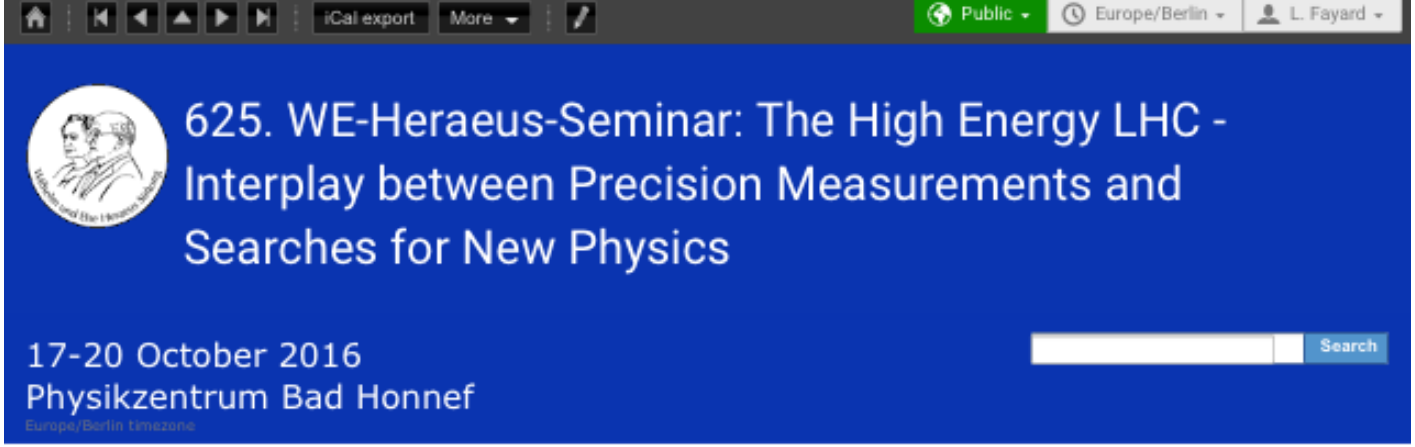



# Status of BEH investigations I

**Louis Fayard**
*LAL Orsay*

***Massimiliano Grazzini***
***Standard Model Higgs Physics (T)  15:00 - 15:50***

***Louis Fayard***
***Status of BEH investigations I (E) 16:20 - 17:10***

(SM Higgs production and decay, mass, couplings, off-shell measurements)

***Adam Falkowski***
***Effective Field Theories and Pseudo-Observables (T) 17:10 - 18:00***

***Chiara Mariotti***
***Status of BEH investigations II (E)  18:00 - 18:50***

(Spin, CP, distributions, EFTs, POs)

***Discussion  18:50 - 19:00***

***Rien n'est cru si fermement que ce que l'on sait le moins***

***Nothing is believed more strongly that which we know the least***

*Montaigne , Essais*

***I will try to be simple !***

***BUT .. DO NOT HESITATE TO INTERRUPT ME***

*I will try to give some feeling of what experimentalists are doing* ***and describe detector properties***

***( mainly with example of $H \rightarrow \gamma\gamma$ )***

- ***LHC and ATLAS run 1 and run 2***
- ***Study of the H(125) or with H(125)***
- ***H(125) : mass***
- ***H(125) : couplings***
- ***H(125) : off-shell measurements***
- ***Conclusions***
- ***Backup***

***This is a course***

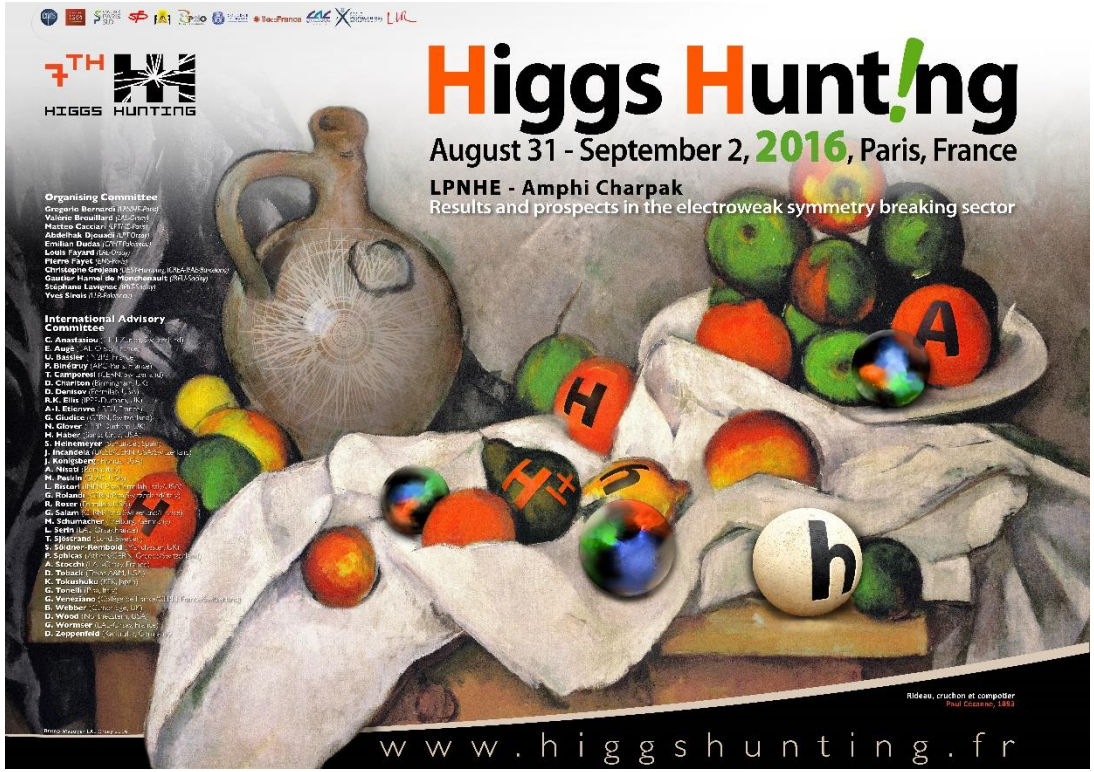
***Only few of the results will be shown here !***

*I will not be exhaustive*

**I will try to show results from ATLAS and CMS but I am not sure I will succeed**

- ***LHC and ATLAS run 1 and run 2***
- ***Study of the H(125) or with H(125)***
- ***H(125) : mass***
- ***H(125) : couplings***
- ***H(125) : off-shell measurements***
- ***Conclusions***
- ***Backup***

## *See also other recent conferences*



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

1959 Nambu

1960 Goldstone

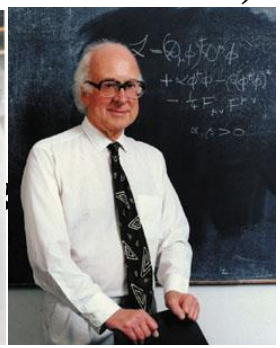
1961 Schwinger

1962 Anderson

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

1967 Weinberg, Salam Faddeev,Popov

1970 Glashow, Iliopoulos,
Maiani, 't Hooft, Veltman…..



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

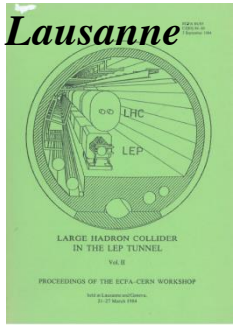
1983 Rubbia, van der Mee

1984 Repell

discovery of W and Z at CERN

1989 construction
beginning of

Lausanne




1992 ← LOI of 'larg

1994 ← TP of ATLA

1995 discovery of

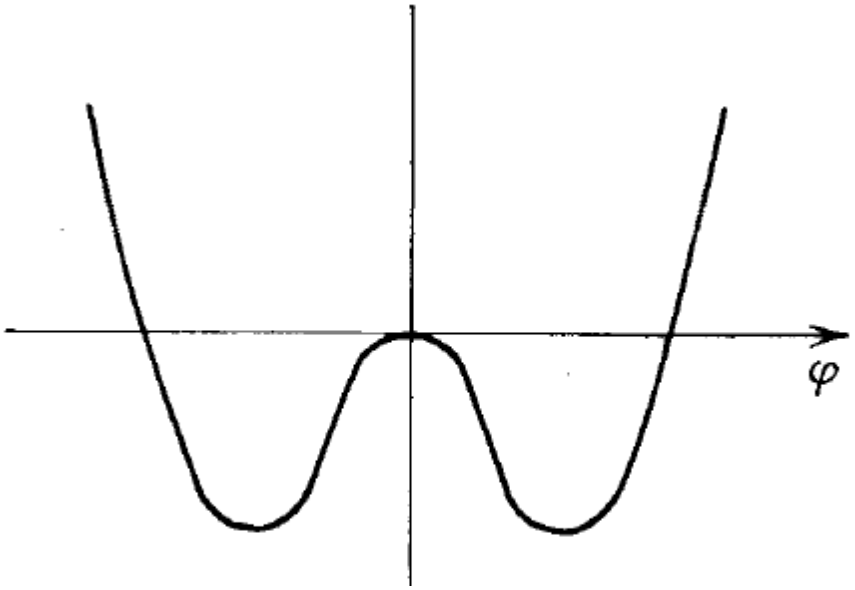
1996 ← approval of

1998 ← approval of

1999 ← ATLAS Phys

CE)

data ended in 2000




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

2006 ← CMS Physic

2008 ← ATLAS Exp

2010 start-up at 3

2012

2013

2014

4th July discovery of boson ( m ~ 125 GeV)

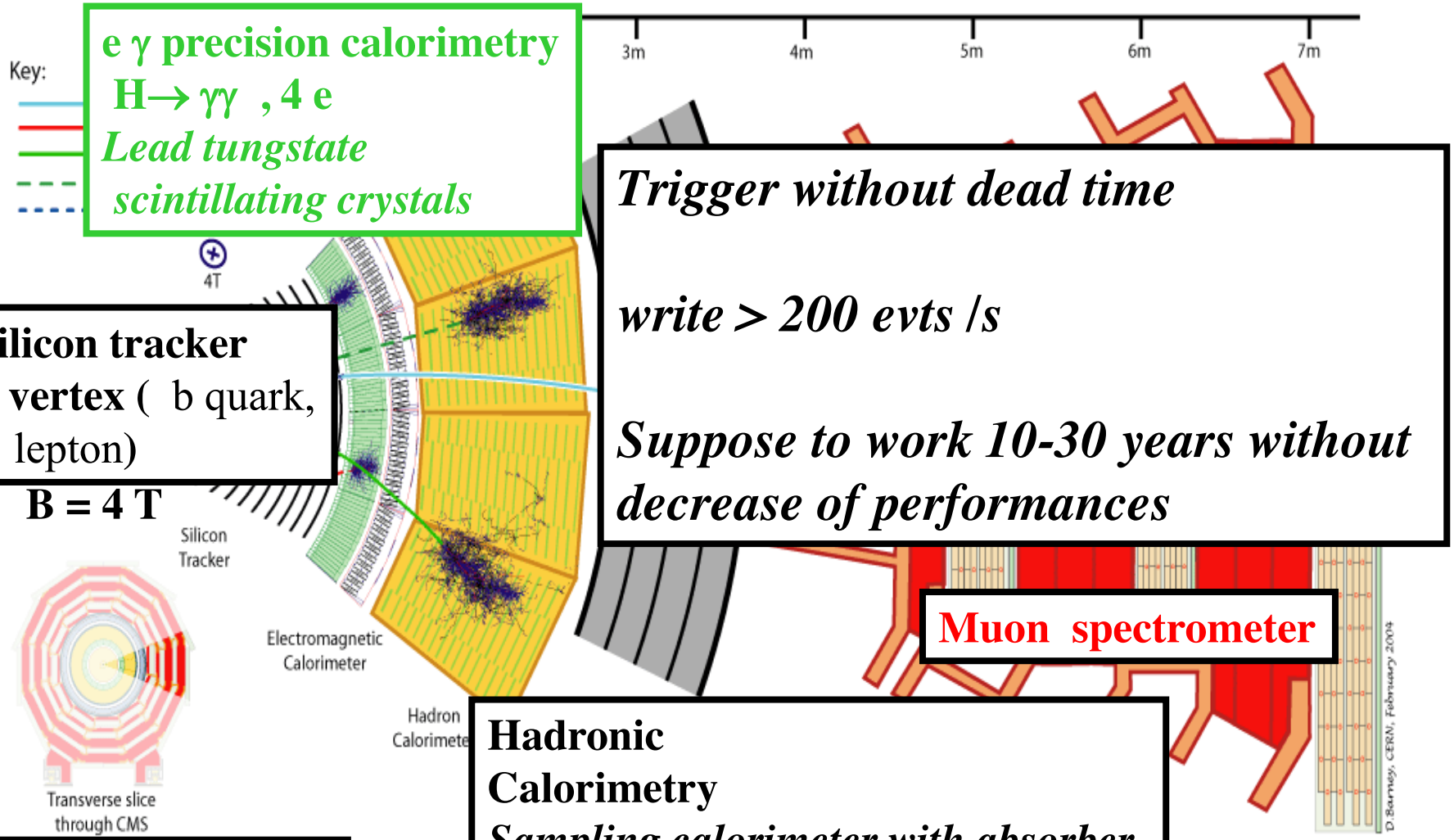
boson like properties

Nobel prize to Englert and Higgs

Tevatron data ended in Sept 2011

# *CMS = (Compact Muon Solenoid)*

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




***Trigger without dead time***

***write > 200 evts /s***

***Suppose to work 10-30 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°)

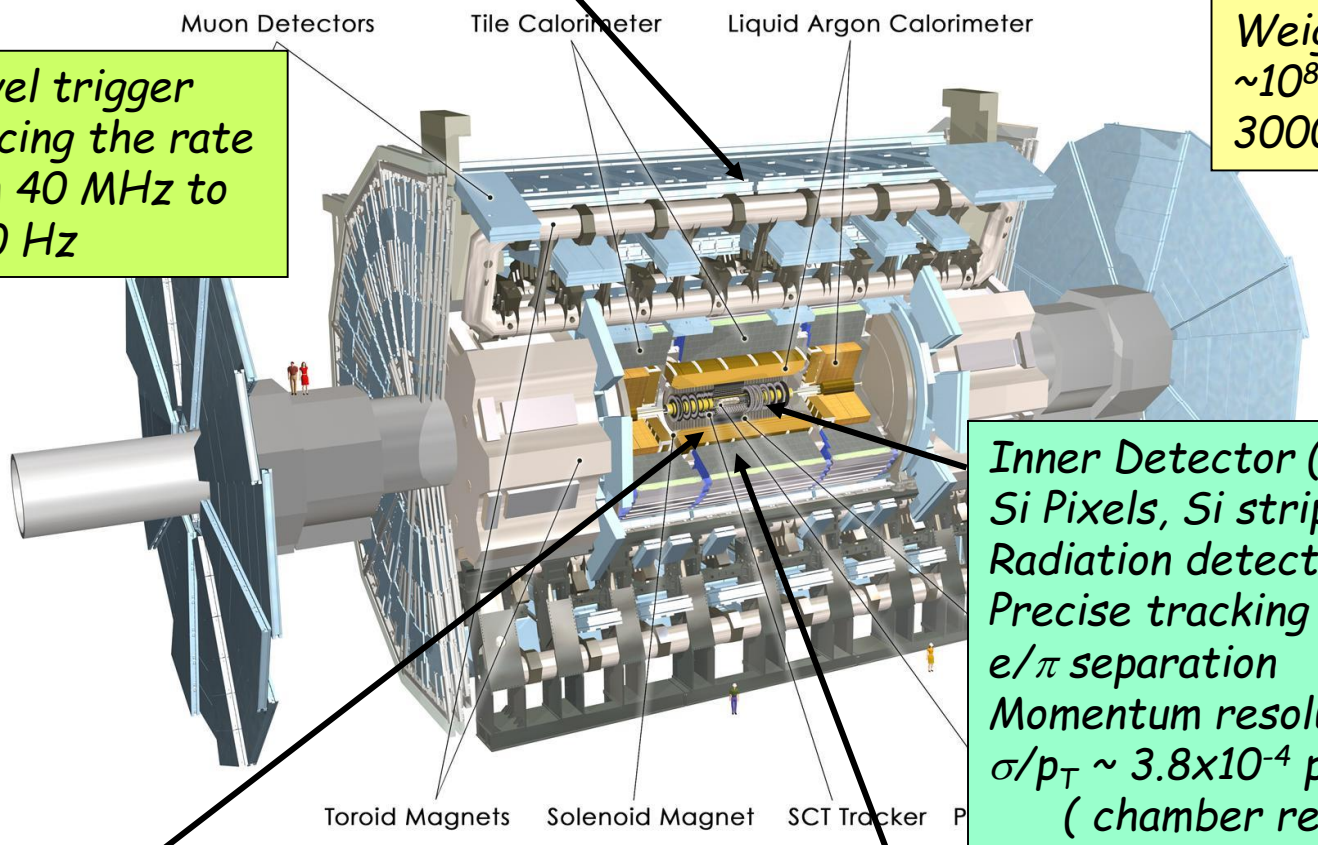
*CMS EM calorimeter more than 75000 cristals of $PbW0_4$*

**CMS CALORIMETER VERY USEFUL FOR $H \rightarrow \gamma\gamma$ (see later) AND FOR $H \rightarrow 4e,\ 2e2\mu$, …**

$$\sigma(E)/E = 3\%/\sqrt{E_{GeV}} \oplus 0.7\ \%$$

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 $E_\mu$ ~ 1 TeV

# *run 1 ATLAS detector*




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

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

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

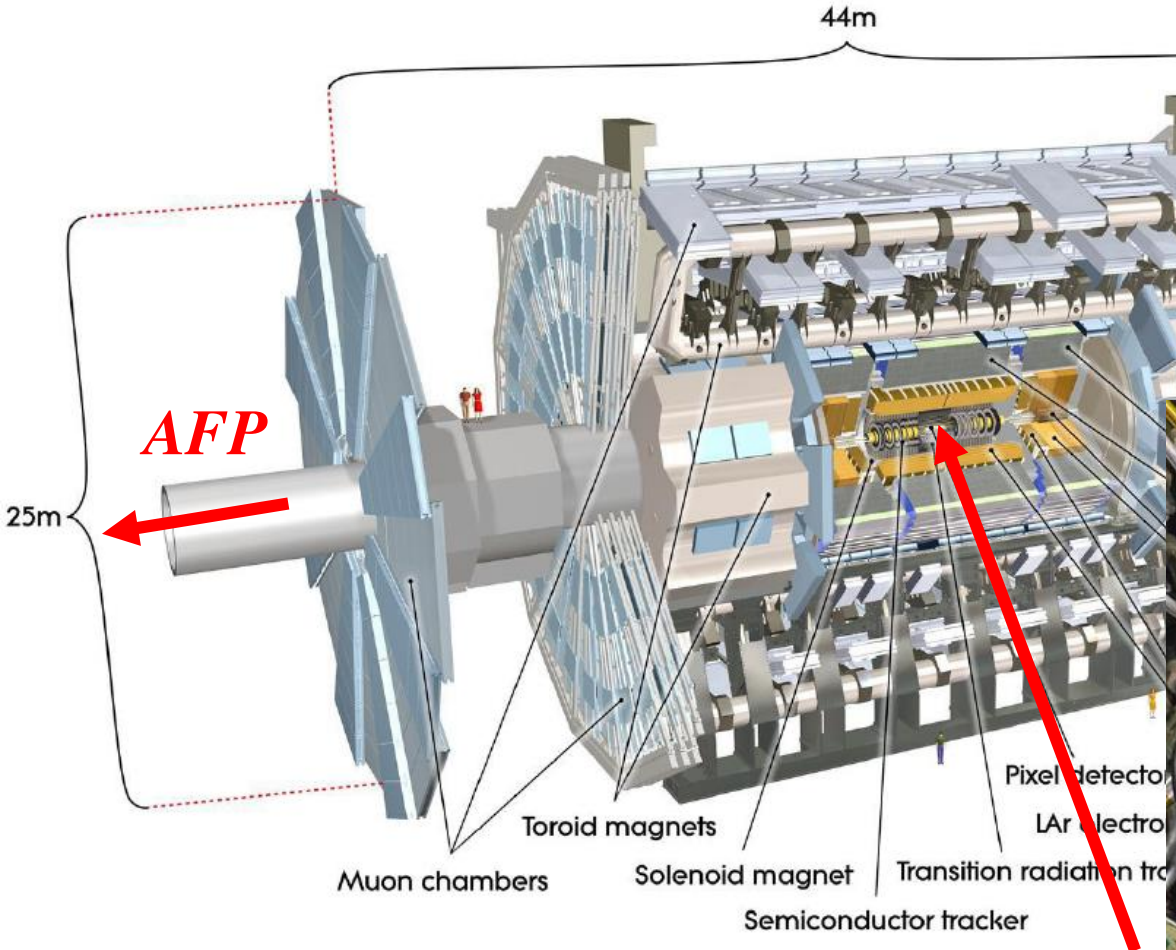
EM calorimeter: Pb-LAr Accordion
$e/\gamma$ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

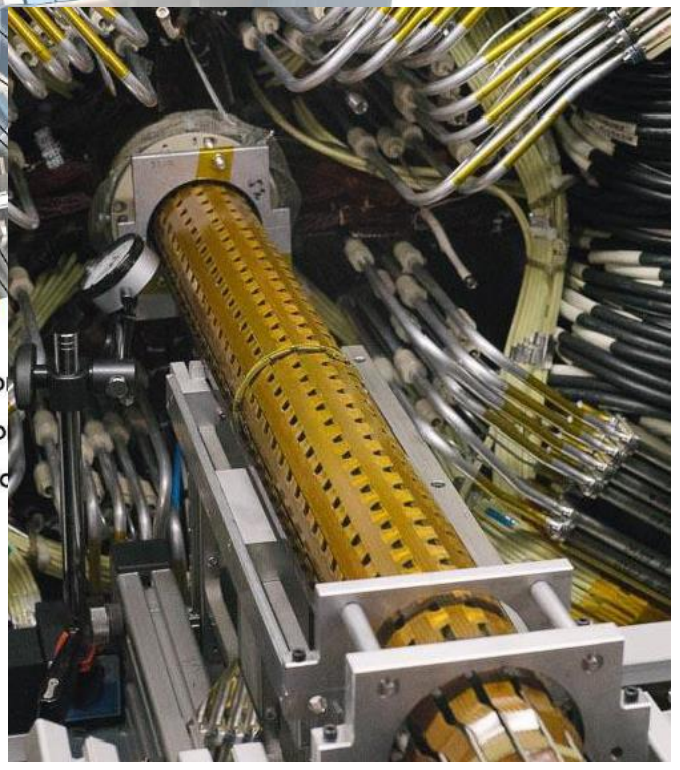
HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing $E_T$
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

***ATLAS in run 2***

New detectors in Run-2:

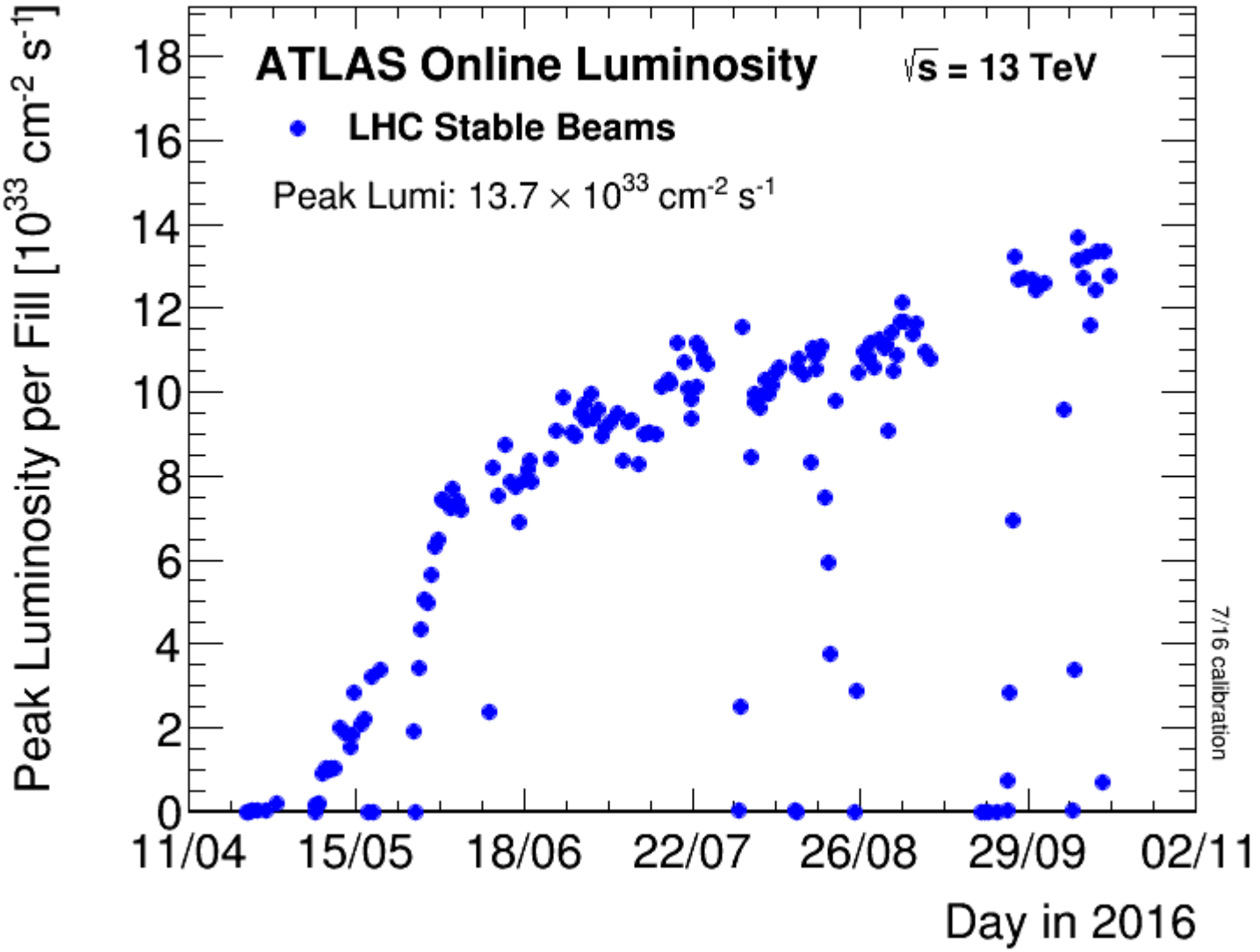
- Innermost pixel layer IBL, 3.4cm from interaction point
- Forward proton detectors (one arm in 2016, 210m from IP)

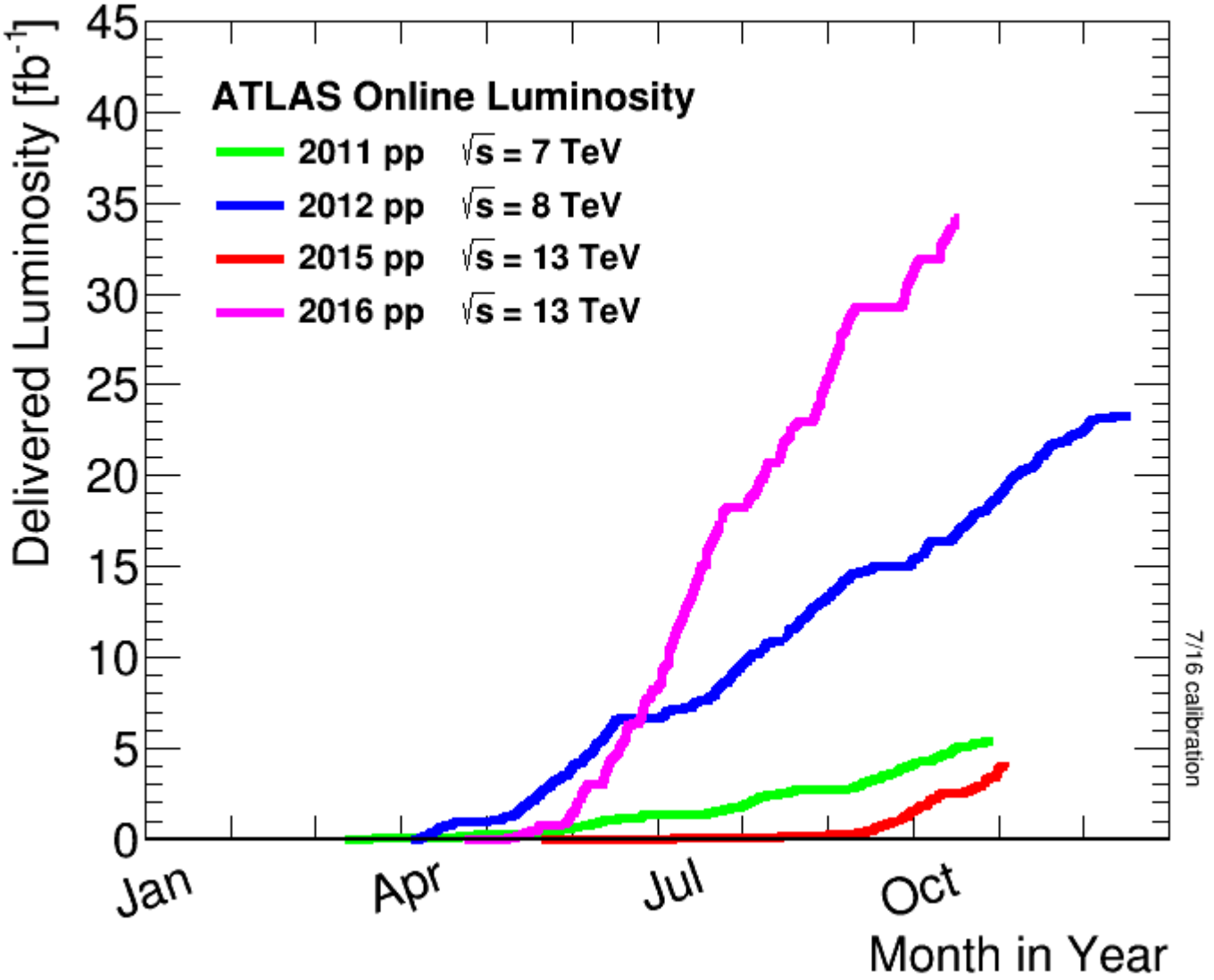


***I will come back to detector when I will discuss $H \rightarrow \gamma\gamma$ with more details ( see later )***

*very good luminosity at 13 TeV !* ***better than design***



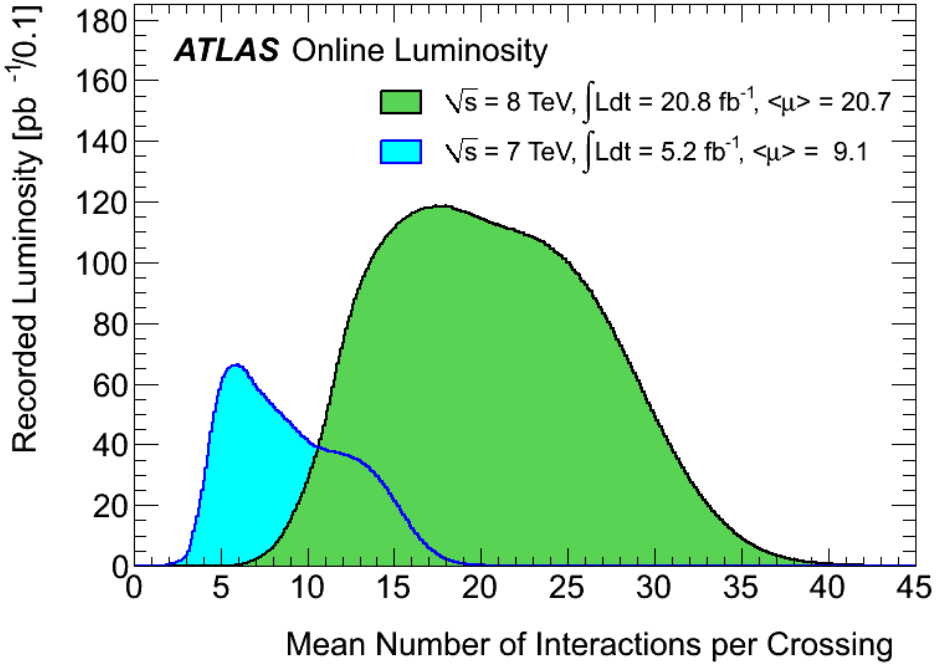

ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
Delivered Luminosity [fb-1]
45
40
35
30
25
20
15
10
5
0
Jan
Apr
Jul
Oct
Month in Year
7/16 calibration

