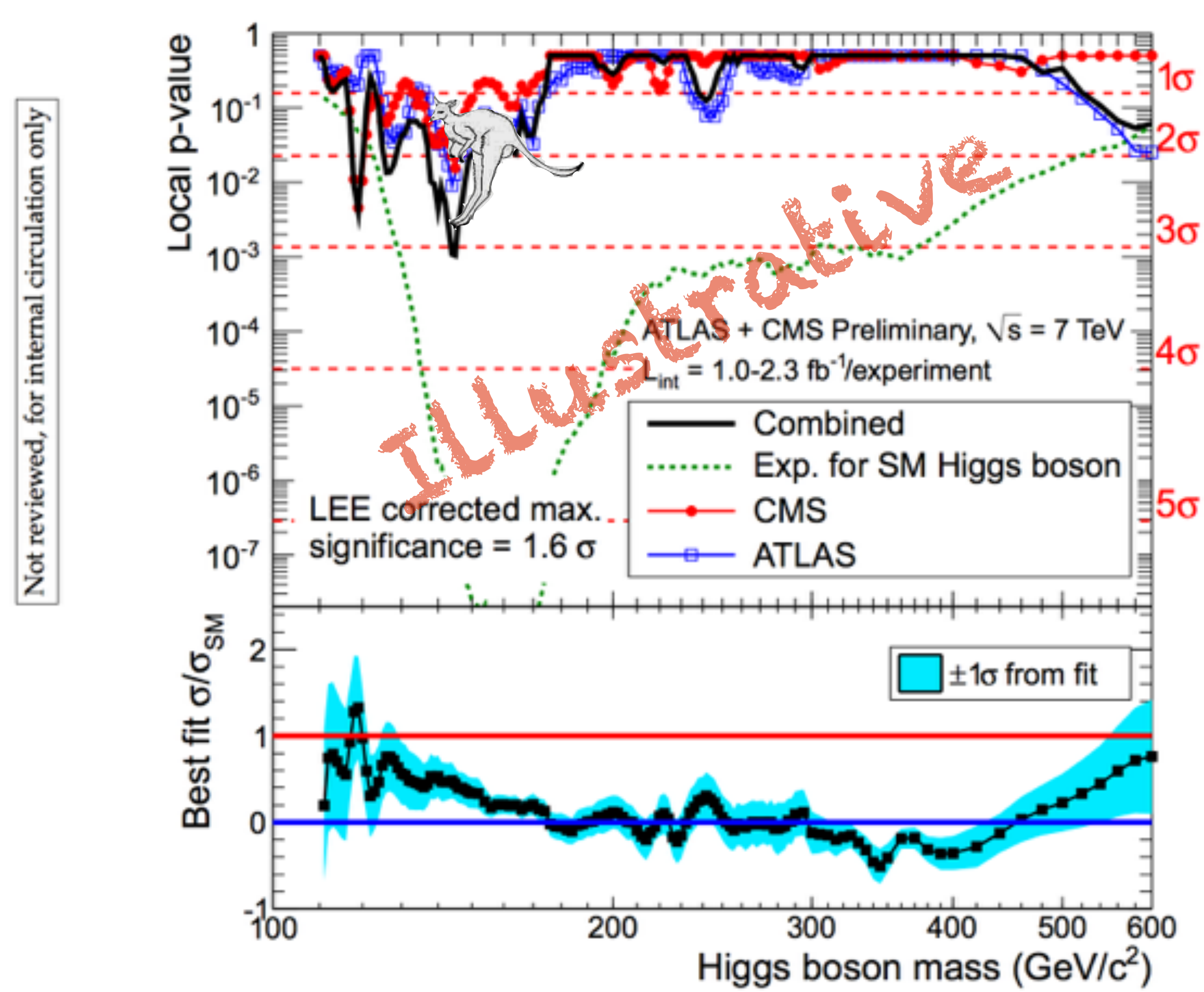
HCP(14-18NOV)2011, PARIS
WHERE IS THE HIGGS

ATLAS-CONF-2011-157
CMS PAS HIG-11-023

Nov 2011, up to 2.3 fb^{-1}/experiment

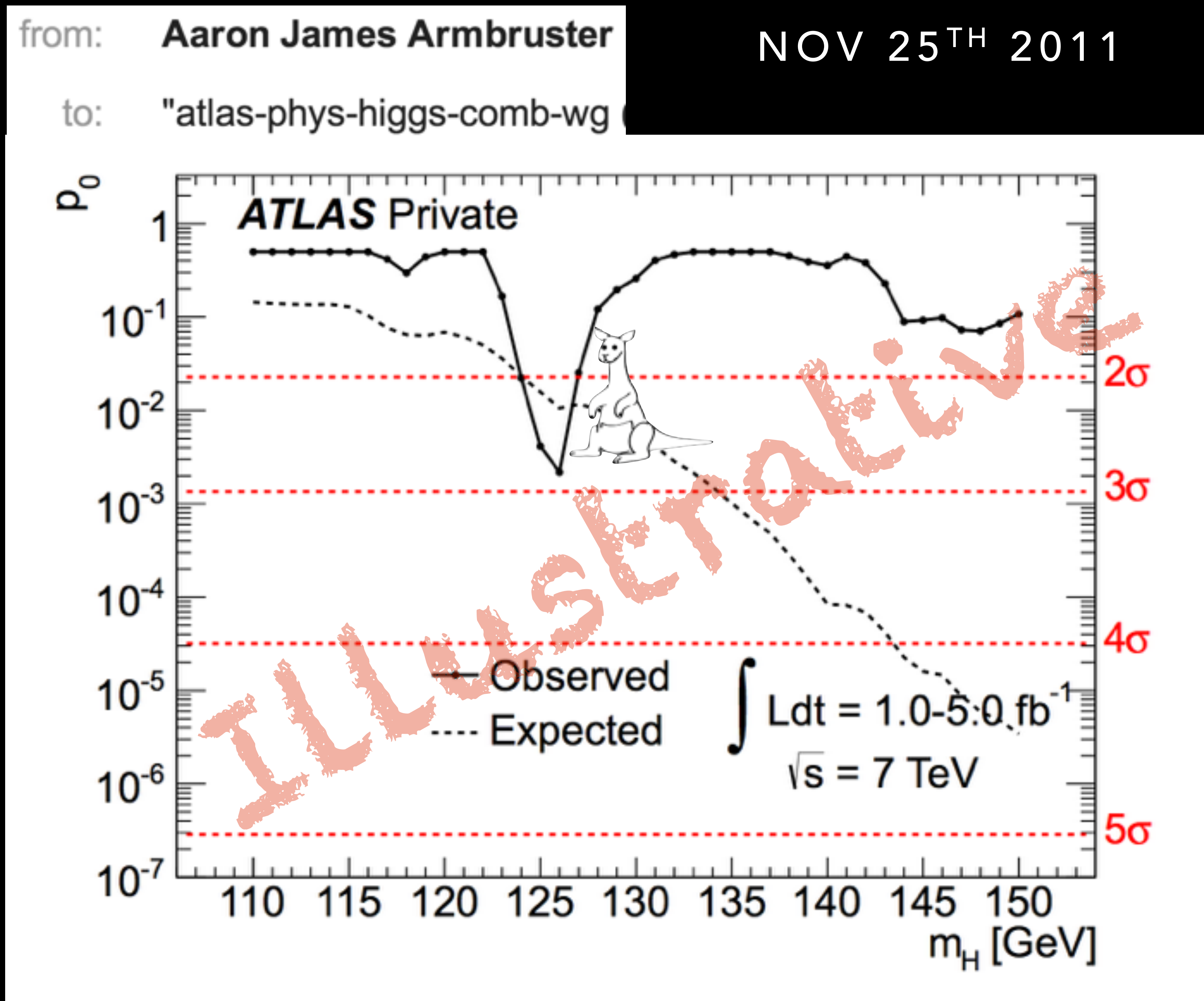
- Dips of p_0(local)
  - 119 GeV (2.6 σ)
  - 126 GeV (2.2 σ)
  - 145 GeV (3.1 σ)
- Roughly 0.9, 0.5, 1.6 σ glob





THE 1ST TANTALISING ATLAS COMBINATION

NOV 25TH 2011

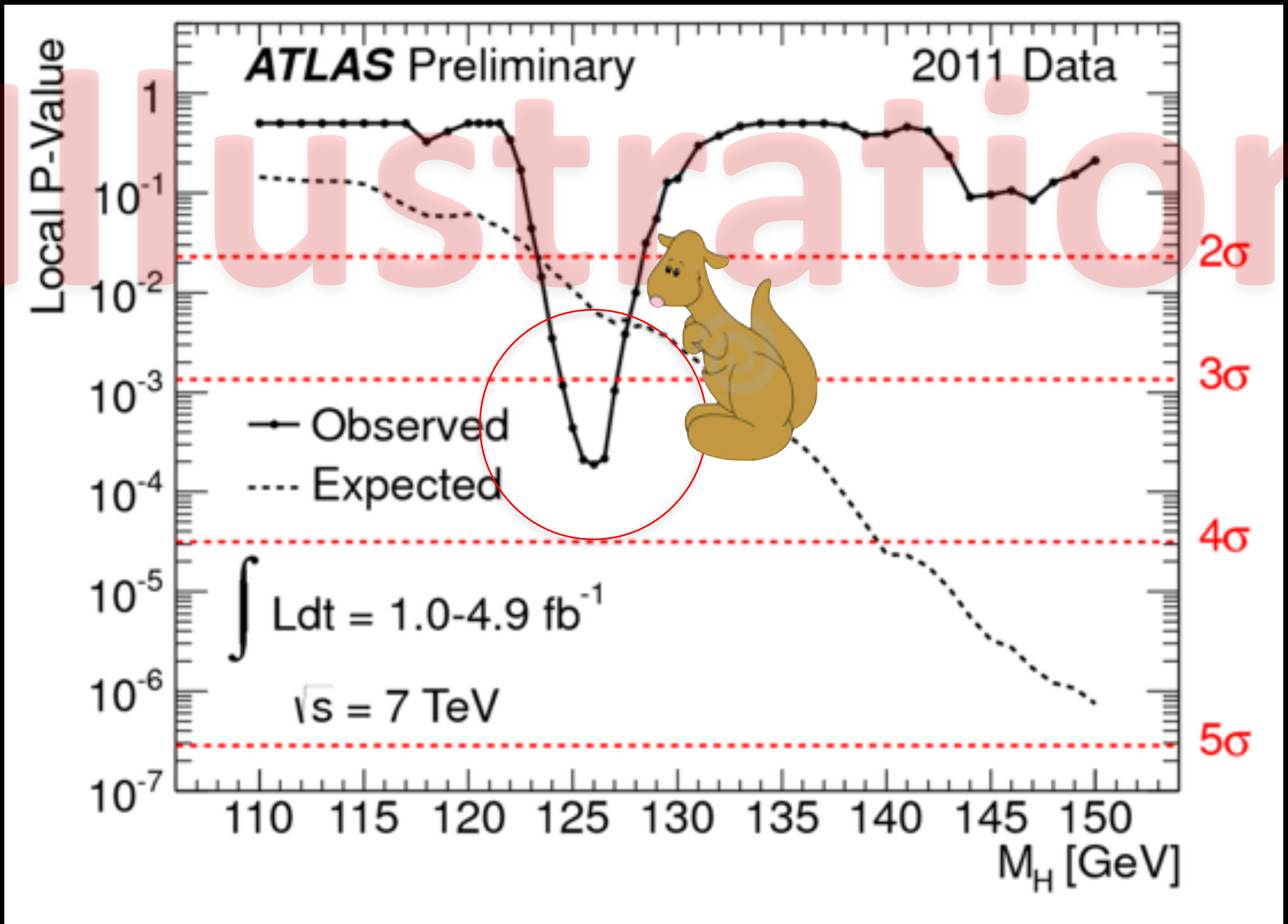


7 DEC 2011
ALEX COUNCIL APPROVAL TALK

- Alex Reed (giving report for ATLAS): Either we have been a bit lucky and seen the first signs of the Higgs or we have been very unlucky with a background fluctuation.

- Council 2011 (December) : The first evidence...

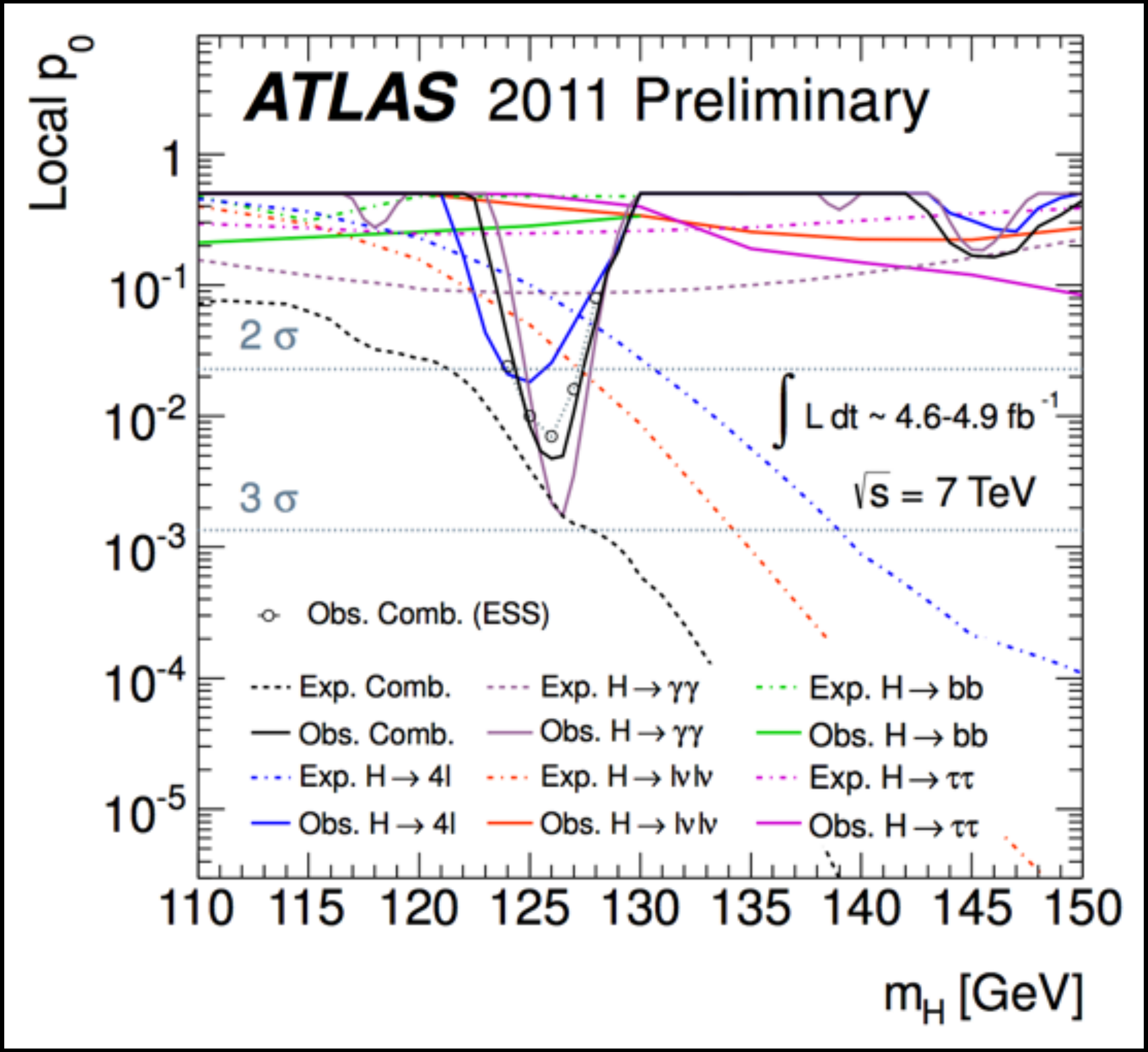
Excess at 126 GeV ~3.6 sigma see:



MORIOND 2012

ATLAS-CONF-2012-019
March 7, 2012

- Excess went down below the expectation (to 2.5 σ) due to the addition of the H->WW channel



