Capitolo 14
Misura delle proprieta' del Bosone di Higgs con ATLAS e CMS

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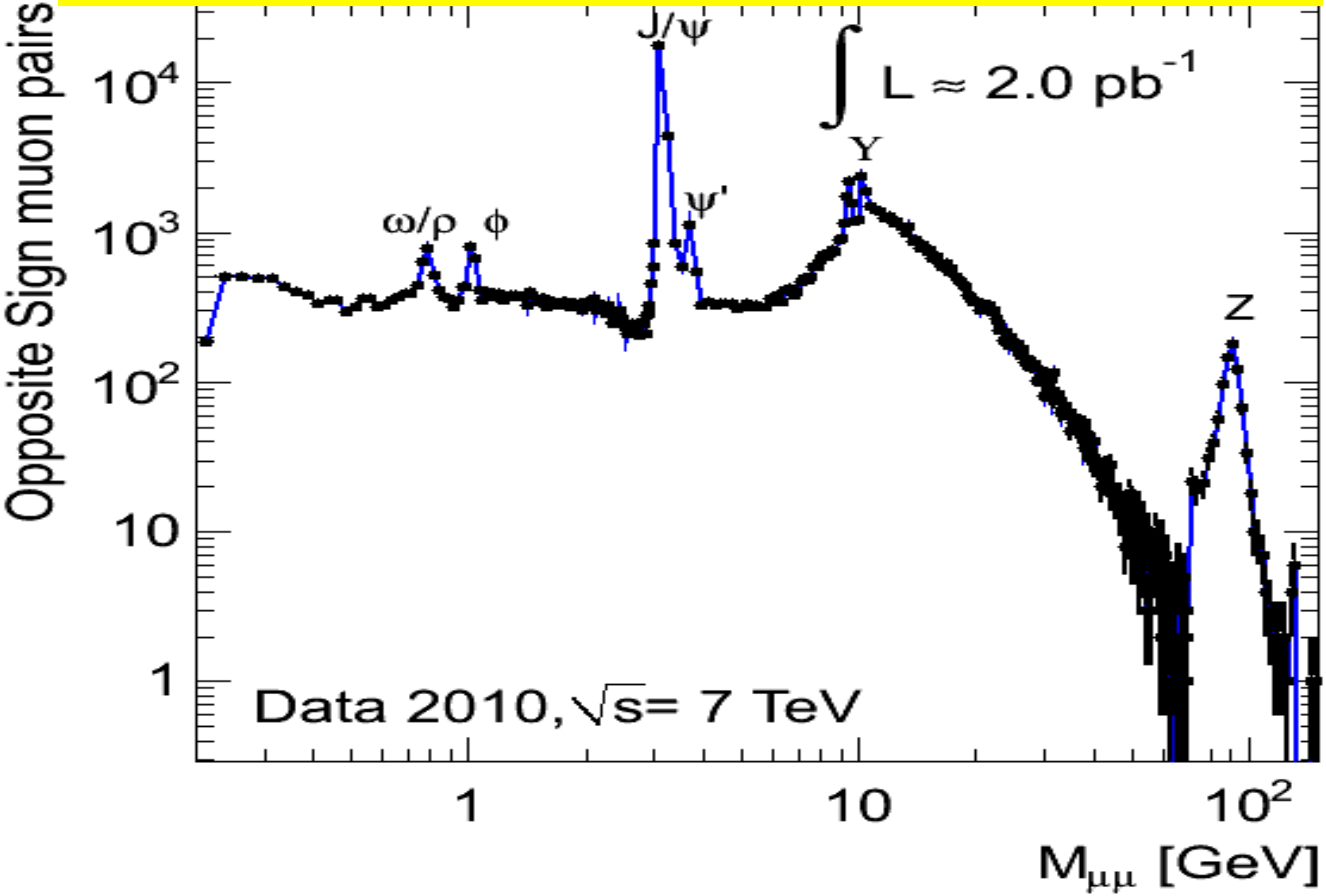
AA 2012-2013, Corso FNSN II

L’ Analisi e la Misura delle Proprieta’ dell’Higgs a LHC

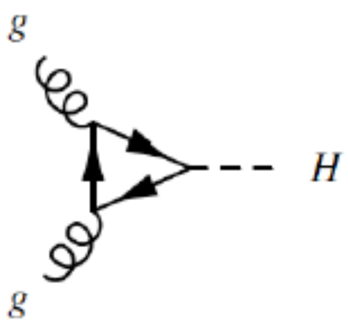
Issue affrontati dal 4 luglio 2012

- Statistica accumulata: ≈ 25 fb^{-1} da ciascun esperimento.
- La nuova particella scoperta e' veramente il Bosone di Higgs ?
  - i) ricerca degli altri canali di decadimento;
  - ii) misura dello spin:
  - iii) misura del "signal strength": $\mu = \sigma/\sigma_{SM}$
- Misura della massa della nuova particella
- Misura degli accoppiamenti
- Ricerca di altre nuove particelle

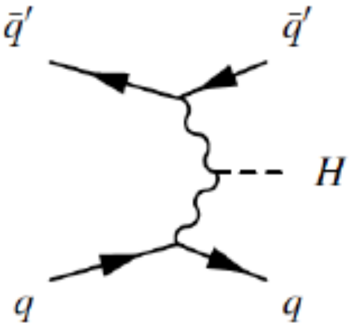
“Candele” di Calibrazione dalle risonanze



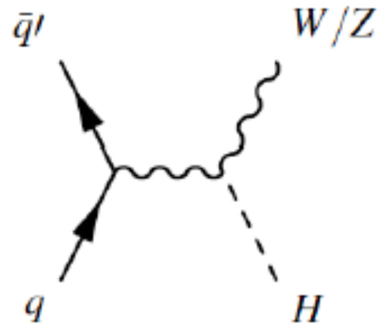
Produzione del Bosone di Higgs da collisioni pp



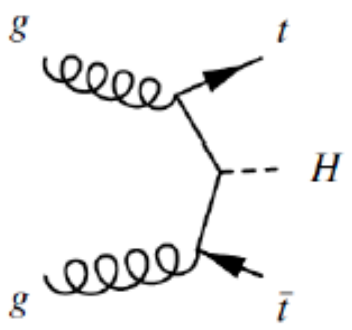
(a) $gg \to H$



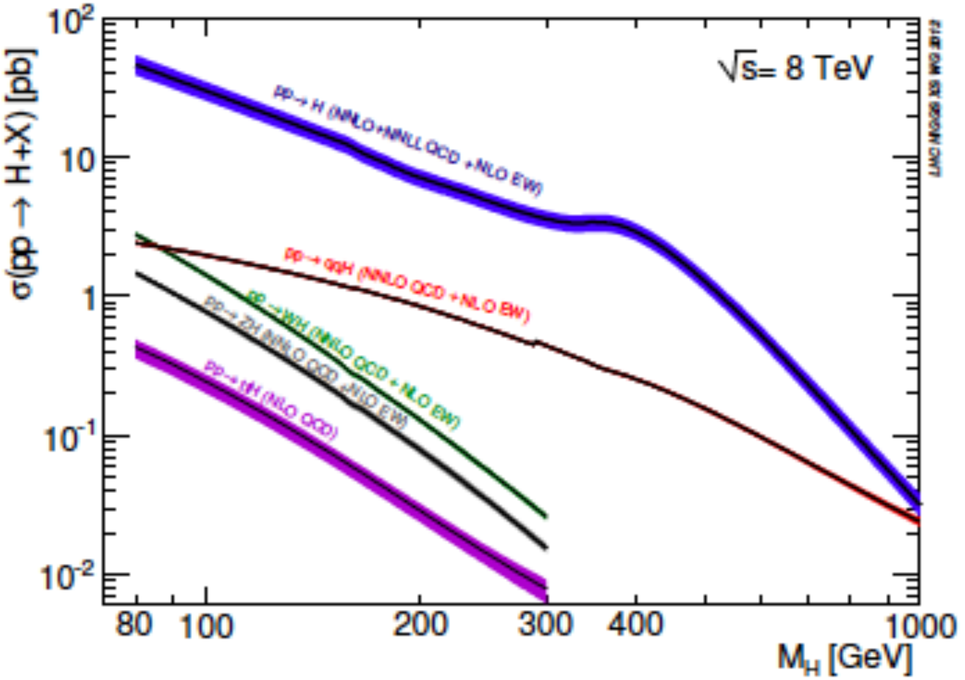
(b) VBF



(c) VH



(d) $t\bar{t}H$



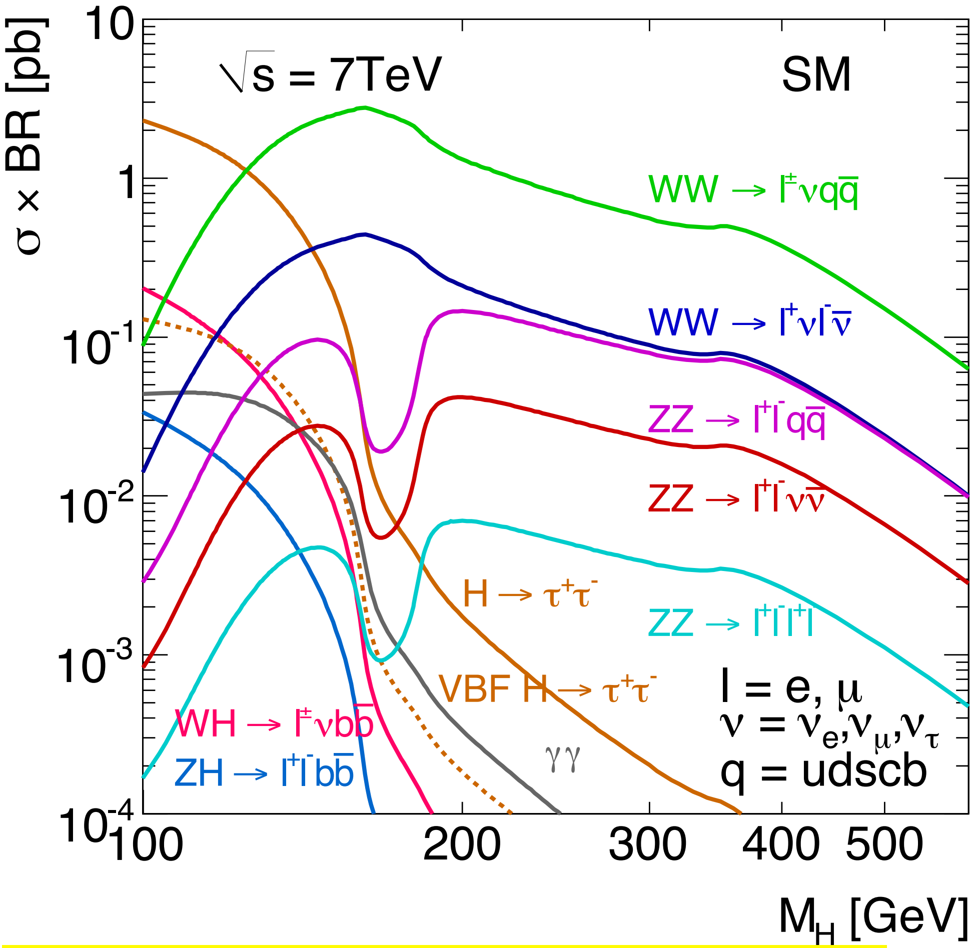
gg→ H is dominant production mechanism

Irreducible backgrounds in H → WW, ZZ, γγ are from q$\bar{q}$ annihilation; S/B better than at Tevatron except in VH

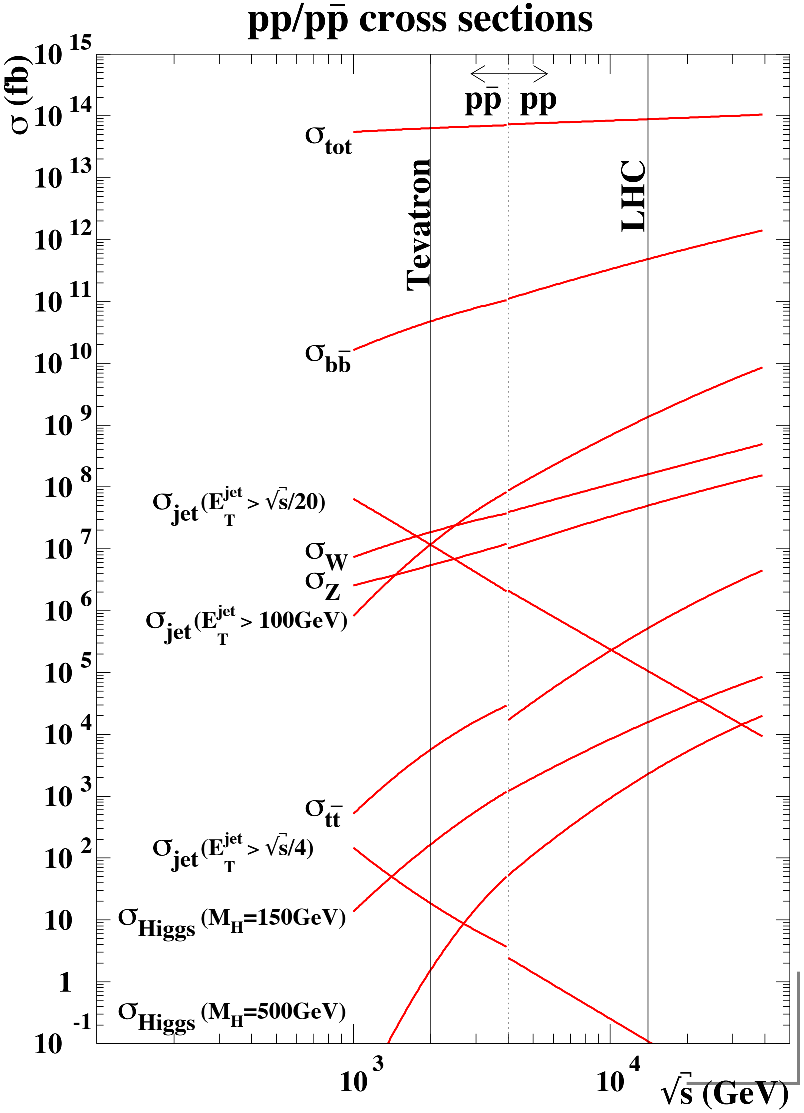
The Higgs Search at LHC

Huge cross section for QCD processes

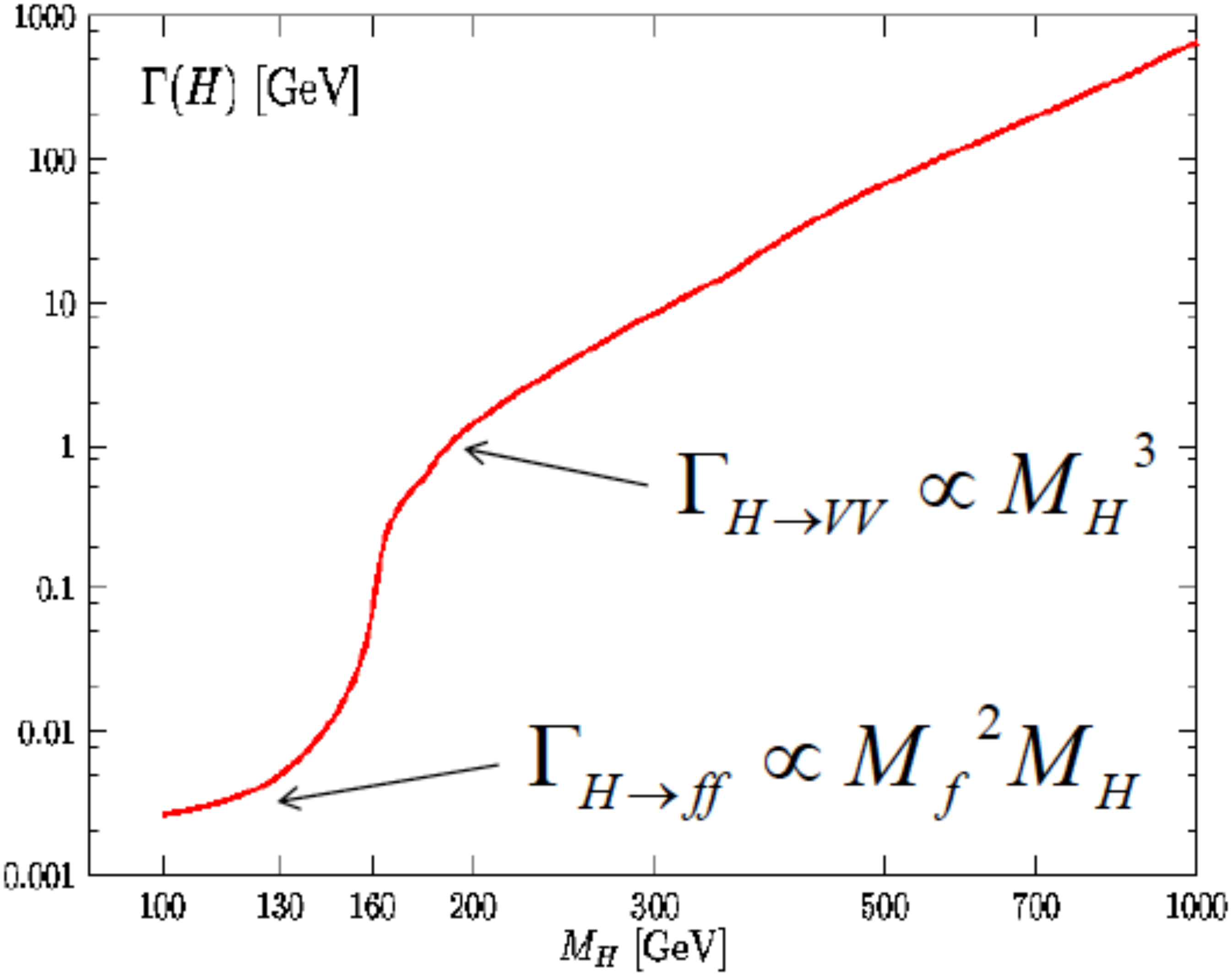
- **$S/B \approx 10^{-10}$ ➔ a needle in a haystack**



- **Production rate of the Higgs as well as its decay possibilities (“Signatures”), depend on its mass**



