Scalar boson into gamma gamma at LHC :

From the design of the experiments to the measurement of the properties

Louis Fayard
LAL-Orsay

♥ **Introduction**

♥ **Short history of scalar boson and LHC**

♥ **History of detectors and of $H \rightarrow \gamma\gamma$**
specificities of detectors relevant to $H \rightarrow \gamma\gamma$

♥ **Discovery**

♥ **Properties**

♥ **Conclusions**

Backup (references)

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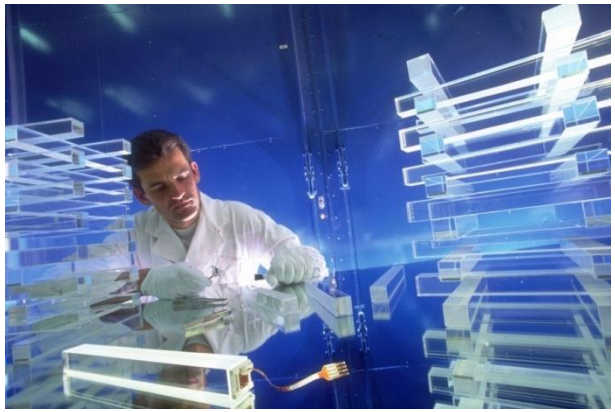
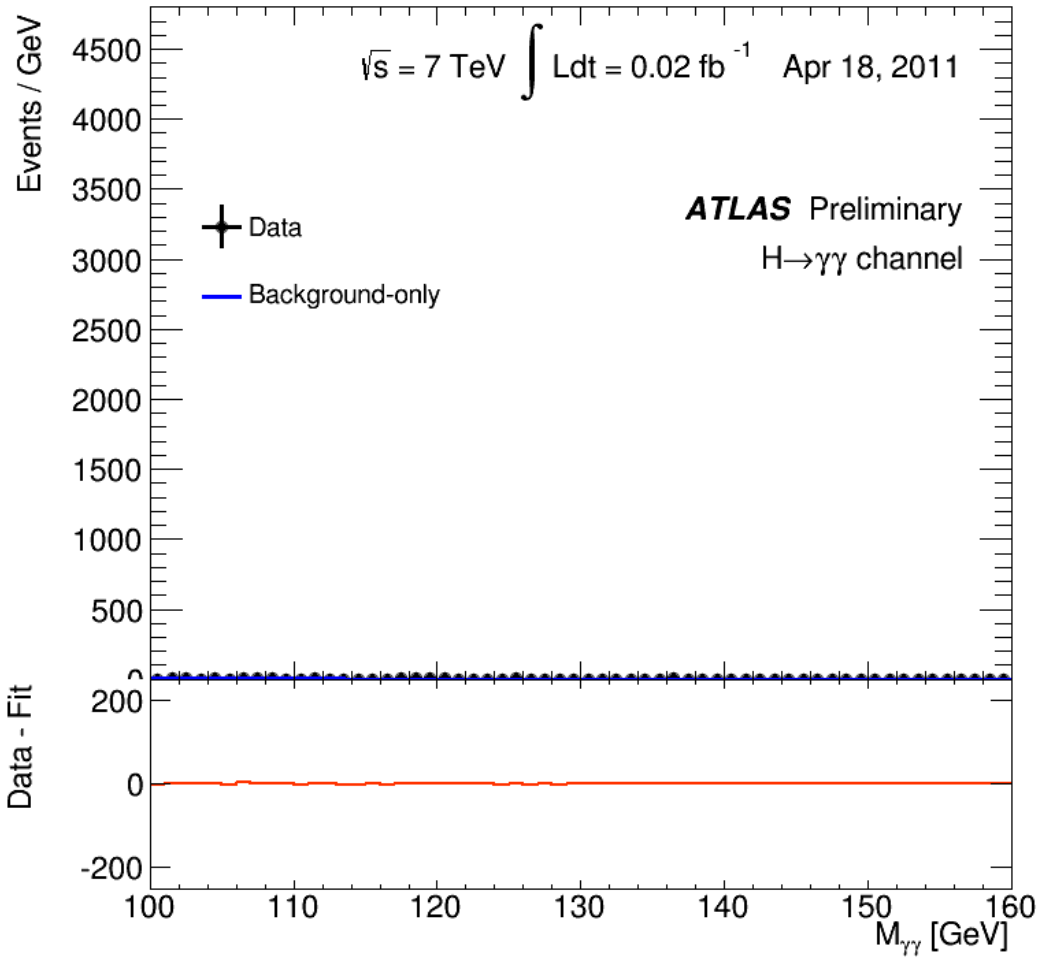
Backup (references)

from detectors



to the discovery



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♥ **Short history of scalar boson and LHC**

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Backup (references)

1950 Ginzburg-Landau *(Meissner-Ochsenfeld effect → London penetration length ~W mass*
→ Pippard coherence length ~ H mass)

1959 Nambu

1960 Goldstone

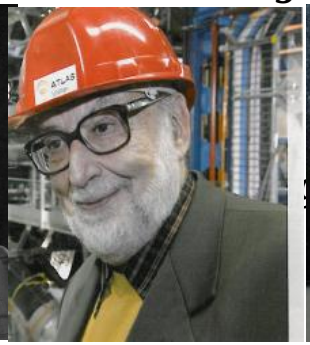
1961 Schwinger

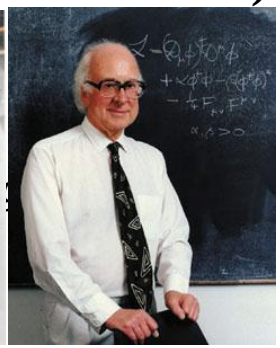
1962 Anderson

1964 Brout, Englert, Higgs, Guralnik,Hagen,Kibble

1967 Weinberg, Salam Faddeev,Popov

1970 Glashow, Iliopoulos,
Maiani, 't H





1983 Rubbia, van

1984

1989 constructic
beginning c

1992 LOI of 'la

1994 TP of ATL

1995 *discovery c*

1996 approval c

1998 approval c

1999 ATLAS Pl

2006 CMS Phys

2008 ATLAS *Expected Performa*

2010 start-up at 3.5 + 3.5 TeV

2012 4th July discovery of boson

2013 boson like properties

particles of mass $\sqrt{-2\mu_0^2}$

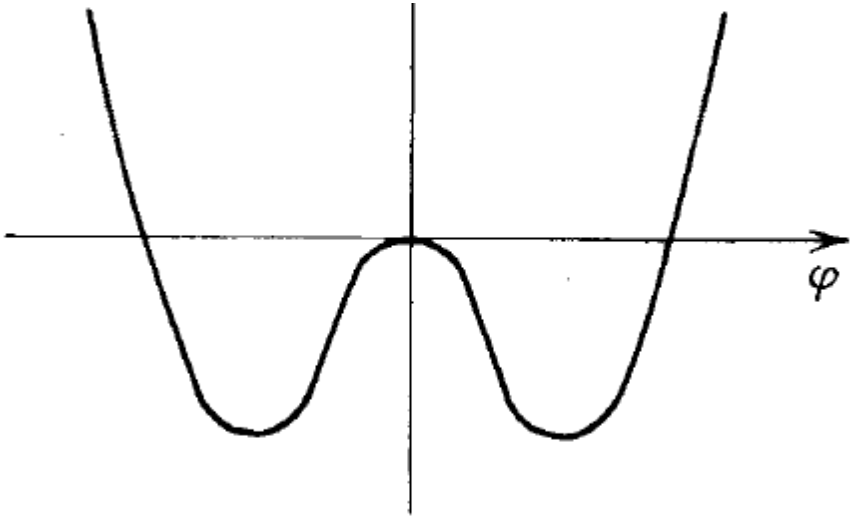
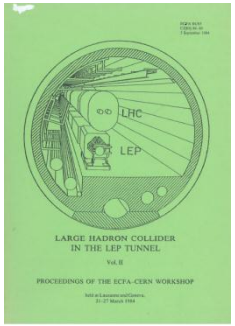


Fig. 7.

$$\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4$$

very of W and Z at CERN

Lausanne



ALICE)

)

2008

10th september 2008 : first beams around
19th september 2008 : incident

14 months of major repairs and consolidation
New Quench Protection system

2009

20th november 2009 : first beams around (*again*)
december 2009 : collisions at 2.36 TeV cms

January 2010 : decided scenario 2010-11 7 TeV cms
instead of 14 TeV

2010

30th march 2010 : first collisions at 7 TeV cms
august 2010 : luminosity of 10^{31} cm^{-2} s^{-1}

2011

may 2011 : luminosity > 10^{33} cm^{-2} s^{-1}
november 2011 : integrated luminosity ~ 5 fb^{-1}
13th december 2011 : first 'signal' around 126 GeV

2012

march 2012 : start again at 8 TeV
4th July 2012 : evidence for a new boson
(*integrated luminosity ~ 6 fb^{-1}*)

2013

(Standard-Model) boson-like properties

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Backup (references)

H → γ γ (historical mode)

Photon decay modes of the intermediate mass Higgs

ECFA Higgs working group

C.Seez and T. Virdee

L. DiLella, R. Kleiss, Z. Kunszt and W. J.Stirling

Presented at the LHC Workshop, Aachen, 4 - 9 October 1990
by C. Seez, Imperial College, London.

CERN 90-10
ECFA 90-133
Volume II
3 December 1990

A report is given of studies of:
(a) H -> γγ (work done by C. Seez and T. Virdee)
(b) W H -> γγ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range (90< $m_{\gamma\gamma}$<150 GeV/c^2).
The study of the two photon decay mode is described in detail.

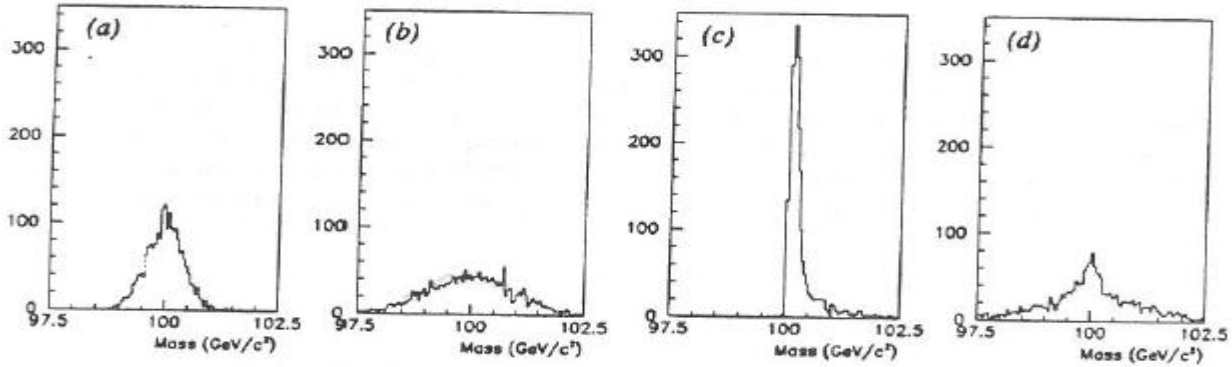
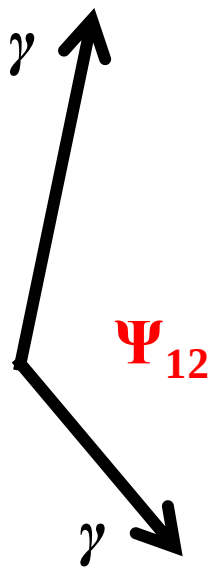
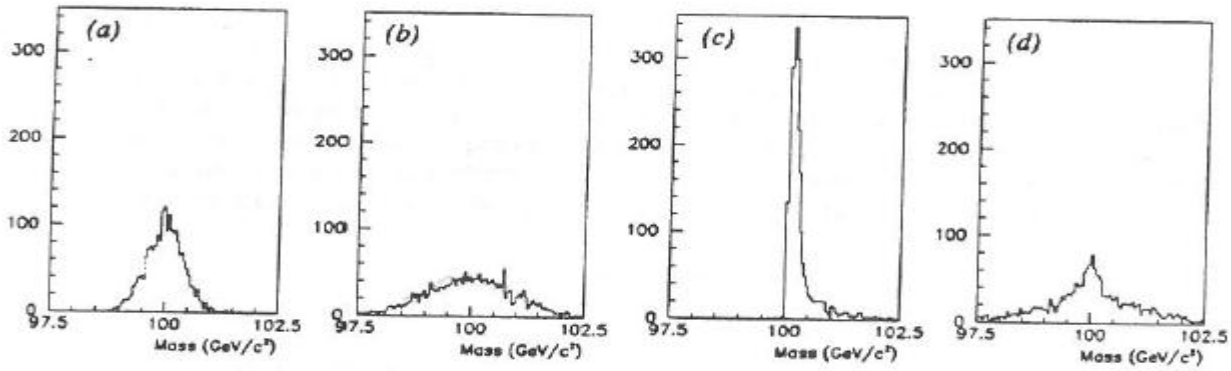


Figure 4: Reconstructed mass plots for Higgs boson, m_H=100GeV/c^2
(a) smeared by: calorimeter energy resolution of $\Delta E/E=2\%/\sqrt{E}\oplus 0.5\%$
(b) smeared by: calorimeter energy resolution of $\Delta E/E=7\%/\sqrt{E}\oplus 1.0\%$
(c) smeared by: pileup energy from, on average, 10 interactions
(d) smeared by: loss of knowledge of the vertex position (σ_{vtx}=5.5 cm)

C.Seez J.Virdee G.Unal

was studied at the LHC
for more than 20 years
(and even before at the SSC)





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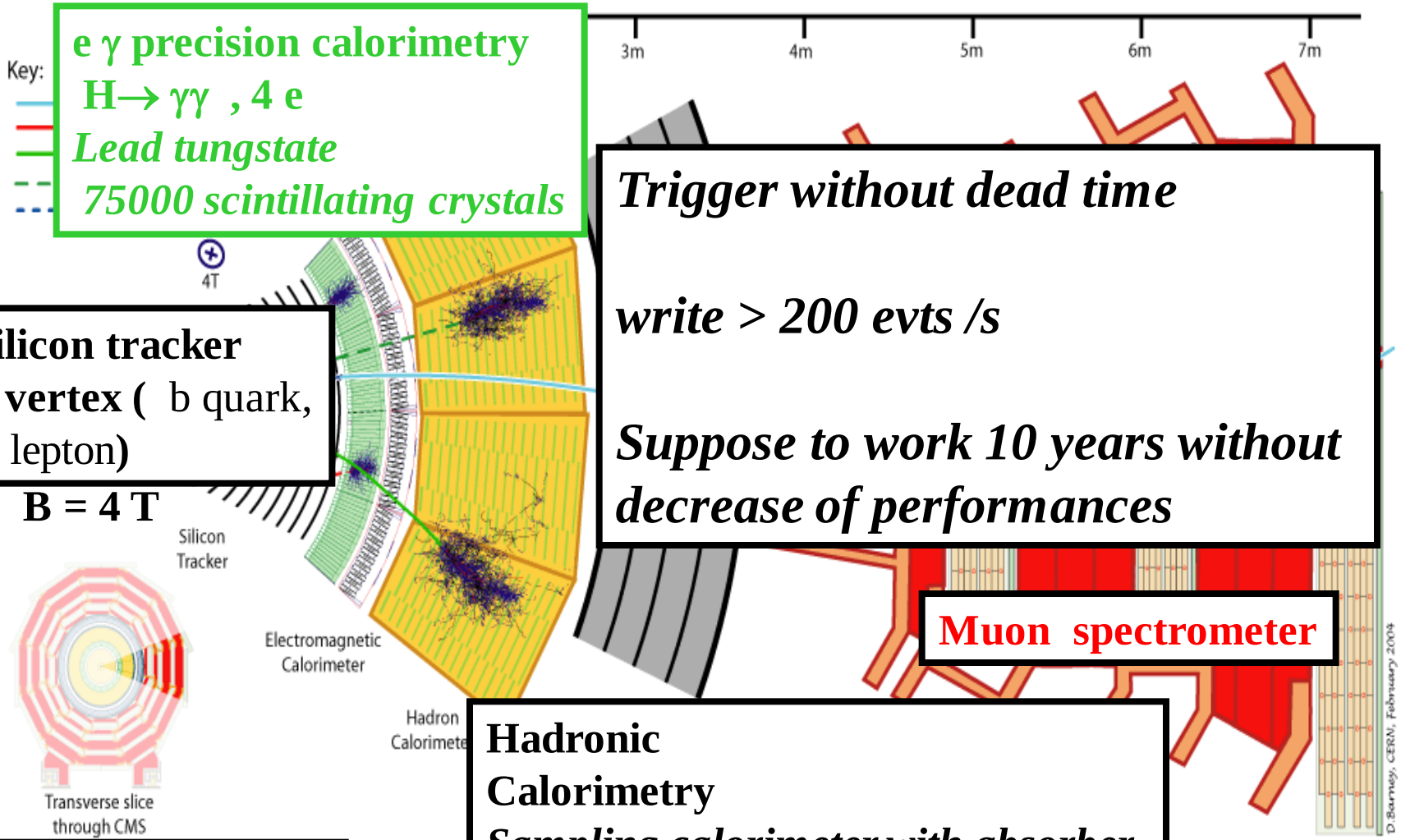
$$M^2 = 2\, E\gamma_1\, E\gamma_2\, (\, 1 - \cos \Psi_{12}\,)$$

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid 4 magnets Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeVstandalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

Exemple of CMS = (Compact Muon Solenoid)

e γ precision calorimetry
H→ γγ , 4 e
Lead tungstate
75000 scintillating crystals



Trigger without dead time

write > 200 evts /s

Suppose to work 10 years without decrease of performances

Silicon tracker
+ vertex (b quark, τ lepton**)**

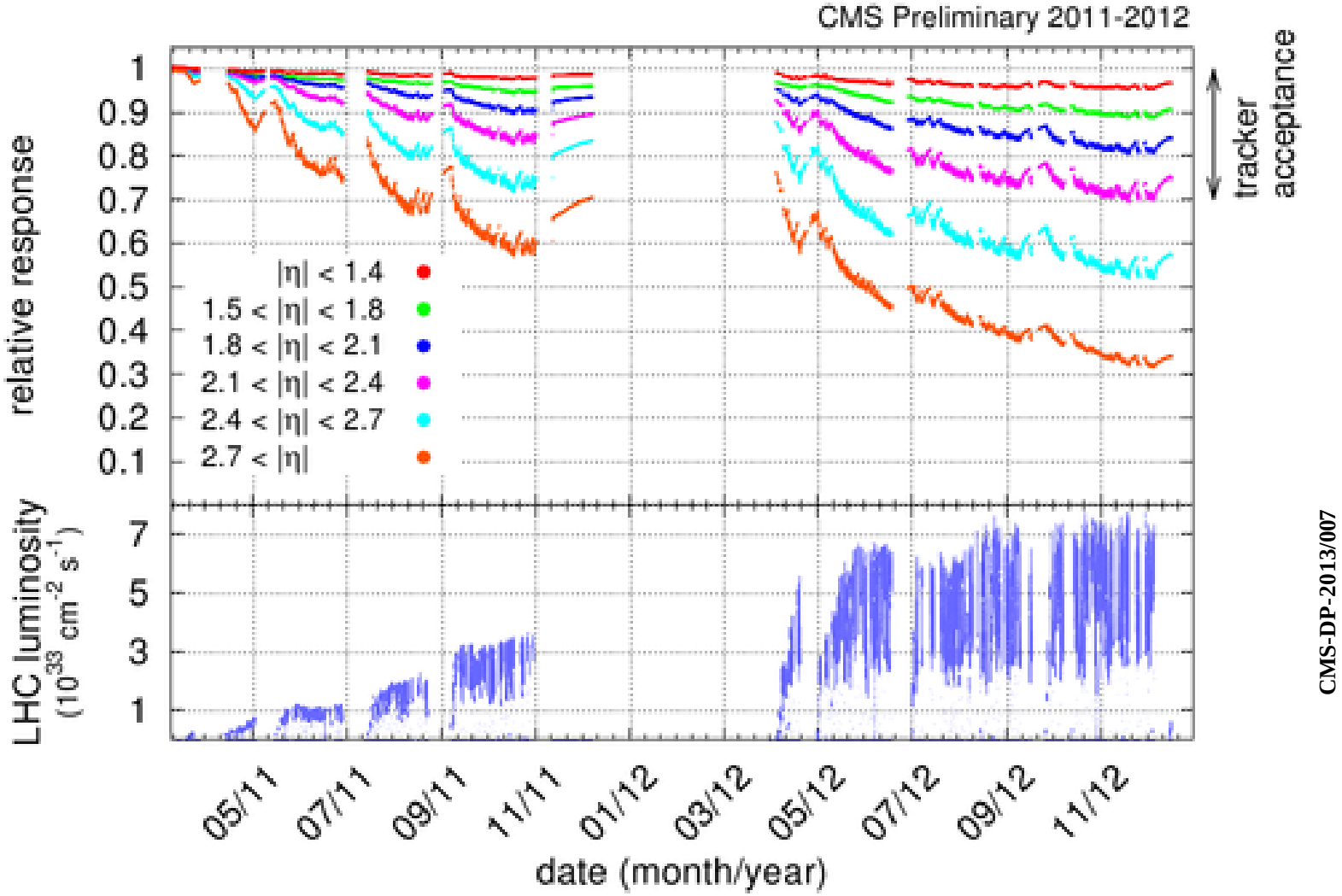
B = 4 T

Muon spectrometer

Hadronic Calorimetry
Sampling calorimeter with absorber (brass) and plastic scintillators
Jets and $E_T$miss

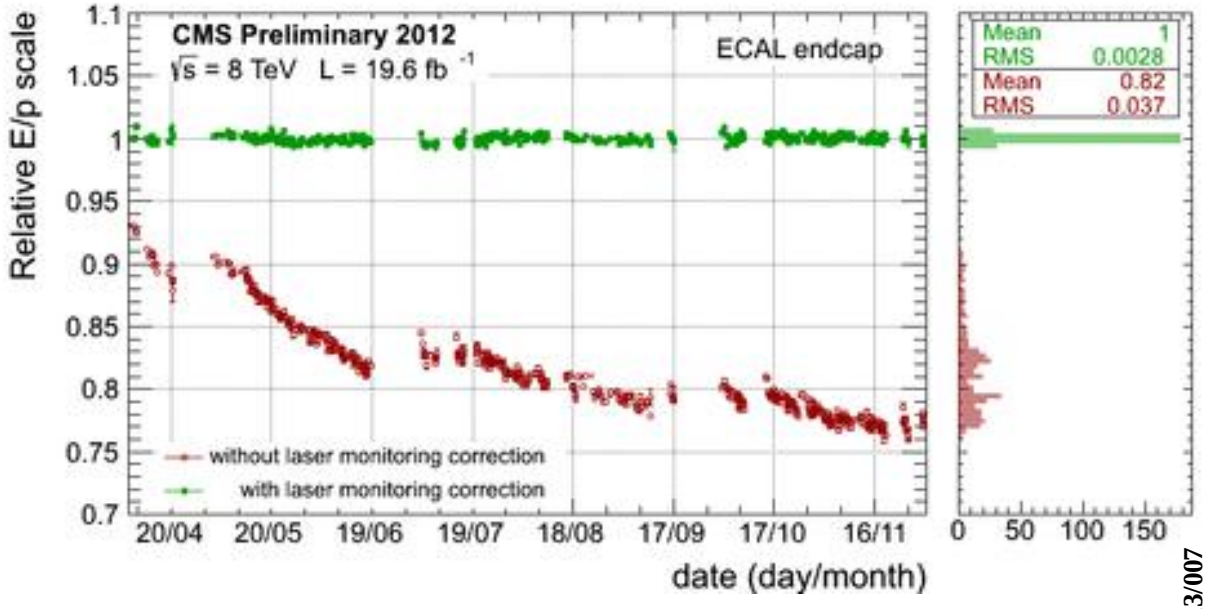
« 4 π » detector
up to η=5
(from θ = 1.35°)

High level quality control !

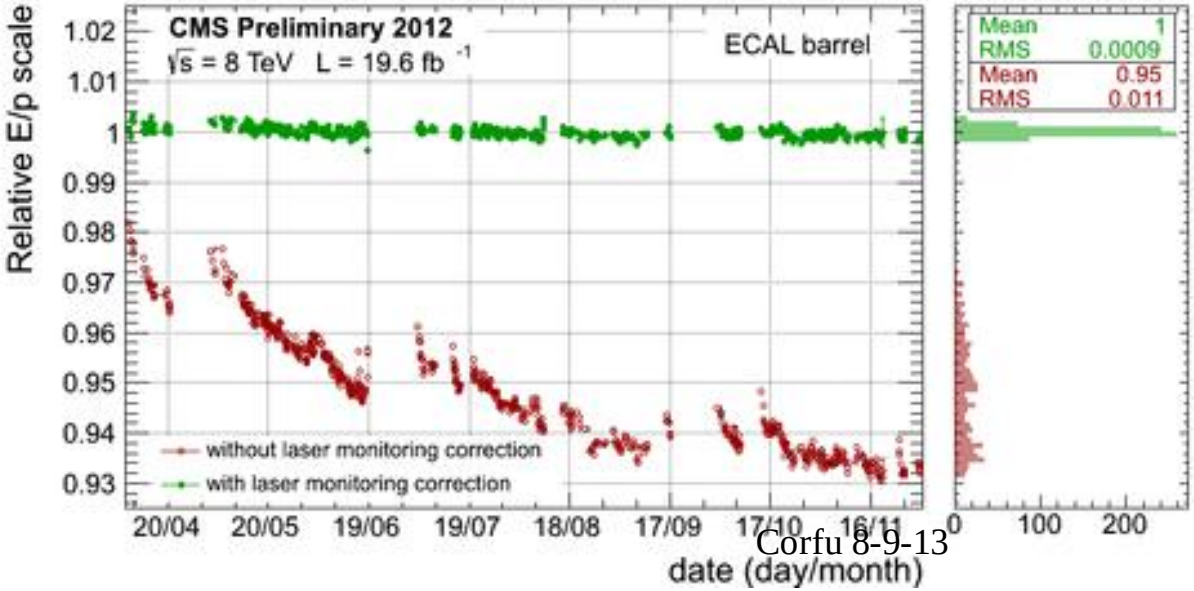


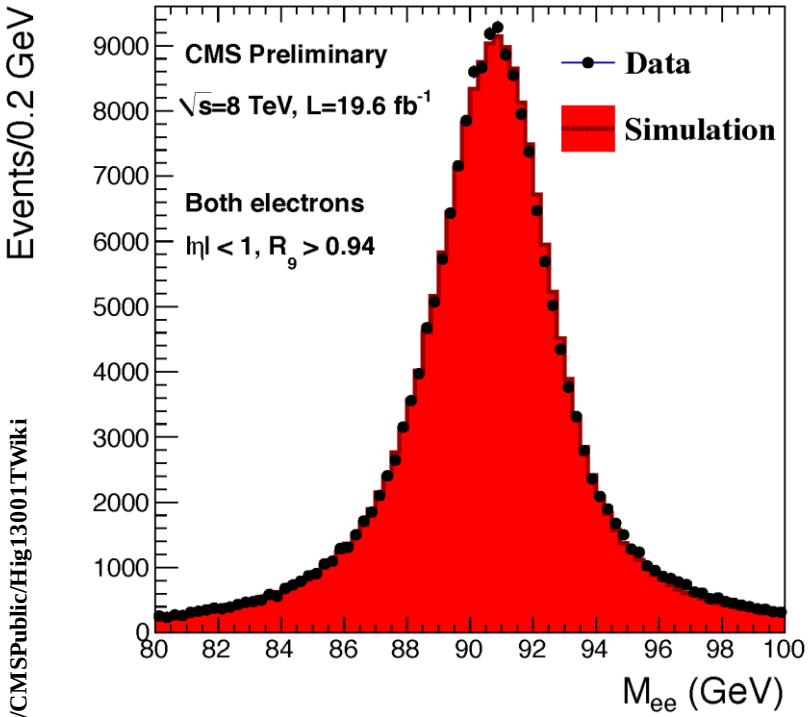
history of relative response

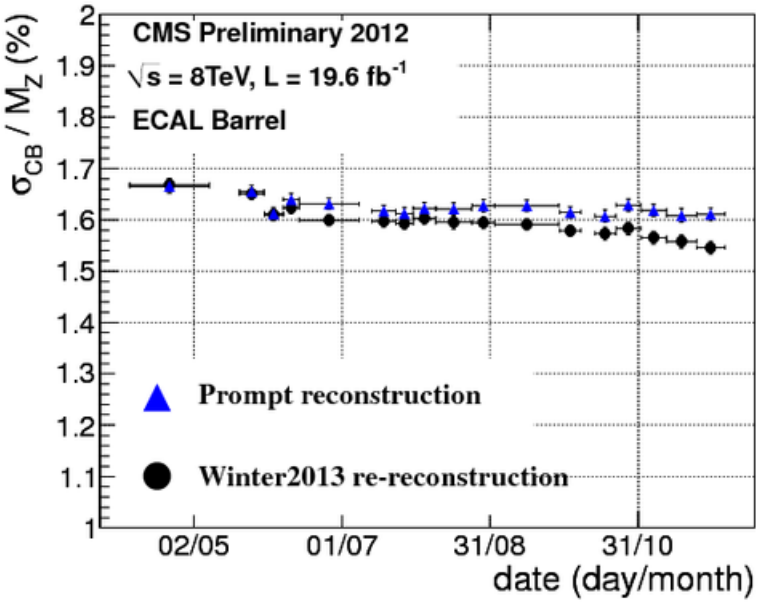
E/p history



CMS-DP-2013/007







https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13001TWiki

CMS-DP-2013/007

Validation and tests with Z → ee

the energy (and the response) of γ from H→ γγ is different from the energy (and response) of e from Z→ ee