***Pile up*** *increases at higher energy ( higher luminosity + higher cross sections )*

→

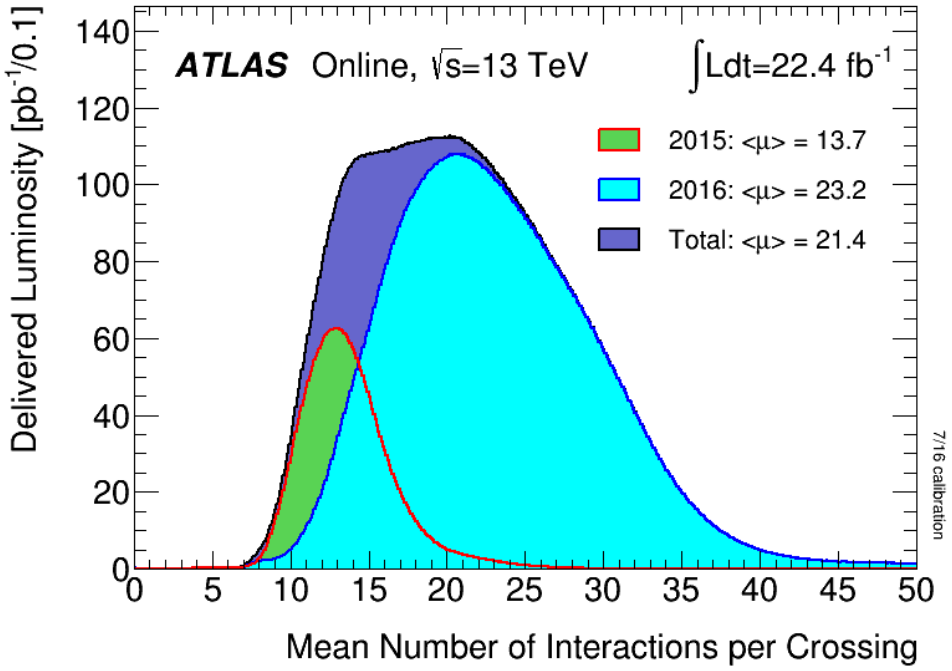
*Experiments have requested* ***25 ns*** *(instead of 50 ns)* ***operation at 13 TeV***

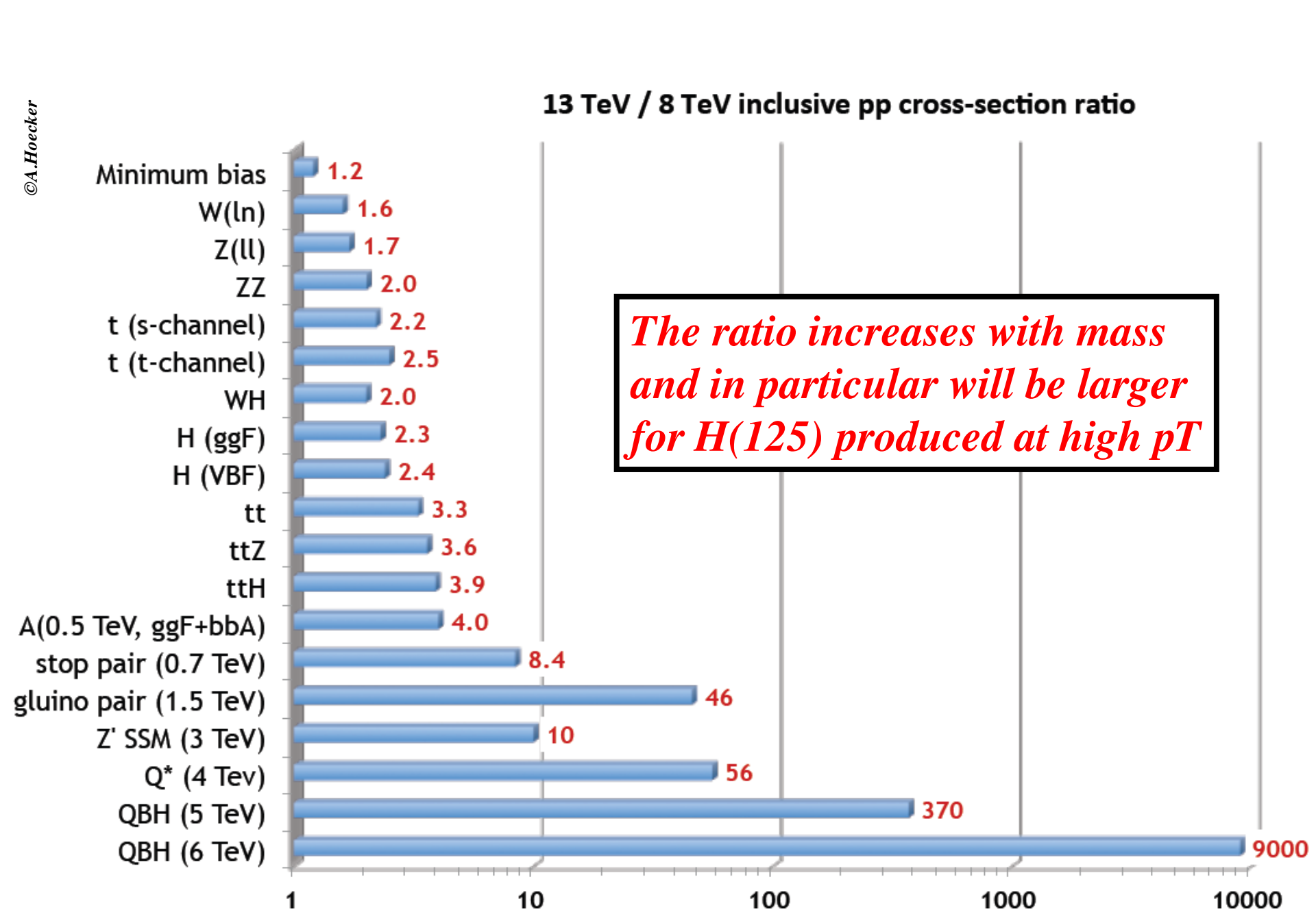
***But if the time constant is larger than 50 ns (i.e integrating time of the LAr calorimeter ) then the pile-up is independent of the bunch spacing ( for a given luminosity )***



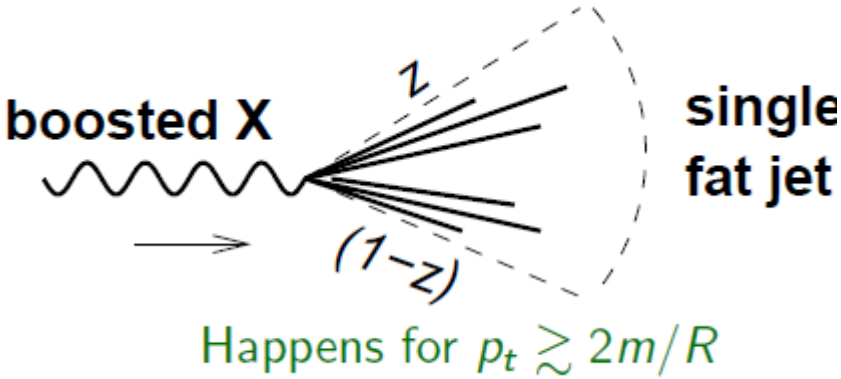

*small increase of <μ>*
*number of interactions*
*per bunch crossing*

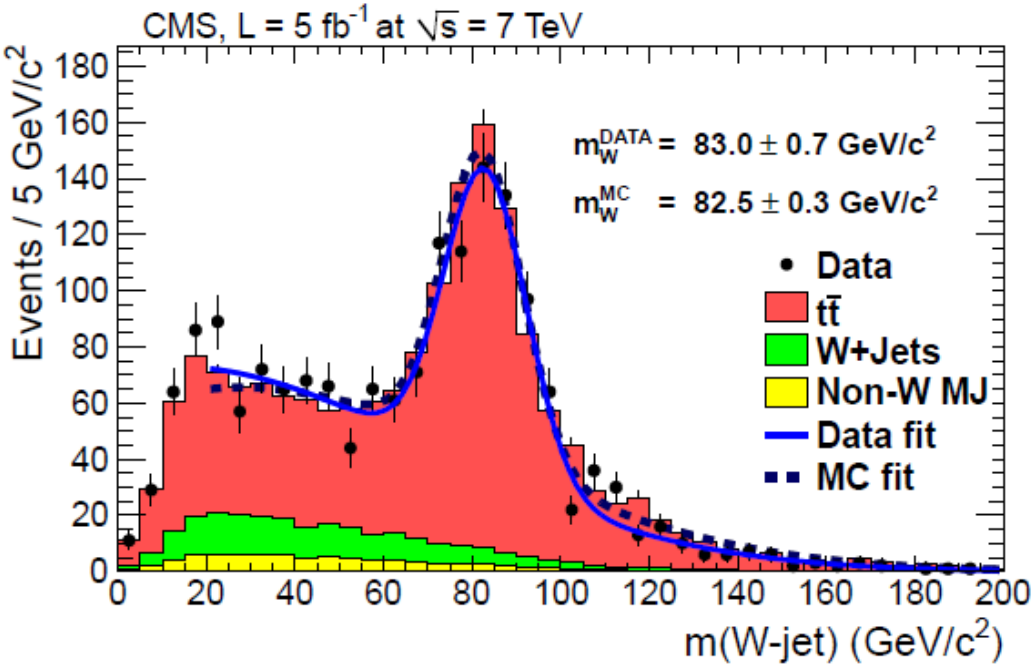
*but remember*
*that Δt was*
*50 ns and*
*is now 25 ns*




©A.Hoecker
13 TeV / 8 TeV inclusive pp cross-section ratio
Minimum bias
W(ln)
Z(ll)
ZZ
t (s-channel)
t (t-channel)
WH
H (ggF)
H (VBF)
tt
ttZ
ttH
A(0.5 TeV, ggF+bbA)
stop pair (0.7 TeV)
gluino pair (1.5 TeV)
Z' SSM (3 TeV)
Q* (4 Tev)
QBH (5 TeV)
QBH (6 TeV)
1.2
1.6
1.7
2.0
2.2
2.5
2.0
2.3
2.4
3.3
3.6
3.9
4.0
8.4
46
10
56
370
9000
1
10
100
1000
10000
The ratio increases with mass and in particular will be larger for H(125) produced at high pT

# *Boosted massive particles (Fat jets)*



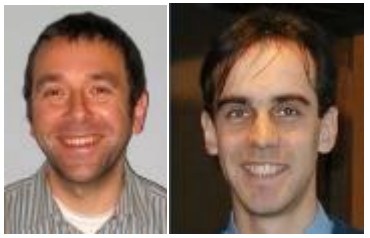

**highest mass jet in Semileptonic top sample**

*arXiv:1204.2488*

## *Futur : boosted Higgs in bb*

**J.Butterworth G.Salam**

Butterworth,Davison,Rubin,Salam
Phys.Rev.Lett. 100 (2008) 242001
*Jet substructure as a new Higgs search channel at the LHC*



♪ *LHC and ATLAS run 1 and run 2*

♪ ***Study of the H(125) or with H(125)***

♪ *H(1*

♪ *H(1*

♪ *H(125) : off-shell measurements*

***I will describe simply the analysis***

***detailed results : Chiara***

***H discovery opened the door on the scalar sector***

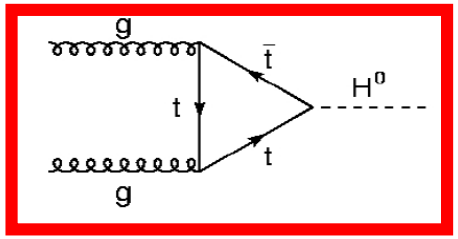
***Run-1***

- ***mass with a precision of ± 0.2%***
- ***spin-parity***
- ***a lot of production processes and decay channels***

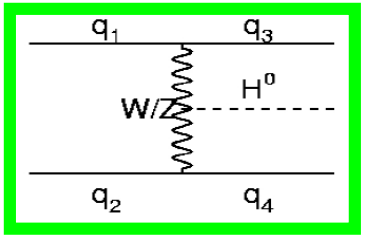
***Run-2 priorities :***

- ***ttH***
- ***H→bb***
- ***refine measurements***
- ***rare decays***

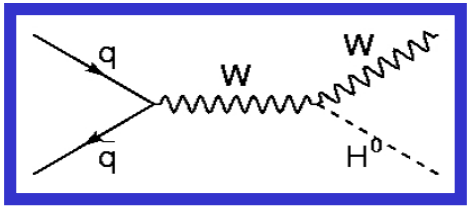
*A.Djouadi Phys.Rept.457:1-216*



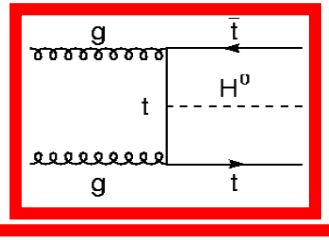

**GF** $H \to WW, ZZ, \gamma\gamma, bb, \tau\tau$



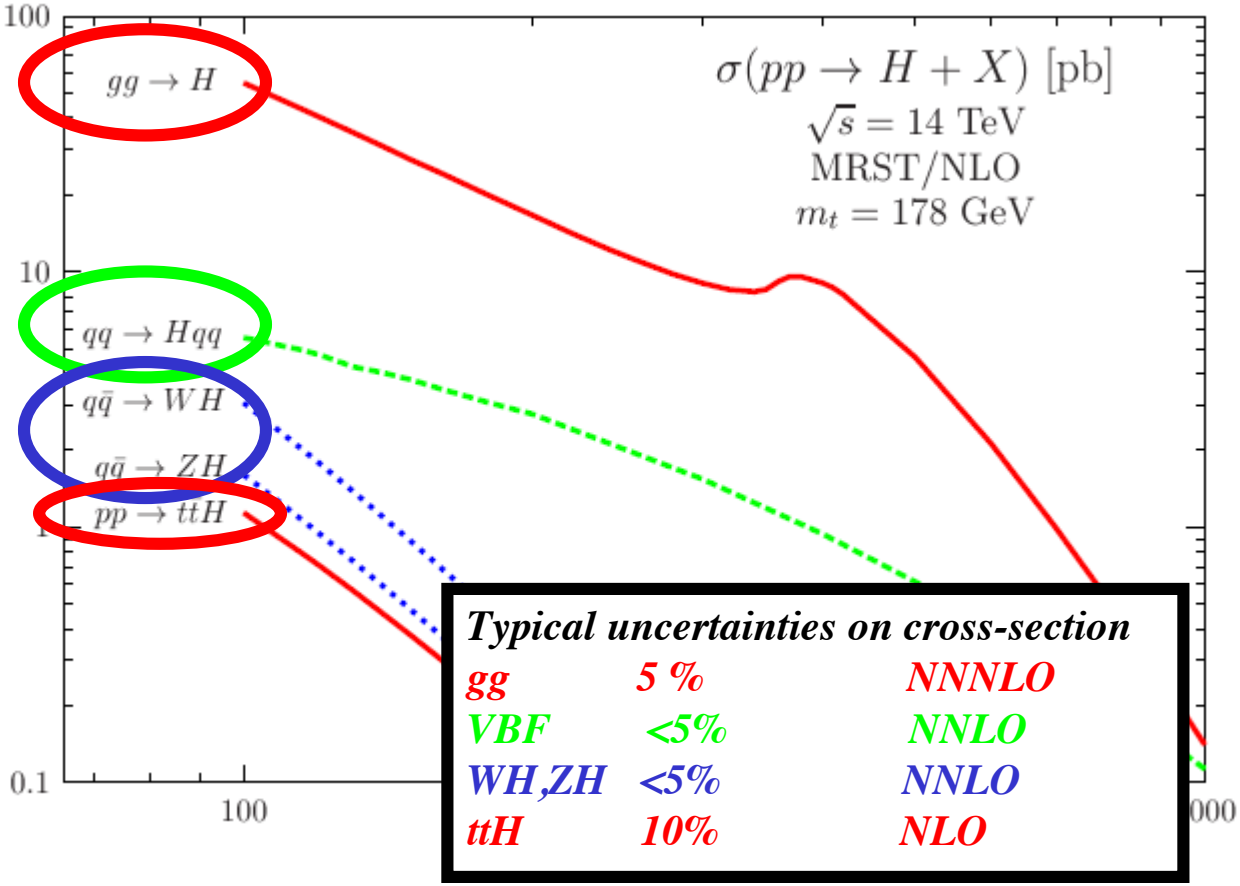

**VBF** $H \to WW, ZZ, \gamma\gamma, \tau\tau$




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




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

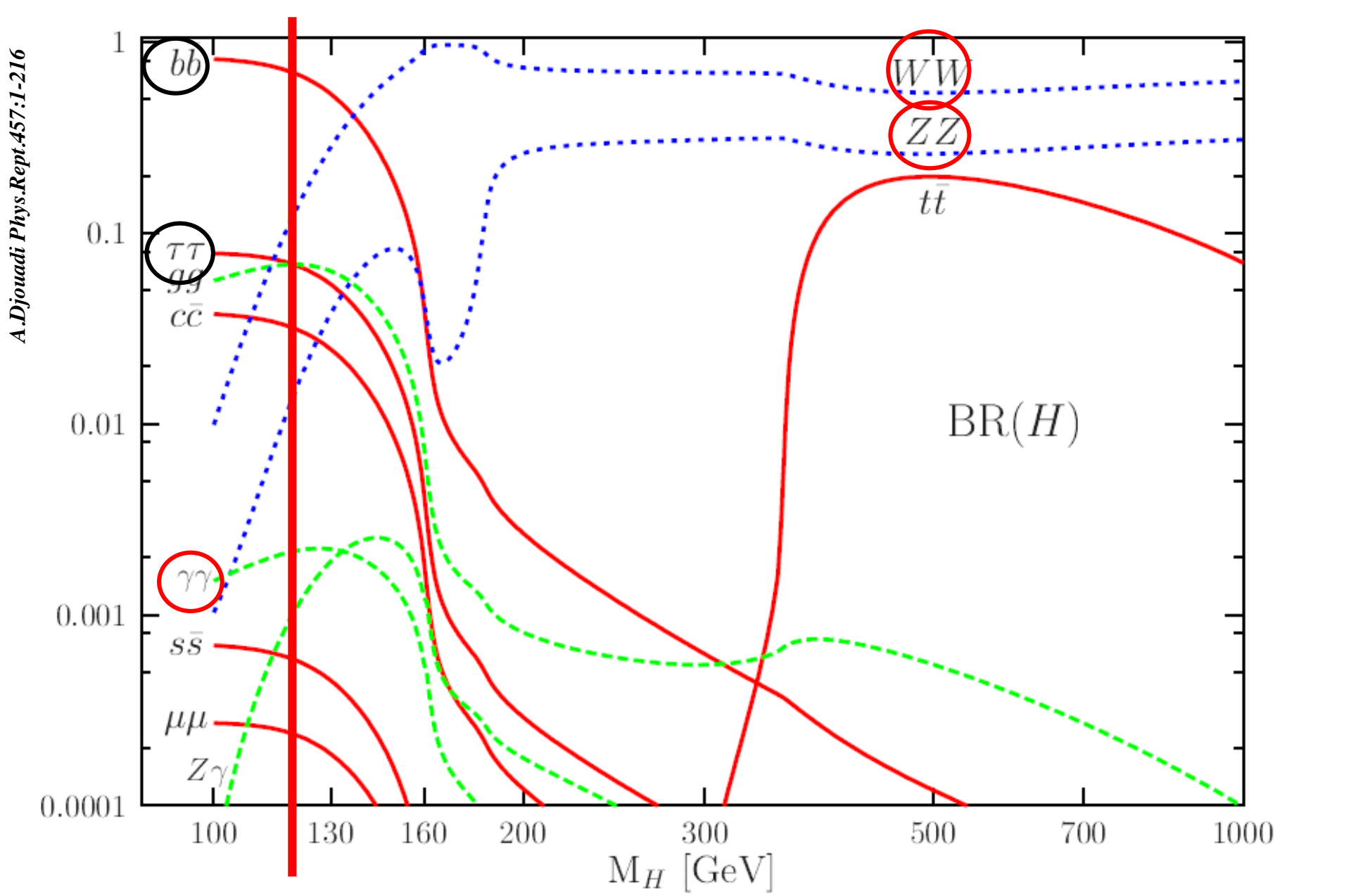


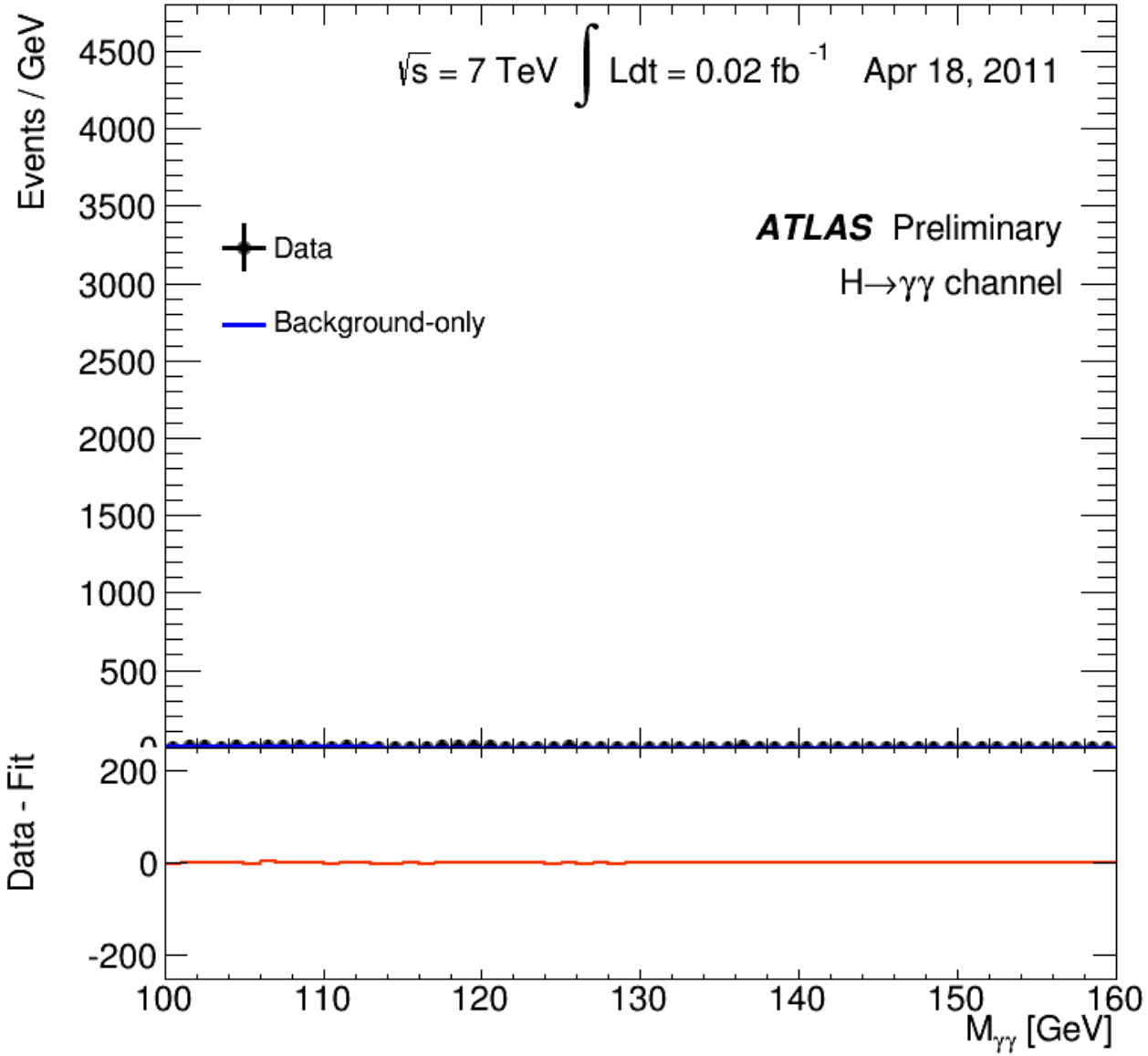

| *Typical uncertainties on cross-section* | | |
|---|---|---|
| *gg* | *5 %* | *NNNLO* |
| *VBF* | *<5%* | *NNLO* |
| *WH,ZH* | *<5%* | *NNLO* |
| *ttH* | *10%* | *NLO* |

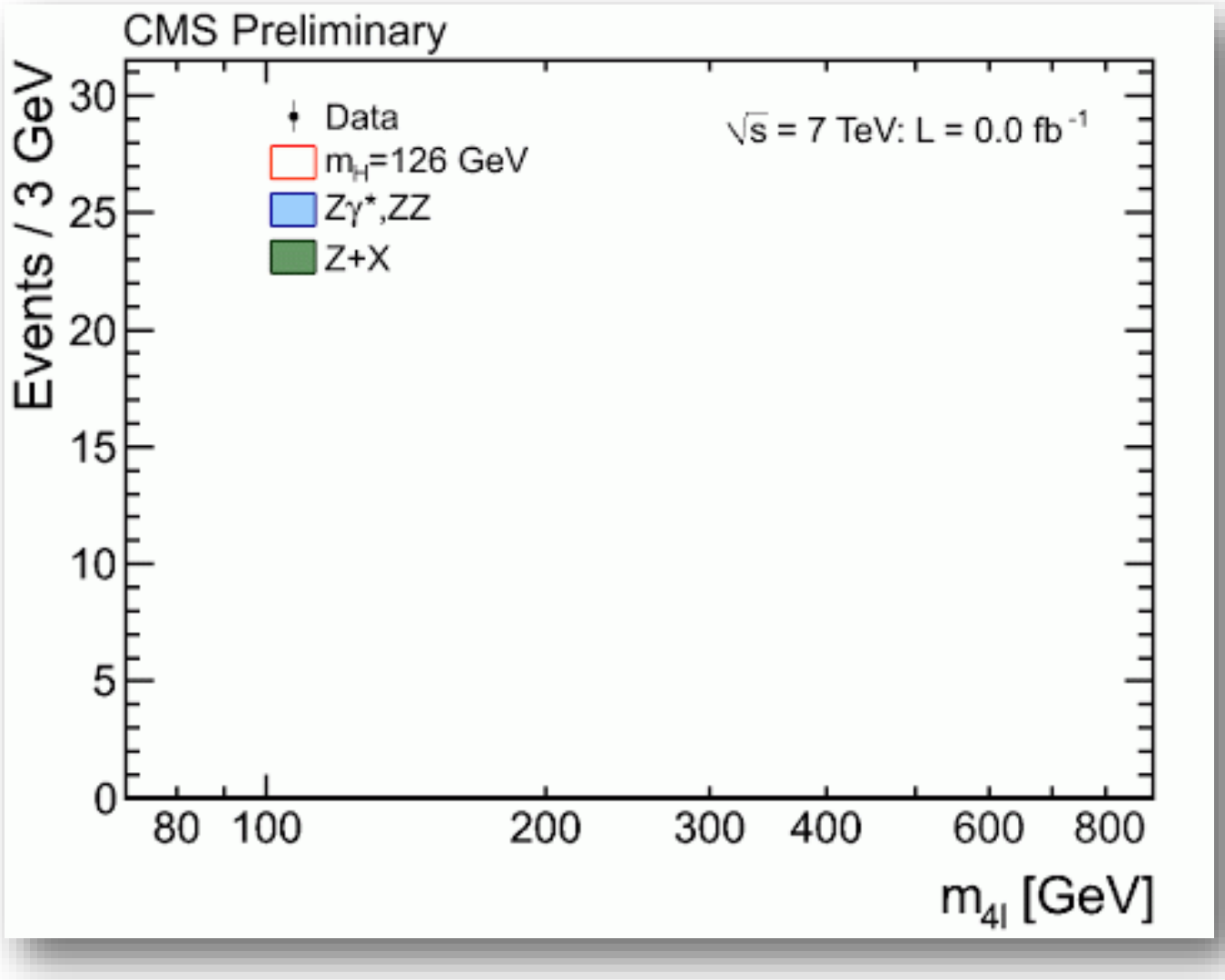
*These production cross sections have to be used with the decays* **bb , ττ , WW , ZZ , γγ**