HAPPY END

Photograph of a Higgs Boson decaying into two photons

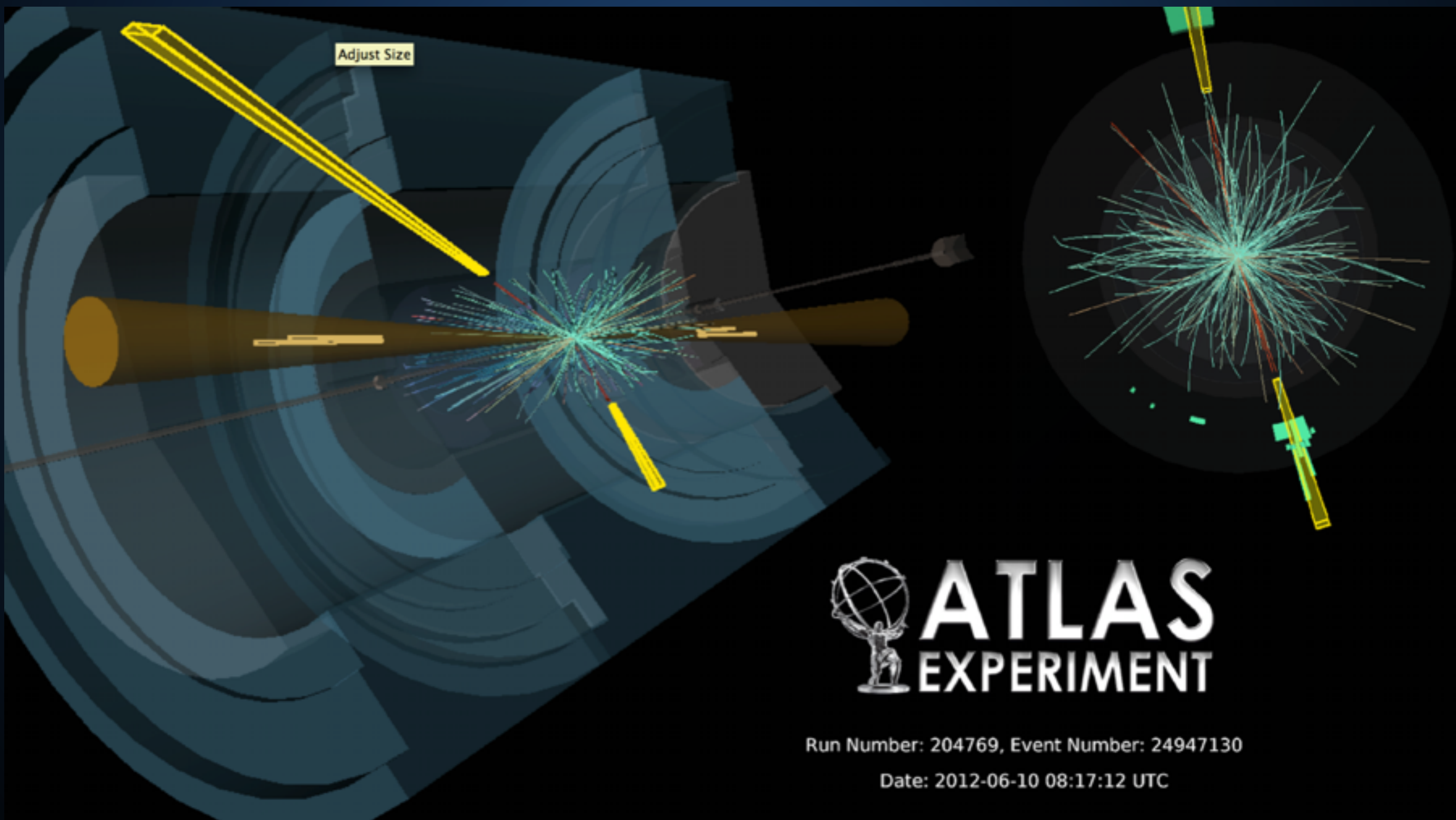
Proton Runs 2010-12

Not currently active

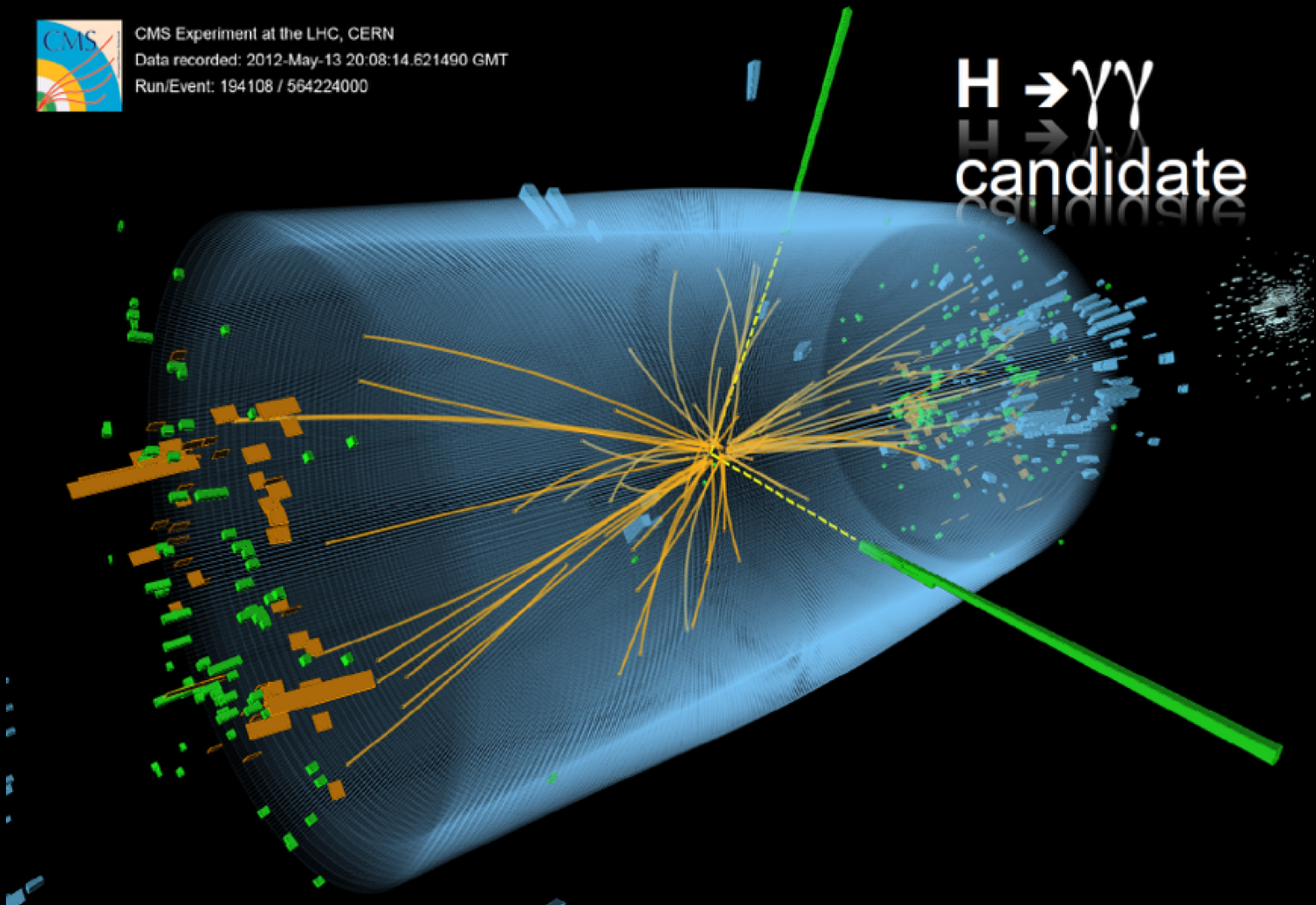
Highest luminosity = $7.73 \cdot 10^{33}$ $cm^{-2}s^{-1}$

Total Collisions = $1.80 \cdot 10^{15}$ = 1 800 000 000 000 000

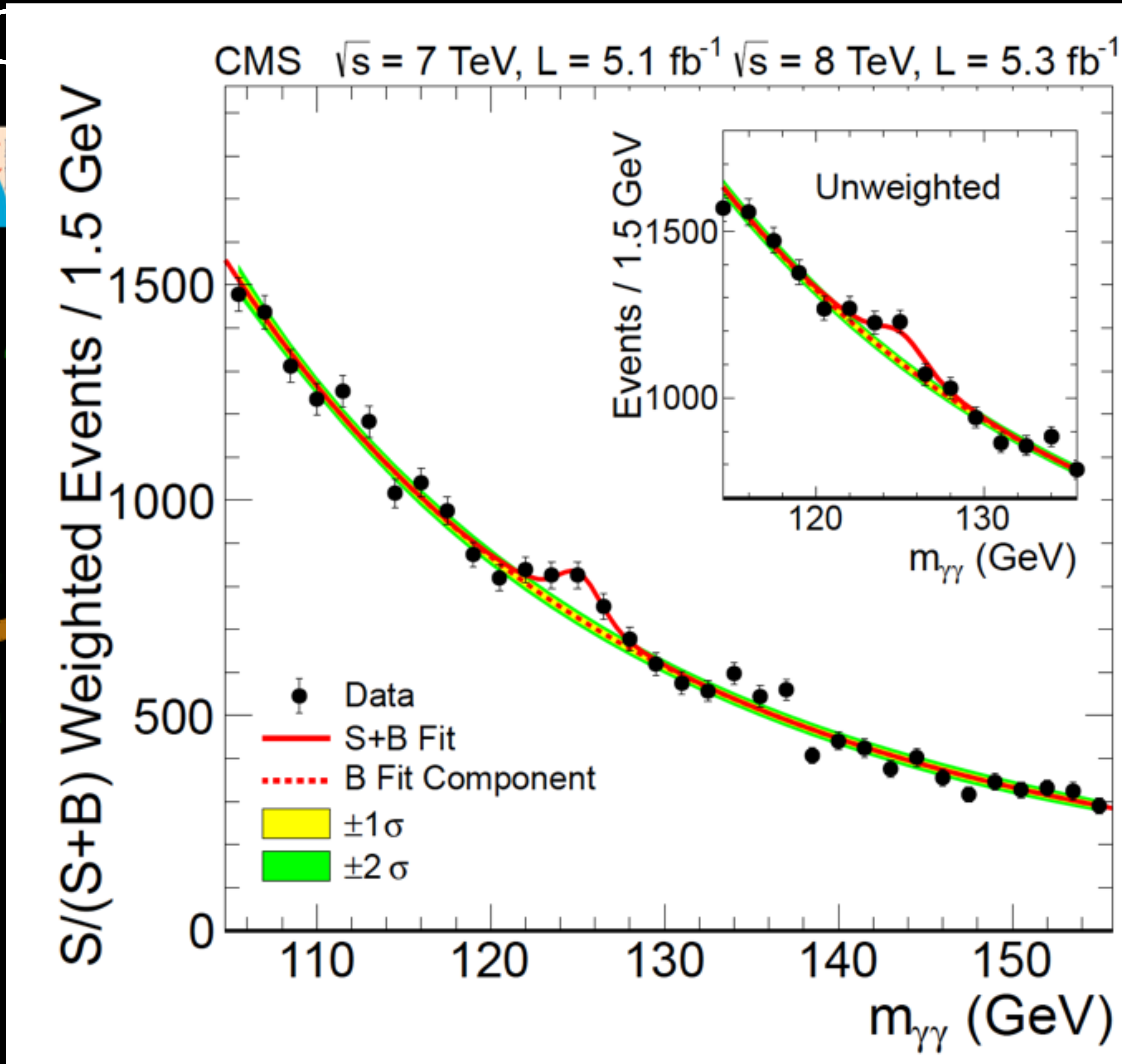
Recorded luminosity = 27.03 fb^{-1}



ANOTHER FAMOUS HIGGS EVENT



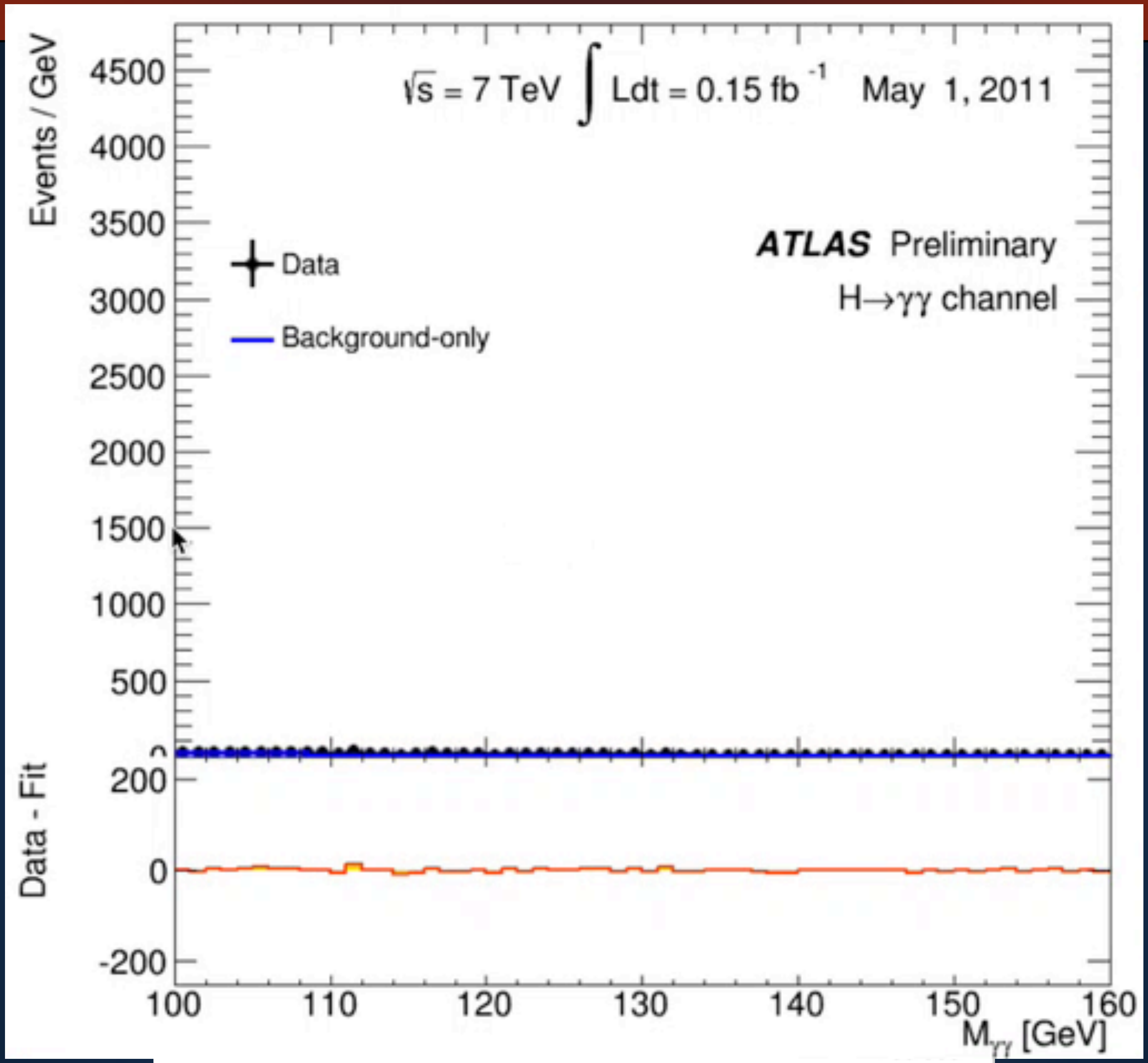
AN VENT

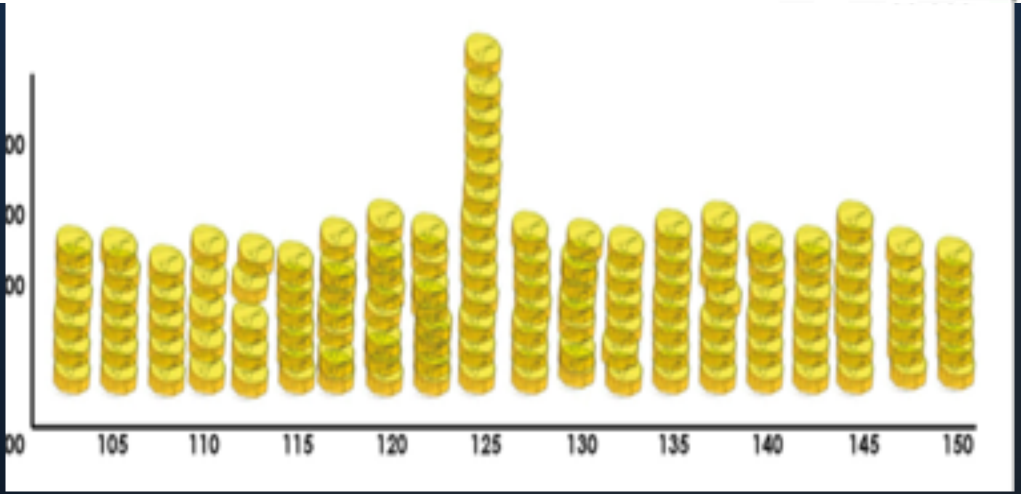


CMS √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 5.3 fb⁻¹
S/(S+B) Weighted Events / 1.5 GeV
0
500
1000
1500
110
120
130
140
150
$m_{\gamma\gamma}$ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2σ
Unweighted
Events / 1.5 GeV
1000
1500
120
130
$m_{\gamma\gamma}$ (GeV)