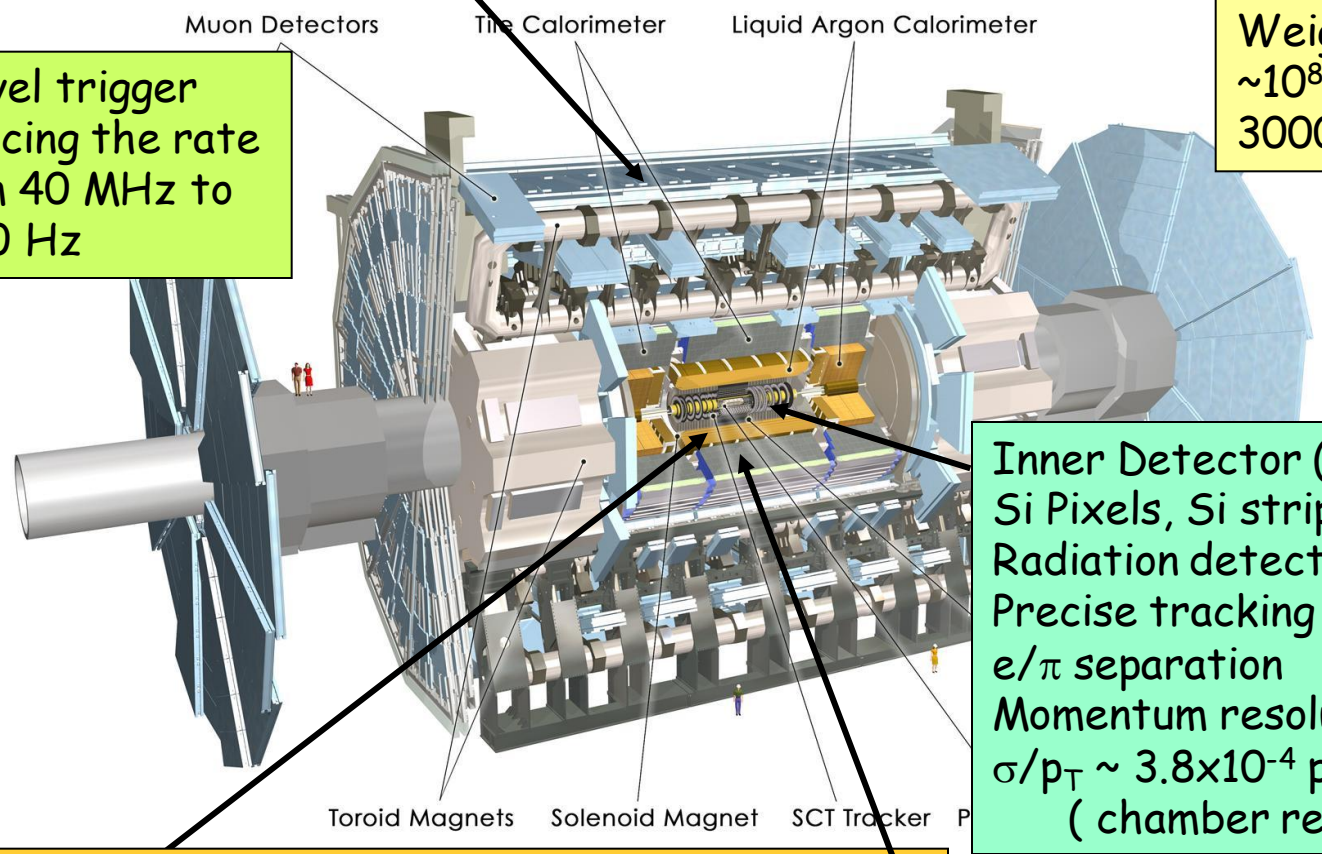
see talk of **Cyril Becot** next Tuesday

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids (B ~ 0.5 / 1T in barrel/ end-cap) with gas-based muon chambers Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

ATLAS detector

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

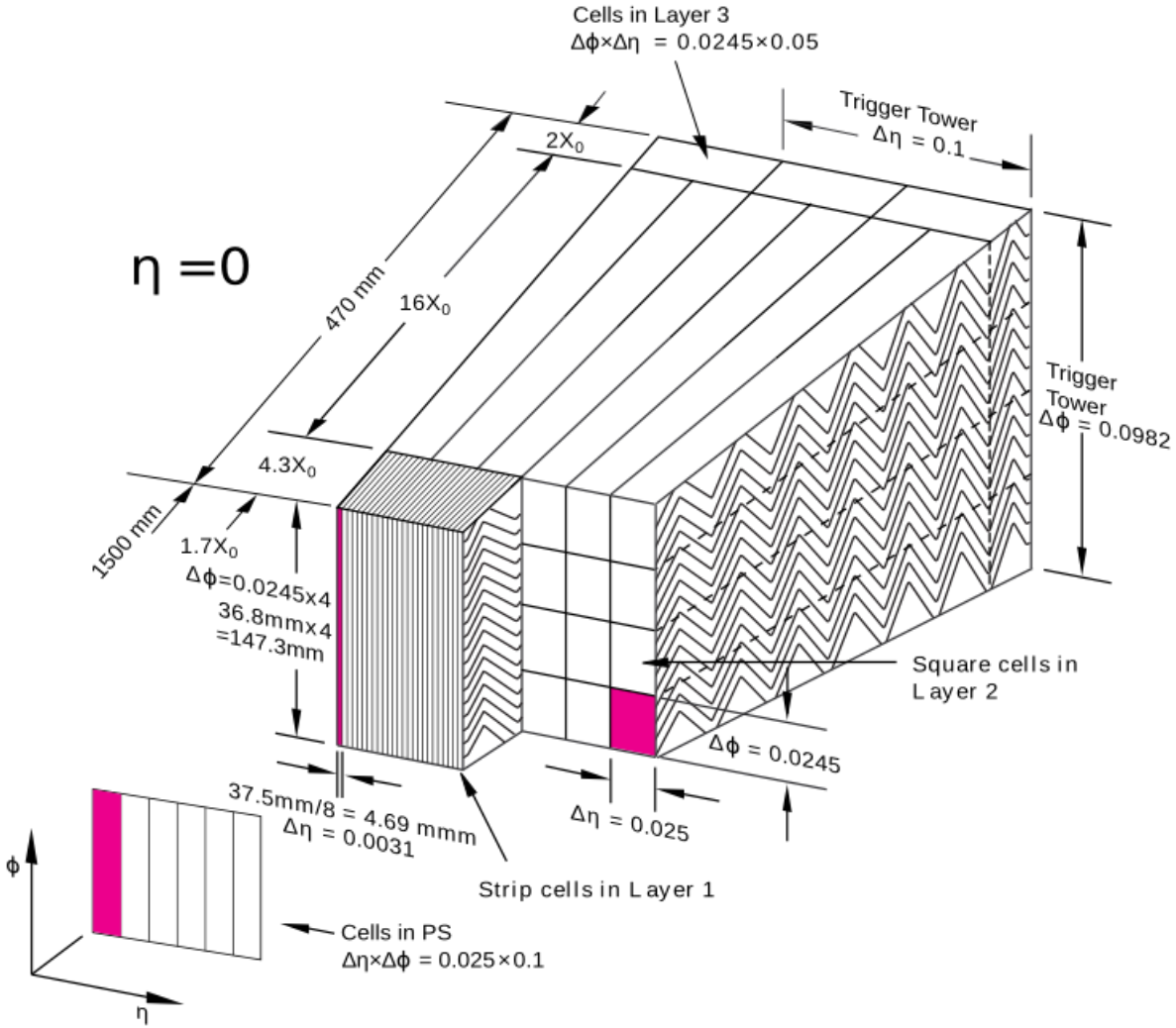


Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$
(chamber resolution $\oplus$ MS)

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

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: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

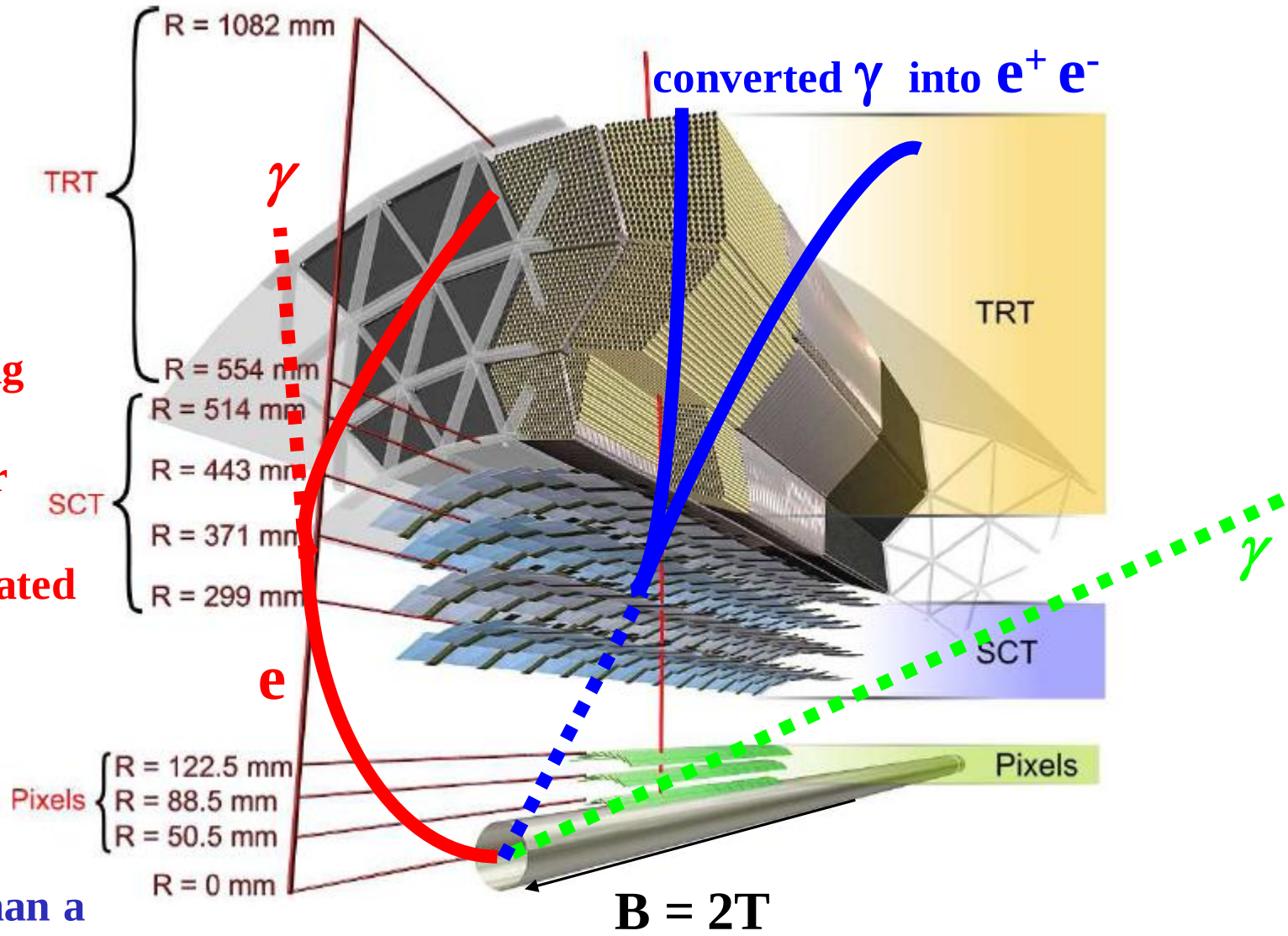
Daniel Fournier



presampler and longitudinal segmentation of the EM (*Liquid Argon*) accordion calorimeter

ATLAS inner detector

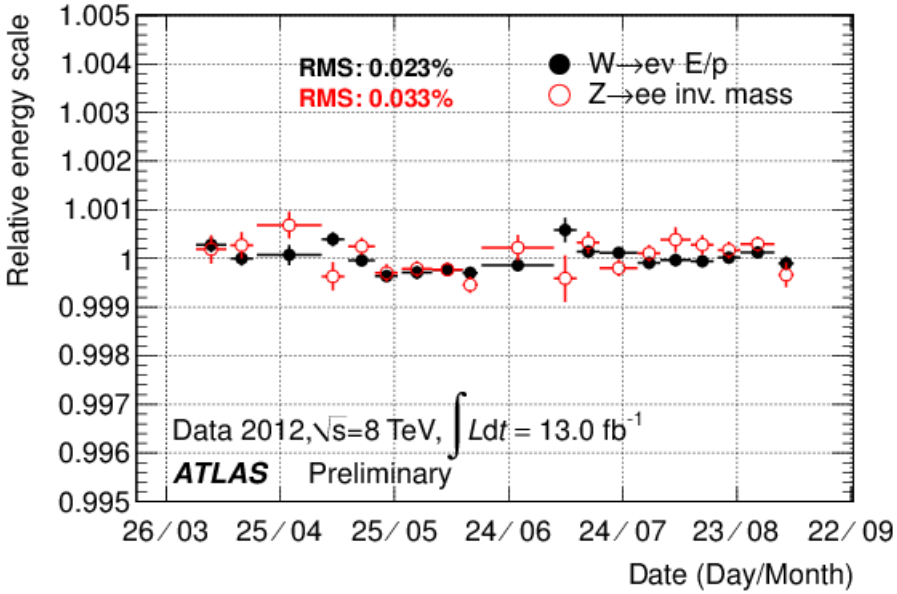
Outside you have the calorimeters and the muon detector



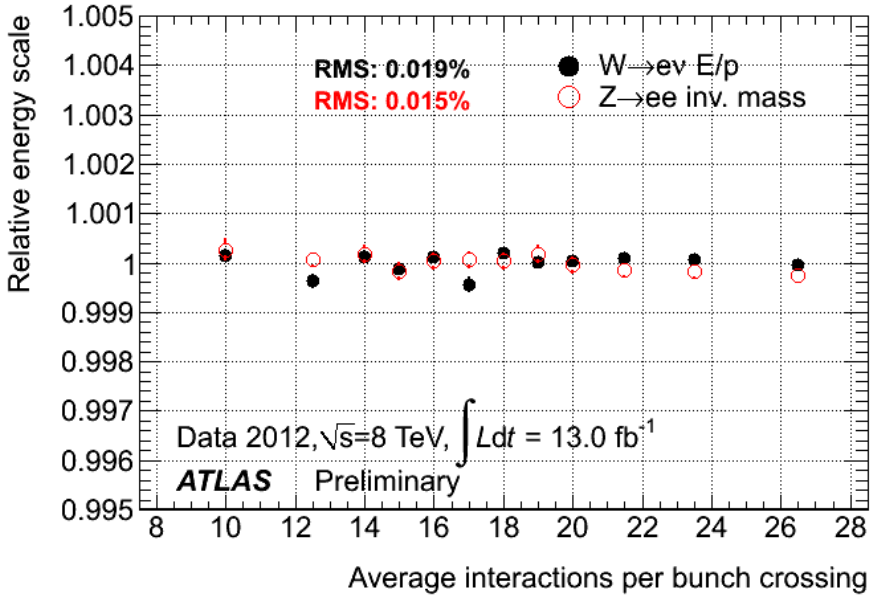
electrons can do some bremsstrahlung in the Inner Detector ⇒ response more complicated

photons can convert ⇒ more complicated than a non converted photon

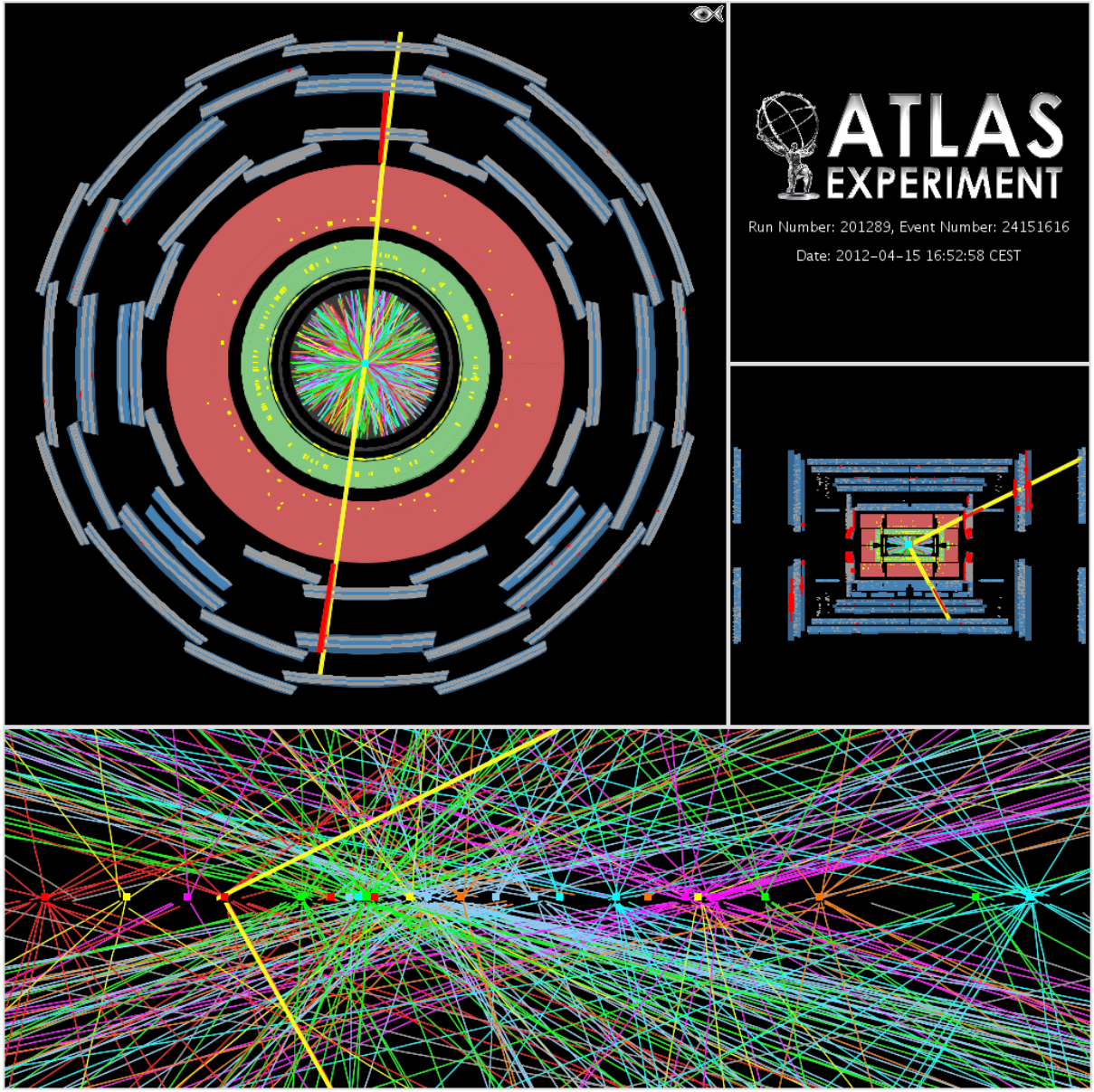
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20121106/ATL-COM-PHYS-2012-1593/index.html



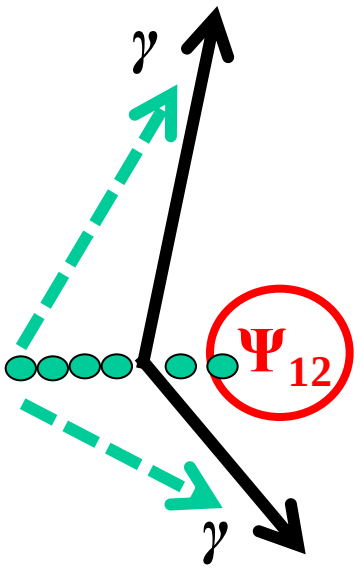
very good stability



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20121129/ATL-COM-PHYS-2012-1668/index.html



Event display with a $Z \rightarrow \mu^+\mu^-$ with 25 reconstructed vertices recorded April 15th 2012



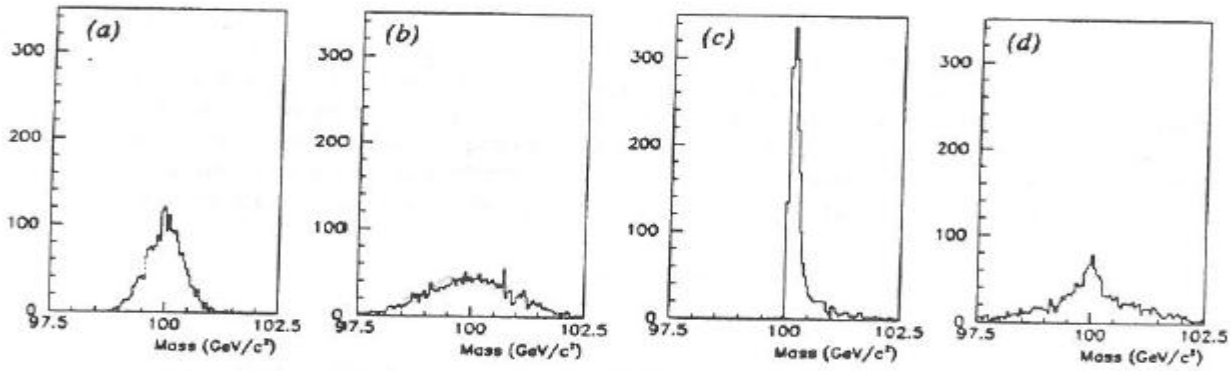


Figure 4: Reconstructed mass plots for Higgs boson, m_H=100GeV/c²
(a) smeared by: calorimeter energy resolution of $\Delta E/E=2\%/\sqrt{E}\oplus 0.5\%$
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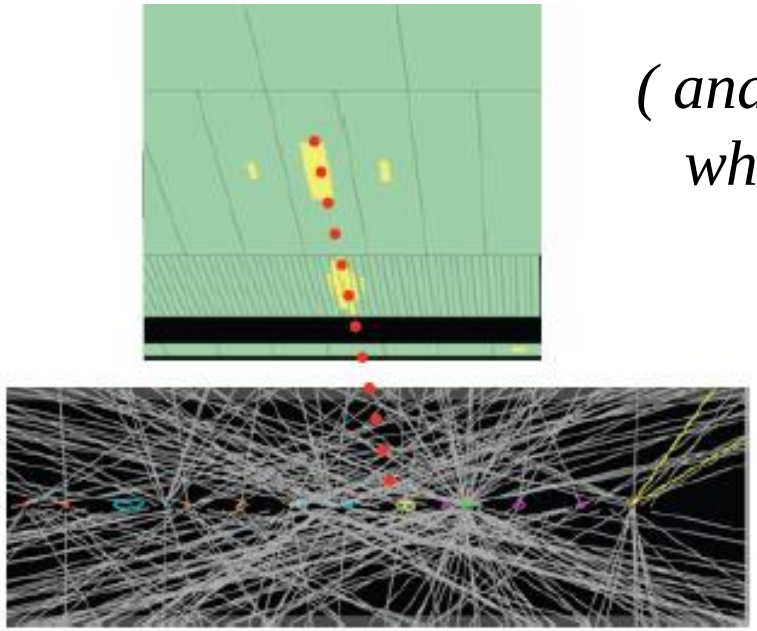
$$M^2 = 2\, E\gamma_1\, E\gamma_2\, (\, 1 - \cos \Psi_{12}\,)$$

A lot of vertex $\Rightarrow$ ***(if the wrong vertex is taken)***

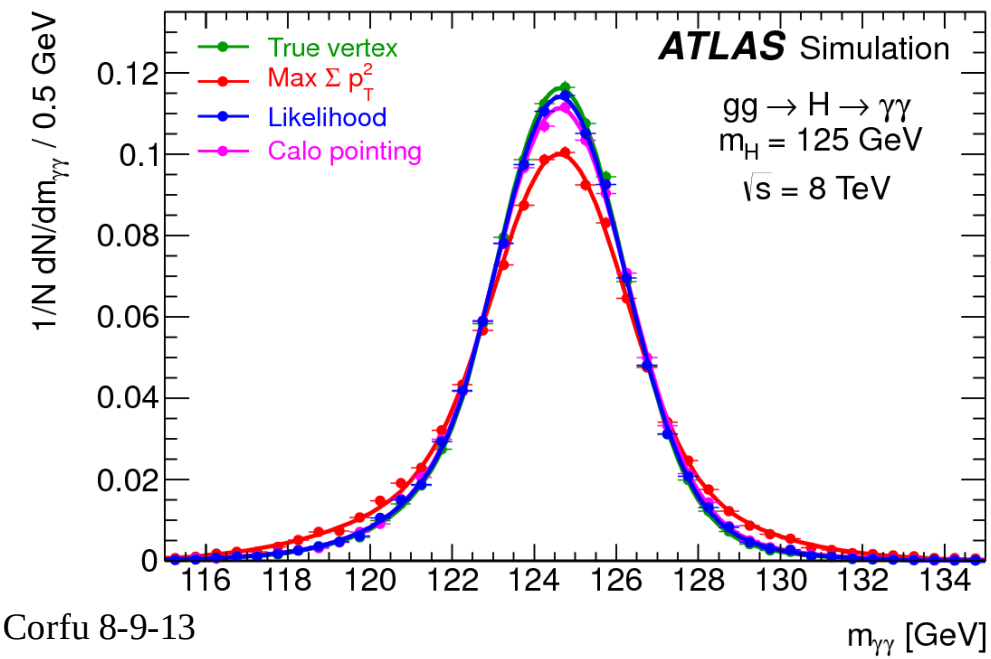
impact on Ψ_{12}

ATLAS : uses the longitudinal segmentation in order to get the vertex

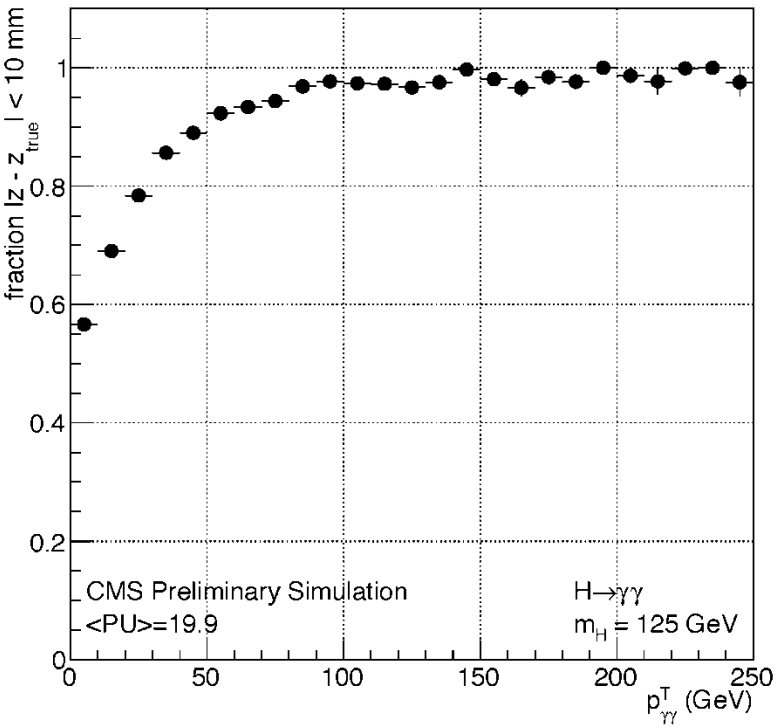
(and also the track conversion(s) when the photon is converted)