*channels with good mass resolution*

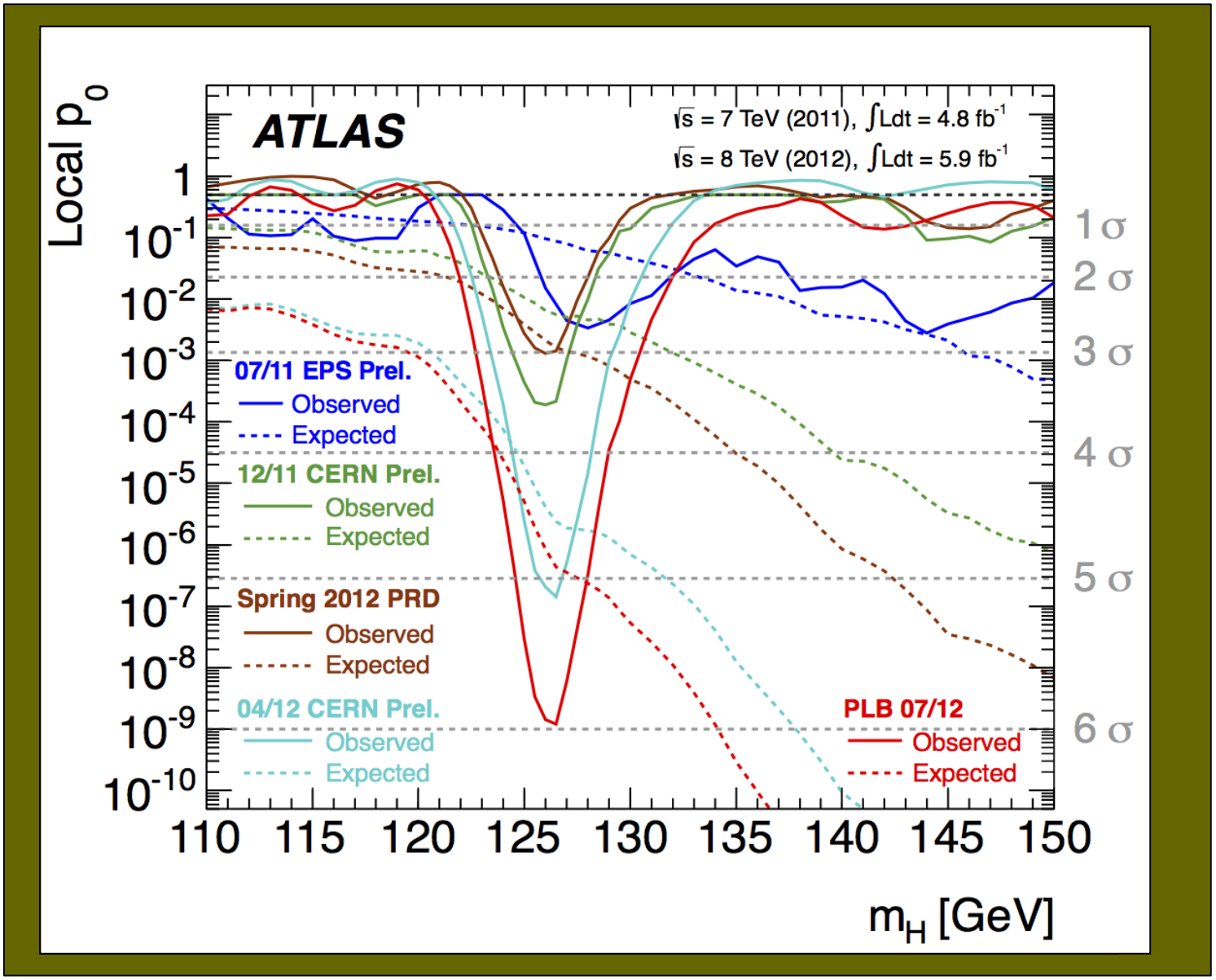
**see talk of Massimiliano**


A.Djouadi Phys.Rept.457:1-216
1
0.1
0.01
0.001
0.0001
$b\bar{b}$
$\tau\tau$
$gg$
$c\bar{c}$
$\gamma\gamma$
$s\bar{s}$
$\mu\mu$
$Z\gamma$
$WW$
$ZZ$
$t\bar{t}$
BR($H$)
100
130
160
200
300
500
700
1000
M$_H$ [GeV]


√s = 7 TeV ∫ Ldt = 0.02 fb -1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]


CMS Preliminary
Data
$m_H$=126 GeV
Zγ*,ZZ
Z+X
$\sqrt{s}$ = 7 TeV: L = 0.0 fb$^{-1}$
Events / 3 GeV
0
5
10
15
20
25
30
80
100
200
300
400
600
800
$m_{4l}$ [GeV]

# *Evolution of the excess with time*

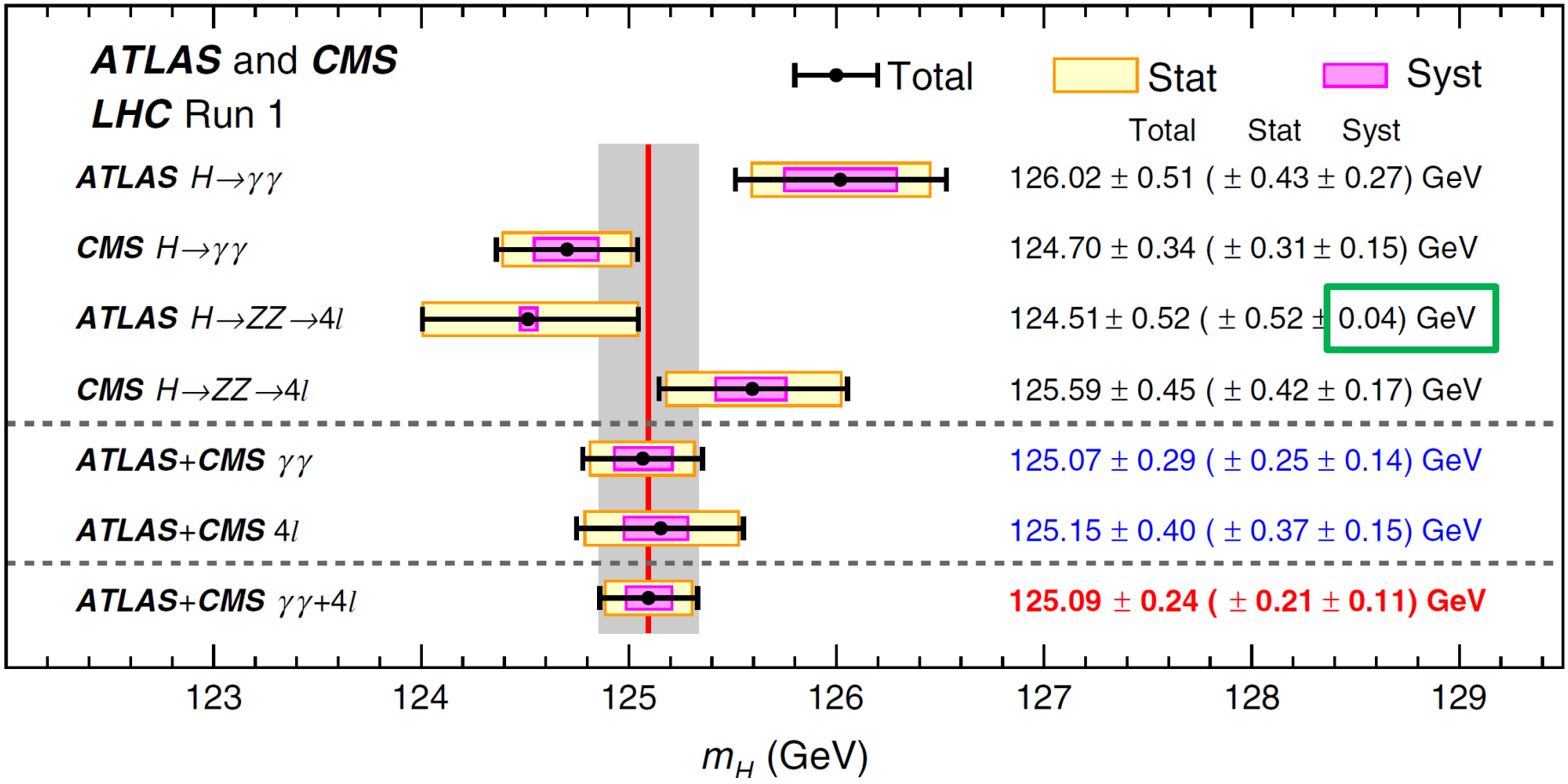



© F.Gianotti



*$p_0$= probability that the background fluctuates more than the observed excess*

- ♪ *LHC and ATLAS run 1 and run 2*
- ♪ *Study of the H(125) or with H(125)*
- ♪ ***H(125) : mass***
- ♪ *H(125) : couplings*
- ♪ *H(125) : off-shell measurements*
- ♪ *Conclusions*
- ♪ *Backup*




PRL 114, 191803 (2015)

***uncertainty on mass < 0.2 % !***

**Remember we want to have an uncertainty on W mass of < 20 (10?) MeV**

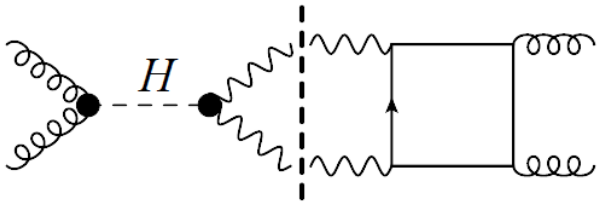
***note that $\Delta m = 0.1$ GeV $\rightarrow \Delta(BR(H\rightarrow ZZ)) / BR(H\rightarrow ZZ) \sim 1\%$***

**At longer term uncertainty will be dominated by 4l**

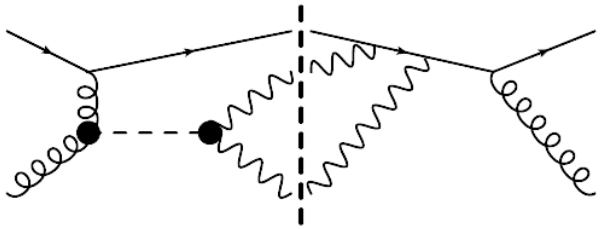
***start to be sensitive to subtle effects like interference ( between signal and background) in γγ***

***Martin, Dixon and Li Phys.Rev.Lett. 111 (2013) 11180***

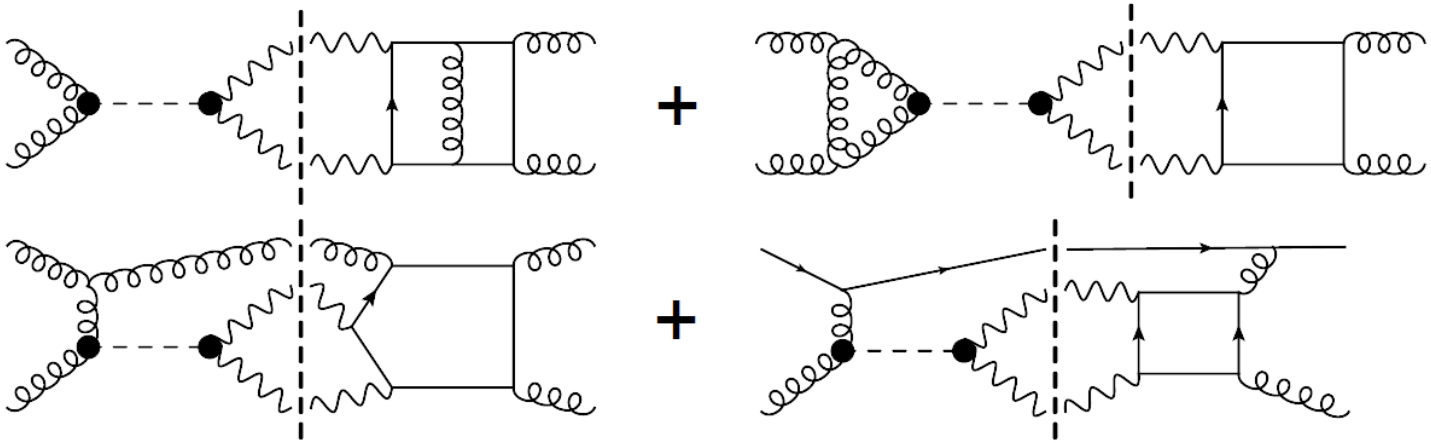
LO (gg):

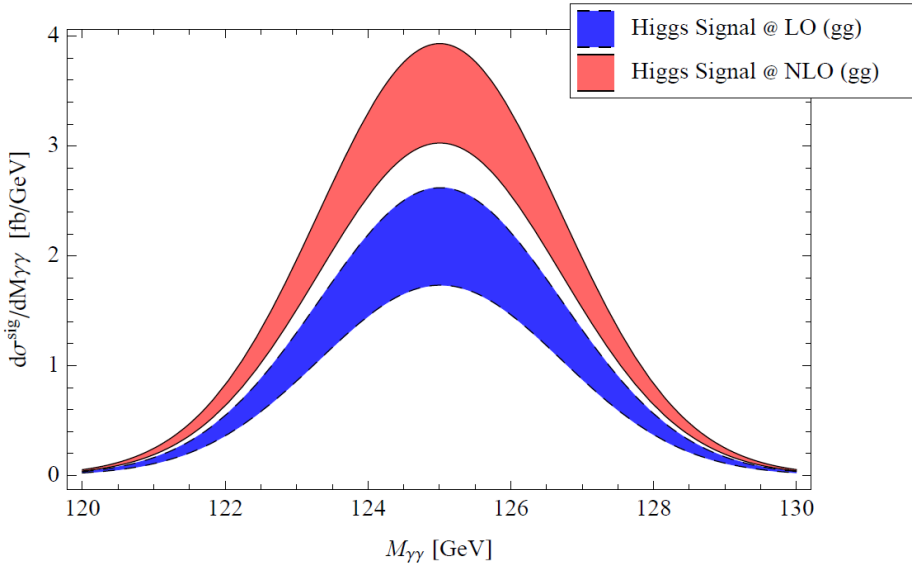


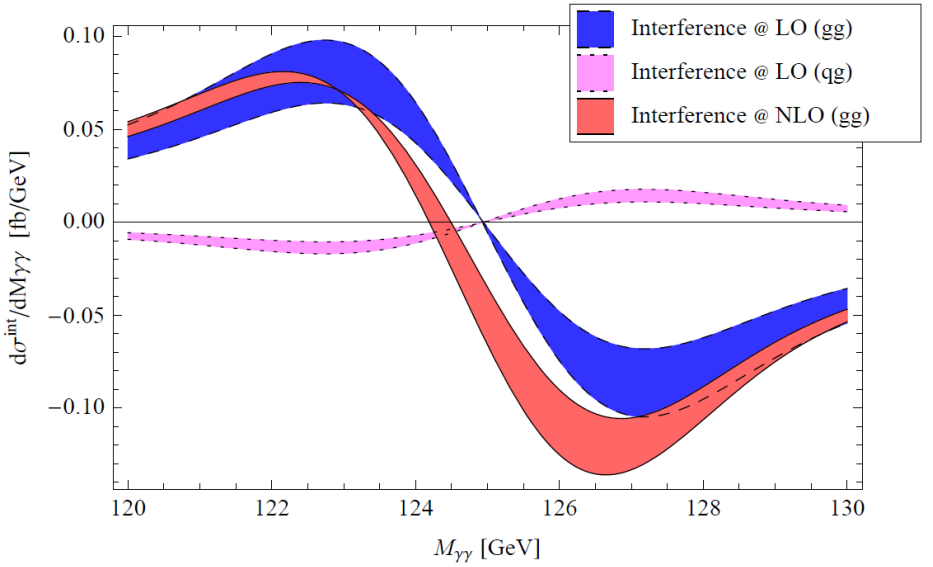

LO (qg):



NLO (gg):






ATL-PHYS-PUB-2016-009

The expected median mass shift is found to be $\Delta m_H = -35 \pm 9$ MeV assuming a Standard Model width of 4 MeV for the Higgs boson

**However the effect is larger for larger H width**
**→ could constrain the H width**

- ♪ *LHC and ATLAS run 1 and run 2*
- ♪ *Study of the H(125) or with H(125)*
- ♪ *H(125) : mass*
- ♪ ***H(125) : couplings***
- ♪ *H(125) : off-shell measurements*
- ♪ *Conclusions*
- ♪ *Backup*

***Run 1 coupling combination***
***Run 1 and Run 2 analysis of various channels***

***A walk with couplings around Run 1 combination***

# *ATLAS + CMS (couplings) combination*

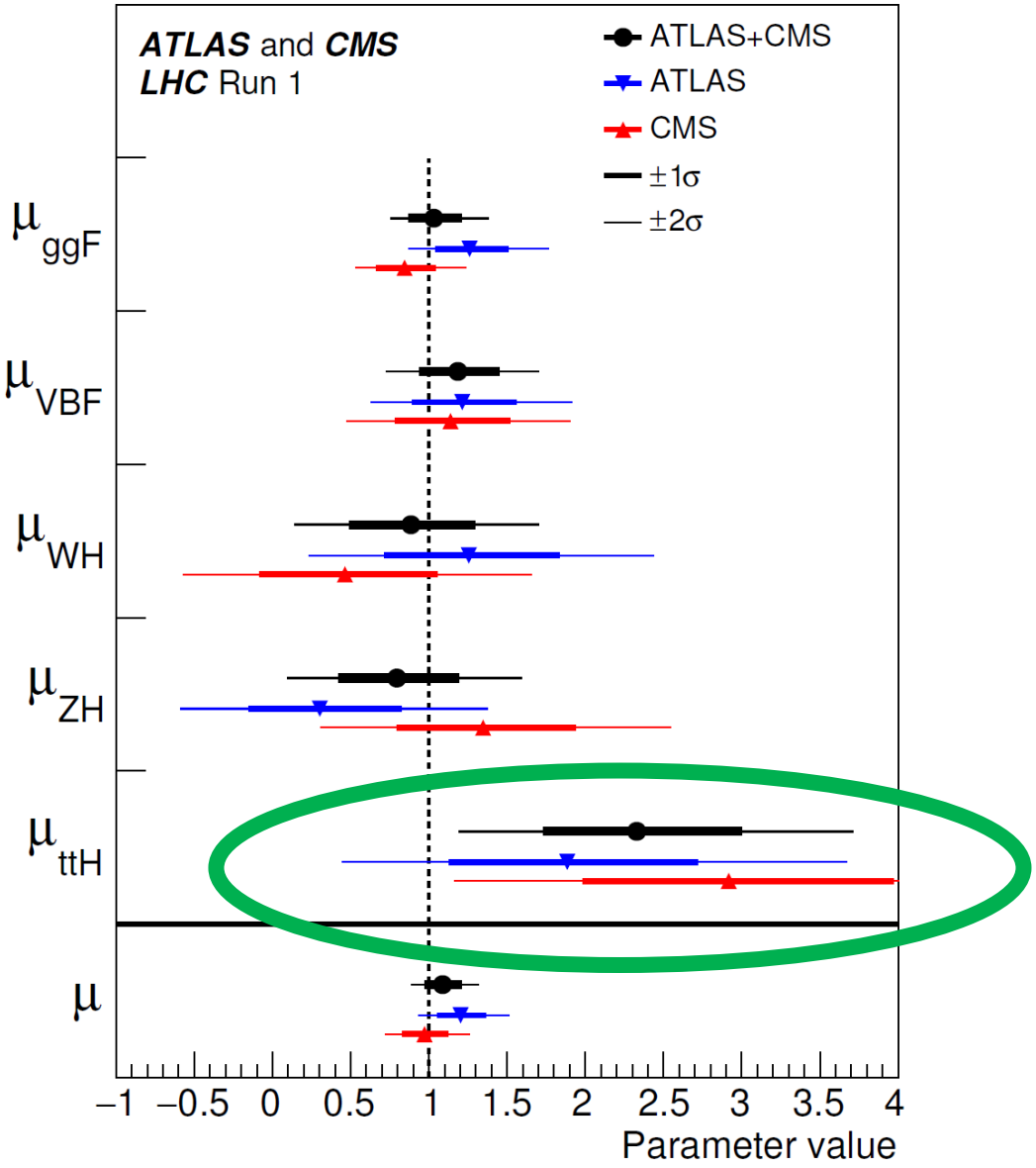
## $\mu = (\sigma \cdot BR) / (\sigma \cdot BR)_{SM}$ *signal strength*

| Channel | References for individual publications | | Signal strength [$\mu$] from results in this paper (section 5.2) | | Signal significance [$\sigma$] | |
|---|---|---|---|---|---|---|
| | ATLAS | CMS | ATLAS | CMS | ATLAS | CMS |
| $H \to \gamma\gamma$ | [92] | [93] | $1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$ | $1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$ | 5.0 (4.6) | 5.6 (5.1) |
| $H \to ZZ$ | [94] | [95] | $1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$ | $1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$ | 7.6 (5.6) | 7.0 (6.8) |
| $H \to WW$ | [96, 97] | [98] | $1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$ | $0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$ | 6.8 (5.8) | 4.8 (5.6) |
| $H \to \tau\tau$ | [99] | [100] | $1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$ | $0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$ | 4.4 (3.3) | 3.4 (3.7) |
| $H \to bb$ | [101] | [102] | $0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$ | $0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$ | 1.7 (2.7) | 2.0 (2.5) |
| $H \to \mu\mu$ | [103] | [104] | $-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$ | $0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$ | | |
| $ttH$ production | [78, 105, 106] | [108] | $1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$ | $2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$ | 2.7 (1.6) | 3.6 (1.3) |

**I will discuss later ttH**

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}}$$

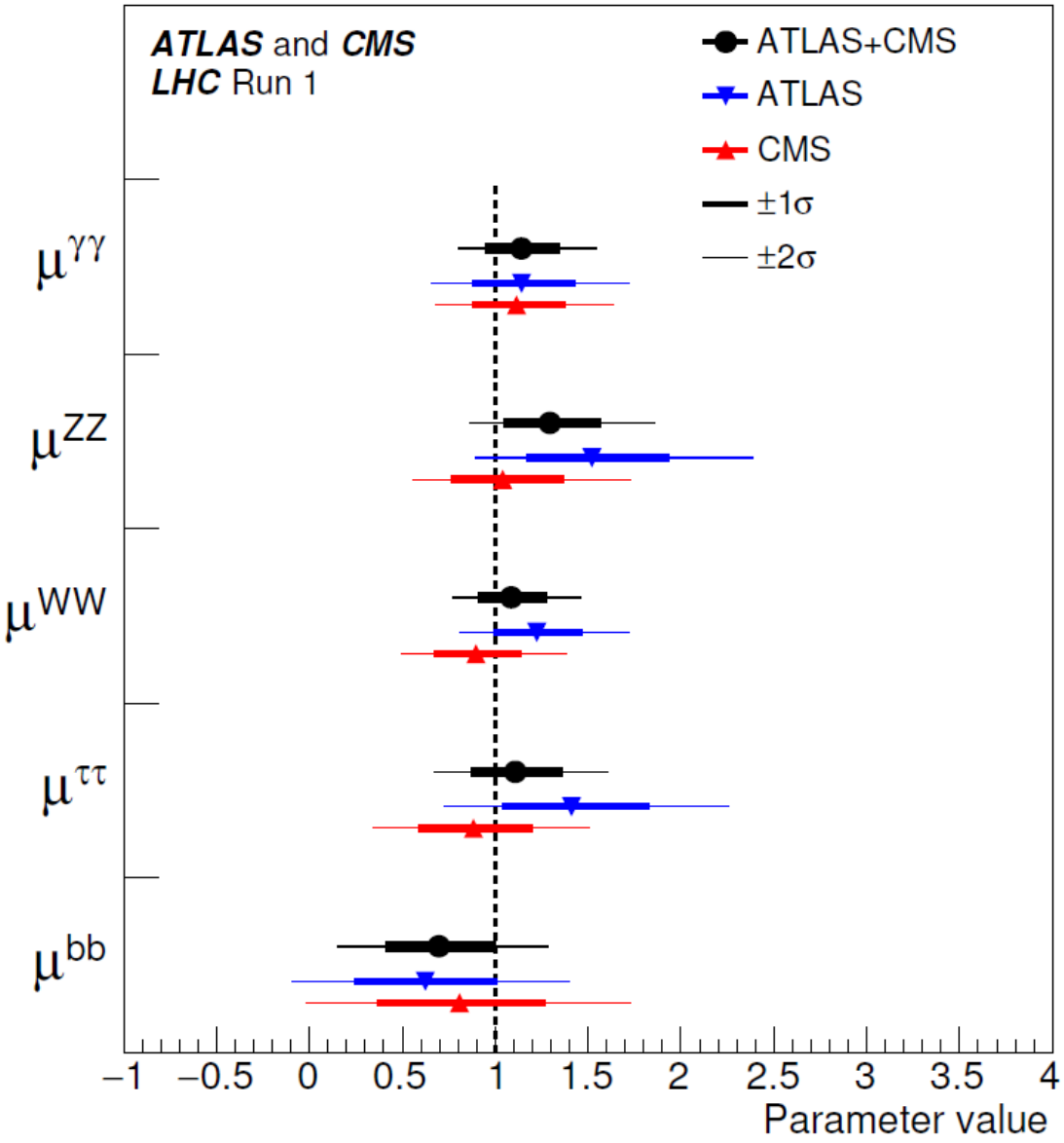
*assuming SM BR's*




$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\mathrm{stat})\ ^{+0.04}_{-0.04}\ (\mathrm{expt})\ ^{+0.03}_{-0.03}\ (\mathrm{thbgd})^{+0.07}_{-0.06}\ (\mathrm{thsig}),$$

$$\mu^f = \frac{\mathrm{B}^f}{(\mathrm{B}^f)_{\mathrm{SM}}}.$$

*assuming SM productions*

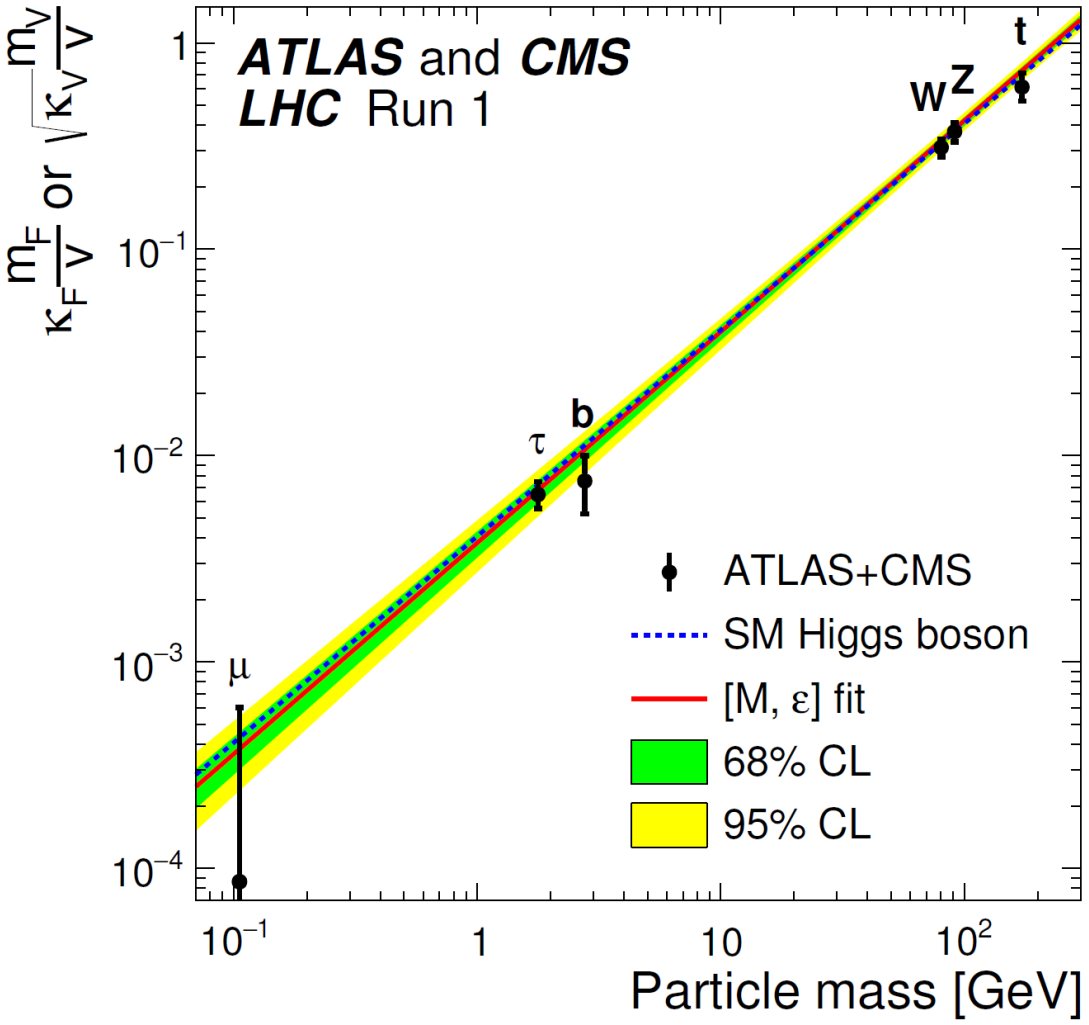


| Production process | Measured significance ($\sigma$) | Expected significance ($\sigma$) |
|---|---|---|
| VBF | 5.4 | 4.6 |
| $WH$ | 2.4 | 2.7 |
| $ZH$ | 2.3 | 2.9 |
| $VH$ | 3.5 | 4.2 |
| $ttH$ | 4.4 | 2.0 |
| Decay channel | | |
| $H \to \tau\tau$ | 5.5 | 5.0 |
| $H \to bb$ | 2.6 | 3.7 |

Not included are the $gg$F production process and the $H \to ZZ$, $H \to WW$, and $H \to \gamma\gamma$ decay channels, which have already been clearly observed.

