High Energy Frontier - Recent Results from the LHC

University of Heidelberg WS 2012/13

Lecture 7

Higgs Physics II

Overview

- Short recap
- Higgs search strategies in different channels
- Results
  - 2010 data
  - 2011 data
  - 2012 data; Higgs discovery
- Outlook/Future

Higgs mechanism

The problem with the gauge invariance can be solved by introducing a new scalar isospin doublet field Φ (instead of a mass constant) which respects gauge invariance.

$$L = (D_\mu \Phi)(D^\mu \Phi) + ... + y_d \phi\, d_L d_R + y_u \phi\, u_L u_R + ... \qquad \Phi = \begin{pmatrix} 0 \\ \phi \end{pmatrix}$$

Yukawa couplings

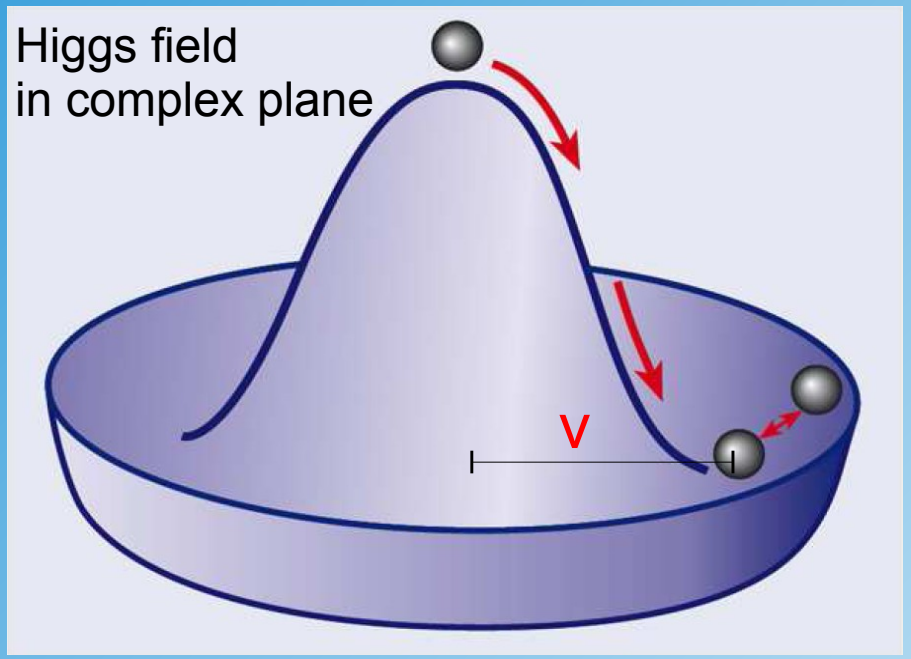
vector boson masses fermion mass terms

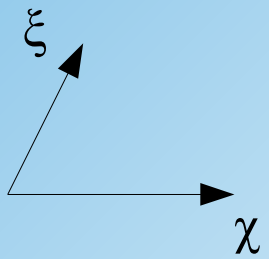
with the covariant derivative:

$$D_\mu = \partial_\mu + (i g W_\mu^j \sigma_j + i g' Y B_\mu)$$

This field creates **simultaneously** vector boson and fermion masses and breaks electroweak symmetry if the vacuum expectation values (vev) of the Higgs field is non-zero!

Higgs Field Parametrisation





choose minimum to be on the real axis (symmetry breaking):

$$\phi = v + \chi + i\xi$$

Mexican hat potential: $-\mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2$

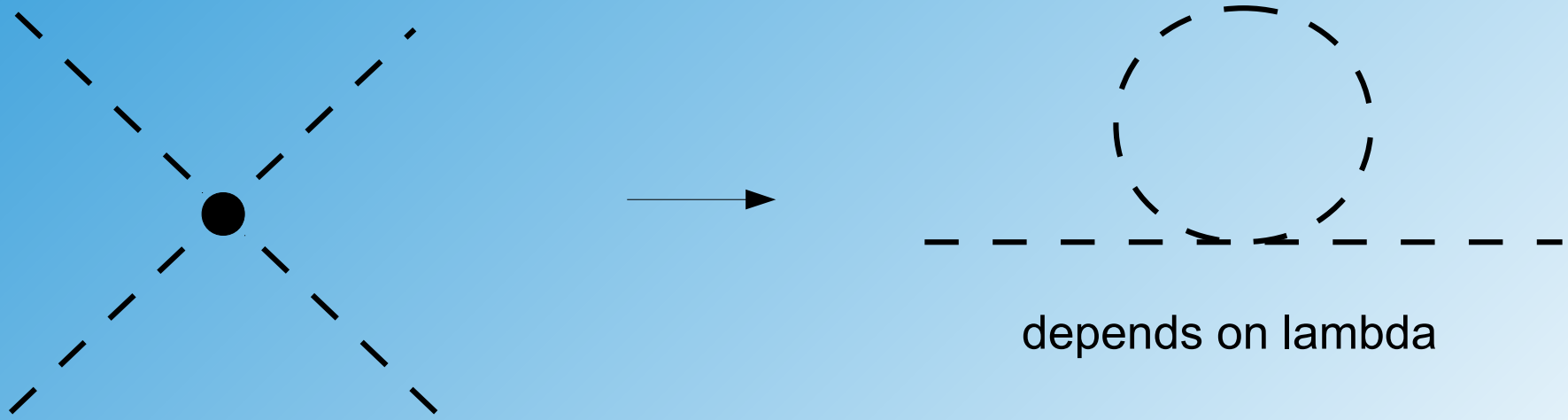
minimum if: $v^2 = \frac{-\mu^2}{2\lambda}$ (vev if lambda negative)

SM Lagrangian with Higgs Field

$$L = (D_\mu \Phi)(D^\mu \Phi) - \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2 + y_d \phi\, d_L d_R + y_u \phi\, u_L u_R + \ldots$$

Higgs self coupling

Higgs self interactions



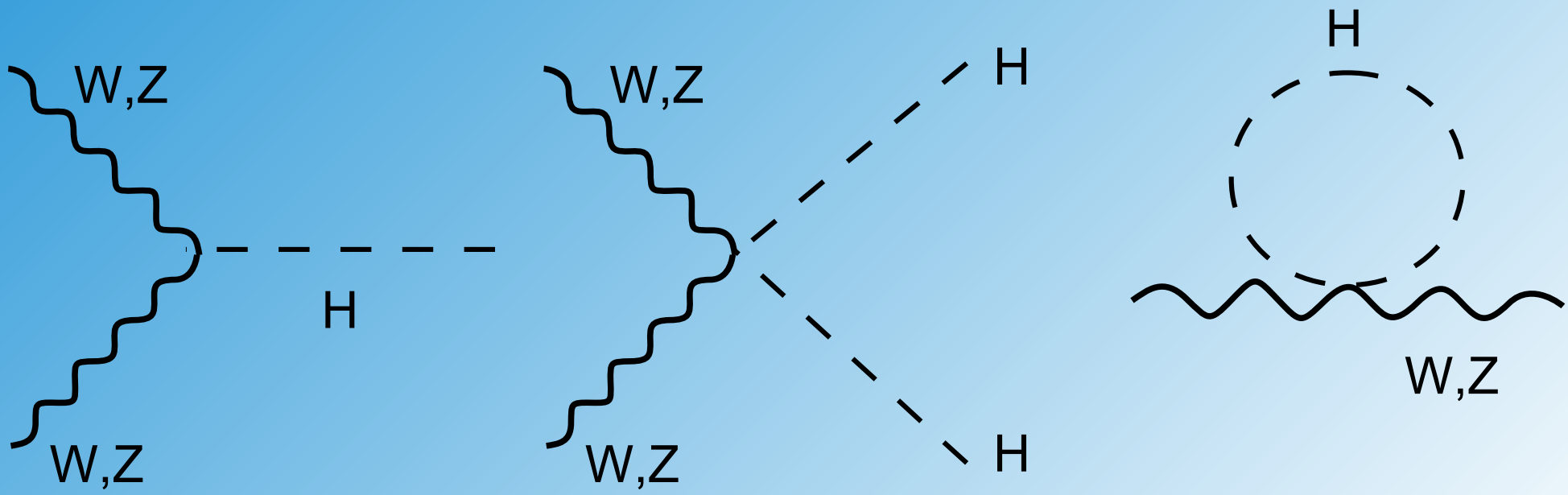
depends on lambda

Higgs-Gauge Boson Interactions

$$L = (D_\mu \Phi)(D^\mu \Phi) - \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2 + y_d \phi\, d_L d_R + y_u \phi\, u_L u_R + \ldots$$

Higgs vector boson interactions: $\tan \Theta_W = \frac{g'}{g}$ (Weinberg angle)

$$m_W^2 = \frac{1}{4} v^2 g^2 \qquad m_Z^2 = \frac{v^2}{4}(g^2 + g'^2) \qquad \rightarrow \text{v=246 GeV}$$



also here, coupling proportional to mass!

Higgs-Fermion Interactions

Higgs-Fermion Coupling:

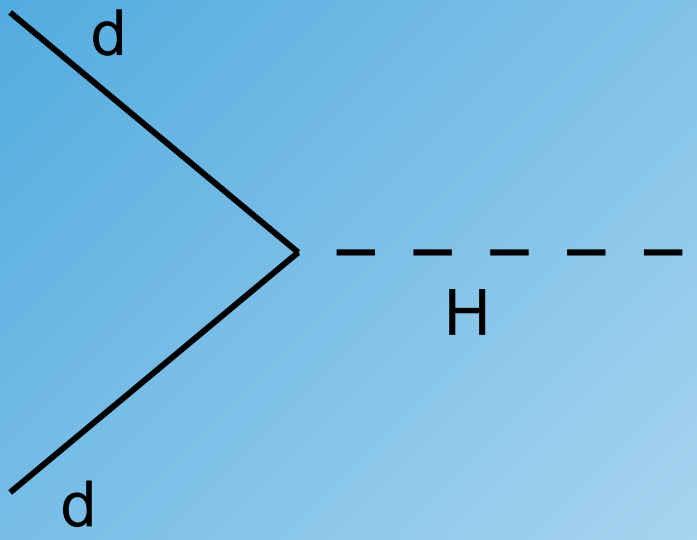
$$L_Y = - y_d \, \bar{L} \Phi d_R - y_u \, \bar{L} \tilde{\Phi} u_R$$

with $L = \begin{pmatrix} t \\ b \end{pmatrix}$, $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$,

$\tilde{\Phi} = i \tau_2 \Phi^*$

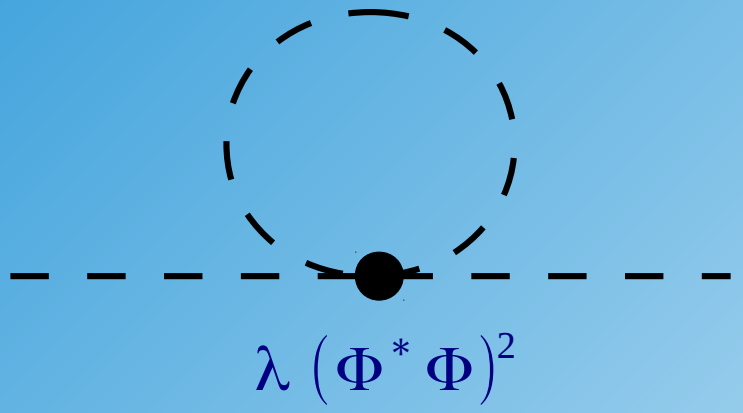
Higgs couples to masses:

$$m_{d,u} = \frac{y_{d,u} v}{\sqrt{2}}$$



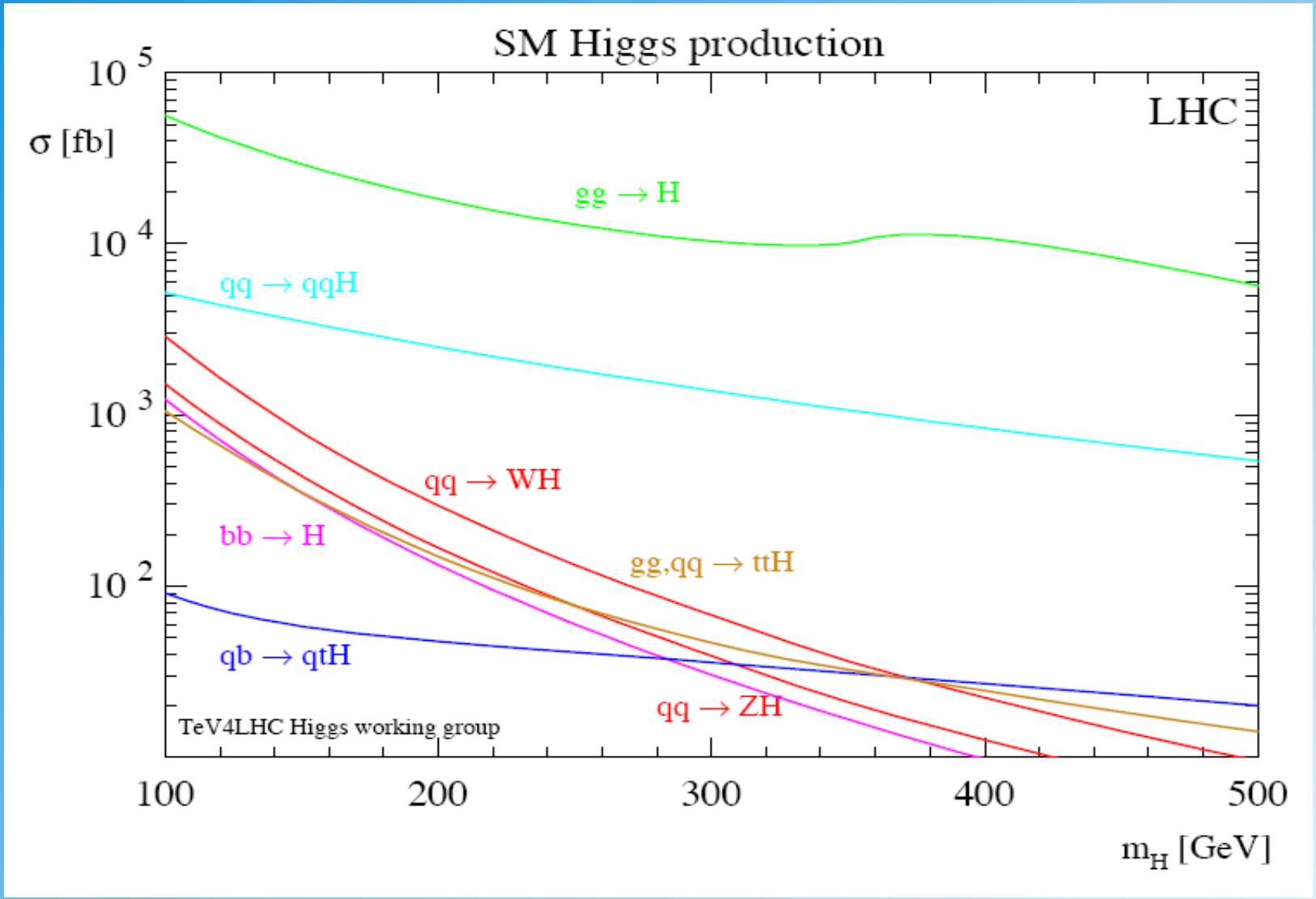
coupling proportional to mass

Higgs Mass?



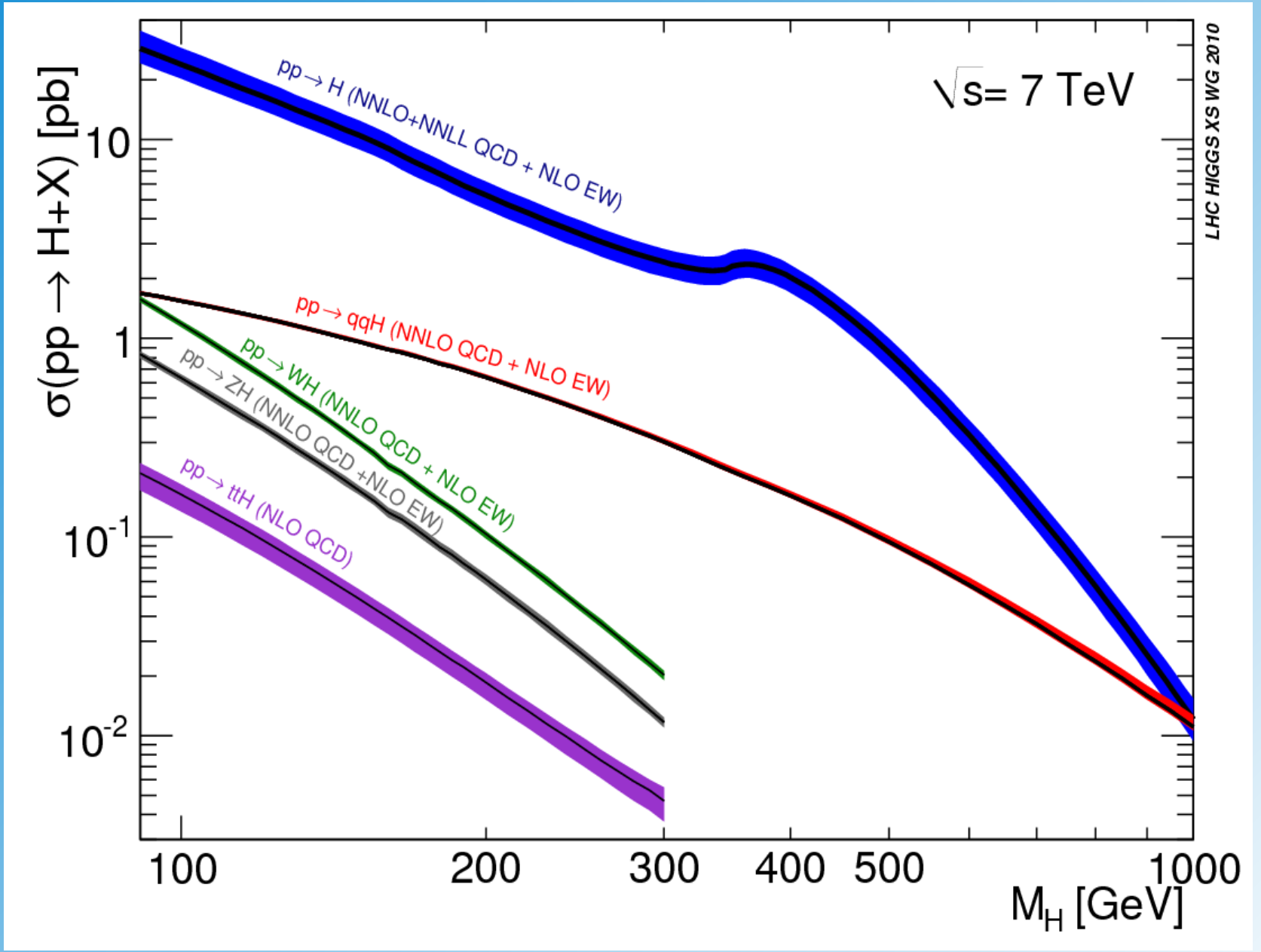
coupling lambda is not known!