late

The Birth of a New Particle

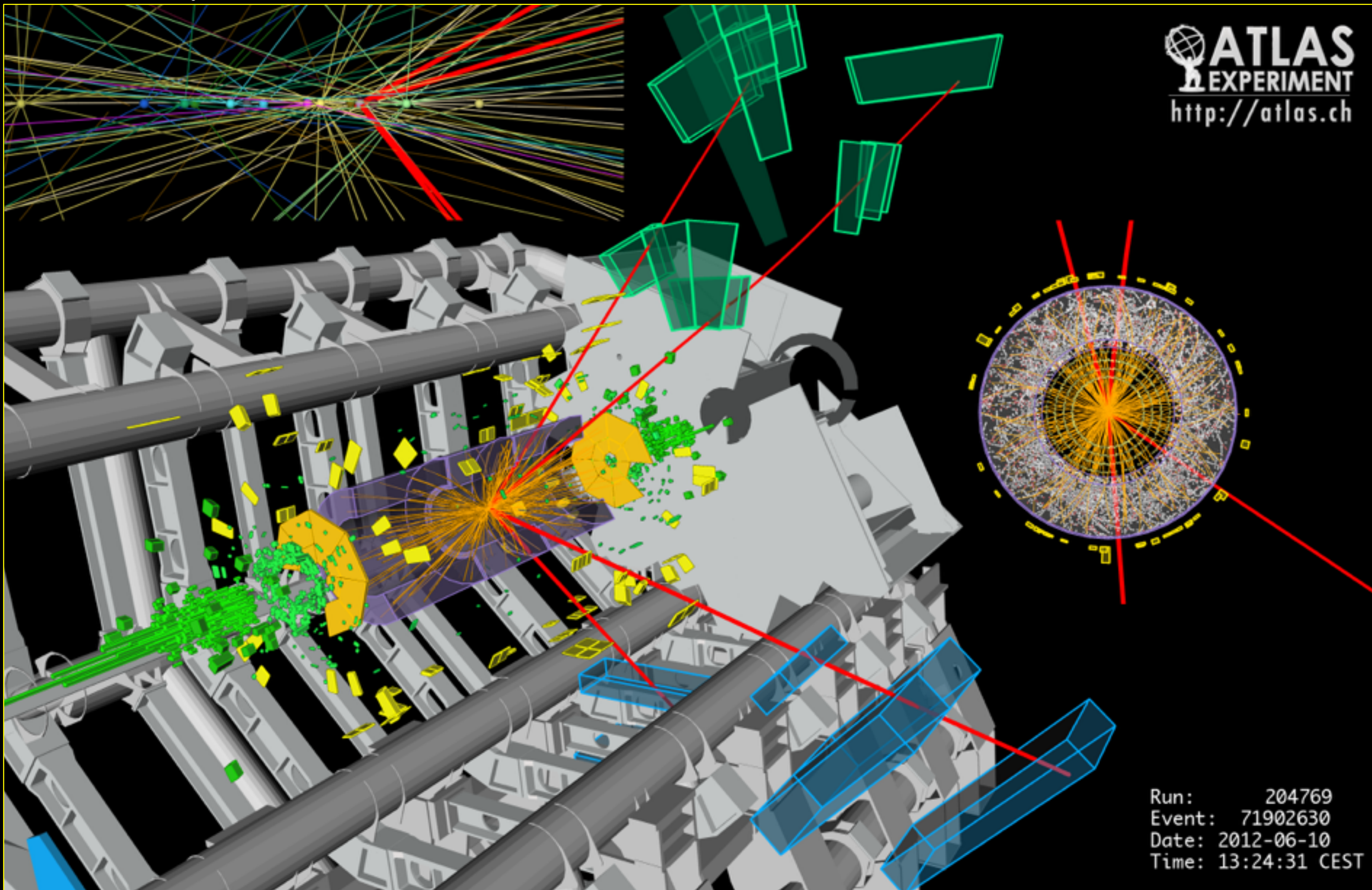




eilam gross, WIS

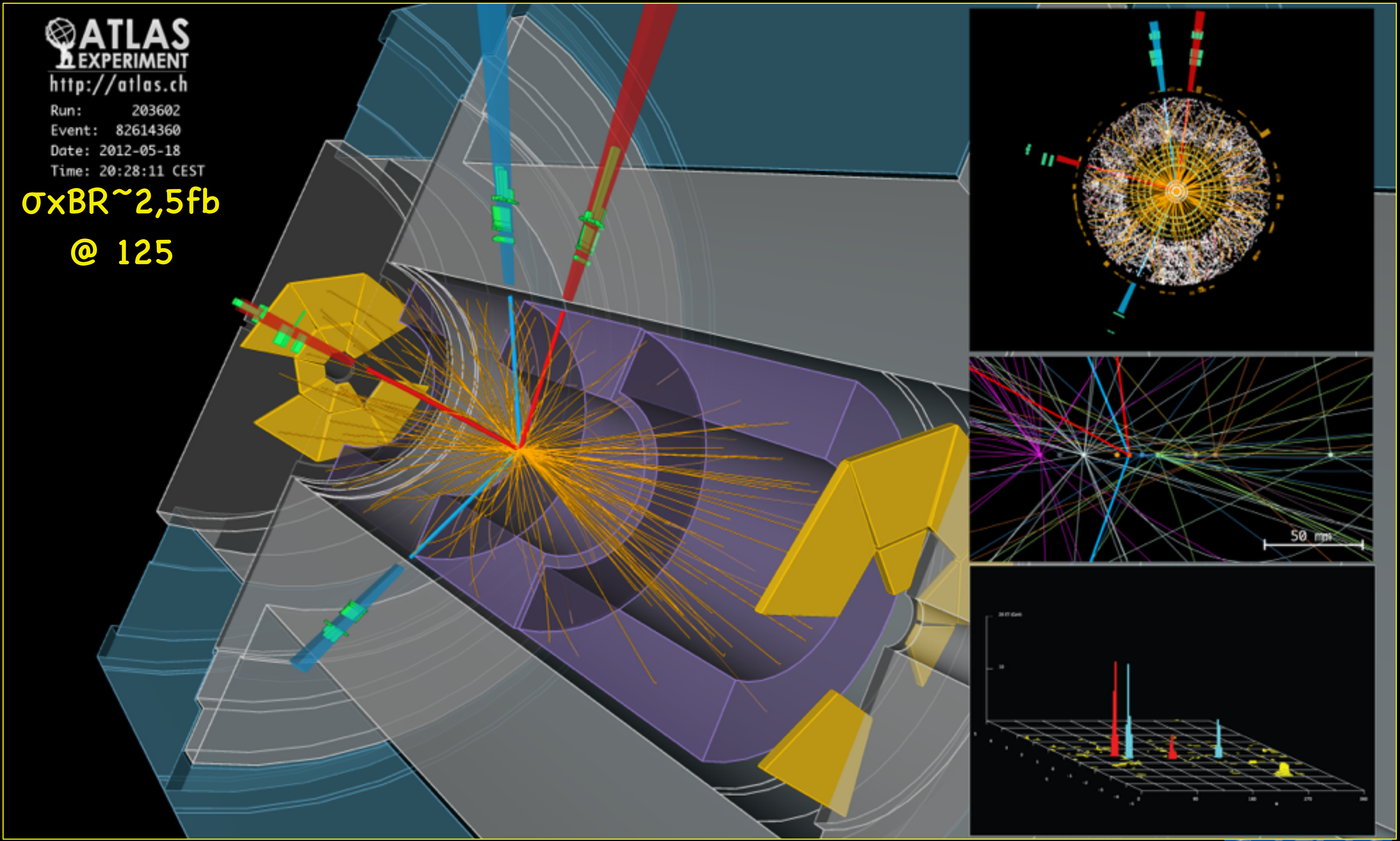
4 leptons

4μ candidate with mass = 124.1 GeV



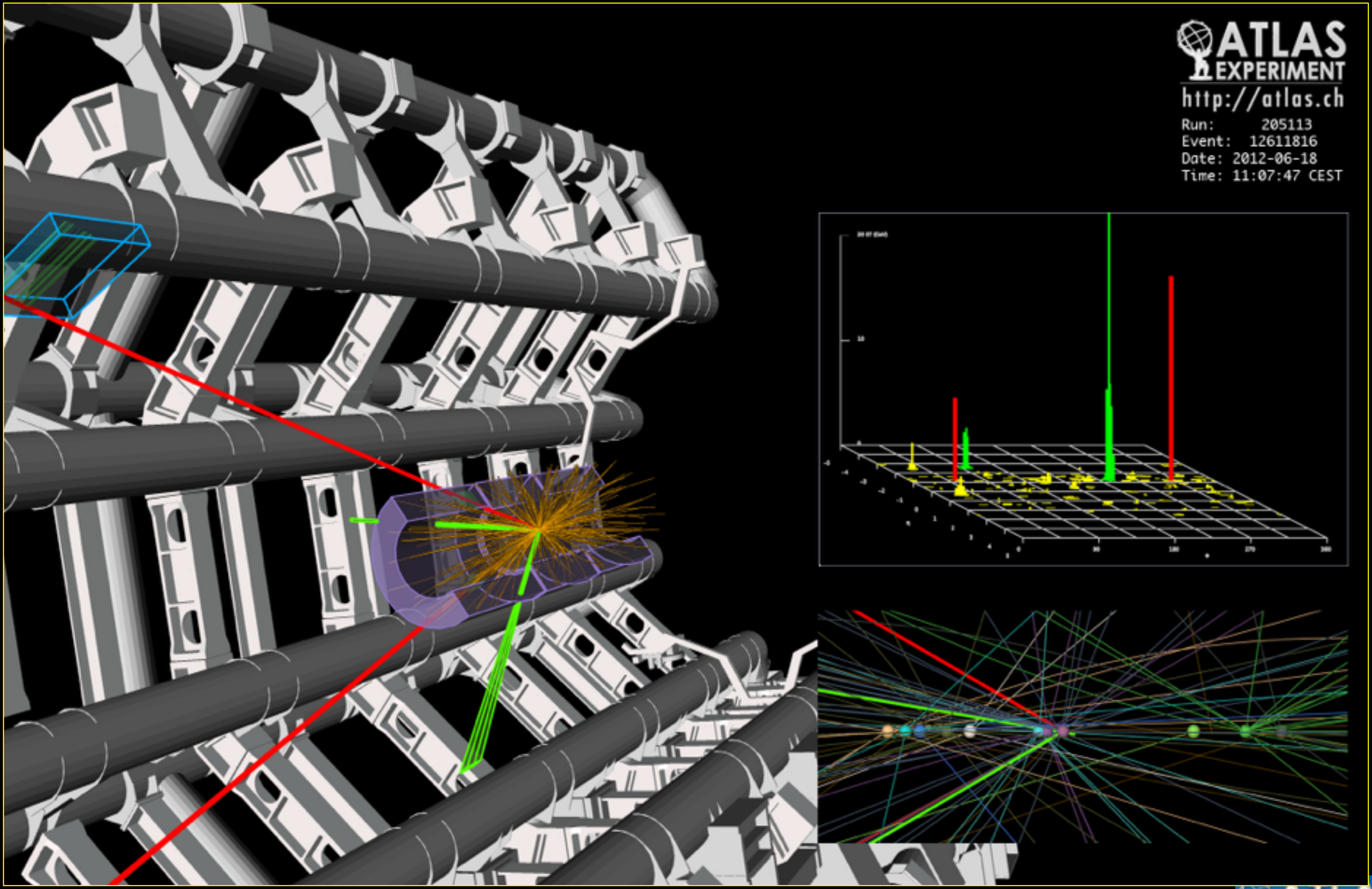
4 leptons

4e candidate with mass = 124.5 GeV



4 leptons

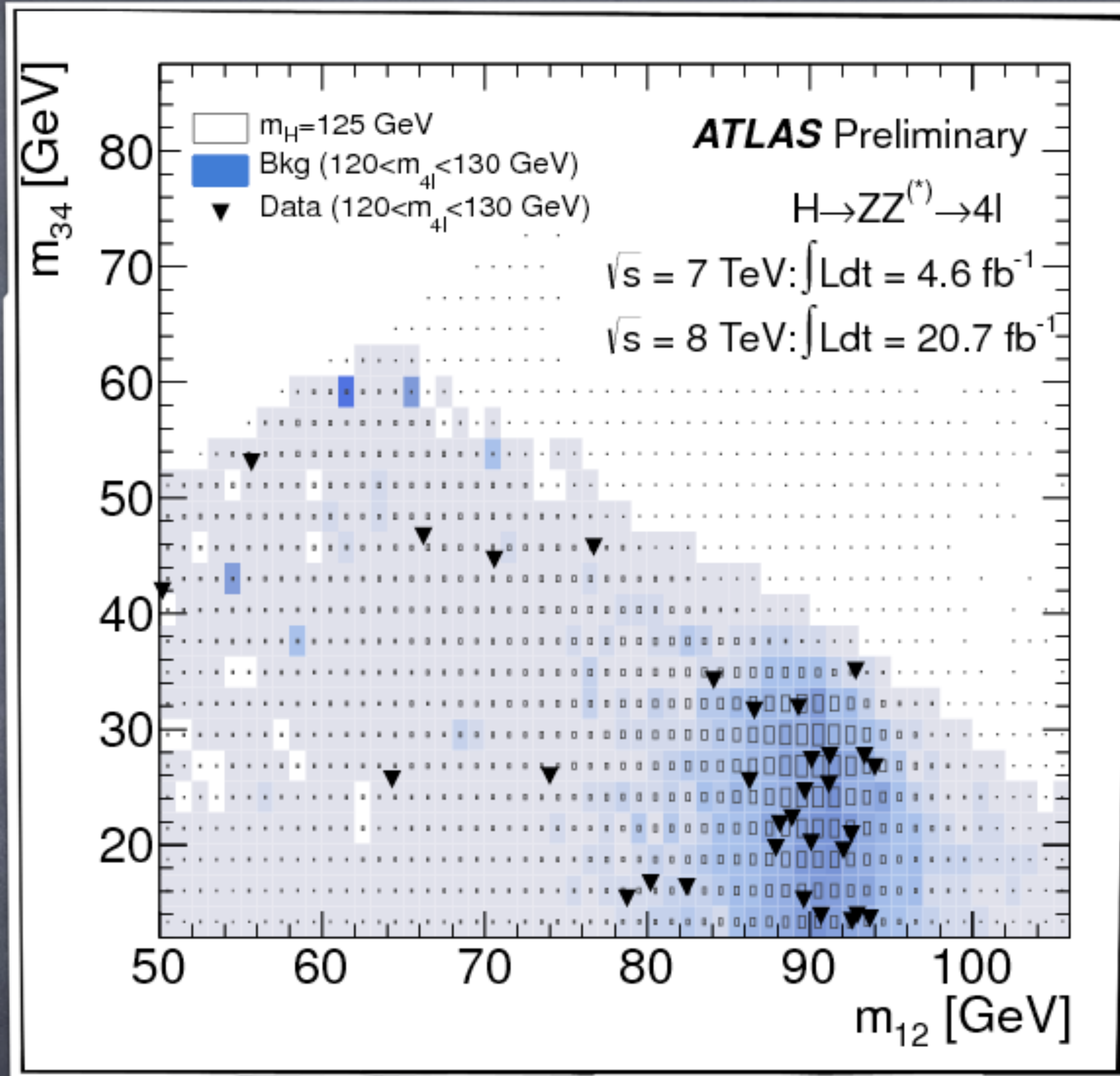
2e2μ candidate with mass = 122.7 GeV



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

FSR γ candidate (E_T>1 GeV) added if 66<M_{12} (μμ) [GeV]<89 ~4% of events

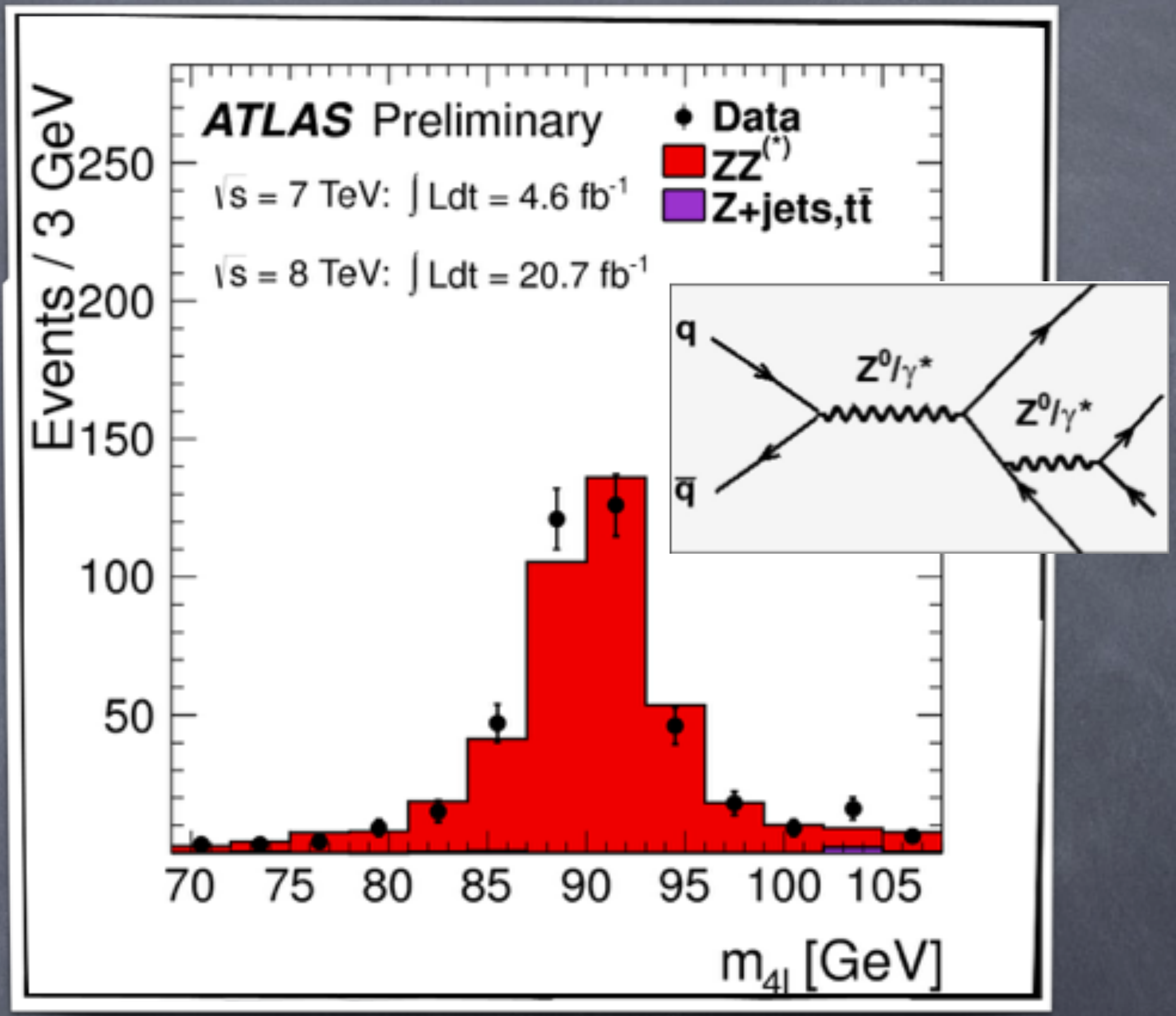
Mass resolution 1.3/1.9% for 4m/4e @125 GeV using Z-mass constraint on leading lepton pair



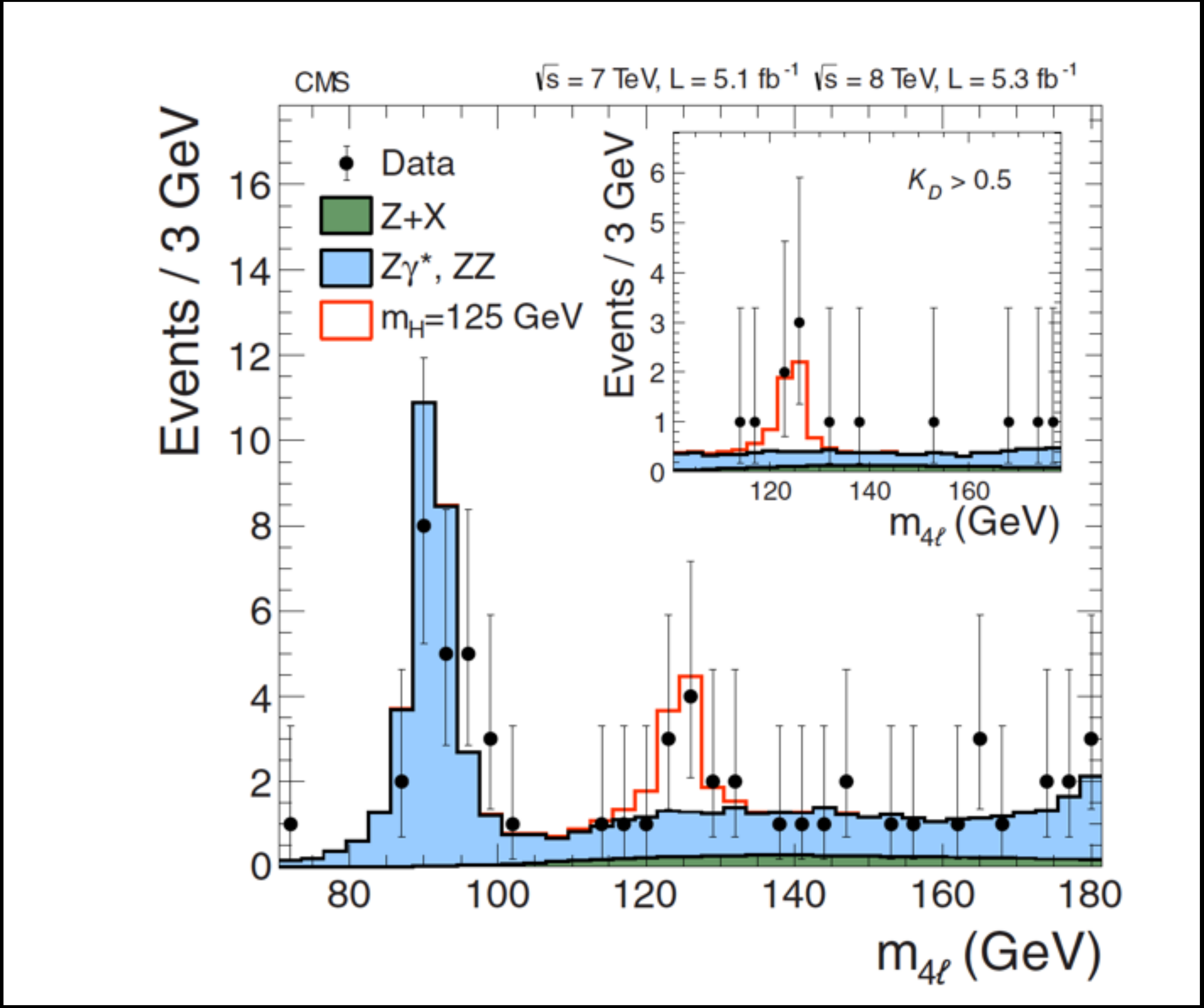
Validating 4ℓanalysis method

- Demonstrating the single-resonant peak
  pp-> Z-> 4leptons

- To improve the acceptance the requirements on m12, m34 and the leptons pT were relaxed