# $\kappa$-framework coupling modifiers

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$



# *Higgs → μμ*

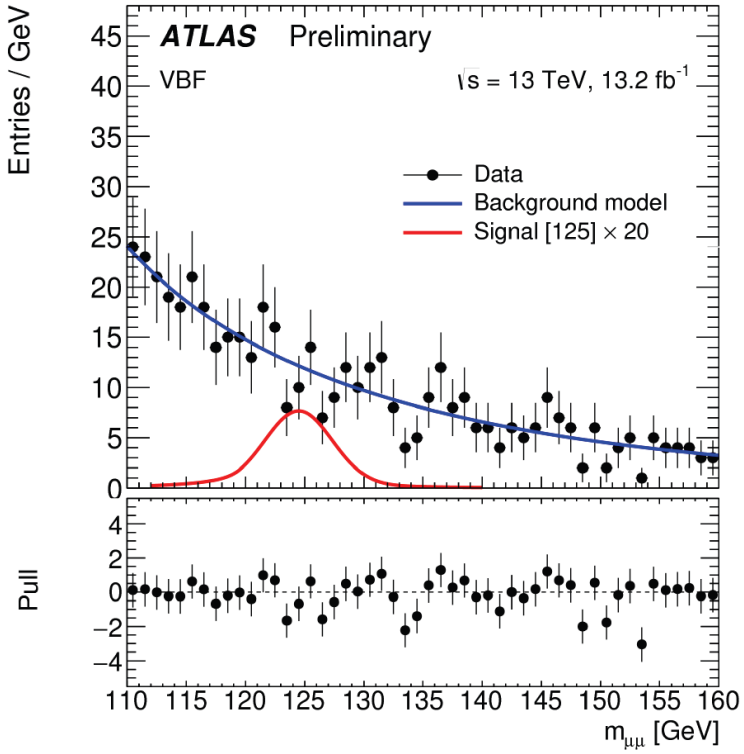
ATLAS-CONF-2016-041

- A very **rare decay** in the SM
  - Probe Yukawa-coupling to 2nd-generation fermions and mass dependence
  - Test of the Higgs coupling to leptons

- **Signature:** Very clean signature from dimuon final state but $Z/\gamma^* \rightarrow \mu\mu$ overwhelming irreducible background

- **Analysis strategy:**

  Search for peak in $m_{\mu\mu}$ spectrum over smoothly falling background
  - Categorize events according to VBF and ggF signature enriched

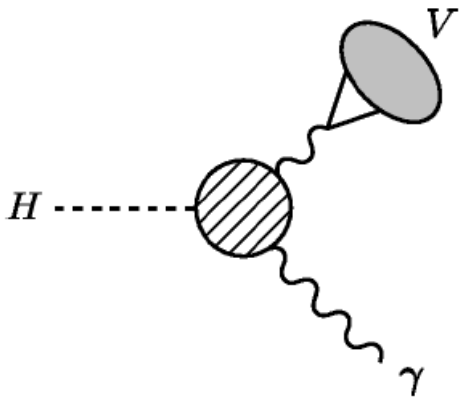


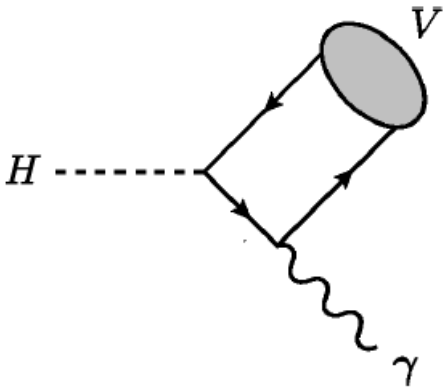

| ATLAS | Upper limit x SM (expected) |
|---|---|
| Run 1 | 7.1 (7.2) |
| Run 2 | 4.4 (5.5) |
| Combined Run 1 and Run 2 | 3.5 (4.5) |

**Hope to be close to 3σ (ATLAS+CMS) at the end of run 3**

© F.Canelli ICHEP 2016

# Light quarks couplings : exclusive decays




Stamou @ HH2016

$$\Gamma_{h\to J/\psi\,\gamma} = |(11.9 \pm 0.2)\kappa_\gamma - (1.04 \pm 0.14)\kappa_c|^2 \cdot 10^{-10}\ \text{GeV}$$

| | 95% $CL_s$ Upper Limits | | | | |
|---|---|---|---|---|---|
| | $J/\psi$ | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ | $\sum^n \Upsilon(nS)$ |
| $\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [ $10^{-6}$ ] | | | | | |
| Expected | $2.0^{+1.0}_{-0.6}$ | $4.9^{+2.5}_{-1.4}$ | $6.2^{+3.2}_{-1.8}$ | $5.4^{+2.7}_{-1.5}$ | $8.8^{+4.7}_{-2.5}$ |
| Observed | 2.6 | 3.4 | 6.5 | 5.4 | 7.9 |
| $\mathcal{B}(H \to \mathcal{Q}\gamma)$ [ $10^{-3}$ ] | | | | | |
| Expected | $1.2^{+0.6}_{-0.3}$ | $1.8^{+0.9}_{-0.5}$ | $2.1^{+1.1}_{-0.6}$ | $1.8^{+0.9}_{-0.5}$ | $2.5^{+1.3}_{-0.7}$ |
| Observed | 1.5 | 1.3 | 1.9 | 1.3 | 2.0 |
| $\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb] | | | | | |
| Expected | $26^{+12}_{-7}$ | $38^{+19}_{-11}$ | $45^{+24}_{-13}$ | $38^{+19}_{-11}$ | $54^{+27}_{-15}$ |
| Observed | 33 | 29 | 41 | 28 | 44 |

*Phys.Rev.Lett. 114 (2015) no.12, 121801*

*Still far from theory*

$$\mathcal{B}(H \to J/\psi\,\gamma) = (2.8 \pm 0.2) \times 10^{-6}$$

$$\mathcal{B}[H \to \Upsilon(nS)\,\gamma] = \left(6.1^{+17.4}_{-6.1}, 2.0^{+1.9}_{-1.3}, 2.4^{+1.8}_{-1.3}\right) \times 10^{-10}$$

# Search for Higgs and Z Boson Decays to $\phi\gamma$

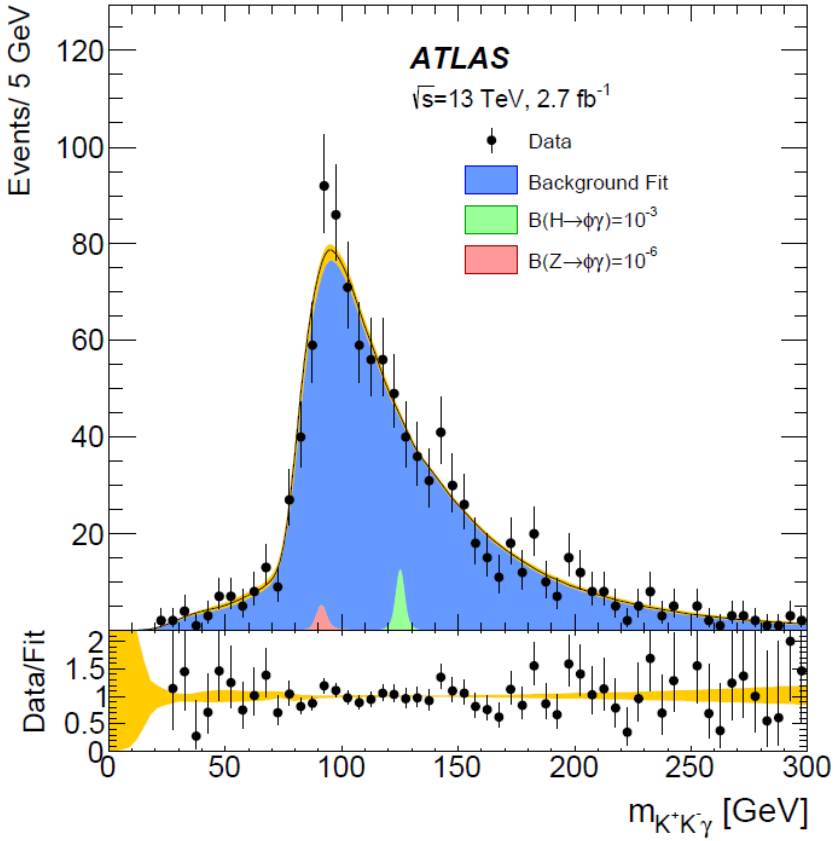
arXiv:1607.03400 Phys. Rev. Lett. 117, 111802

*Expected SM*

$$\mathcal{B}(H \to \phi\gamma) = (2.3 \pm 0.1) \times 10^{-6}$$

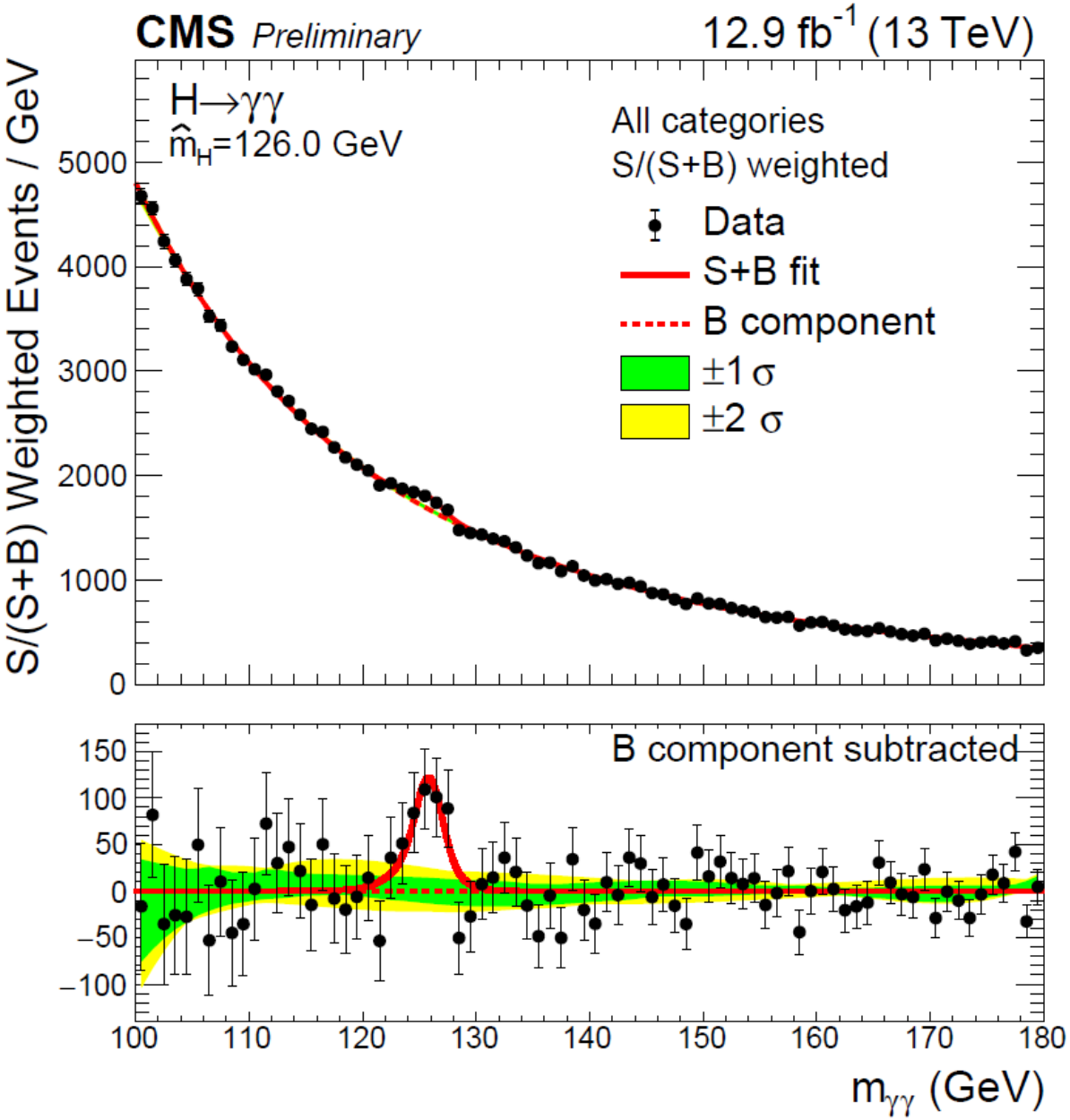
*Measured*

| Branching Fraction Limit (95% CL) | Expected | Observed |
|---|---|---|
| $\mathcal{B}(H \to \phi\gamma)$ [ $10^{-3}$ ] | $1.5^{+0.7}_{-0.4}$ | 1.4 |



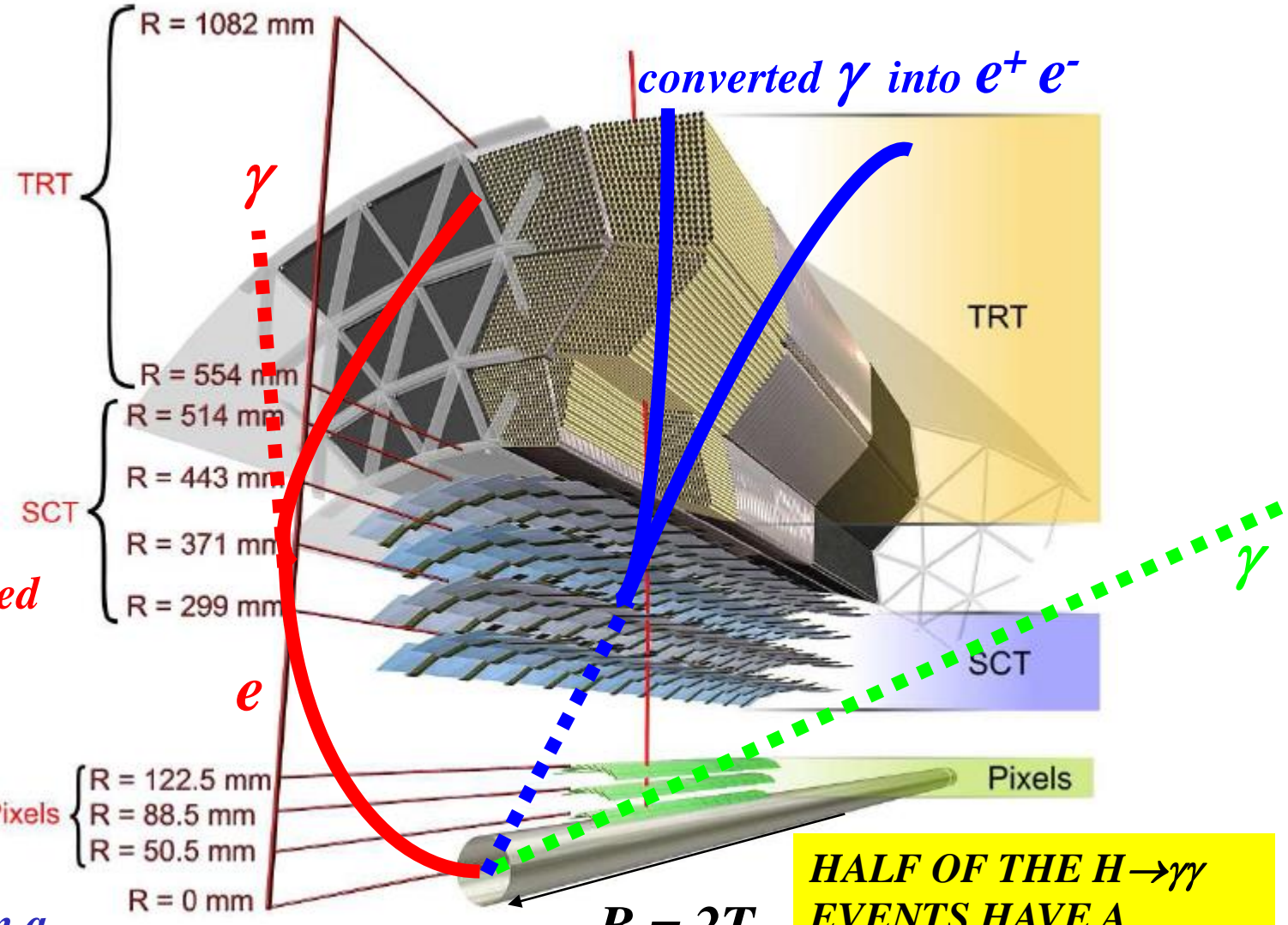
***Look at H decays with run 2***
***example of H $\rightarrow\gamma\gamma$***

# CMS PAS HIG-16-020



***ATLAS***
***inner detector***

*Outside you have the calorimeters and the muon detector*



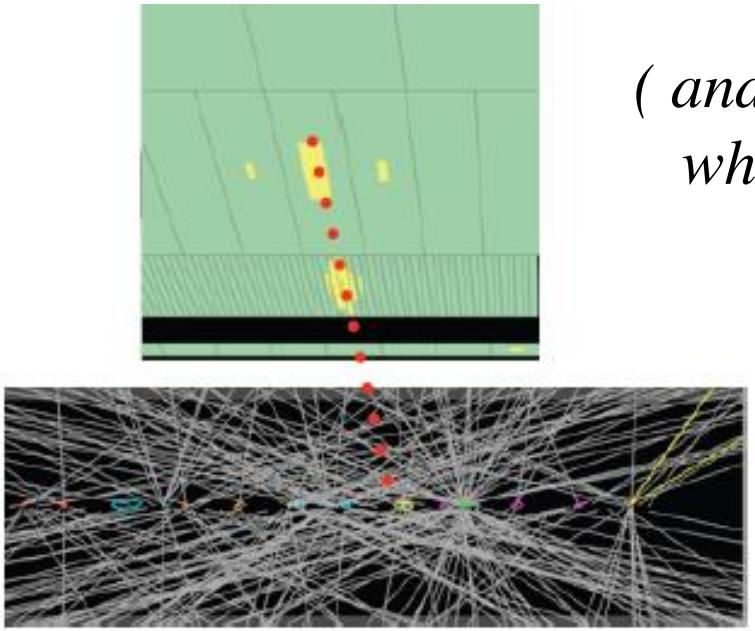

*electrons can do some bremsstrahlung in the Inner Detector ⇒ response more complicated*

*photons can convert ⇒ more complicated than a non converted photon*

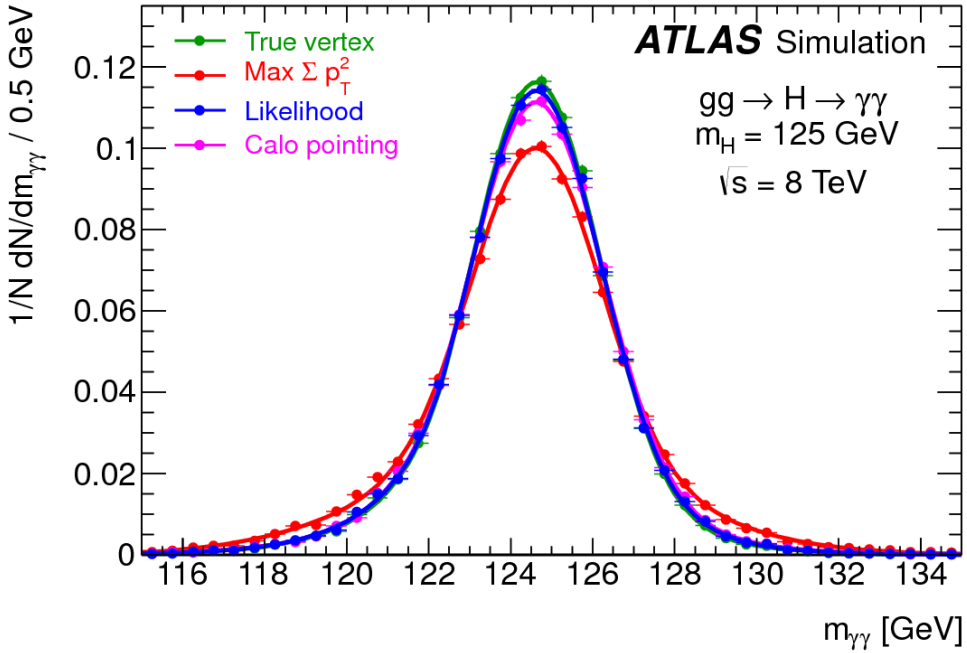
***HALF OF THE H→γγ EVENTS HAVE A CONVERTED PHOTON***

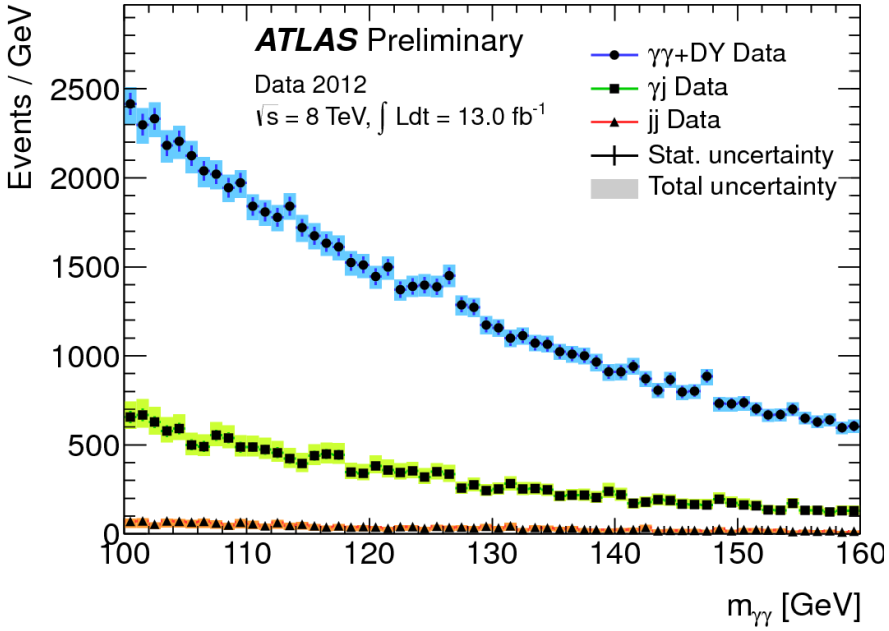
***ATLAS : uses the longitudinal segmentation in order to get the vertex***

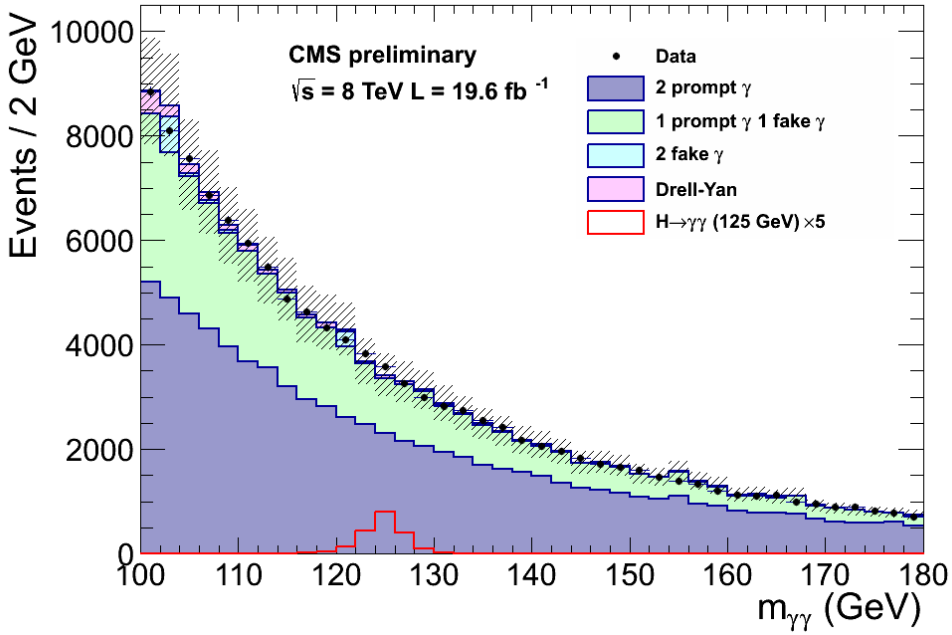
*( and also the track conversion(s) when the photon is converted )*



***⇒No degradation of the resolution***





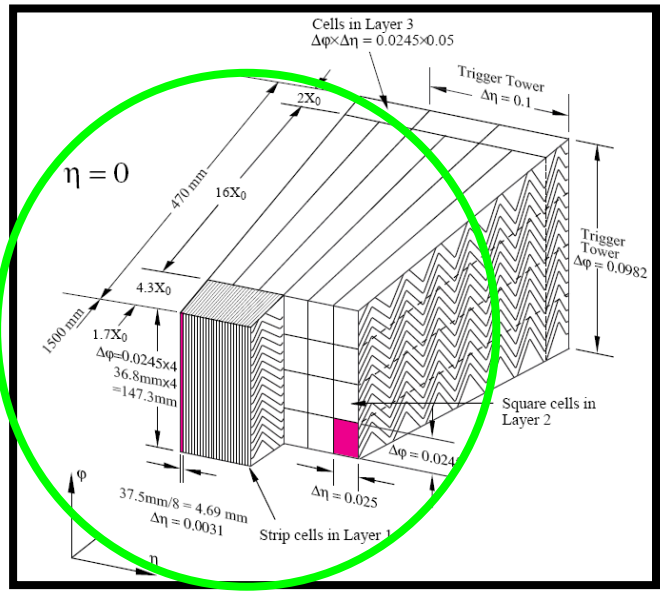

***large ( non photon ) background***

***due to jets fragmenting mainly into $\pi^0$ 's***

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

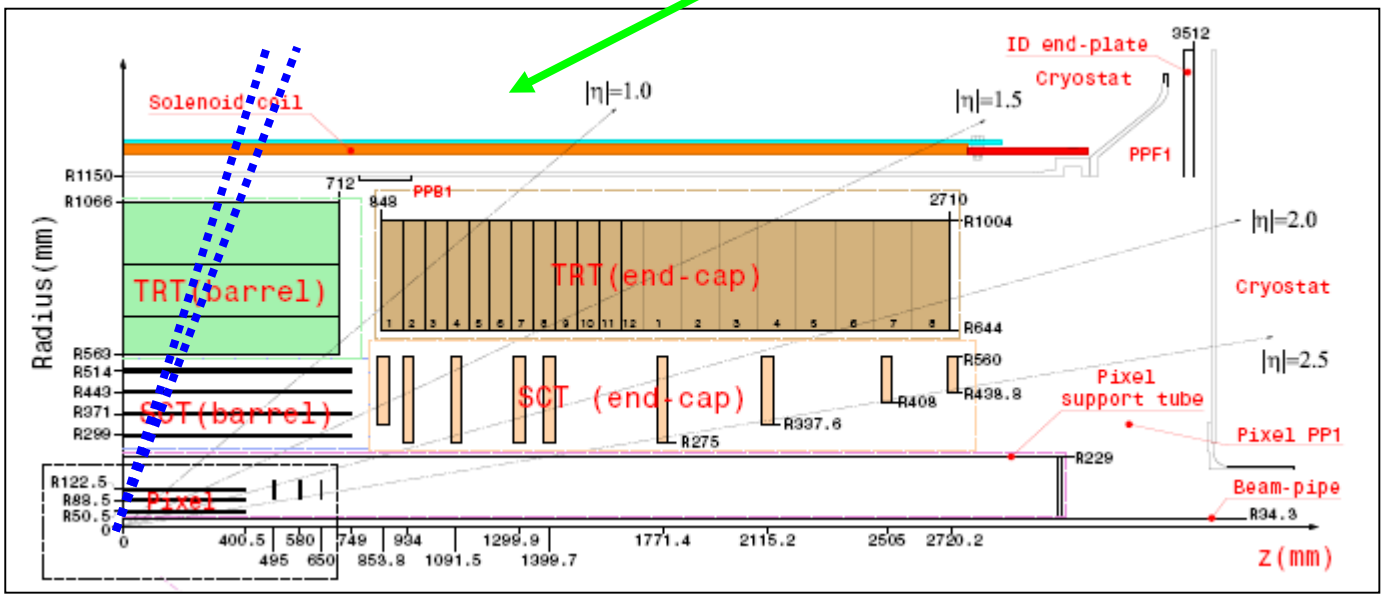
♦ *good jet rejection essential ( to reduce γj and jj backgrounds)*