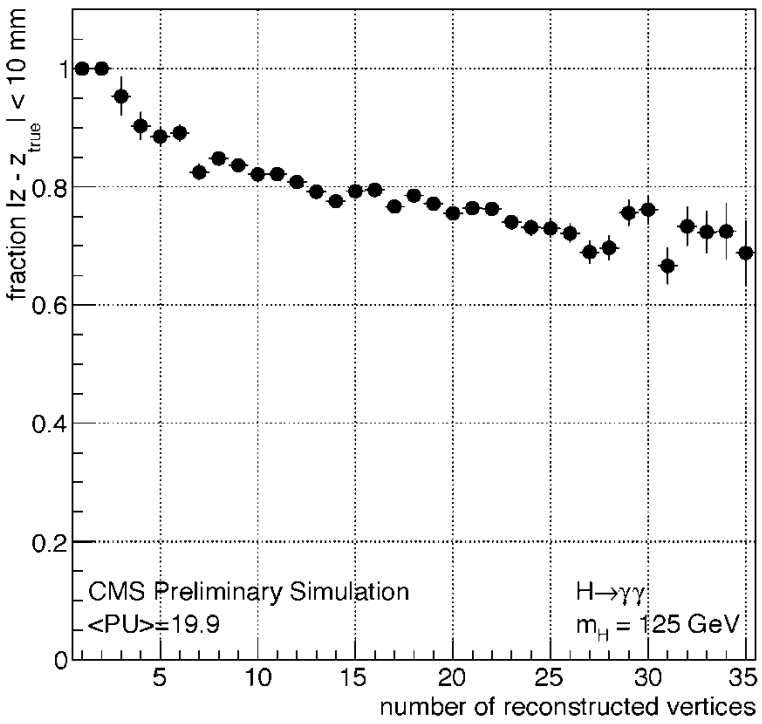


⇒ No degradation of the resolution

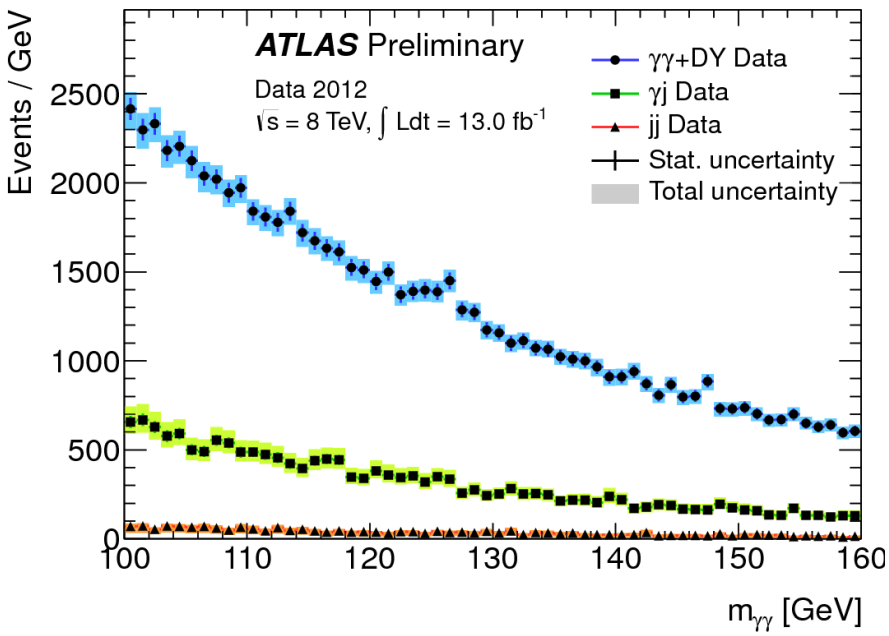


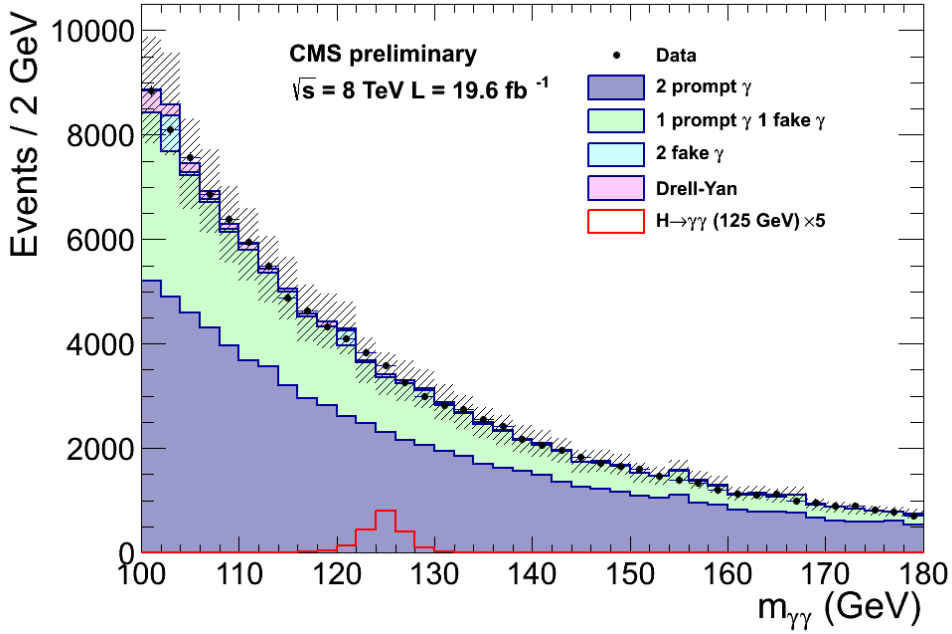
CMS : sophisticated kinematical cuts *(and the conversions)* in order to get ‘the’ vertex





Fraction of ‘good’ vertices





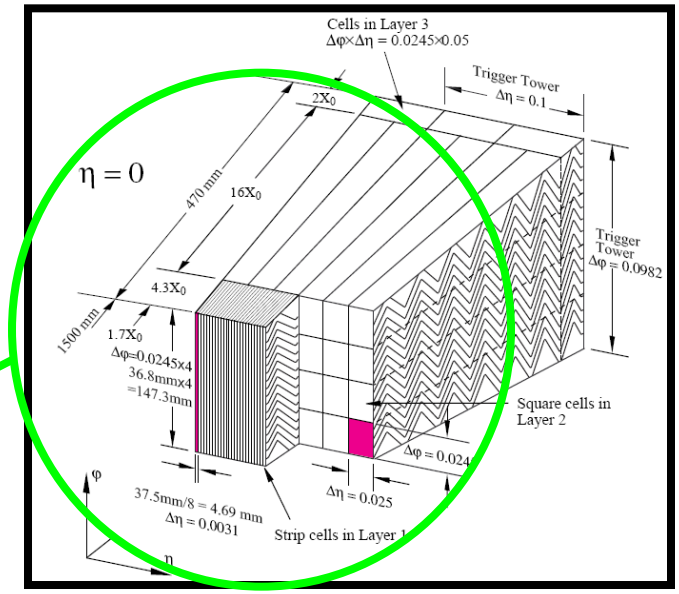
large (non photon) background

due to jets fragmenting mainly into π^0 's

background 'photon candidates' coming from jets are less isolated than real photons

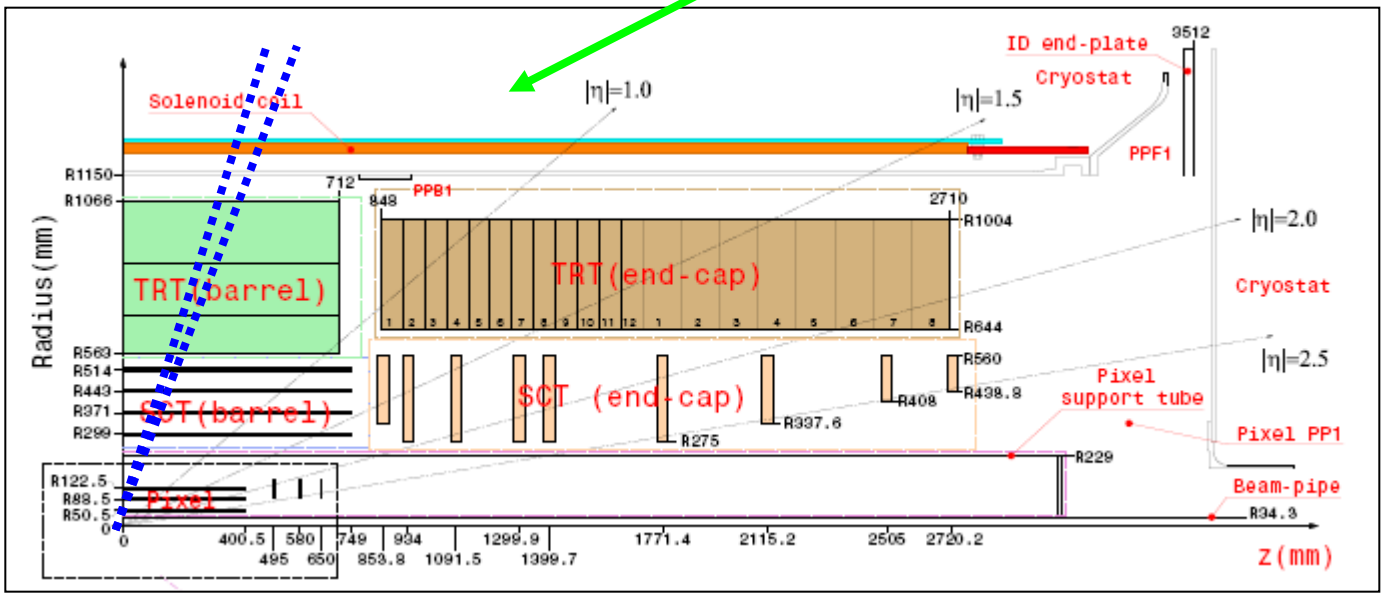
♦ good jet rejection essential (to reduce γj and jj backgrounds)

The granularity of the electromagnetic ATLAS detector is very useful to reject the π^0 background



opening of photons coming from a π^0 (p_T=40 GeV)

$\Delta R > .007$

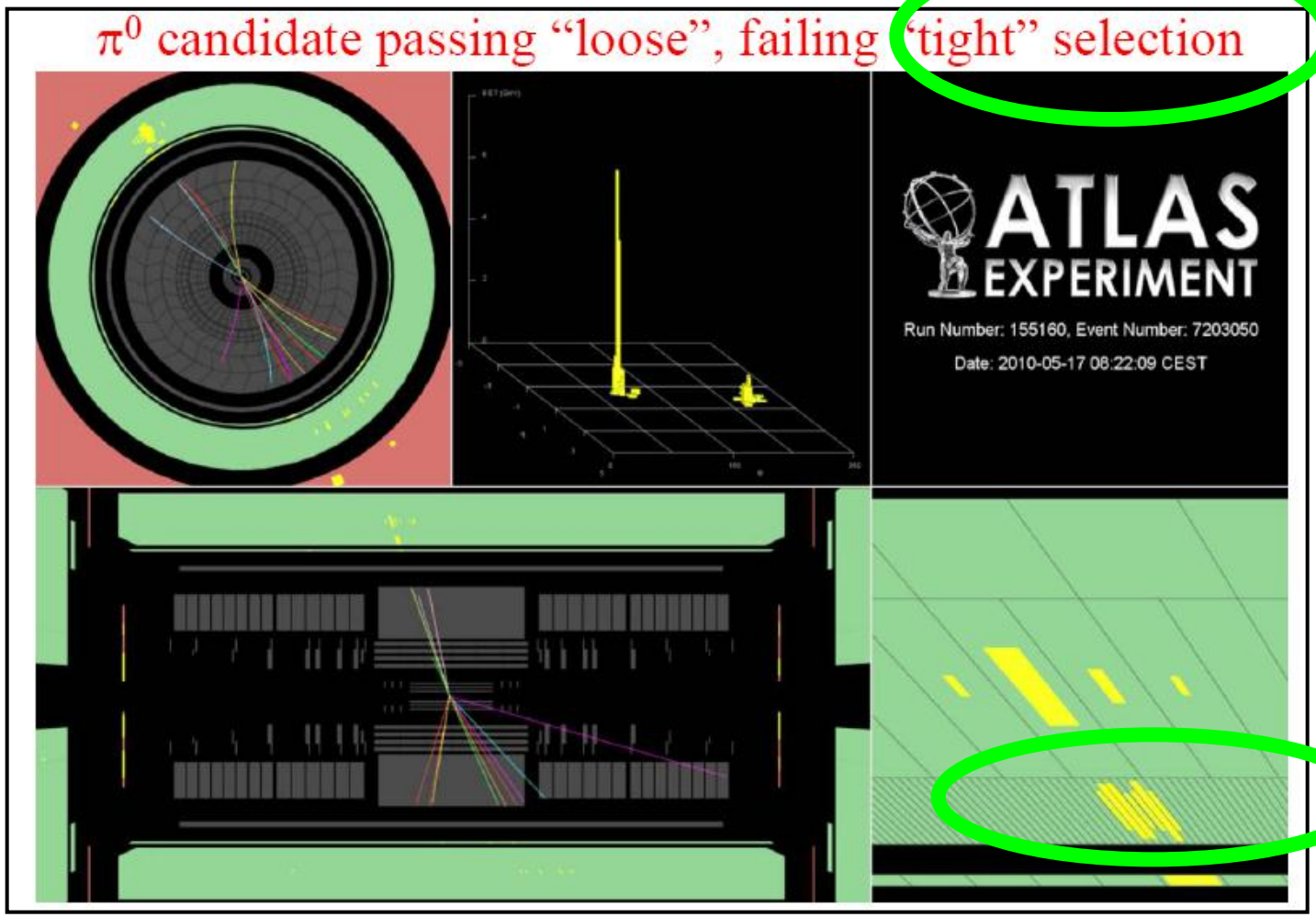


granularity of 1st sampling of calorimeter

$\Delta\eta \sim .003$

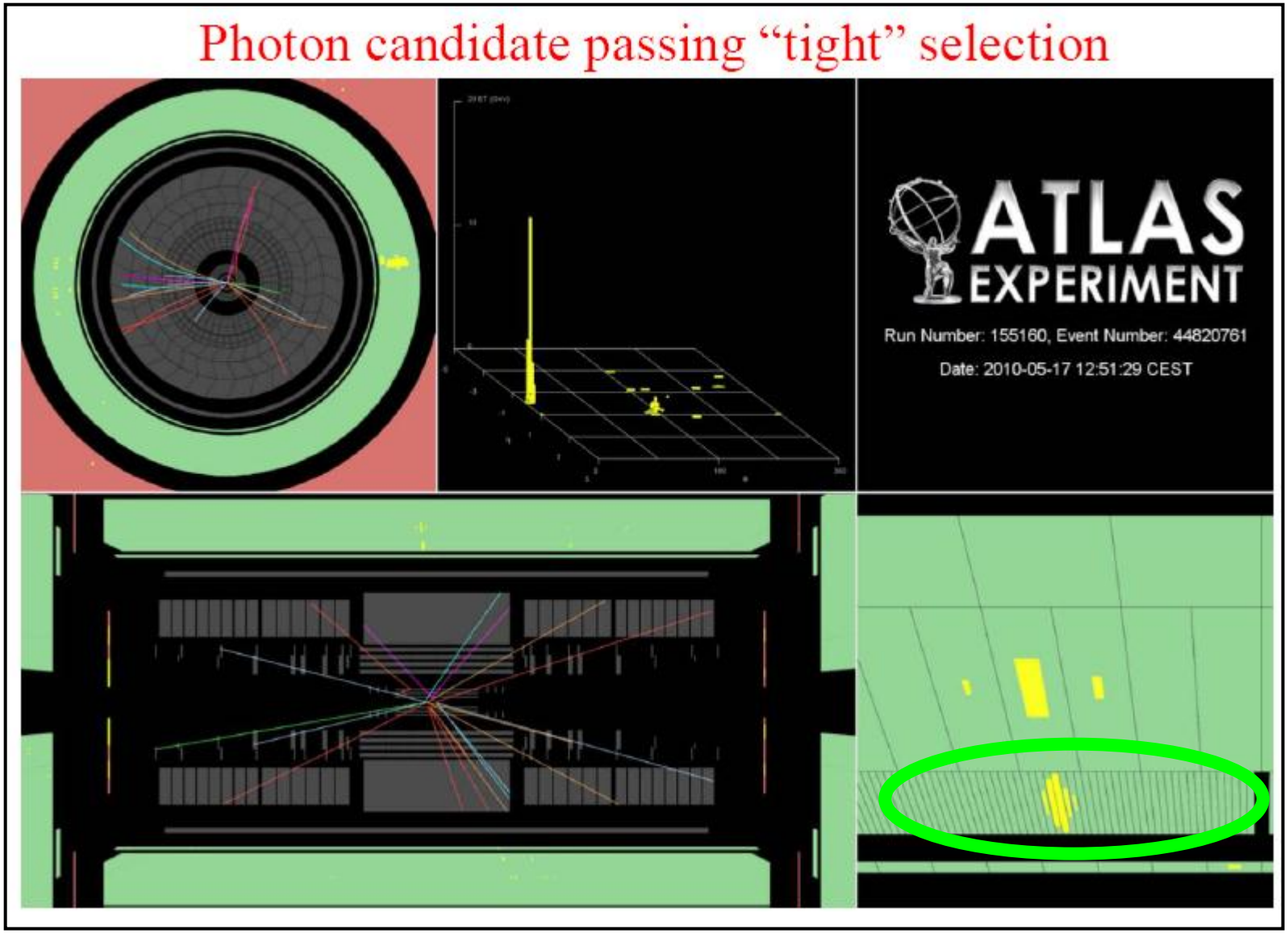
Photon identification with shower shapes

reminder: opening angle between the two photons of a π^0 of p_T =40 GeV ***is > 0.007 to be compared with size of strip calo 1st sampling ~0.003***

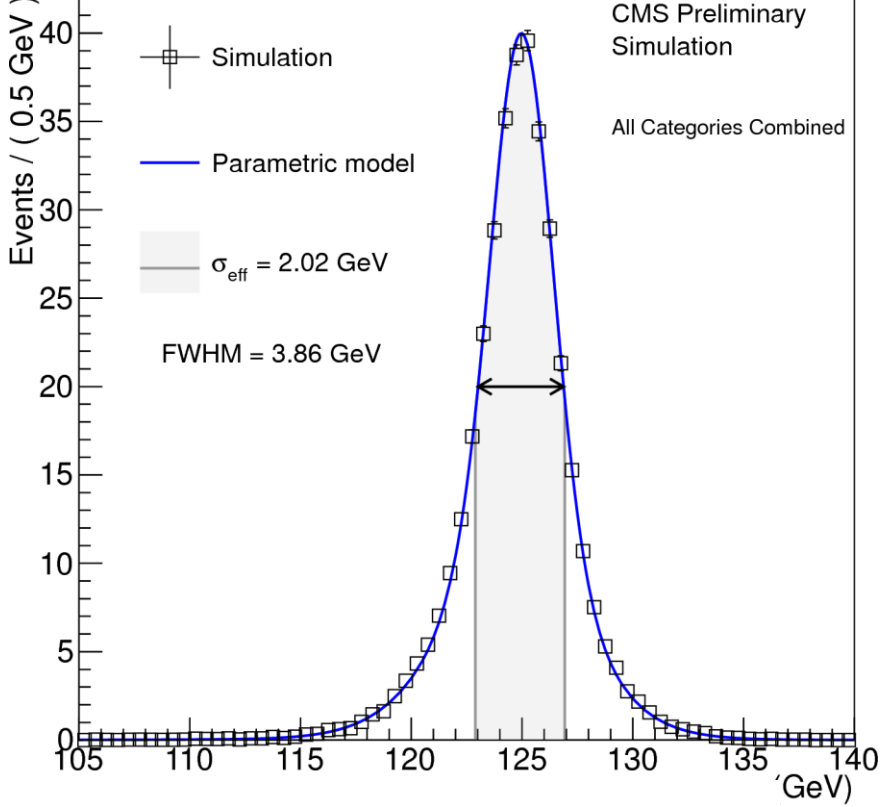


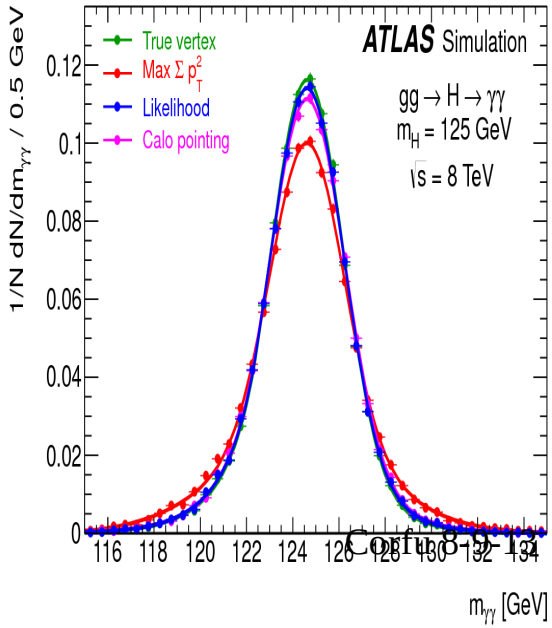
tight selection uses mainly calo 1st sampling

Photon candidate passing "tight" selection



Nice shape in first sampling of EM calormeter



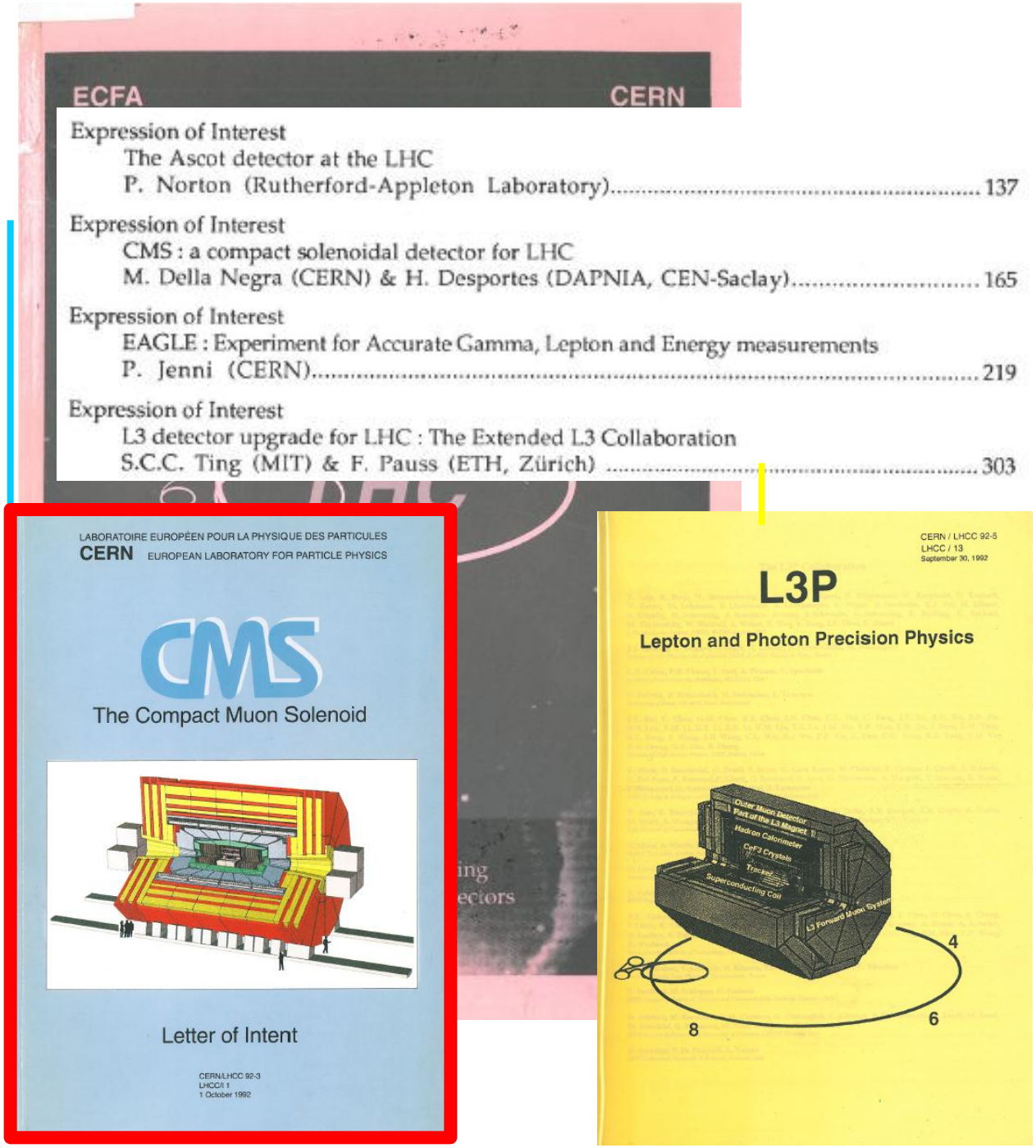


slightly better resolution in CMS but more tails

but there are different categories

very similar 'effective' resolutions

back 21 years ago


ECFA
CERN
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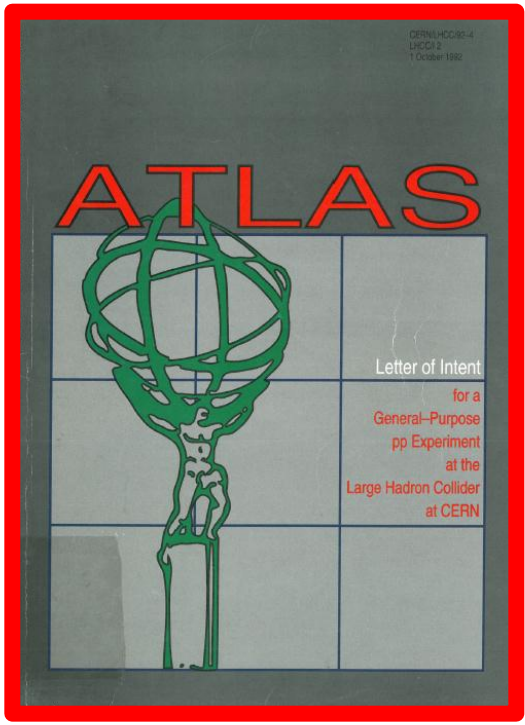
LHCC/I 1
1 October 1992
CERN / LHCC 92-5
LHCC / 13
September 30, 1992
L3P
Lepton and Photon Precision Physics
Outer Muon Detector
Part of the L3 Magnet
Hadron Calorimeter
CsF2 Crystals
Tracker
Superconducting Coil
L3 Forward Muon System
4
6
8


ATLAS
Letter of Intent
for a
General–Purpose
pp Experiment
at the
Large Hadron Collider
at CERN

chosen

♥ **Introduction**

♥ **Short history of scalar boson and LHC**

♥ **History of detectors and of $H \rightarrow \gamma\gamma$**

specificities of detectors relevant to $H \rightarrow \gamma\gamma$

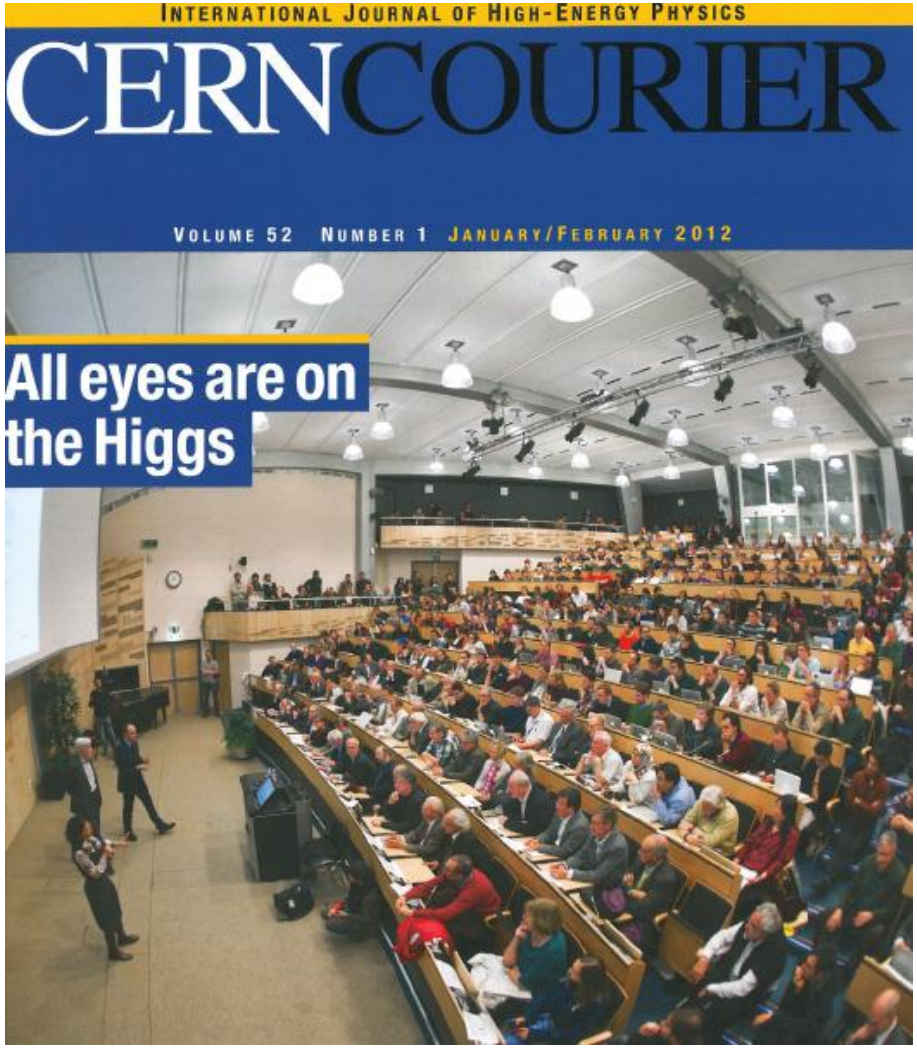
♥ **Discovery**

♥ **Properties**

♥ **Conclusions**

Backup (references)

