Search for high mass resonances in the diphoton and Zγ channels at LHC

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Diphoton and flavor anomalies

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Why Are We Here

1. LHC Run2 started one year ago at 13 TeV (unexplored $\sqrt{s}$)

2. ATLAS and CMS presented 2015 preliminary results in mid-december with an **update at Moriond conference**

3. Excess of events in the diphoton channel at ~750 GeV invariant $\gamma\gamma$ mass shown by both experiments

2015 end-of-year event

ATLAS NOTE

ATLAS-CONF-2015-081

December 15, 2015

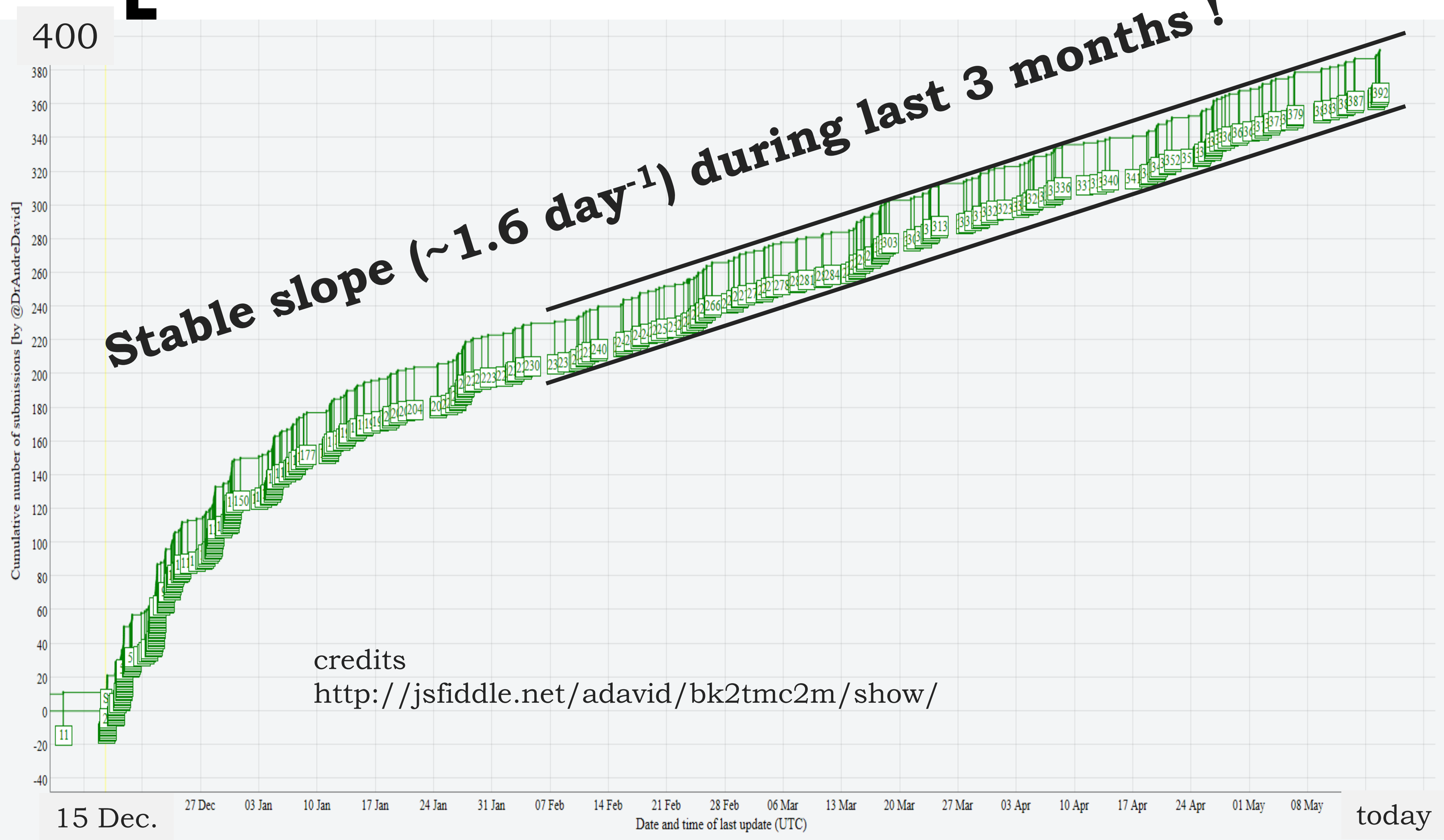
Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Available on the CERN CDS information server **CMS PAS EXO-15-004**

CMS Physics Analysis Summary

Search for new physics in high mass diphoton events in proton-proton collisions at $\sqrt{s} = 13$ TeV

Number of γγ-related arXiv submissions after the Run2 seminar @ CERN



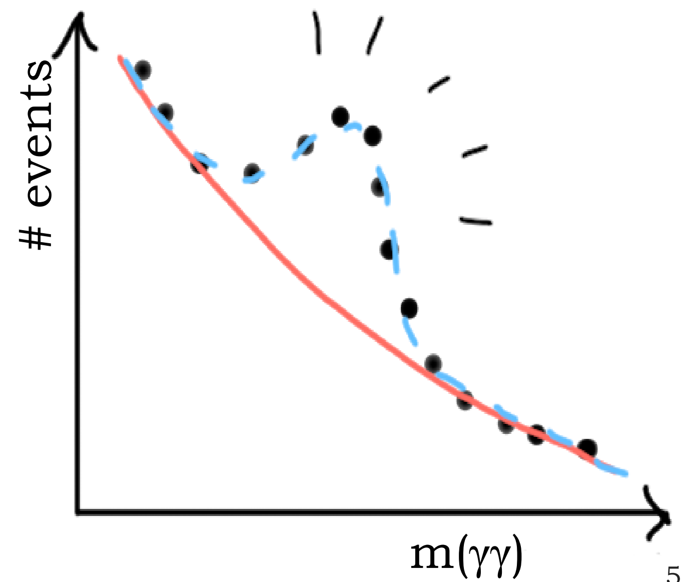
credits
http://jsfiddle.net/adavid/bk2tmc2m/show/

Diphoton search at high mass: motivations

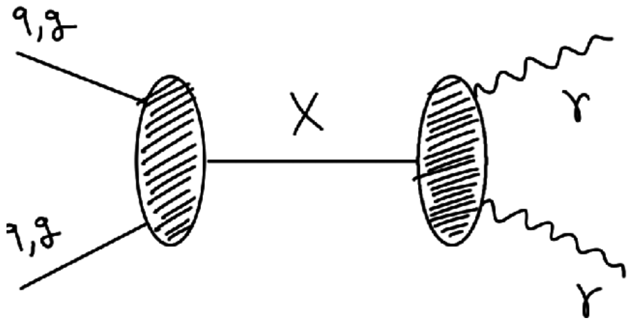
Looking for fully reconstructed resonances at higher center-of-mass energy (→LHC Run2) is the golden way to new particle discoveries.

Very clear signature at hadron collider (signal over smooth well known background)

- Model independent probe to new physics
  - several extensions of the Standard Model predict high-mass states decaying to $\gamma\gamma$
- Inspired to the Higgs→$\gamma\gamma$ Run1 analysis
  - very solid techniques (e.g. cut based selection)
- Small systematic effects



Diphoton bump search



Clean final state at hadron colliders

1) Define the event selection: 2 isolated photons
   ✓ must be loose and model-independent

2) Reconstruct the γγ invariant mass

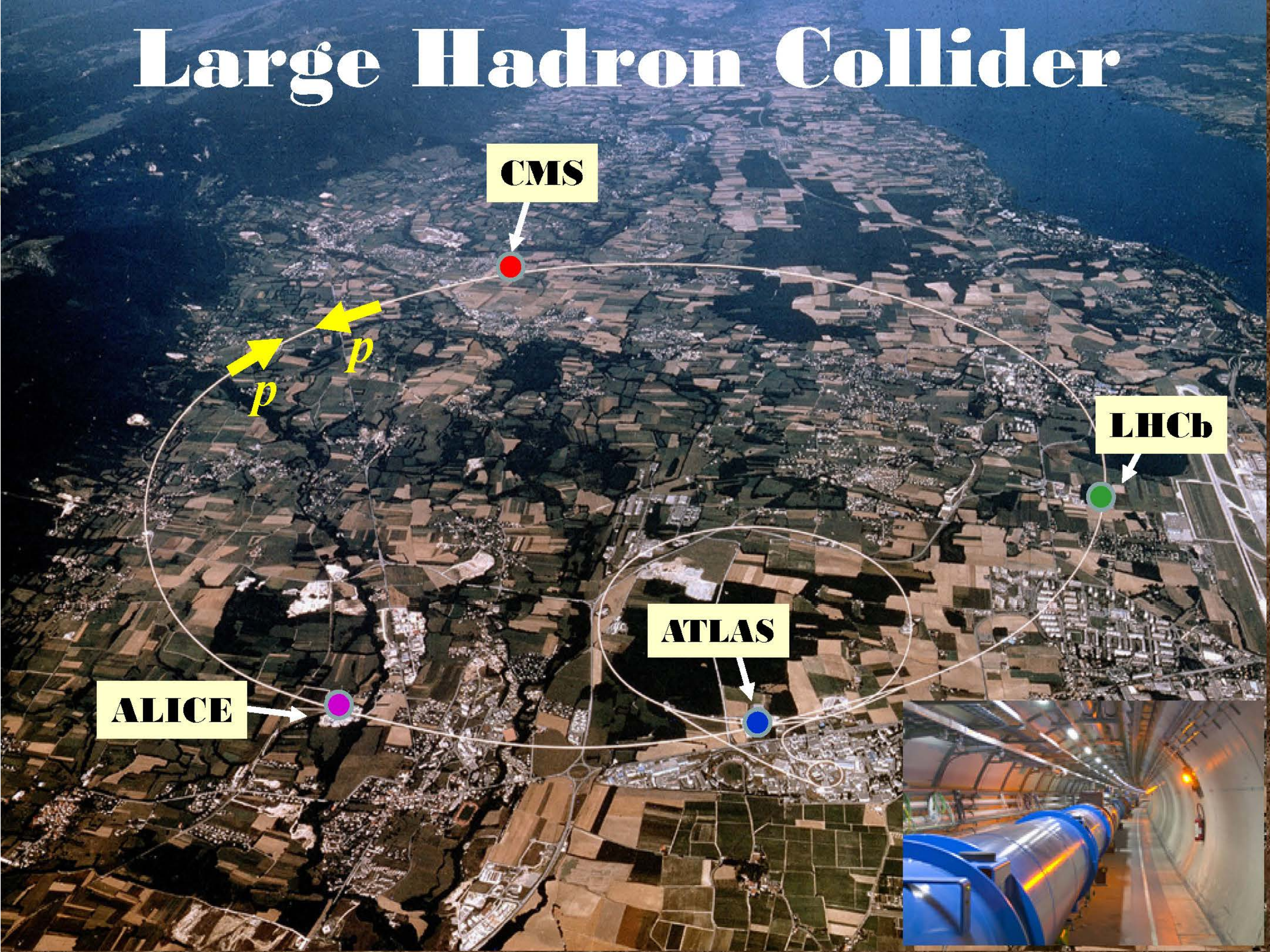
$$M = \sqrt{2E_1E_2(1 - cos\theta)}$$

✓ photon reconstruction
✓ energy resolution and scale
✓ dedicated vertex identification technique

Electromagnetic calorimeter performances are crucial for the analysis achievement.

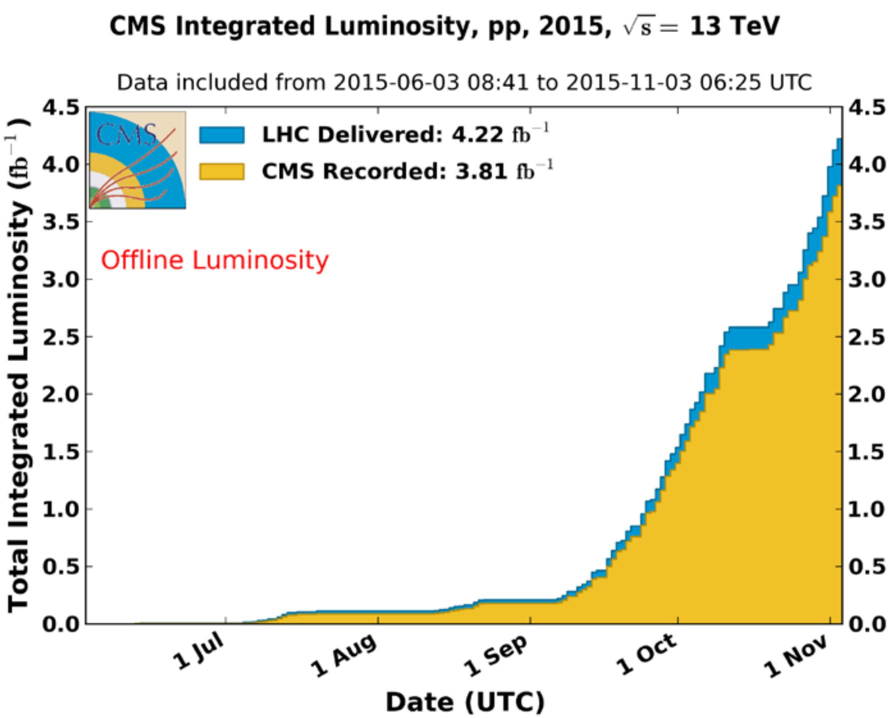
3) Signal extraction

Fully blind analysis.


Large Hadron Collider
CMS
p
p
LHCb
ATLAS
ALICE

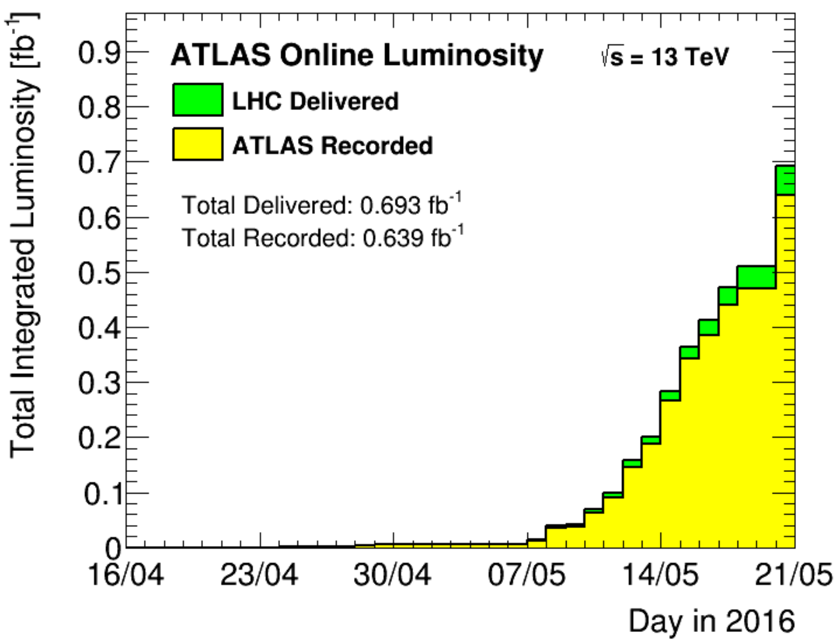
LHC operations @ 13TeV

2015 Luminosity



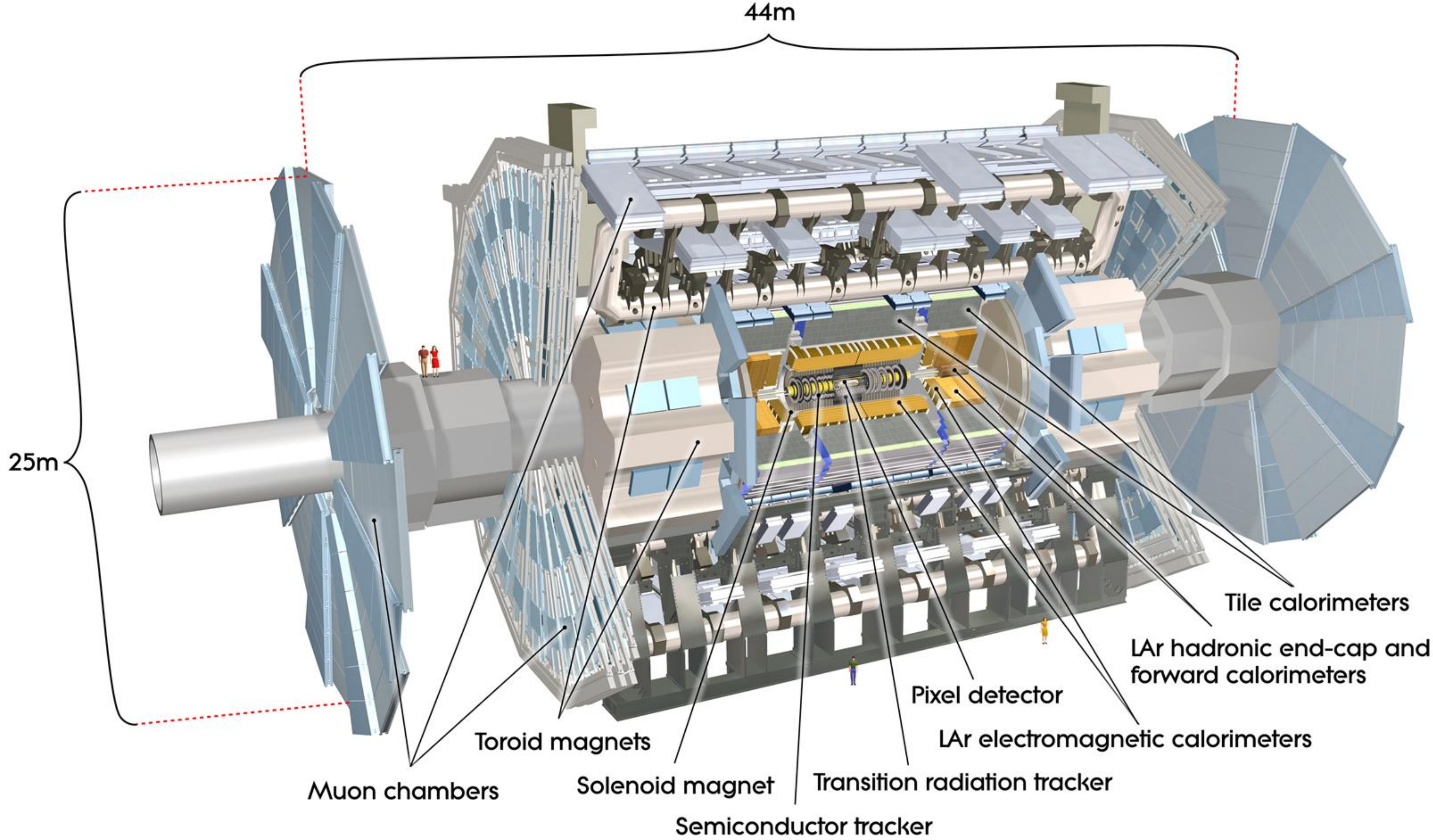
~ 25% of the data recorded by CMS with the magnet @ 0 T