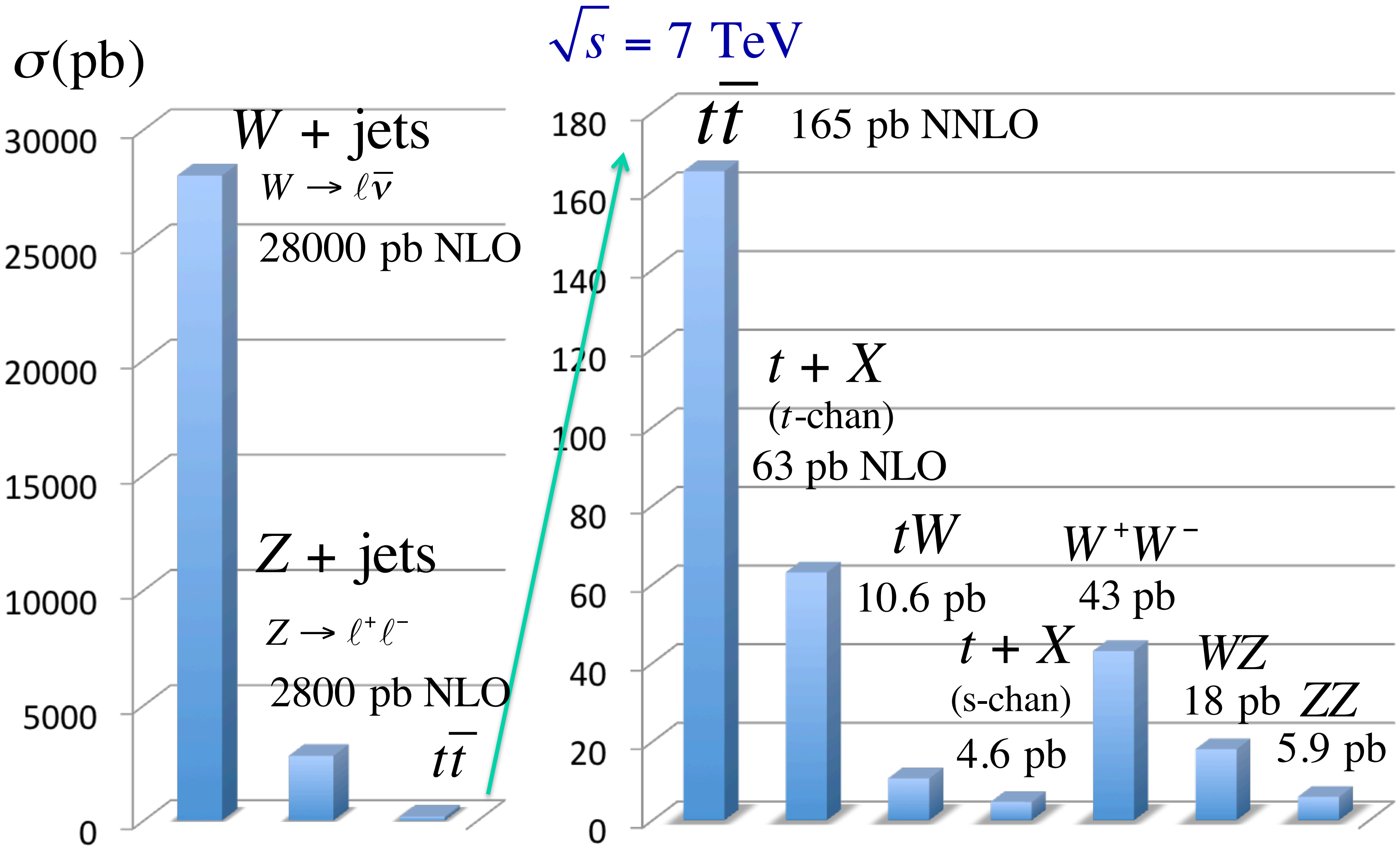
Larghezza del Bosone di Higgs



$\Gamma_{H\to VV} \propto M_H^{\;3}$

$\Gamma_{H\to ff} \propto M_f^{\;2} M_H$

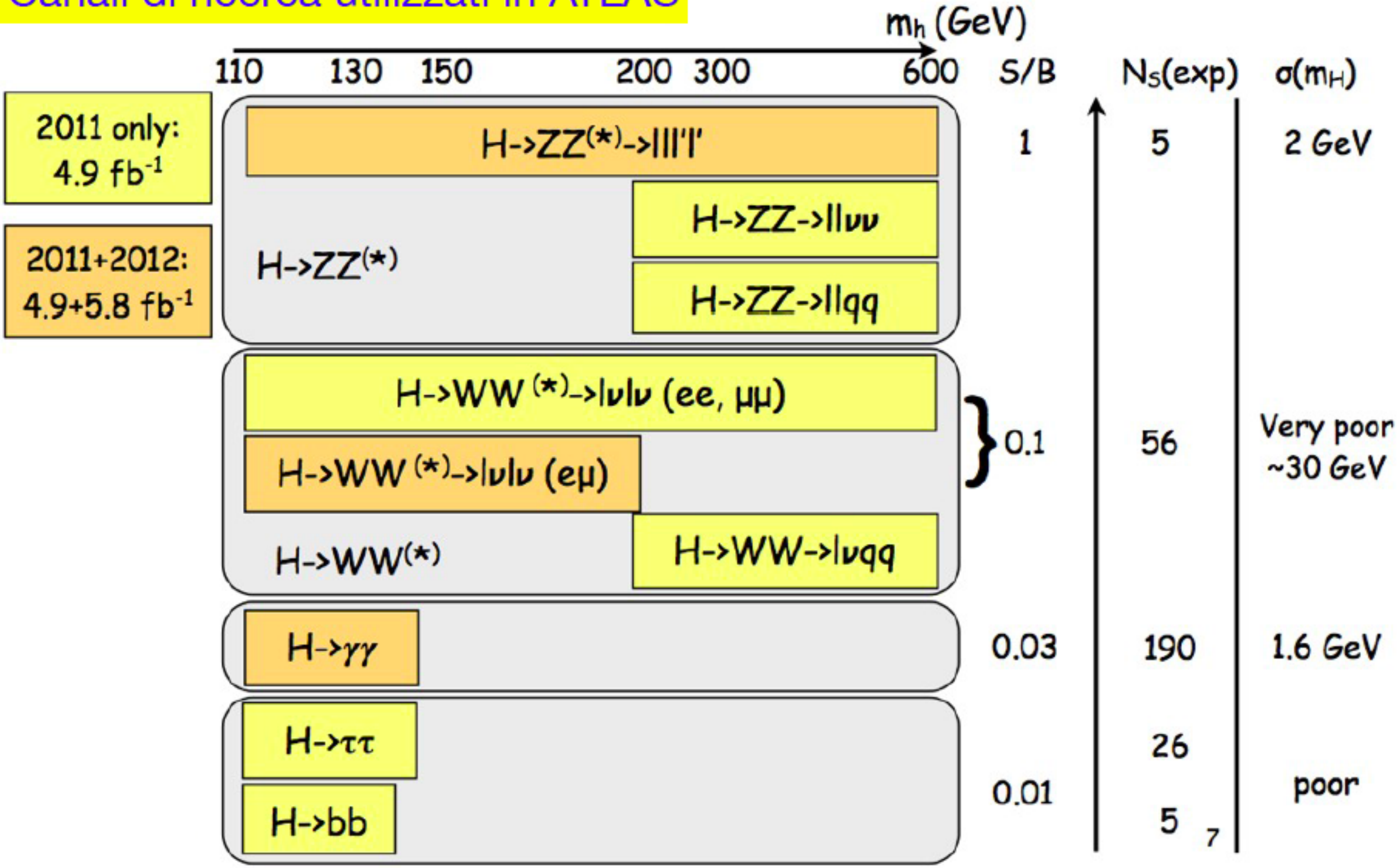
Cross Sections of SM Background processes



The Higgs Search at LHC

Mode
H → $\gamma\gamma$
H → bb
H → $\tau\tau$
H → WW → 2l 2ν
H → ZZ → 4l
H → ZZ → 2l2τ
H → ZZ → 2l2j
H → ZZ → 2l2ν

Canali di ricerca utilizzati in ATLAS



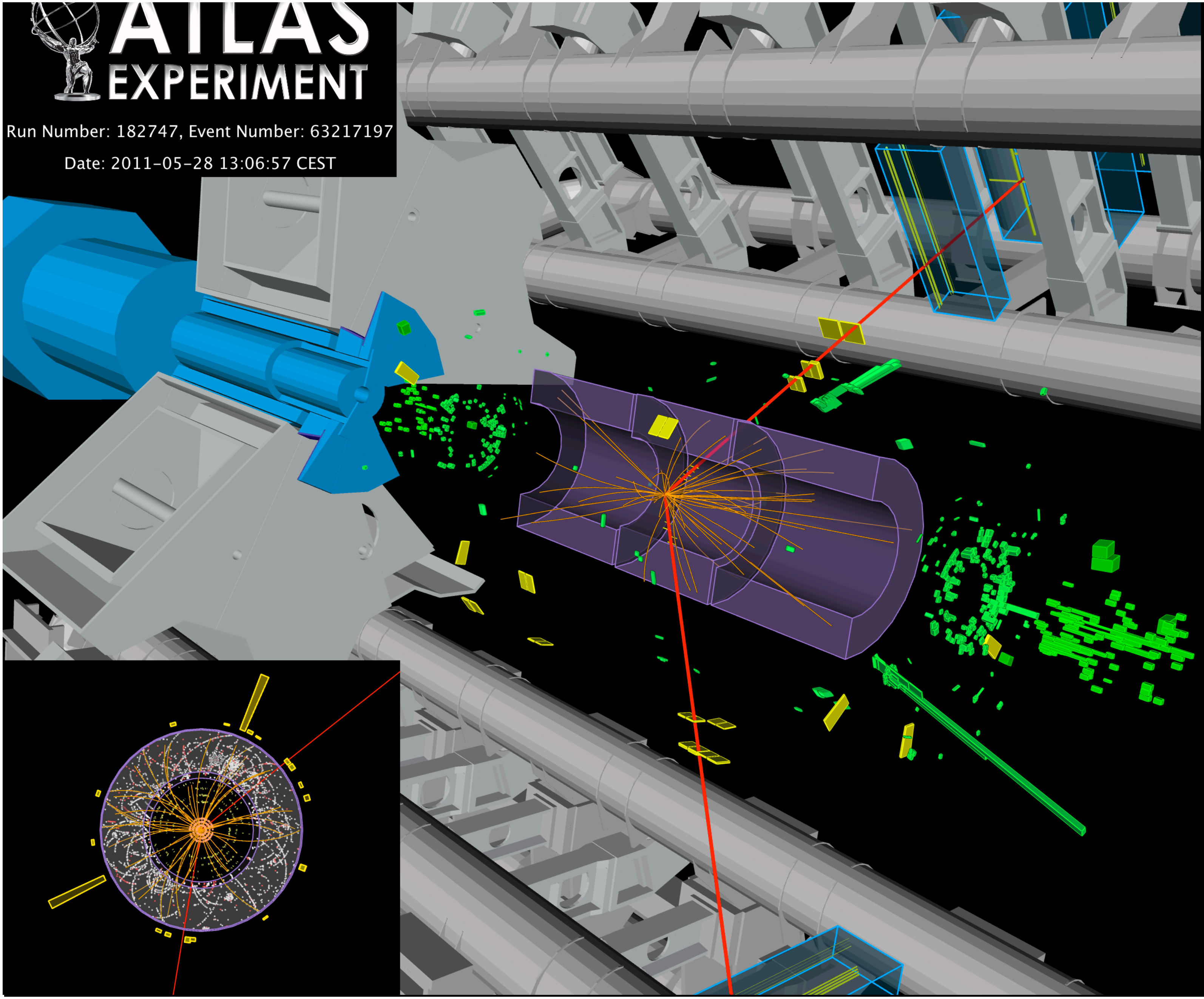
2011 only: 4.9 fb^{-1}

2011+2012: 4.9+5.8 fb^{-1}

m_h (GeV)

110 130 150 200 300 600

Canale	S/B	N_S(exp)	$\sigma(m_H)$
H->ZZ$^{(*)}$: H->ZZ$^{(*)}$->lll'l', H->ZZ->llνν, H->ZZ->llqq	1	5	2 GeV
H->WW$^{(*)}$: H->WW$^{(*)}$->lνlν (ee, μμ), H->WW$^{(*)}$->lνlν (eμ), H->WW->lνqq	0.1	56	Very poor ~30 GeV
H->γγ	0.03	190	1.6 GeV
H->ττ	0.01	26	poor
H->bb		5 7	



2μ2e candidate:

m_{lead}: 85.9 GeV

m_{subl}: 85.5 GeV

m_{4l}: 210 GeV

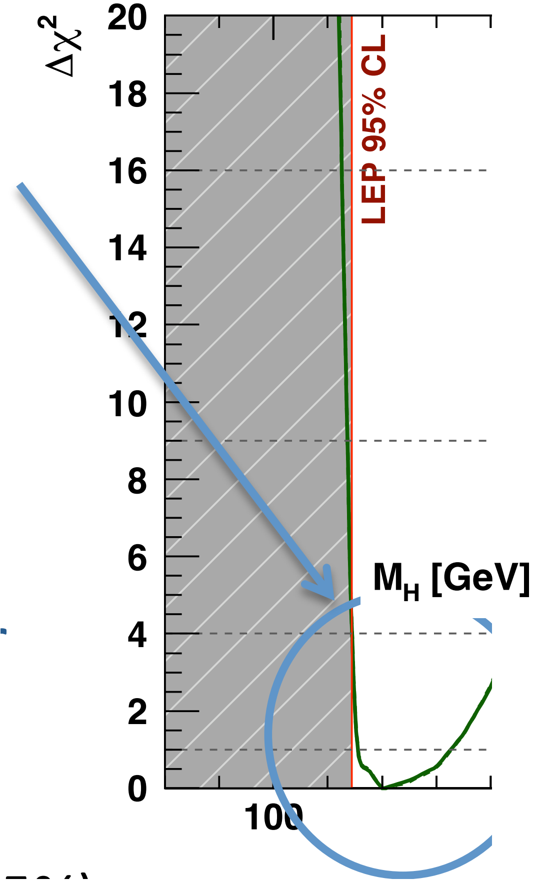
❖ H → $\gamma\gamma$: a suitable "case for treatment"

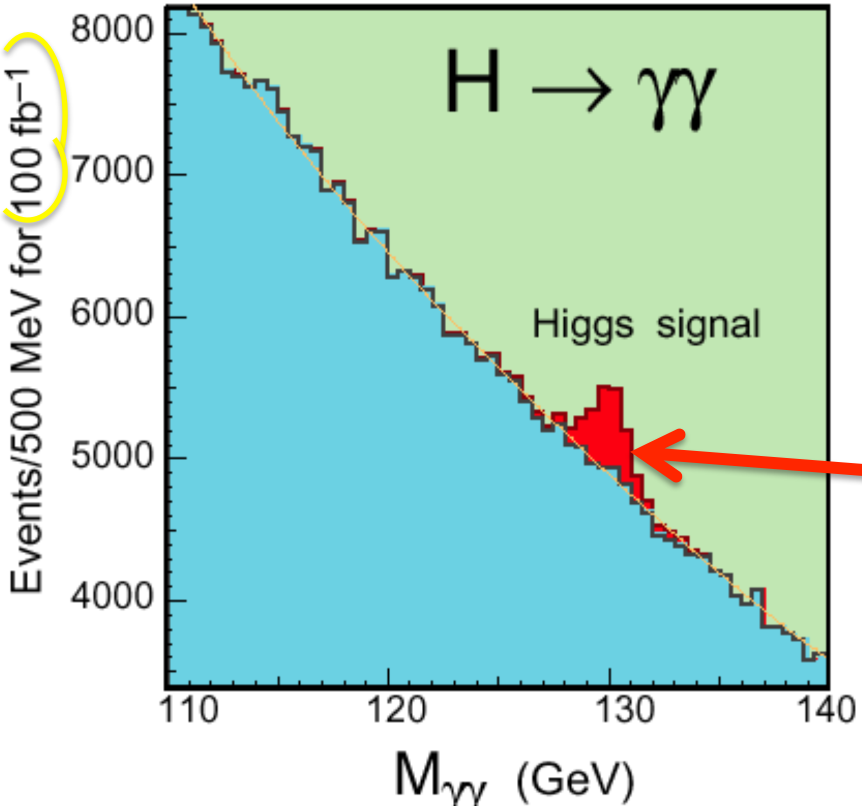
- ❖The focus is now on the region between 114-145 GeV !

- ❖The lower the mass the harder it is at LHC !

Relevance of the γγ Channel

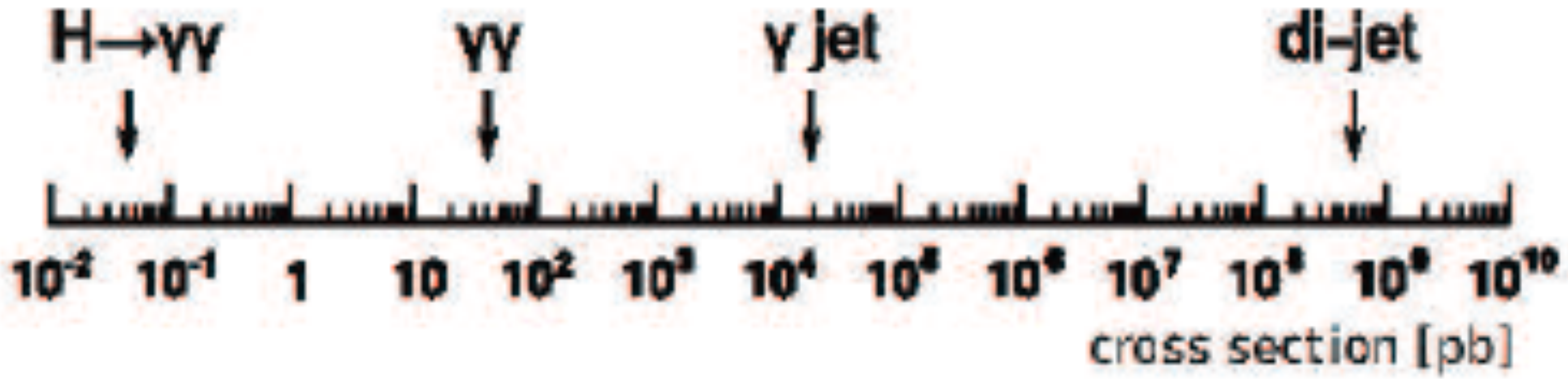
- Dominant Channel in the very low mass range (110-125 GeV) where the SM Higgs is prefered
- We expect to see a Mass Peak !





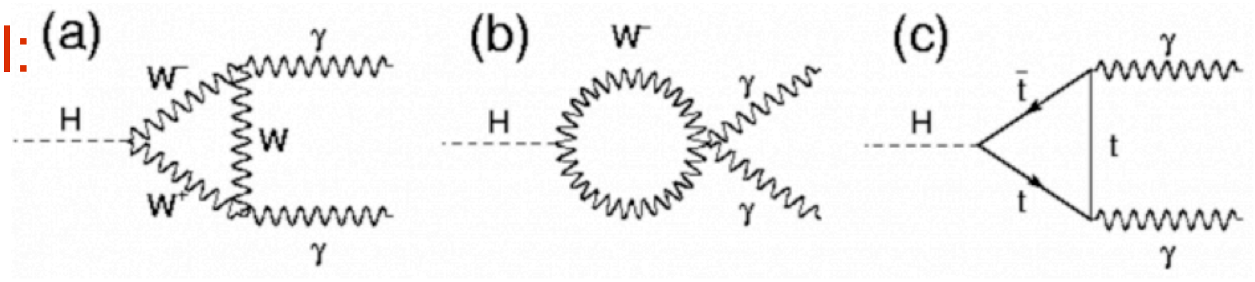
Some years from now……

Valori delle sezioni d'urto del segnale e dei fondi



Signal VS Backgrounds

Signal:

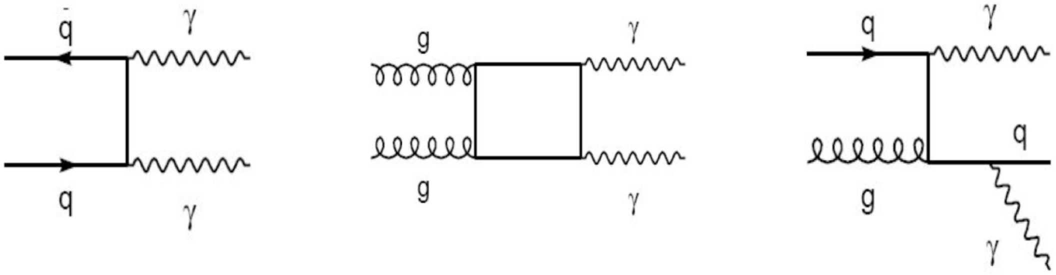


$\sigma = 0.04$ pb

Irreducible BG: prompt diphoton (+jets).

Born, box or fragmentation processes

qqbar, qg, $\sigma \approx 21$ pb
gg $\sigma \approx 8$ pb



γ-jet $\sigma \approx 1.8 \times 10^5$ pb
jet-jet $\sigma \approx 4.8 \times 10^8$ pb

Reducible backgrounds: γj, dijet (jj)

Drell-Yan BG also contributes (misidentified e)

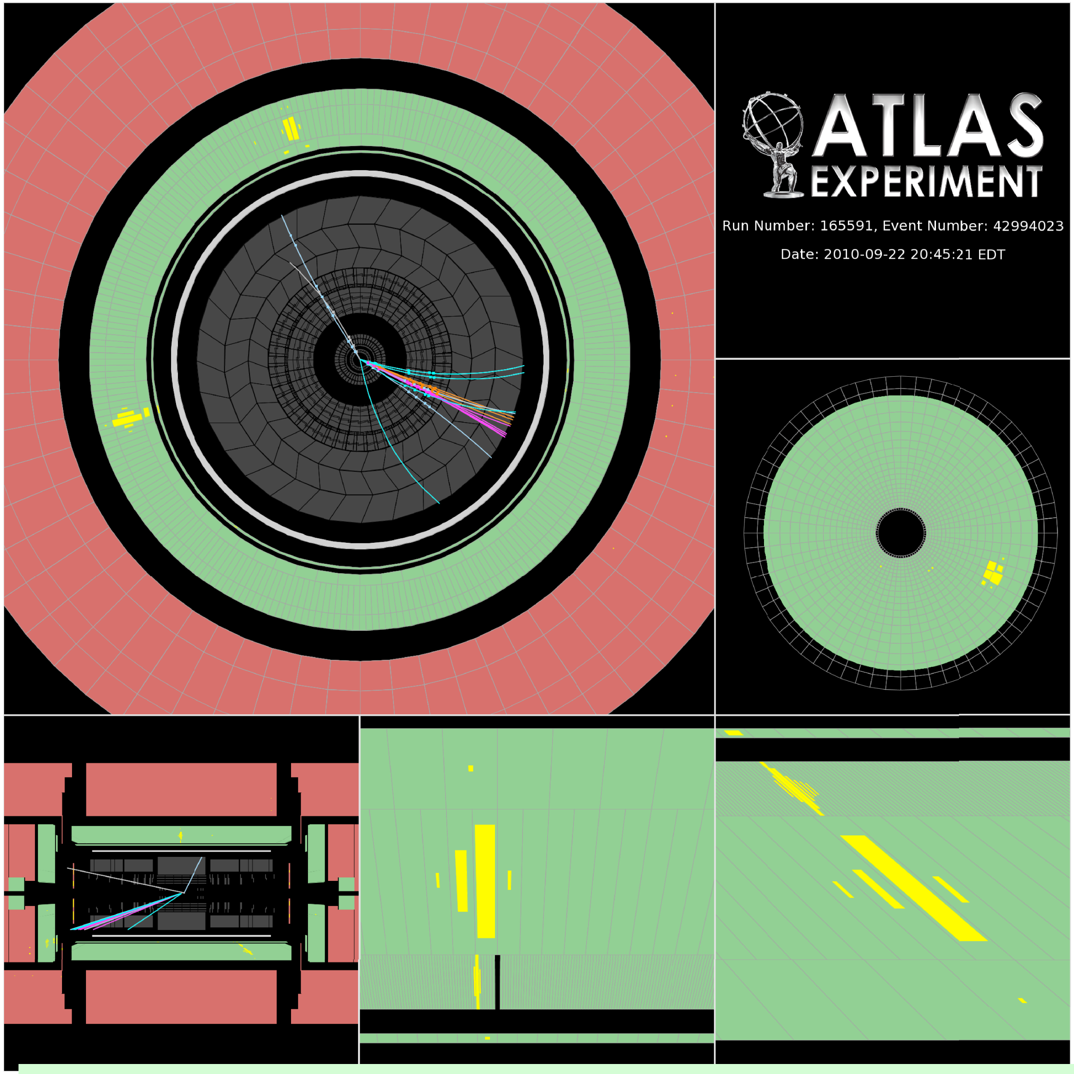
γ-jet need rejection R~O(10^4)
jet-jet need rejection R~O(10^7)

Experimental Issues

➪ H ➔$\gamma\gamma$ mass reconstruction: the discovery potential depend on the di-photon invariant mass resolution:

- Energy resolution via calibration
- Photon reconstruction
- Vertex reconstruction
- Pile Up condition
- $\pi^0 - \gamma$ rejection

Simple Signature Channel



Very simple signature (and analysis selection):

Two tightly identified and isolated photons with:

$P(\gamma_1)_T > 40$ GeV/c

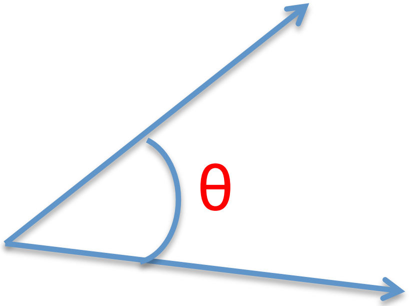
$P(\gamma_2)_T > 25$ GeV/c

- $|\eta(\gamma_1,\gamma_2)| < 2.37$, excluding [1.37,1.52]

- Calorimetric isolation < 5 GeV

Photon identification based both on the longitudinal and the lateral segmentation of the calorimeter