Hints of signal were already there in 13th december 2011



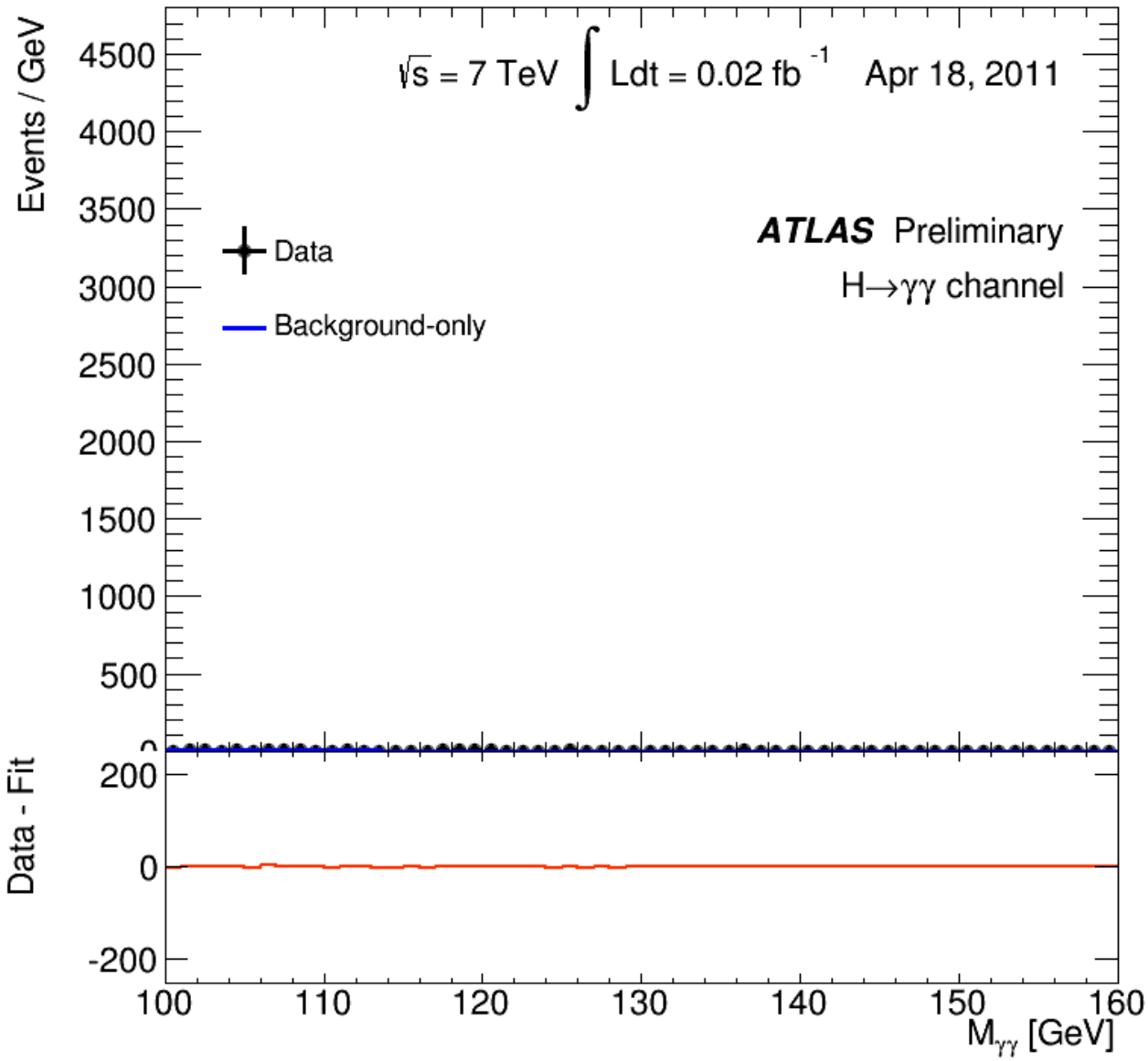
The 4th July seminar

before

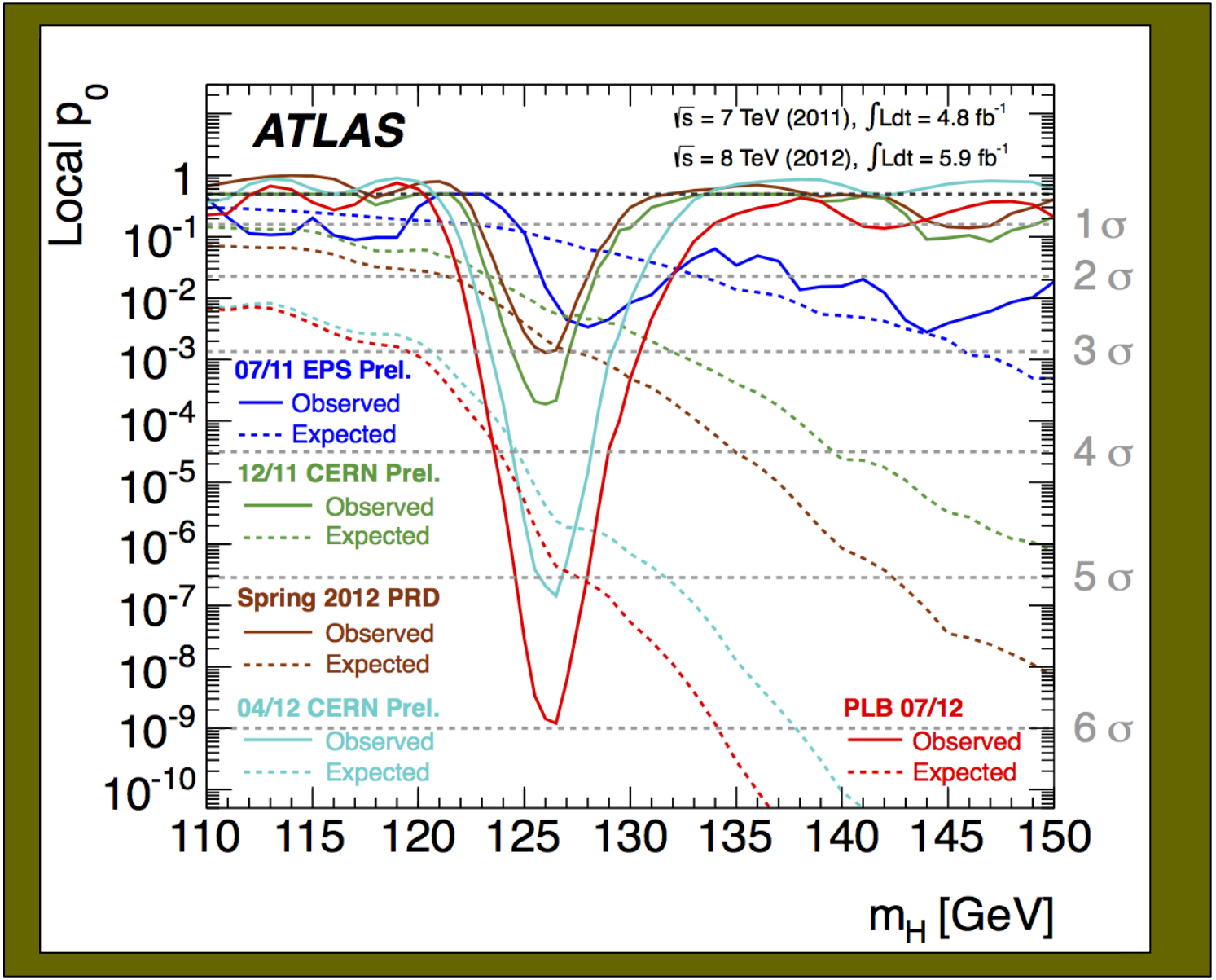
after

during


accelerators – experiments – Grid computing
Observation of a new particle consistent with
a Higgs Boson (but which one…?)
Historic Milestone but only the beginning
Global Implications for the future
R-D Heuer
CERN


√s = 7 TeV ∫ Ldt = 0.02 fb⁻¹ Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
Data - Fit
M_γγ [GeV]

Evolution of the excess (all channels) with time



Several categories are made in order to enhance the sensitivity in order to have different S/B , based on

- number of jets

- different resolutions

- different kinematics giving different S/B

S/B has to be different for various categories

This is needed if we want to gain in statistical significance

if $S_1 / B_1 = S_2 / B_2$

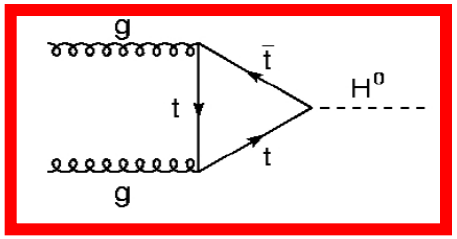
then $S_1 / \sqrt{B_1} \oplus S_2 / \sqrt{B_2} = (S_1+S_2) / \sqrt{(B_1+B_2)}$

and one does not gain making categories

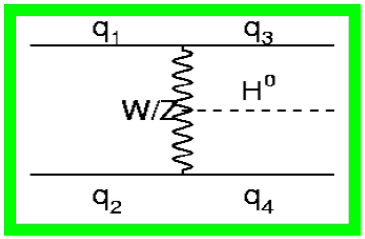
(one of) the work of the experimentalist is to find categories with different S/B !

In fact finding and using different categories allows us to « see » the various production modes

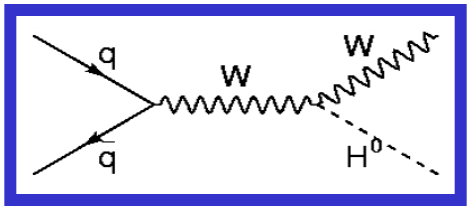
A.Djouadi Phys.Rept.457:1-216



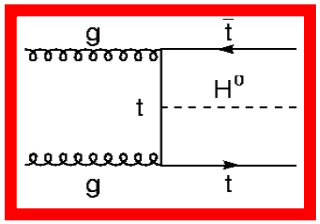
GF $H \to WW, ZZ, \gamma\gamma, bb, \tau\tau$



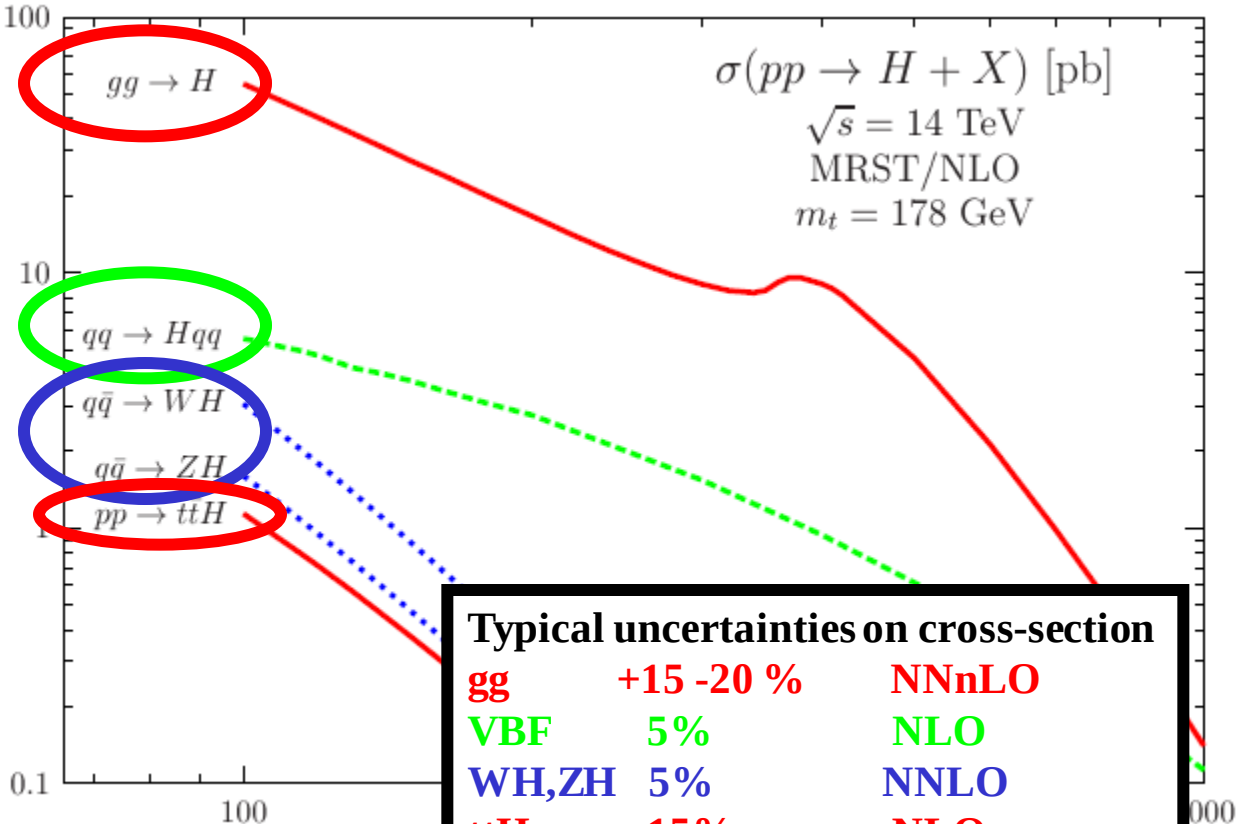
VBF $H \to WW, ZZ, \gamma\gamma, \tau\tau$



$H \to WW, \gamma\gamma, bb$



$H \to WW, \gamma\gamma, bb$



Typical uncertainties on cross-section

gg	+15 -20 %	NNnLO
VBF	5%	NLO
WH,ZH	5%	NNLO
ttH	15%	NLO

These production cross sections have to be used with the decays **bb , ττ , WW , ZZ , γγ**

♥ **Introduction**

♥ **Short history of scalar boson and LHC**

♥ **History of detectors and of $H \rightarrow \gamma\gamma$**

specificities of detectors relevant to $H \rightarrow \gamma\gamma$

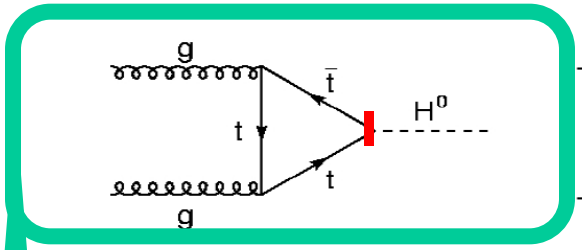
♥ **Discovery**

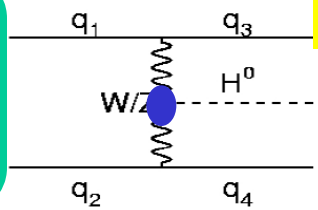
♥ **Properties**

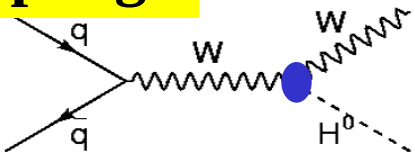
♥ **Conclusions**

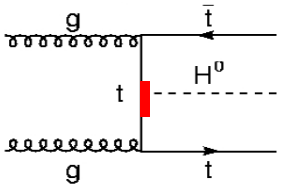
Backup (references)

couplings









A way to have access to H couplings to bosons ● and fermions ▮

We are looking $\mu = \sigma / \sigma_{SM}$ SM = SM boson
and we can study

$\mu_{ggH} = \sigma_{ggH} / \sigma_{ggH_{SM}}$

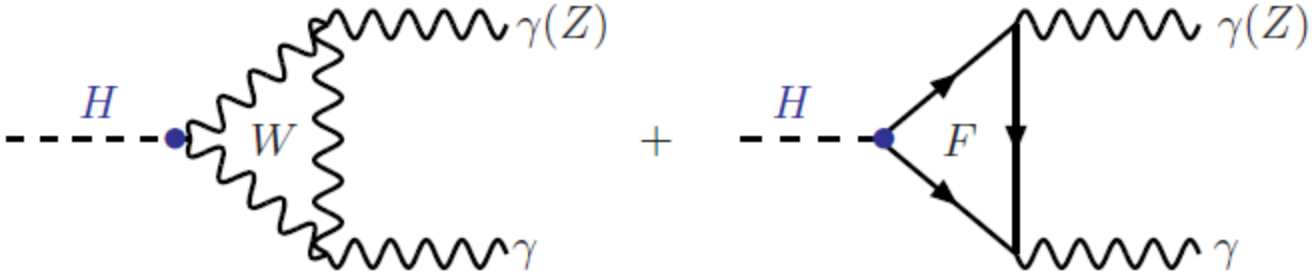
$\mu_{VBFH} = \sigma_{VBFH} / \sigma_{VBFH_{SM}}$

$\mu_{WH} = \sigma_{WH} / \sigma_{WH_{SM}}$

.....

In fact $\mu = (\sigma . B) / (\sigma . B)_{SM}$

Scalar boson decays : example of $H \to \gamma\gamma$



Interference between

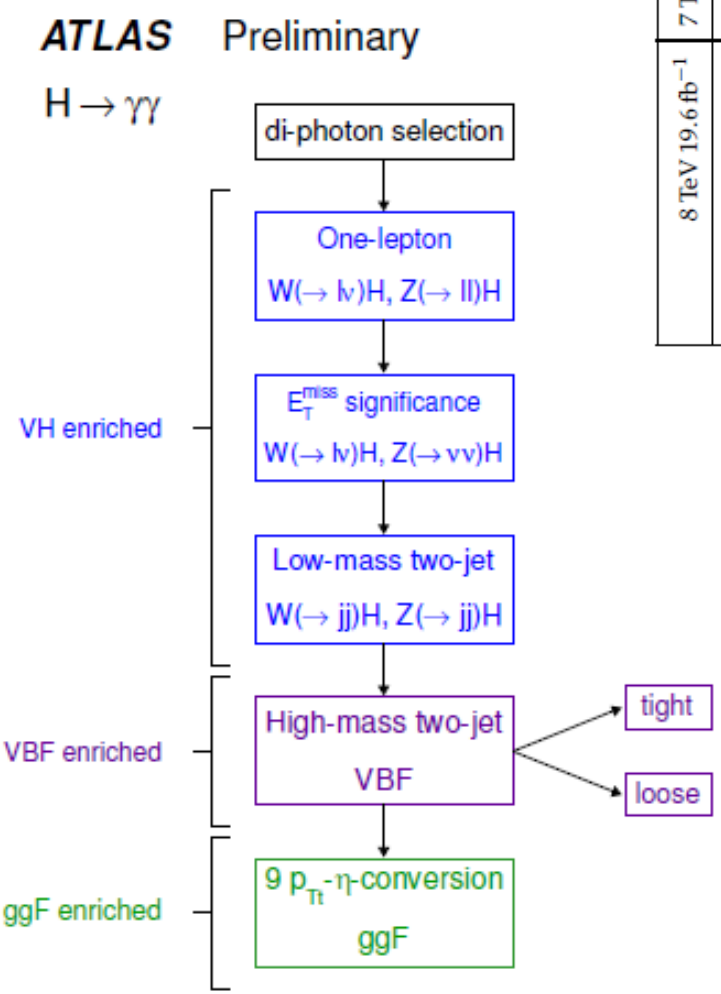
W loop ***top loop***

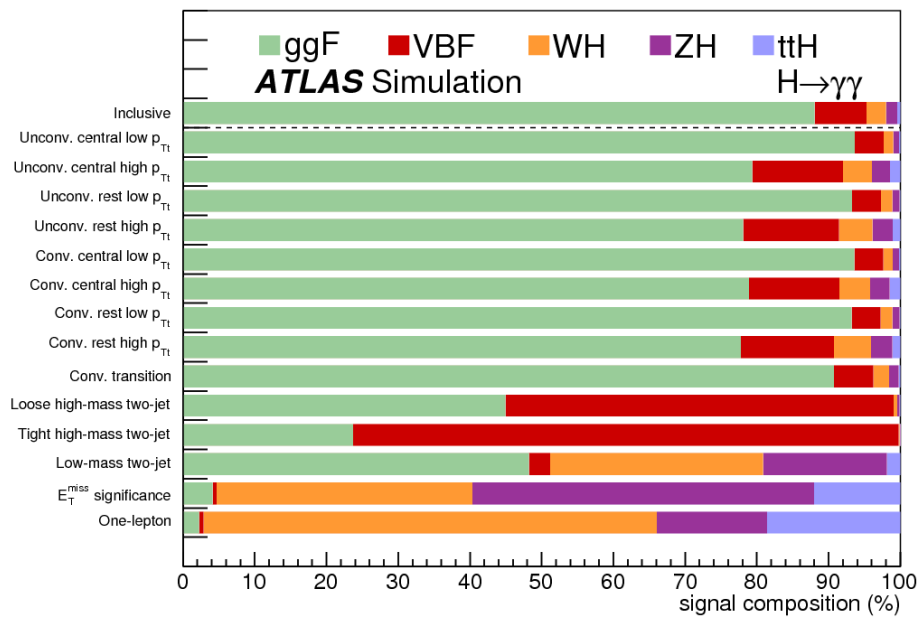
$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \, \alpha^2 \, M_H^3}{128\sqrt{2}\,\pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

$\propto$ ***1.8*** ***- 8***

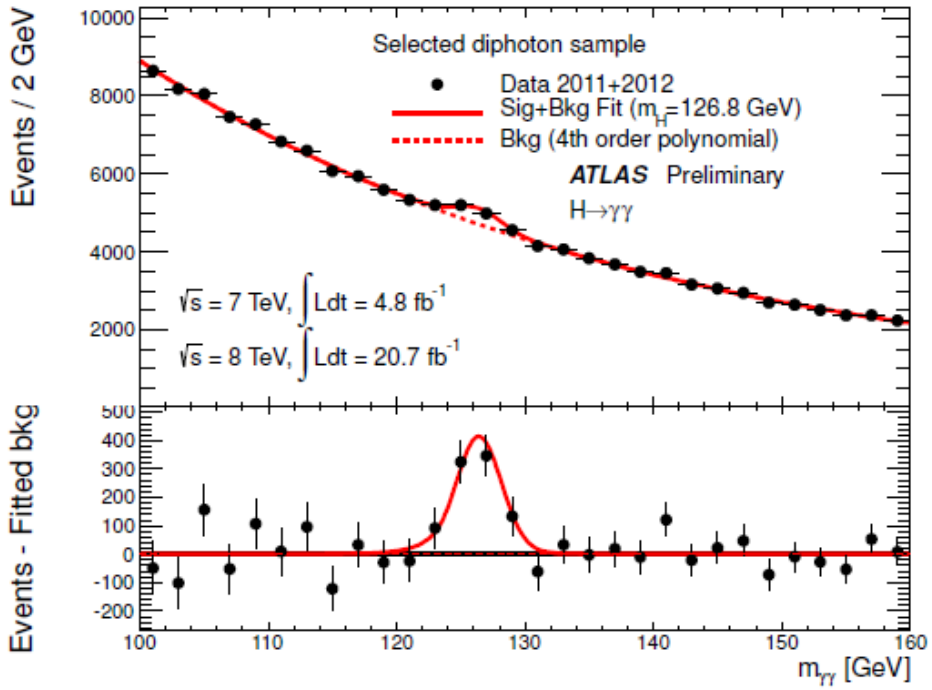
A.Djouadi Phys.Rept.457:1-216

Expected signal and estimated background										
Event classes		SM Higgs boson expected signal (m_H=125 GeV)							Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)	
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)		
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3	± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5	± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8	± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6	± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7	± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	22.1	± 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	94.3	± 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	570.5	± 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	1060.9	± 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	3.4	± 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	12.4	± 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	0.7	± 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	0.7	± 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	1.8	± 0.1





Flow-chart of the event categorisation, giving the order of selection of the different categories.



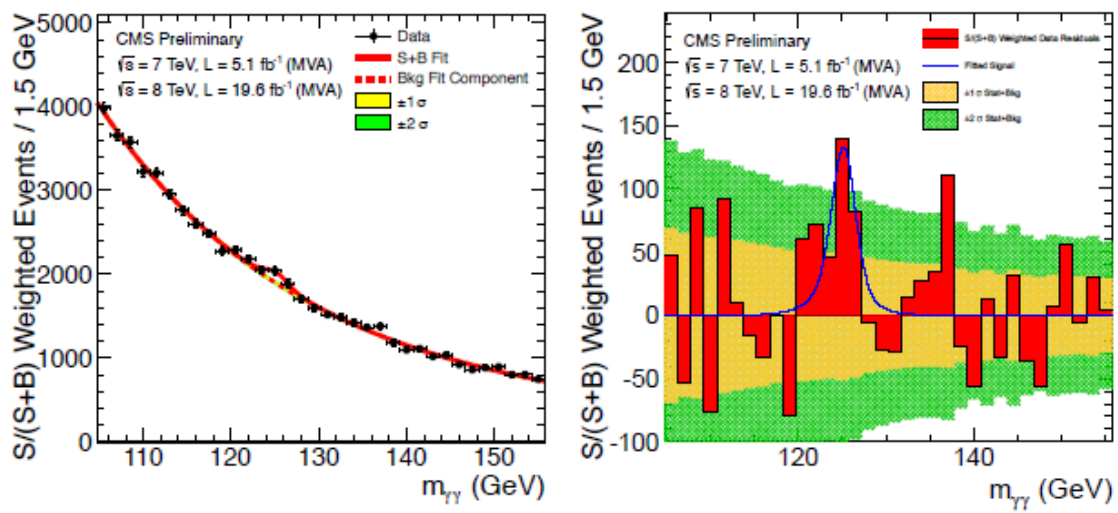
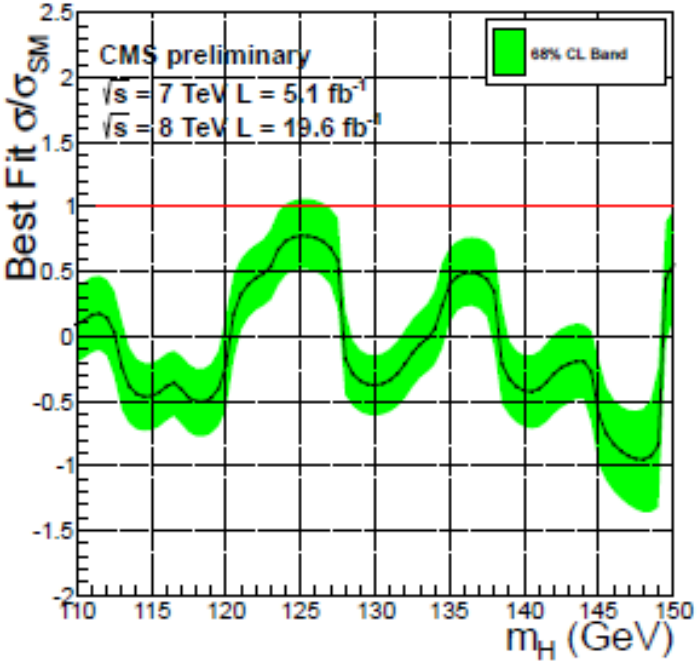
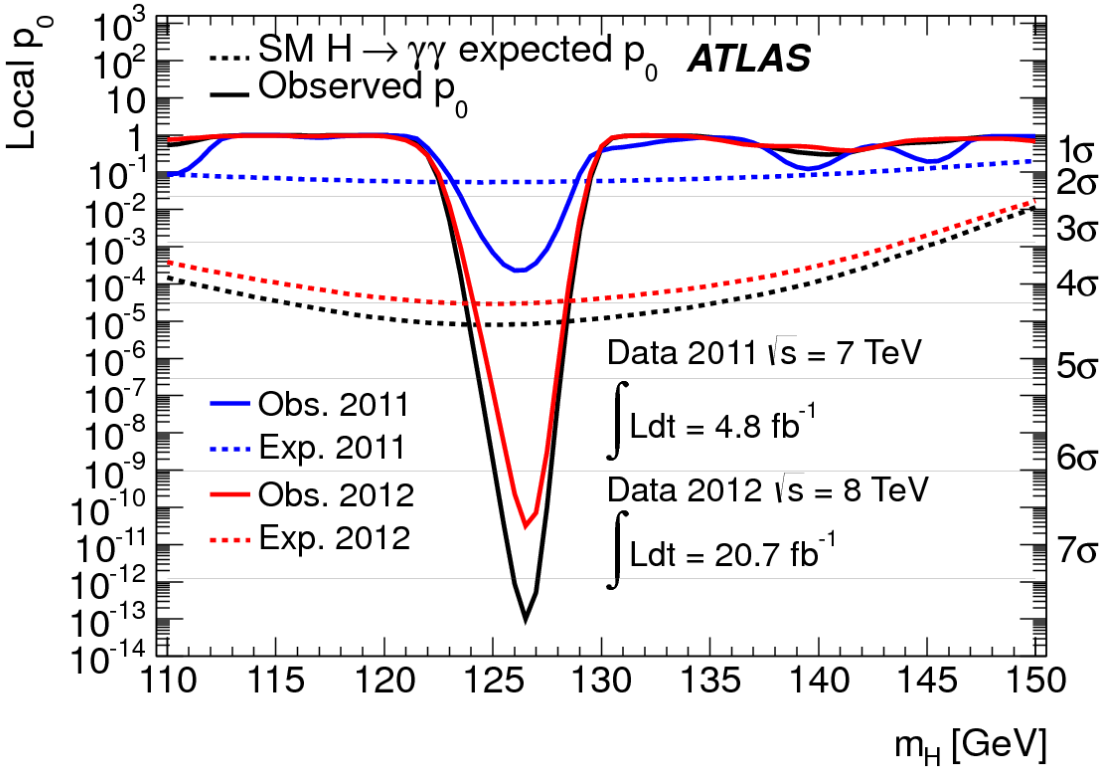
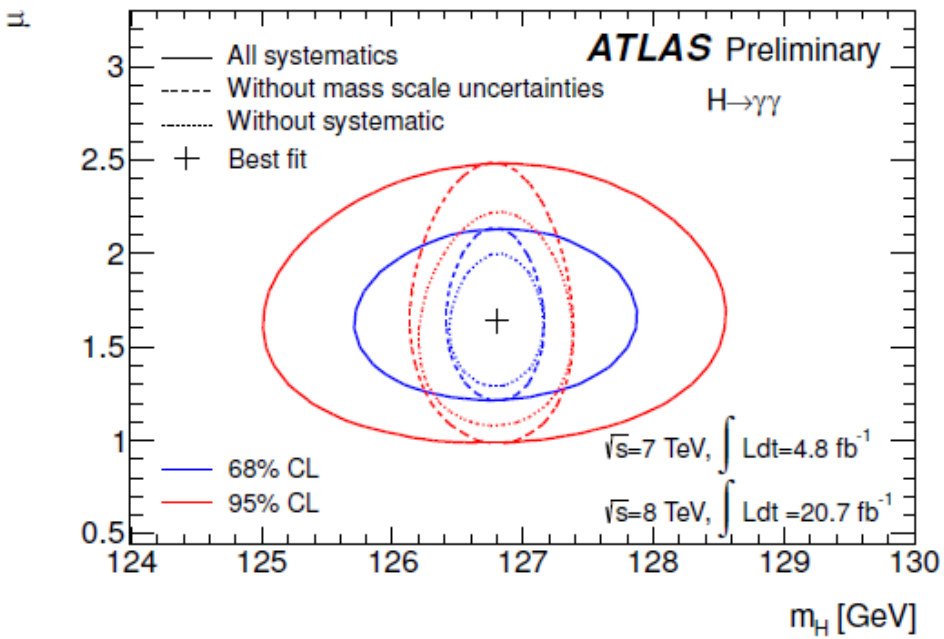
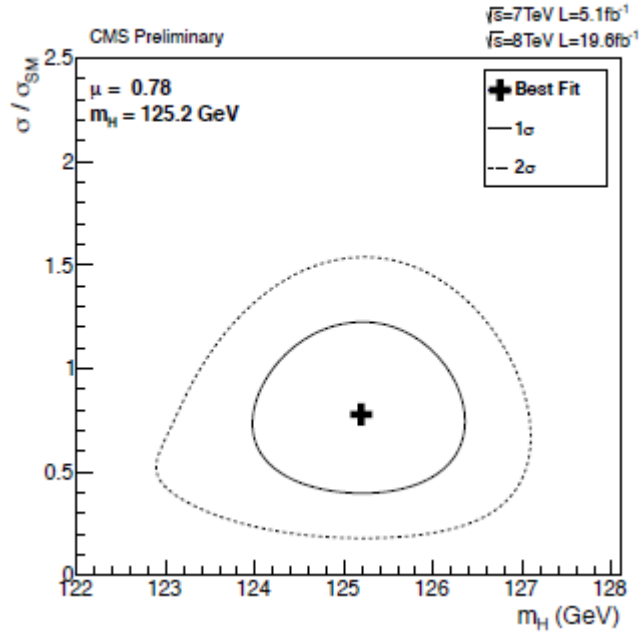


Figure 10: (left) The diphoton mass spectrum weighted by the ratio of signal-to-background in each event class for the mass-fit-MVA analysis. (right) The background-subtracted weighted mass spectrum.