2016 Luminosity



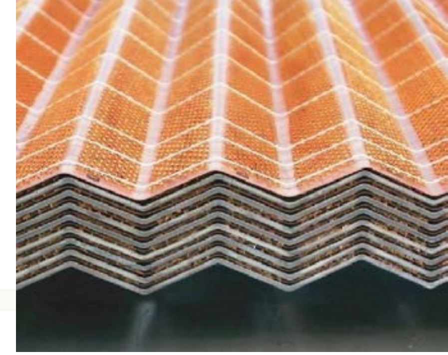
Expected ~1 fb^{-1} for LHCP and ~5-10 fb^{-1} for ICHEP conference

ATLAS



44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

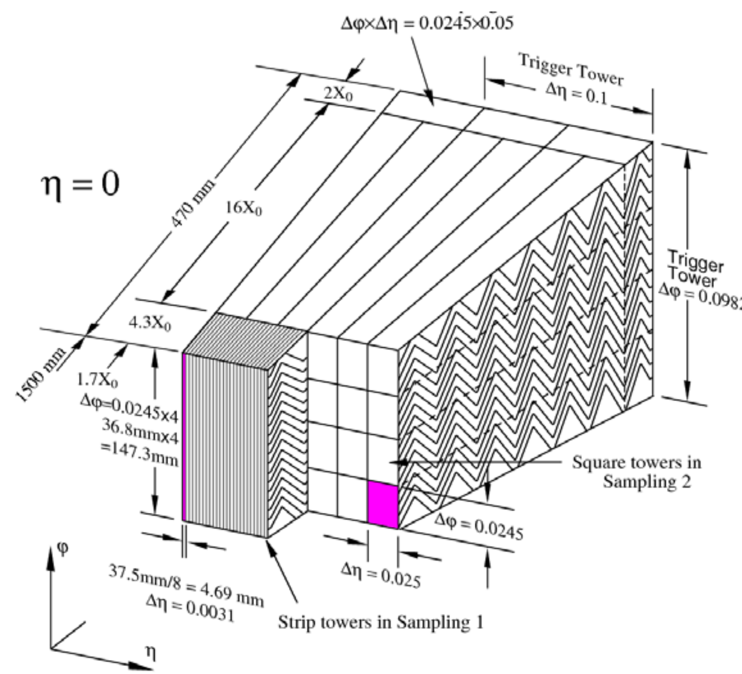
ATLAS Electromagnetic Calorimeter



Lead – liquid Argon sampling calorimeter with accordion geometry

Longitudinal segmentation for particle ID and vertexing.

- S1 (Strips) — γ/π^0 separation — $4.3\ X_0$
- S2 (Middle) — Main energy deposit — $16\ X_0$
- S3 (Back) — High energy showers — $2\ X_0$

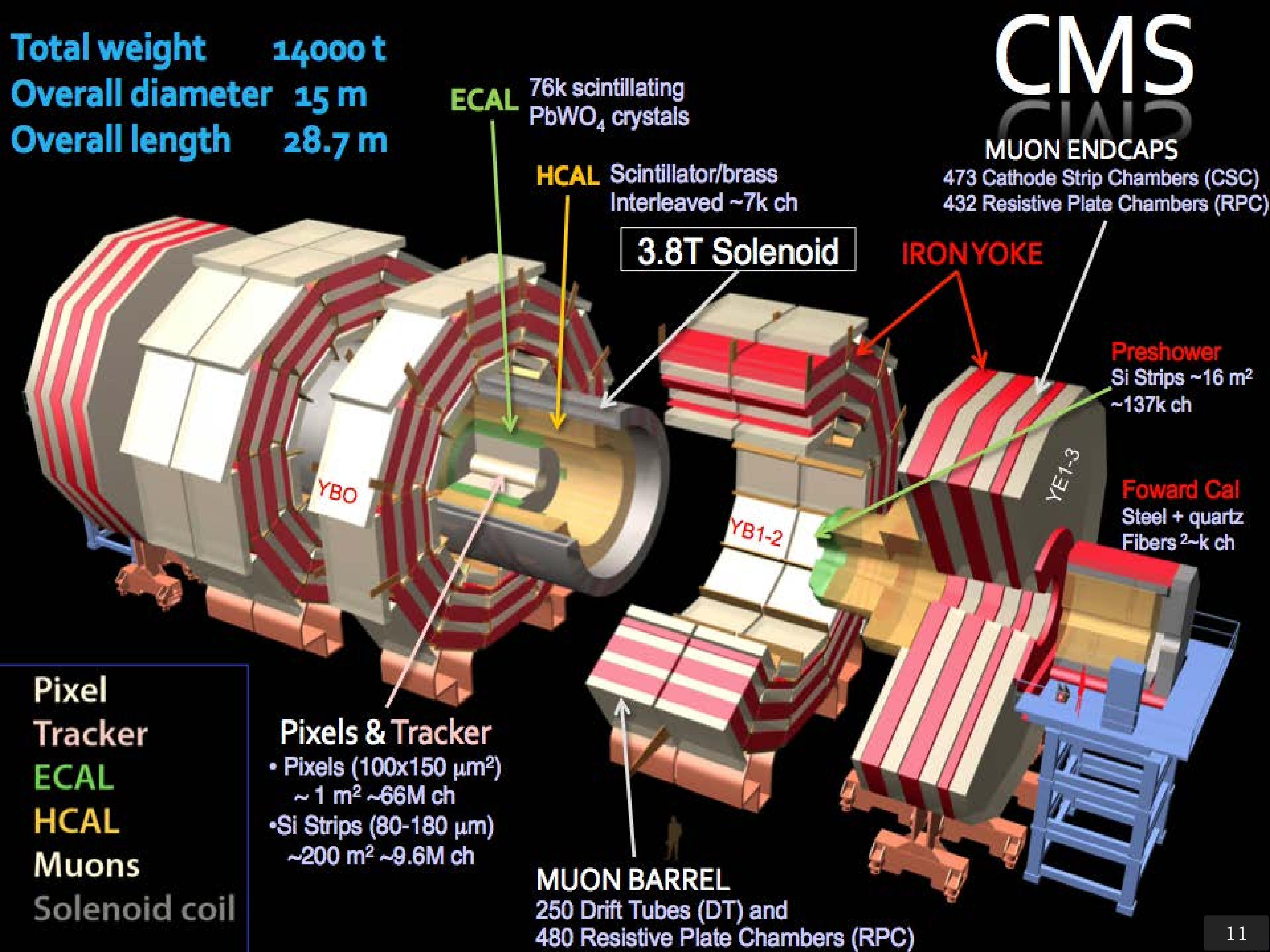


High granularity: almost 200k channels

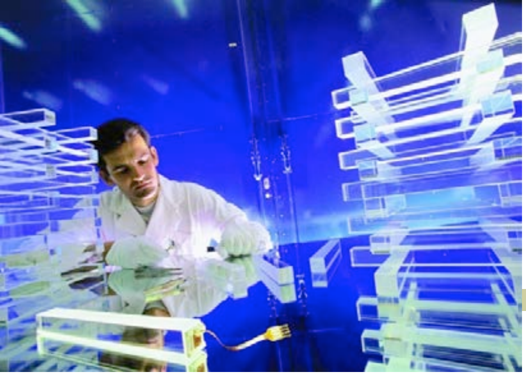
Design energy resolution:

0.5-0.7% constant term

- Critical issues:
  - Material in front of the calorimeter
  - Temperature and HV dependence



Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL
76k scintillating
$PbWO_4$ crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
3.8T Solenoid
IRON YOKE
Preshower
Si Strips ~16 m^2
~137k ch
YE1-3
Foward Cal
Steel + quartz
Fibers ^{2}~k ch
YBO
YB1-2
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)



CMS Electromagnetic Calorimeter

Lead Tungstate ($PbWO_4$) homogeneous crystal calorimeter

Crystal qualification and module construction in Rome (Casaccia) and at Cern

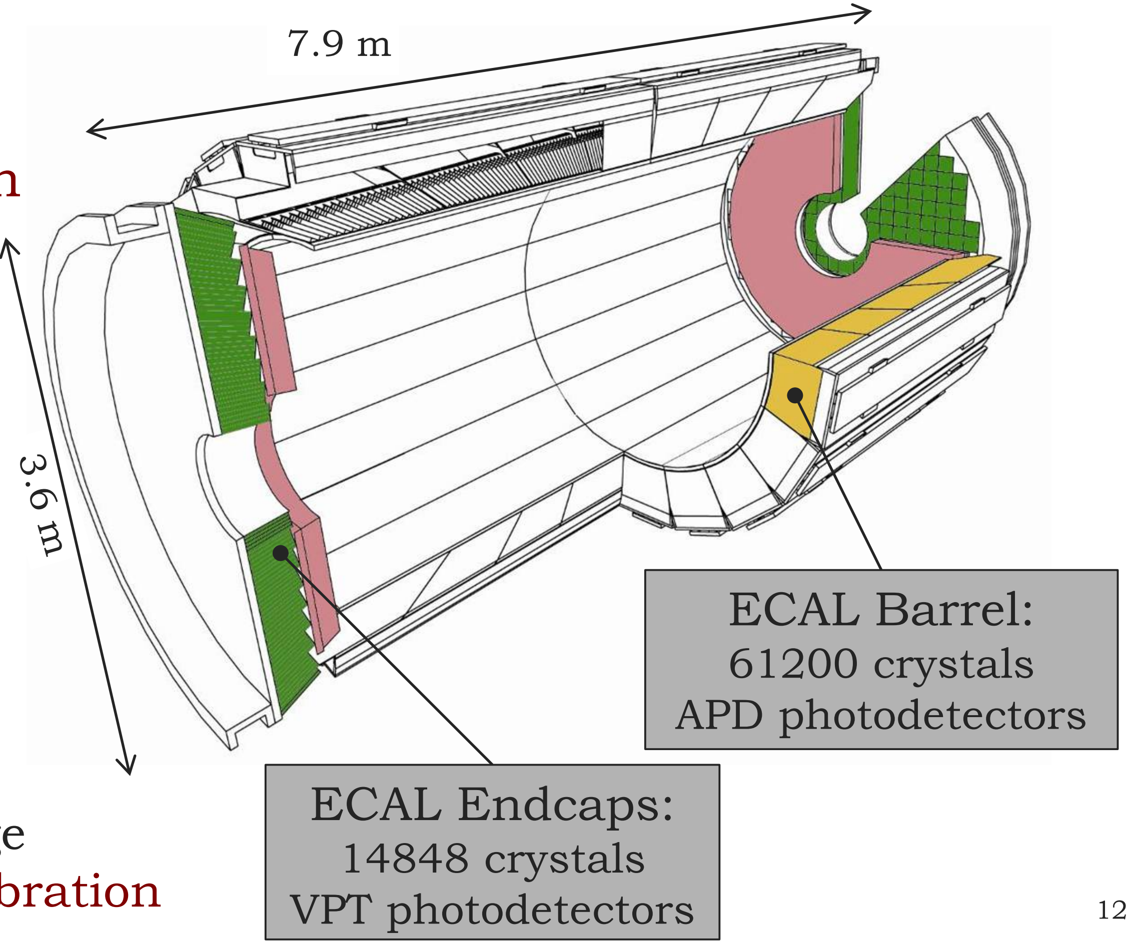
Design energy resolution:

0.5% for E > 100 GeV

(as measured at Test Beam)

Low stochastic term (< 3%)

- Critical issues:
  - Transparency loss due to radiation damage
  - Precision of in-situ calibration



Energy resolution

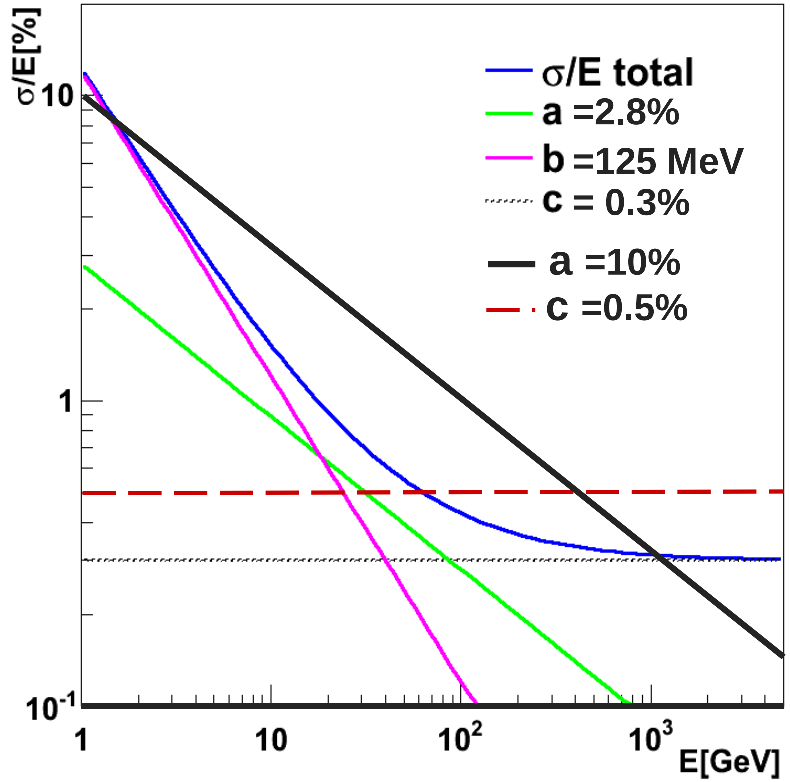
The diphoton invariant mass resolution:

$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta \theta_{\gamma\gamma}}{\tan(\theta_{\gamma\gamma}/2)}\right]$$

[Angular contribution is negligible: primary vertex position from high momentum tracks]

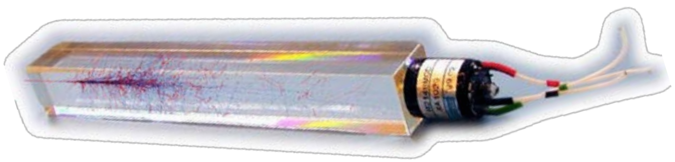
$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- a: stochastic term from Poisson-like fluctuations
- b: noise term from electronic and pile-up
- c: constant term
  dominant at high energy