***The granularity of the electromagnetic ATLAS detector is very useful to reject the $\pi^0$ bakground***




***opening of photons coming from a $\pi^0$ ($p_T$=40 GeV)***

***$\Delta R > .007$***

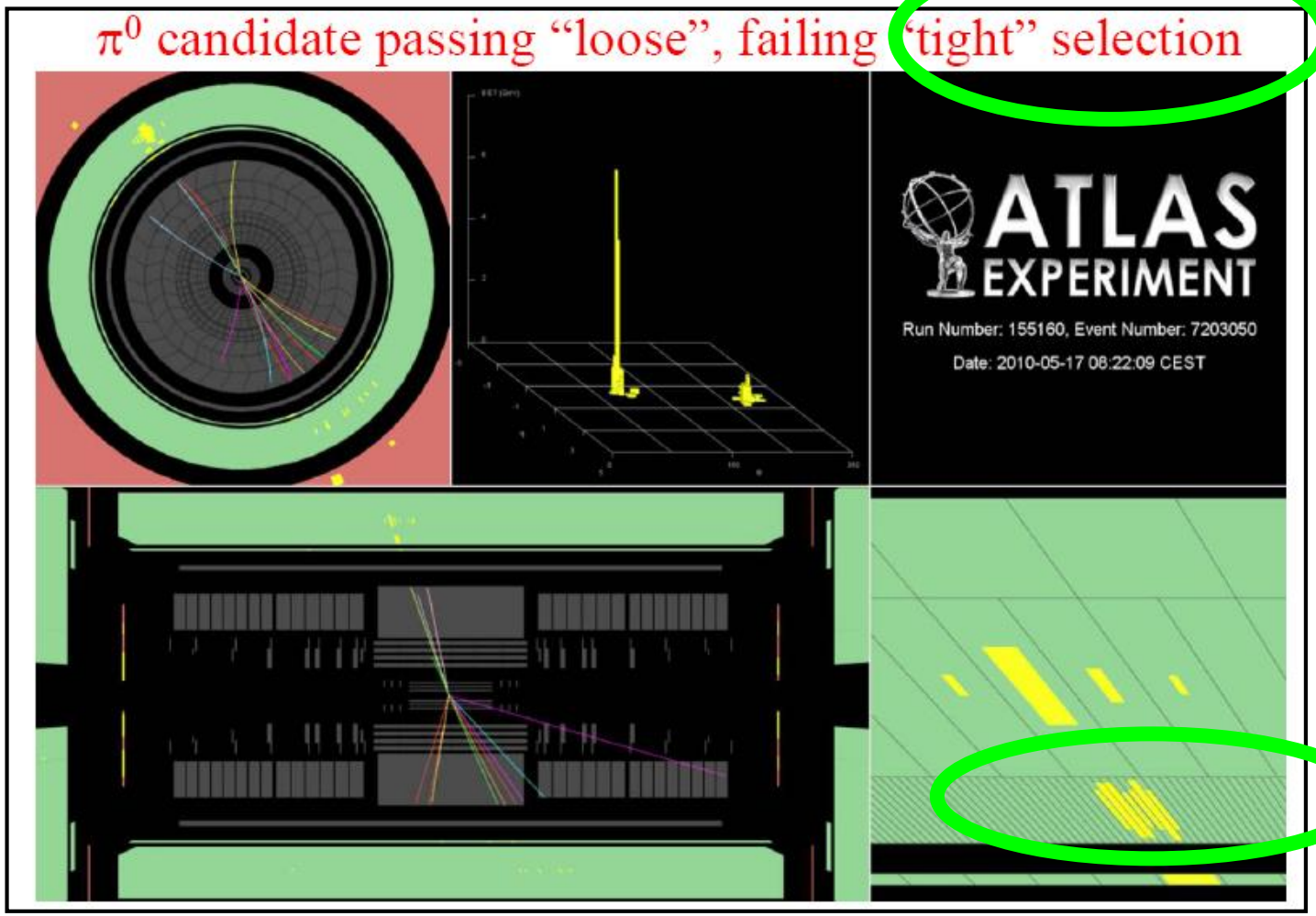



***granularity of 1st sampling of calorimeter***

***$\Delta\eta \sim .003$***

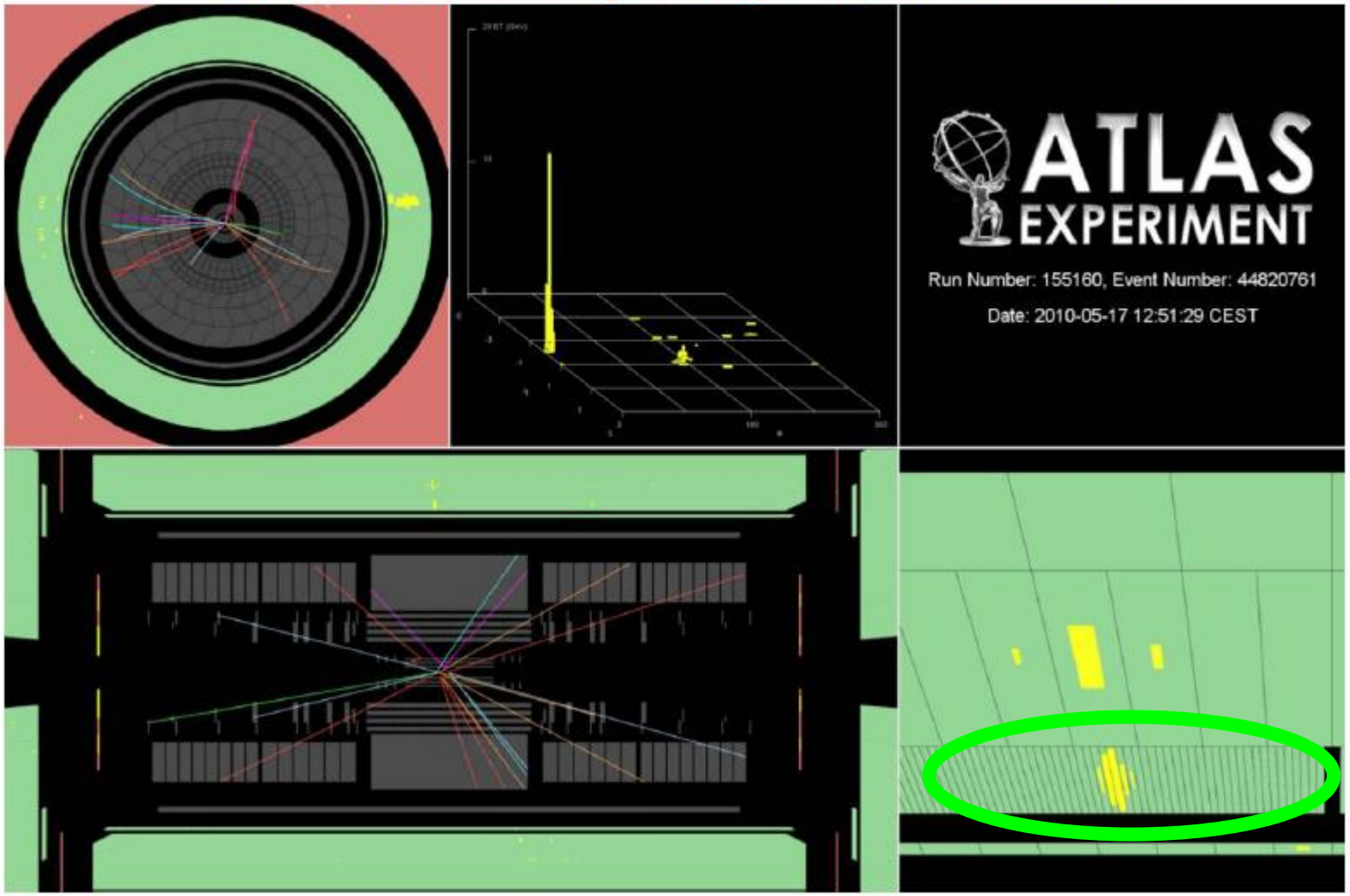
## *Photon identification with shower shapes*

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



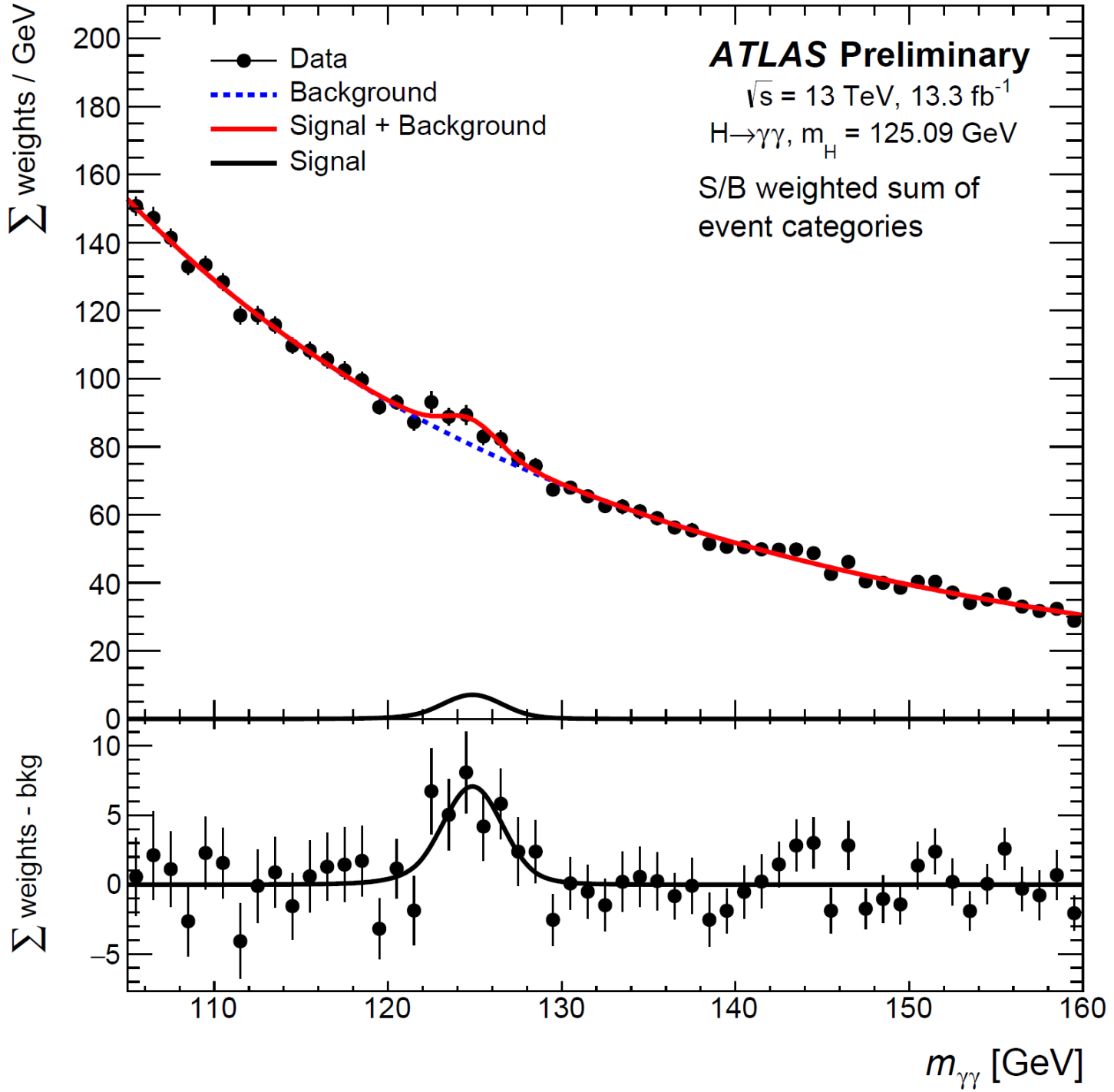

***tight selection uses mainly calo 1st sampling***

# Photon candidate passing "tight" selection



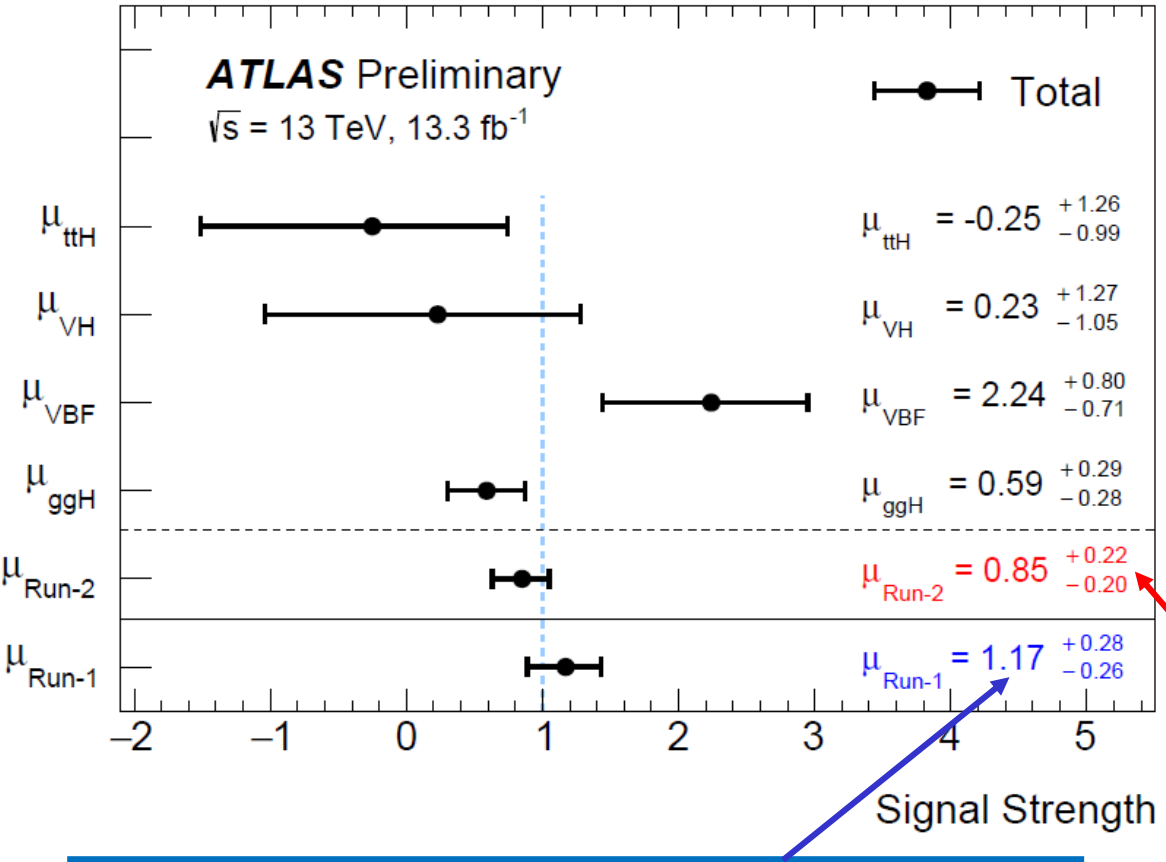

***Nice shape in first sampling of EM calorimeter***

ATLAS-CONF-2016-067



ATLAS-CONF-2016-067

# Measurement of fiducial, differential and production cross sections in the $H \to \gamma\gamma$ decay channel with 13.3 $fb^{-1}$ of 13 TeV proton-proton collision data with the ATLAS detector




$$\mu = 1.17 \pm 0.23\ (\text{stat.})\ ^{+0.10}_{-0.08}\ (\text{syst.})\ ^{+0.12}_{-0.08}\ (\text{theory})$$

*Phys.Rev. D90 (2014) no.11, 112015*

*theoretical ggH predictions different for Run-1(N3LO) and Run-2 (N2LO+N2LL)*

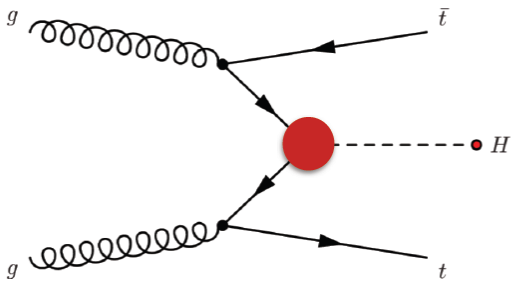
***already error smaller than for Run-1***

***with 35 $fb^{-1}$ stat error on μ ~ .11***

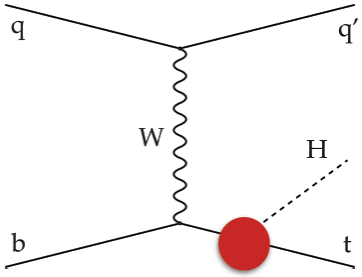
© N.Chanon Precision Vietnam 2016

# Associated production of top quarks with the Higgs boson

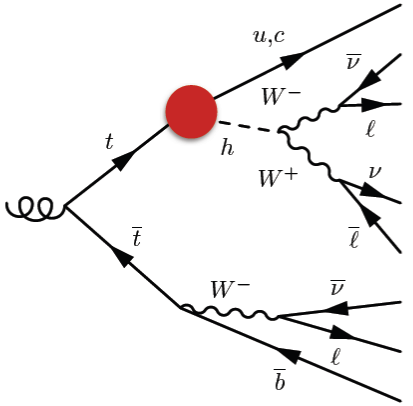
**ttH production :** direct probe of top Yukawa coupling




**tHq production :** probing the sign of top Yukawa coupling

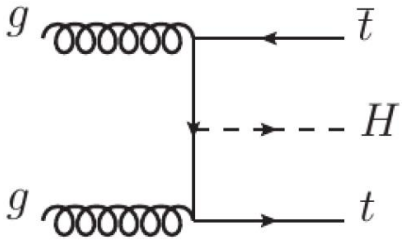



**Flavour changing neutral current** (FCNC) **tH coupling**




**Remember : small excess in run 1**

# ATLAS 13 TeV ttH combination




***Direct probe of top Yukawa coupling***

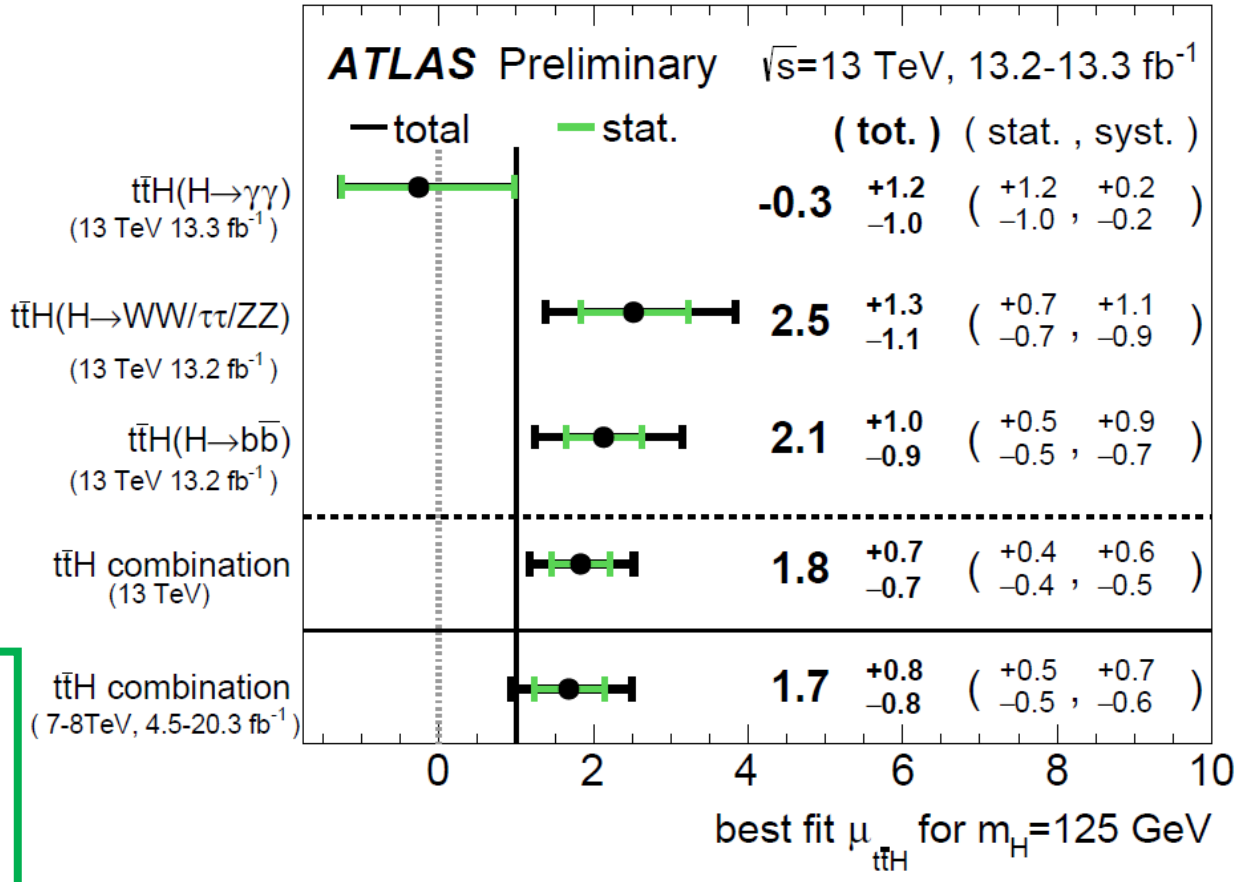
***Cross section @13 TeV 4 times larger than @ 8TeV***

***Results presented with 2015+2016 data for***

- *ttH, H→bb*
- *ttH, multilepton final states ( several decay chains contribute )*
- *ttH, H→γγ*

Combine all three 13 TeV analyses

Signal strength μ expressed relative to SM expectation




**Observed significance**
**2.8σ (expect 1.8σ)**
Cf Run-1 expected 1.5σ

**CMS**

- ttH, **H→bb** (2015):
**$\mu = -2.0^{+1.8}_{-1.8}$**

- ttH **multilepton**
(2015+2016): **$\mu = 2.0^{+0.8}_{-0.7}$**

- ttH, **H→γγ** (2016):
**$\mu = 1.9^{+1.5}_{-1.2}$**

*to be followed*

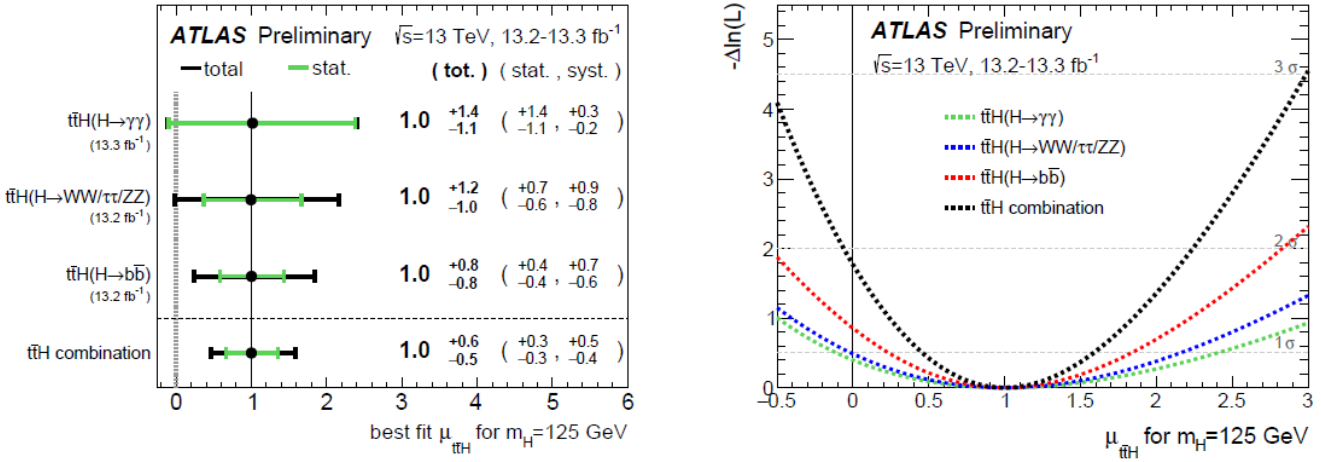


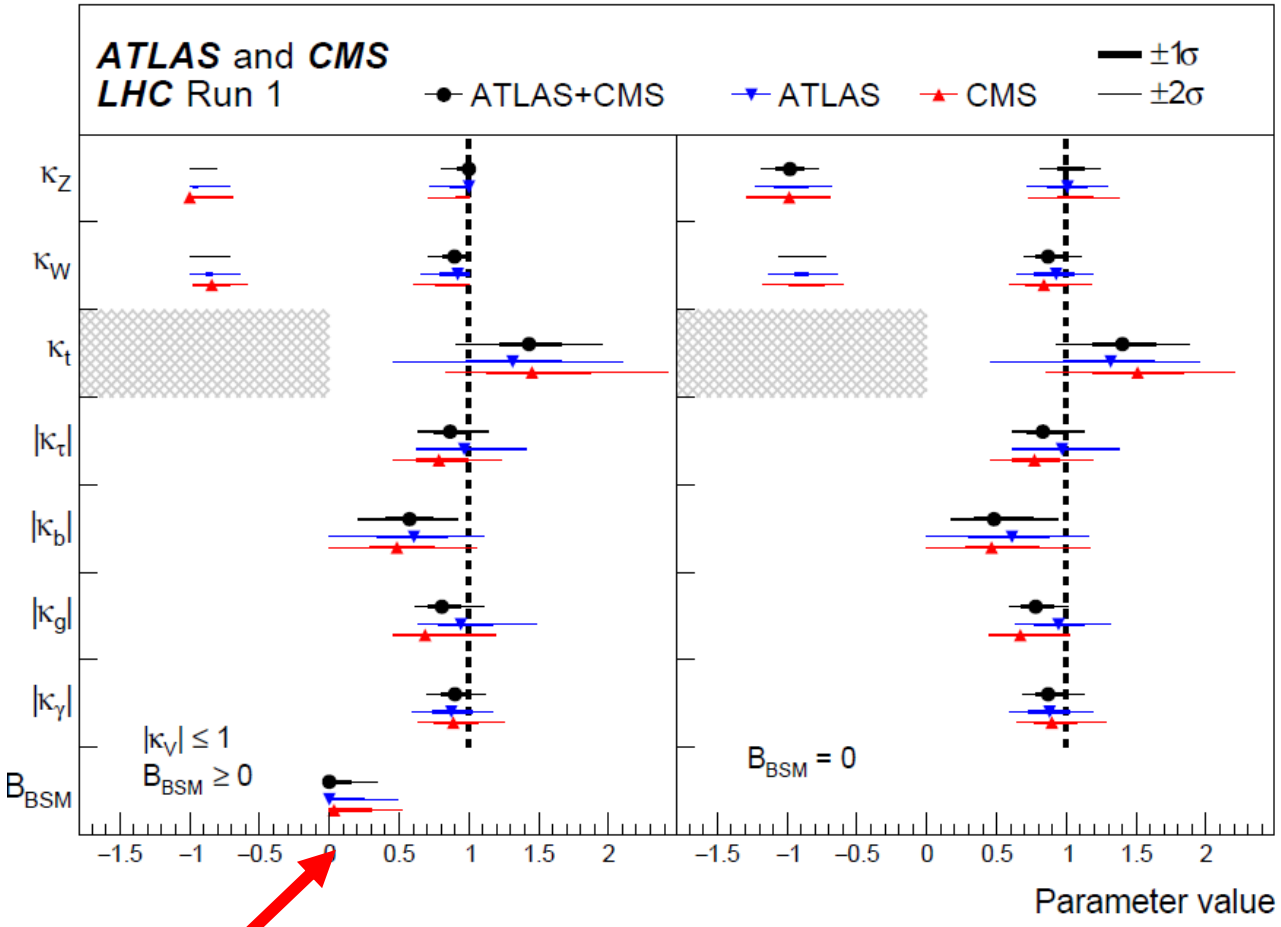

Figure 4: Expected $\mu_{t\bar{t}H}$ measurements (left) and expected negative logarithm of the likelihood ratio as a function of the signal strength for the individual analyses and for their combination (right), assuming $m_H = 125$ GeV.

| Channel | Significance | |
|---|---|---|
| | Observed [$\sigma$] | Expected [$\sigma$] |
| $t\bar{t}H, H \to \gamma\gamma$ | –0.2 | 0.9 |
| $t\bar{t}H, H \to (WW, \tau\tau, ZZ)$ | 2.2 | 1.0 |
| $t\bar{t}H, H \to b\bar{b}$ | 2.4 | 1.2 |
| $t\bar{t}H$ combination | 2.8 | 1.8 |

***With 3 times more statistics close to 3 σ expected ( for one experiment ) ?***

***One can allow contributions of BSM particles in loops (γ,g) and in decays***

$$\kappa_H^2 = \sum_j B_{SM}^j \kappa_j^2 \qquad \Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - B_{BSM}}$$

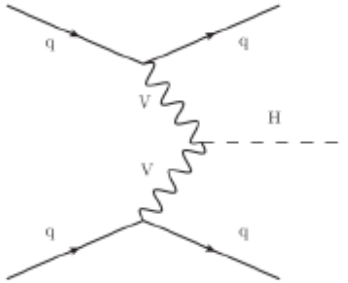



**Limit (ATLAS+CMS) on $B_{BSM}$ at 0.34 @95%CL**

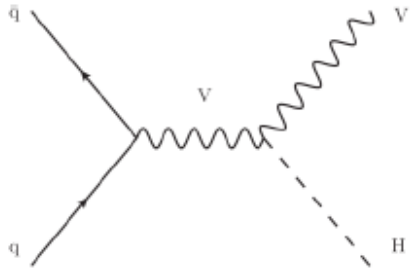
CMS-PAS-HIG-16-016

# Higgs Invisible

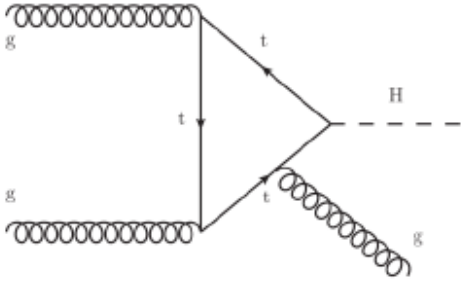
- SM BR(H → inv.) ~1.2e-3
  - H → 4ν




VBF



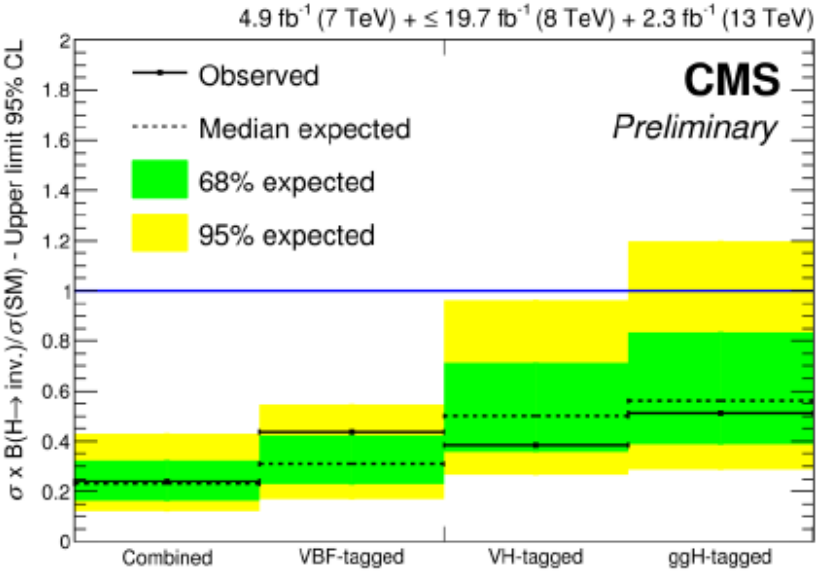

VH




ggH

- Dedicated VBF trigger
  - Large η separation
  - High dijet invariant mass

Combination of several analyses in 7, 8, and 13 TeV




© D.Taylor HH 2016

- ♪ *LHC and ATLAS run 1 and run 2*
- ♪ *Study of the H(125) or with H(125)*
- ♪ *H(125) : mass*
- ♪ *H(125) : couplings*
- ♪ ***H(125) : off-shell measurements***
- ♪ *Conclusions*
- ♪ *Backup*

# Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs

arXiv:1405.3455v1 [hep-ex]