CMS preliminary
√s = 7 TeV L = 5.1 fb-1
√s = 8 TeV L = 19.6 fb-1
68% CL Band
Best Fit σ/σSM
mH (GeV)


SM H → γγ expected p0
Observed p0
ATLAS
Local p0
Obs. 2011
Exp. 2011
Obs. 2012
Exp. 2012
Data 2011 √s = 7 TeV
∫Ldt = 4.8 fb-1
Data 2012 √s = 8 TeV
∫Ldt = 20.7 fb-1
1σ
2σ
3σ
4σ
5σ
6σ
7σ
mH [GeV]





μ slightly above SM

$\mu = 1.55^{+.33}_{-.28}$

7.4 σ

mH = 126.8 ± .2 ± .7 GeV

μ slightly below SM

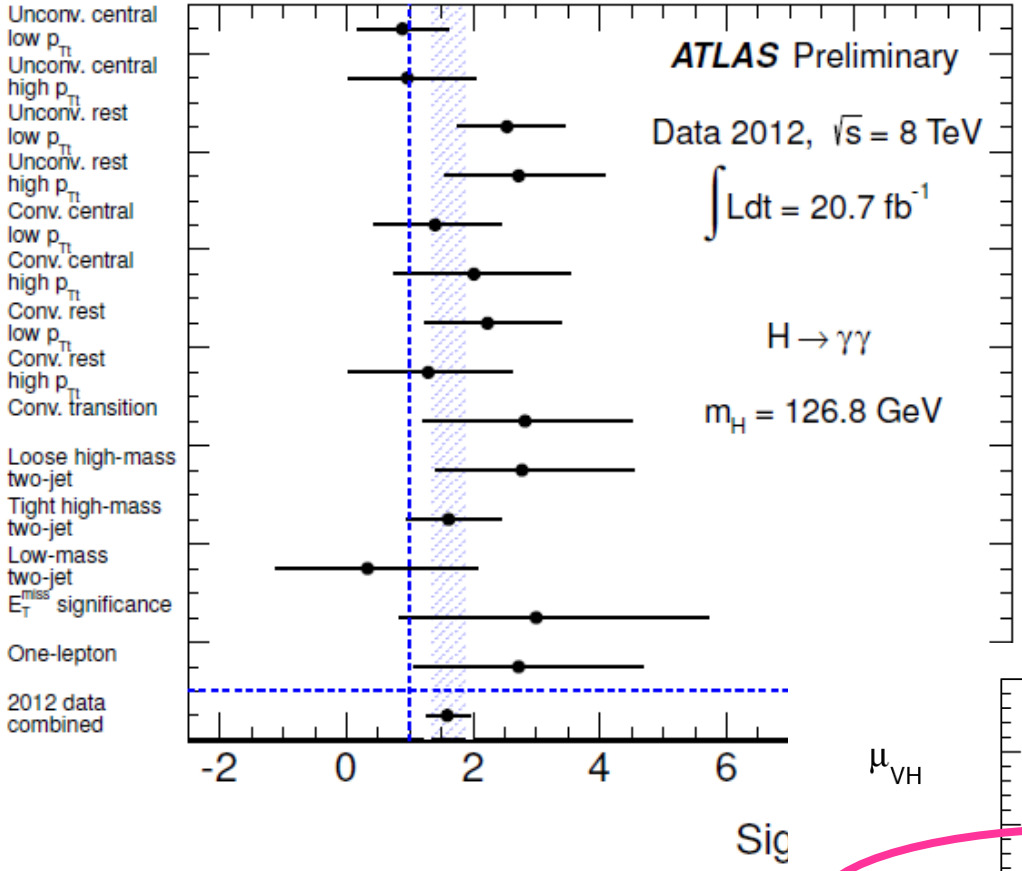
$\mu = .78^{+.28}_{-.26}$

3.2 σ

mH = 125.4 ± .5 ± .6 GeV

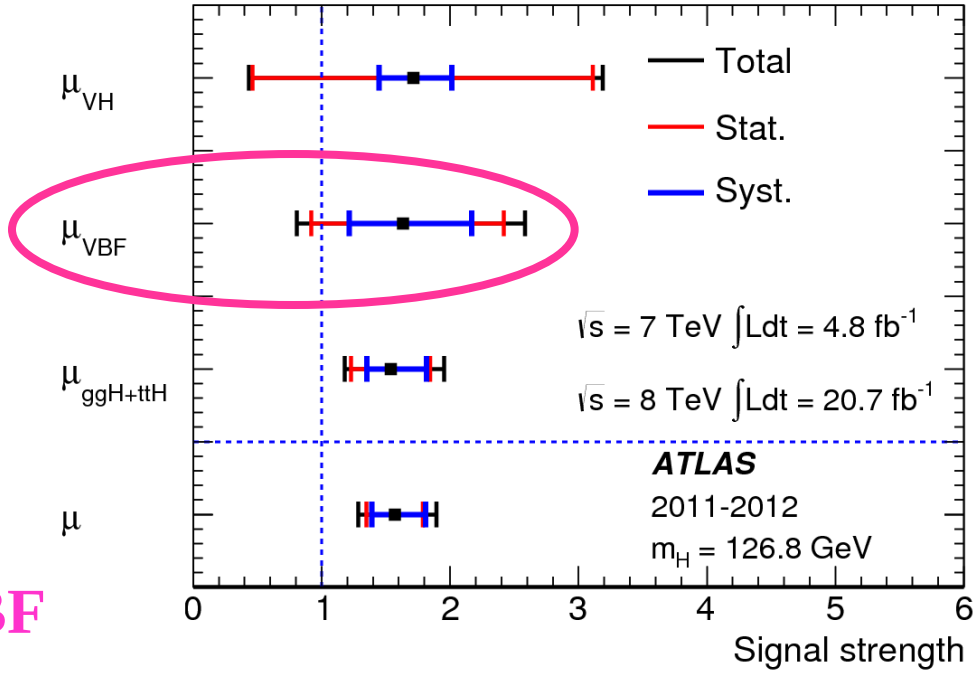
syst uncertainty : non linearity between Z and H energies and difference between e and γ (see talk of Cyril Becot next tuesday)

errors : ± .23(stat) ± .15(syst) ±. 15 (th) *similar errors*

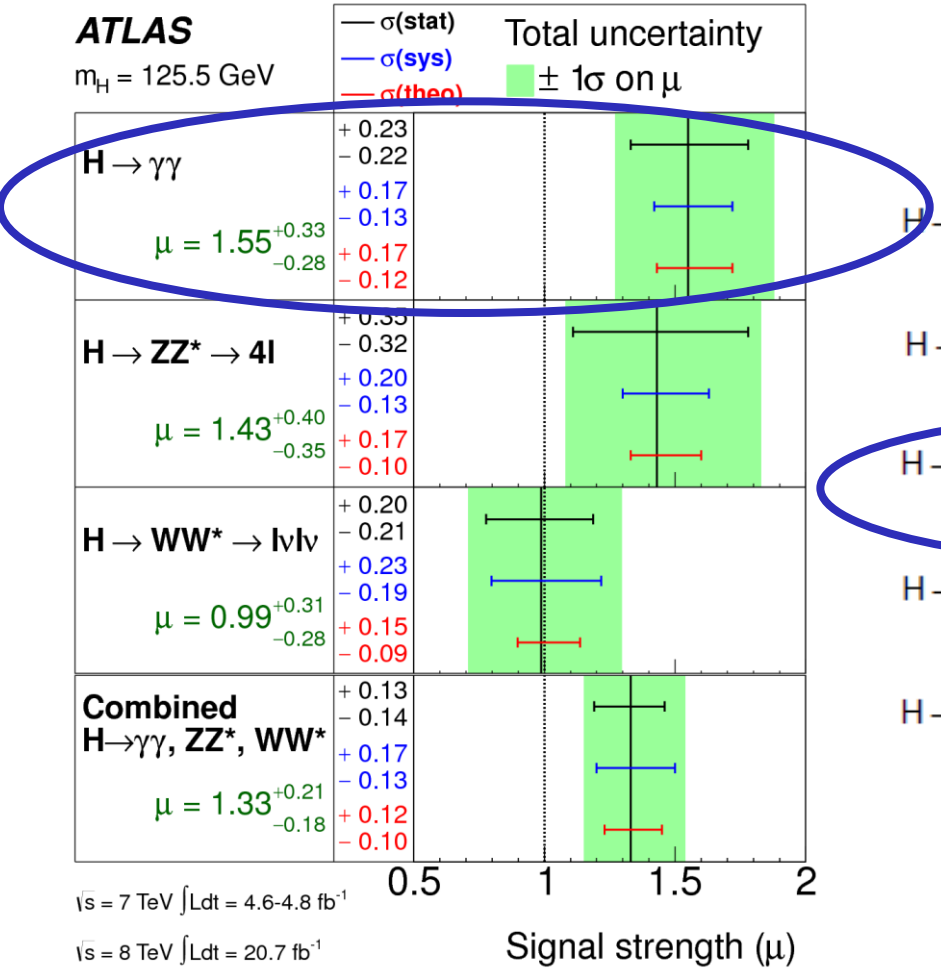


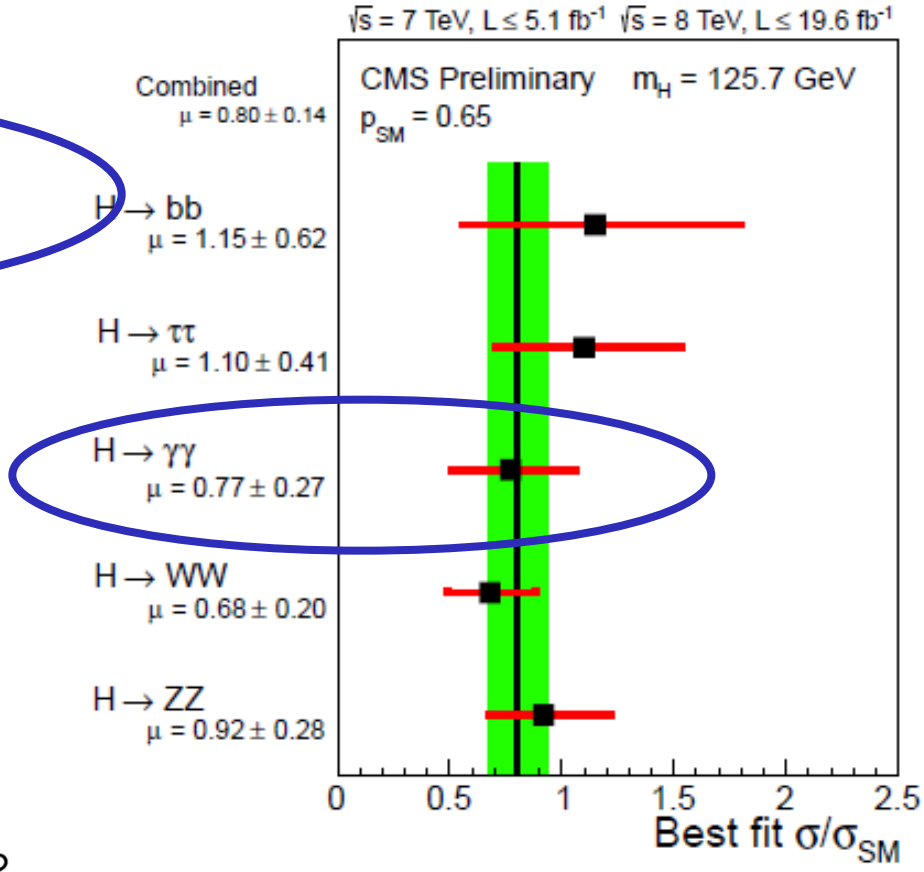
couplings measured in all categories

signal strengths for different subprocesses



start to see evidence for VBF

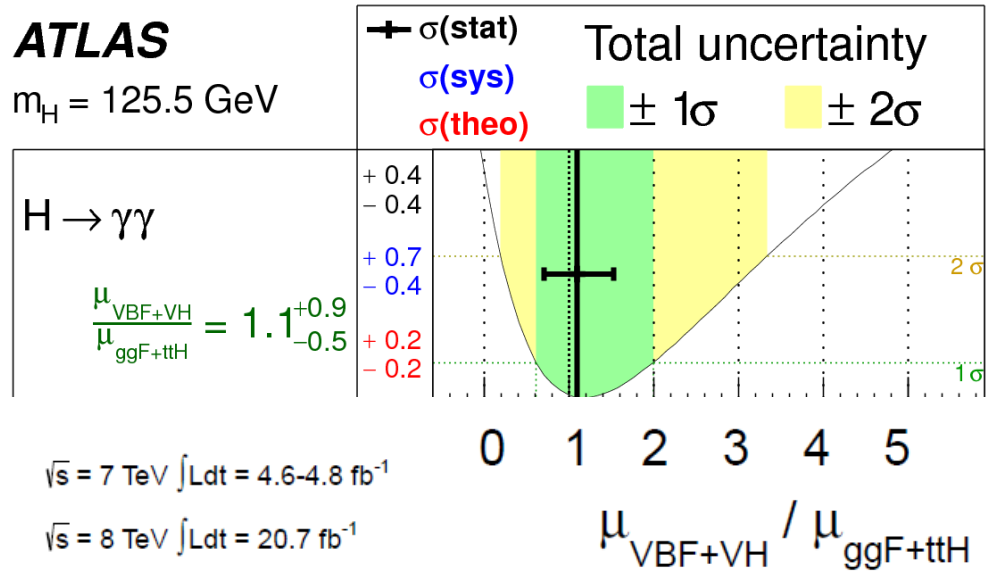




General good agreement with the Standard Model in particular γγ *(see lesson of Bruno Mansoulié)*

$$\mu_{\mathrm{VBF}}/\mu_{\mathrm{ggF}+ttH}$$

$$\mu_{\mathrm{VBF}}/\mu_{\mathrm{ggF}+ttH} = 1.4^{+0.4}_{-0.3}\,(\mathrm{stat})\,^{+0.6}_{-0.4}\,(\mathrm{sys})$$



3.3 σ effect ⟶

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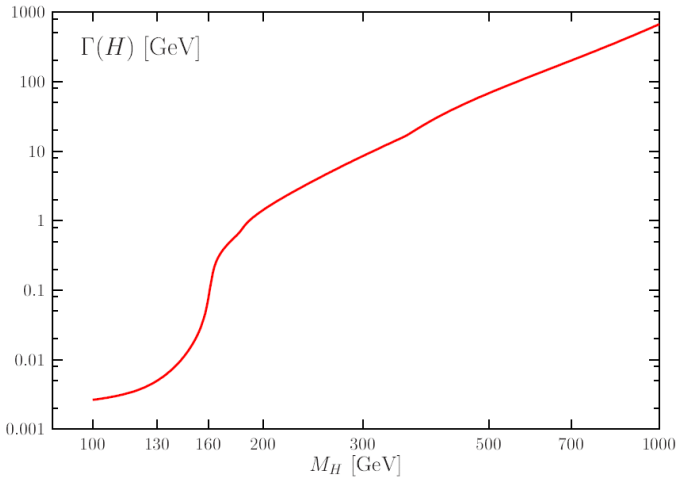


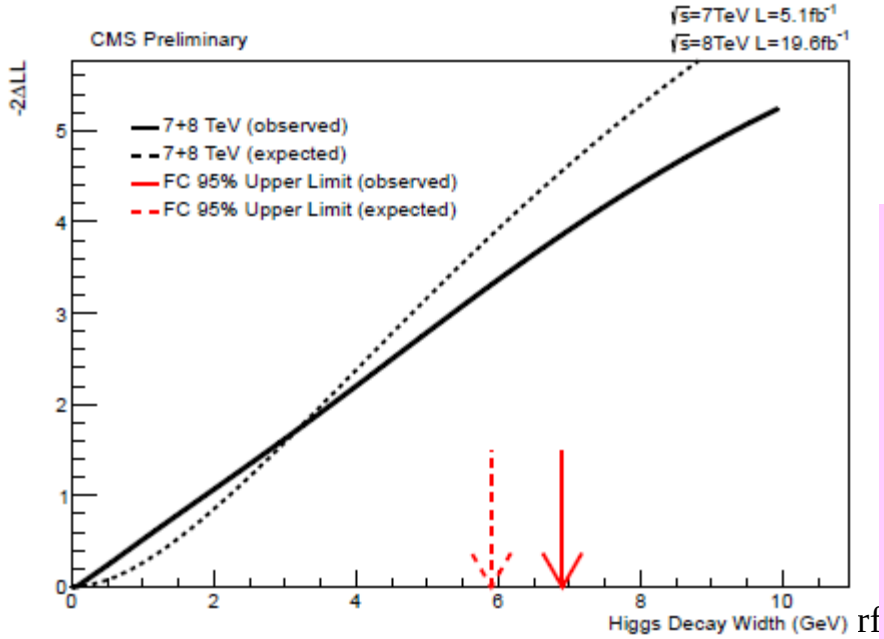
scalar boson width

compared to the experimental resolution FWHM ~ 4 GeV

and it is very difficult to obtain
$\Gamma \sim \sqrt{(FWHM_{(meas)}^2 - FWHM_{(pred)}^2)}$

the width of the SM scalar is small (Γ =4.2 MeV)

CMS PAS HIG-13-006



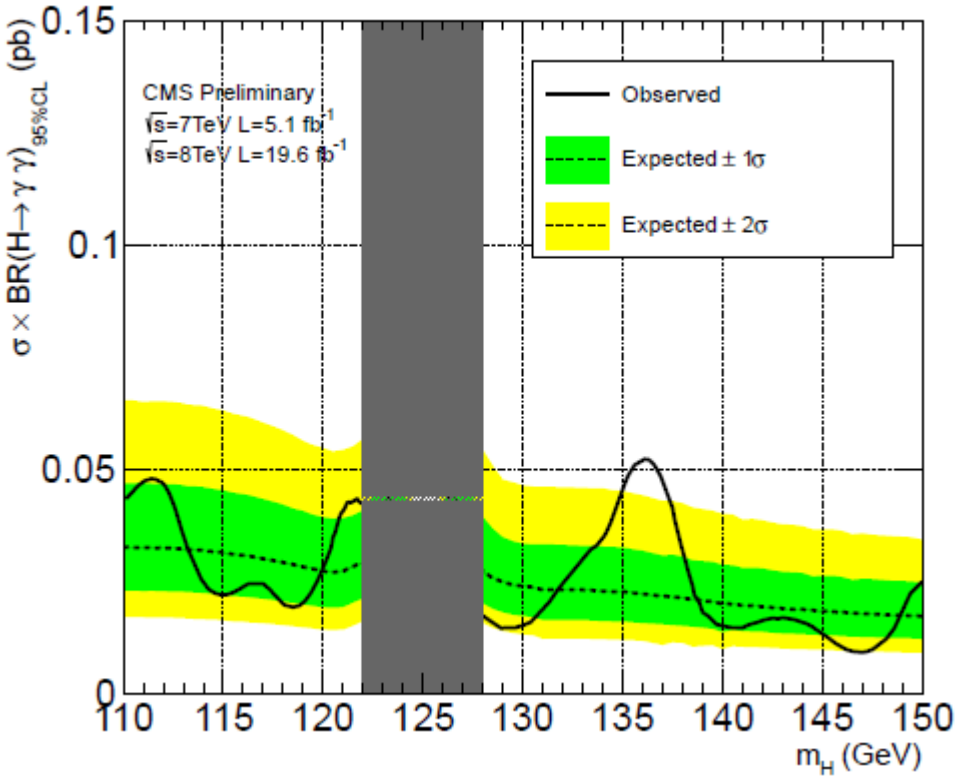
still a limit is set for Γ at 6.9 GeV 95%CL

There are other (indirect) ways of putting limits (with few hypothesis) on invisible width or invisible branching ratio

- ♥ **ZH , H → inv**
- ♥ **couplings analysis**

search for additional scalar-boson-like states

In this search the observed state around 125 GeV is considered as part of the 'background'



Once sufficiently away from 125 GeV, we recover the same limit as in the search for a single SM Higgs boson. The p-value at the most significant excess, where m_H=136.5 GeV, is found to be 2.93σ.

ATLAS-CONF-2013-072

differential cross sections

relatively high signal yield (~ 620 fitted in ATLAS at √s=8 TeV)

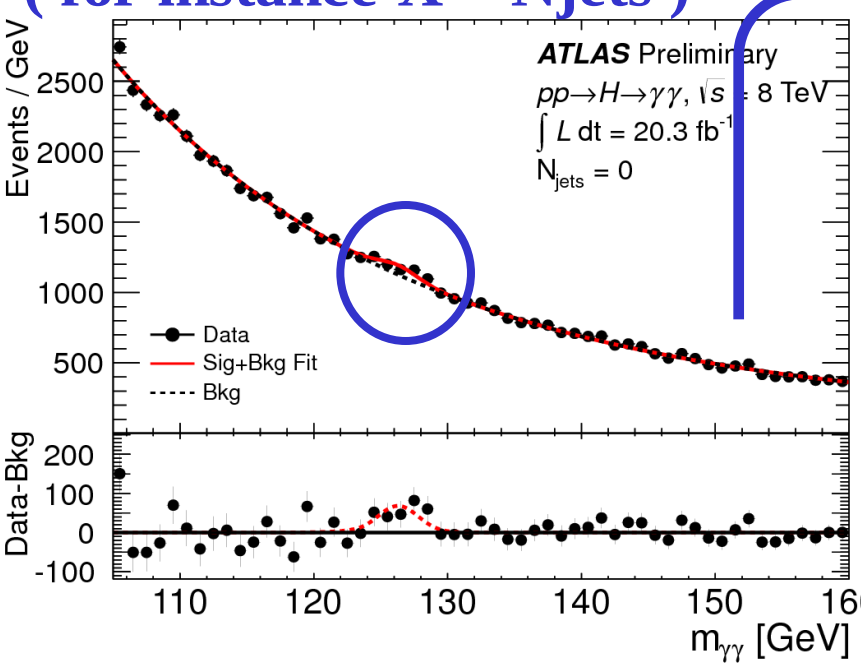
⇒ can be used to probe the underlying kinematic properties of production and decay

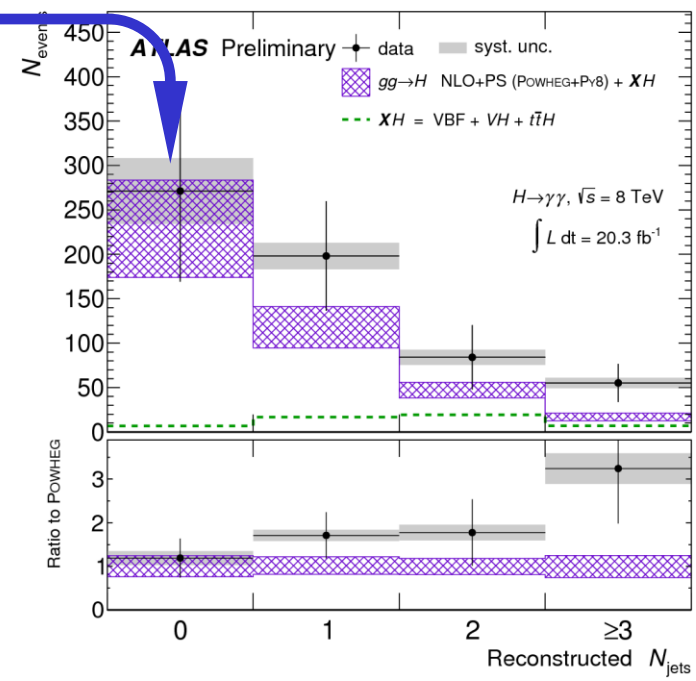
Inclusive	$p_T^{\gamma\gamma}$	Fundamental kinematics, H.O.
	$\lvert y^{\gamma\gamma}\rvert$	Fundamental kinematics, pdf
	N_{jets}	VH, VBF, $t\bar{t}H$ vs ggH, H.O.
	$\sigma_i/\sigma_{\geq i}$	H.O.
	$\lvert\cos\theta^*\rvert$	Spin
1-jet	$p_T^{leading\ jet}$	H.O.
2-jet	$\Delta\phi_{jj}$	Spin-Parity, VBF, H.O.
	$p_T^{\gamma\gamma jj}$	VBF, H.O.

Methodology :

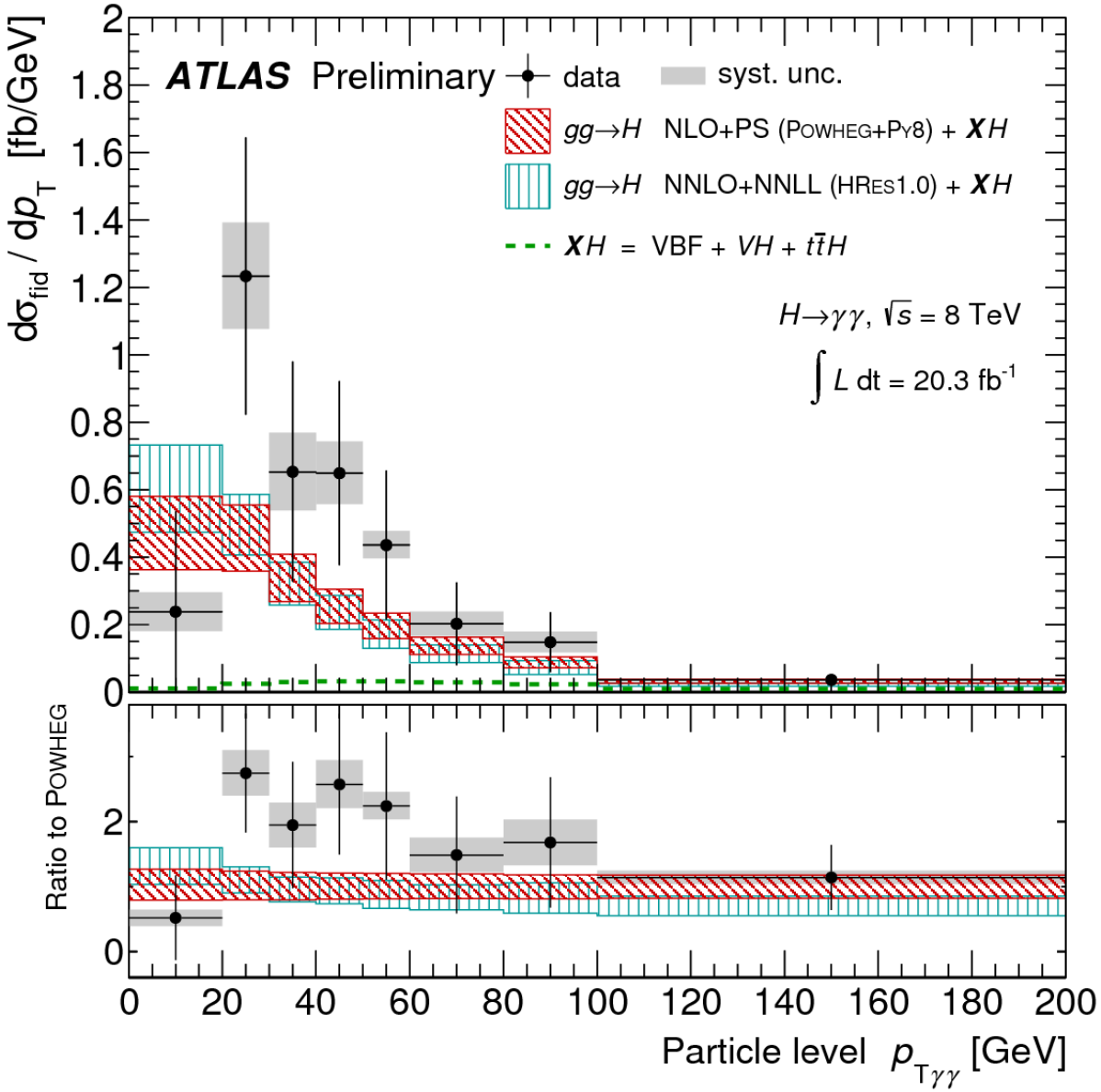
- Choose a binning for variable X
- For each bin get signal yield from $m_{\gamma\gamma}$ distribution
- Bin-by-bin unfolding (correct yields for acceptance, eff, resolution) ⇒ dσ/dX

(for instance X = Njets)