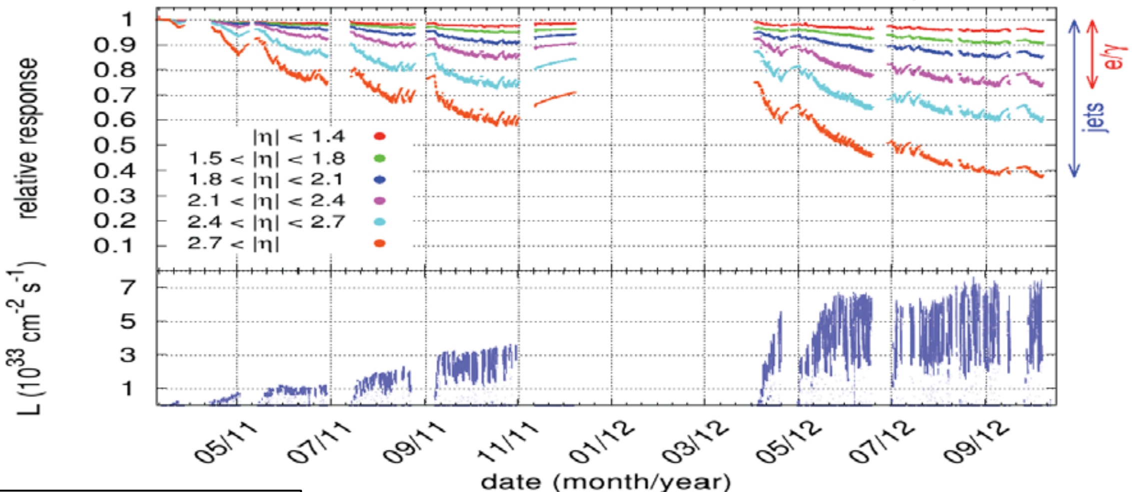


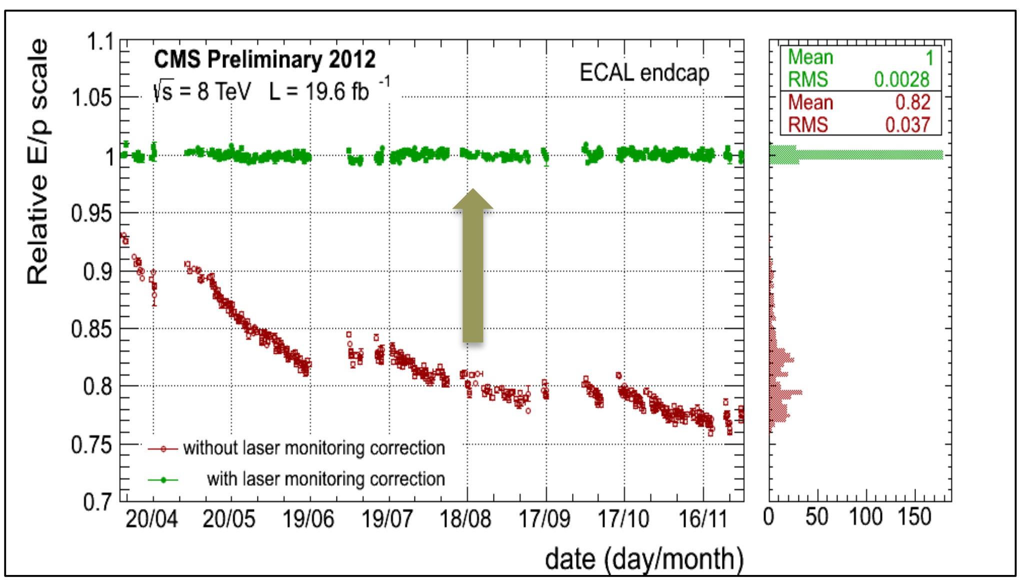
Crystal transparency loss in CMS

Relative crystal response to laser light vs time



Cycle of response loss during irradiation and recovery in beam-off periods





Stable energy scale achieved after laser correction

Stability (RMS):

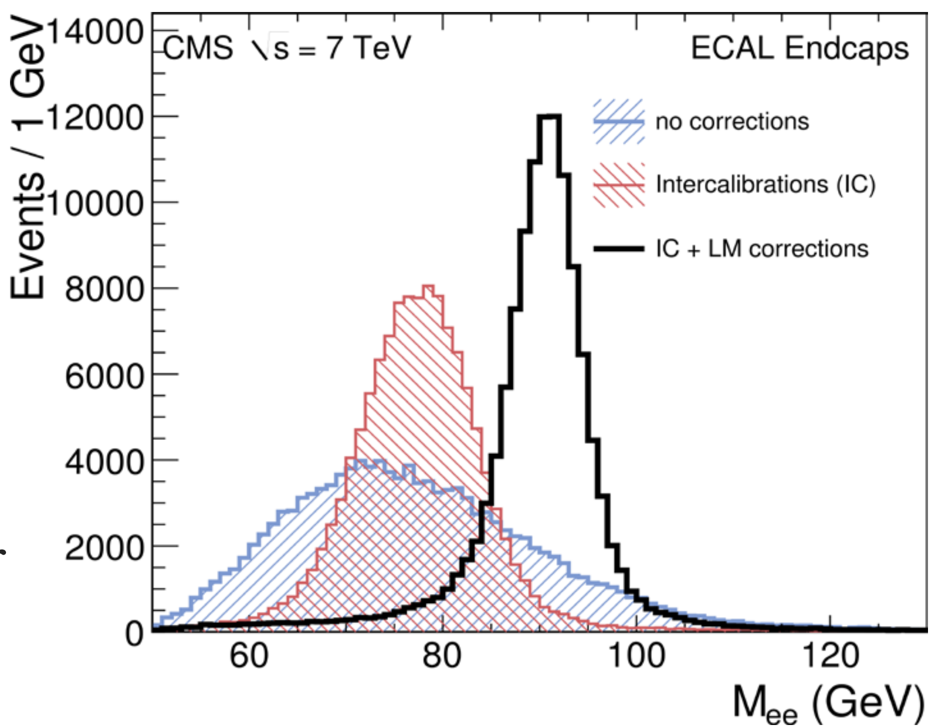
- ✓ Barrel ~ 0.1%
- ✓ Endcap ~0.3%

Effect of Calibration in CMS

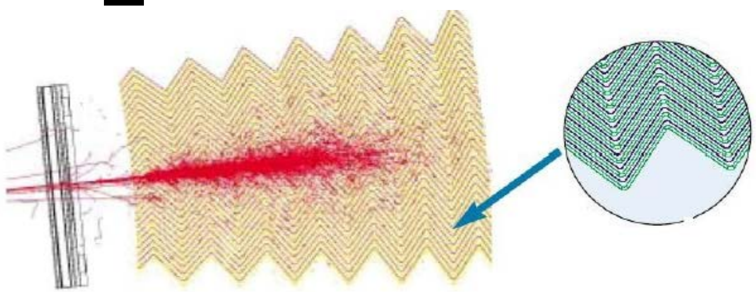
- Crystal LY spread ~ 20% → 0.5-1.0% after calibration
- Transparency losses in the crystals up to ~60% (strong position dependence) → 0.1-0.3% stability with laser corrections

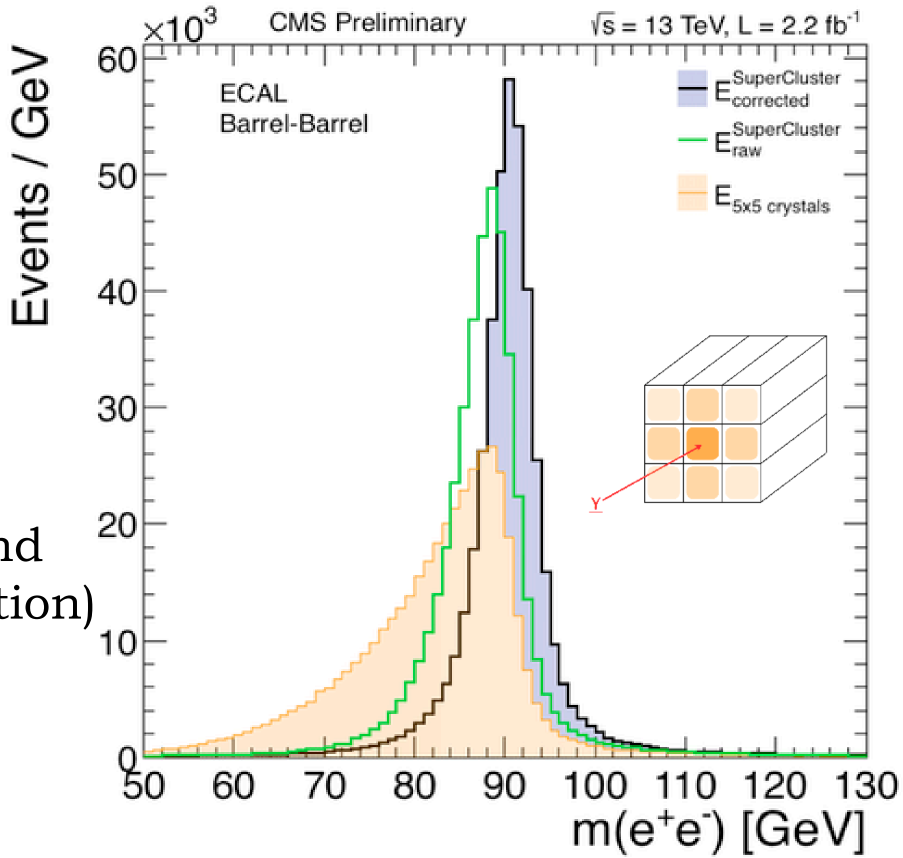
Effect of calibration on Zee invariant mass distribution in data:

- raw data
- channel Inter-Calibration
- Inter-Calibration and Laser Monitoring corrections



Photon clustering





Photon = energy deposits in clusters of ECAL channels

- ✓ clustering optimized to collect energy radiated from conversions and bremsstrahlung (best energy resolution)
- ✓ clusters are then associated with inner tracker and classified as electrons, γ or $\gamma_{converted}$

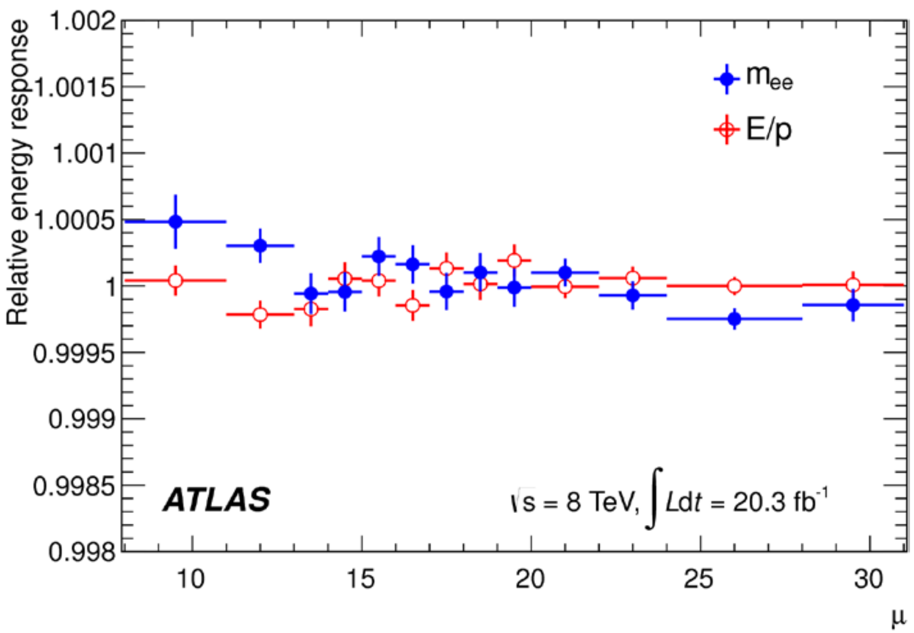
Final energy corrections from multivariate regression trained on MC

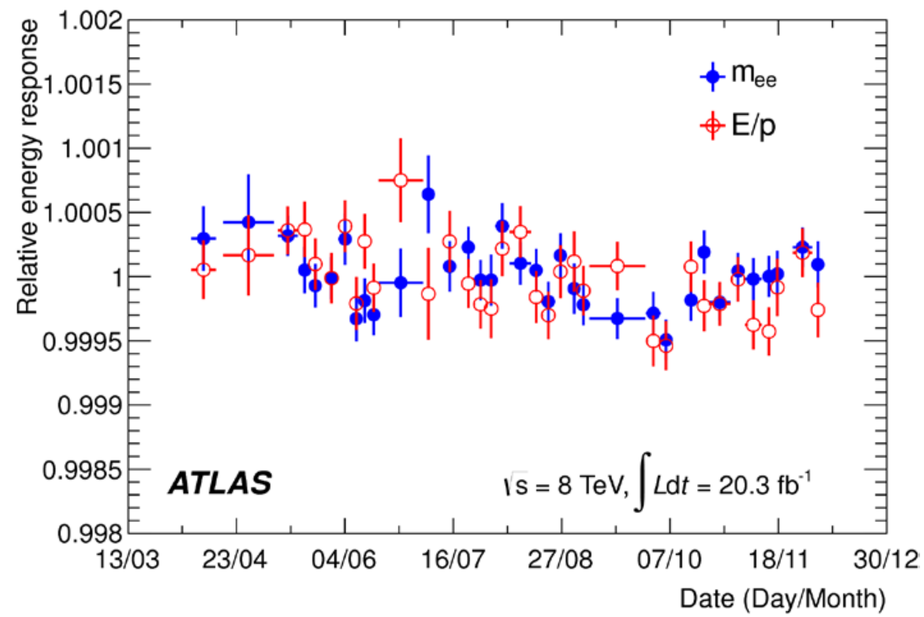
– further correct material effects, gaps, PU contamination

– can provide also a per photon resolution estimate

Response stability

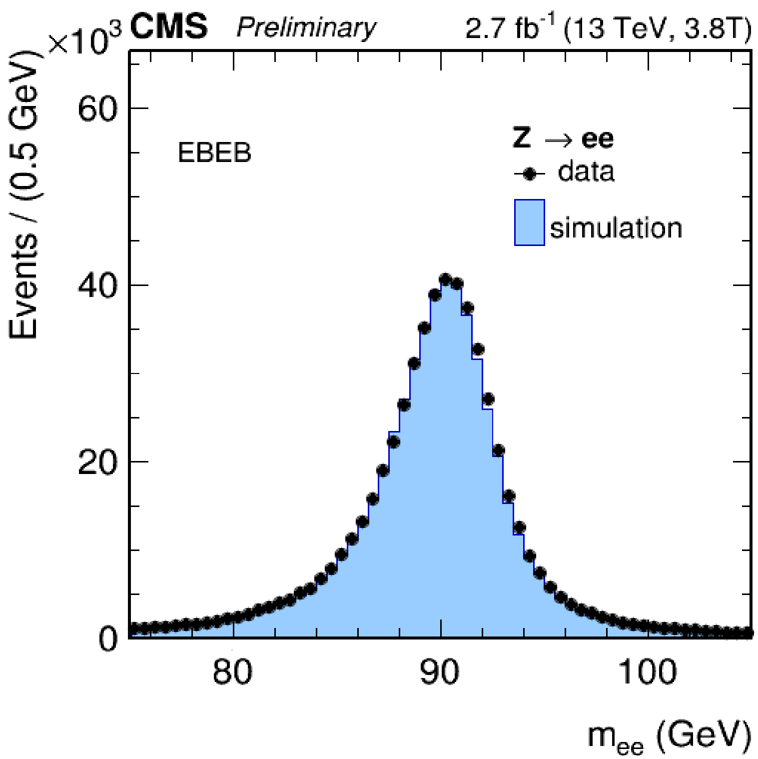
- Energy calibration determined in Run1 Z→ee events and corrected for the13 TeV data taking conditions.
- Energy scale stability with electrons from Z and W as a function of the number of reconstructed vertices (left) and vs time (right).
  - peak of the dielectron invariant mass distribution with Z event selection
  - MPV of E/p distribution with W event selection

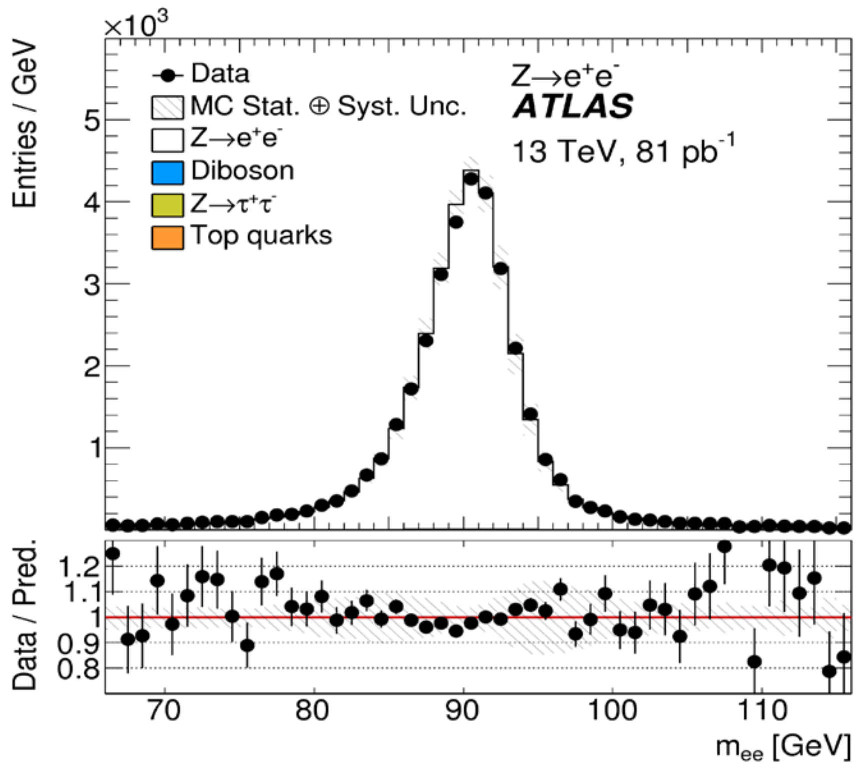




Photon reconstruction performance

- Energy scale and resolution corrections estimated using 13 TeV Z→ ee with electrons reconstructed as photons.
- Photon energy smeared on MC to match data.
- Linearity checked with boosted Z→ ee up to pT ~ 200 GeV and with high mass DY events