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

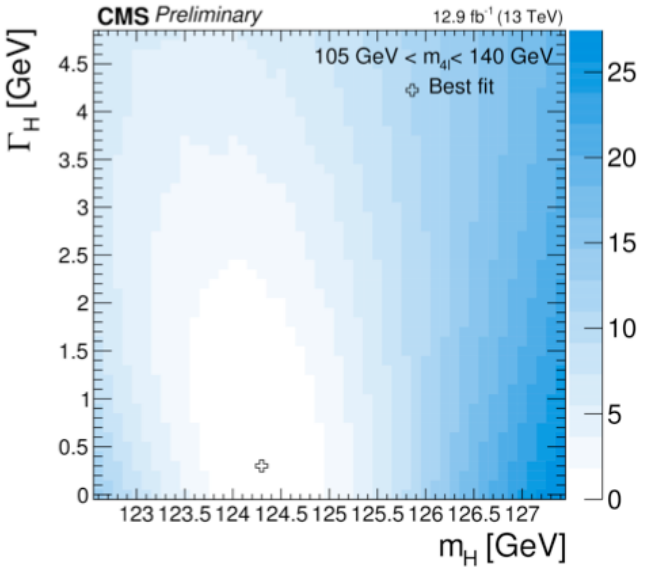
**Since off-shell one has ZZ , while on-shell it is ZZ* , there is an important signal off-shell and one can constraint $\Gamma_H$ (Caola, Melnikov) provided the g's are the same in both equations**

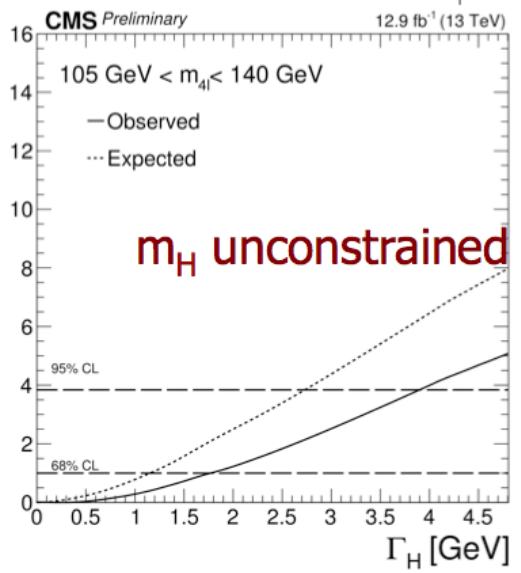
# CMS results ( © M.Pieri HH 2016 ) CMS-PAS-HIG-16-033

- Using on-shell only
  (105 < m4l < 140 GeV)

$\Gamma_H = 0.3^{+1.4}_{-0.0}$ GeV (68% CL)

**$\Gamma_H$ < 3.9 GeV (95% CL)**



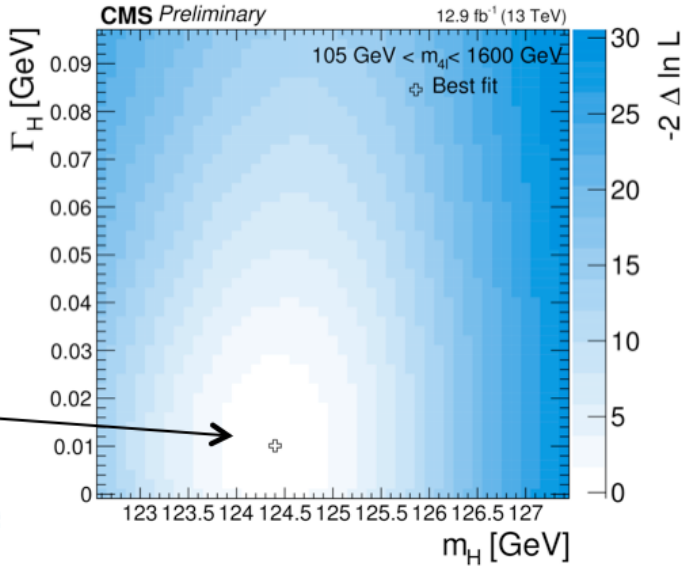



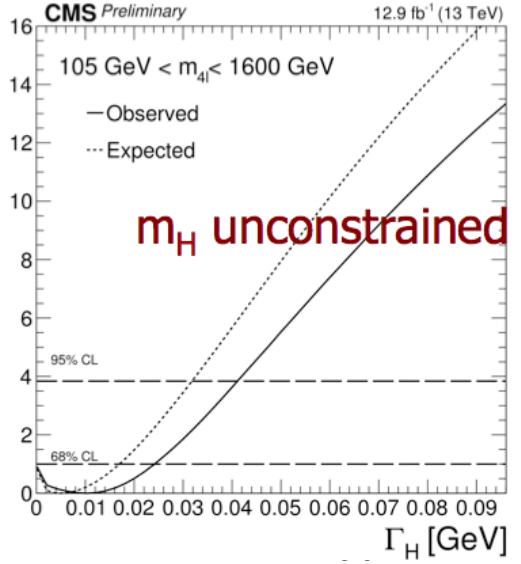

- Using on-shell & off-shell
  (100 < m4l < 1600 GeV)

$\Gamma_H = 0.010^{+0.014}_{-0.010}$ GeV (68% CL)

**$\Gamma_H$ < 41 MeV (95% CL)**

Mass fit not dependent on the mass range



♪ LHC and ATLAS – run 1 and run 2

**LHC Run-2 started full speed**
**ATLAS and CMS detectors working very well will pileup level well above design**

♪ H(125) : couplings

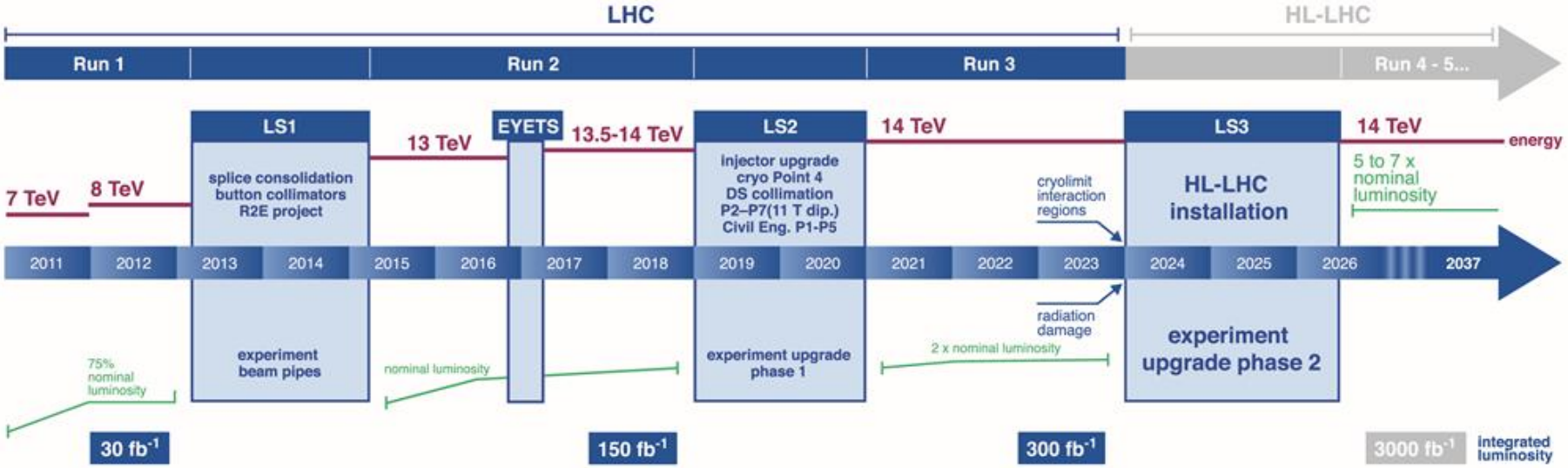
♪ H(125) : off-shell measurements

♪ **Conclusions**

♪ Backup

**Wealth of H measurements already with 13 TeV data**
- **simple and complex final states**
- **starting precise measurements of H(125) at 13 TeV**

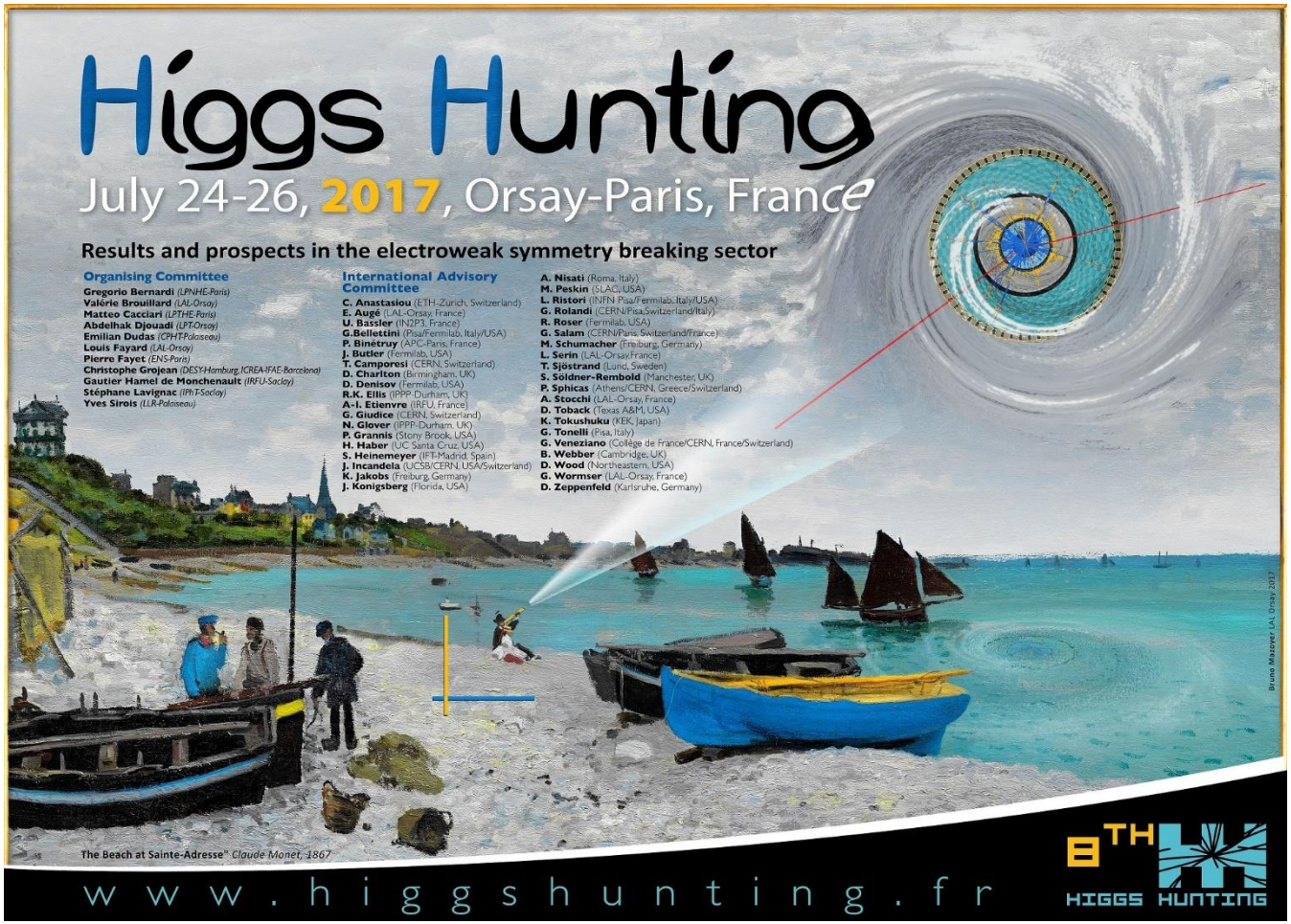
# LHC / HL-LHC Plan




# HL-LHC Plan

***Thank you for your attention***

***and some publicity***

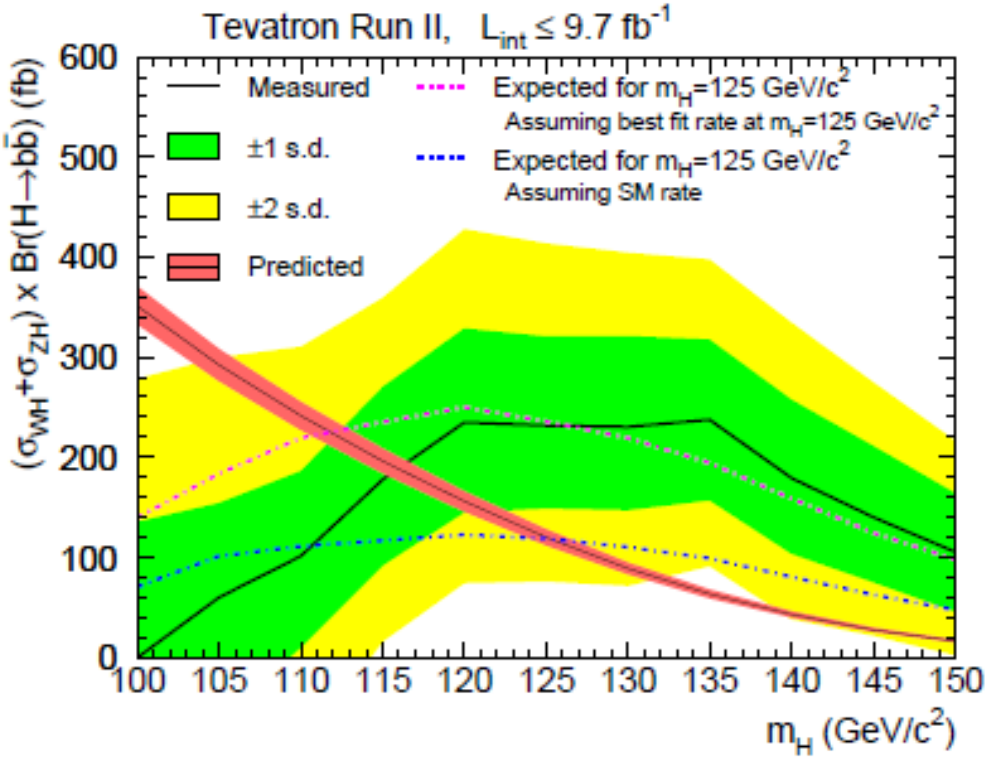


- ♪ *LHC and ATLAS run 1 and run 2*
- ♪ *Study of the H(125) or with H(125)*
- ♪ *H(125) : mass*
- ♪ *H(125) : couplings*
- ♪ *H(125) : off-shell measurements*
- ♪ *Conclusions*
- ♪ ***Backup***

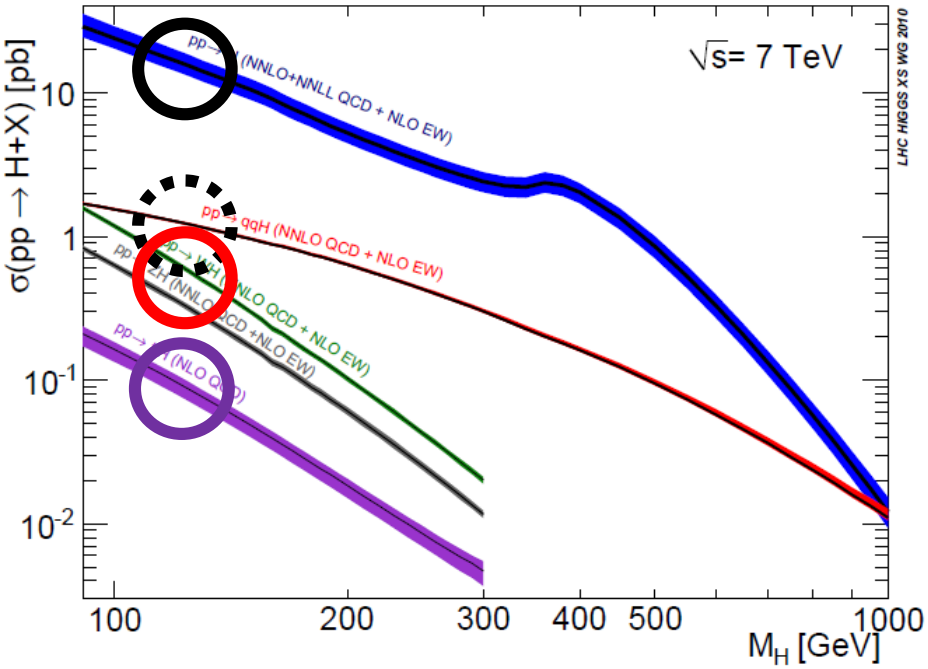
- ***LHC and ATLAS run 1 and run 2***
- ***Study of the H(125) or with H(125)***
- ***H(125) : mass***
- ***H(125) : couplings***
- ***H(125) : off-shell measurements***
- ***Conclusions***
- ***Backup***

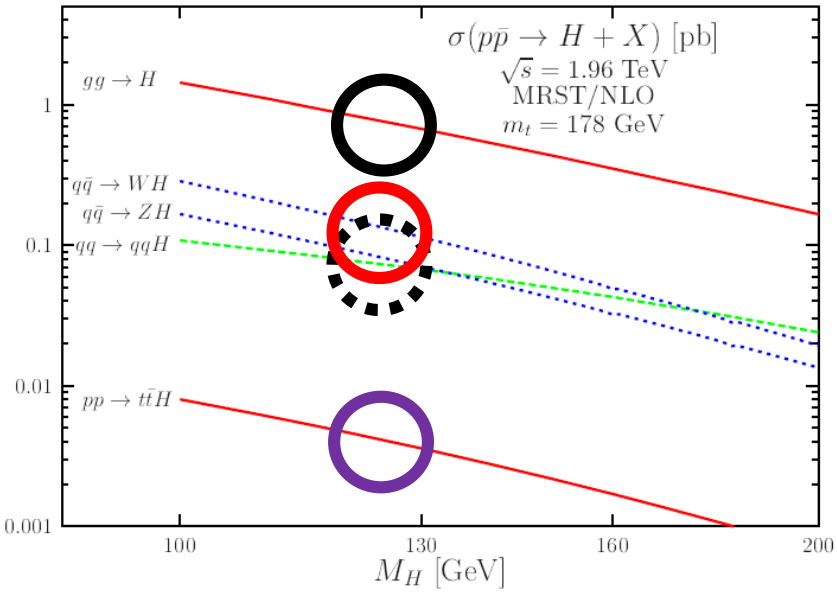
# ( *Tevatron data (proton –antiproton √s =1.96 TeV) ended in september 2011* )

***CDF and D0 (at Tevatron) have paved the way and brought sophistication and maturity into Higgs boson searches at hadron colliders***




We combine searches by the CDF and D0 Collaborations for the associated production of a Higgs boson with a $W$ or $Z$ boson and subsequent decay of the Higgs boson to a bottom-antibottom quark pair. The data, originating from Fermilab Tevatron $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, correspond to integrated luminosities of up to 9.7 fb$^{-1}$. The searches are conducted for a Higgs boson with mass in the range 100–150 GeV/$c^2$. We observe an excess of events in the data compared with the background predictions, which is most significant in the mass range between 120 and 135 GeV/$c^2$. The largest local significance is 3.3 standard deviations, corresponding to a global significance of 3.1 standard deviations. We interpret this as evidence for the presence of a new particle consistent with the standard model Higgs boson, which is produced in association with a weak vector boson and decays to a bottom-antibottom quark pair.




***comparison between LHC and Tevatron :***

***gg cross section at least 10 × higher at LHC***

***backgrounds to WW , ZZ , γγ are q qbar annihilation***

*( Remember Tevatron was a p pbar collider)*

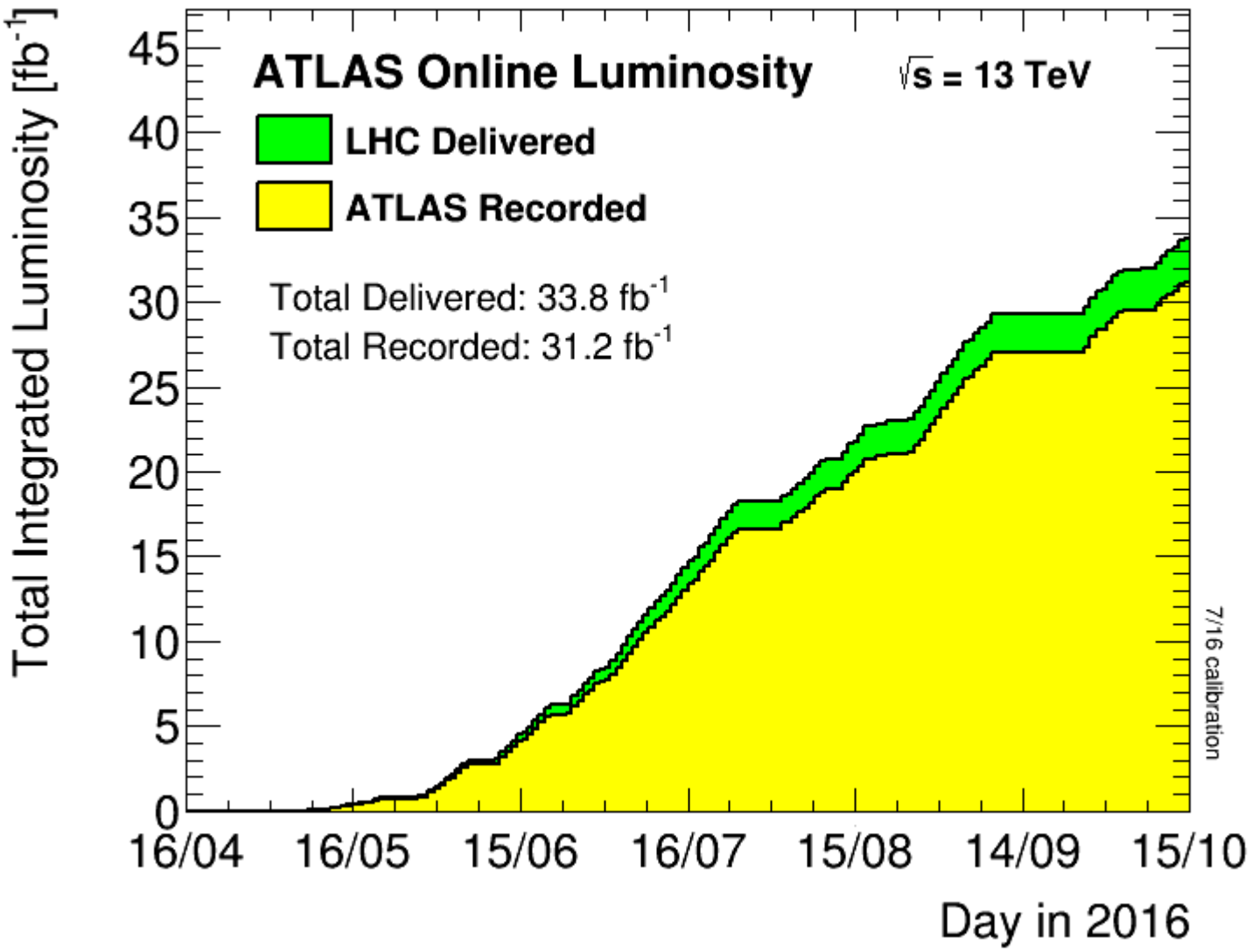
***→ S/B better in these channels at LHC than at Tevatron***

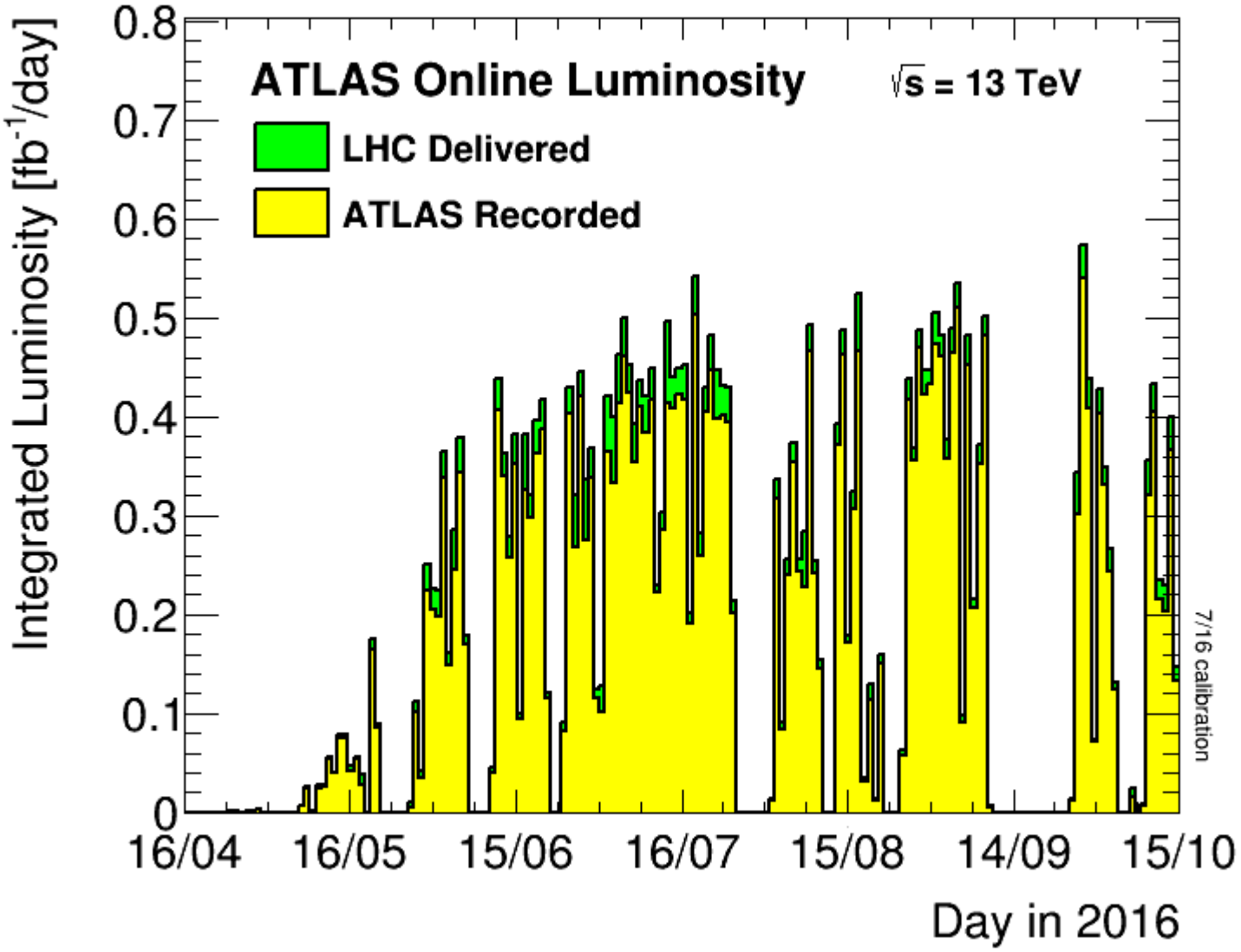
***however it is worse in associated modes*** ⚠

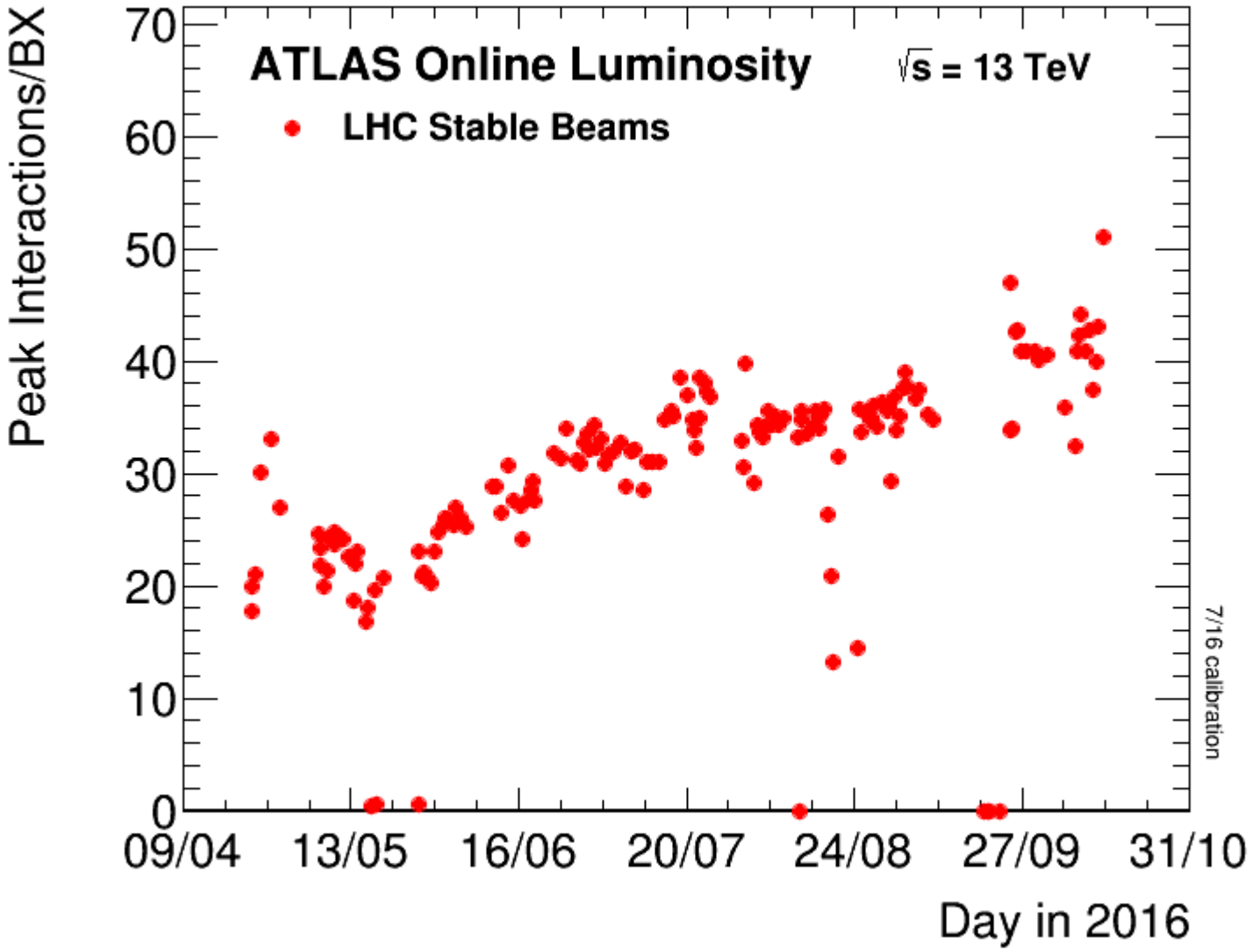
| | ATLAS | CMS |
|---|---|---|
| MAGNET (S) | Air-core toroids + solenoid **2T**<br>4 magnets<br>Calorimeters in field-free region | Solenoid **4T**<br>1 magnet<br>Calorimeters inside field |
| TRACKER | Si pixels+ strips<br>TRT → particle identification<br>B=2T $\sigma/p_T \sim 5\times10^{-4}\ p_T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