H➔γγ mass reconstruction



$$m^2 = 2p_1p_2(1-\cos\theta)$$

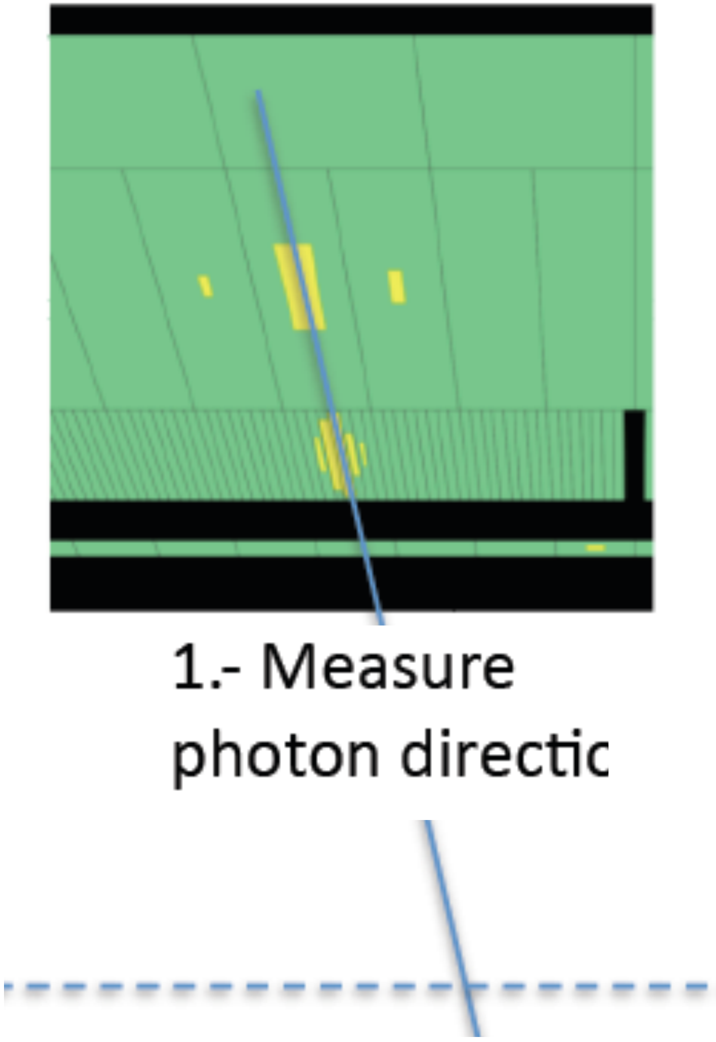
$$\delta m/m = \frac{1}{\sqrt{2}}\frac{\delta p}{p} \oplus \frac{\delta\theta}{\theta}$$

- **Energy resolution contribution δp ≈ 1.3 GeV**
  - **energy scale calibration from Z ➔ e+e-**

- **Interaction point spread:**
  - **σ(z) ≈ 5.6 cm ➔ δm(θ) ≈ 1.4 GeV**

- **Resolution with pointing: σ(z) ≈ 1.5 cm;**
  - **Use of recoil tracks less effective with large number of pile-up collisions**

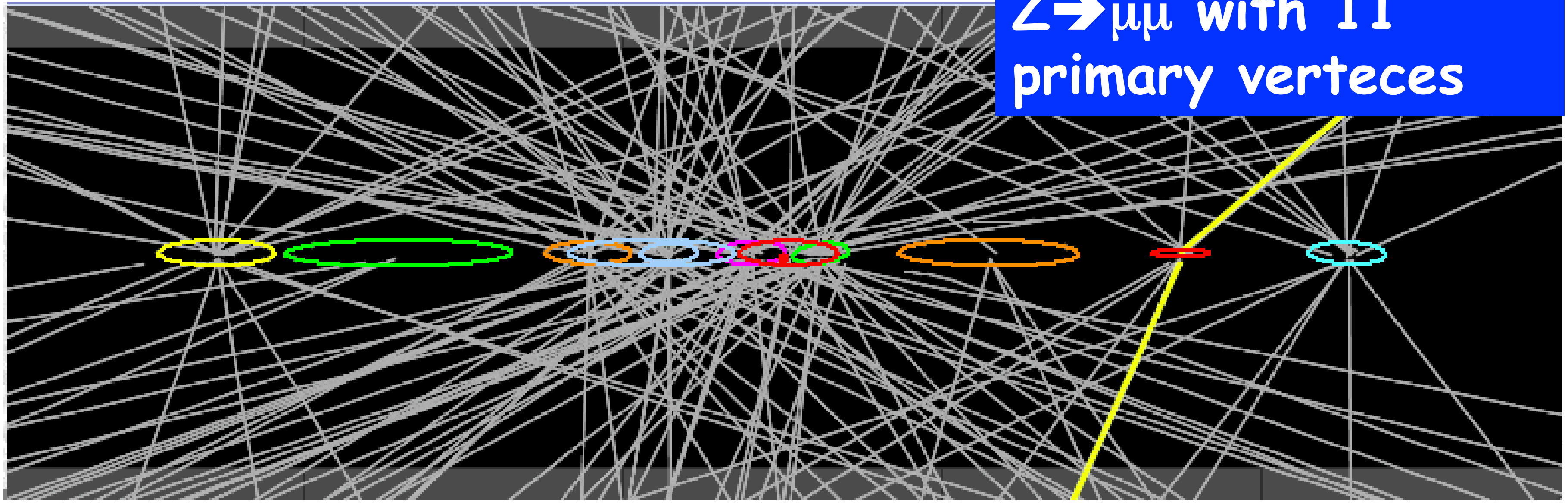
- **Use conversion tracks as well**



2.- Deduce z of PV

ATLAS

Pile Up Event



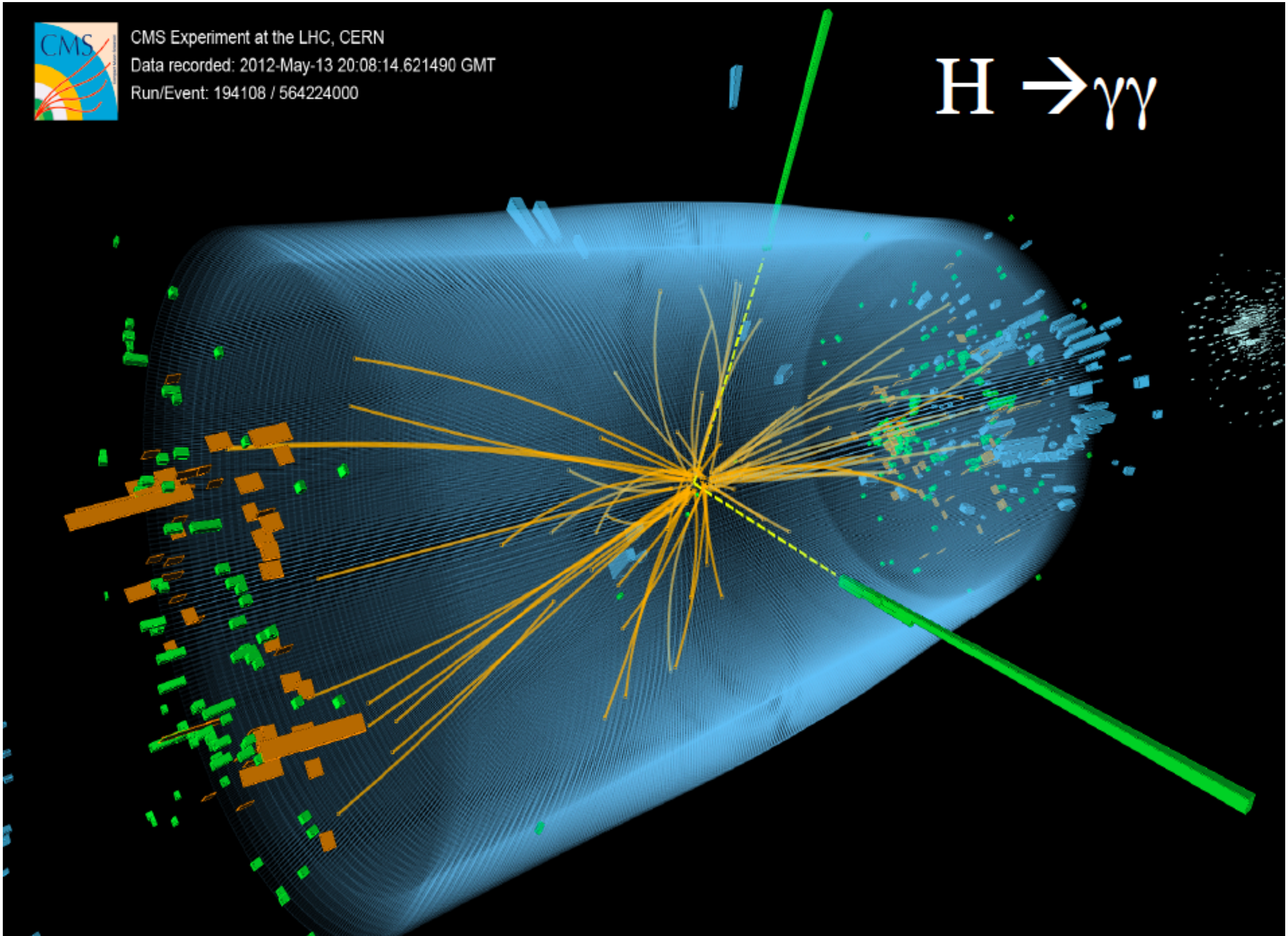
Z→μμ with 11 primary verteces

Pile-up challenge:

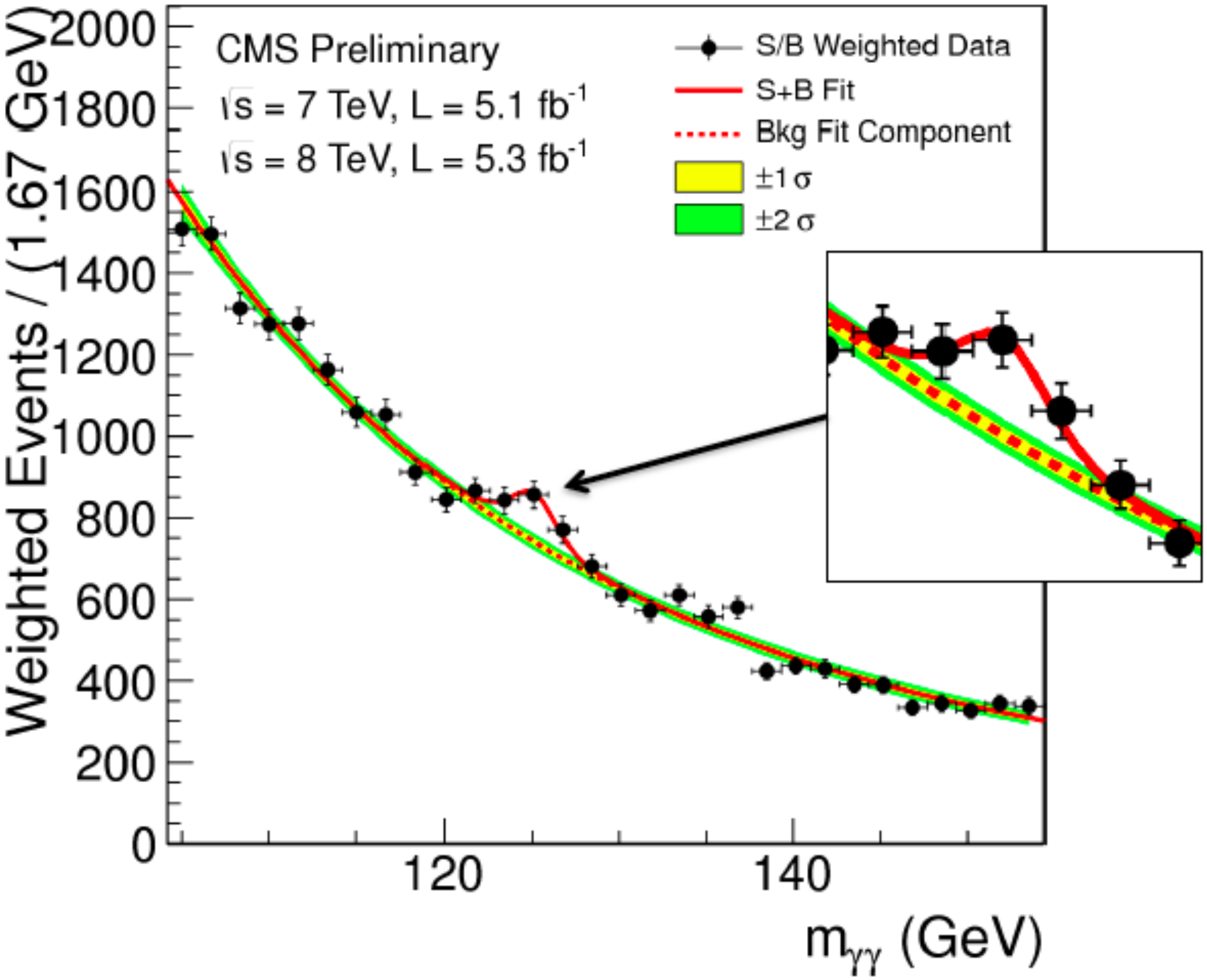
- 50 ns bunch trains for ~all 2011 data

→ **Substantial in- and out-of-time pileup: μ ≈ 6**

→**At 5 × e^{33} two possible scenarios:** **i) <μ> ≈ 21**
ii) <μ> ≈ 11


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ

S/B weighted mass distribution

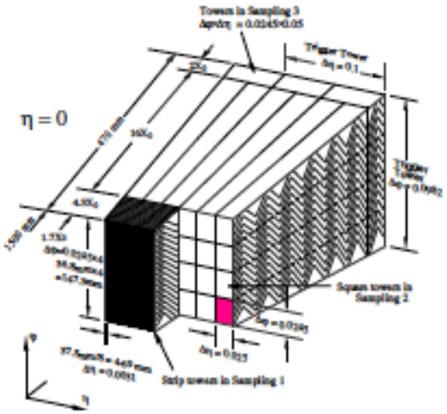


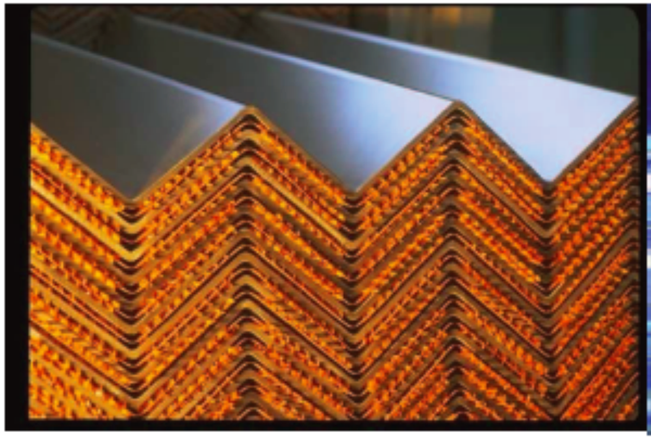
- Sum of mass distributions for each event class, weighted by S/B
- B is integral of background model over a constant signal fraction interval

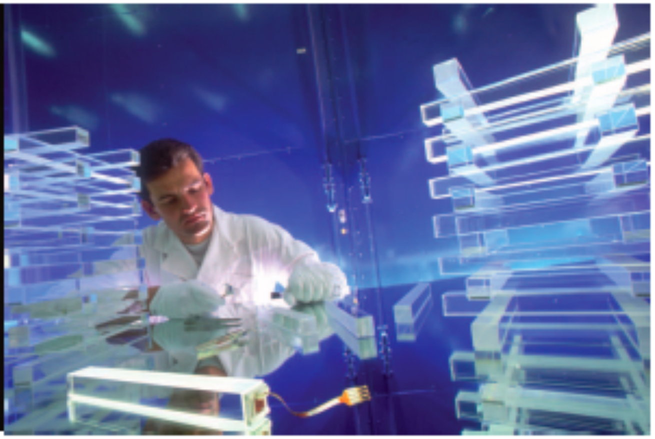
Different calorimeter design

- LAr/Pb sampling calorimeter, $22X_0$
- accordion shape: full azimuthal coverage, fast signal extraction
- longitudinally segmented (strip, middle, back) + presampler
- middle segmentation: 0.025×0.025
- fine η segmentation of strip layer, $\Delta\eta = 0.003$, γ/π^0 separation
- nominal $\sigma/E = \frac{10 \div 17\%}{\sqrt{E/\mathrm{GeV}}} \oplus 0.7\%$

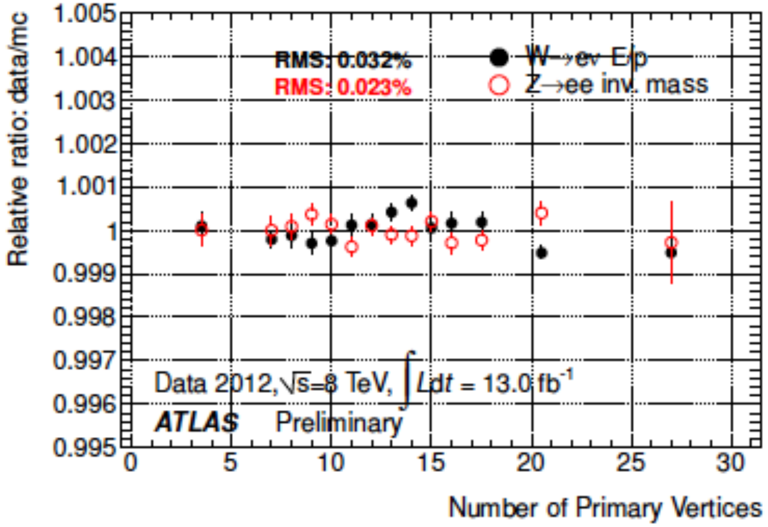
- homogeneous calorimeter
- high resolution $PbWO_4$ scintillating crystals, avalanche photodiodes + endcap silicon preshower
- 0.017×0.017 (barrel), 0.018×0.003 to 0.088×0.015 (endcap)
- lateral segmentation, no longitudinal segmentation
- nominal $\sigma/E = \frac{3\%}{\sqrt{E/\mathrm{GeV}}} \oplus 0.5\%$

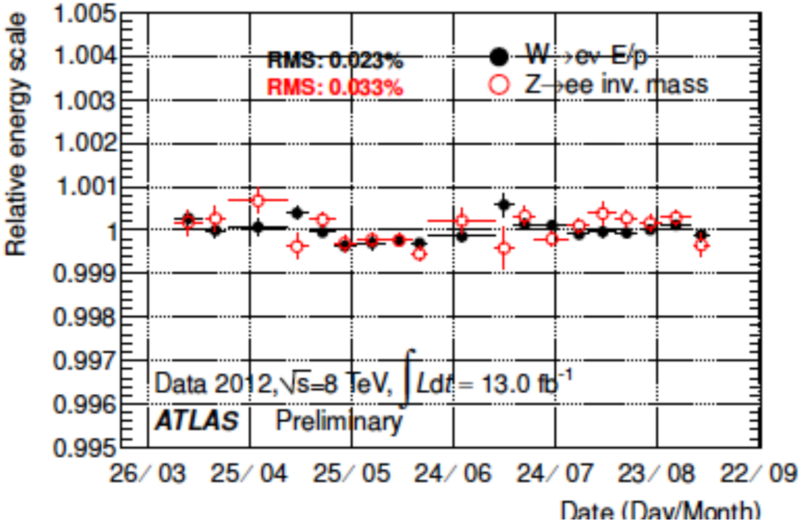




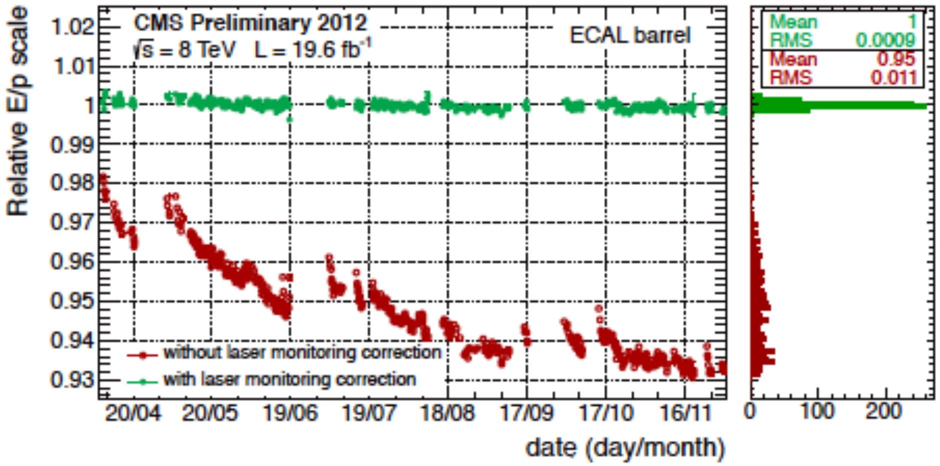


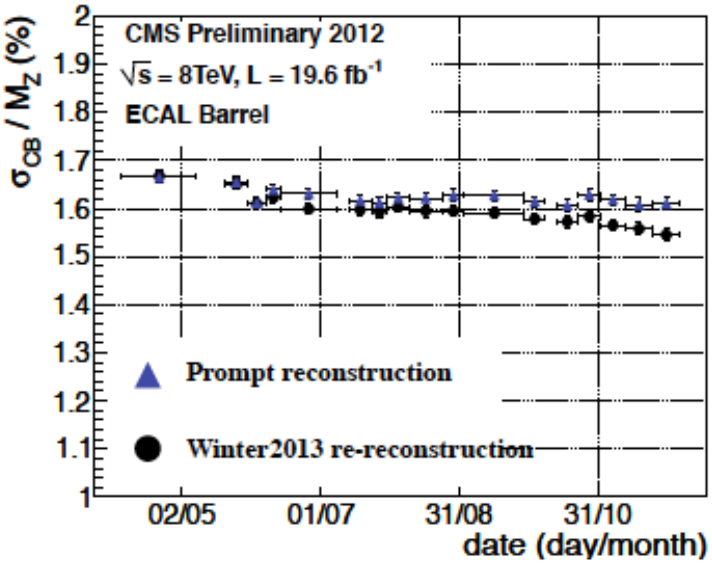
EMC stability < 0.1% vs time and pileup





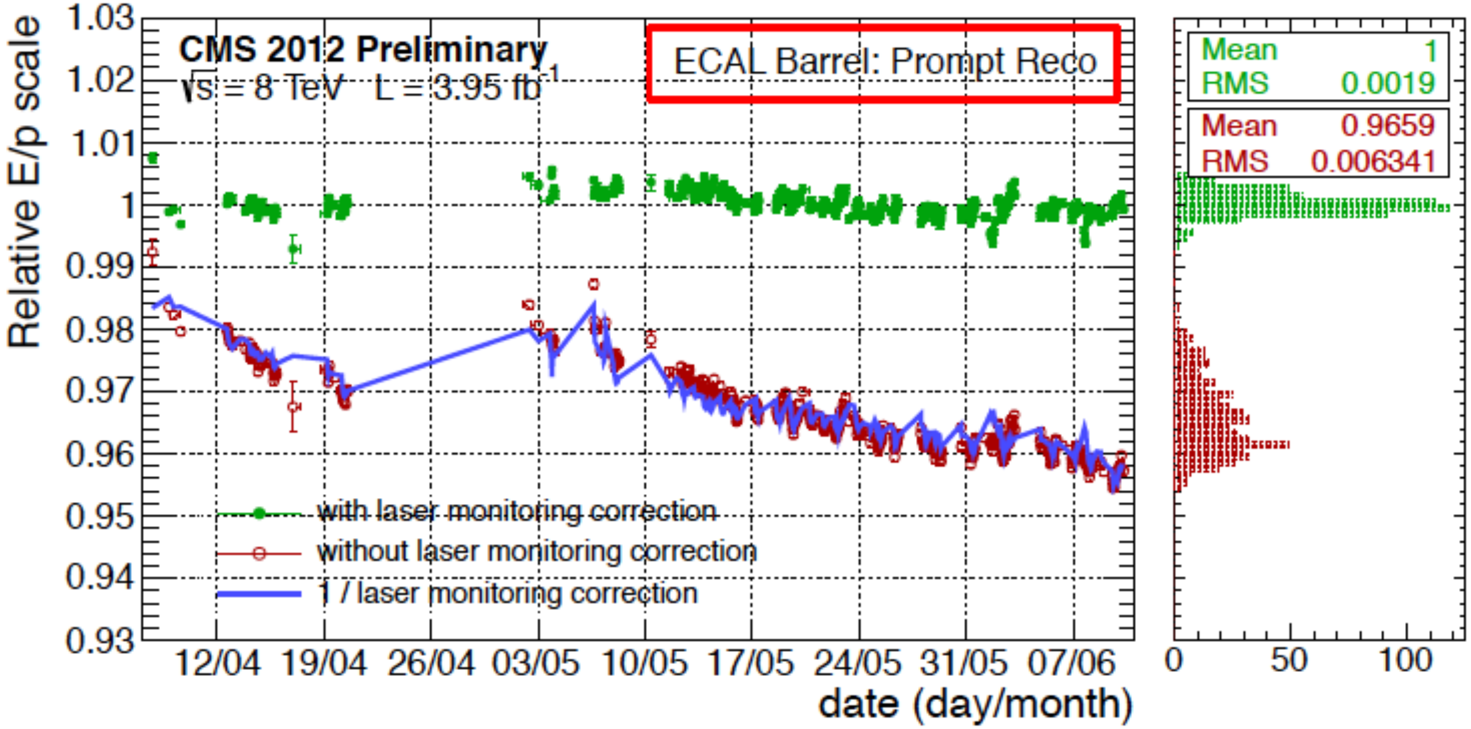
important correction for CMS





ECAL calibration:2012

Single electron energy scale (E/p) stability in
the ECAL barrel measured using W →eν events