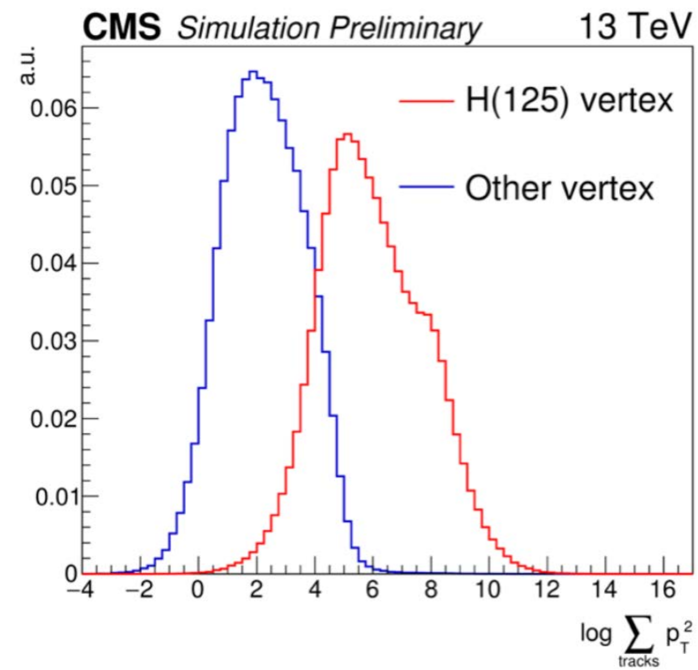


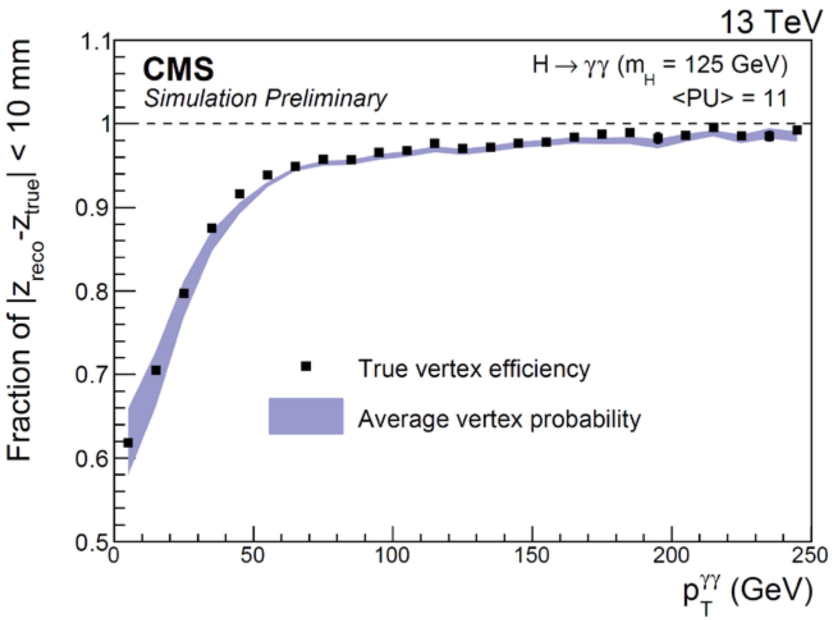


Diphoton vertex identification

- Spread of primary vertex position is ~ 5 cm in z
- If vertex is located within 1 cm, contribution to the mass resolution from angle negligible
- The vertex is selected using recoiling tracks (and reconstructed conversion when present)
- Multivariate approach for optimal performance

$$\Sigma p_T^2,\ p_T(\gamma\gamma) \text{ vs } p_T(\text{tracks}),\ z_{conv}$$

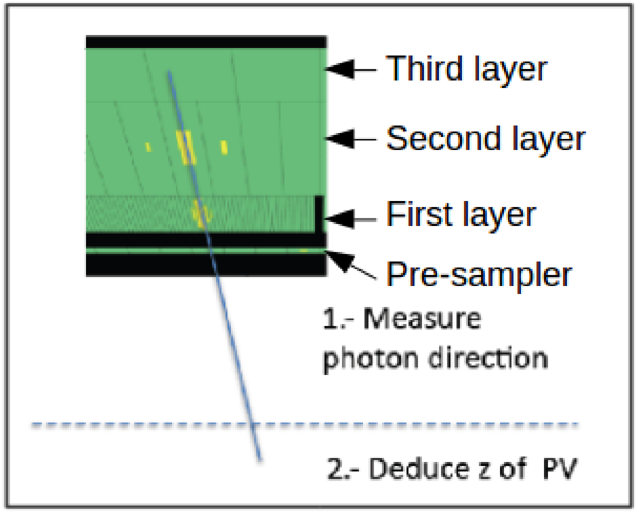


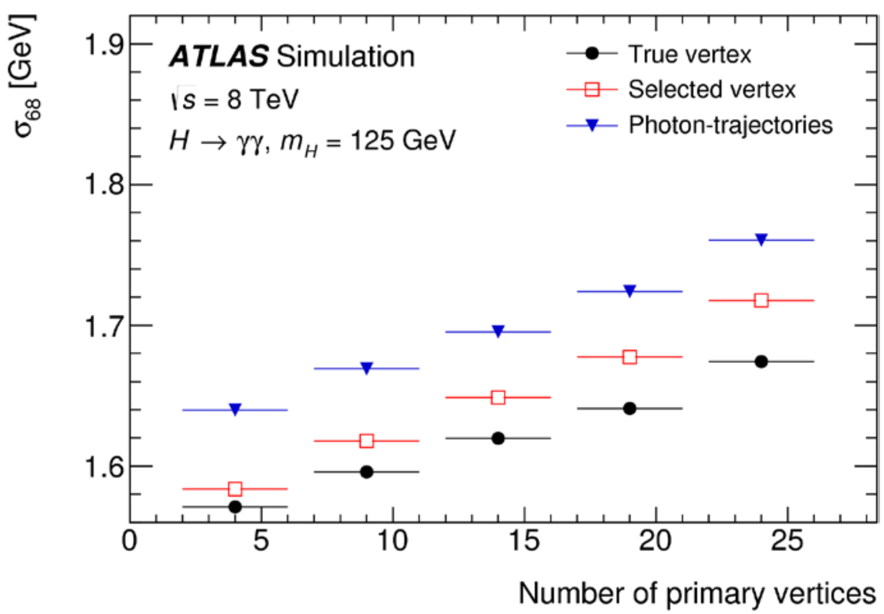


- Probability to assign the correct vertex depends on the pT(γγ).
- Average probability is ~ **90%**.
- Performance validated in data with Z→μμ events

Diphoton vertex identification

- γ trajectories measured exploiting the calorimeter longitudinal segmentation
- The vertex is selected among the reconstructed vertices with a **neural network (NN) algorithm**
  - Inputs: z position of extrapolation, sum pT2, sum pT, $\delta\varphi$ between di-photon system and vector sum of track momenta





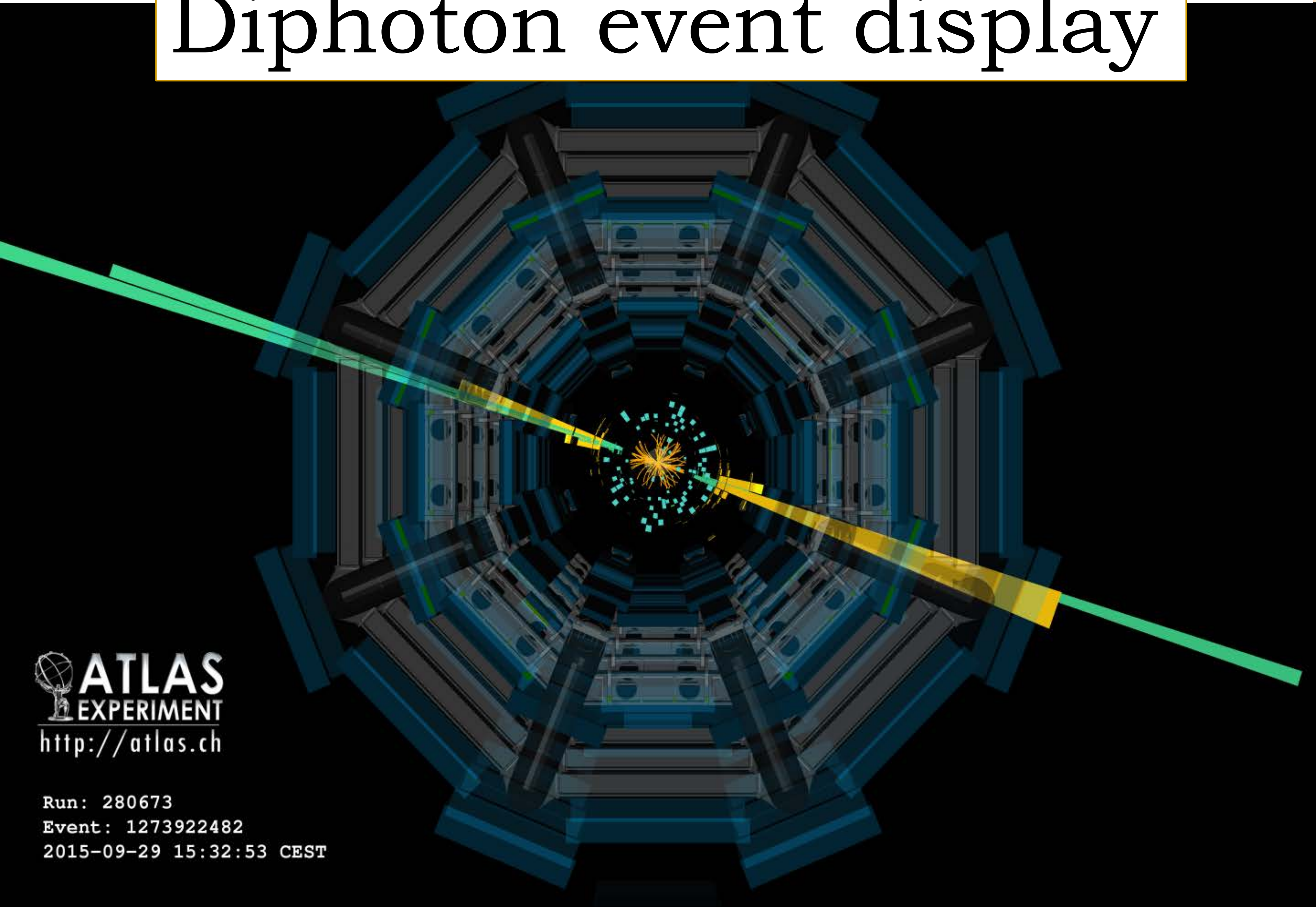
Efficiency of **identifying a vertex** within **0.3 mm** for the true one is **80-95%**, depending on the number of reconstructed vertices in the event

Analysis update (Moriond)

ATLAS and CMS diphoton preliminary results already shown here in Sapienza in a seminar in January.
Focus of this presentation on diphoton updates at Moriond conference (march 2016) and recent Z+photon results.

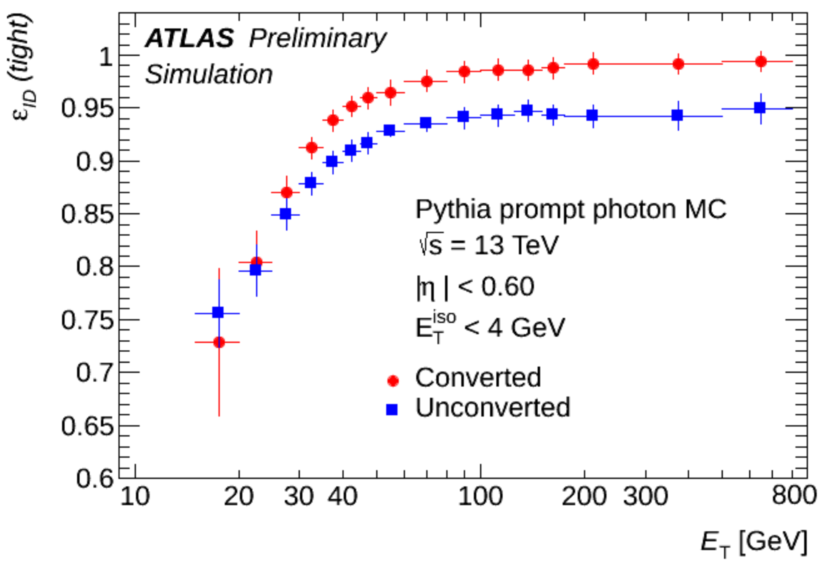
ATLAS	CMS
Spin 2 interpretation added (was only Spin 0 in december)	Spin 0 interpretation added (was only Spin 2 in december)
diphoton 8 TeV data re-analysis and compatibility with 13 TeV analysis	0.6 fb^{-1} of additional data recorded without magnetic field
p-value scan in 2D (mass-width, was only mass in december)	re-reconstruction of data with the new ECAL calibration
kinematic properties of events in the excess region w.r.t. sidebands	combination with 8 TeV results
$Z\gamma \rightarrow ee\gamma/\mu\mu\gamma/jj\gamma$ channels at 13 TeV	**$Z\gamma \rightarrow ee\gamma/\mu\mu\gamma$ channels at 13 TeV**

Diphoton event display



ATLAS event selection

Central photon ID efficiency at 13 TeV



Cut-based event selection

- ✓ Trigger: E_{1T}>35 GeV and E_{2T}>25 GeV
- ✓ Offline pre-selection:
  - ✓ E_{1T}>40 GeV and E_{2T}>30 GeV
  - ✓ ECAL fiducial region
  - ✓ dedicated photon selection (isolation, H/E, shower shape)
- ✓ two event selections:

Spin-0 analysis
(extended Higgs sector)

Higgs-like signal optimization
- $E_T(\gamma_1)>0.4\ m_{\gamma\gamma}$, $E_T(\gamma_2)>0.3\ m_{\gamma\gamma}$ → +20% significance for m_X> 600 GeV

Search range
m_X : [0.2, 2] TeV and Γ_X/m_X : [0% - 10%]

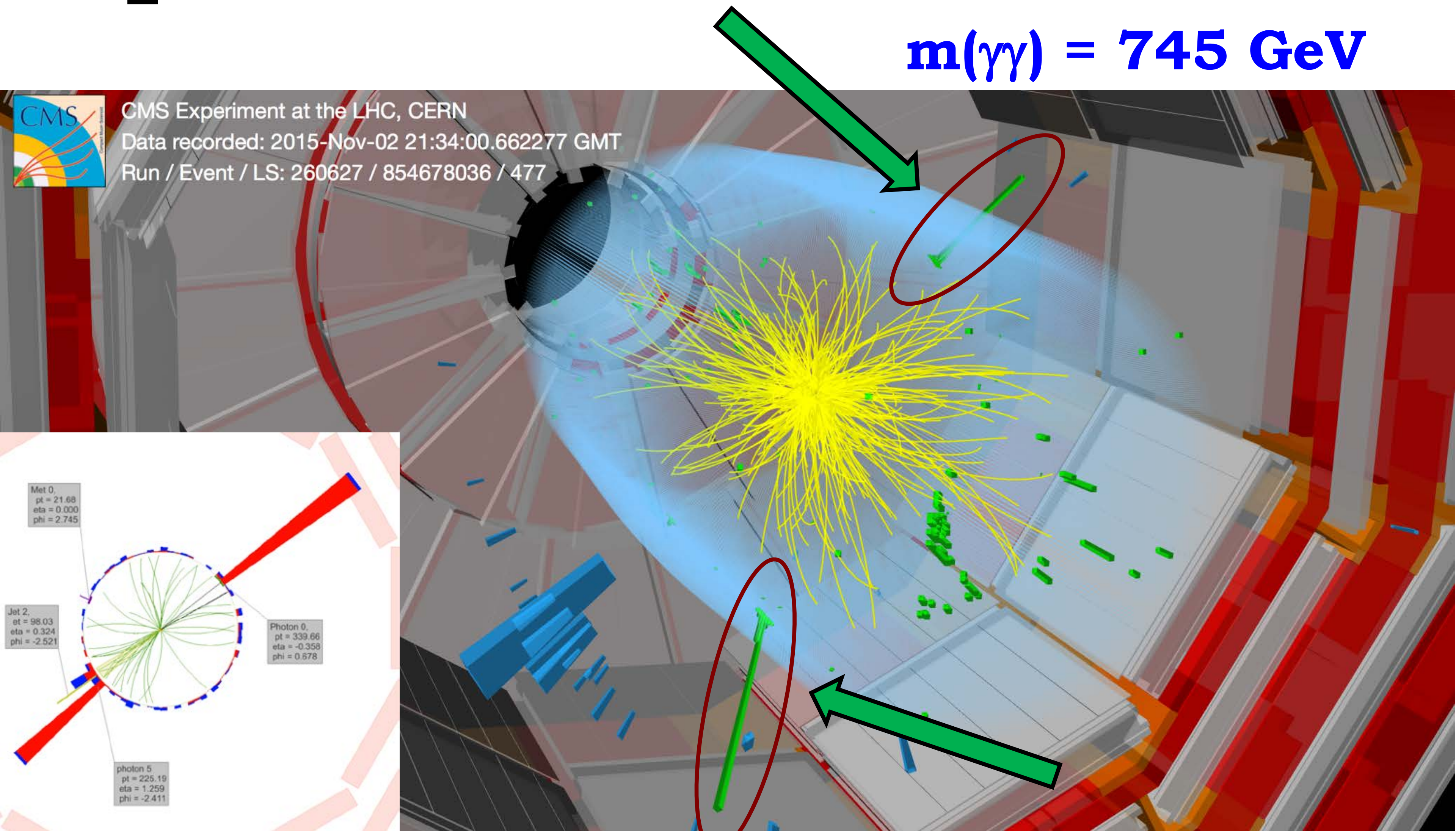
Spin-2 analysis
(Randall-Sundrum graviton)

Looser selection
- $E_T(\gamma_1)$>55 GeV , $E_T(\gamma_2)$>55 GeV → preserve acceptance at high mass

Search range
m_G : [0.5, 3] TeV and Γ_G/m_G : [0.01% - 11%]

Diphoton event display

m(γγ) = 745 GeV

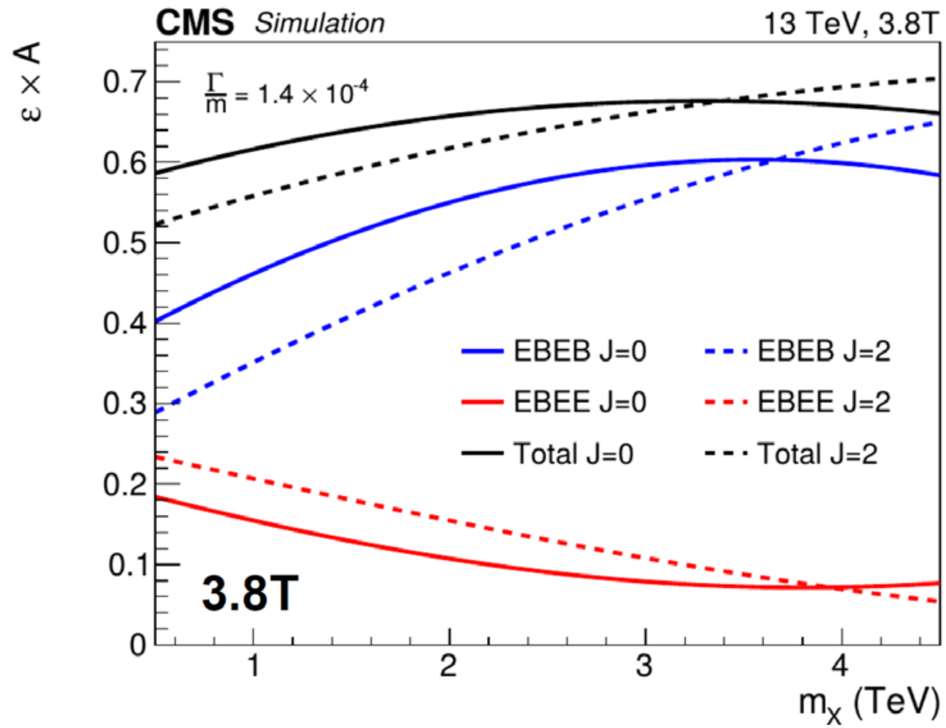


CMS event selection

Cut-based event selection

(same selection for both benchmark models)

- ✓ HLT: 2 photons, E_T>60 GeV
- ✓ Offline selection:
  - ✓ E_T > 75 GeV
  - ✓ ECAL fiducial region
  - ✓ dedicated photon selection (isolation, H/E, shower shape)
- ✓ 2 event categories:
  - ✓ EBEB: both γ in the barrel
  - ✓ EBEE: one γ in EB, one in EE



10-15% improvement from adding the barrel-endcap category

Per-photon efficiency in the barrel (endcaps): ~90%(~85%).

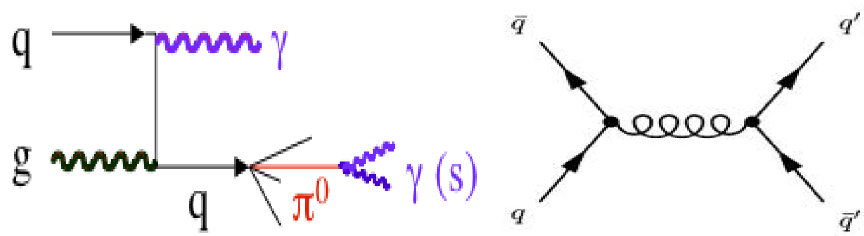
Zee to check efficiencies

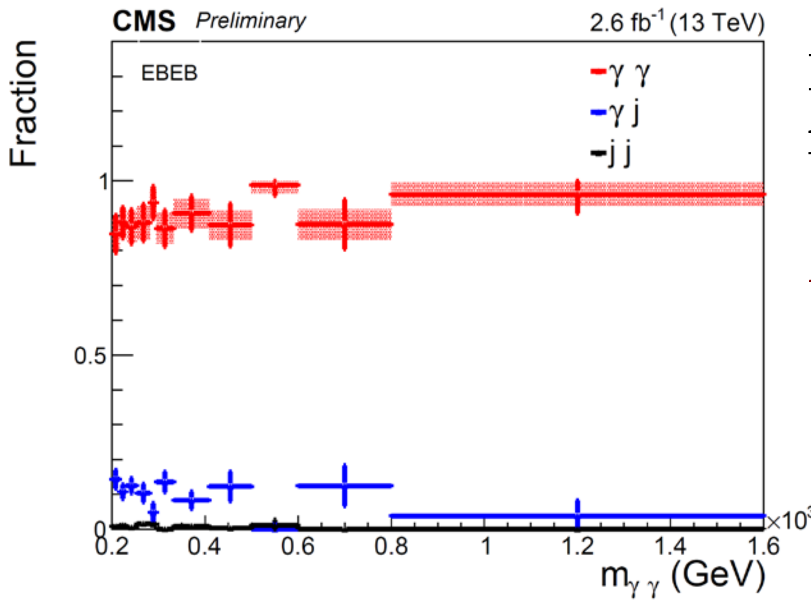
✓ data/MC scale factors compatible with 1, constant at high p_T

Backgrounds

Direct γγ SM production
irreducible

Dijet and γ+jet production
reducible





Background composition measured in data using template fits

Dominant contribution: 2 prompt photons

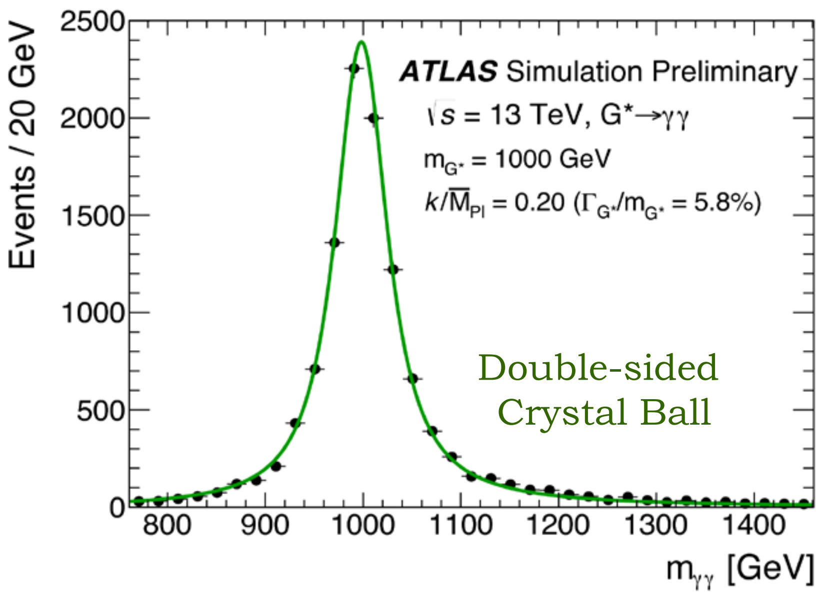
QCD and photon+jets: 10%-20%

Signal modelling

- Shape of the signal: combination of the intrinsic width of the resonance and the calorimeter detector response.
- Benchmark model: spin0 and spin2
  - scan of the mass in the range 500-5000 GeV
  - spin 0: scan of the width up to ~10%
  - spin 2: scan of the RS graviton coupling: 0.01-0.2 → Γ_G/m_G = 0%-6%
- Detector response modeled on fully simulated signal sample with negligible intrinsic width

CMS

m (GeV)	$\sigma_{FWHM}^{3.8T}/m$	
	EBEB	EBEE
500	0.94×10^{-2}	1.5×10^{-2}
1000	0.94×10^{-2}	1.5×10^{-2}
2000	0.96×10^{-2}	1.4×10^{-2}
4500	1.11×10^{-2}	1.4×10^{-2}



Background modelling

Background $m_{\gamma\gamma}$ shape:

✓ parametric fit to data (several function tested)

✓ model coefficients: nuisance parameters in the hypothesis test

CMS

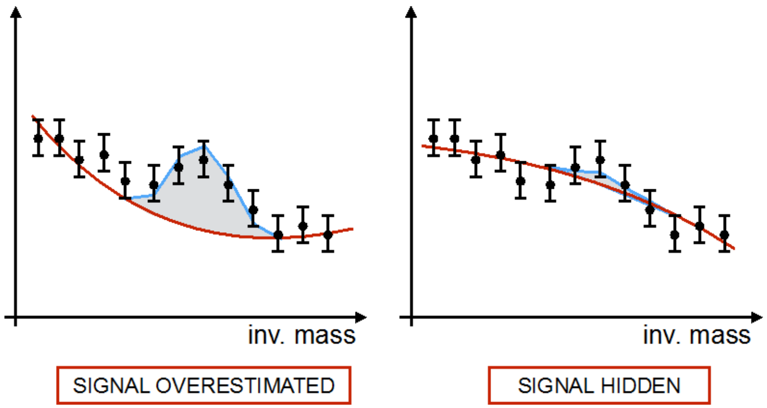
$$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$$

ATLAS (Spin 0)

$$f = (1 - x^{1/3})^b x^a, \text{ with } x = m_{\gamma\gamma}/\sqrt{s}$$

ATLAS (Spin 2)

Irreducible γγ background from MC
Reducible (γ+jets,jj) background from data



Accuracy of the background determination is assessed using MC simulations and quantified by studying the difference between the true and predicted number of background events

Data re-reconstruction with new ECAL calibration

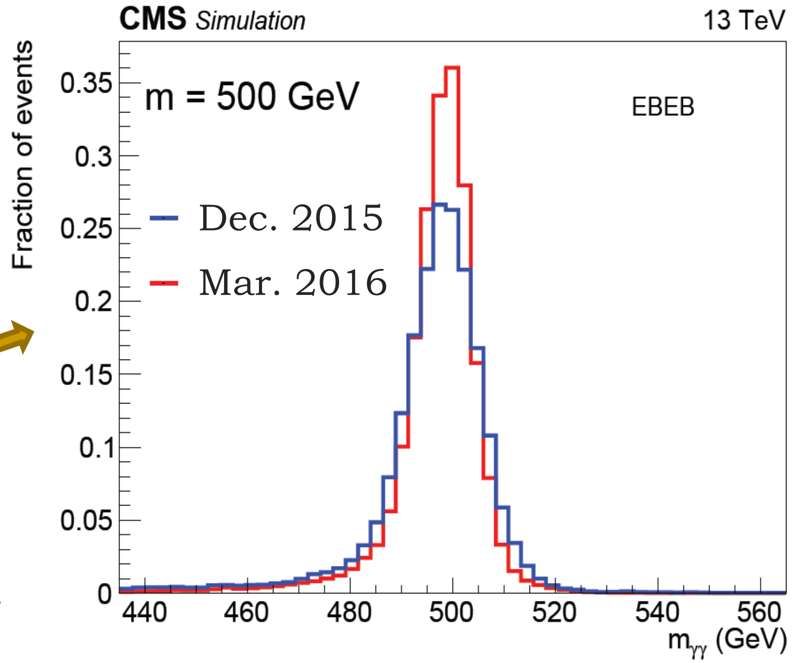
CMS improved the analysis for Moriond conference thanks to:

1. re-reconstruction of data with the new ECAL calibration
2. 0.6 fb^{-1} of additional data recorded without magnetic field (next slide).

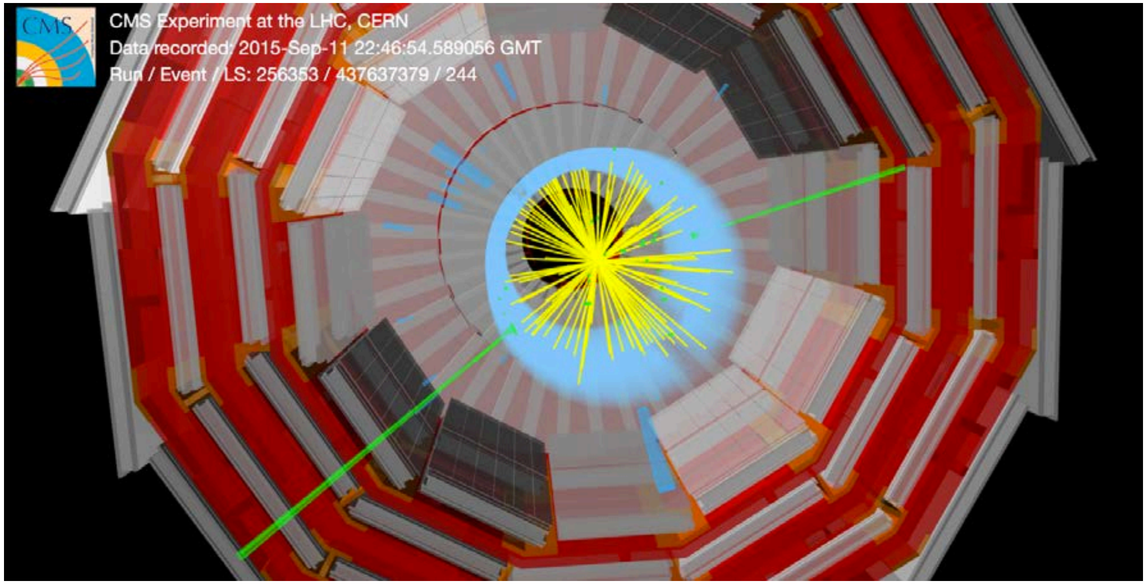
Both the improvements rely on a <u>deep ability to make the best usage of data taken with the Electromagnetic Calorimeter</u>

New ECAL calibration derived with the full 2015 data sample:

- ~30% improvement in mass resolution
- ~10% improvement in expected sensitivity

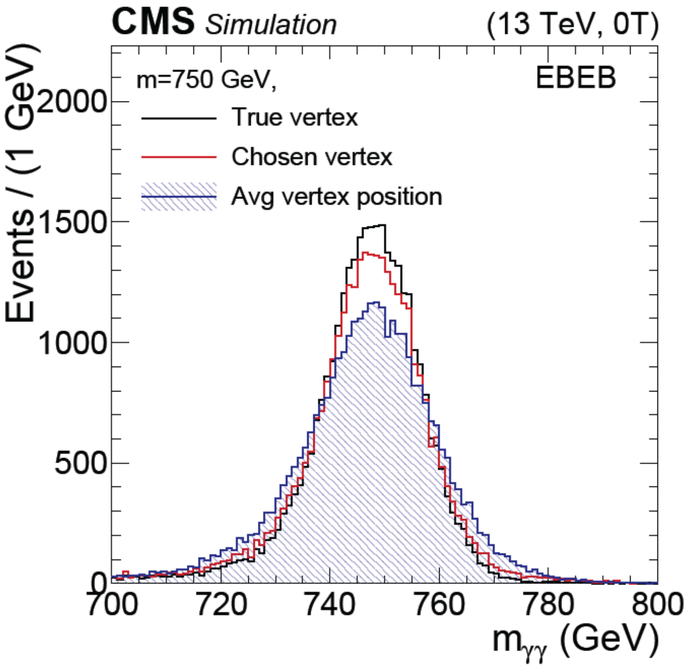


Data with B=0 Tesla



No measurement of charged particle momenta

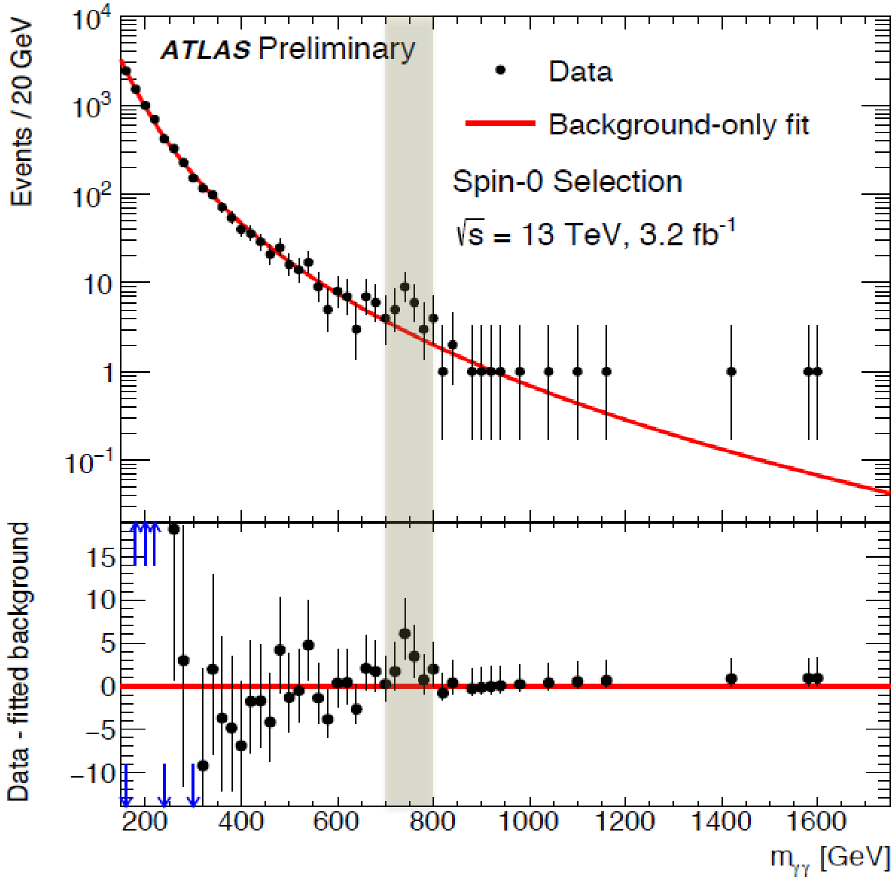
Reduced energy spread from conversion/brem.

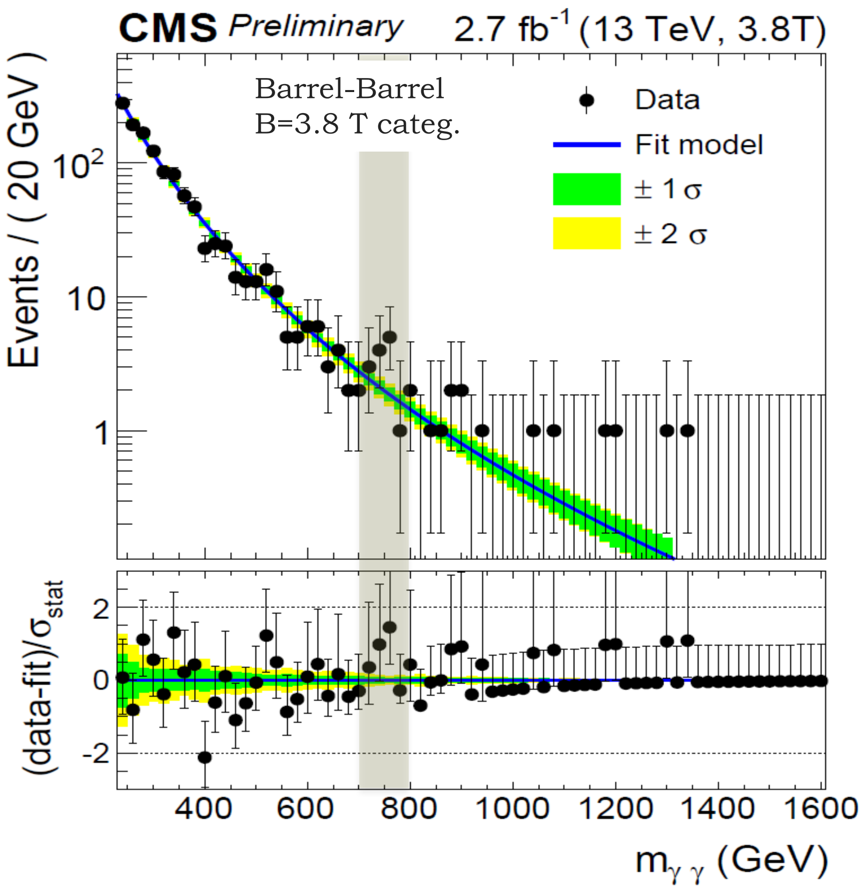


- Significant re-thinking of the analysis needed to use data without magnetic field (very first case in CMS)
- Dedicated calibration and photon ID
- Identification of production vertex by counting the associated tracks.

Diphoton mass spectra

$m_{\gamma\gamma}$ distribution @ 13 TeV - Moriond updates



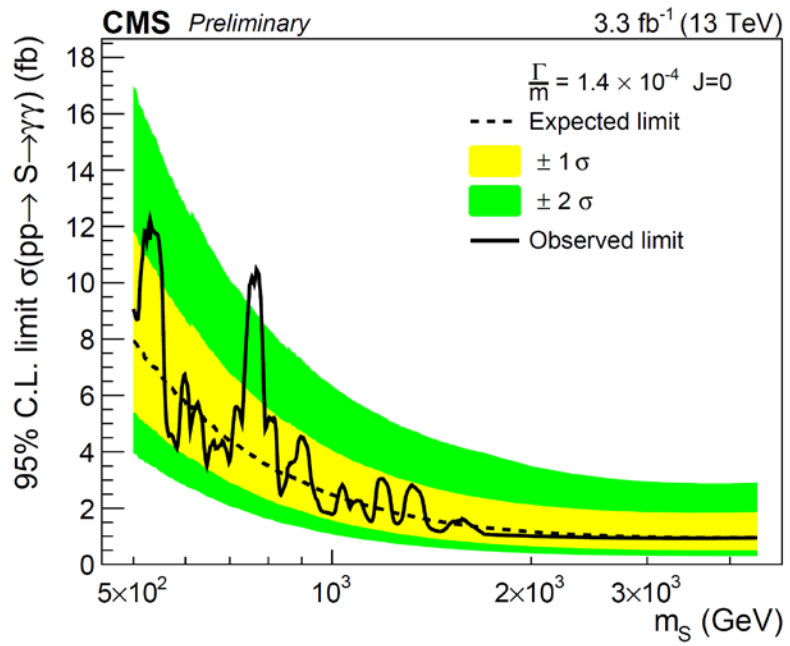


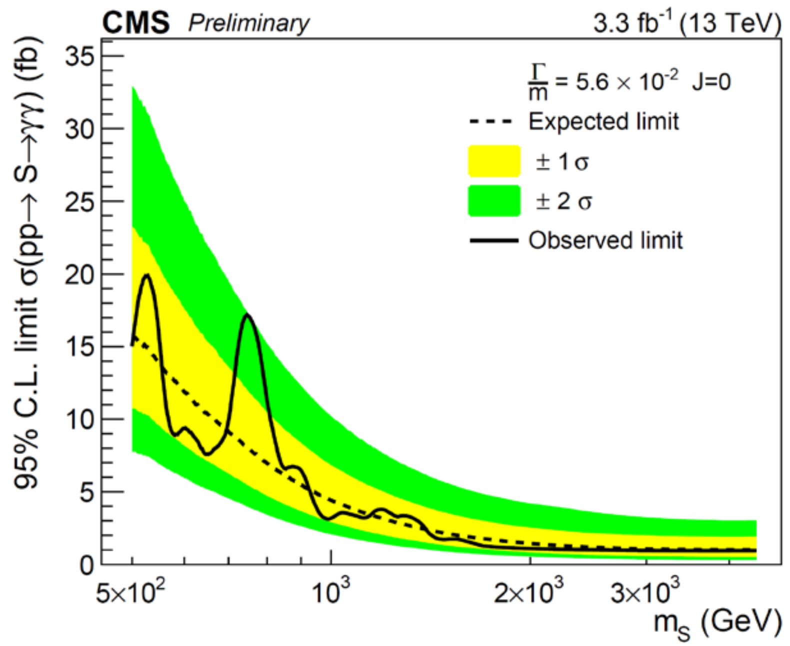
ATLAS-CONF-2016-018

CMS-PAS-EXO-16-018

Interpretation: exclusion limits

Spin-0 / narrow width	**Spin-0 / 5.6% width**





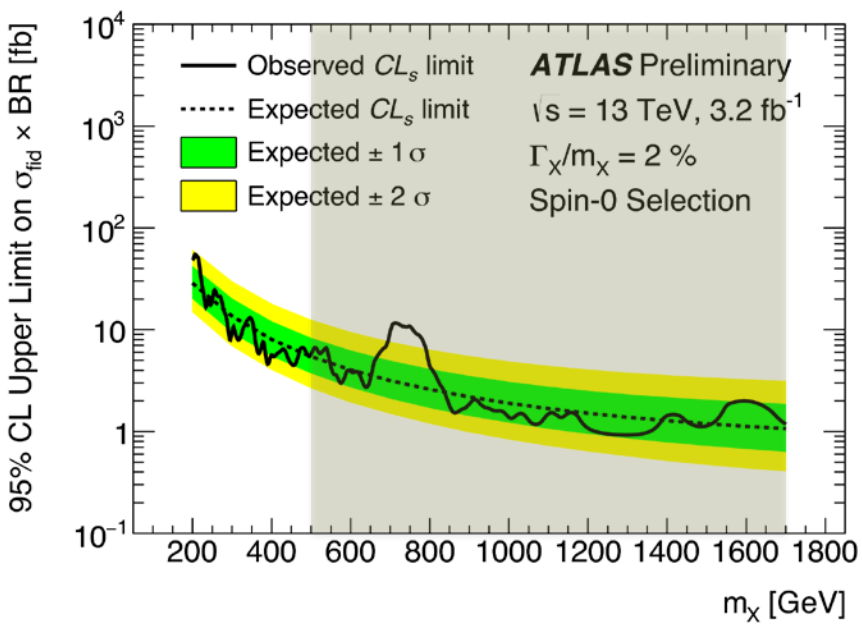
Expected and observed limits on cross section x diphoton BR based on simultaneous unbinned likelihood fit in all analysis categories. (ATL-PHYS-PUB-2011-11 / CMS NOTE-2011/005):

- ✓ Spin 2 results very similar (in the backup).
- ✓ Observed limit deviation from expected due to excess in data

Interpretation: exclusion limits

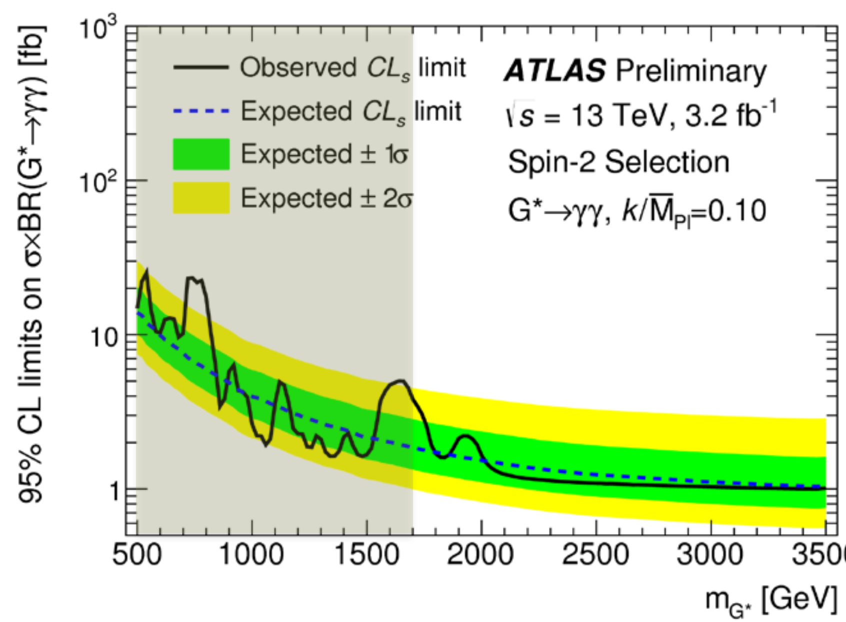
Spin-0 analysis

Limit on fiducial cross section



Spin-2 analysis

Limit on production cross section

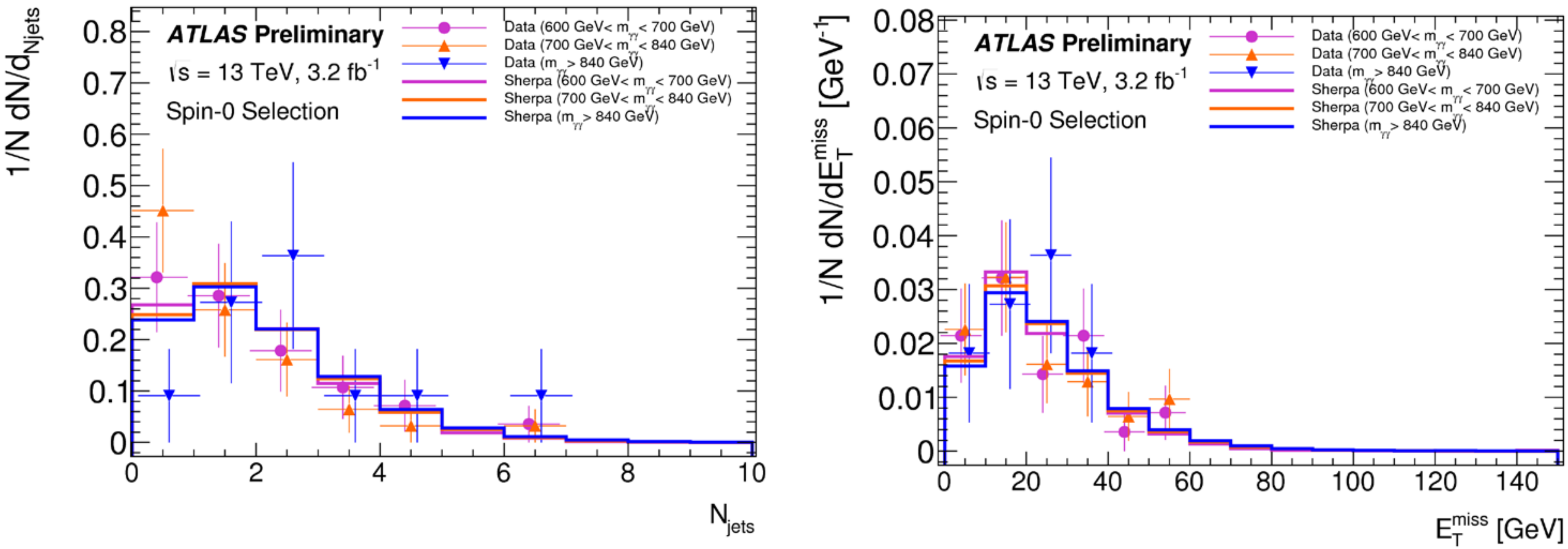


Expected and observed limits on cross section x diphoton BR (ATL-PHYS-PUB-2011-11 / CMS NOTE-2011/005):

✓ Observed limit deviation from expected due to excess in data

Event kinematic properties: sidebands and excess region

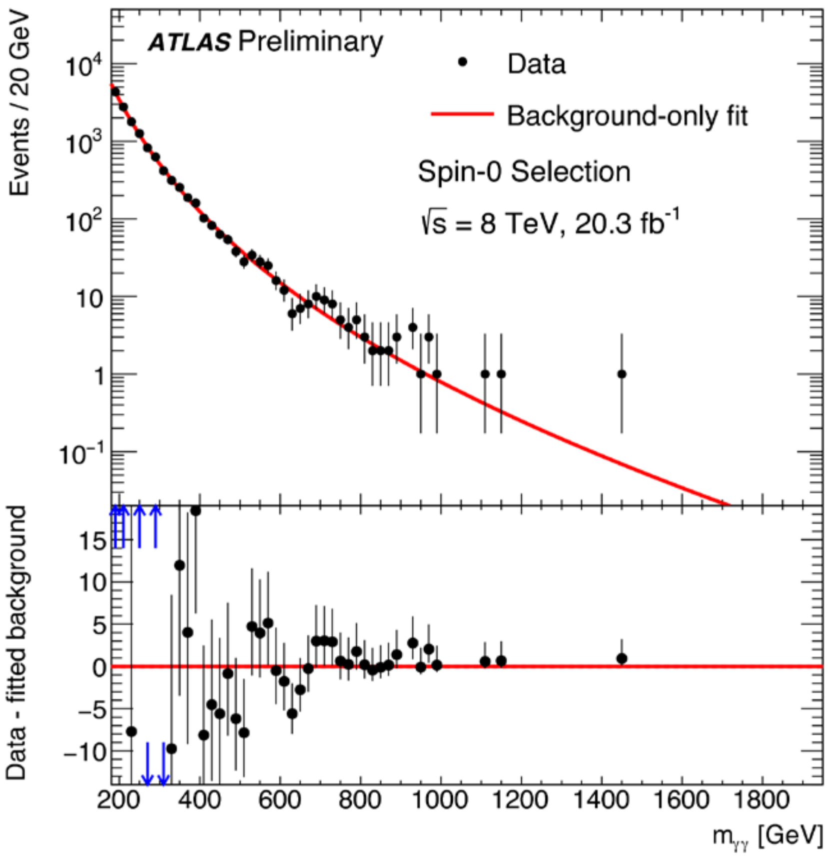
Spin-0 analysis

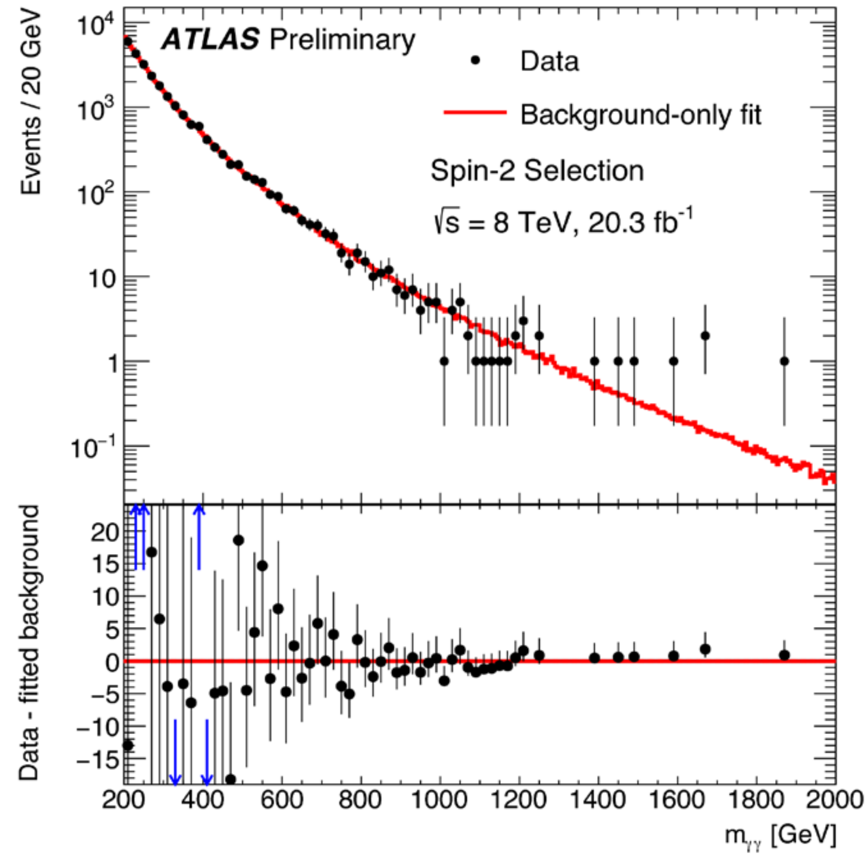


- No additional activities (with the current size of the data sample) in the diphoton events belonging to the excess region with respect to the events in sidebands.
- No additional activities also in ATLAS spin 2 and in CMS selections.

Comparison with 8 TeV results

8 TeV data re-analyzed: latest run1 calibration, run1 selection, **13 TeV analysis methods**



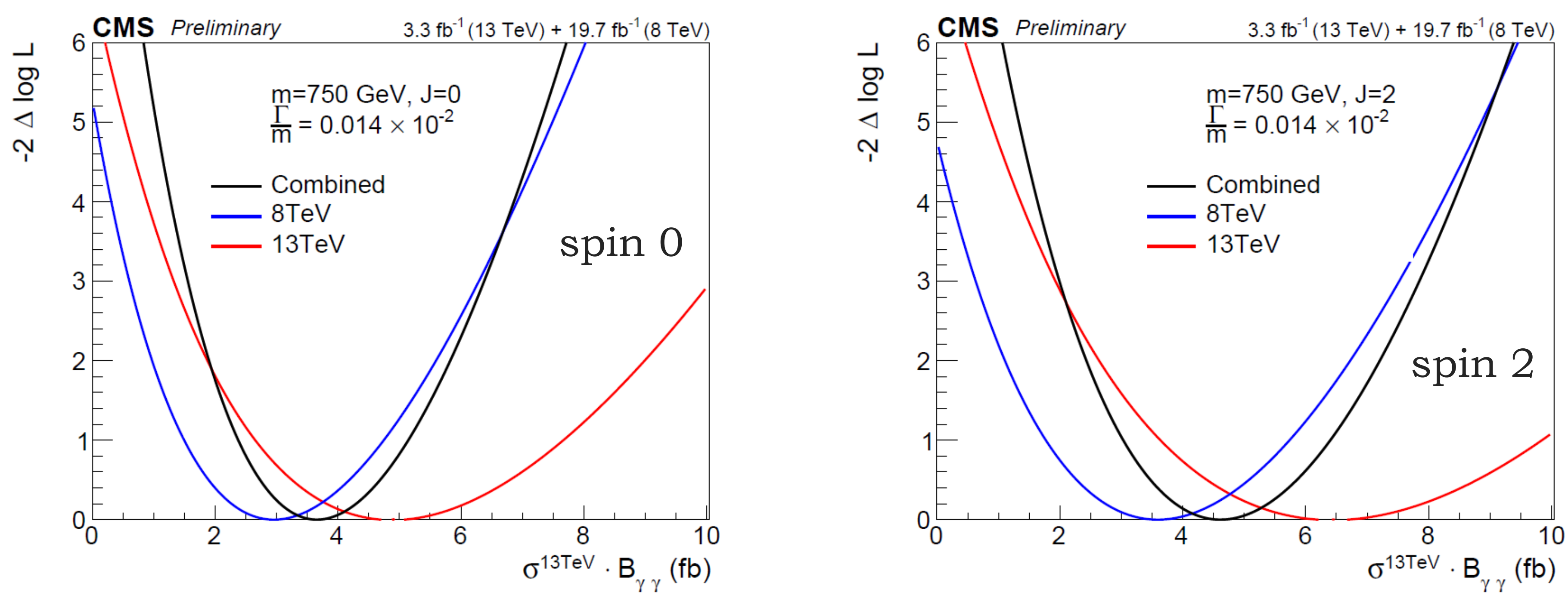


1.9 σ at the same m_X, Γ_X combination
- Compatible with 13 TeV results at 1.2σ

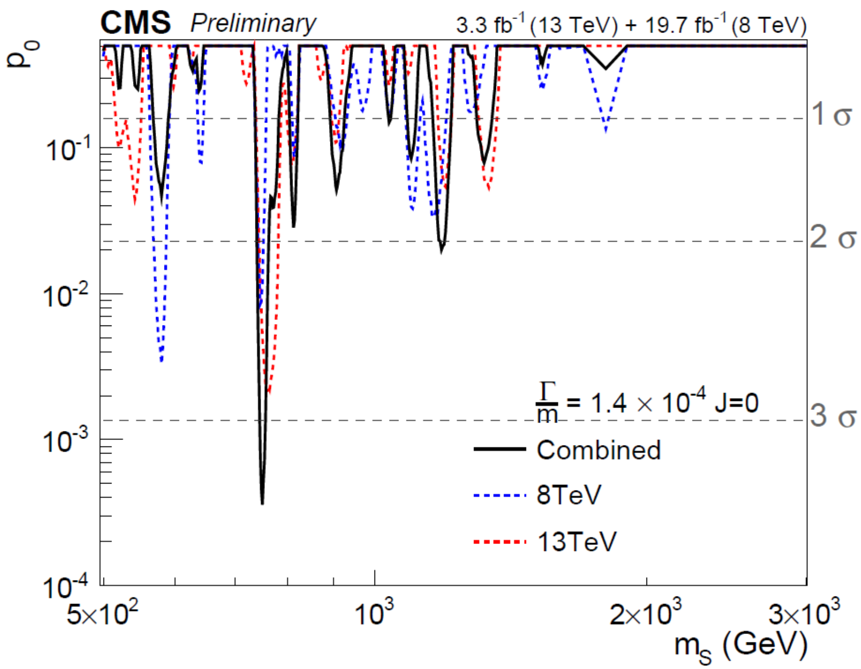
No significant excess
- Compatible with 13 TeV results at 2.7σ

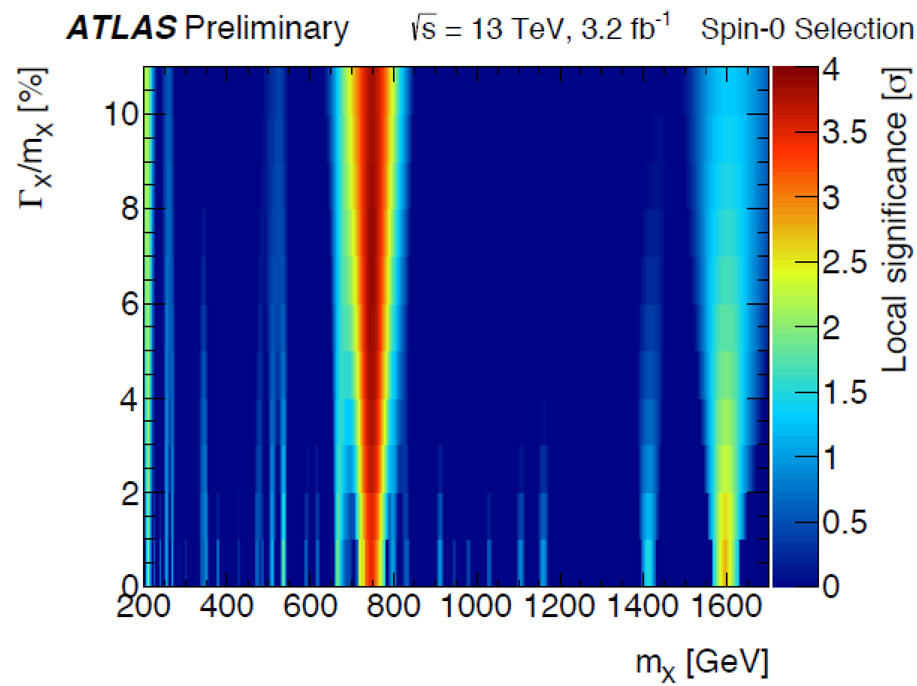
Combination with 8 TeV results

- Combination with 8 TeV results in narrow width hypothesis
  - different acceptance and categorizations
- Consistency between 8 and 13 TeV results evaluated with likelihood scan at 750 GeV.
  - 8 TeV results rescaled by the expected cross-section ratio (4.7/4.2 for spin 0/2)
- Compatible results in both spin hypotheses.



Excess significance





- ✓ **Largest excess for m_X = 750 GeV in both experiments**
- ✓ Local significance 3.4σ (CMS) and 3.9σ (ATLAS)
- ✓ Significance reduced to 1.6σ (CMS) and 2.0σ (ATLAS) when accounting for Look Elsewhere Effect in mass and width (trial factor derived as in arXiv:1005.1891v3)

ATLAS vs CMS

	ATLAS	CMS
Calorimeter (complementary technology)	Lead – Argon sampling Ionization Longitudinal segmentation	PbWO homogeneous Scintillation light Excellent stochastic term
13 TeV Luminosity	3.2 fb^{-1}	2.7 fb^{-1}+0.6 fb^{-1} (B=0T)
Benchmark models	Spin 0 + Spin 2	Spin 0 + Spin 2
diphoton selection	spin 0: scaling E_T cut spin 2: fixed E_T cut (55 GeV)	fixed E_T cut (75 GeV)
efficiency x **acceptance**	55%-70% @ 200-700 GeV 45%-60% @ 0.5-3.0 TeV	spin0: 60% @ 750 GeV spin2: 55% @ 750 GeV
compatibility with 8TeV	OK: small excess with spin0 selection	OK: combination
Significance @750GeV	3.9σ local 2.0σ global	3.4σ local 1.6σ global

Complementary search: high mass resonances in Zγ channels

- Assuming no extra tree-level decays other than an effective coupling to gluons and to SM gauge bosons implies a large contribution to the Zγ decay

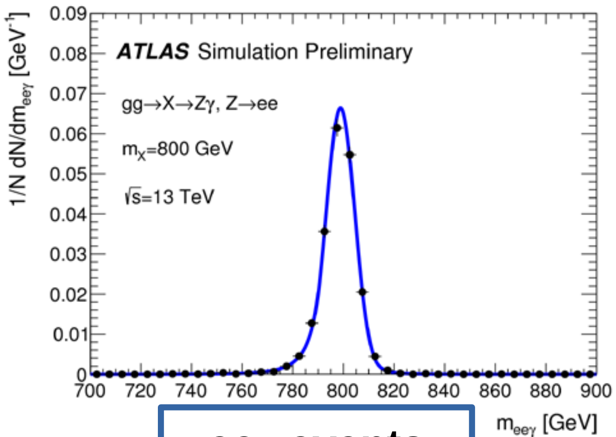
Search for scalar resonances in Zγ→ee γ/μμγ/jjγ final states at √s = 13 TeV (and 8 TeV) in ATLAS and CMS

(additional channels investigated – e.g. ZZ, dijets,… - and no excess observed)

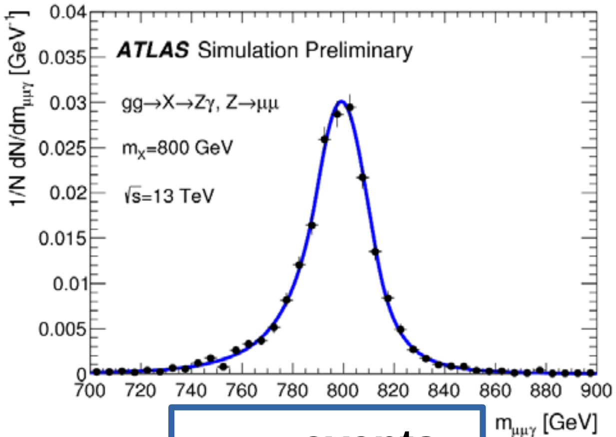
- The dominant background process is SM production of non-resonant Z+γ in the leptonic channel and Z+jet with the latter misidentified as photon in the hadronic channel.
- Mass range:
  - ATLAS ee γ/μμγ → 250 GeV – 1.5 TeV
  - ATLAS ee γ/μμγ @ 8 TeV → 200 GeV – 1.6 TeV
  - ATLAS jjγ → 720 GeV – 2.75 TeV
  - CMS ee γ/μμγ → 350 GeV – 2.0 TeV
  - CMS ee γ/μμγ @ 8 TeV → 200 GeV – 1.2 TeV

ATLAS Zγ → eeγ/μμγ/jjγ

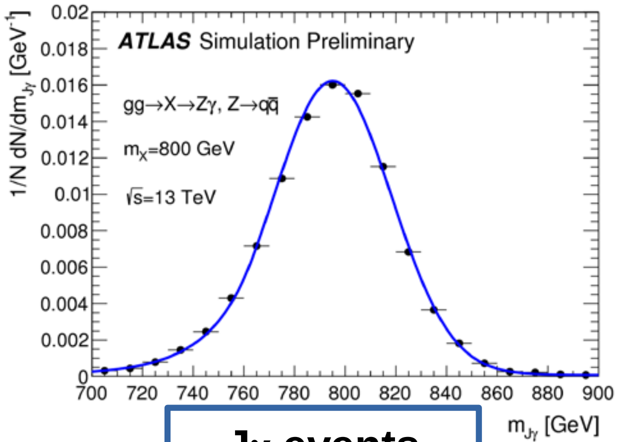
- Considered separately leptonic and hadronic Z decays: very different detector resolution
- Zγ→llγ: 2 same flavor, opposite sign leptons consistent with a Z
- Zγ→Jγ: jet-pair reconstructed as a large radius single jet (**J**) with p_T> 200 GeV