© F.Gianotti

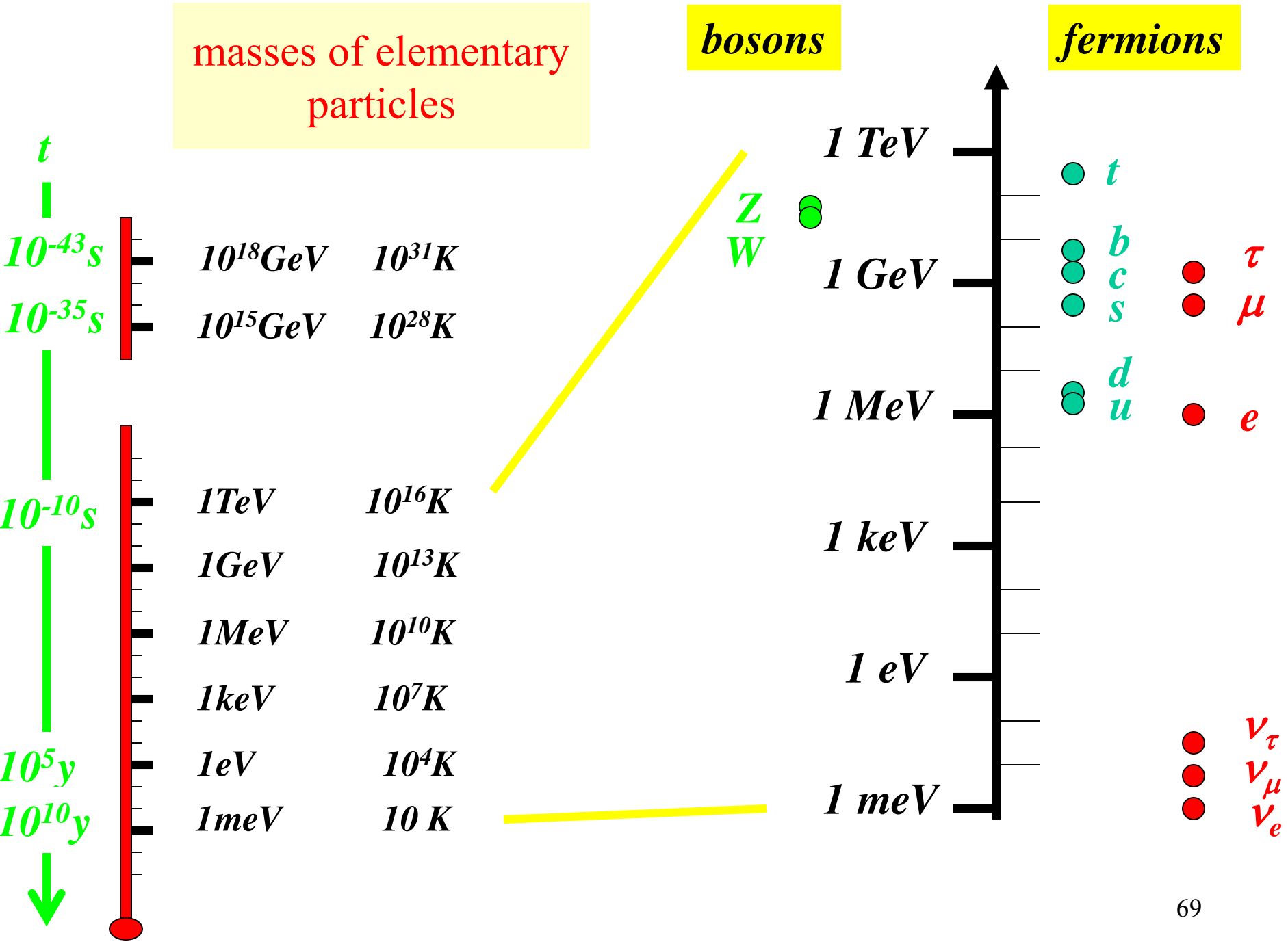
Louis Fayard 7-9-2015


ATLAS Online Luminosity
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 33.8 fb-1
Total Recorded: 31.2 fb-1
Total Integrated Luminosity [fb-1]
0
5
10
15
20
25
30
35
40
45
16/04
16/05
15/06
16/07
15/08
14/09
15/10
Day in 2016
7/16 calibration


ATLAS Online Luminosity
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Integrated Luminosity [fb-1/day]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
16/04
16/05
15/06
16/07
15/08
14/09
15/10
Day in 2016
7/16 calibration


ATLAS Online Luminosity
√s = 13 TeV
LHC Stable Beams
Peak Interactions/BX
70
60
50
40
30
20
10
0
09/04
13/05
16/06
20/07
24/08
27/09
31/10
Day in 2016
7/16 calibration

# masses of elementary particles



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 $10^{31}$ $cm^{-2}$ $s^{-1}$*

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

2011

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

2012

*(Standard-Model) boson-like properties*
*peak luminosity 7 $10^{33}$ $cm^{-2}$ $s^{-1}$*
*integrated luminosity ~ 5+ 20 $fb^{-1}$*

2013

***luminosity* is a property of beams**

***event rate [ events $s^{-1}$ ]***
***= luminosity [ $nb^{-1}$ $s^{-1}$ ] * cross section [nb]***

$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}$$

***Number of protons in a bunch***

***Number of bunches in collision***

***energy***

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} E}{m_p 4\pi\beta^*\epsilon} F$$

***Transverse size of the beams***

***Important parameters***

***(instantaneous) luminosity***

***LHC : in 2012***

***peak luminosity was $7\ 10^{33}\ cm^{-2}\ s^{-1}$***

***other unit = $nb^{-1}\ s^{-1}$***

***Integrated luminosity***

***for ATLAS and CMS each***

***it was ~ 5 $fb^{-1}$ at $\sqrt{s} = 7$ TeV and ~ 20 $fb^{-1}$ at $\sqrt{s} = 8$ TeV***

*Notion of pile-up : in a bunch-crossing , in addition to the 'nice' event there are additional p-p interactions ( ~35 for $7\ 10^{33}\ cm^{-2}\ s^{-1}$ ) which make the 'nice' event more complicated to analyze*

***We can reconstruct its mass $m_H$ by measuring the sum of the energies ( in the center of mass ) of its decay products***

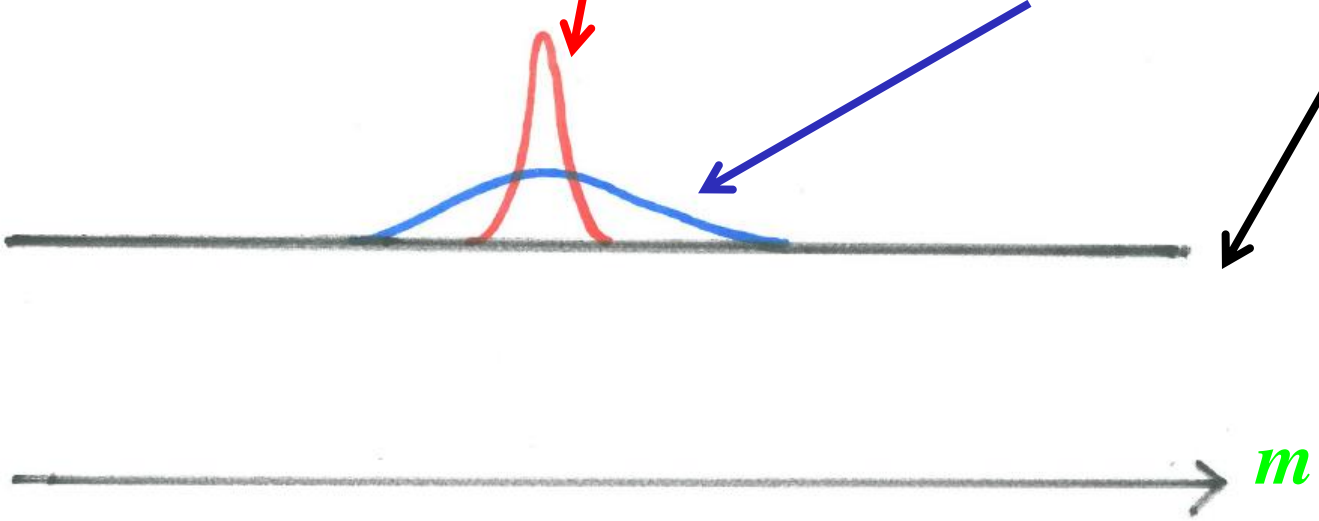
***E***

***then $E = m_H c^2$***

***Considering the mass distribution m of events 'candidates BEH'***

***We have background events***

***A signal with a good resolution will be better seen than a signal with a bad resolution***




***We need detectors with a good resolution***

*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*

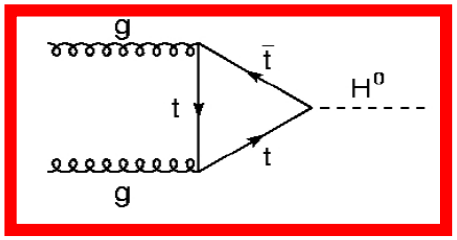
*if* $S_1 / B_1 = S_2 / B_2$

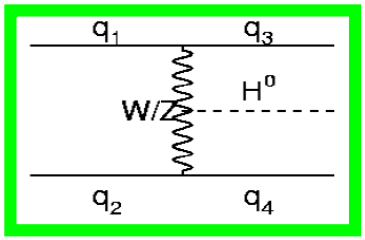
*then* $S_1 / \sqrt{B_1} \oplus S_2 / \sqrt{B_2} = (S_1+S_2) / \sqrt{(B_1+B_2)}$

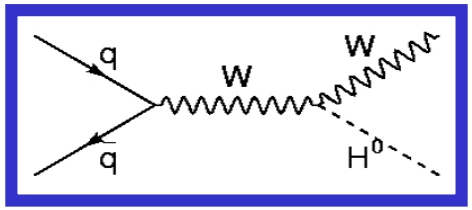
*and one does not gain making categories*

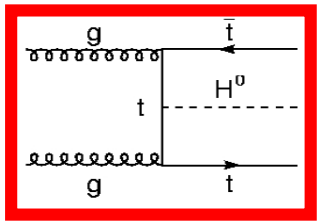
***(one of) the work of the experimentalist is to find categories with different S/B !***

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

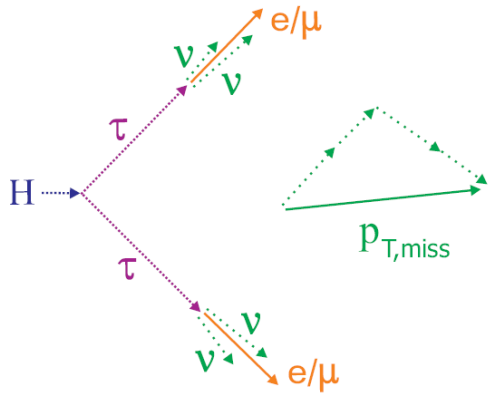


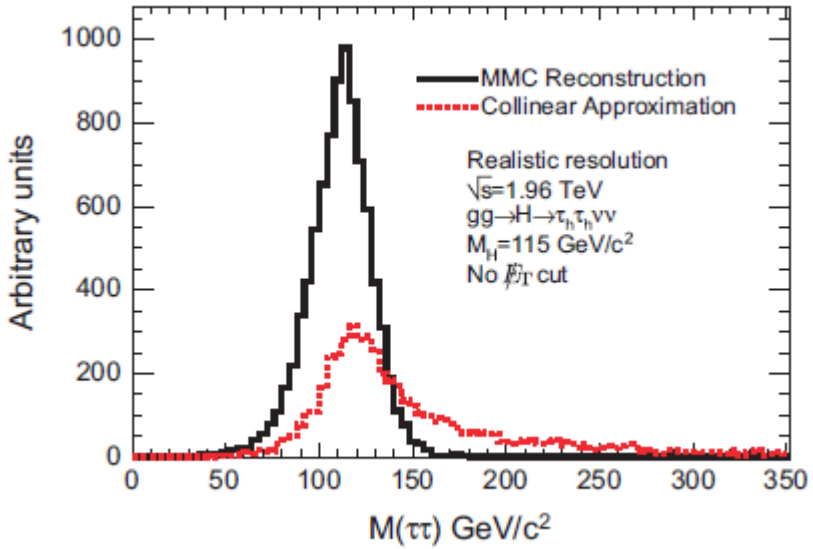



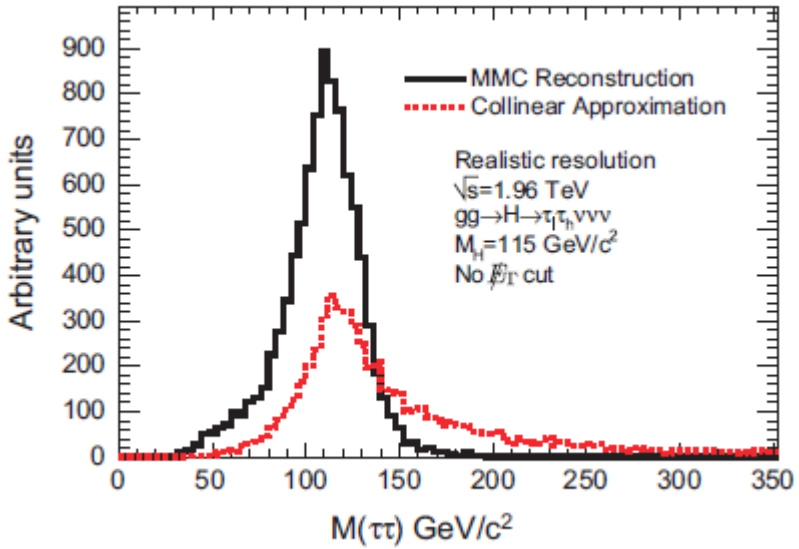



# Tau reconstruction




***reconstruction of Higgs mass with collinear approximation and angle between the two τ***




***Improvement comes from requiring that the relative orientations of the neutrinos and other decay products are consistent with the mass and kinematics of a τ lepton decay***

# ATLAS Diphoton Searches

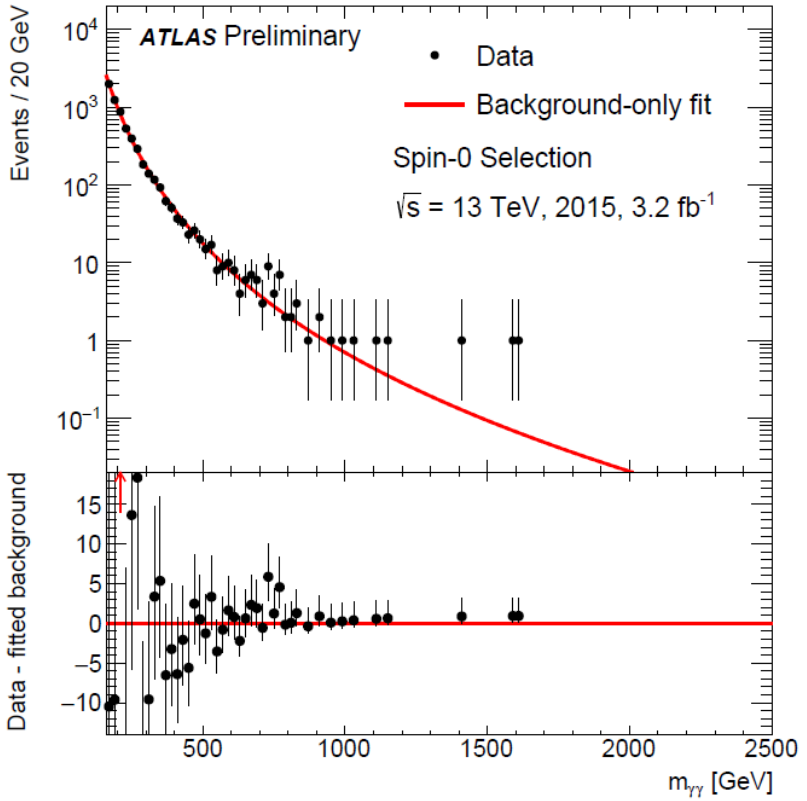
ATLAS-CONF-2016-059

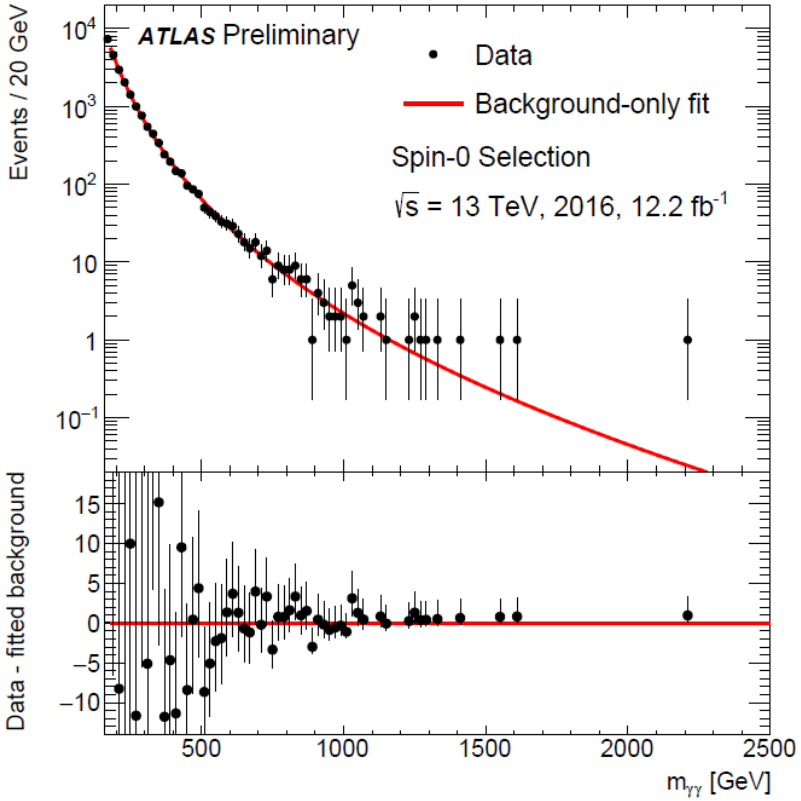
*JHEP 1609 (2016) 001 arXiv:1606.03833 [hep-ex]*

Localised excess seen in 2015 ATLAS data

- 2.1σ global (3.9σ local) significance at 750 GeV (spin-0 search), width ~50 GeV

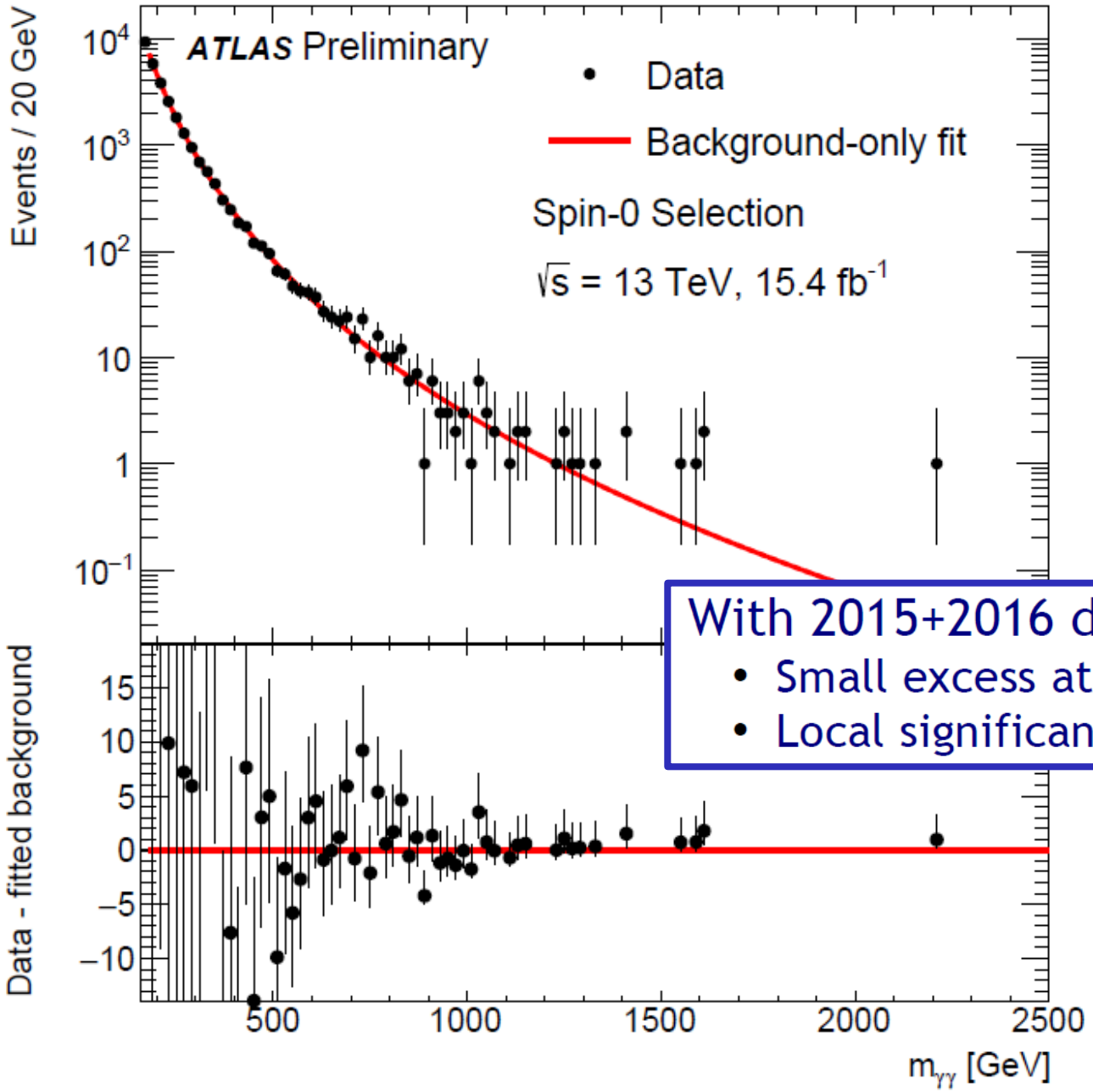
- After reprocessing, new 2016 reconstruction → 3.4σ local, at ~730 GeV




2016 data: no clustering around 730-750 GeV, and 3.8x more data

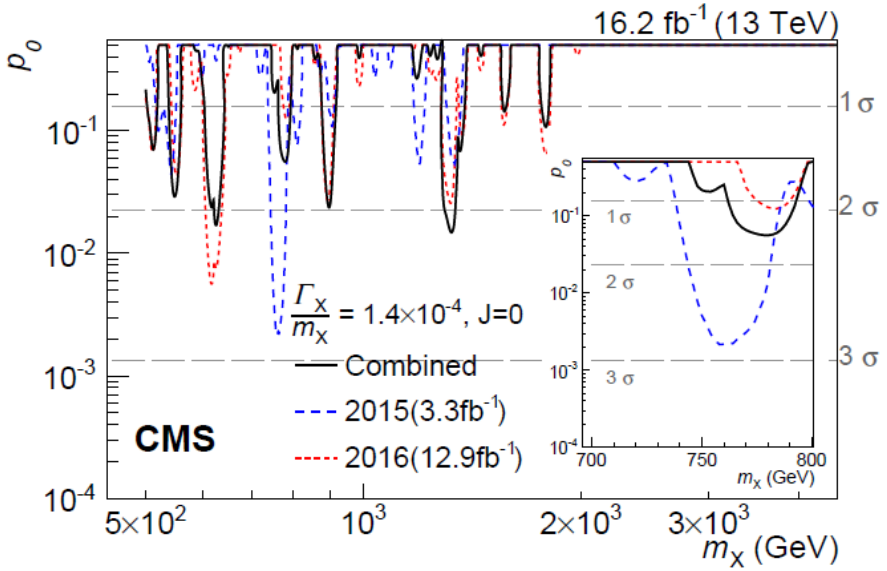
- 2016 data consistent with 2015 at the 2.7σ level
- Appears that the 2015 excess was a statistical fluctuation

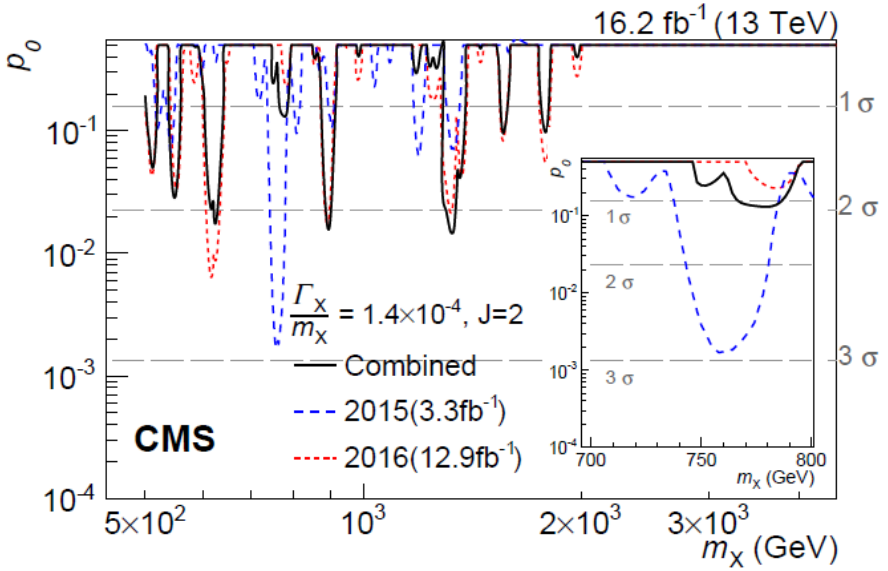


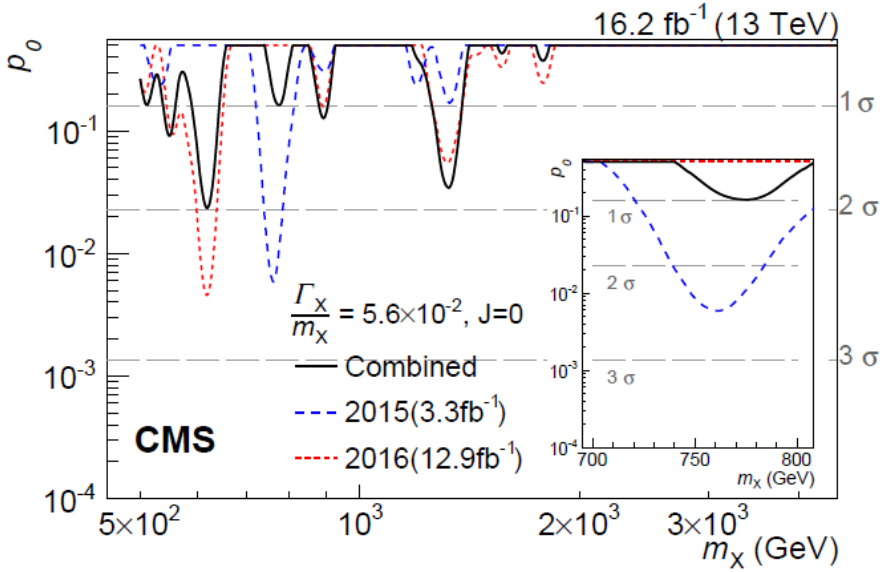

With 2015+2016 data:

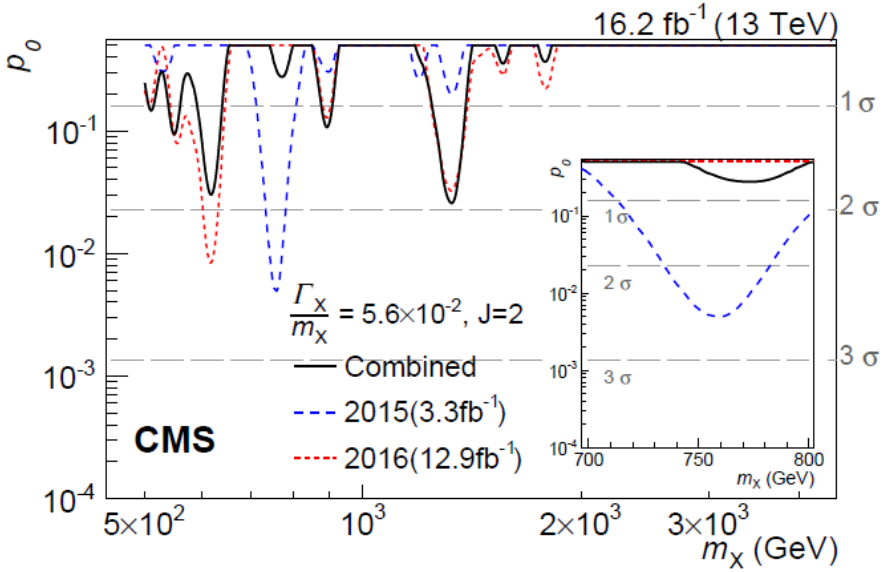
- Small excess at 710 GeV ($\Gamma/m \sim 10\%$)
- Local significance $1.4\sigma$, global $<1\sigma$