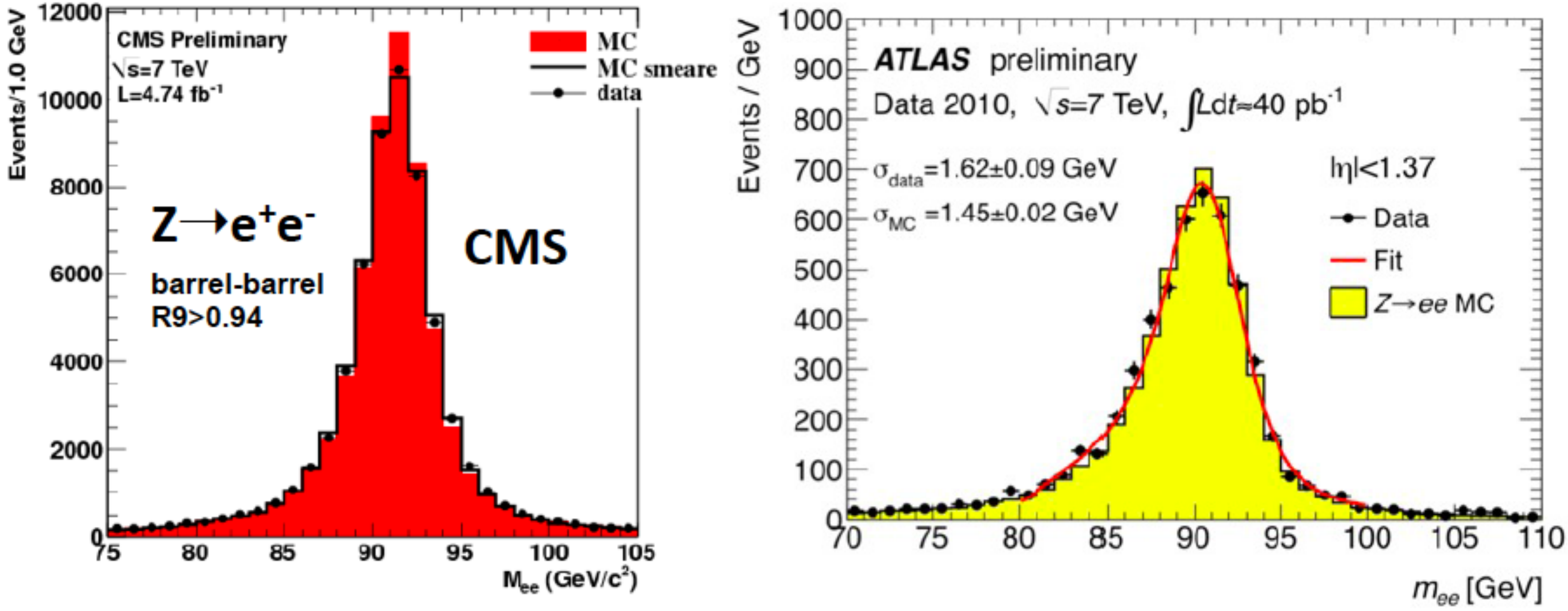
E/p: stable energy scale during 2012 run after applying laser monitoring corrections:

EB: RMS stability after corrections 0.19%

PHOTON ENERGY SCALE AND RESOLUTION

- **$Z \rightarrow e^+e^-$ invariant mass** to determine **energy scale and resolution from data**
- **photon energy smeared** on MC to match data to model Higgs signal

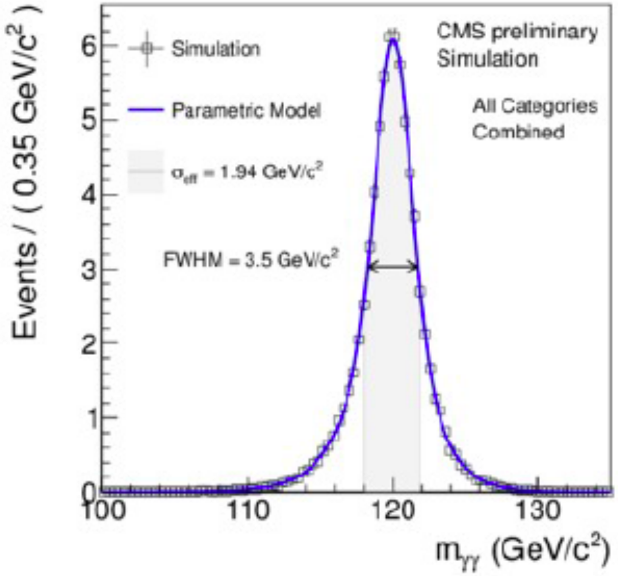
examples of resolution monitoring using $Z \rightarrow ee$ events

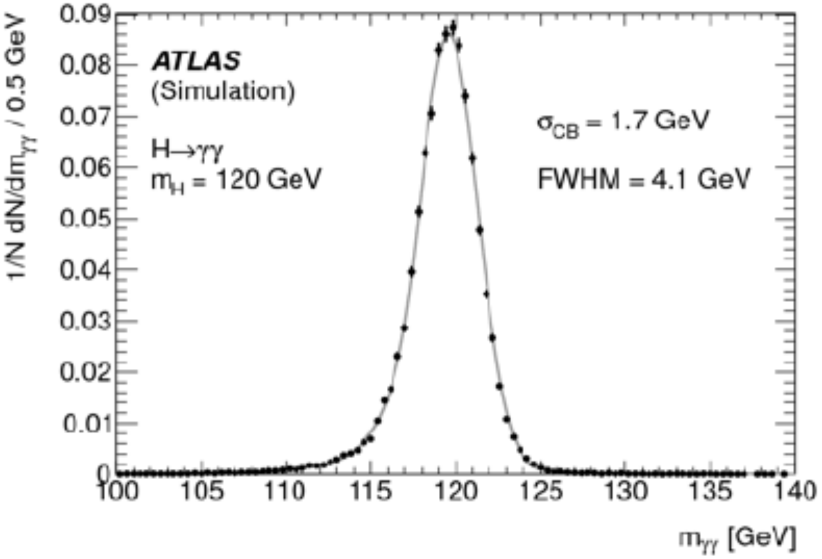


M(γγ) RESOLUTION

- In both detectors **m(γγ) resolution** depends on **photon kinematics, conversion probability, and pseudorapidity**
- CMS performs better in central region, ATLAS in forward
- Overall **performance for Higgs signal quite similar**

CMS		**ATLAS**	
best resolution cat.	worst resolution cat.	best resolution cat.	worst resolution cat.
FWMH ~ 2.8GeV	FWMH ~ 7.2GeV	FWMH~3.3GeV	FWMH~5.9GeV

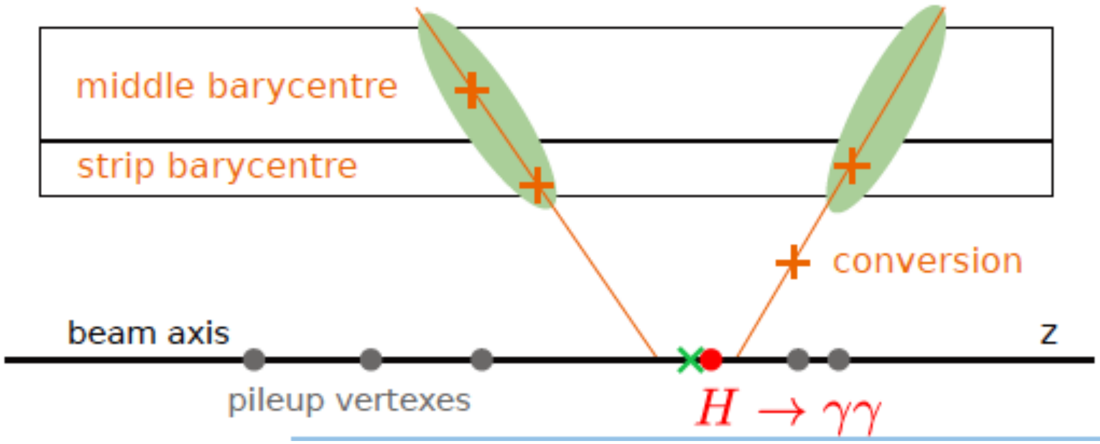


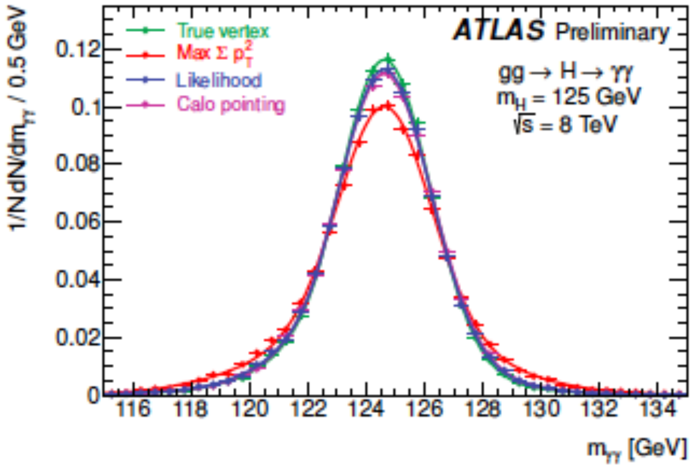


Pointing

ATLAS

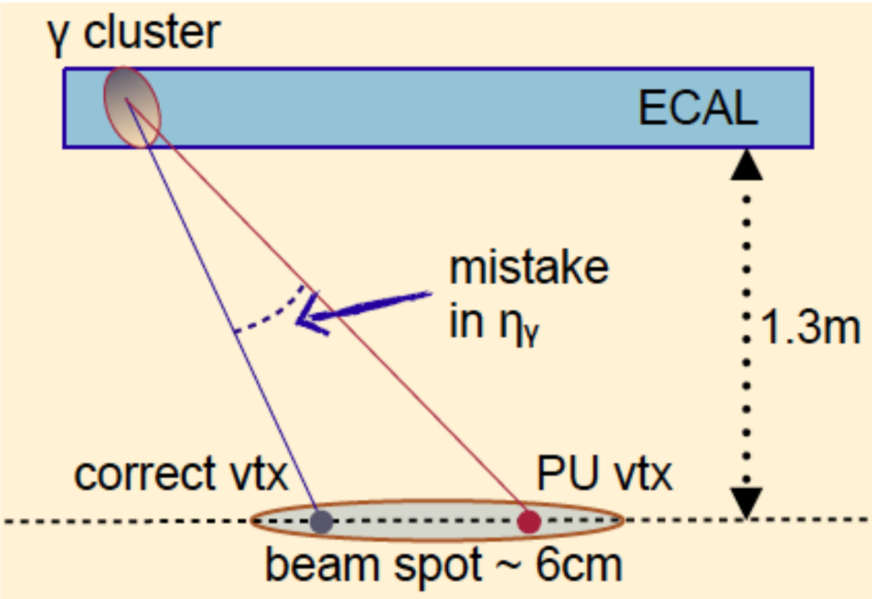
- ability to measure direction with the calorimeter only thanks to the longitudinal segmentation
- unconverted photons using the barycentre of the cluster measured in the first and the second layer
- converted photons from the conversion point and the position in the first layer of the accordion
- for each of the two photons the intersection between the flight line and the beam line gives the estimate of the z-coordinate of the photon origin
- a weighted average of the two gives the estimate, with its uncertainty
- $\sigma_z = 15\,\mathrm{mm}$ (6 mm using conversion)

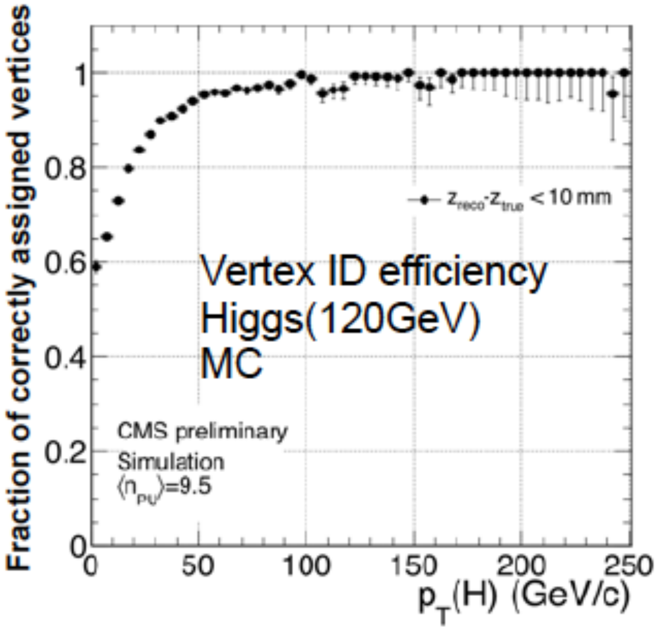




CMS VERTEX DETERMINATION

- **large pile-up conditions**
  - ➪ $\langle N_{PU} \rangle \sim 10$
- di-photon invariant **mass resolution affected by vertex** choice
- CMS **vtx determination** based on
  - **tracks belonging to vertex** combined **with di-photon kinematics**
    - use of $\Sigma p_T{}^2{}_{trk}$ and p_T balancing
  - **conversion-track** finding and projection on beam spot
- performance **cross-checked using $Z \rightarrow \mu^+\mu^-$** after removing muon tracks

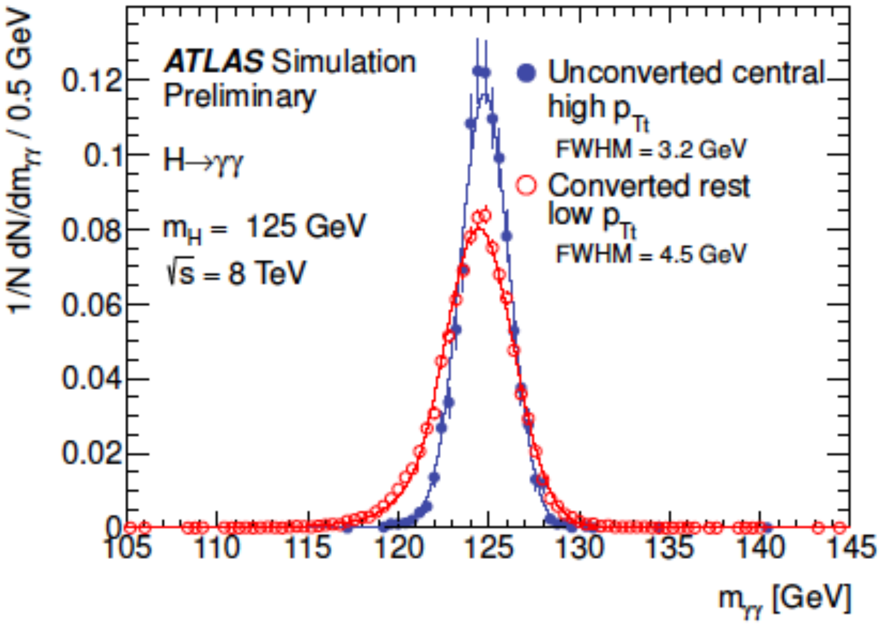




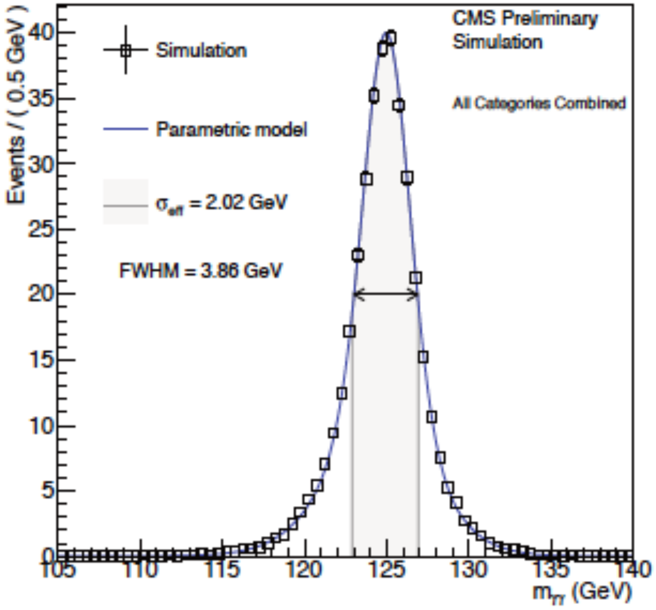
Vertex ID efficiency
Higgs(120GeV)
MC

Invariant mass resolution

- Fit: Crystall Ball + wide gaussian
  - gaussian component $\lesssim 12\%$



- Fit: sum of two or three gaussians



FWHM / 2.35:

	ATLAS[1]	CMS
overall	1.77 GeV	1.64 GeV
best cat	1.40 GeV	1.27 GeV
other cats	1.50–2.52 GeV	1.39–2.14 GeV

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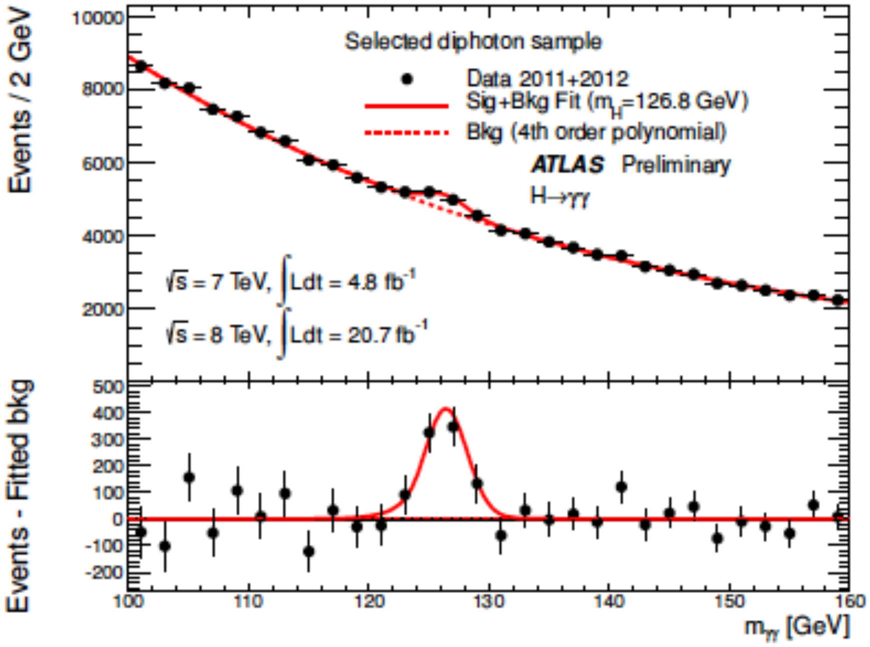
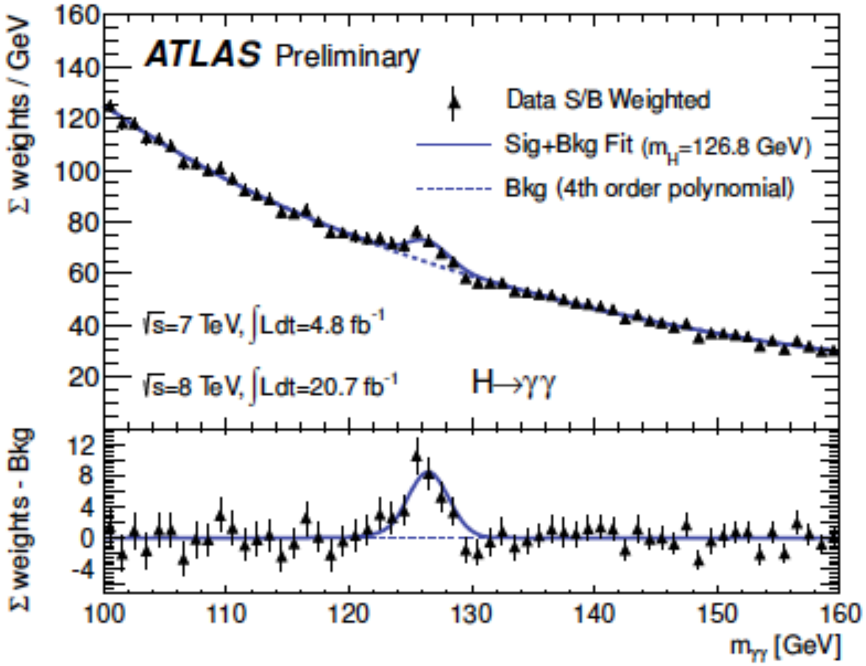
[1] ATLAS only quotes σ_{CB} in the last public document. FHWM is obtained scaling σ_{CB} for the FHWM/σ_{CB} in HCP note.