Higgs Production at Hadron Colliders

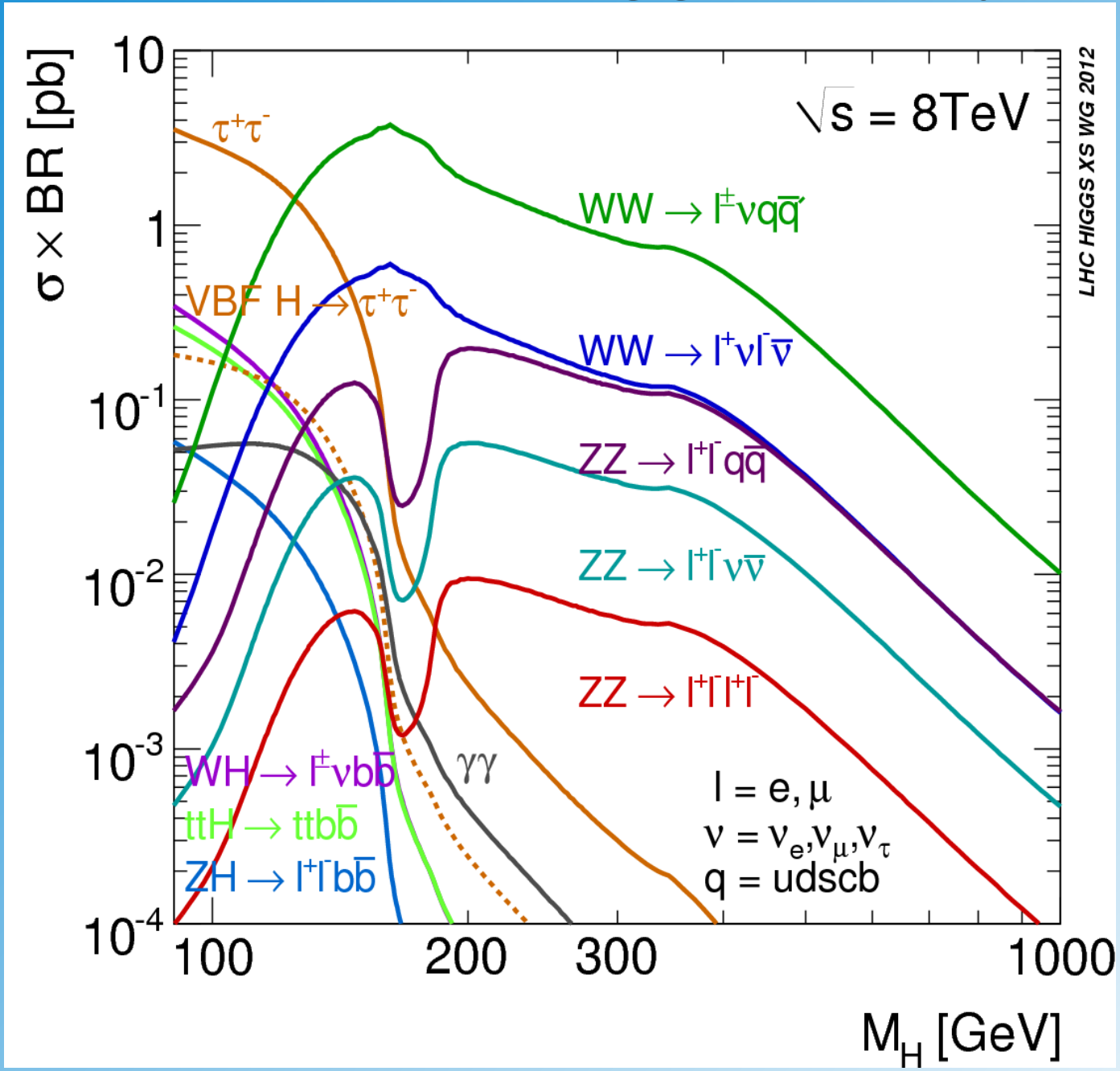


proton-proton at LHC $s^{1/2}$=14 TeV

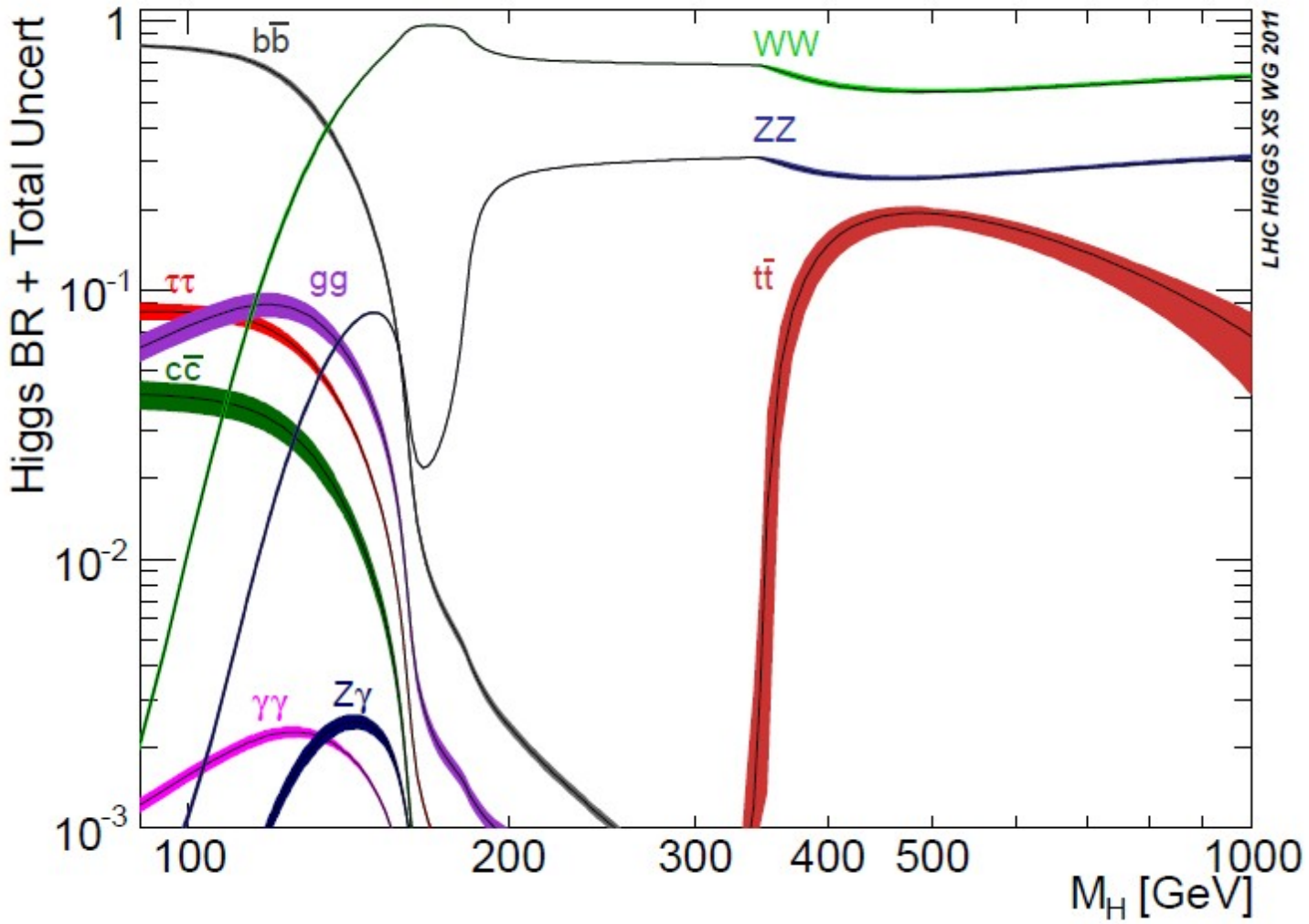
Higgs Production at Hadron Colliders



Cross Sections in Higgs Decay Channels



Higgs Decays

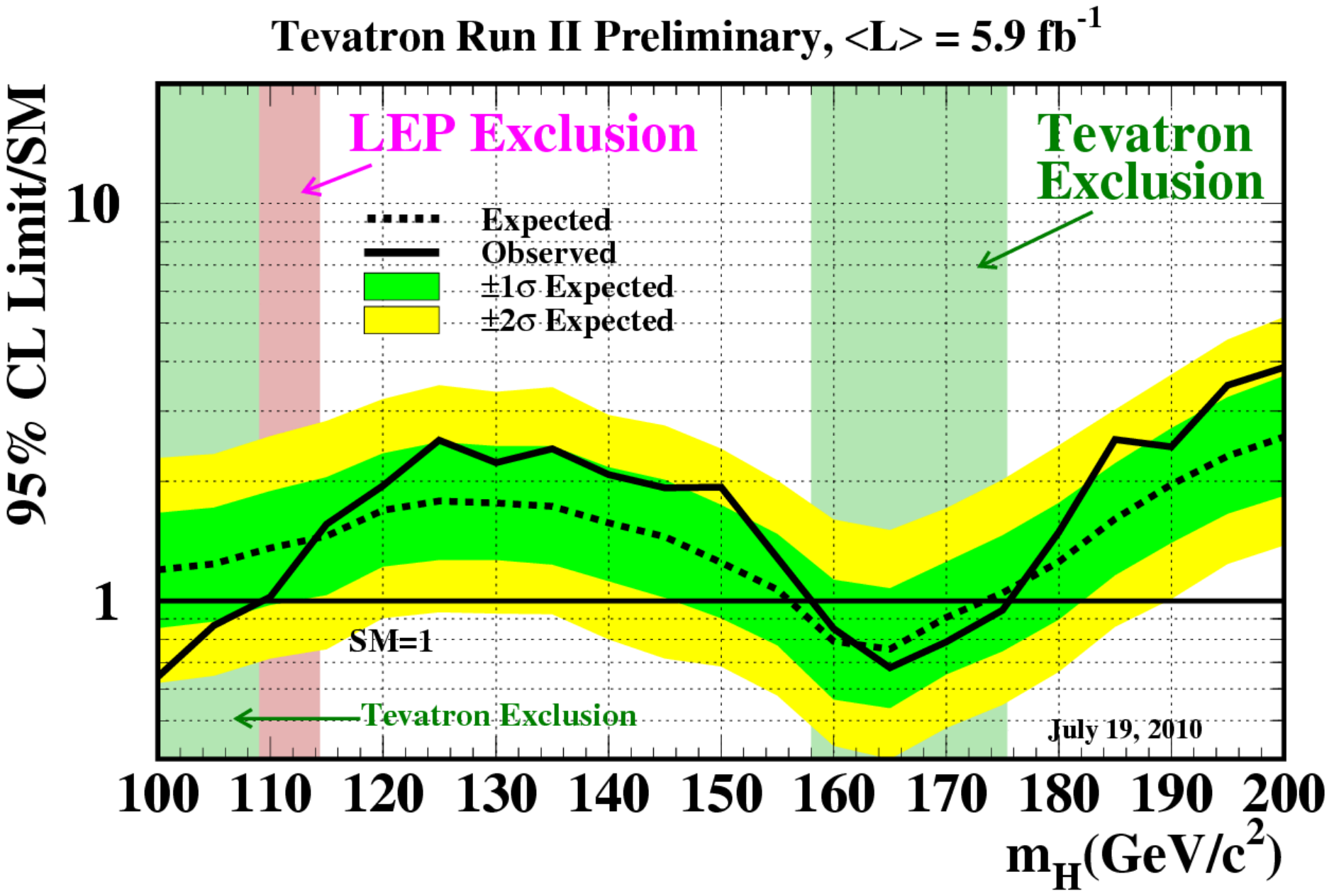


$$\Gamma(h \to l^+ l^-) = \frac{G_F M_l^2}{4\sqrt{2}\pi} M_h \beta_l^3$$

$$\Gamma(h \to W^+ W^-) = \frac{G_F M_h^3}{8\pi\sqrt{2}} \sqrt{1 - r_W}(1 - r_W + \tfrac{3}{4} r_W^2)$$

$$\Gamma(h \to ZZ) = \frac{G_F M_h^3}{16\pi\sqrt{2}} \sqrt{1 - r_Z}(1 - r_Z + \tfrac{3}{4} r_Z^2),$$

$$r_V \equiv 4M_V^2/M_h^2$$


Tevatron Run II Preliminary, <L> = 5.9 fb-1
95% CL Limit/SM
10
1
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 19, 2010
100 110 120 130 140 150 160 170 180 190 200
mH(GeV/c2)

MC Simulation Studies

ATLAS NOTE

November 8, 2010

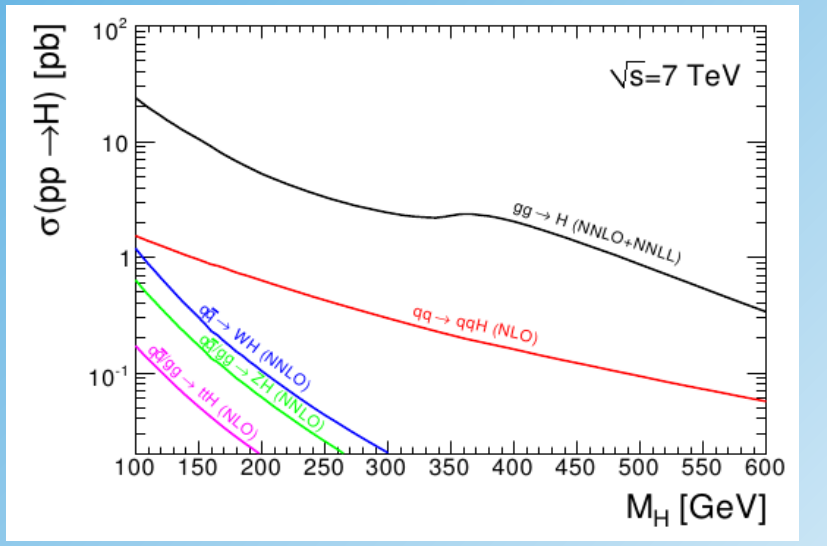
ATLAS Sensitivity Prospects for Higgs Boson Production at the LHC Running at 7, 8 or 9 TeV

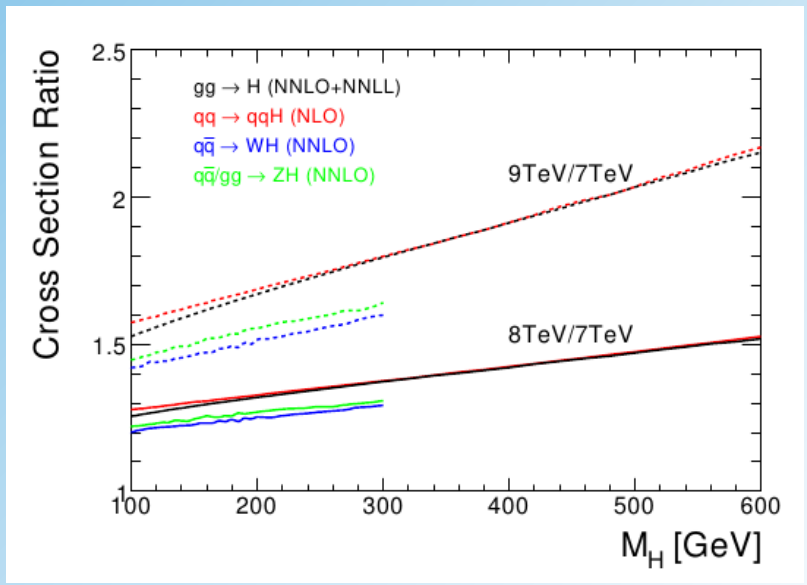
The ATLAS Collaboration

Cross Section Expectations

Table 2: Production cross-sections in pb of the Standard Model Higgs boson in pp collisions for different centre-of-mass energies and Higgs boson masses. Cross-section uncertainties are estimated to be ~ 10% for $gg \to H$ and ~ 5% for VBF and W/ZH processes.

$\sqrt{s}$ = 7 TeV															
m_H (GeV)	110	115	120	130	140	150	165	170	180	190	200	300	400	500	600
$gg \to H$	19.8	18.1	16.6	14.1	12.1	10.5	8.35	7.76	6.76	5.92	5.27	2.42	2.03	.865	.336
VBF	1.38	1.32	1.25	1.14	1.04	.948	.840	.805	.736	.682	.628	.296	.159	.093	.056
WH	.876	.757	.657	.501	.386	.300	.211	.188	.152	.125	.103	.020			
ZH	.473	.412	.360	.278	.217	.171	.123	.111	.089	.074	.061	.012			
$\sqrt{s}$ = 8 TeV															
m_H (GeV)	110	115	120	130	140	150	165	170	180	190	200	300	400	500	600
$gg \to H$	25.0	22.9	21.1	18.0	15.6	13.6	10.8	10.1	8.84	7.78	6.95	3.33	2.88	1.27	0.51
VBF	1.77	1.69	1.61	1.47	1.35	1.24	1.10	1.06	.970	.902	.833	.407	.226	.137	.086
WH	1.06	.919	.799	.611	.472	.368	.260	.233	.189	.156	.129	.026			
ZH	.579	.506	.443	.343	.269	.213	.154	.139	.112	.093	.077	.015			
$\sqrt{s}$ = 9 TeV															
m_H (GeV)	110	115	120	130	140	150	165	170	180	190	200	300	400	500	600
$gg \to H$	30.6	28.1	25.9	22.2	19.3	16.9	13.6	12.7	11.1	9.82	8.80	4.35	3.88	1.76	.723
VBF	2.19	2.09	2.00	1.83	1.68	1.55	1.38	1.33	1.23	1.14	1.06	.053	.304	.189	.122
WH	1.25	1.09	.945	.723	.561	.439	.311	.279	.227	.188	.156	.032			
ZH	.690	.603	.530	.412	.324	.257	.187	.169	.137	.114	.095	.019			





2010-2011: running at 7 TeV

Higgs cross sections ~ O(pb)

Higgs Decay Channels

Main Higgs Branching Ratios

m_H (GeV)	110	115	120	130	140	150	165	170	180	190	200	300
bb	74.5	70.5	64.9	49.4	31.4	15.6	1.19	0.793	0.497	0.315	0.239	0.056
$\tau^+\tau^-$	8.02	7.65	7.10	5.49	3.54	1.78	0.138	0.093	0.059	0.038	0.029	0.007
$\gamma\gamma$	0.216	0.234	0.246	0.245	0.208	0.145	0.024	0.017	0.011	0.007	0.006	0.001
WW	4.89	8.79	14.4	30.8	50.7	70.1	96.0	96.5	93.2	78.7	74.3	69.4
ZZ	0.442	0.880	1.61	4.02	6.90	8.23	2.21	2.36	6.02	20.8	25.4	30.5

Pros and Cons of Higgs Decay channels

H → bb: largest BR at low mass, b-tagging : huge QCD BG

H → ττ: large BR at low mass, clear signature : BG +issing neutrinos

H → γγ: clearest signature : large BG + tiny BR

H → WW: clear signature : SM WW BG + missing neutrinos

H → ZZ: very clear signature : SM ZZ BG + small BR at low mass

$H \rightarrow ZZ$

Which decay channel(s)?

M_H (GeV)	120	140	150	170	180	190	200	240	300	400	500	600
$\sigma_{l^+l^-l^+l^-}$ [fb]	1.30	4.12	4.27	0.92	2.04	6.23	6.77	5.34	3.75	2.65	1.13	0.48
$\sigma_{l^+l^-b\bar{b}}$ [fb]	5.8	18.5	19.2	4.1	9.2	28.0	30.4	24.0	16.9	11.9	5.1	2.2
$\sigma_{l^+l^-\nu\bar{\nu}}$ [fb]	7.7	24.5	25.4	5.5	12.1	37.0	40.2	31.7	22.3	15.7	6.7	2.9

most promising llνν final state allows no Higgs mass reconstruction

But Higgs Mass estimate:

$$m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{P}_T^{ll}|^2} + \sqrt{m_Z^2 + |\vec{P}_T^{miss}|^2} \right]^2 - \left[\vec{P}_T^{ll} + \vec{P}_T^{miss} \right]^2$$

$m_T^2 = E_T^2 - p_T^2$

$H \rightarrow ZZ \rightarrow llνν$

Selection:

- two leptons; invariant mass compatible with Z-mass
- $E_t^{miss} > 0.4\ m_H$ -30 GeV

expected signal →

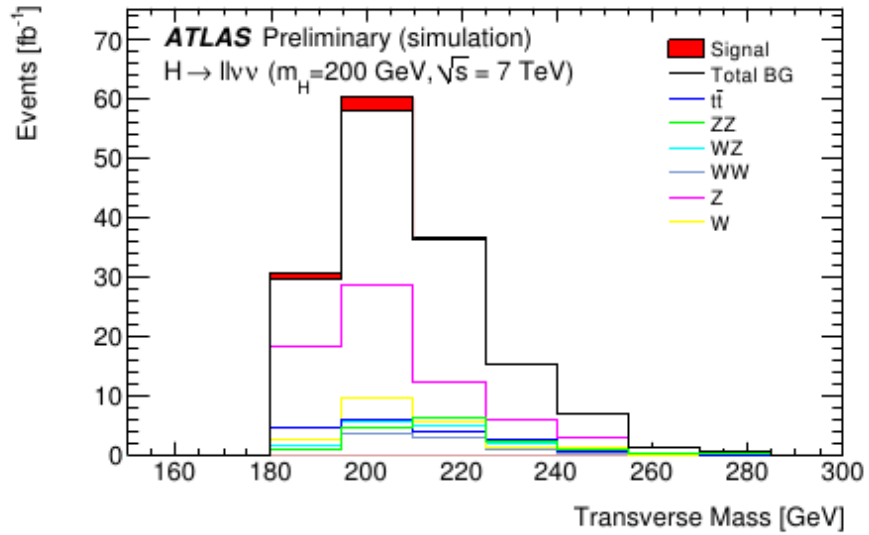
Backgrounds

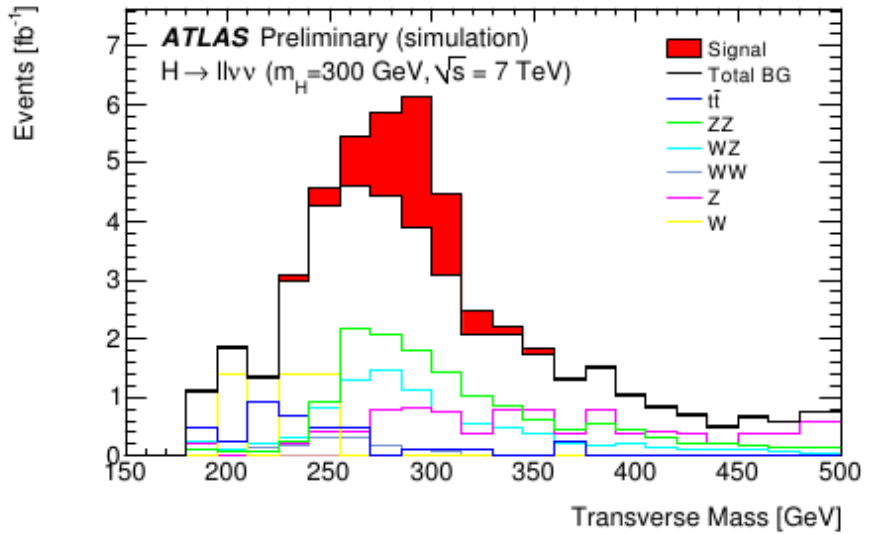
m_H (GeV)	200	300	400	500	600
$H \rightarrow llνν$	3.79	7.25	5.78	2.50	0.96
$t\bar{t}$	18.3	3.72	0.23	0.00	0.00
ZZ	16.0	14.5	5.54	2.44	1.12
WW	9.05	1.35	0.19	0.06	0.03
WZ	15.2	8.92	2.46	0.90	0.39
Incl. Z	69.2	9.87	1.92	0.39	0.00
Incl. W	20.6	4.15	1.38	0.00	0.00

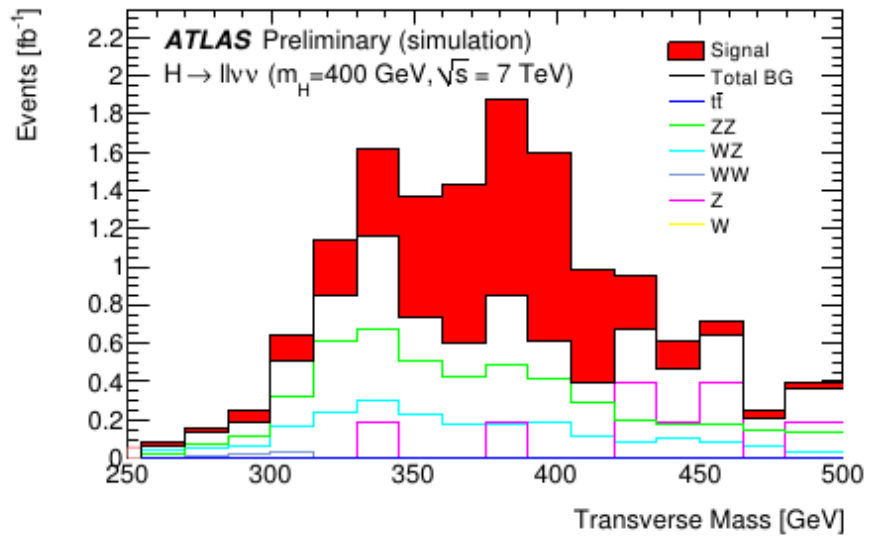
this channel is promising at high masses!

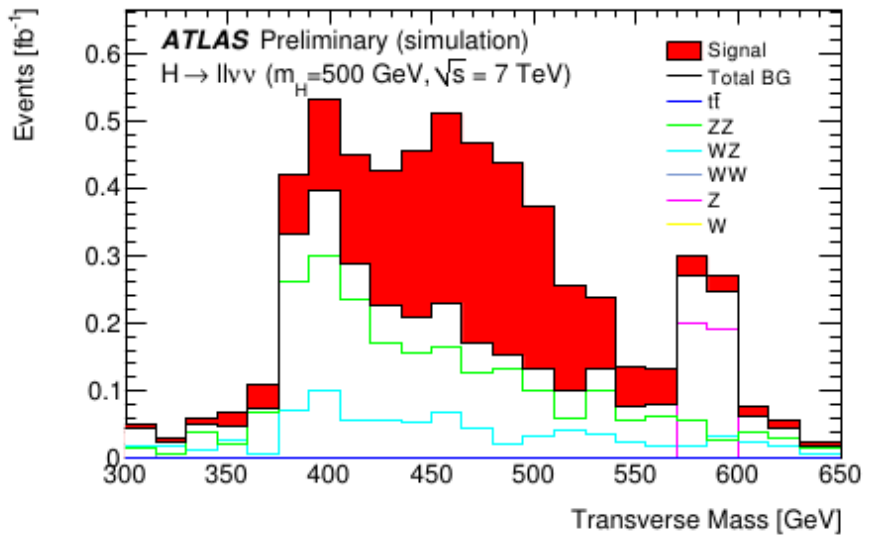
$H \rightarrow ZZ \rightarrow llvv$

MC expectations







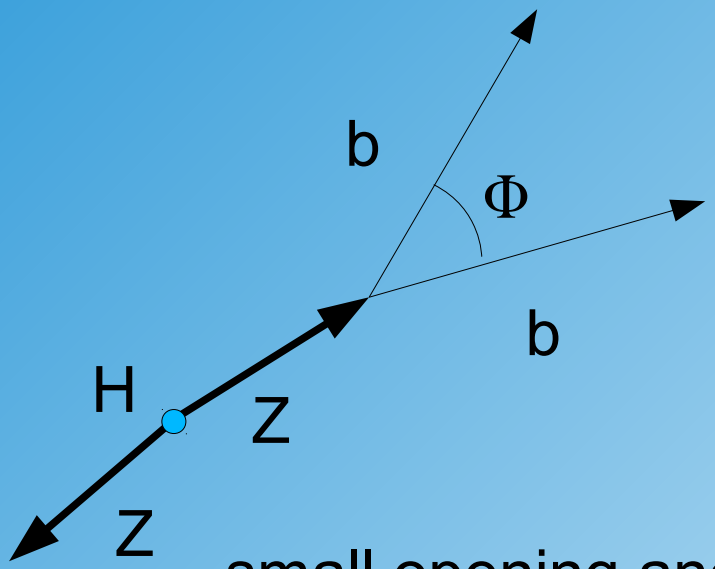


H → ZZ → llbb

Selection:

- two leptons; invariant mass compatible with Z-mass
- two b-tagged jets, invariant mass compatible with Z-mass

additional cut on azimuthal opening of the two b-jets

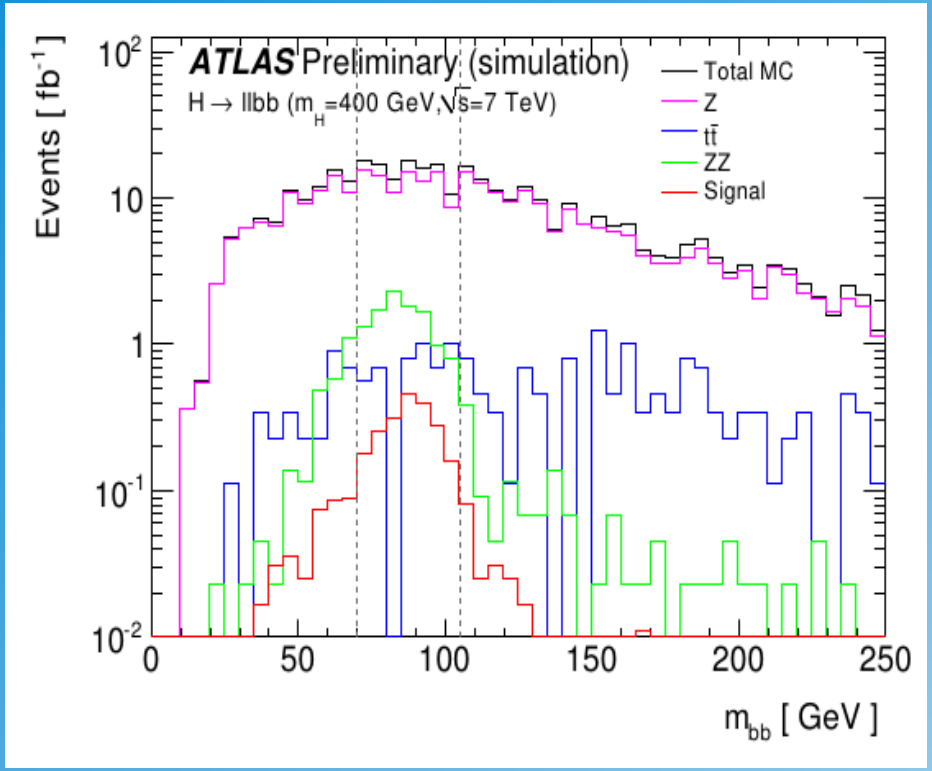


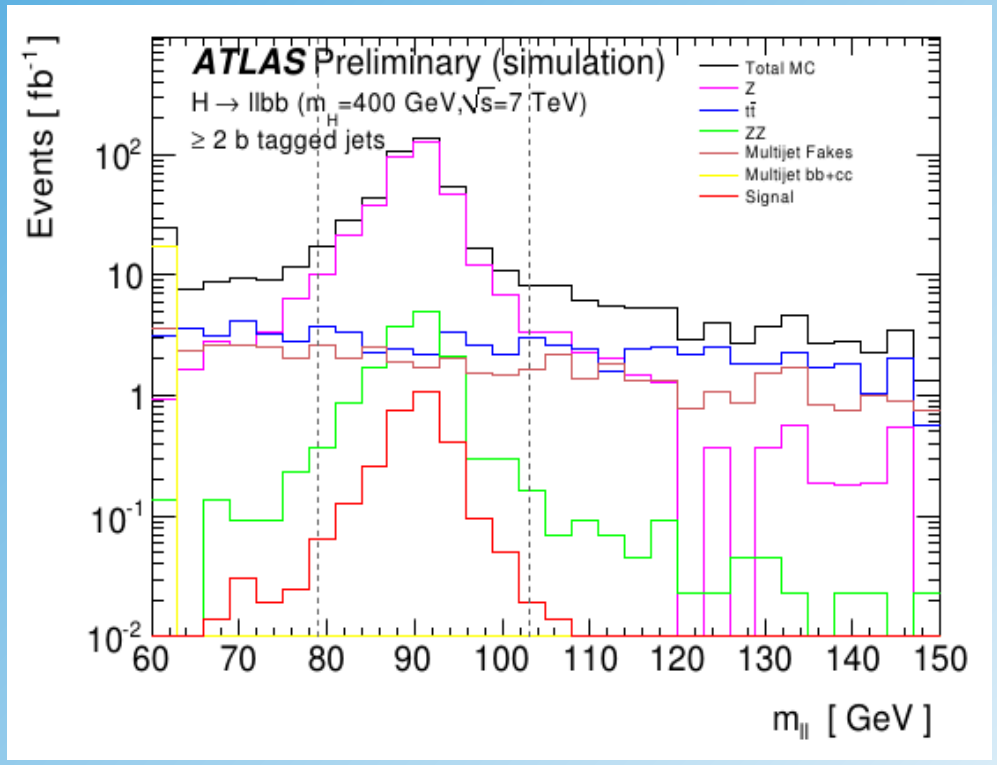
Sample	No $\Delta\phi_{jj}$ Cut	$\Delta\phi_{jj} < 90°$
m_H = 200 GeV	2.03	–
m_H = 300 GeV	–	1.43
m_H = 400 GeV	–	1.86
m_H = 500 GeV	–	0.96
m_H = 600 GeV	–	0.40
Z	92.91	30.02
Top	4.74	2.14
ZZ	9.17	2.88

→ reduces BG

small opening angle of Z is boosted (m_H large)

H → ZZ → llbb





expectation for L=1fp^{-1}

$H \rightarrow ZZ \rightarrow llll$

Combine: 2e and 2μ decay channels of Z pair:

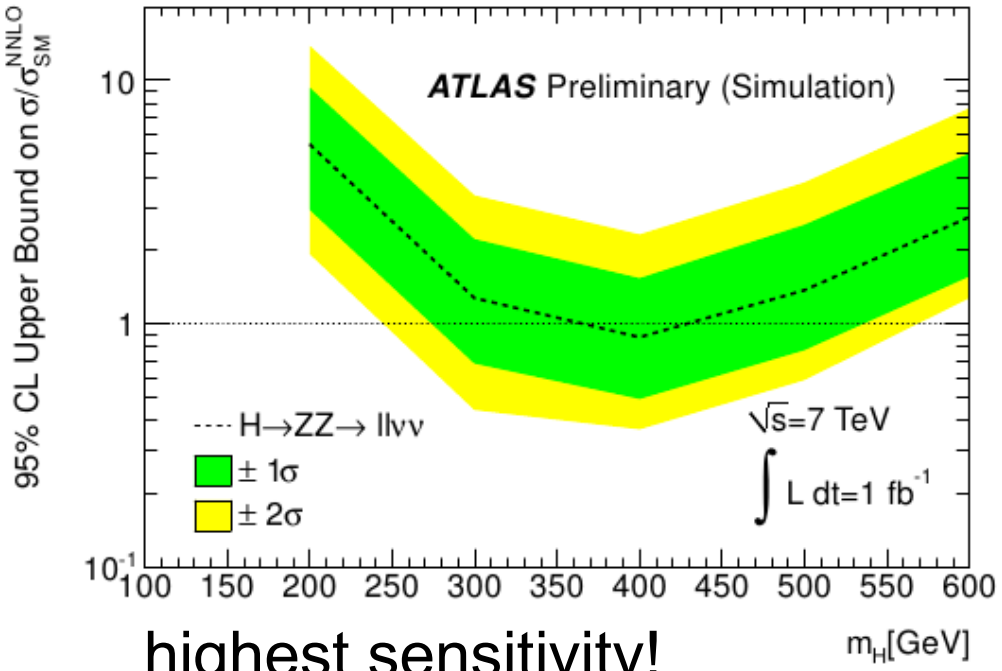
Expected number of events for L=1 fb^{-1}

M_H(GeV)	120	130	140	150	165	170	180	190
SM ZZ	0.093	0.097	0.086	0.092	0.125	0.152	0.388	1.012
top & Z+jets	0.012	0.009	0.008	0.006	0.004	0.004	0.003	0.003
Total background	0.105	0.106	0.094	0.098	0.129	0.156	0.391	1.015
Signal	0.152	0.455	0.840	0.995	0.258	0.271	0.651	2.105
M_H(GeV)	200	220	240	260	300	400	500	600
SM ZZ	1.33	1.21	0.94	0.92	0.75	0.49	0.51	0.40
Signal	2.25	2.04	1.75	1.51	1.24	0.95	0.42	0.18

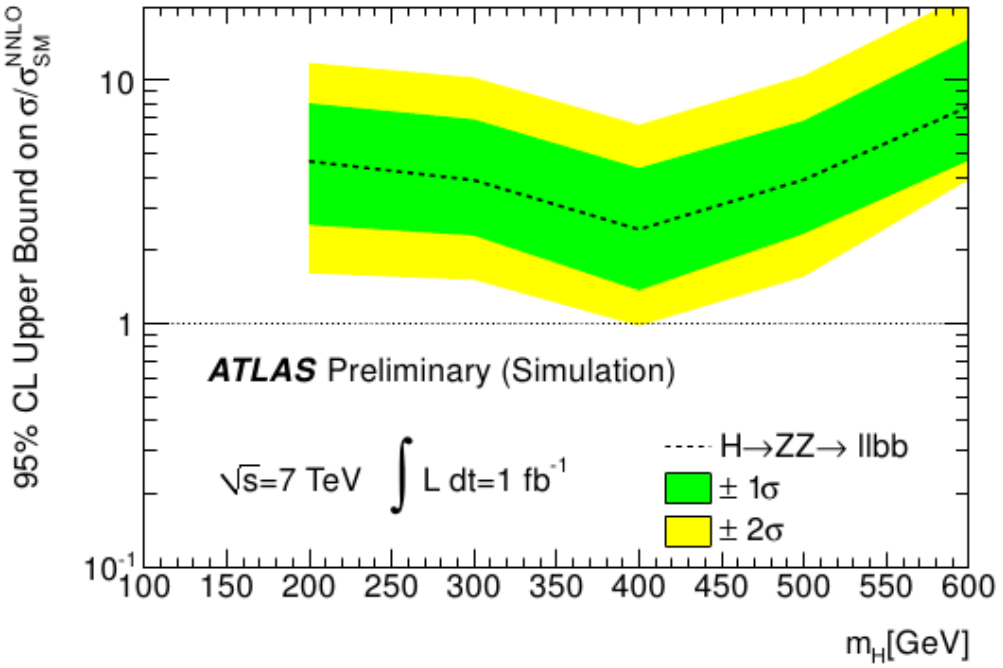
very small Higgs yields in this channel due to small Z branching fractions

$B(Z \rightarrow l_i\, l_i) = 0.03$ c.t. $B(Z \rightarrow \nu\nu) = 0.30$

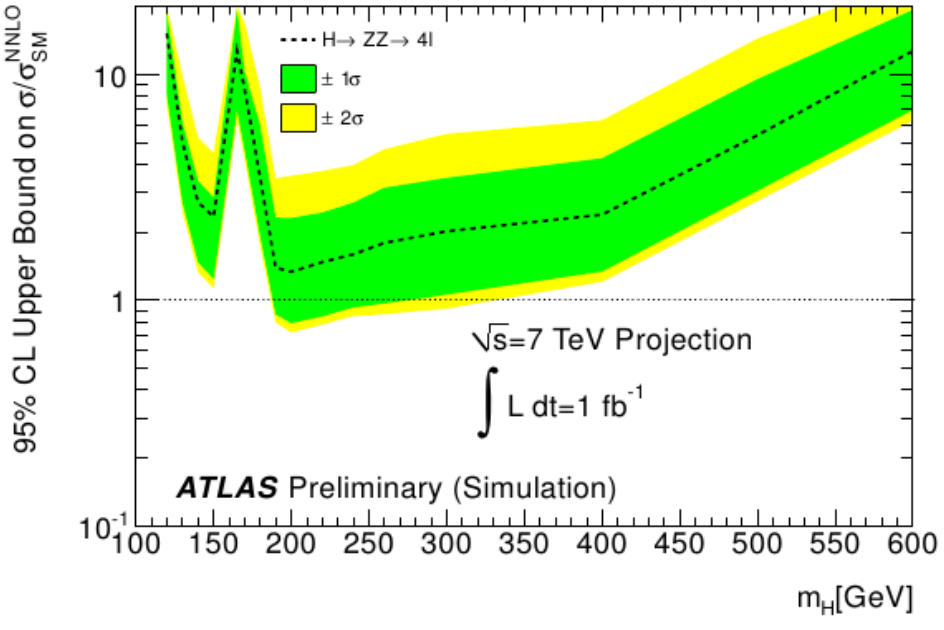
Expected Sensitivity: H → ZZ



highest sensitivity!



test Higgs high mass region even with small integrated luminosity



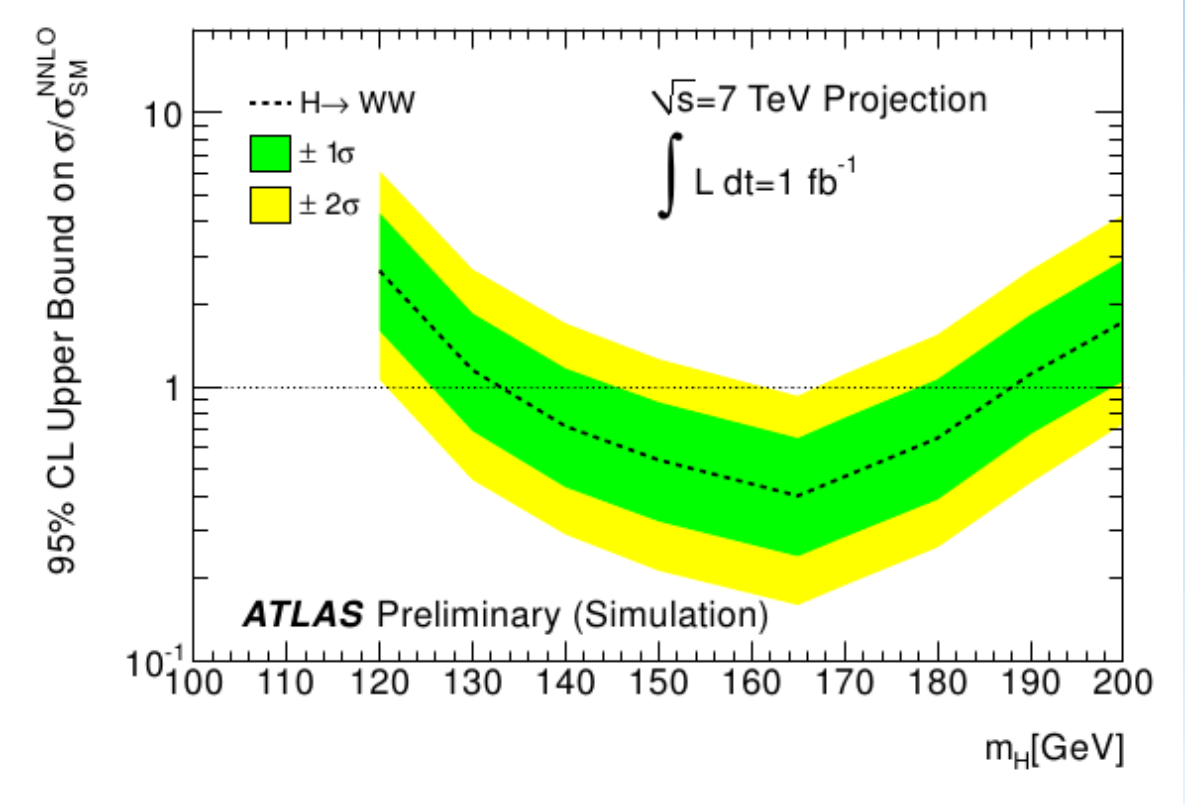
$H \rightarrow WW \rightarrow l\nu\nu$

Selection:

- two leptons (electron or muon) with p_T >15 GeV (trigger!)
- if leptons identical flavor, then Z mass veto (no $Z \rightarrow ll$)
- missing transvere energy (2 neutrinos): p_T^{miss} >30 GeV

expected exclusion limit

high sensitivity in WW mass threshold region



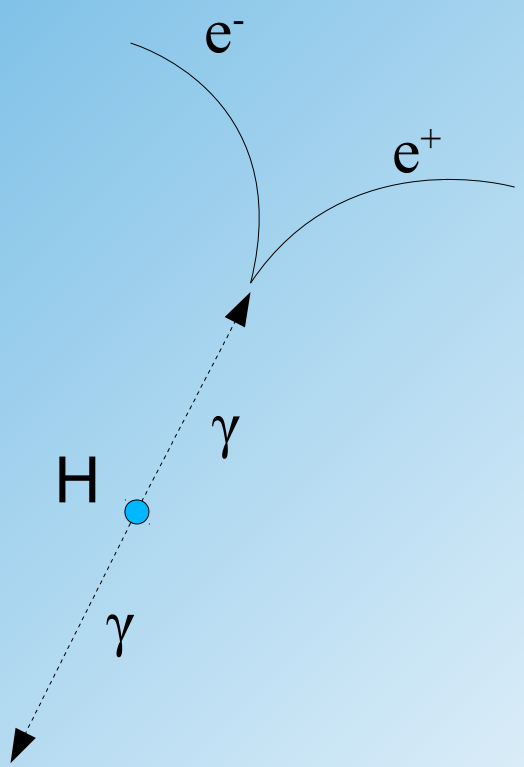
$H \rightarrow \gamma\gamma$

Selection:

- two photons (em. cluster with no track match)
- photons are also identified if converted: $\gamma \rightarrow e^+ e^-$
- no missing transverse momentum

Background:

- misidentified pions
- accidental coincidence of $\pi^0 \rightarrow \gamma\gamma^-$ and π^+ track
- no missing transverse momentum

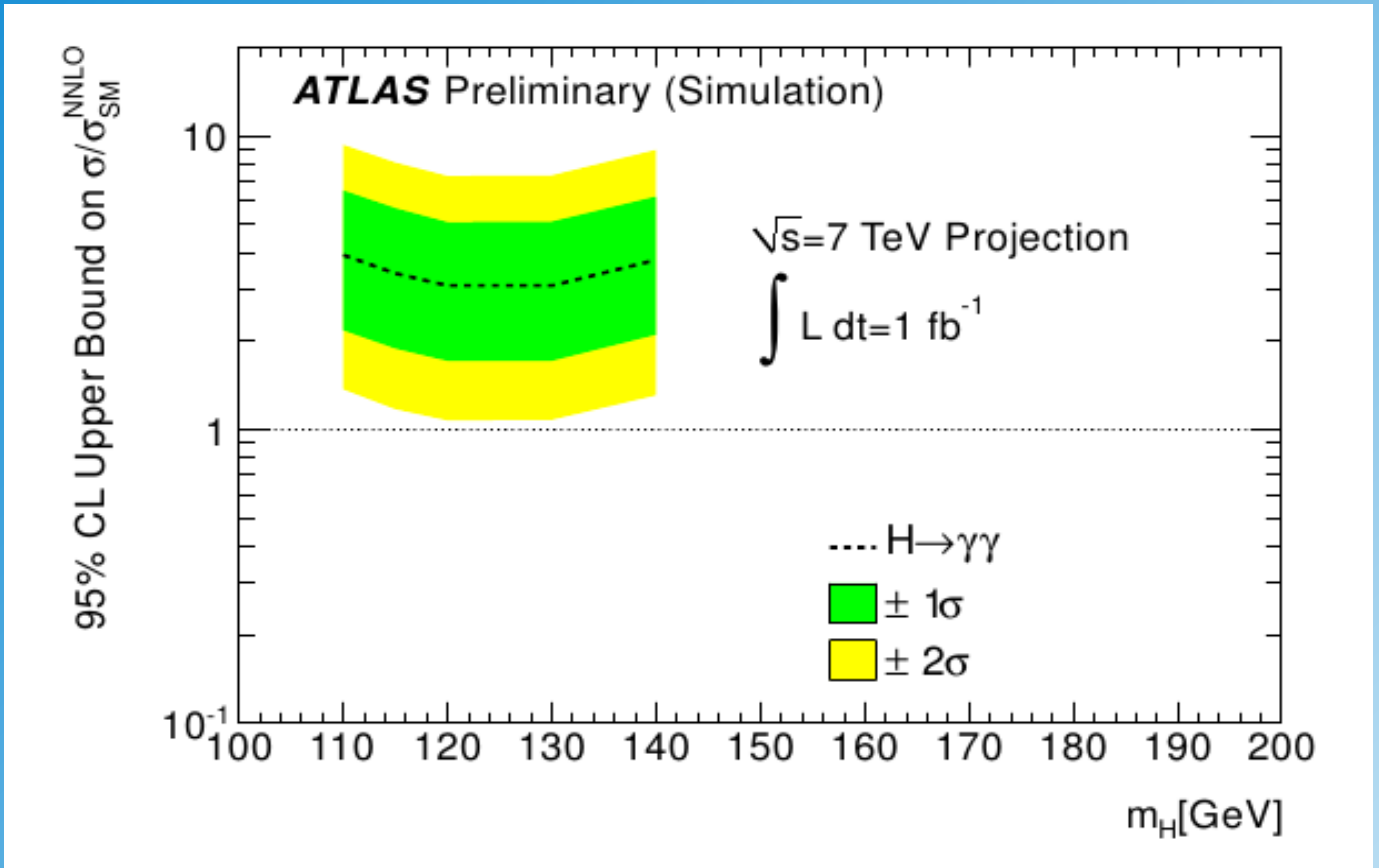


M_H (GeV)	110	115	120	130	140
Signal	20.1	20.4	20.7	18.5	14.1
$\gamma\gamma$			5540		
γj			2500		
jj			360		
Drell Yan			90		
Total background			8490		

for L=1fb^{-1} at 7 TeV

high BG!!

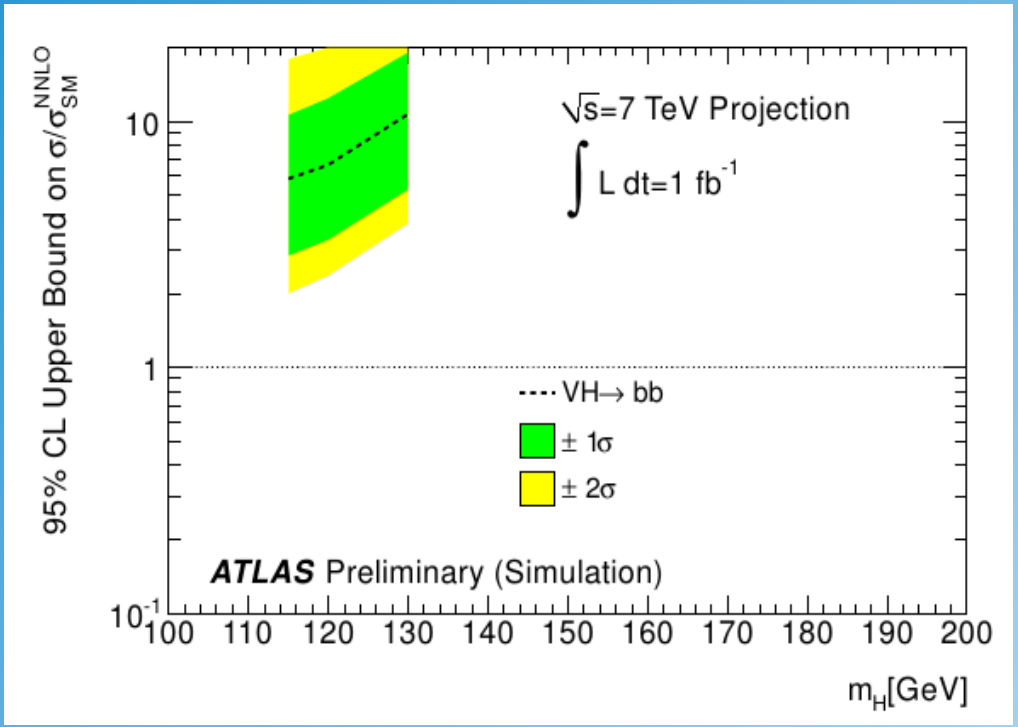
Expected Exclusion for H → γγ

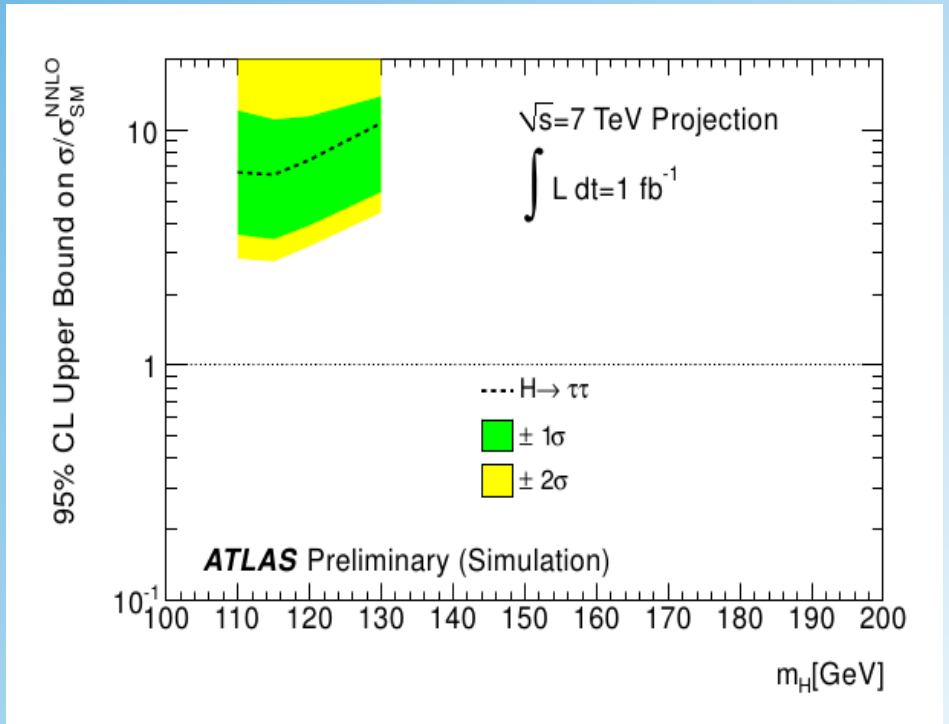


- best sensitivity at m_H = 125 GeV
- BG dominated: sensitivity scales with $\propto \frac{1}{\sqrt{L}}$
- factor 10 needed for 95% exclusion
- much much more needed for 5 sigma discovery

H → bb and H → ττ

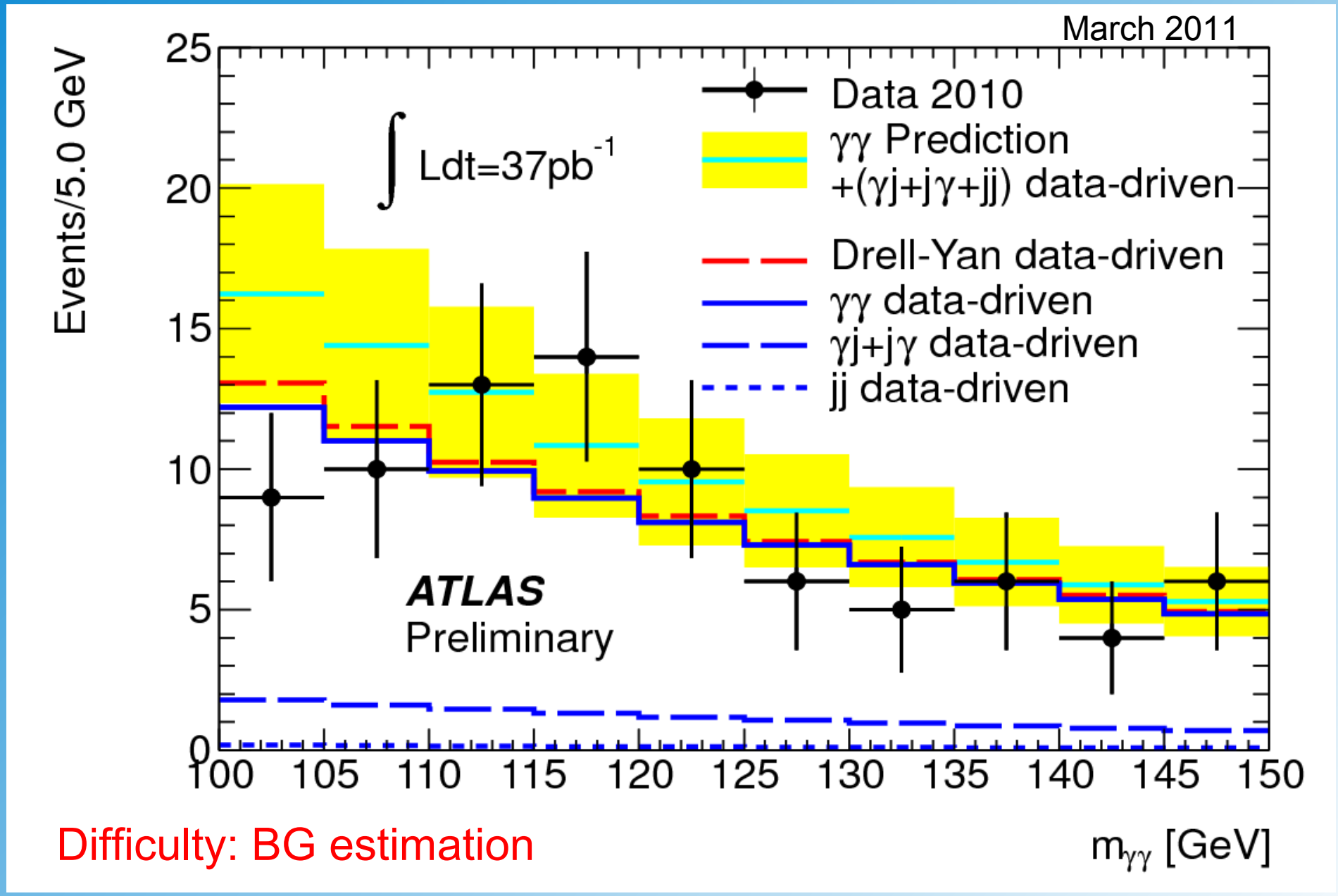
- low selection efficiencies and high backgrounds
- not highly sensitive discovery channel
- but only ones testing Yukawa coupings! (fermiophobic Higgs?)