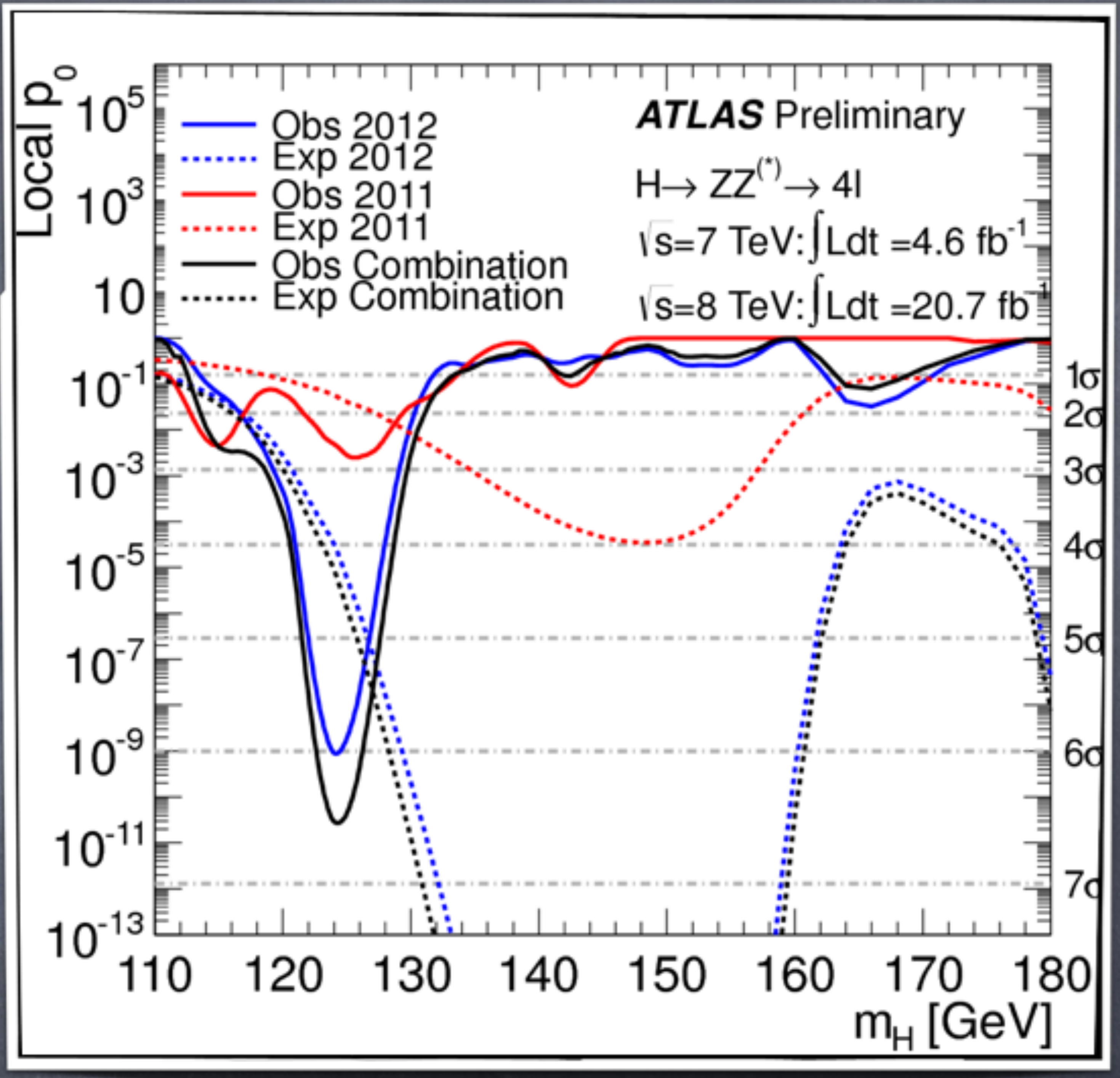
4 LEPTONS



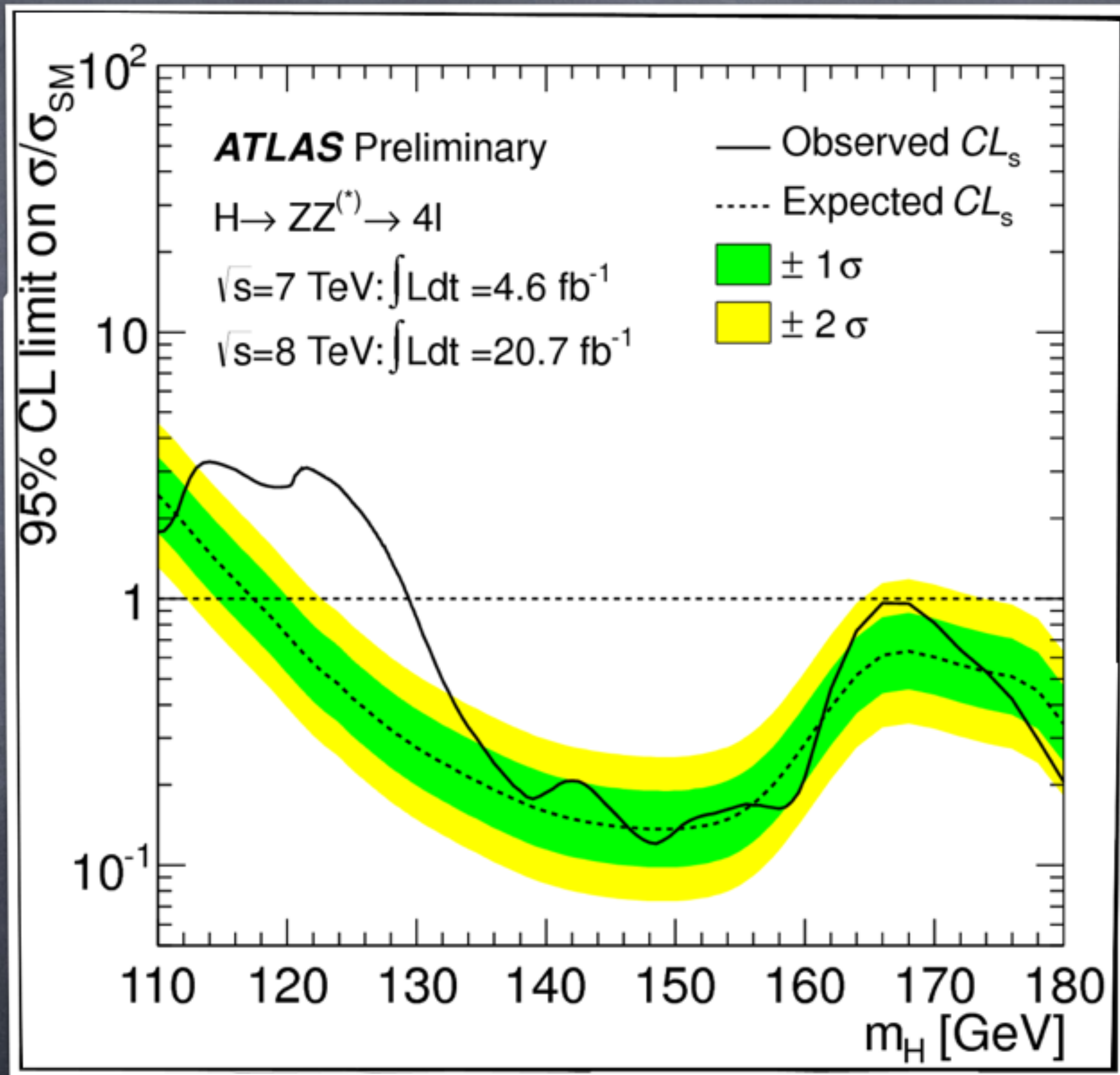
CMS
√s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
Data
Z+X
Zγ*, ZZ
mH=125 GeV
Events / 3 GeV
m4ℓ (GeV)
KD > 0.5

4ℓdiscovery excess is confirmed

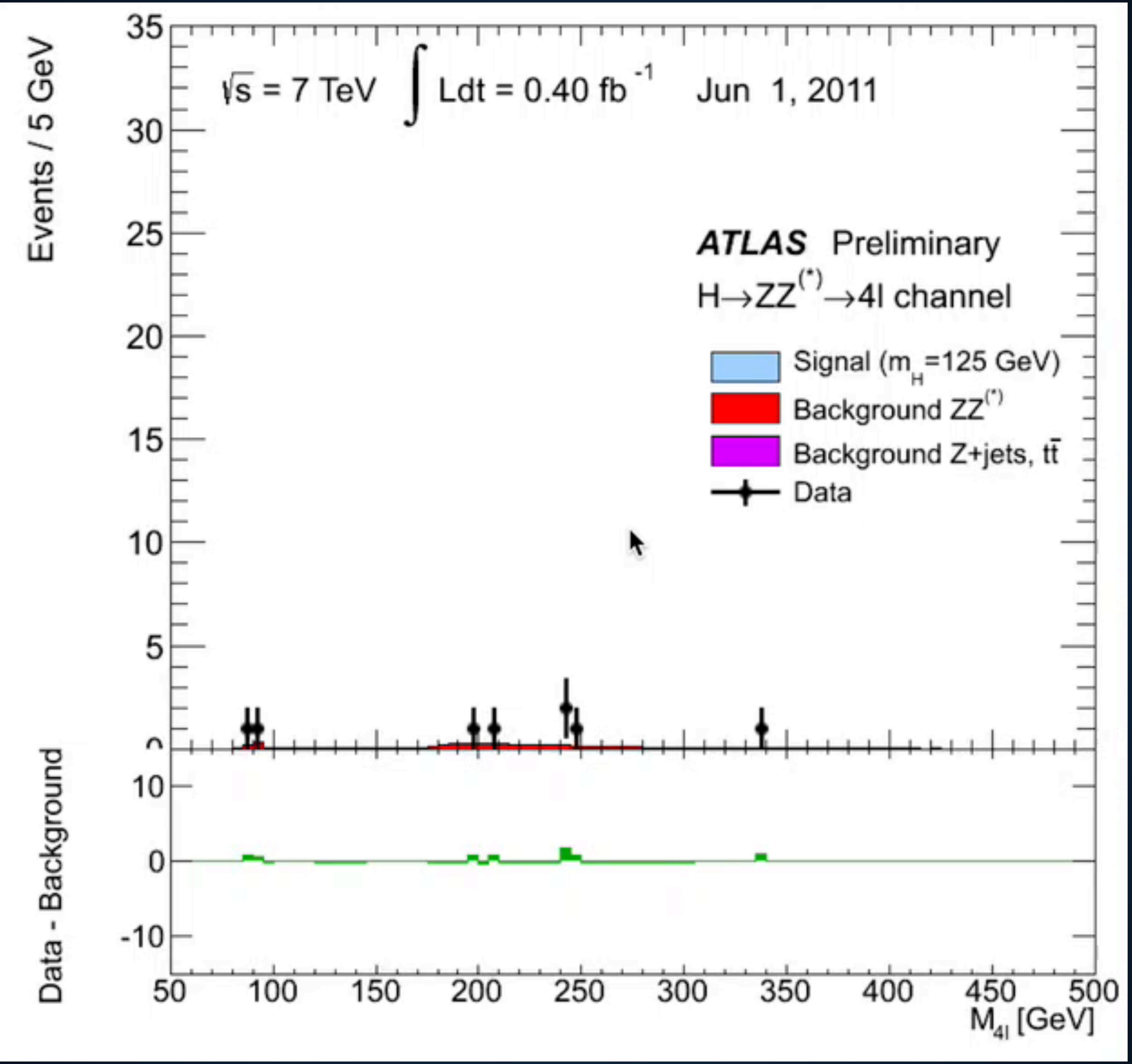
	2011	2012	Combined
Mass	125.6 GeV	124.1 GeV	124.3 GeV
Exp	1.8σ	4.0σ	4.4σ
Obs	2.8σ	6.0σ	6.6σ



Exclusion



ATLAS Preliminary
H→ ZZ(*)→ 4l
√s=7 TeV: ∫Ldt =4.6 fb-1
√s=8 TeV: ∫Ldt =20.7 fb-1
Observed CLs
Expected CLs
± 1σ
± 2σ
95% CL limit on σ/σSM
10
1
110
120
130
140
150
160
170
180
mH [GeV]



$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.40 fb^{-1} Jun 1, 2011
ATLAS Preliminary
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel
Signal (m_H=125 GeV)
Background $ZZ^{(*)}$
Background Z+jets, $t\bar{t}$
Data
Events / 5 GeV
Data - Background
M_{4l} [GeV]