# *CMS results*




arXiv:1609.02507v1 [hep-ex] 8 Sep 2016

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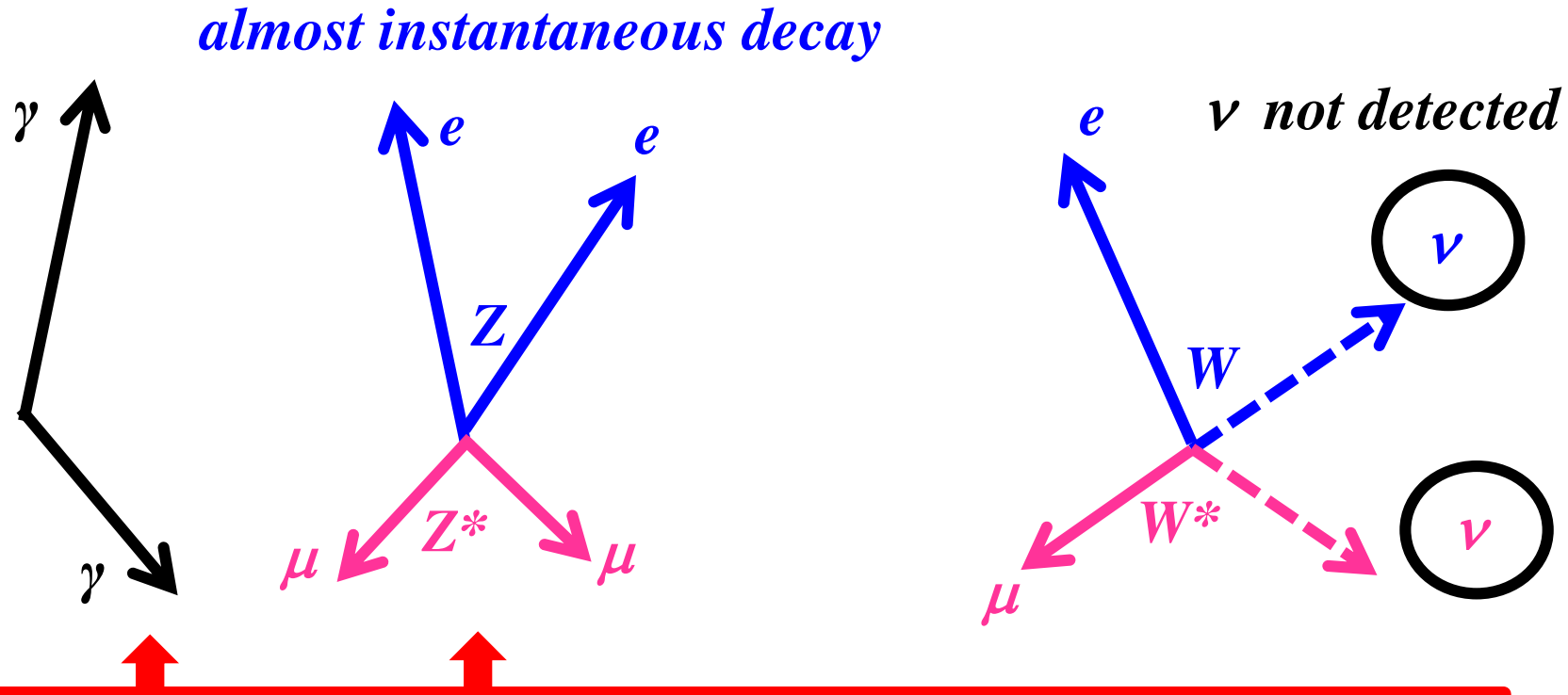
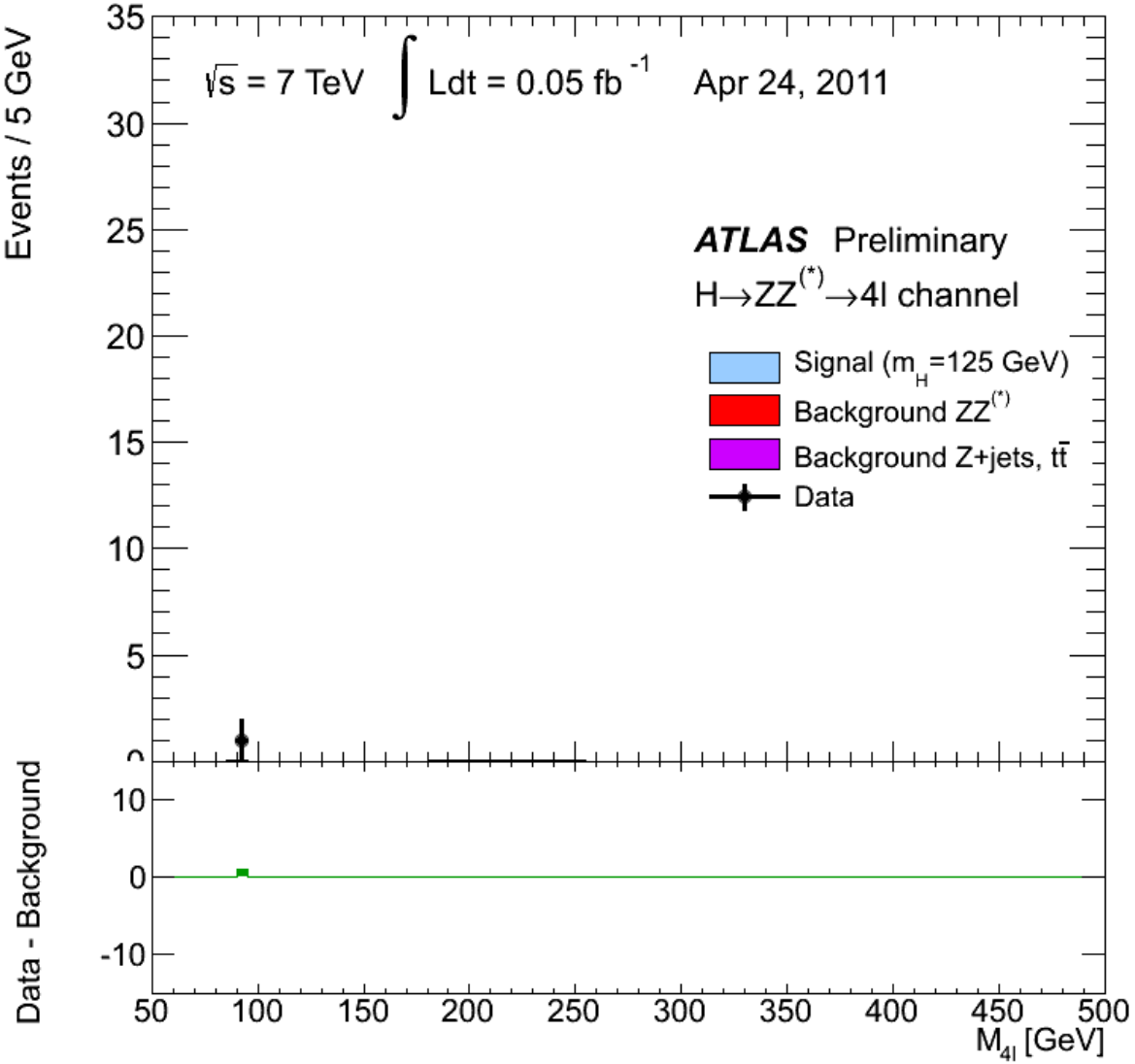
- ♪ *H(125) : couplings*
- ♪ *H(125) : off-shell measurements*
- ♪ *Conclusions*
- ♪ *Backup*

***Fundamental scalar (Higgs) boson searches have guided the conception, design and technological choices of ATLAS and CMS***

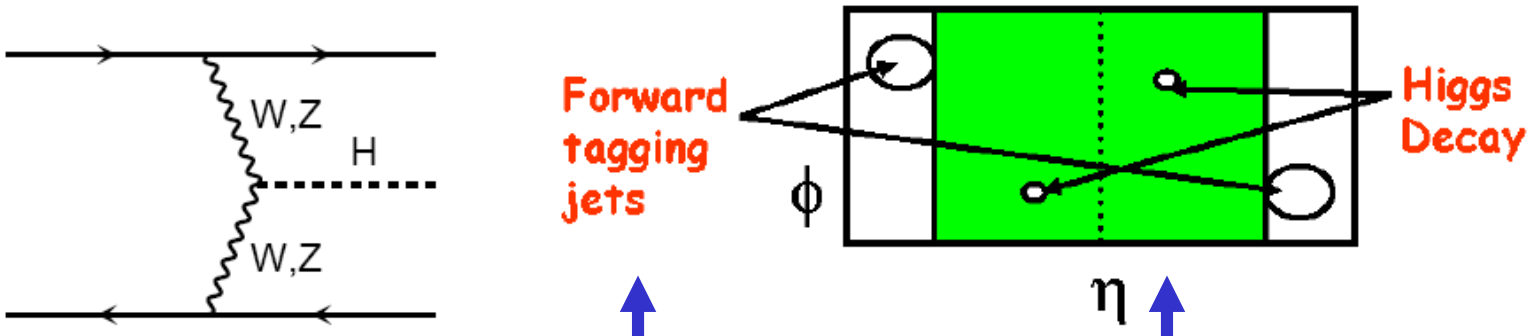



**In these 2 cases the boson mass is computed reconstructing the invariant mass of the decay products**

**⇒ the mass resolution ( and E and p) is very important in order to have a good significance S/√ B, often ∝ 1/√(resolution) since the natural width of the boson is (*almost always*) negligible**


Events / 5 GeV
√s = 7 TeV ∫ Ldt = 0.05 fb -1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M4l [GeV]

# Low mass VBF

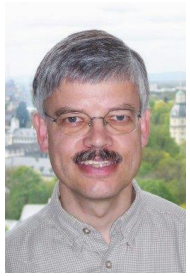



**2 high $p_T$ tag jets at large rapidity**

**no color flow between tag jets ⇒ rapidity gap**
***central jet veto effective to reduce backgrounds***

***VBF was used for high mass searches but was used (on Monte-Carlos) at low mass at the end of the 90's***

D.Rainwater and D.Zeppenfeld JHEP 9712 (1997) 005



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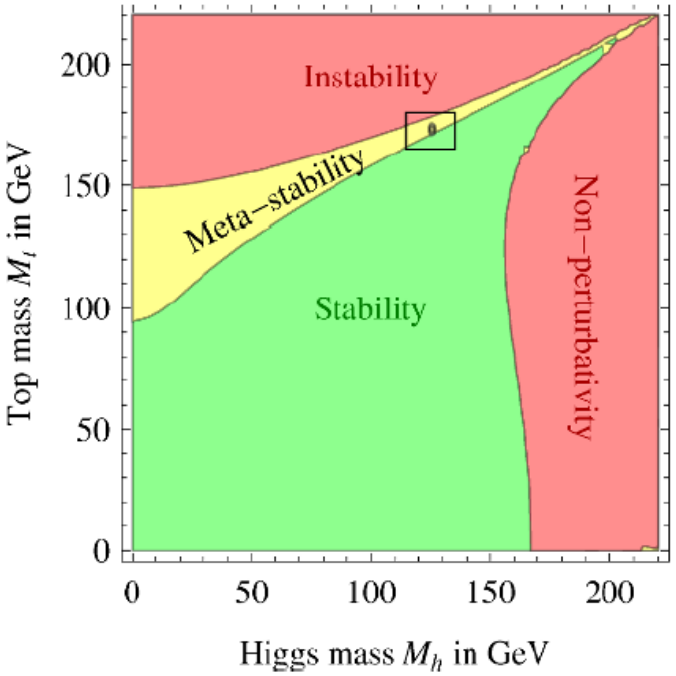
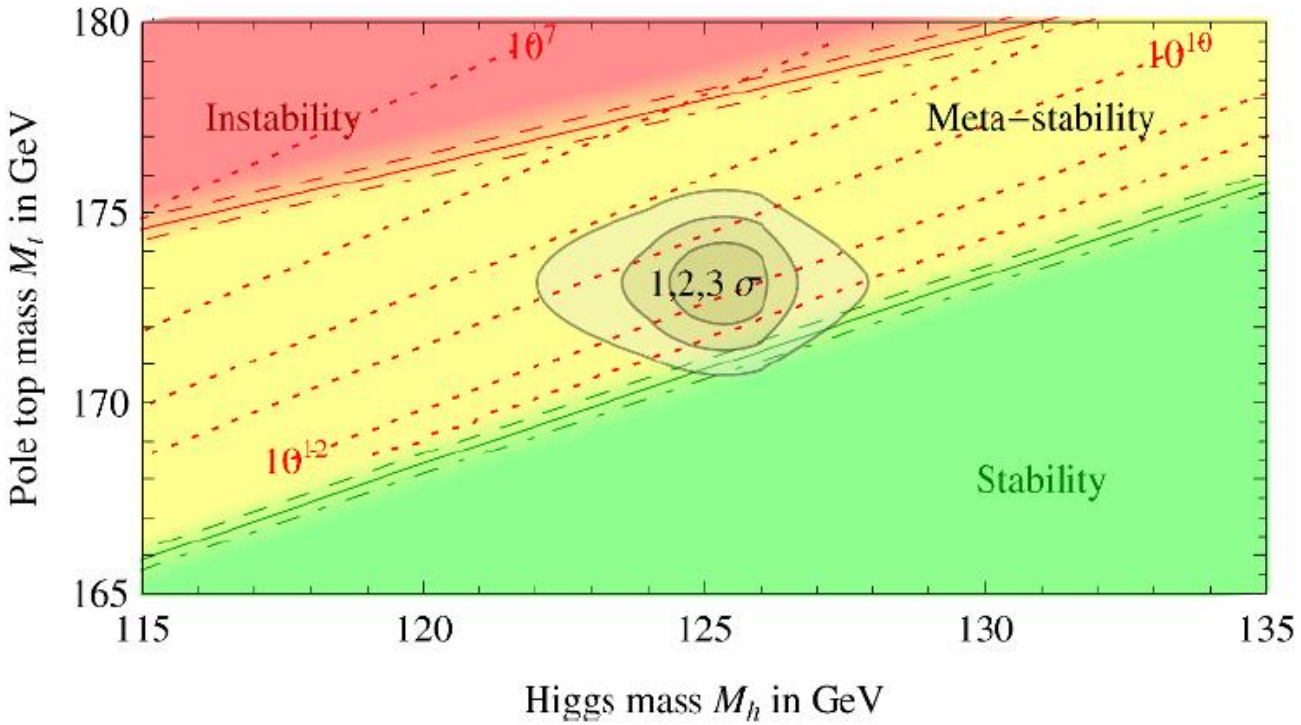



**H mass important for (meta) stability of vacuum**

***But top mass is more important ( and more difficult to measure )***




JHEP 1208 (2012) 098

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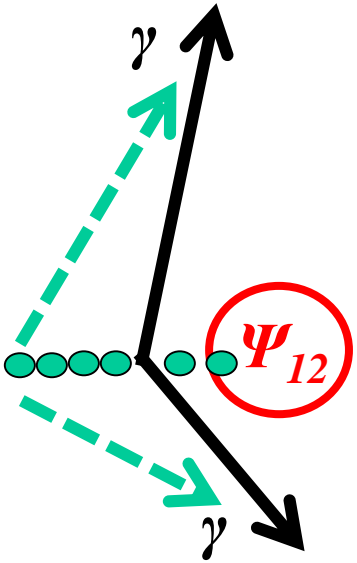
- ♪ *Backup*

# >25 years ago at LHC ( and even before at SSC)



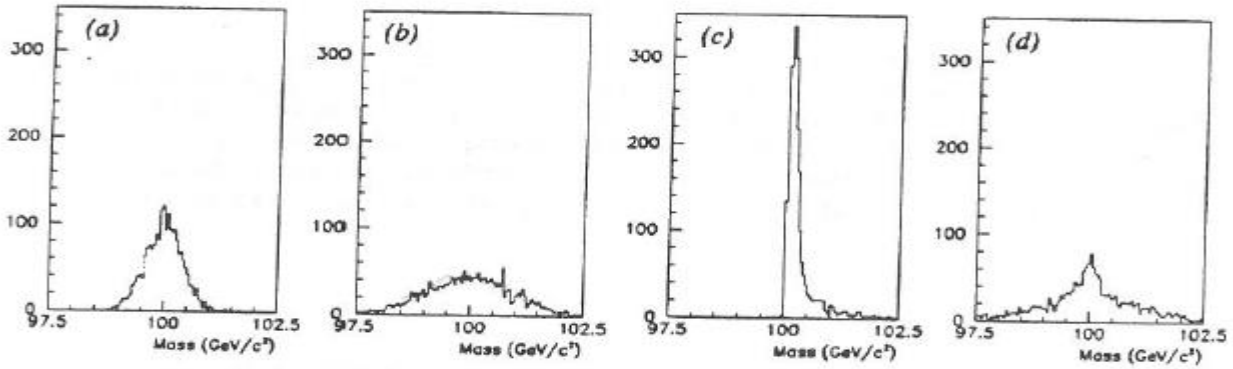
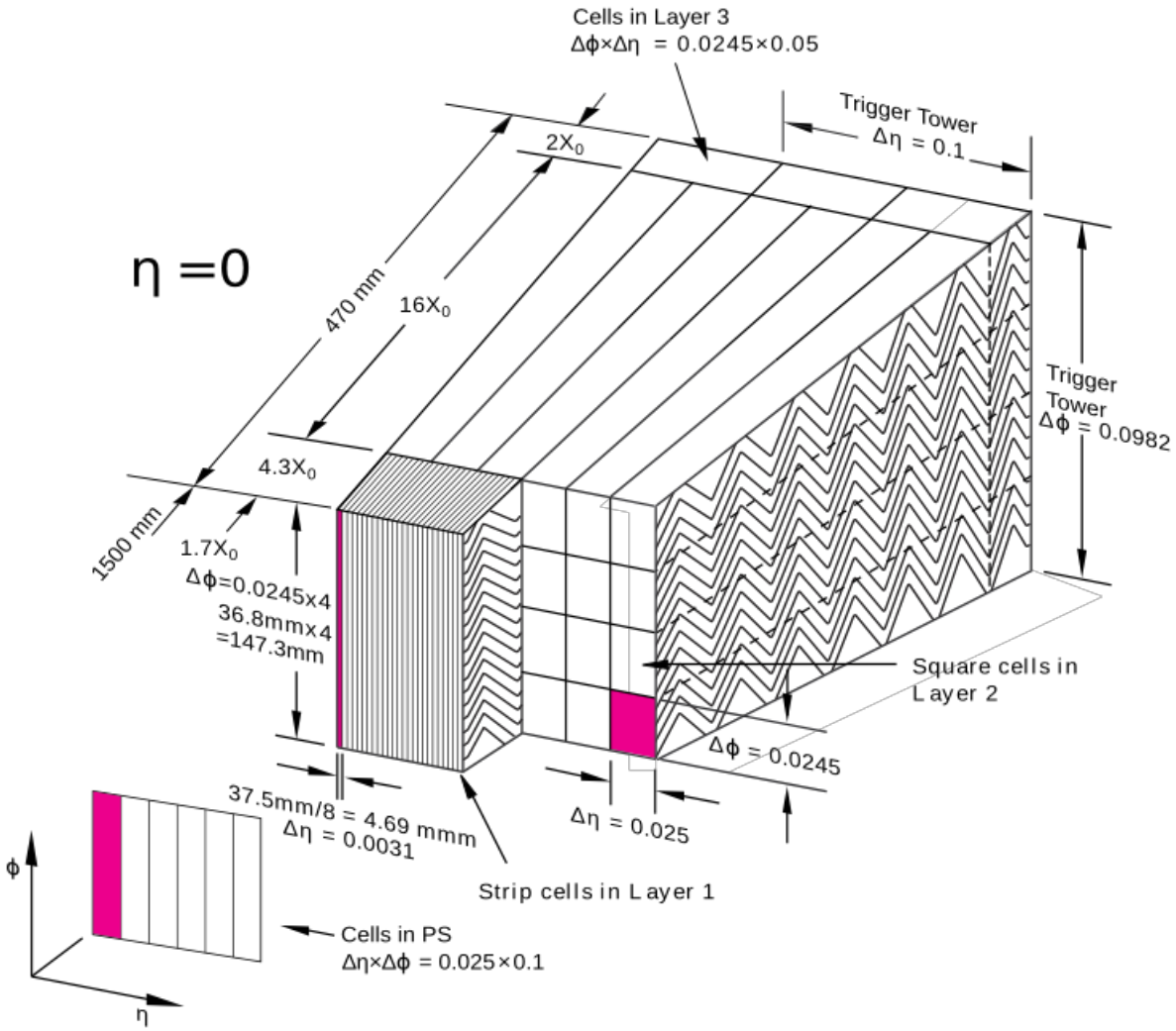




*Figure 4: Reconstructed mass plots for Higgs boson, $m_H$=100GeV/c²*
*(a) smeared by: calorimeter energy resolution of $\Delta E/E = 2\%/\sqrt{E} \oplus 0.5\%$*
*(b) smeared by: calorimeter energy resolution of $\Delta E/E = 7\%/\sqrt{E} \oplus 1.0\%$*
*(c) smeared by: pileup energy from, on average, 10 interactions*
*(d) smeared by: loss of knowledge of the vertex position ($\sigma_{vtx}$=5.5 cm)*

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

*A lot of vertices ⇒ ( if the wrong vertex is taken)*
*impact on $\Psi_{12}$*




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

(a) Energy scale factor $\alpha$ and (b) additional constant term $c'$ for energy resolution from $Z \rightarrow ee$ events

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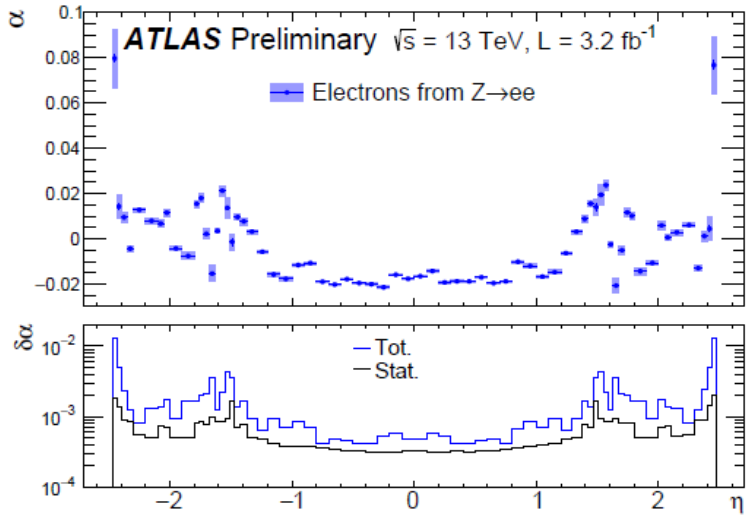
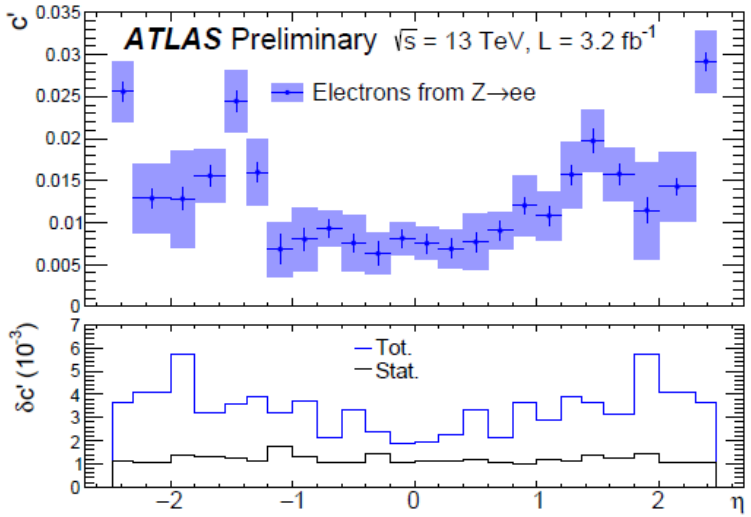
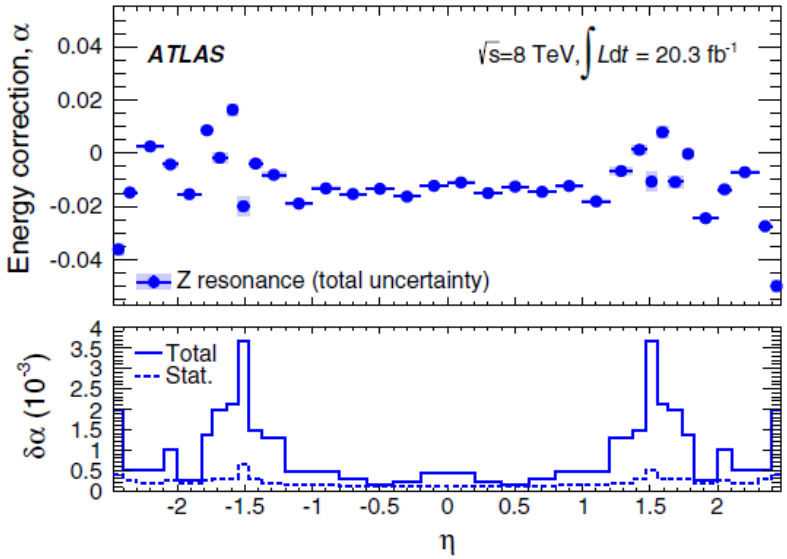


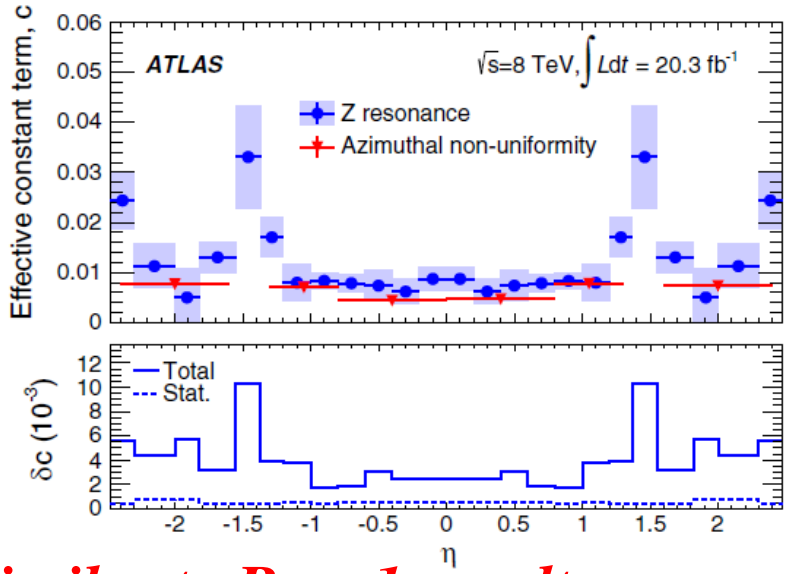

(a)




(b)

Eur. Phys. J. C (2014) 74:3071




***results for Run-2 already similar to Run-1 results***

# *Very good stability !*

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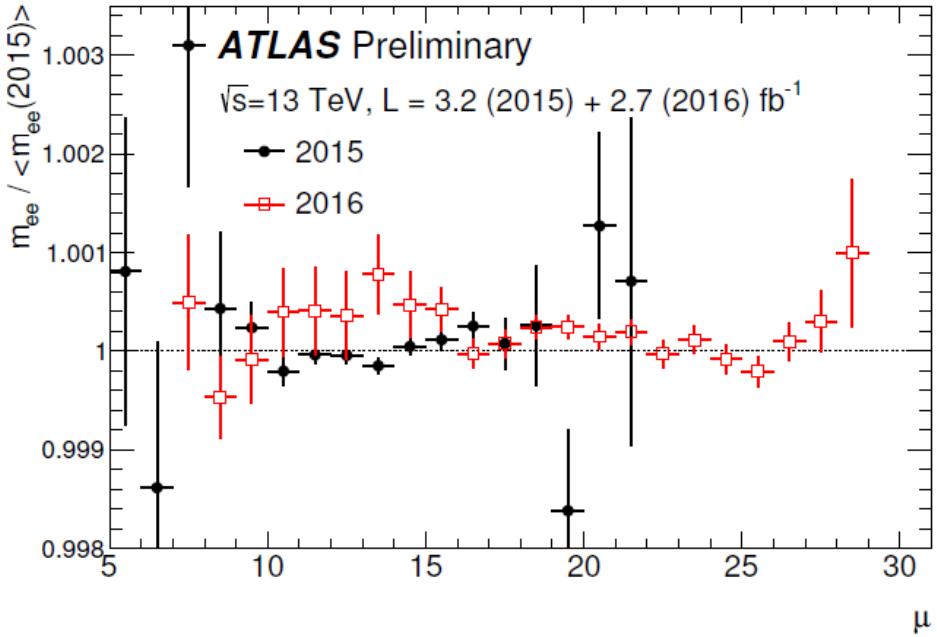


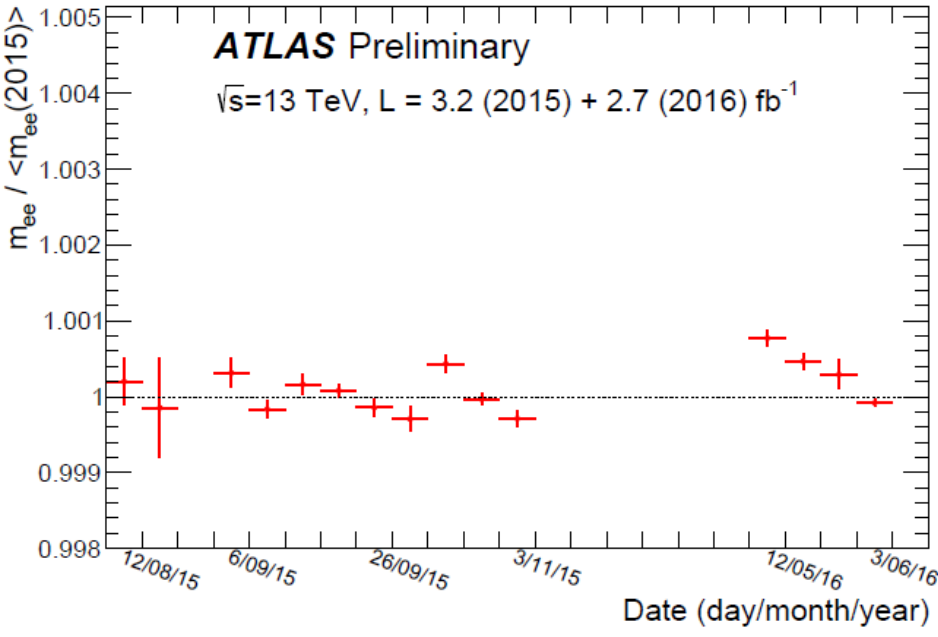

- ♪ *LHC and ATLAS run 1 and run 2*
- ♪ *Study of the H(125) or with H(125)*
- ♪ *H(125) : mass*
- ♪ *H(125) : couplings*
- ♪ ***H(125) : off-shell measurements***
- ♪ *Conclusions*
- ♪ *Backup*

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