Signal yield

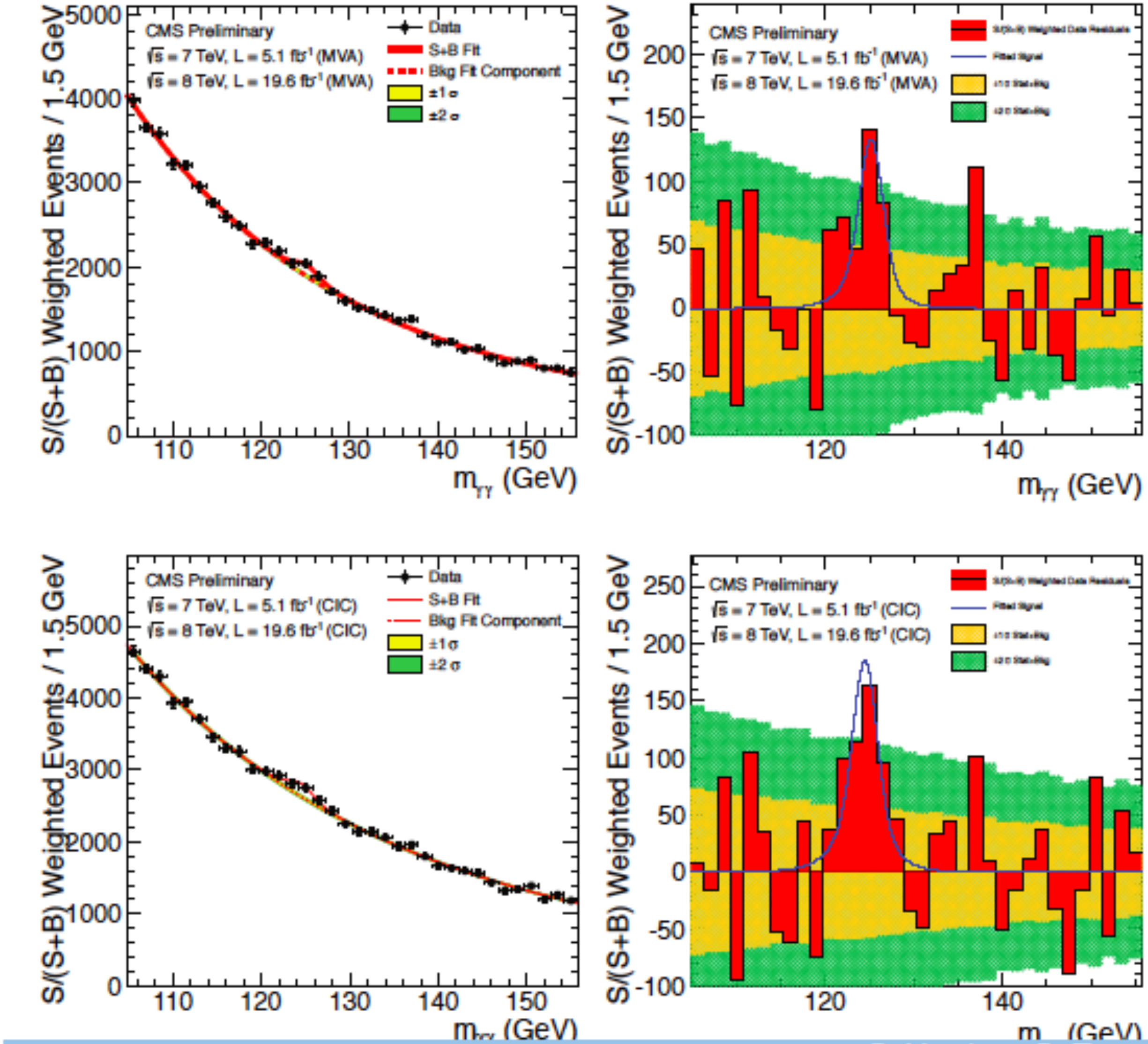
ATLAS (non-weighted/weighted)





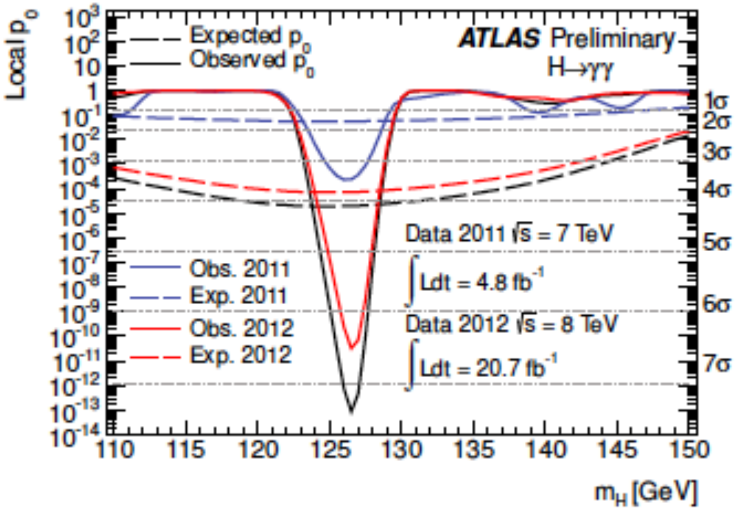
Signal yield

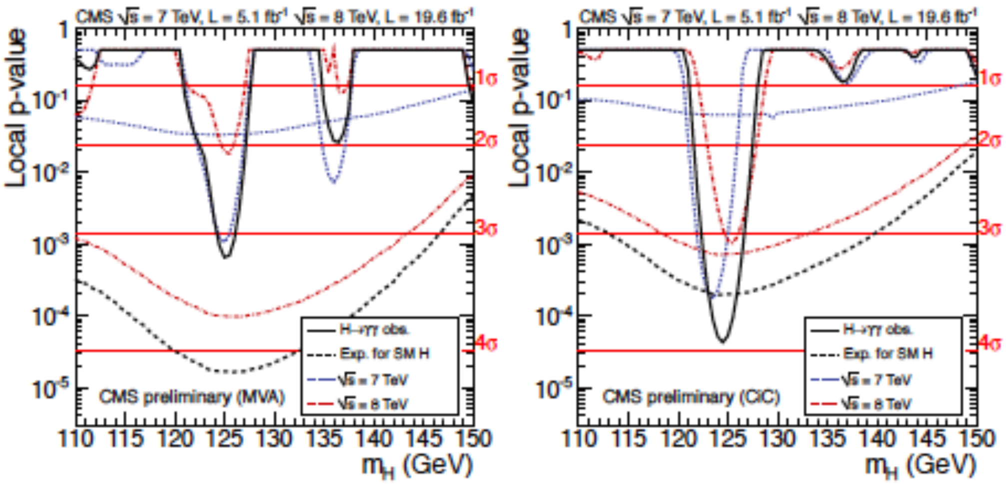
CMS (MVA/cut-based)



Results

local p-value



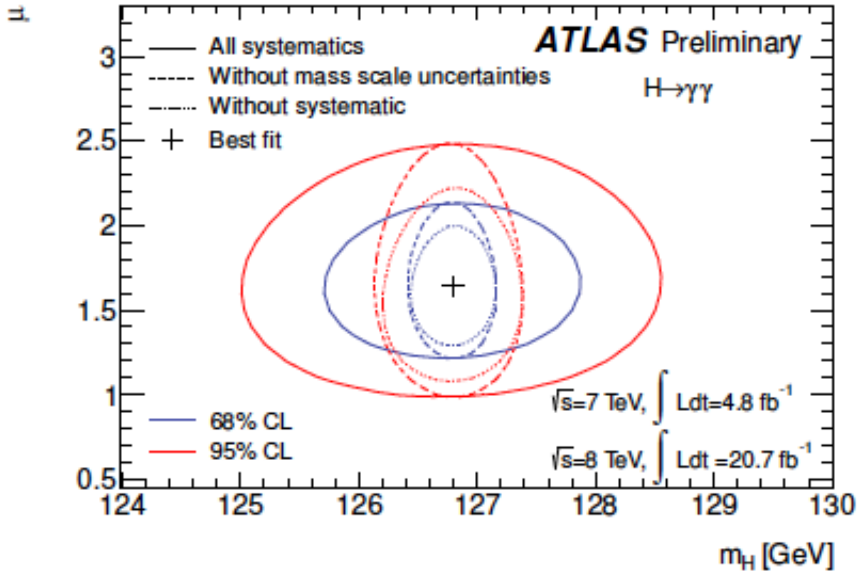


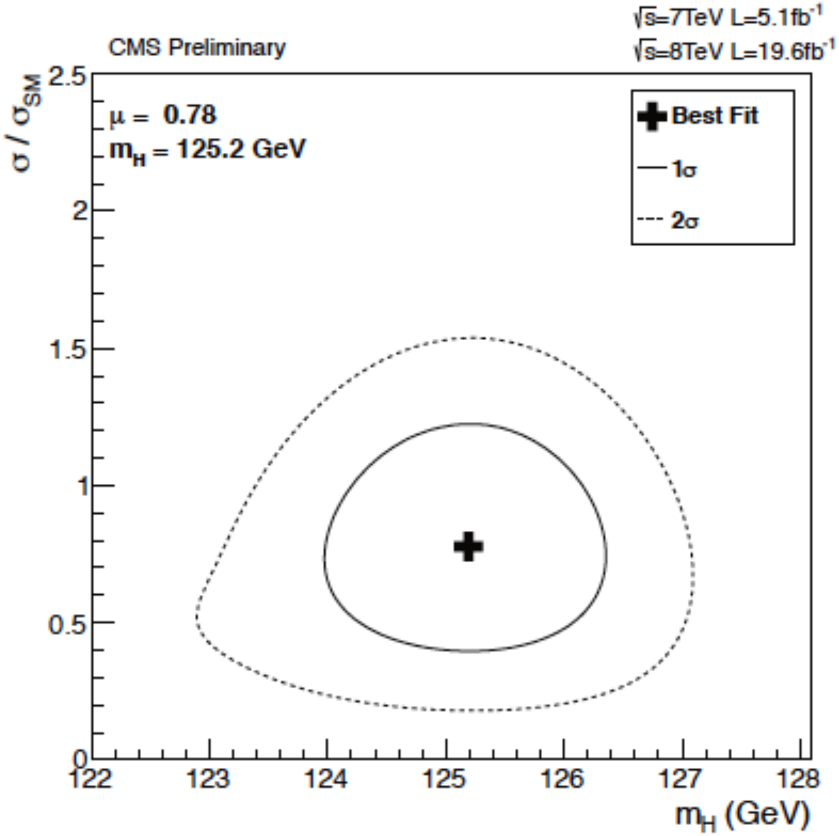
$\sqrt{s} = 7 + 8$ TeV	exp	obs	$\hat{\mu} = \sigma/\sigma_{SM}$
ATLAS no category	2.9	6.1	
ATLAS	4.1	7.4	$1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}$ @ 126.8 GeV
CMS MVA	4.2	3.2	$0.78^{+0.28}_{-0.26}$ @ 125 GeV
CMS cut-based	3.5	3.9	$1.11^{+0.32}_{-0.30}$ @ 124.5 GeV

- Comparable expected significance between ATLAS and CMS MVA analysis
- ATLAS is 2.3 standard deviations from the SM expectation
- ATLAS has worse precision on the observed $\hat{\mu}$
  - there can be an effect related to the background model and treatment of systematics
  - the best would be to compare the expected precision on $\hat{\mu}$

Results

mass



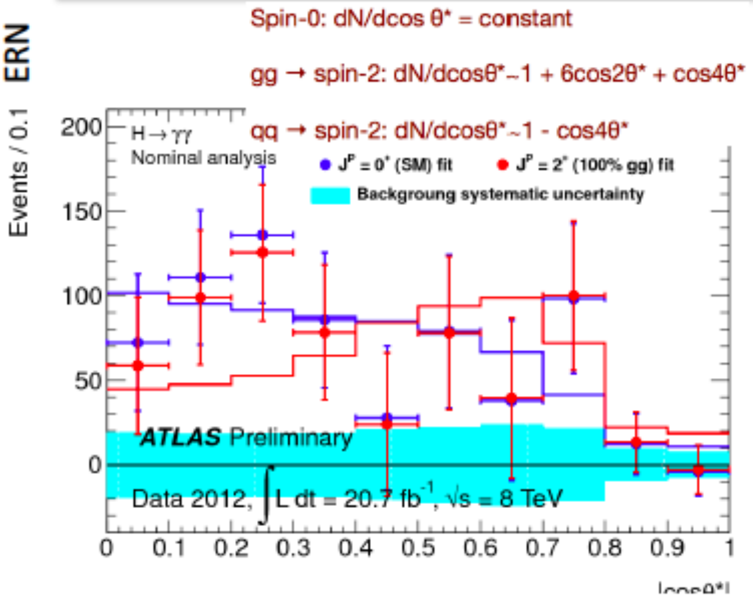


- The best-fit for the mass value is $m_H = 126.8 \pm 0.2(stat) \pm 0.7(syst)$GeV

- The best-fit for the mass value is $m_H = 125.4 \pm 0.5(stat) \pm 0.6(syst)$GeV

Comparable systematics errors

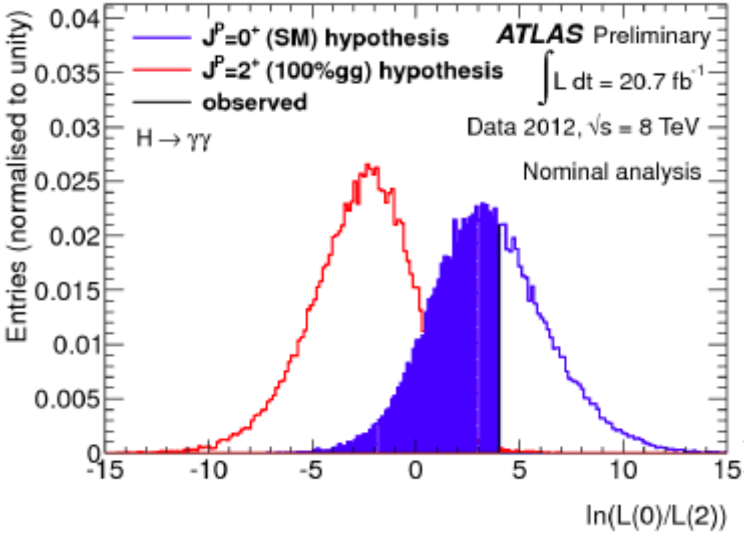
Spin measurement in H→ γ γ



- $|\cos(\theta^*)|$ used as discriminating variable
  - For spin 0 isotropic distribution before kinematic cuts

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}}\,\frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}.$$

- Signal region: 122 GeV<$m_{\gamma\gamma}$<130 GeV
- Background shape taken from data



	$f_{q\bar{q}}$ (%)	Spin hypothesis	p-values (%) expected	observed	$1 - \mathrm{CL_S}(2^+)$ (%)
2^+_m	0	0^+ 2^+	1.2 0.5	58.8 0.3	99.3
	25	0^+ 2^+	5.2 3.9	60.9 2.1	94.6
	50	0^+ 2^+	19.8 18.7	70.8 7.6	74
	75	0^+ 2^+	31.9 30.5	90.2 3.3	66
	100	0^+ 2^+	14.8 13.5	79.8 2.5	88

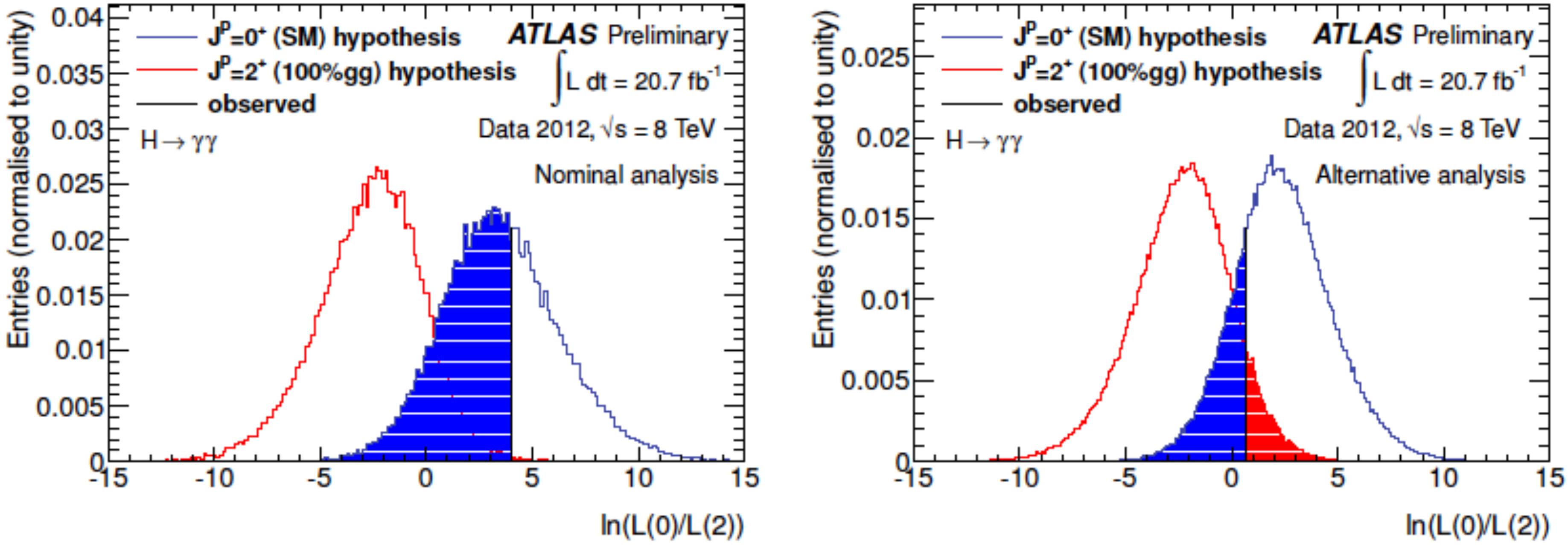
Data exclude $J^P=2^+_m$ in favor of $J^P=0^+$ at 99.3% CL

ATLAS CONF 2013-029

Results

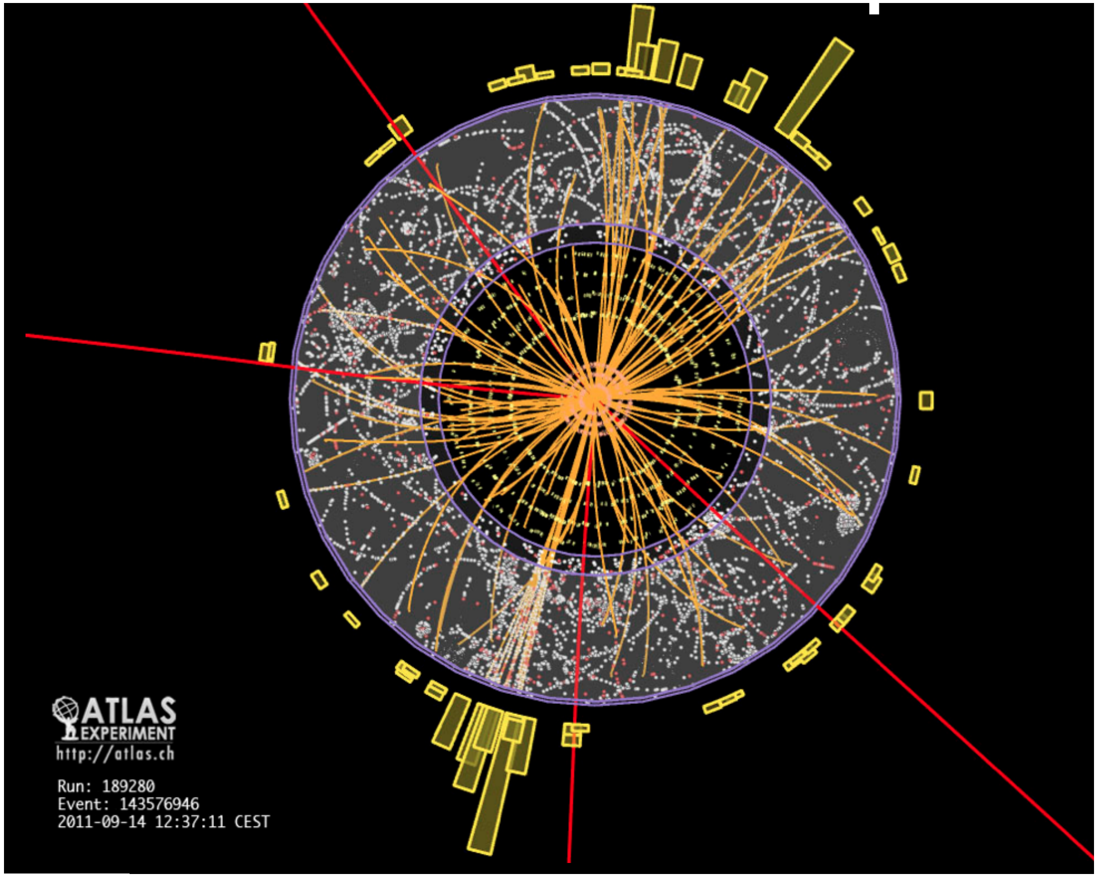
Spin (ATLAS)

- no categories, $p_T / m_{\gamma\gamma}$ cut instead of p_T to avoid correlation with $\cos(\theta^*)$
- Two methods to discriminate 0^+ / 2^+
  - bidimensional model $|\cos\theta^*| \otimes m_{\gamma\gamma}$
  - independent fit of $m_{\gamma\gamma}$ in $|\cos\theta^*|$ bins



- data compatible with 0^+
- considering 100% gluon fusion: 2^+ excluded 99.3% (89.4%) CL.