THE DISCOVERY CONF NOTE

ATLAS-CONF-2012-093 July 5, 2012

The proof of the desert assumption

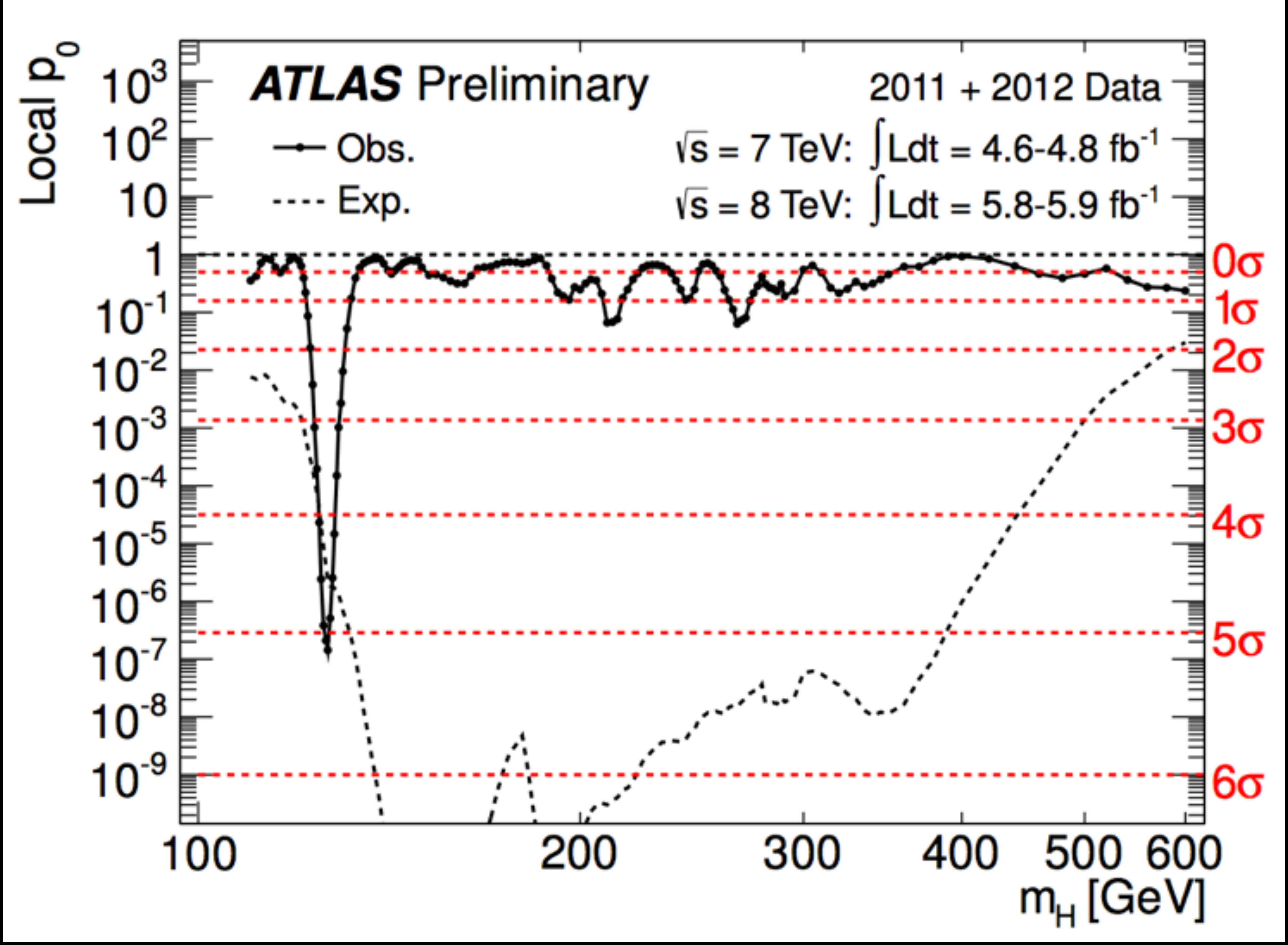
or

The heartbeat plot

THE DISCOVERY CONF NOTE

ATLAS-CONF-2012-093 July 5, 2012

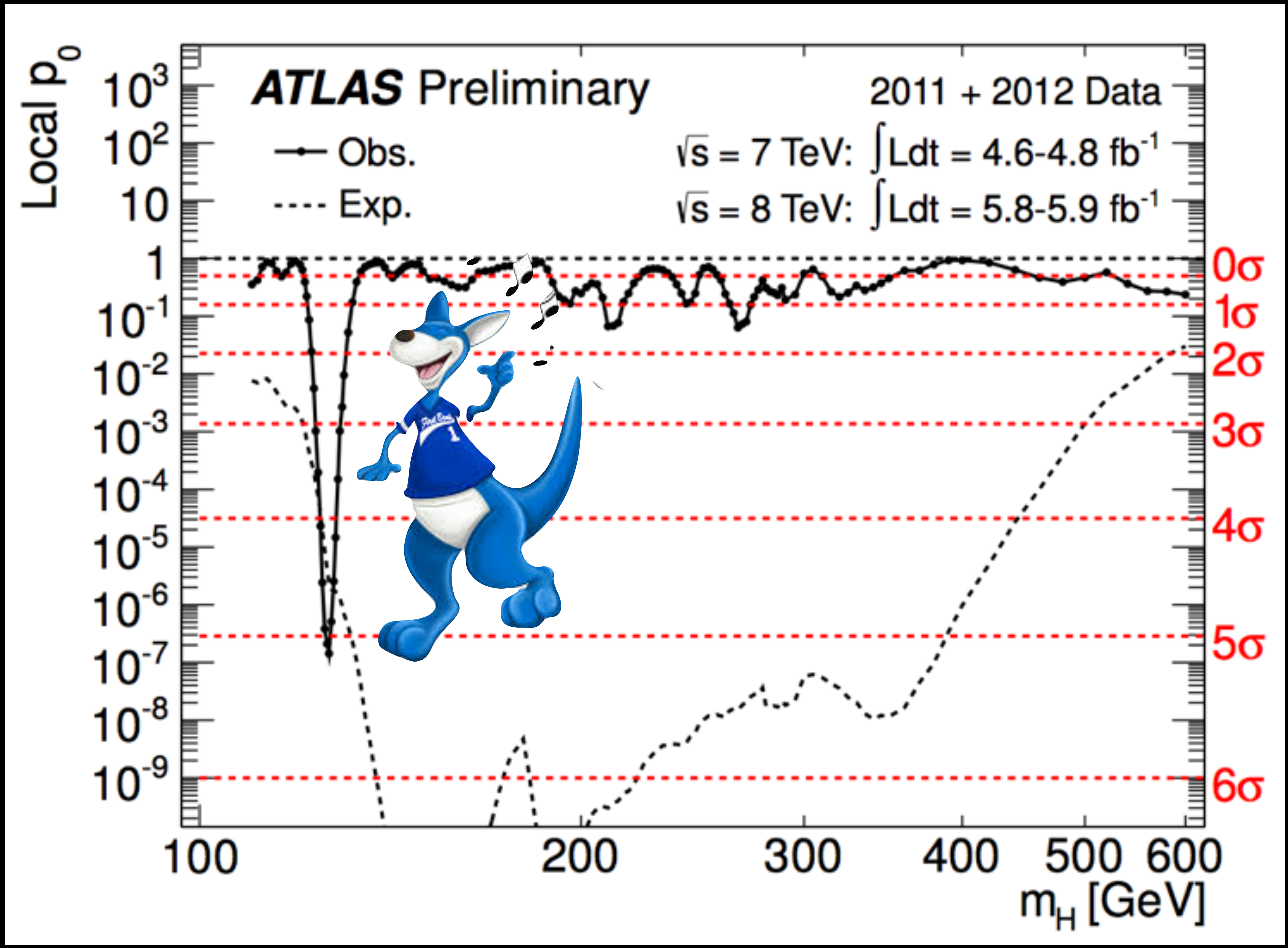
The heartbeat plot



THE DISCOVERY CONF NOTE

ATLAS-CONF-2012-093 July 5, 2012

The heartbeat plot



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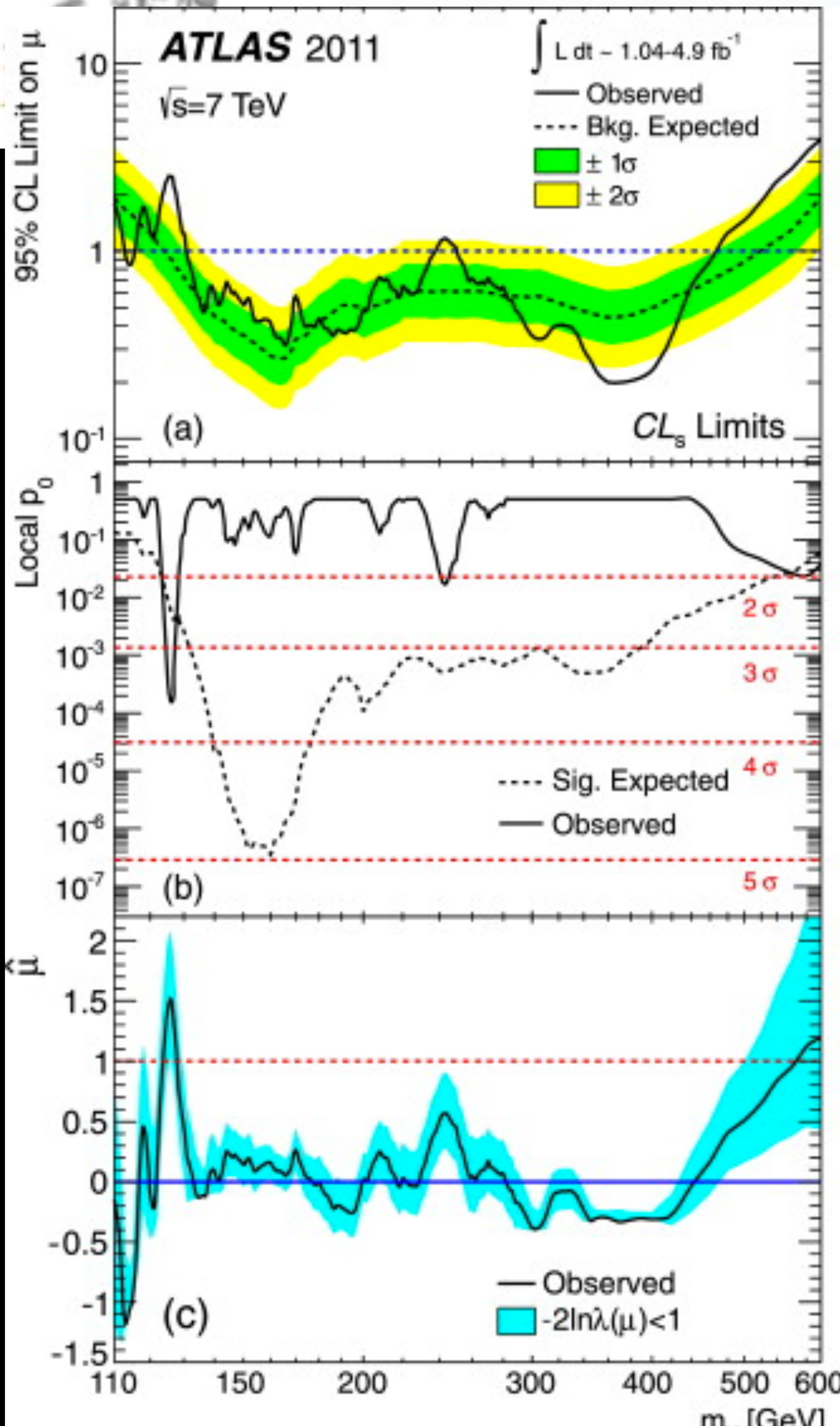
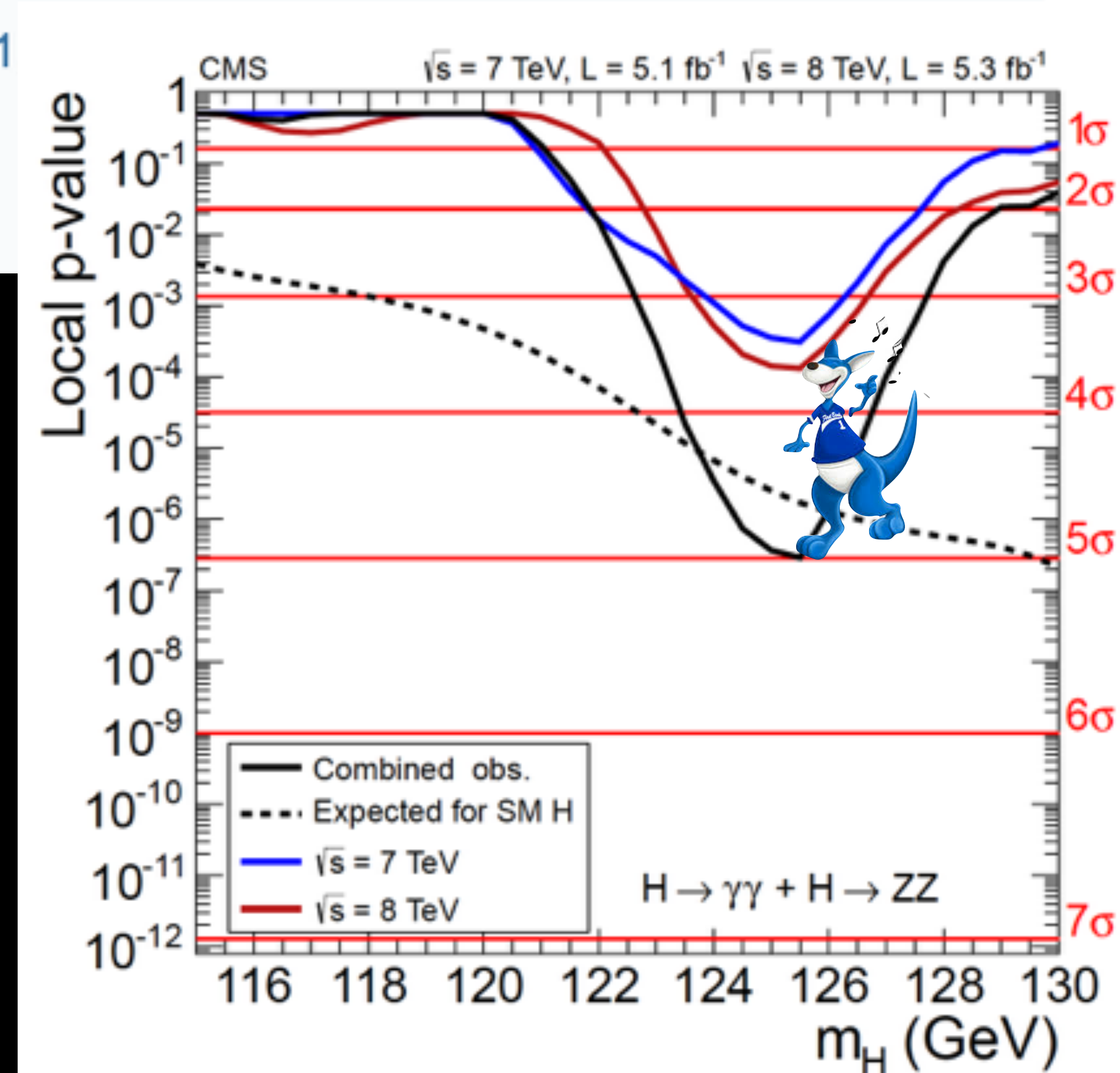
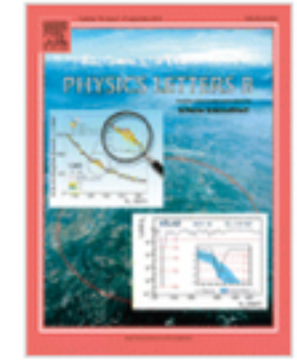






THE SEMINAR POTENTIAL SLEEPERS

CMS

ATLAS

THE SEMINAR SLEEPERS


I was looking for you for over 20 years
Now you have found me

HIGGS PARTY

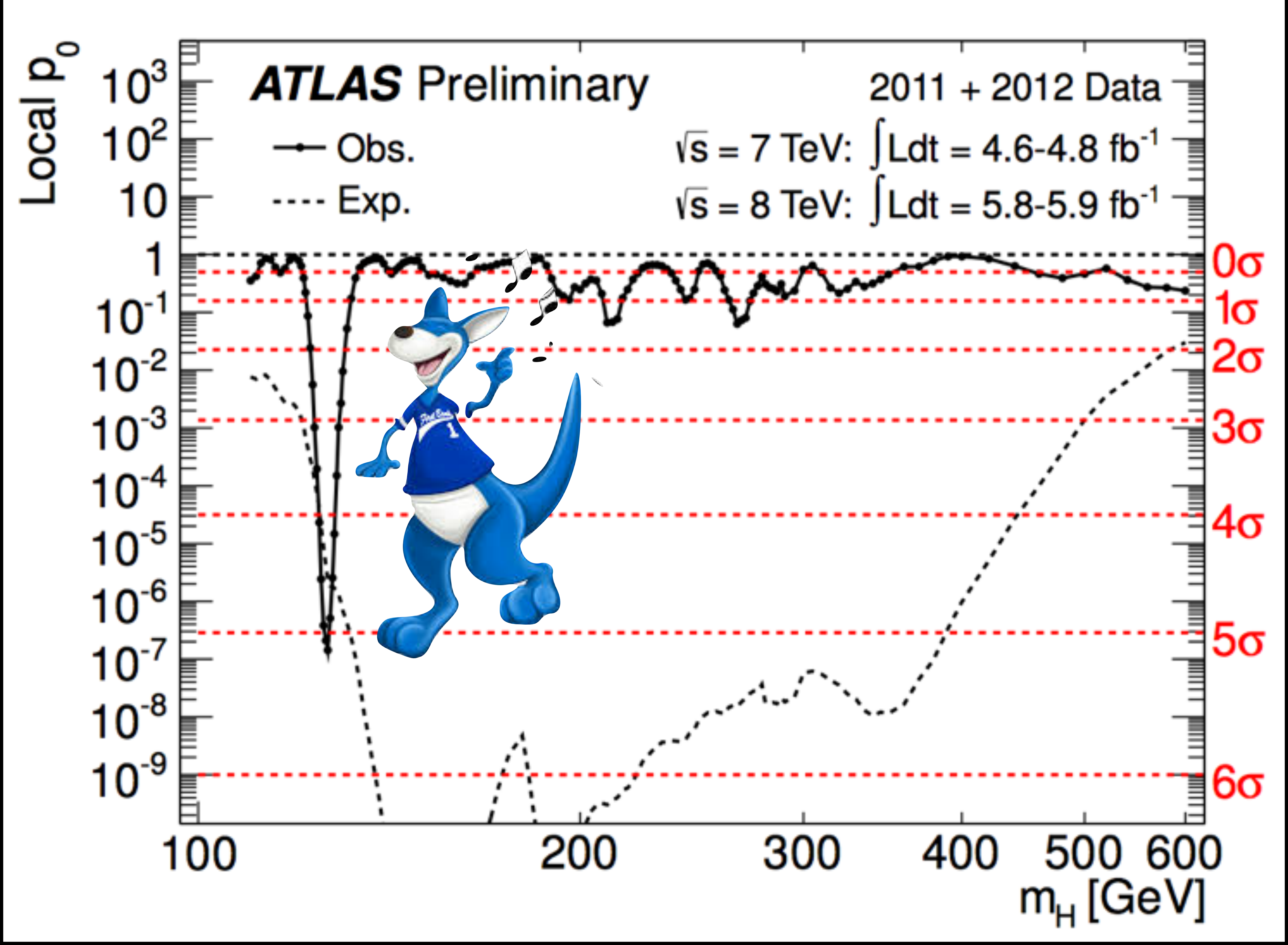
WHY IS EVERYBODY LOOKING UP?

WHY IS EVERYBODY LOOKING UP?

THE DISCOVERY CONF NOTE

ATLAS-CONF-2012-093 July 5, 2012

The heartbeat plot



WW Results

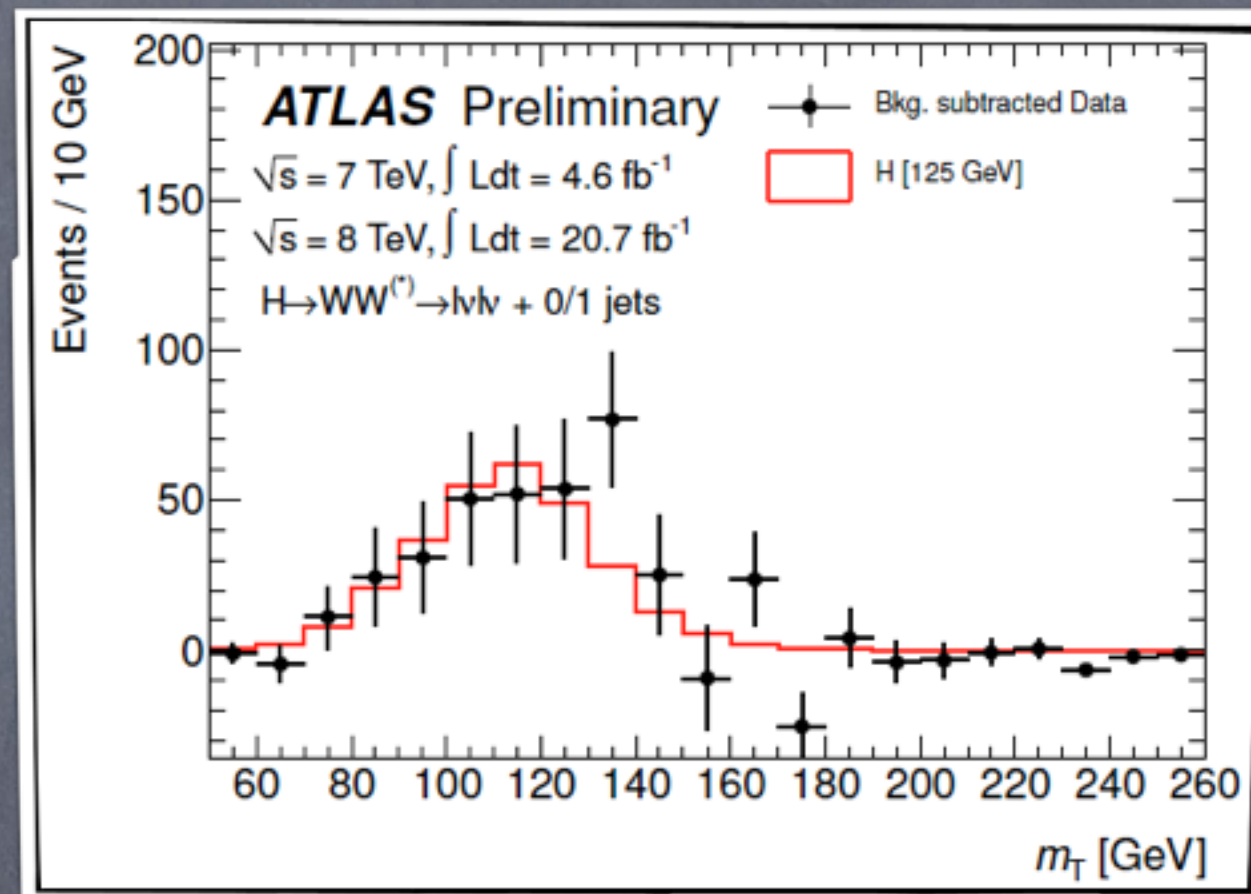
Event Yields

Numbers quoted for 0.75 mH < mT < mH   w/mH =125 GeV
(mT < 1.2 mH for 2-jet ch)