No significant deviation from SM predictions



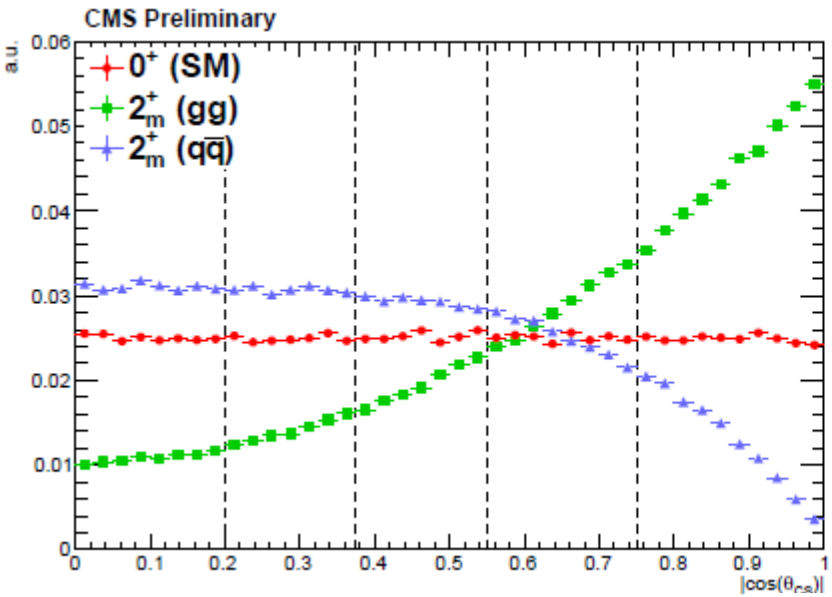
still large uncertainties

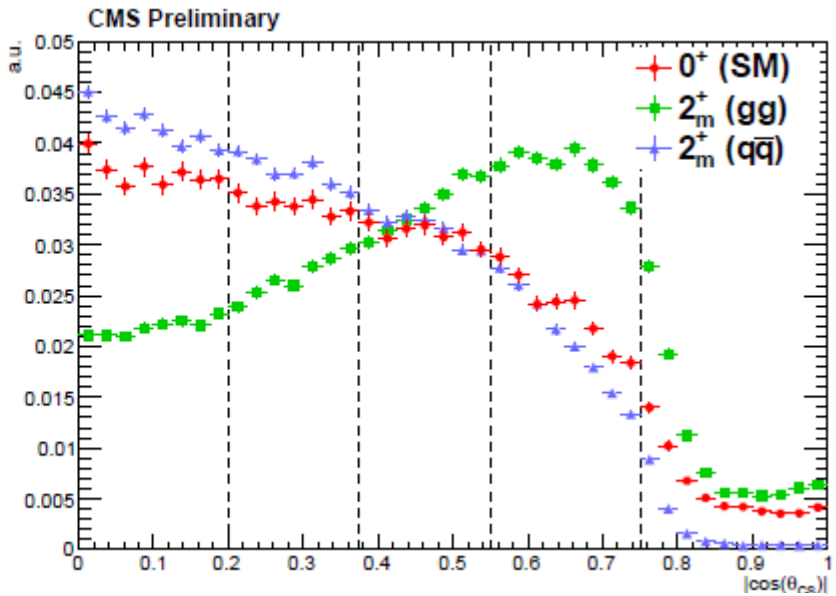
$P(\chi^2) = 0.55$
(POWHEG)

$P(\chi^2) = 0.39$
(HRES)

spin

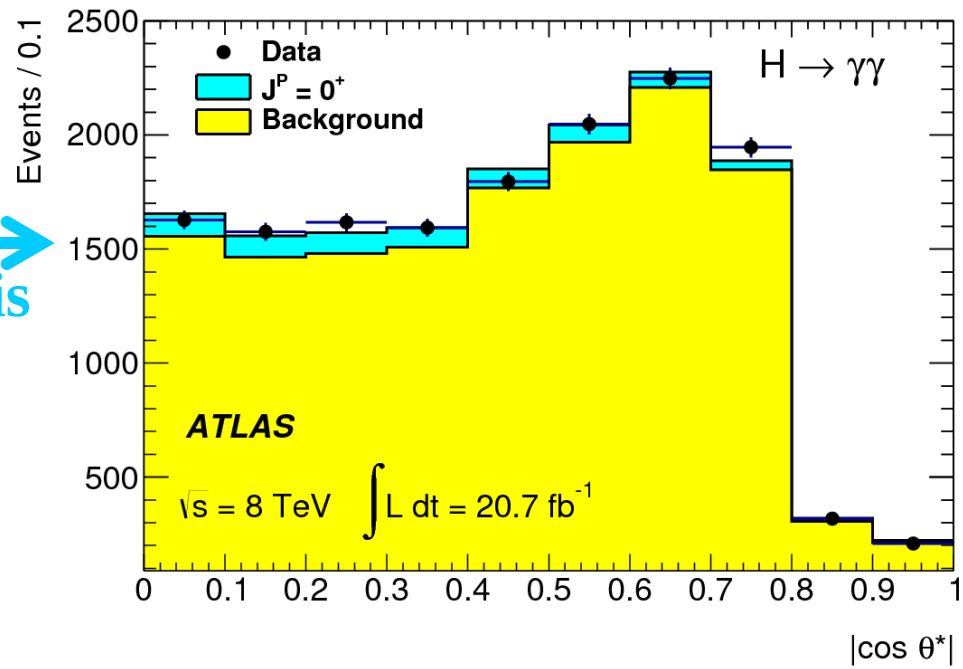
spin 1 excluded by Landau-Yang theorem



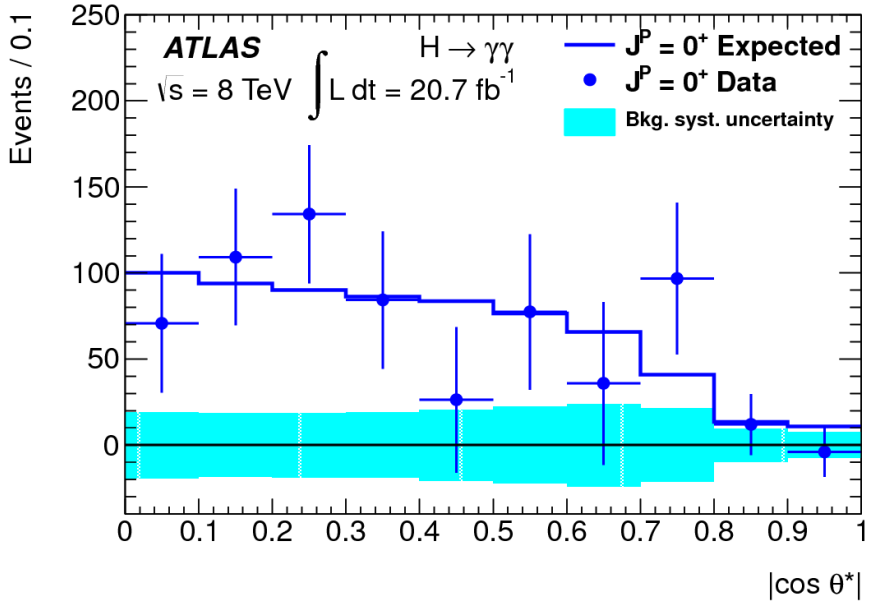


different angular distributions

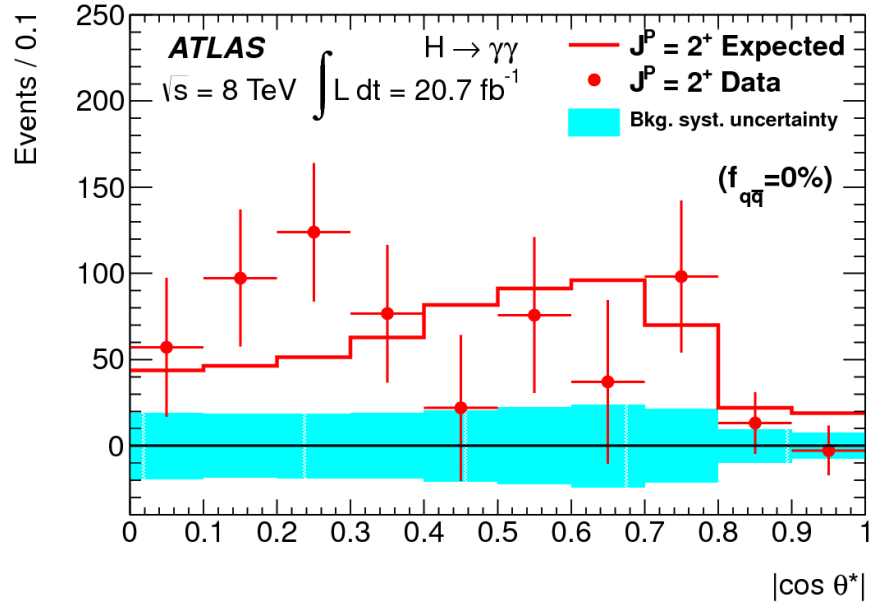
difficult analysis



fit assuming SM



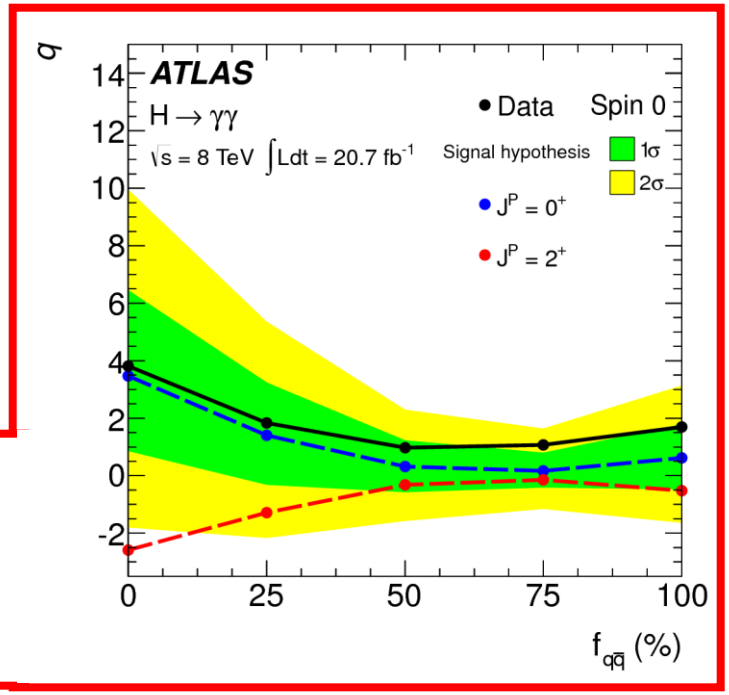
fit assuming spin 2 100% gg



For spin 2 100% gg production

- compatibility data/SM : **58.8 %**
  (**0.5 %** expected if spin 2 true)
- spin 2 model p-value : **0.3%**
  (**1.2%** expected if SM)

$\Rightarrow$ **minimal spin 2 strongly disfavoured**



large decrease of sensitivity for large q-qbar production fraction

recovered with WW channel

♥ **Introduction**

♥ **Short history of scalar boson and LHC**

♥ **History of detectors and of $H \rightarrow \gamma\gamma$**

specificities of detectors relevant to $H \rightarrow \gamma\gamma$

♥ **Discovery**

♥ **Properties**

♥ **Conclusions**

Backup (references)

Intense period of discovery , where the channel $H \rightarrow \gamma\gamma$ was very important

Followed more than 20 years of work on this subject

After the discovery this channel will be (and is already) used in order to make some measurements which can test the Standard Model

All the data is analysed . Final results will come soon (waiting for final calibrations)

yery nice (*at least for experimentalists* **) to have several channels ($\gamma\gamma$, bb , ZZ , WW , $\tau\tau$) opened for mH= 125 GeV**

Several results were not shown , like

- *search for two near-mass degenerate states*
- *dedicated ttH search*
- *FCNC tt with $t \rightarrow cH$ ...*

Thank you for your attention

♥ **Introduction**

♥ **Short history of scalar boson and LHC**

♥ **History of detectors and of $H \rightarrow \gamma\gamma$**
specificities of detectors relevant to $H \rightarrow \gamma\gamma$

♥ **Discovery**

♥ **Properties**

♥ **Conclusions**

Backup (references and additional plots)

Historical references

For a list of historical references see

Nansi Andari (Orsay, LAL) CERN-THESIS-2012-144
Observation of a BEH-like boson decaying into two photons with the ATLAS detector at the LHC

Early H→γγ theory references

L. Resnick, M.K. Sundaresan and P.J.S. Watson, *Is there a light scalar boson*, Phys.Rev.D8:172-178, 1973.

J. Ellis, M. K. Gaillard and D. Nanopoulos, *A Phenomenological Profile of the Higgs Boson*, Nucl.Phys.B106:292, 1976.

M. Shifman, A. Vainshtein, M. Voloshin, and V. Zakharov, *Low-energy theorems for Higgs boson couplings to photons*, Sov.J.Nucl.Phys.30:711-716, 1979 [Yad.Fiz.30:1368-1378, 1979]

Early phenomelogical/experimental references (pre-LHC)

J. Gunion et al., *Searching For The Intermediate Mass Higgs Boson*, Phys.Rev.D34:101, 1986.

J. Gunion, G. Kane and J. Wudka, *Search Techniques for Charged and Neutral Intermediate Mass Higgs Bosons*, Nucl.Phys.B299:231, 1988.

C. Barter et al., *Detection of $H \to \gamma\gamma$ at the SSC*, Proceedings of the Summer Study on HEP in the 1990's, june 1988, Snowmass, Colorado

M. Mangano, *Production of $WH \to W\gamma\gamma$*, SSC-SDC-90-00113.

Early phenomelogical/experimental references (LHC)

C. Seez and J. Virdee, *Photon decay modes of the intermediate masss Higgs*, Large Hadron Collider Workshop, Aachen October 1990 (ed by G. Jarlskog and D. Rein), vol 2 report CERN 90-10 ECFA 90-133 page 474

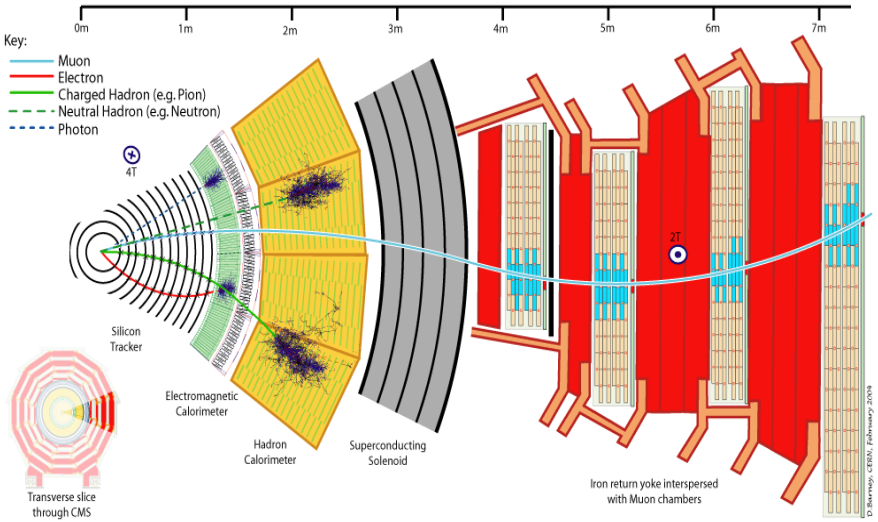
D. Fournier, *Liquid Argon Calorimetry*, Large Hadron Collider Workshop, Aachen, October 1990, vol 3, CERN-90-10, ECFA90-133 page 356.

L. Fayard and G. Unal, *Search for Higgs decay into photons with EAGLE*, ATL-PHYS-92-001.

The LOI's of ATLAS,CMS and L3P

B.Mansoulié et al. ATL-CAL-92-008
Study of the rejection of pi-zeros by a cold preshower behind, the coil and cryostat (Dice-A): rapidity dependance, noise dependance

CMS references



CMS-PAS-EGM-10-005
Photon reconstruction and identification at sqrt(s) = 7 TeV

CMS-PAS-EGM-10-006
Isolated Photon Reconstruction and Identification at √s = 7 TeV

CMS-PAS-HIG-11-010
Search for a Higgs boson decaying into two photons in the CMS detector *(1 fb-1*
8 categories : pT - converted , non-converted - Barrel , End-Cap)

CMS-PAS-HIG-11-011
SM Higgs Combination *(1 fb-1)*

CMS-PAS-HIG-11-021
Search for a Higgs boson decaying into two photons in the CMS detector *(1.7 fb-1)*

CMS-PAS-HIG-11-023
Combined Standard Model Higgs boson searches with up to 2.3 inverse femtobarns of pp collision data at sqrt(s)=7 TeV at the LHC (ATLAS + CMS)

CMS-PAS-HIG-11-030
Search for a Higgs boson decaying into two photons in the CMS detector *(5 fb-1*
4 categories : converted , non converted - Barrel , Endcap , local significance of 2.3 σ)

CMS-PAS-HIG-11-032
Combination of SM Higgs Searches *(5 fb-1)*

Phys.Lett. B710 (2012) 26-48
Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s}$ =7 TeV

Phys.Lett. B710 (2012) 403-425
Search for the standard model Higgs boson decaying into two photons in pp collisions at $\sqrt{s}$ =7 TeV *(5 categories , in addition dijet à la VBF , local significance of 3.1 σ)*

CMS-PAS-HIG-12-001
A search using multivariate techniques for a standard model Higgs boson decaying into two photons *(7 TeV , MVA , local significance of 2.9 σ , 5 categories : 4 from BDT and a dijet one à la VBF)*

CMS-PAS-HIG-12-008
Combination of SM, SM4, FP Higgs boson searches *(like 12-001 , 7 TeV , excludes fermiophobic)*

CMS-PAS-HIG-12-002
Search for the fermiophobic model Higgs boson decaying into two photons
(7 categories : 4 from converted, non converted – barrel , endcap a dijet tag à la VBF , an electron tag one and a muon tag one)

JHEP 1209 (2012) 111
Search for a fermiophobic Higgs boson in pp collisions at $\sqrt{s}$ =7 TeV
($\gamma\gamma$ like 12-002, ZZ,WW)

CMS-PAS-HIG-12-015

Evidence for a new state decaying into two photons in the search for the standard model Higgs boson in pp collisions *(local significance = 4.1 σ, 5 categories at 7 TeV , 6 at 8 TeV , 4 by BDT at 7 and 8 TeV , 1 additional dijet category at 7 TeV , 2 additional dijet categories at 8 TeV)*

CMS-PAS-HIG-12-020

Observation of a new boson with a mass near 125 GeV

CMS-PAS-HIG-12-022

Higgs to gamma gamma, Fermiophobic *(5+ 5 fb-1*
2011 : 7 categories like in JHEP 1209 (2012) 111
2012 : 9 categories : converted, unconverted – Barrel-Endcap , 2 dijet categories , 1 e category , 1 μ category and 1 Etmiss category)

Phys.Lett. B716 (2012) 30-61

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
(uses 12-015 for $\gamma\gamma$ mH comb = 125.3 $\pm$ .4 $\pm$ .5 GeV)

CMS-PAS-HIG-12-045
Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV *(5 + 13 fb-1 , but H→γγ 5 + 5 fb-1 uses Phys.Lett. B716 (2012) 30-61)*

CMS-PAS-HIG-12-049
Search for a Light Higgs boson in the Z boson plus a Photon Decay Channel *(5 + 5 fb-1)*

Phys.Lett. B725 (2013) 36-59
Searches for Higgs bosons in pp collisions at sqrt(s) = 7 and 8 TeV in the context of four-generation and fermiophobic models *(γγ like in Phys.Lett. B716 (2012) 30-61 5 + 5 fb-1)*

CMS-PAS-HIG-13-006
Search for the standard model Higgs boson in the Z boson plus a photon channel in pp collisions at √s = 7 and 8 TeV *(5 + 20 fb-1)*

JHEP 06 (2013) 081
Observation of a new boson with mass near 125 GeV in pp collisions at sqrt(s) = 7 and 8 TeV

CMS-PAS-HIG-13-001

Updated measurements of the Higgs boson at 125 GeV in the two photon decay channel

(3.2 σ mH = 125.4 $\pm$.5 $\pm$.6 GeV

MVA analysis : 5 categories at 7 TeV , 9 at 8 TeV ,

4 by BDT at 7 and 8 TeV , 1 additional dijet category at 7 TeV ,

2 additional dijet categories , 1 muon-tag, 1 e-tag and 1 Etmiss tag at 8 TeV

There is also a cut-based analysis described)

CMS-PAS-HIG-13-005

Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV *($\gamma\gamma$ uses 13-001 , mH comb = 125.7 $\pm$.3 $\pm$.3 GeV)*

CMS-PAS-HIG-13-015

Search for ttH production in events where H decays to photons at 8 TeV collisions

(2 analysis : 2 top hadronic

1 hadronic and 1 leptonic)

arXiv:1306.2016

Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s} = 7$ TeV

CMS-PAS-HIG-13-016

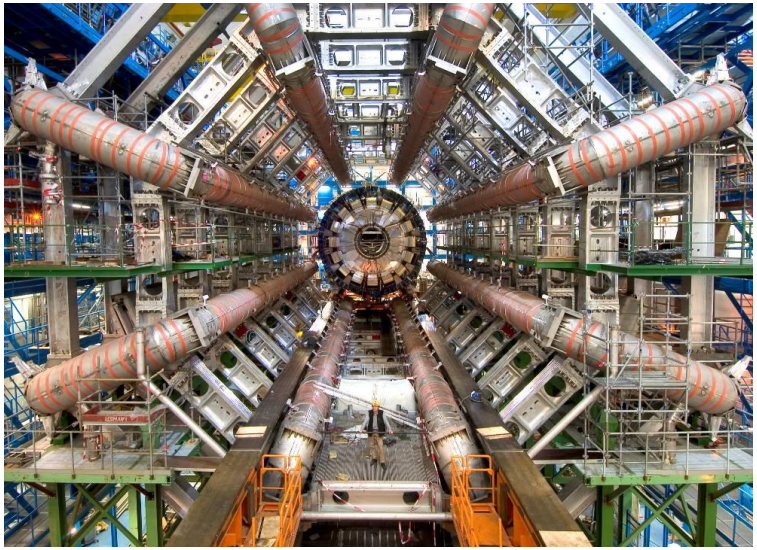
Properties of the observed Higgs-like resonance using the diphoton channel **S**

(like 13-001 . natural width and second Higgs scenario uses MVA analysis , spin uses cut based analysis)

arXiv:1307.5515

Search for a Higgs boson decaying into a Z and a photon in pp collisions at $\sqrt{s} = 7$ and 8 TeV

ATLAS references



Lampl, W ; Laplace, S ; Lelas, D ; Loch, P ; Ma, H ; Menke, S ;
Rajagopalan, S ; Rousseau, D ; Snyder, S ; Unal, G

ATL-LARG-PUB-2008-002

Calorimeter Clustering Algorithms : Description and Performance

ATLAS-CONF-2011-004
Measurement of the backgrounds to the Higgs To gammagamma search and reappraisal of its sensitivity with 37 pb-1 of data recorded by the ATLAS detector

ATLAS-CONF-2011-025
Search for the Higgs boson in the diphoton final state with 38 ipb of data recorded by the ATLAS detector in proton-proton collisions at sqrt(s)=7 TeV *PCL*

ATL-PHYS-PUB-2011-007
Expected photon performance in the ATLAS experiment

ATLAS-CONF-2011-085
Search for the Higgs Boson in the Diphoton Channel with the ATLAS Detector using 209 pb-1 of 7 TeV Data taken in 2011 *PCL*

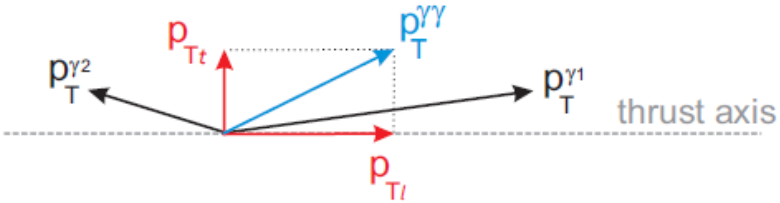
Eur.Phys.J. C71 (2011) 1728
Limits on the production of the Standard Model Higgs Boson in pp collisions at $\sqrt{s}$ =7 TeV with the ATLAS detector *1st combination H 40 pb-1*

ATLAS-CONF-2011-135
Update of the Combination of Higgs Boson Searches in 1.0 to 2.3 fb−1 of pp Collisions Data Taken at $\sqrt{s}$ = 7 TeV with the ATLAS Experiment at the LHC

Phys.Lett. B705 (2011) 452-470
Search for the Standard Model Higgs boson in the two photon decay channel with the ATLAS detector at the LHC *(1 fb^{-1})*

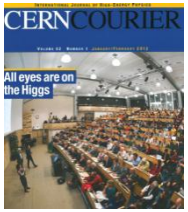
ATLAS-CONF-2011-149
Search for a fermiophobic Higgs boson in the diphoton channel with the ATLAS detector *(1 fb^{-1} , pT categories)*

ATLAS-CONF-2011-157
Combined Standard Model Higgs boson searches with up to 2.3 fb-1 of pp collision data at sqrt{s} = 7 TeV at the LHC (ATLAS+CMS)



ATLAS-CONF-2011-161
Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 fb-1 of ATLAS data at sqrt(s)=7 TeV *(PTt and conversion categories : 9 categories local significance = 2.8 σ)*

ATLAS-CONF-2011-163
Combination of Higgs Boson Searches with up to 4.9 fb-1 of pp Collision Data Taken at sqrt(s)=7 TeV with the ATLAS Experiment at the LHC



Phys.Lett. B710 (2012) 49-66
Combined search for the Standard Model Higgs boson using up to 4.9 fb -1 of pp collision data at $\sqrt{s}$ =7 TeV with the ATLAS detector at the LHC

Phys.Rev.Lett. 108 (2012) 111803
Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 fb -1 of pp collisions at $\sqrt{s}$ =7 TeV with ATLAS *(local significance = 2.8 σ)*

ATLAS-CONF-2012-013
Search for a fermiophobic Higgs boson in the diphoton decay channel with 4.9/fb of ATLAS data at sqrt(s)= 7 TeV *(using 9 categories)*

ATLAS-CONF-2012-019
An update to the combined search for the Standard Model Higgs boson with the ATLAS detector at the LHC using up to 4.9 fb-1 of pp collision data at $\sqrt{s}$ = 7 TeV

Eur.Phys.J. C72 (2012) 2157
Search for a fermiophobic Higgs boson in the diphoton decay channel with the ATLAS detector (5 fb-1)

ATLAS-CONF-2012-048

Performance of the ATLAS Electron and Photon Trigger in p-p Collisions at sqrt{s} = 7 TeV in 2011

ATLAS-CONF-2012-091

Observation of an excess of events in the search for the Standard Model Higgs boson in the gamma-gamma channel with the ATLAS detector *(10 categories , including a 2 jet – à la VBF – one , 5 (2011) + 6 (2012) fb^{-1} local significance = 4.5 σ)*

ATLAS-CONF-2012-093

Observation of an Excess of Events in the Search for the Standard Model Higgs boson with the ATLAS detector at the LHC *(WW only 2011)*

Phys.Lett. B716 (2012) 1-29

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC *(with WW 2012 mH comb = 126.0 $\pm$.4 $\pm$.4 GeV)*

ATLAS-CONF-2012-123

Measurements of the photon identification efficiency with the ATLAS detector using 4.9 fb−1 of pp collision data collected in 2011

ATLAS-CONF-2012-127
Coupling properties of the new Higgs-like boson observed with the ATLAS detector at the LHC *(5+6 fb^{-1})*

ATLAS-CONF-2012-162
Updated ATLAS results on the signal strength of the Higgs-like boson for decays into WW and heavy fermion final states *(includes 13fb^{-1} of 2012 except $\gamma\gamma$ 5+6 fb^{-1})*

ATLAS-CONF-2012-168
Observation and study of the Higgs boson candidate in the two photon decay channel with the ATLAS detector at the LHC *(mH = 126.6 $\pm$.3 $\pm$.7 GeV local significance = 6.1 σ 5+ 13 fb^{-1} 12 categories in 2012 with two 2-jet categories and a one-lepton category)*

ATLAS-CONF-2012-170
An update of combined measurements of the new Higgs-like boson with high mass resolution channels *(mH comb = 125.2 $\pm$.3 $\pm$.6 GeV 5+13 fb^{-1})*

ATLAS-CONF-2013-009
Search for the Standard Model Higgs boson in the H $\rightarrow$ Zγ decay mode with pp collisions at $\sqrt{s}$ = 7 and 8 TeV *(5+ 20 fb^{-1})*

ATLAS-CONF-2013-012

Measurements of the properties of the Higgs-like boson in the two photon decay channel with the ATLAS detector using 25 fb−1 of proton-proton collision data **S**

(14 categories including two 2-jet high mass , one 2-jet low mass , lepton , ETmiss local significance = 7.4 σ , mH=126.8 $\pm$.2 $\pm$.7 GeV)

ATLAS-CONF-2013-014

Combined measurements of the mass and signal strength of the Higgs-like boson with the ATLAS detector using up to 25 fb-1 of proton-proton collision data

(mH comb= 125.5 $\pm$.2 $^{+.5}_{-.6}$ GeV)

ATLAS-CONF-2013-029

Study of the spin of the Higgs-like boson in the two photon decay channel using 20.7 fb-1 of pp collisions collected at sqrt(s) = 8 TeV with the ATLAS detector **S**

ATLAS-CONF-2013-034

Combined coupling measurements of the Higgs-like boson with the ATLAS detector using up to 25 fb-1 of proton-proton collision data *(10 σ)*

ATLAS-CONF-2013-040

Study of the spin of the new boson with up to 25 fb−1 of ATLAS data **S**

arXiv:1307.1427
Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-02/

arXiv:1307.1432
Evidence for the spin-0 nature of the Higgs boson using ATLAS data **S**
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-01/

ATLAS-CONF-2013-072
Differential cross sections of the Higgs boson measured in the diphoton decay channel with the ATLAS detector using 8 TeV proton-proton collision data

ATLAS-CONF-2013-080
Search for ttH production in the $H \rightarrow \gamma\gamma$ channel at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS-CONF-2013-081
Search for flavour changing neutral currents in top quark decays $t \rightarrow cH$, with $H \rightarrow \gamma\gamma$, and limit on the tcH coupling with the ATLAS detector at the LHC