Search for the Higgs Boson in the $H \to ZZ^{(*)} \to 4l$ channel



The Golden Channel

charged leptons give the cleanest signatures:

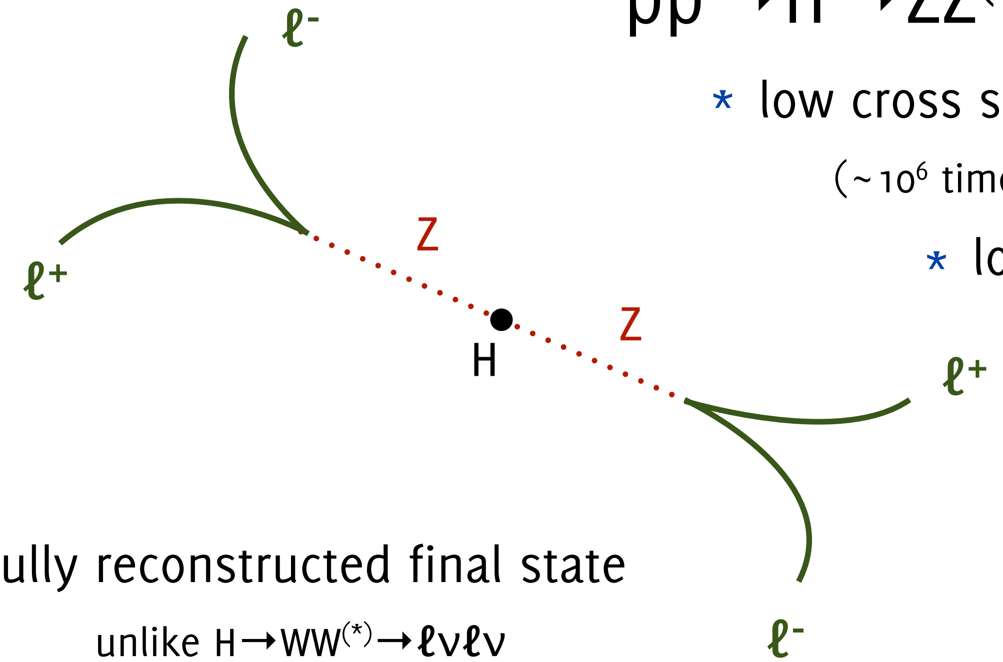
$pp \to H \to ZZ^{(*)} \to 4\ell$ [m_H=100÷600 GeV]

- low cross section: 2-5 fb

  (~10^6 times less probable than $pp \to Z \to \ell^+\ell^-$)

- low background contamination

  from other processes faking signal



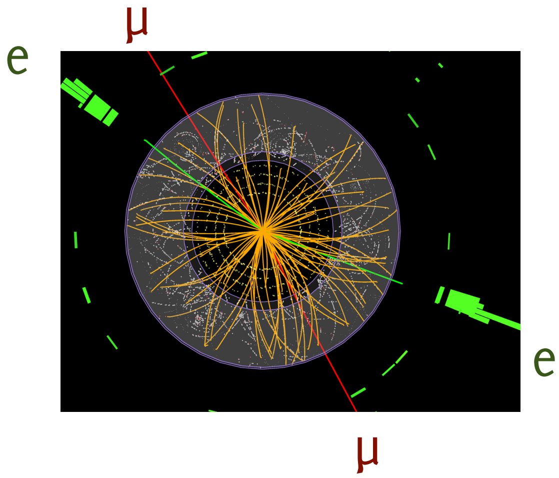
- fully reconstructed final state

  unlike $H \to WW^{(*)} \to \ell\nu\ell\nu$

- if $m_H < 2m_Z$, only one Z boson is on-shell!

  let's call it Z_1

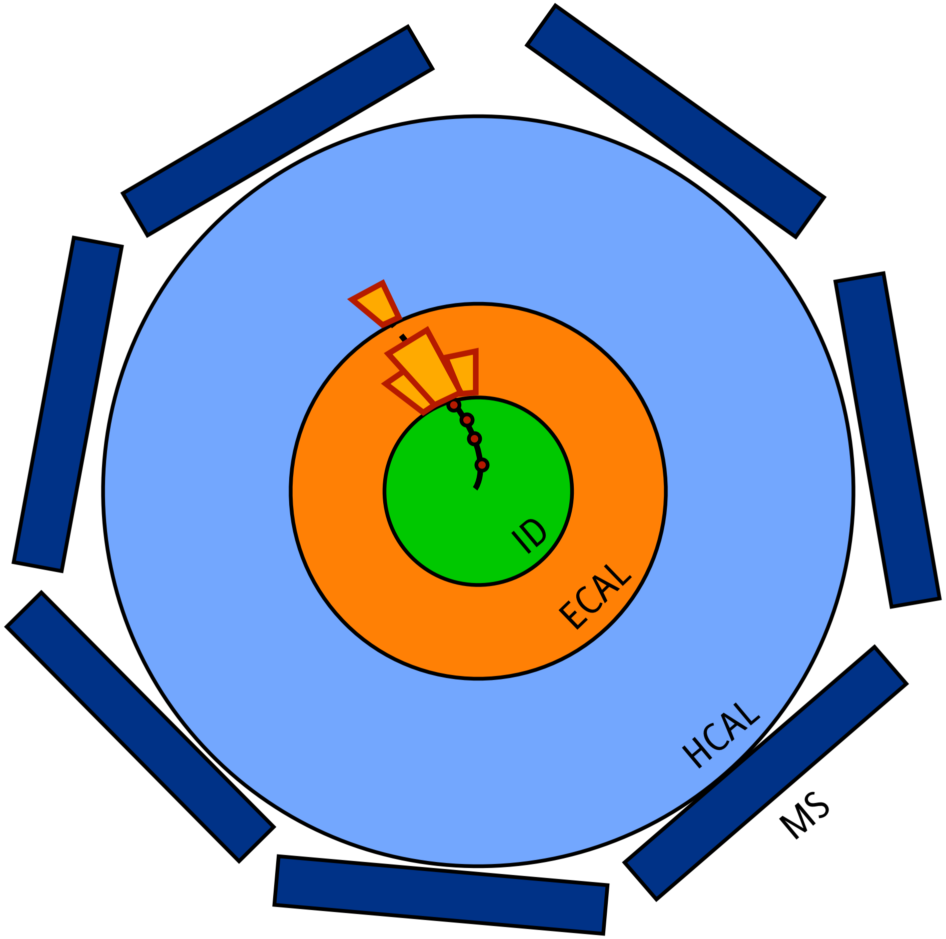
  we have two different "subchannels"



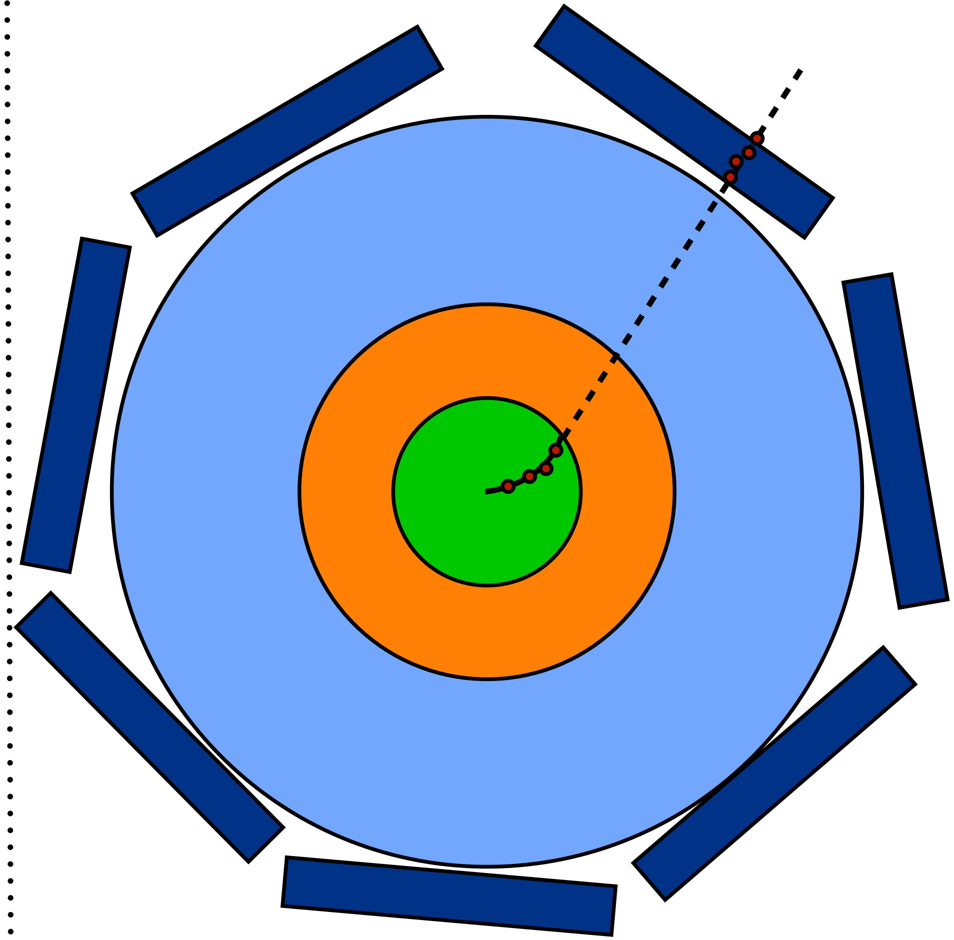
Valerio Ippolito - Search for $H \to 4\ell$ at ATLAS (May 10th, 2012)

Reconstructing leptons

ELECTRONS



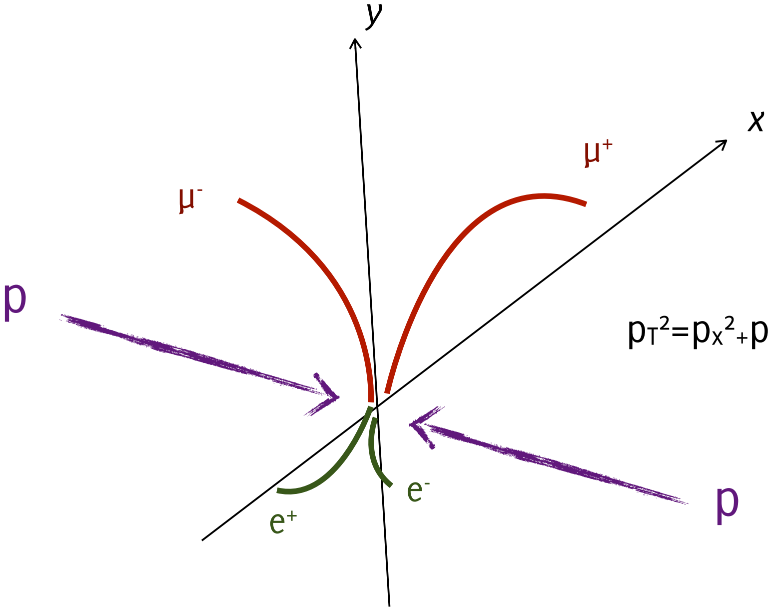
MUONS



high lepton reconstruction efficiency (~95%)

Event selection

Valerio Ippolito - Search for **H→4ℓ** at ATLAS (May 10th, 2012)



$p_T^2 = p_x^2 + p_y^2$

- ask two pairs of opposite charge leptons (e, μ)

  two with $p_T > 20$ GeV, two with $p_T > 7$ GeV

  separate in 4μ, 2e2μ, 4e final states

- build two Z candidates

  call Z1 the one with mass closest to the Z mass

- make sure Z1 is an on-shell Z

  $m_{Z1} = m_Z \pm 15$ GeV

- make a m_H-dependent cut on Z2

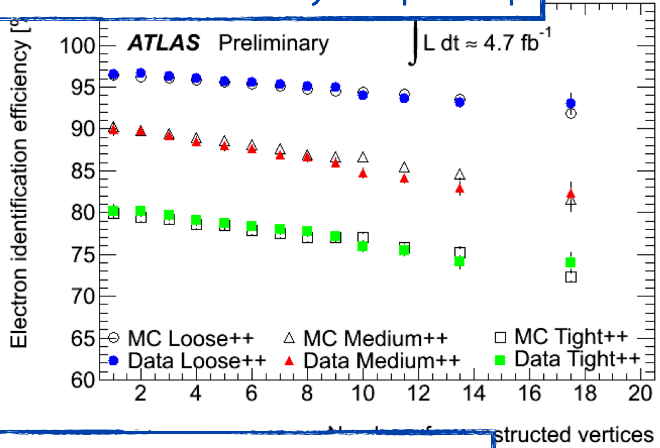
  $m_{Z2} > 15 \div 60$ GeV

overall ~15% efficiency on a simulated Higgs sample with $m_H = 125$ GeV

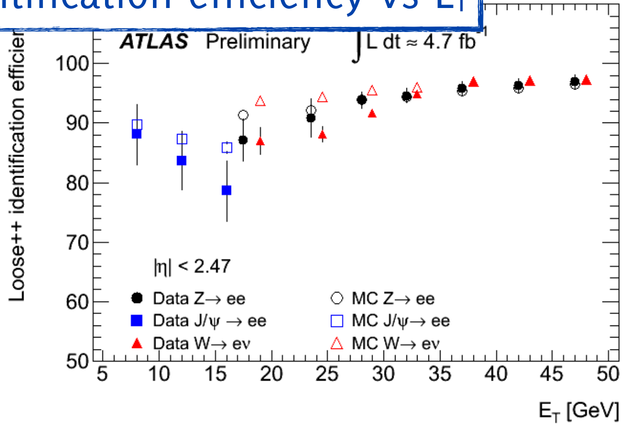
Lepton reconstruction performances

ELECTRONS

identification efficiency vs pile-up

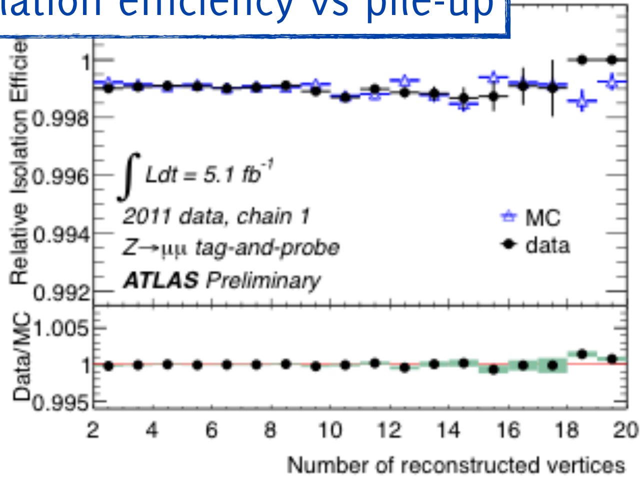


identification efficiency vs E_T

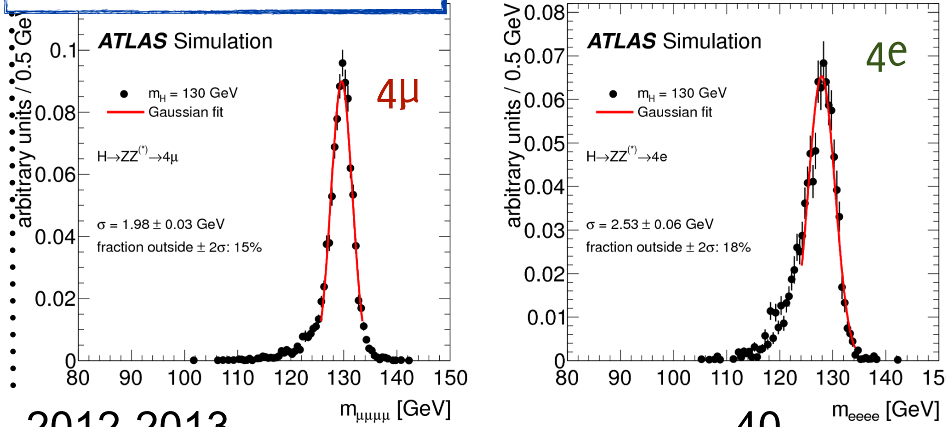


MUONS

isolation efficiency vs pile-up



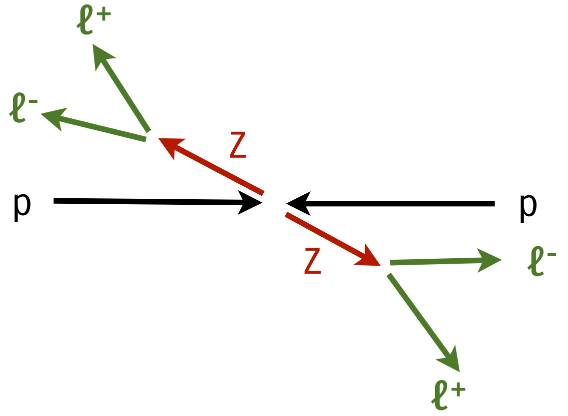
Higgs mass resolution



Background processes

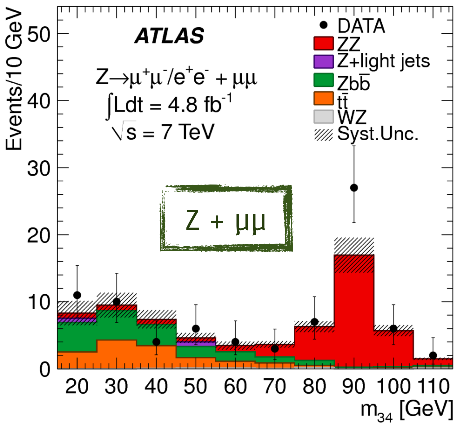
irreducible background

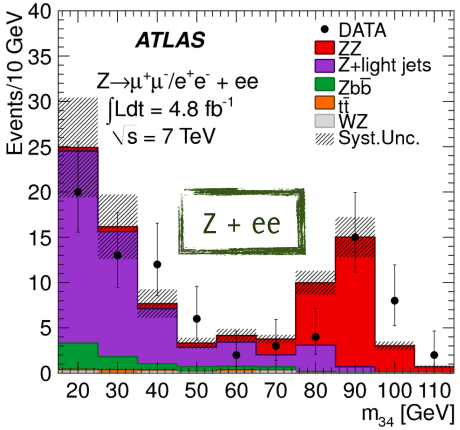
- $pp \rightarrow ZZ^{(*)} \rightarrow \mathbf{4\ell}$ [MC]
- same final state as signal
- dominant at high m_H

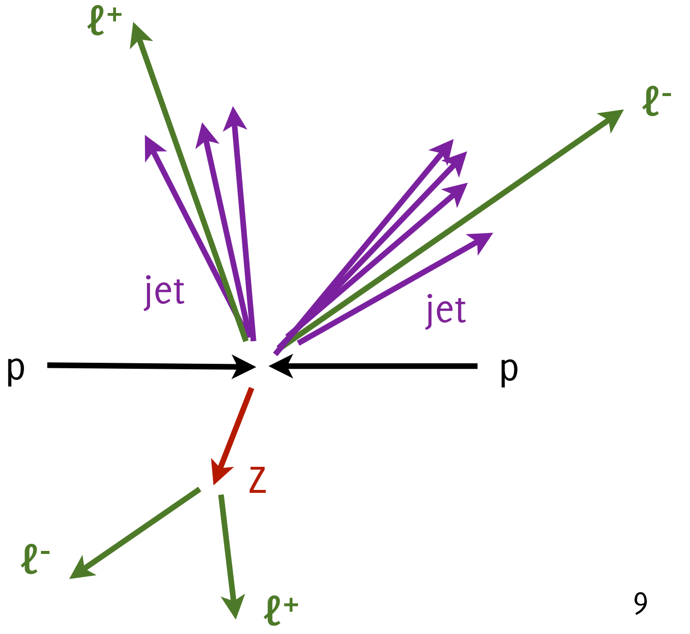


reducible backgrounds

- Z+bb, Z+jets, tt [data, MC]
- relevant contribution at low m_H
- rejection: ask leptons to be isolated







H→ZZ→4ℓ: analysis strategy

Reconstruct 4 leptons in final state (electrons and muons)

p_T thresholds:

20, 15, 10, 7 (6 for muons)

20, 15, 7, 7 (5 for muons)

$M_{\ell\ell}$ cuts:

Closest di-lepton to M_Z^{PDG} (Z_1)

$50 < M_{Z1}$ [GeV/c^2] < 106

$40 < M_{Z1}$ [GeV/c^2] < 120

Remaining di-lepton (Z_2)

$12 < M_{Z2}$ [GeV/c^2] < 115

$12 < M_{Z2}$ [GeV/c^2] < 120

Isolation

Track Iso less than 15% ($\Delta R<0.2$)

Calo Iso less than 20% ($\Delta R<0.2$)

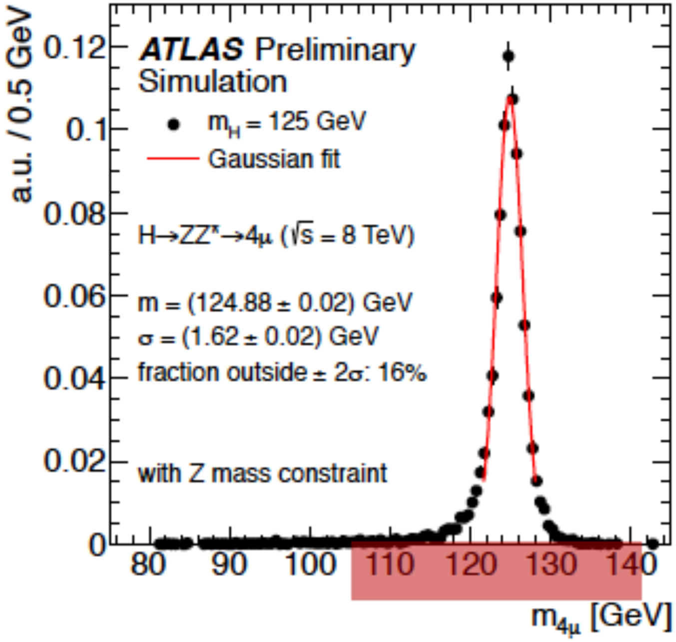
Isolation less than 40% ($\Delta R<0.4$)