8 TeV	Signal Expectation	Total Bkg	Data
0 jet	97 ± 20	739 ± 39	831
1 jet	40 ± 13	261 ± 28	309
2 jet	10.6 ± 1.4	36 ± 4	55

7 TeV	Signal Expectation	Total Bkg	Data
0 jet	25 ± 5	161 ± 11	154
1 jet	7 ± 2	47 ± 6	62
2 jet	1.4 ± 0.2	4.6 ± 0.8	2

Excess after BG subtraction

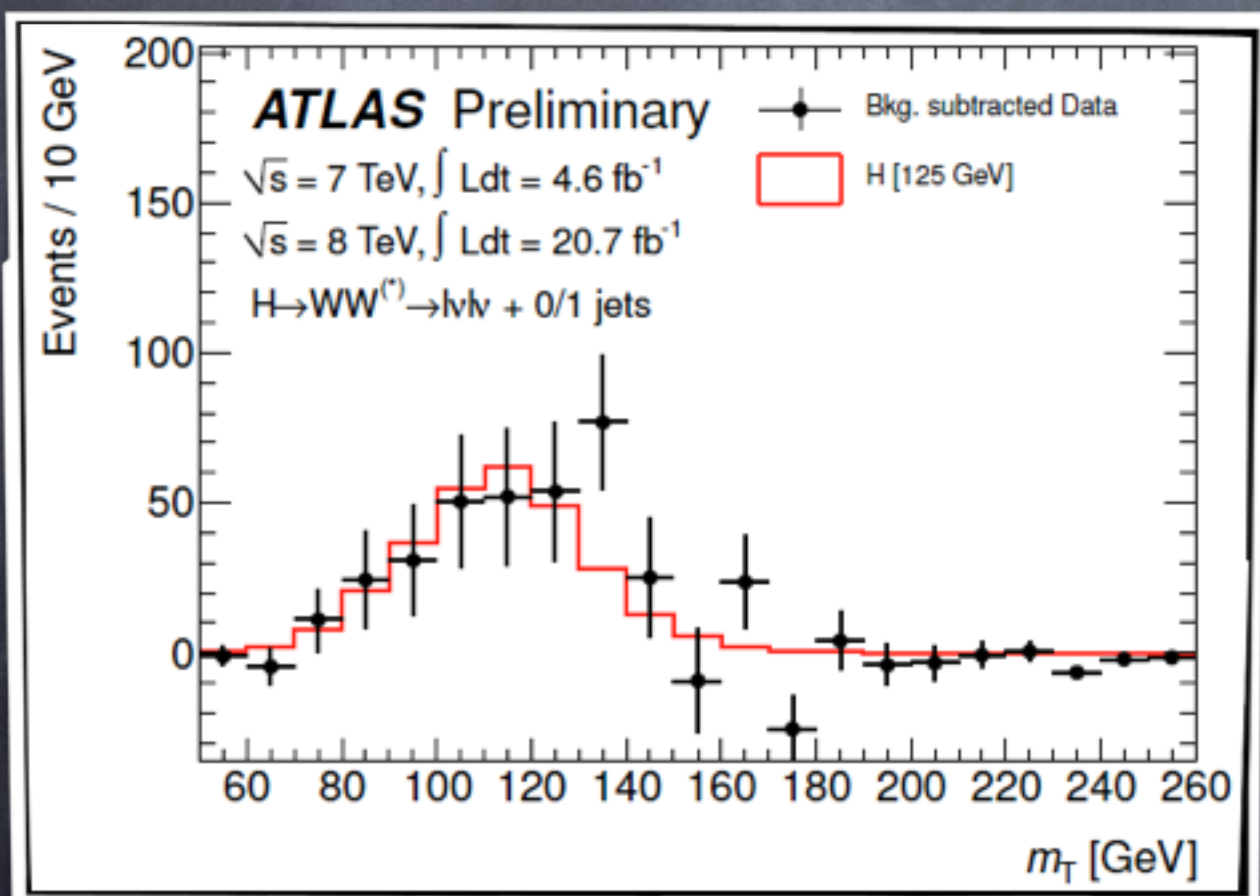


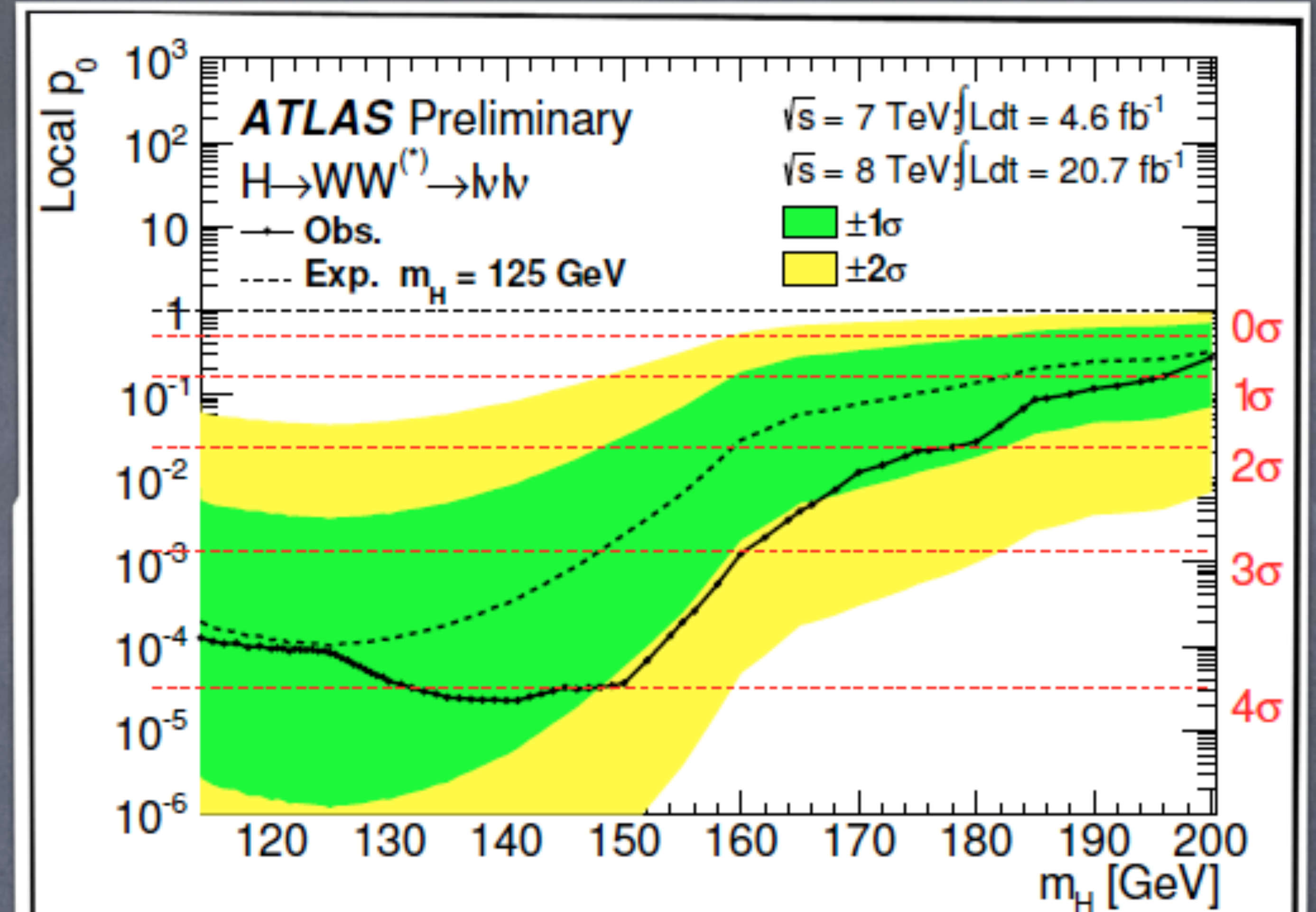
$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 + (p_T^{ll} + p_T^{miss})^2}$$

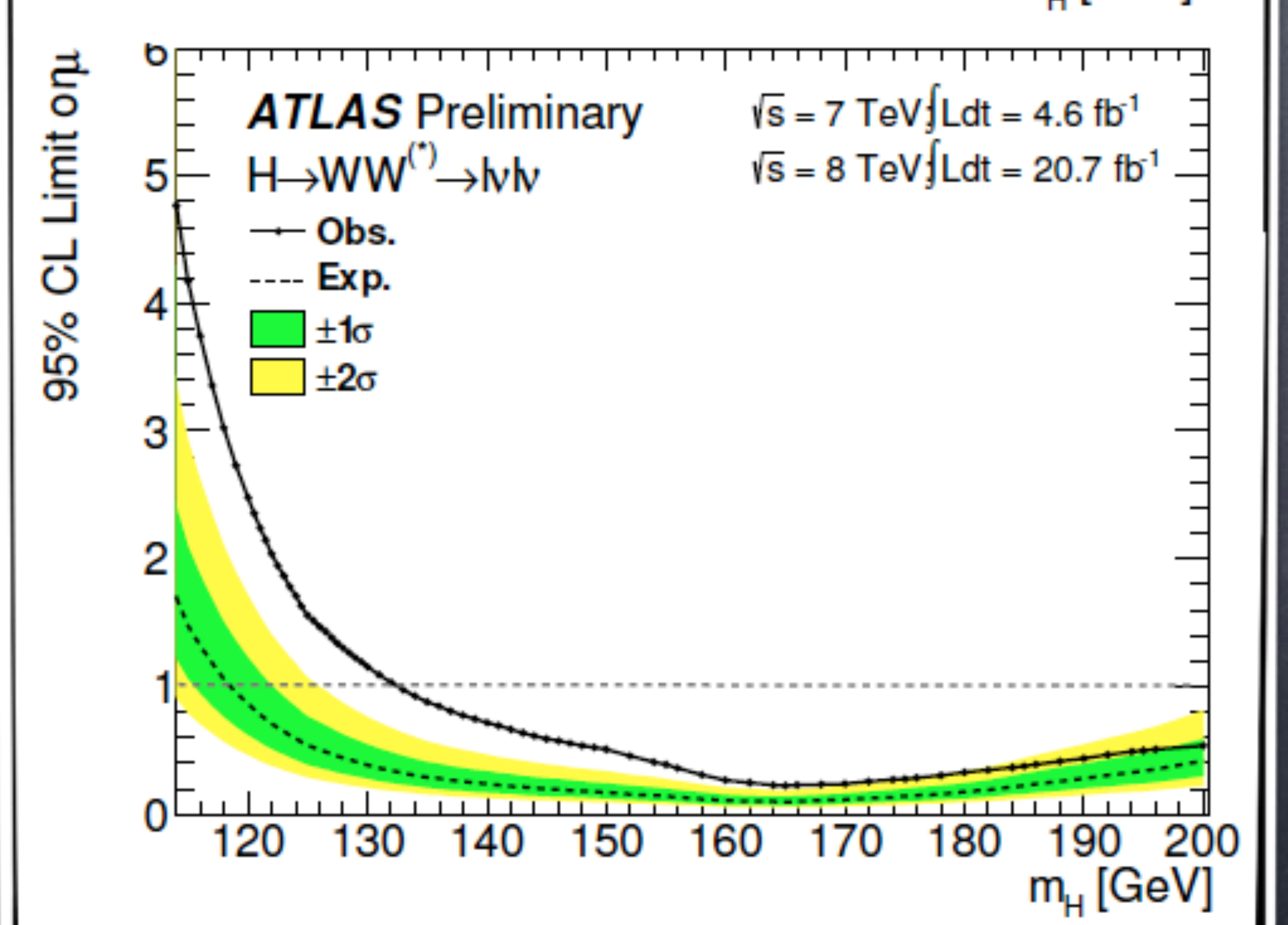
H->WW->$e\nu\mu\nu$

- Observed excess @ 125 GeV: 3.8σ
  Expected significance @ 125 GeV is 3.7σ

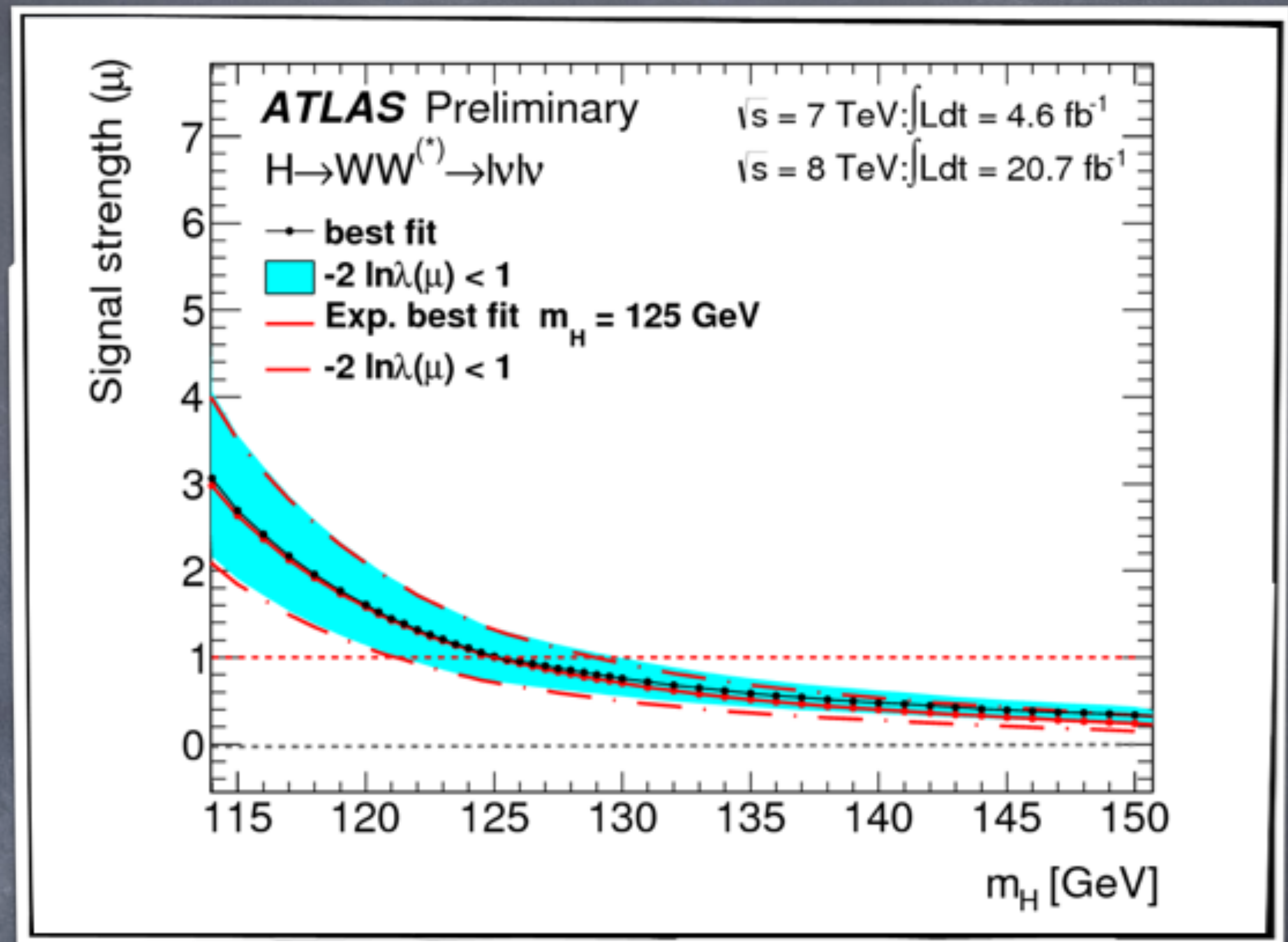
Excess after BG subtraction







H->WW->e$\nu\mu\nu$



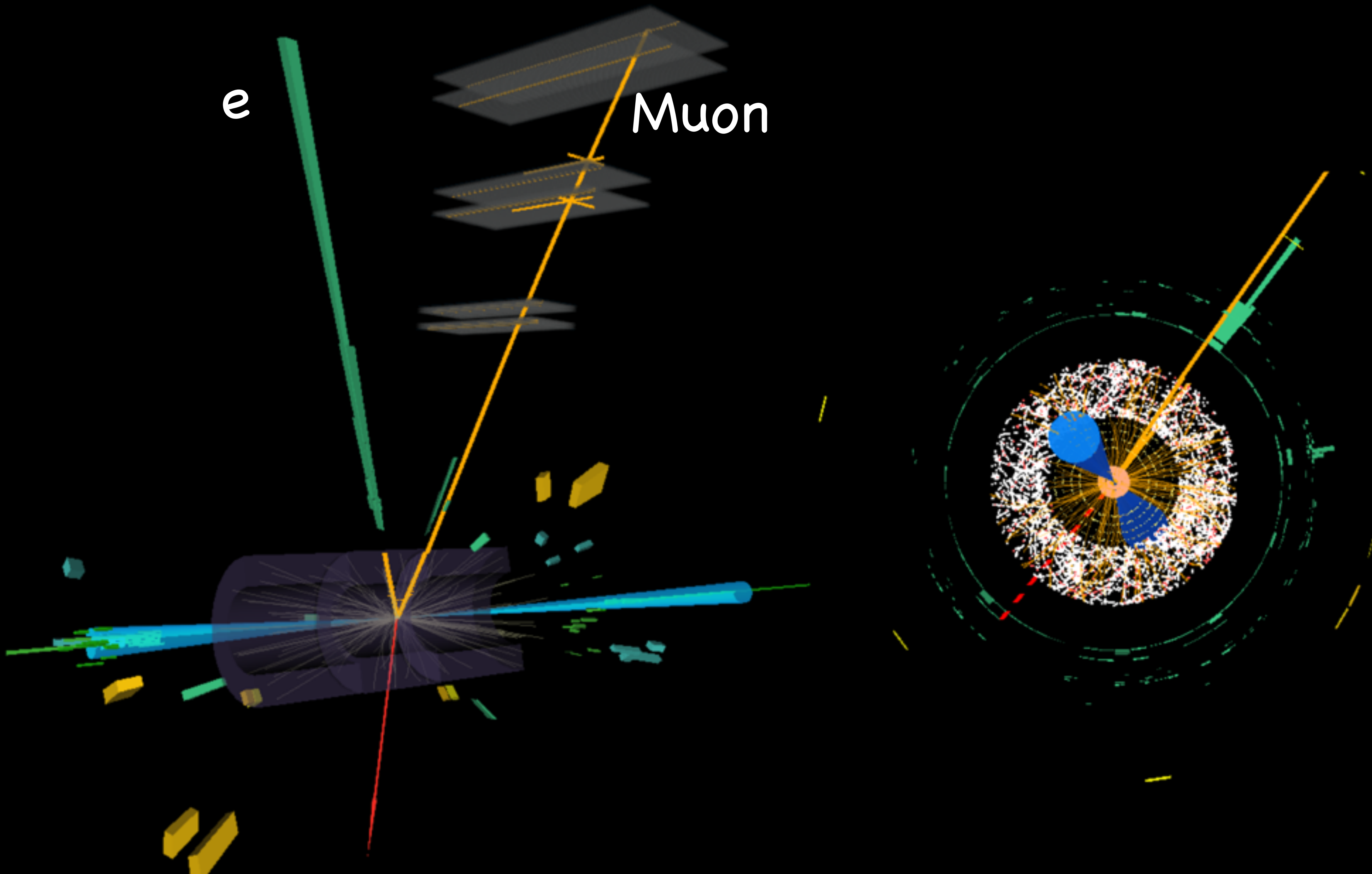
$$\hat{\mu}(125 GeV) = 1.01 \pm 0.31$$

- Consistent with SM Higgs Boson

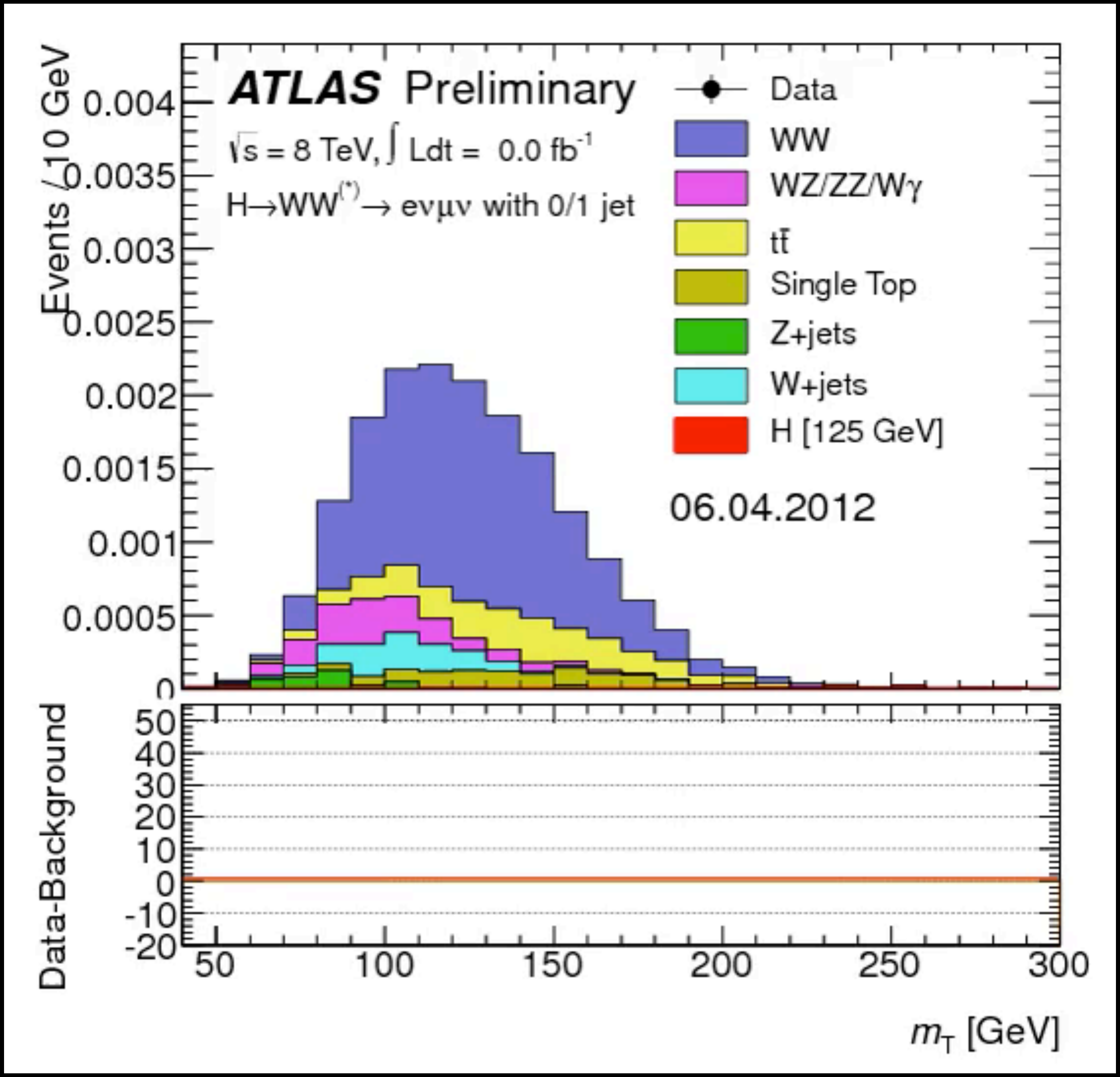
$\mu_{obs} = 1.01 \pm 0.21$ (stat.) ± 0.19 (theo. syst.) ± 0.12 (expt. syst.) ± 0.04 (lumi.)

ATLAS EXPERIMENT

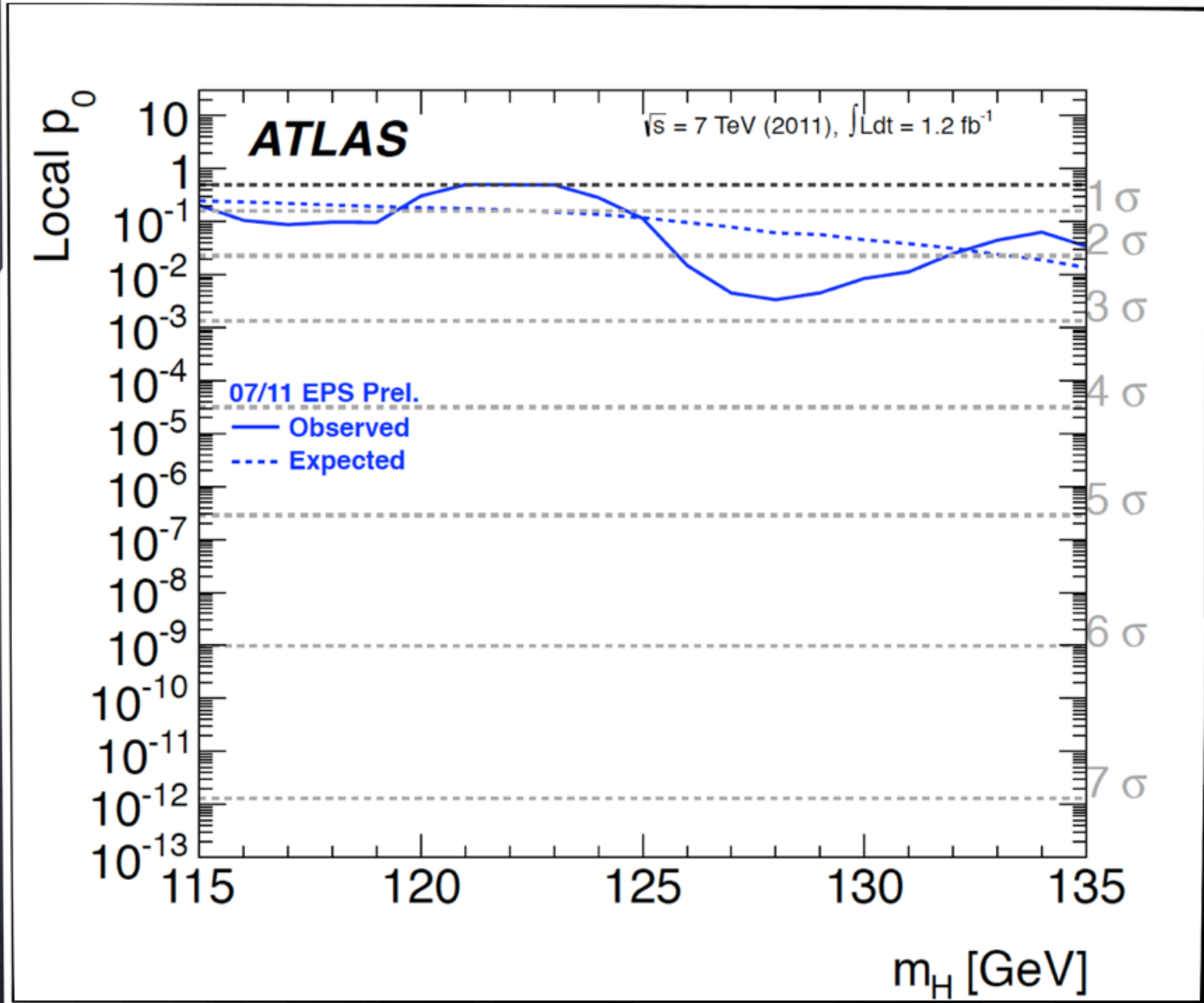
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET



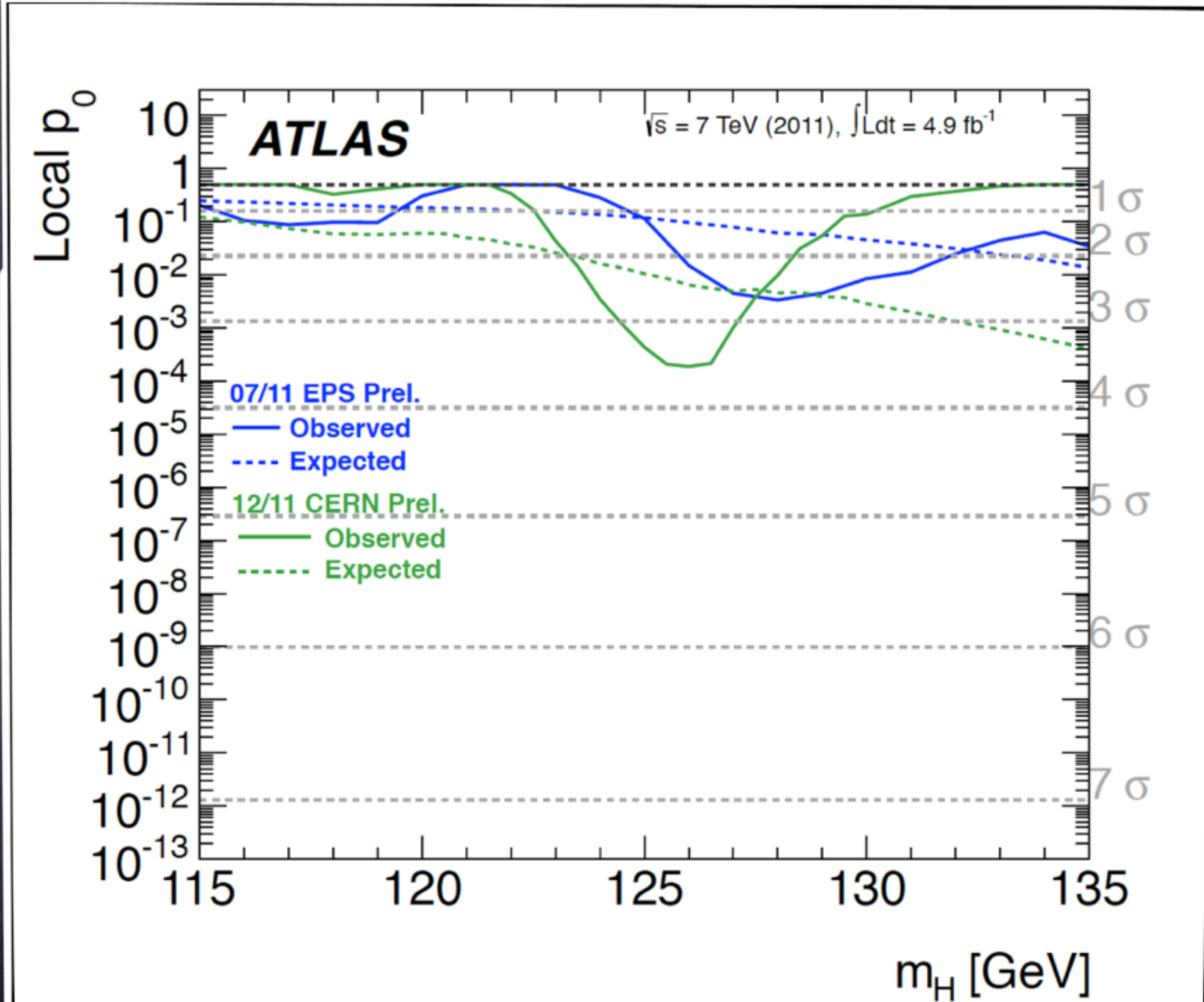
WW BIRTH OF A PARTICLE



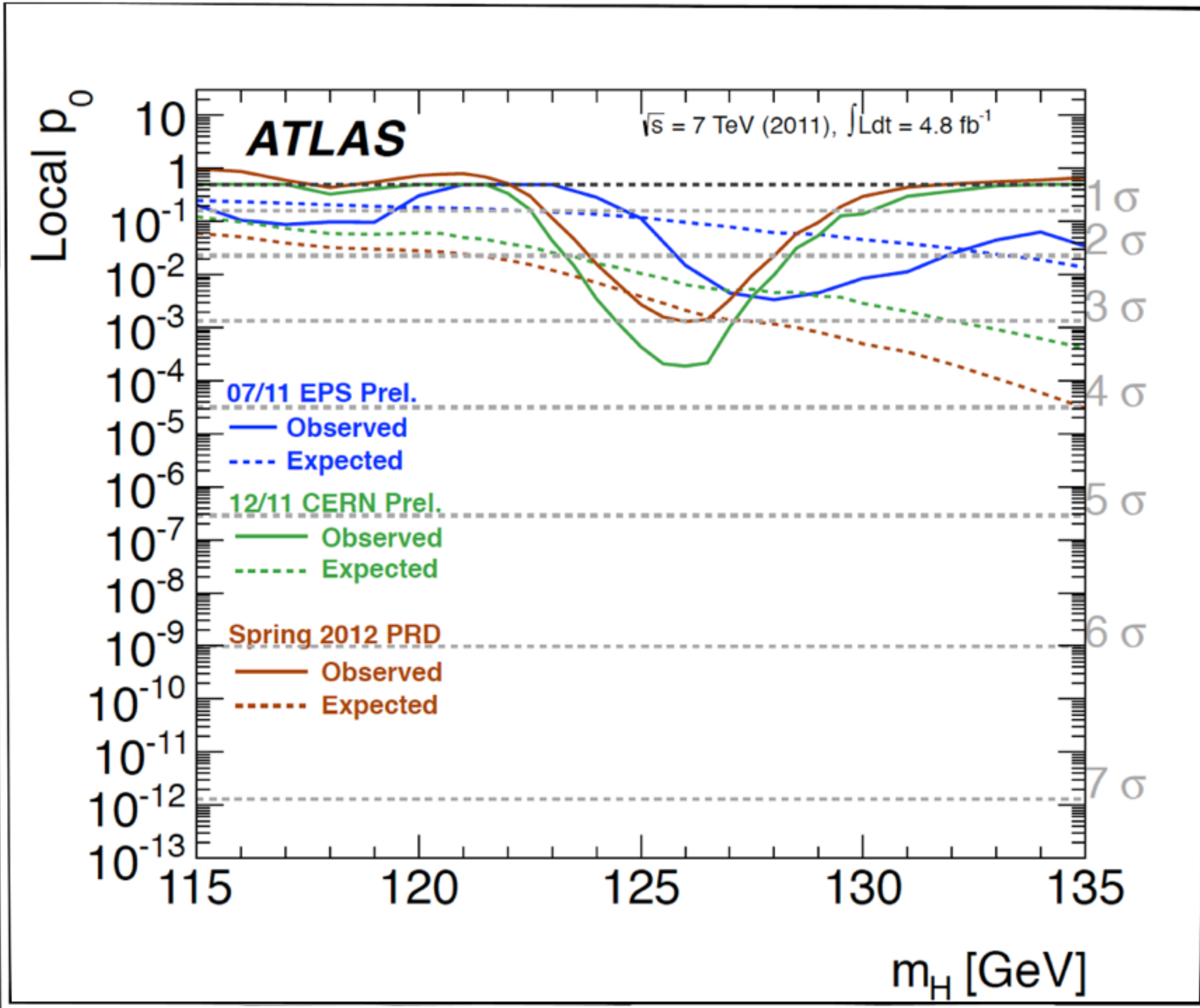
$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 + (p_T^{ll} + p_T^{miss})^2}$$



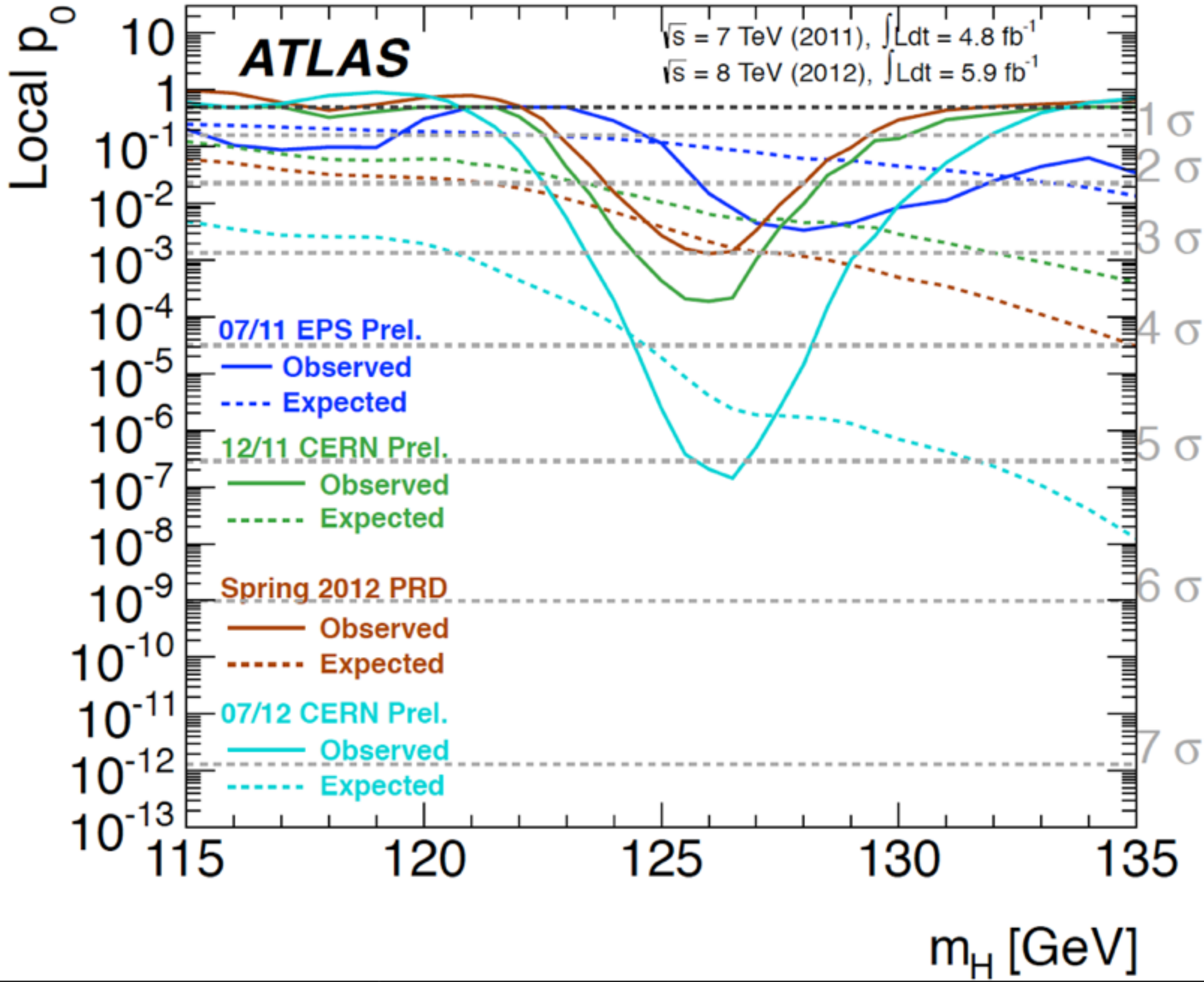
ATLAS
$\sqrt{s}$ = 7 TeV (2011), $\int Ldt$ = 1.2 fb^{-1}
Local p_0
m_H [GeV]
07/11 EPS Prel.
Observed
Expected
1 σ
2 σ
3 σ
4 σ
5 σ
6 σ
7 σ
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
115
120
125
130
135



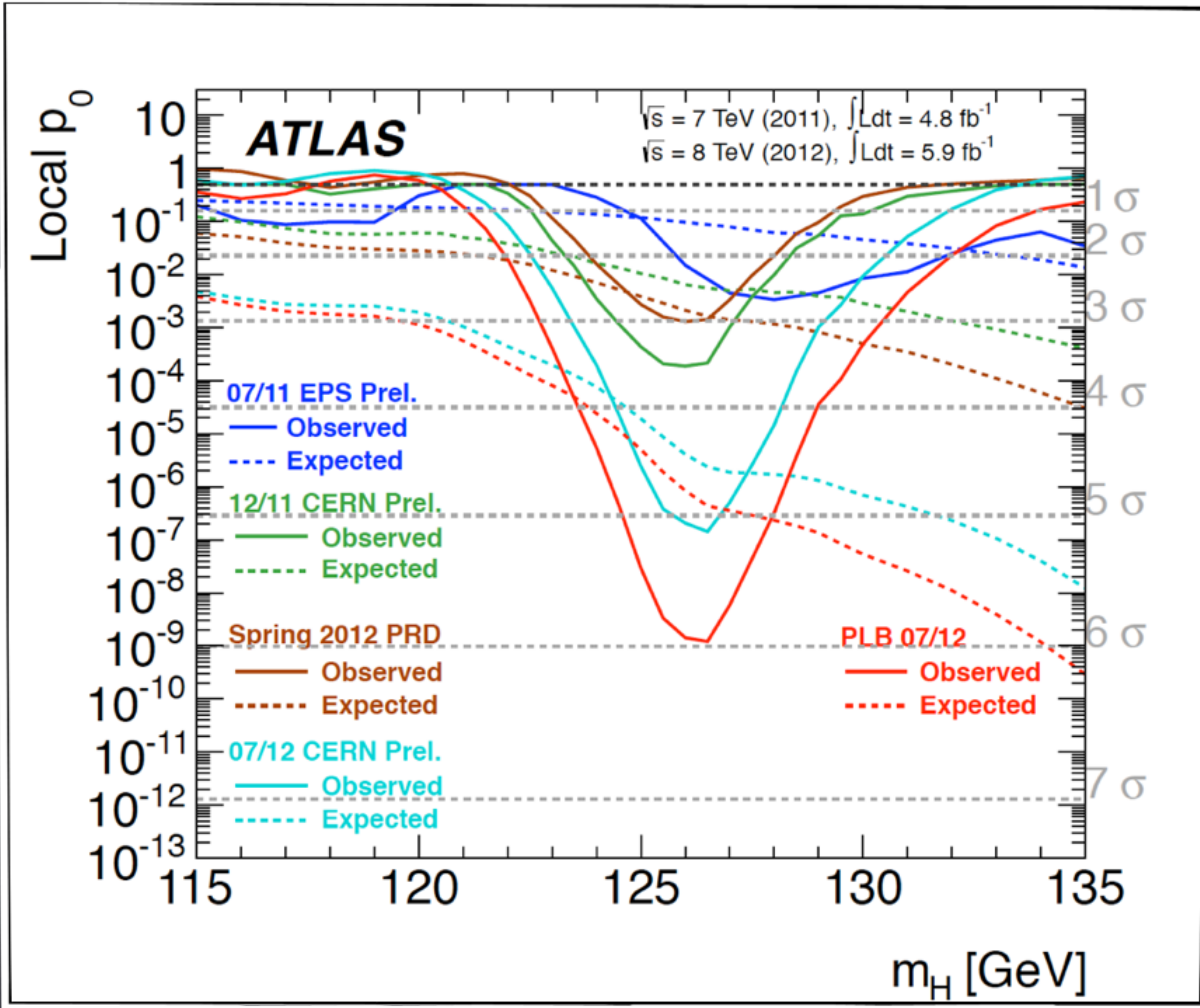
ATLAS
√s = 7 TeV (2011), ∫Ldt = 4.9 fb-1
Local p0
mH [GeV]
07/11 EPS Prel.
Observed
Expected
12/11 CERN Prel.
Observed
Expected
1 σ
2 σ
3 σ
4 σ
5 σ
6 σ
7 σ
10
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
115
120
125
130
135



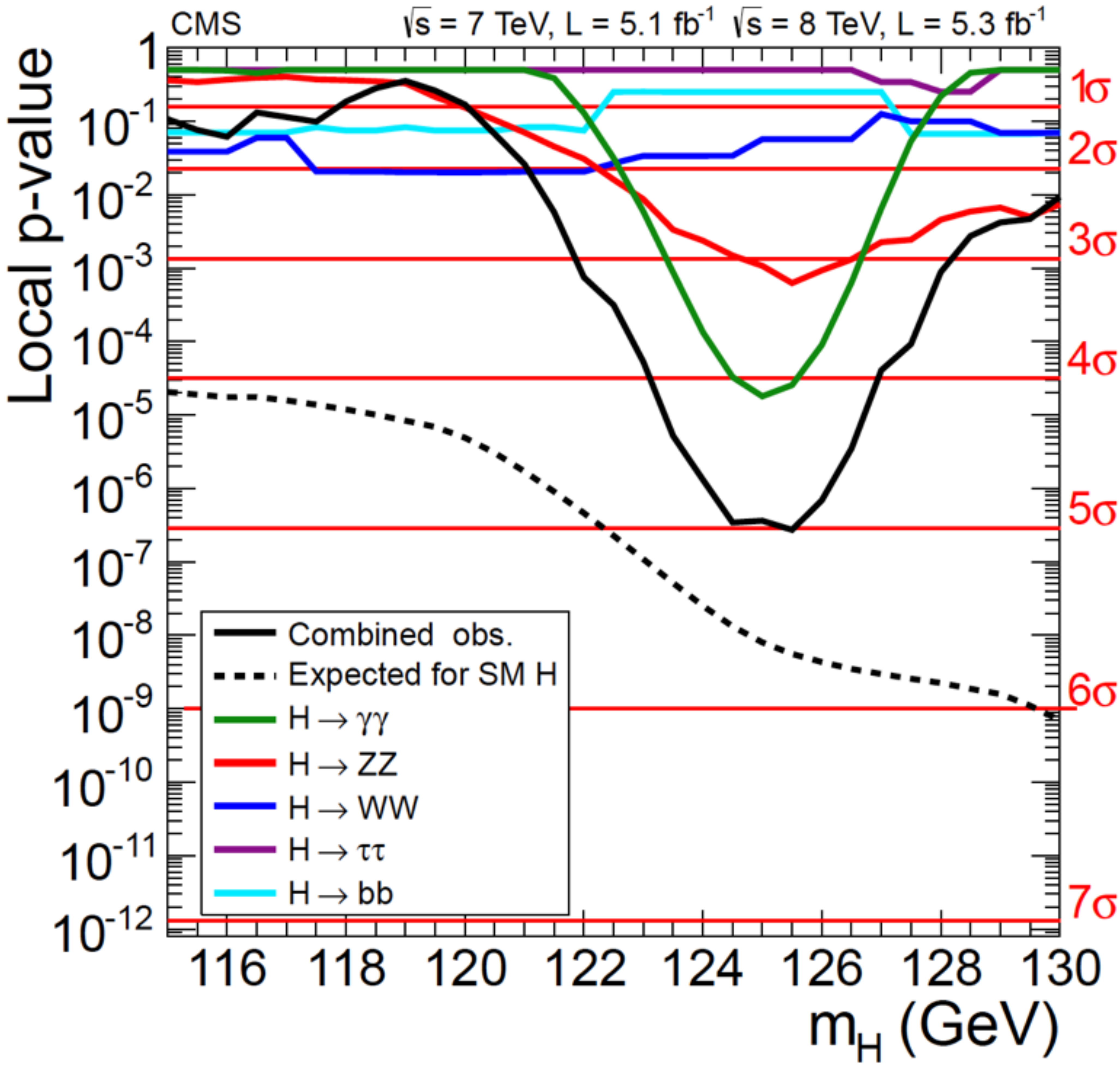
Local p_0
ATLAS
$\sqrt{s}$ = 7 TeV (2011), $\int Ldt$ = 4.8 fb^{-1}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
1 σ
2 σ
3 σ
4 σ
5 σ
6 σ
7 σ
07/11 EPS Prel.
Observed
Expected
12/11 CERN Prel.
Observed
Expected
Spring 2012 PRD
Observed
Expected
115
120
125
130
135
m_H [GeV]



ATLAS
√s = 7 TeV (2011), ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV (2012), ∫Ldt = 5.9 fb⁻¹
Local p0
mH [GeV]
1 σ
2 σ
3 σ
4 σ
5 σ
6 σ
7 σ
07/11 EPS Prel.
Observed
Expected
12/11 CERN Prel.
Observed
Expected
Spring 2012 PRD
Observed
Expected
07/12 CERN Prel.
Observed
Expected



Local p_0
ATLAS
$\sqrt{s}$ = 7 TeV (2011), $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV (2012), $\int Ldt$ = 5.9 fb^{-1}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
1 σ
2 σ
3 σ
4 σ
5 σ
6 σ
7 σ
07/11 EPS Prel.
Observed
Expected
12/11 CERN Prel.
Observed
Expected
Spring 2012 PRD
Observed
Expected
07/12 CERN Prel.
Observed
Expected
PLB 07/12
Observed
Expected
115
120
125
130
135
m_H [GeV]



CMS
√s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 5.3 fb⁻¹
Local p-value
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
1σ
2σ
3σ
4σ
5σ
6σ
7σ
Combined obs.
Expected for SM H
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
116
118
120
122
124
126
128
130
m_H (GeV)

THE PUBLICATION

- Then came the ww, elevating us to 6σ

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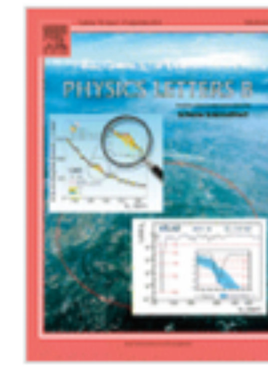
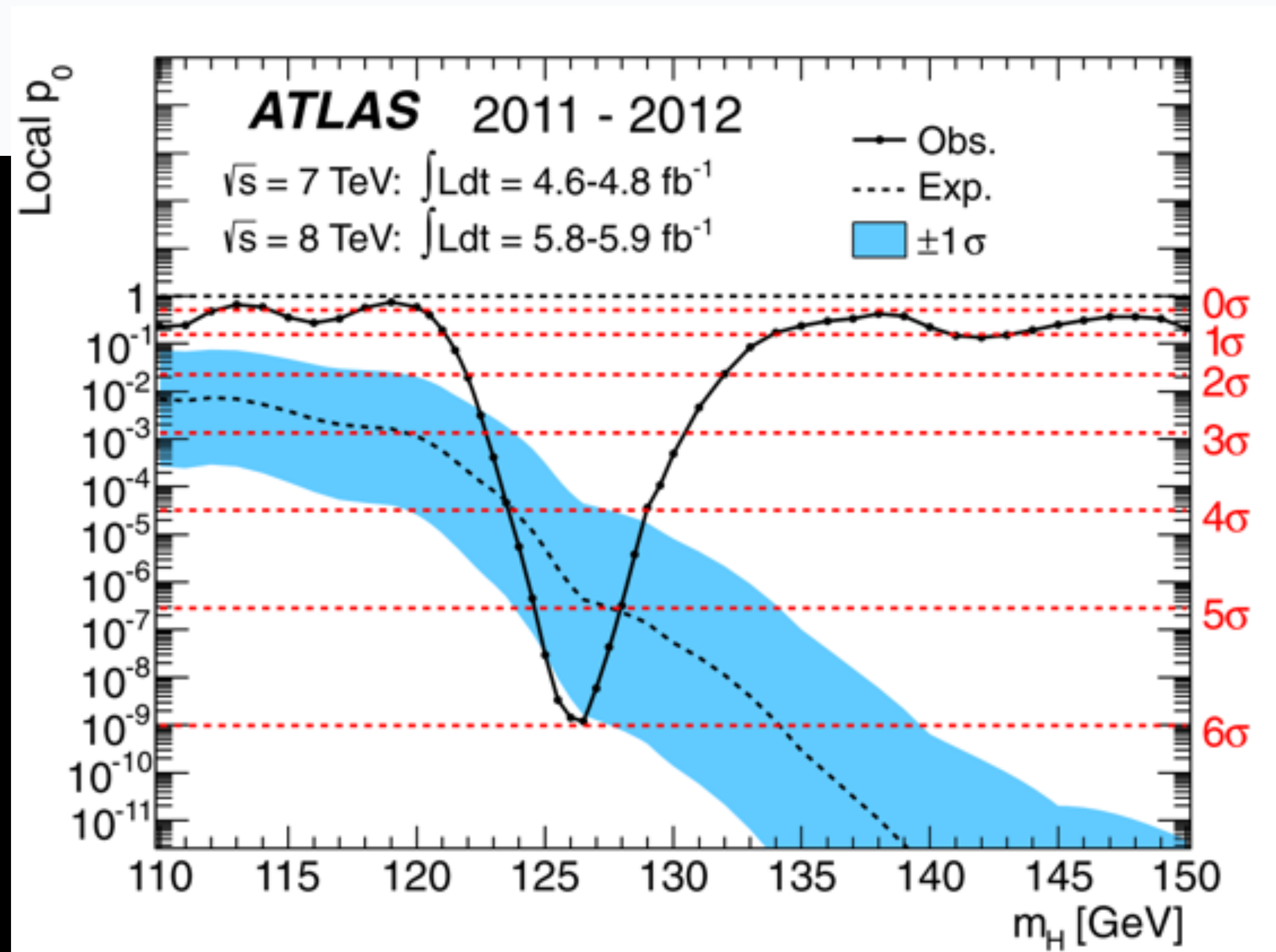
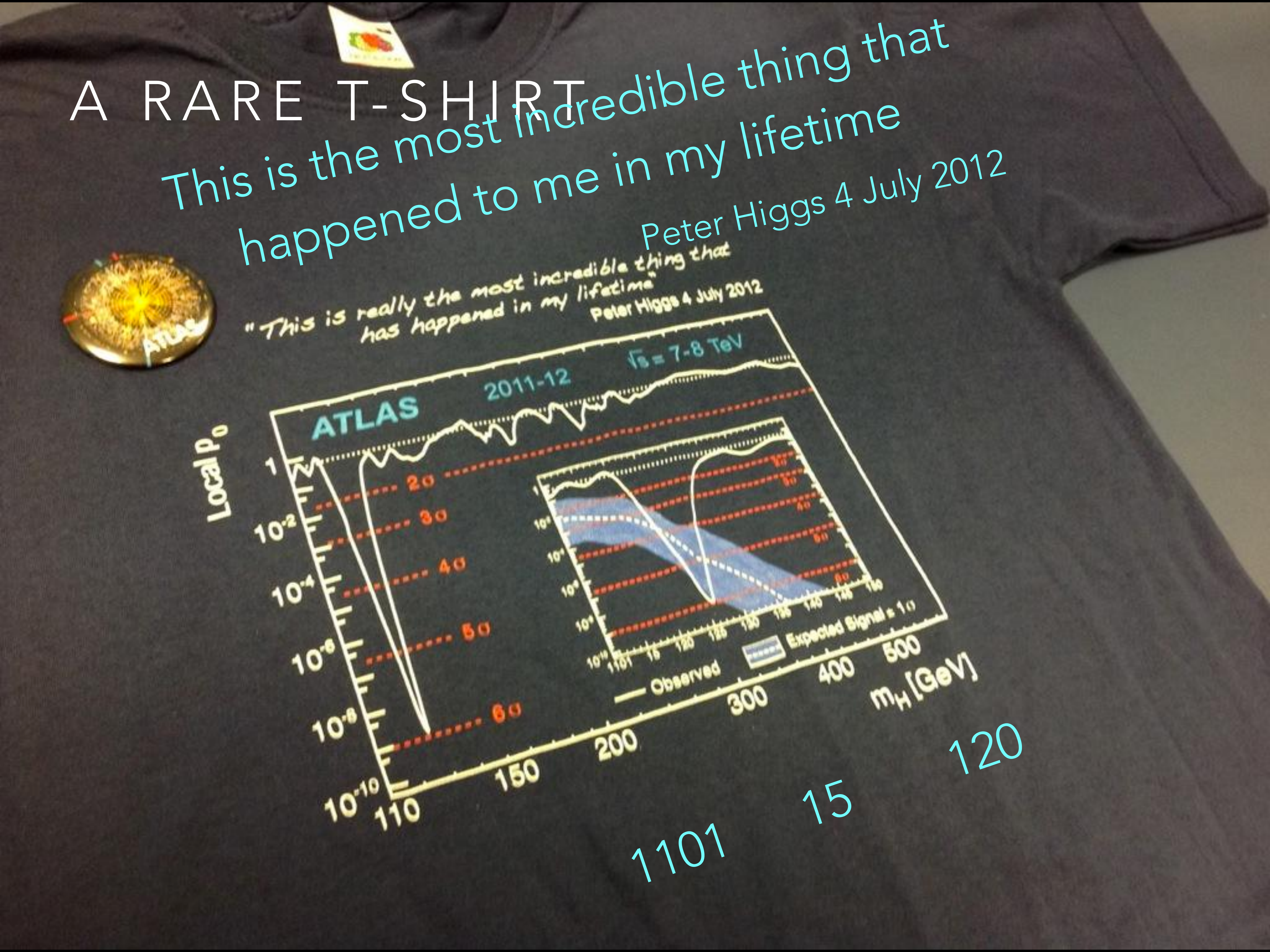




A RARE T-SHIRT



PHYSICS LETTERS B

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0370-2693(20120917)716:1;1-H

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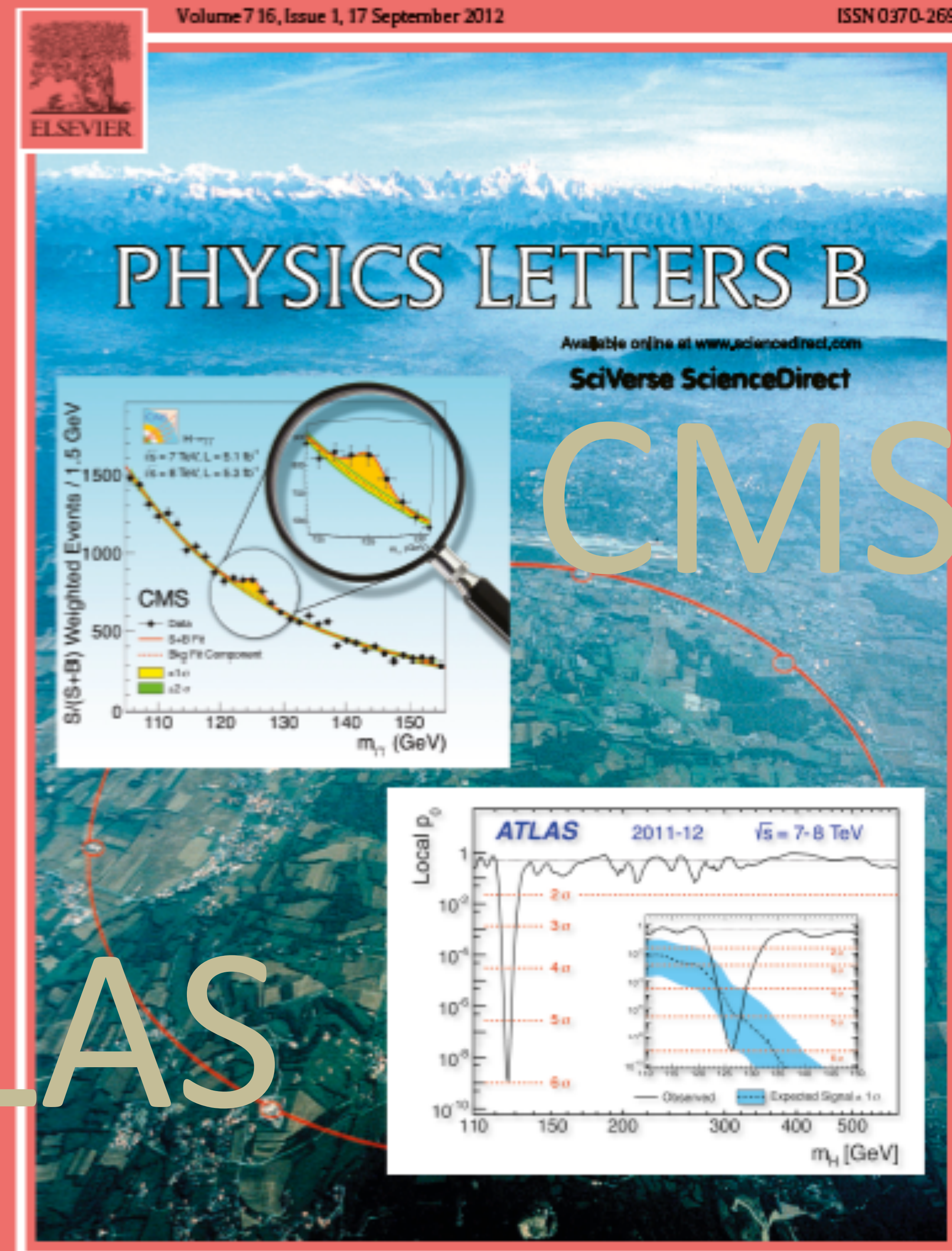

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CMS

ATLAS

6000 Signatures

6000 Higgs Hunters

D. Fortin[159a], D. Fournier[115], A.J. Fowler[45], H. Fox[71], P. Francavilla[12], M. Franchini[20a,20b], S. Franchino[119a,119b],
D. Francis[30], T. Fra … T. French[28],
C. Friedrich[42], F. Fr … E. Fullana Torregrosa[30],
B.G. Fulsom[143], J. … . Gadomski[49],
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M.H. Genest … niger[58a],
H. Ghazlane … bbe[12],
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A.R. Gillman[129], D.M. Gingrich[3,d], J. Ginzburg[153], N. Giokaris[9], M.P. Giordani[164c], R. Giordano[102a,102b],
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V. Grassi[148], V. Gratchev[121], N. Grau[35], H.M. Gray[30], J.A. Gray[148], E. Graziani[134a], O.G. Grebenyuk[121],
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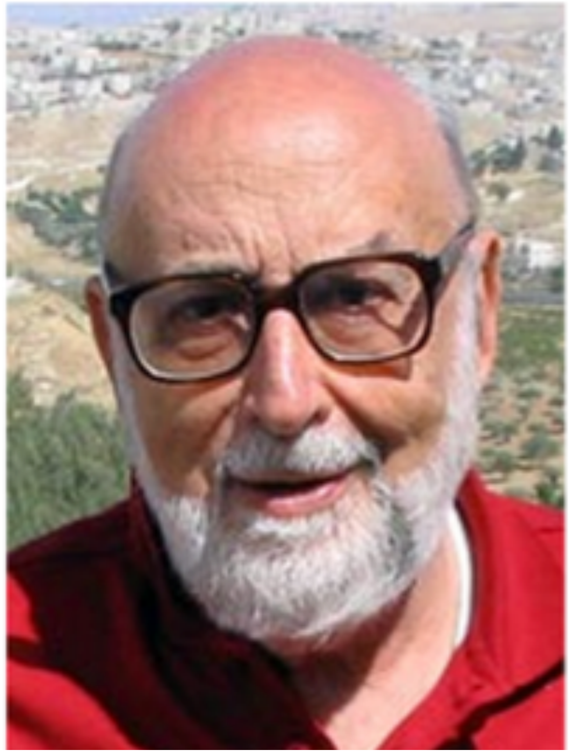
The Nobel Prize in Physics 2013



The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*