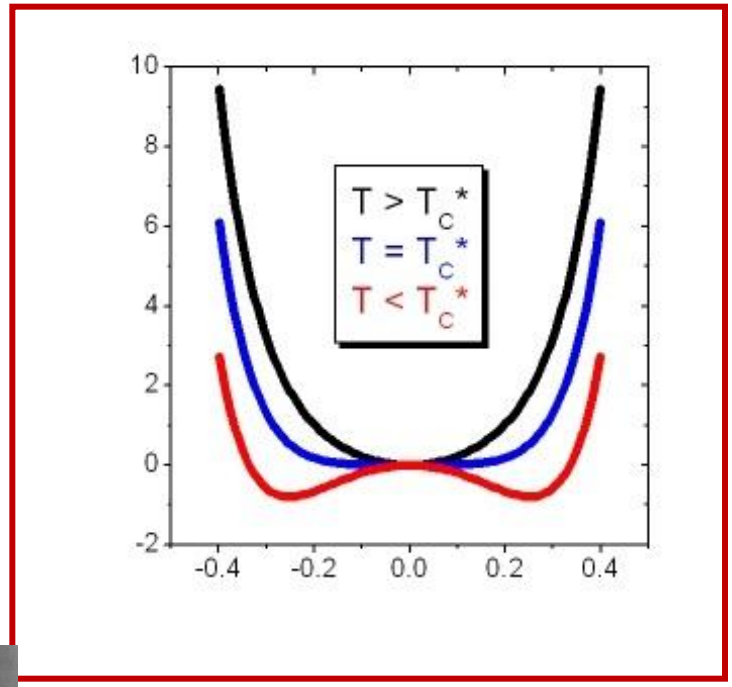
Condensed matter physics

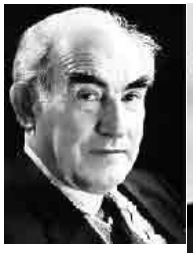
SSB = Spontaneous Symmetry Breaking :There are symmetries of the Lagrangian that are not symmetries of the fundamental state (vacuum)

1928 (Heisenberg) For $T<T_C$ dipoles are aligned in some arbitrary direction

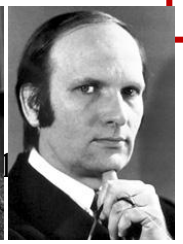
1950 (Ginzburg Landau) : phase transition in superconductivity

1957 (Bardeen, Cooper, Schrieffer) SSB of EM gauge invariance







Particle physics - strong interaction (global symmetry)

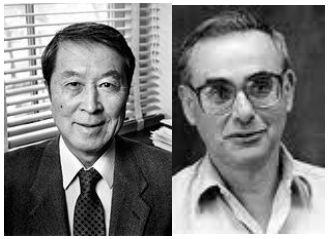
1959 (Nambu Jona-Lasinio**) : SSB transmitted from condensed matter to particle physics**
SSB of (global) chiral symmetry → pseudoscalar boson π^0
massless boson if exact symmetry

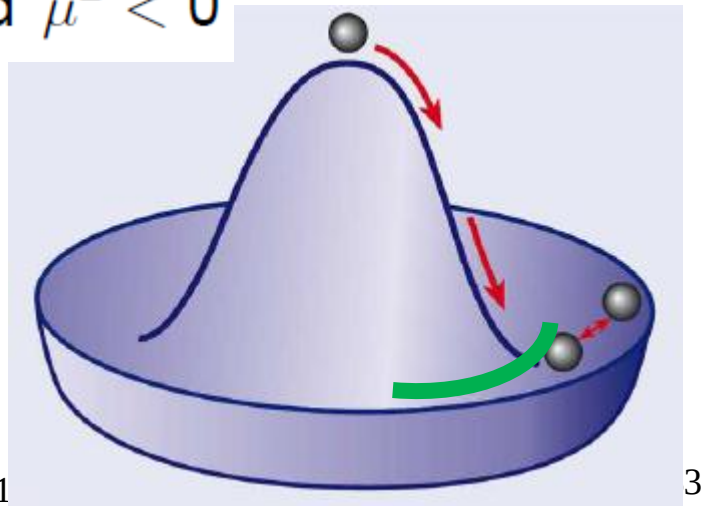
1960 (Goldstone) : generalization : SSB of continuous global symmetry → massless (Nambu-Goldstone) bosons

$$L = \partial^\mu \phi^\dagger \partial_\mu \phi - V(\phi^\dagger \phi)$$

$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2; \quad \lambda > 0 \text{ and } \mu^2 < 0$$

and massive boson mass $\sqrt{(-2\,\mu^2)}$
$\sigma = f_0(600)$





Particle physics - strong interaction (local symmetry)

1964 (Brout,Englert, Higgs, Guralnik, Hagen,Kibble)

SSB of gauge symmetries

The BEH mechanism : no massless particles
massive gauge bosons

mass of gauge boson acquired by 'eating' the N-G boson

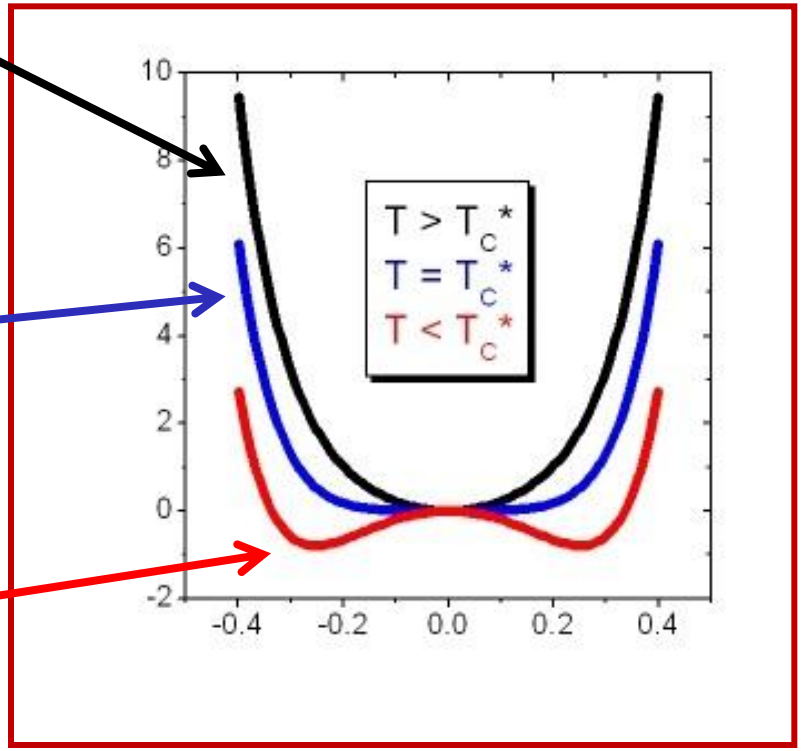
one massive particle $\sqrt{(-2\mu^2)}$: BEH boson (or Higgs boson)



Mass of the 4 scalar bosons positive
W and Z mass = 0
fermion masses =0

10^{-10} s

Mass of one scalar (BEH) boson positive
W and Z mass positive
fermion have their masses



Searching for the intermediate-mass Higgs boson

John F. Gunion
Physics Department, University of California, Davis, California 95616

Pat Kalyniak
Physics Department, Carleton University, Ottawa, Ontario, Canada K1S 5B6

M. Soldate
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Peter Galison
Physics Department, Stanford University, Stanford, California 94305
(Received 30 September 1985)

We study the feasibility of detecting a neutral Higgs boson H^0, with mass between $2m_t \approx 80$ GeV (by assumption) and $2m_W$ at an e^+e^- machine or the Superconducting Super Collider (SSC). Backgrounds to the production at an e^+e^- machine of H^0 in association with a Z are calculated with particular emphasis on the case when $m_H \approx m_z$. We present a detailed survey of the signals for and backgrounds to the inclusive or associated production at the SSC of H^0 followed by the decay of H^0 into one of the available channels. There is no signature which is established to be identifiable at the SSC. Only a few signatures remain to be studied, and the further calculations of most immediate interest are pointed out.

SEARCH TECHNIQUES FOR CHARGED AND NEUTRAL INTERMEDIATE-MASS HIGGS BOSONS*

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Received 12 October 1987

J.Gunion **G.Kane**

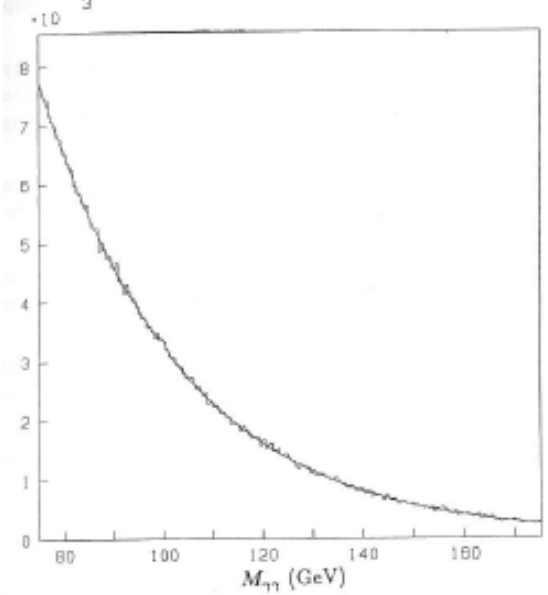

FIG. 6. Simulated mass distribution for 100 GeV Higgs in detector with extraordinary resolution.

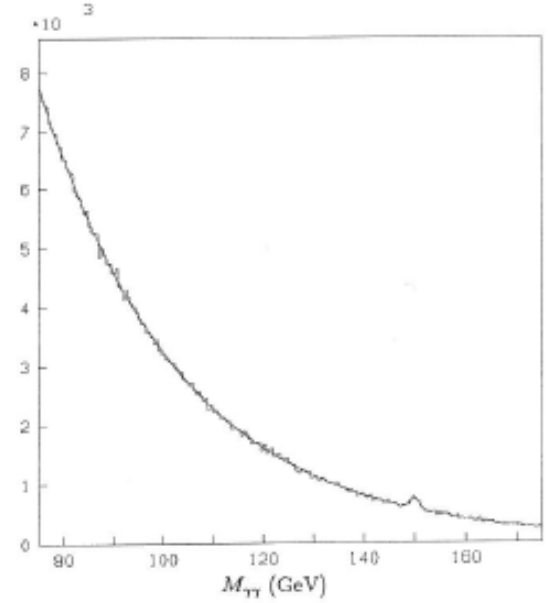

FIG. 7. Simulated mass distribution for 150 GeV Higgs in detector with extraordinary resolution.

DETECTION OF $H^0 \to \gamma\gamma$ AT THE SSC

C. Barter and R. Partridge
Brown University, Providence, Rhode Island 02912

A. Bay and A. Spadafora
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A. Abashian
University of Virginia, Chalottesville, Virginia 22901

R. Kass
Ohio State University, Columbus, Ohio 43210

Proceedings of the Summer Study on
High Energy Physics in the 1990s

June 27 – July 15, 1988
Snowmass, Colorado

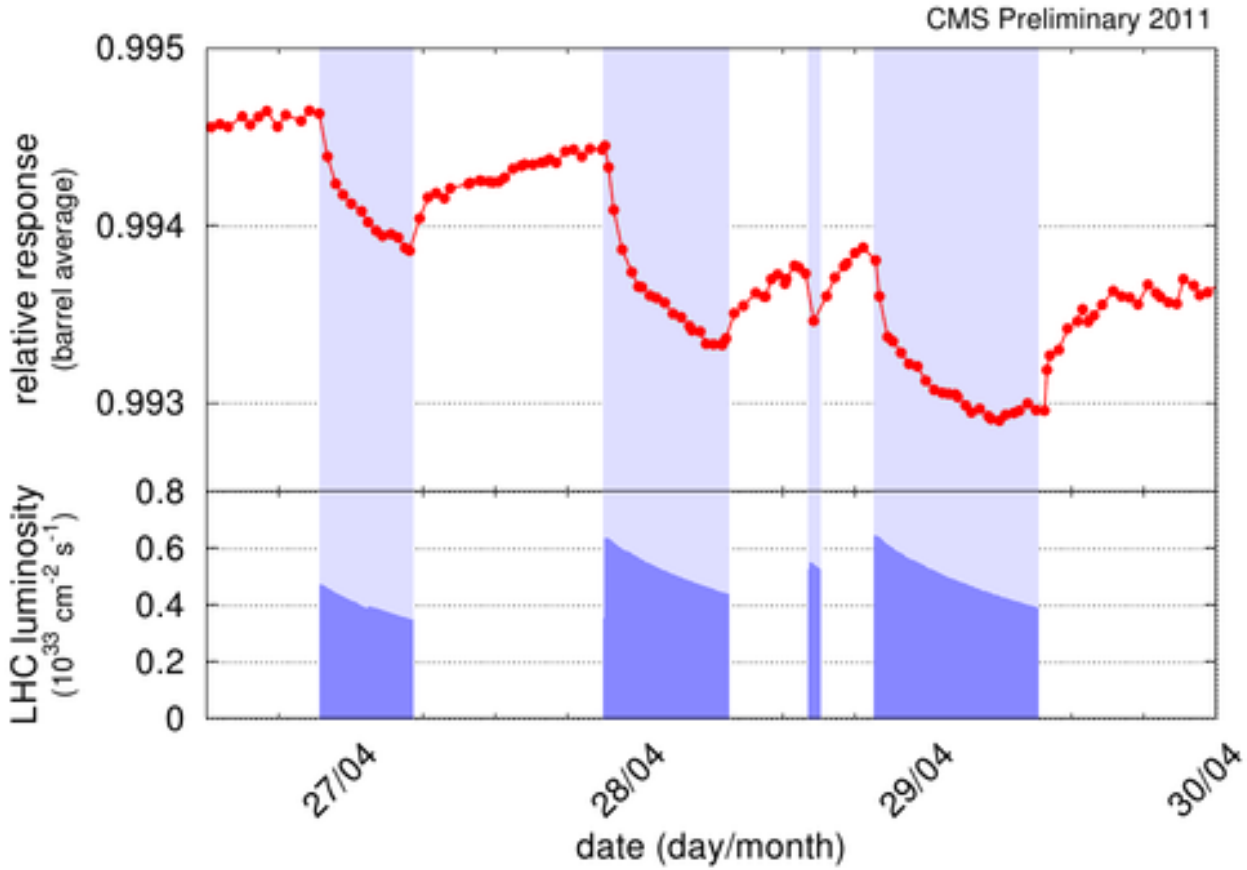
Editor
Sharon Jensen

SSC-SDC-90-00113

PRODUCTION OF $WH \to W\gamma\gamma \to e/\mu\gamma\gamma$

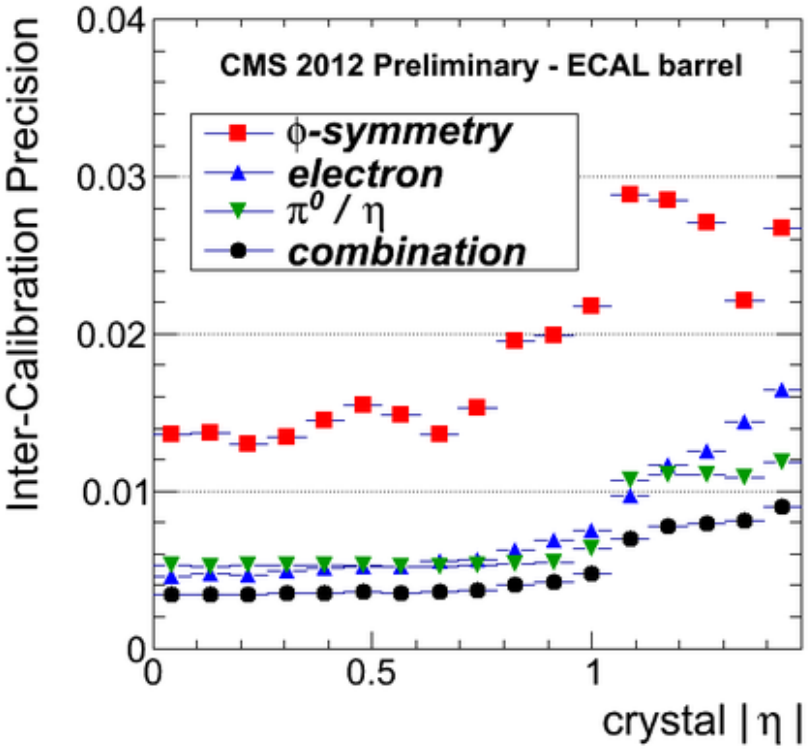
Michelangelo L. MANGANO

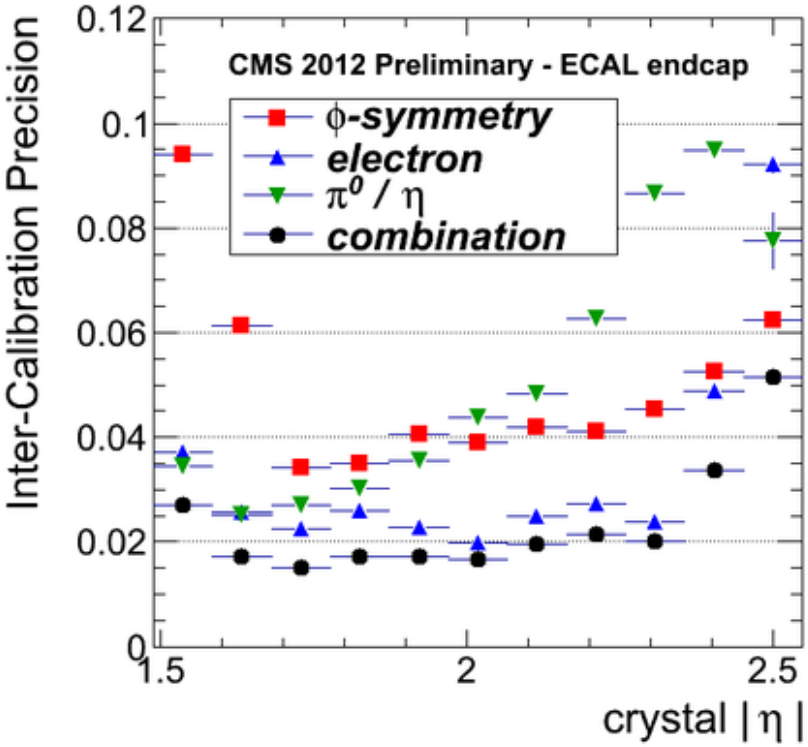
Istituto Nazionale di Fisica Nucleare
Scuola Normale Superiore and
Dipartimento di Fisica, Pisa, ITALY



CMS-DP-2013/007

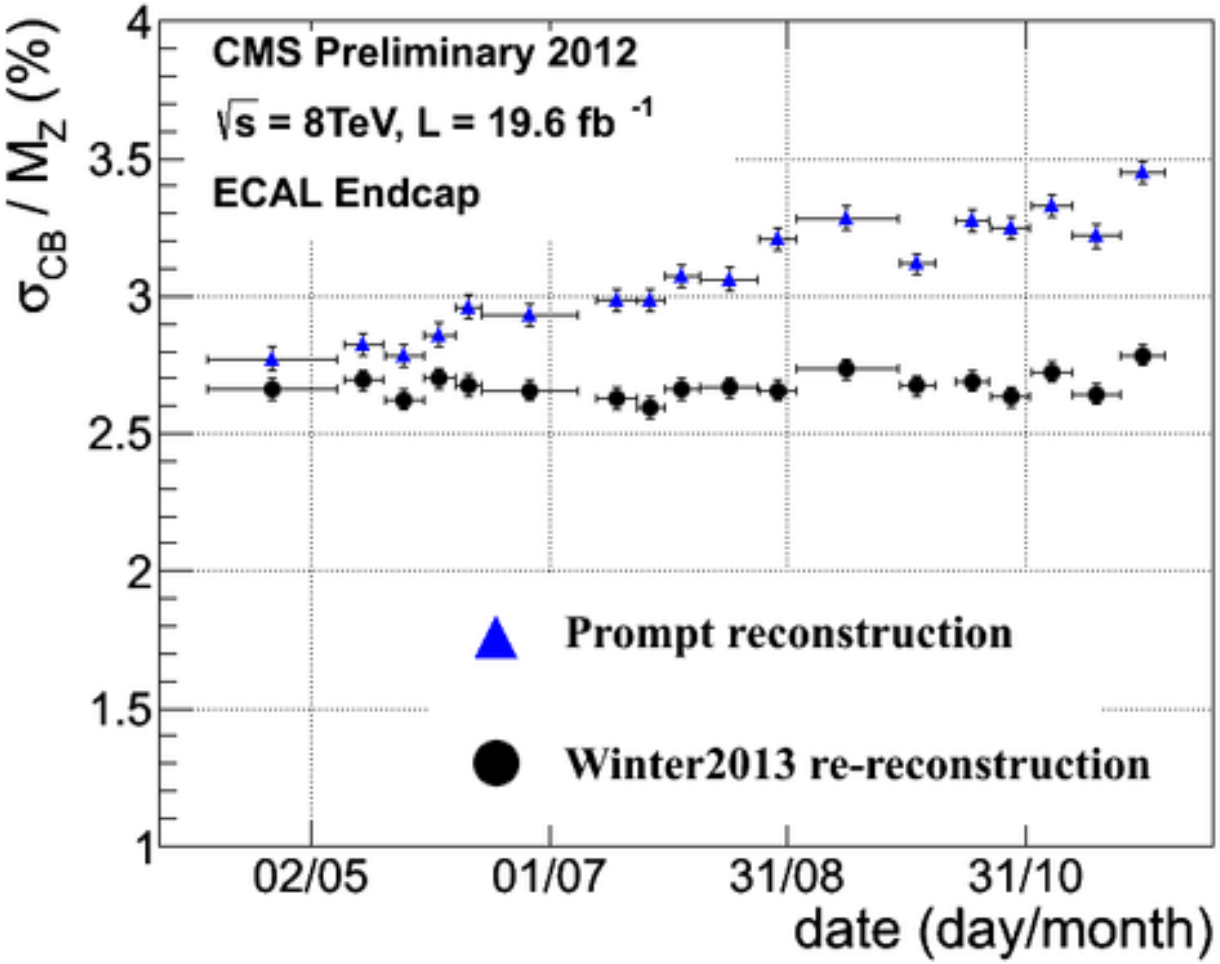
loss in a fill and recovery in interfill