(charged and neutral particles from PF)

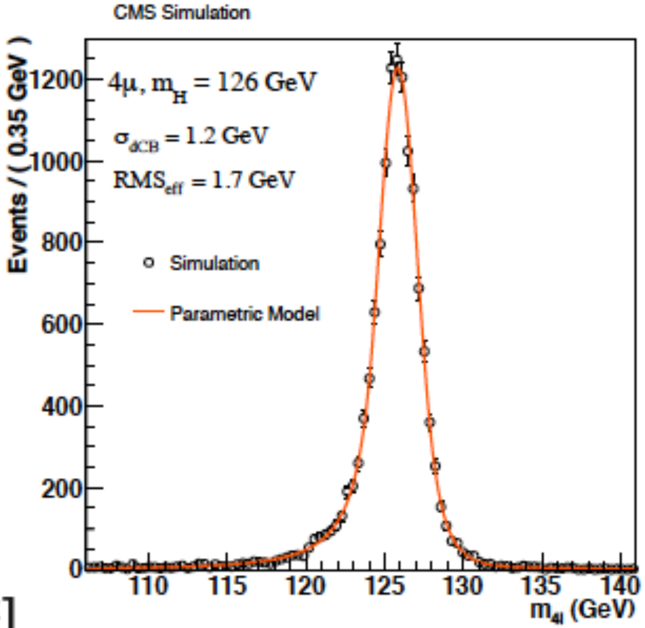
M_{4l} resolution

Mass constraint on Z_1 : refit momentum parameters of leptons, using covariance matrix and Z line shape

No refitting, strong magnetic field provides great resolution and M_{Z1} directly used in definition of K_D



ATLAS-CONF-2013-013



CMS-PAS-HIG-13-002

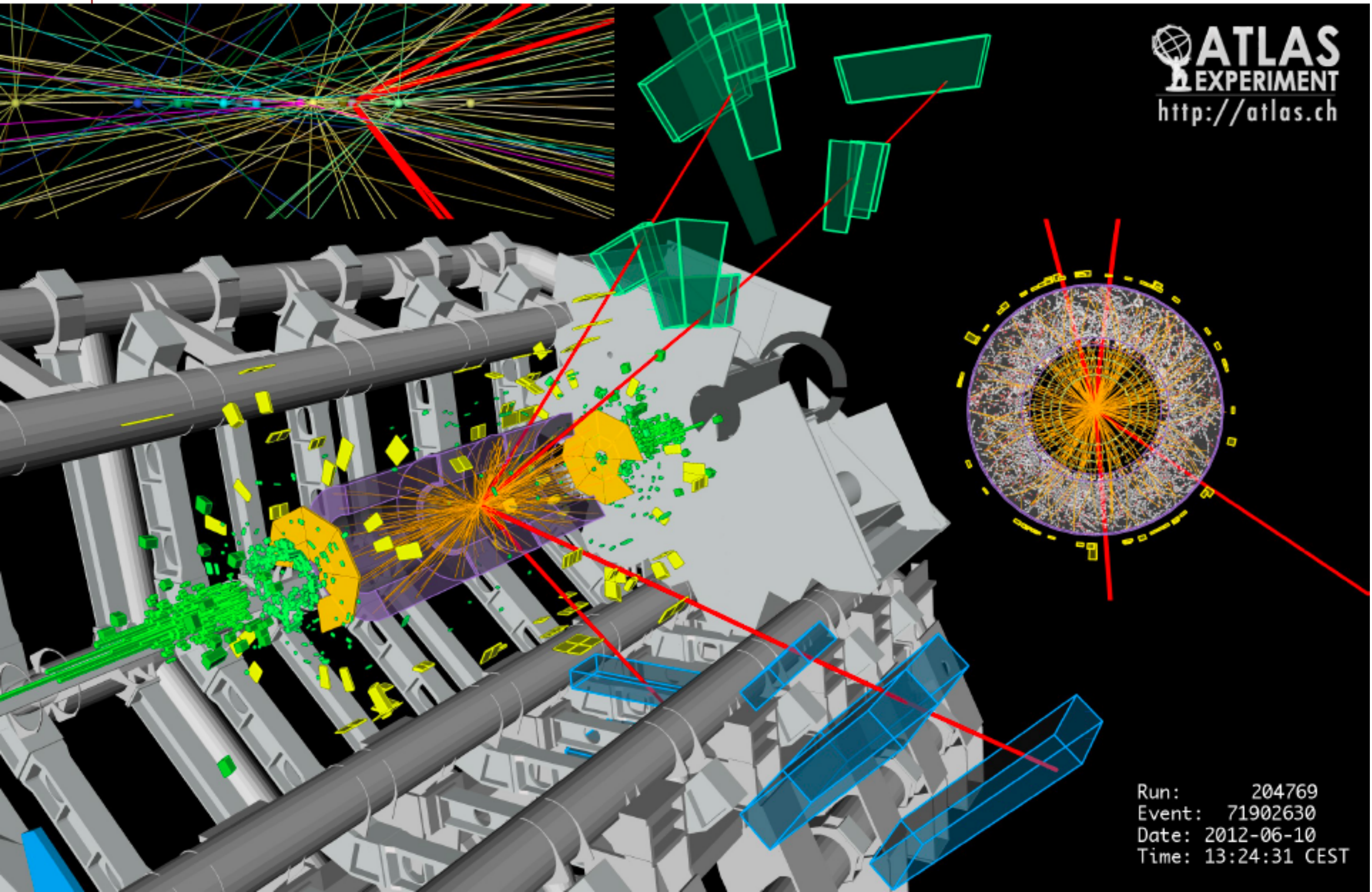
Resolution [GeV/c²]

4μ	2μ2e	4e
1.6	1.9	2.4

4μ	2μ2e	4e
1.2	1.7	2.0

4μ candidate

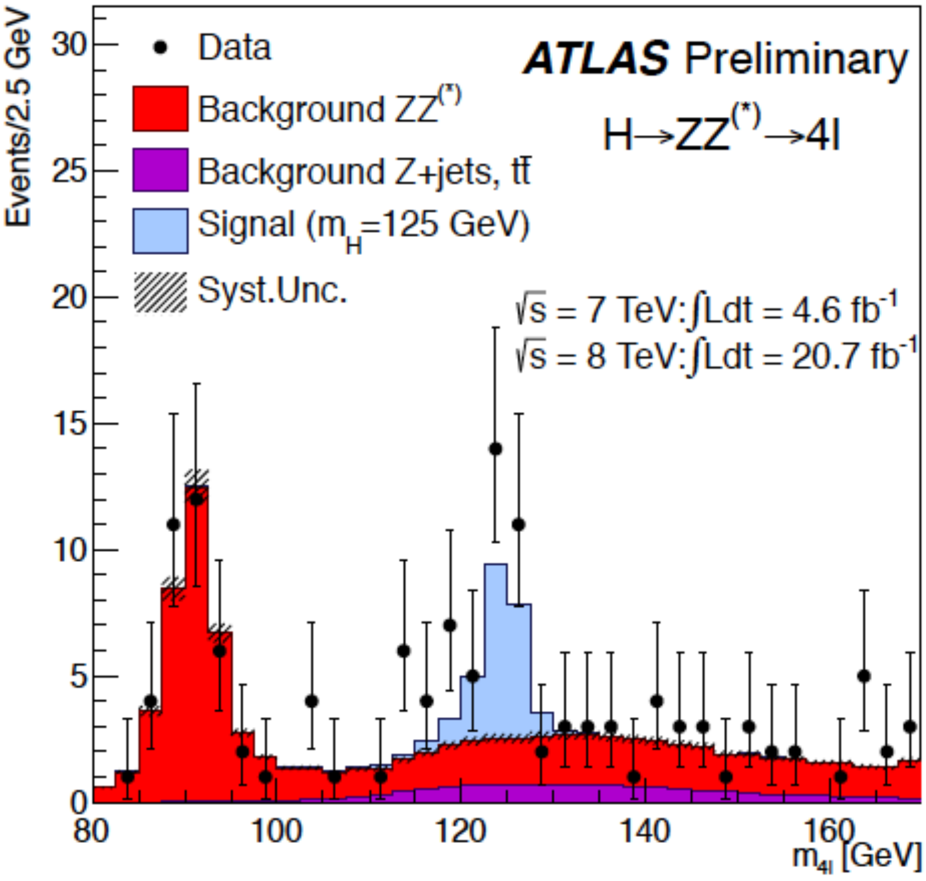
pT (muons)= 36.1, 47.5, 26.4, 71 .7GeV
m12= 86.3 GeV, m34= 31.6 GeV
m4μ= 125.1 GeV
15 reconstructed vertices



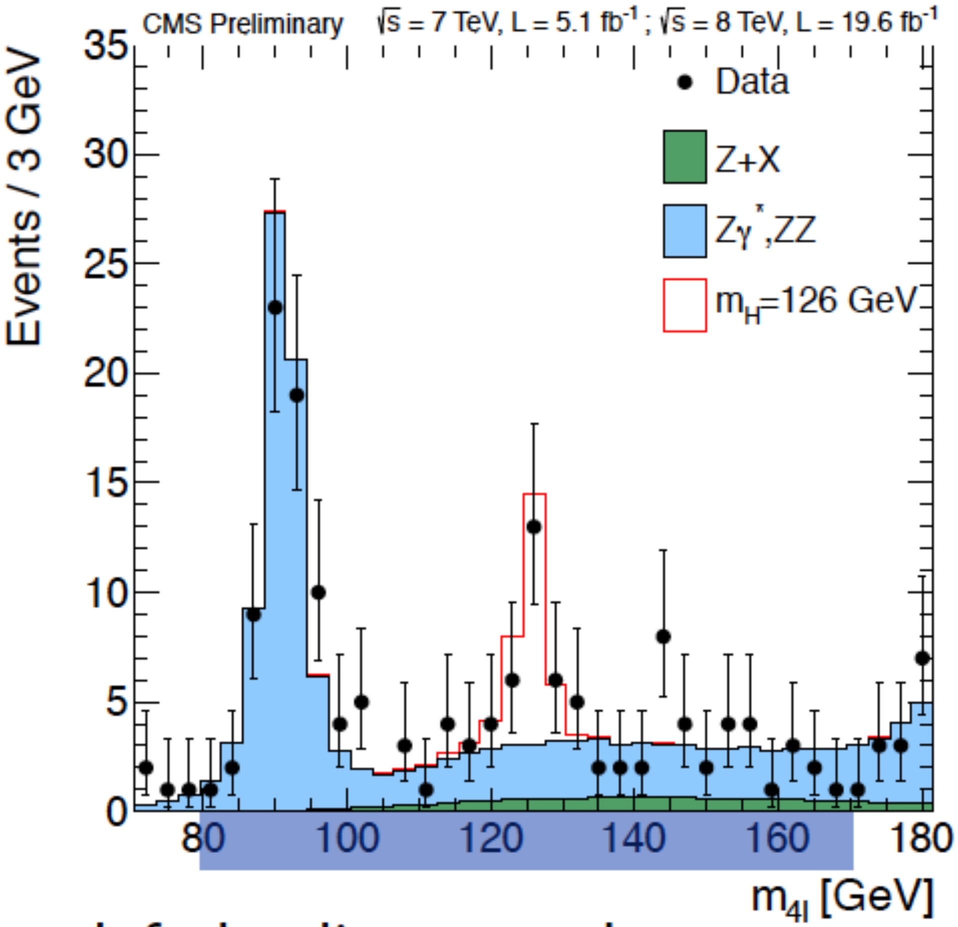
Results of event selection

	ATLAS (25.3 fb^{-1})	CMS (24.7 fb^{-1})	
M_H range [GeV/c^2]	100-160	110-160	
Signal (M_H=125)	6.8 ± 0.7	6.8 ± 0.8	**4μ**
ZZ	14.6 ± 0.6	13.8 ± 1.0	
Reducible Bkg.	2.1 ± 0.6	1.6 ± 0.6	
Total expected	**23.5 ± 1.1**	**22.2 ± 1.4**	
Observed	**35**	**23**	
Signal (M_H=125)	8.1 ± 0.9	8.9 ± 1.0	**2e2μ**
ZZ	17.2 ± 0.9	18.1 ± 1.3	
Reducible Bkg.	8.5 ± 0.2	4.0 ± 1.6	
Total expected	**33.8 ± 1.3**	**31.0 ± 2.3**	
Observed	**33**	**32**	
Signal (M_H=125)	3.3 ± 0.4	3.5 ± 0.5	**4e**
ZZ	6.2 ± 0.5	6.6 ± 0.8	
Reducible Bkg.	4.5 ± 0.8	2.5 ± 1.0	
Total expected	**14.0 ± 1.0**	**12.6 ± 1.4**	
Observed	**15**	**16**	

ATLAS-CONF-2013-013

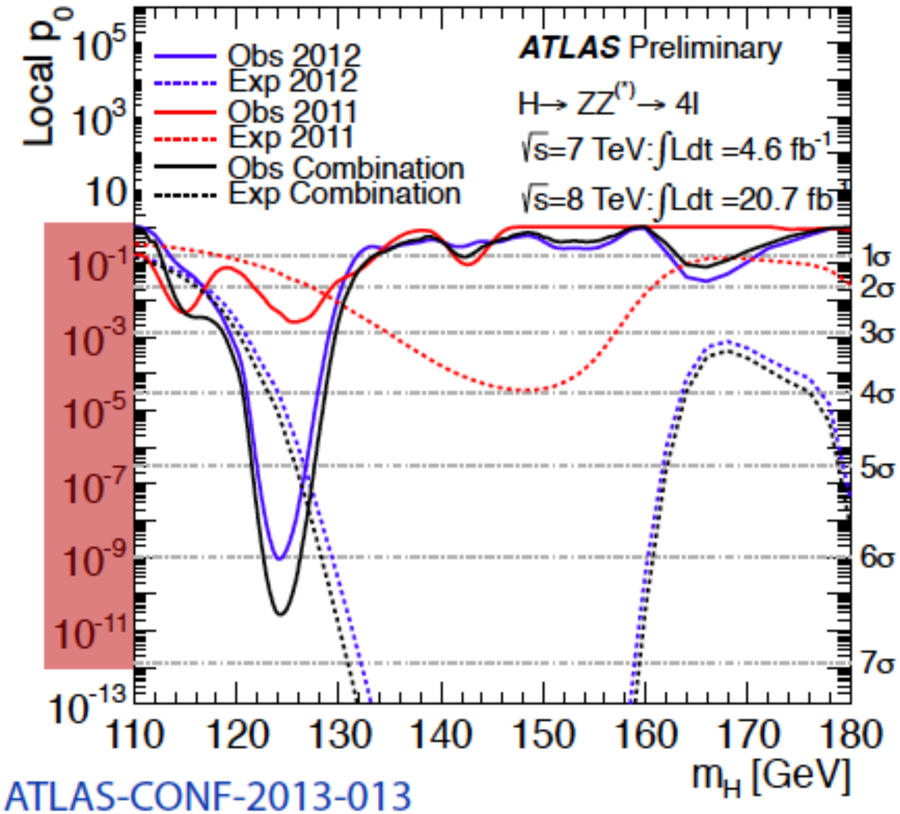


CMS-PAS-HIG-13-002

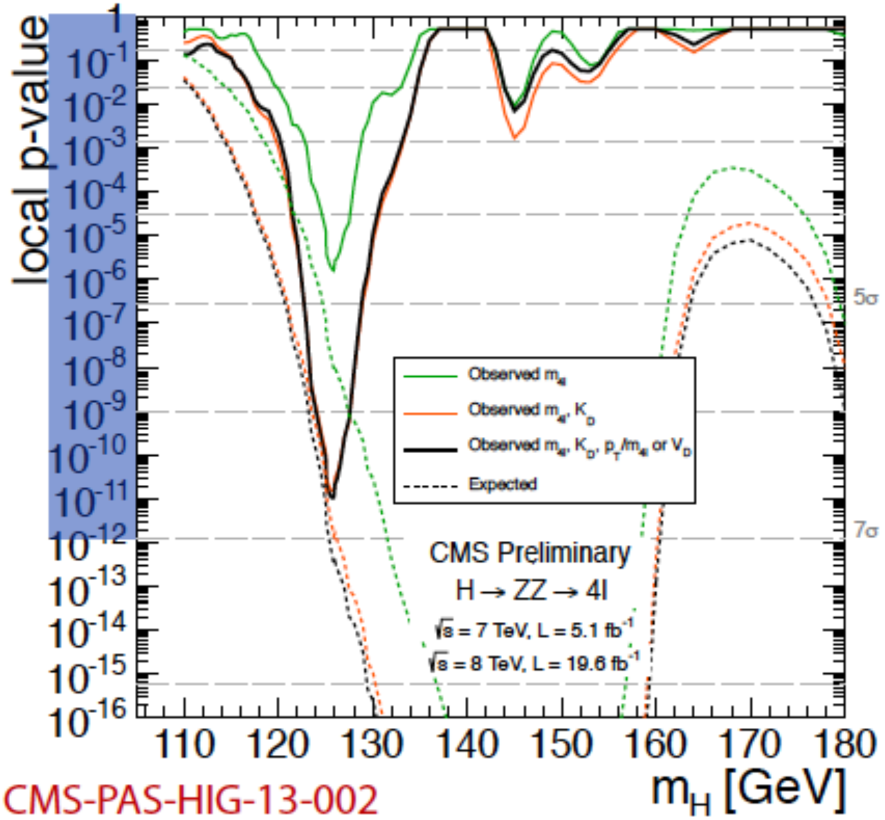


Focus on H→ZZ→4ℓ: we have left the discovery phase and we are now entering the measurement phase!

Significance



ATLAS-CONF-2013-013



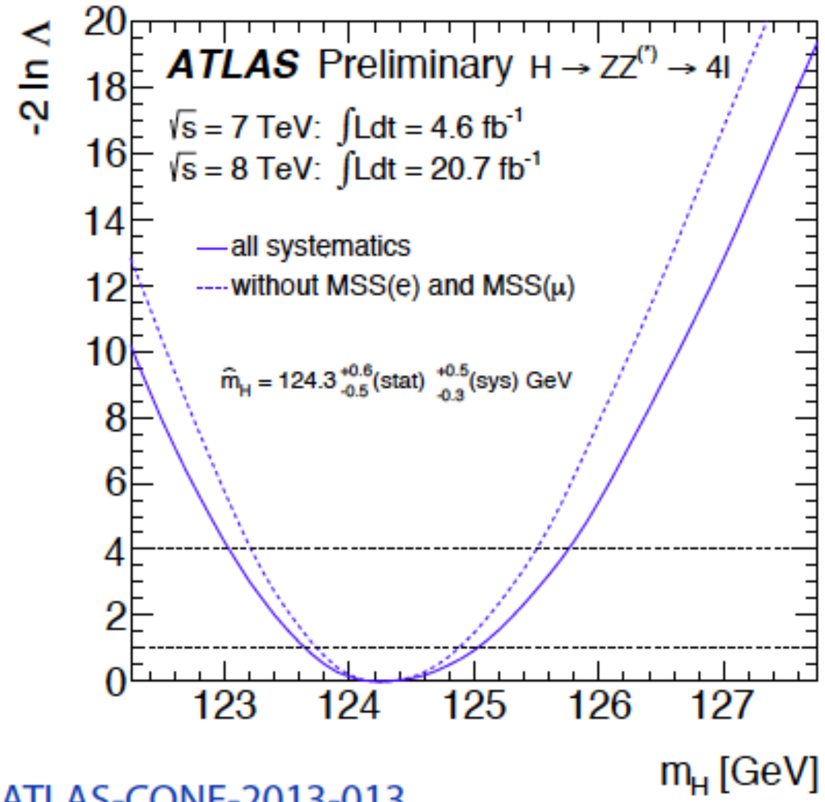
CMS-PAS-HIG-13-002

	Expected*	Observed
only M_{4l}	4.4 σ	6.6 σ

	Expected*	Observed
only M_{4l}	5.6 σ	4.7 σ
with K_D and categories	7.2 σ	6.7 σ

*evaluated at minimum p_0

Mass measurement



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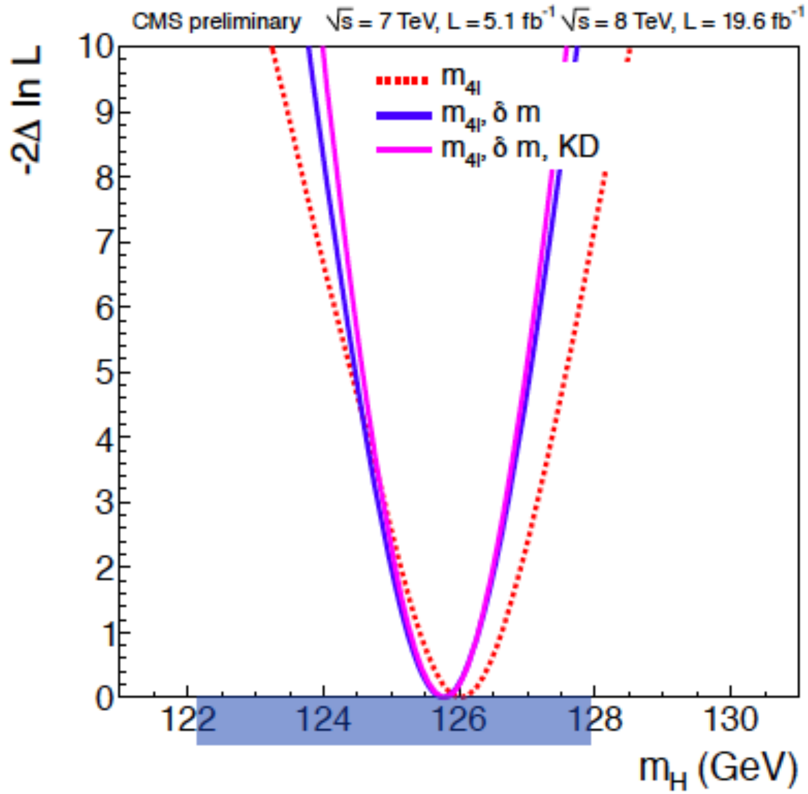