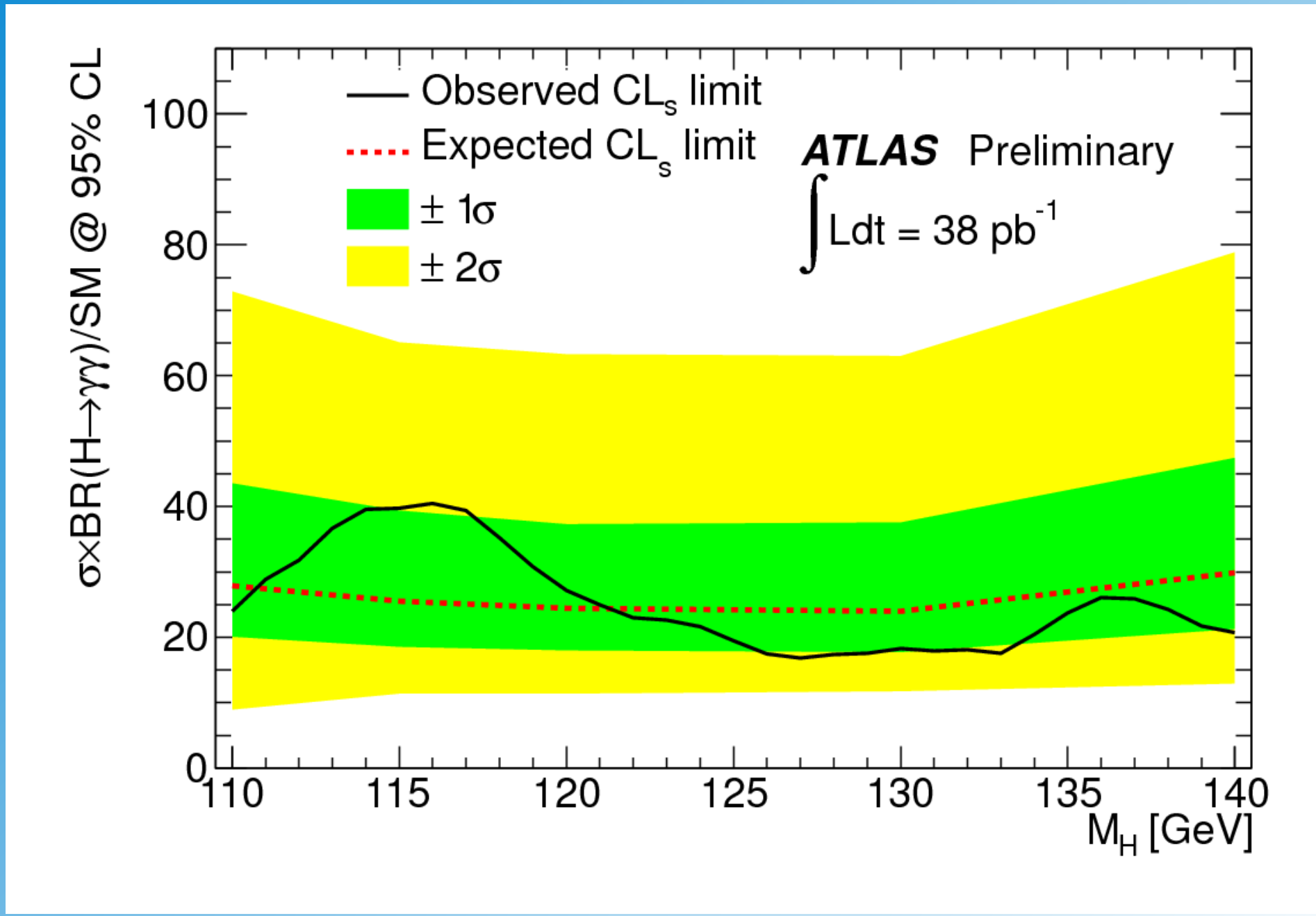
At mass 125 GeV at least 7^2 = 50 fb^{-1} needed for firm statements

ATLAS Result Moriond Conference



Difficulty: BG estimation

ATLAS Result Moriond Conference



...one month later

Higgs Blogs I

Home

← This Week's Hype

Short Items →

This Week's Rumor

Posted on April 21, 2011 by woit

A commenter on the previous posting has helpfully given us the abstract of an internal ATLAS note claiming observation of a resonance at 115 GeV. It's the sort of thing you would expect to see if there were a Higgs at that mass, but the number of events seen is about 30 times more than the standard model would predict. Best guess seems to be that this is either a hoax, or something that will disappear on further analysis. But, since spreading well-sourced rumors is more or less in the mission statement of this blog, I think I'll promote this to its own posting. Here it is:

Internal Note
Report number ATL-COM-PHYS-2011-415

Higgs Blogs II

Update: Via Slashdot, some more comment about this, including disclosure of another vector of information transfer out of ATLAS:

> *Someone left a copy of the note on the printer in my office building. (I work on CDF at Fermilab, but there are others in the building who work on ATLAS at CERN.) The gist of the article is that they found a bump in the diphoton mass spectrum at a mass of ~115 GeV. If the Higgs exists, it is expected to produce a bump in that spectrum, and 115 GeV is a very probable value for the mass of the Higgs. (Experiments at LEP ruled out masses up to 114 GeV, but a mass as low as possible above that fits best with other measurements.)*
>
> *Now, the inconsistencies: The bump that they found is ~30 times as large as the Higgs mass peak is expected to be. However, due to field theory that I don't want to get into here, the Higgs peak in this spectrum could be larger than expected if there exist new, heavy particles that we haven't discovered yet. The latest published result from CDF sets a limit of about 30 times the expected rate at 115 GeV in the diphoton channel. (Yes, this means that, if you're optimistic enough, there's just enough wiggle room to fit a Higgs in there while accommodating both measurements.)*
>
> *The internal note is very preliminary and uses a crude background estimate; I'll have to see a more thorough analysis before I make any judgment on it. We shouldn't have to wait very long; I expect that after this leak, they'll be working overtime to push out a full published result as soon as possible.*

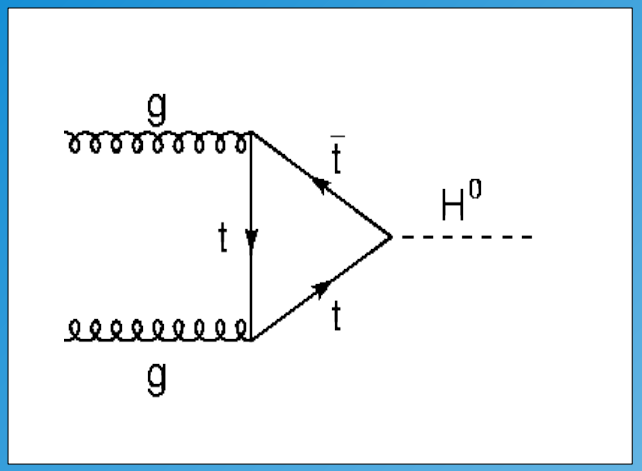
Update: Since I don't traffic in rumors of dubious source, you'll have to go here to get the latest rumors from someone younger who knows about this whole Twitter kind of thingy…

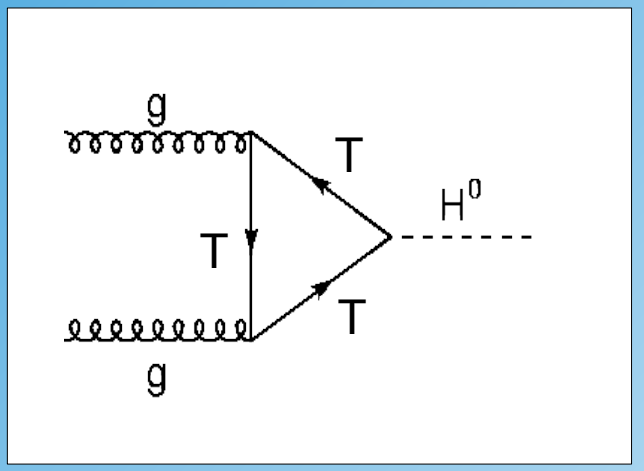
This entry was posted in Experimental HEP News. Bookmark the permalink.

In the following days Easter 2011 many people in ATLAS were very busy!

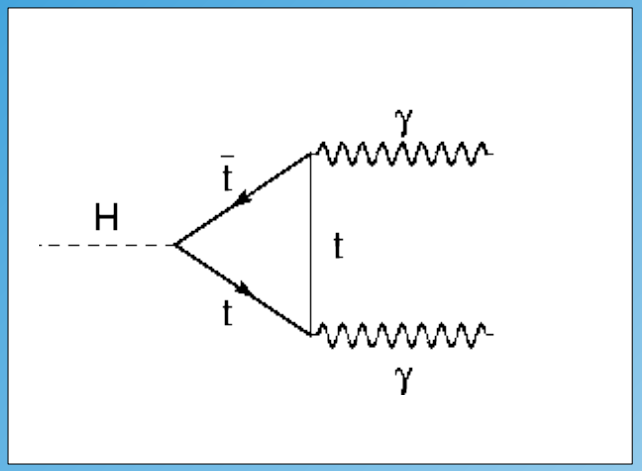
Is it possible to have a Higgs signal 30 times larger than expected from the SM?

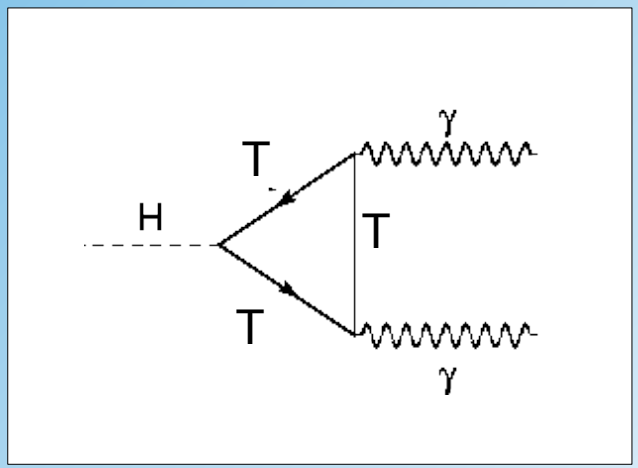
Higgs beyond the SM





4th generation top partner can enhance the Higgs production cross section!





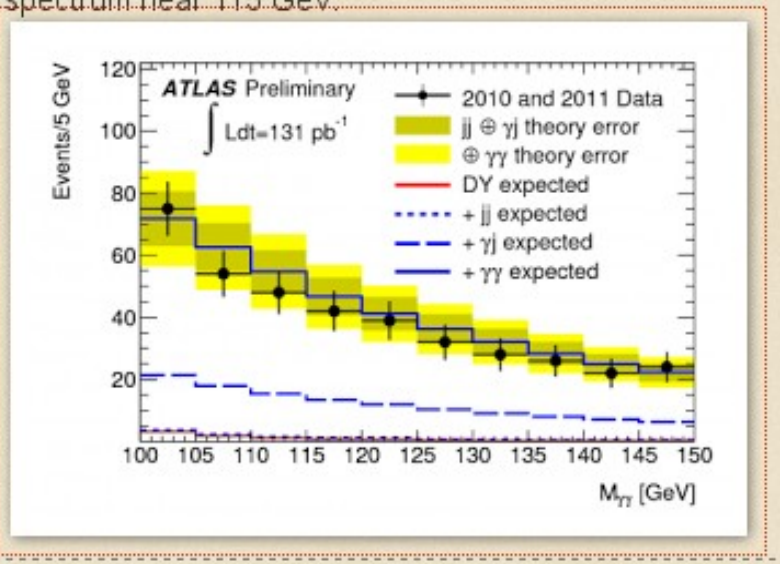
… and the decay rate into two photons!

ATLAS shrugged

A new rumor propagating via twitter, social networks and other attributes of modern civilization says that the old rumor was just a rumor. The ATLAS collaboration was working hard this last week to investigate the possible signal of Higgs decaying to photons. Observations of such a signal was claimed in an internal memo written by 4 of its members. However, after analyzing about 100 pb-1 of currently available data ATLAS concluded that the suspicious excess in the γγ invariant mass distribution is going away. C'est la vie, as the local folks would say. A parallel rumor says that CMS sees nothing unusual in the γγ channel. That would pretty much end the career of the first LHC rumor. Maybe it's for the better. Otherwise *the Higgs boson* would have to be renamed to *the Wu boson* which could lead to some confusion.

Anyway, same time tomorrow, we must have a winner one day...

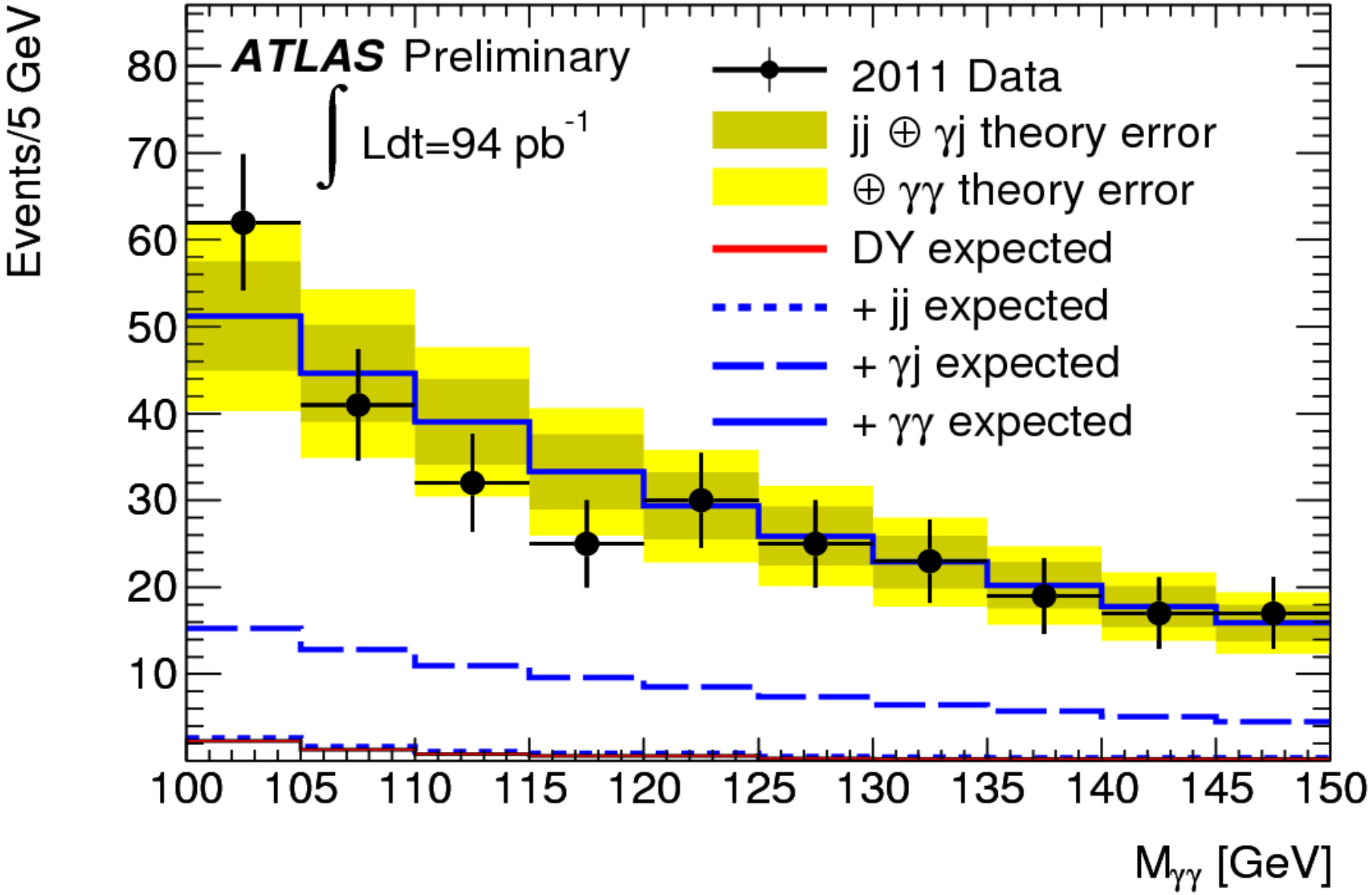
Update: ATLAS officially quashes the rumor. With 131 pb-1 of data there is no peak in the γγ invariant mass spectrum near 115 GeV.



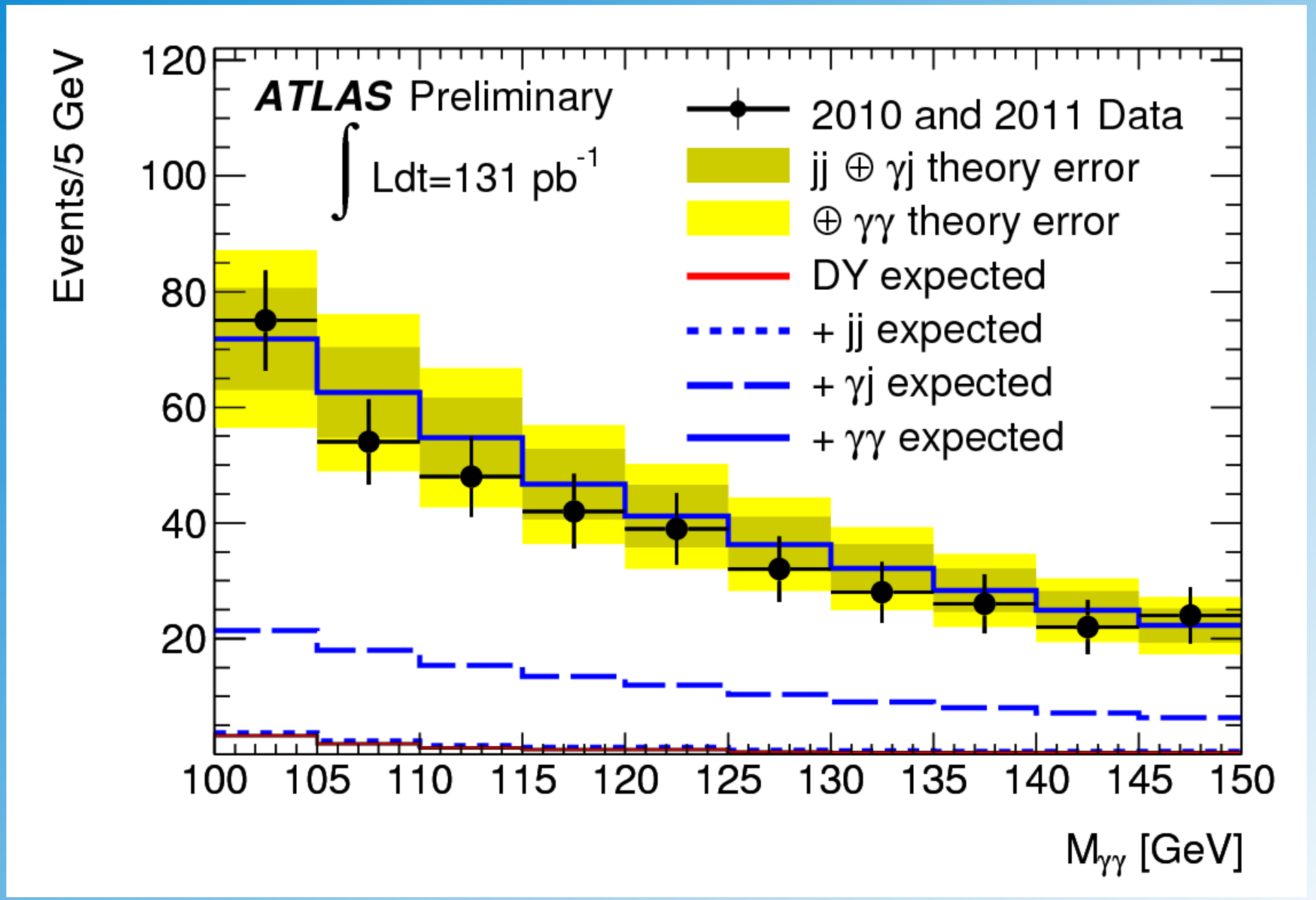
28.04.2011

The Higgs at m_H = 115 GeV had only a very short lifetime!

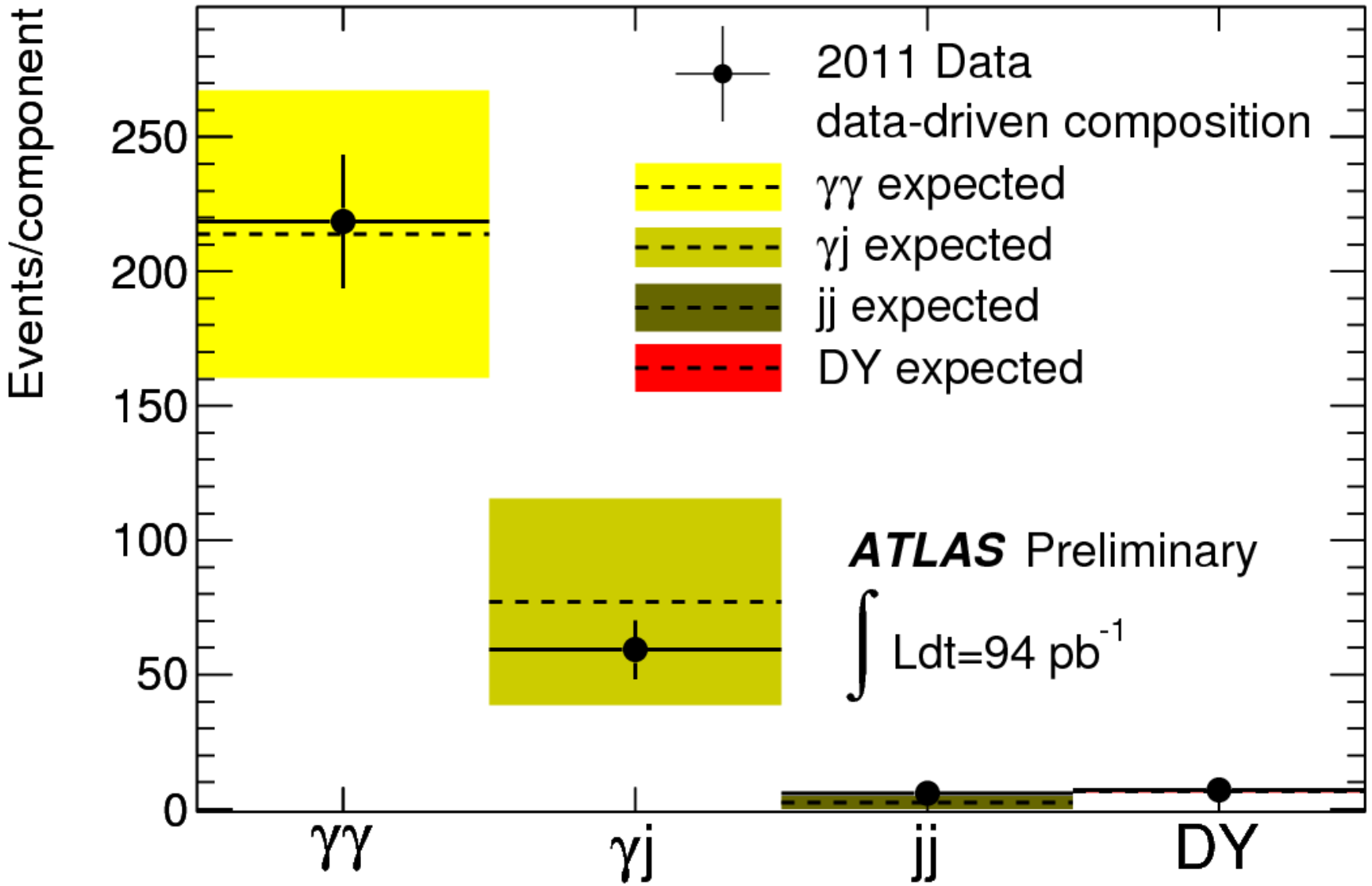
The official ATLAS Result



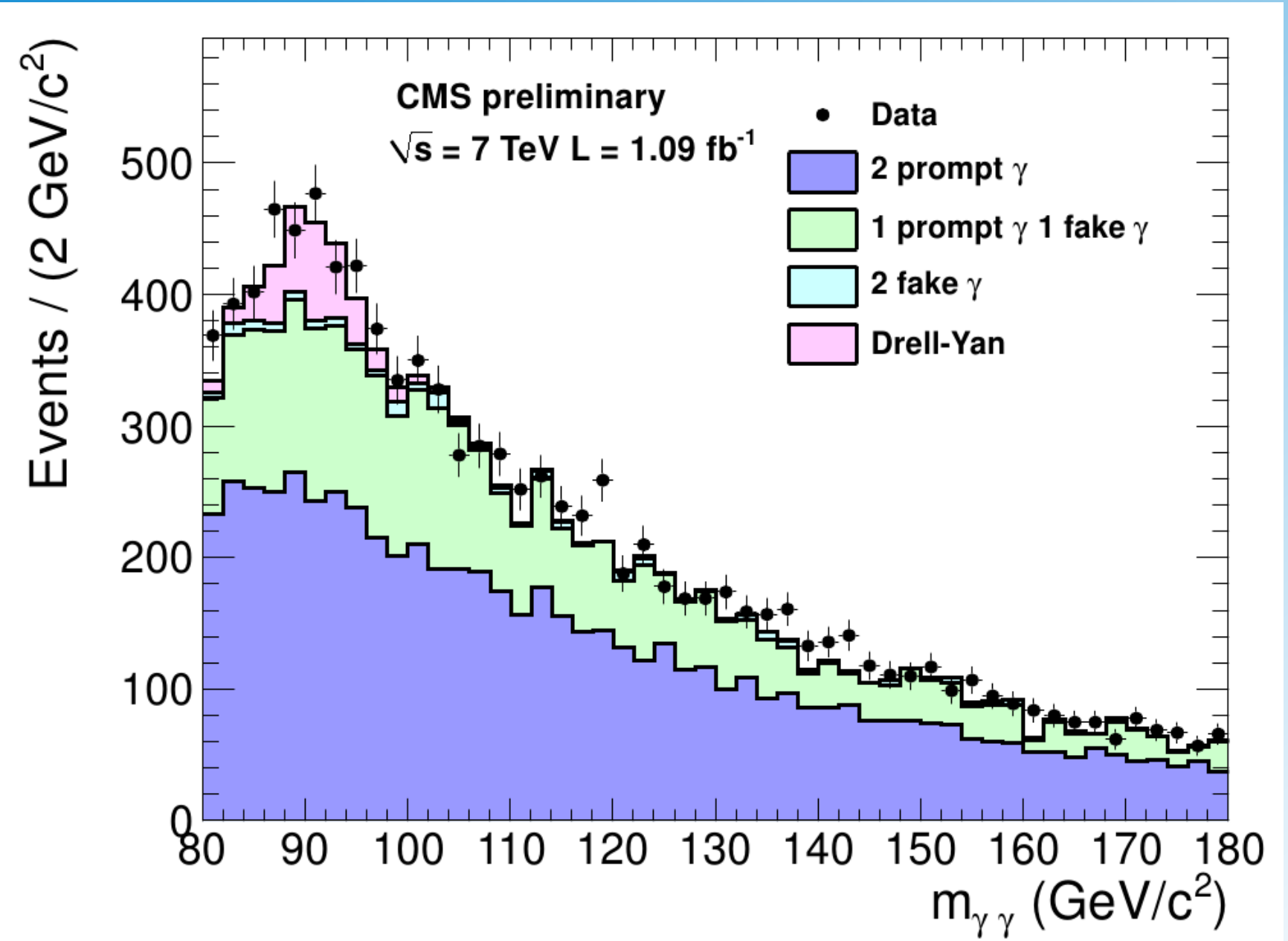
The official ATLAS Result



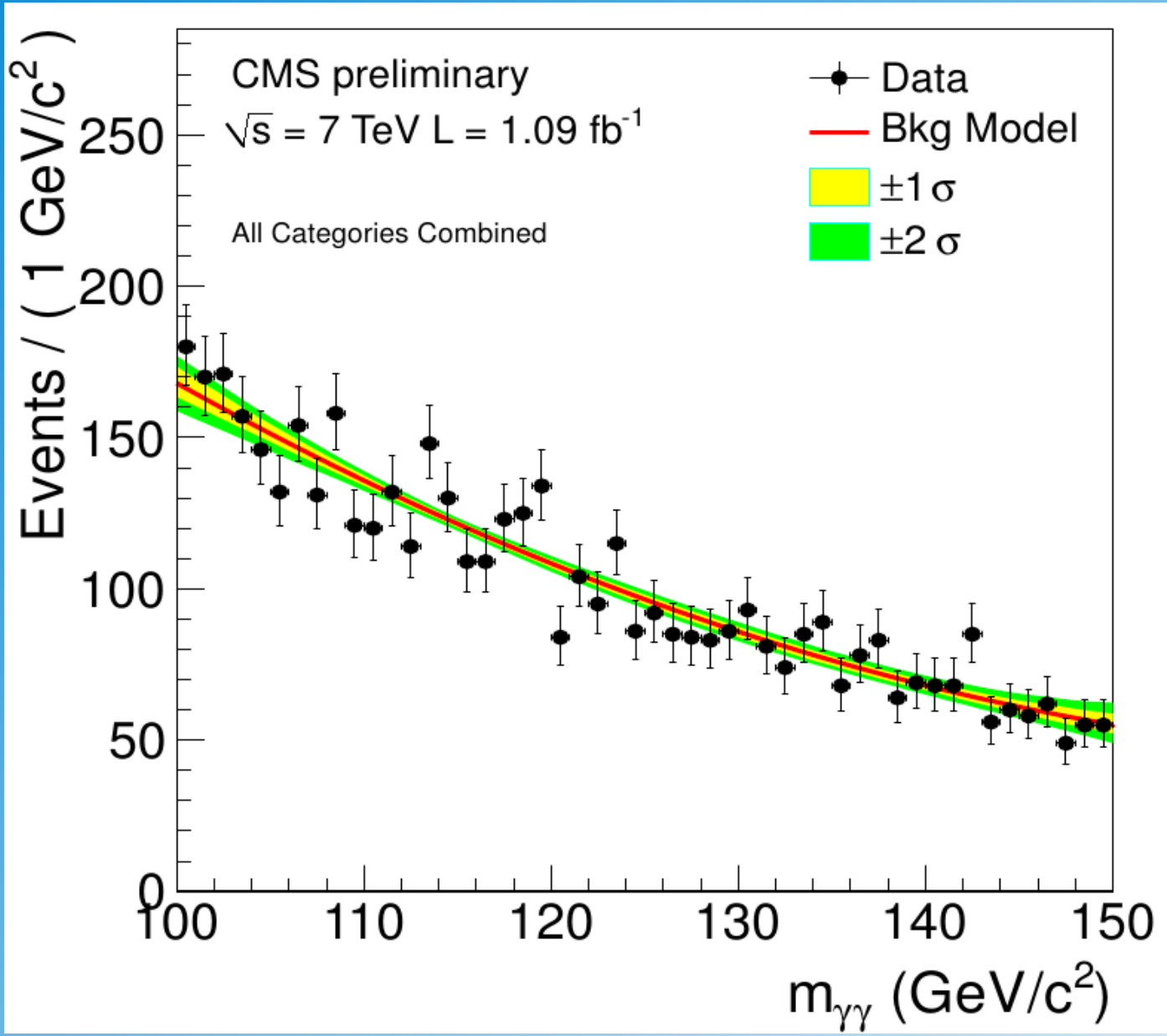
The official ATLAS Result



… And CMS?

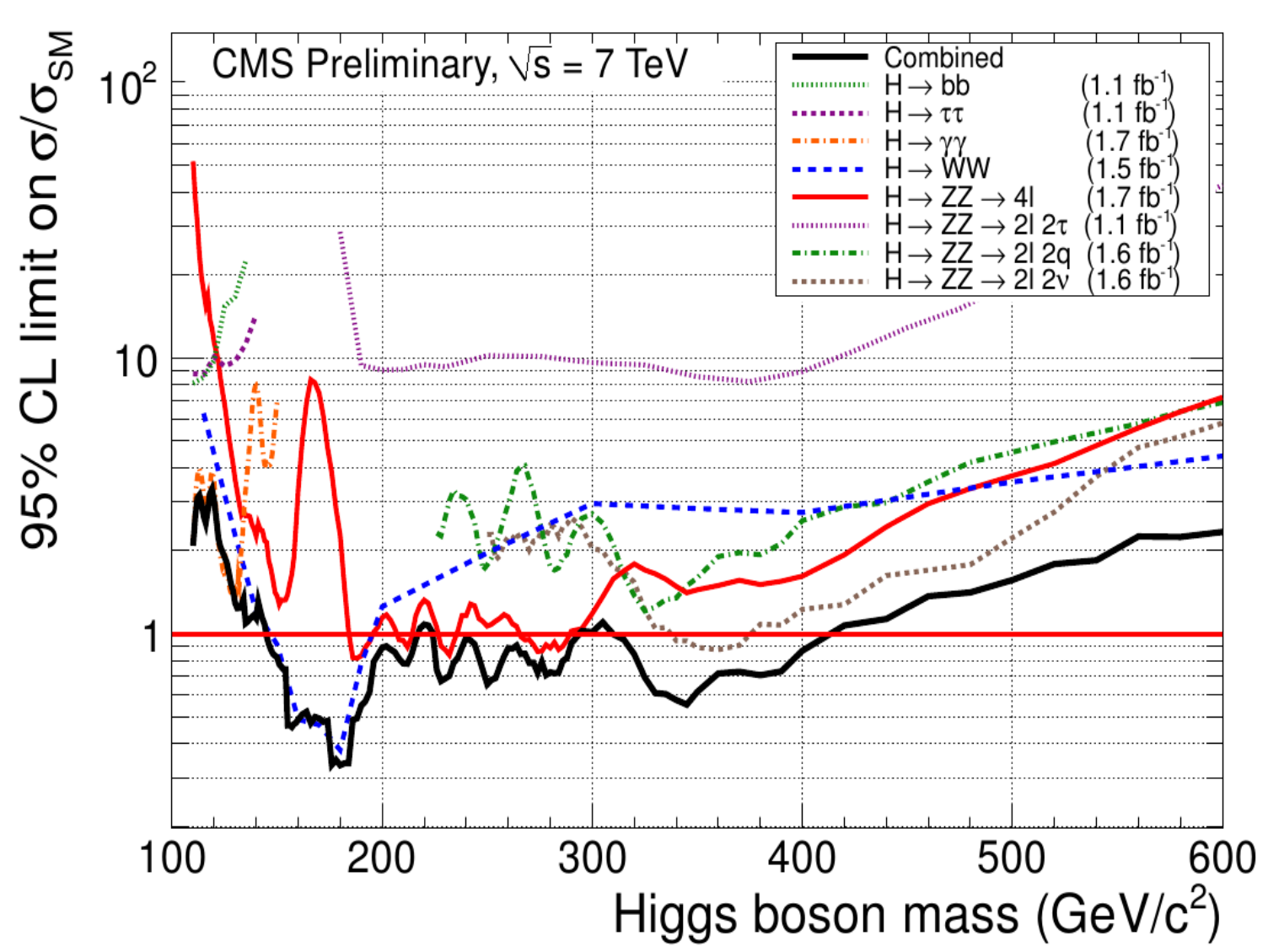

CMS preliminary
$\sqrt{s}$ = 7 TeV L = 1.09 fb^{-1}
Data
2 prompt γ
1 prompt γ 1 fake γ
2 fake γ
Drell-Yan
Events / (2 GeV/c^2)
0
100
200
300
400
500
80
90
100
110
120
130
140
150
160
170
180
$m_{\gamma\,\gamma}$ (GeV/c^2)

… And CMS?



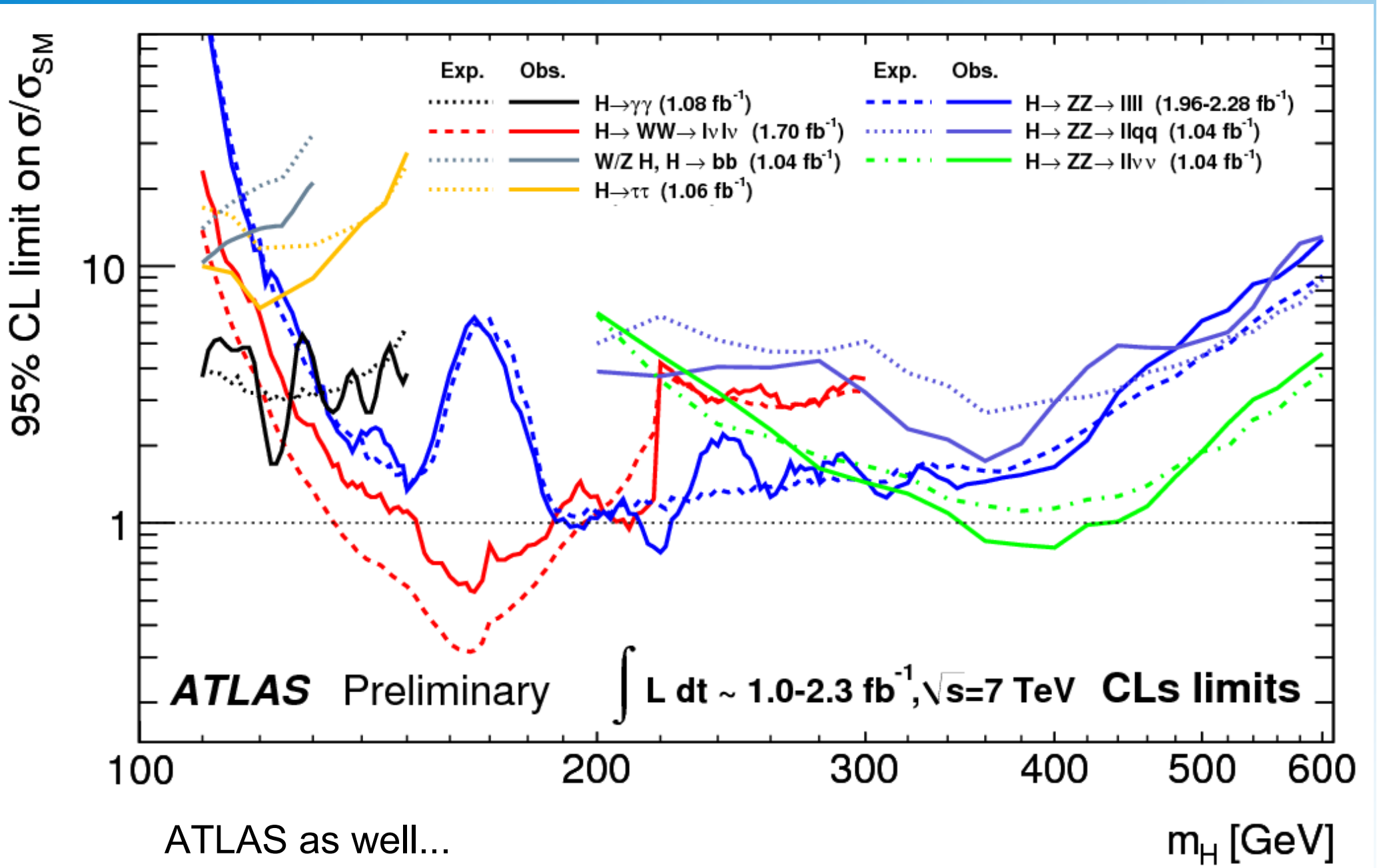
no sign of signal!

2011 Summer Conferences CMS



CMS overtakes Tevatron experiments and can also exclude 160 GeV region with the WW-channel!

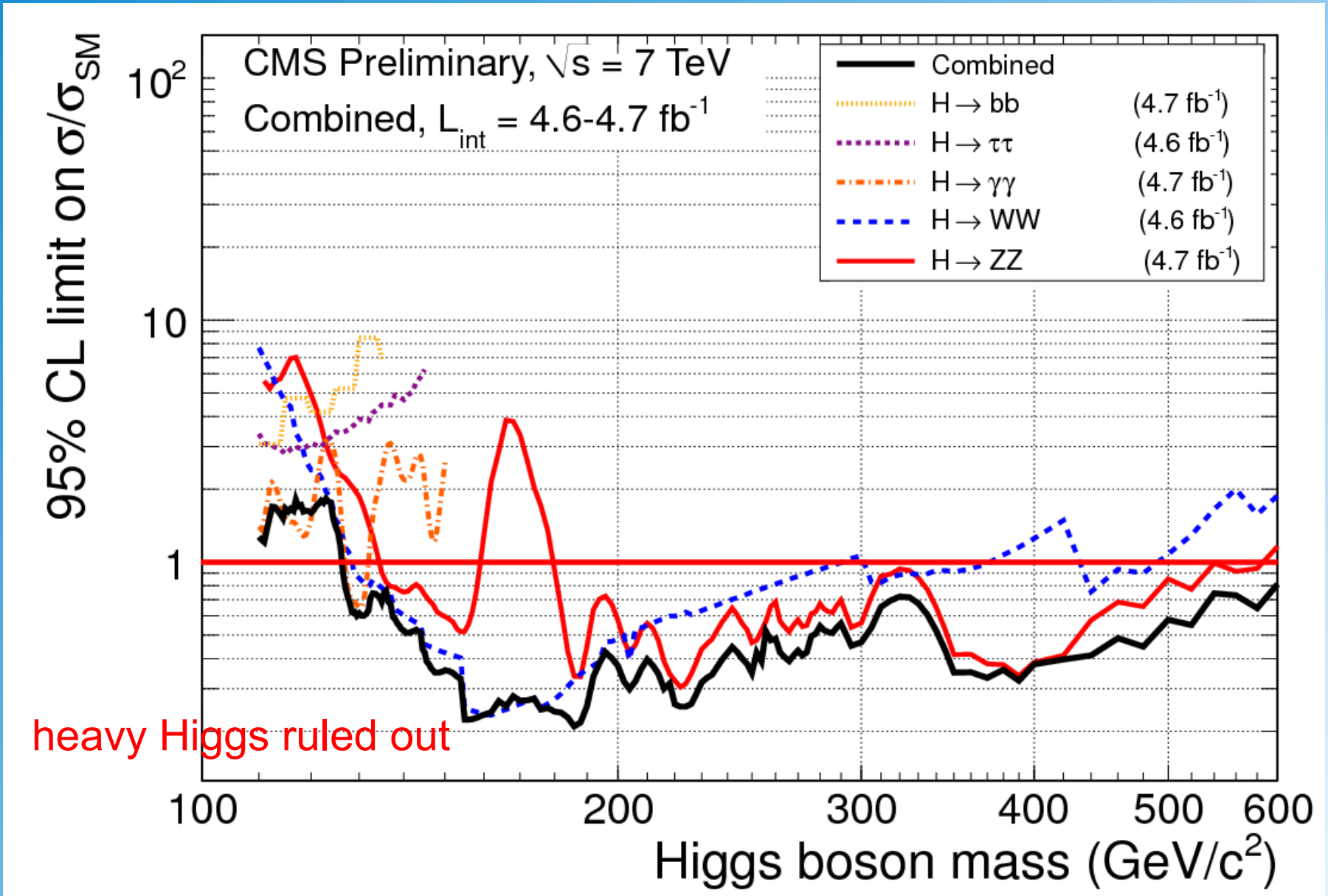
2011 Summer Conferences ATLAS

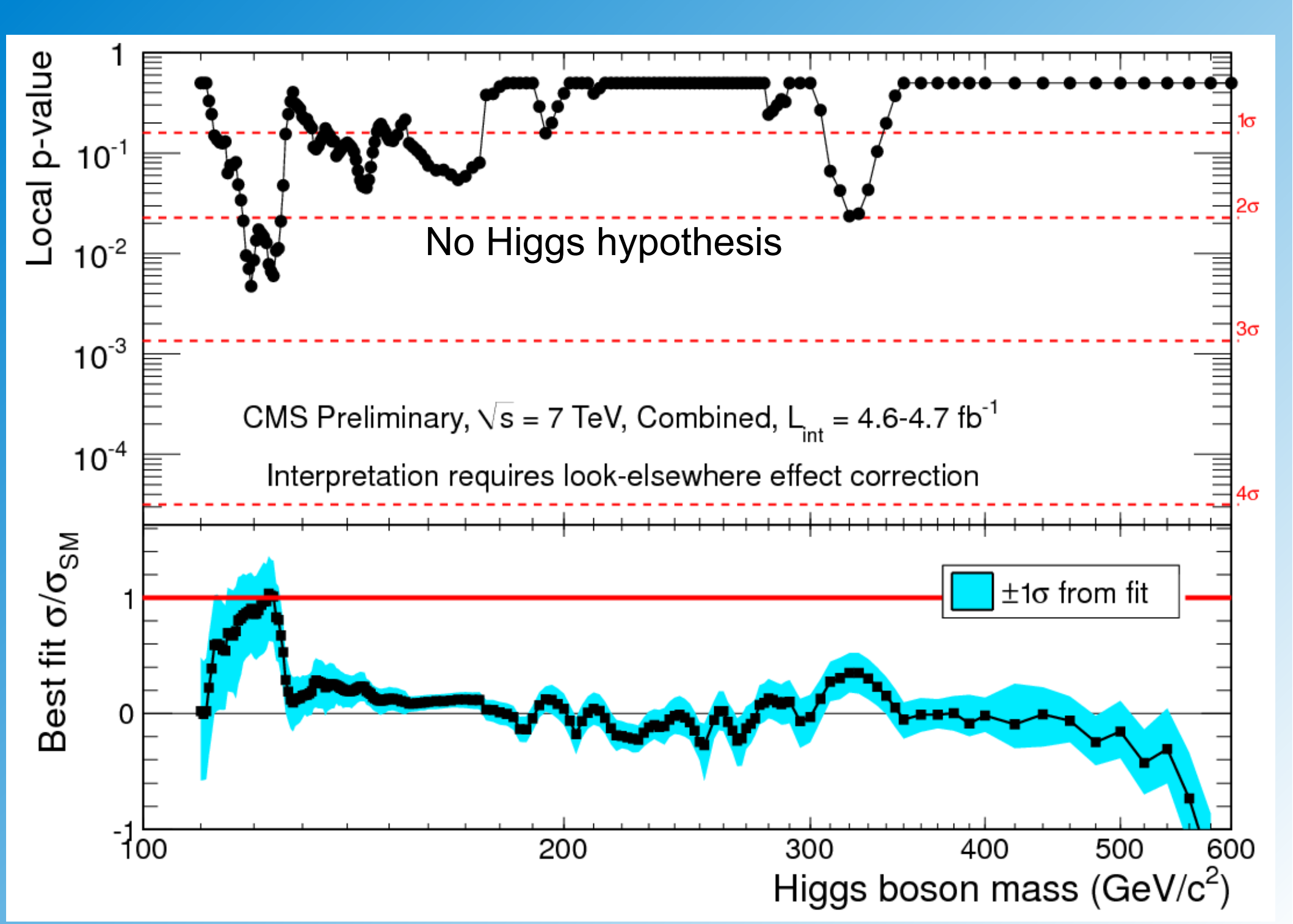


ATLAS as well...

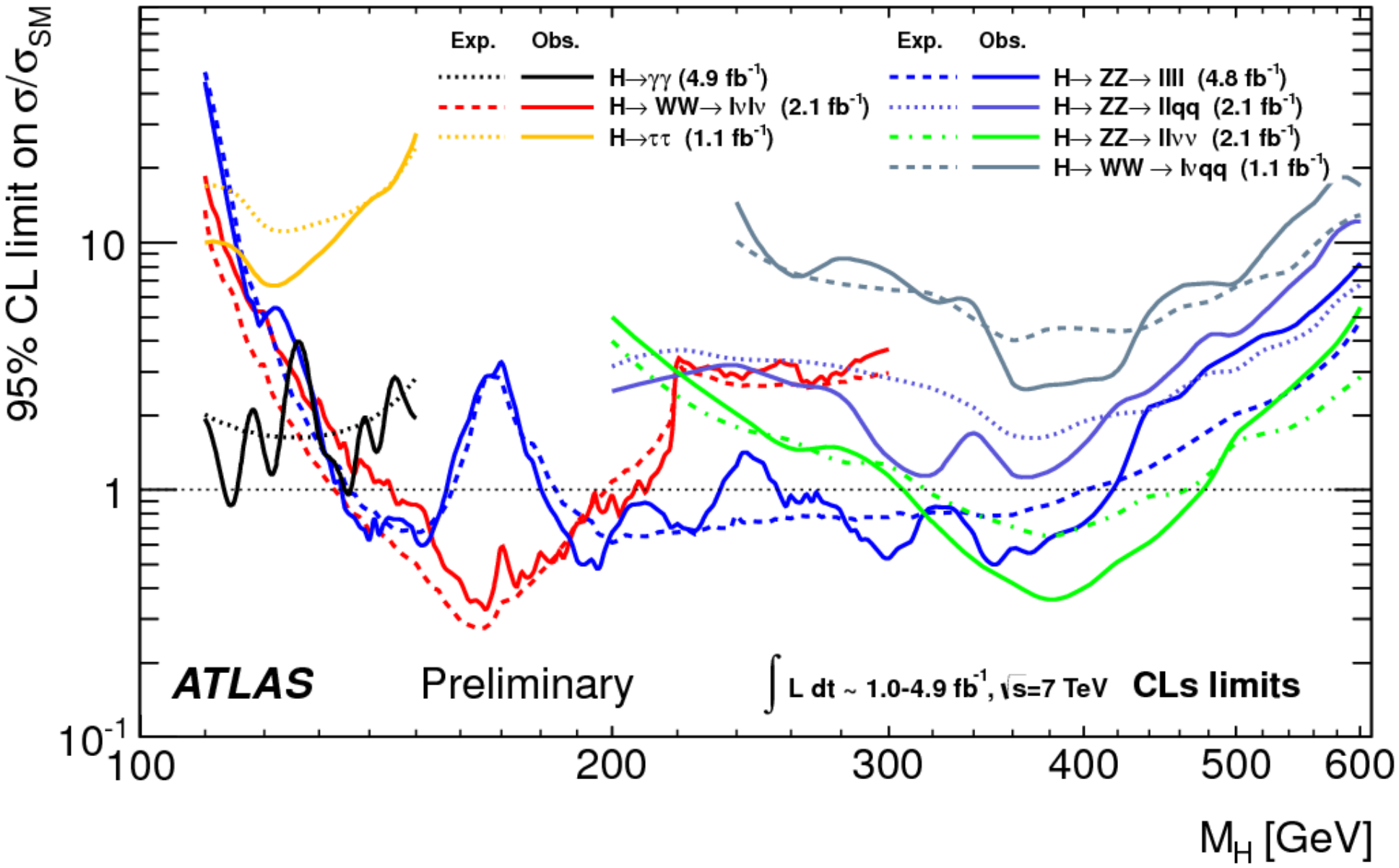
CERN Jamboree before Christmas 2011

New Results from 2011

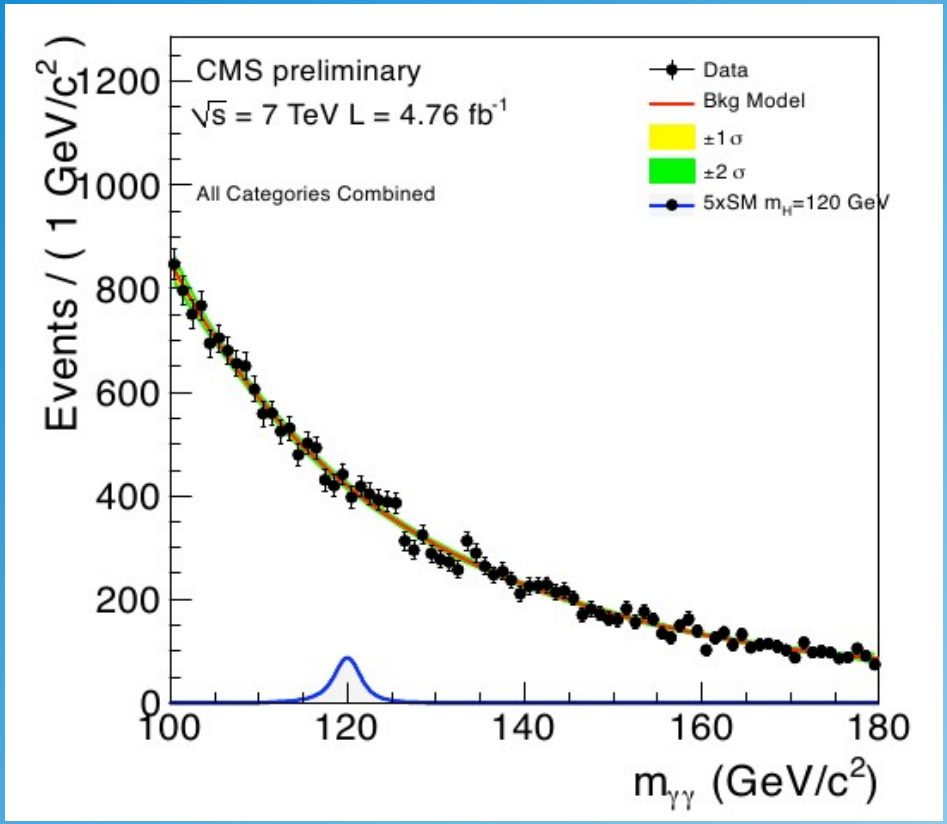



Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1σ
2σ
3σ
4σ
No Higgs hypothesis
CMS Preliminary, $\sqrt{s}$ = 7 TeV, Combined, L_{int} = 4.6-4.7 fb^{-1}
Interpretation requires look-elsewhere effect correction
Best fit σ/σ_{SM}
±1σ from fit
1
0
-1
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)

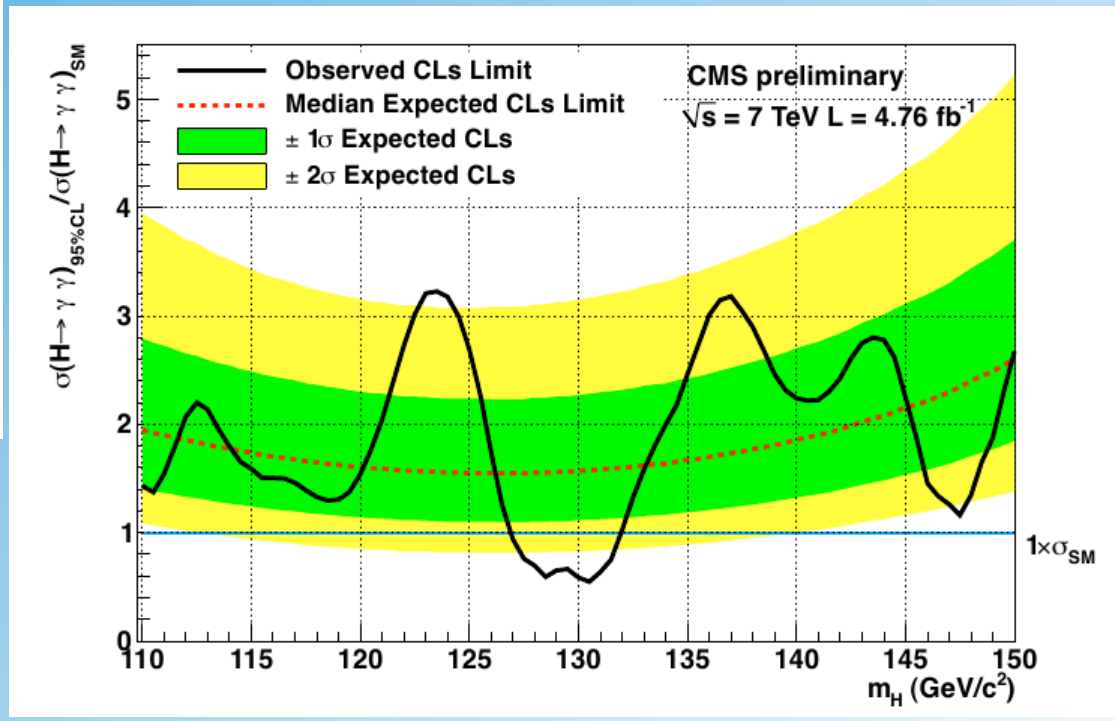
Higgs Exclusion Plots ATLAS



H → γγ Search at CMS



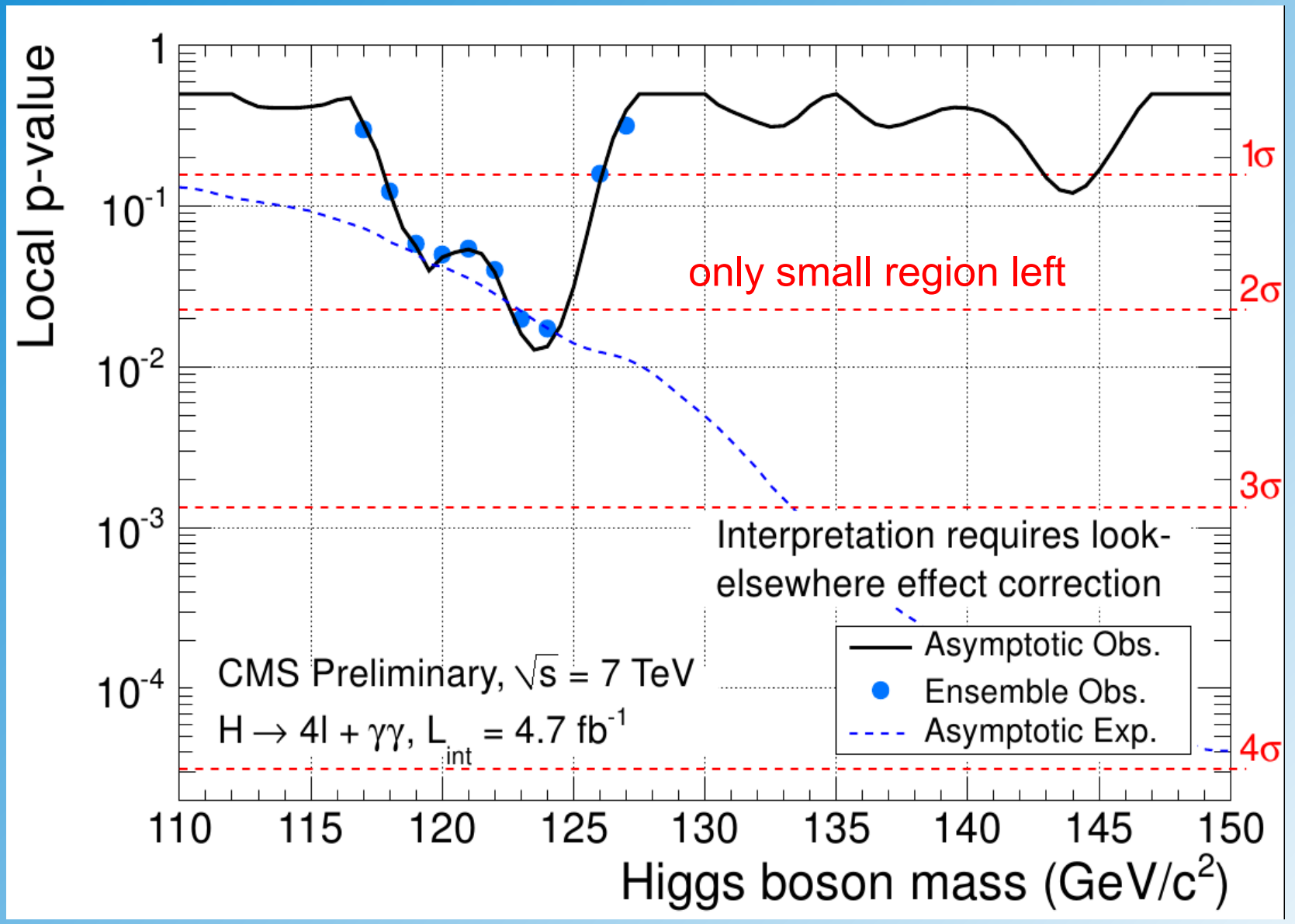
statistical fluctuations much larger than Higgs signal expectation!



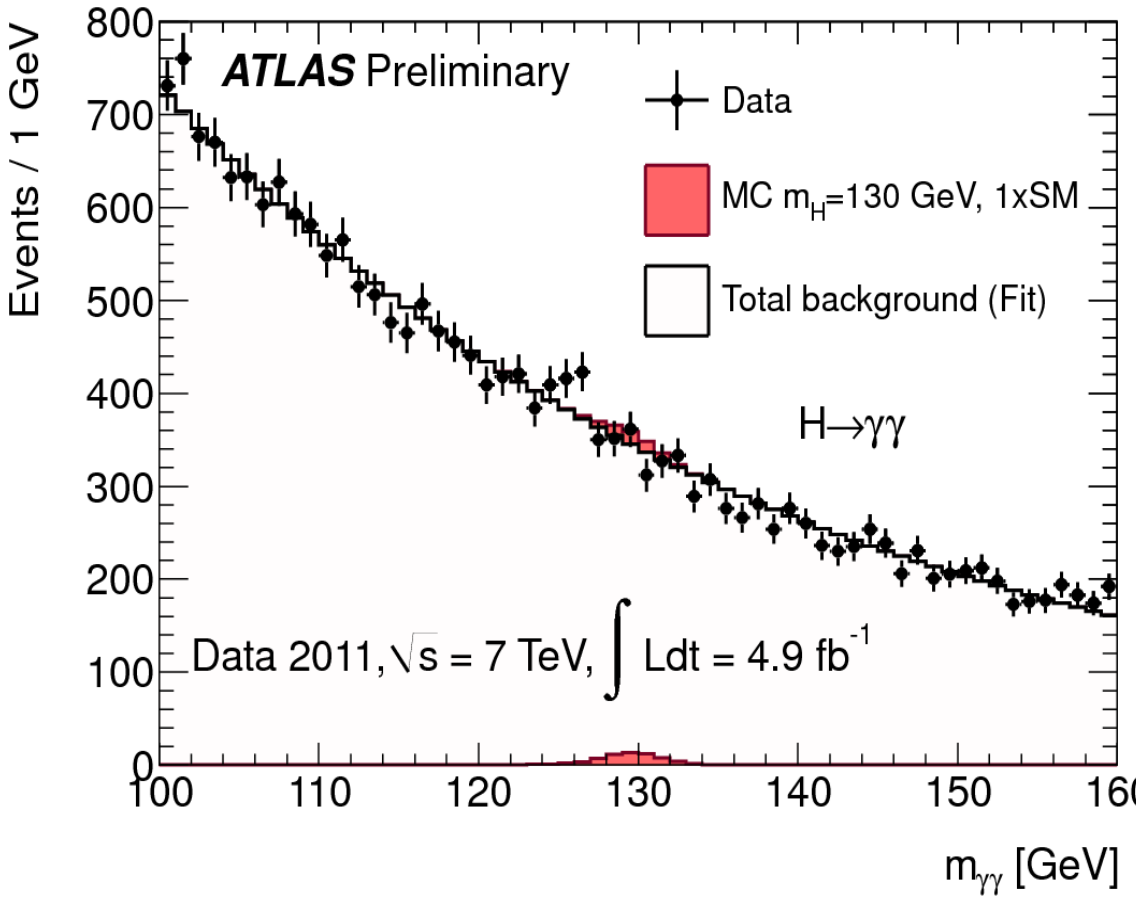
where is the Higgs?

CMS: ZZ and γγ Combination

No Higgs hypothesis

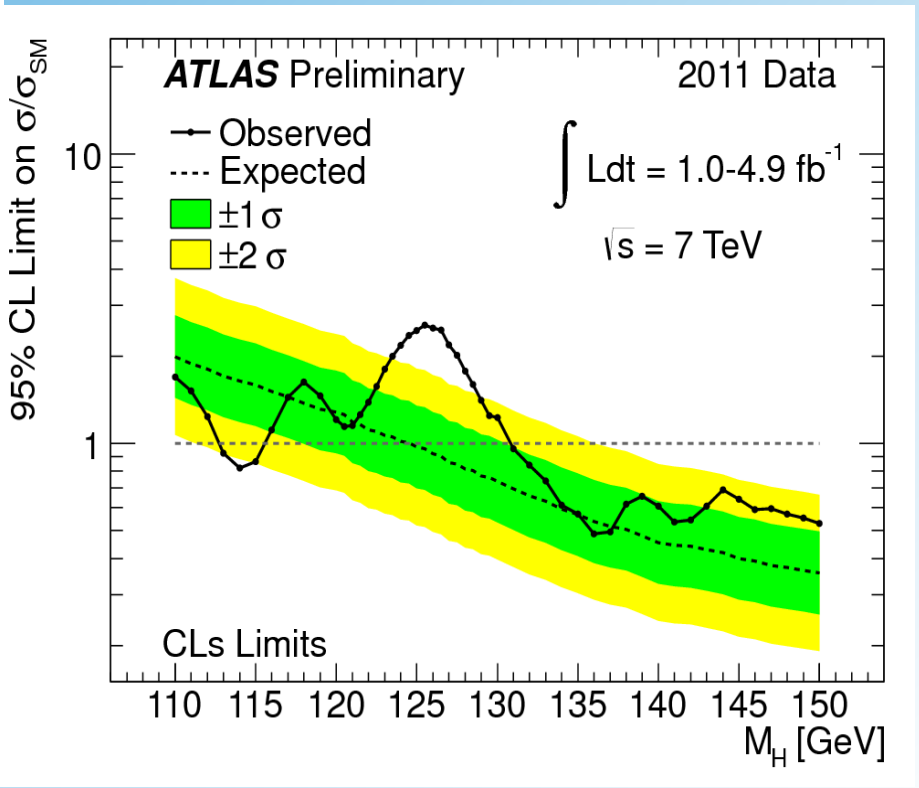


H → γγ Search at ATLAS

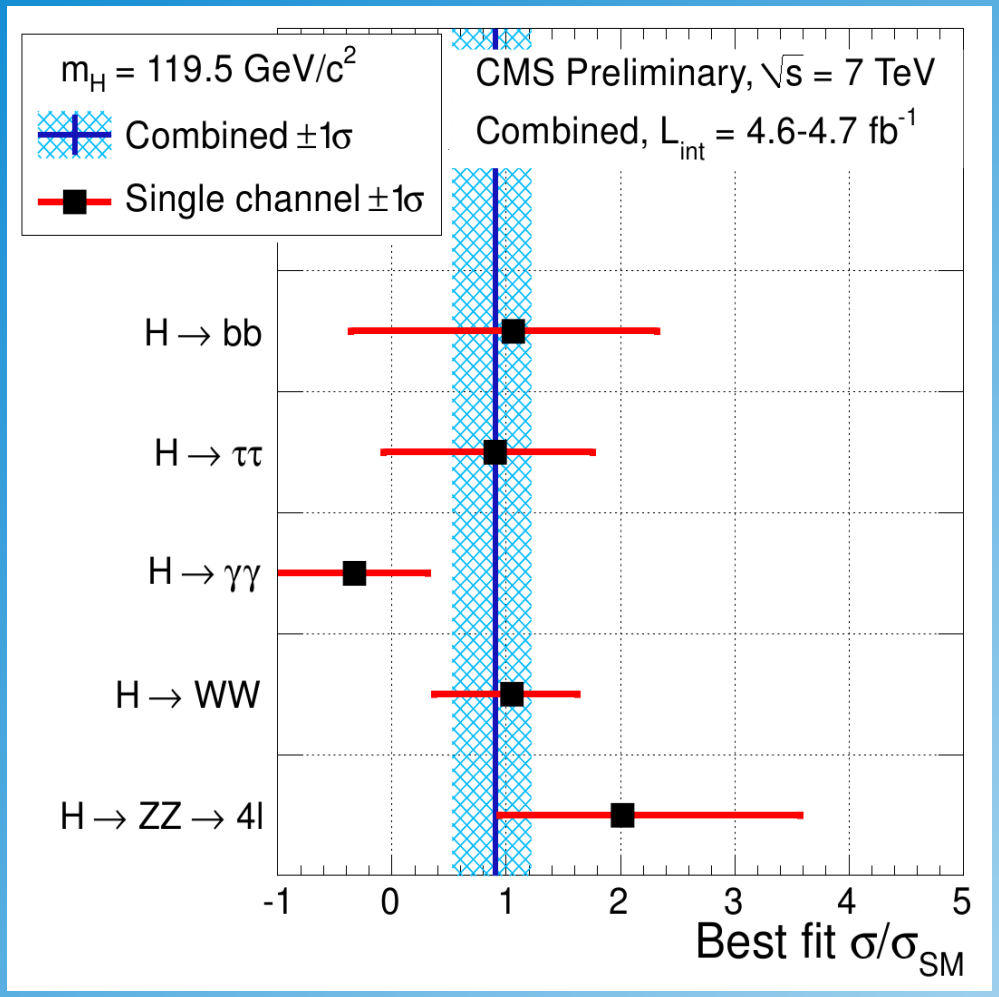


"bump" at 125 GeV

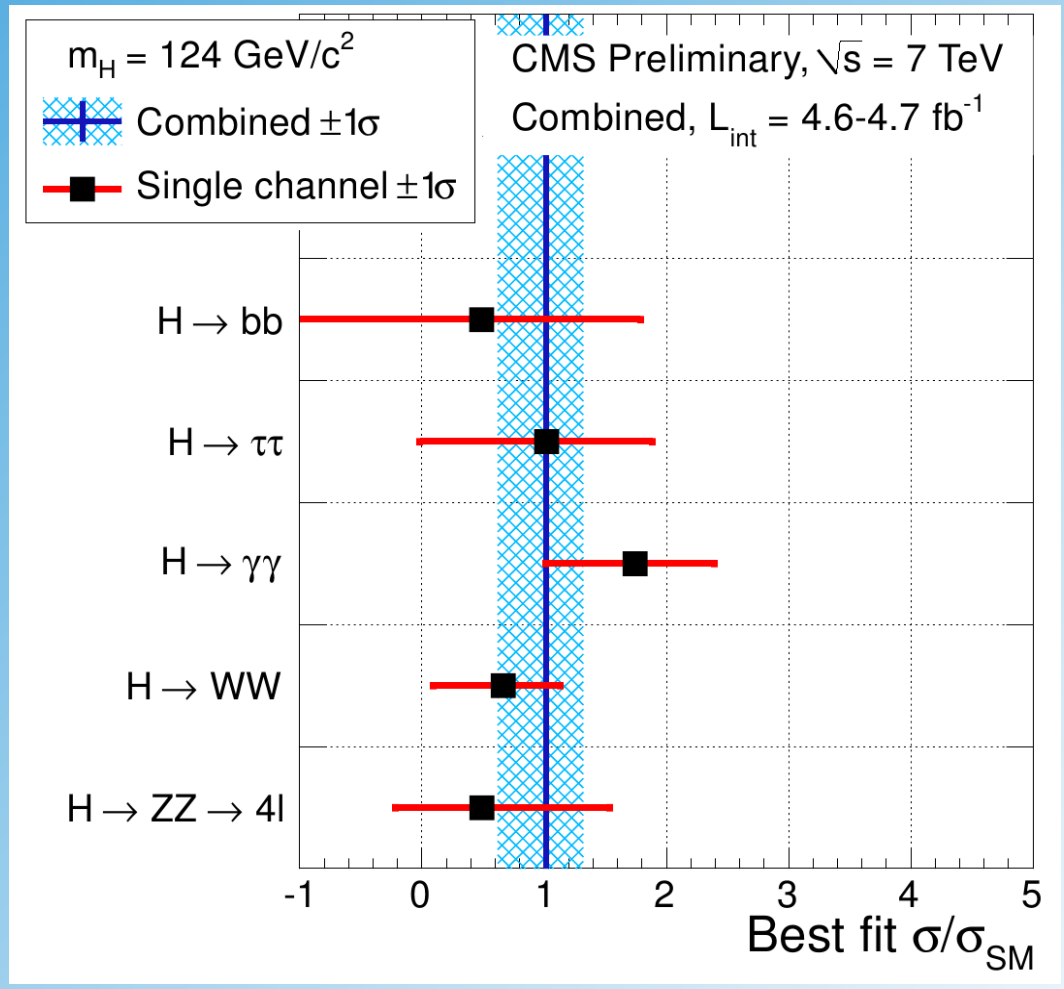
region above 130 Gev excluded



Summary of Higgs Channels at CMS



indication of Higgs at 119 GeV?

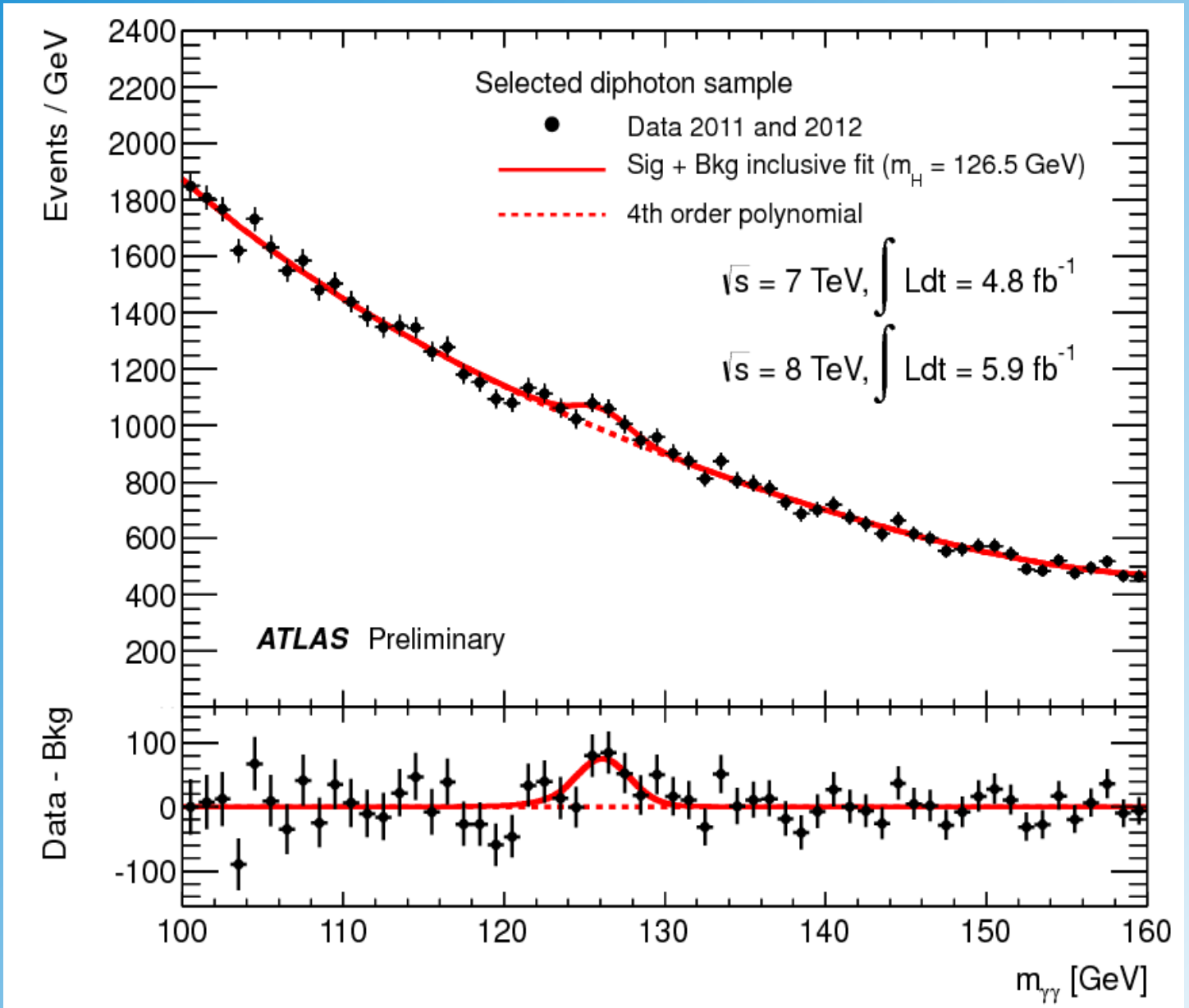


indication of Higgs at 124 GeV?

Summer 2012 (ICHEP conference)

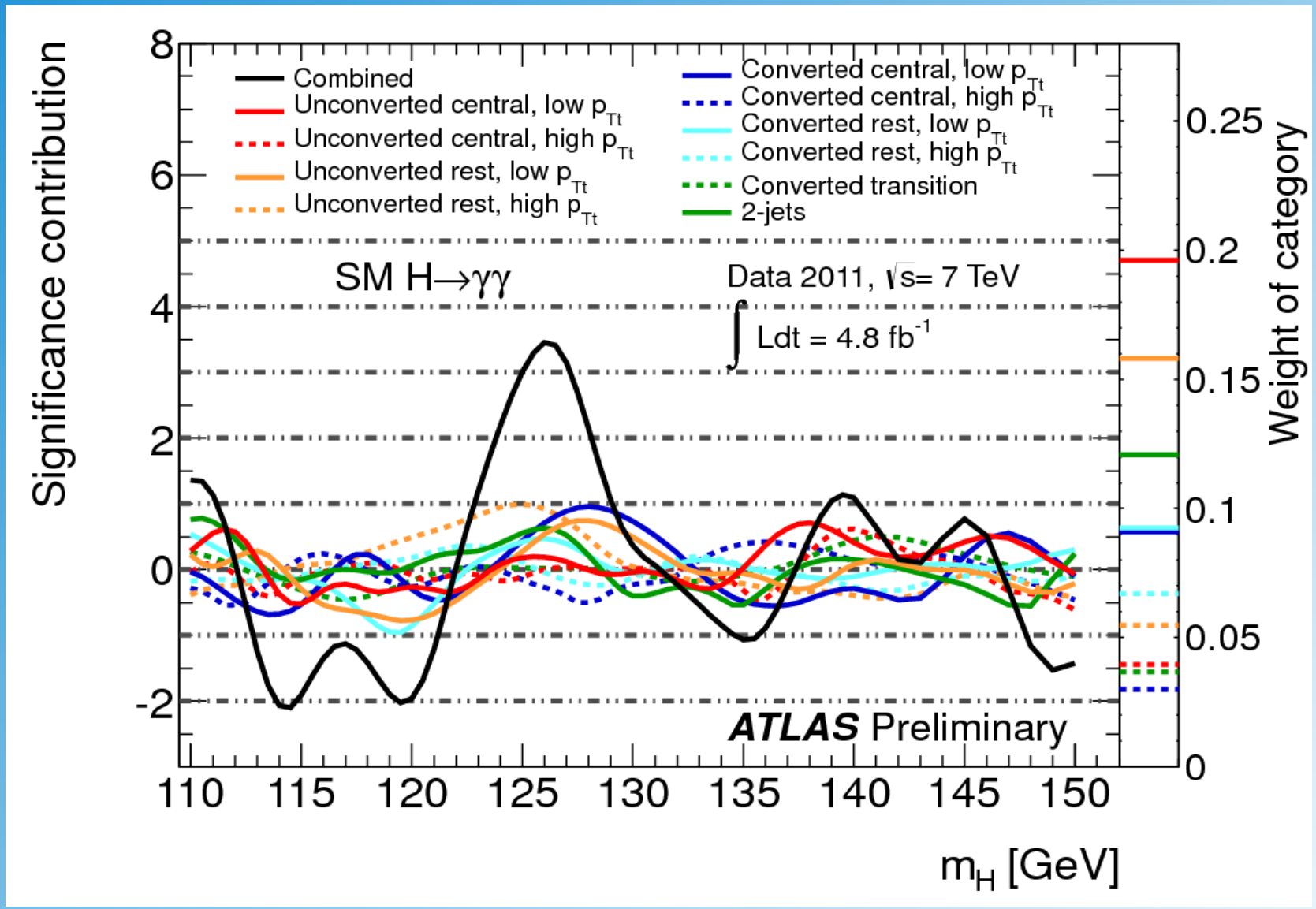
H → γγ Search at ATLAS

combined

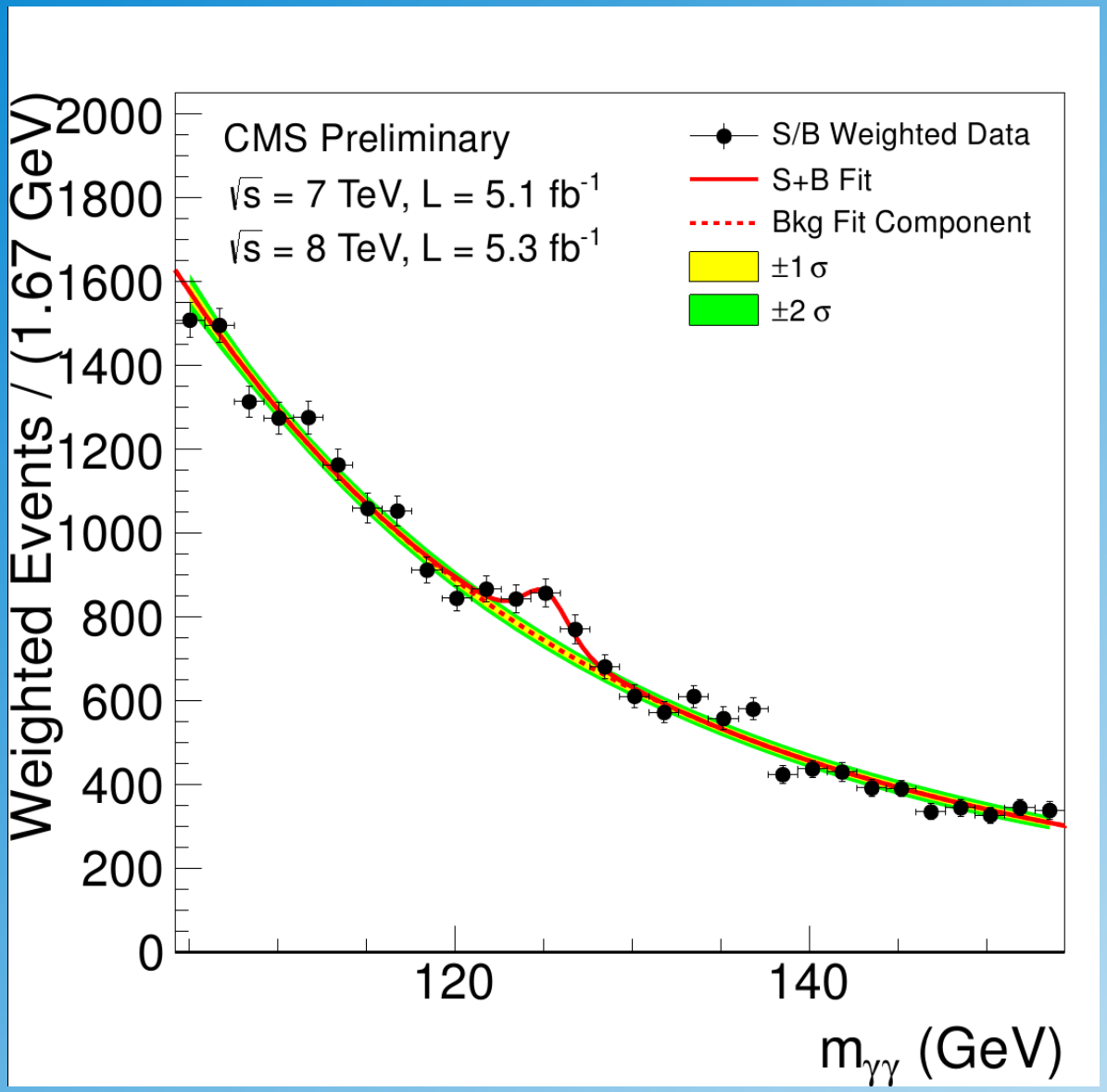


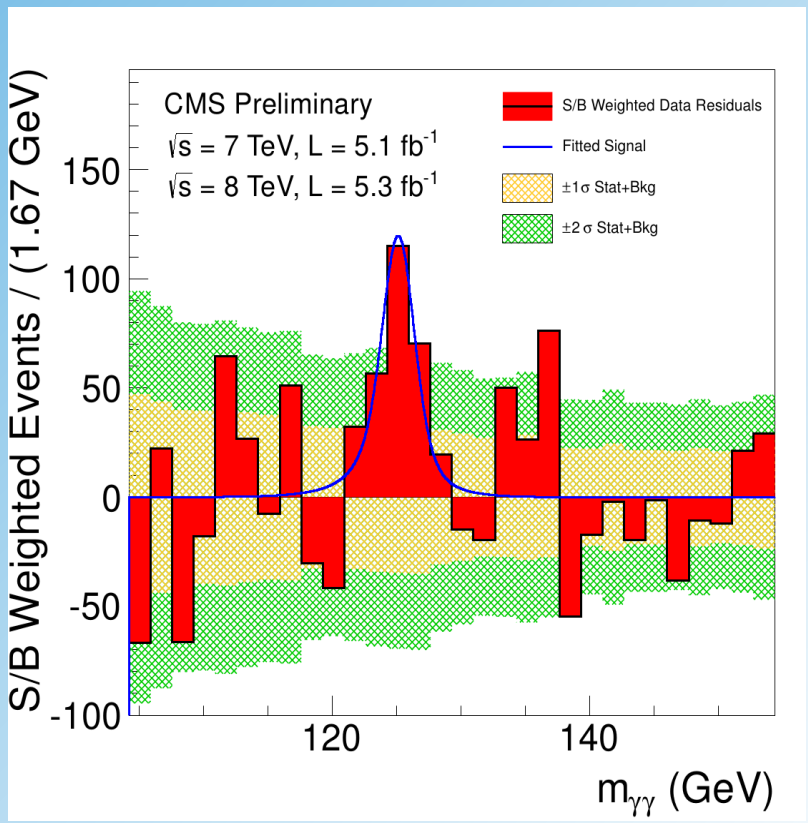
H → γγ Search at ATLAS

breakdown of different categories



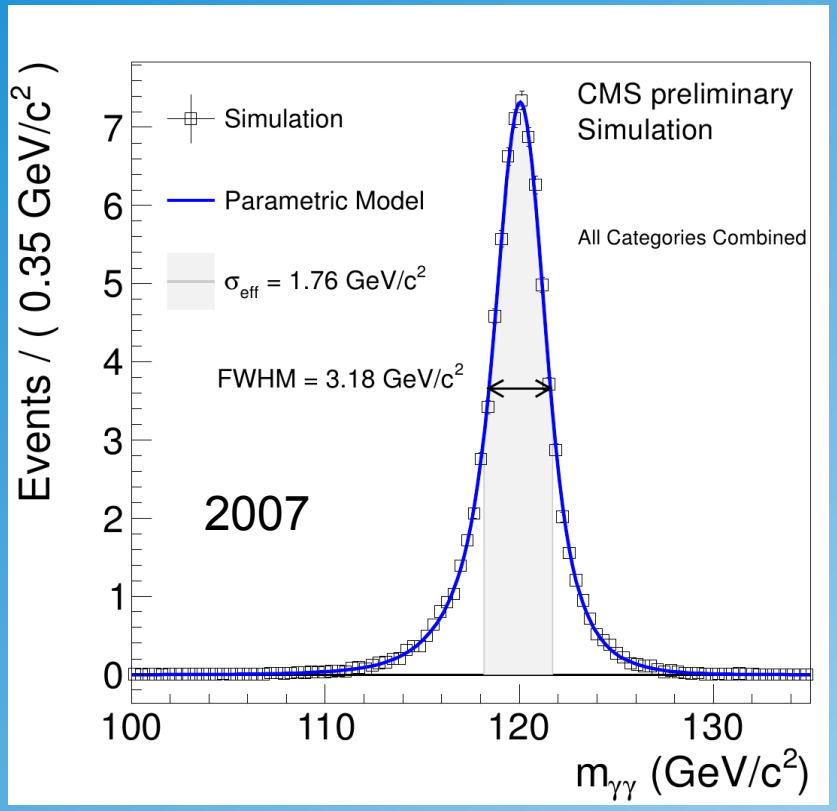
H → γγ Search at CMS

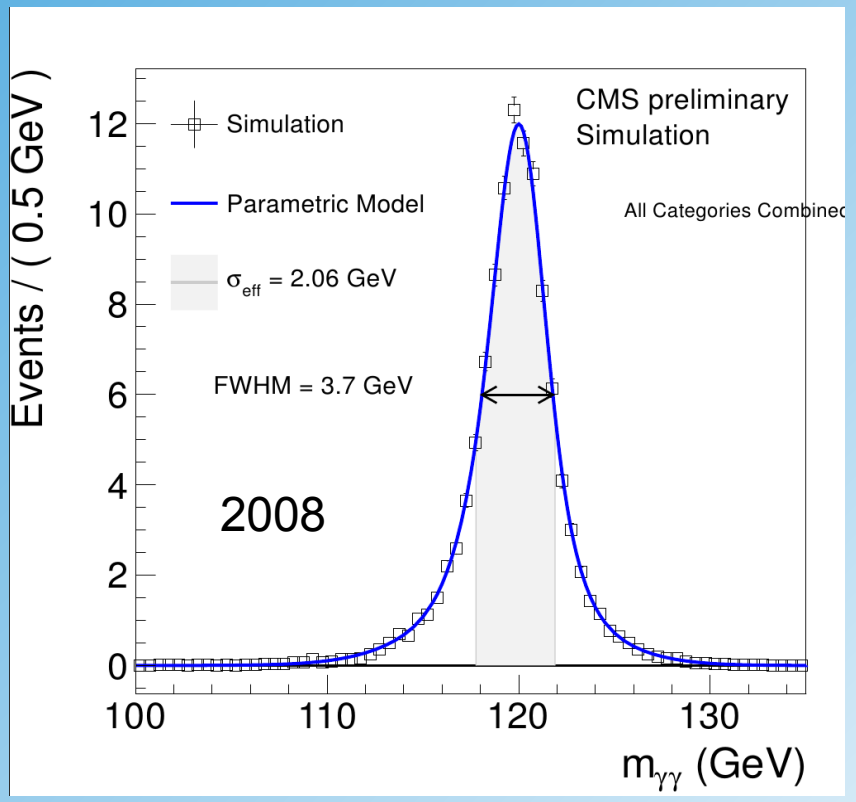




derived by summing up six different H→γγ event classes using weights

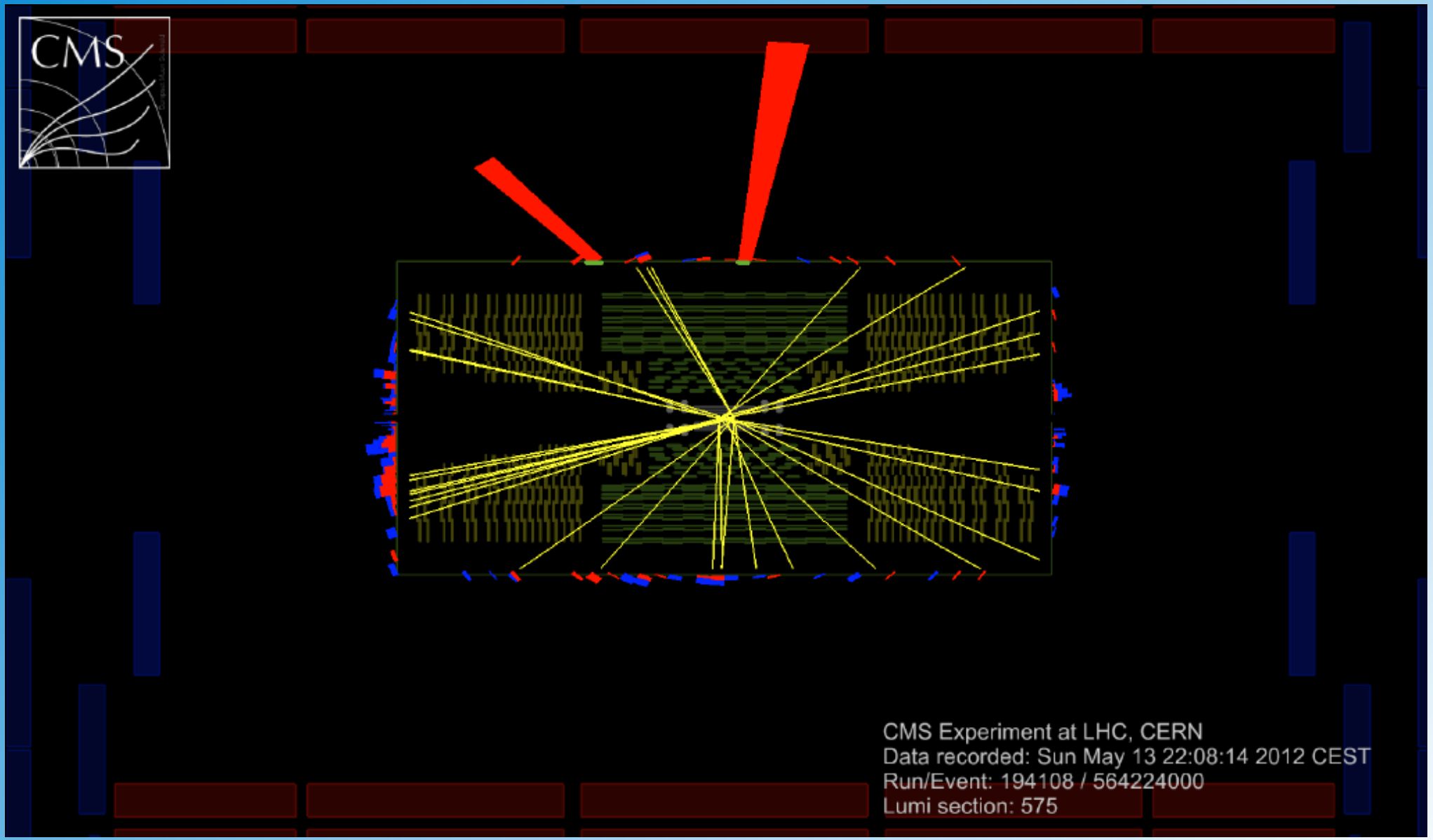
Photon Energy Calibation at CMS



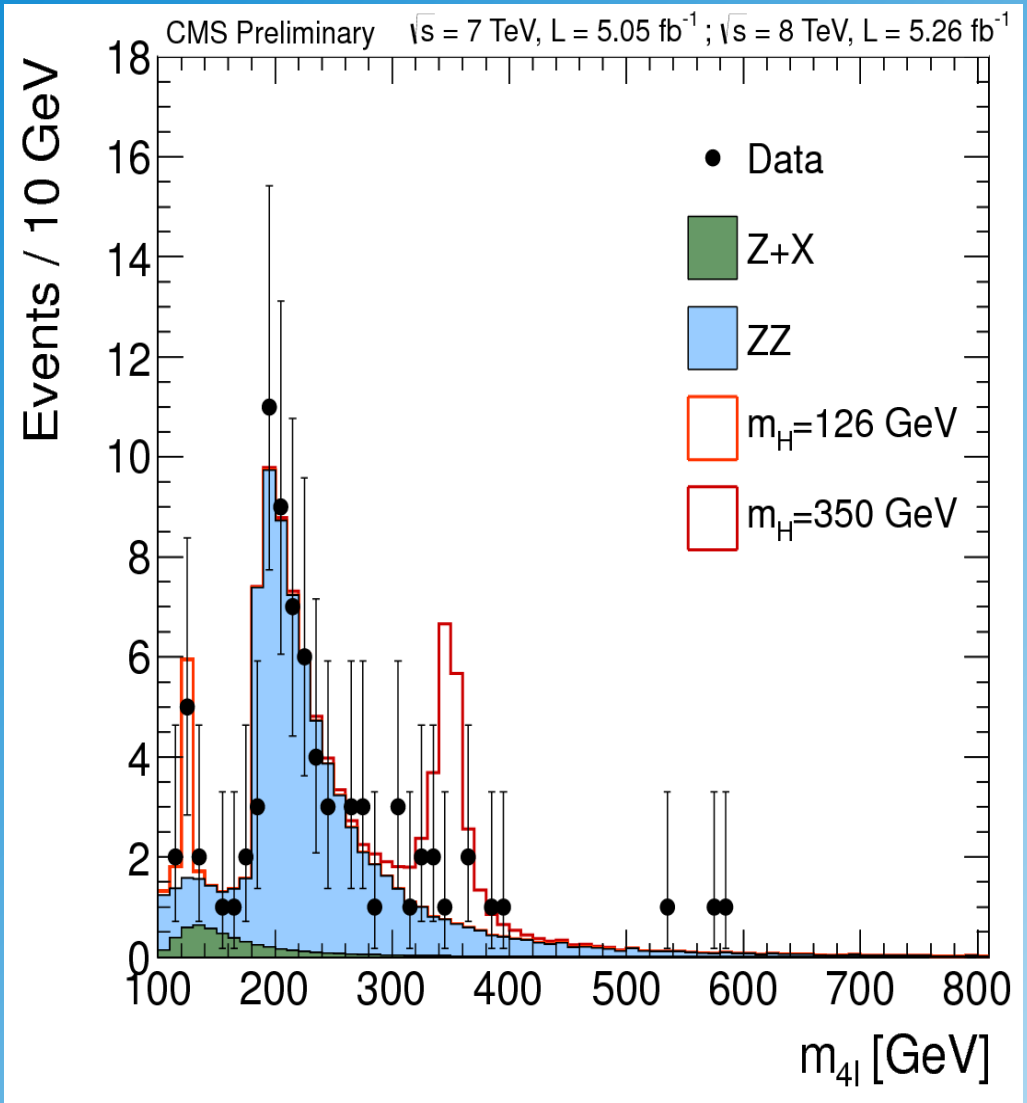


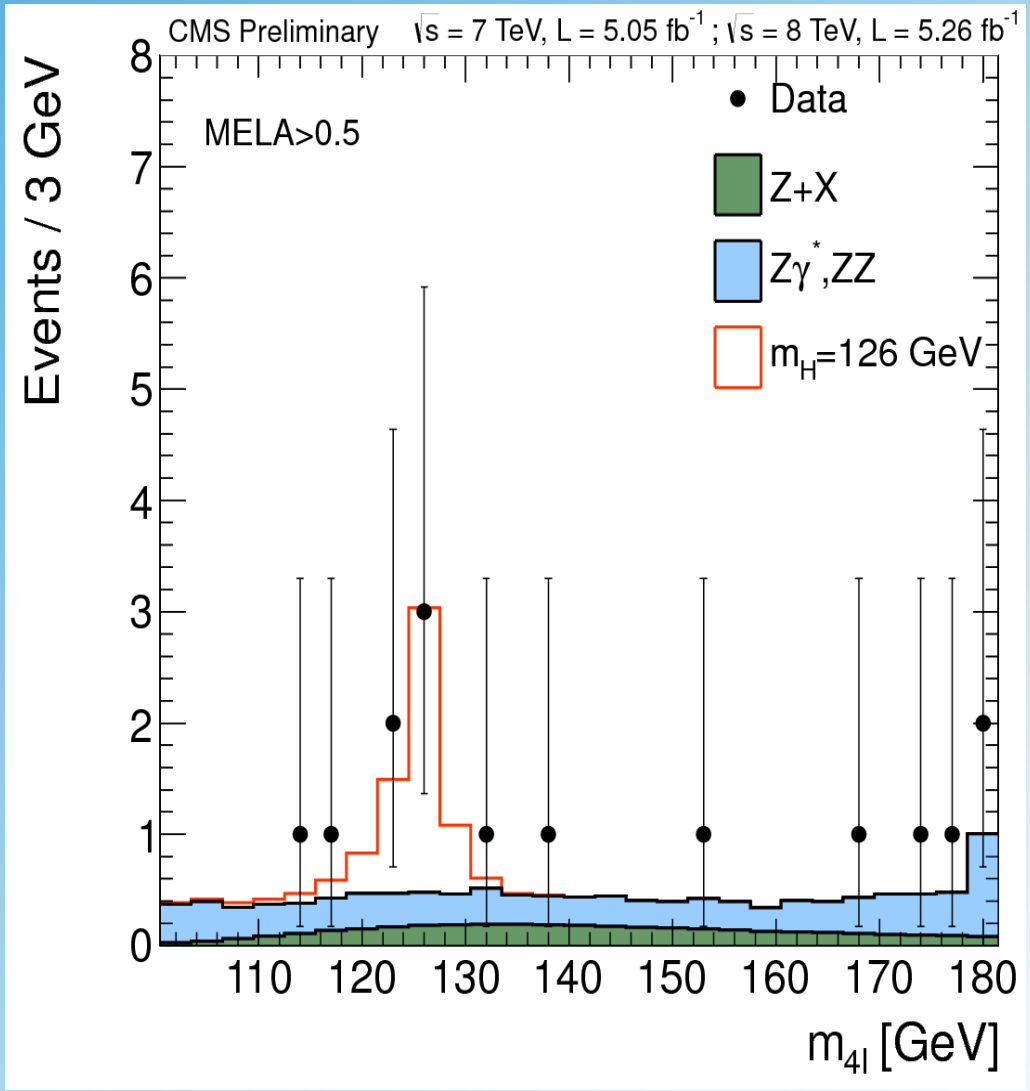
Search sensitivity depends crucially on the energy calibration!

$H \rightarrow \gamma\gamma$ Candidate at CMS



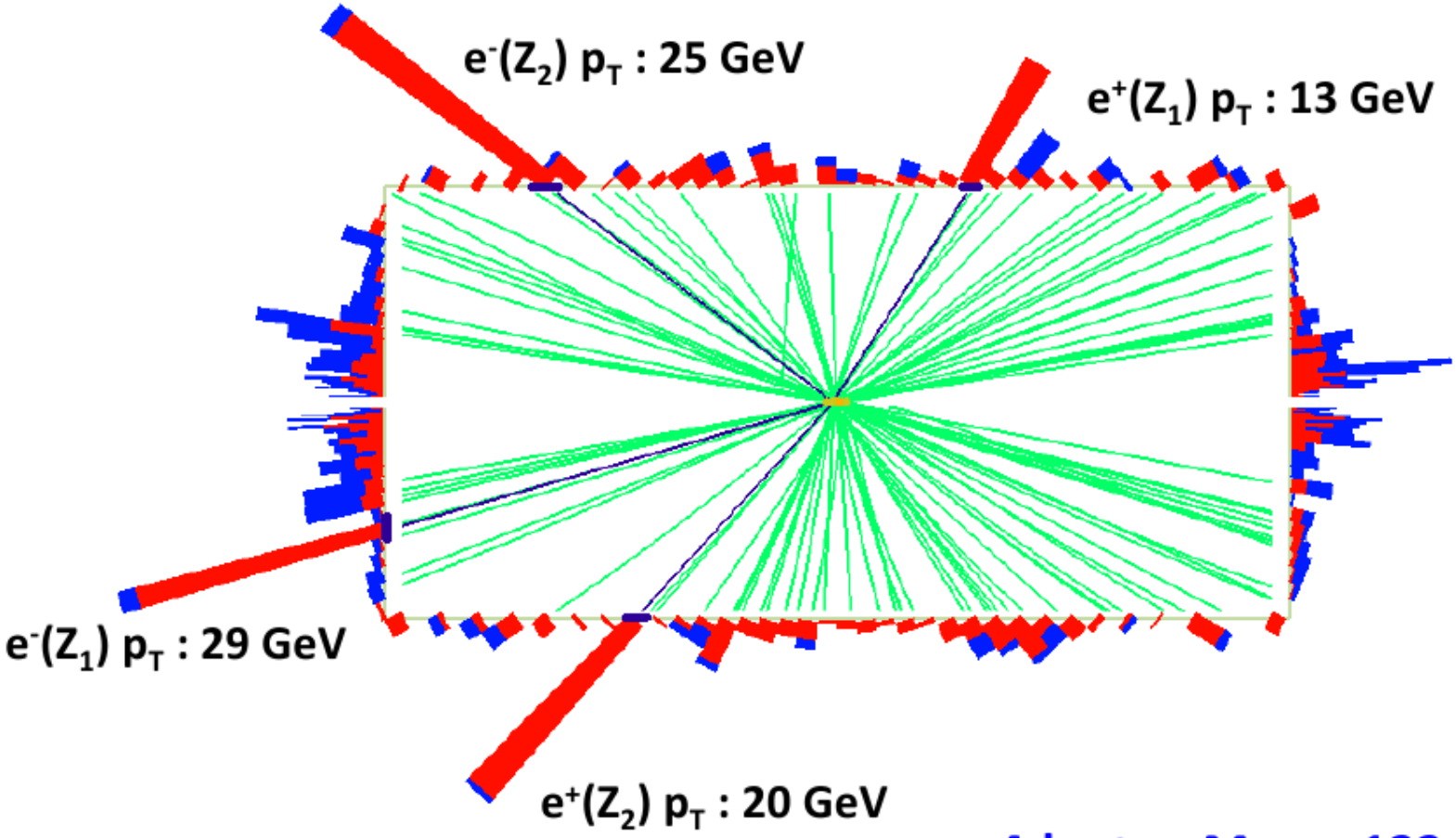
H → ZZ Search at CMS





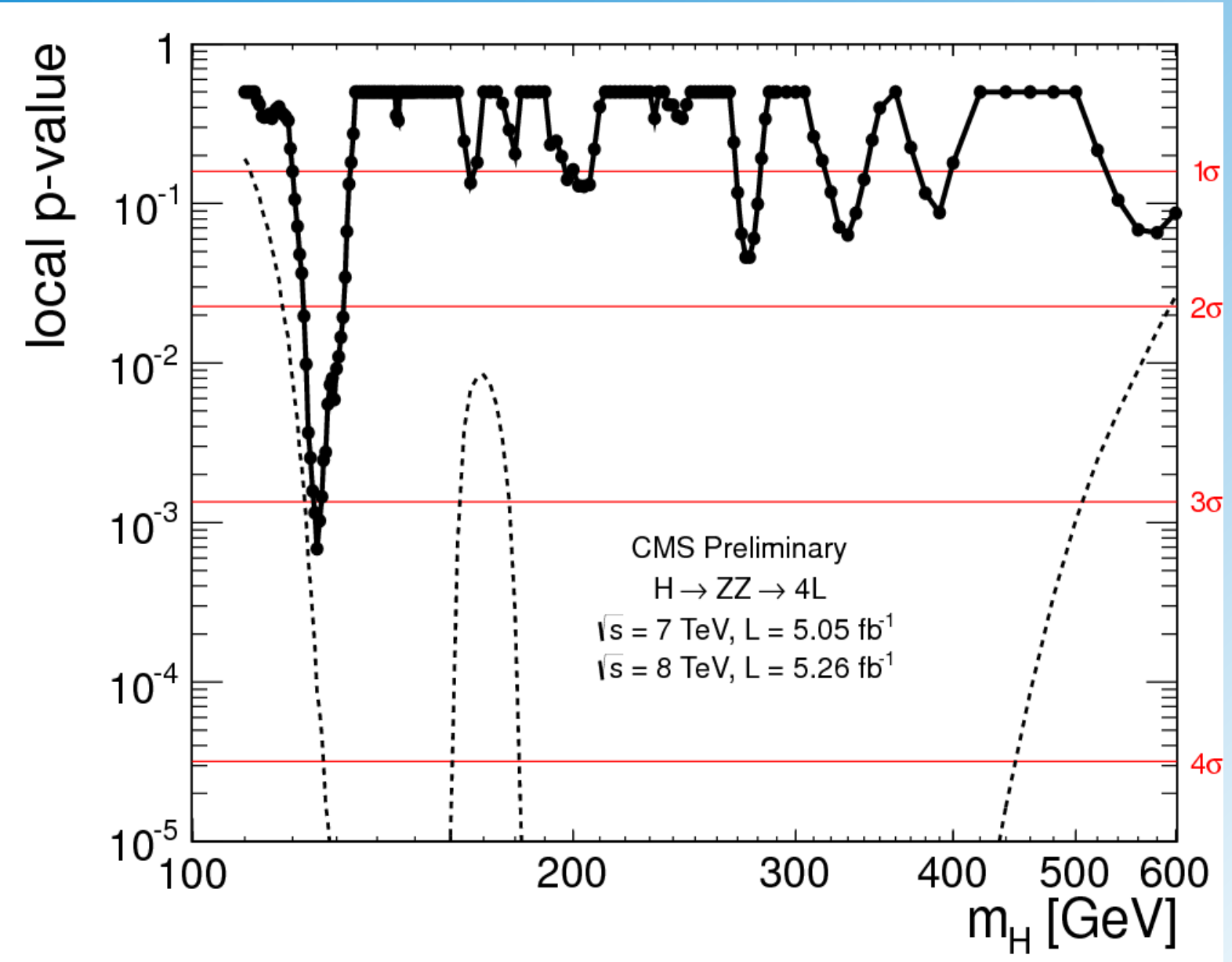
H → ZZ → eeee Candidate

CMS Experiment at LHC, CERN
Data recorded: Mon May 7 09:46:20 2012 CEST
Run/Event: 193575 / 400912970
Lumi section: 523

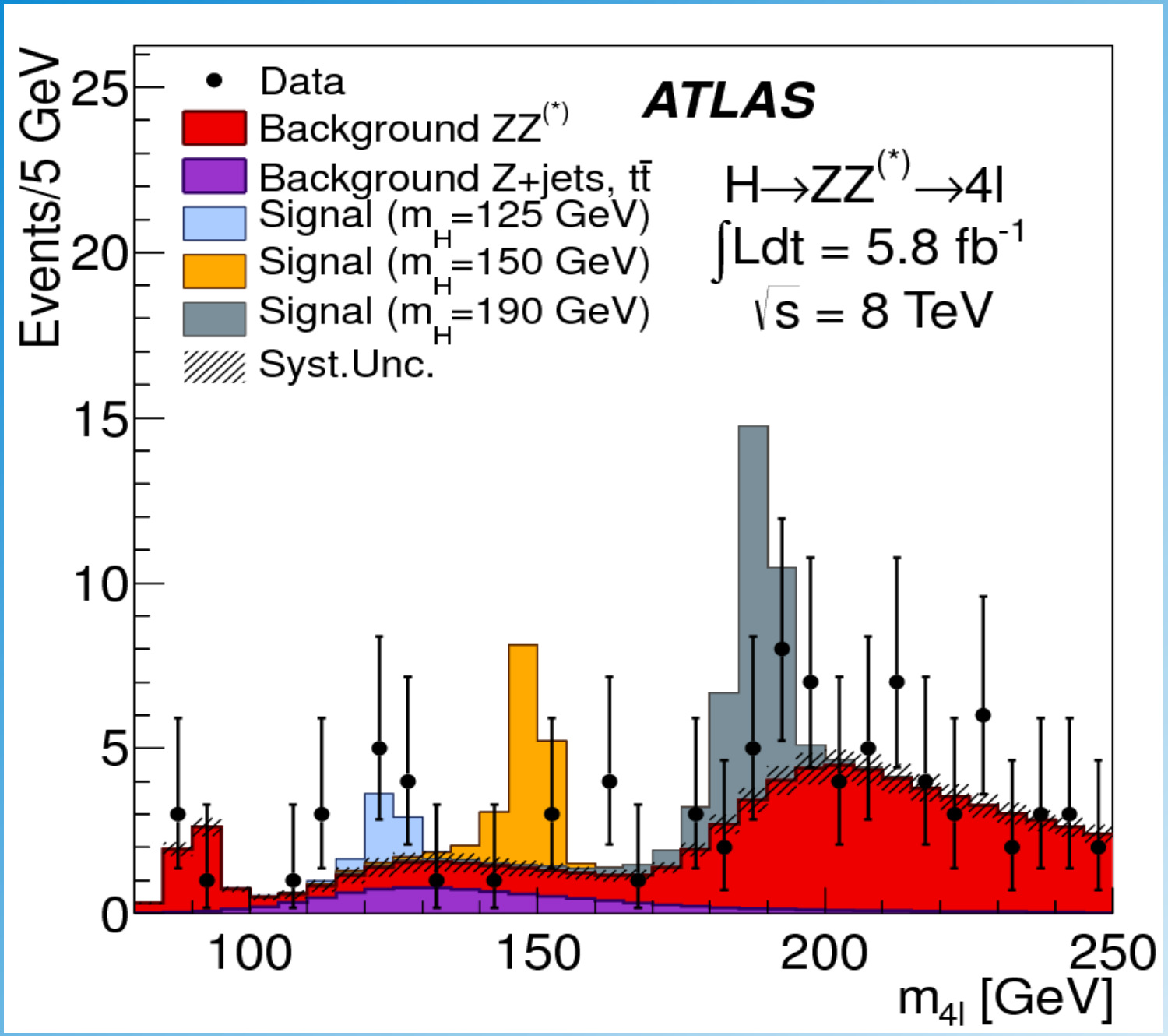


4-lepton Mass : 122.4 GeV

H → ZZ Search at CMS

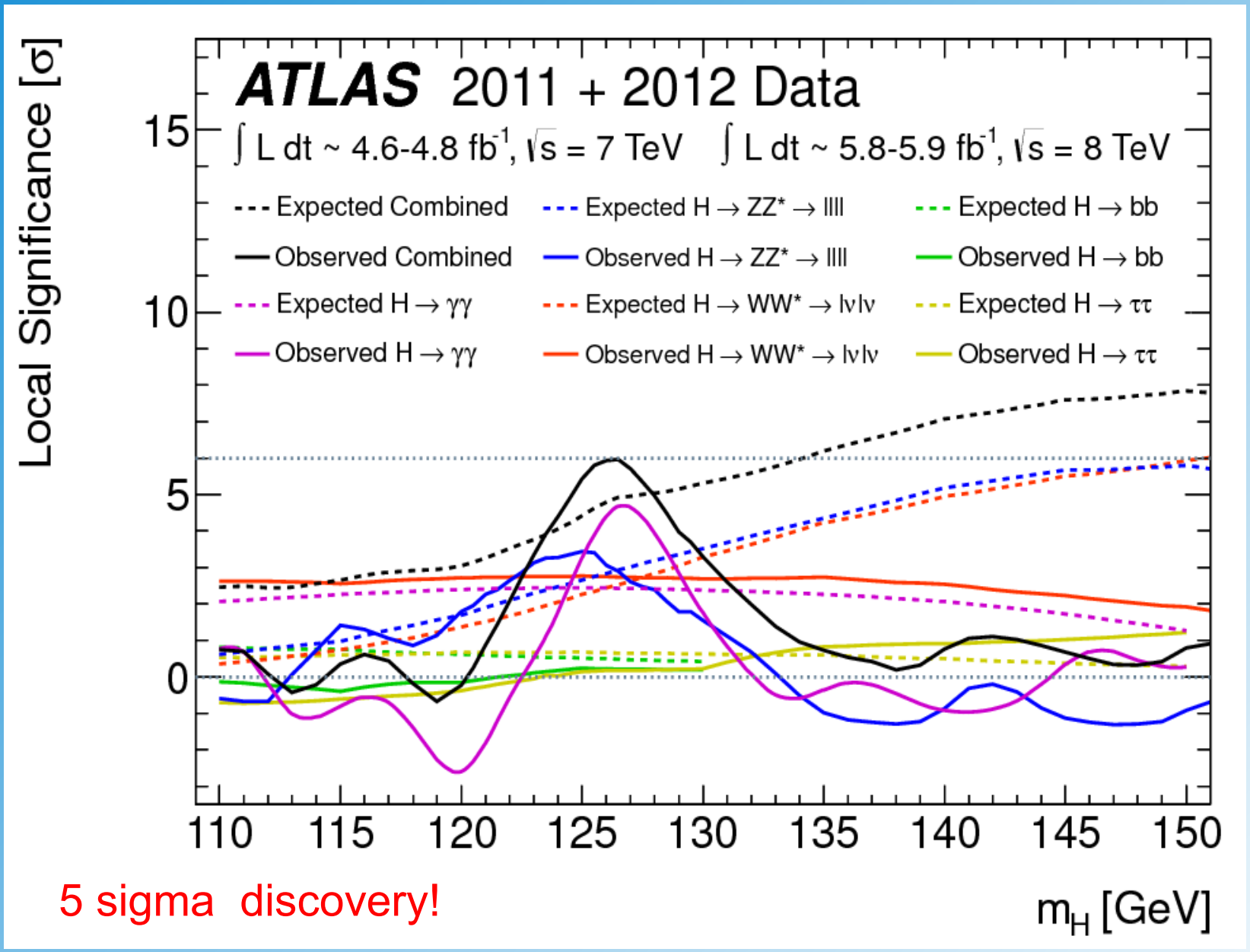


H → ZZ Search at ATLAS



can only be interpreted in combination with other channels

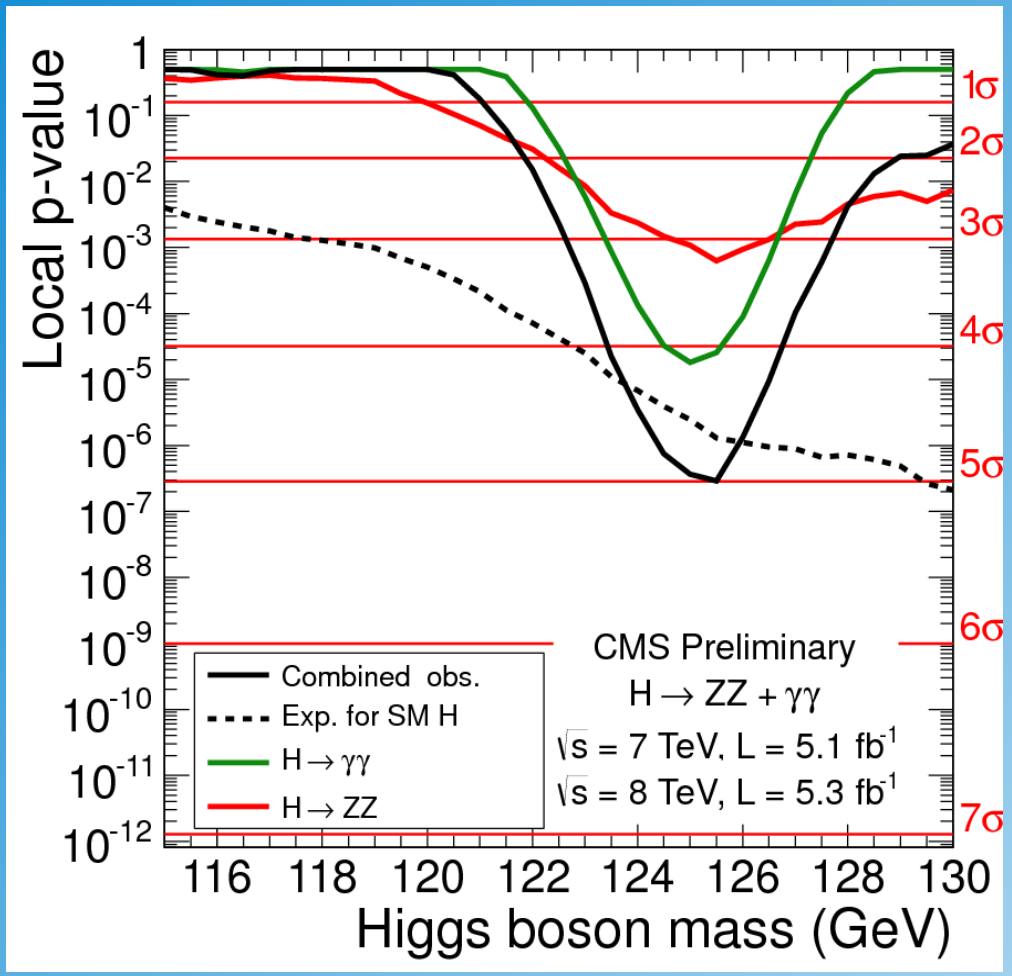
ATLAS Higgs Significance!



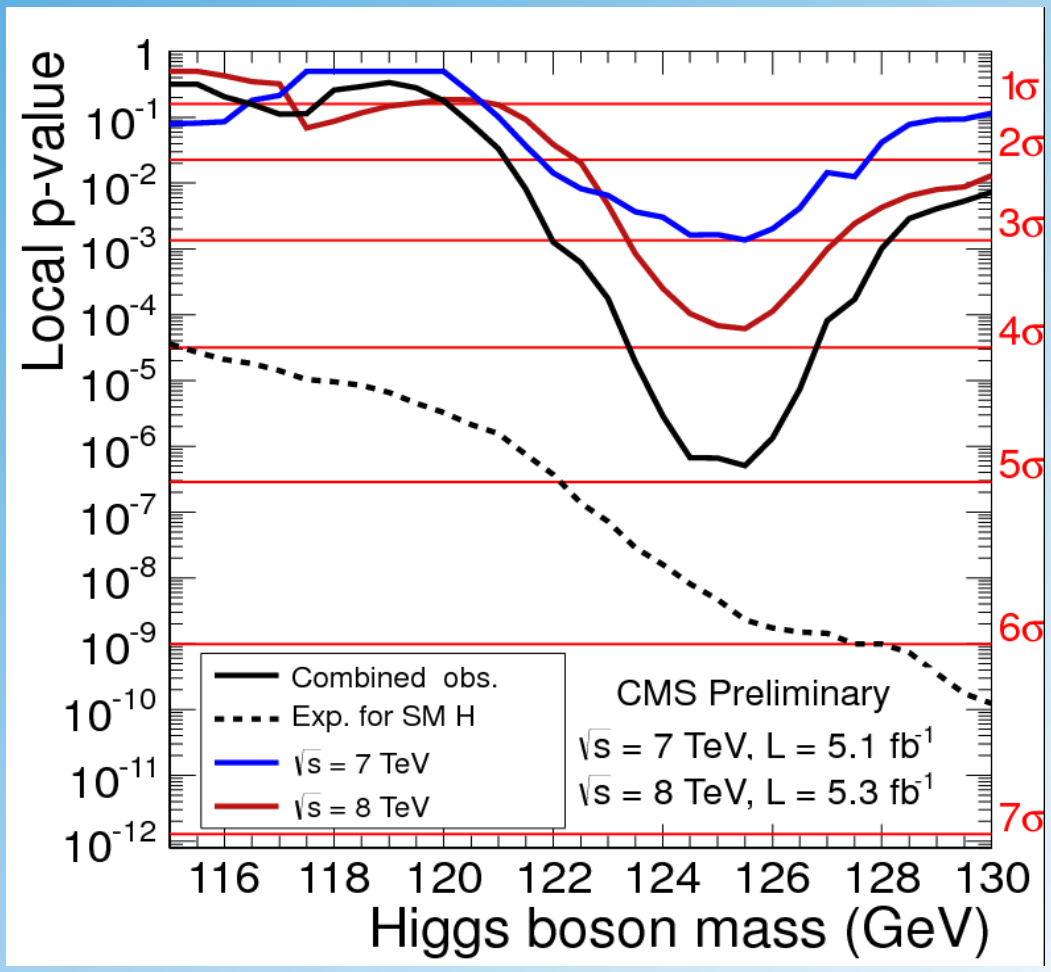
5 sigma discovery!

The 125 GeV region at CMS

Two dominant channels



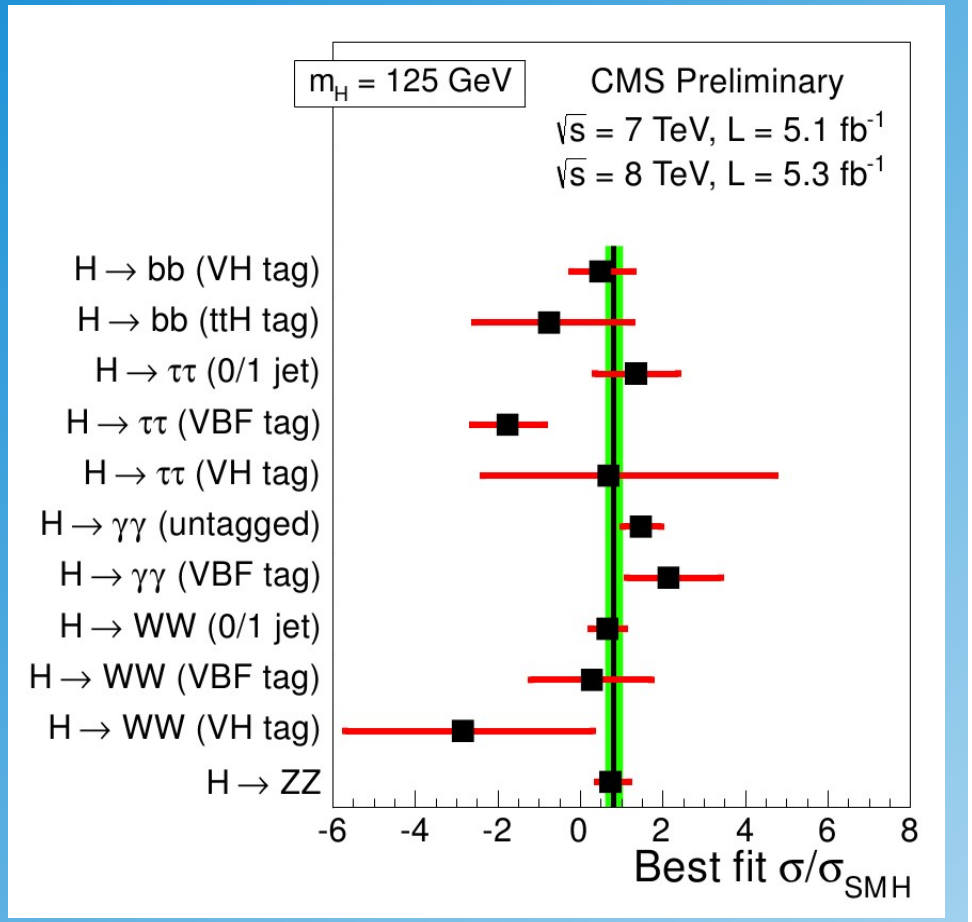
All channels



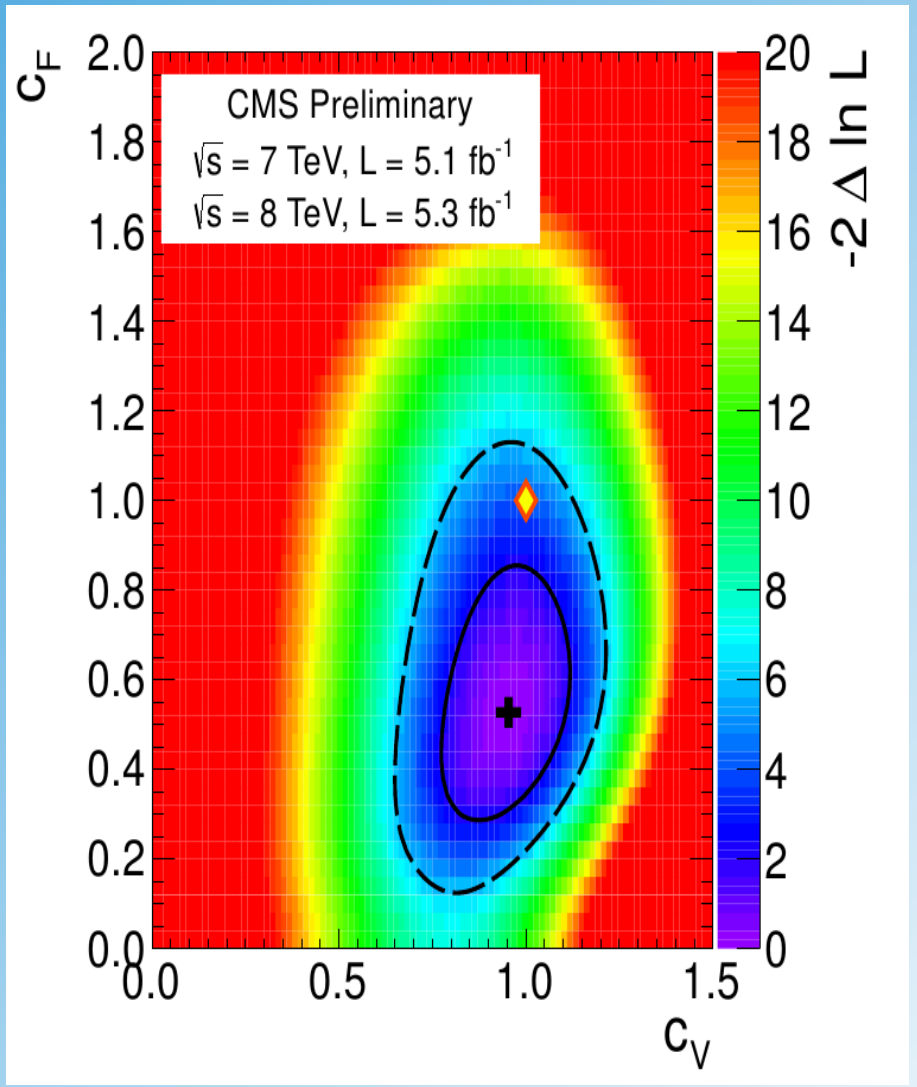
5 sigma discovery!

Higgs Branching Ratios

CMS: branching ratios



coupling to vector bosons and fermions



“semi-fermiophobic”?

What is it?

Question to R.Heuer, CERN director general:
why do you call the newly discovered particle Higgs-like particle?

Answer by R.Heuer:
Because we all like the Higgs!

What is it?

- It looks like a Higgs
- It smell like a Higgs
- It sounds like a Higgs

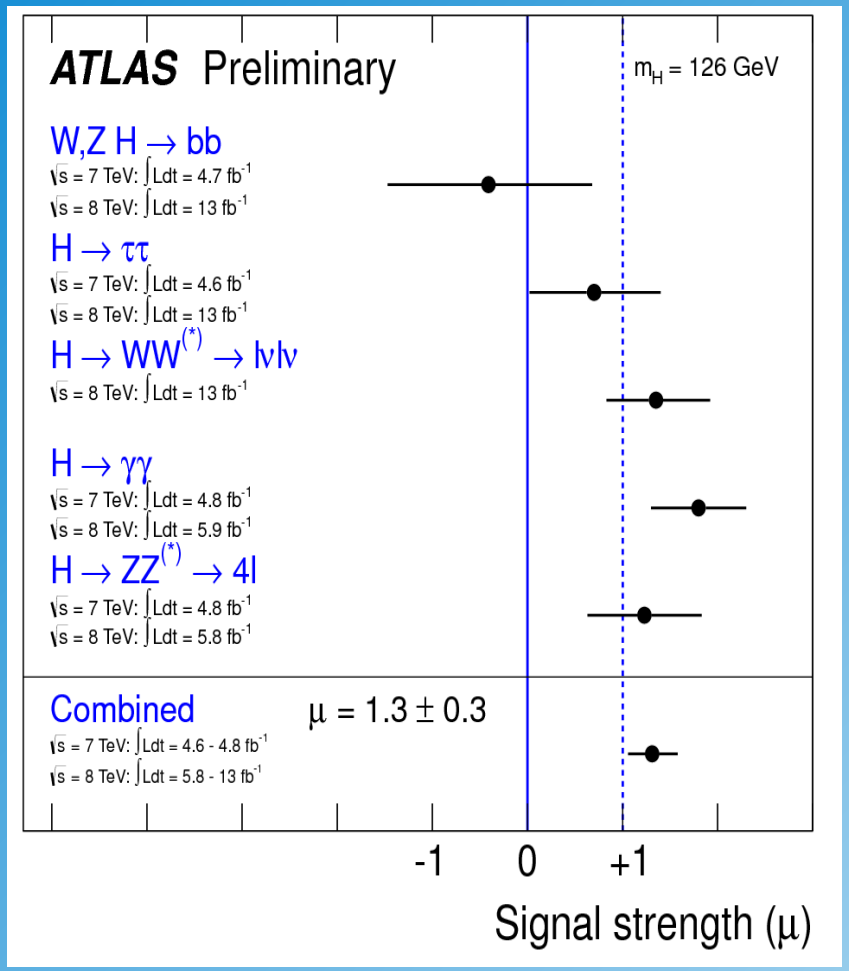
The real and important Question

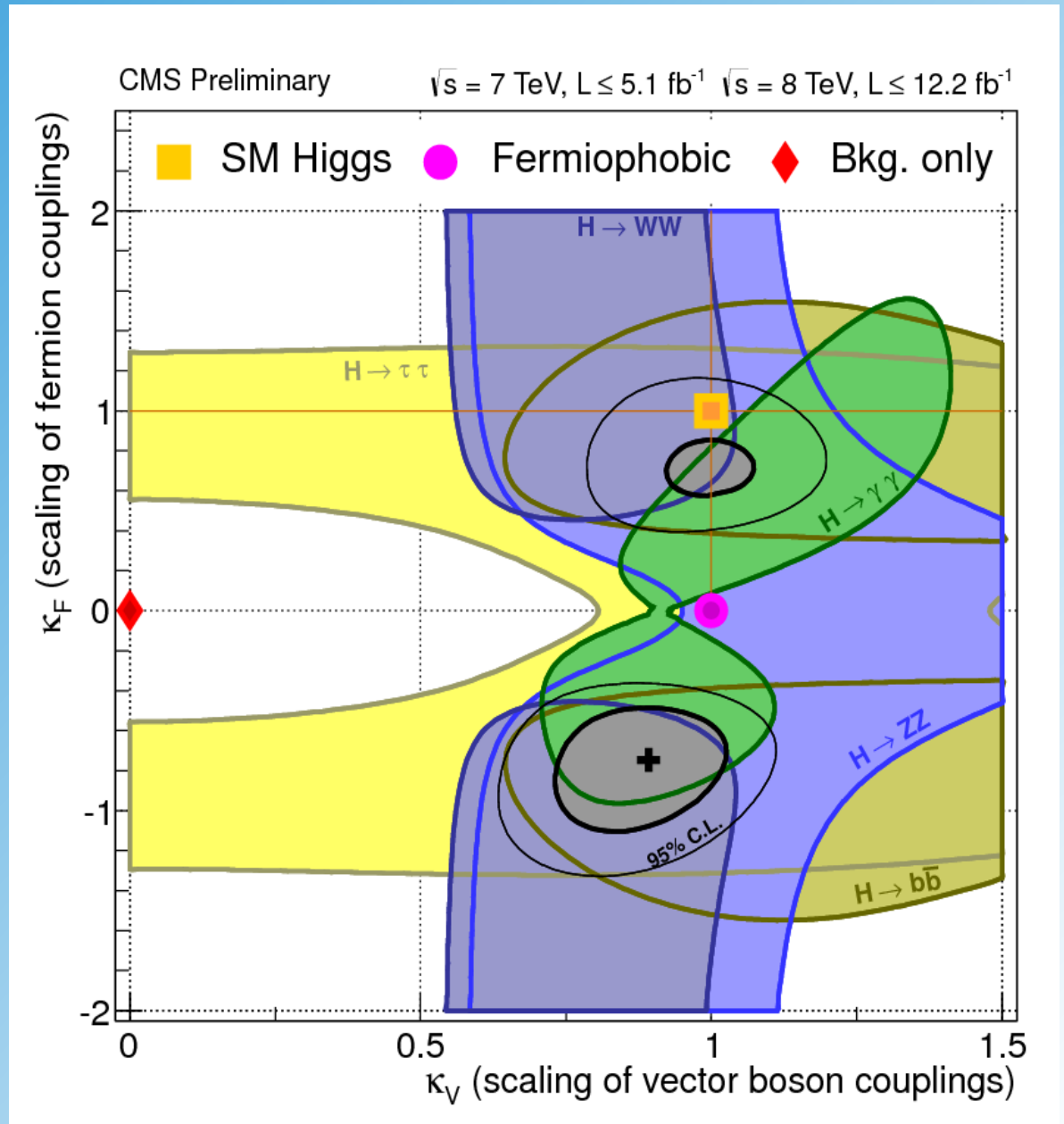
Is it the SM Higgs?

Answer:

Measure the couplings

Status HCP conference (Nov 2012)





OUTLOOK

- Main task is the precise measurement of the Higgs couplings
- New Physics like Supersymmetry predict one light Higgs boson with mass < 130 GeV with (slightly) different couplings
- LHC cannot measure the absolute value of the Higgs couplings. A linear Collider (ILC or CLIC) is required for measuring **invisible** Higgs decays.
- High precision requires high rates and high luminosity
→ LHC luminosity upgrade 2021/22

ATLAS Sensitivity Study