Search for new physics in high mass diphoton events in CMS

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Motivation

Fully reconstructed resonances: simplest way to discover new particles

Statistically significant peak over a smooth background
- ✓ experimentally robust
- ✓ small systematics
- ✓ difficult for unknown backgrounds to mimic

=> ***simple yet striking signature!***

The most important search method when new energies are explored
- ✓ particularly relevant at LHC Run2 startup
- ✓ model independent probe to new physics

Resonances in past discoveries

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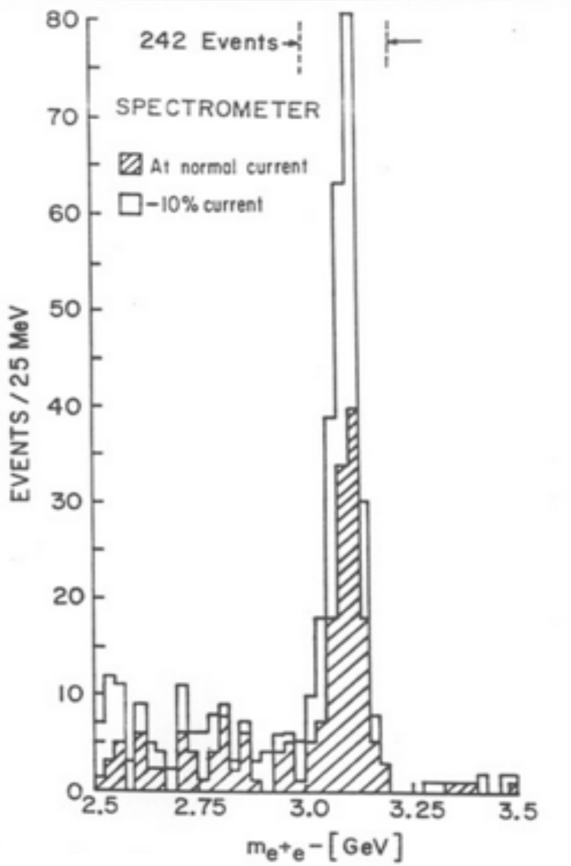
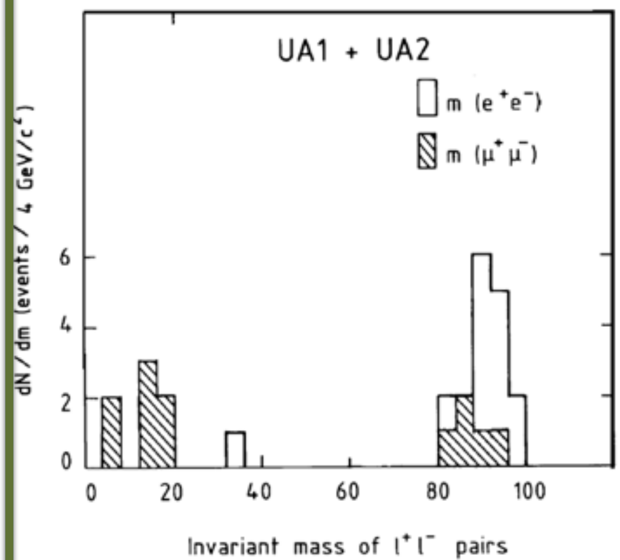
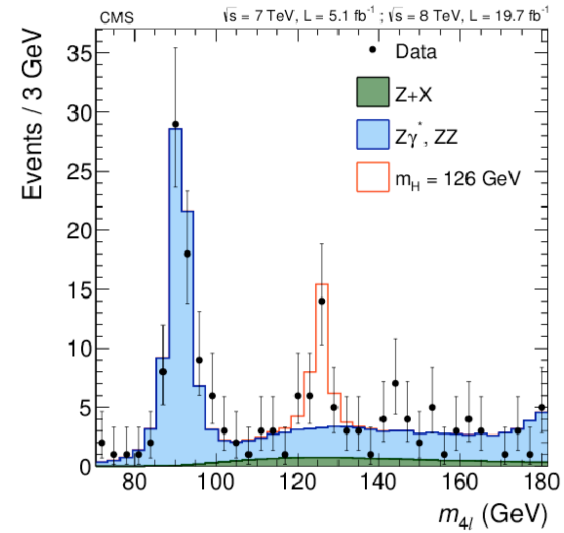


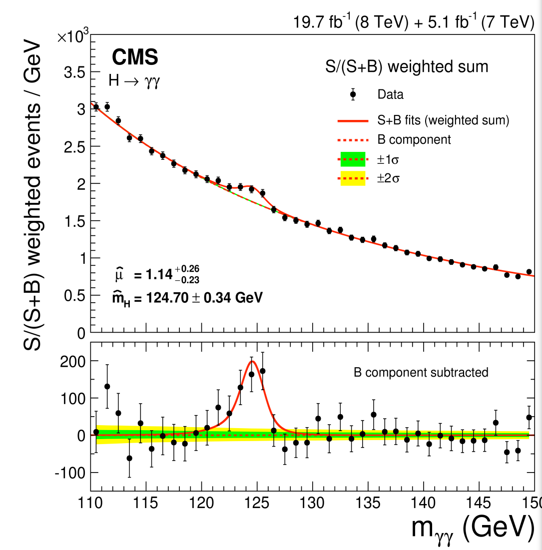
FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted owing that the peak is independent of spectrometer rrents. The run at reduced current was taken two nths later than the normal run.

J/Psi



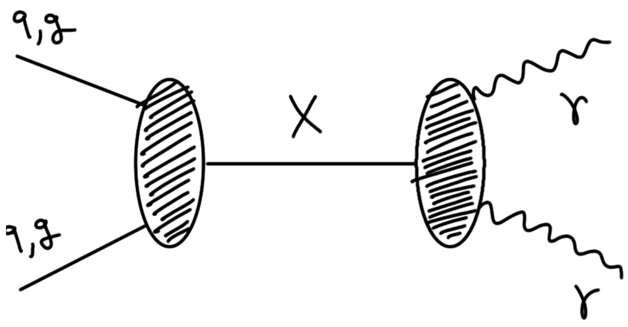
Z





Higgs

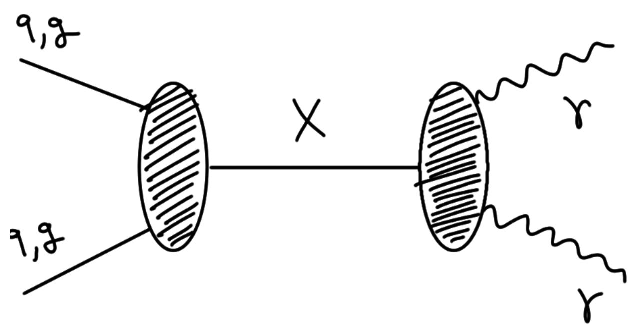
Diphoton bump search



Clean final state at hadron colliders

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

Diphoton bump search



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1) Define the event selection: 2 isolated photons
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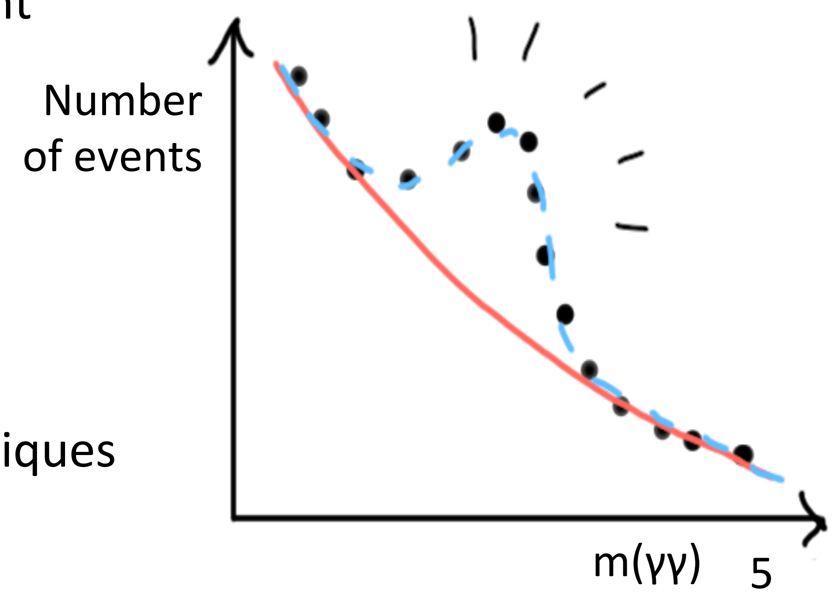
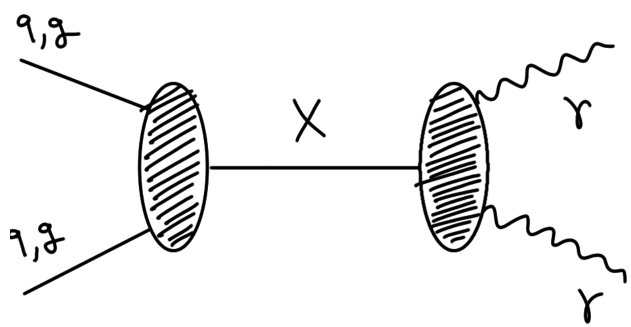
2) Reconstruct the γγ invariant mass

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

- ✓ photon reconstruction
- ✓ detector resolution and scale
- ✓ dedicated vertex identification techniques



Diphoton bump search



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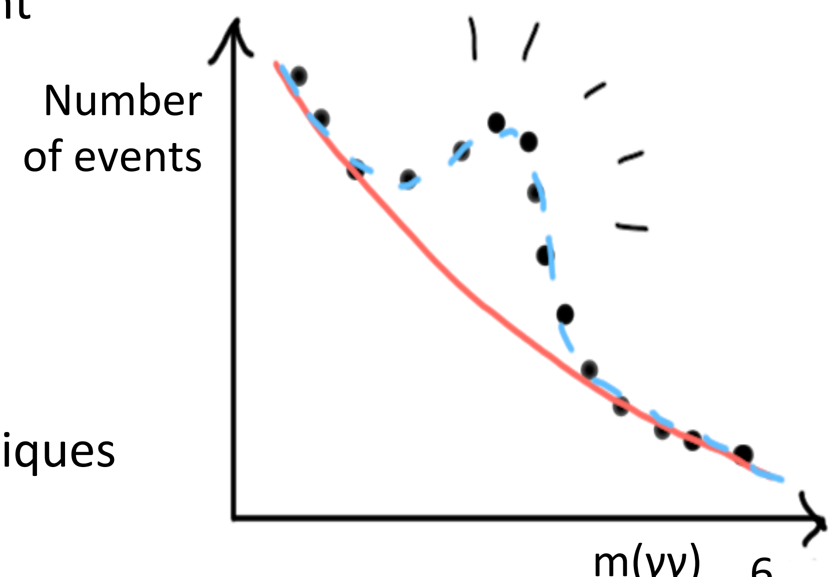
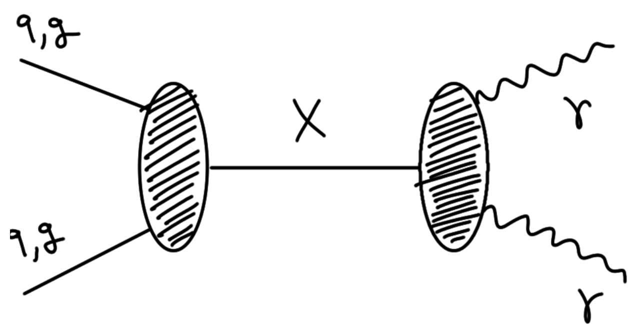


3) Signal extraction

Diphoton bump search



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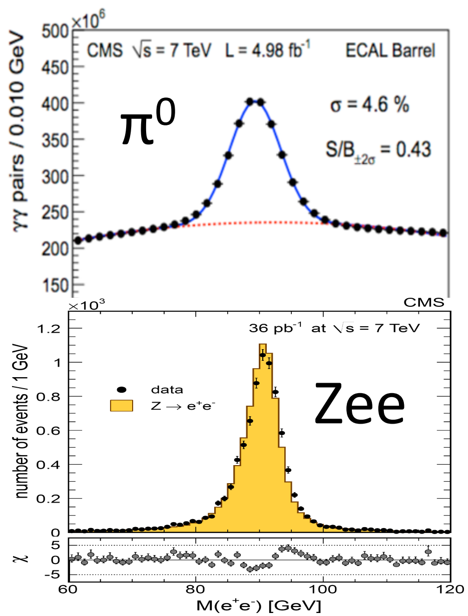
✓ detector resolution and scale
✓ dedicated vertex identification techniques

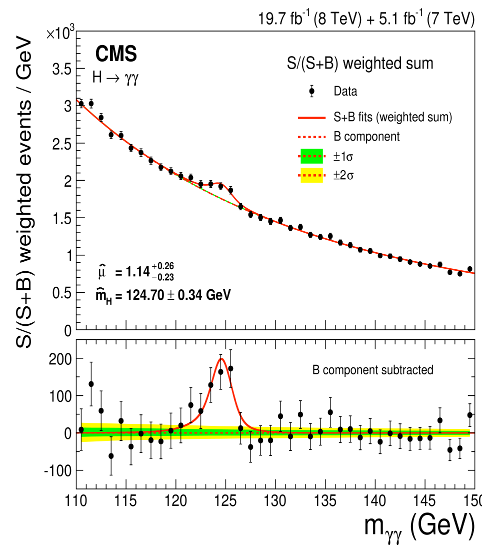
Crucial expertise in reconstruction and detector

3) Signal extraction

Diphoton search roadmap

<=2009	2010	2011/2012	now
R&D on ECAL elements. Construction and commissioning	First checks and measurements with candles	Searching for the "expected": Higgs	Searching for unexpected





?

Leading contribution of Roma CMS group to all these aspects

CMS Electromagnetic calorimeter

Homogeneous lead tungstate crystal calorimeter

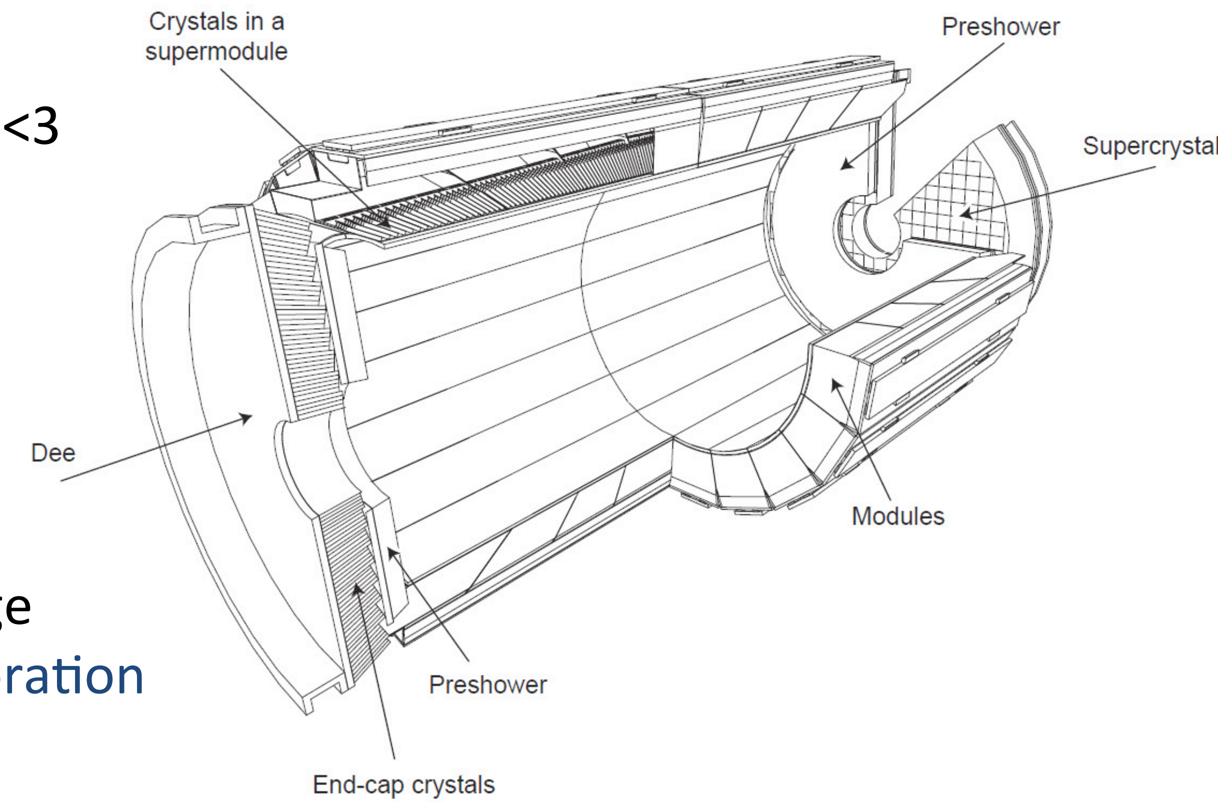
- 75848 $PbWO_4$ crystals
- Barrel (EB): |η|<1.48
- Endcaps (EE): 1.48<|η|<3

Design energy resolution:
~0.5% for E(γ)>100GeV

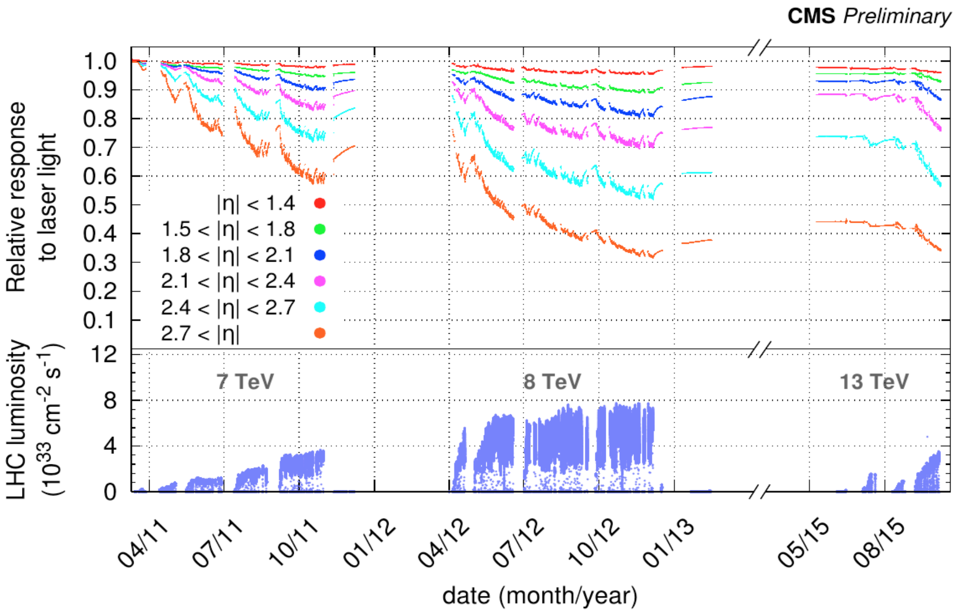
Critical issues:

✓ Transparency loss
due to radiation damage

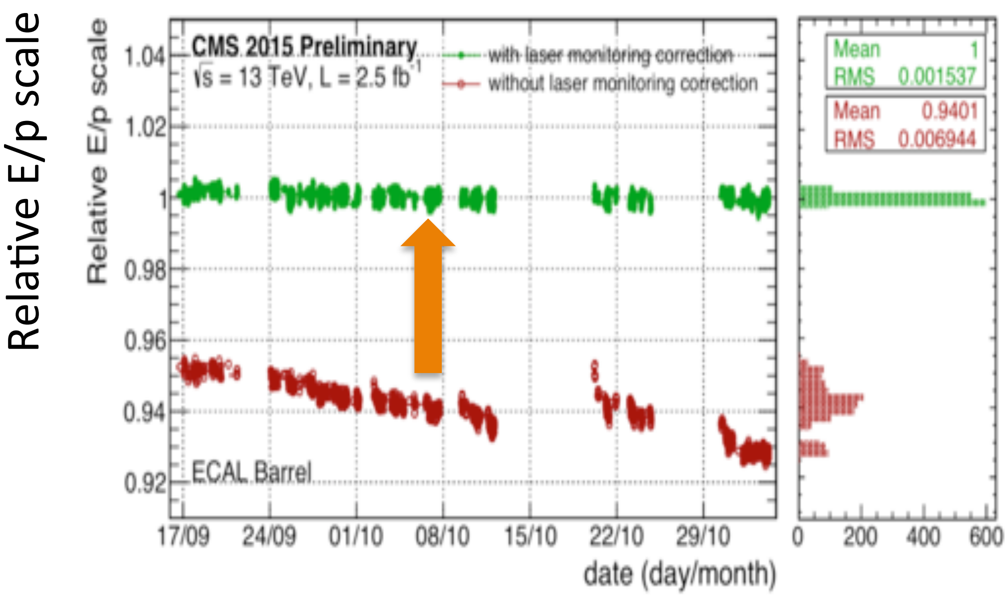
✓ Precision of in-situ calibration



Crystal transparency



Relative crystals response to laser light vs time



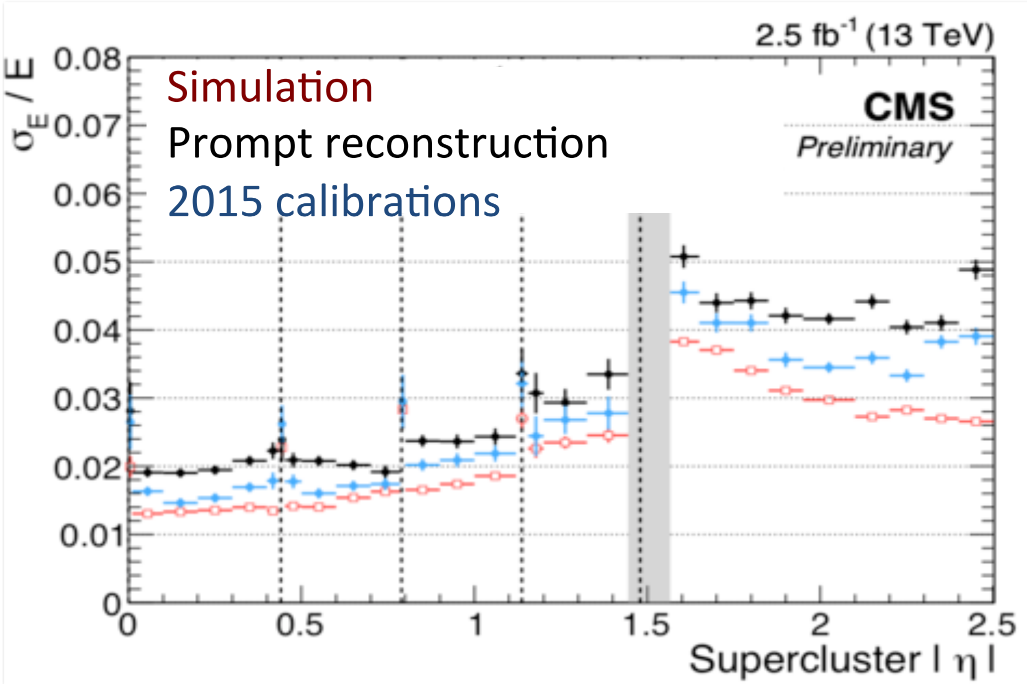
Stable energy scale achieved after laser corrections ***in prompt reconstruction***

Barrel:

✓ average signal loss ~6%

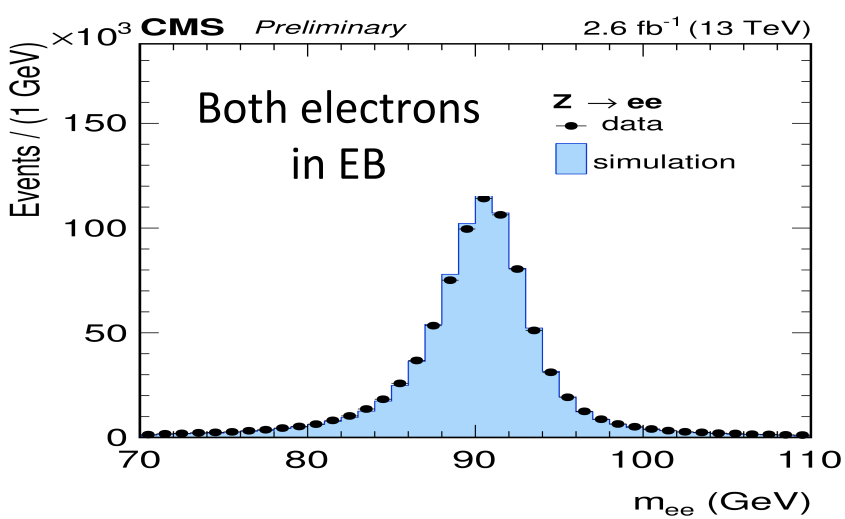
✓ RMS stability ~0.15%

Energy scale and resolution



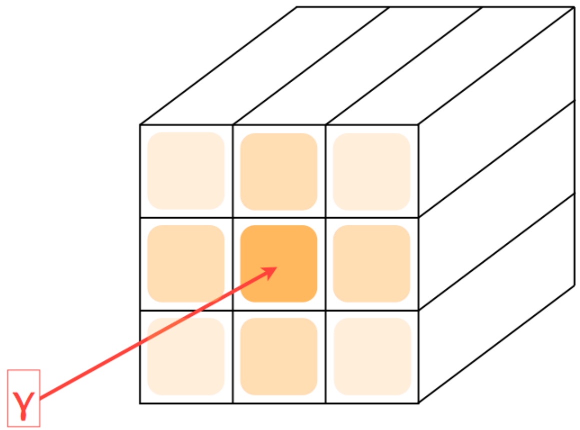
Prompt reconstruction used for the analysis.
New calibration coefficients (2015 data) available.

Significant improvement in energy resolution with new calibrations:
- ✓ barrel: resolution ~Run1
- ✓ endcaps: still worse (statistical precision)

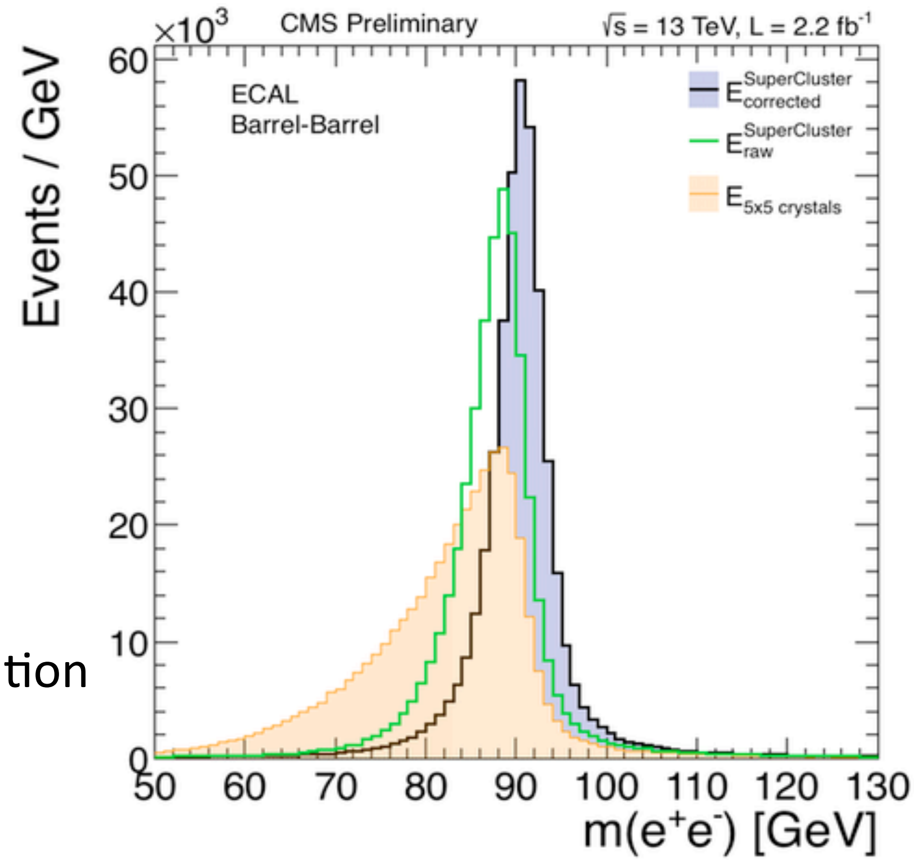


Energy scale and resolution checked in data => analysis-level corrections applied

Photons



Photon =
energy deposits in clusters of ECAL crystals
✓ clustering optimized to have good resolution



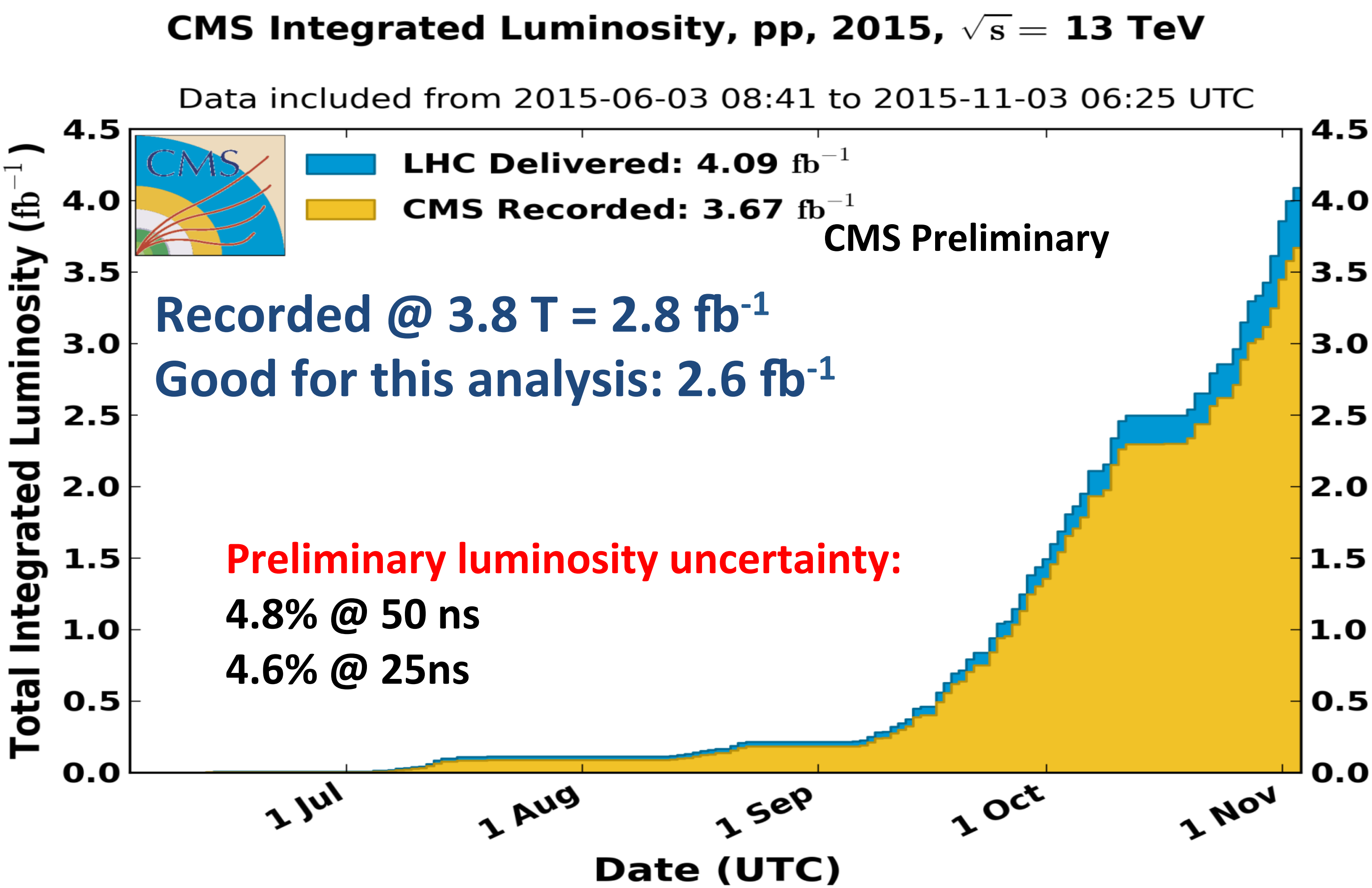
Reconstruction and selection strategies:
✓ tuned on simulation and validated in data
✓ main control samples: Z->ee and Z->μμγ

High mass diphoton searches

Ref	Title	M_X [GeV]	√s [TeV]
CMS-PAS-EXO-15-004	Search for new physics in high mass diphoton events in proton-proton collisions at √s = 13 TeV	500-4500	13
PLB750 (2015) 494–519	Search for diphoton resonances in the mass range from 150 to 850 GeV in pp collisions at √s = 8 TeV	150-850	8
CMS-PAS-EXO-12-045	Search for high-mass diphoton resonances in pp collisions at √s = 8 TeV with the CMS Detector	500-3000	8

Leading contribution from INFN Roma group

CMS operation @ 13TeV



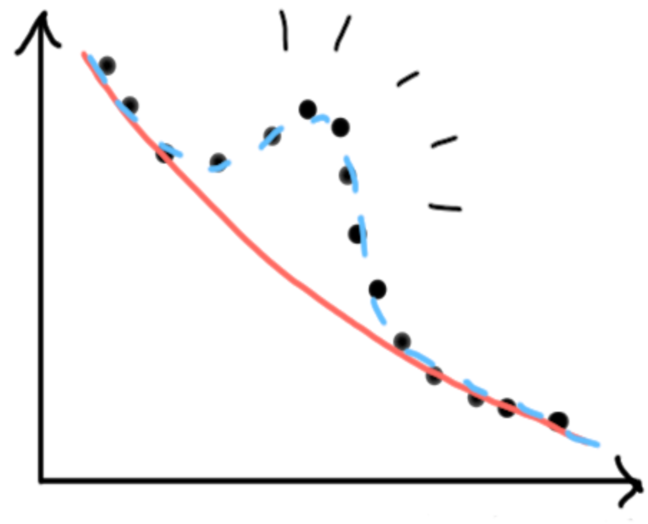
- ✓ 2015 operations strongly affected by a contamination of the magnet cold box
- ✓ Thanks to the effort of many, *~¾ of delivered luminosity collected with full B field*

Analysis in a nutshell

1) Define the event selection: 2 isolated photons

2) Reconstruct the γγ invariant mass:

3) Signal extraction



Some considerations:

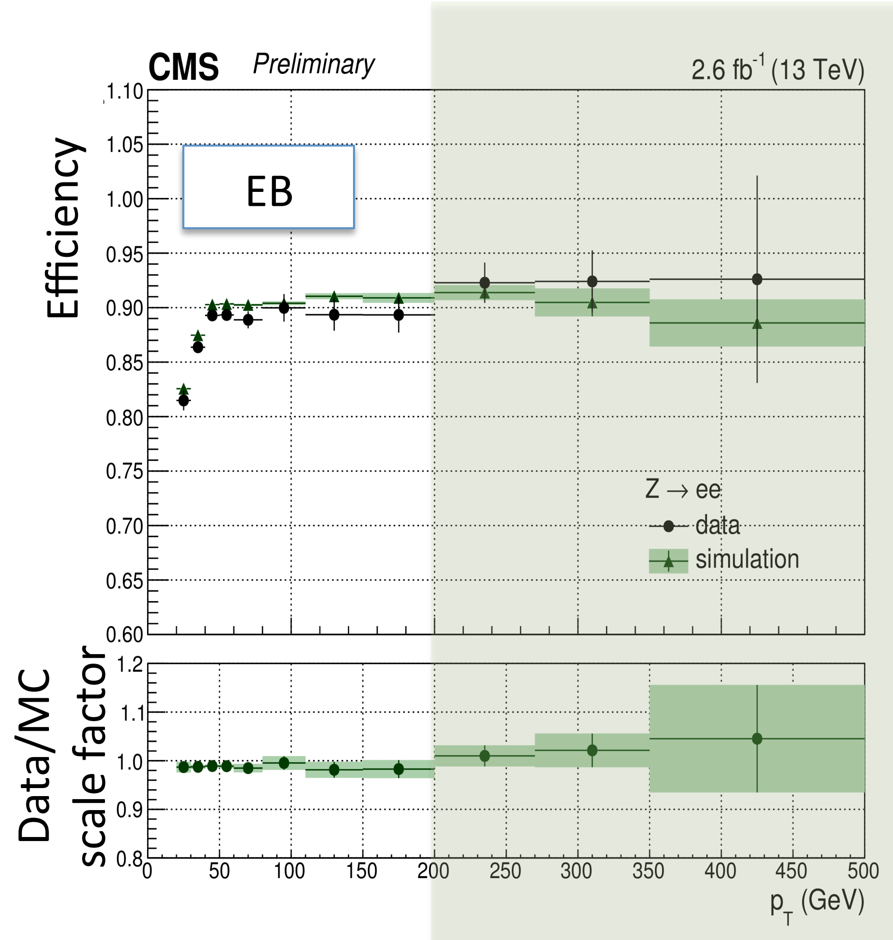
- ✓ *Analysis built on SM Higgs search experience*
  - ✓ *same techniques used*
- ✓ *Only solid techniques exploited*
  - ✓ *nothing very fancy for this first round*
- ✓ *Selection developed before looking to the data:*
  - ✓ *fully blind analysis*

=> Goal: have a robust analysis up to high p_T

Event selection

Simple event selection

- ✓ HLT: 2 photons, p_T>60 GeV
- ✓ Offline selection:
  - ✓ p_T > 75GeV
  - ✓ ECAL fiducial region
  - ✓ dedicated photon selection
- ✓ 2 event categories:
  - ✓ EBEB: both γ in the barrel
  - ✓ EBEE: one γ in EB, one in EE
  - ✓ events with 2γ in EE discarded



Zee to check efficiencies

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

Zee and high mass DY to check scale and resolution

- ✓ results compatible within 0.5%

Signal modelling

Benchmark model: spin2 RS Graviton

- ✓ two parameters: mass and effective coupling

Mass range: 500-4500GeV

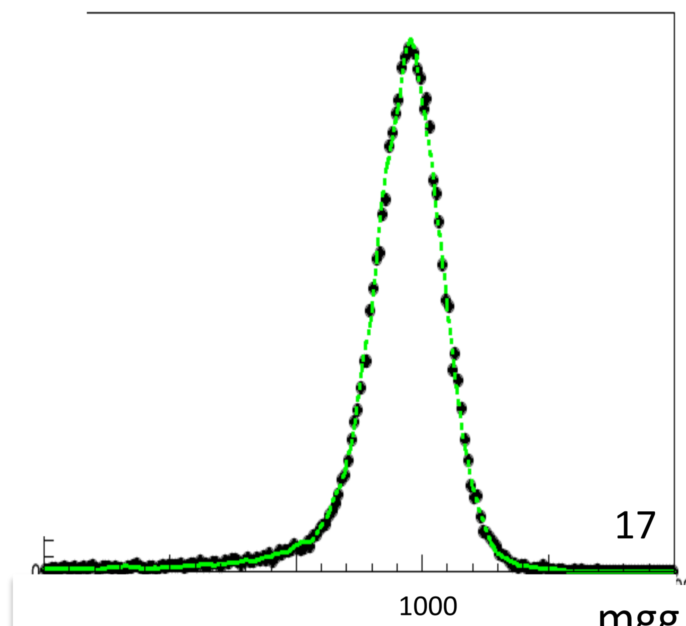
Effective couplings: k=0.01 -> k=0.2

- ✓ $\Gamma_G / m_G = 1.4\ k^2$ ==> $k=0.2 = \Gamma_G / m_G \sim 6\%$
- ✓ ***chosen a priori***

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

- ✓ convolution of gen-level mass shape (PYTHIA) and detector resolution

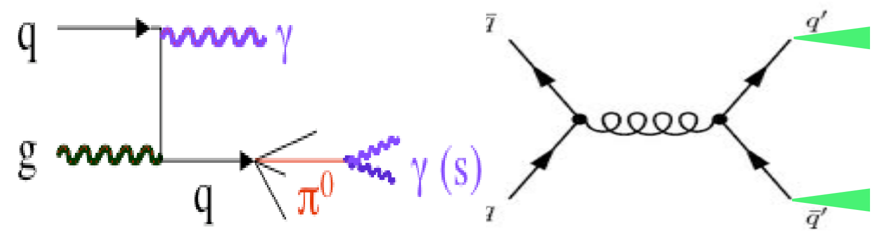
m_G (GeV)	category	$\tilde{\kappa}$	FWHM (GeV)	$\tilde{\kappa}$	FWHM (GeV)
500	EBEB	0.01	14	0.2	36
500	EBEE	0.01	22	0.2	42
1000	EBEB	0.01	27	0.2	74
1000	EBEE	0.01	43	0.2	85

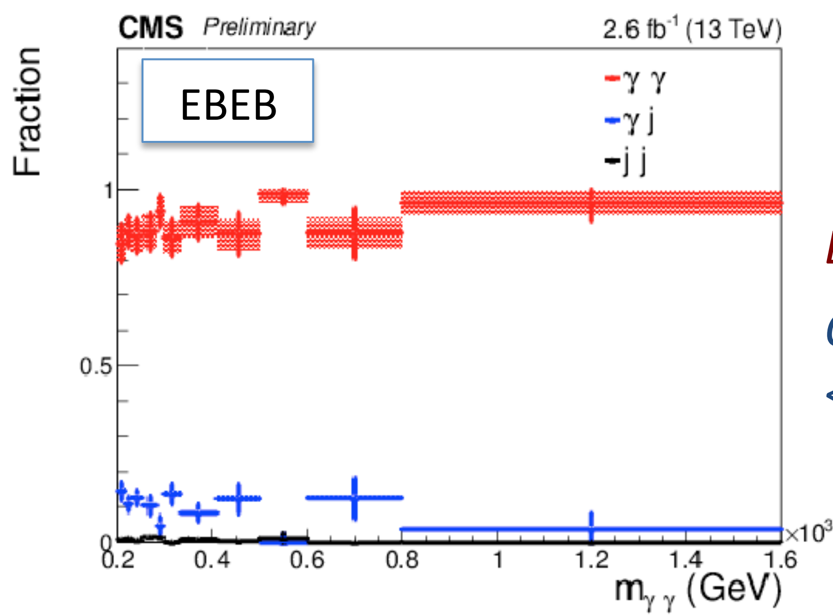


Backgrounds

Direct γγ SM production, irreducible

Dijet and γ+jet production, reducible





Dominant contribution: 2 prompt photons

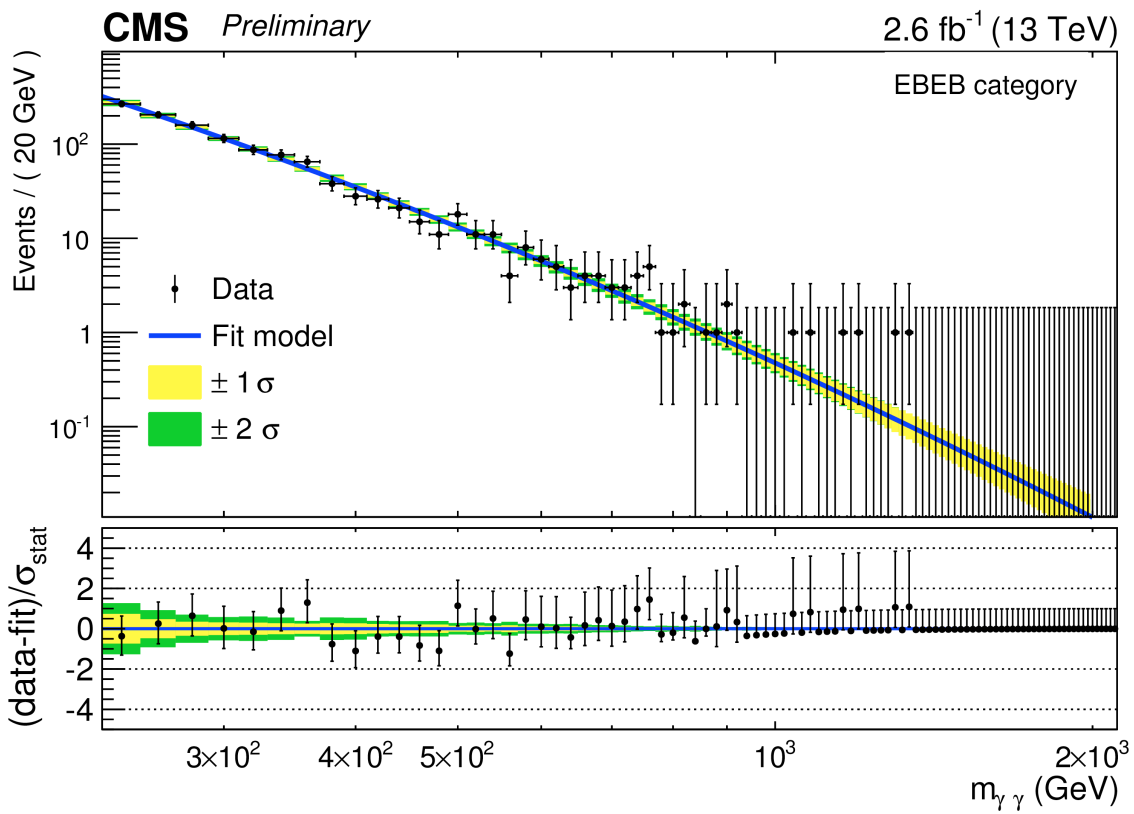
QCD and photon+jets:
<10% (20%) in EBEB (EBEE)

Background modelling

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

✓ parametric fit to data $$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$$

✓ model coefficients: nuisance parameters in the hypothesis test



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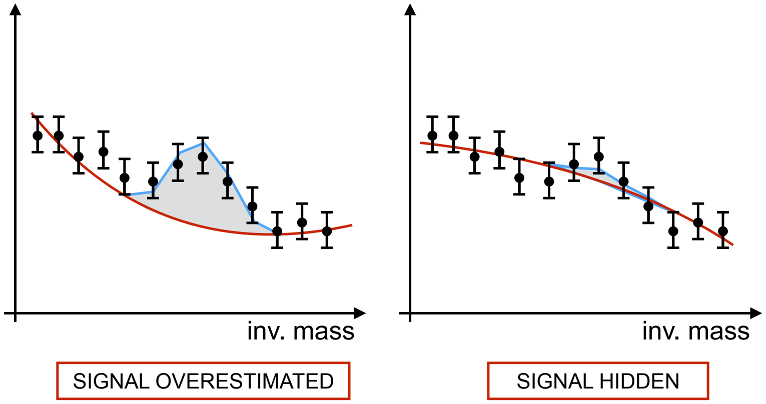
✓ model coefficients: nuisance parameters in the hypothesis test

Background fit accuracy determined using MC

✓ possible mis-modelling:
<1/2 background statistical uncertainty

✓ extra uncertainty:
signal-like component added to the model



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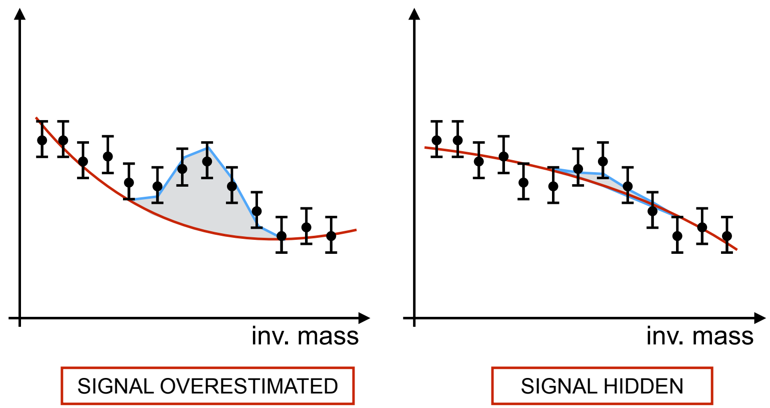
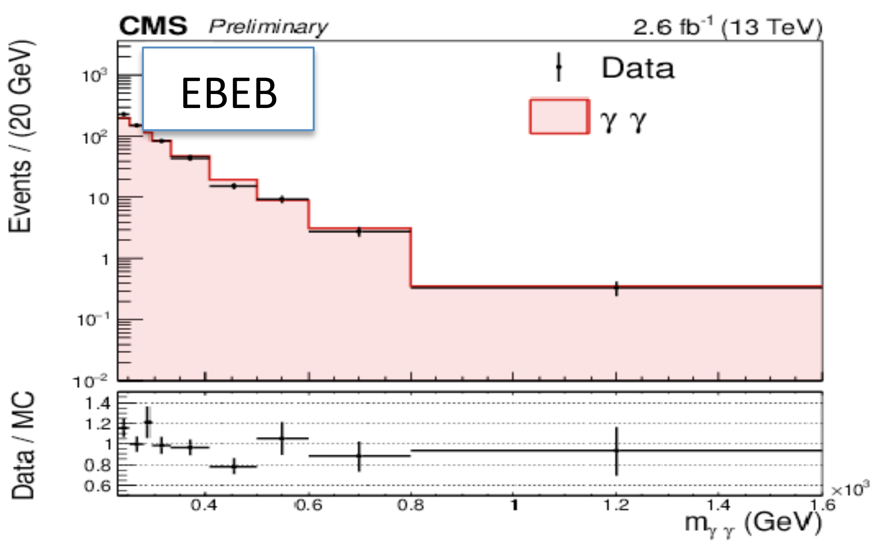
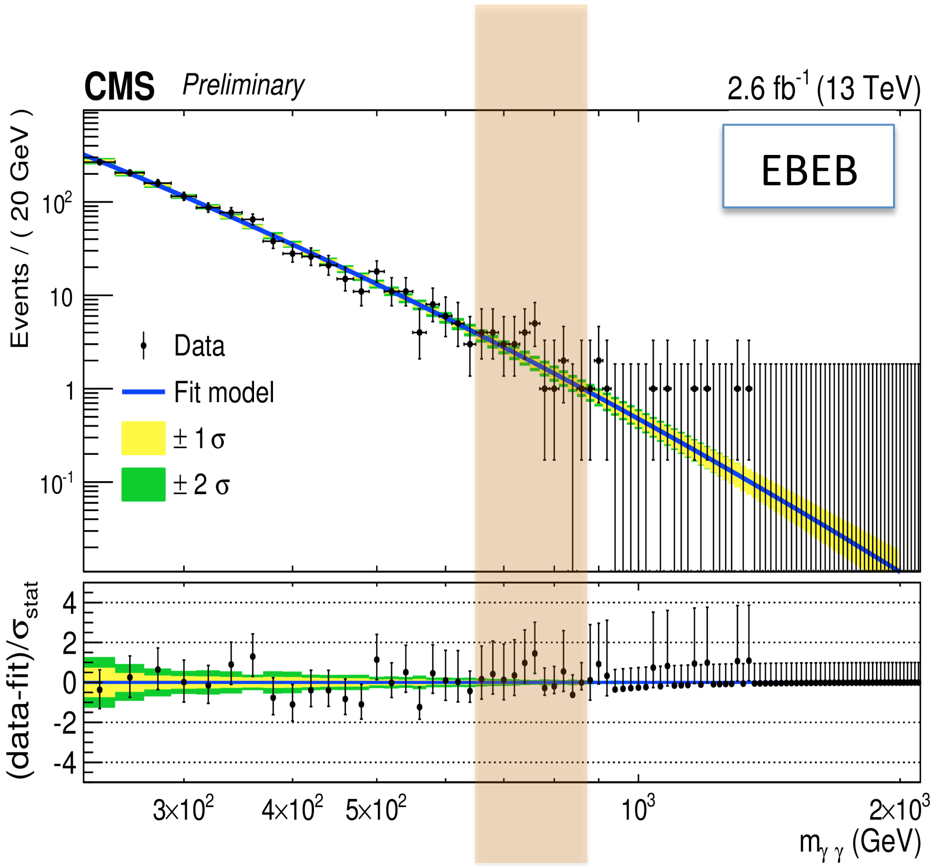
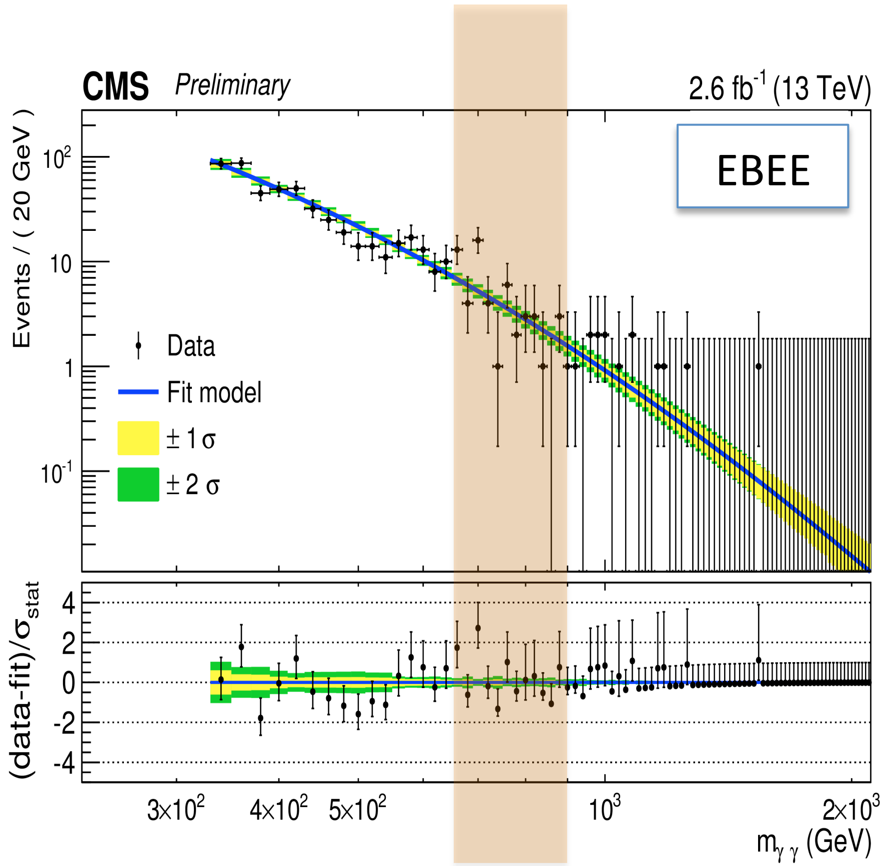




Can we trust MC for the bias study?
Yes! Background under control

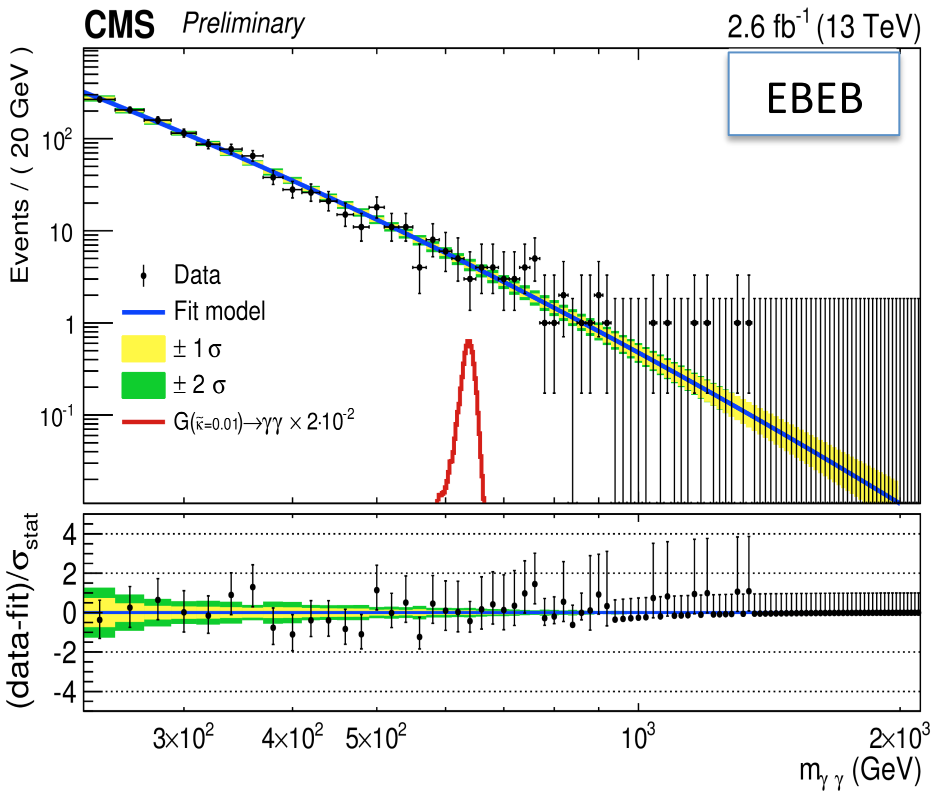
Mass spectra

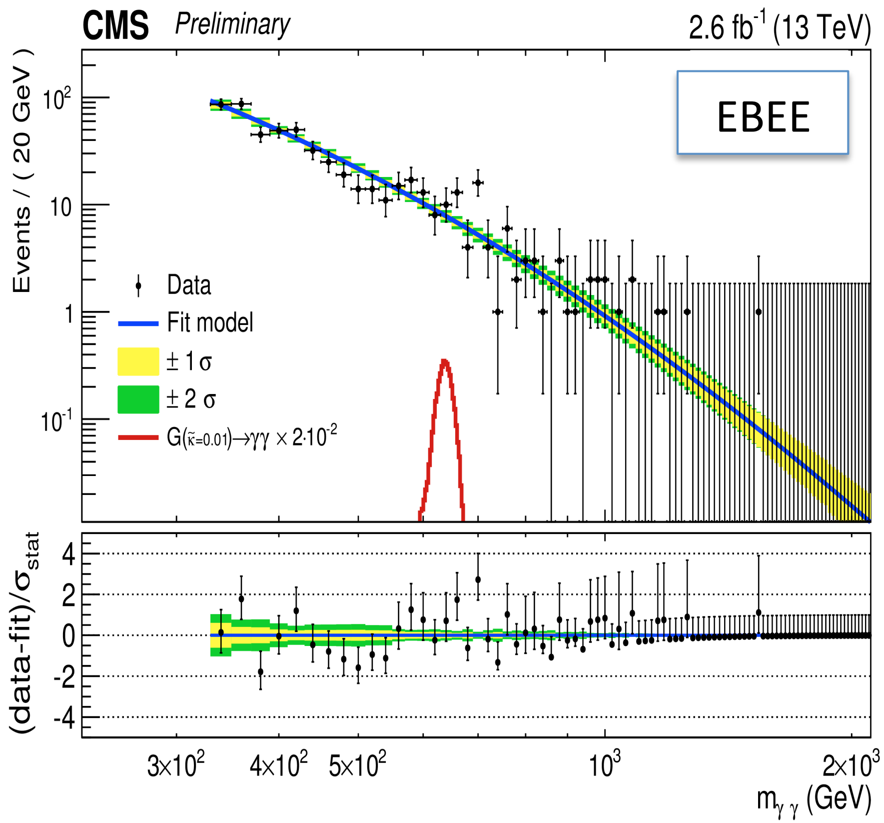




Selected events $m_{\gamma\gamma}$ spectra in the two categories

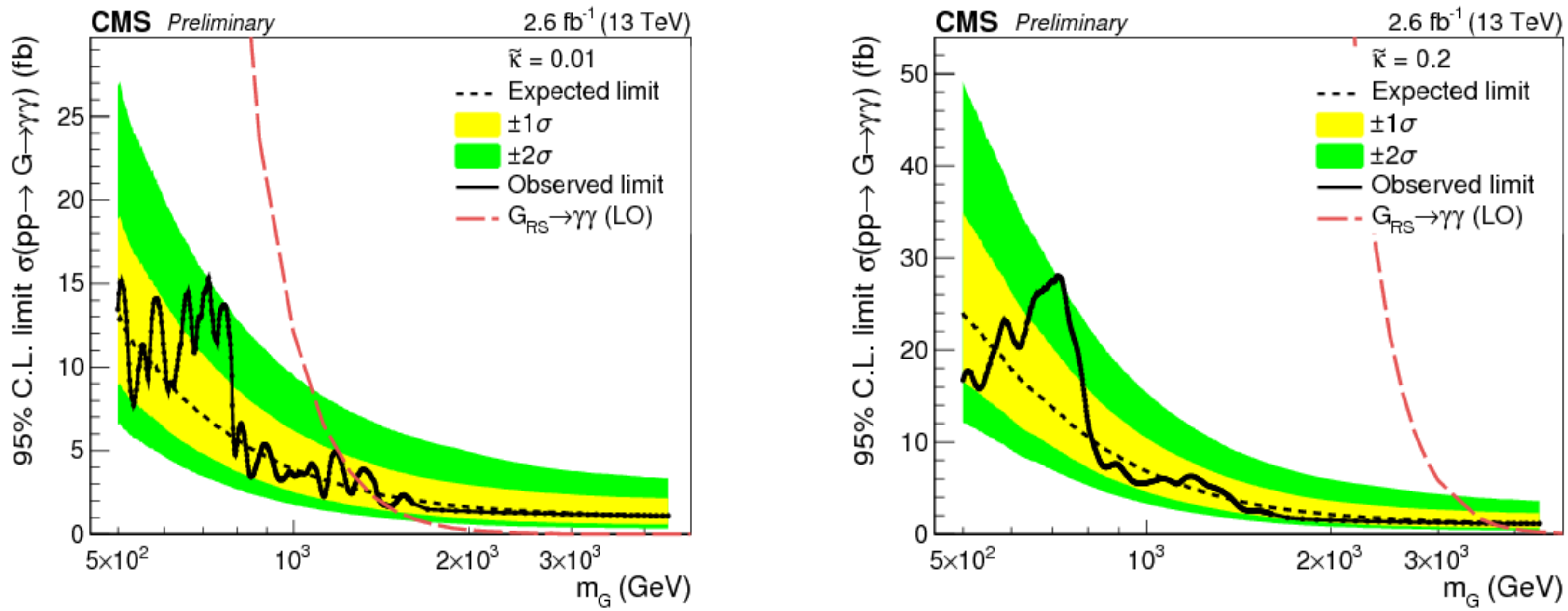
Mass spectra





Selected events $m_{\gamma\gamma}$ spectra in the two categories
Signal m=650GeV, k=0.01

Interpretation: exclusion limits



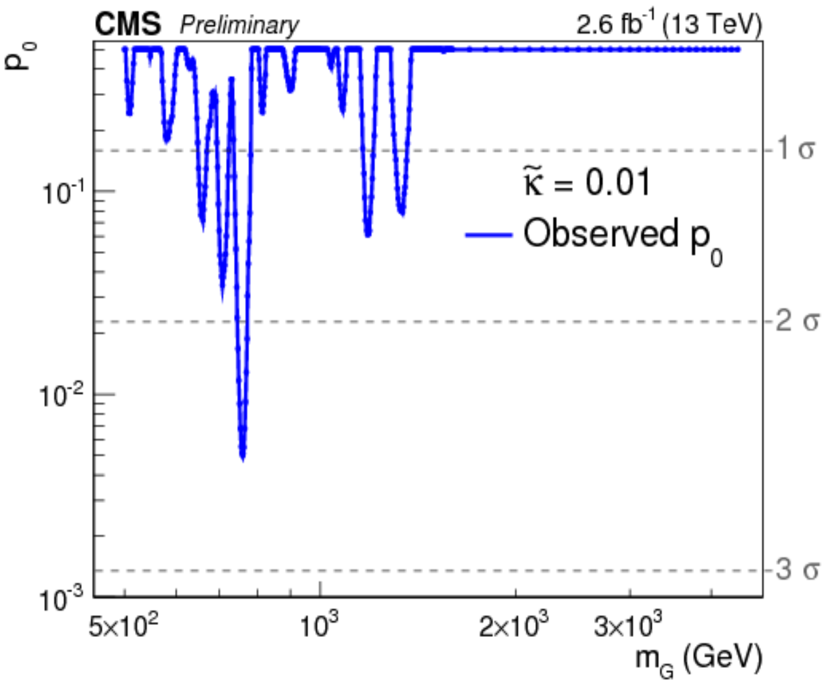
Narrow-width

$\Gamma_G / m_G \sim 6\%$

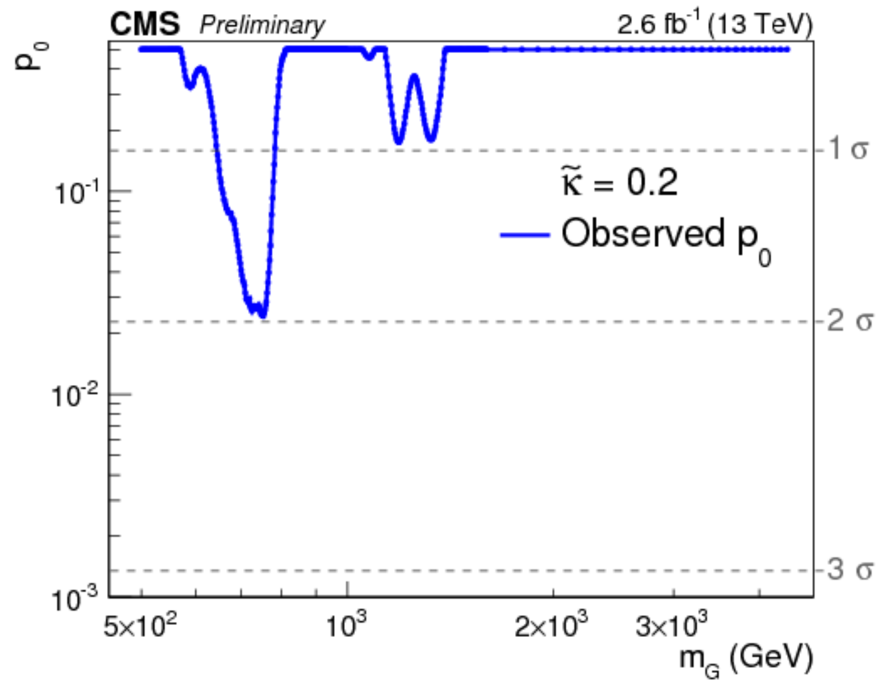
Expected and observed limits on Graviton cross section x diphoton BR:

- ✓ m_G < 1.3/3.8 TeV excluded (k = 0.01/0.2)
- ✓ Excluded range in agreement with expectations
- ✓ Observed limit deviation from expected due to excess in data

Interpretation: pValue



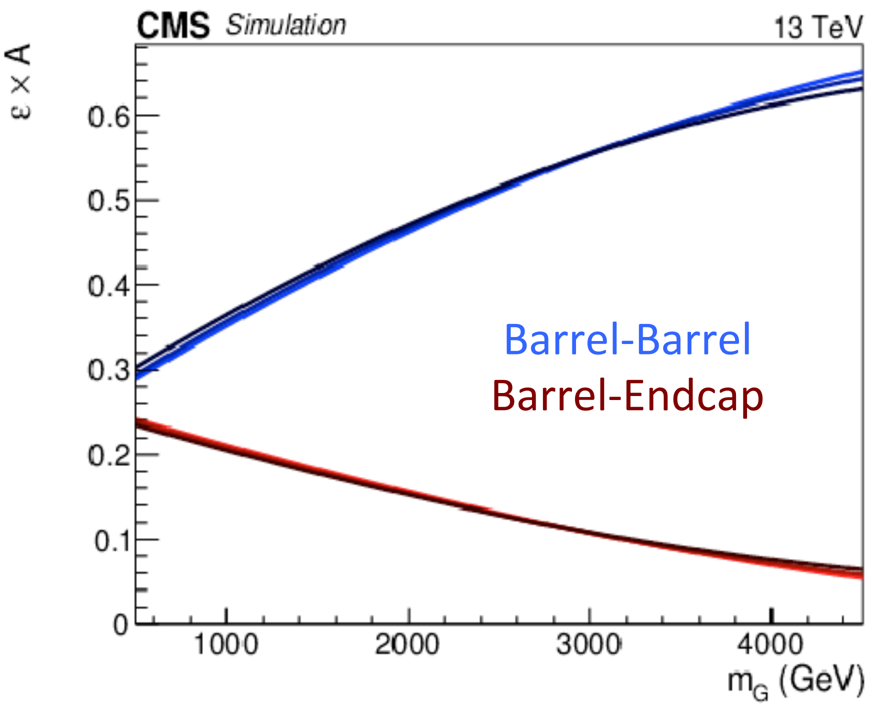
Narrow-width

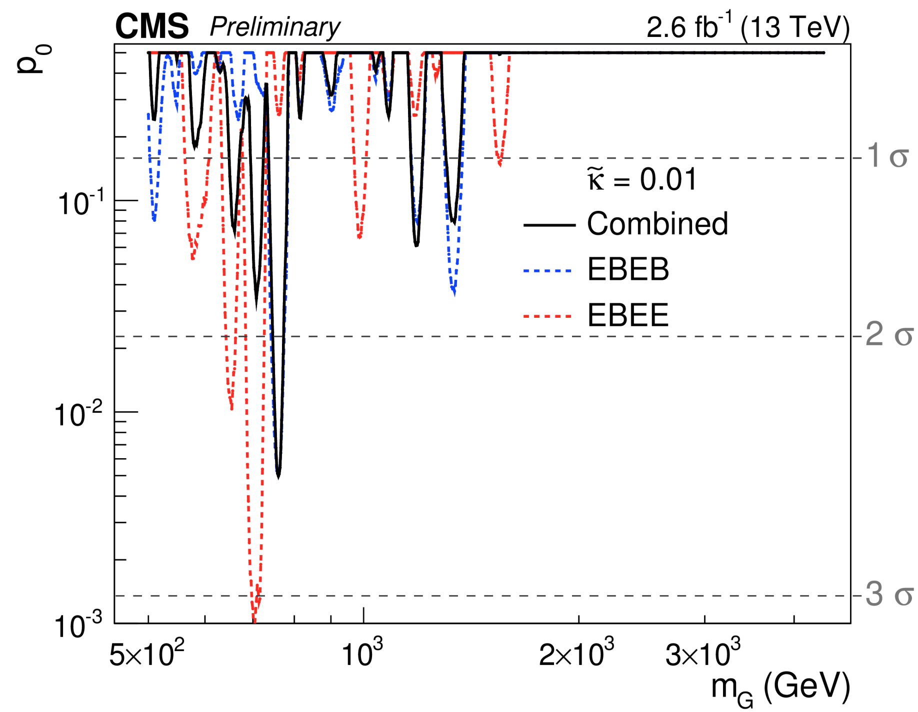


Γ_G / m_G ~ 6%

- ✓ **Largest excess for m_G=760GeV in the narrow width hypothesis**
- ✓ Local significance 2.6σ
  - ✓ significance reduced to 1.2σ when accounting for Look Elsewhere Effect in m_G
  - ✓ LEE in k further decreases significance

Analysis categories





Overall efficiency x acceptance ~55% for RSG at 600GeV

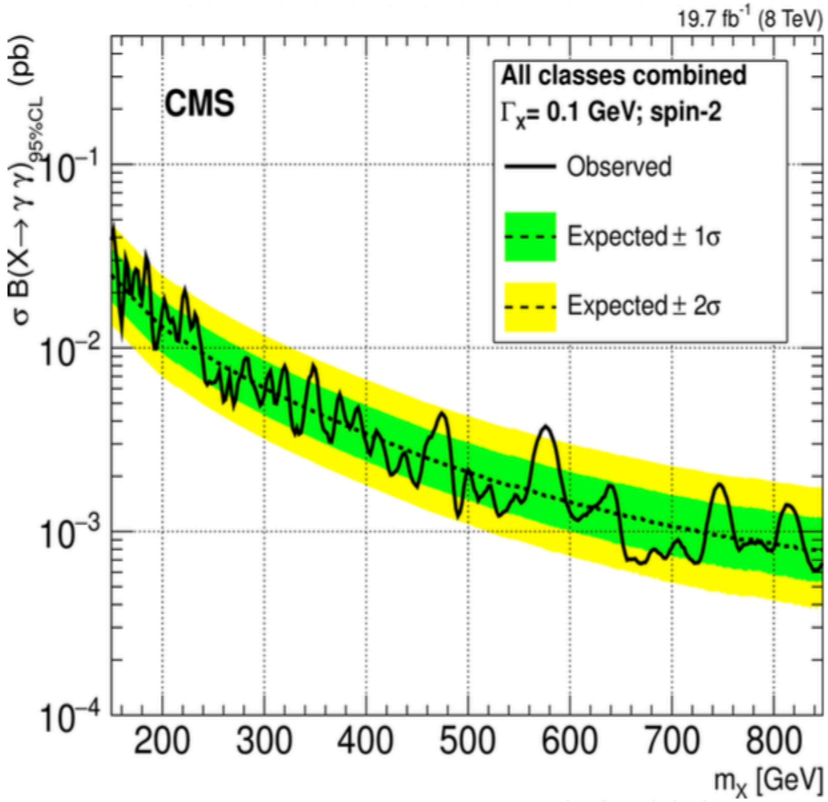
Fraction of EBEE events: 10 to 45%

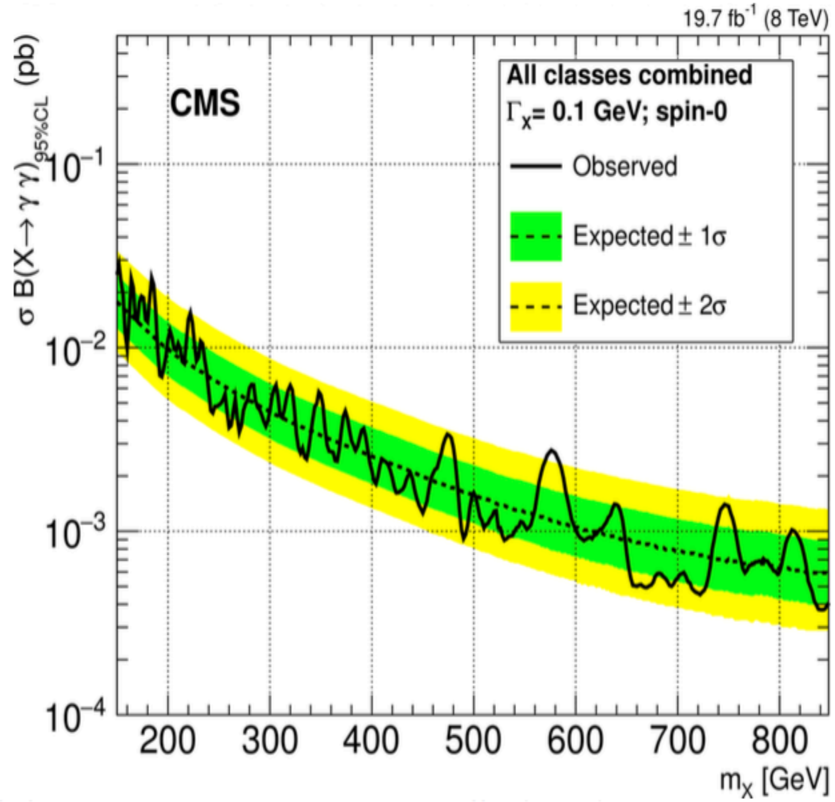
10-15% improvement from adding the barrel-endcap category

Excess at 760GeV mostly in barrel

Spin hypothesis

Spin2 vs spin0: different acceptance and categories weight
but **analysis not much sensitive to these differences**



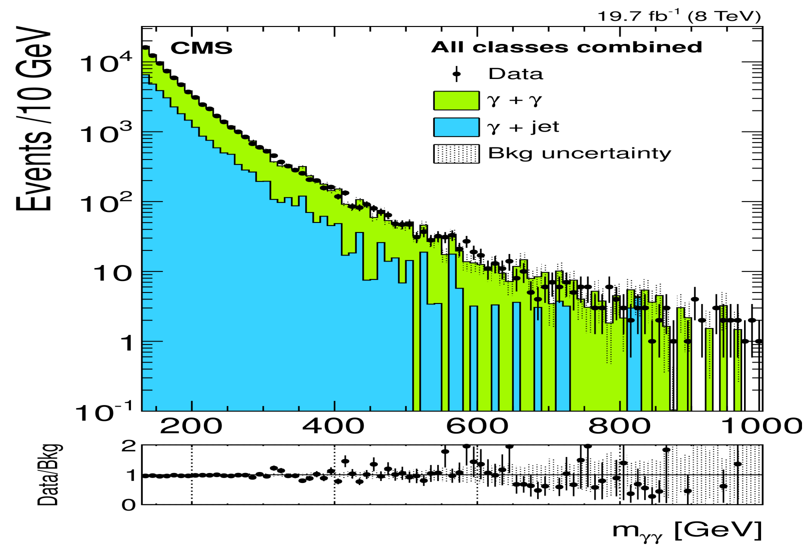


8TeV analysis: limit shape is quite similar

Comparison to 8TeV search

Combination with 8TeV results
in narrow width hypothesis

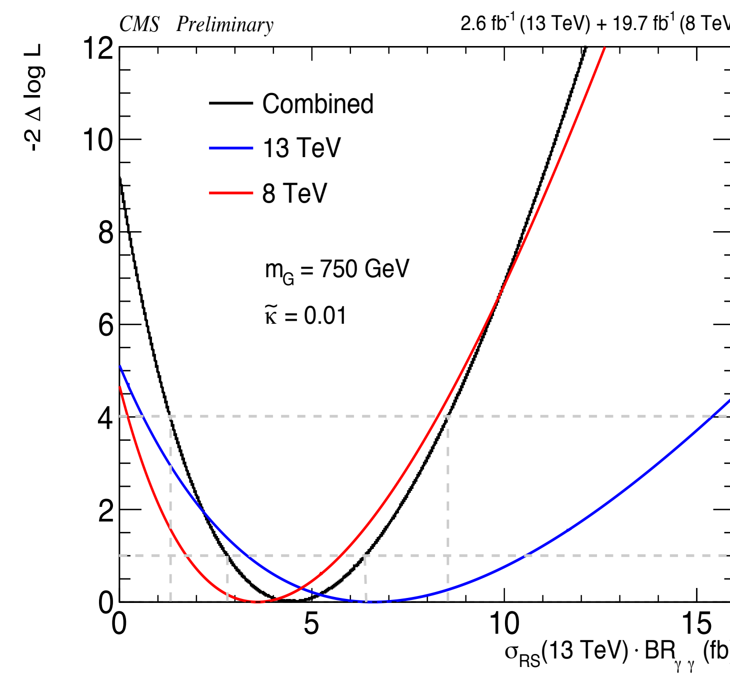
- ✓ different acceptance and categorizations
- ✓ most sensitive 8TeV analysis in each mass range considered



Likelihood of fits to S+B hypothesis
vs 13TeV equivalent cross-section:

- ✓ 8TeV limits scaled by xsec ratio
- ✓ S=RS Graviton, m_G=750GeV, k=0.01
  - ✓ production: 90% gg, 10% qqbar
  - ✓ xsec(8TeV)/xsec(13TeV)=1/4.2=0.24

Compatible equivalent cross-sections within uncertainties
13TeV result not in contradiction with 8TeV

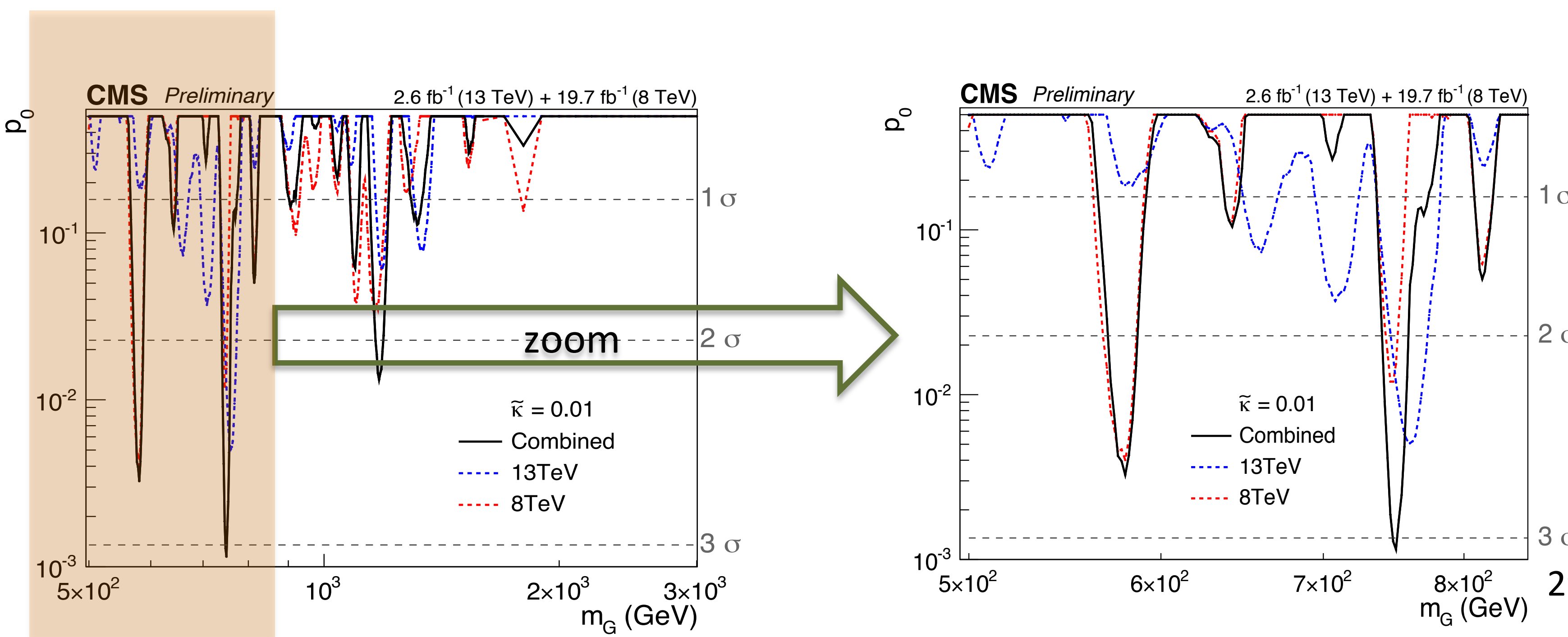


8-13 TeV combination

m_G<~1.5TeV: combined limits 20-30% better than single inputs

Largest excess for m_G=750GeV

- ✓ local significance ~3σ
- ✓ reduced to <1.7σ accounting for LEE



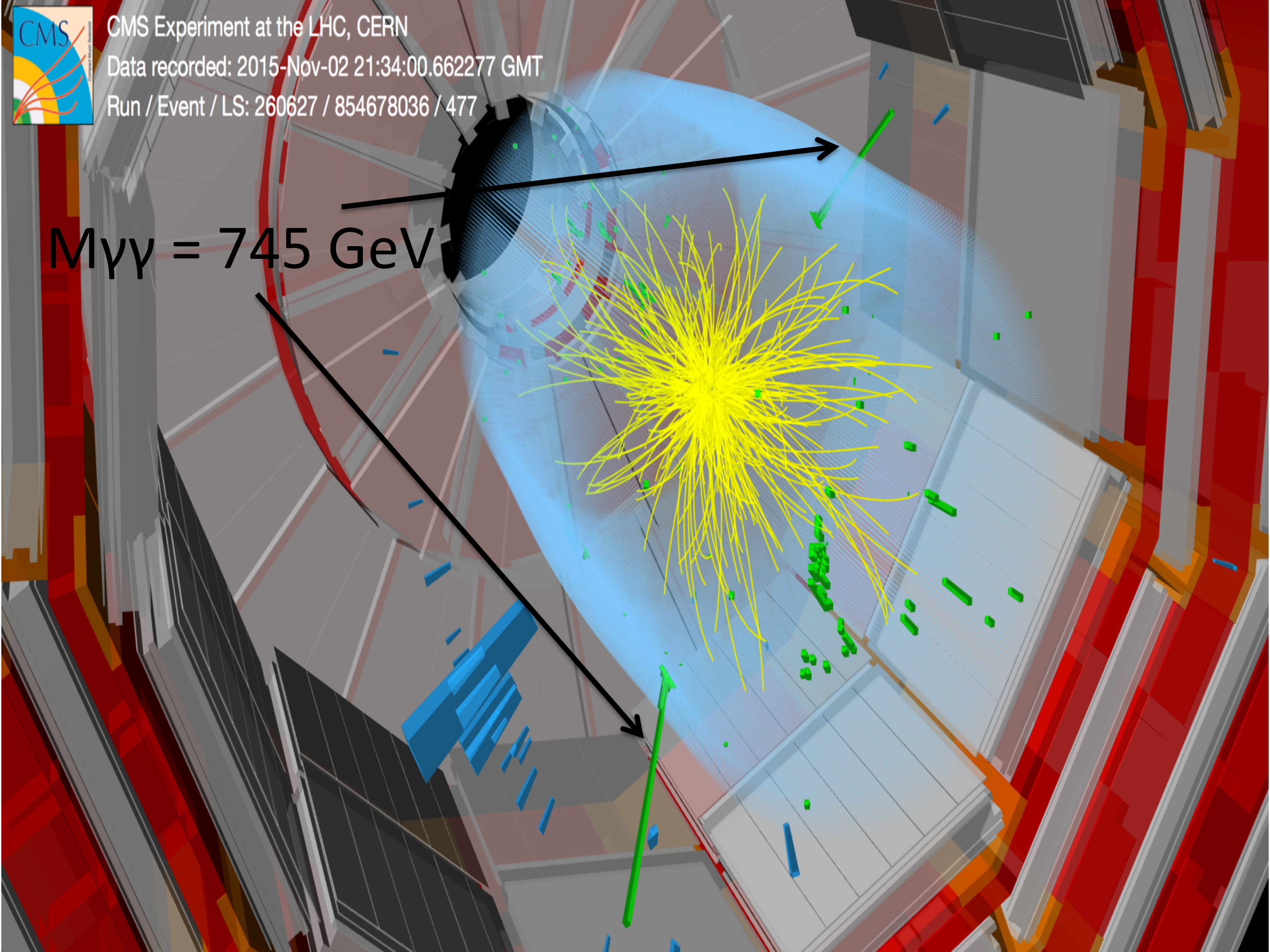
Outlook

- ✓ Observed diphoton mass spectrum **in agreement with Standard Model expectations**
- ✓ Strongest constraint on production cross-section set
- ✓ **Modest excess for mass ~760GeV assuming narrow width signal**
  - ✓ local significance of 2.6σ
  - ✓ global significance of <1.2σ
  - ✓ still consistent with 8TeV search

More data needed to determine the origin of the excess:
statistical fluctuation or manifestation of new physics

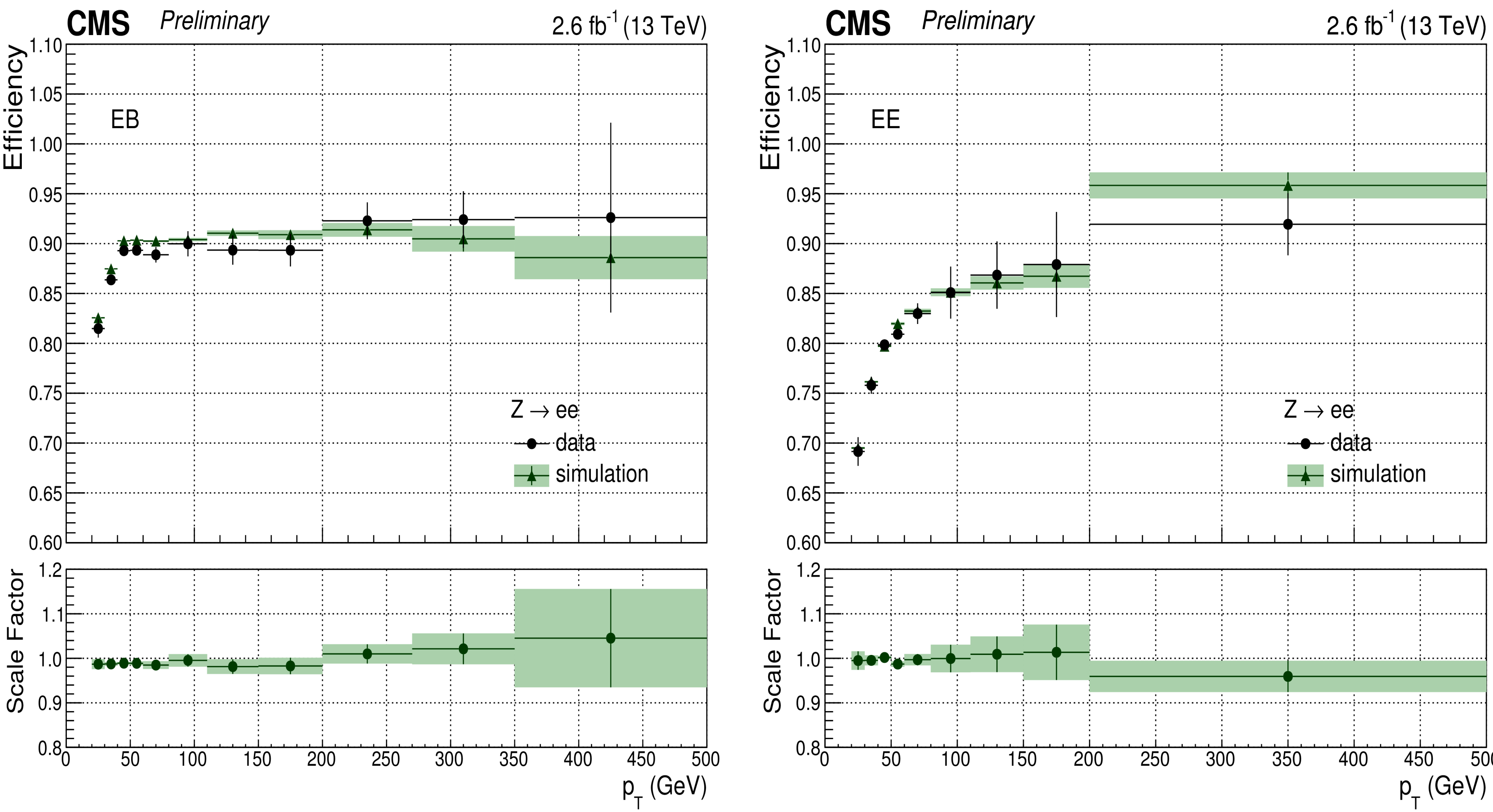
LHC will start taking data again in a few months

- ✓ ~10-15/fb needed to confirm the excess


CMS Experiment at the LHC, CERN
Data recorded: 2015-Nov-02 21:34:00.662277 GMT
Run / Event / LS: 260627 / 854678036 / 477
Mγγ = 745 GeV

Backup

Photon selection efficiencies



Photon energy scale and resolution

Energy scale and resolution corrections estimated using 13TeV Z->ee events

- ✓ in different photon categories
- ✓ maximum likelihood analysis performed while modifying energy

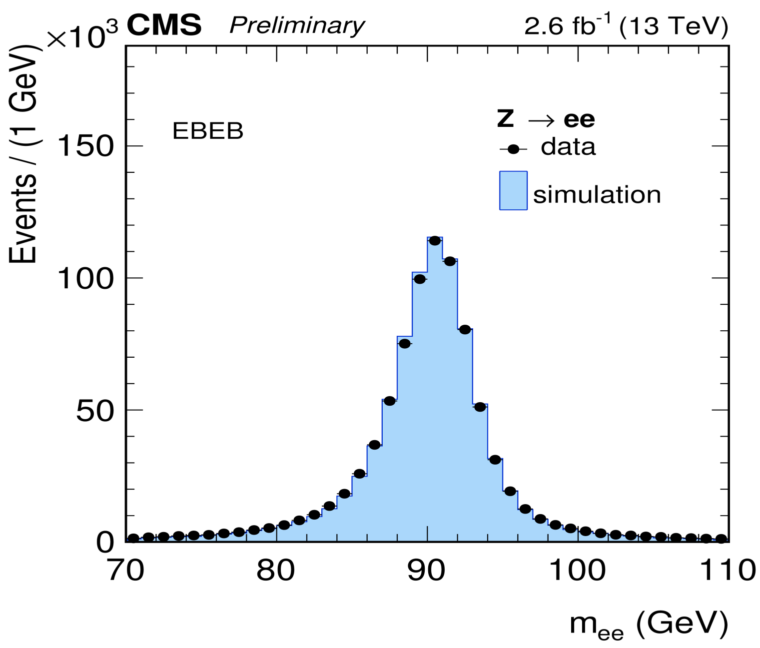
Extrapolation to high mass checked with high mass DY events

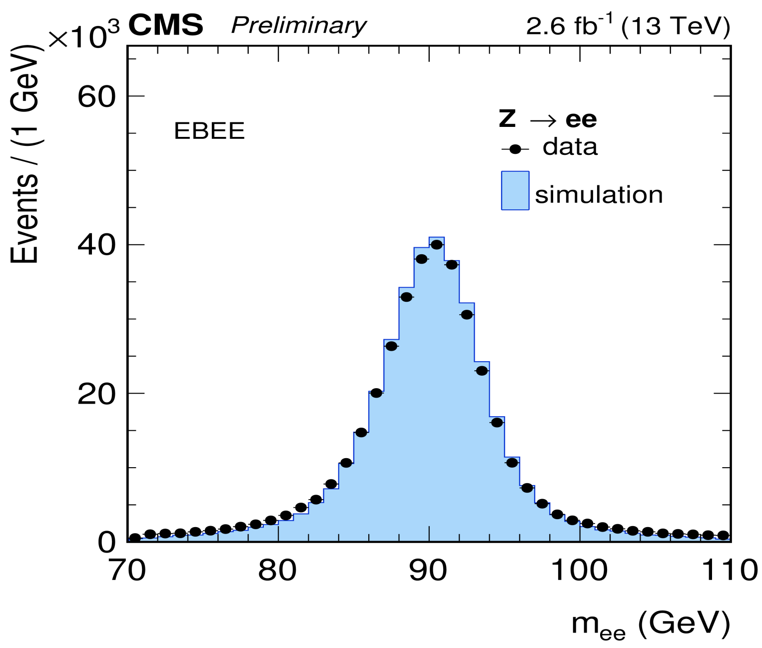
- ✓ compatible with a precision of 0.5% for m_{ee}>200 GeV

Photon energy smeared on MC to match data

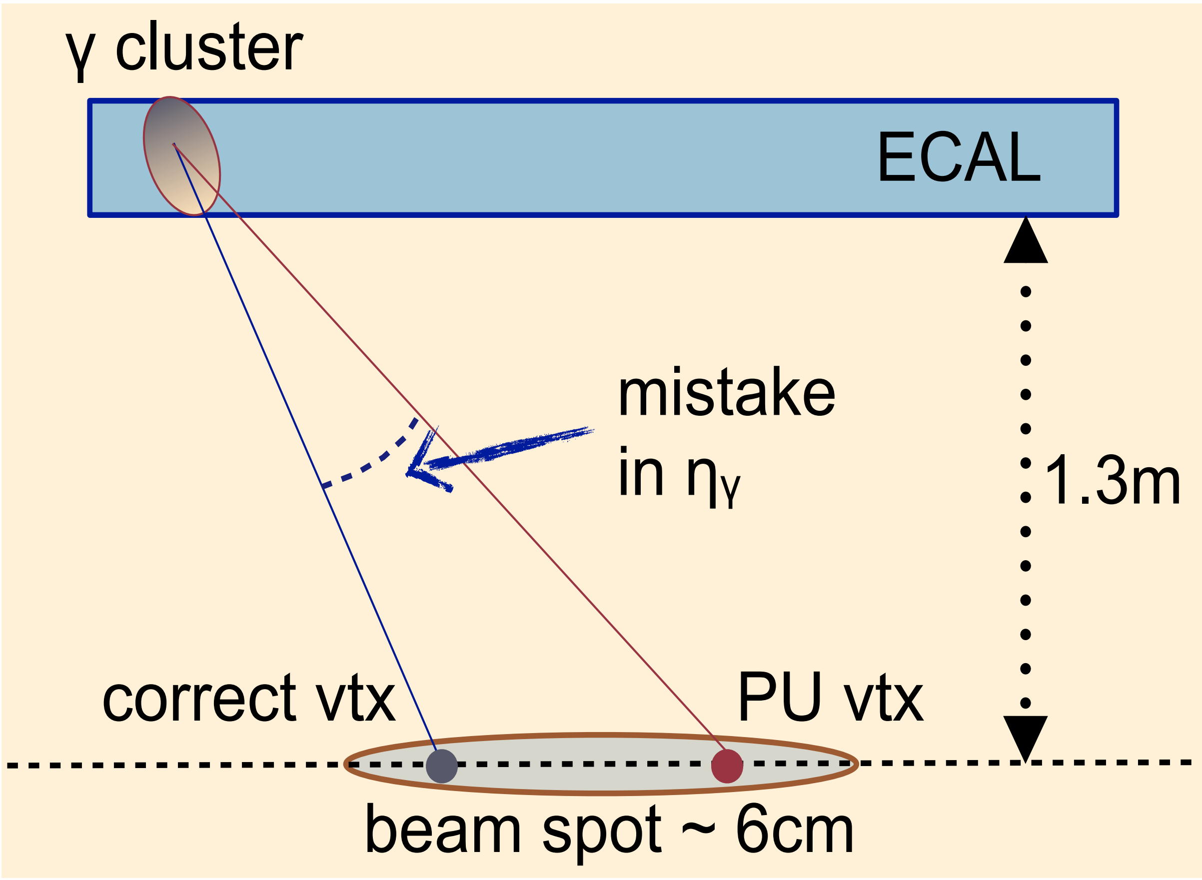
- ✓ additional smearings

still room for improvement





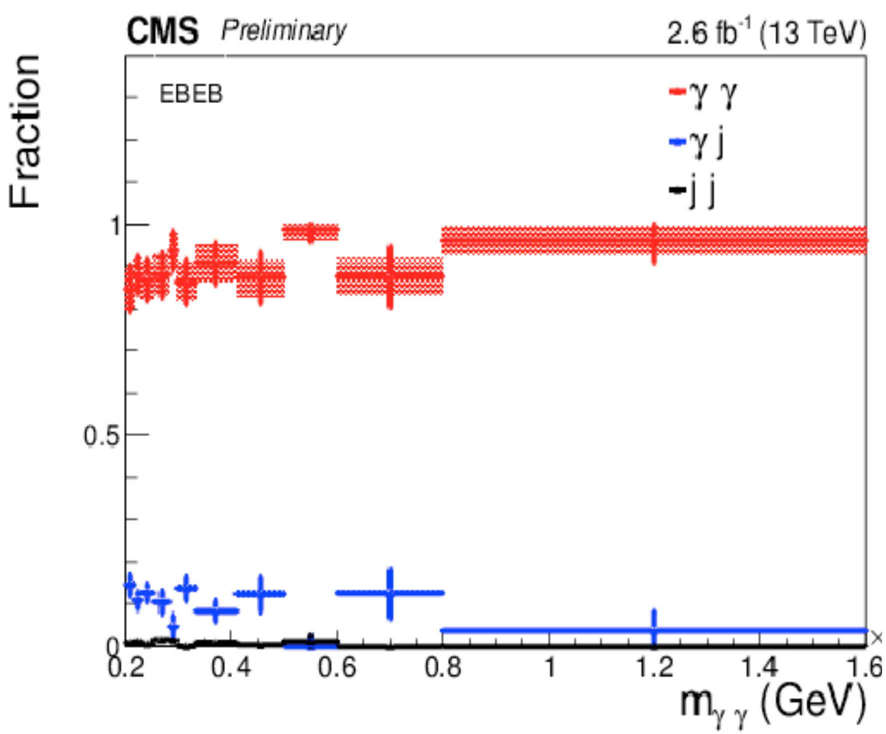
Vertex determination

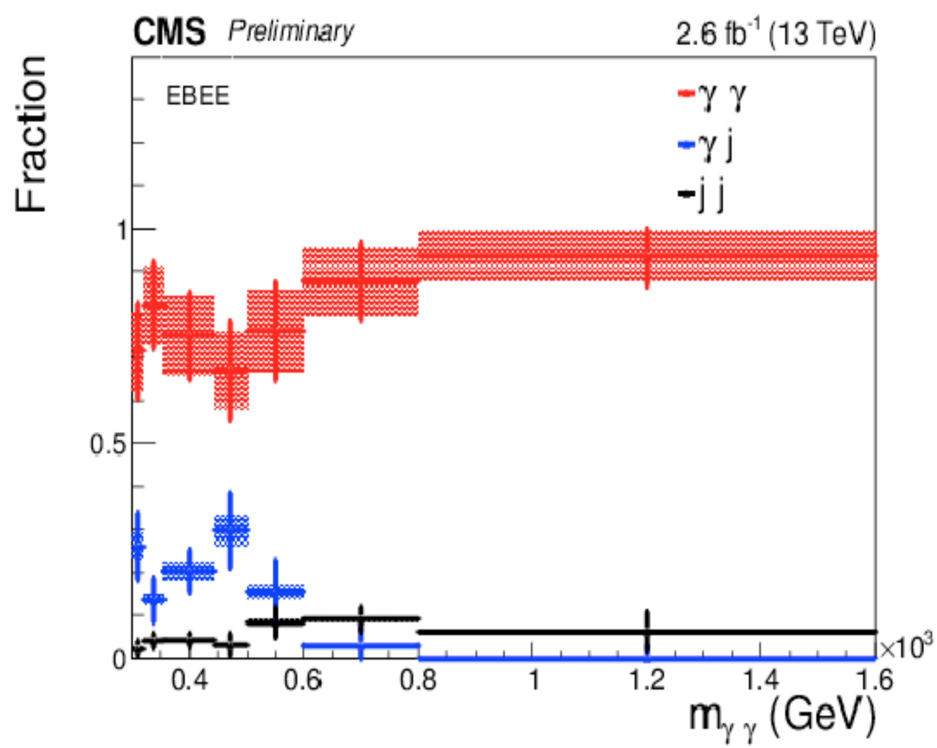


Background composition

Background estimate fully data driven => no simulation used
BUT good control of background gives confidence in the analysis

Background composition measured in data using template fits





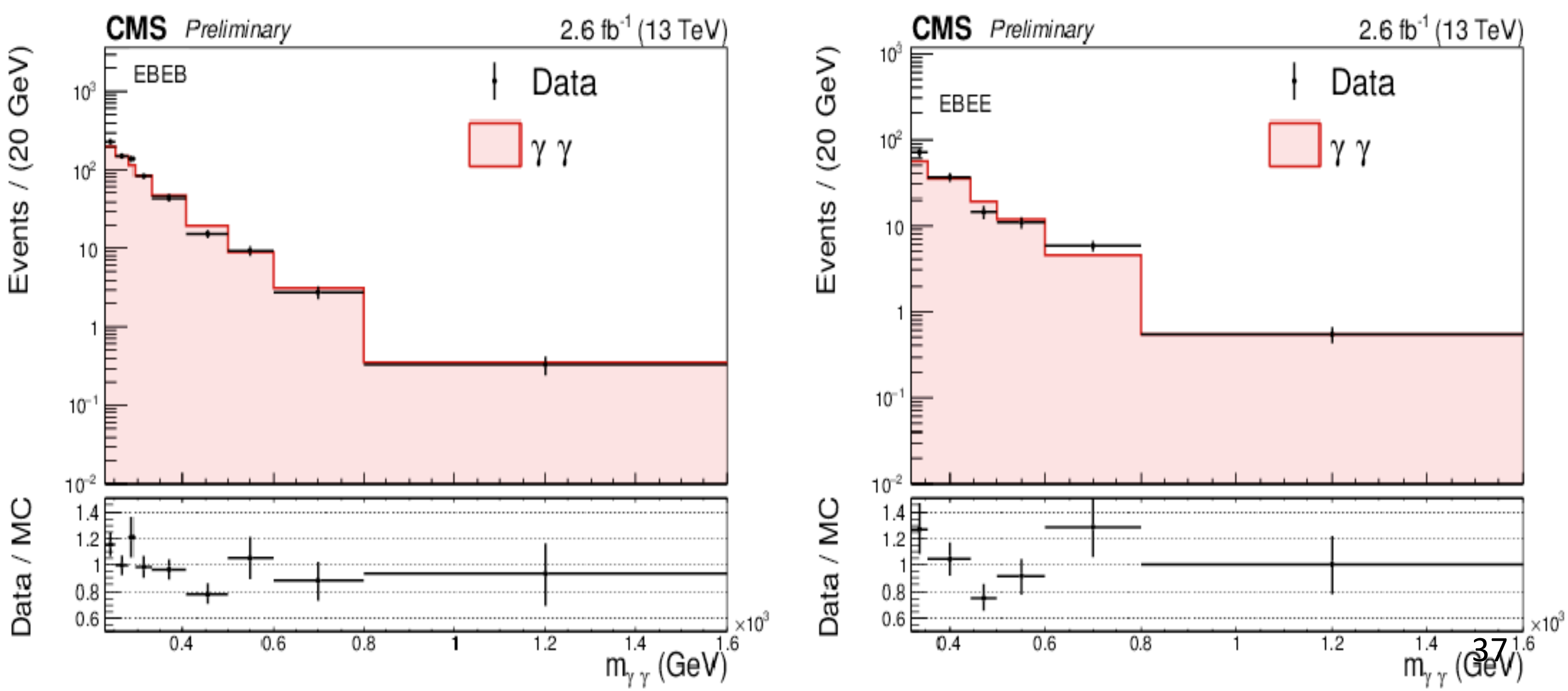
Dominant contribution: events with 2 prompt photons
Events where 1 or 2 candidates from jet fragmentation <10% (20%) in EBEB (EBEE)

Background composition, closure test

Data driven prediction for the prompt-prompt component compared with theory

✓ Sherpa generator rescaled to 2γNNLO

Good agreement observed



Systematics

Signal model:

- ✓ Luminosity: 4.6% on signal normalization
- ✓ Trigger and photon selection: 10% on signal normalization
- ✓ Photon energy scale: 1%
- ✓ PDF: 6% on signal normalization

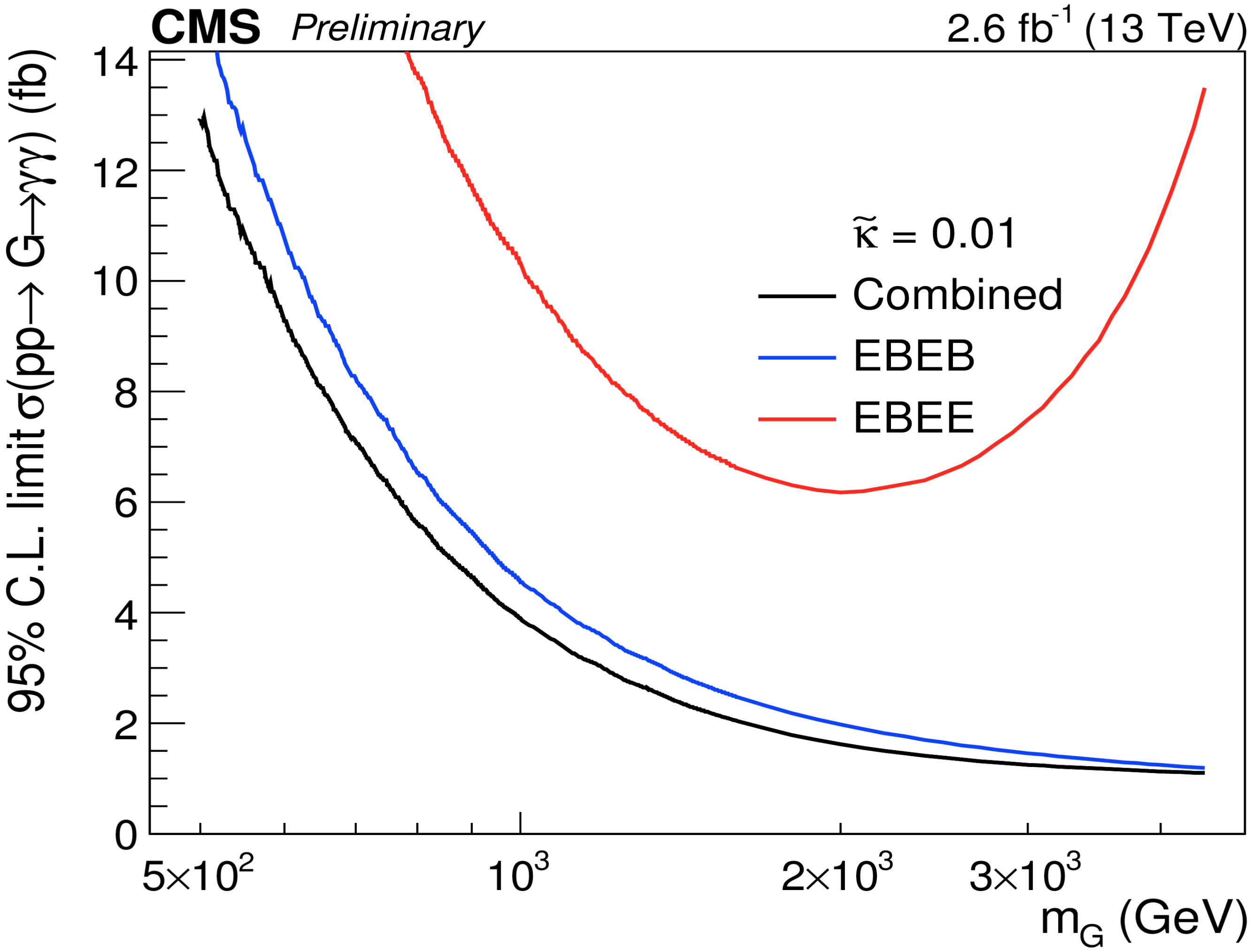
Background model:

- ✓ Bias term only
- ✓ [Parameter coefficients: unconstrained nuisance parameters
  - ✓ contribute to statistical error]

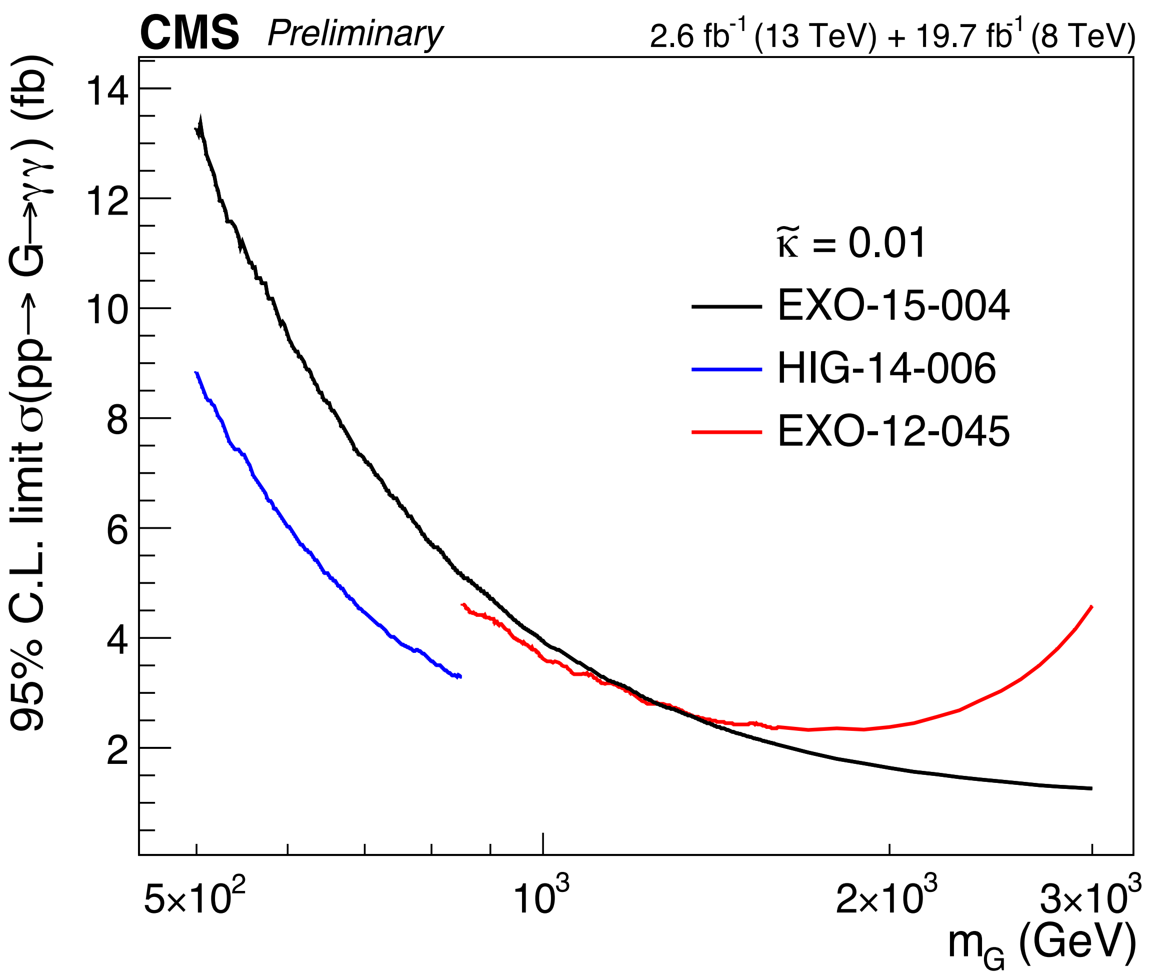
Signal model

m_G (GeV)	category	$\tilde{\kappa}$	FWHM (GeV)	$\tilde{\kappa}$	FWHM (GeV)
500	EBEB	0.01	14	0.2	36
500	EBEE	0.01	22	0.2	42
1000	EBEB	0.01	27	0.2	74
1000	EBEE	0.01	43	0.2	85
2000	EBEB	0.01	54	0.2	147
2000	EBEE	0.01	76	0.2	163
3000	EBEB	0.01	96	0.2	225
3000	EBEE	0.01	110	0.2	254
4000	EBEB	0.01	121	0.2	320
4000	EBEE	0.01	150	0.2	326

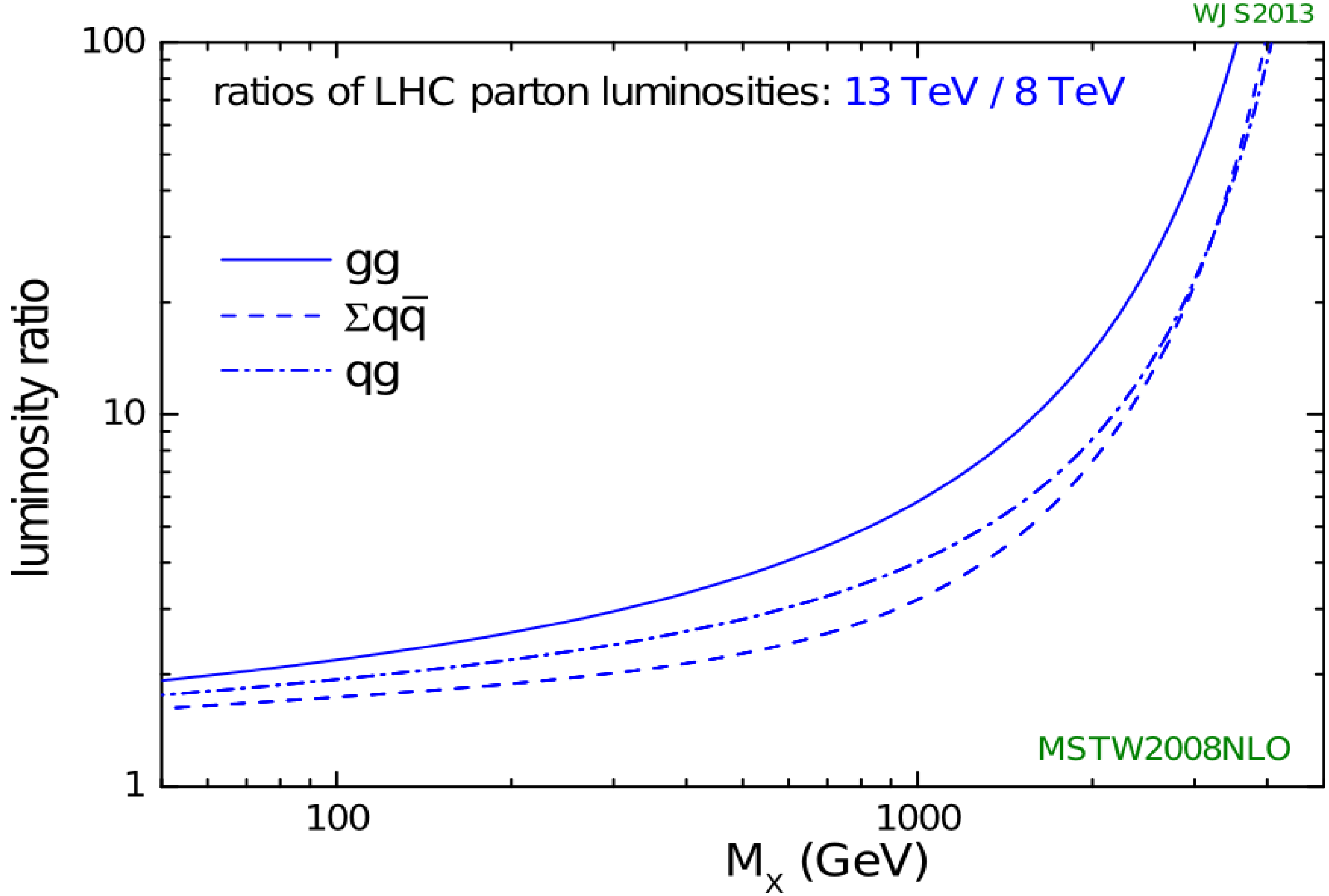
Analysis categories



8TeV analyses

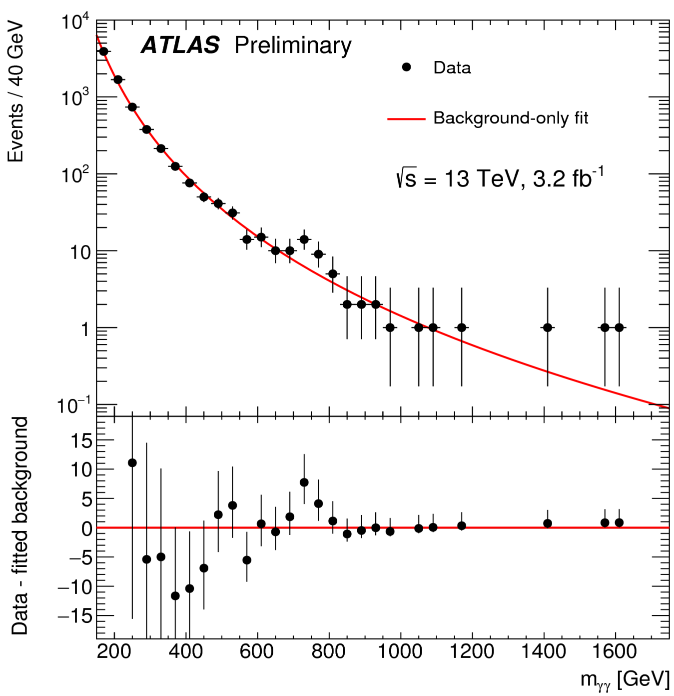


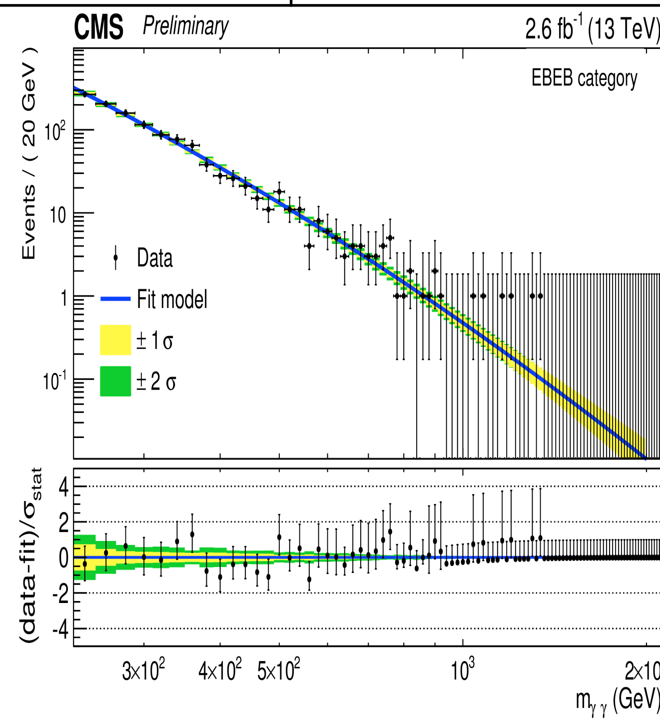
8TeV vs 13TeV



CMS vs ATLAS

	cms	atlas
luminosity	2.6/fb	3.2/fb
benchmark	spin2	spin0
eff x acc 600GeV	~0.55	~0.4
background model	m^(a + b*log(m))	(1-x^1/3)^b x^a
fit bias	< ½ stat.uncertainty	< 1/5 stat.uncertainty
Preferred width	narrow	~6%



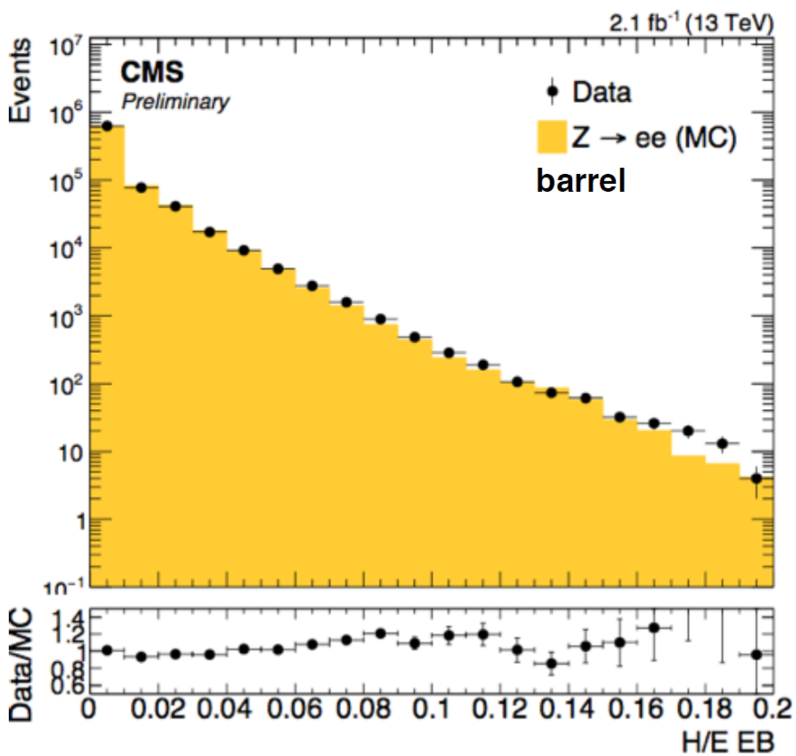


Physics objects @ 13 TeV

Excellent comprehension of electrons, photons, muons, jets, MET @ 13 TeV

Electrons from Z decays

- HCAL / ECAL energy



Photons from radiative Z decays

- Relative e.m. isolation