eeγ events

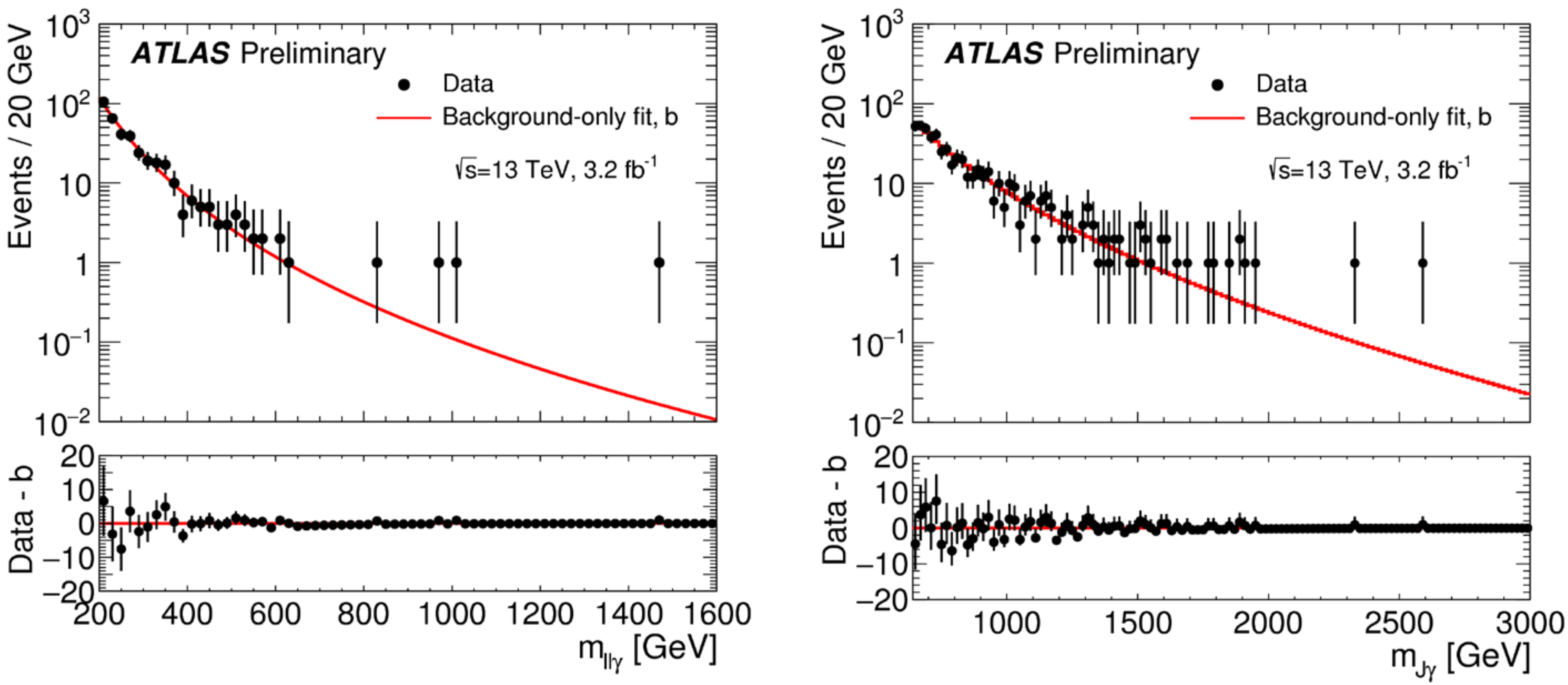


μμγ events



Jγ events

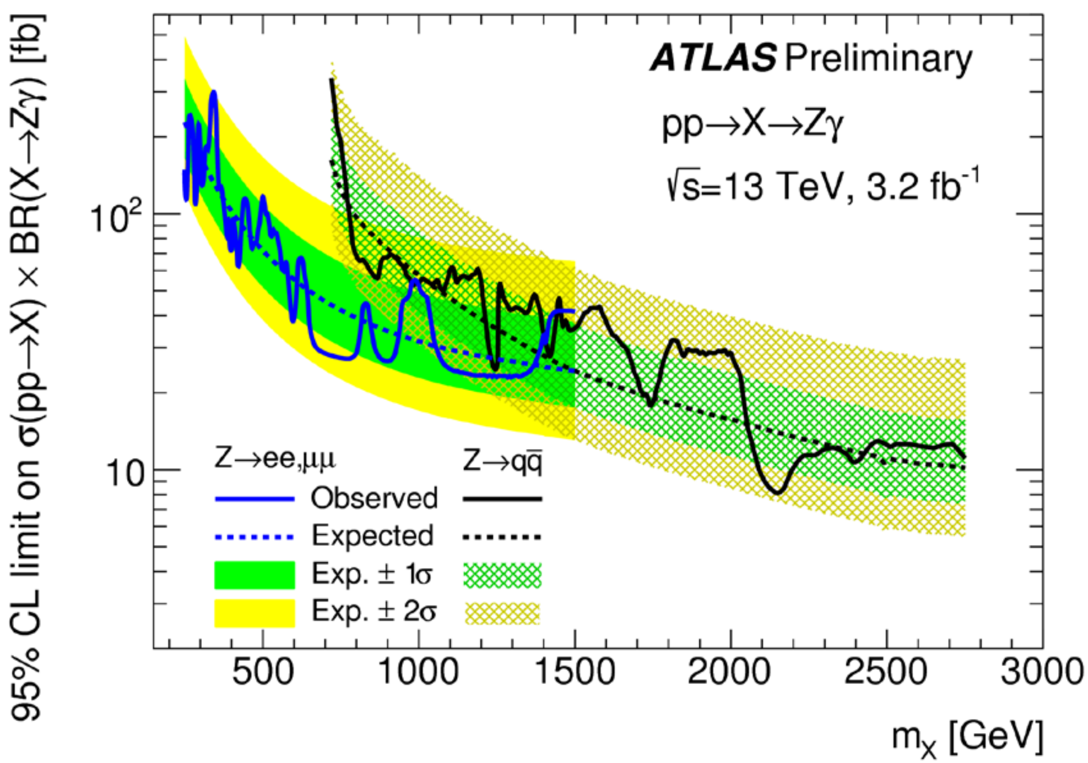
ATLAS $Z\gamma \to ee\gamma/\mu\mu\gamma/jj\gamma$

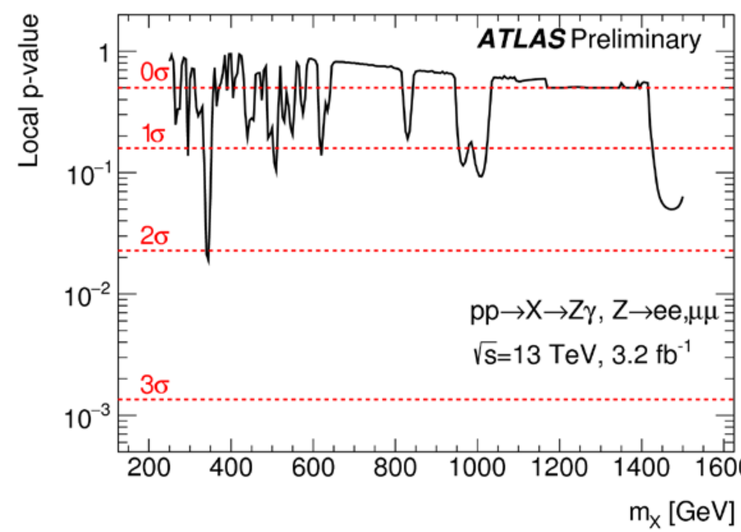


- In both cases the smoothing falling background is fitted with the analytical function $F = N(1-x^k)^{p1+\xi p2} x^{p2}$ ($x=m_{Z\gamma}/\sqrt{s}$)
- Signal benchmark: generic Higgs-like resonance with a narrow width (Γ_X=4 MeV) simulated using POWHEG+PYTHIA

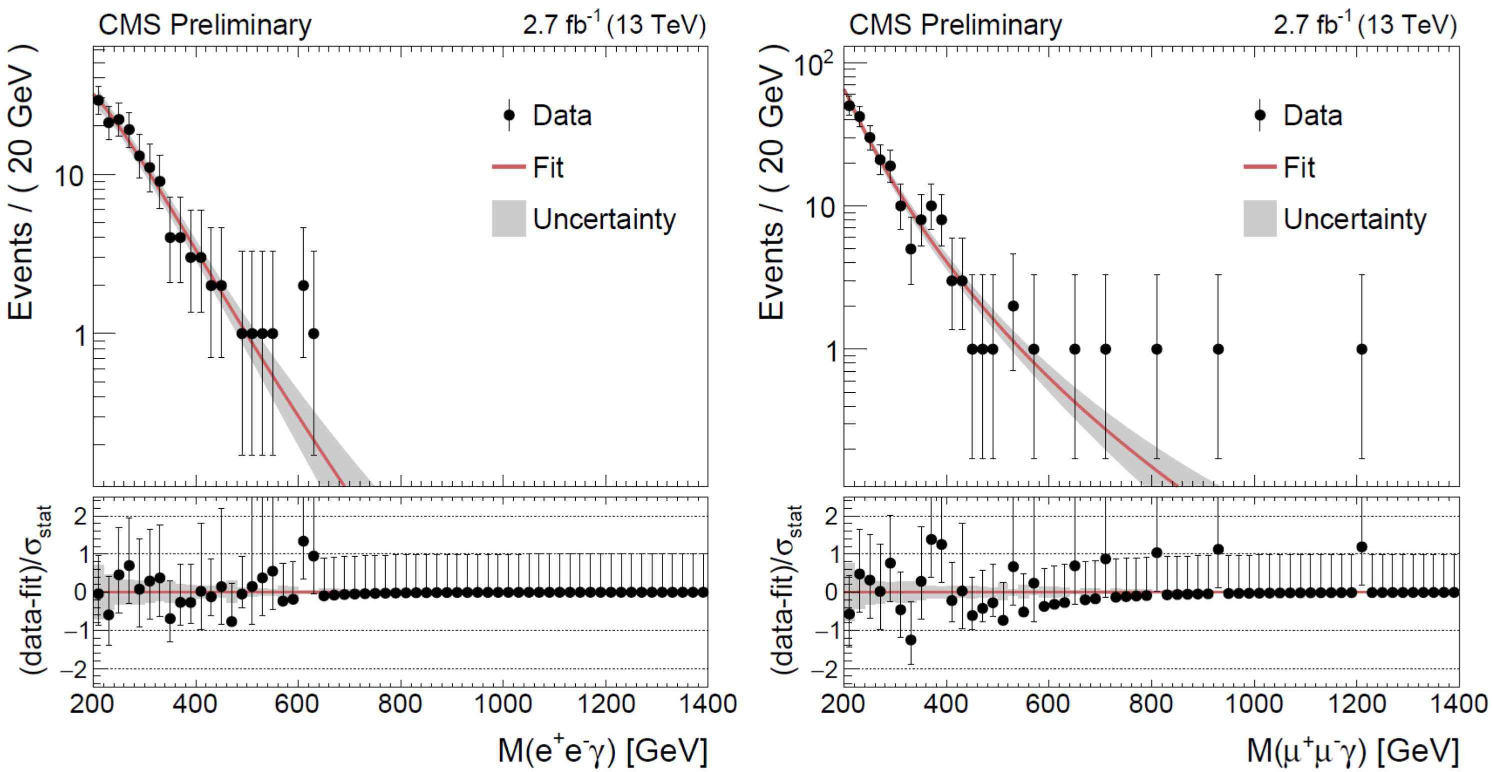
ATLAS $Z\gamma \rightarrow ee\gamma / \mu\mu\gamma / jj\gamma$

- No significant excess over the background-only hypothesis (largest deviation in m_X ~ 350 GeV at the level of 2 σ)
- The observed limits (narrow-width) are between ~8 and 260 fb





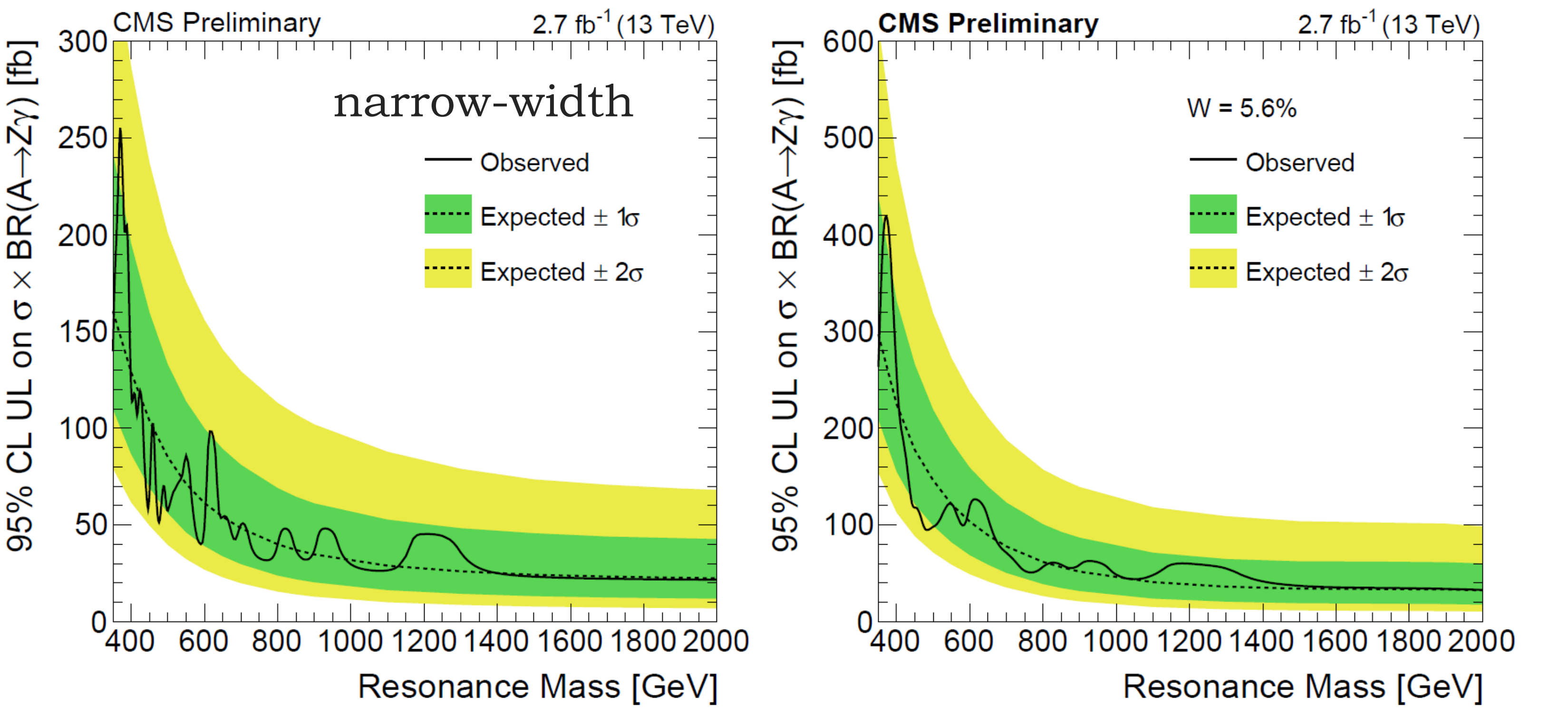
CMS $Z\gamma \rightarrow ee\gamma / \mu\mu\gamma$



- The photon is required to have a distance $\Delta R > 0.4$ from each of the two leptons, to minimize the effect of lepton FSR.
- The SM background is described by the function $f(m_{Z\gamma}) = m_{Z\gamma}^{a+b\log m_{Z\gamma}}$ with a fit on data events.

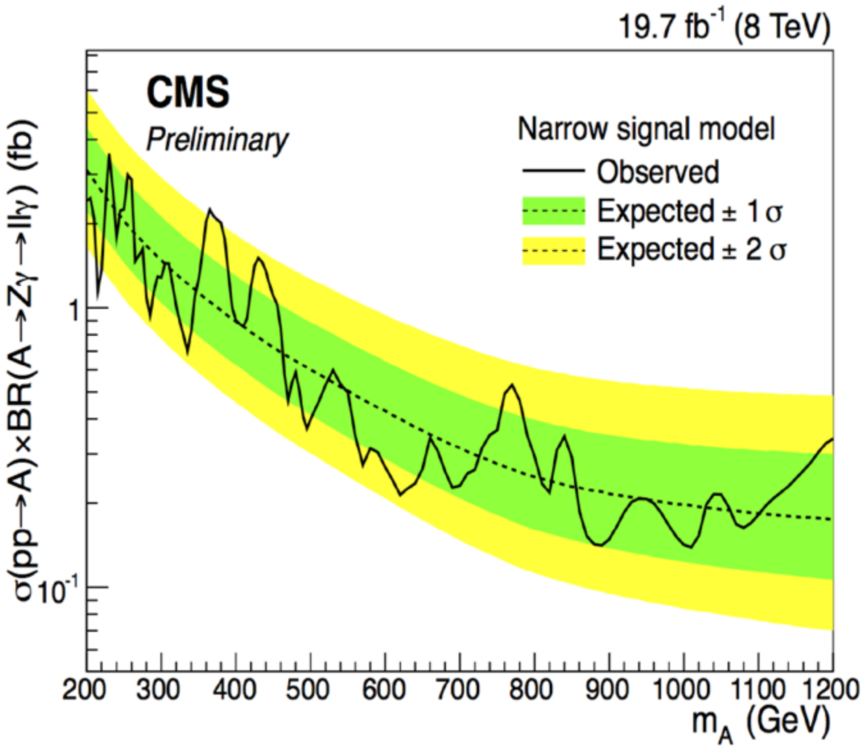
CMS $Z\gamma \rightarrow ee\gamma / \mu\mu\gamma$

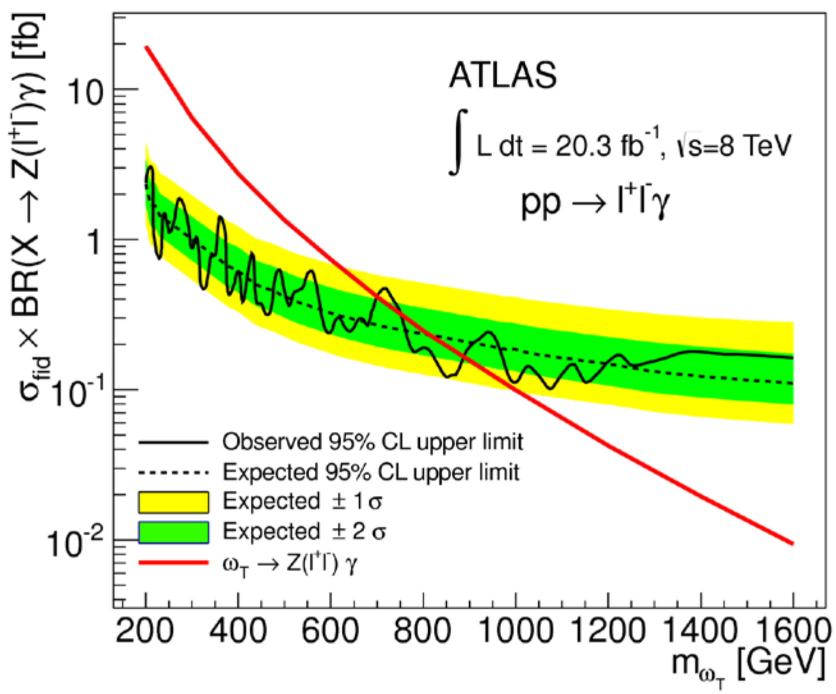
- No significant excess over the background-only hypothesis.
- The observed limits (narrow-width) are between ~20 and 250 fb



CMS and ATLAS results of Zγ→eeγ/μμγ @ 8 TeV

- No significant excess over the background-only hypothesis.
- The observed limits (on llγ) in the mass range 200 GeV – 1.2 TeV are between 0.1 and 3.8 fb





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Clouds will thin out with the next ~10 fb^{-1}