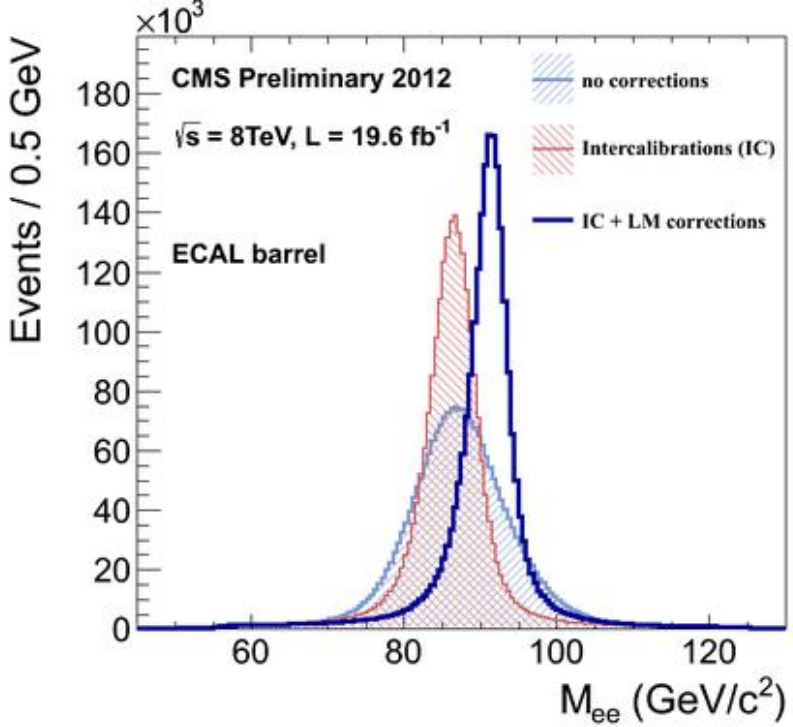


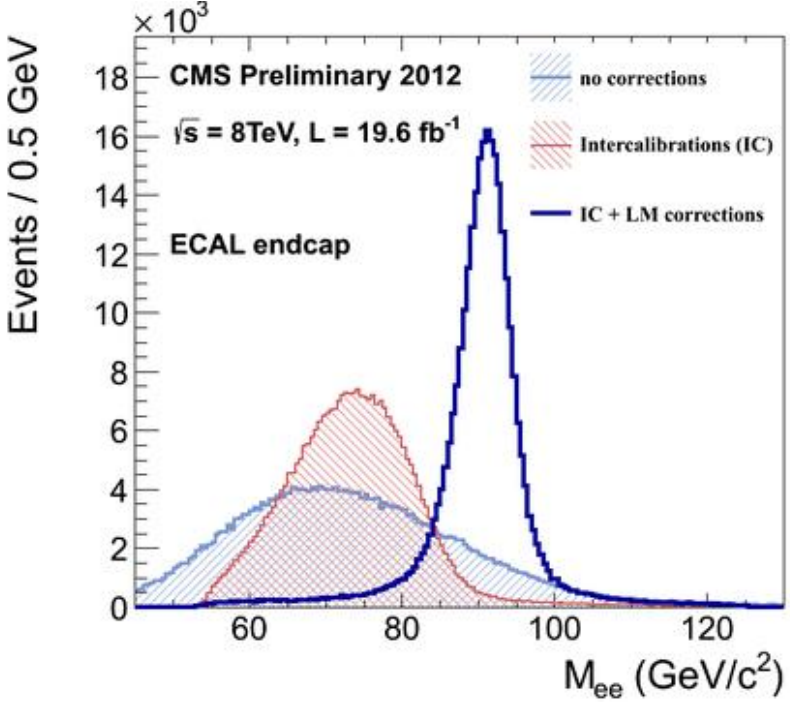
CMS-DP-2013/007

2012 intercalibration precision



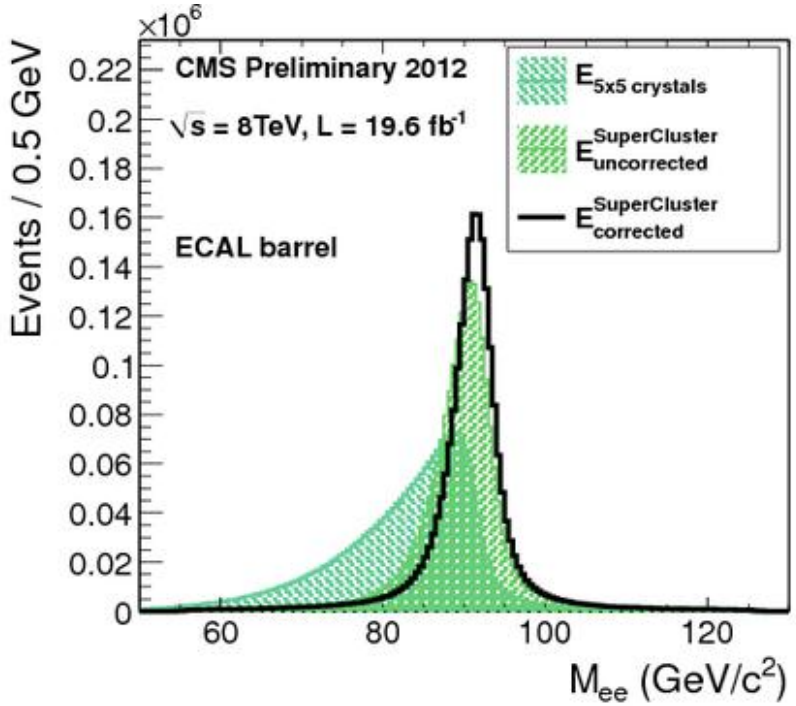
CMS-DP-2013/007

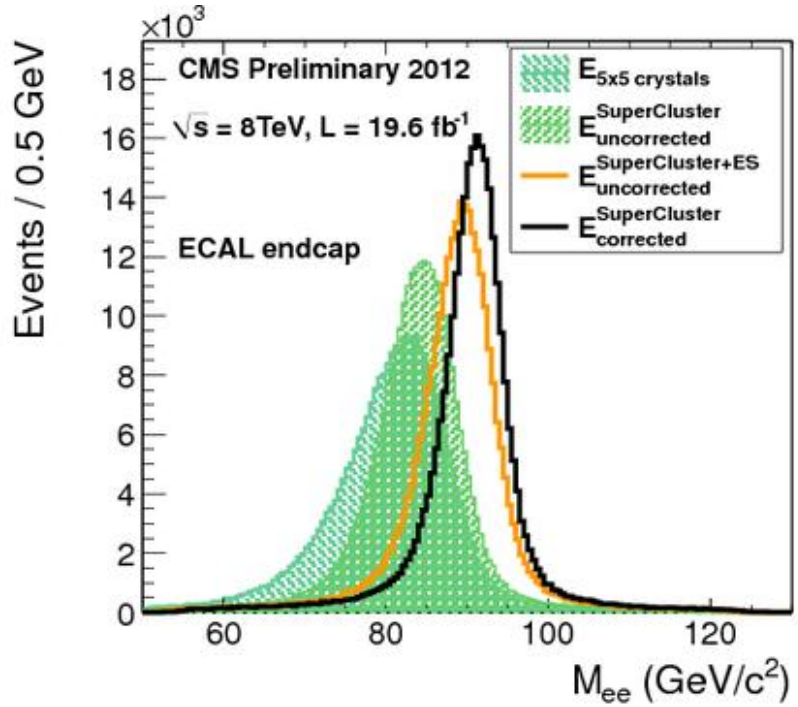




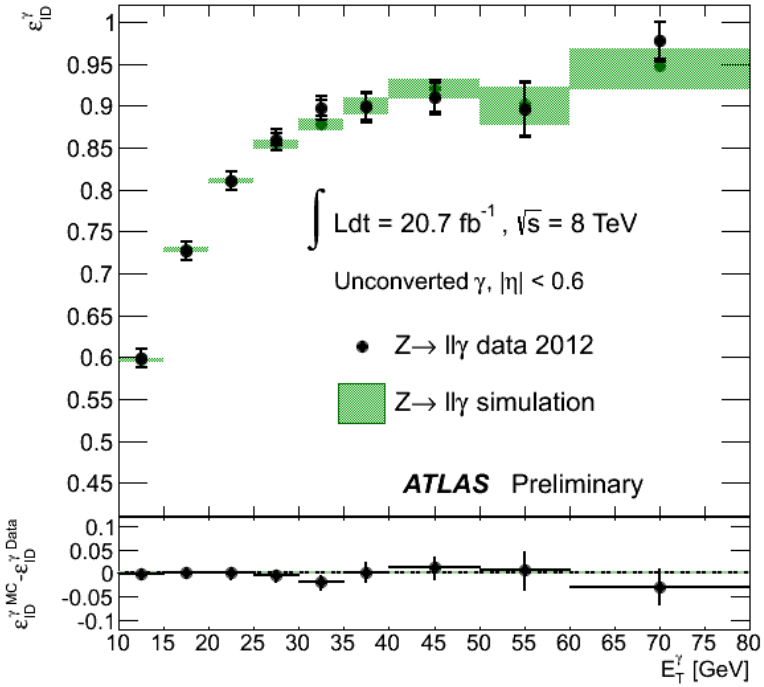
CMS-DP-2013/007

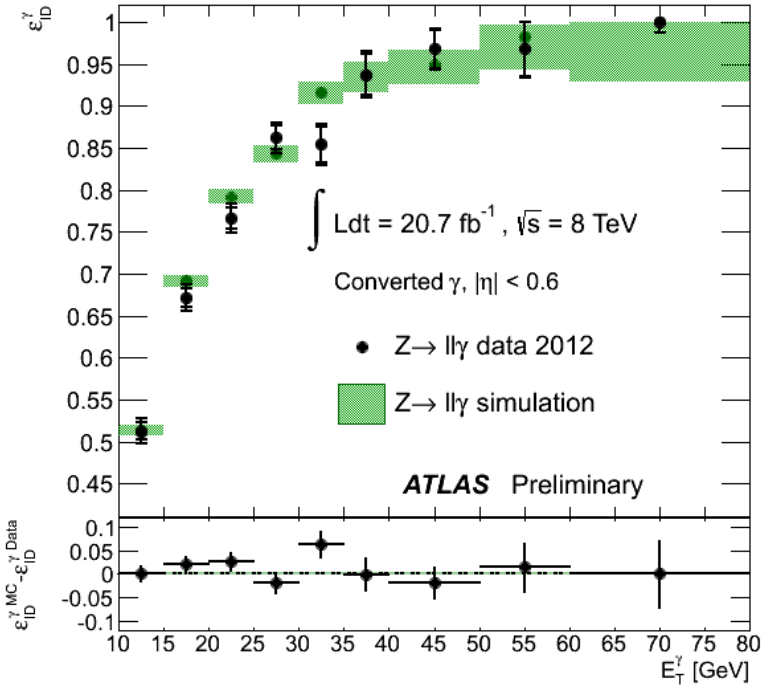
energy scale corrections





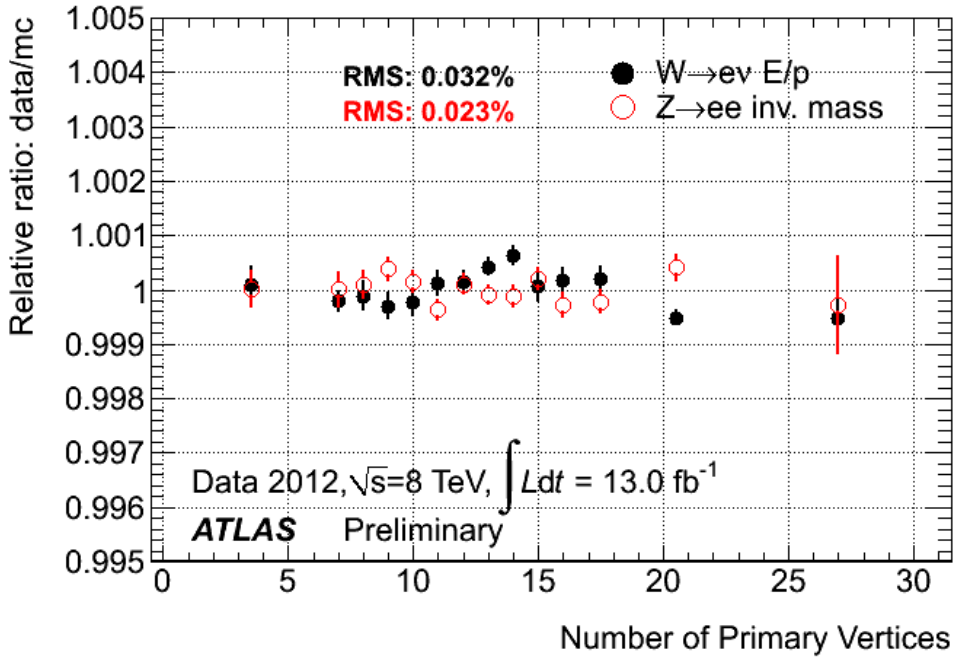
ECAL supercluster energy

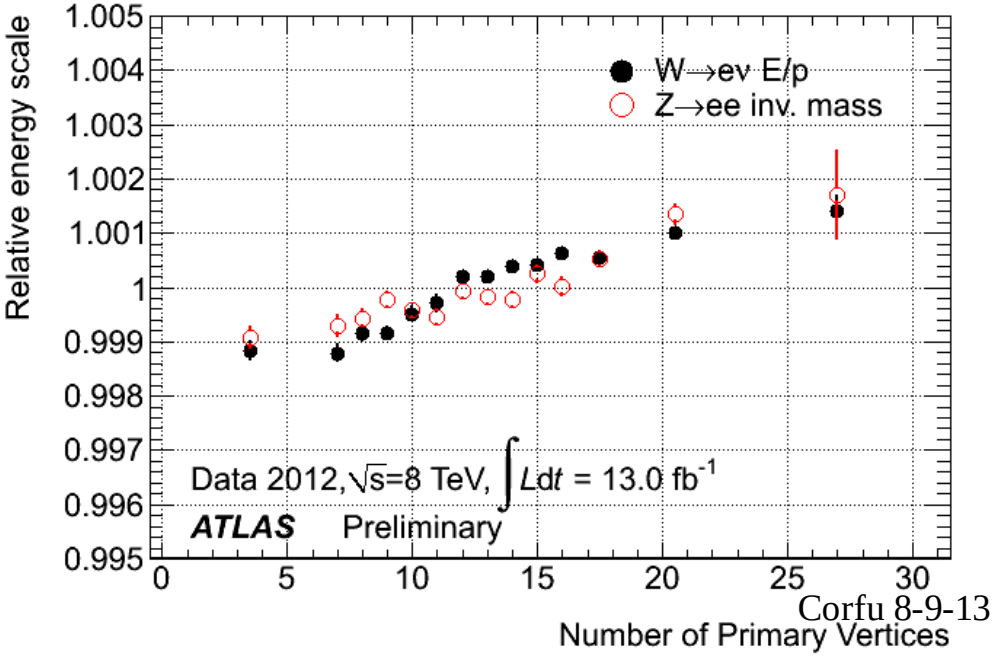




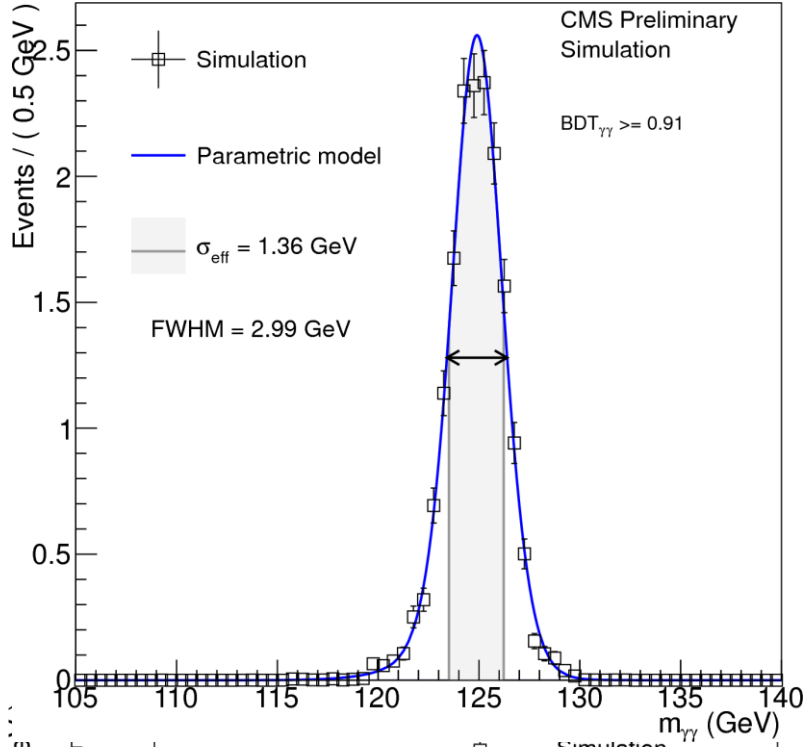
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20130304/ATL-COM-PHYS-2013-244/index.html

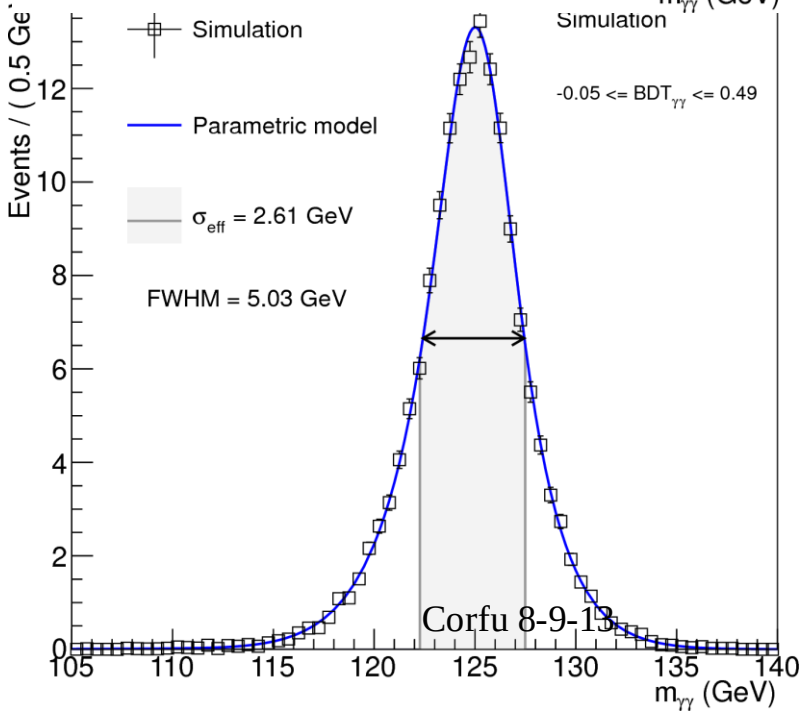
efficiency of photons





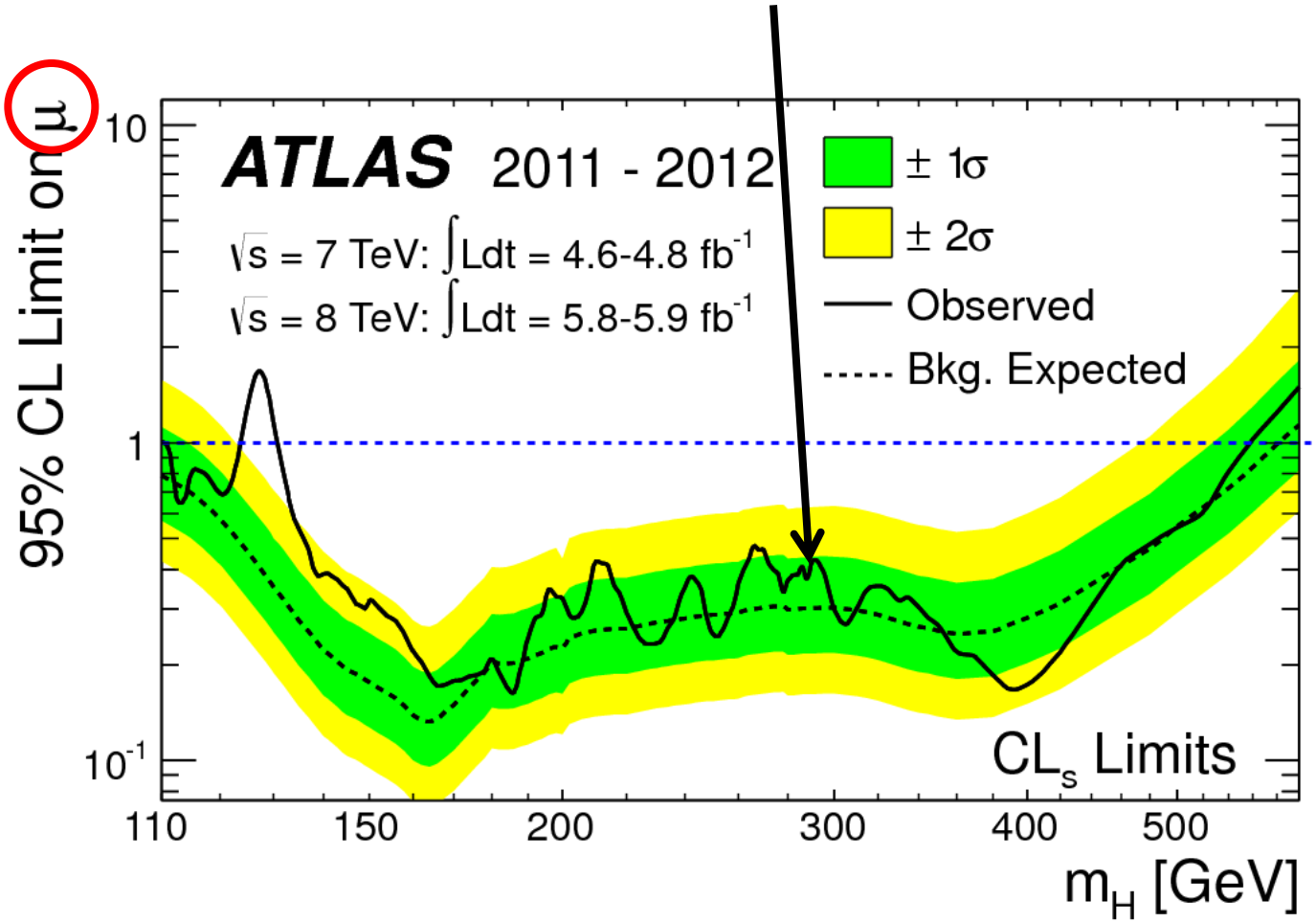
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20121129/ATL-COM-PHYS-2012-1668/index.html


CMS Preliminary
Simulation
Simulation
Parametric model
σ_{eff} = 1.36 GeV
FWHM = 2.99 GeV
$BDT_{\gamma\gamma}$ >= 0.91
Events / (0.5 GeV)
$m_{\gamma\gamma}$ (GeV)


Simulation
Simulation
Parametric model
σ_{eff} = 2.61 GeV
FWHM = 5.03 GeV
-0.05 <= $BDT_{\gamma\gamma}$ <= 0.49
Events / (0.5 GeV)
$m_{\gamma\gamma}$ (GeV)

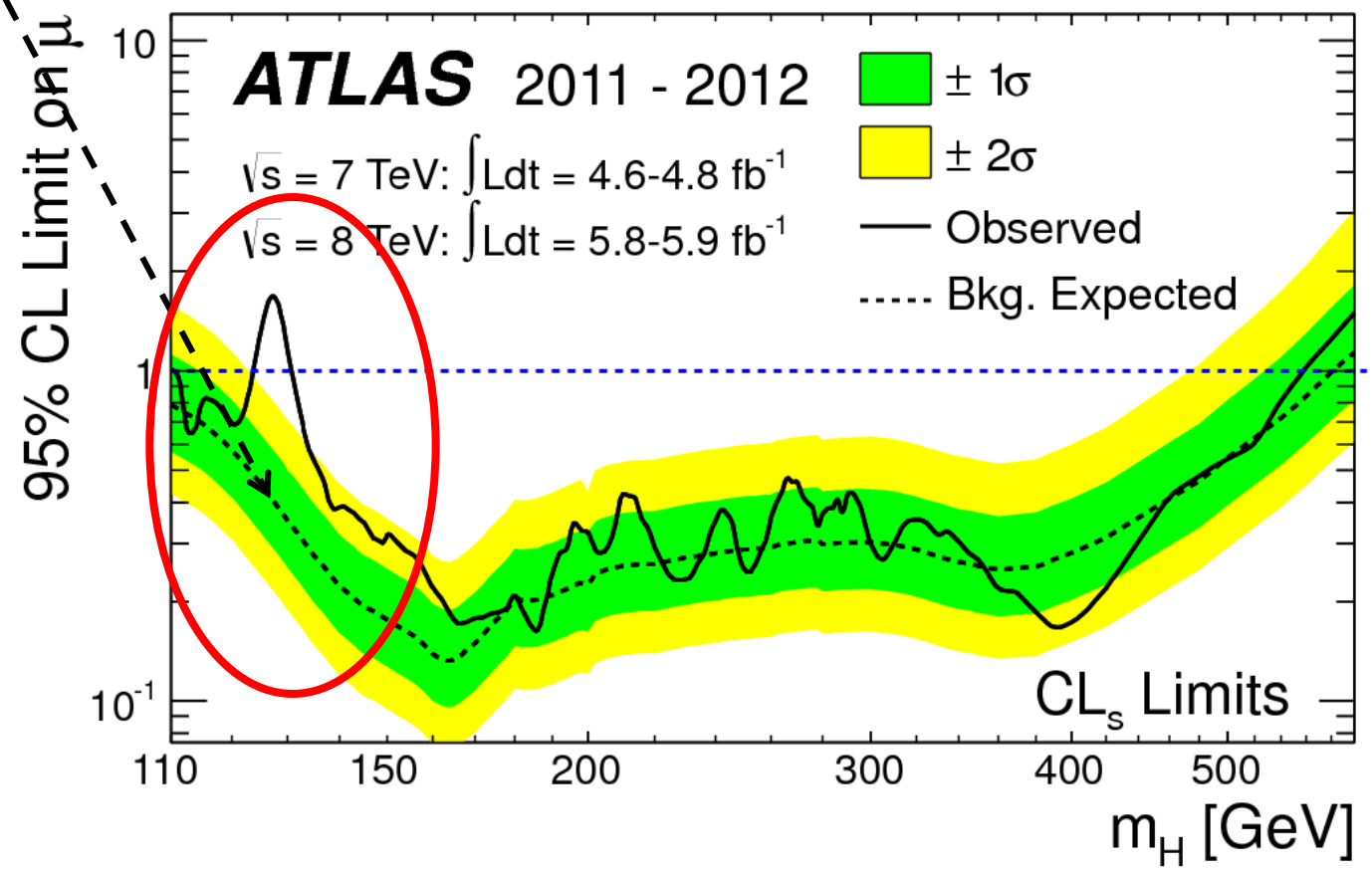
Exclusion on $\mu = \sigma / \sigma_{SM}$ SM = SM boson

Everything above the black line is excluded



The dashed line show the limit we would expect if the data would be without any boson . The green and yellow bands show where , without any boson , the limits would be allowed to move at the 1 σ or 2 σ level (depending of the statistical fluctations of the background)

The fact that the observed limit is above the expected + 2σ limit is a hint that the data are not well simulated by the backgrounds (stat fluctuation , mismodeling , signal)



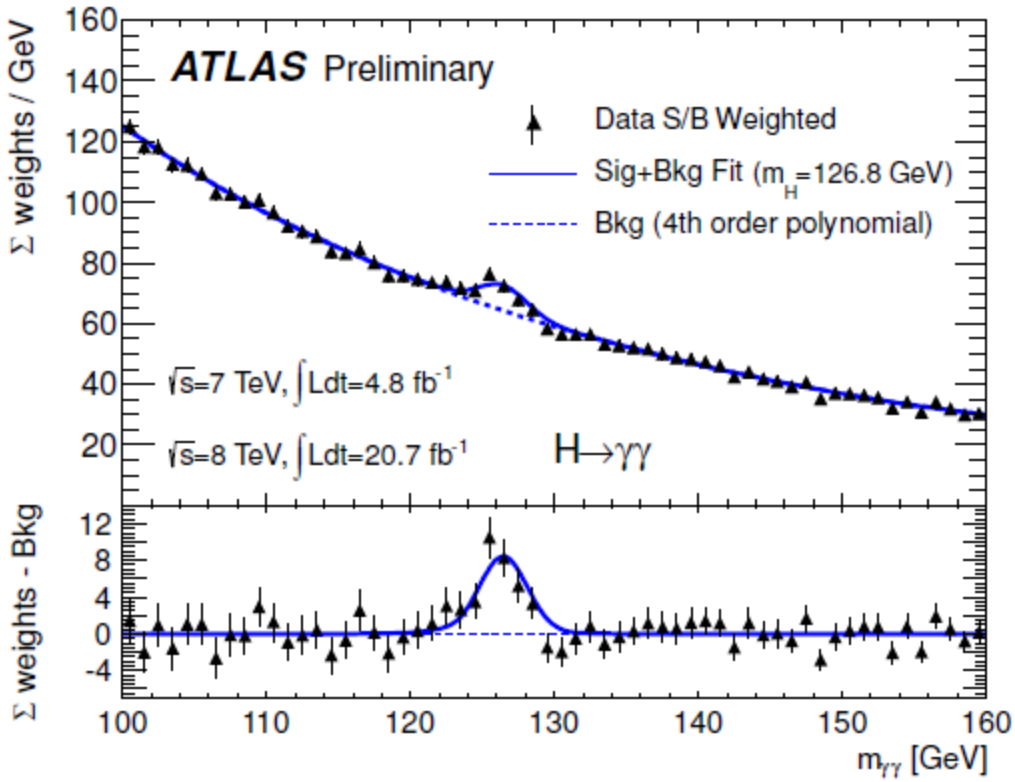
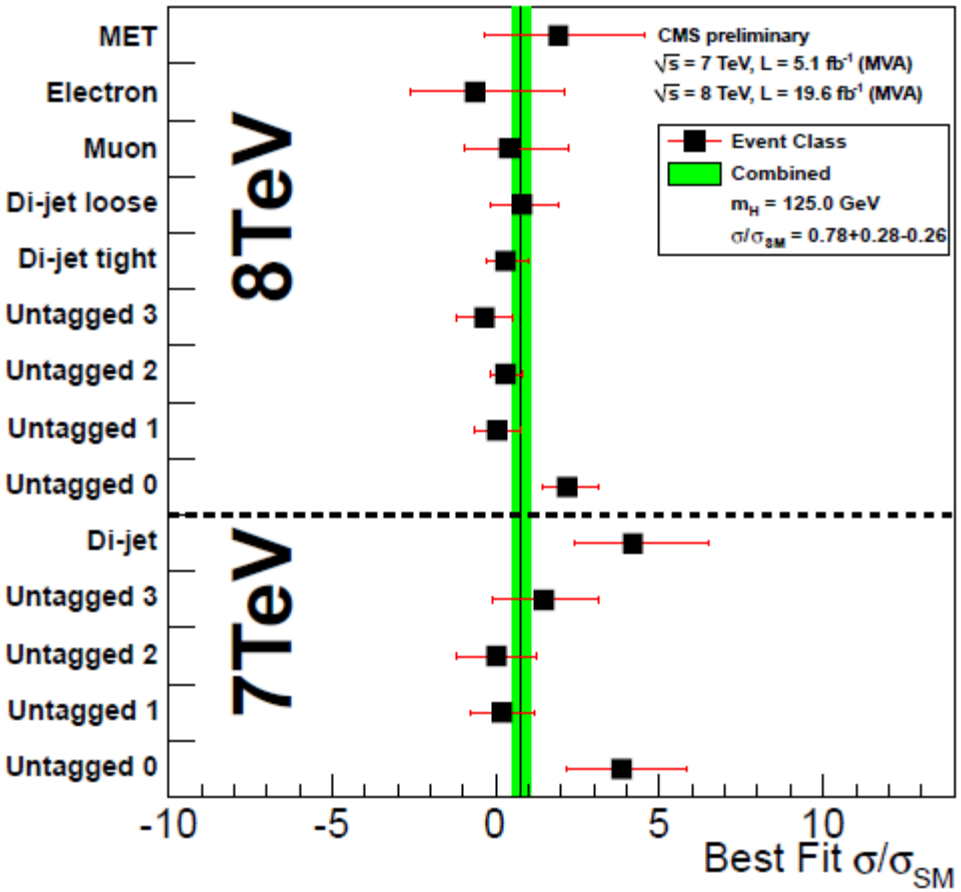


Figure 12: The weighted distribution of the invariant mass of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The weight w_i for category i from [1, 14] is defined to be $ln(1 + S_i/B_i)$, where S_i is the expected number of signal events in a mass window that contains 90% of the signal events, and B_i is the integral in the same window of a background-only fit.


MET
Electron
Muon
Di-jet loose
Di-jet tight
Untagged 3
Untagged 2
Untagged 1
Untagged 0
8TeV
Di-jet
Untagged 3
Untagged 2
Untagged 1
Untagged 0
7TeV
CMS preliminary
√s = 7 TeV, L = 5.1 fb⁻¹ (MVA)
√s = 8 TeV, L = 19.6 fb⁻¹ (MVA)
Event Class
Combined
m_H = 125.0 GeV
σ/σ_SM = 0.78+0.28-0.26
-10
-5
0
5
10
Best Fit σ/σ_SM

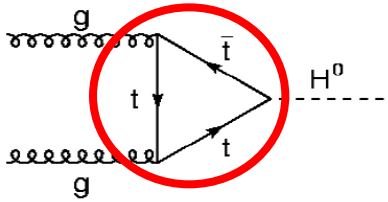
There are other ways of parametrizing the cross sections via couplings *(see talk of Bruno Mansoulié)*

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

zero width approximation

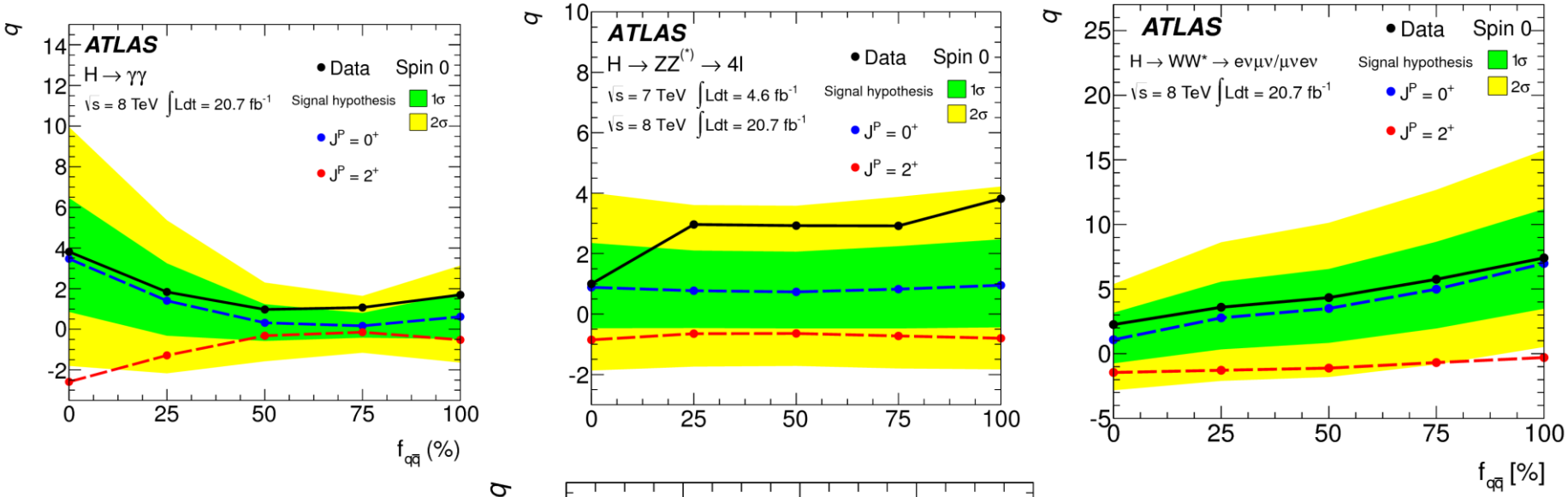
coupling scale factors κ_j

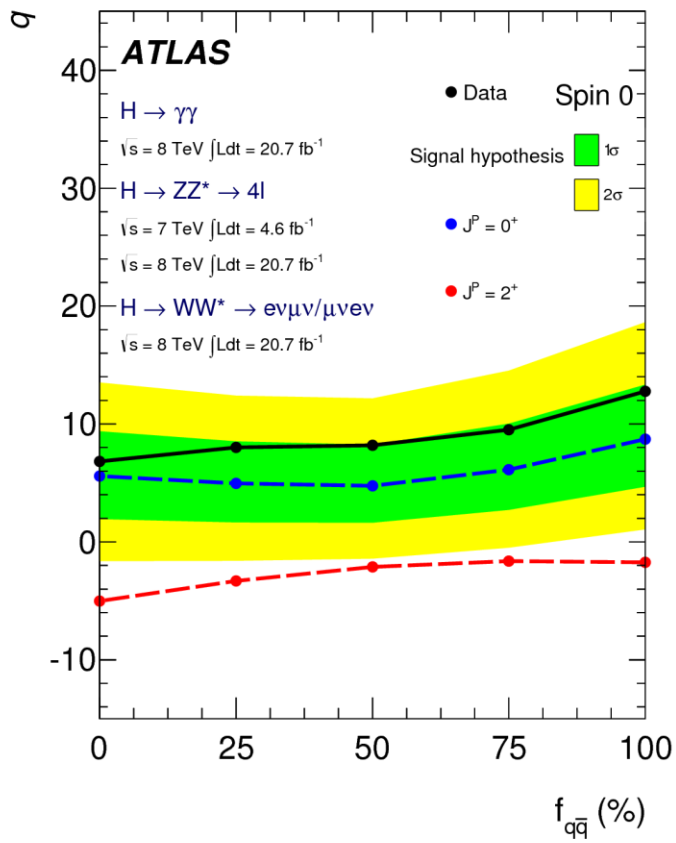
$$\frac{\sigma \cdot \mathrm{B}\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



κ_g

κ_g includes t (and b) loop but also 'exotic' particles





large sensitivity for all qq/gg