CMS-PAS-HIG-13-002

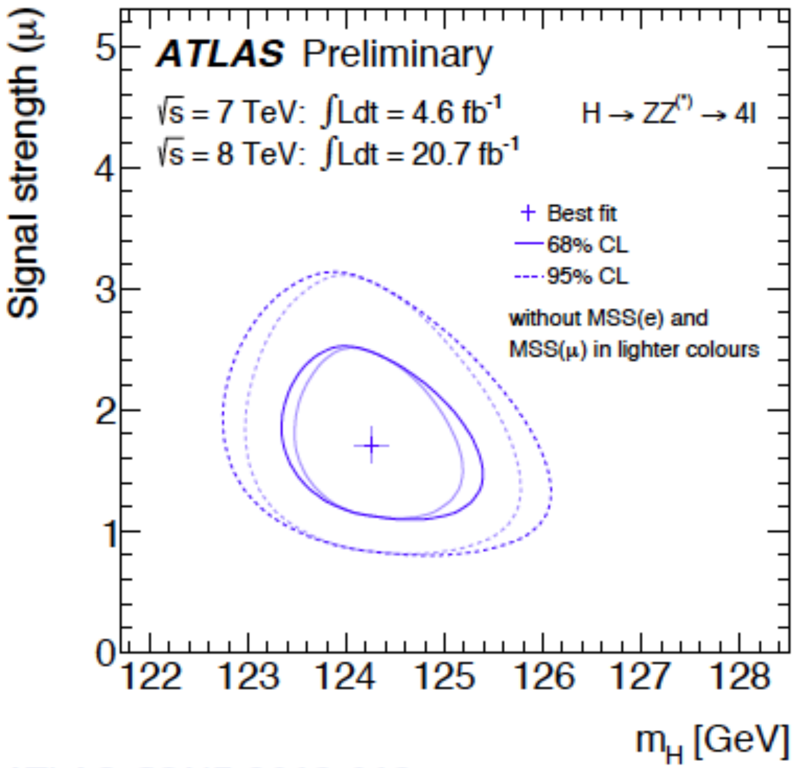
Inclusive fit to M_{4l}

Inclusive fit to M_{4l}, K_D and per-event errors

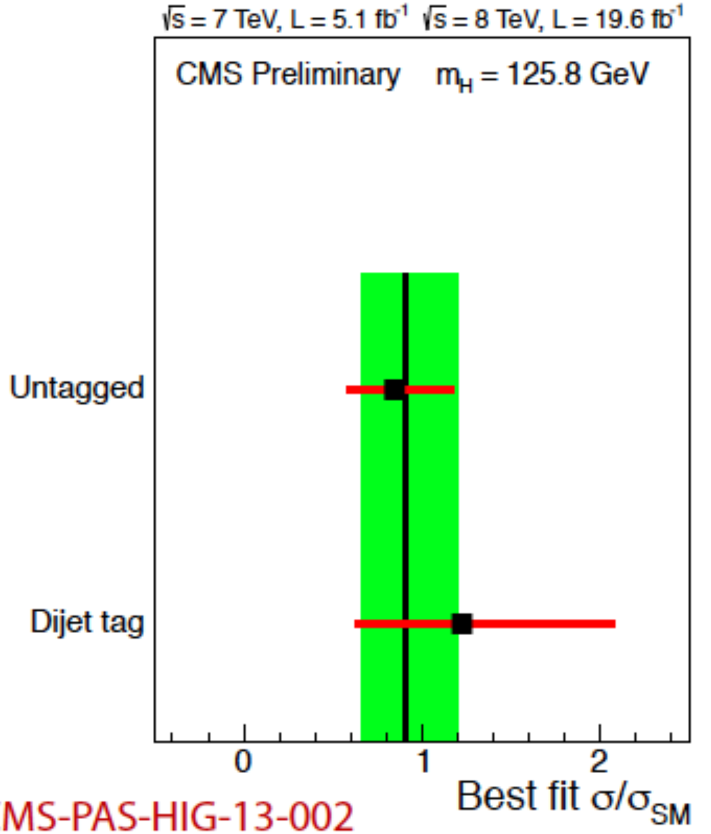
$M_H = 124.3\,^{+0.6}_{-0.5}\,^{+0.5}_{-0.3}$ GeV/c^2

$M_H = 125.8 \pm 0.5 \pm 0.2$ GeV/c^2

Signal strength



ATLAS-CONF-2013-013



CMS-PAS-HIG-13-002

Inclusive fit to M_{4l}

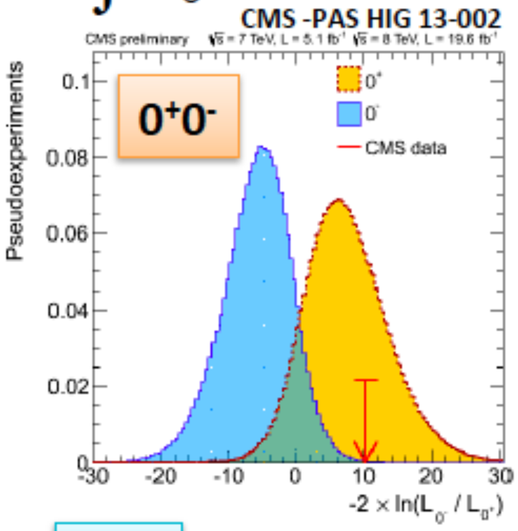
Inclusive fit to M_{4l}, K_D and p_T/M_{4l} (V_D) for Category 1 (2)

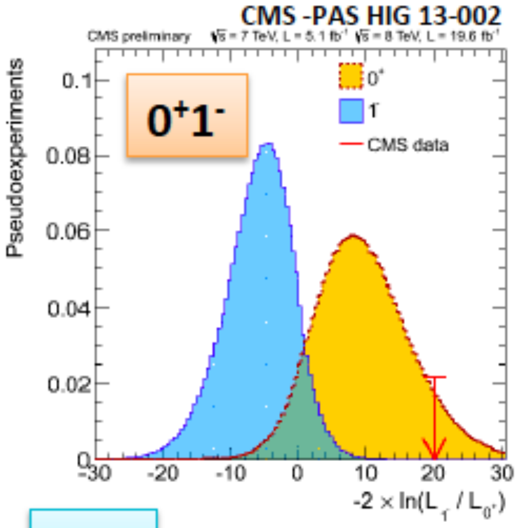
μ at 124.3 GeV/c² : $1.7^{+0.5}_{-0.4}$

μ at 125.8 GeV/c² : $0.91^{+0.3}_{-0.24}$

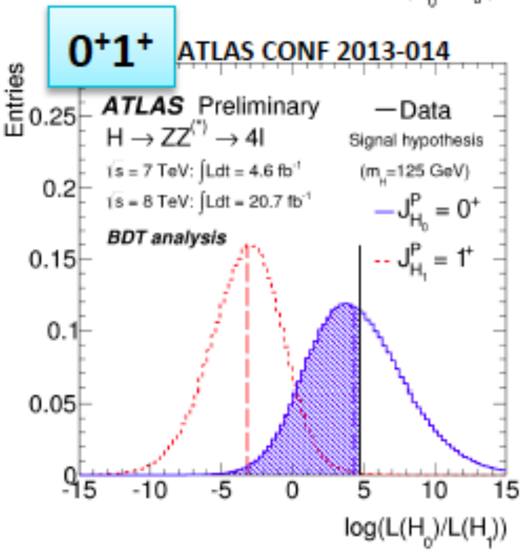
Spin parity measurement in H→ ZZ*→4l

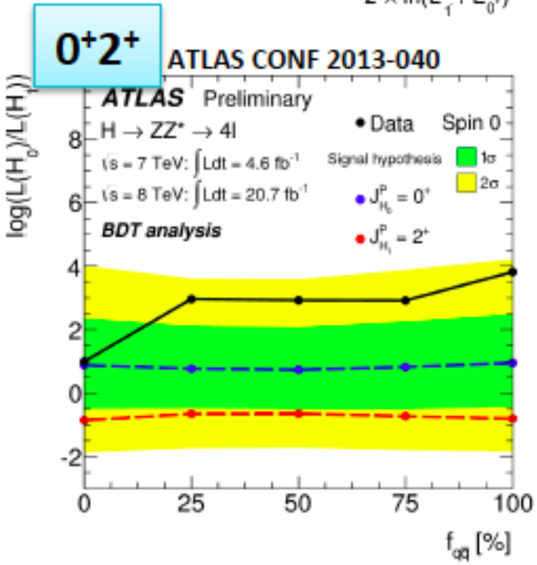
- **Observed exclusion for alternative hypotheses in favor of Standard Model $J^P=0^+$**





J^P	CL_s (CMS)	CL_s (ATLAS)
0^-	0.16%	0.4%
0^+_h	8.1%	-
2^+_{mgg}	1.5%	16.9%
2^+_{mqq}	<0.1%	11.5%
1^-	<0.1%	3.1%
1^+	<0.1%	0.2%





- **Data prefers $J^P=0^+$**
- **$J^P = 0^-, 1^+, 1^-, 2^+_{mgg}, 2^+_{mqq}$ excluded at >95% CL**

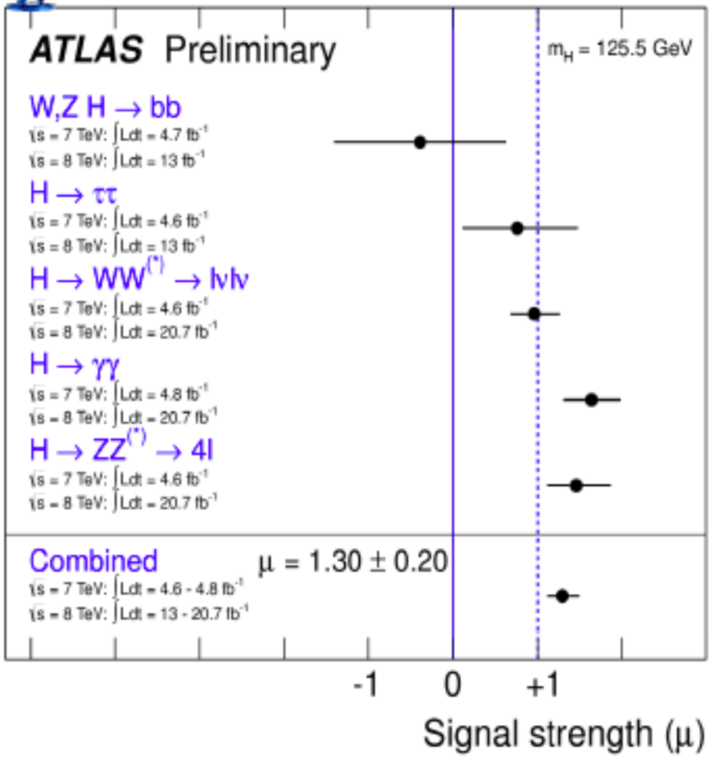
Results

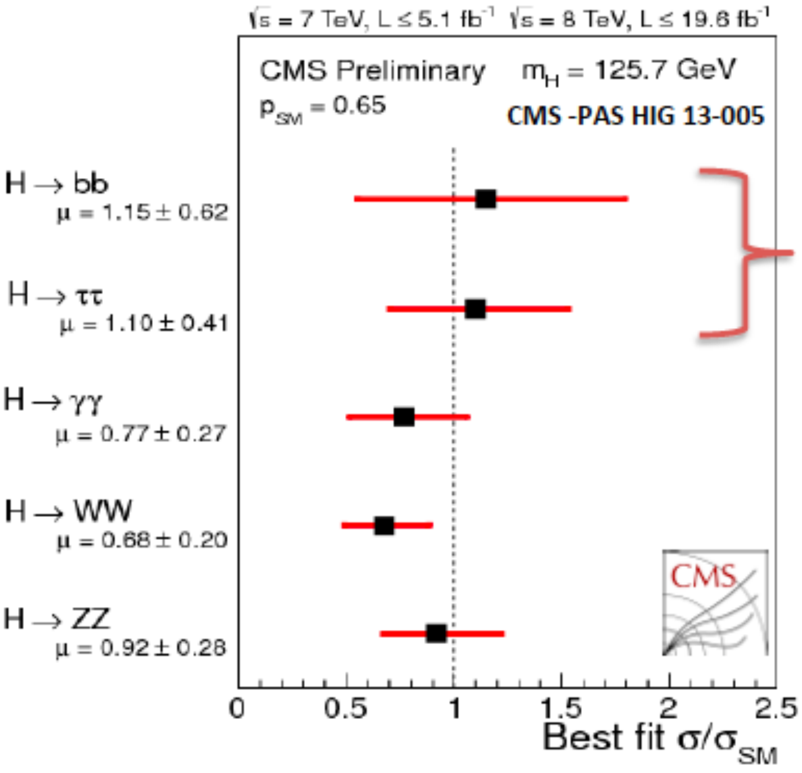
	ATLAS (BDT)				ATLAS (j^P MELA)			
j^P	expected	obs. 0^+	obs. j^P	CL_s	expected	obs. 0^+	obs. j^P	CL_s
0^-	2.7σ	0.5σ	2.2σ	0.022	3.1σ	0.2σ	2.8σ	0.004
1^-	2.7σ	1.0σ	1.6σ	0.060	3.1σ	1.2σ	1.9σ	0.031
1^+	2.9σ	-0.1σ	3.1σ	0.002	2.7σ	0.0σ	2.8σ	0.006
2^+_{mgg}	1.3σ	-0.1σ	1.4σ	0.168	1.5σ	0.3σ	1.2σ	0.182
2^-	2.5σ	1.8σ	0.7σ	0.258	2.7σ	1.4σ	1.2σ	0.116

	CMS			
j^P	expected	obs. 0^+	obs. j^P	CL_s
0^-	2.6σ	0.5σ	3.3σ	0.0016
0^+_m	1.7σ	0.0σ	1.7σ	0.081
1^-	2.8σ	1.4σ	>4.0σ	<0.001
1^+	2.3σ	1.7σ	>4.0σ	<0.001
2^+_{mgg}	1.8σ	0.8σ	2.7σ	0.015
2^+_{mqq}	1.7σ	1.8σ	4.0σ	<0.001

Signal strength by decay mode

ATLAS CONF 2013-034

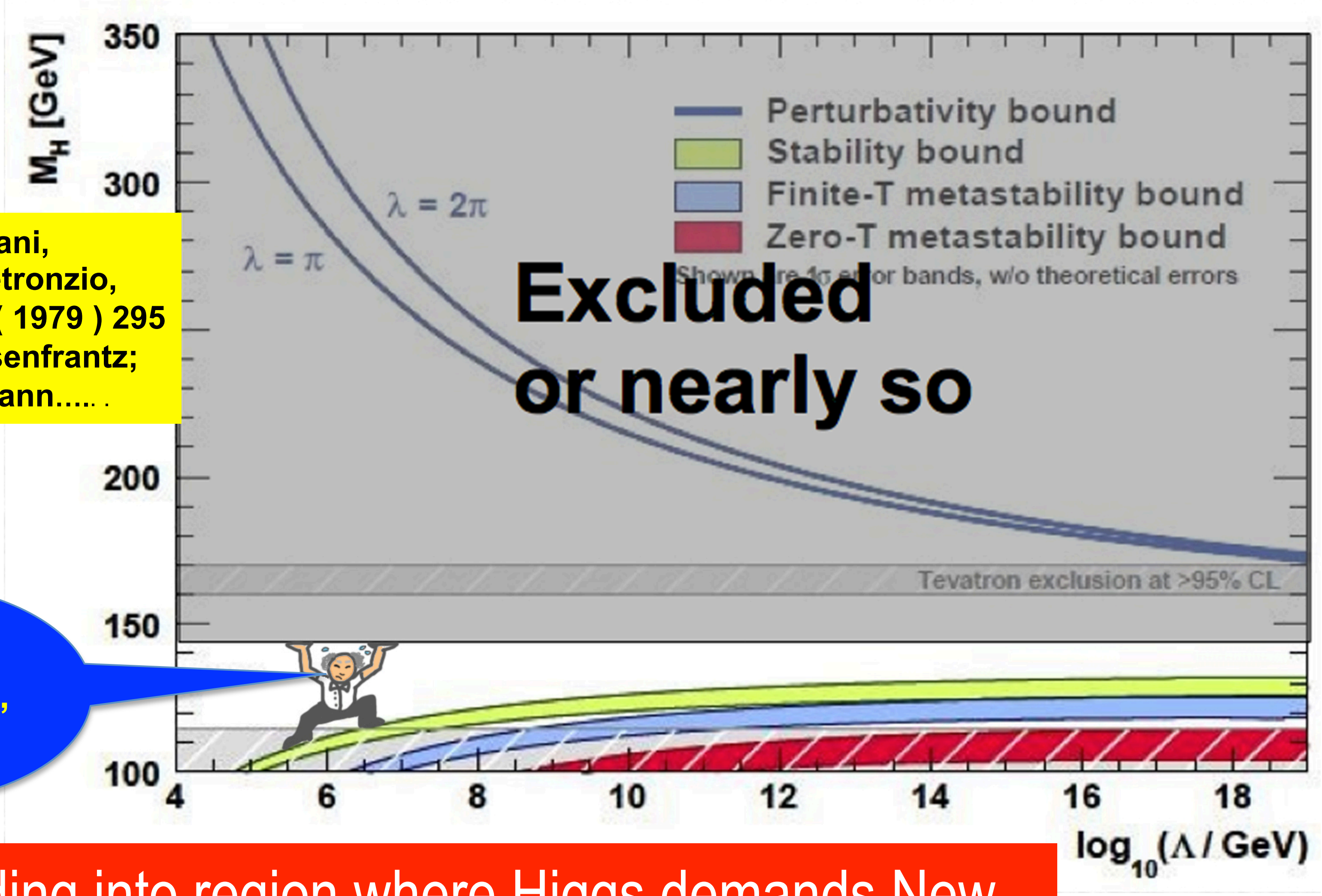




3.4σ signif. for H->ff comb.

- Fair compatibility between the different channels.
- Lower p-value in ATLAS result, 8% mostly driven by overall μ value $\mu = 1.3 \pm 0.2$.

Higgs Stability



Excluded or nearly so

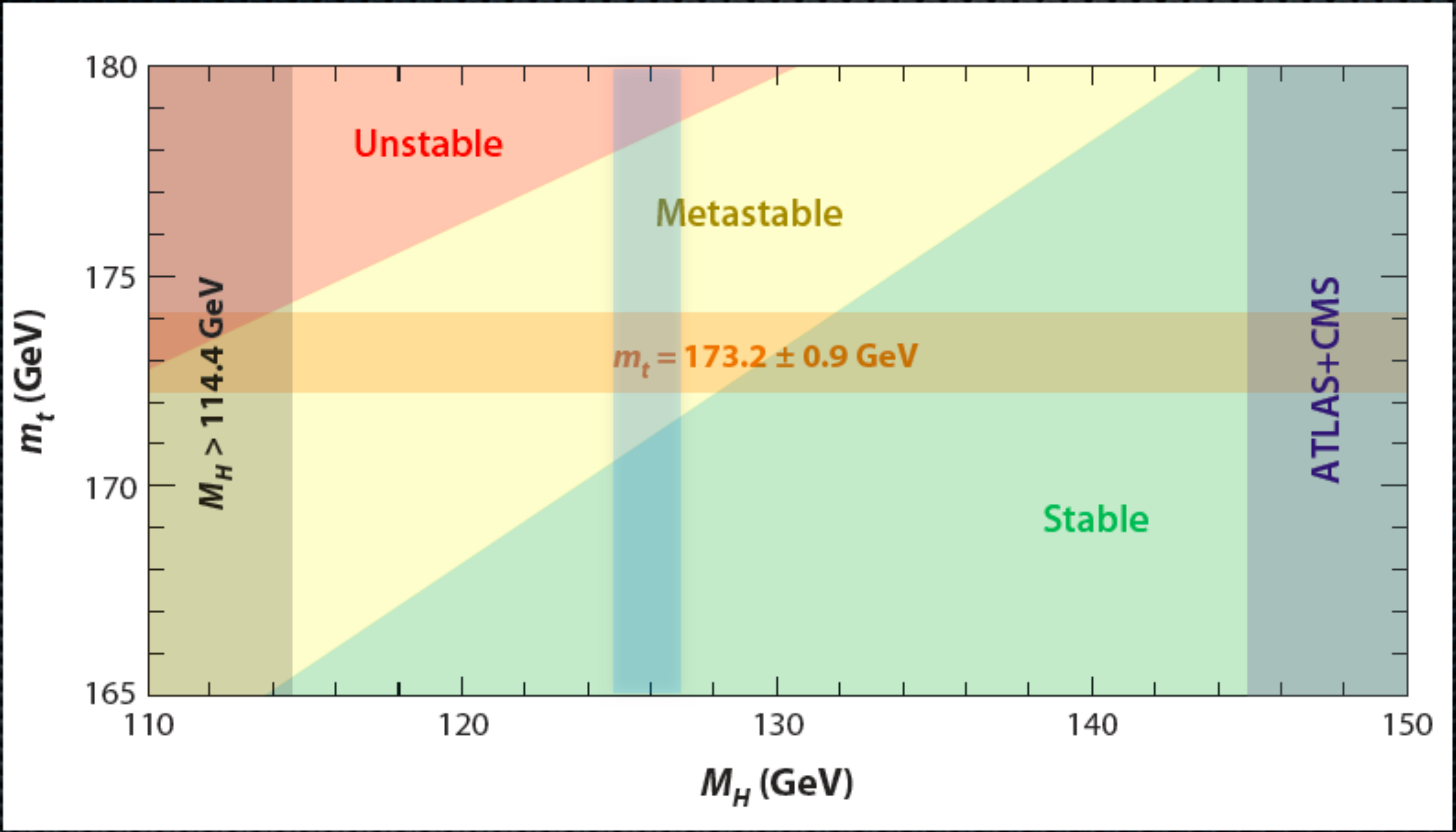
N. Cabibbo, L. Maiani, G. Parisi and R.Petronzio, Nucl. Phys. B 158 (1979) 295
Sher; Lindner; Hasenfrantz; Hambey, Riesselmann….. .

Pretty tight stable region, isn't it ?!

Are we heading into region where Higgs demands New Physics ?

We will know very soon !!

Might we live in a metastable vacuum?



LHC

- LHC ha preso dati dal 2010 alla fine del 2012 raggiungendo una luminosita' di picco di 7.5 10^{33} cm^{-2} s^{-1}, con una statistica finale di ≅ 24 fb^{-1}

- L' acceleratore e i due rivelatori hanno avuto prestazioni di assoluta eccezione

- La scoperta epocale del bosone di Higgs, annunciata al mondo il 4 luglio del 2012, ci prepara ad altre scoperte che ci auguriamo a loro volta epocali

Bibliografia

http://cms.web.cern.ch/org/cms-papers-and-results

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults