"וְעֵילָם נָשָׂא אַשְׁפָּה..."

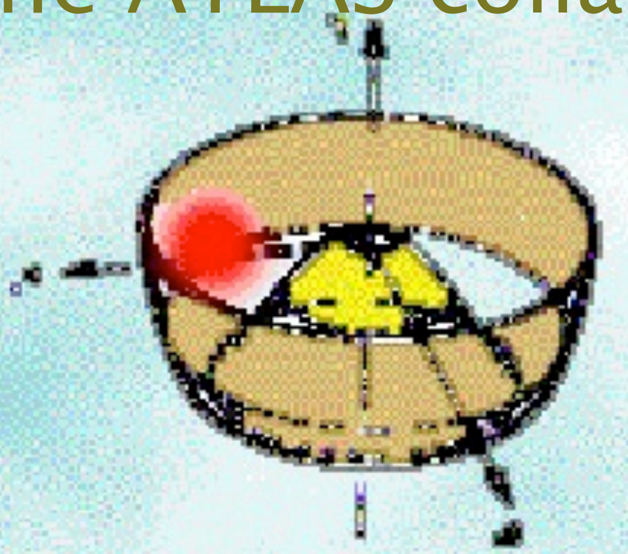
ישעיה כב

Eilam Gross

Weizmann & CERN

Hunting the Higgs

On behalf of the ATLAS collaboration



ATLAS EXPERIMENT

Higgs Symposium

Edinburgh, January 2013

"And Eilam bare the quiver..."

Jesaia 22


On Behalf of the ATLAS Collaboration
C
D

A Phenomenological Profile of the Higgs Boson

1976

Nuclear Physics B106 (1976) 292–340
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A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. Higgs bosons are introduced to give intermediate vector bosons masses through spontaneous symmetry breaking. However, this symmetry breaking could be achieved dynamically [10] without elementary Higgs bosons. Thus the confirmation or exclusion of their existence would be an important constraint on gauge theory model building. Unfortunately, no way is known to calculate the mass of a Higgs boson, at least in the context of the popular Weinberg-Salam [11]

A Phenomenological Profile of the Higgs Boson

1976

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A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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CERN, Geneva

Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A Phenomenological Profile of the Higgs Boson

Jan 2012

KCL-PH-TH/2012-04, LCTS/2012-01, CERN-PH-TH/2012-009
LBNL-, UCB-PTH-12/01
ACT-1-12, MIFPA-12-01

January 2012

A Historical Profile of the Higgs Boson

John Ellis[a], Mary K. Gaillard[b] and Dimitri V. Nanopoulos[c]

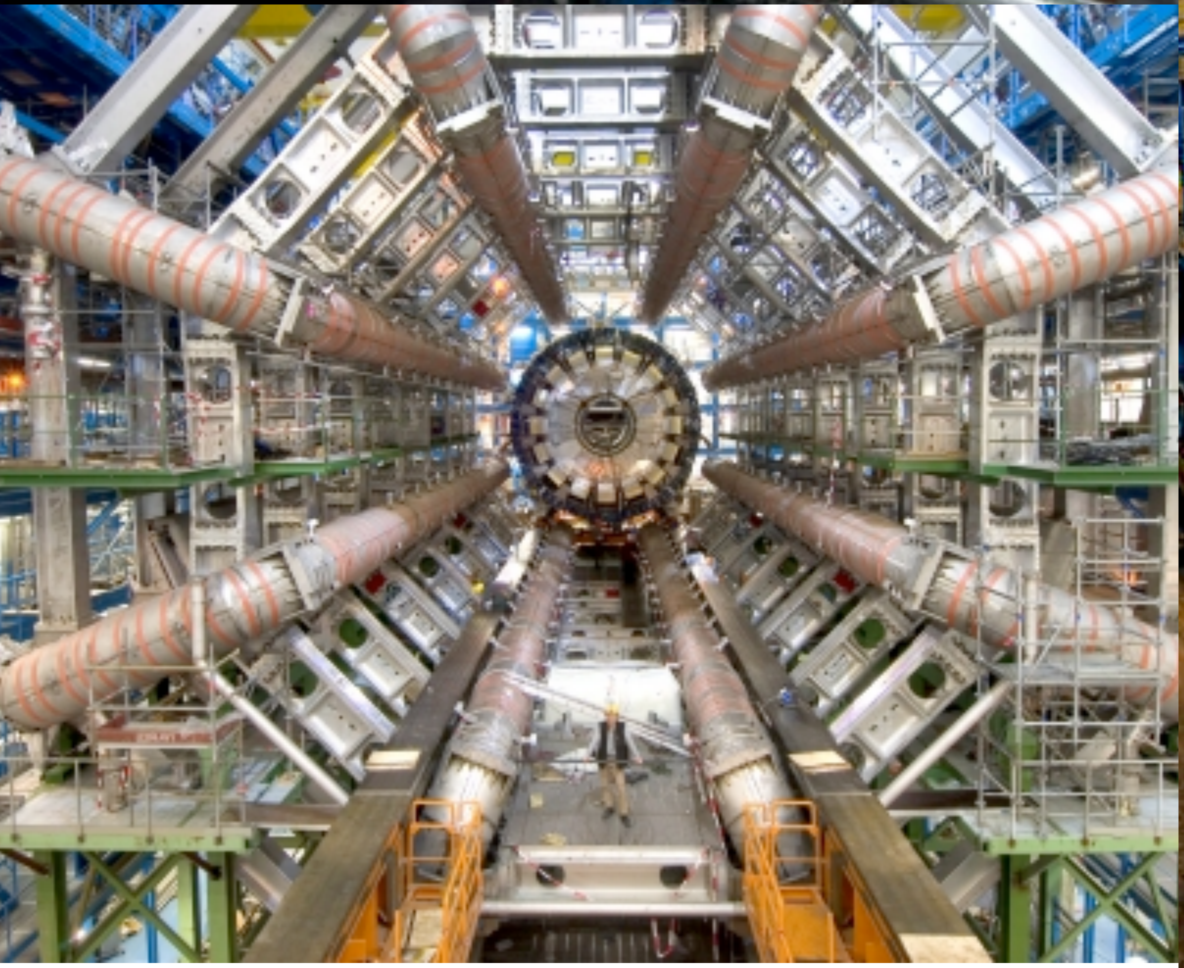
Already in 1975, before the experimental discovery of charm was confirmed, we considered that the discovery of the Higgs boson would be the culmination of the experimental verification of the Standard Model, and we published a paper outlining its phenomenological profile [12]. At the time, the Higgs boson was not on the experimental agenda, but its star has risen over the subsequent years, first in e^+e^- collisions [13] and subsequently in $\bar{p}p$ and pp collisions [14, 15], until now it is widely (though incompletely) perceived as the primary objective of experiments at the LHC. We anticipate that the ATLAS and CMS experiments will soon deliver their verdict on the possible existence of the Higgs boson, providing closure on half a century of theoretical conjecture.

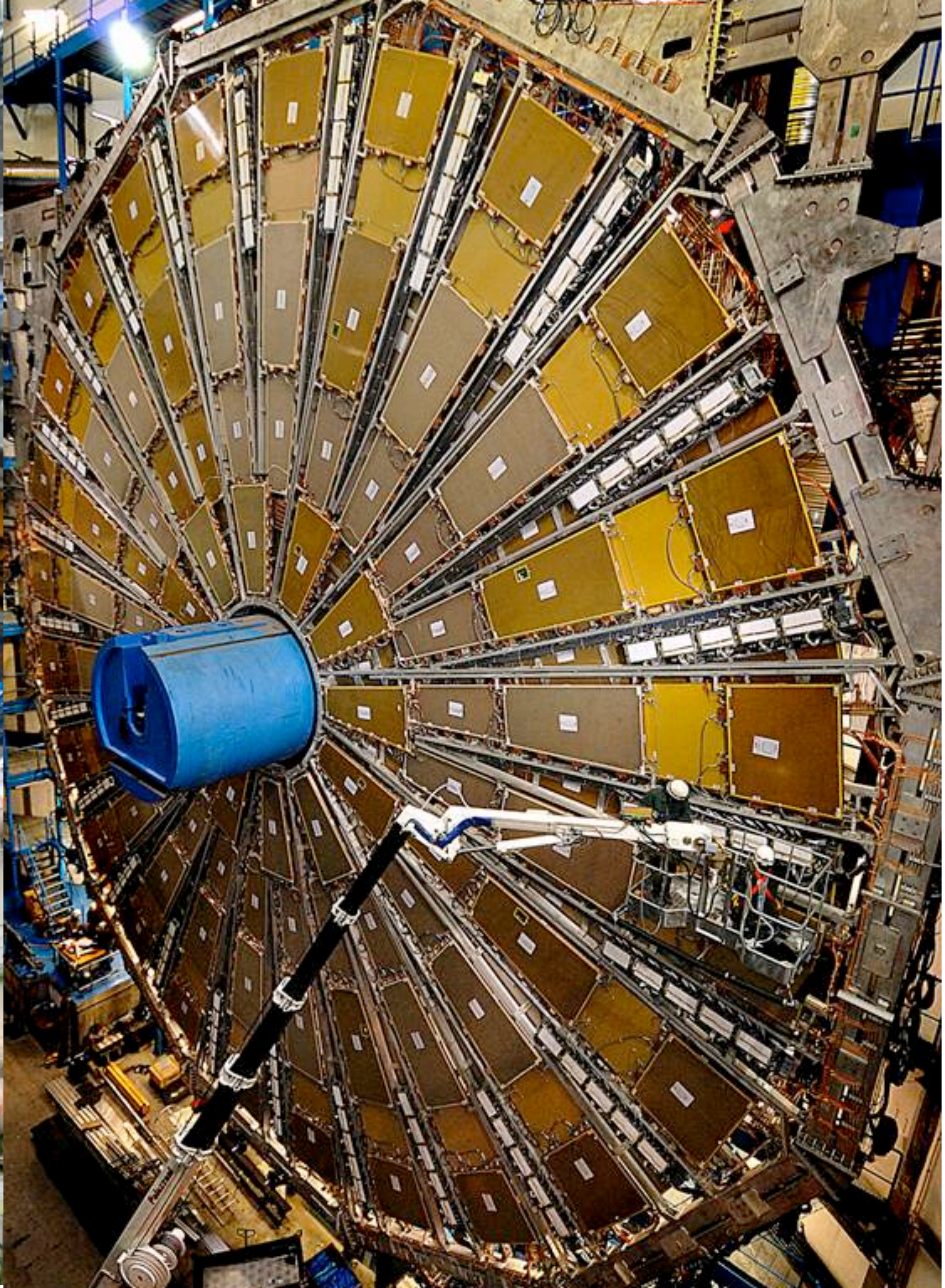

I was looking for you for over 20 years


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

4th JULY 2012
Higgs Hunters' Independence Day

17 september 2012

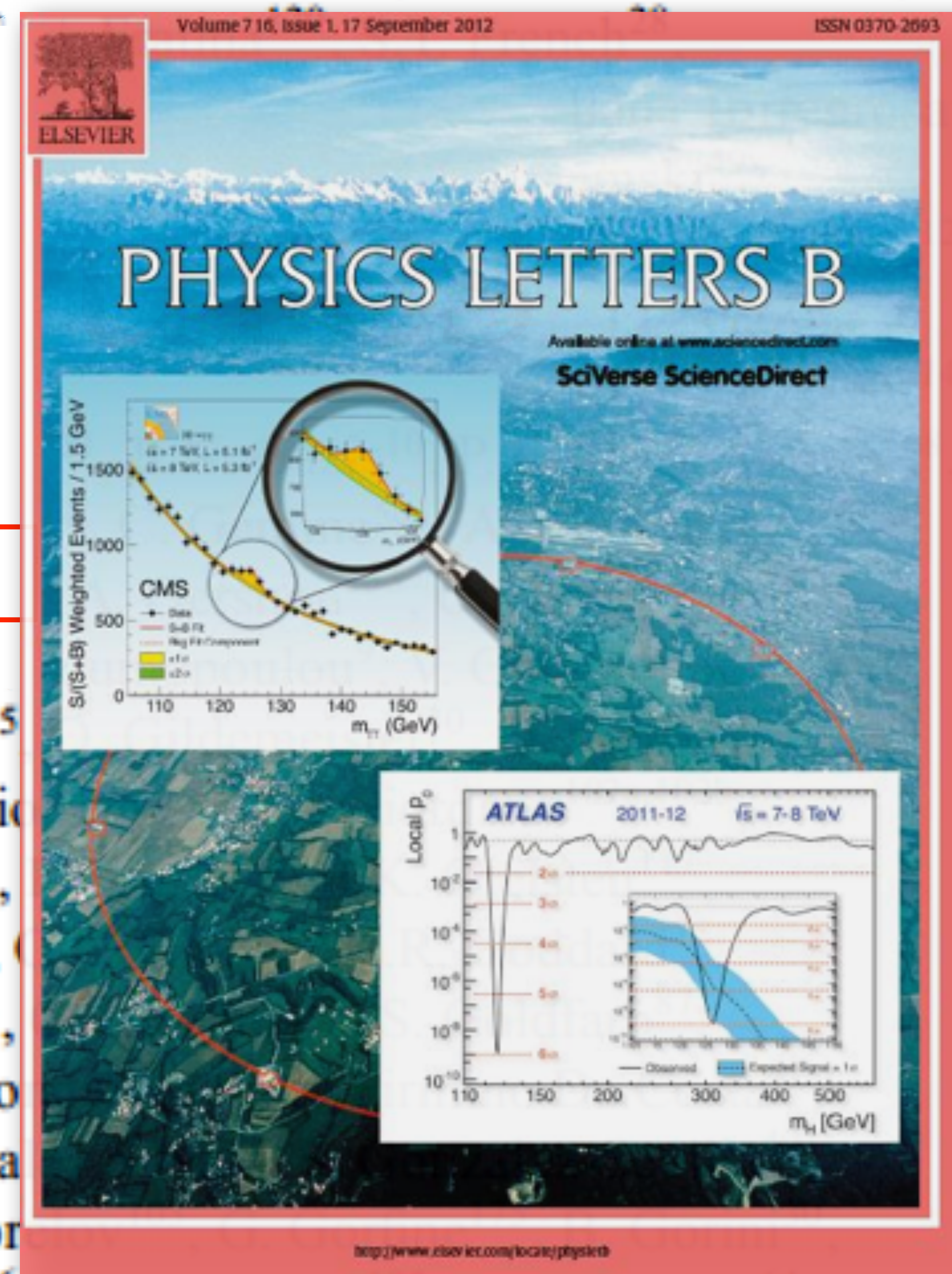




Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

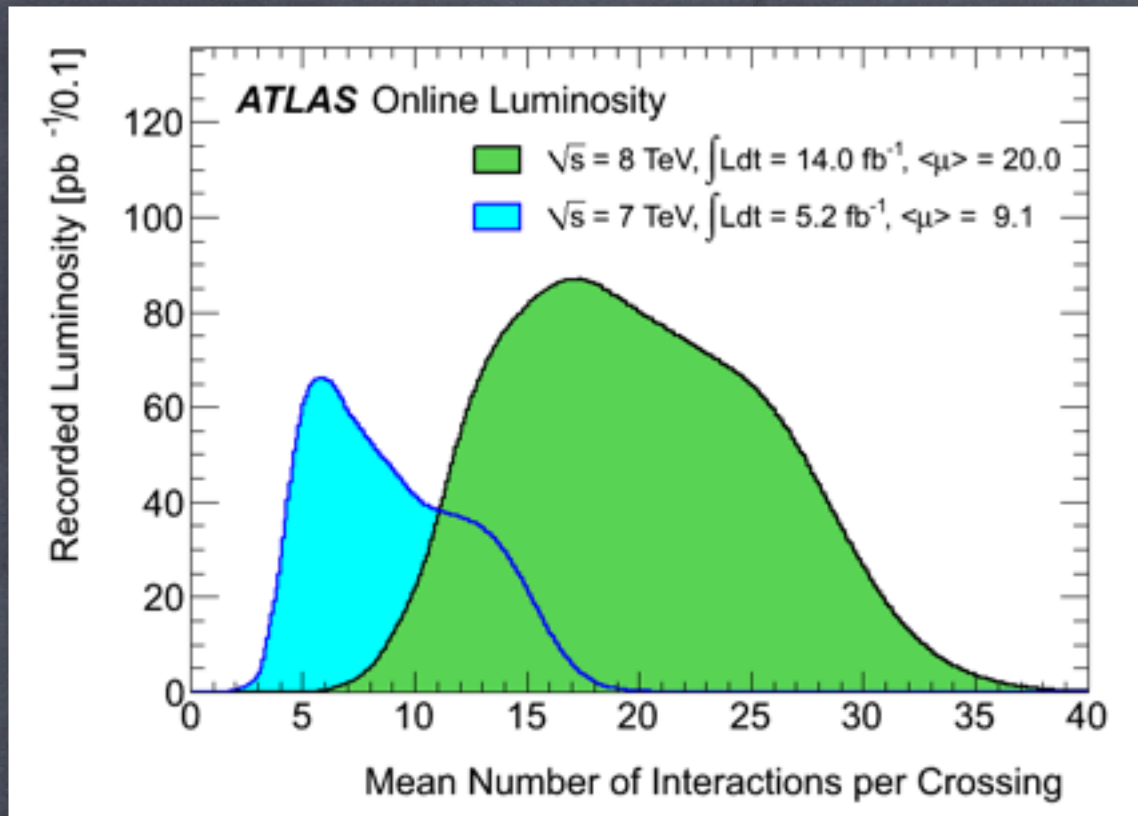


F. Gianotti[30], B. Gibbard[25], A. Gibson[158], S.M. Gibson[30], M. Gilchriese[15
A.R. Gillman[129], D.M. Gingrich[3,d], J. Ginzburg[153], N. Giokaris[9], M.P. Gi
F.M. Giorgi[16], P. Giovannini[99], P.F. Giraud[136], D. Giugni[89a], M. Giunta[93],
L.K. Gladilin[97], C. Glasman[80], J. Glatzer[21], A. Glazov[42], K.W. Glitza[175],
J. Godfrey[142], J. Godlewski[30], M. Goebel[42], T. Göpfert[44], C. Goeringer[81],
T. Golling[176], A. Gomes[124a,b], L.S. Gomez Fajardo[42], R. Gonçalo[76], J. Go
L. Gonella[21], S. González de la Hoz[167], G. Gonzalez Parra[12], M.L. Gonza
J.J. Goodson[148], L. Goossens[30], P.A. Gorbounov[95], H.A. Gordon[25], I. Gor
E. Gorini[72a,72b], A. Gorišek[74], E. Gornicki[39], B. Gosdzik[42], A.T. Goshaw[6], M. Gosselink[105], M.I. Gostkin[64],
I. Gough Eschrich[163], M. Gouighri[135a], D. Goujdami[135c], M.P. Goulette[49], A.G. Goussiou[138], C. Goy[5], S. Gozpinar[23],
I. Grabowska-Bold[38], P. Grafström[20a,20b], K-J. Grahn[42], E. Gramstad[117], F. Grancagnolo[72a], S. Grancagnolo[16],
V. Grassi[148], V. Gratchev[121], N. Grau[35], H.M. Gray[30], J.A. Gray[148], E. Graziani[134a], O.G. Grebenyuk[121],
T. Greenshaw[73], Z.D. Greenwood[25,m] iths[8], N. Grigalashvili[64],
A.A. Grillo[137], S. Grinstein[12], Ph. Gr Grosse-Knetter[54],
J. Groth-Jensen[172], K. Grybel[141], D. [54], U. Gul[53],
J. Gunther[125], B. Guo[158], J. Guo[35], P. Gutierrez[111], N. Guttman[153], O. Gutzwiller[173], C. Guyot[136], C. Gwenlan[118],
C.B. Gwilliam[73], A. Haas[143], S. Haas[30], C. Haber[15], H.K. Hadavand[8], D.R. Hadley[18], P. Haefner[21], F. Hahn[30],
S. Haider[30], Z. Hajduk[39], H. Hakobyan[177], D. Hall[118], J. Haller[54], K. Hamacher[175], P. Hamal[113], K. Hamano[86],
M. Hamer[54], A. Hamilton[145b,p], S. Hamilton[161], L. Han[33b], K. Hanagaki[116], K. Hanawa[160], M. Hance[15], C. Handel[81]

3000 Signatures

Thanks to the LHC Team

A dream comes true: 27 fb^{-1} by 2012



Proton Runs 2010-12

Not currently active

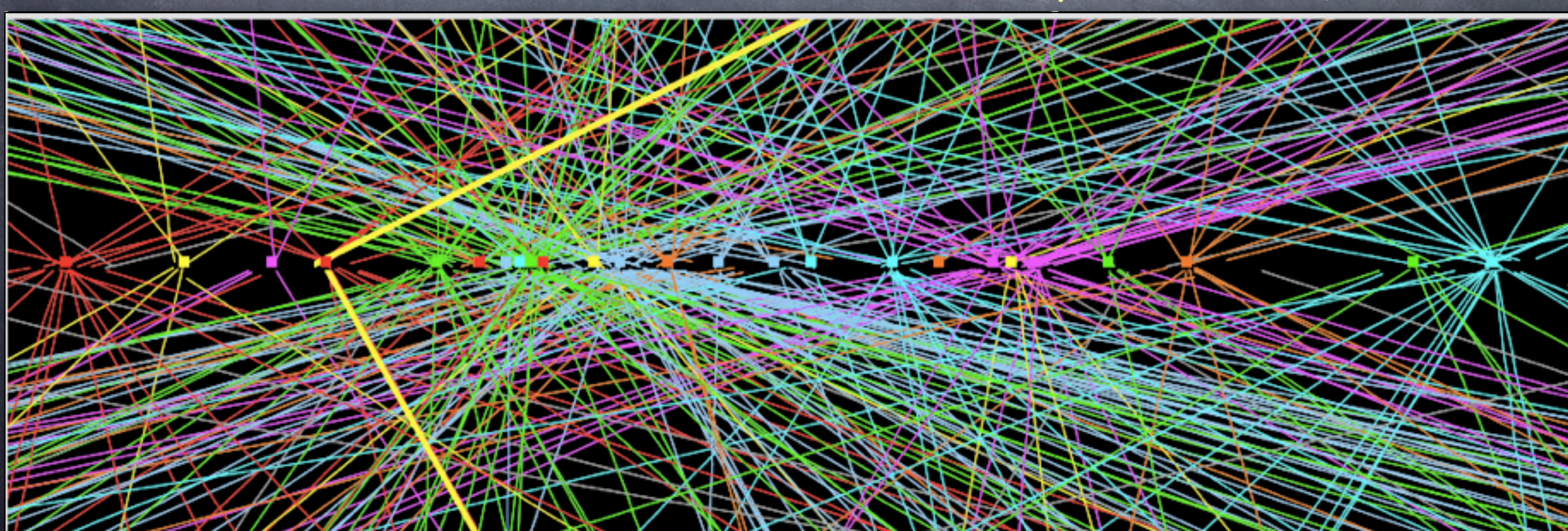
Highest luminosity = $7.73 \cdot 10^{33}$ $cm^{-2}s^{-1}$

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

Recorded luminosity = 27.03 fb^{-1}

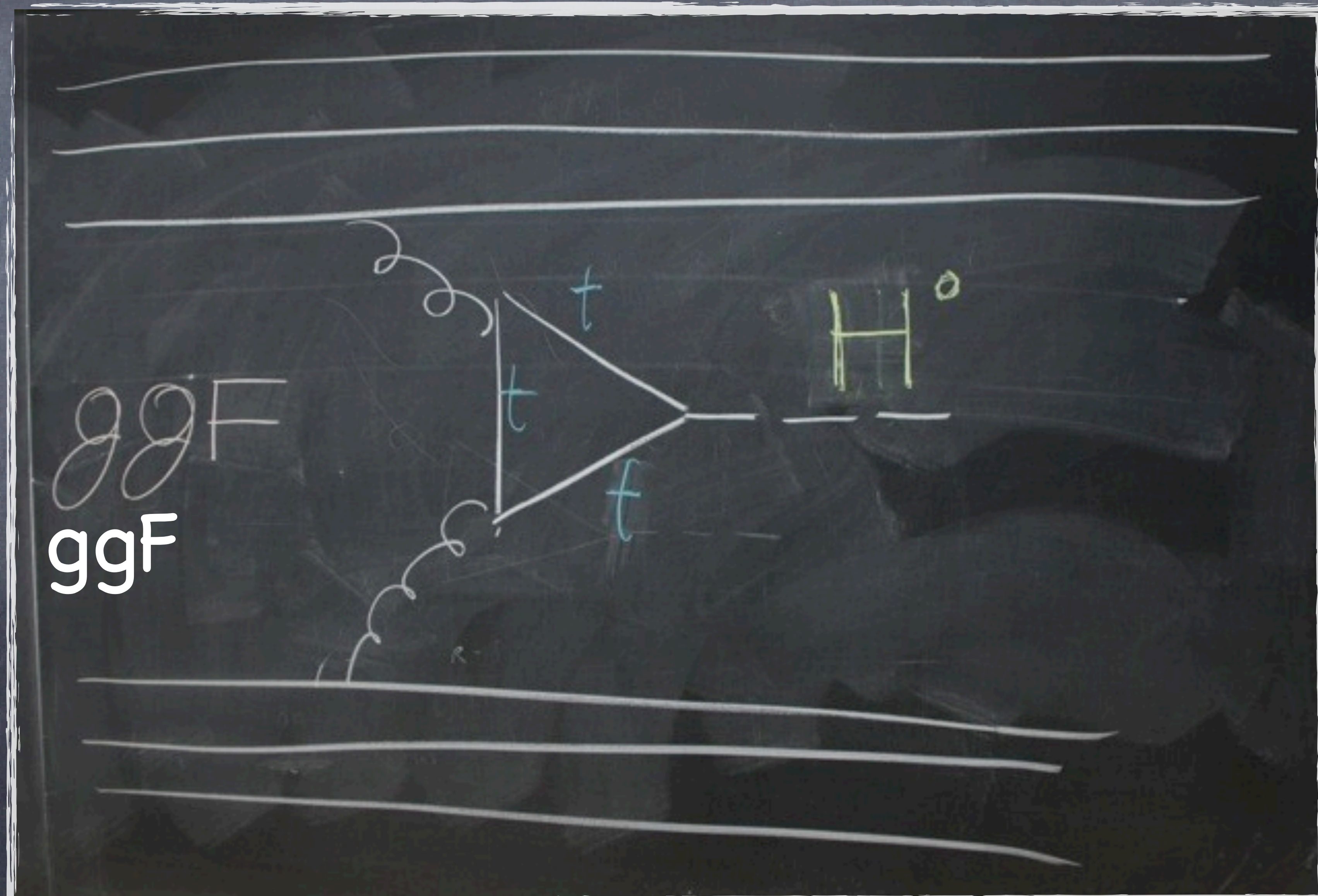
~1 H->γγ is produced every 50' at 7×10^{33}

~1 1H->4l is produced every 14h at 7×10^{33}



Higgs Production @ the LHC

- Higgs hardly couples to u & d quarks (which make protons)
- To produce a Higgs Boson in P-P collisions 4 processes are used: ggF, VBF, Associate Production and ttH



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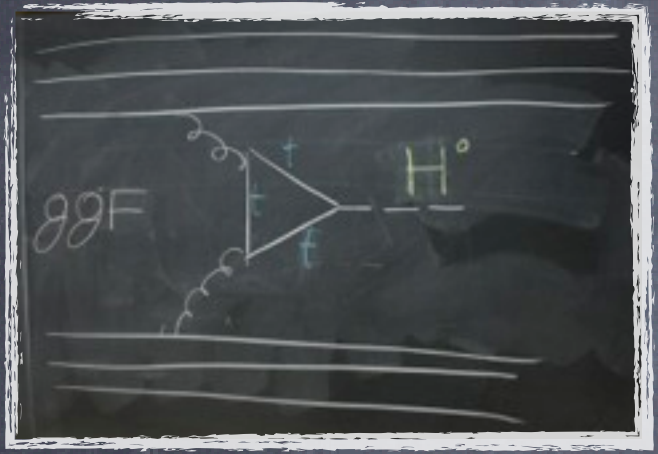

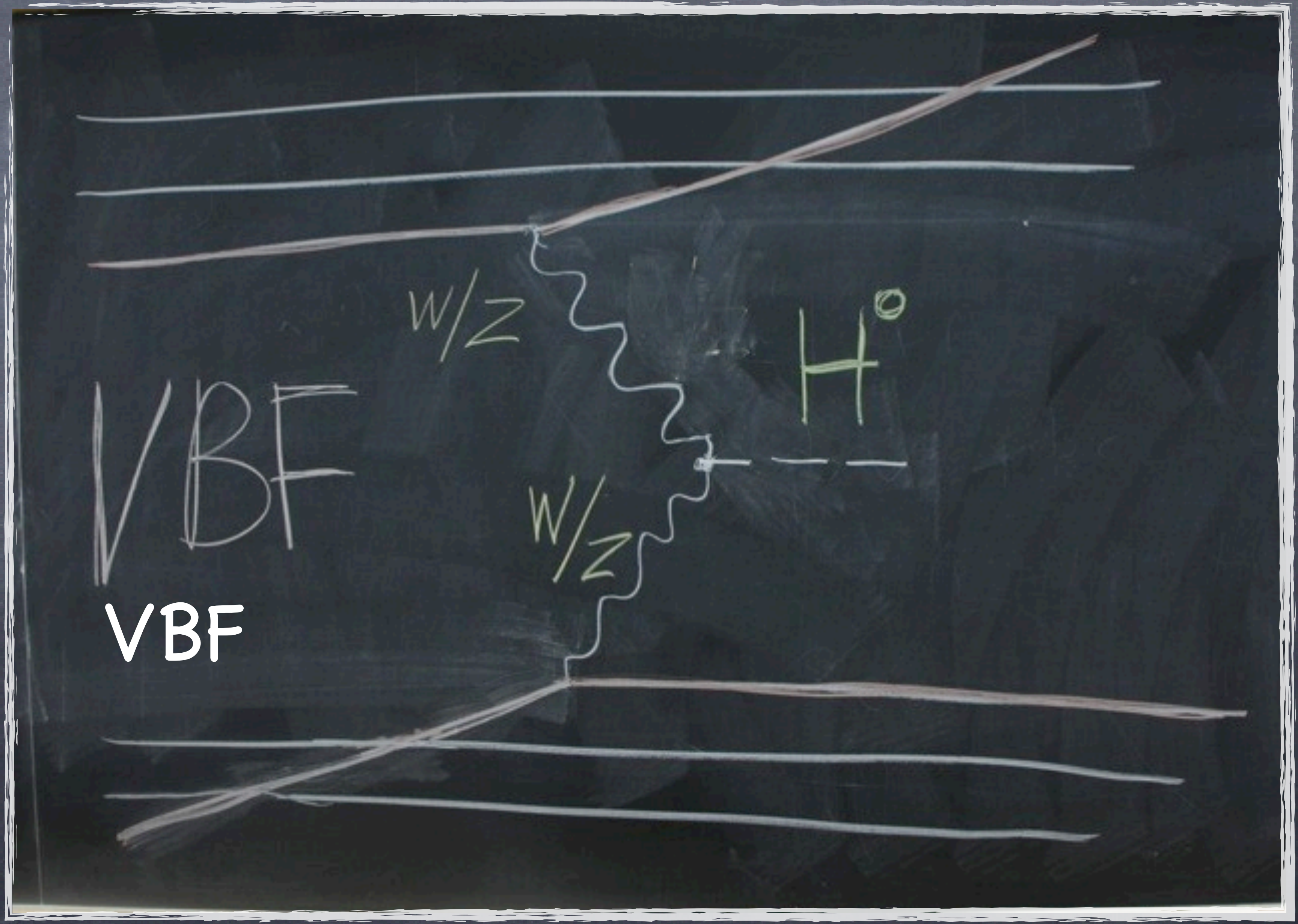

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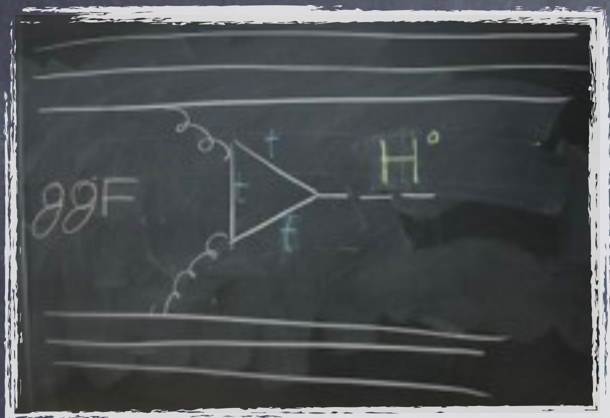

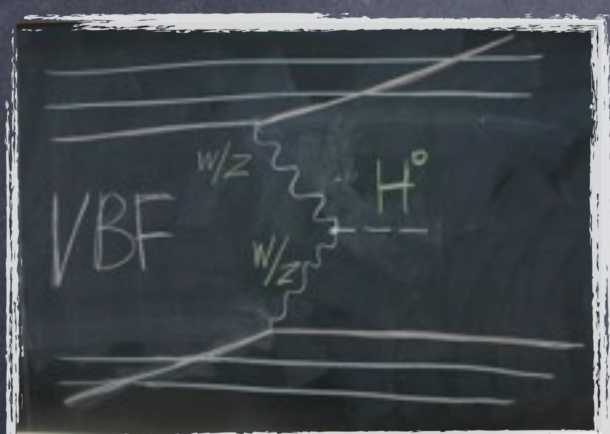

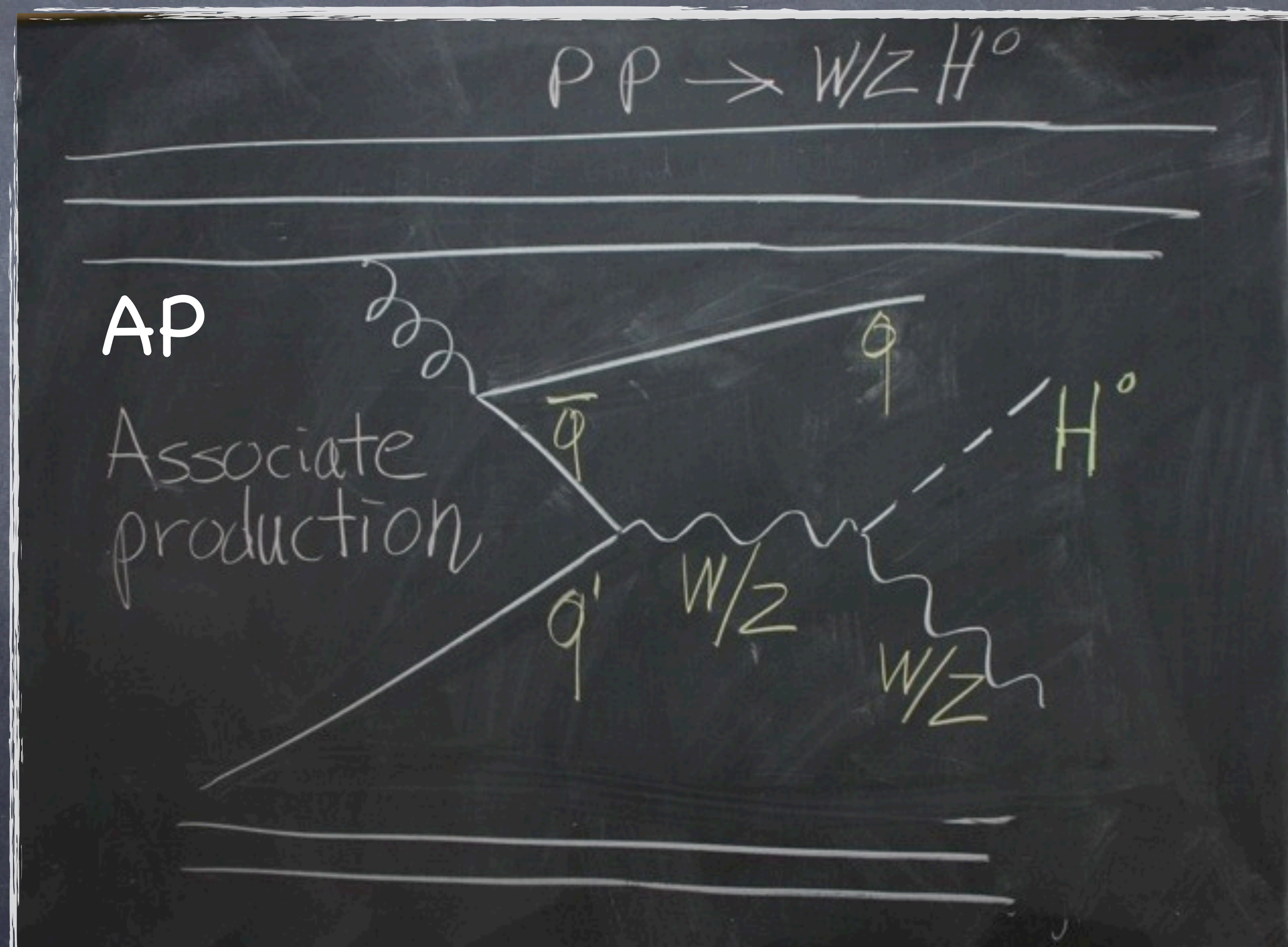

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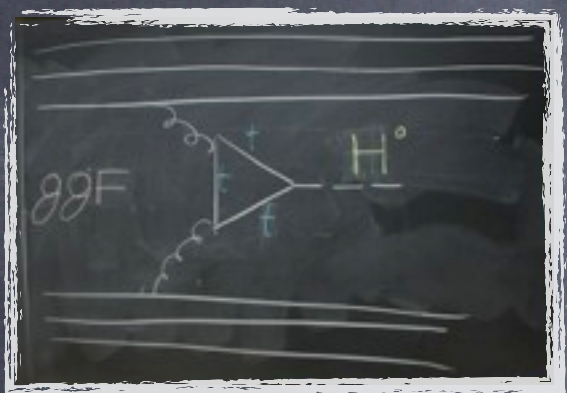
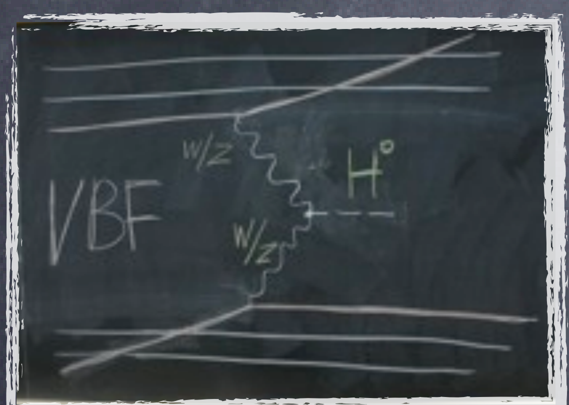
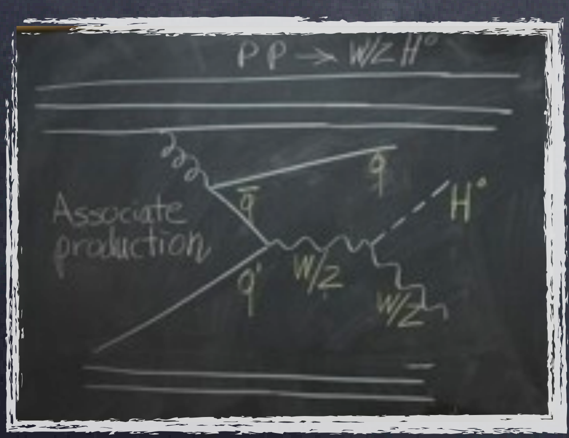
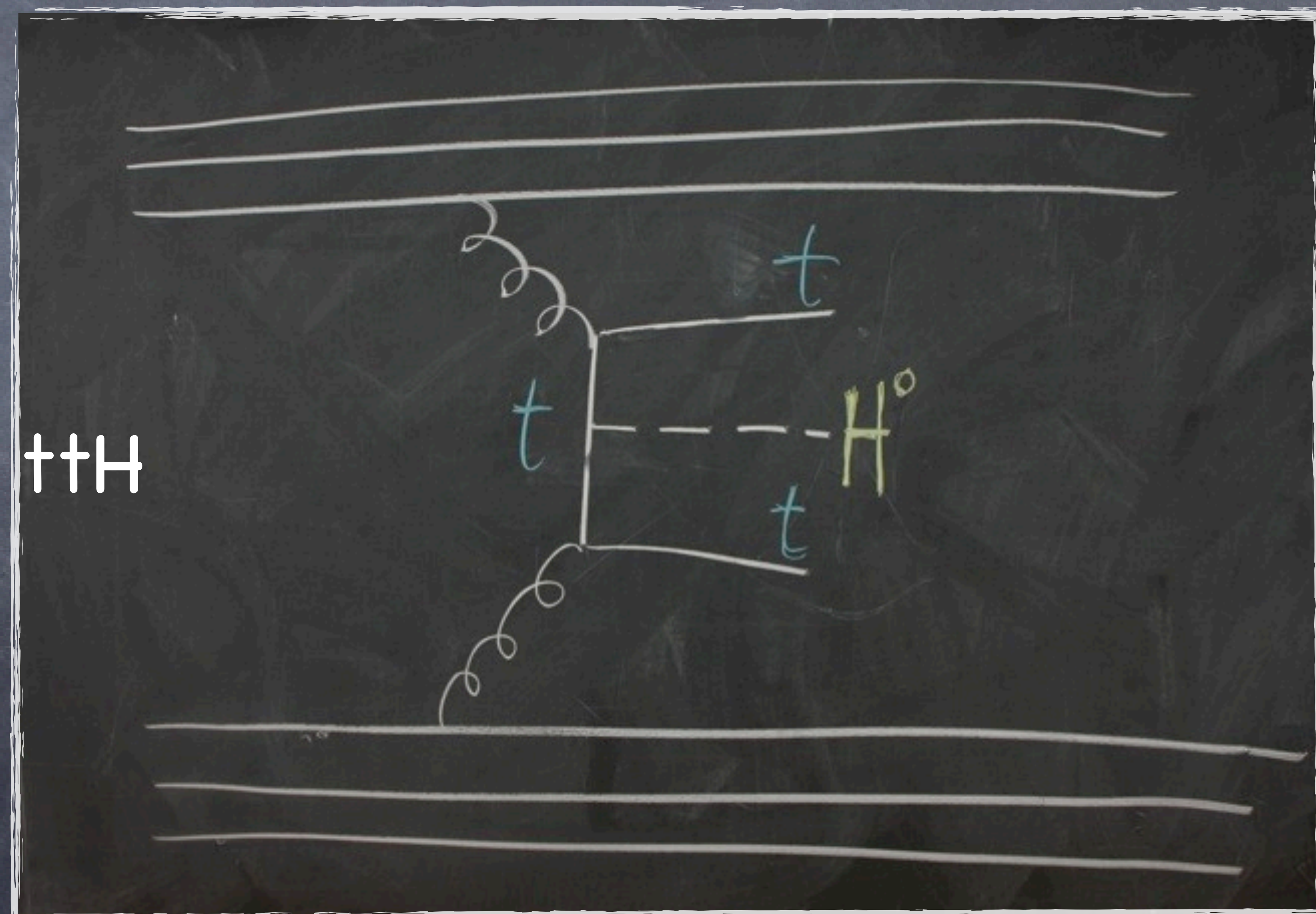


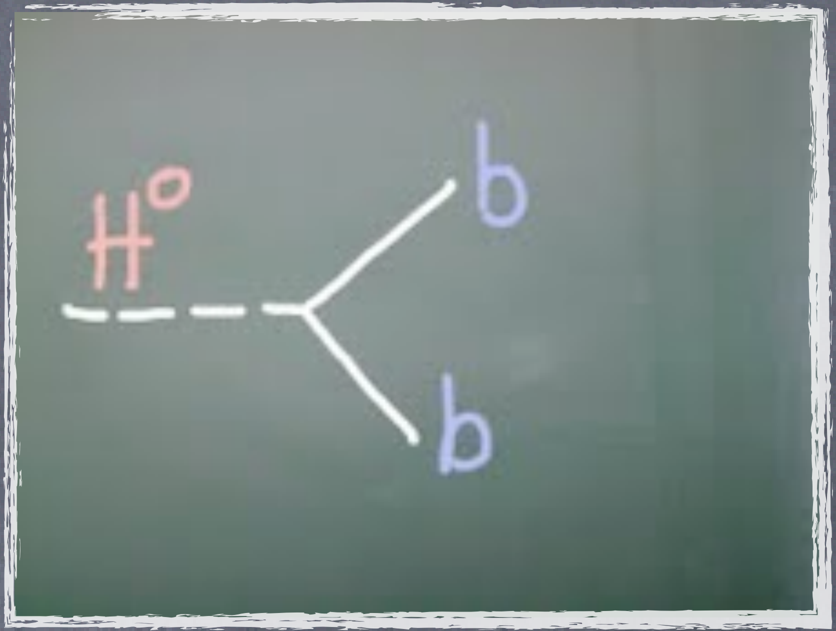


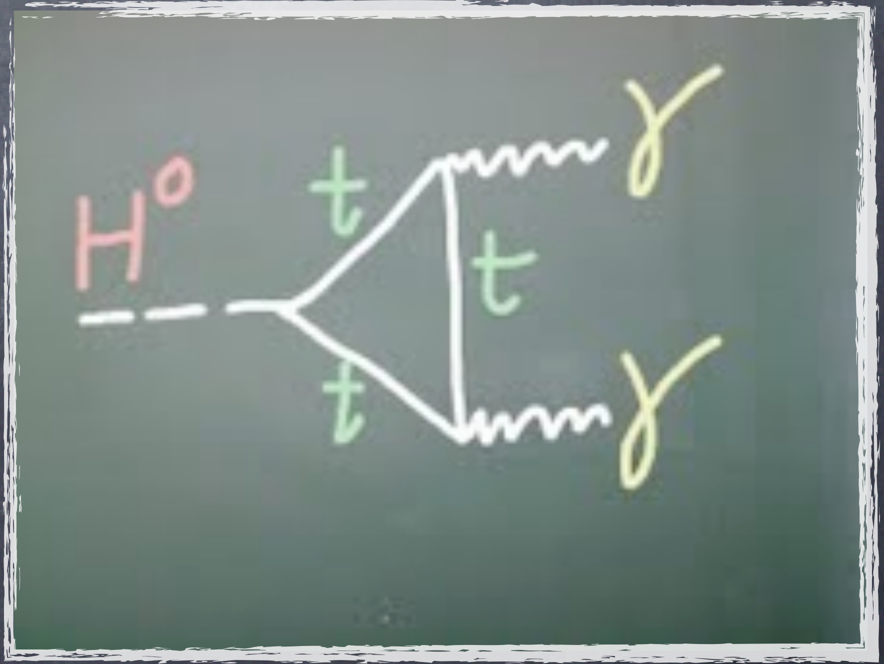




Higgs Decay Modes

- The Higgs Boson couples stronger to the heaviest kinematically available particles pair
- A light Higgs (mH~125 GeV) decays to $\tau\tau$ and mainly to a pair of bottom Quarks (bb)
- But H->bb is hard to detect or trigger on (only via its association 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 the favorite experimental channel for a Higgs with mH~110-130

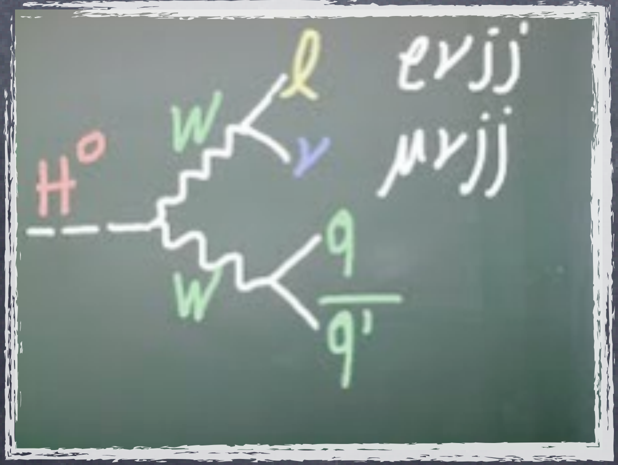




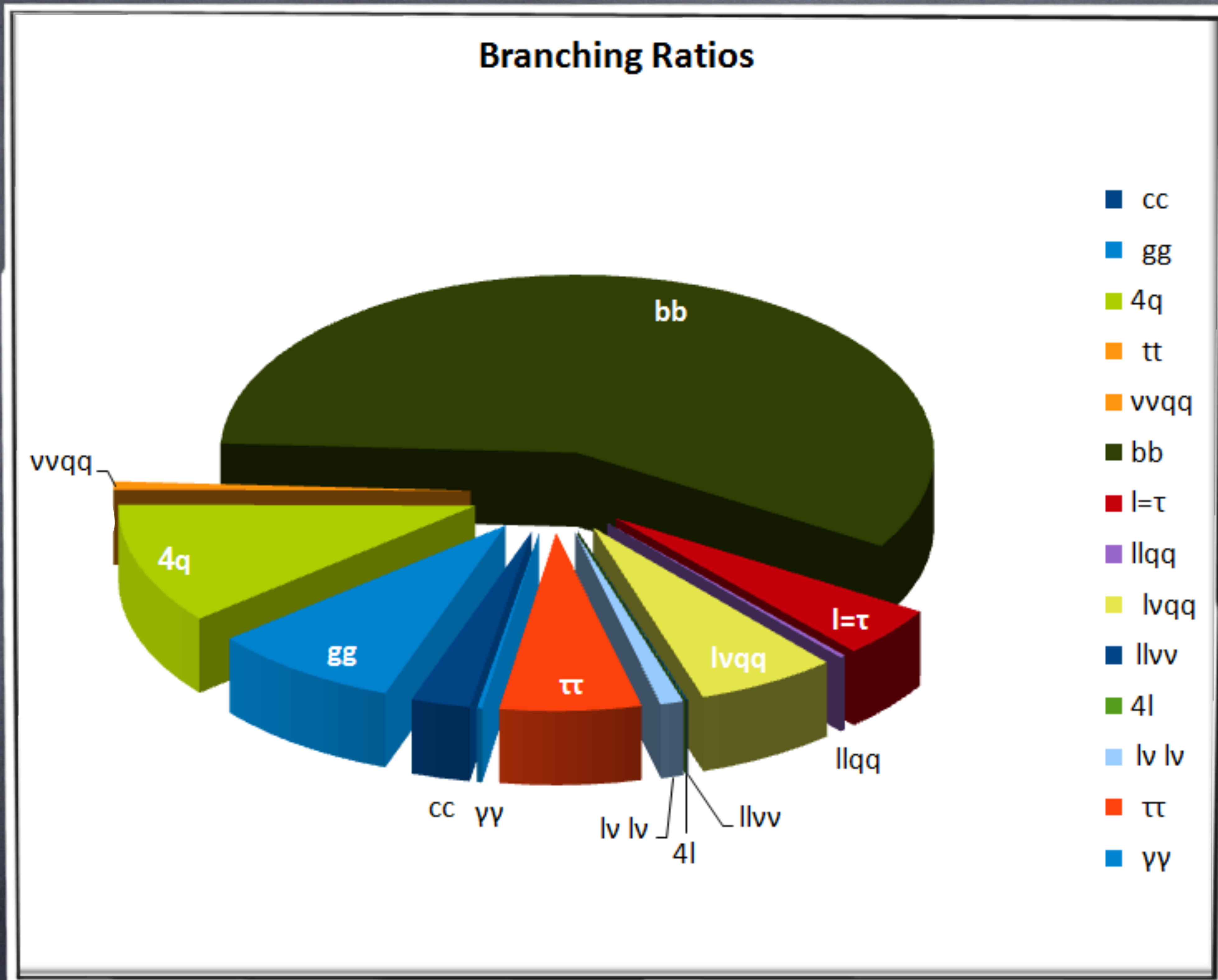
Higgs Decay Modes

- Once the Z and W channels are open (mH>120) 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



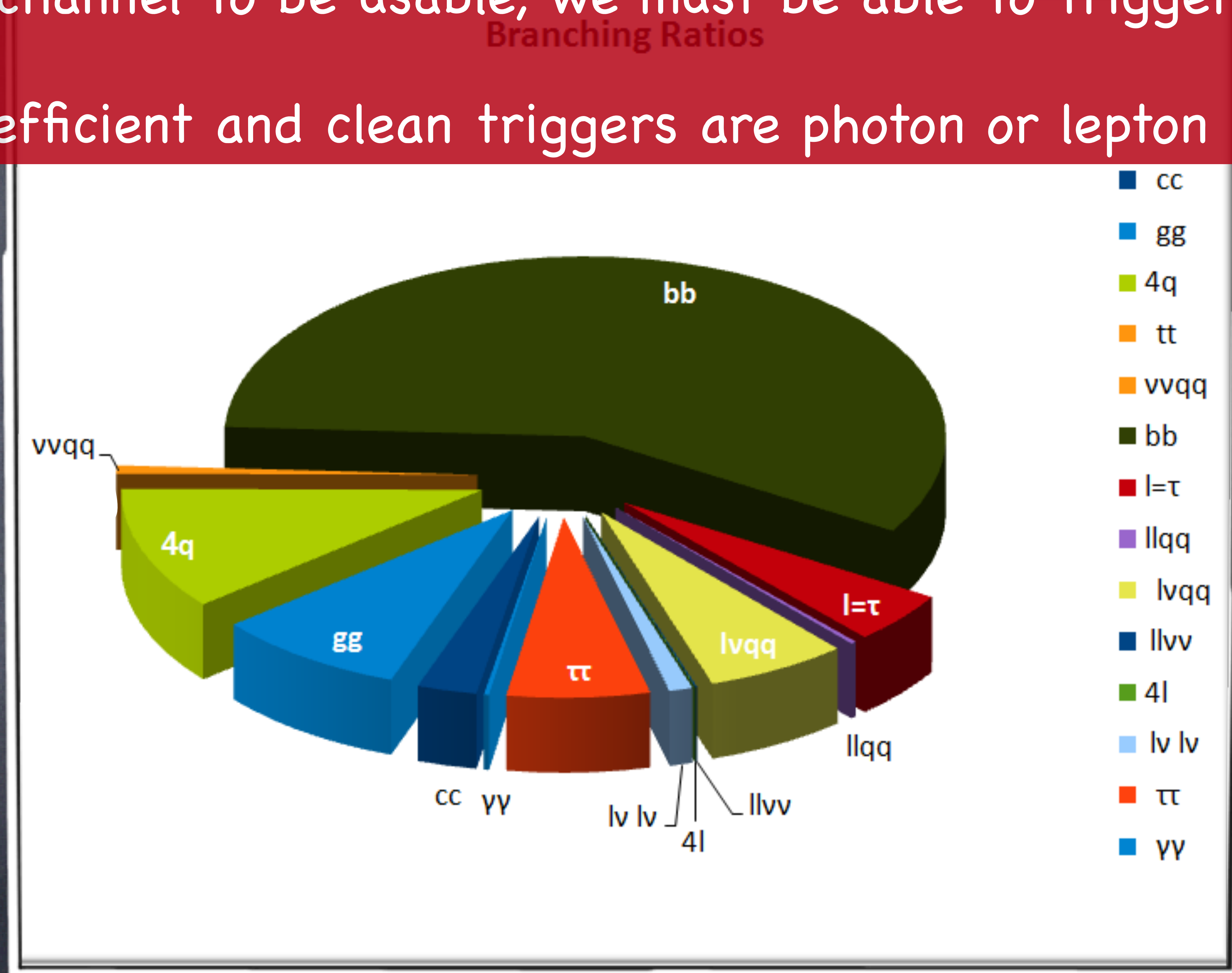
m_H=125 GeV



ATLAS EXPERIMENT

m_H=125 GeV

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



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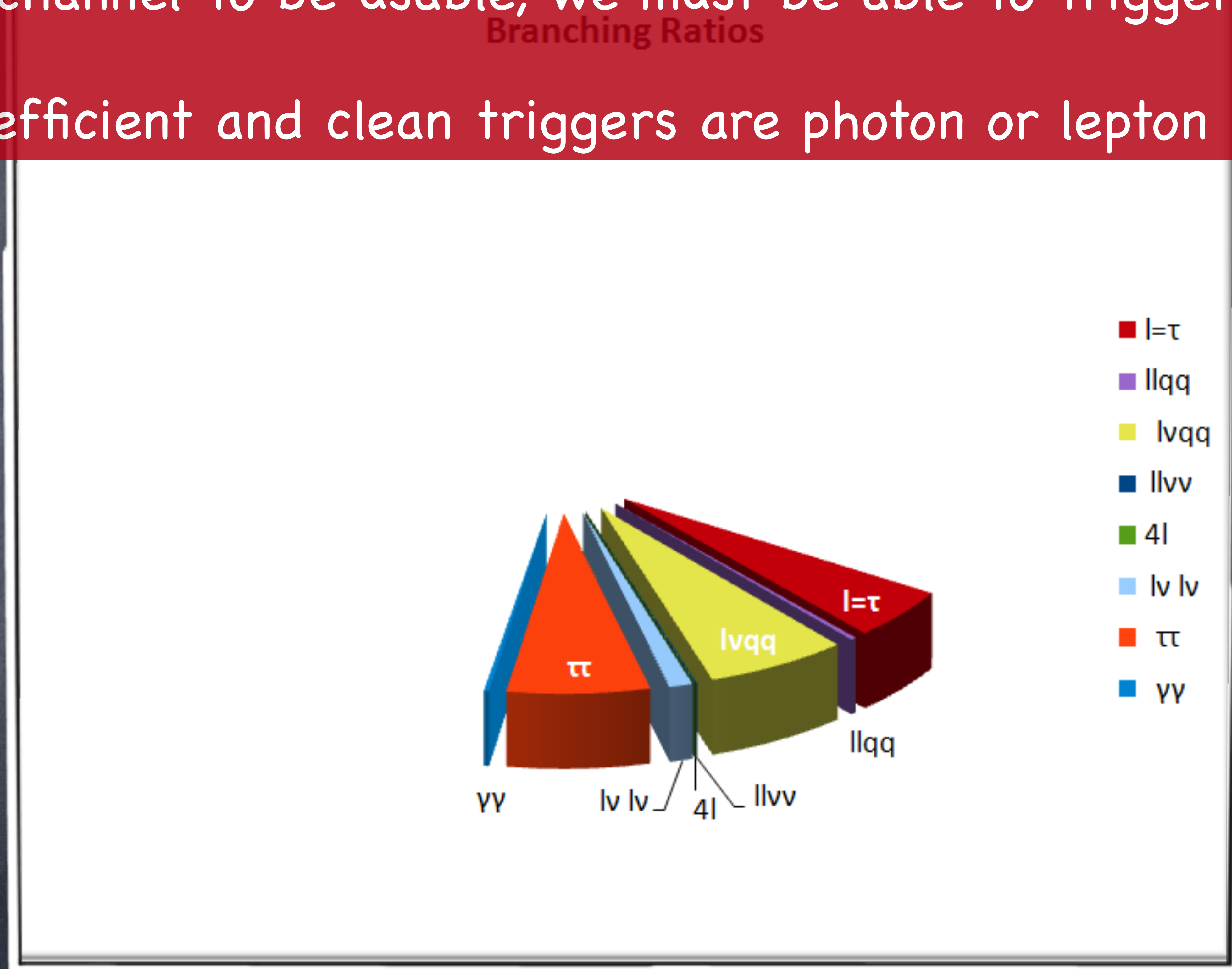
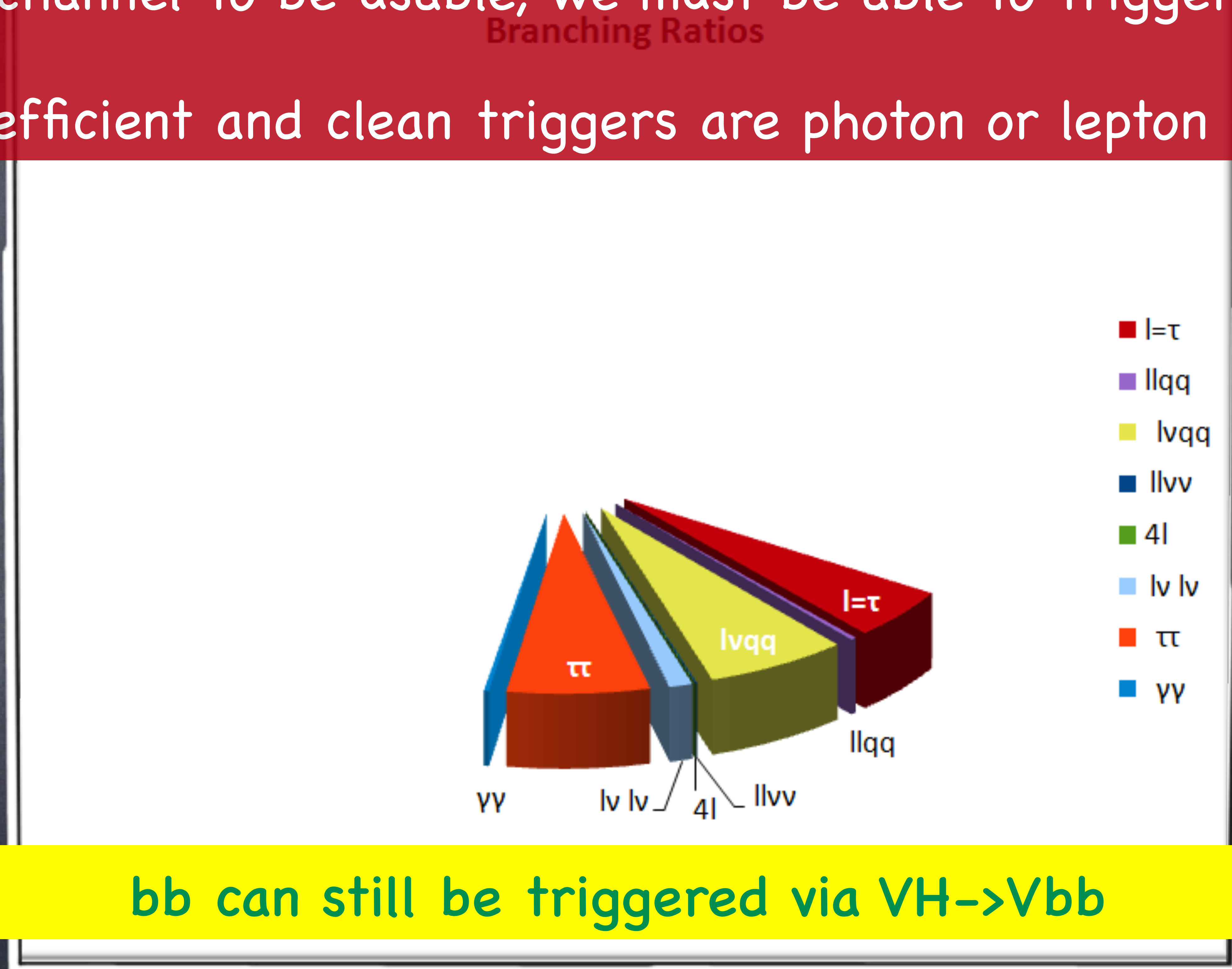


m_H=125 GeV

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



bb can still be triggered via VH->Vbb

Electroweak measurements are **Higgs backgrounds**

Number of events selected in full 2010-2012 dataset ($25\ fb^{-1}$)

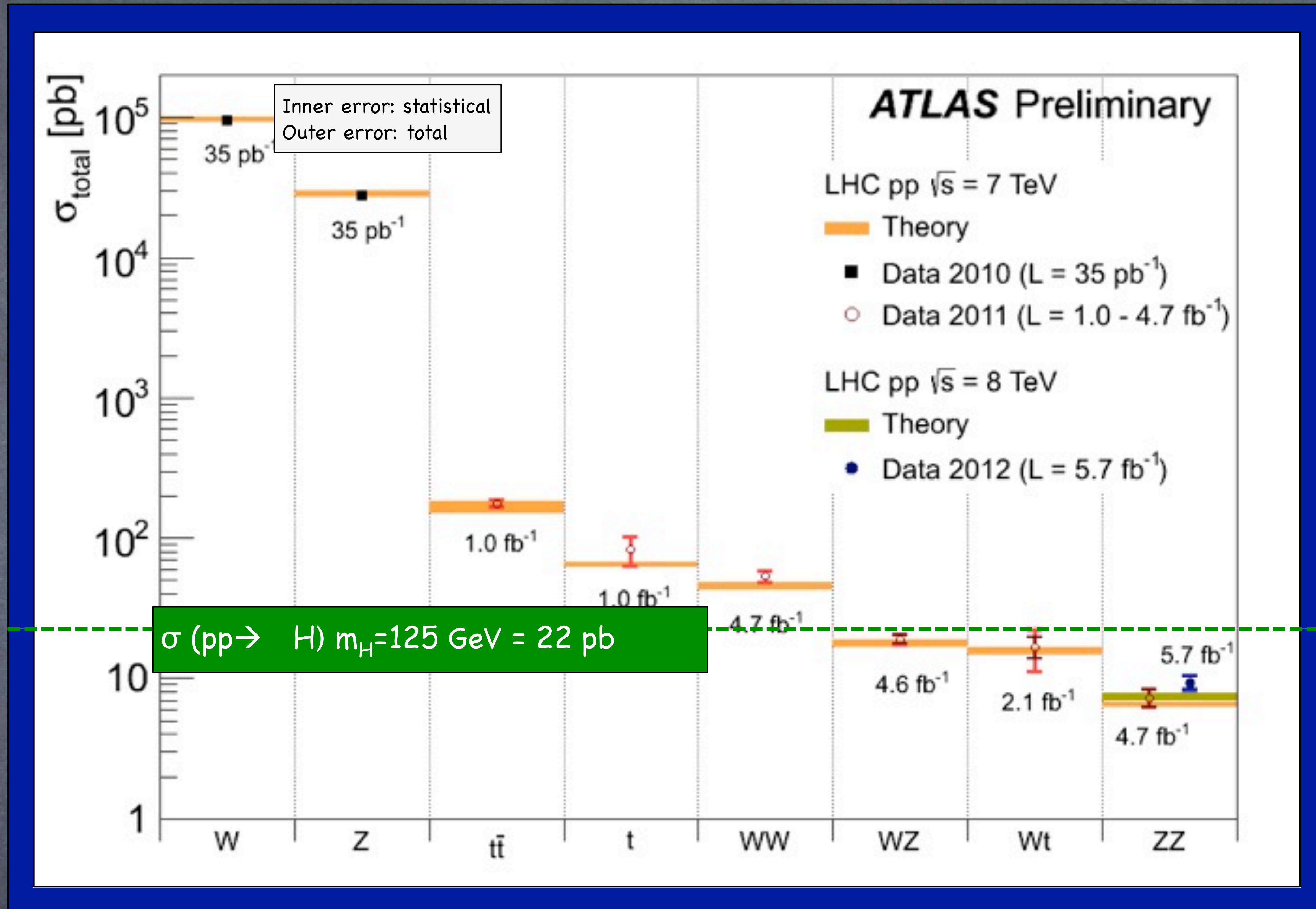
W -> ℓ ν ~ 100 M

Z->ll ~ 10 M

tt-> ℓ +X ~ 0.4 M (top factory)

SM Higgs ~400

~1 H->γγ (1H->4l) produced every 50' (14h) at 7×10^{33}



- 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)

m_H=125 GeV Channels Weight

$$w_i \simeq \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

- Probing mH=125 GeV
- Probing channels:

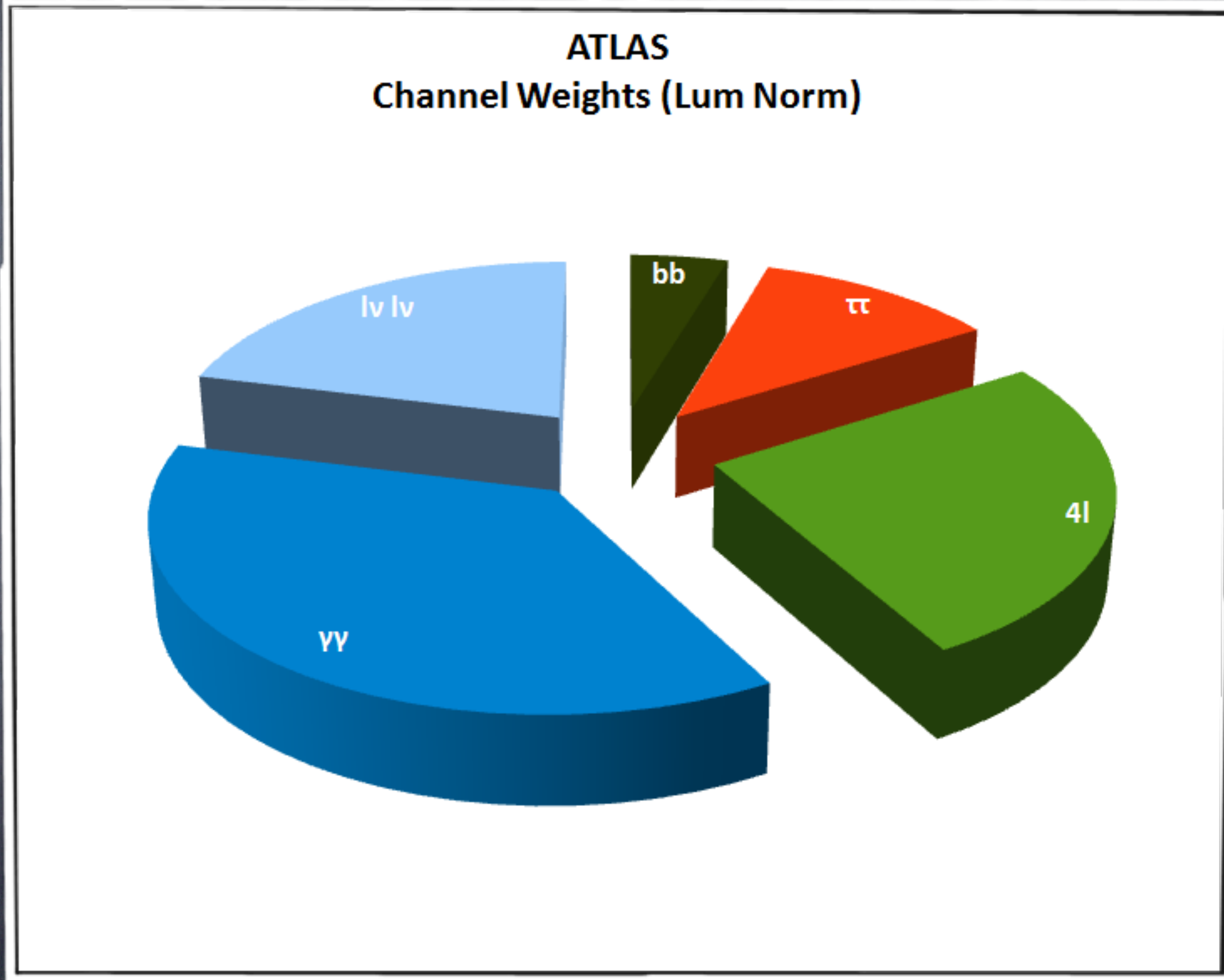
H-> $\gamma\ \gamma$

H->4l

H->WW->lvlv

VH-> Vbb,

H-> $\tau\ \tau$



H->γγ the "grey" became gold

$$w_i \simeq \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

- Probing mH=125 GeV
- Probing channels:

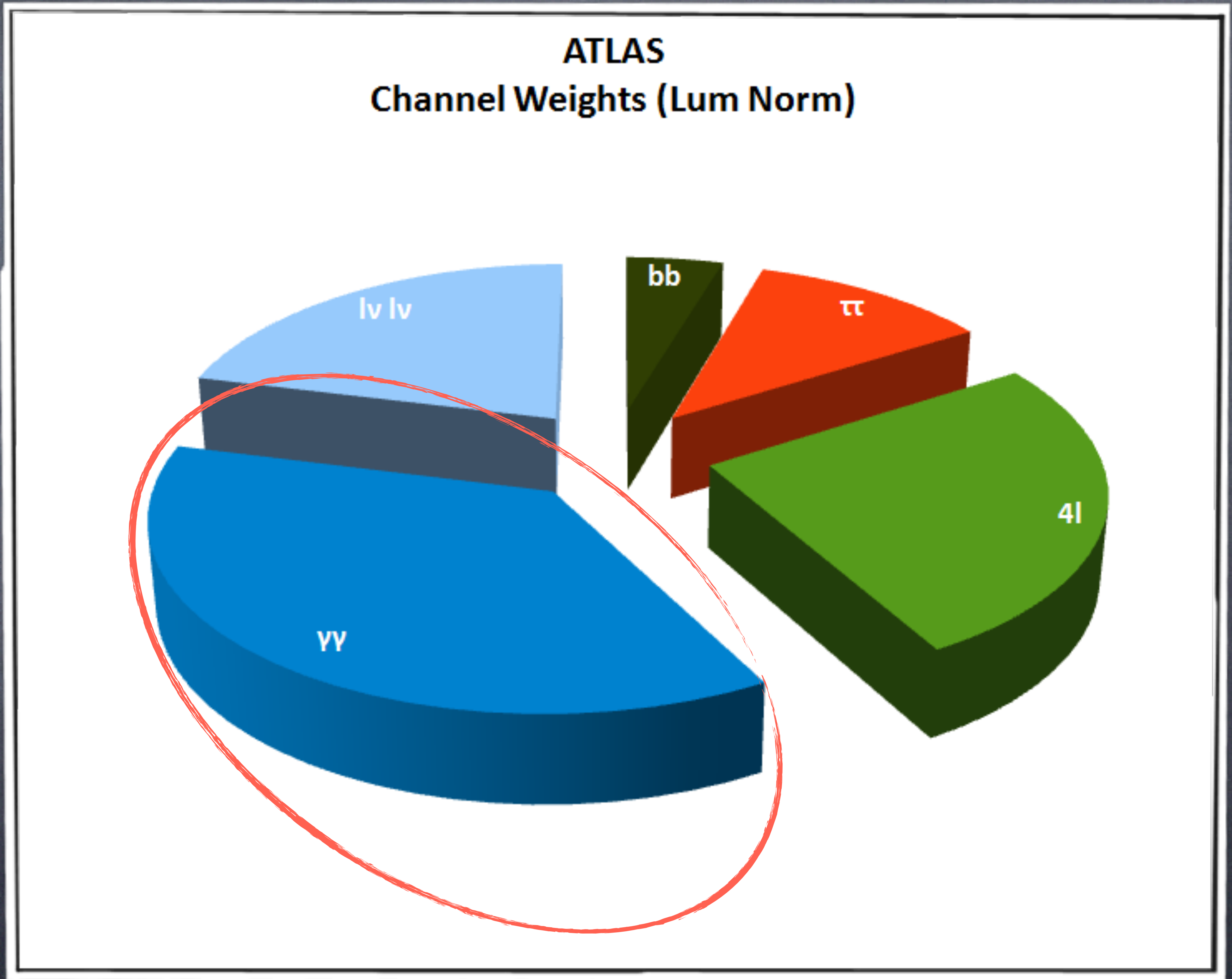
H-> γ γ

H->4l

H->WW->lvlv

VH-> Vbb,

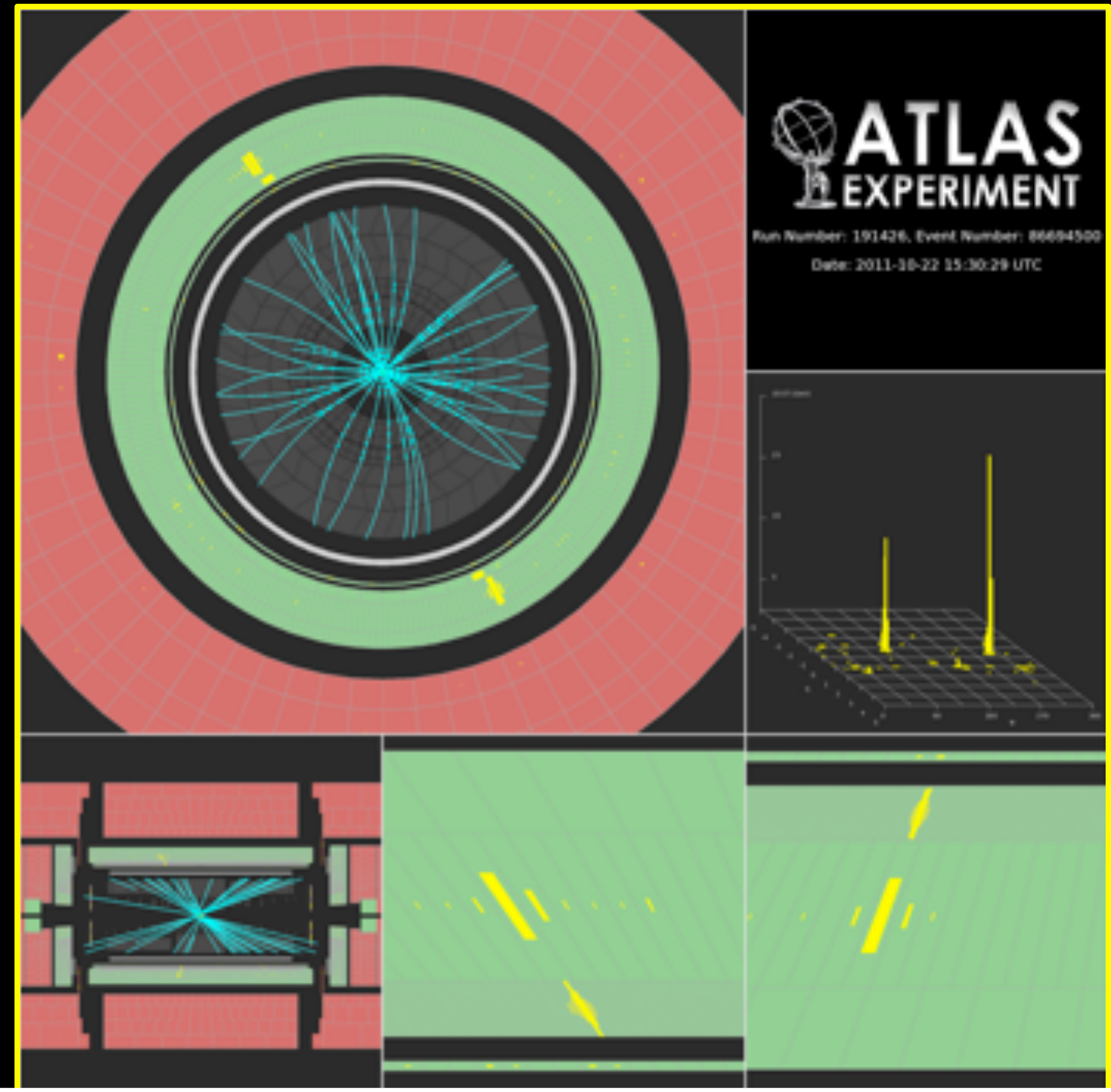
H-> τ τ



H->$\gamma\gamma$

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

E^T (γ 1, γ 2) > 40, 30 GeV



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

σxBR~50fb

@ mH=125

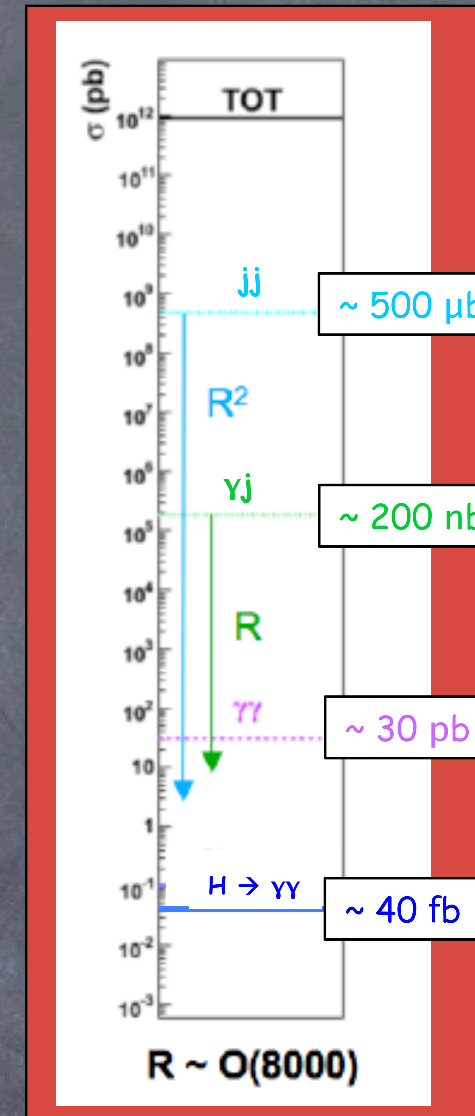
Prod	Luminosity	BG	Signal (126.5 GeV)	s/b
ggF, VBF, VH	4.9+13 fb^{-1}	$\gamma\gamma$,jj,γj	~2-30 (total ~300)	2%-20%

H->γγ Experimental Aspects

Needs a powerful γ/jet separation to suppress γj and jj background

with jet -> π^0 faking single γ

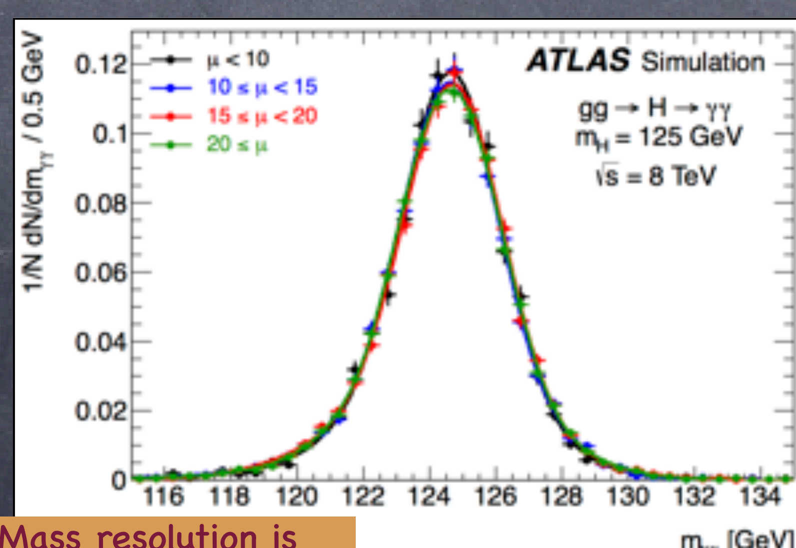
$$m^2_{\gamma_1\gamma_2} = 2E_{\gamma_1}E_{\gamma_2}\left(1 - cos\measuredangle(\gamma_1,\gamma_2)\right)$$



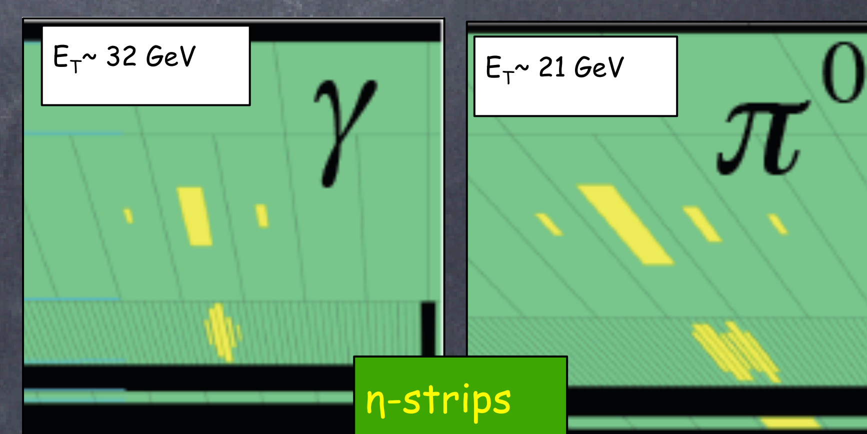
The fine longitudinal and lateral segmentation and pointing geometry of the ATLAS EM calorimeter enable good γγ angular separation and better Z-vertex determination. This is crucial in high pile up environment and in identifying fake photons from pions

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

Excellent mass resolution



Mass resolution is not affected by pile up



ATLAS EXPERIMENT

$H \to \gamma\gamma$

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

To increase sensitivity Data are split into 12 exclusive categories based on direction of photons (detector region) ,

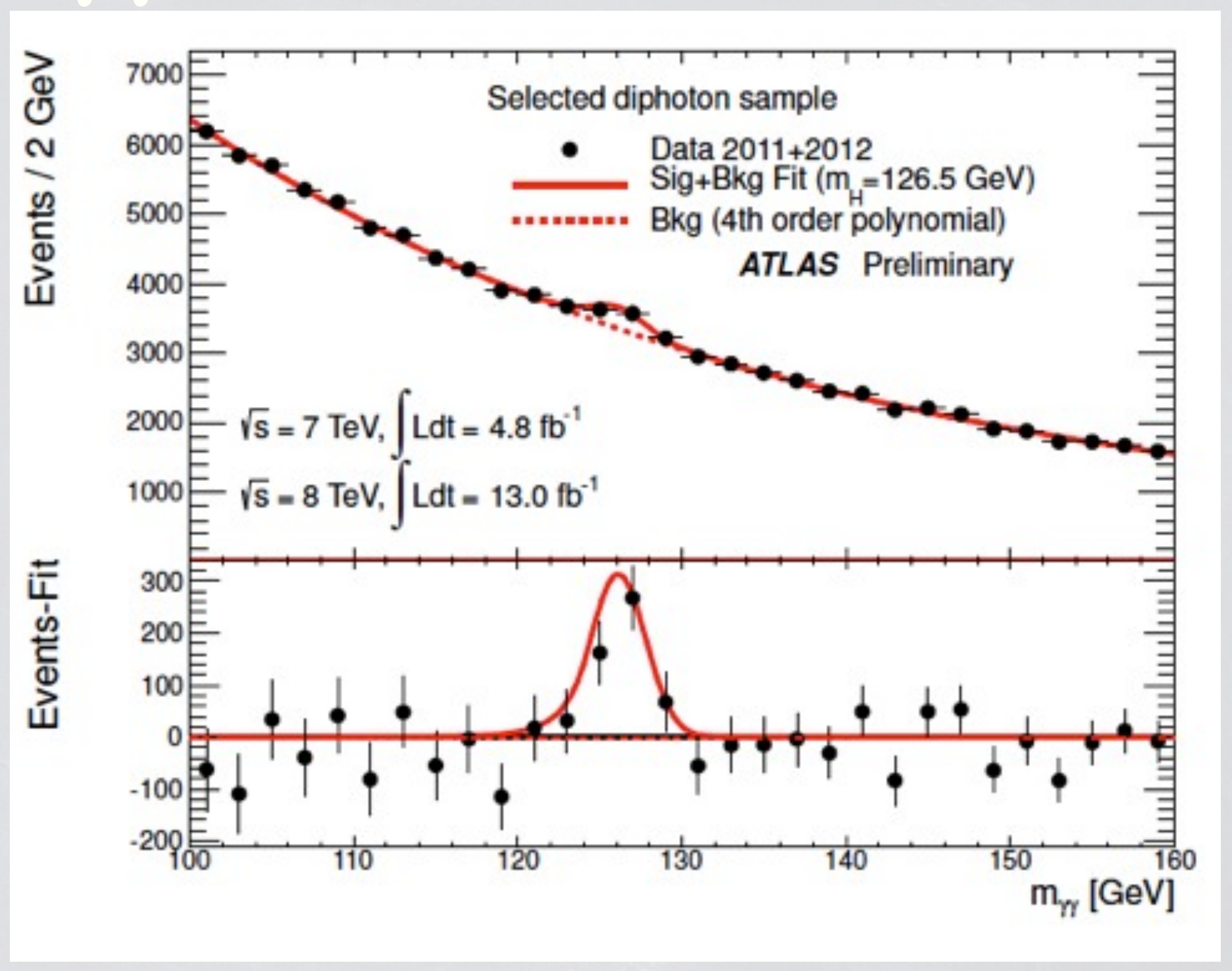
conversion mode (which affect $\gamma\gamma$ mass resolution, which is excellent)
and $p^T_{\gamma\gamma}$ perpendicular to $\gamma\gamma$ thrust axis

High mass di-jet - High mass dijet (400 GeV) with large η separation (targetting VBF)

1-lepton - target W/Z/ttH

Low mass di-jet - Low mass dijet (60<mjj<100 GeV) (targetting W/ZH)

New 2012



- $m_{\gamma\gamma}$ was fit (per category) with exponential or polynomial functions for background plus a sum of Crystal Ball and Gaussian (tails) for signal.
- Background was fitted from data

H->γγ

After all selections with *TeV & 13 fb-1 @126 GeV:

77430 events observe

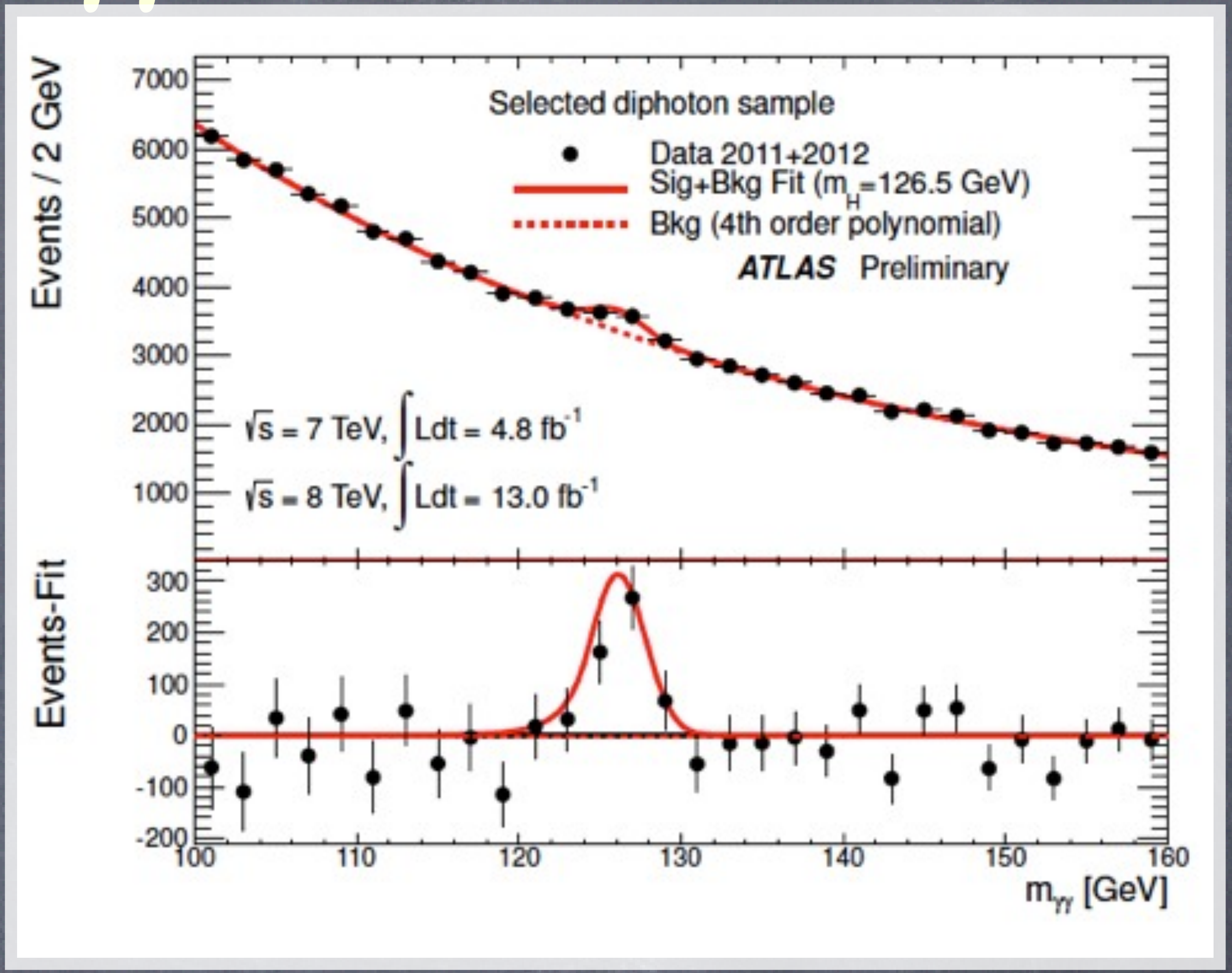
Expected signal 250 Eventsd (10% from VBF/VH)

~8280 BG events expected in signal region (inclusive)

~8800 observed (inclusive)

S/B~3% inclusive

(20% for VBF)



Overall mass resolution 1.6 GeV

Photon Efficiency ~85%

BG composition:

75%γγ, 22%γj, 3%jj

Exclusion: CLs

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

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

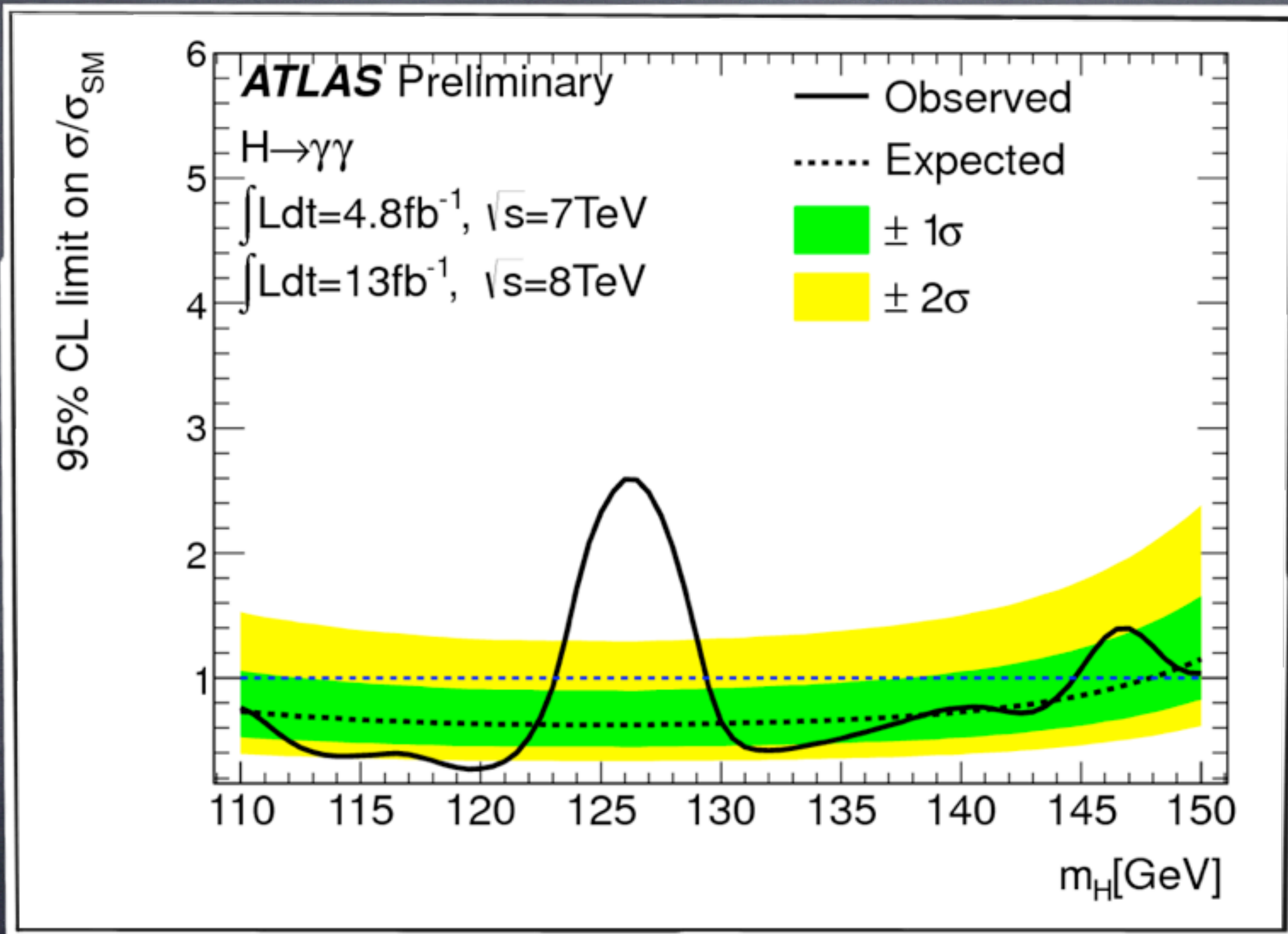
->If CLs<5% the signal hypothesis is excluded at the 95% CL

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

-> If $\mu_{up}<1$ => $\sigma(m_H)<\sigma_{SM}$

=>m_H is excluded at the 95% Confidence Level

γγ Exclusion



Discovery p_0

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

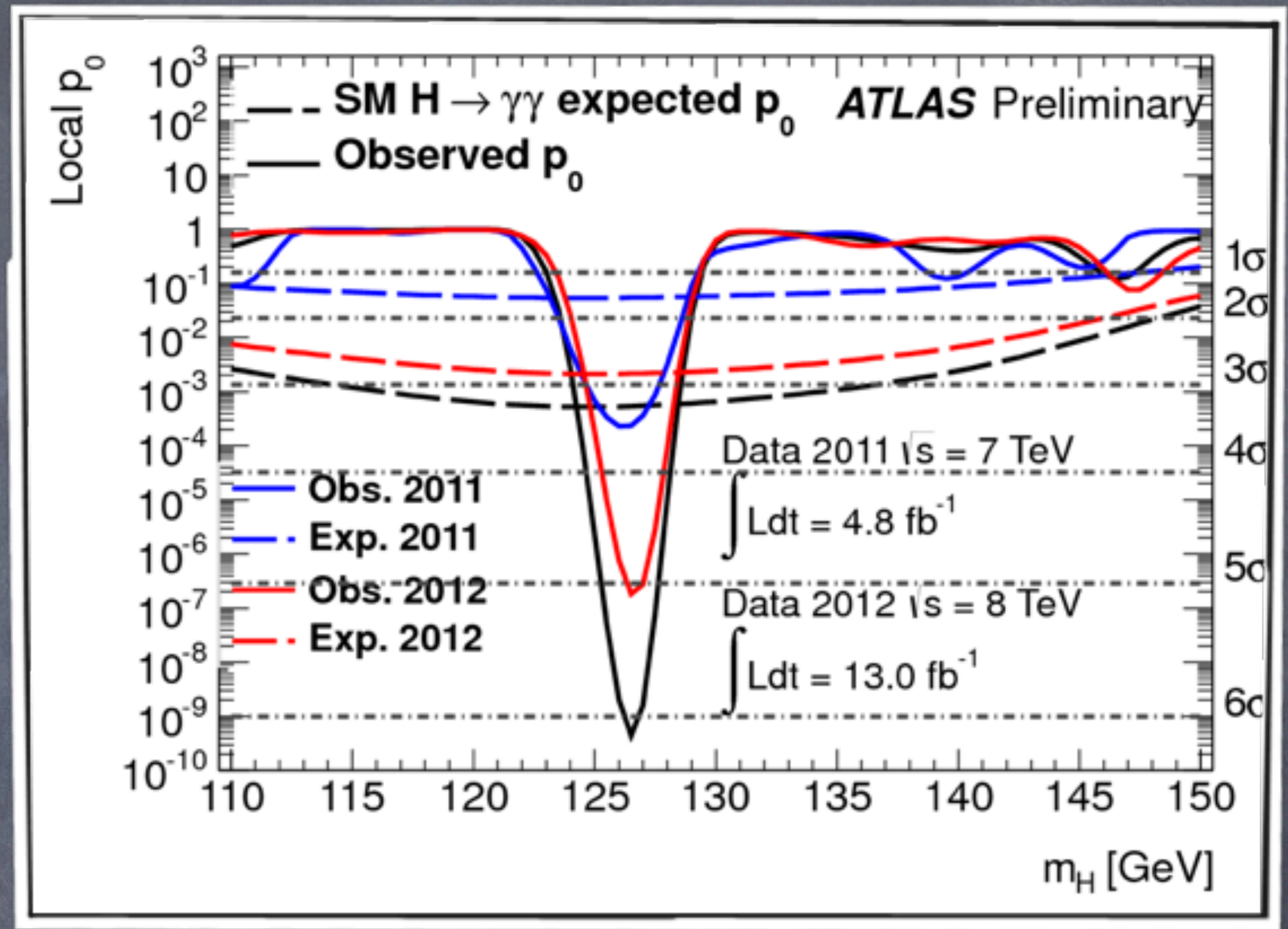
->p_0 measures the compatibility of the data with the NO-HIGGS hypothesis.

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

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

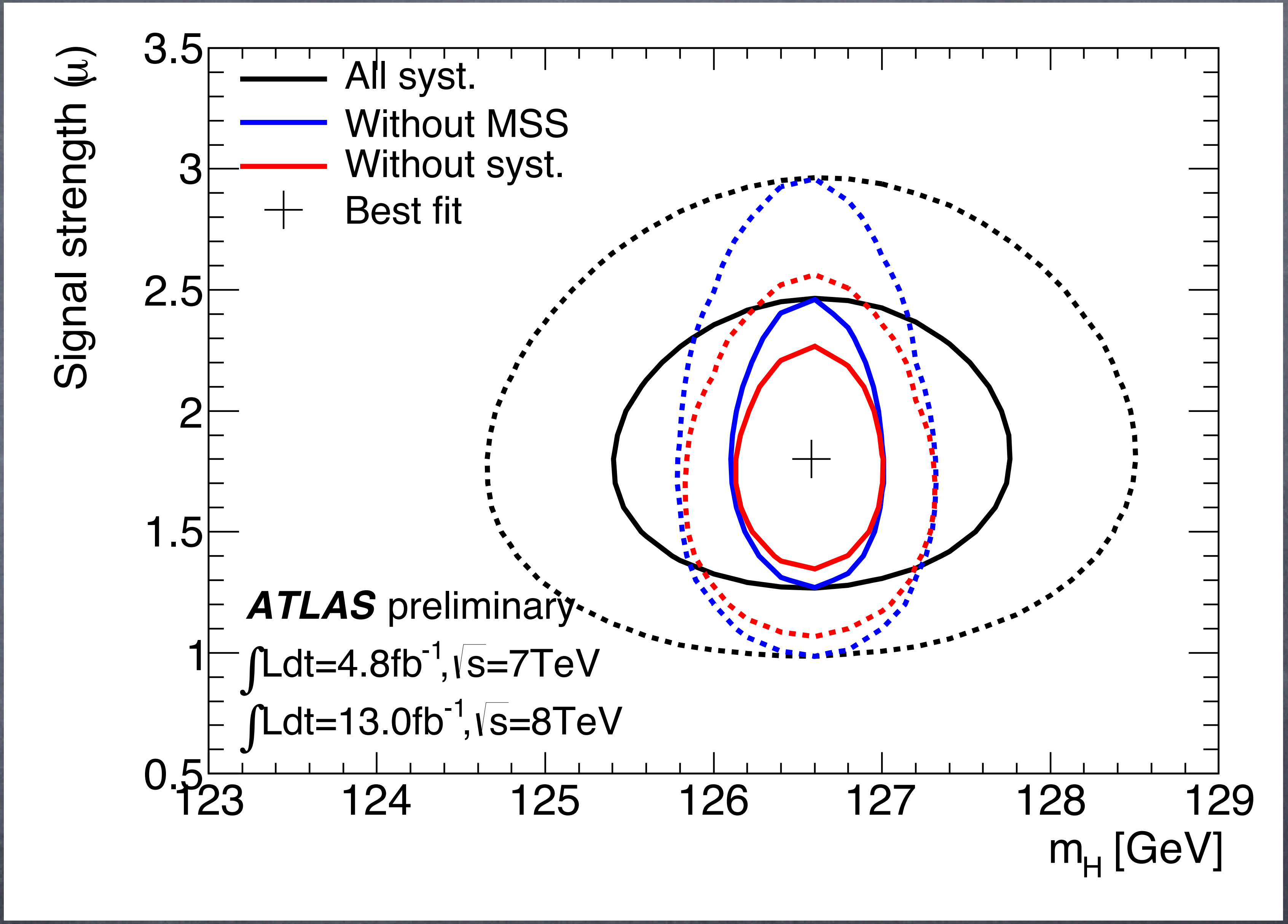
γγ p0

	Mass @ peak	Exp.	Obs.
2011	126	1.6σ	3.3σ
2012	126.5	2.9σ	5.1σ
Comb.	126.5	3.3σ	6.1σ



Global significance (LEE) is 5.4σ confirming the discovery of a new particle

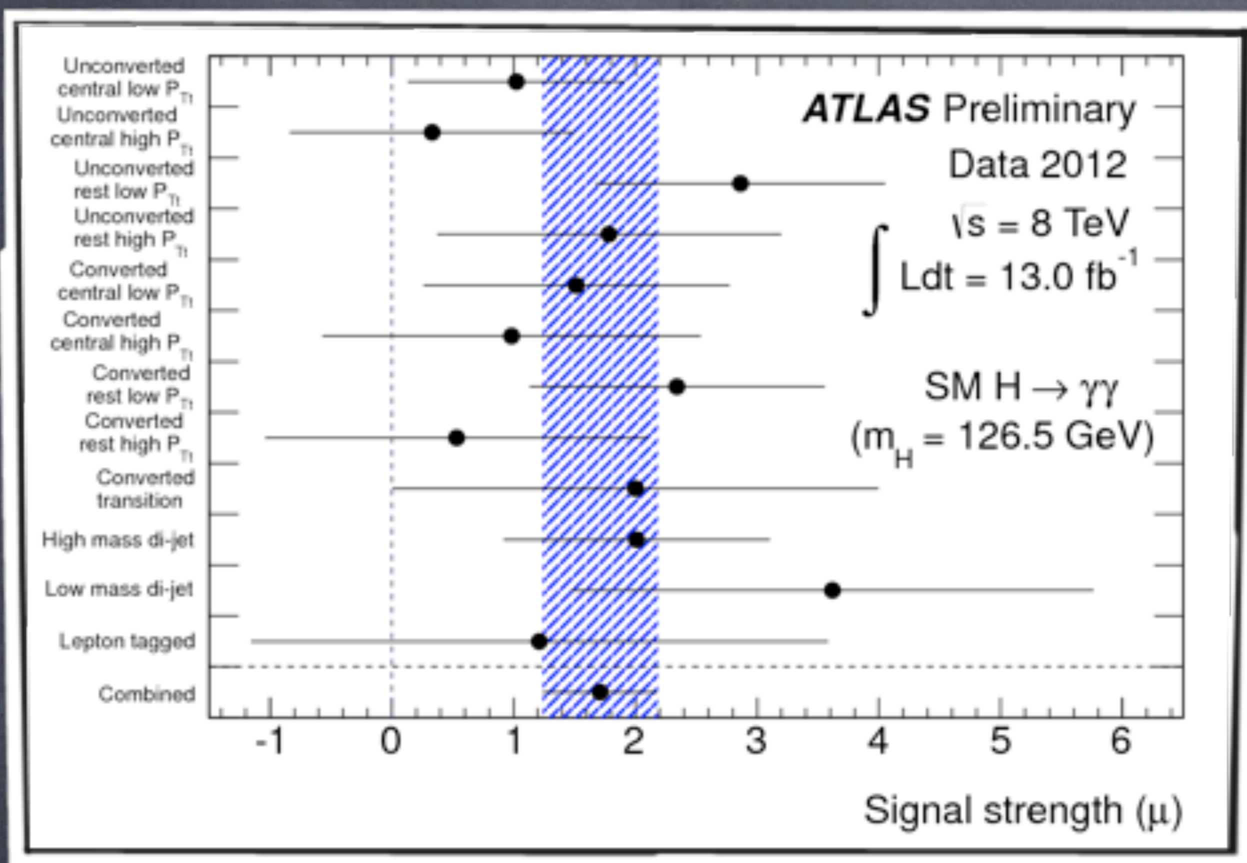
Mass Measurement

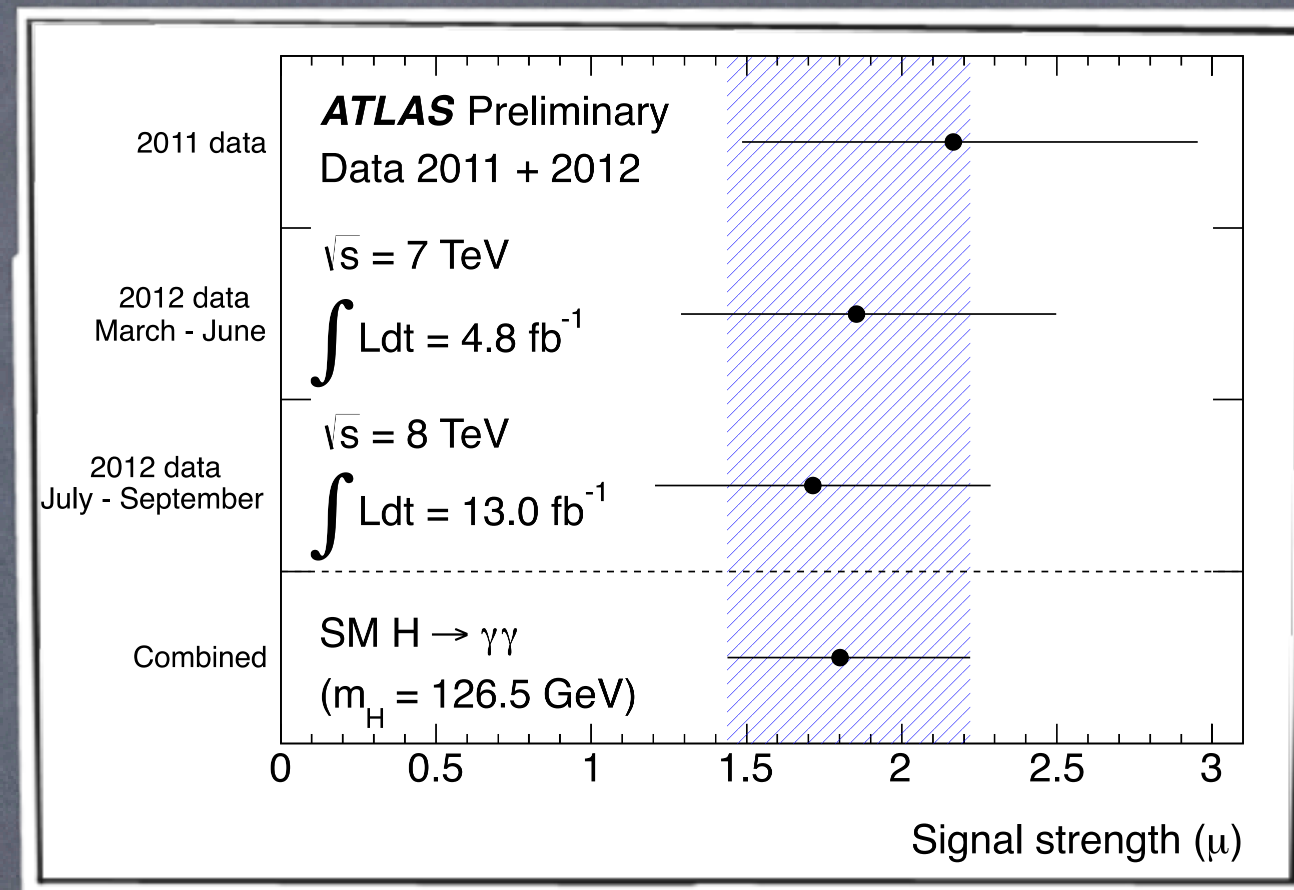


$$m_H = 126.6 \pm 0.3\ (stat) \pm 0.7\ (syst)\ \text{GeV}$$

γγ Signal Strength

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





- Best fit mass 126.6 GeV

$$\hat{\mu} = 1.8 \pm 0.3\ (stat)^{+0.29}_{-0.15} (syst)^{+0.21}_{-0.14}\ (theory)$$

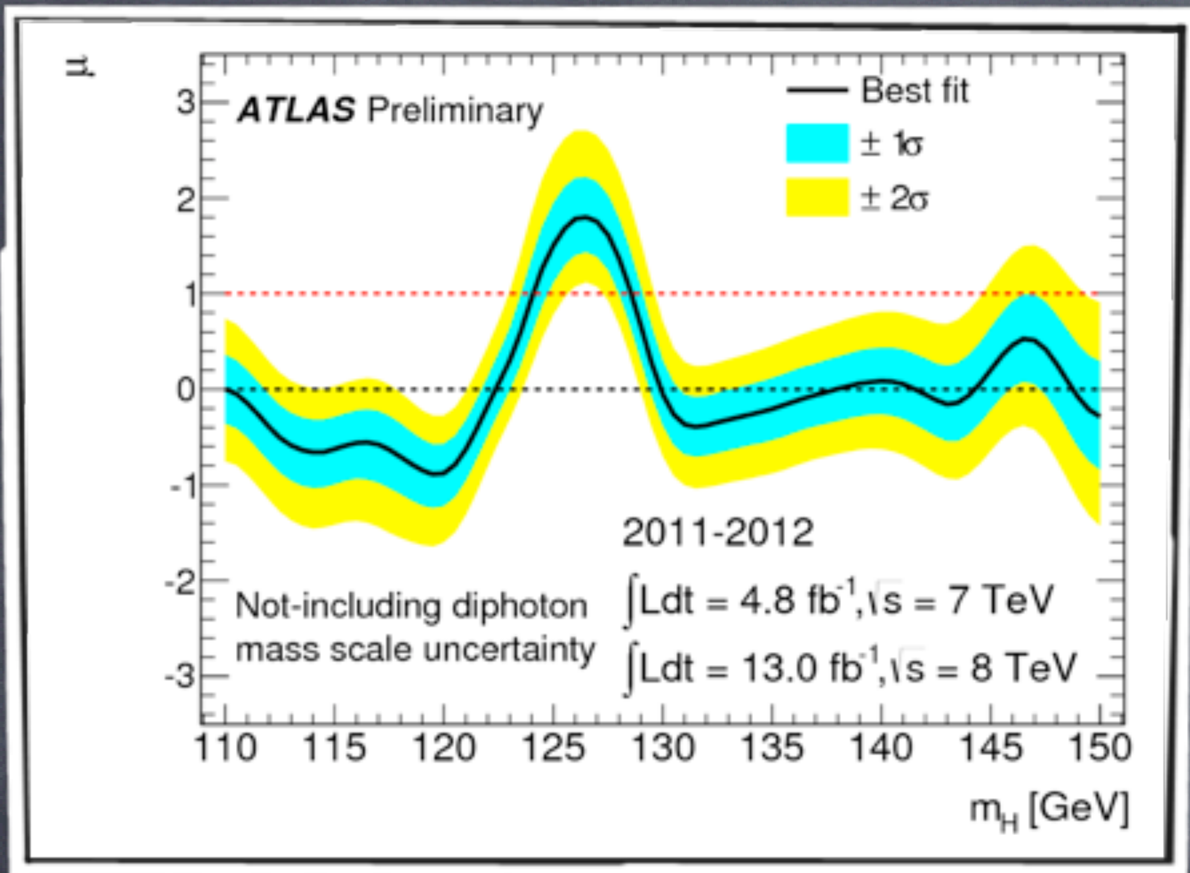
Theory contains QCD scale, PDF+αs and BR unc.

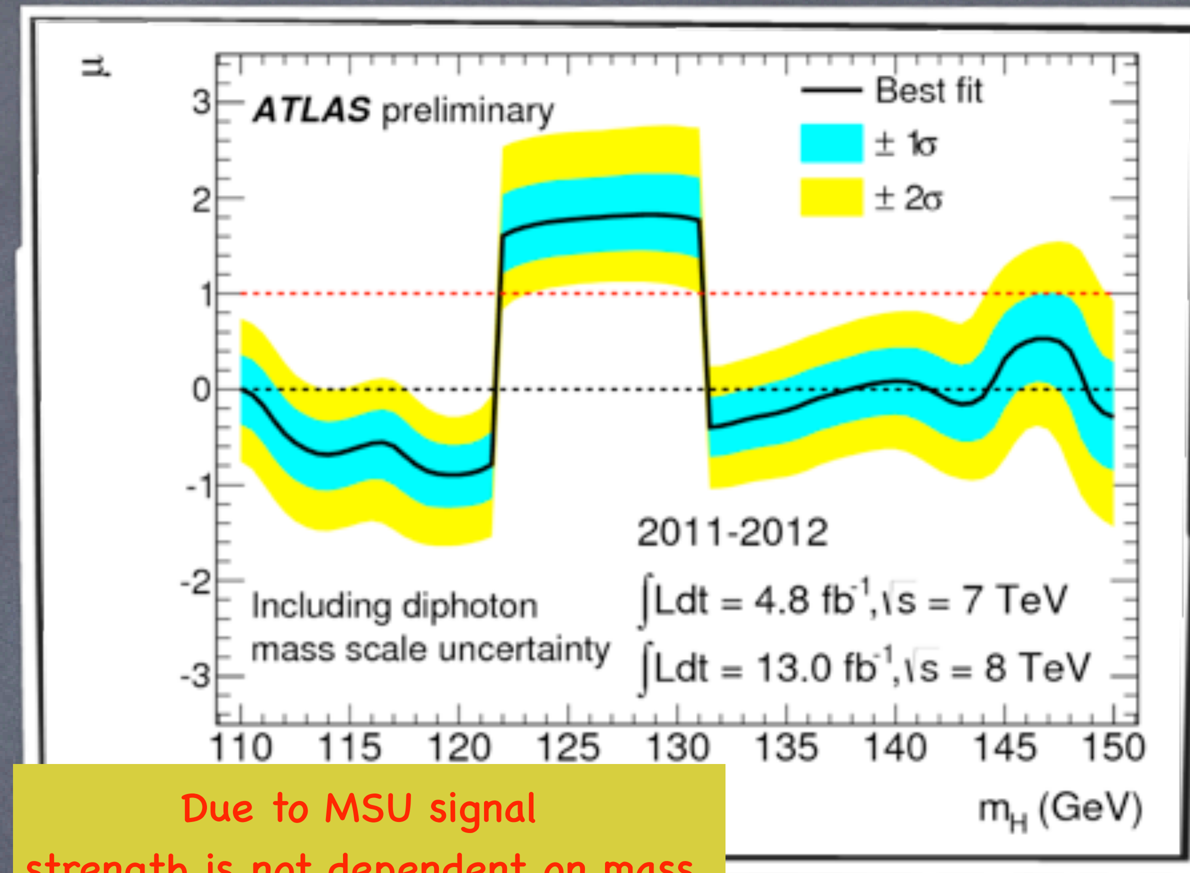
The probability for SM Higgs to fluctuate to the observed μ is 2.4σ

ATLAS EXPERIMENT

Diphoton Mass Scale Uncertainty

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



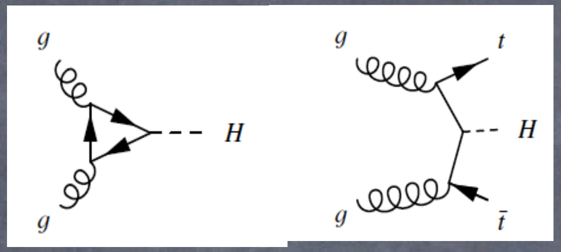


Due to MSU signal strength is not dependent on mass

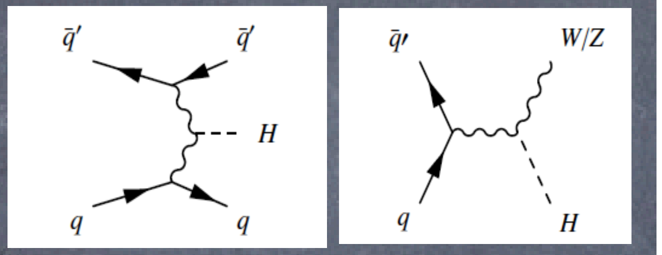
- The statistical significance of the peak being at the level of ~ 6 sigma, and the overall uncertainty at the level of 650 MeV
- The Likelihood has a second maximum, around mu=0., occurs when the hypothesized pdf is too far away from the data bump and the diphoton mass scale uncertainty nuisance parameters cannot make up for it.

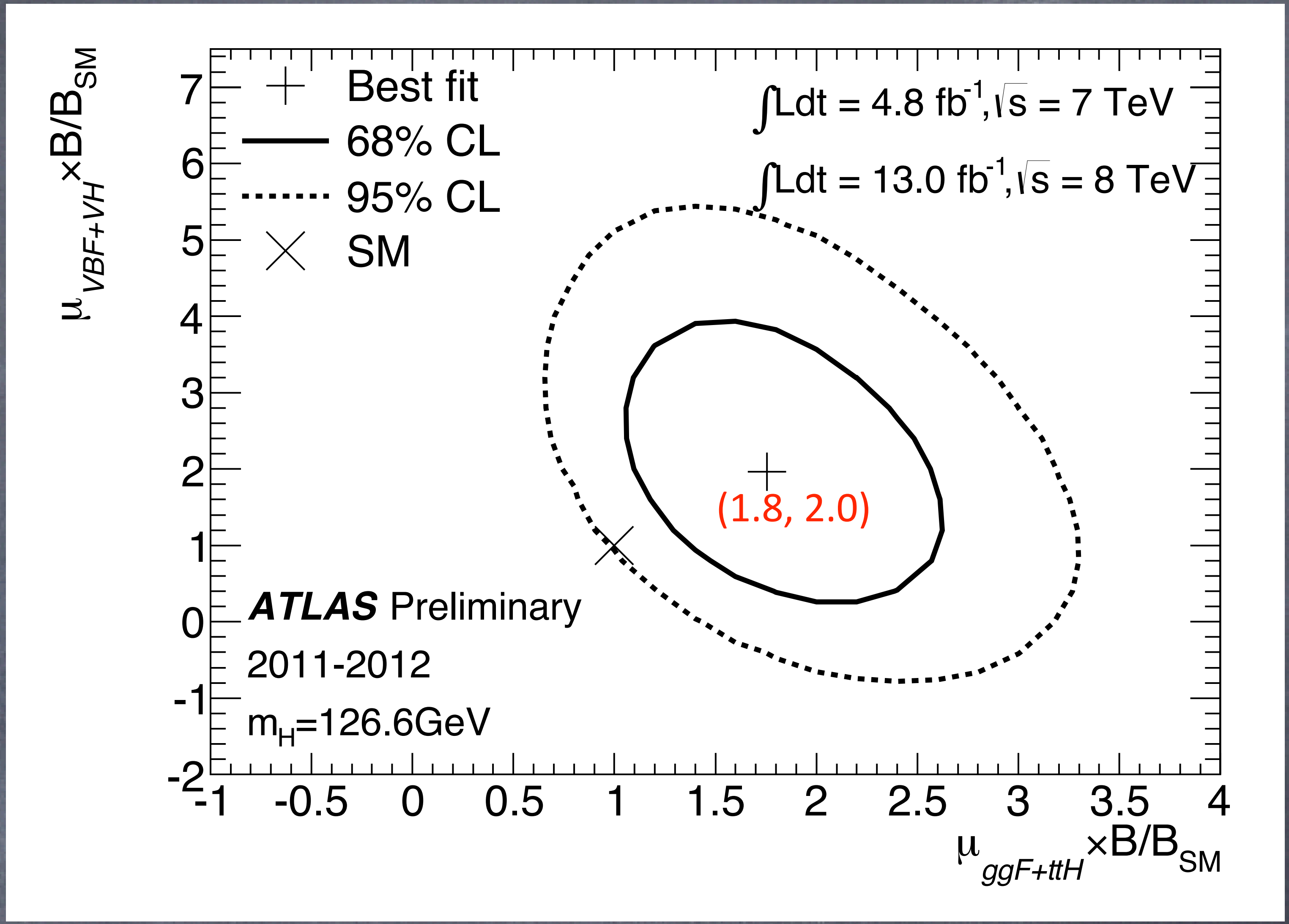
γγ Signal Strength

Fermion couplings ggF+ttH



Vector Boson coplings VBF+VH

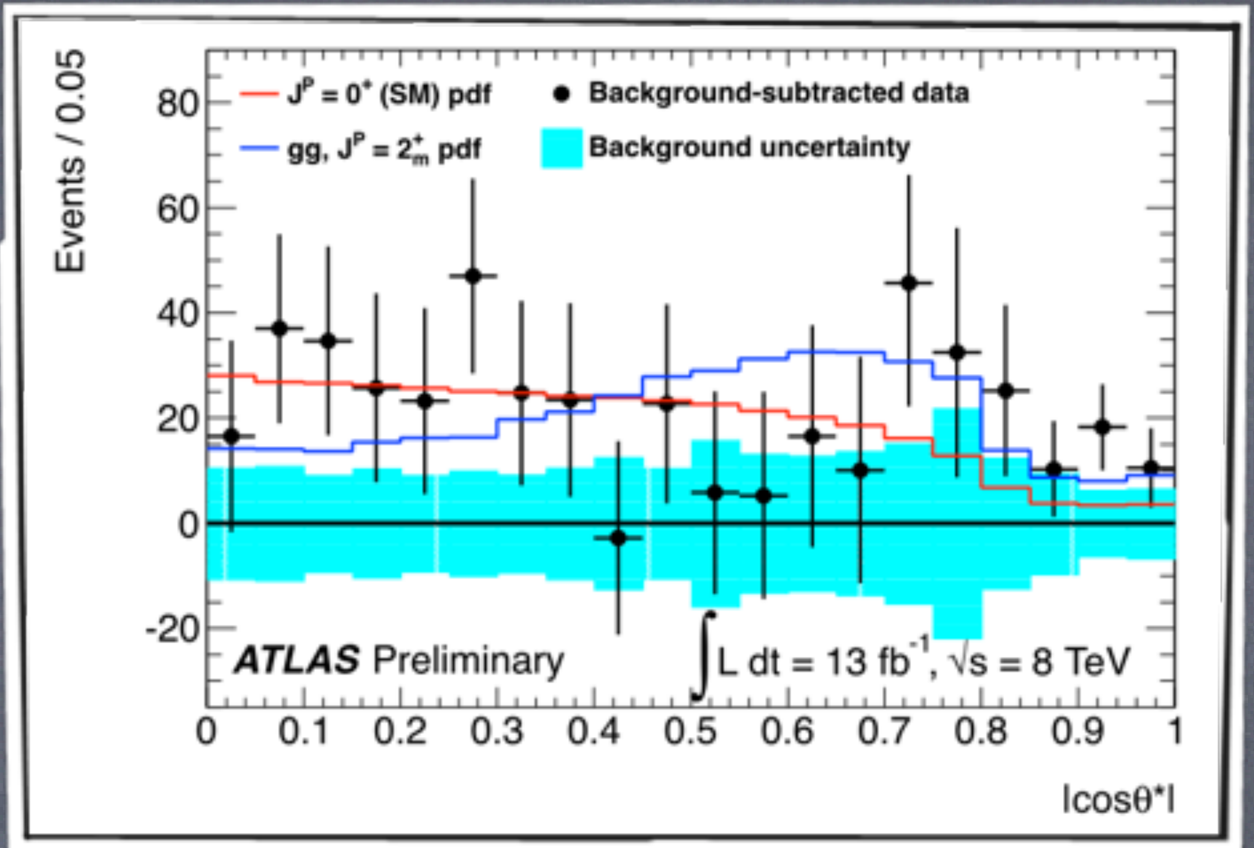


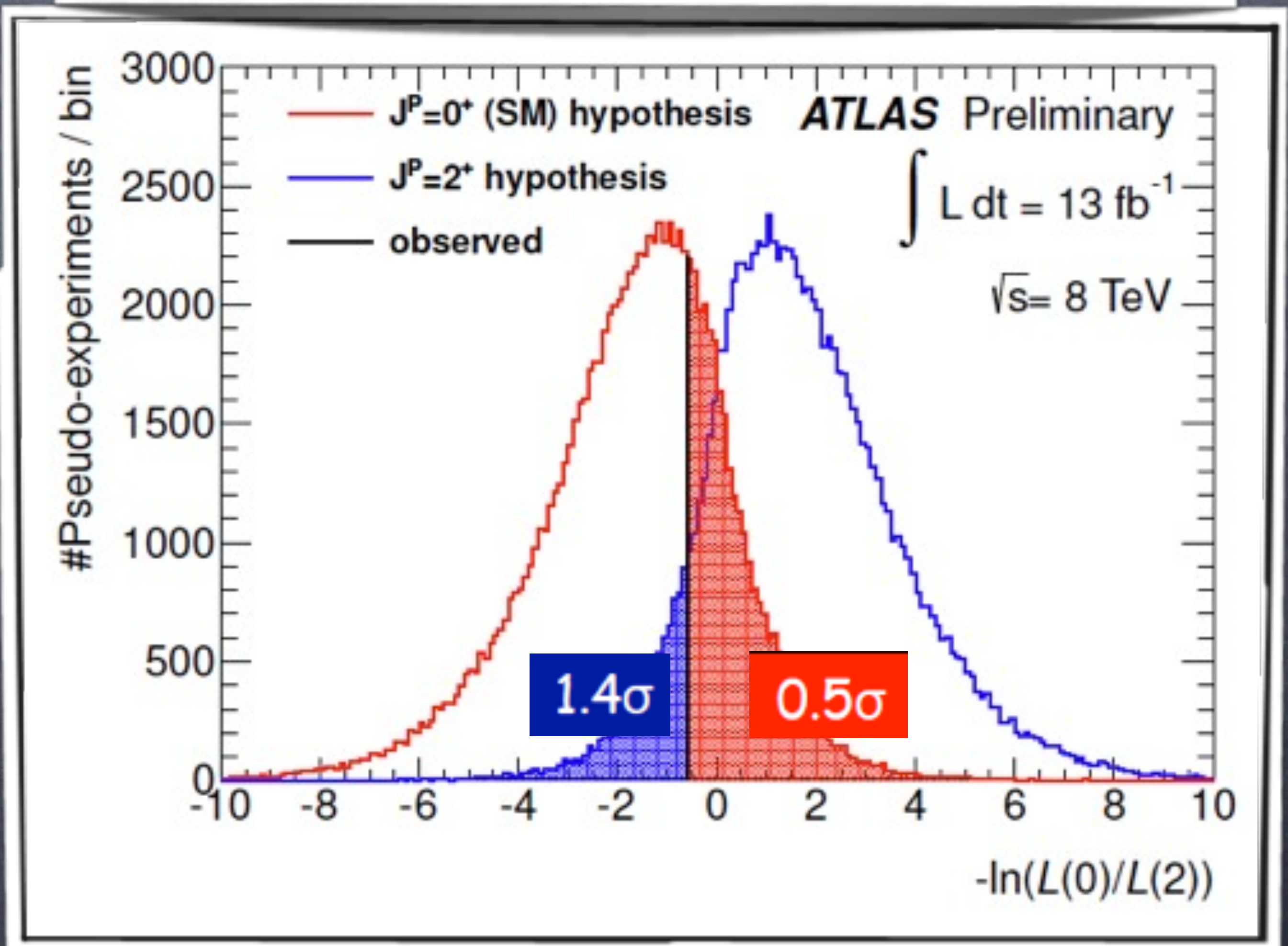


	Value	Statistic uncertainty	Systematic uncertainty	Theoretical uncertainty
$\mu_{ggF+ttH} \times B/B_{SM}$	1.8	±0.4	±0.2	±0.2
$\mu_{VBF} \times B/B_{SM}$	2.0	±1.2	±0.6	±0.3
$\mu_{VH} \times B/B_{SM}$	1.9	±2.5	±0.6	±0.4

γγ Spin

- Using the angular distribution of the photons in the helicity ref frame (Collins-Soper)
- Spin 0 hypothesis
  $dN/d\cos\theta^* \sim$ flat (before cuts)
- Spin 2 hypothesis
  $dN/d\cos\theta^* \sim 1+6\cos^2\theta^*+\cos^4\theta^*$
- We find a slight preference for spin 0 over spin 2 (graviton-like particle)





The Golden Channel H->ZZ->4l

$$w_i \simeq \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

- Probing mH=125 GeV
- Probing channels:

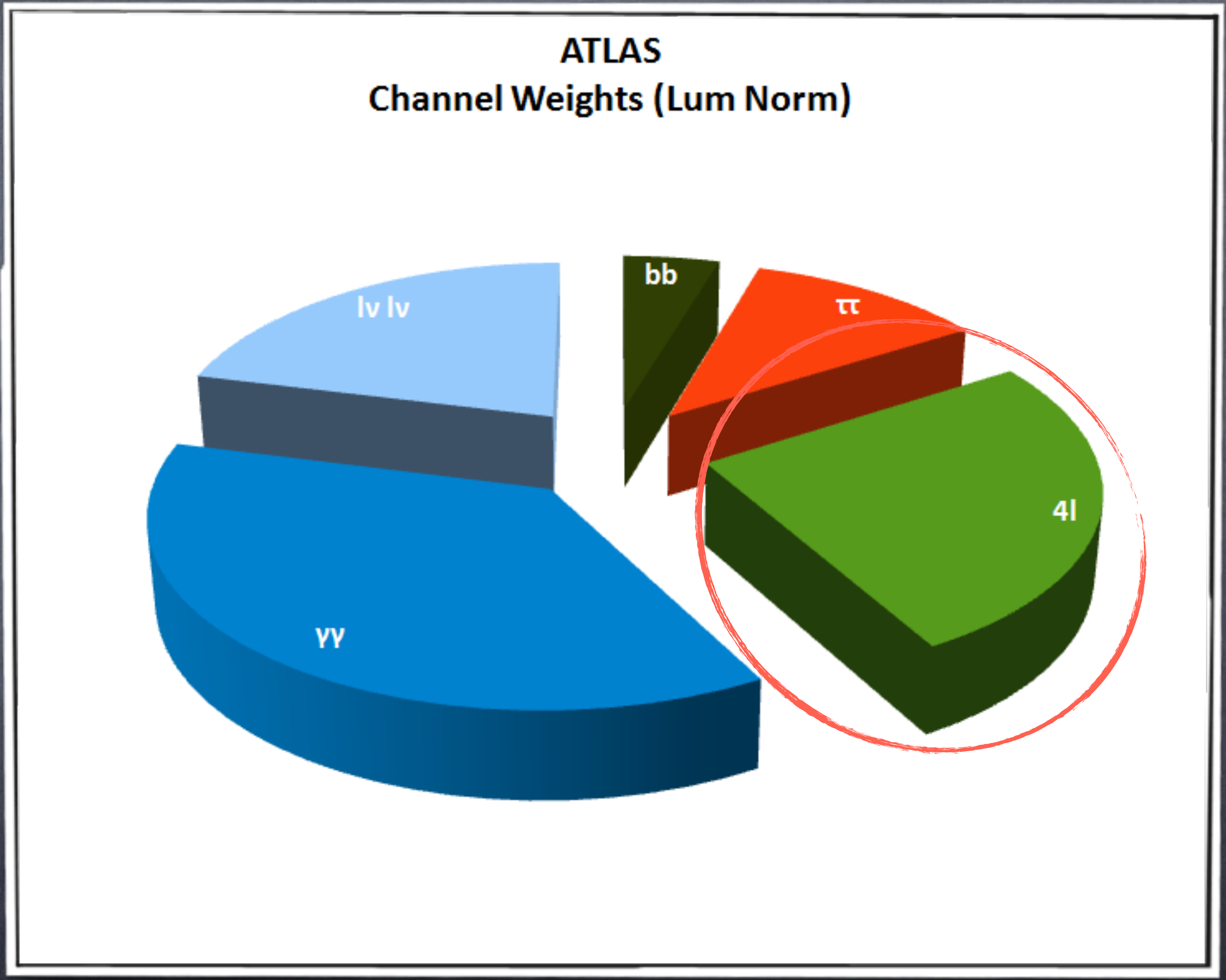
H-> $\gamma\ \gamma$

H->4l

H->WW->lvlv

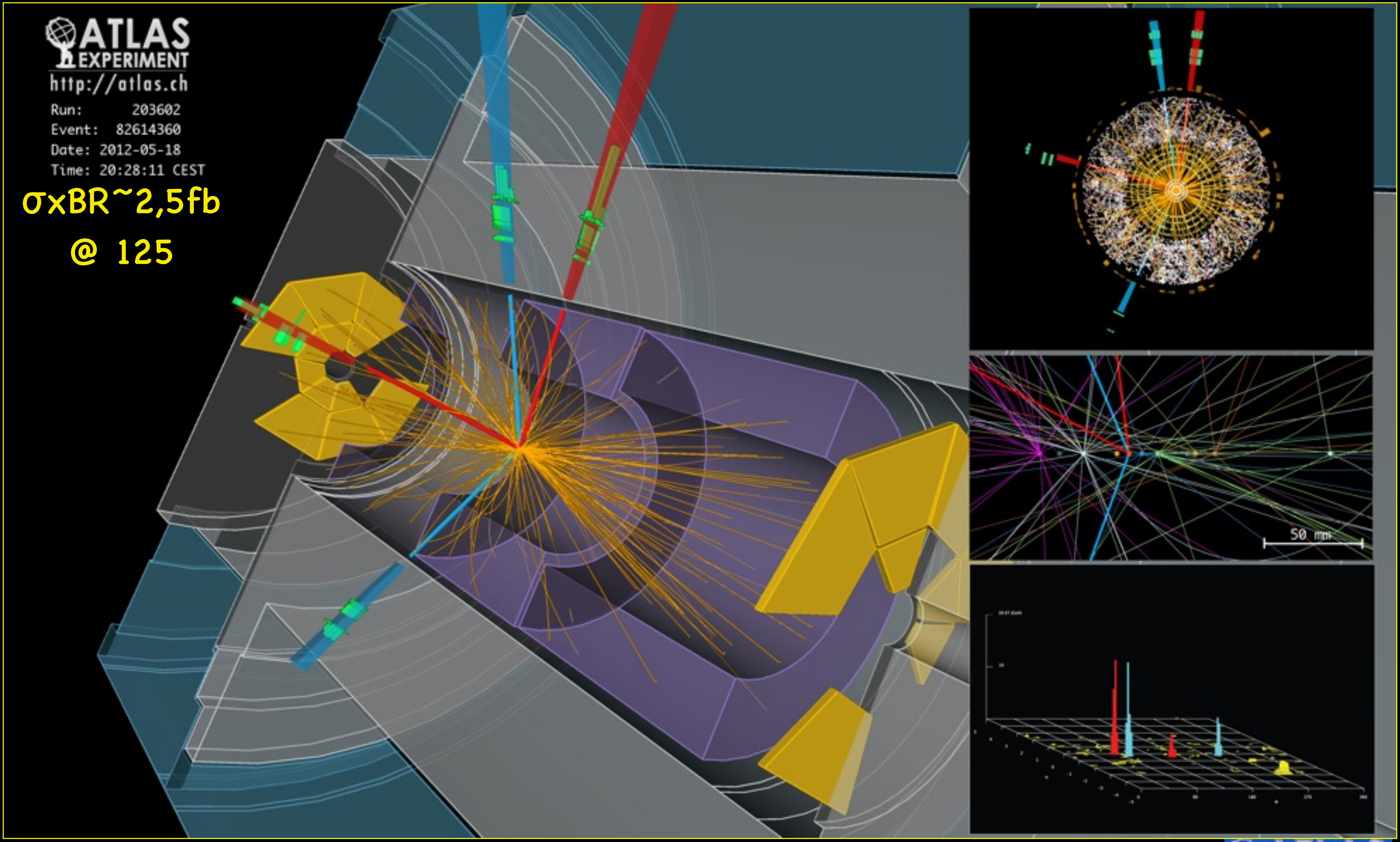
VH-> Vbb,

H-> $\tau\ \tau$



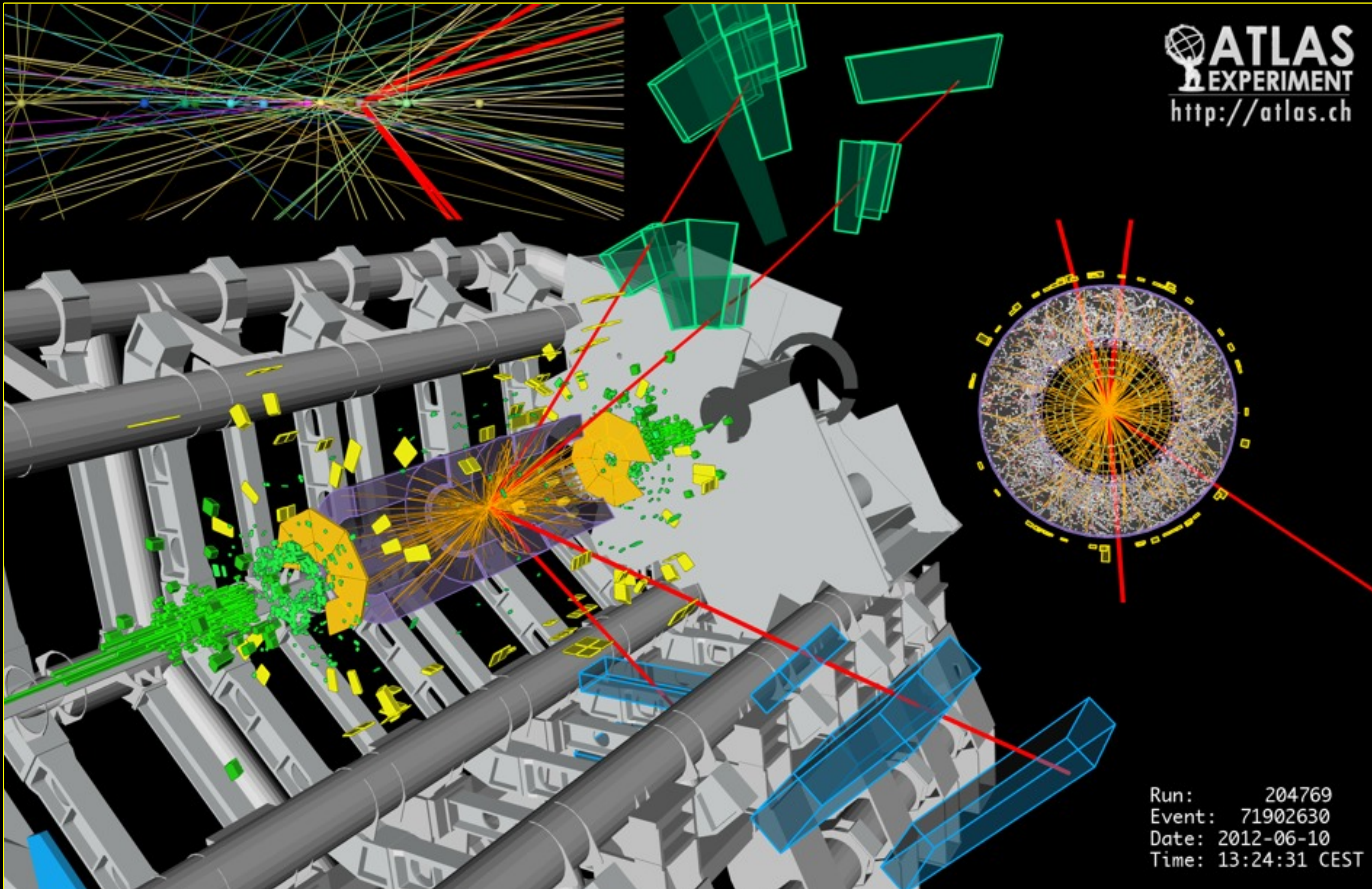
4 leptons

4e candidate with mass = 124.5 GeV



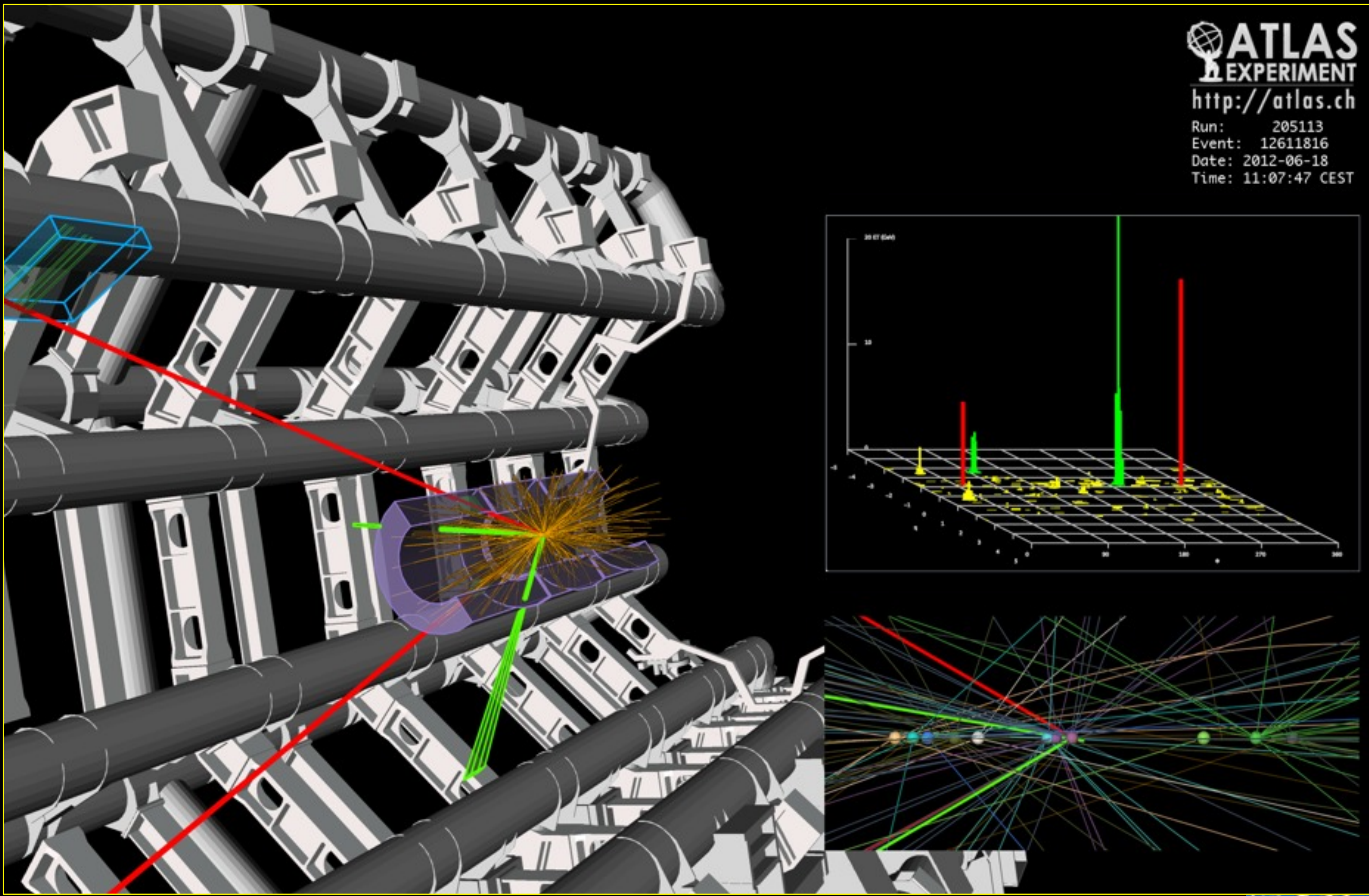
4 leptons

4μ candidate with mass = 124.1 GeV



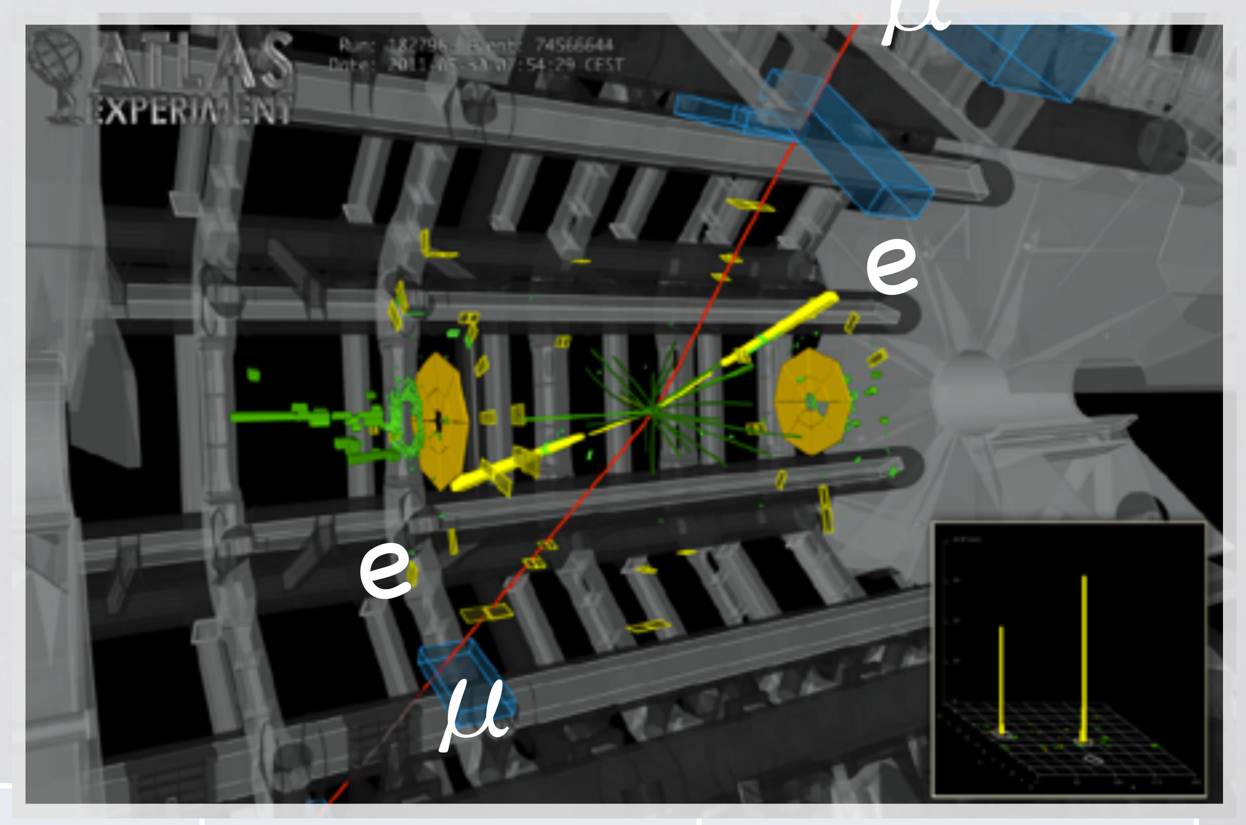
4 leptons

2e2μ candidate with mass = 122.7 GeV



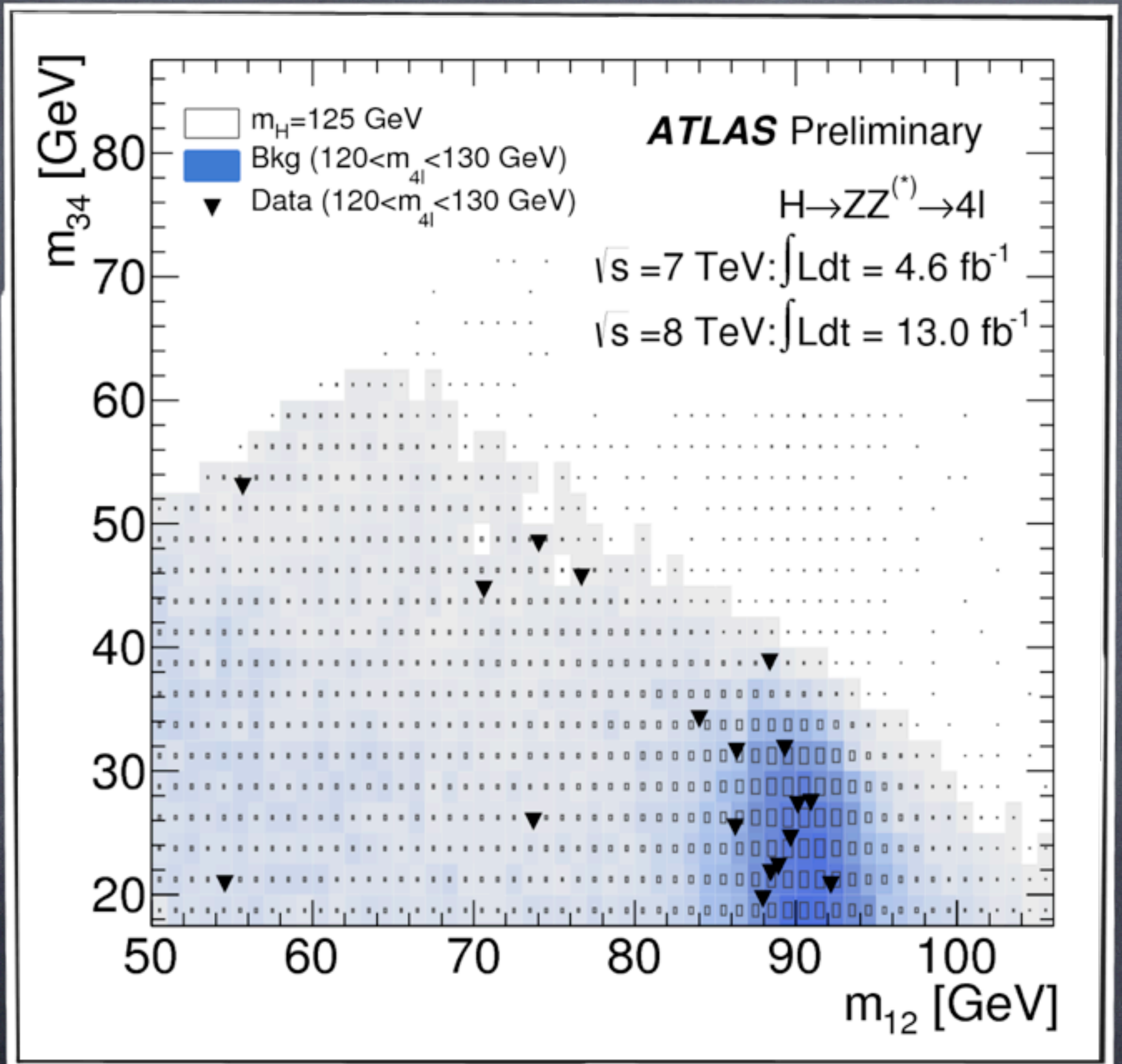
The Golden Channel: H->ZZ->4l

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



Prod	Luminosity	BG	Signal (126.5 GeV)	s/b
Inclusive	4.9+13 fb^{-1}	ZZ*,Zbb, Z+jets, top	~10	~1

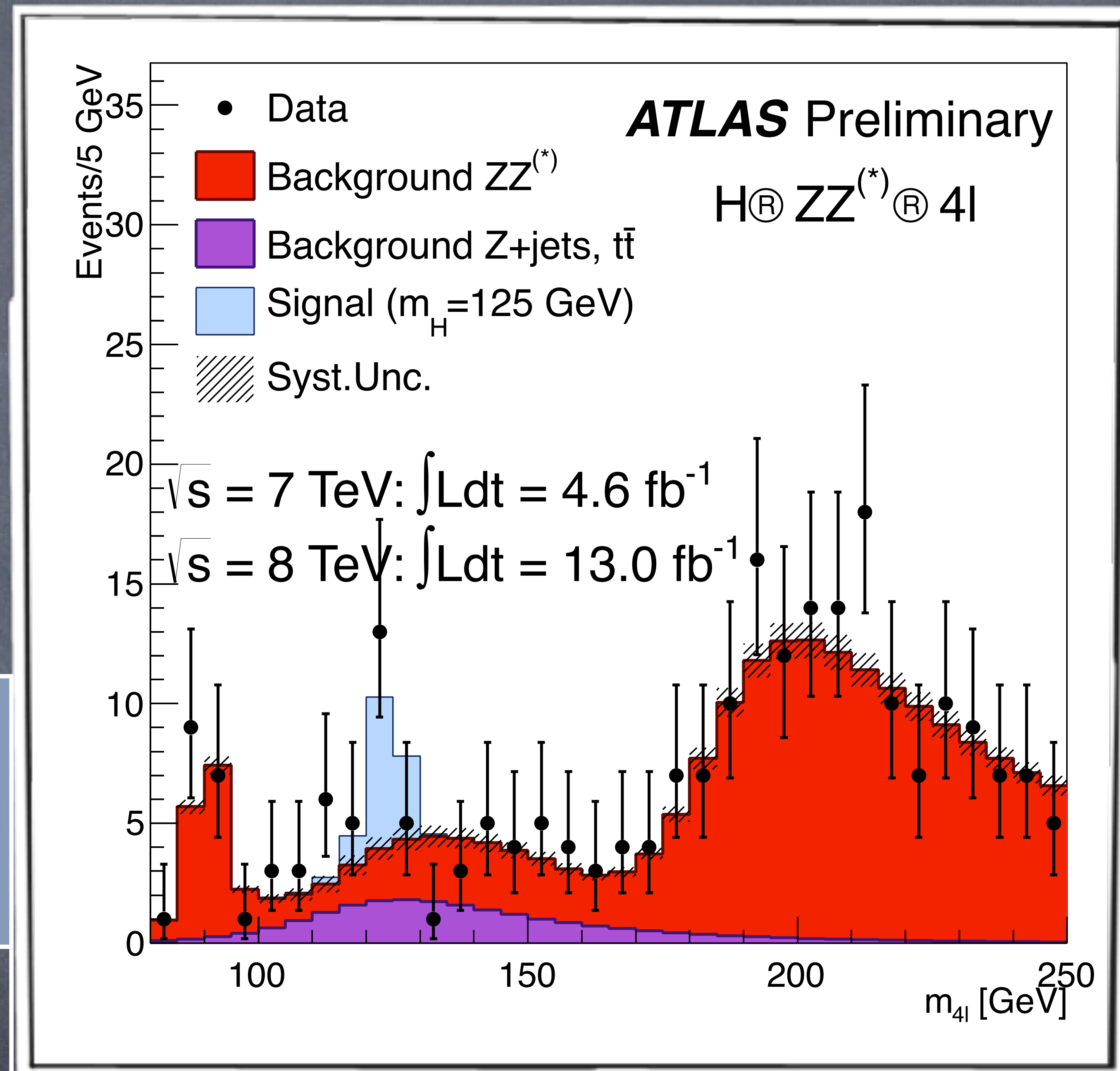
The Golden Channel: H->ZZ->4l



4 ℓ

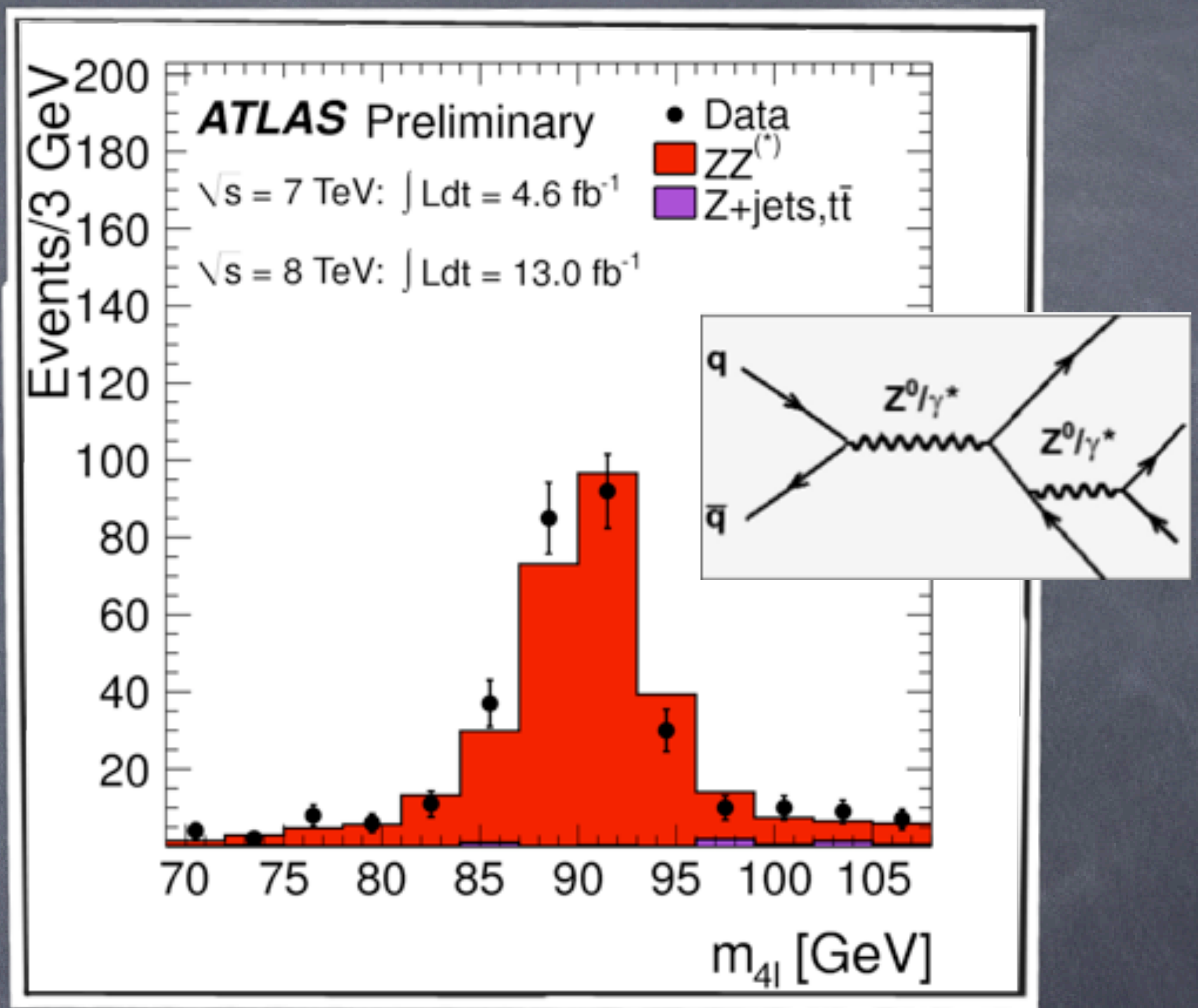
- The resolution of the reconstructed Higgs boson mass is dominated by detector resolution at low mH values and by the Higgs boson width at high mH.
- Candidates account:

Expected from BG	mH=125 GeV	Observed
8.3±0.3	9.9±1.3	18

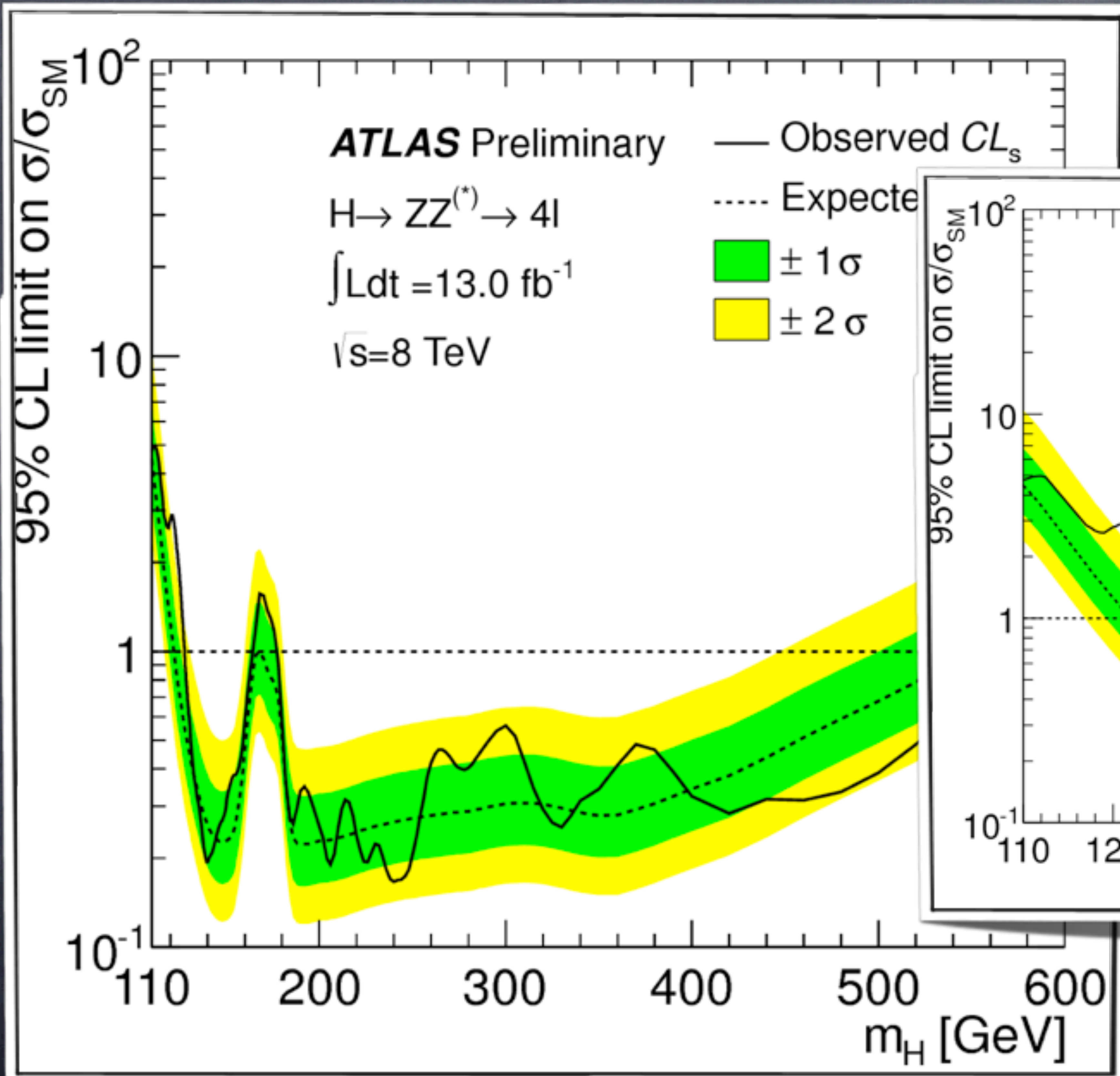


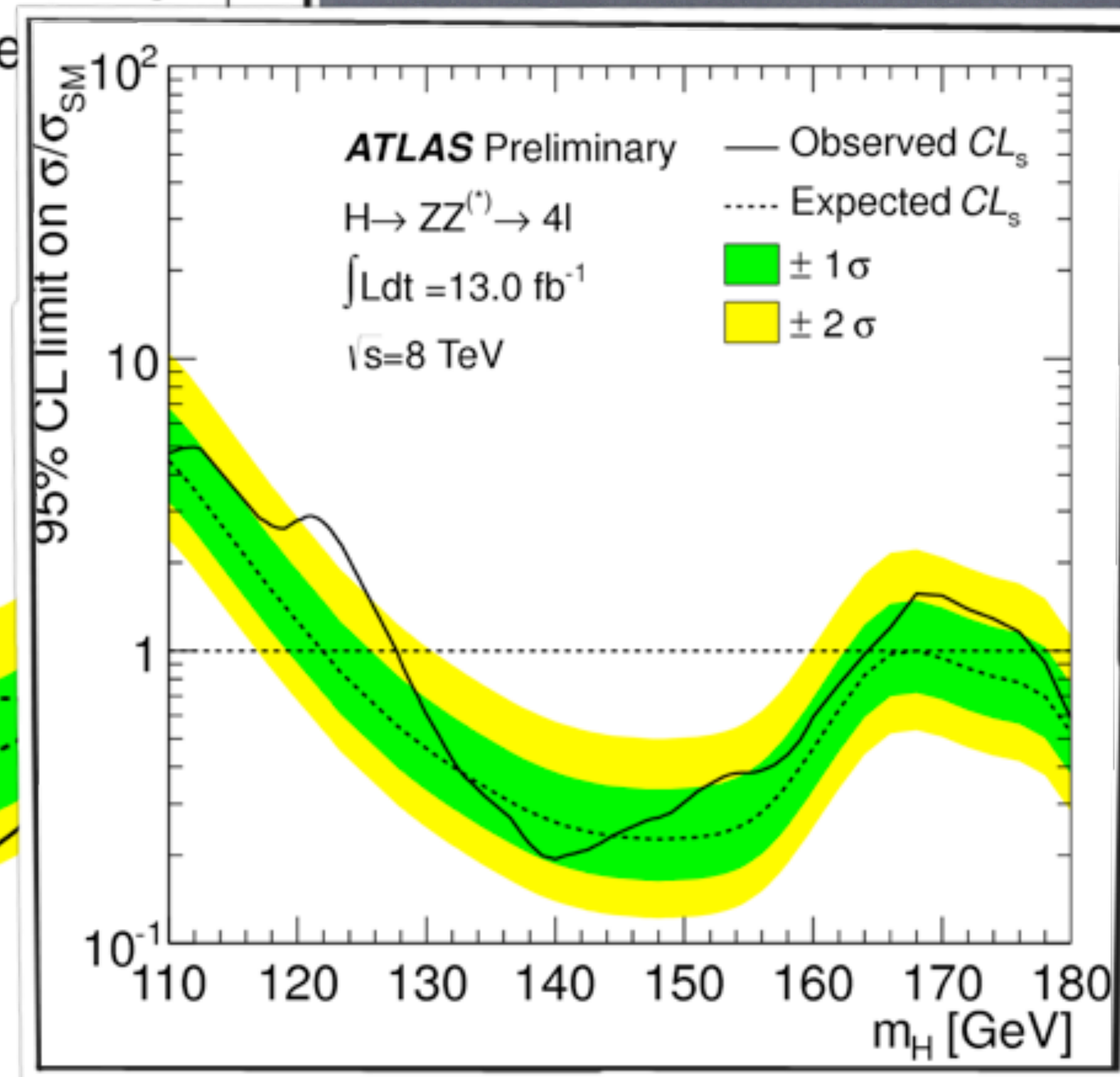
Validating 4 ℓ analysis method

- Demonstrating the single-resonant peak
  pp-> Z-> 4leptons
- To improve the acceptance the requirements on m12, m34 and the leptons pT were relaxed



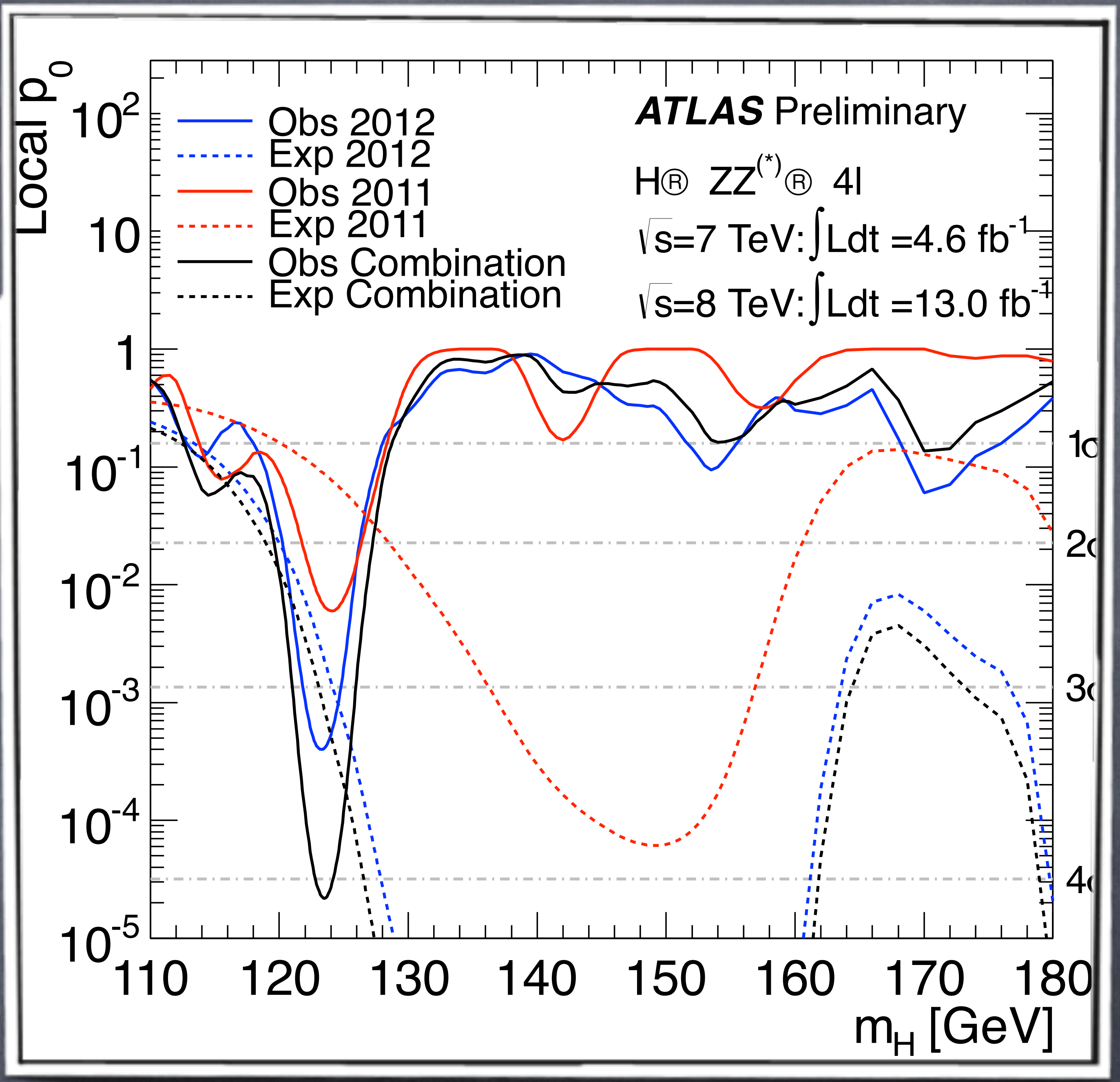
Exclusion


ATLAS Preliminary
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
$\int L dt = 13.0\ fb^{-1}$
$\sqrt{s} = 8$ TeV
Observed CL_s
Expecte
$\pm 1\sigma$
$\pm 2\sigma$
95% CL limit on σ/σ_{SM}
10^2
10
1
10^{-1}
110
200
300
400
500
600
m_H [GeV]


ATLAS Preliminary
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
$\int L dt = 13.0\ fb^{-1}$
$\sqrt{s} = 8$ TeV
Observed CL_s
Expected CL_s
$\pm 1\sigma$
$\pm 2\sigma$
95% CL limit on σ/σ_{SM}
10^2
10
1
10^{-1}
110
120
130
140
150
160
170
180
m_H [GeV]

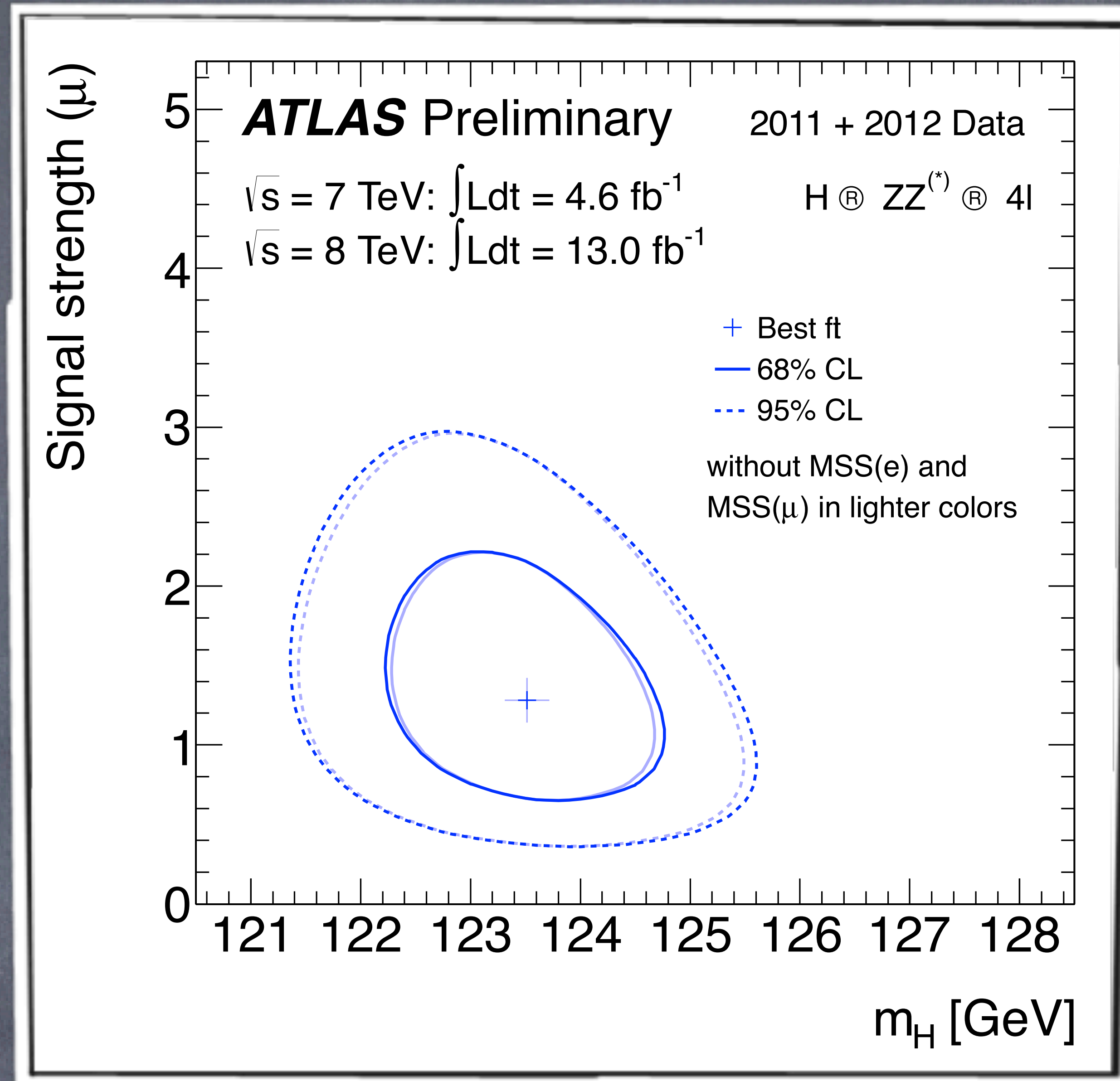
4 ℓ discovery excess is confirmed

	2011	2012	Combined
Mass	124.1 GeV	123.3 GeV	123.5 GeV
Exp	1.4 σ	2.8 σ	3.1 σ
Obs	2.5 σ	3.4 σ	4.1 σ



$4\,\ell$ discovery excess is confirmed

	2011	2012	Combined
Mass	124.1 GeV	123.3 GeV	123.5 GeV
Exp	1.4 σ	2.8 σ	3.1 σ
Obs	2.5 σ	3.4 σ	4.1 σ

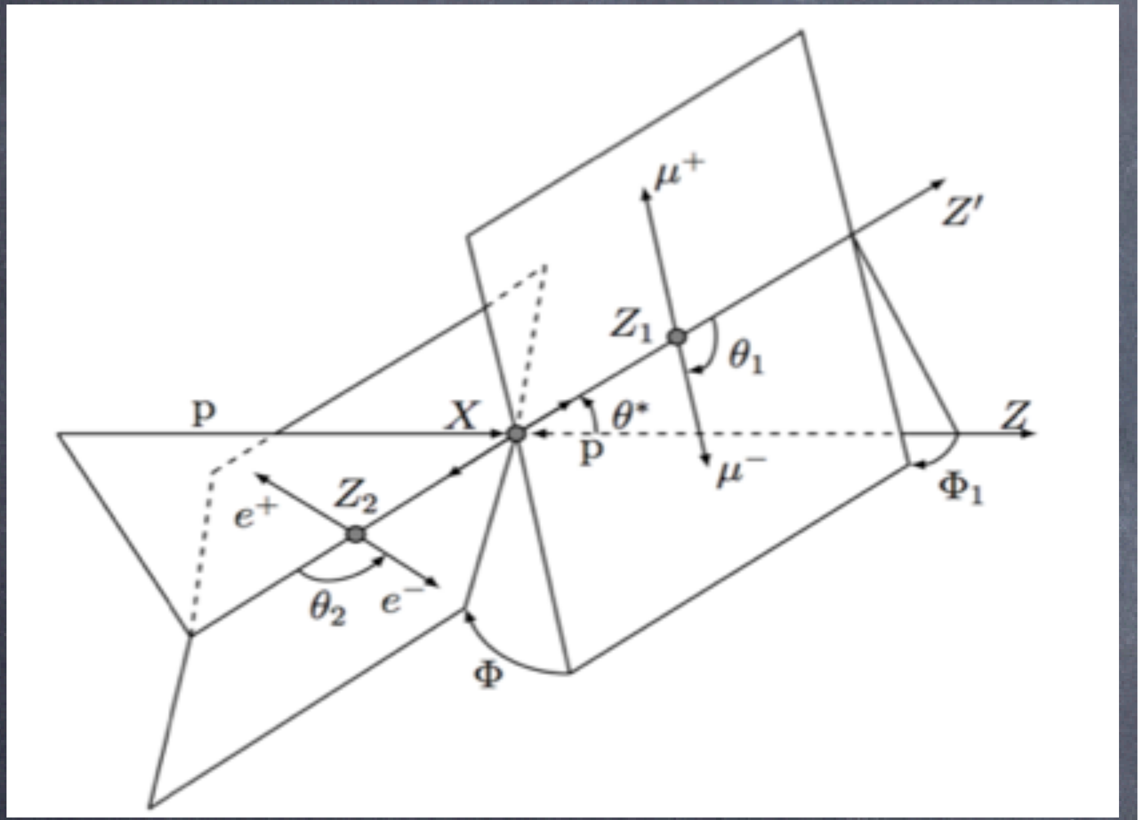


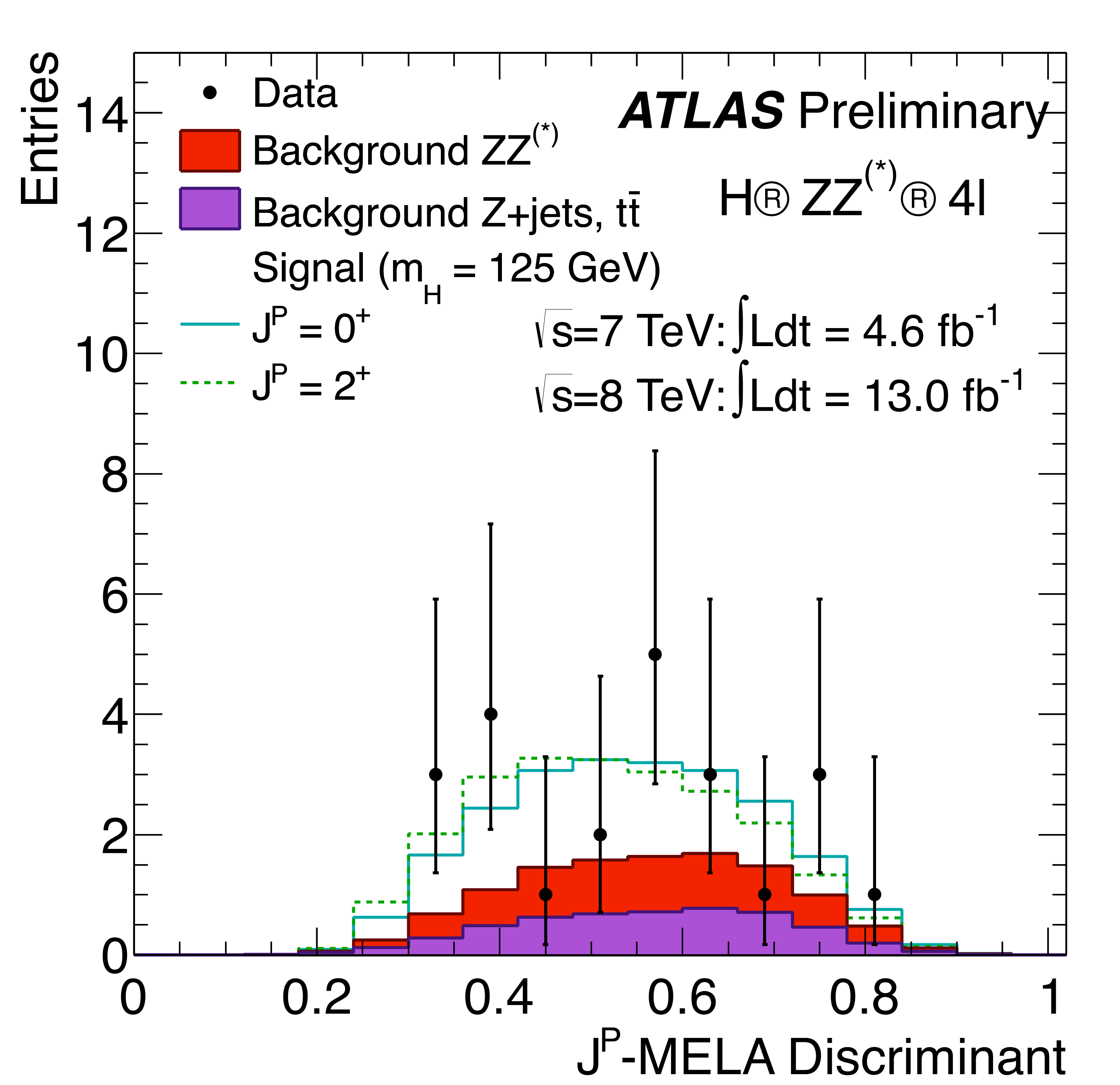
$$\hat{\mu} = 1.3 \pm 0.4$$

$$m_H = 123.5 \pm 0.9(stat) \pm 0.3(syst)$$

4 ℓ Spin & CP

$$H_1 = 2^+$$
$$H_0 = 0^+$$





Use the distributions of
5 production and decay angles, m12 and m34 fed into BDT or MELA (Matrix Element) discriminant.

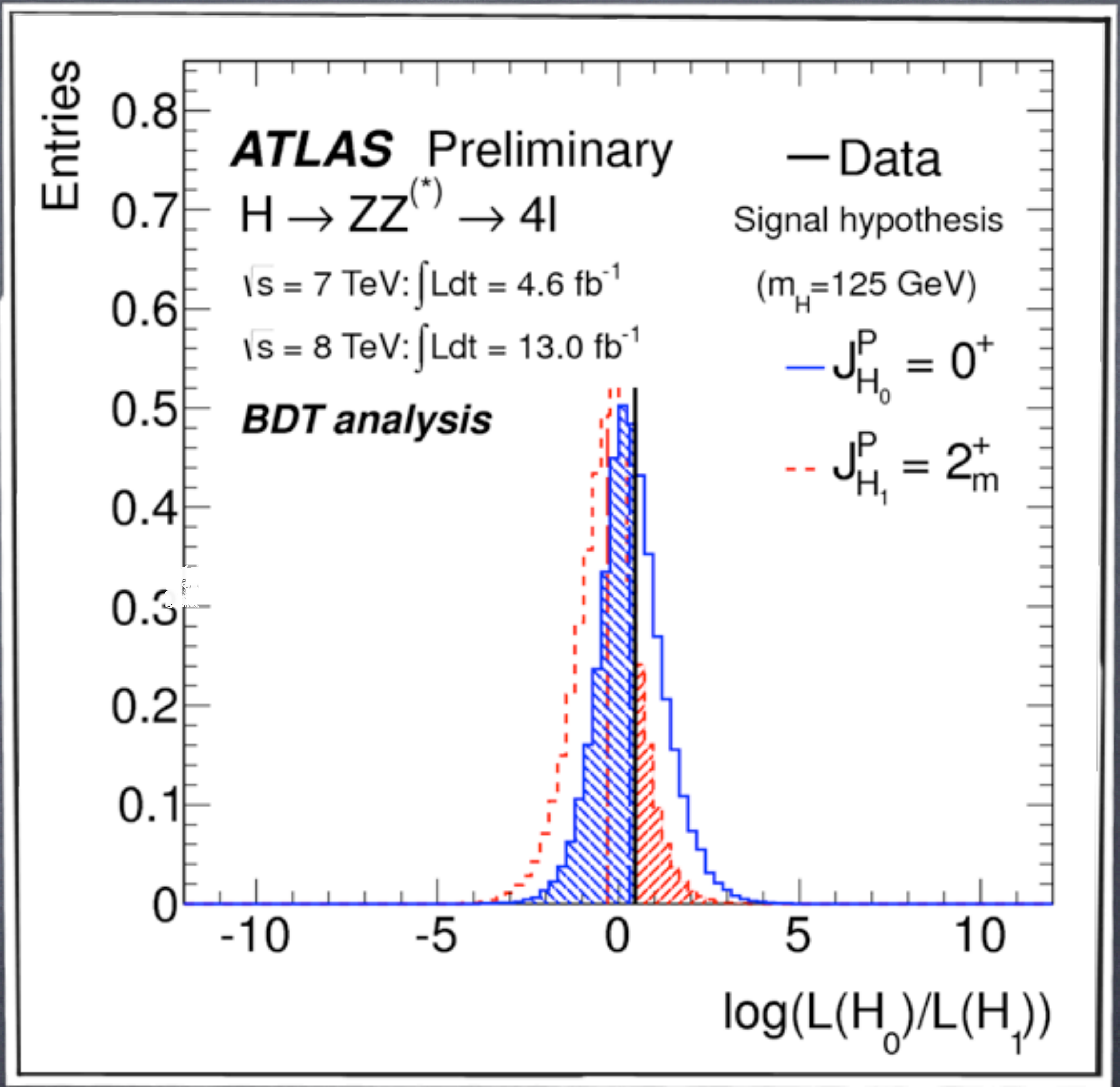
ATLAS EXPERIMENT

4 ℓ Spin & CP test $J^P=2^+$

$$H_1 = 2^+$$
$$H_0 = 0^+$$

$$q = \log \frac{L(H_0)}{L(H_1)}$$

$$p_{H_1} = \mathrm{Prob}(\mathrm{more}\ H_1\text{-like} \mid H_1)$$
$$p_{H_1}(\exp \mid H_0) = 20\%(0.86\sigma),$$
$$p_{H_1}(obs) = 16\%(1\sigma)$$
$$p_{H_0}(obs) = 57\%(-0.18\sigma)$$



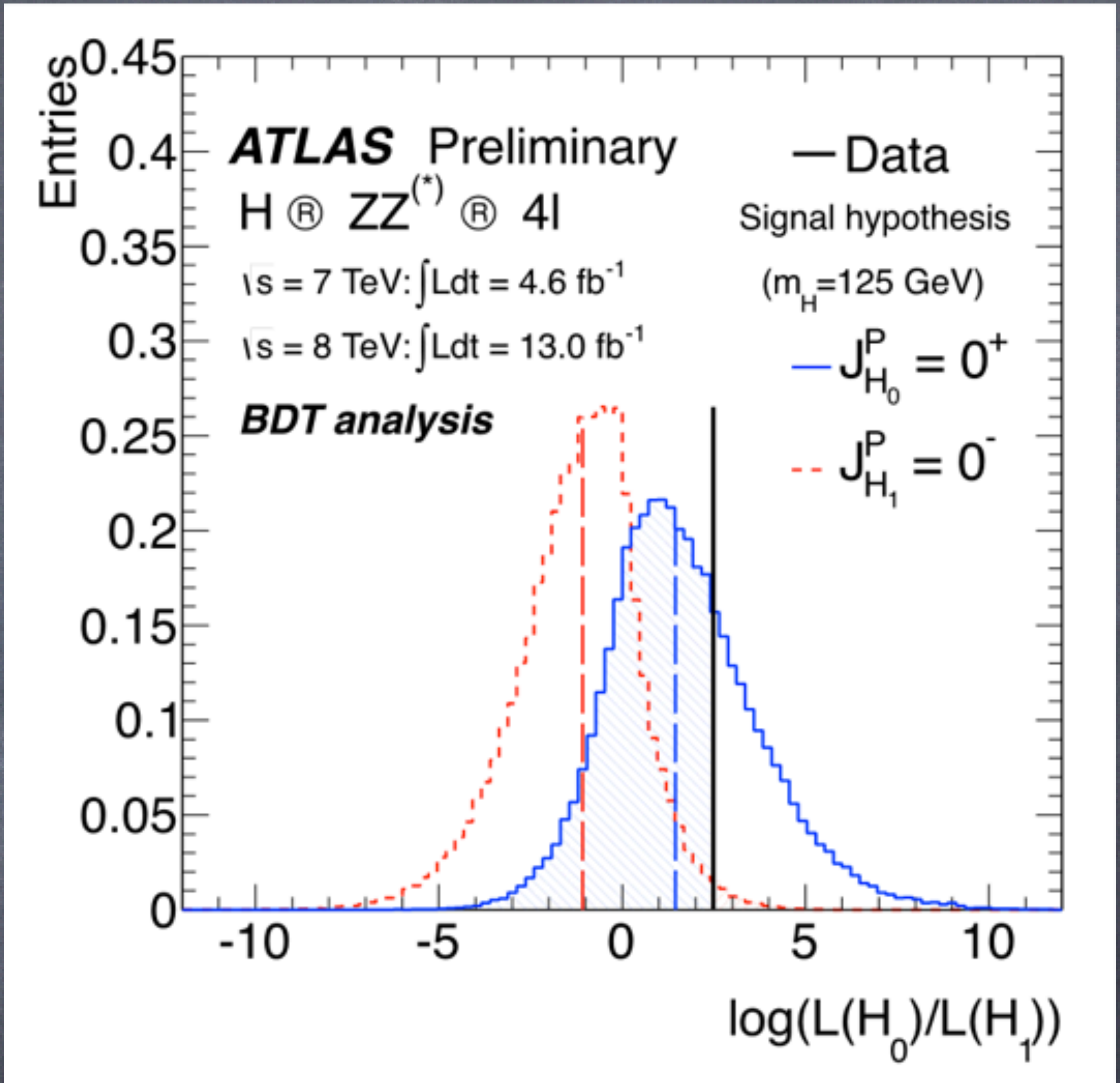
Which means assuming $J^P=0^+$ One has the sensitivity to exclude 2^+ at the 80% CL and excludes it at the 84% CL

4 ℓ Spin & CP, test $J^P=0^-$

$$H_1 = 0^-$$
$$H_0 = 0^+$$

$$q = \log \frac{L(H_0)}{L(H_1)}$$

$$p_{H_1} = \mathrm{Prob}(\text{more } H_1\text{-like} \mid H_1)$$
$$p_{H_1}(\exp \mid H_0) = 4.1\%(1.7\sigma),$$
$$p_{H_1}(obs) = 1.1\%(2.3\sigma)$$
$$p_{H_0}(obs) = 69\%(-0.5\sigma)$$



Which means assuming $J^P=0^+$ One has the sensitivity to exclude 0^- at the 96% CL and excludes it at the 99% CL

H->WW

$$w_i \simeq \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

- Probing mH=125 GeV
- Probing channels:

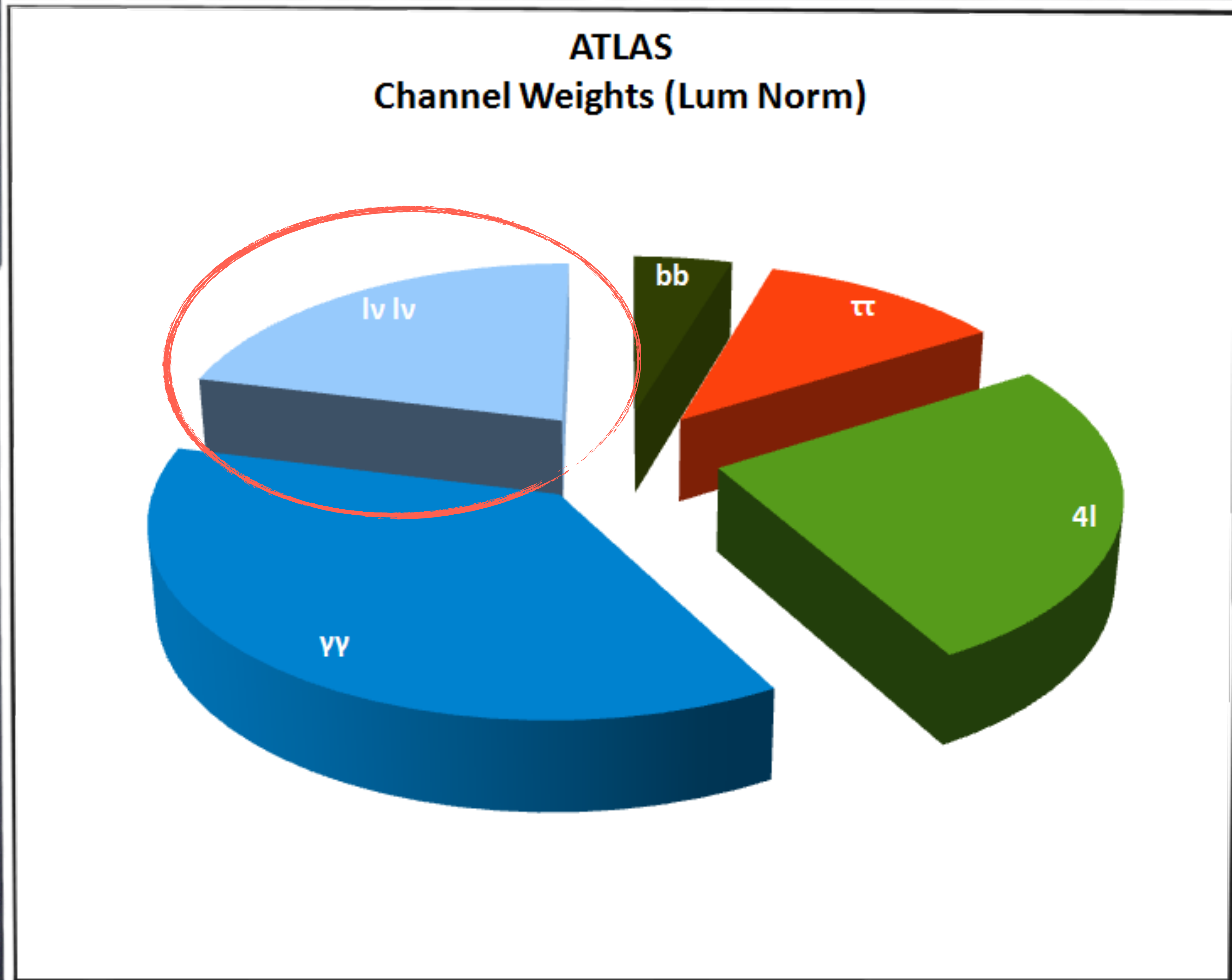
H-> γ γ

H->4l

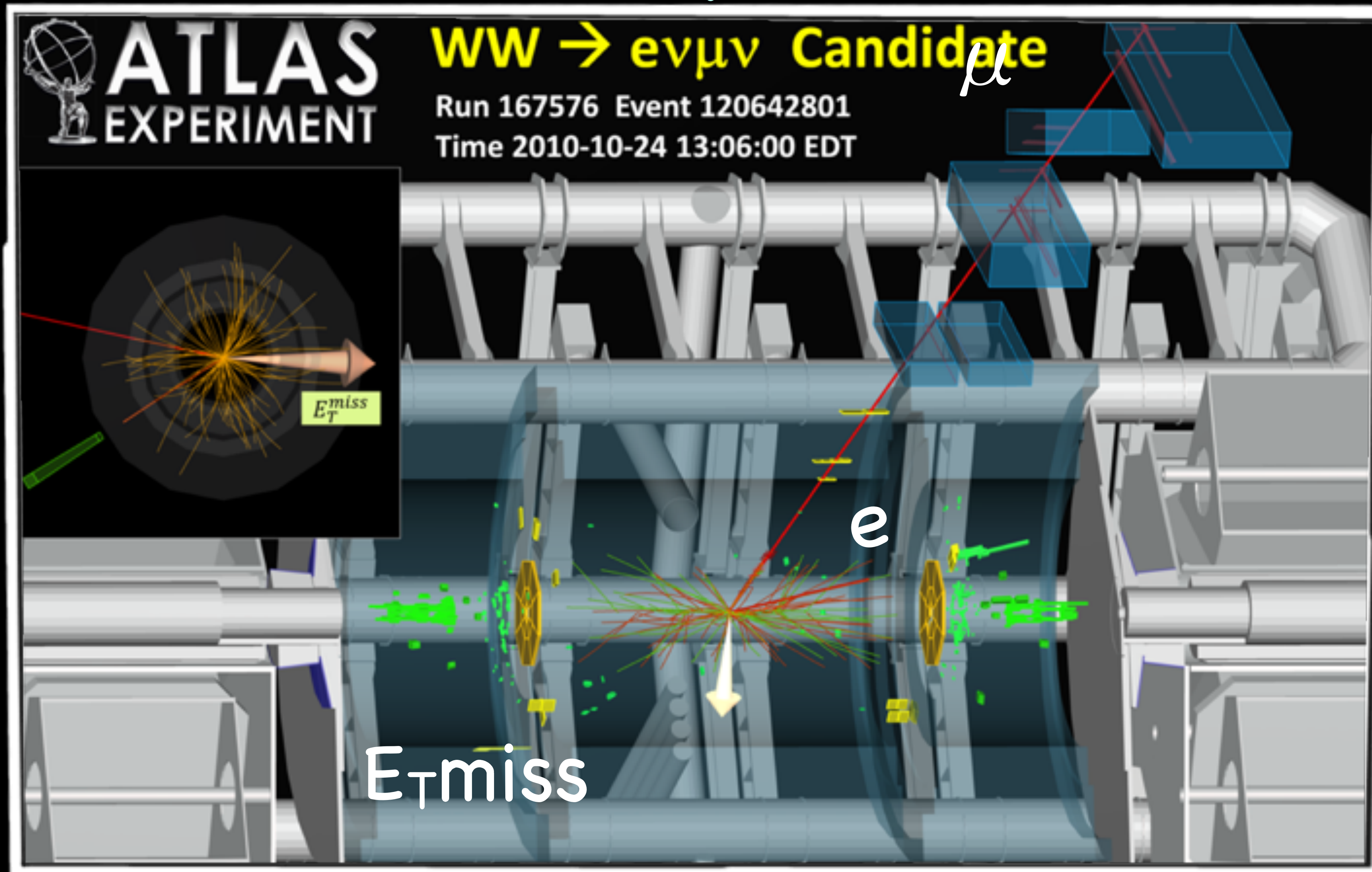
H->WW->lvlv

VH-> Vbb,

H-> τ τ



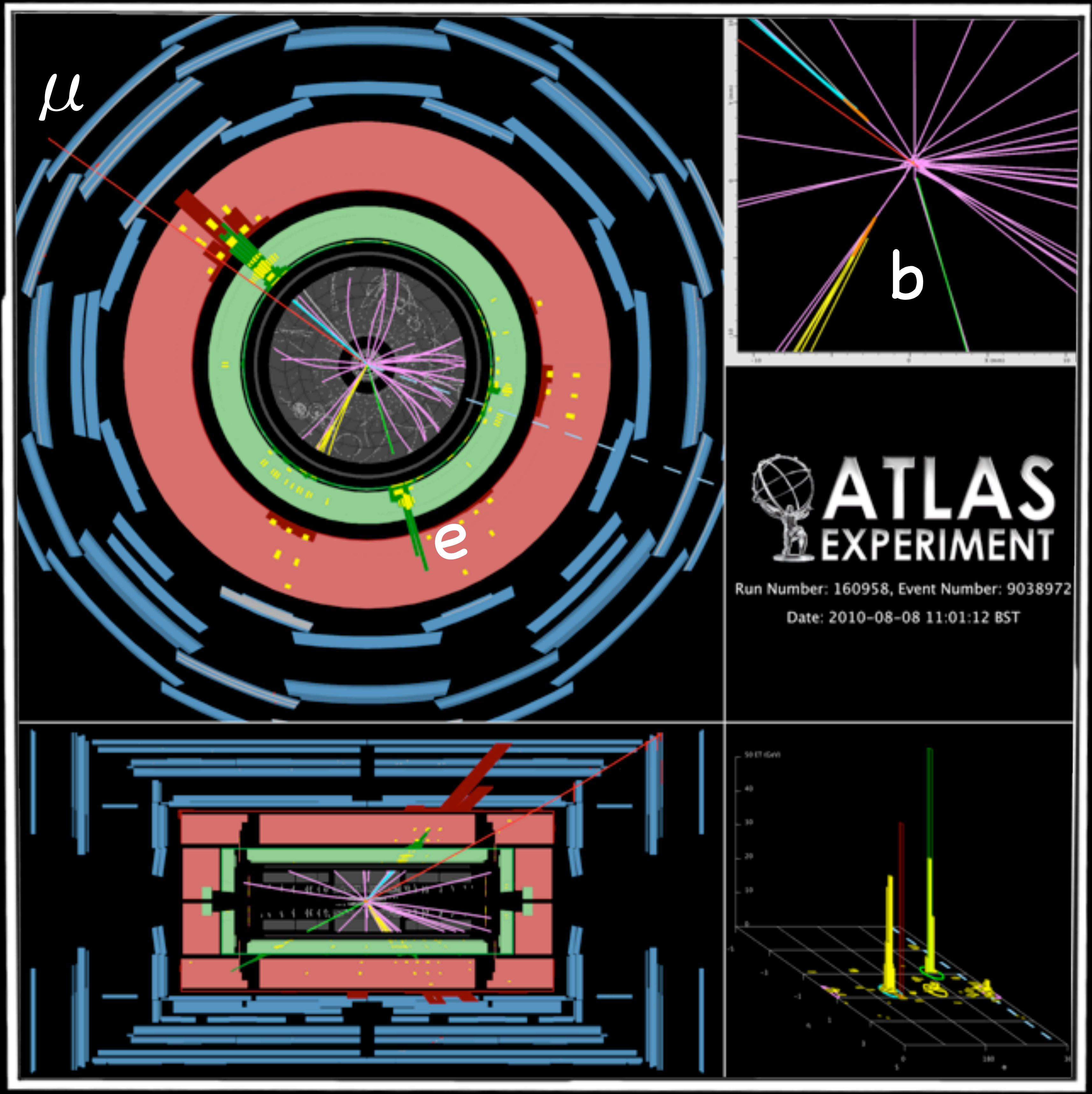
H->WW->eνμν



σxBR~200 fb
@ 125

Prod	Luminosity	BG	Signal (126.5 GeV)	s/b
ggF	13 fb^{-1} 8 TeV only	WW, W+jets, top	~110	~1/10

H->WW->e ν μ ν

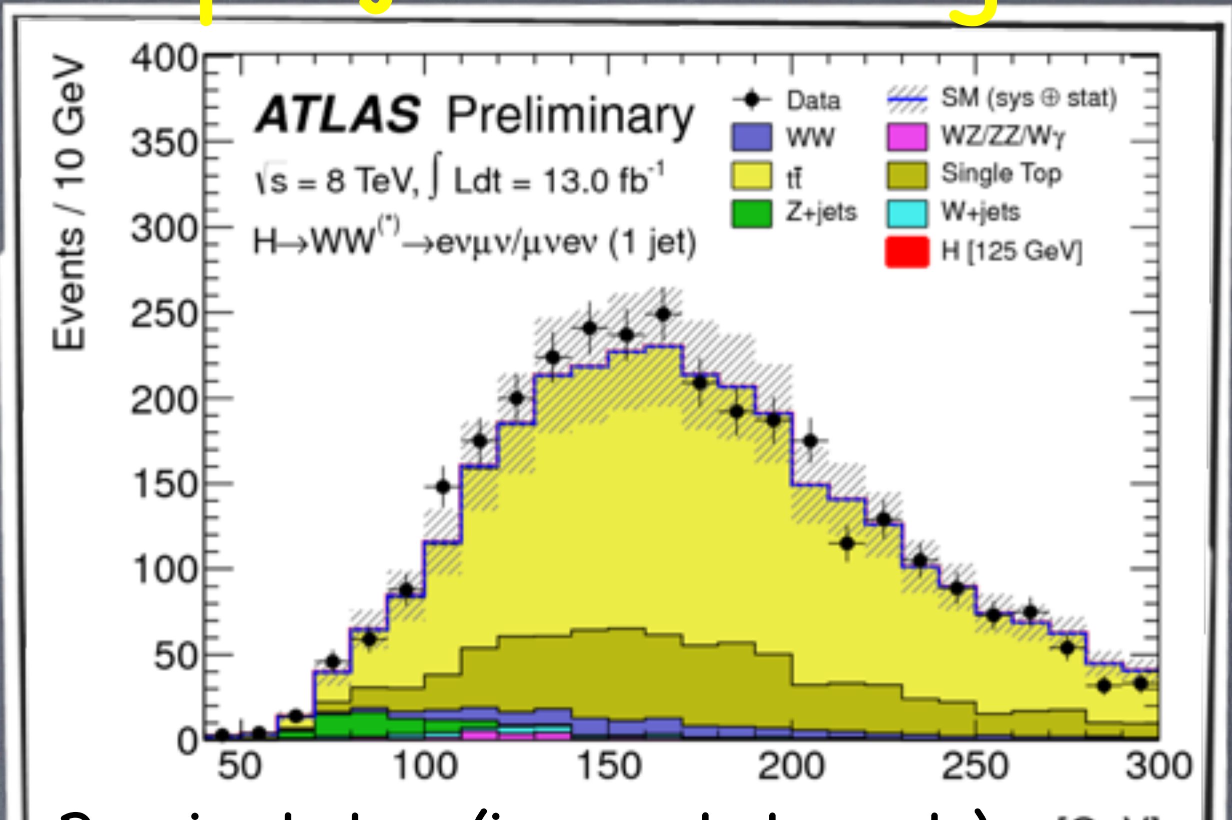


- top BG, Rejected by b-tag veto
- WW can be reduced by exploiting the Higgs spin, require small $\Delta\Phi_{ll}$

H->WW->l ν l ν

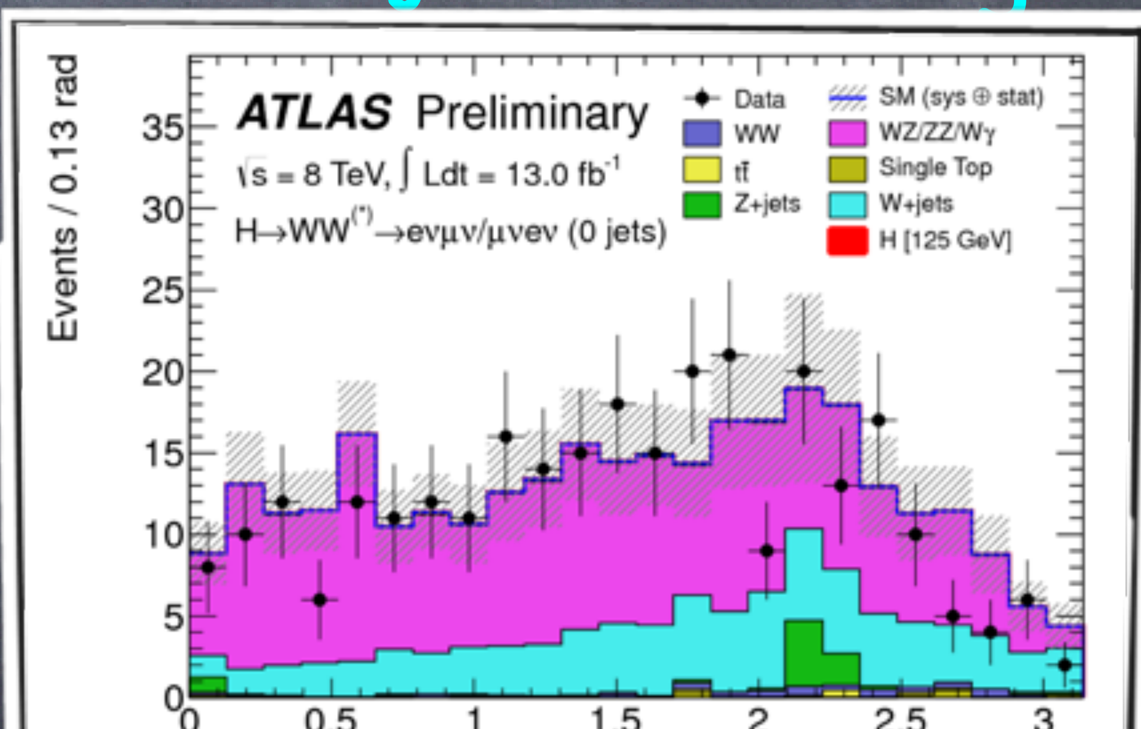
- Main background from WW, top, Z+jets, W+jets
  ->Use of control regions to estimate fakes
- A control region is defined rich in the measured BG (e.g. WW or top), contaminations are being subtracted and then the BG is extrapolated to the signal region (mostly using MC)
  Example: b-tag is inverted to estimate Top BG

top 1j control region



Require b-tag (inverse b-tag veto)

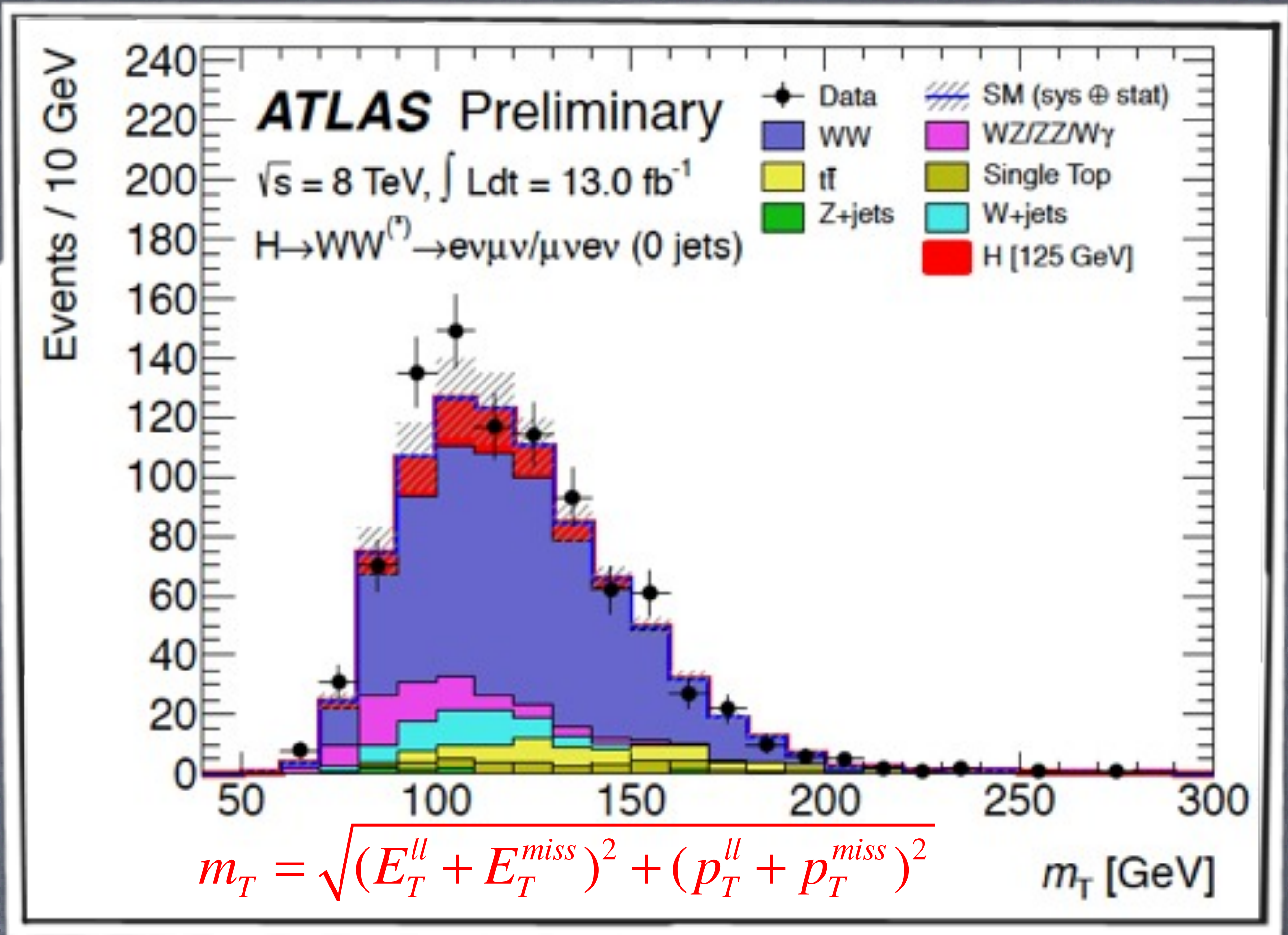
WW 0j control region



same sign 0 j control region

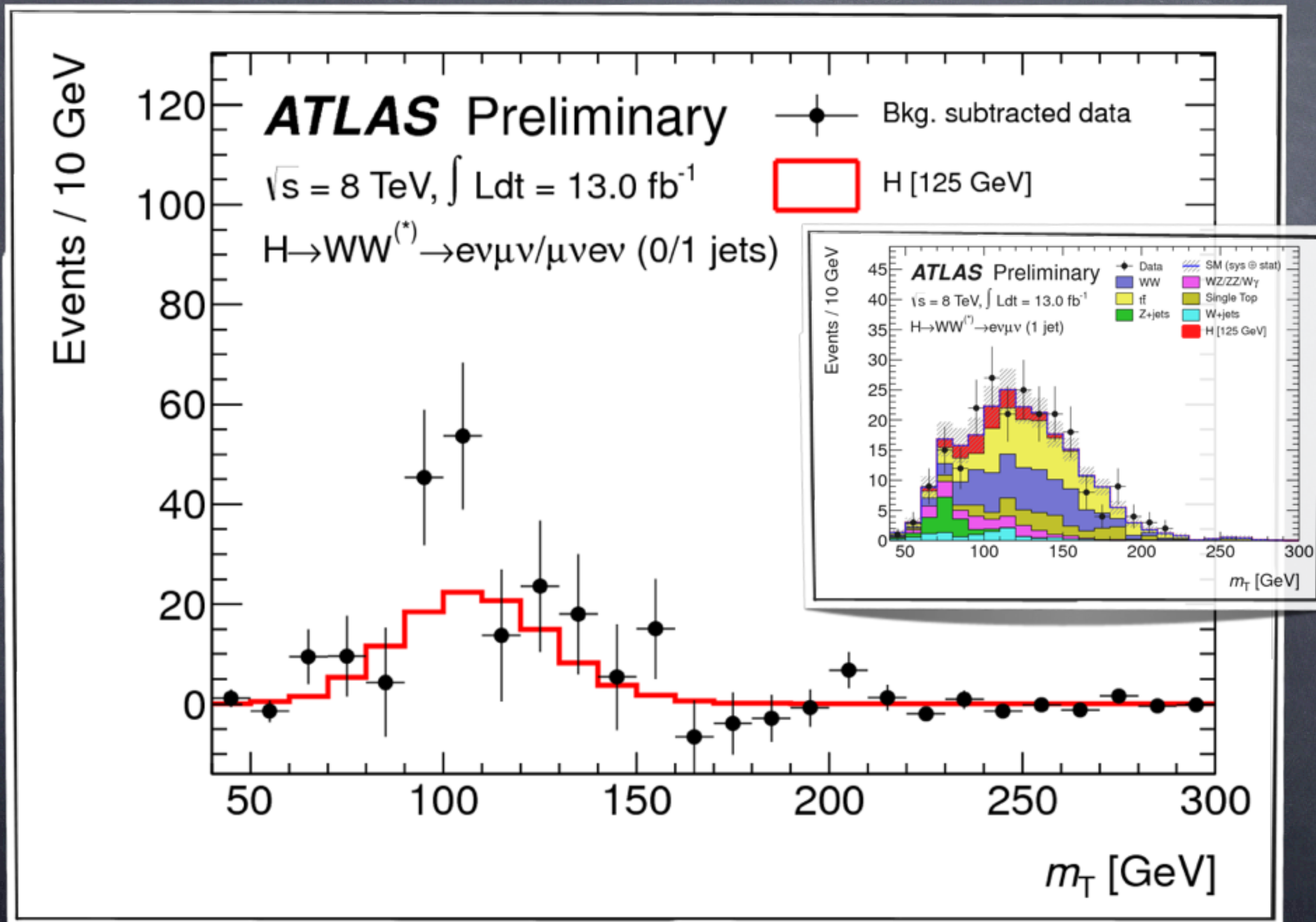
H->WW->l ν l ν

Obs in mass bin 0.75mH<mT<mH	546 Events
Exp (BG)	448±45
Exp (Higgs)	63±13



- 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
- Two Jet bins: +0j, +1
- -> large E_T^{miss}, m_{ll} incompatible with m_Z (DY),
  -> b jet veto (tt),
  ->Topological cuts against irreducible WW ($\Delta\Phi_{ll}$)
- Discriminating variable mT

H->WW->e ν μ ν

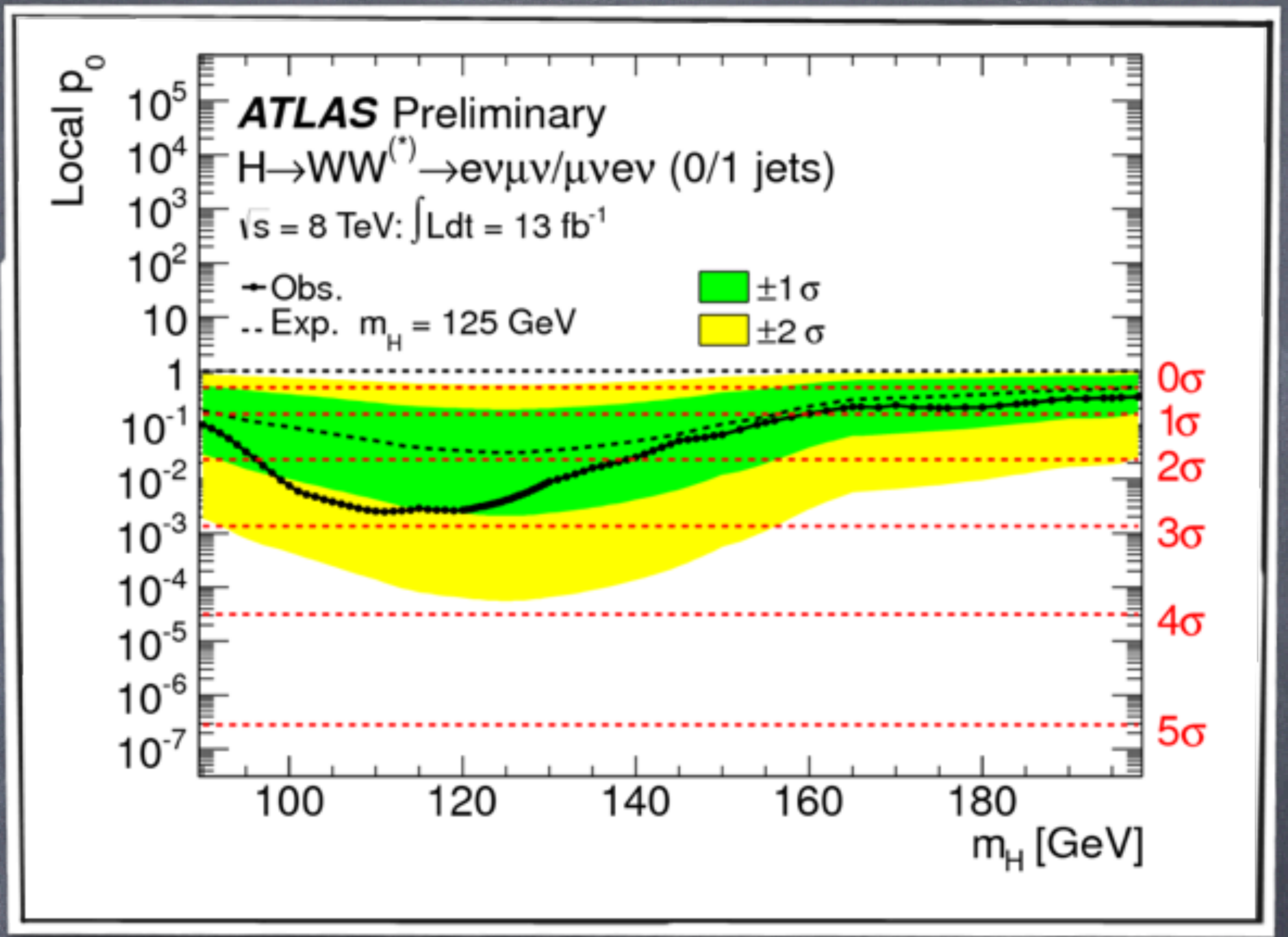


ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 13.0 fb^{-1}
H→WW$^{(*)}$→eνμν/μνeν (0/1 jets)
Bkg. subtracted data
H [125 GeV]
Events / 10 GeV
m_T [GeV]
120
100
80
60
40
20
0
50
100
150
200
250
300
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 13.0 fb^{-1}
H→WW$^{(*)}$→eνμν (1 jet)
Data
WW
tt̄
Z+jets
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Events / 10 GeV
m_T [GeV]

H->WW->e ν μ ν

- Observed p_0 @ 125 GeV: 4×10^{-3} (corresponds to 2.6 σ)

- Expected significance @ 125 GeV is 1.9 σ

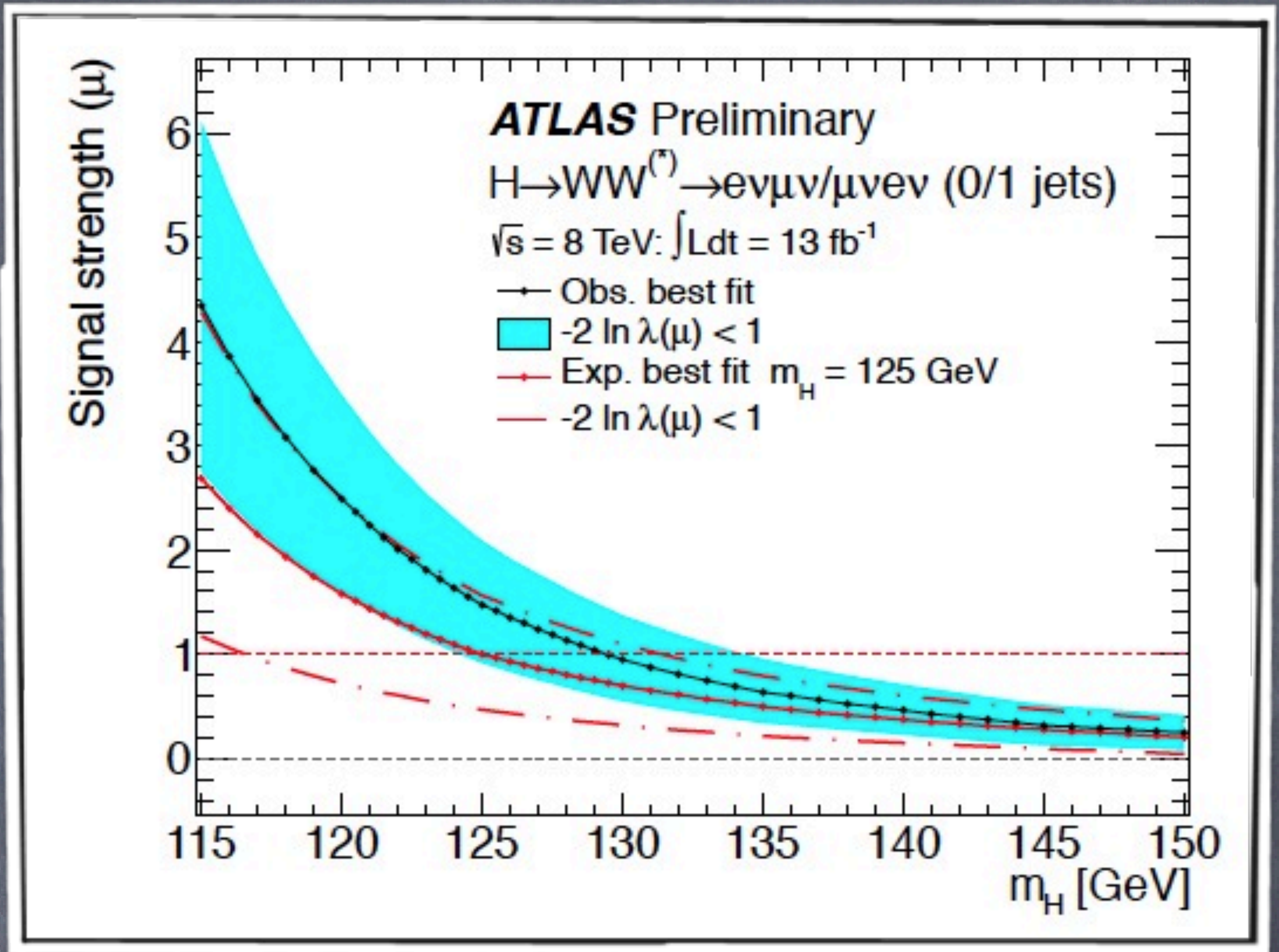


H->WW->eν μ ν

- Observed p_0 @ 125 GeV: 4×10^{-3} (corresponds to 2.6σ)

- Expected significance @ 125 GeV is 1.9σ

$$\hat{\mu}(125GeV)=1.5\pm0.6$$



$$\mu = 1.48^{+0.35}_{-0.33}\,(\text{stat})^{+0.41}_{-0.36}\,(\text{syst theor})\,^{+0.28}_{-0.27}\,(\text{syst exp}) \pm 0.05\,(\text{lumi})$$

- Consistent with SM Higgs Boson

The Fermionic Channels

$$w_i \simeq \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

- Probing mH=125 GeV
- Probing channels:

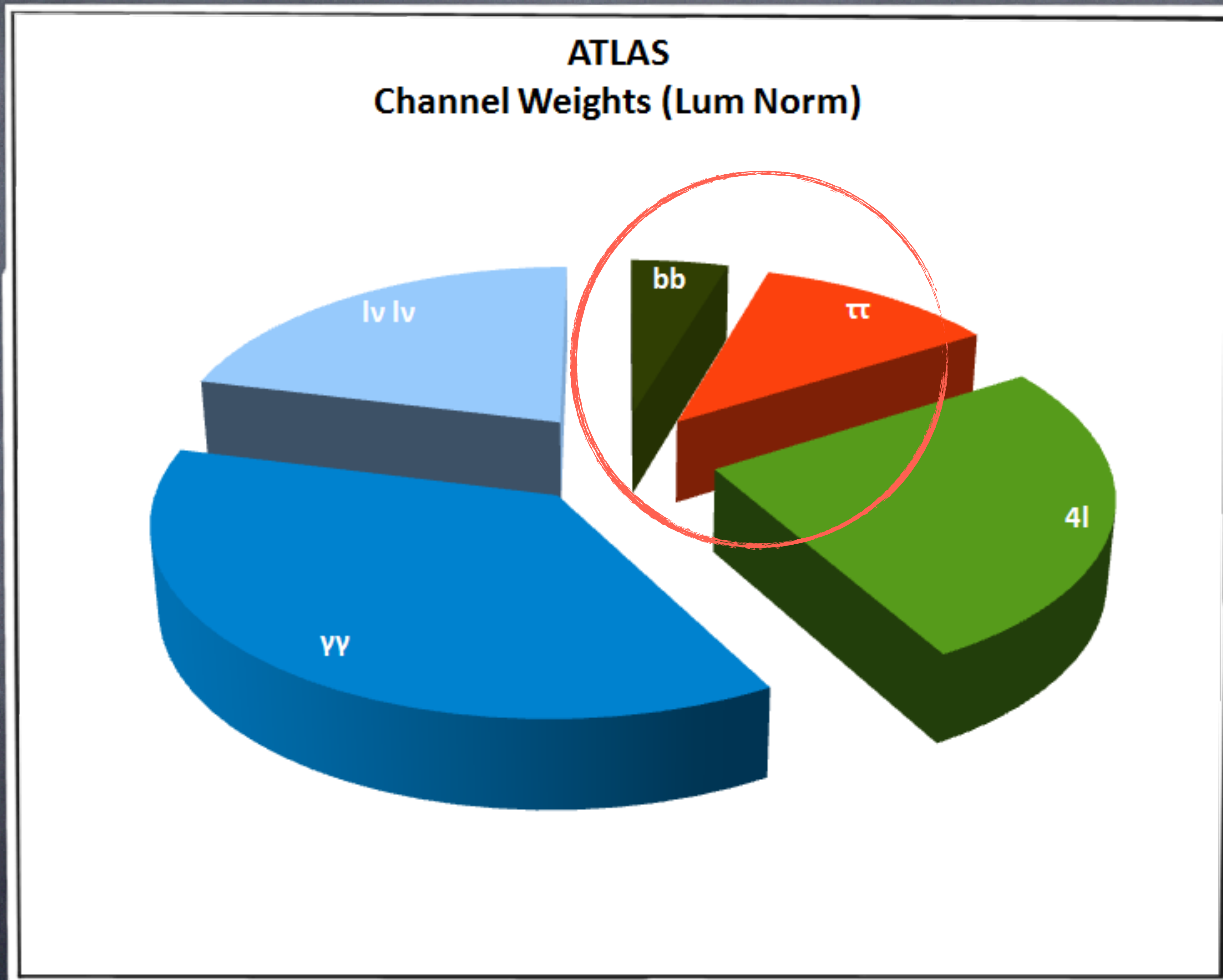
H-> $\gamma\ \gamma$

H->4l

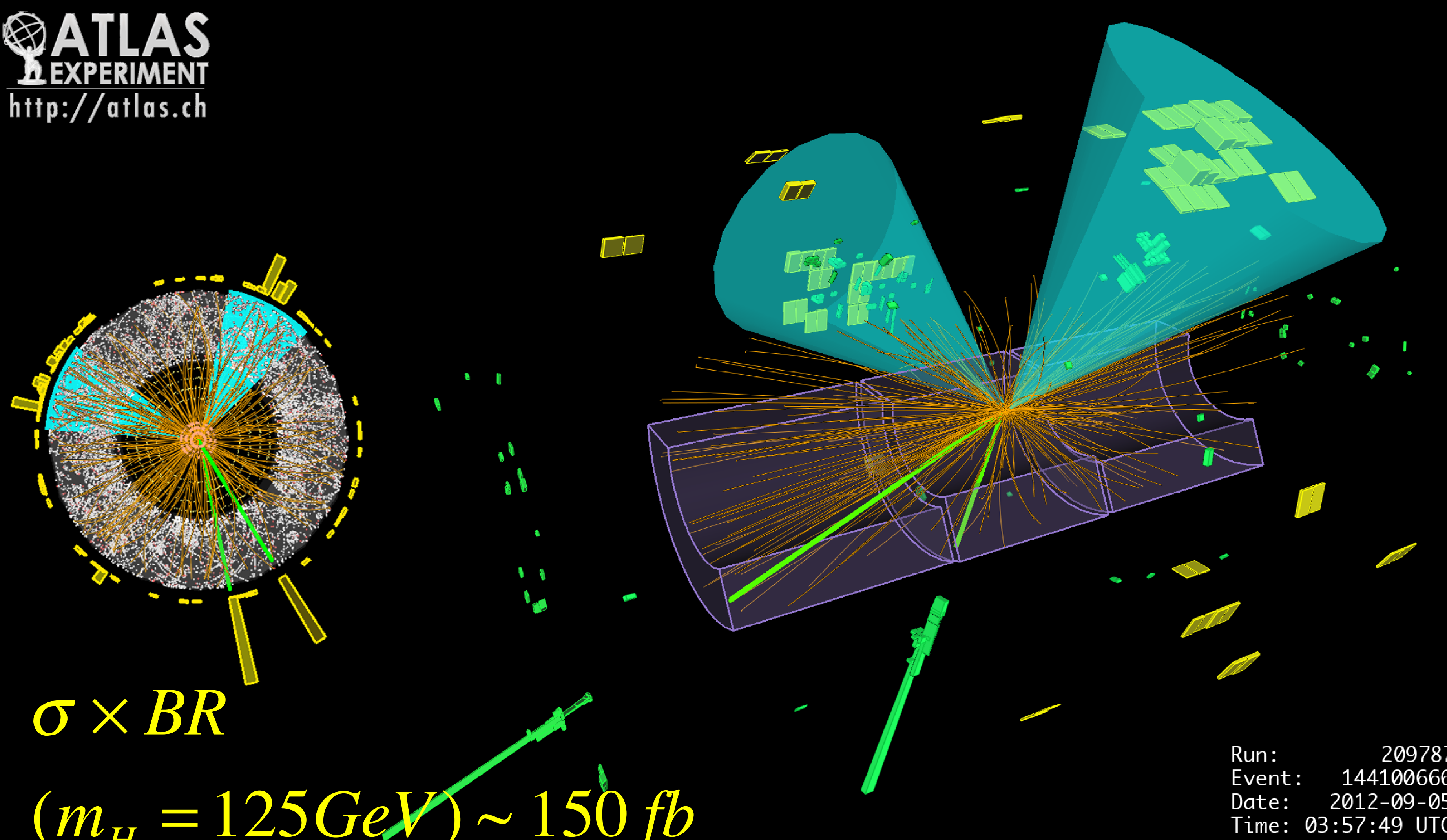
H->WW->lvlv

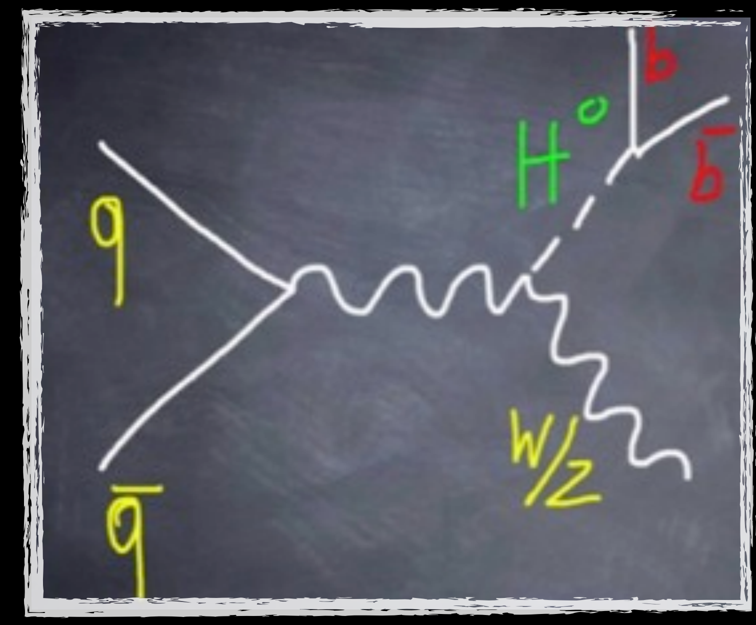
VH-> Vbb,

H-> $\tau\ \tau$



H->bb: W/ZH->W/Zbb





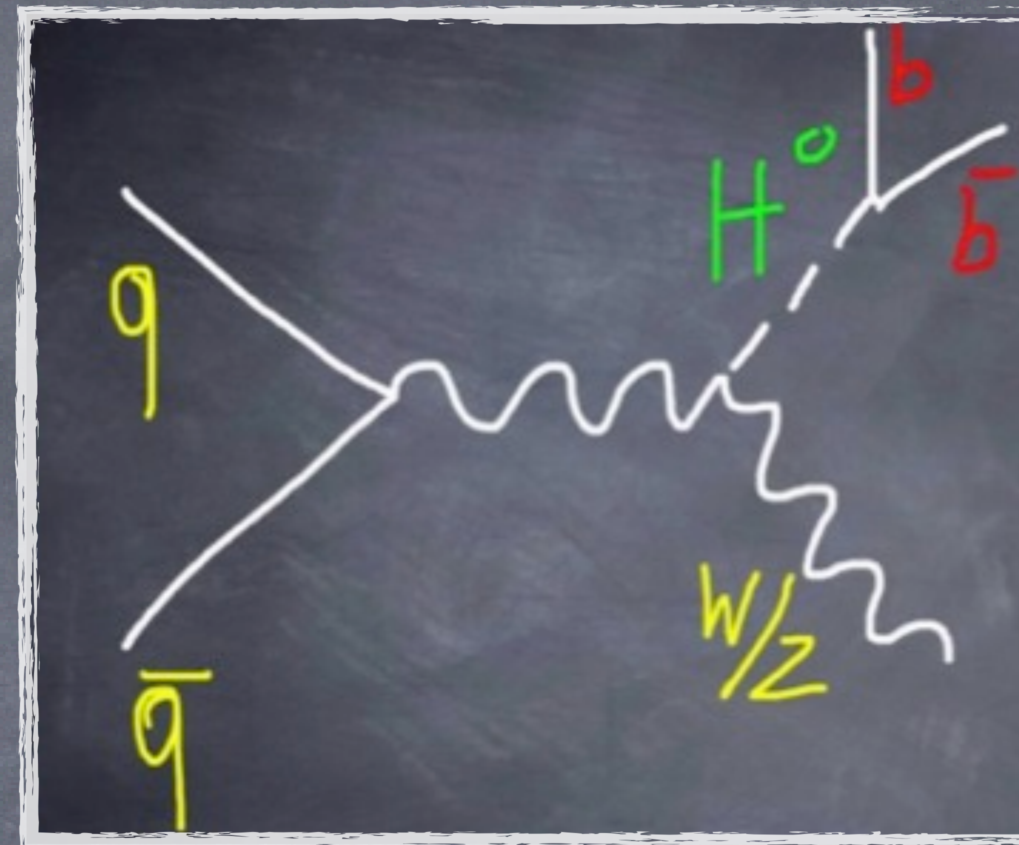
$\sigma \times BR$

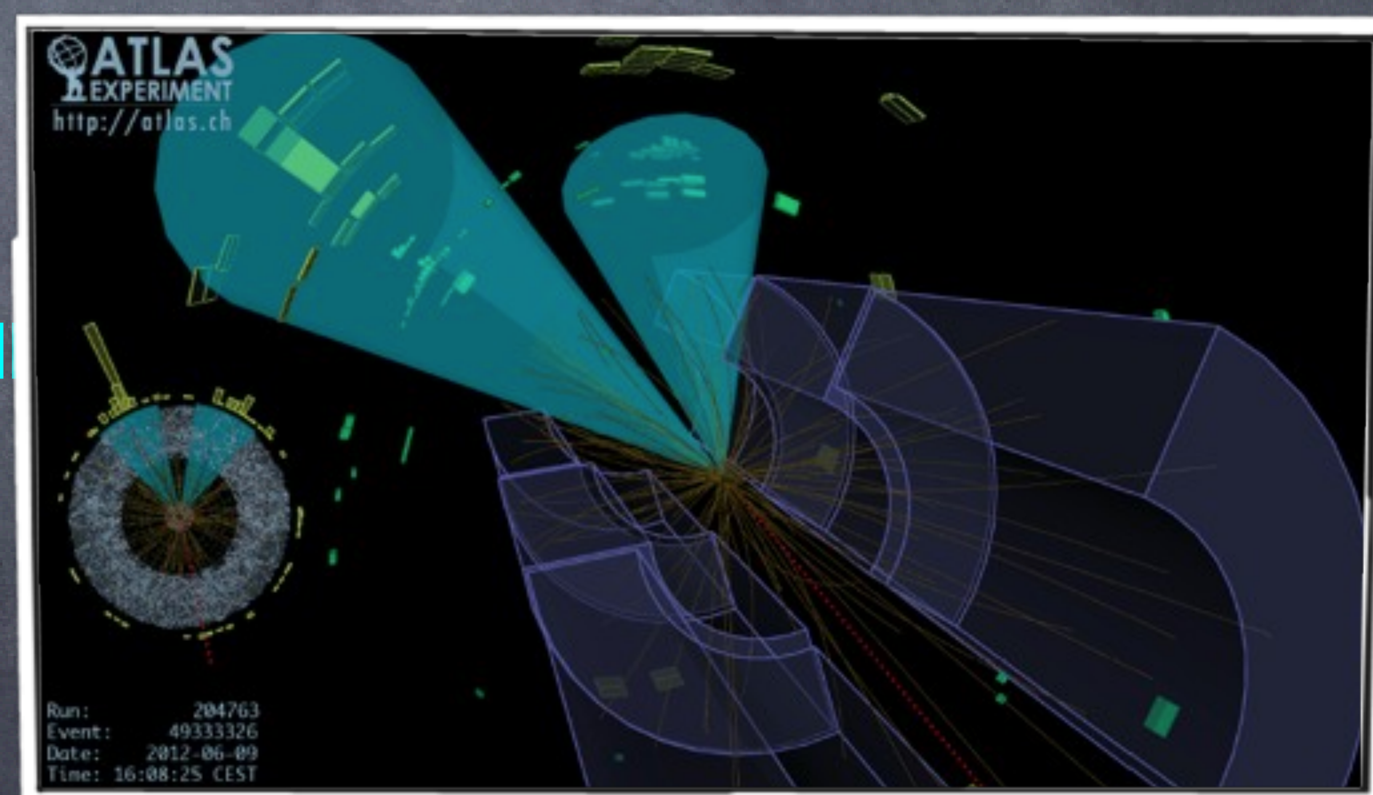
$(m_H = 125 GeV) \sim 150\, fb$

Prod	Luminosity	BG	Signal (126.5 GeV)	s/b
VH	4.9+13 fb^{-1}	W/Zbb, top	~50	~1-5%

H->bb: W/ZH->W/Zbb

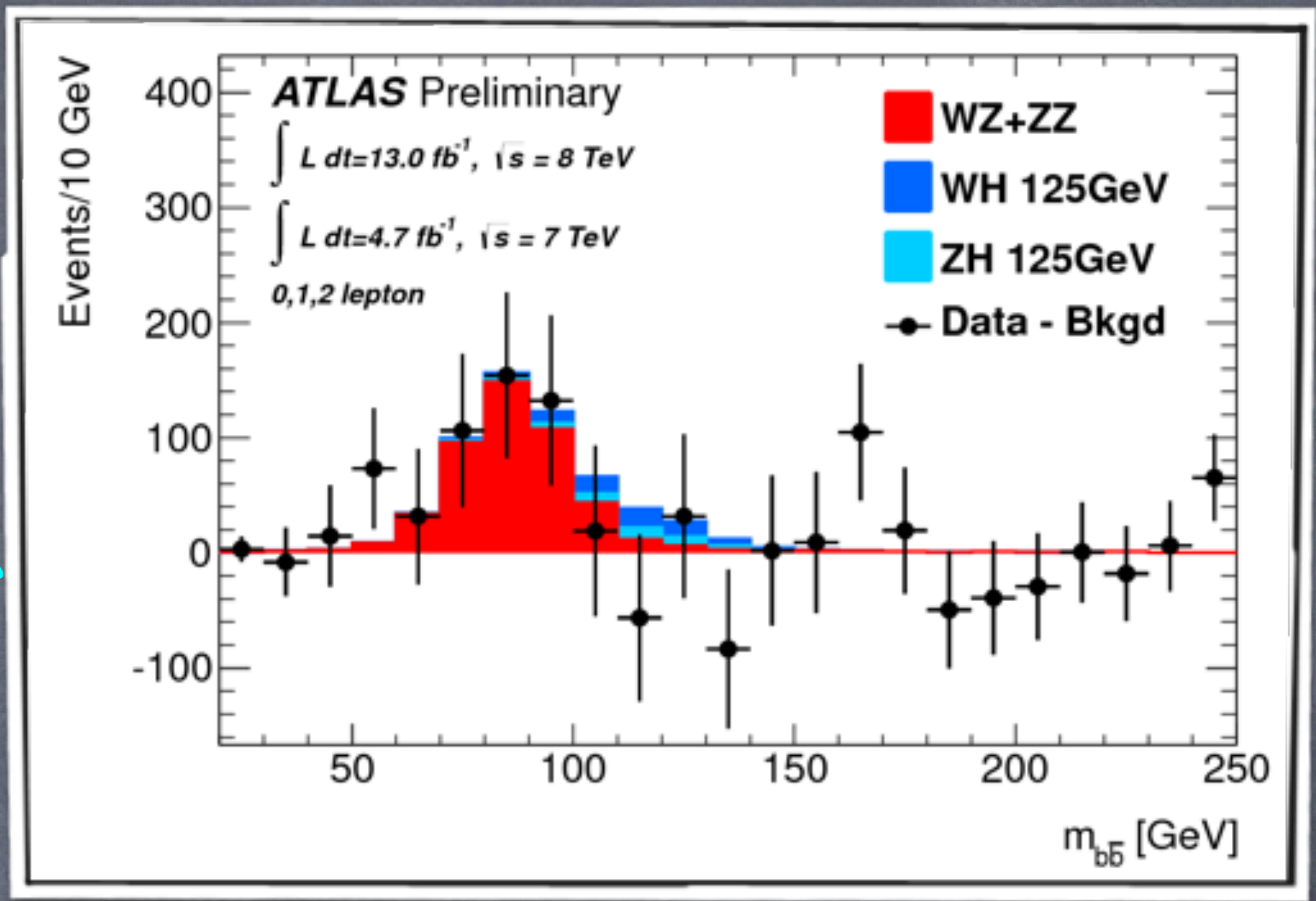
- H->bb is the dominant decay of a low mass Higgs.
  It also extremely important to measure Higgs couplings.
- Multi-jet background kills its inclusive production
- W/ZH is feasible for low Higgs mass channels: $l\nu$ bb,llbb and $\nu\nu$bb
- Signature (0,1,2)leptons,MET and 2 b-tagged jets
- Z/W+jets and tt BG can be reduced by requiring **boosted Higgses** with tight b-tag (no substructure)





H->bb: W/ZH->W/Zbb

- Proof of feasibility:
  - Observation of WZ/ZZ with Z->bb peak from data after subtraction of all non-di-Boson backgrounds



  - 4 σ excess
  - Measured rate μ=1.09±0.28

H->bb: W/ZH->W/Zbb

7TeV data: 2σ deficit

8TeV data: 1σ excess

Sensitivity still far from SM

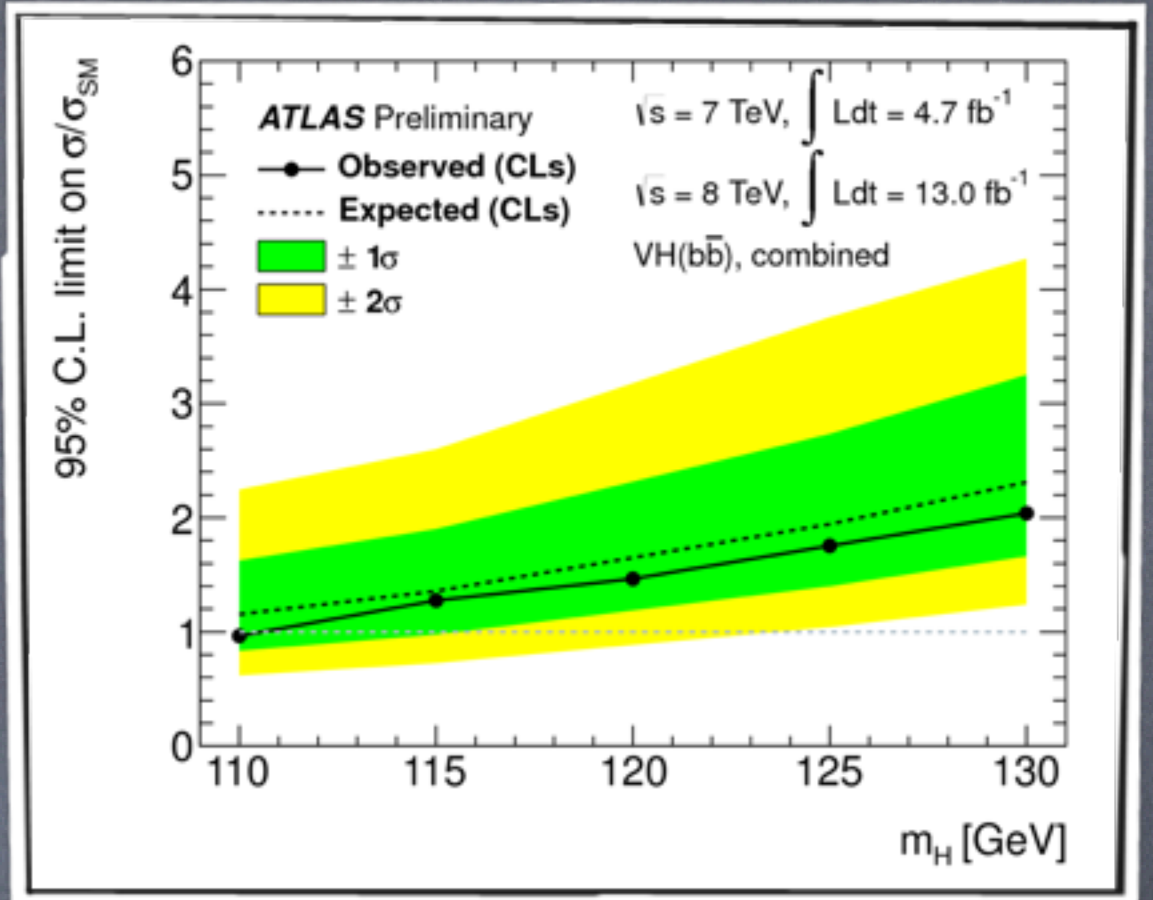
p0 expected (obs) @ 125=

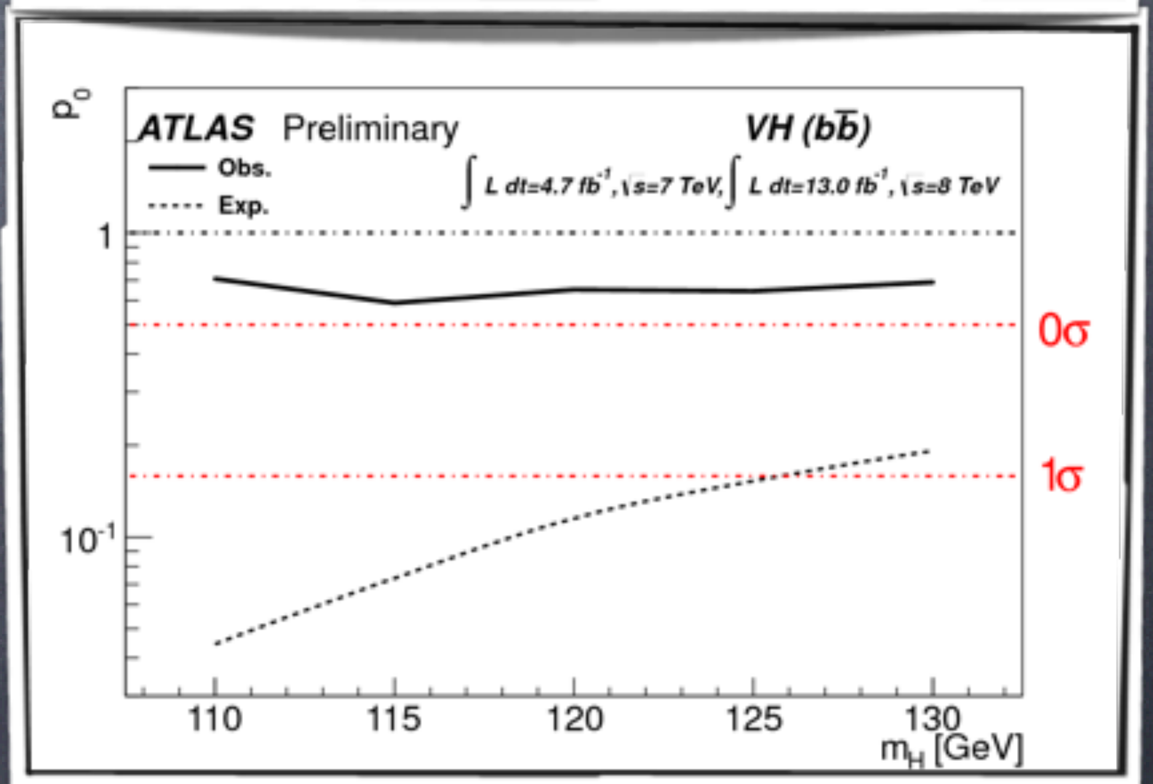
0.15 (0.64)

$7TeV : \hat{\mu} = -2.7 \pm 1.1(stat) \pm 1.1(syst)$

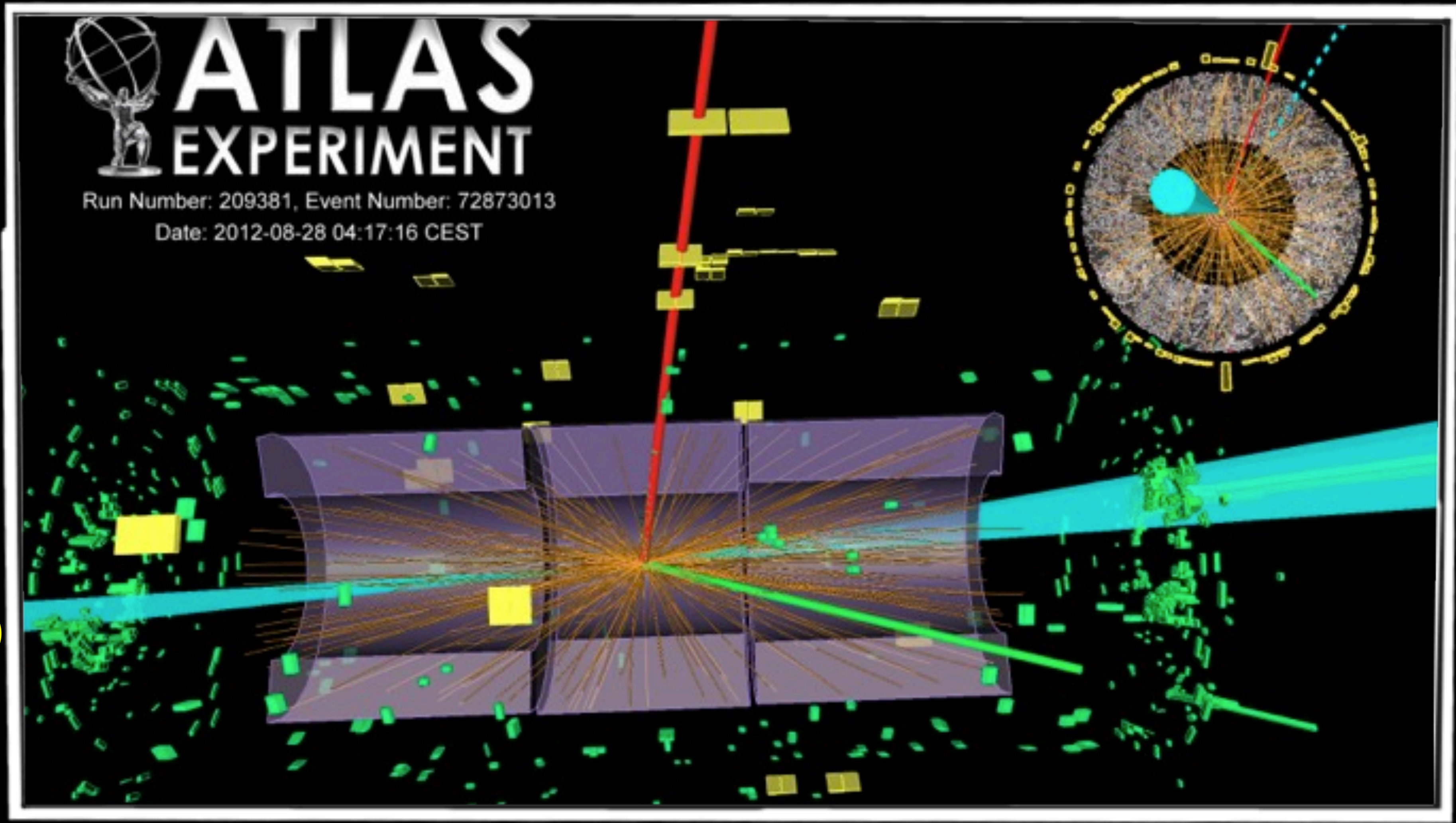
$8TeV : \hat{\mu} = 1.0 \pm 0.9(stat) \pm 1.1(syst)$

$Combined : \hat{\mu} = -0.4 \pm 0.7(stat) \pm 0.8(syst)$





H->ττ

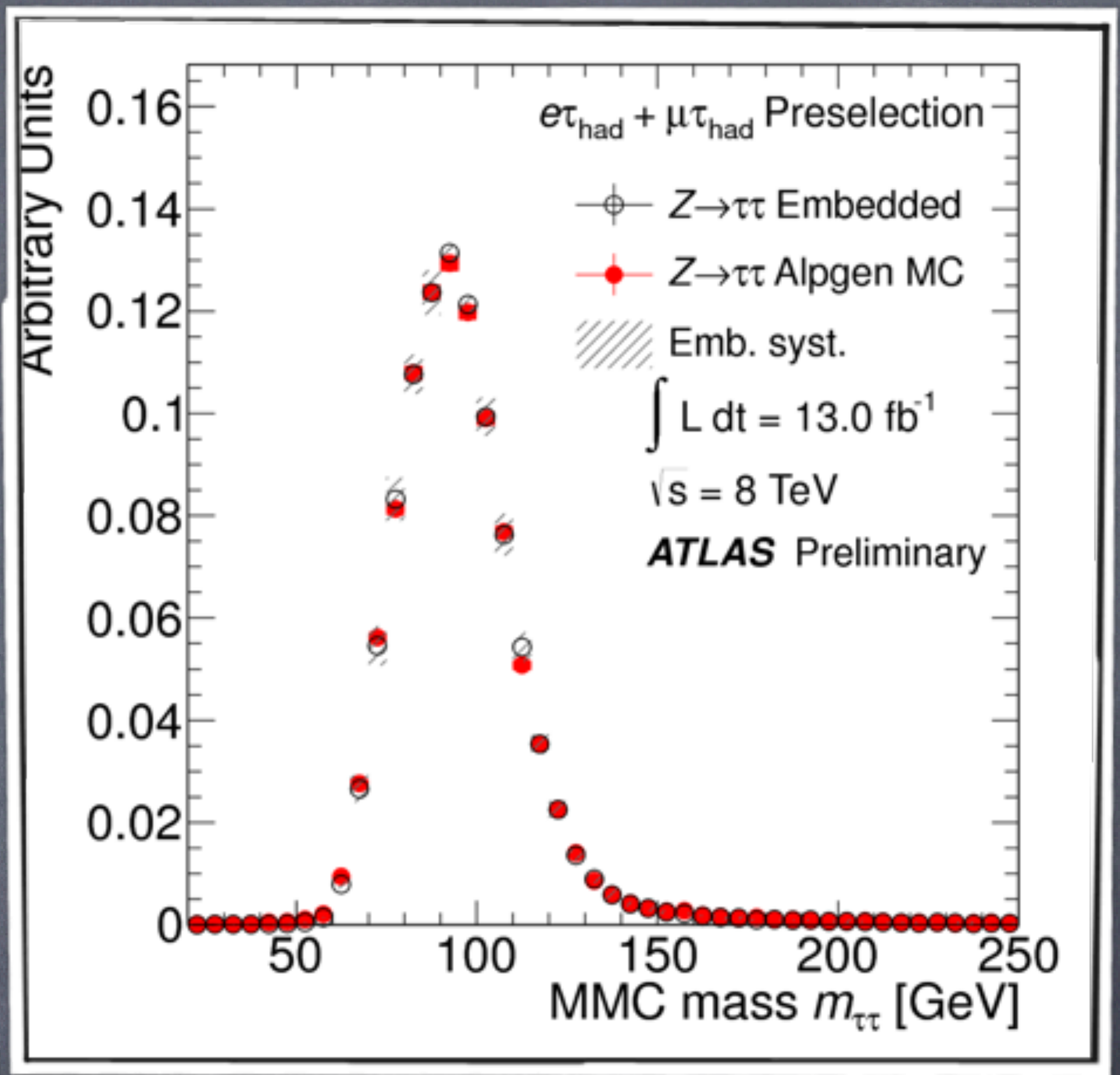


$\sigma \times BR$
$(m_H = 125 GeV)$
$\sim 1.3 pb$

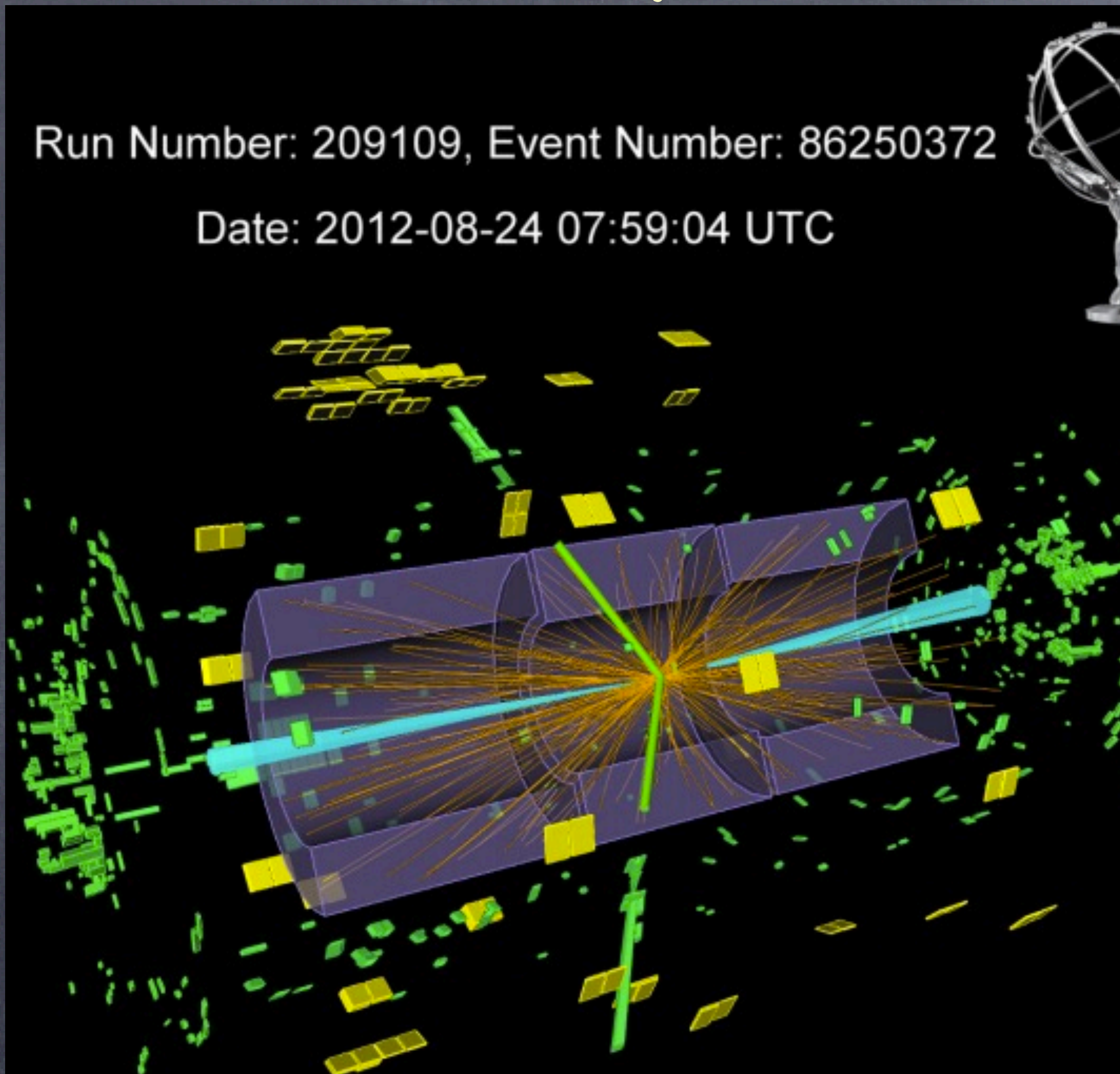
Prod	Luminosity	BG	Signal (126.5 GeV)	s/b
ggF,VH,VBF	4.9+13 fb^{-1}	Z+jets, W+jets, QCD, top	~330	~0.3-10%

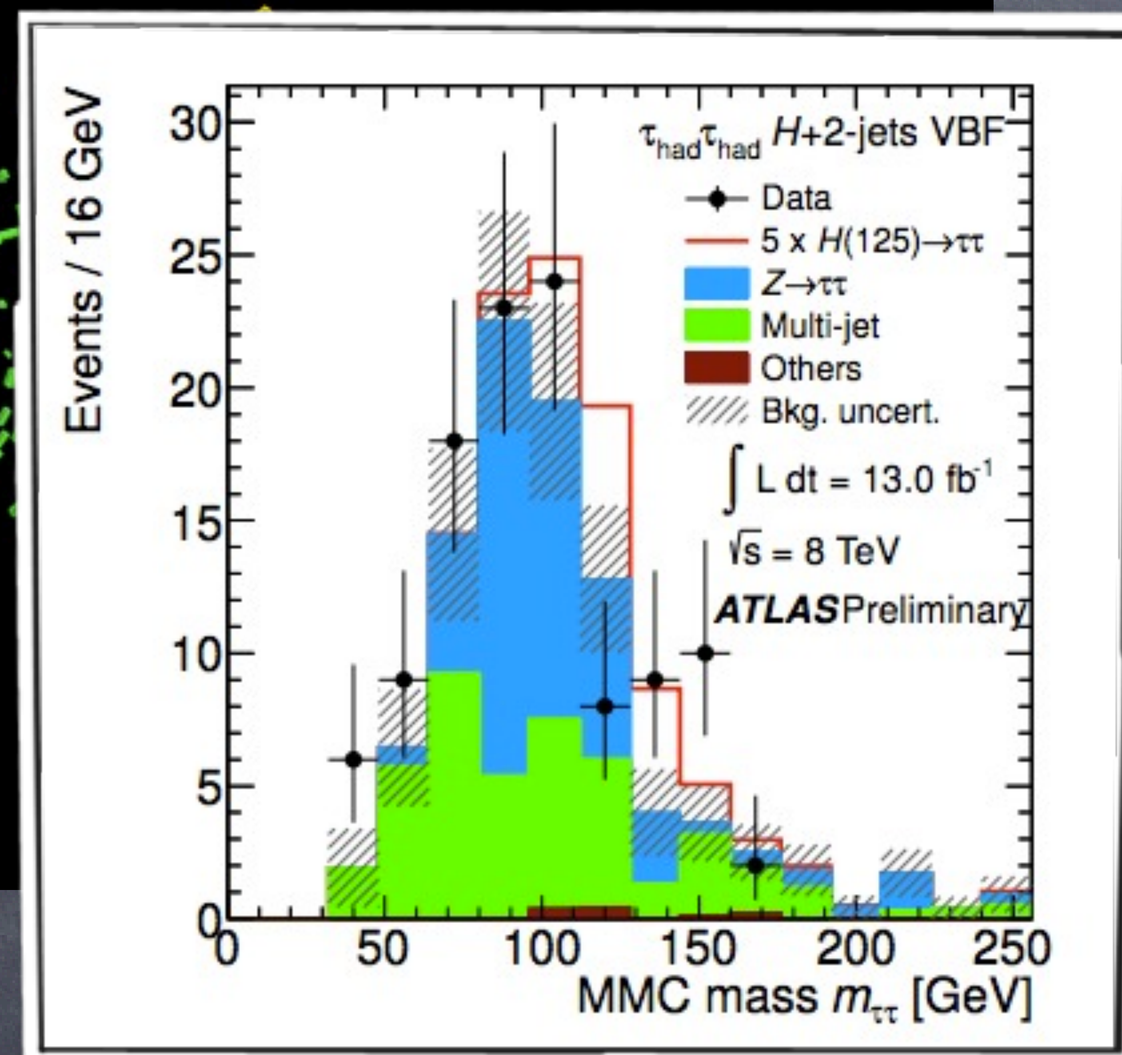
H->ττ (ℓ ℓ , ℓ had, had had)

- Important for couplings
- Huge BG from Z+jets, top and fakes
- Z->ττ from embedding (Z->μμ. replace Muon by Tau)
- Discrimination based on MMC ττ mass



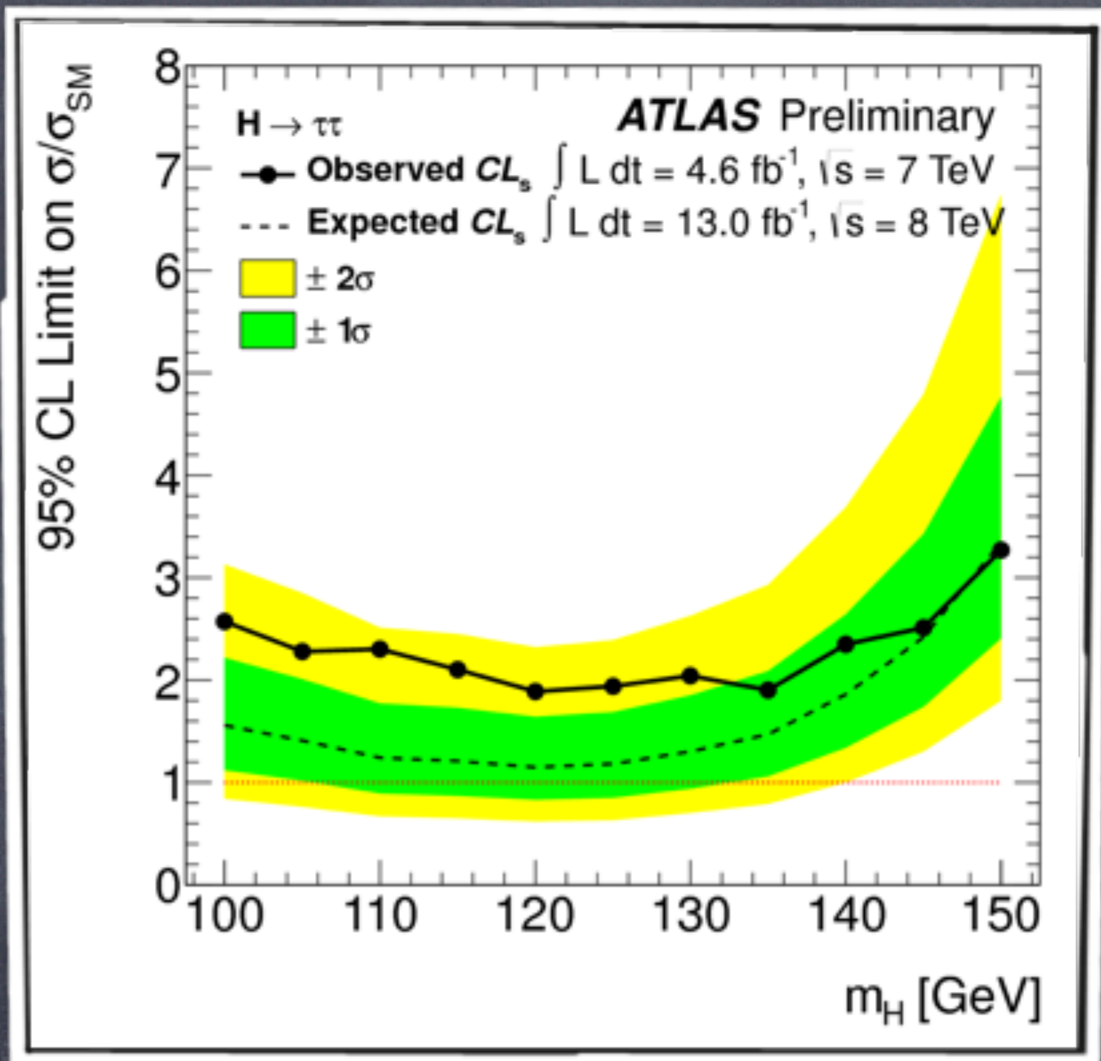
H->ττ (ℓ ℓ , ℓ had, had had)

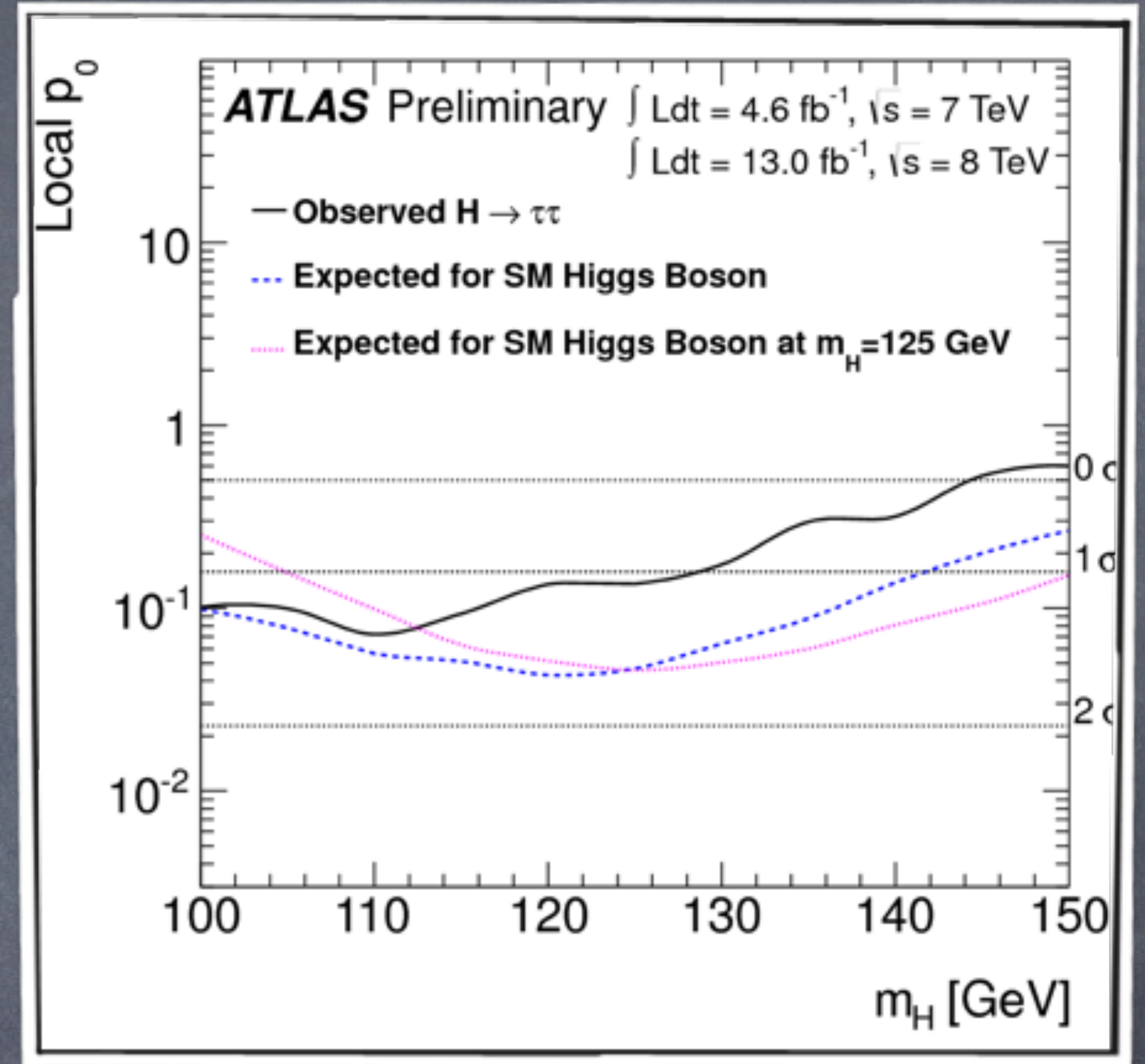




- hadhad VBF
  MMC=131 GeV

H->ττ (ℓ ℓ , ℓ had, had had)



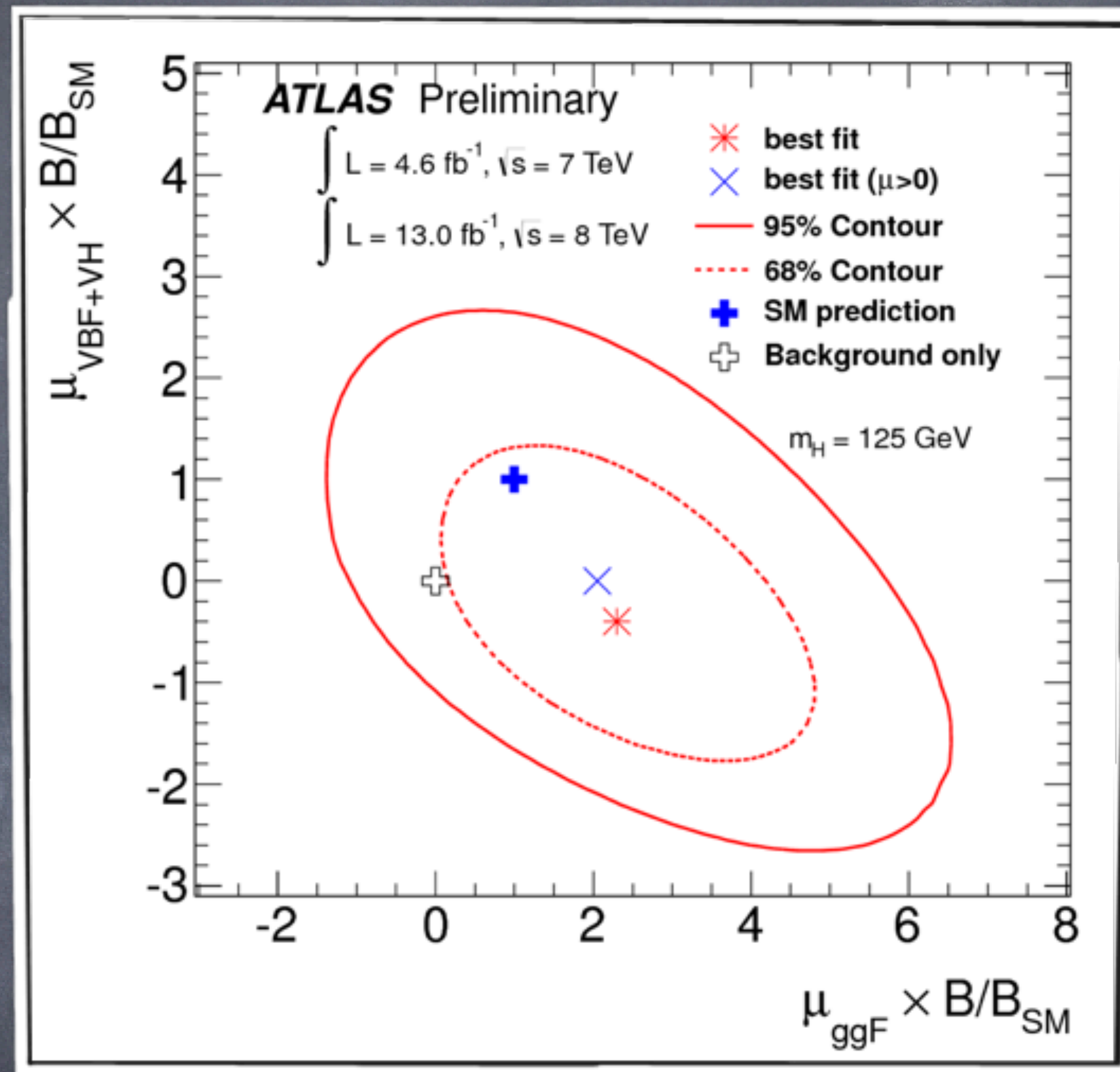


- Sensitivity is not yet enough
- @ mH=125, expected (obs) limit = 1.2 (1.9 x SM) - a slight excess
- @mH=125, a 1.1 σ observed

  1.7 σ expected

H->ττ (ℓ ℓ , ℓ had, had had)

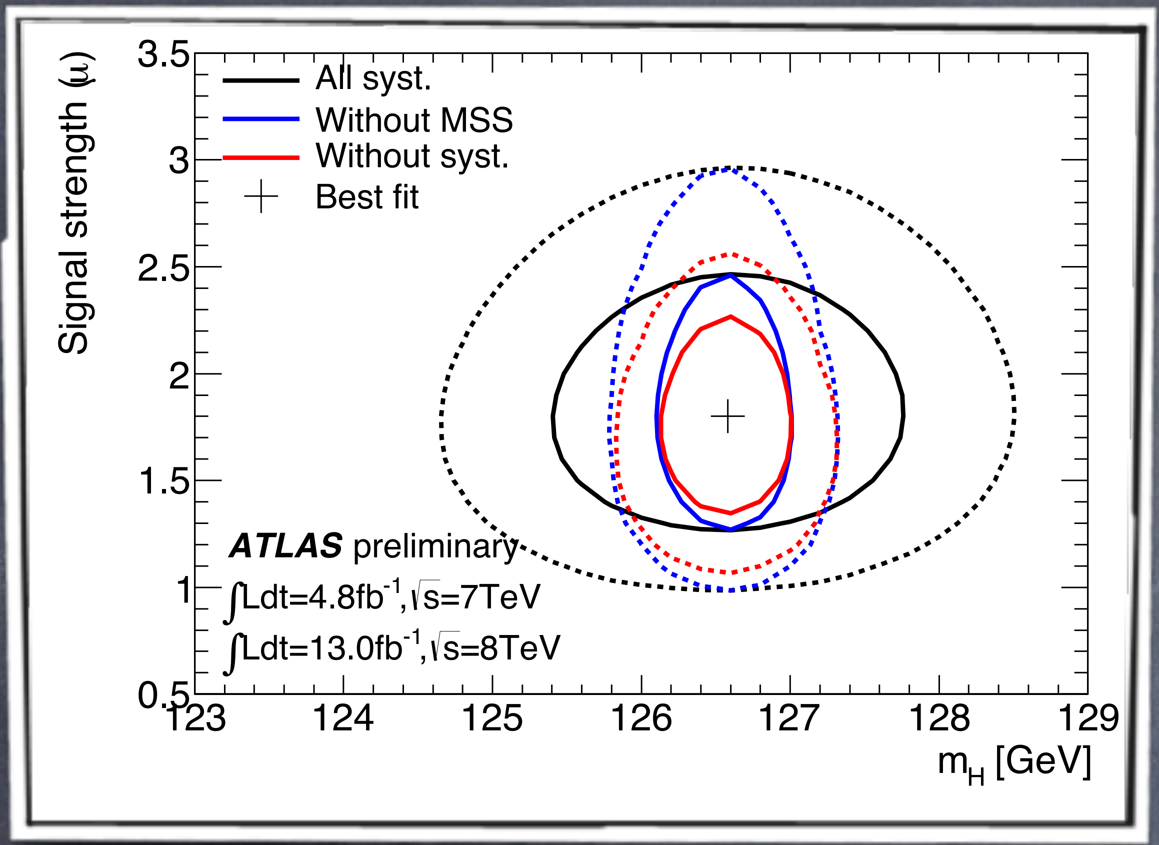
- Couplimgs are consistent with SM within 1 σ, but no significant statement about H->tautau can be made yet

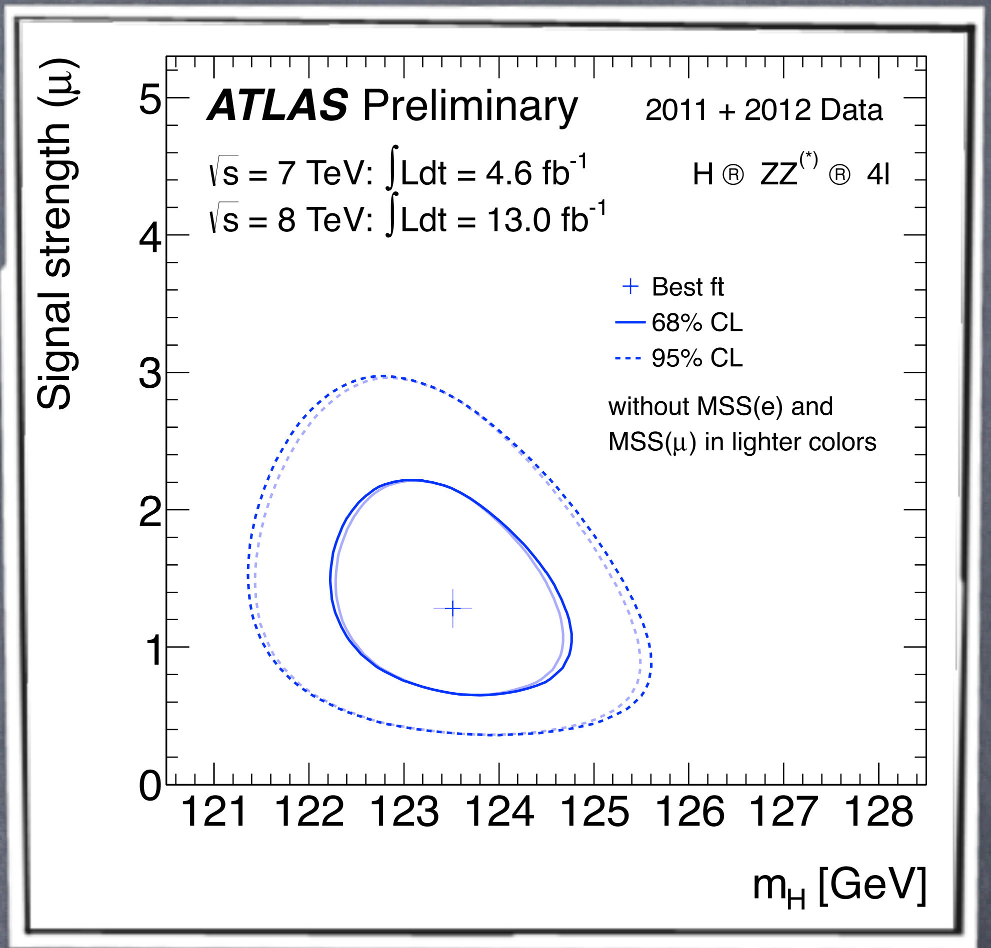


1.7 σ expected

Combining Results

Combining 4 ℓ and γγ





$$\hat{\mu} = 1.8 \pm 0.3\ (stat)^{+0.29}_{-0.15} (syst)^{+0.20}_{-0.14}\ (theory)$$

$$m_H = 126.6 \pm 0.3\ (stat) \pm 0.7\ (syst)\ \text{GeV}$$

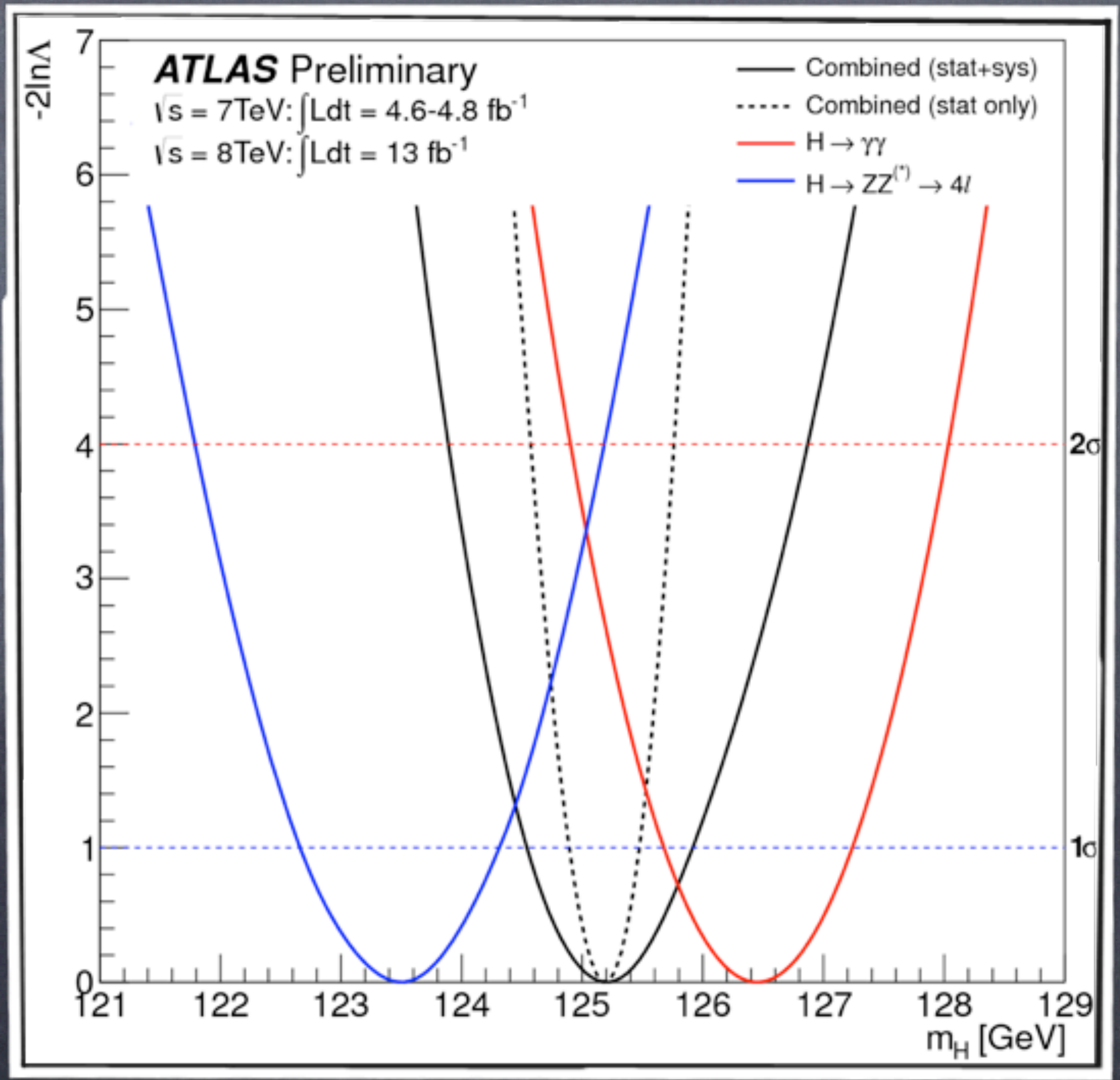
$$\hat{\mu} = 1.3 \pm 0.4$$

$$m_H = 123.5 \pm 0.9 (stat)^{+0.4}_{-0.2} (syst) GeV$$

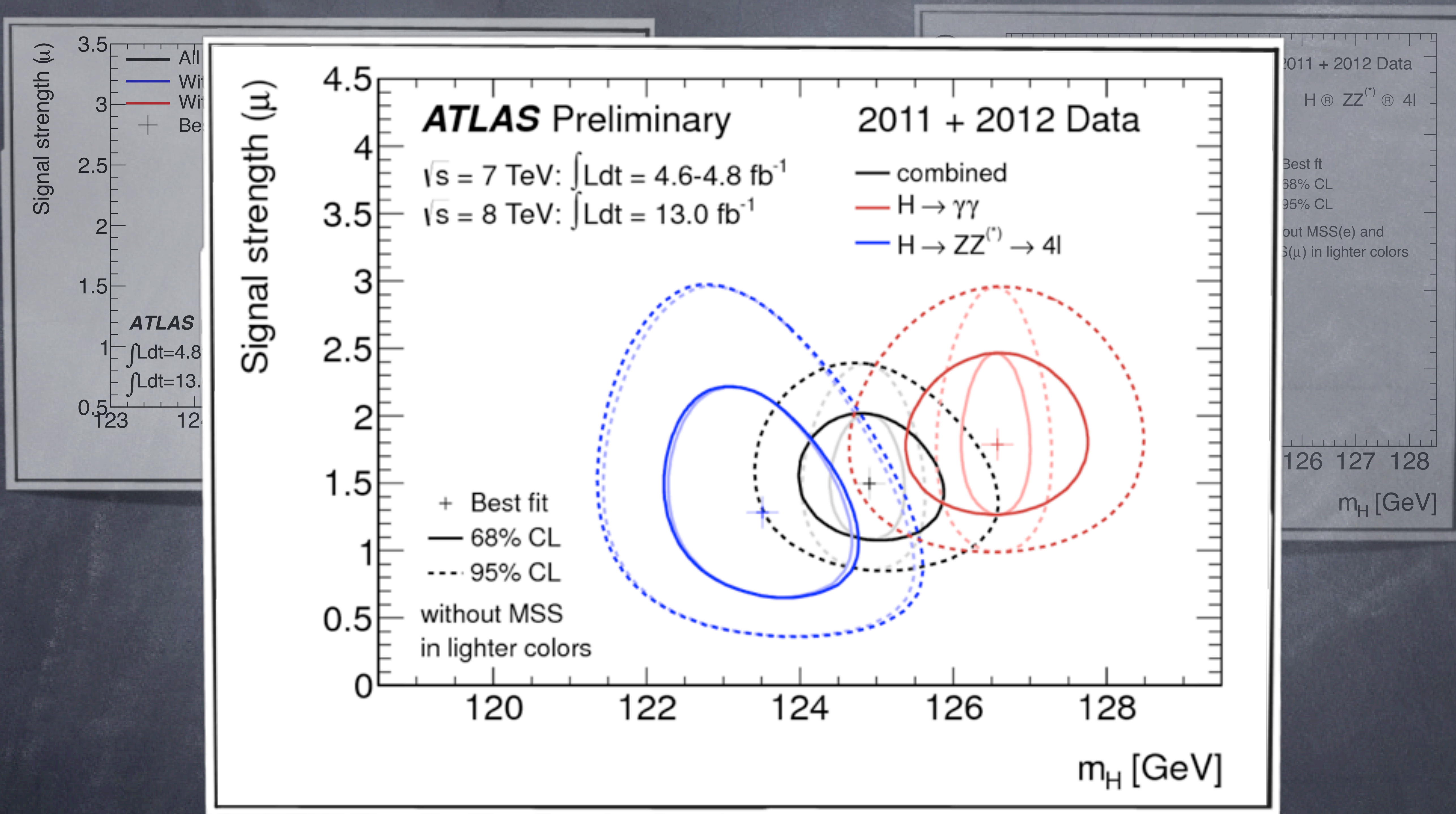
Combining 4 ℓ and $\gamma\gamma$

$$\Lambda(m_H) = \frac{L(m_H\,,\,\hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(m_H)\,,\,\hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\theta})}$$

Here, the signal strengths are left free in the fit



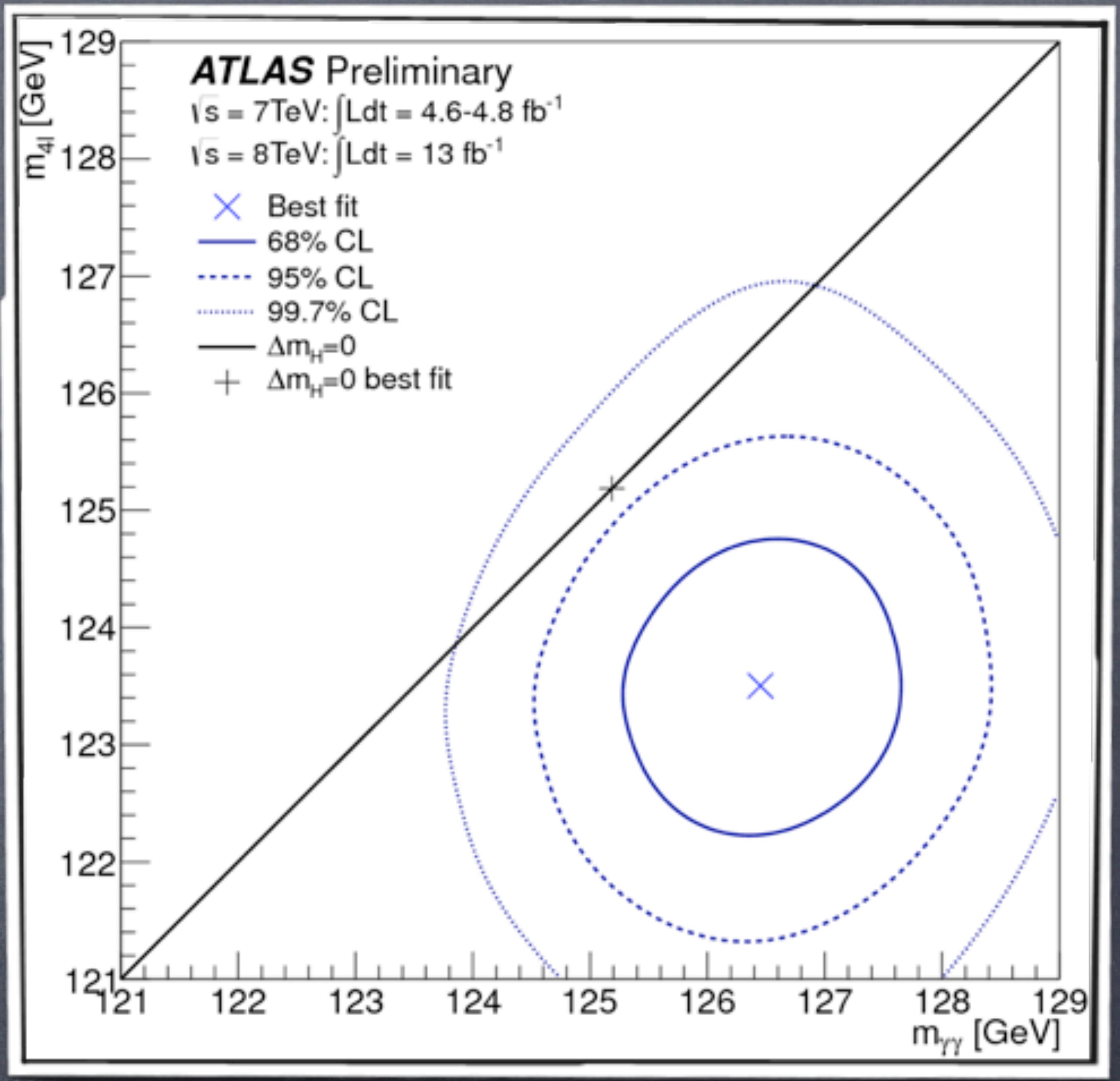
Combining 4 ℓ and $\gamma\gamma$



$$m_H = 125.2 \pm 0.3\ (stat)\ \pm\ 0.6\ (syst)\ \text{GeV}$$

Consistency of 4 ℓ and $\gamma\gamma$ mass measuremenst

- The two mass measurements are almost uncorrelated
- Largest correlation is the overall e/γ energy scale (from Z->ee calibration) affecting mostly the $\gamma\gamma$ channel



Consistency of 4 ℓ and $\gamma\gamma$ mass measuremenst

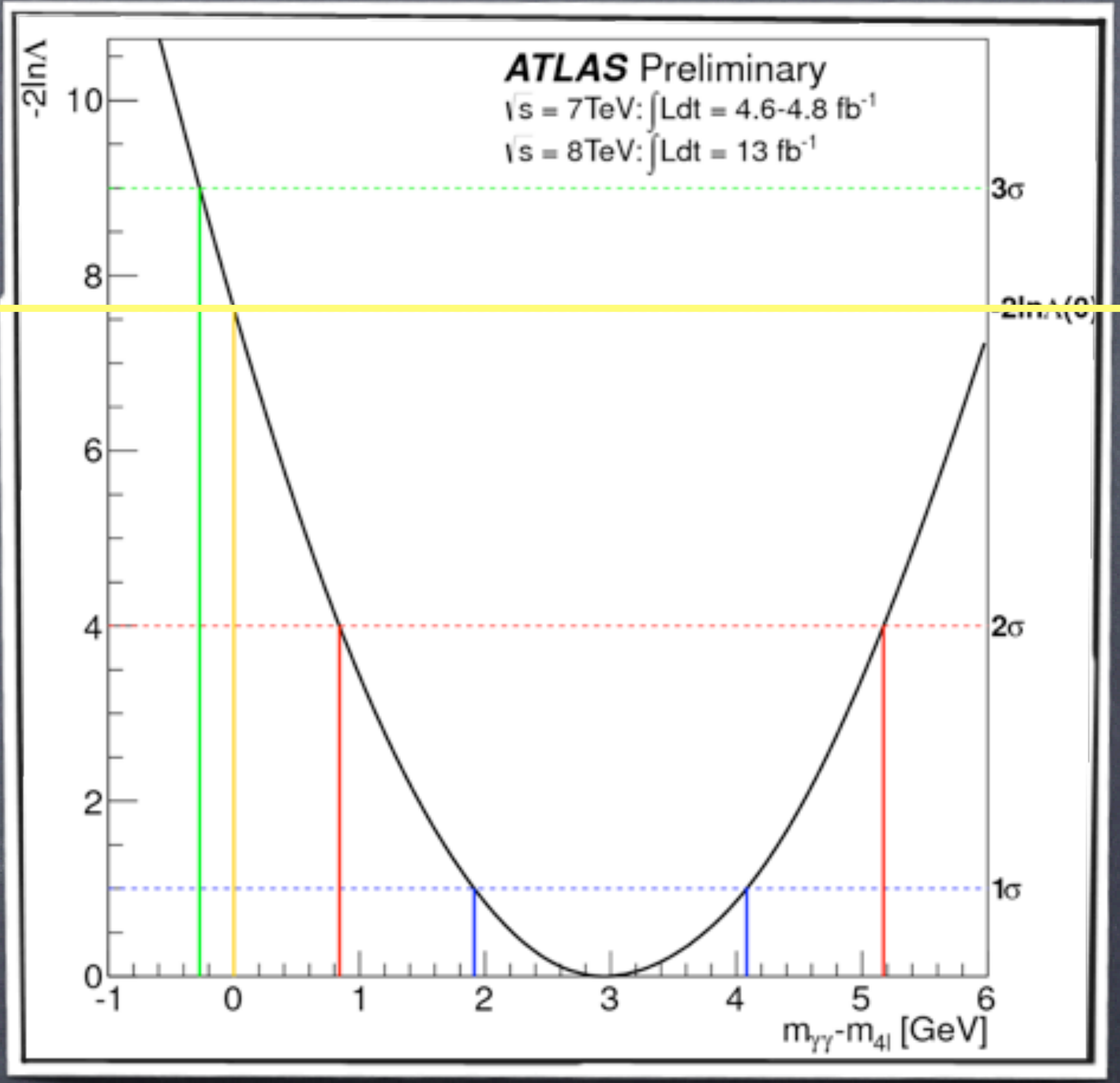
$$\Lambda(\Delta m_H) = \frac{L(\Delta m_H\,,\,\hat{\hat{\mu}}_{\gamma\gamma}(\Delta m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(\Delta m_H)\,,\,\hat{\hat{m}}_H(\Delta m_H)\,,\,\hat{\hat{\theta}}(\Delta m_H))}{L(\hat{\Delta m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{m}_H, \hat{\theta})}$$

- Test the $\Delta m_H=0$ hypothesis

$$q = -2\log\Lambda(\Delta m_H)$$

$$\sqrt{q(\Delta m_H = 0)} = 2.7\sigma$$

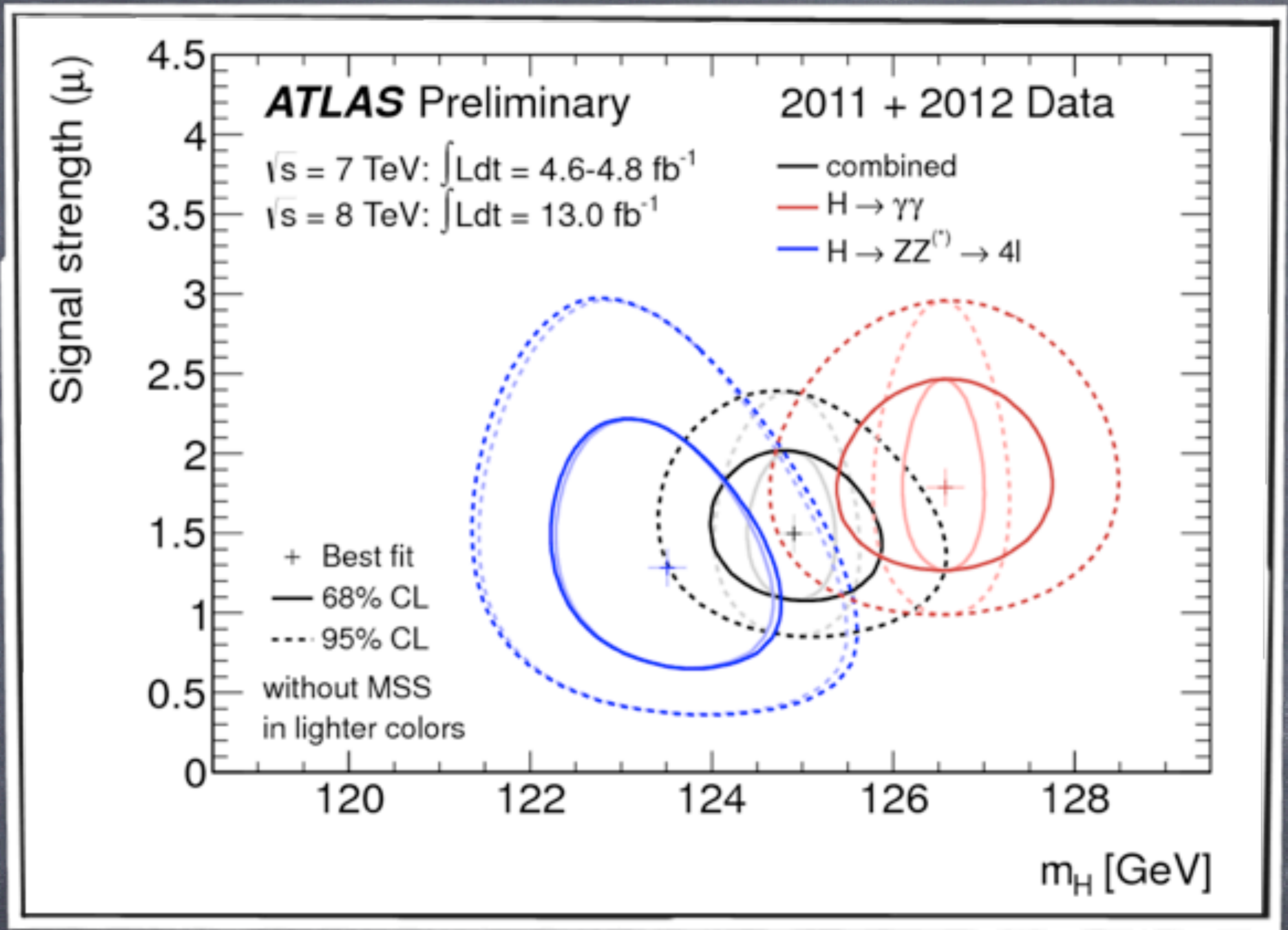
- The (2-sided) probability for a single Higgs Boson to produce a value of the test statistic disfavoring the $\Delta m_H=0$ hypothesis more than the observed is 0.6% (2.7 σ)
- Using toy experiments similar results are achieved
- Using rectangular pdf for ESS, the mass difference significance is reduced to 2.3 σ (p-value=2.3%)



$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 3.0^{+1.1}_{-1.0}\ \mathrm{GeV} = 3.0 \pm 0.8\,(\mathrm{stat})\,^{+0.7}_{-0.6}\,(\mathrm{sys})\ \mathrm{GeV}$$

Combining 4 ℓ and $\gamma\gamma$

- Let $q = -2\log\Lambda(\mu, m_H; \theta)$ (2 parameters of interest)

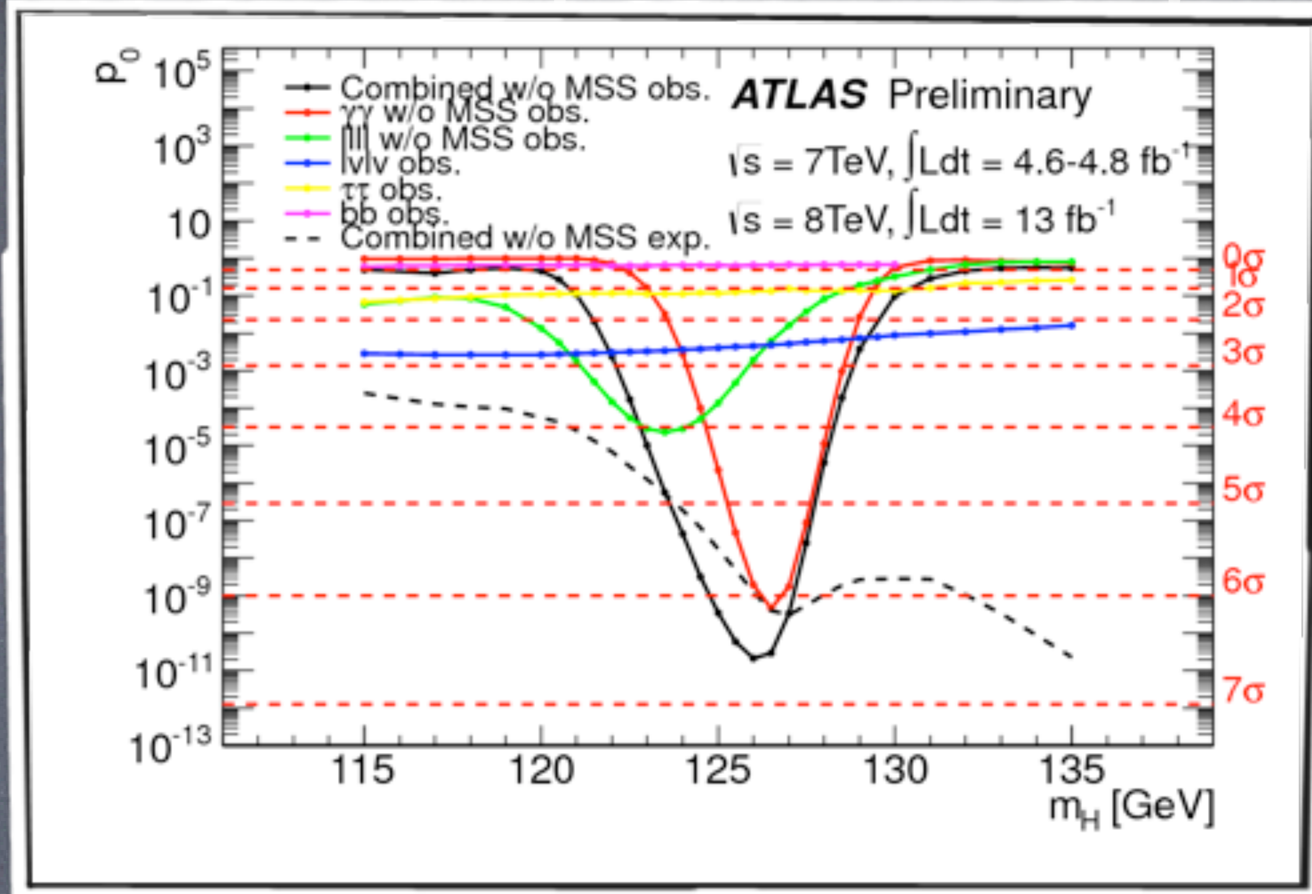


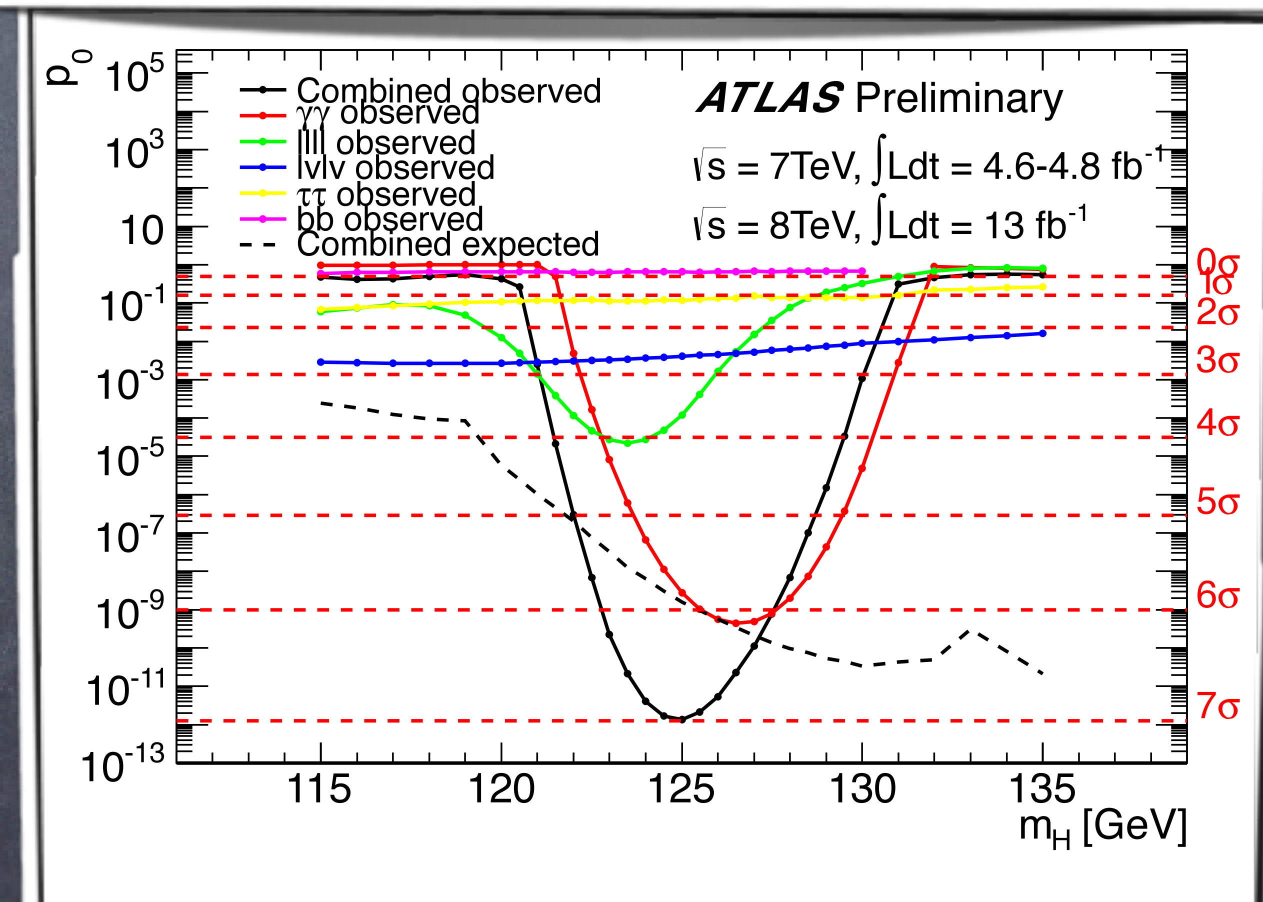
$$\hat{\mu} = 1.35 \pm 0.19\ (stat) \pm 0.15\ (syst)$$

$$m_H = 125.2 \pm 0.3\ (stat)\ \pm\ 0.6\ (syst)\ \text{GeV}$$

Significance and Production Signal Strength

	expected	observed
W/O MSS		6.6 σ
With MSS	5.9 σ	7.0 σ





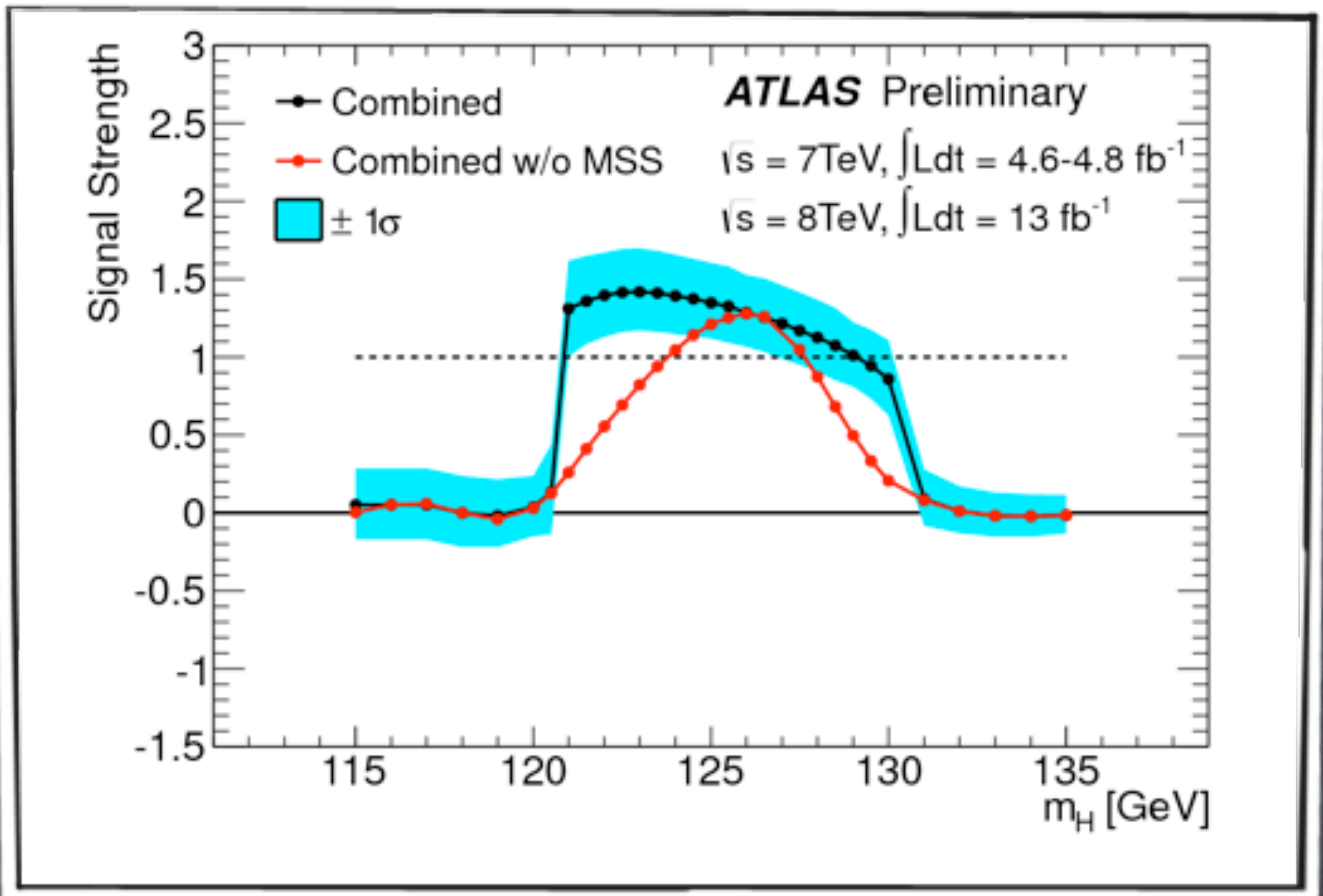
- The MSS are taken into account with asymptotic approximation which known to increase the significance by O(0.1 σ)

Significance and Production Signal Strength

$$\Lambda(\mu; m_H) = \frac{L(\mu, \hat{\hat{\theta}}(\mu); m_H)}{L(\hat{\mu}, \hat{\theta}; m_H)}$$

$$\hat{\mu} = 1.35 \pm 0.19\ (stat) \pm 0.15\ (syst)$$

- The signal strength is consistent with a SM Higgs (μ=1)

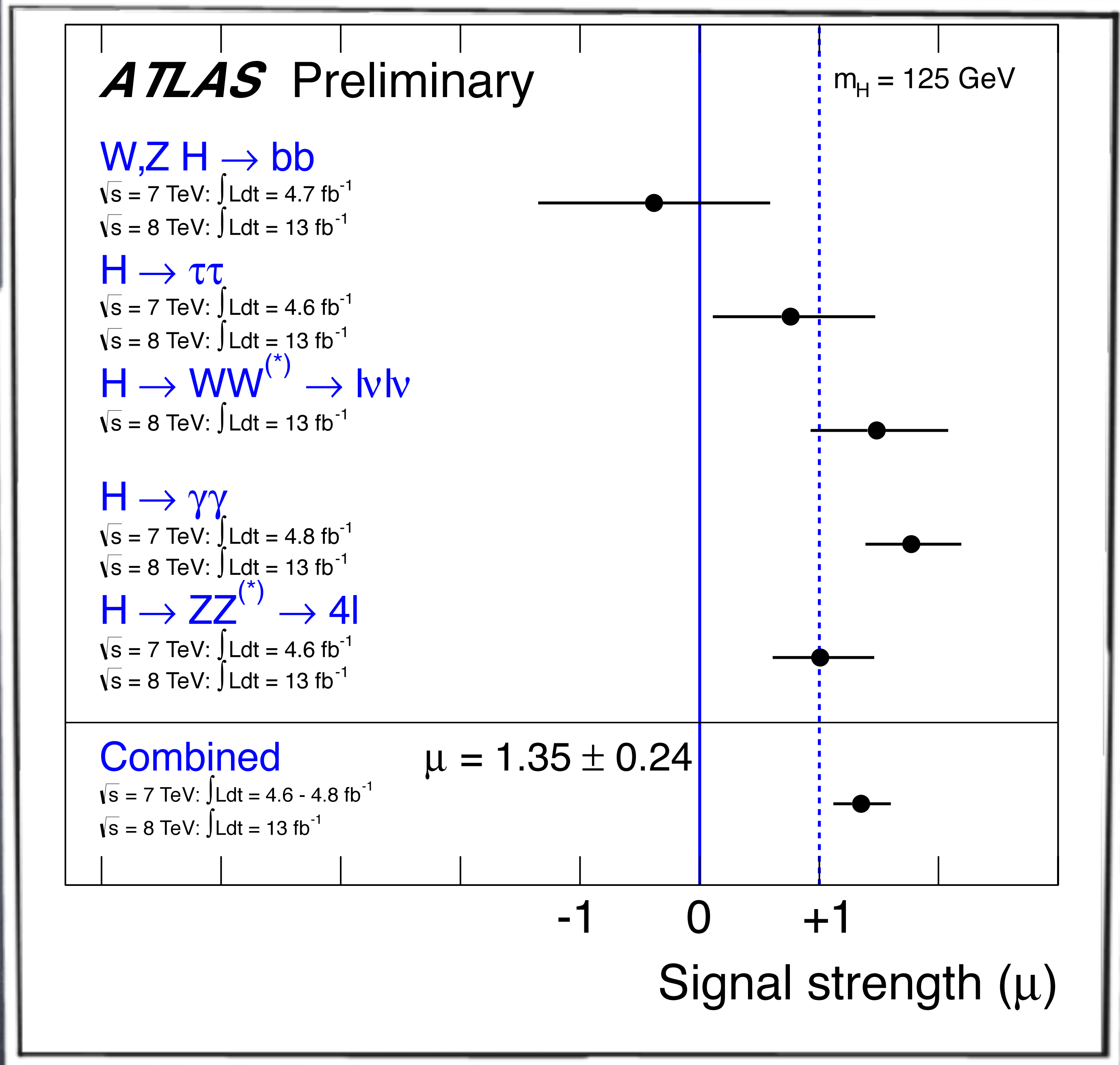


Significance and Production Signal Strength

$$\Lambda(\mu; m_H) = \frac{L(\mu, \hat{\hat{\theta}}(\mu); m_H)}{L(\hat{\mu}, \hat{\theta}; m_H)}$$

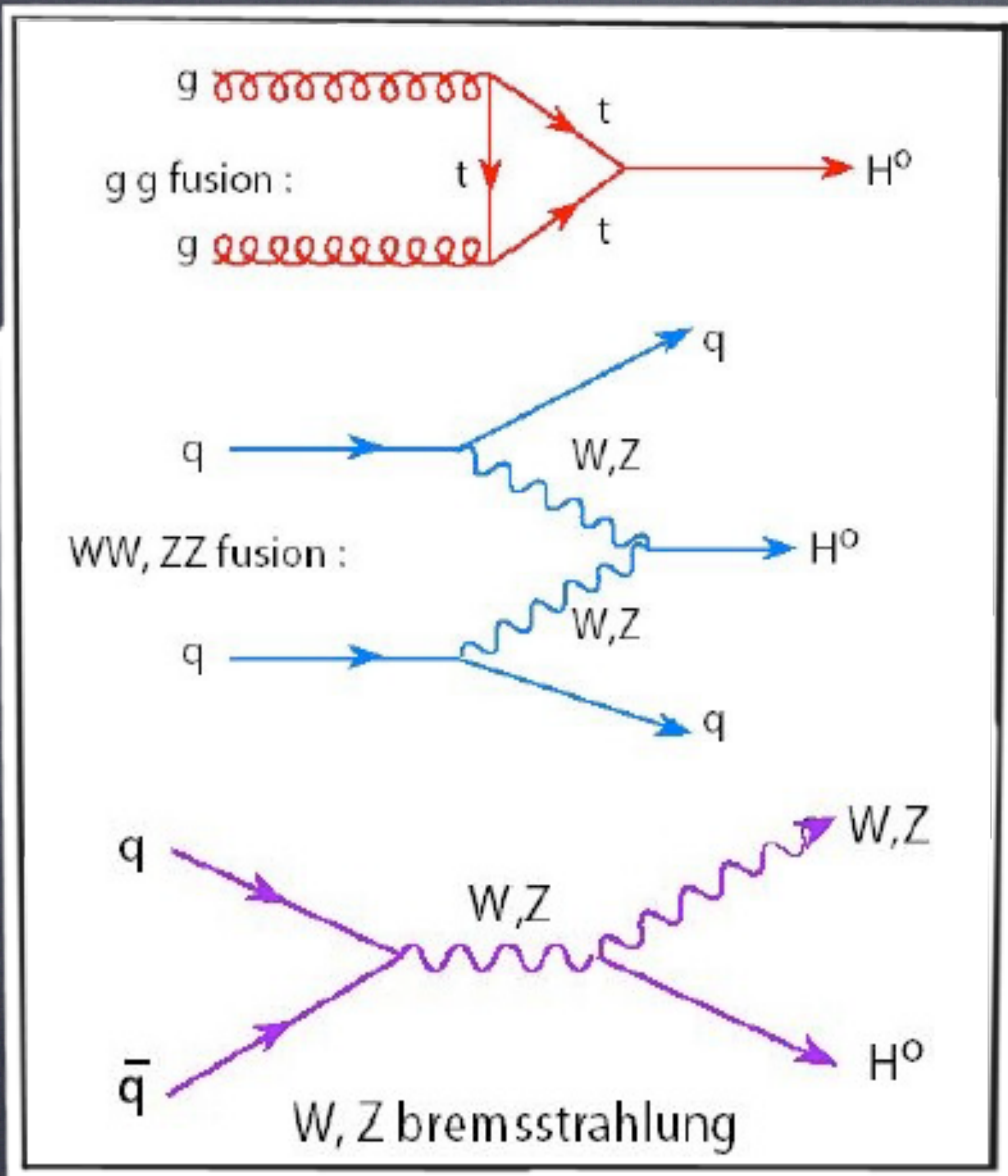
$$\hat{\mu} = 1.35 \pm 0.19\ (stat) \pm 0.15\ (syst)$$

Higgs Boson Decay	μ (m_H=125 GeV)
$VH \to Vbb$	-0.4 ± 1.0
$H \to \tau\tau$	0.8 ± 0.7
$H \to WW^{(*)}$	1.5 ± 0.6
$H \to \gamma\gamma$	1.8 ± 0.4
$H \to ZZ^{(*)}$	1.0 ± 0.4
Combined	1.35 ± 0.24

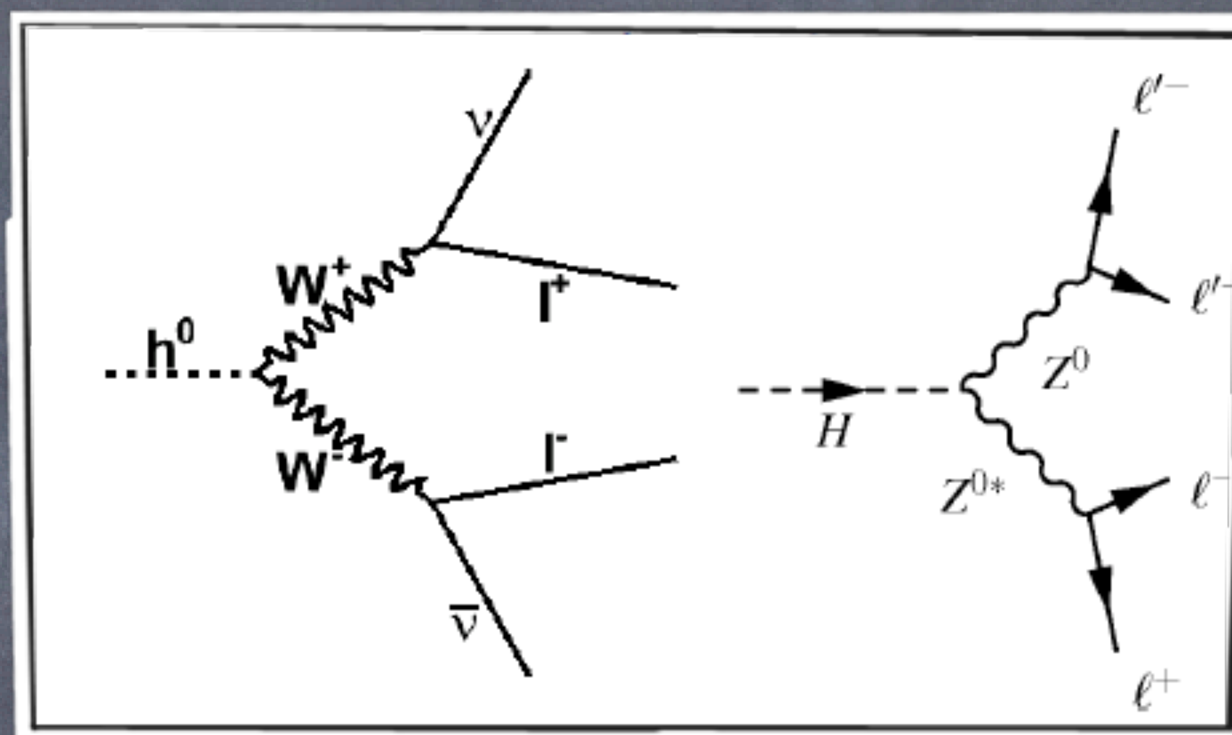


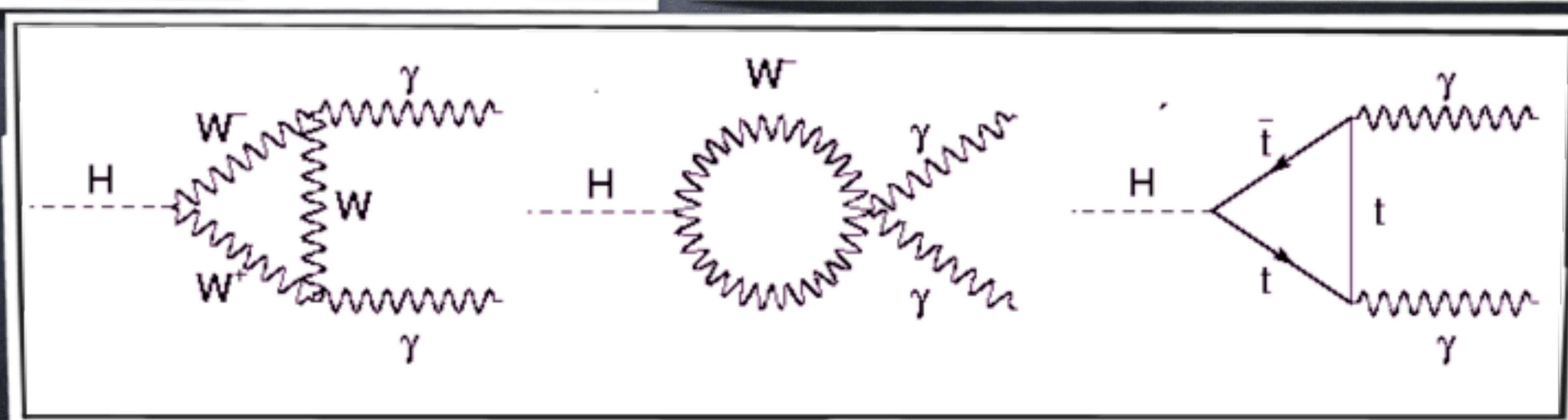
- Changing the mass value between 123.5-126.5 GeV changes the best fitted signal strength by 10%

Analysis of Higgs Couplings



- A lot of information is contained in the various production and decay modes of the Higgs allowing us to perform various tests (direct and indirect via loops)

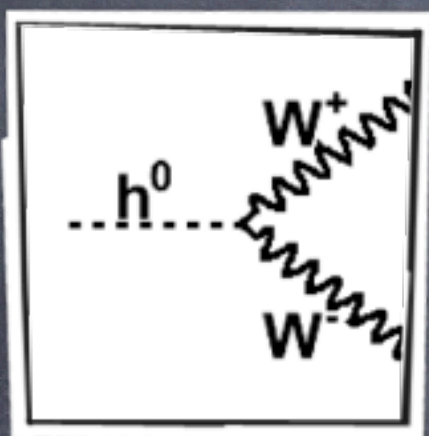




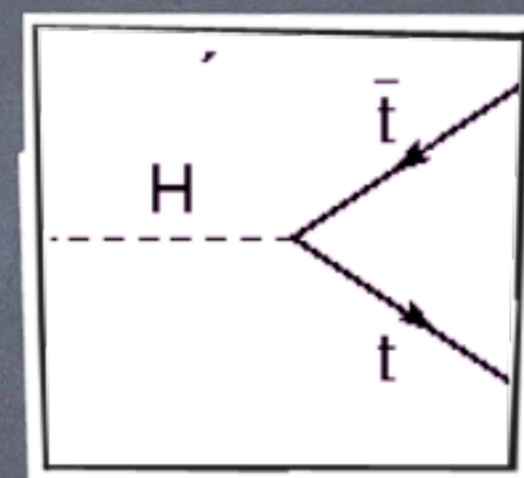
Analysis of Higgs Couplings

- The wealth of couplings and possibilities led to defining some benchmarks by the LHC Higgs Cross Section group

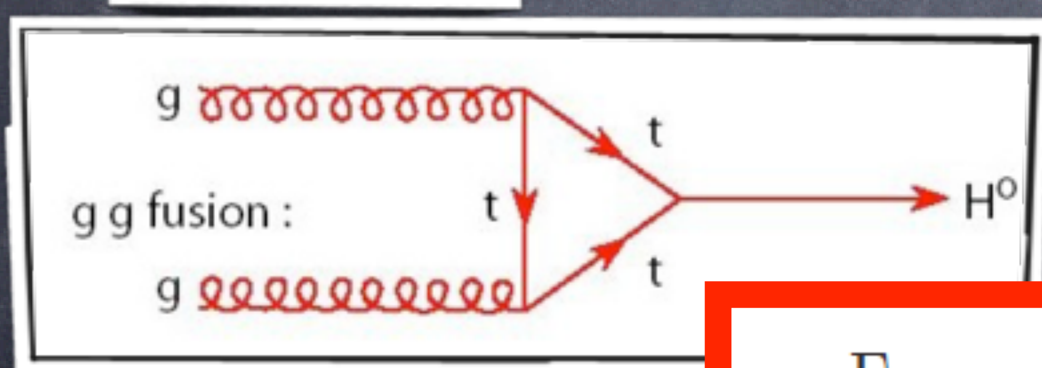
- For each coupling g_i, define $k_i = g_i / g_i^{SM}$, so if the coupligs are SM like we find that $k_i = 1$



$$\frac{\Gamma_{WW}}{\Gamma_{WW}^{SM}} = k_W^2$$

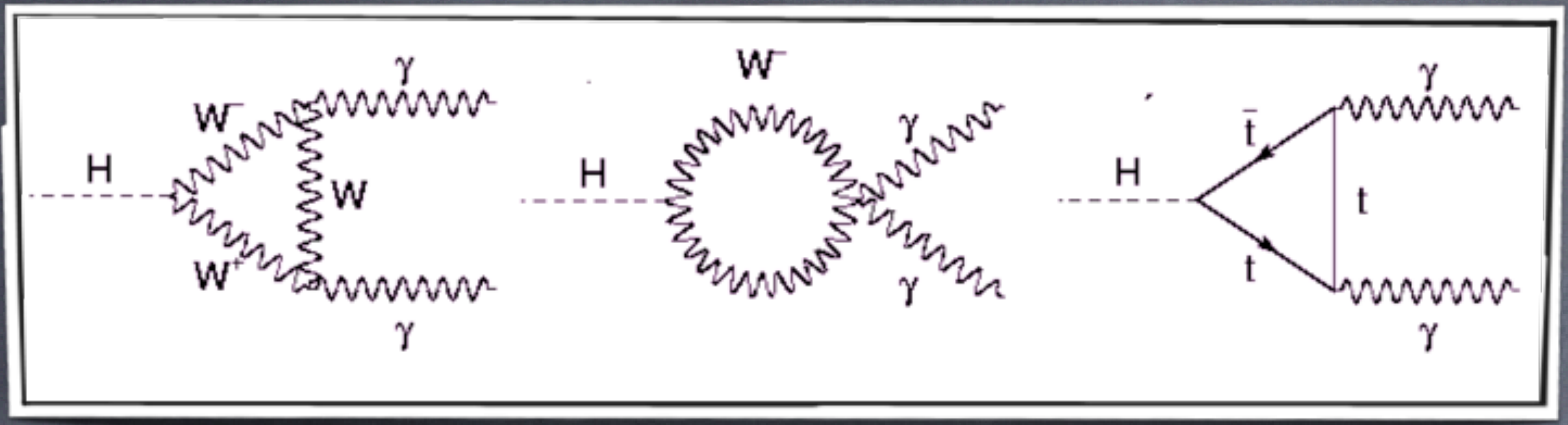


$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = k_t^2$$



$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}(m_H)} = \frac{\kappa_t^2 \cdot \Gamma_{gg}^{tt}(m_H) + \kappa_b^2 \cdot \Gamma_{gg}^{bb}(m_H) + \kappa_t \kappa_b \cdot \Gamma_{gg}^{tb}(m_H)}{\Gamma_{gg}^{tt}(m_H) + \Gamma_{gg}^{bb}(m_H) + \Gamma_{gg}^{tb}(m_H)}$$

Analysis of Higgs Couplings



$$k_\gamma^2 = \left|1.28 k_W - 0.28 k_t\right|^2$$

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = k_H^2(k_i, m_H)$$

$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{k_g^2 \cdot k_\gamma^2}{k_H^2}$$

Analysis of Higgs Couplings

Make assumptions to test various couplings in the context of a SM Higgs

Simplest assumption, the universal coupling:

$\mu = k^2$

Common scale factor

Free parameter: $\kappa (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_W = \kappa_Z)$.

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^- \tau^+$
ggH					
$t\bar{t}H$					
VBF			κ^2		
WH					
ZH					

Analysis of Higgs Couplings

Make assumptions to test various couplings in the context of a SM Higgs

- **κ = sqrt(μ):** Universal scaling of couplings to all particles
- **κ_V vs. κ_F:** Spin, vector bosons vs. fermions
- **κ_W vs. κ_Z:** Custodial symmetry, W vs. Z boson
- **κ_q vs. κ_l:** Fermion flavor, quarks vs. leptons
- **κ_u vs. κ_d:** Fermion type, up vs. down

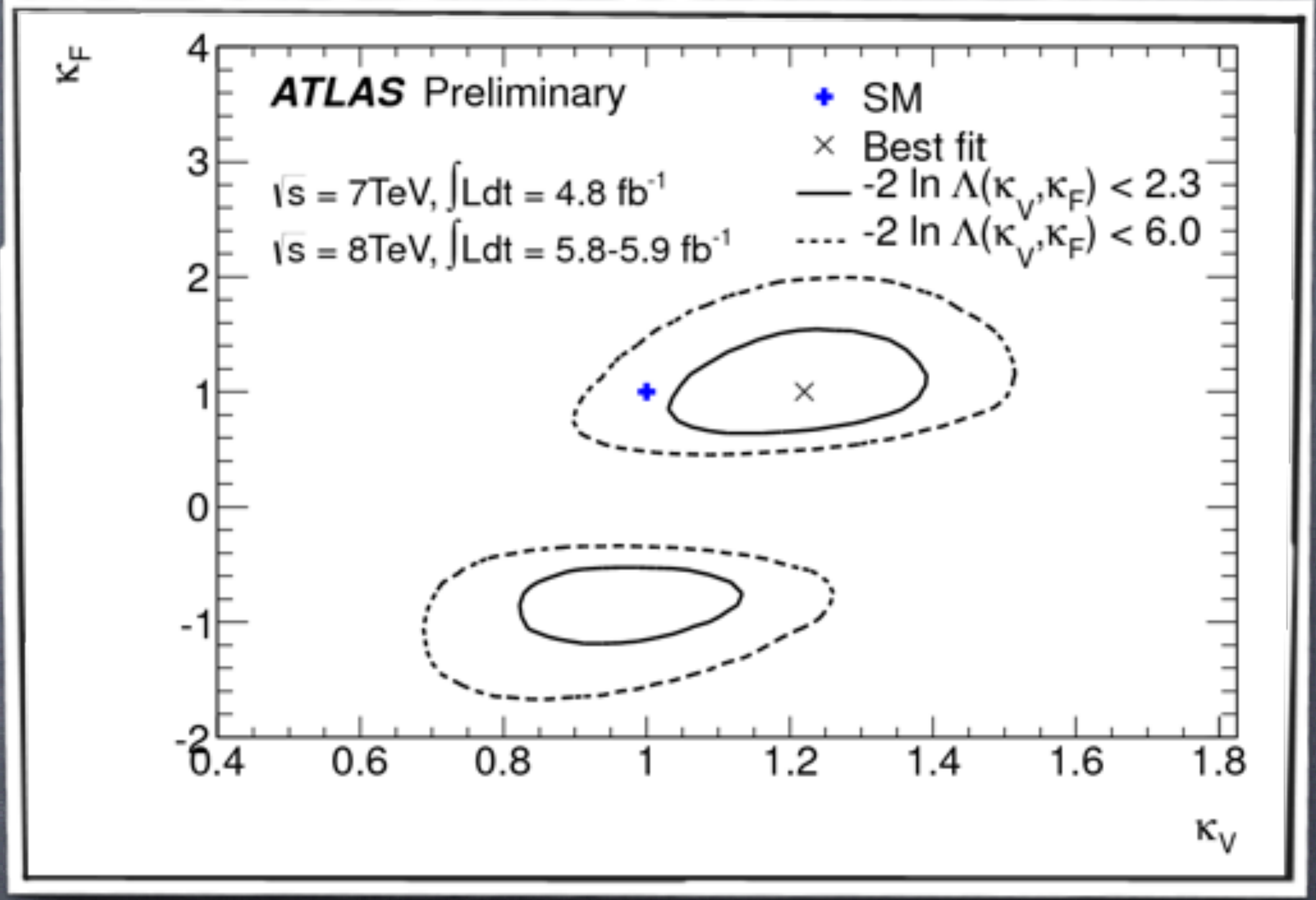
Analysis of Higgs Couplings

ATLAS fully analyzed only the HCP data set ($\sim$5.9 fb^{-1} @ 8 TeV), $\tau\tau$ and bb not included

Assume

$k_V=k_W=k_Z,\ k_f=k_t=k_b=\ldots$

Assume no invisiible width



2D scan in $L(k_v,k_f)$ reveals double minima due to interference

Couplings are consistent with SM

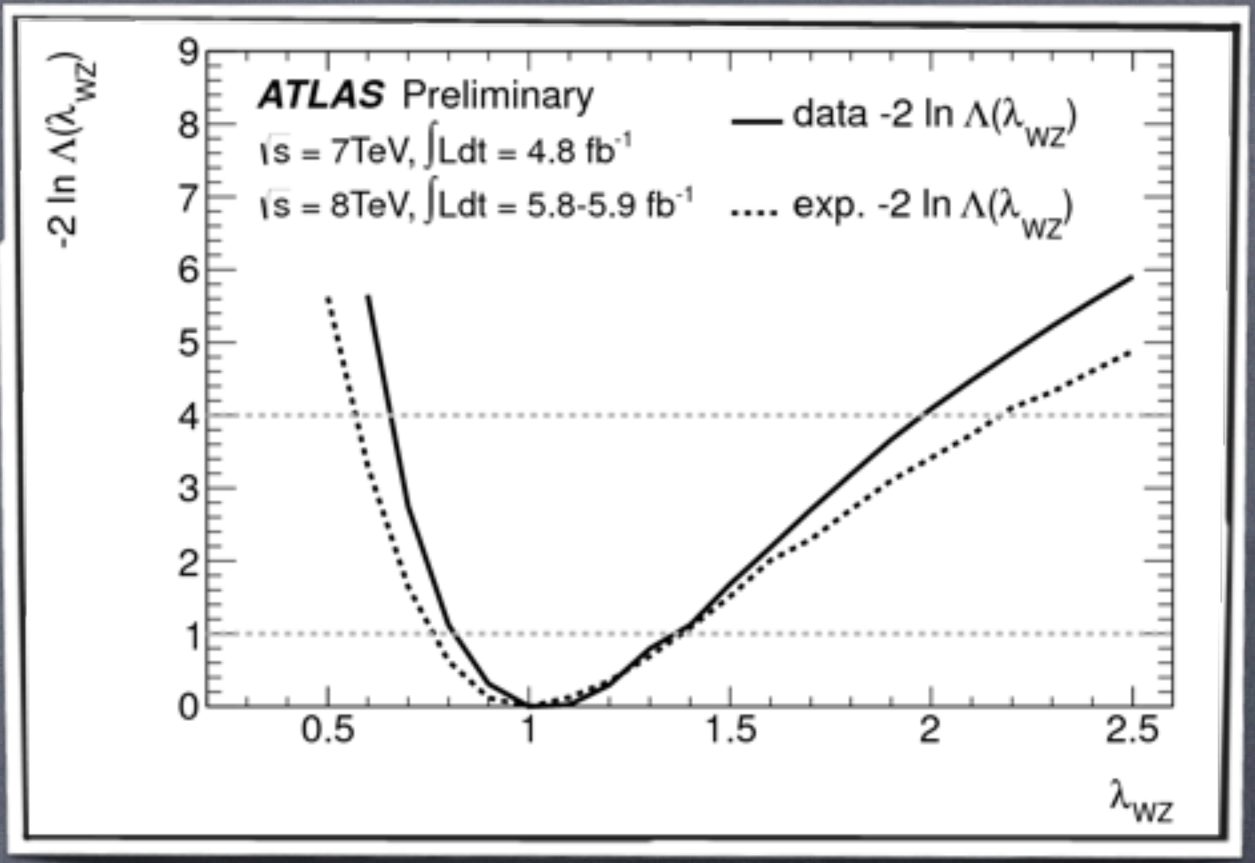
Analysis of Higgs Couplings

Probing custodial symmetry

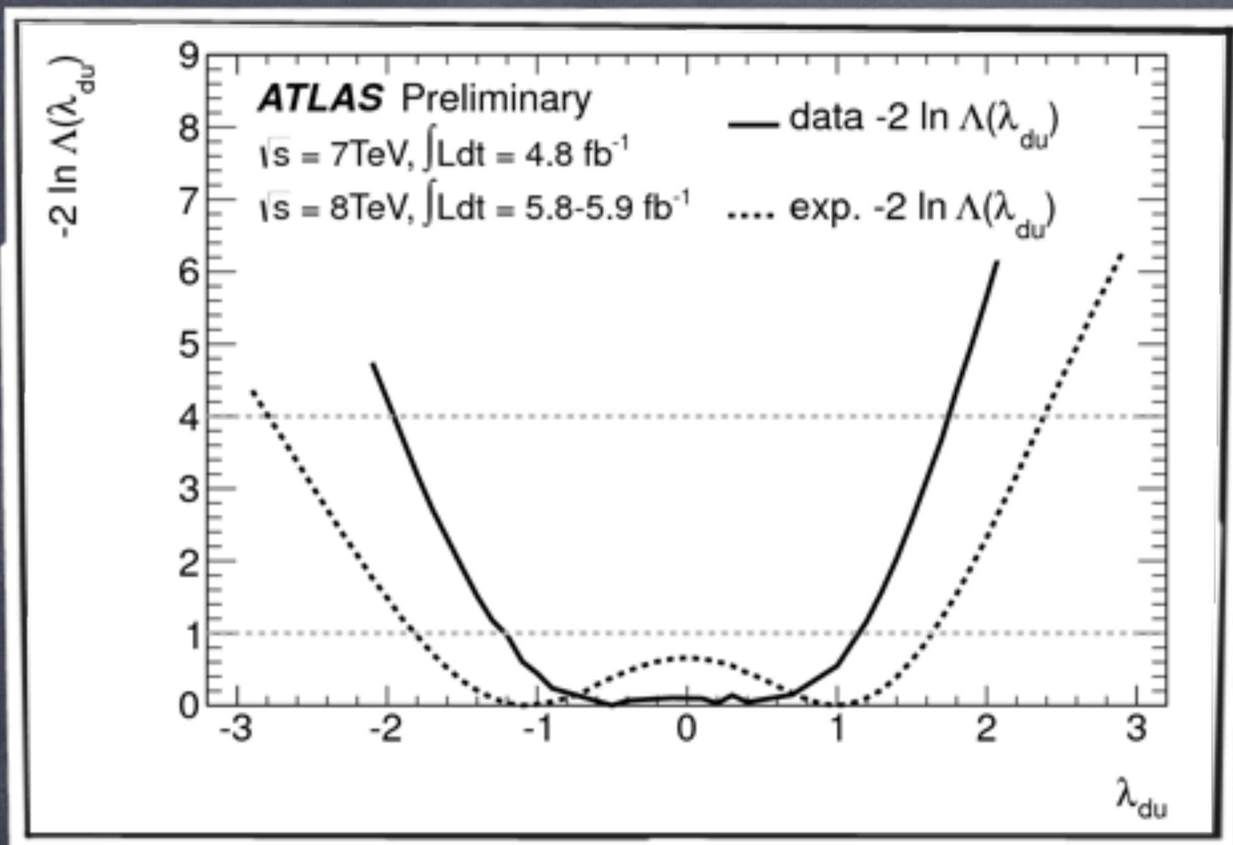
Define

$\lambda_{WZ}=k_W/k_Z$ to avoid assumption on the width

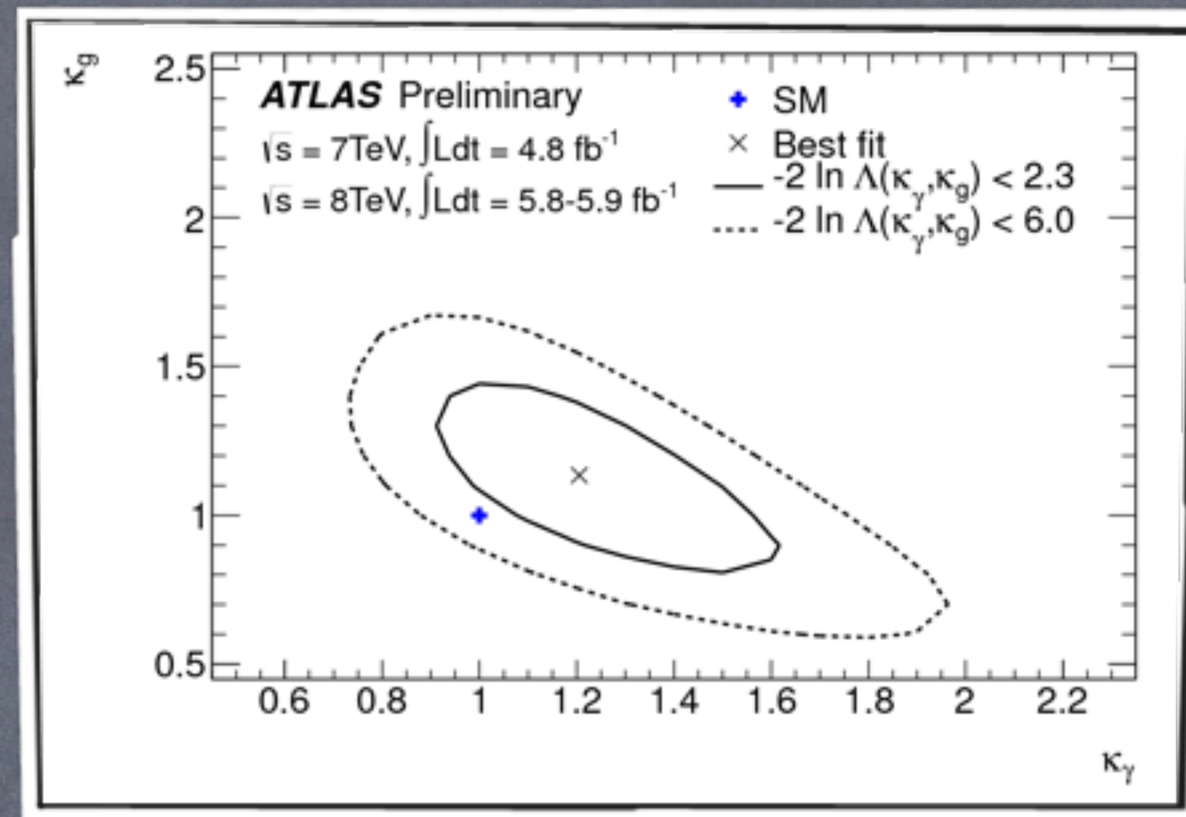
$$\lambda_{WZ} = 1.07^{+0.35}_{-0.27}$$



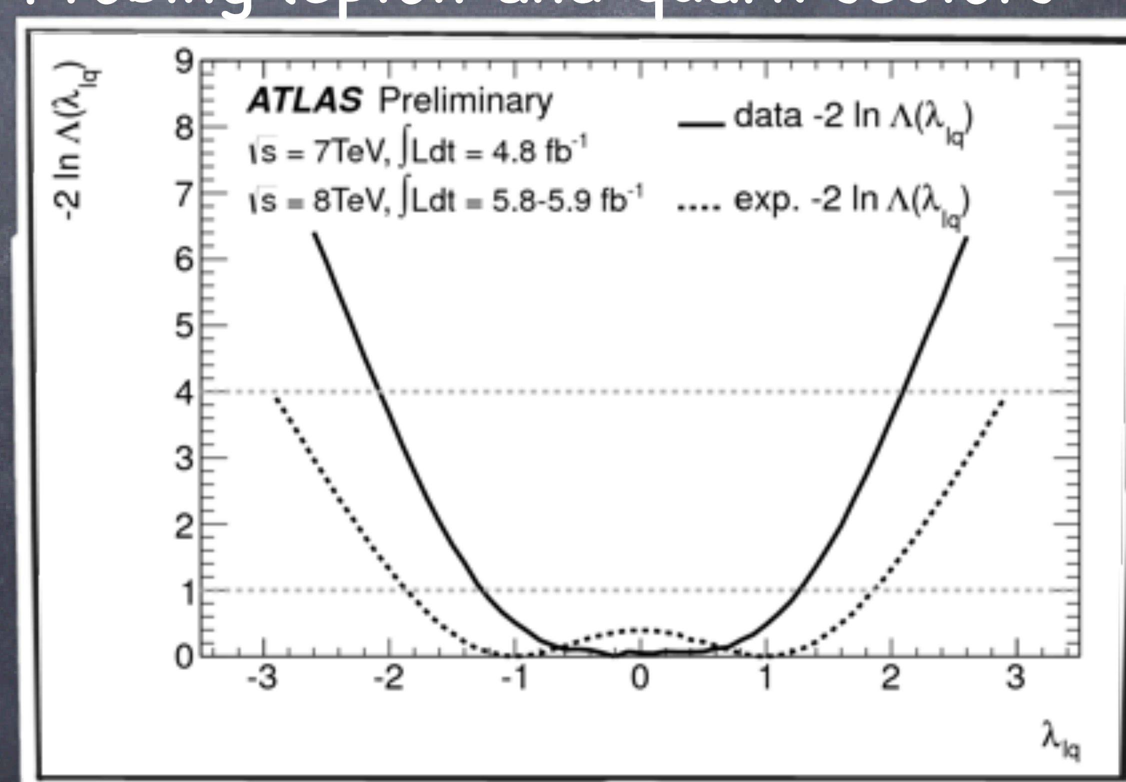
Probing up and down sectors



Probing non SM particles in the loops

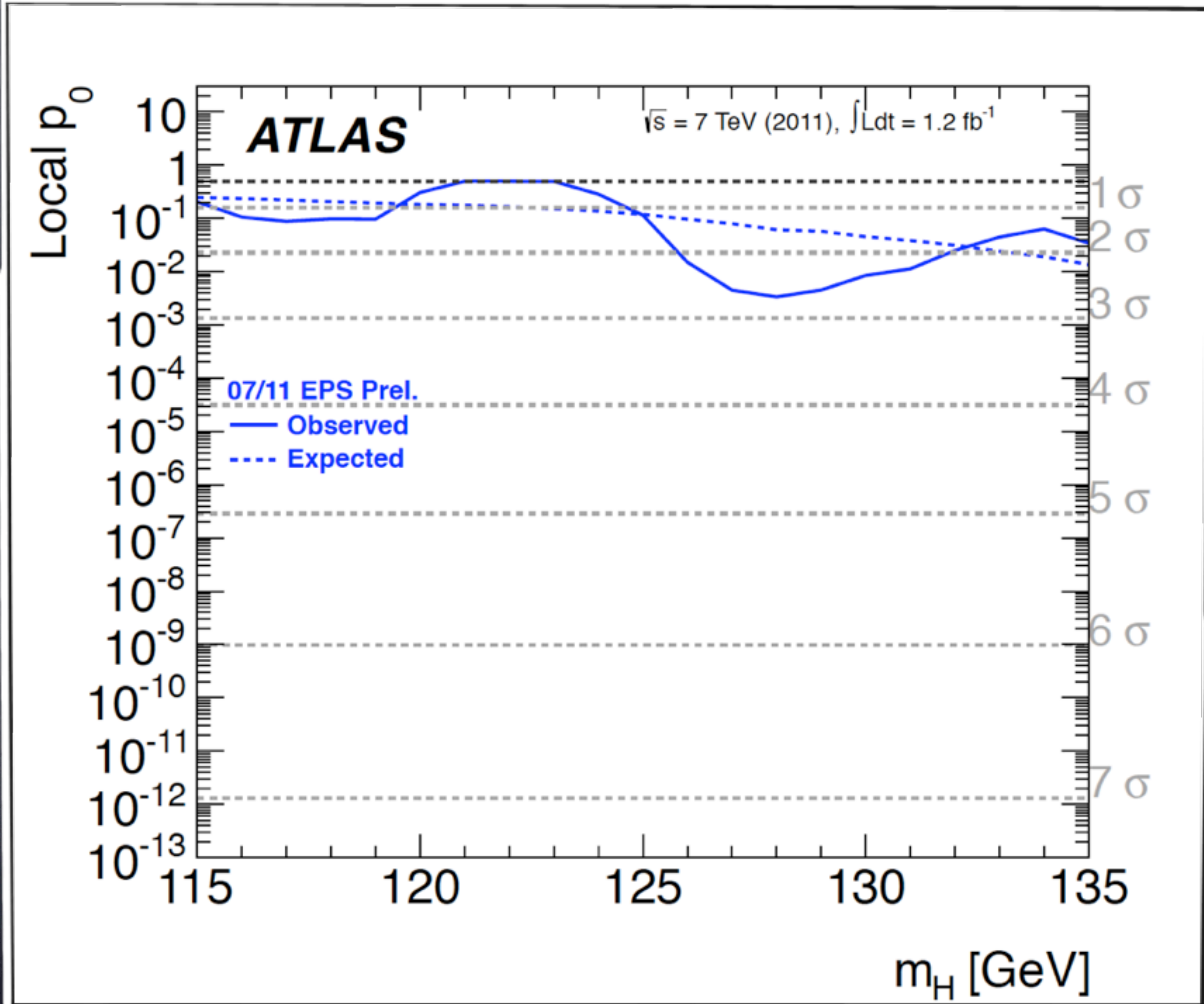


Probing lepton and quark sectors

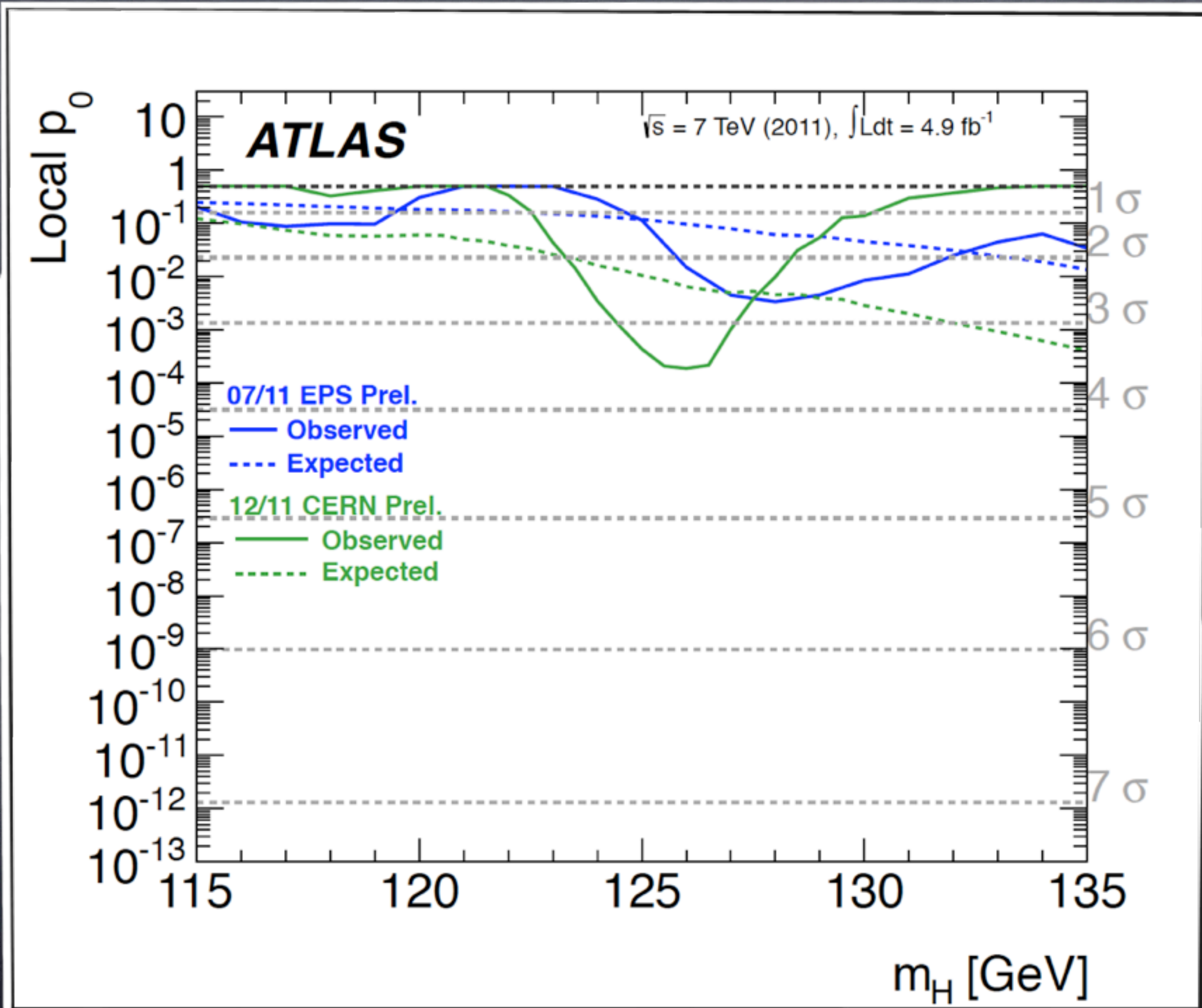


Analyzing now the full data set

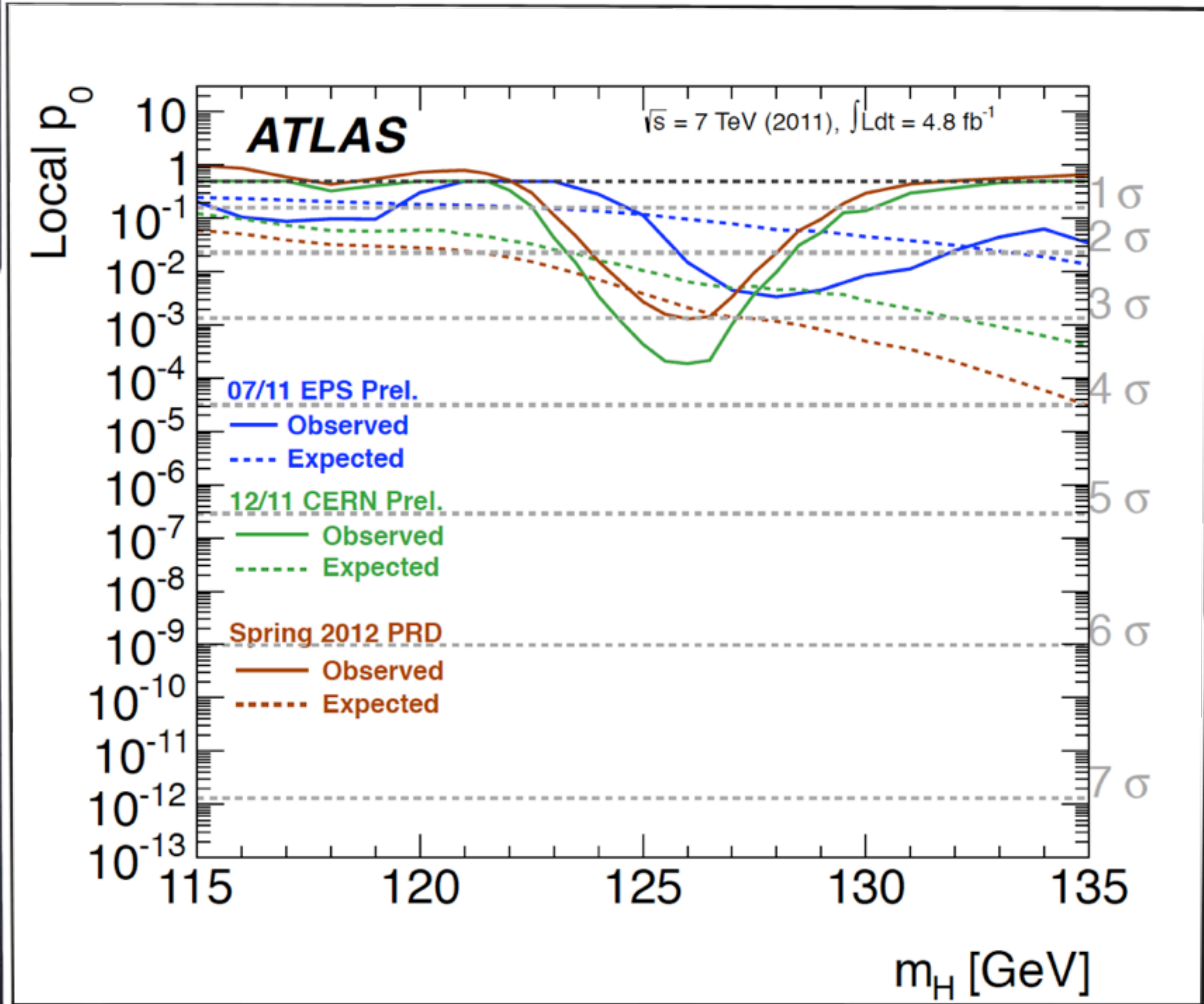
Conclusions



ATLAS
$\sqrt{s}$ = 7 TeV (2011), $\int$Ldt = 1.2 fb^{-1}
Local p_0
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
115
120
125
130
135
m_H [GeV]



ATLAS
$\sqrt{s}$ = 7 TeV (2011), $\int Ldt$ = 4.9 fb^{-1}
Local p_0
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
115
120
125
130
135
m_H [GeV]



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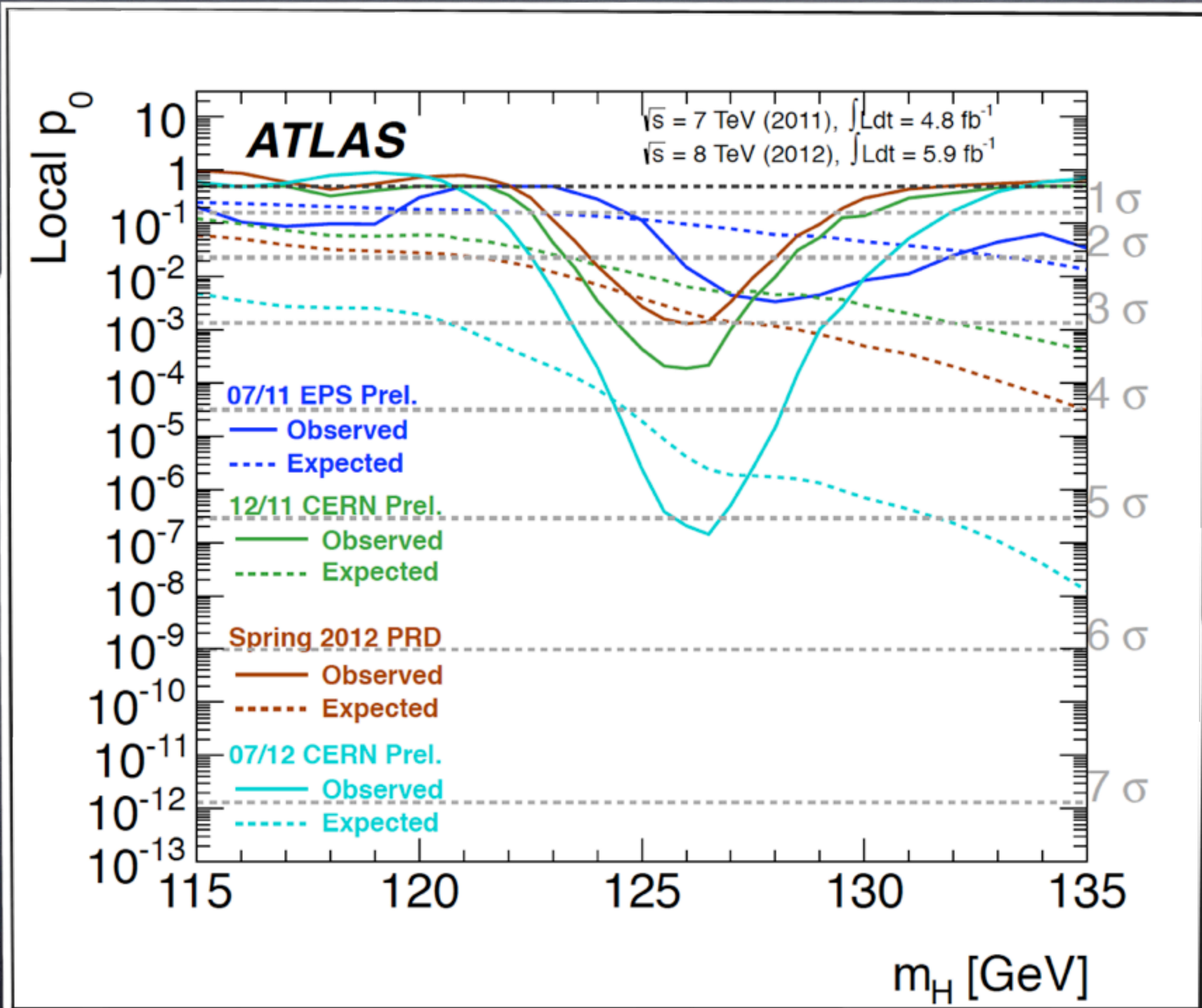
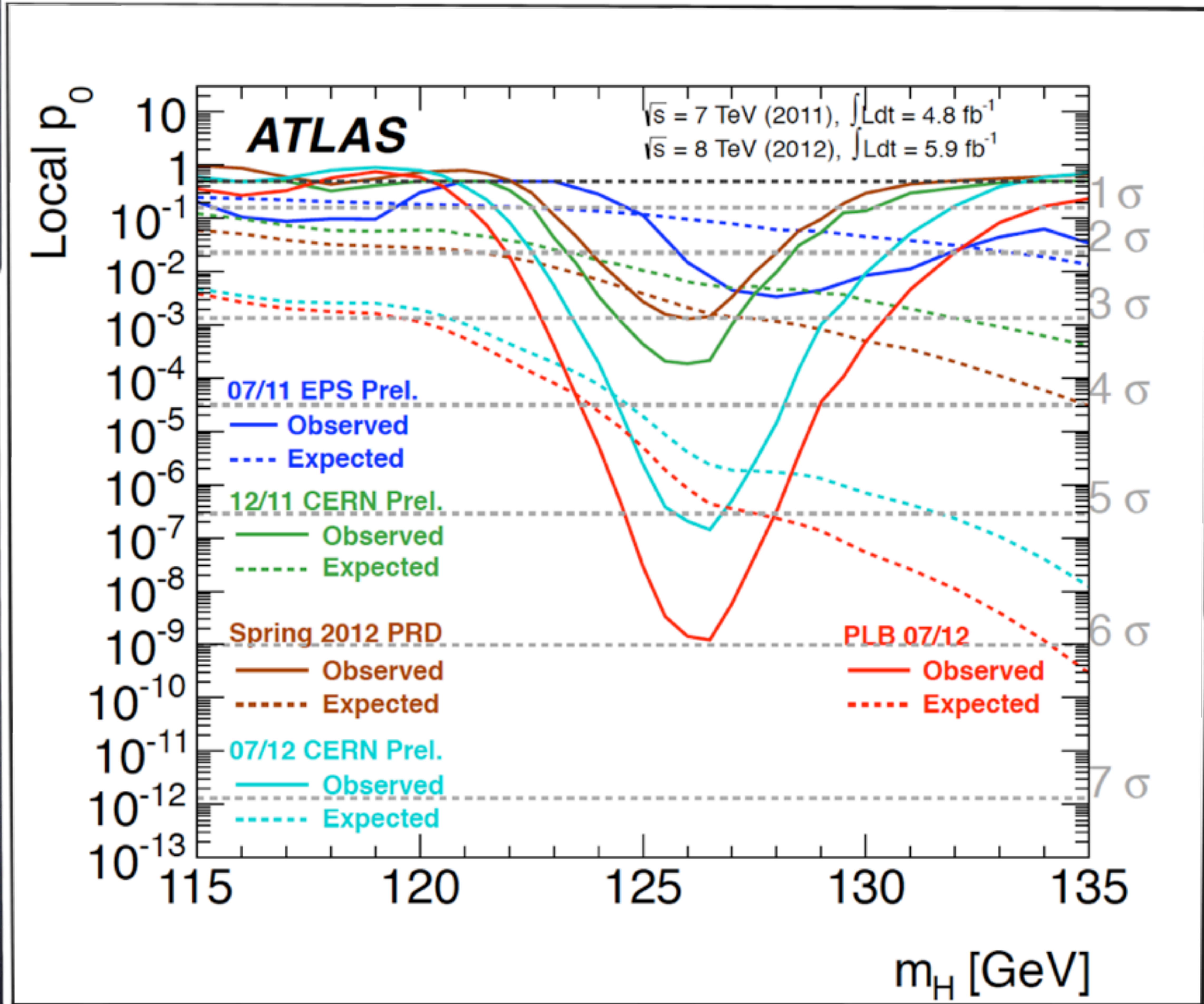
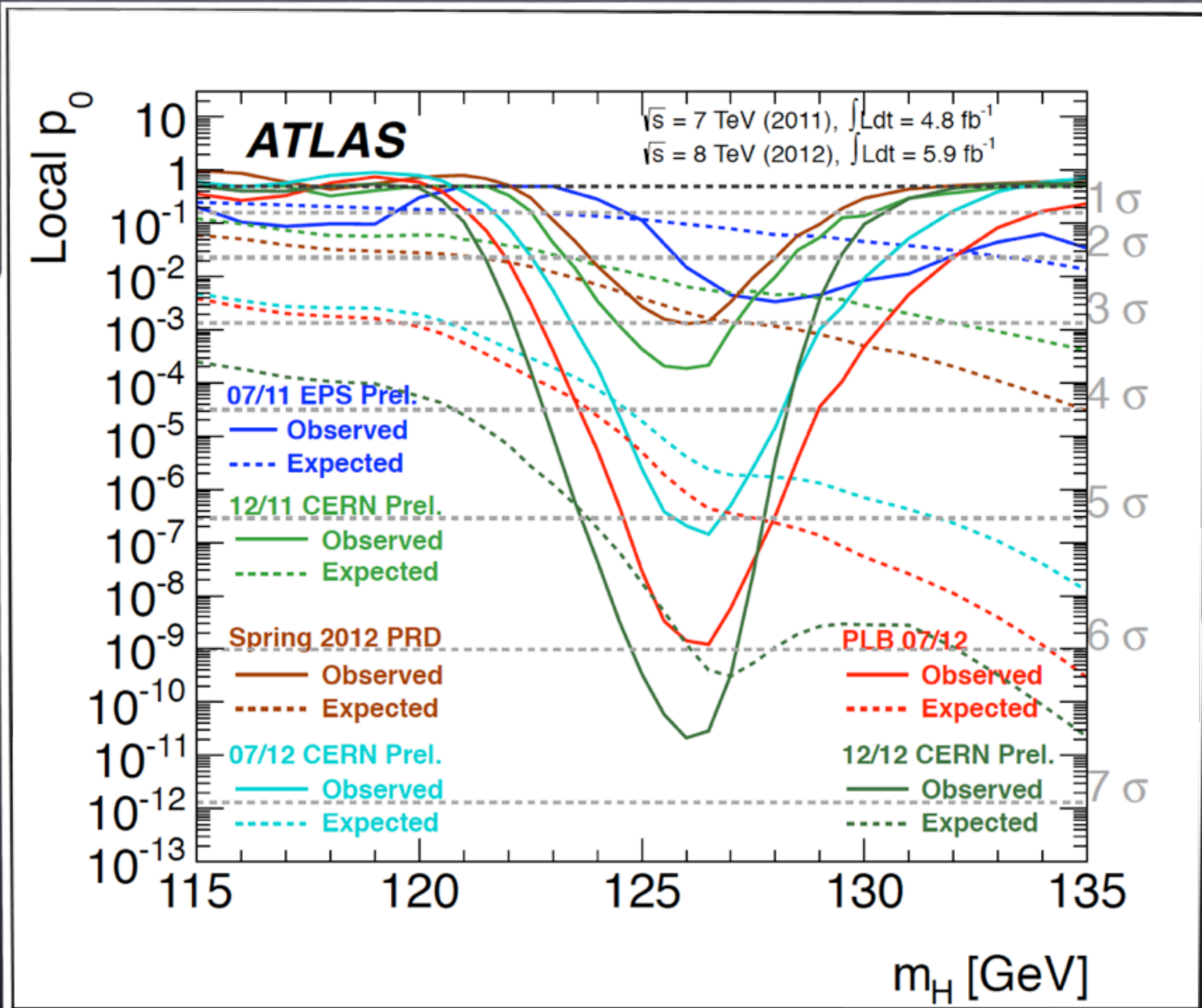
115
120
125
130
135
m_H [GeV]



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



ATLAS
$\sqrt{s}$ = 7 TeV (2011), $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV (2012), $\int Ldt$ = 5.9 fb^{-1}
Local p_0
m_H [GeV]
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
1 σ
2 σ
3 σ
4 σ
5 σ
6 σ
7 σ



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
PLB 07/12
Observed
Expected
12/12 CERN Prel.
Observed
Expected

Conclusions

- The first LHC proton-proton run (2009-2012) ended. ATLAS has recorded a total of 26.9 fb-1, with a data-taking efficiency of ~ 93.5%.

- Very effective and smooth operation of the experiment in all its components (from detector/ trigger to software and computing and release of physics results) during three challenging and demanding years. Experiment (and people !) stressed beyond "design performance"

- The physics output, summarized in > 220 papers on collision data and 430 Conference notes, includes the gorgeous discovery of the Higgs-like Boson

- Higgs results including 13 fb-1 of 8 TeV data:

  - Overall signal strength: μ=1.35 ± 0.4 of SM expectation

    Largest "deviation" from H-> $\gamma\gamma$: μ =1.8 ± 0.4

  - 2.7 σ difference between masses measured in H-> 4l and H->$\gamma\gamma$ channels

    likely largely due downward statistical fluctuation in the 4l channel

  - First spin studies, indicate 0+ is favoured, although far from being conclusive

Thank You

Backup

Combining 4 ℓ and $\gamma\gamma$

Main Mass Scale systematic uncertainties (considered sonce ICHEP studies) :

Source	Relative Mass Scale Effect
Absolute Energy scale calibration from Z	0.3%
Upstream material simulation inaccuracies	0.3%
Pre-Sampler energy scale	0.1%

Further investigation and extensive checks lead to find additional sources of systematic uncertainties :

- LAr Strips relative calibration (0.2%)
- Photon energy resolution (0.15%)
- Calibration of the high gain (0.15%)
- Mis-classification due to fake conversions (0.13%)
- Backgound modeling (0.1%)
- Lateral shower development simulation (0.1%)
- Effect of PV choice (0.03%)

Main 4l Mass Scale systematic uncertainties :

Source	Relative Mass Scale Effect
Absolute Energy scale calibration from Z	0.4%
Low transverse energy electrons	0.2%
Muon momentum scale	0.2%

Further investigation and extensive checks have not lead to additional substantial sources of systematic uncertainty :

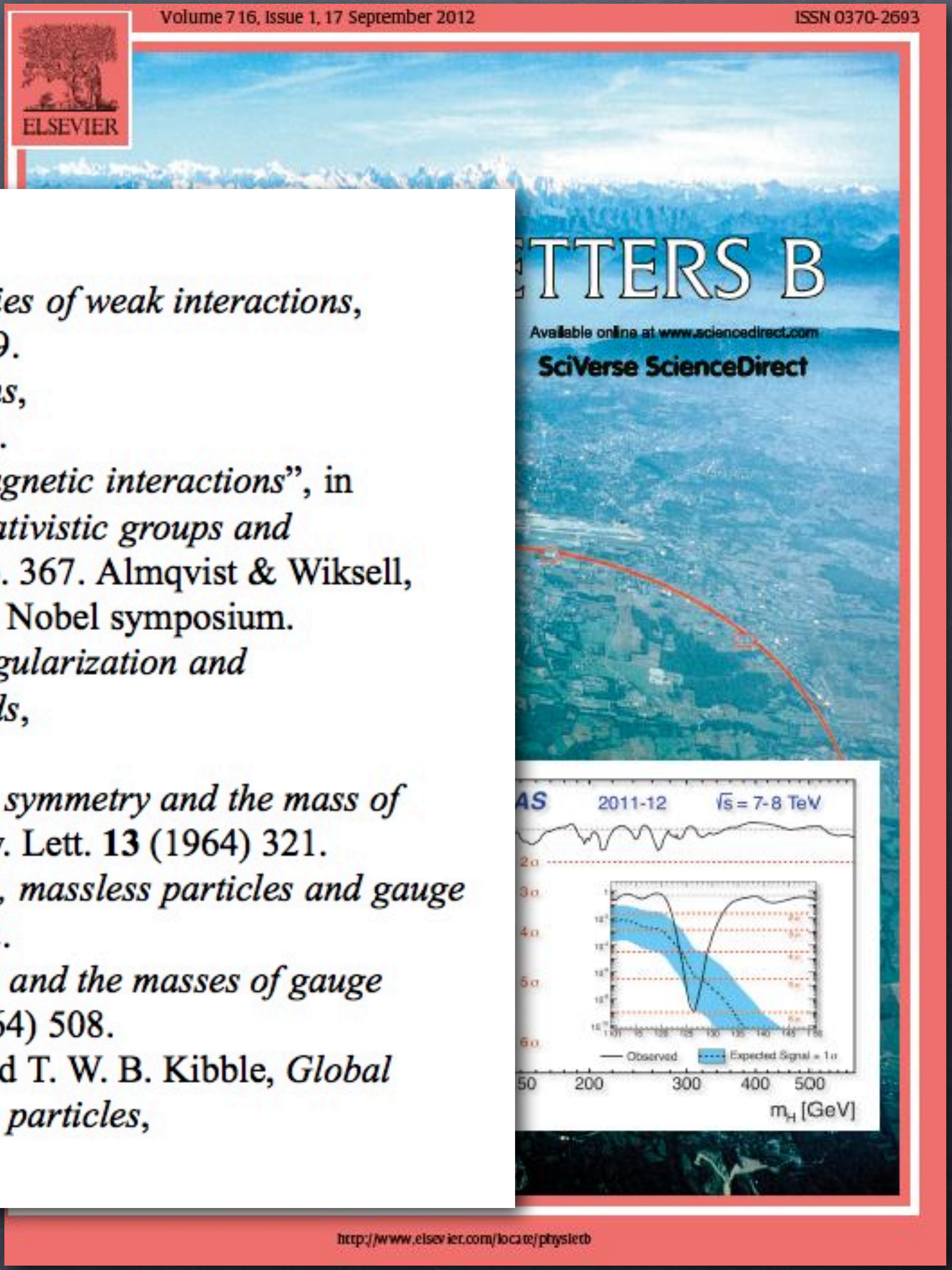
- Measurement with MS and ID alone
- Local detector biases checked event by event
- Local resolution effects checked using event-by-event error;
- kinematic distributions in agreement with expectation
- FSR simulation
- Different mass reconstruction using Z-mass constraint (+400 MeV shift)

$\gamma\ \gamma$ systematic uncertainties

Main systematic uncertainties	
Theory γ efficiency Background model	~ 20% (30% for 2j) ~ 5% ~ 3%
Higgs p_T modeling Conv/Unconv γ Jet E-scale Underlying event Jet vertex fraction	up to ~ 10% ~ 4% up to 18% (2j/HM) up to 30% (2j/ggF) up to 20% (2j)
H→ γγ mass resolution	14%
γ E-scale	0.5%

ATLAS EXPERIMENT

17 september 2012



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[1] S. L. Glashow, *Partial-symmetries of weak interactions*, Nucl. Phys. **22** no. 4, (1961) 579.

[2] S. Weinberg, *A Model of Leptons*, Phys. Rev. Lett. **19** (1967) 1264.

[3] A. Salam, "*Weak and electromagnetic interactions*", in *Elementary particle theory: relativistic groups and analyticity*, N. Svartholm, ed., p. 367. Almqvist & Wiksell, 1968. Proceedings of the eighth Nobel symposium.

[4] G. 't Hooft and M. Veltman, *Regularization and Renormalization of Gauge Fields*, Nucl. Phys. **B44** (1972) 189.

[5] F. Englert and R. Brout, *Broken symmetry and the mass of gauge vector mesons*, Phys. Rev. Lett. **13** (1964) 321.

[6] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, Phys. Lett. **12** (1964) 132.

[7] P. W. Higgs, *Broken symmetries and the masses of gauge bosons*, Phys. Rev. Lett. **13** (1964) 508.

[8] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, *Global conservation laws and massless particles*, Phys. Rev. Lett. **13** (1964) 585.


Air Mail
2010
90P
Dr Eilam Gross
Particle Physics Department
Weizmann Institute of Science
76100 Rehovoth
ISRAEL
FROM
Peter Higgs
2 Darnaway Street
Edinburgh EH3 6BG

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)

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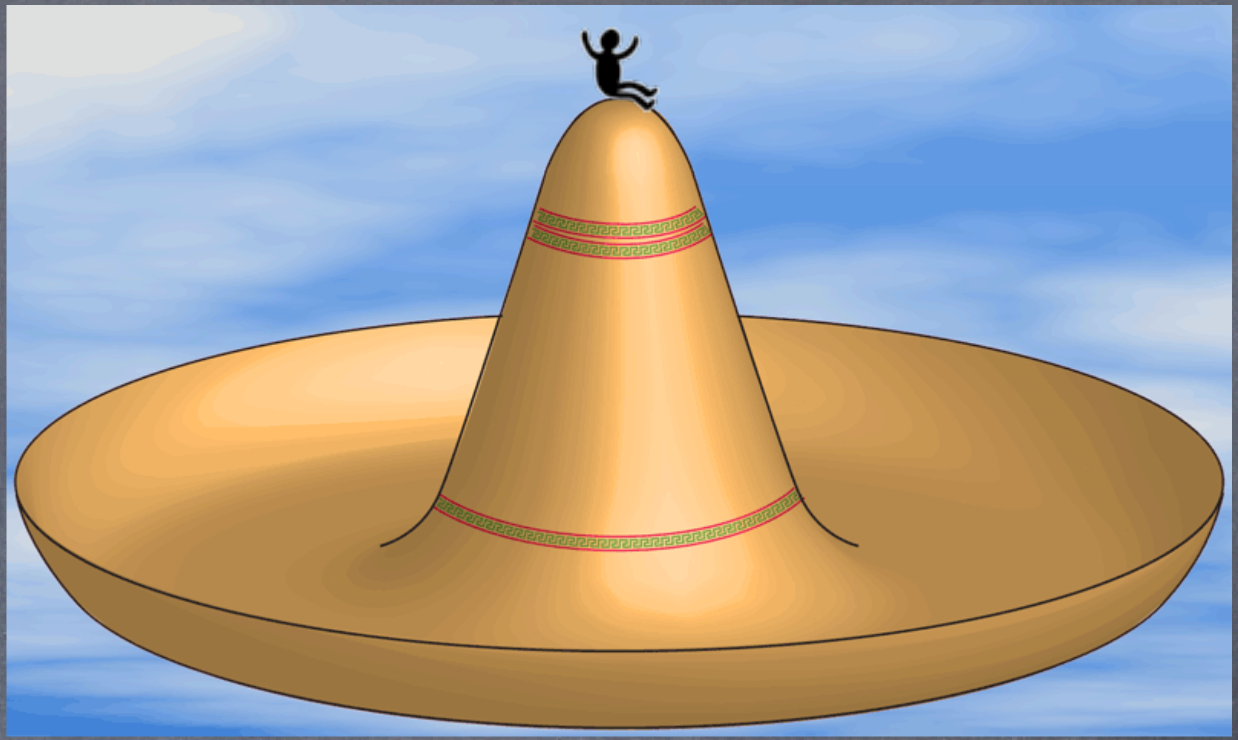
A Prelude to the Nobel Prize

- 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"

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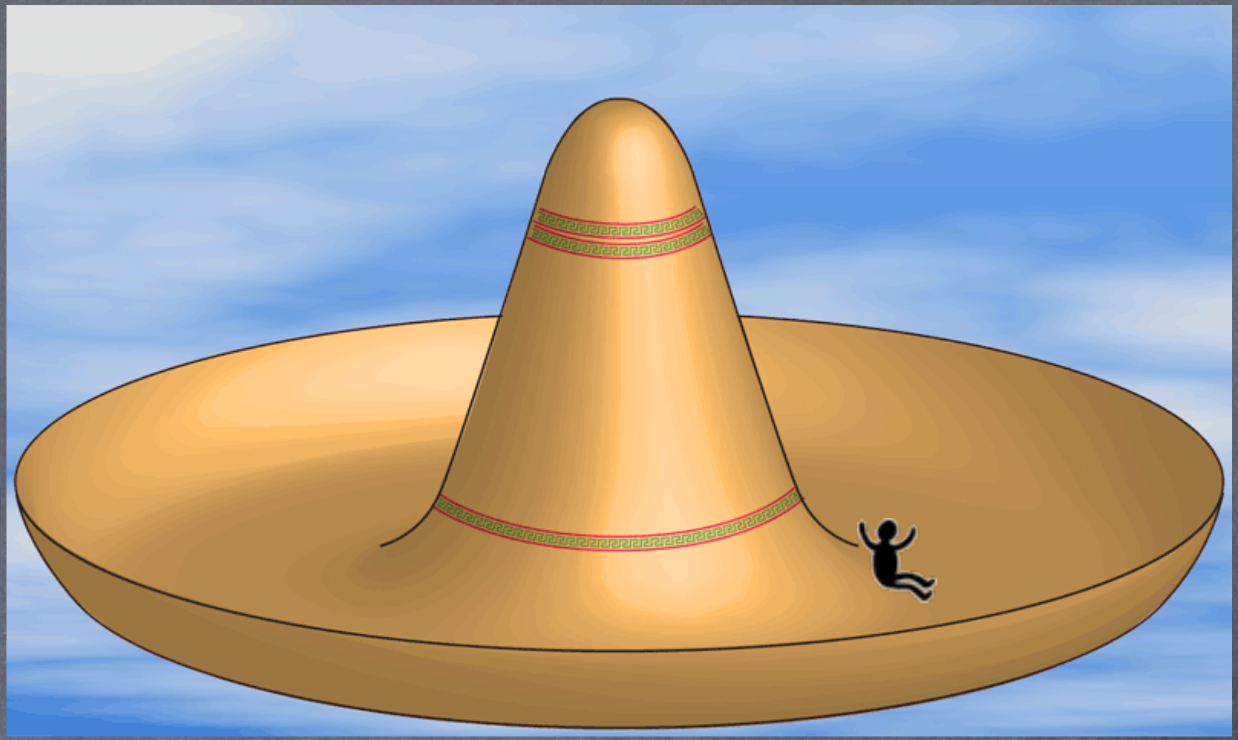

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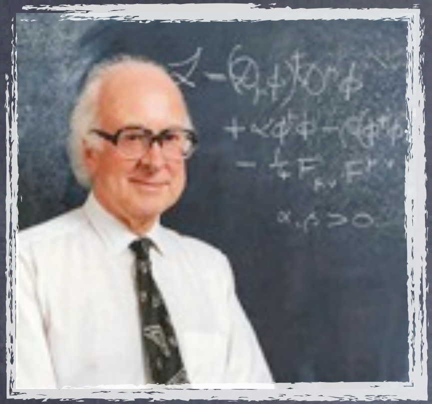
Spontaneous Symmetry Breaking

- 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

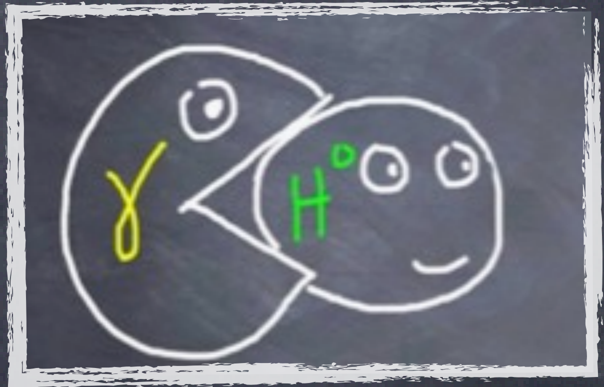
Philip Anderson (1963) points out that in a superconductor the Goldstone mode becomes a massive plasmon-mode, due to its electromagnetic interaction.



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 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

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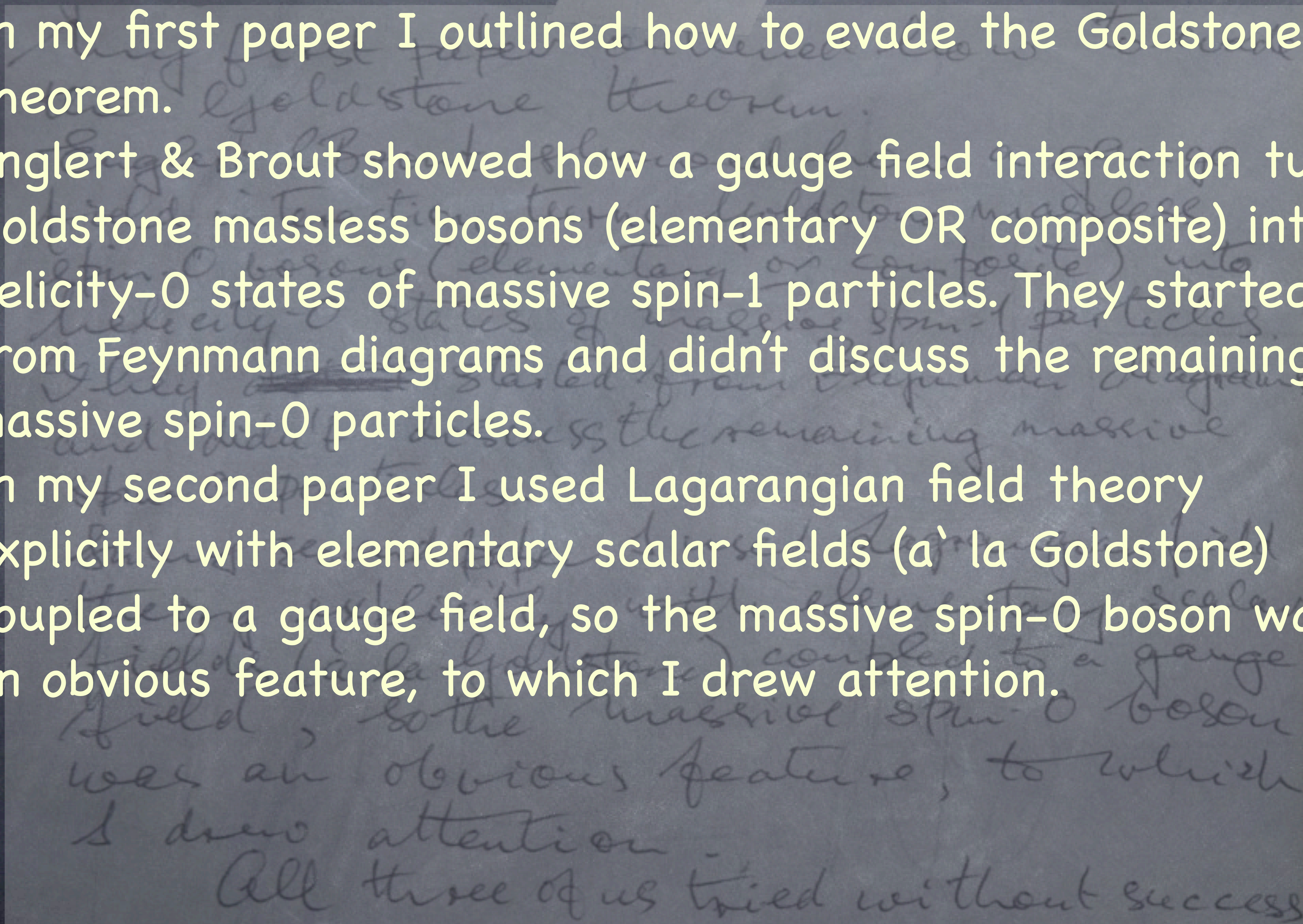

The Birth of the Standard Model

-  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
- 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.

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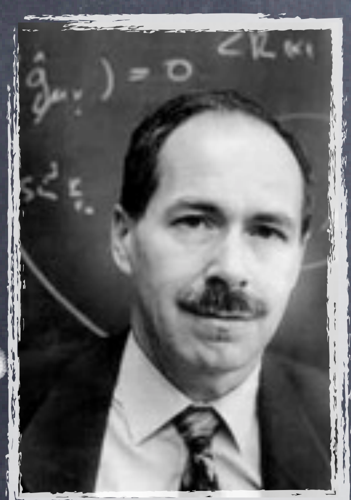
  (one of the most quoted . .... >8000 citations).
- Weinberg predicts that the mass of the weak interaction force carriers is mW=80 GeV and mZ=90 GeV, but it took another 14 years to confirm it experimentally.

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.

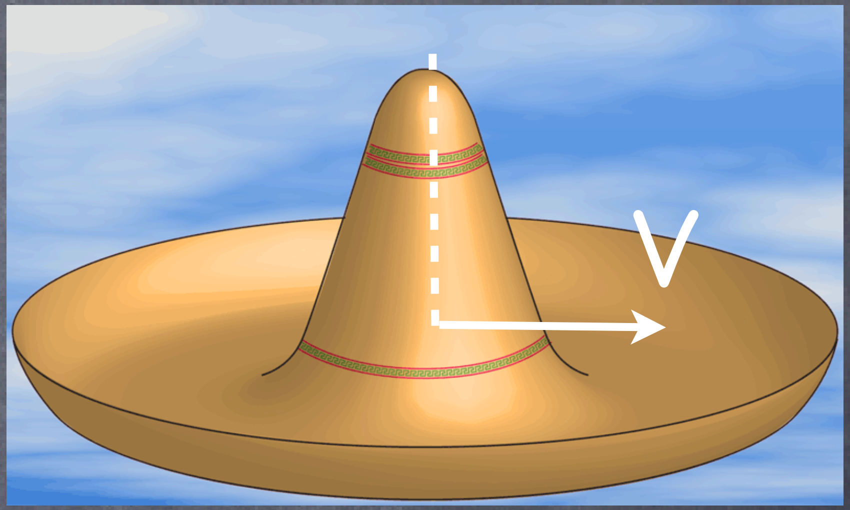
- All that is left is to find the mass generator, the Higgs Boson

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")

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

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

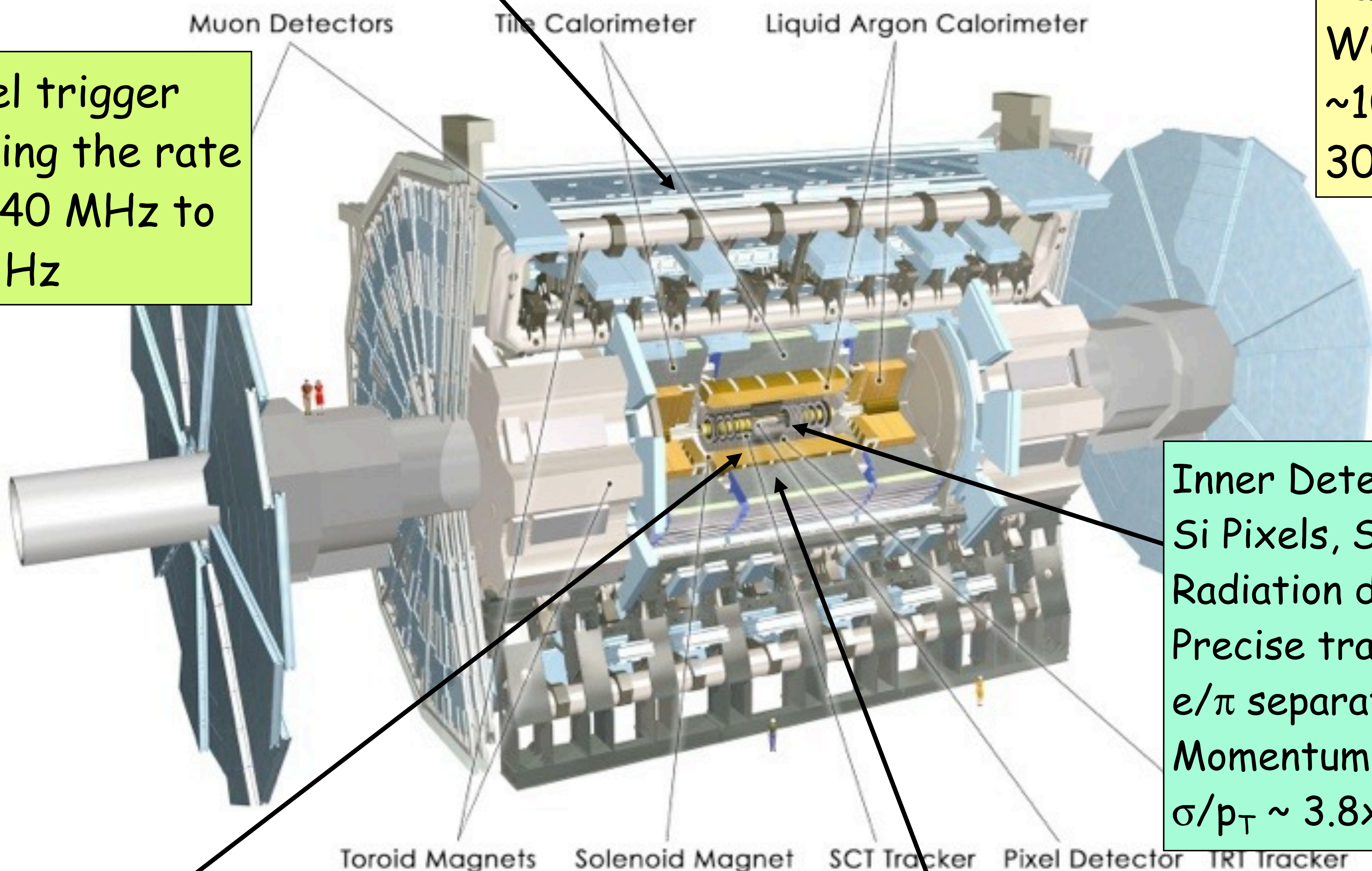


- The coupling of the Higgs to particles is proportional to the particles' mass
- The Higgs Boson will therefore decay with a higher probability to the heaviest particle kinematically available

Muon Spectrometer ($|\eta|$<2.7) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_{μ} ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

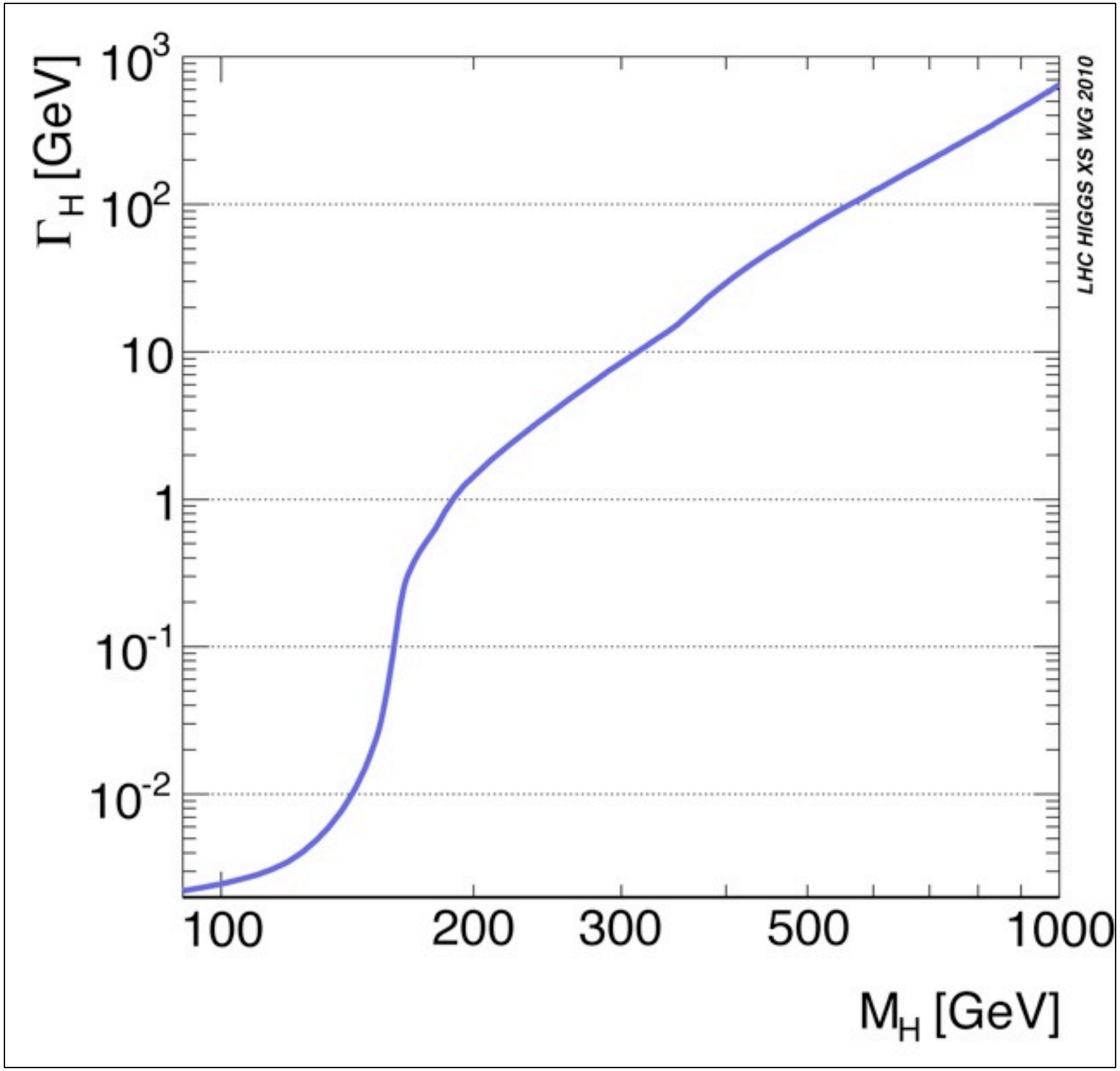
3-level trigger reducing the rate from 40 MHz to ~200 Hz



Inner Detector ($|\eta|$<2.5, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
σ/p_T ~ 3.8×10^{-4} p_T (GeV) $\oplus$ 0.015

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: σ/E ~ 10%/$\sqrt{E}$

HAD calorimetry ($|\eta|$<5): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: σ/E ~ 50%/$\sqrt{E}$ $\oplus$ 0.03

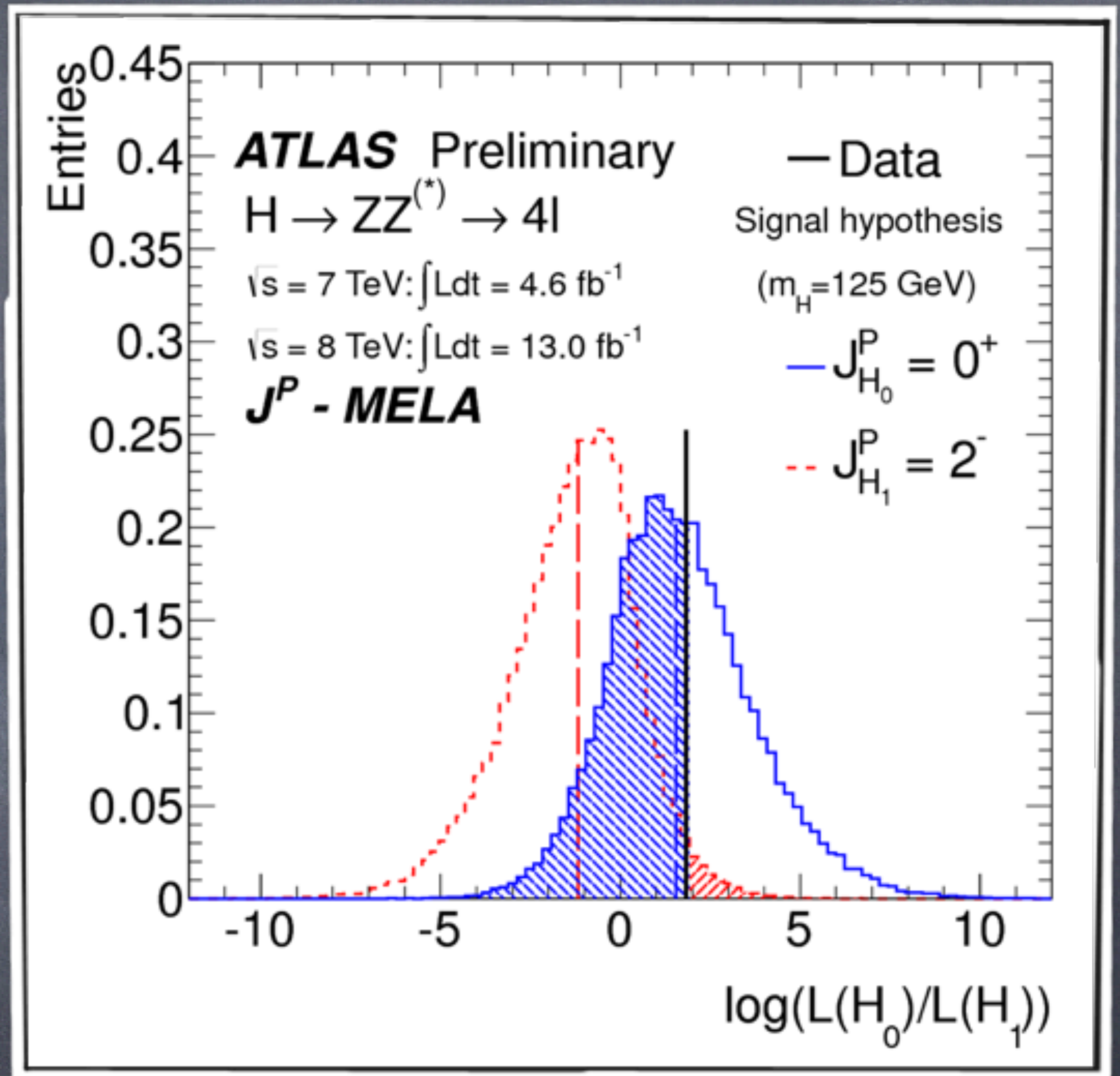

Γ_H [GeV]
10^3
10^2
10
1
10^{-1}
10^{-2}
100
200
300
500
1000
M_H [GeV]
LHC HIGGS XS WG 2010

4 ℓ Spin & CP, test $J^P=2^-$

$$H_1 = 2^-$$
$$H_0 = 0^+$$

$$q = \log \frac{L(H_0)}{L(H_1)}$$

$$p_{H_1} = \mathrm{Prob}(\text{more } H_1\text{-like} \mid H_1)$$
$$p_{H_1}(\exp \mid H_0) = 4\% (1.7\sigma),$$
$$p_{H_1}(obs) = 2.5\% (2\sigma)$$
$$p_{H_0}(obs) = 56\% (-0.15\sigma)$$



Which means assuming $J^P=0^+$ One has the sensitivity to exclude 2^- at the 96% CL and exclude it at the 97.5% CL

Future prospects

- Expected measurement precision with 300 & 3000 fb^{-1} @ 14 TeV on Higgs:
  - Signal strengths, μ_i
  - Partial widths, Γ_i (proportional to coupling constants)
- Long-term program requiring high luminosity (see talk by N. Styles)