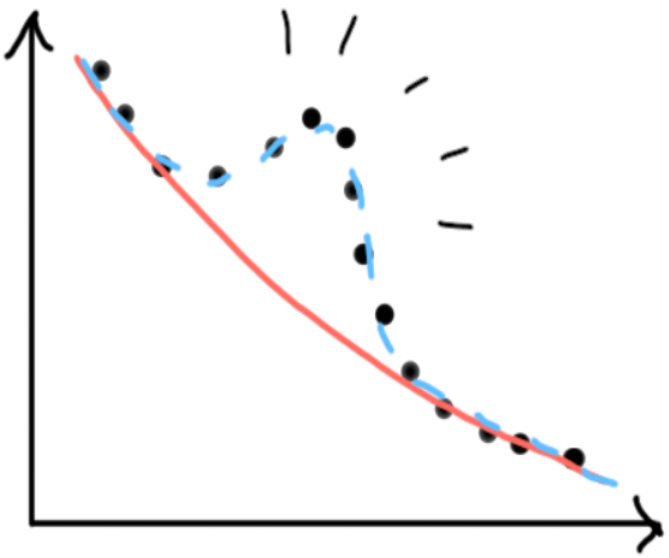
High mass diphoton resonance search at CMS

Josh Bendavid (Caltech)
for the CMS Collaboration

Aug. 5, 2016

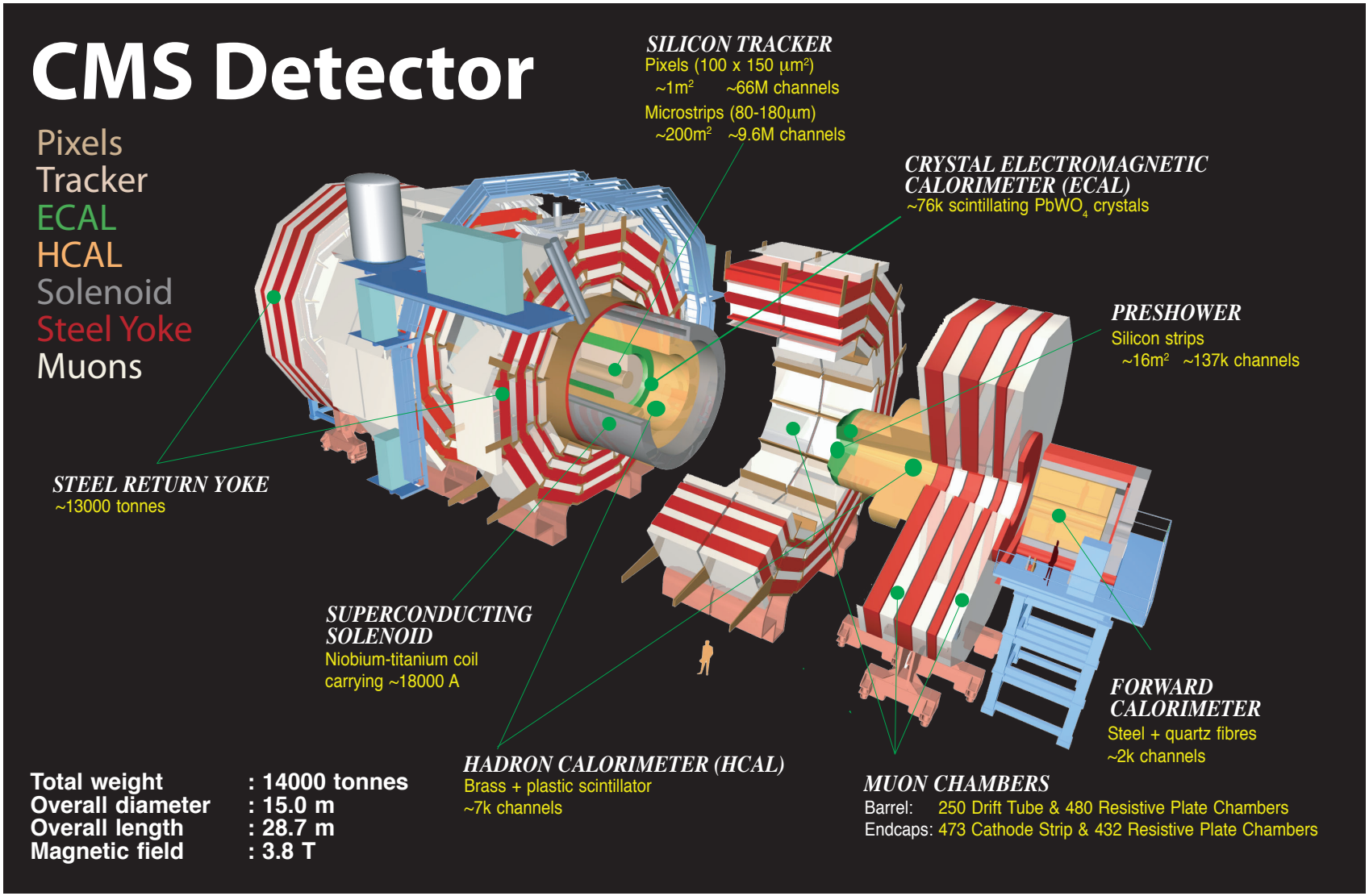
Introduction

- New resonances at high mass might decay to photons
- Fully reconstructed mass peak with excellent detector resolution in this case
- Standard Model backgrounds are relatively low
- SM Higgs $\rightarrow$ demonstrates our ability to observe such a signal even with relatively low S/B at lower mass

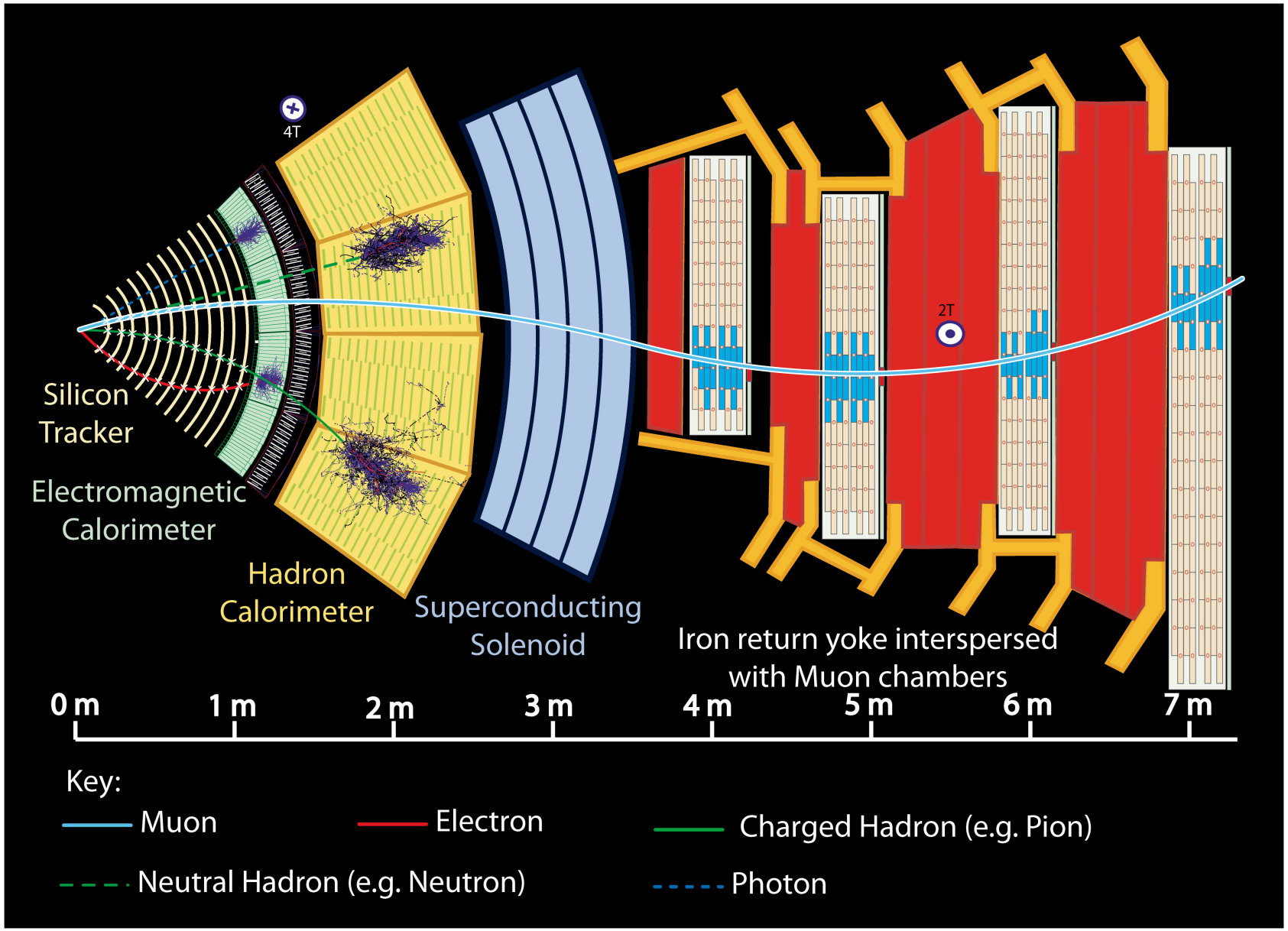


$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$$

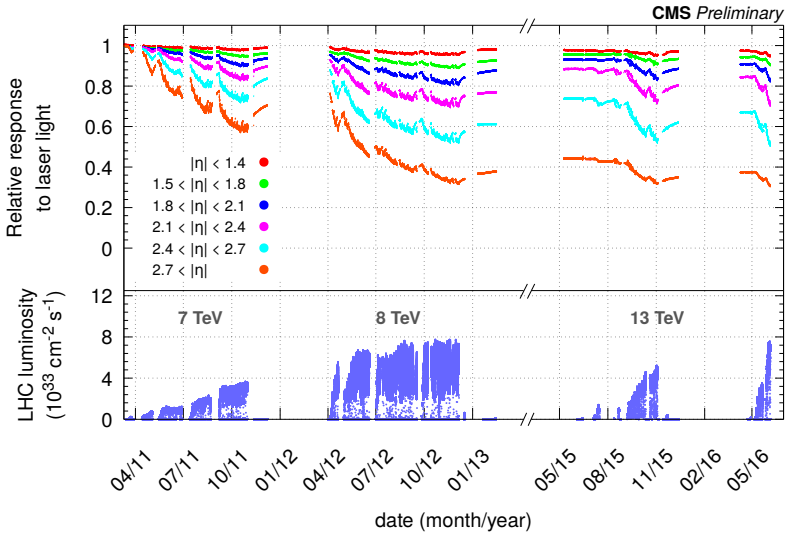
The CMS Detector



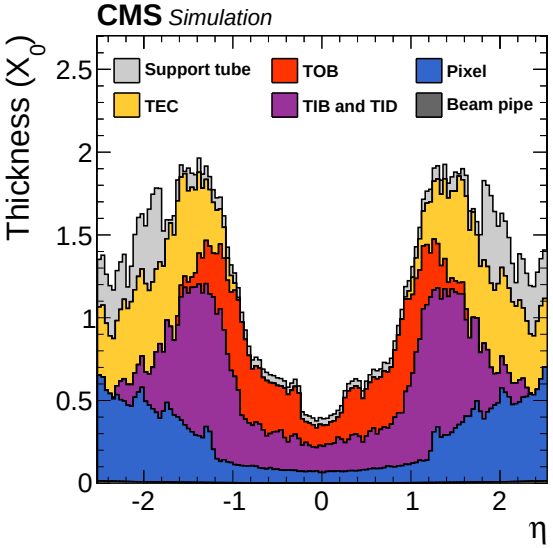
The CMS Detector



The CMS Detector: Some Challenges



(a) ECAL Transparency Change

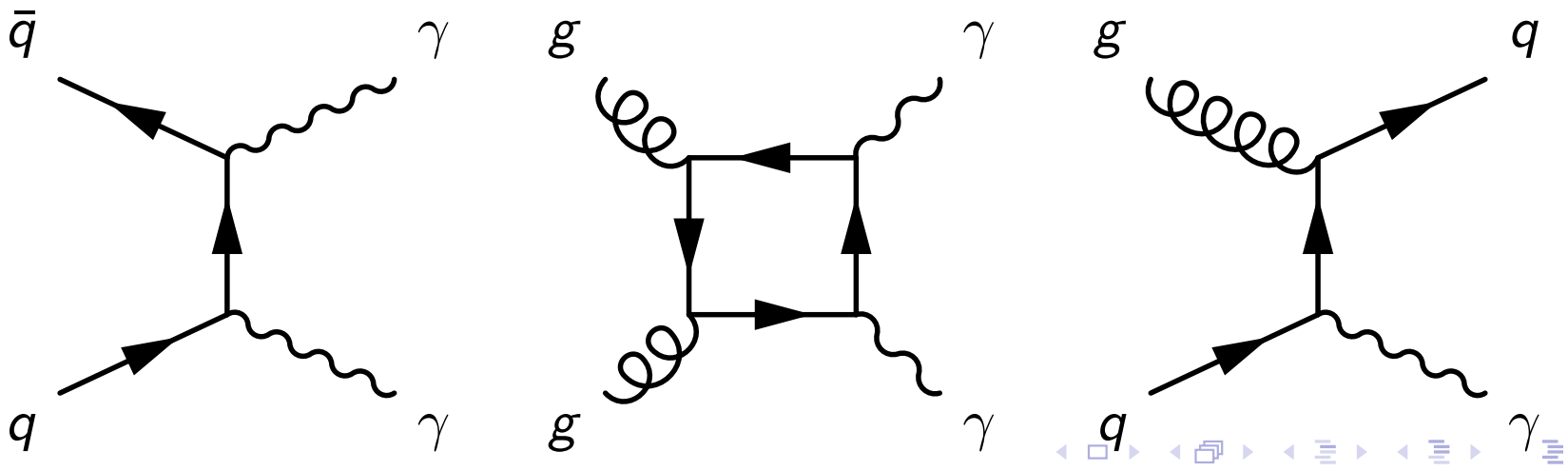


(b) Tracker Material Budget

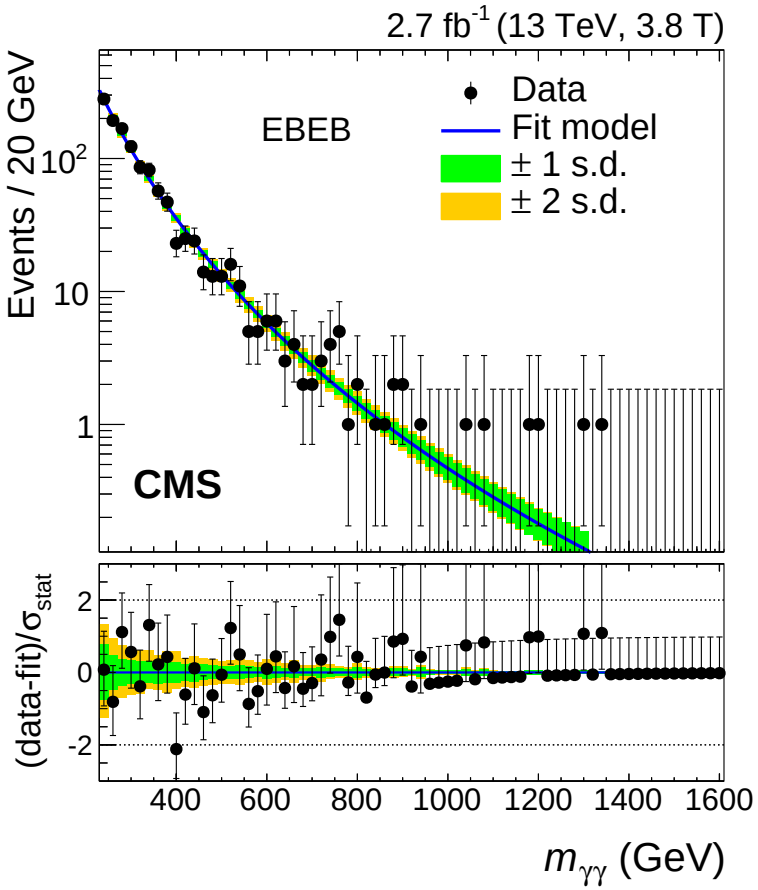
- ECAL crystals lose and recover transparency under exposure to radiation
- Monitored in situ with laser monitoring system, but still a major challenge for calibration
- Lots of material in front of the ECAL

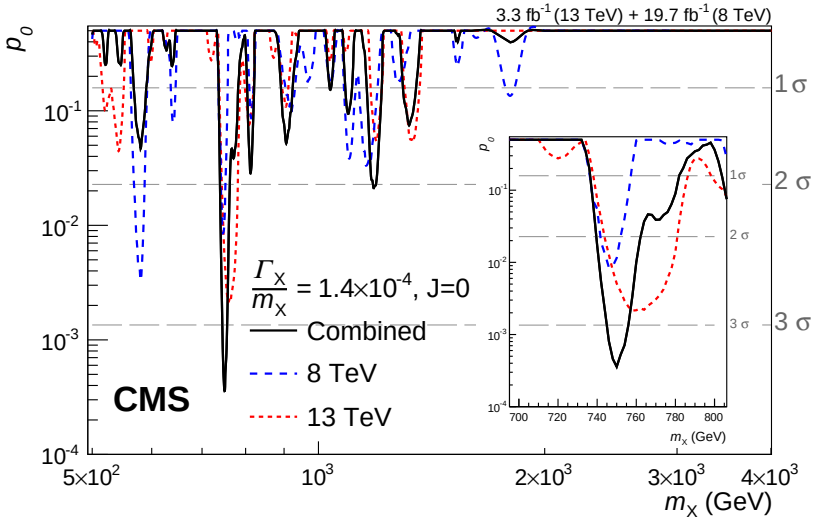
Diphoton Analysis Overview

- Diphoton search at CMS simple in principle: Search for a possibly narrow mass peak on a smoothly falling background
- Irreducible background from QCD di-photon production, reducible background from QCD γ+jets and multi-jet production with one or more jets faking a photon
- Analysis categorized in EBEB and EBEE categories (EBEB category dominates expected sensitivity for all reasonable signal hypotheses)



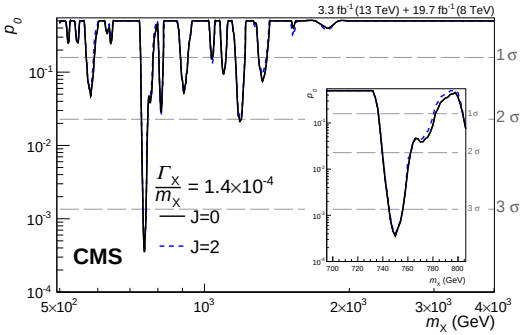
Reminder: CMS 2015 (+8 TeV) Results



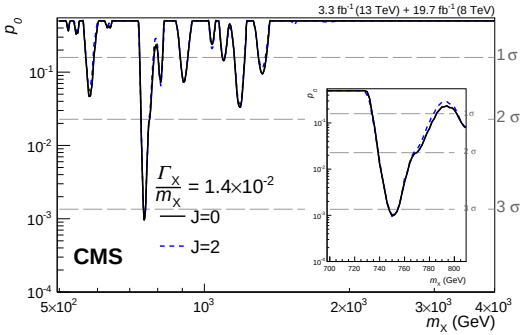


Most Significant Excess	2015	2015+8 TeV
Mass (GeV)	760	750
Local Significance	2.9σ	3.4σ
Global Significance	$< 1\sigma$	1.6σ

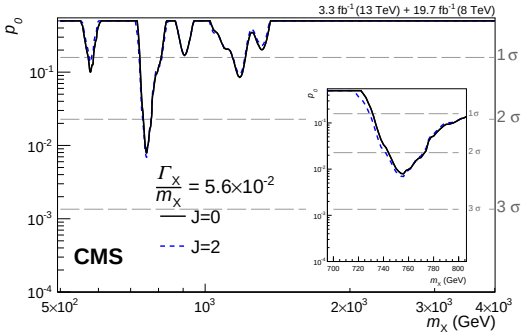
Reminder: CMS 2015 (+8 TeV) Results



(c) Narrow



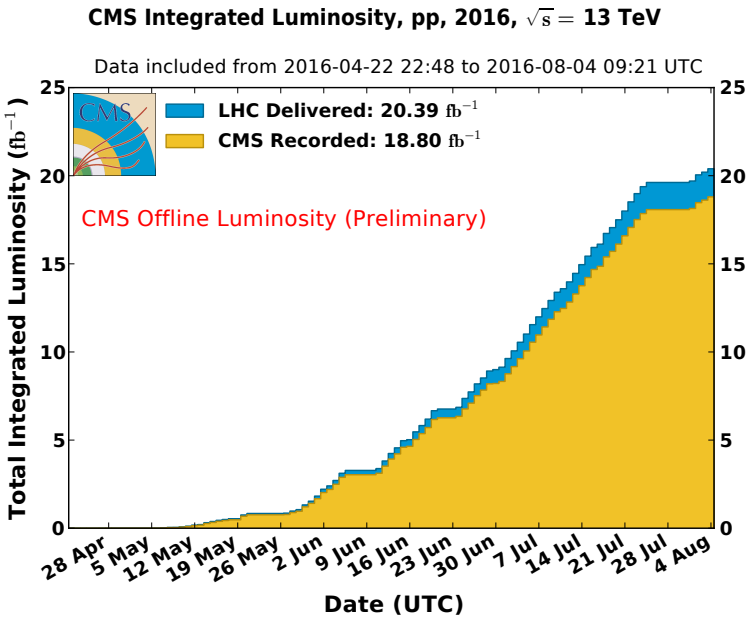
(d) Medium



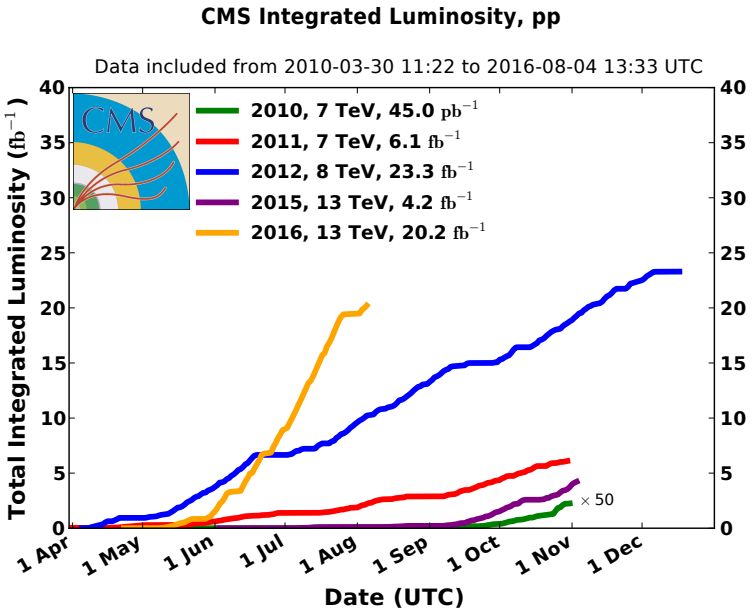
(e) Wide

- **From these results, need more data to exclude a statistical fluctuation**
- Interpreting as a signal, narrow resonance interpretation (slightly) favoured
- Search analysis not designed to disentangle spin 0 vs spin 2 hypotheses

And now we have it! (more data that is)



(f) 2016



(g) Comparison across years

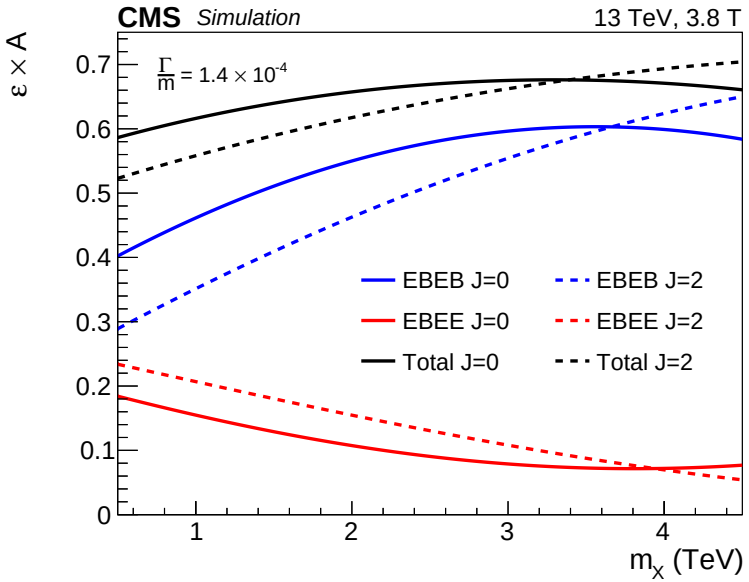
- Spectacular LHC performance in 2016
- Data for this (and most ICHEP) results included up to July 14-15 overnight fill $\rightarrow$ 12.9 fb^{-1} certified for physics

Analysis Strategy

- Diphoton search at CMS simple in principle: Search for a possibly narrow mass peak on a smoothly falling background
- Simple event selection with two isolated high p_T photons
- Background modelling with parametric fit to the $m_{\gamma\gamma}$ distribution in data with appropriate functional form $g(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\log(m_{\gamma\gamma})}$ and residual uncertainties
- Modelling of a possible signal from simulation with data-driven corrections for selection efficiency and energy resolution
  - Gluon-produced scalar and RS graviton models used as proxies for possible signal
  - Several widths considered ranging from $\Gamma_X/m_X = 1.4 \times 10^{-4}$ (negligible compared to detector resolution) up to 5.6×10^{-2}
- Search carried out for signal hypotheses between $m_X = 0.5$ and 4.5 TeV
- Results extracted from maximum likelihood fit to $m_{\gamma\gamma}$ distribution

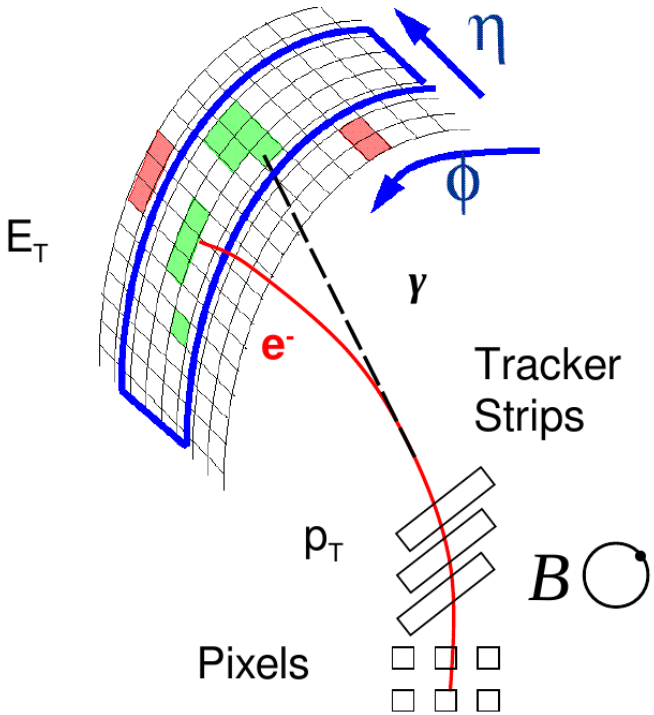
Event Selection

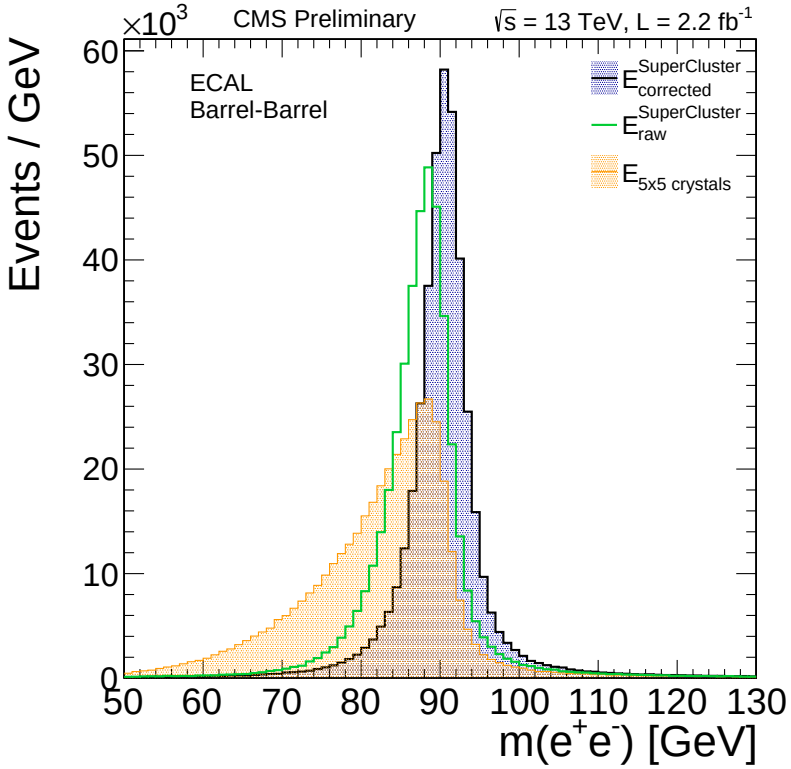
- Two isolated high p_T photons:
  - $p_T > 75$ GeV offline, $p_T > 60$ GeV at High Level Trigger
- Cut-based photon identification based on shower shapes and isolation (plus electron-veto)
- Photons selected in ECal Barrel ($|\eta| < 1.44$) and Endcap ($1.56 < |\eta| < 2.5$) regions
- Events split into barrel-barrel and barrel-endcap categories given different energy resolution and S/B
- Selection essentially unchanged from 2015 (no significant improvements found in blinded studies on 2016 data)



- Beyond difference in acceptance, analysis is essentially insensitive to spin/parity of a possible signal

Photon Energy Reconstruction

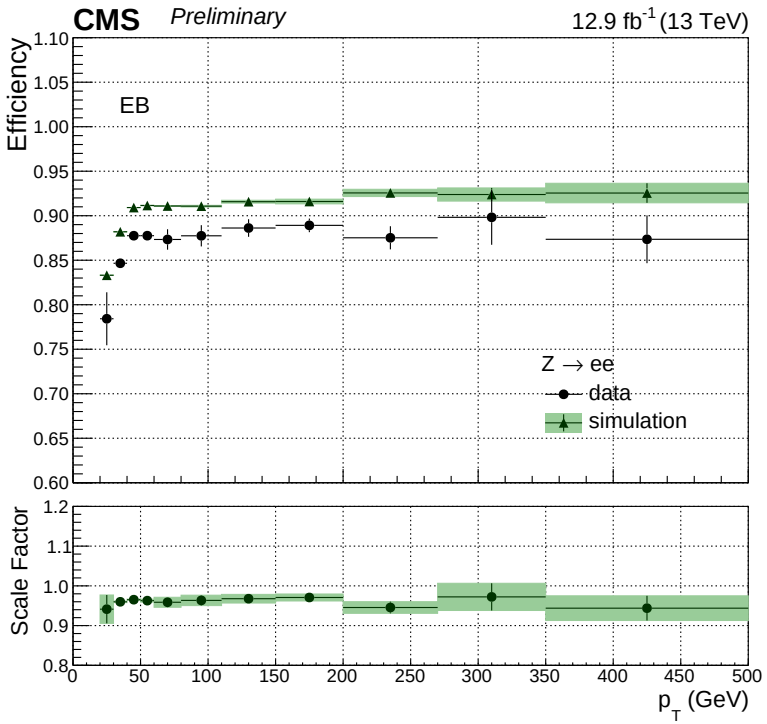




- Reconstruction forms Superclusters extended in ϕ to collect conversion legs/bremsstrahlung spread out by magnetic field
- After all crystal-level calibrations, BDT-based regression algorithm corrects energy for gaps/cracks/showering/pileup based on cluster position, shower shapes, and pileup inputs

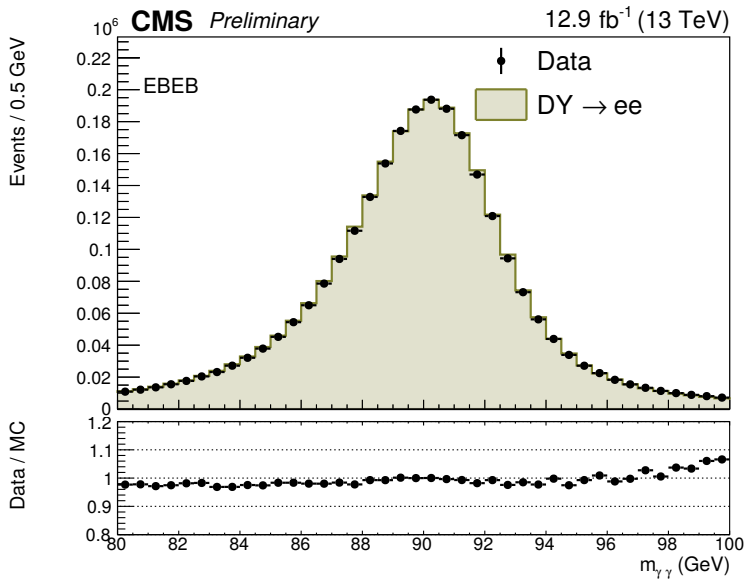
Event Selection

- Photon identification efficiency measured with tag and probe from $Z \to ee$ events
- Electron veto efficiency measured in $Z \to \mu\mu\gamma$ events
- Scale factors flat in p_T, a few % below 1, used to correct signal MC
- Systematic uncertainty on efficiency of 6%

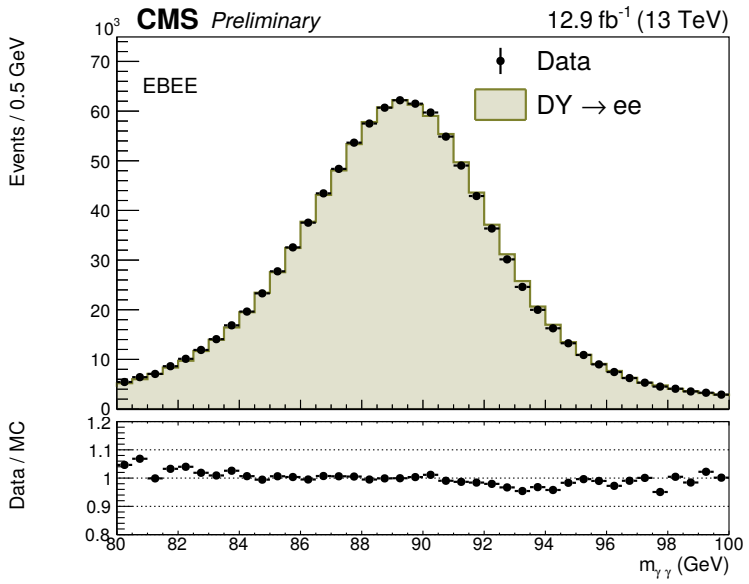


Energy Scale and Resolution Corrections

- Energy scale and resolution measured in $Z \to ee$ events
- Energy scale correction applied to data
- Energy resolution correction applied to signal MC
- Systematic uncertainties for energy scale and resolution included in signal model (1% uncertainty on energy scale given extrapolation in energy)

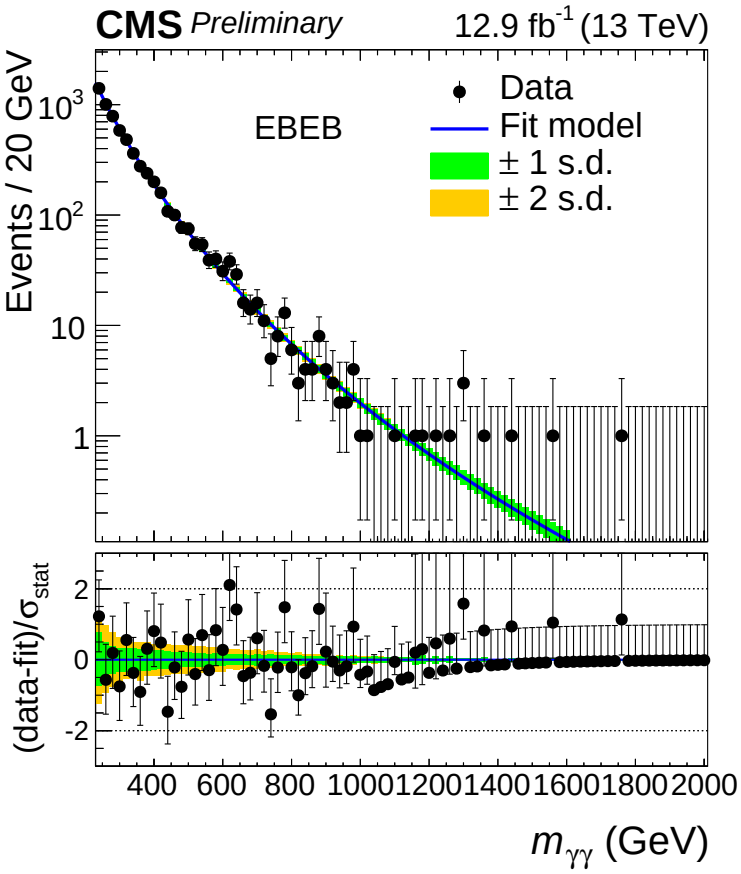


(a) EBEB

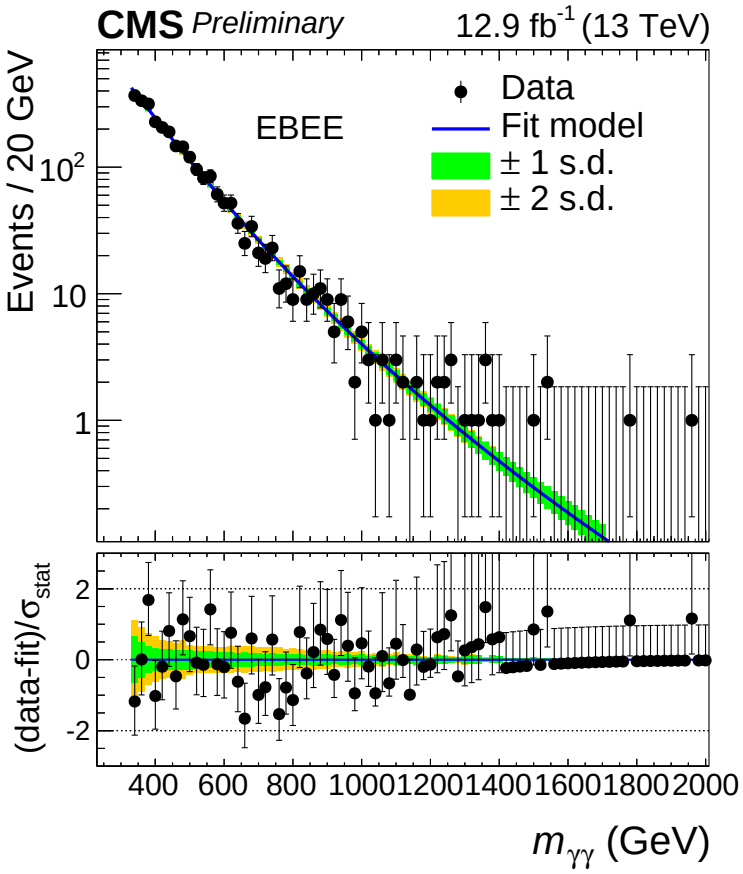


(b) EBEE

2016 Data + Bkg-only Fits



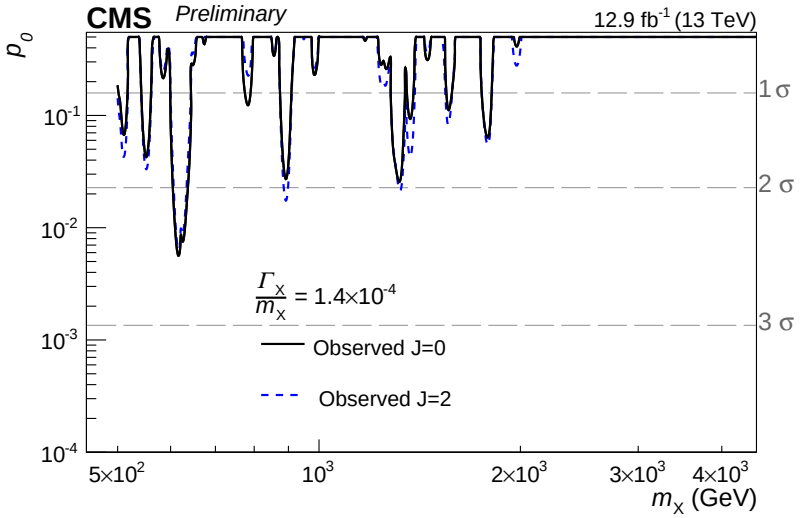
(a) EBEB



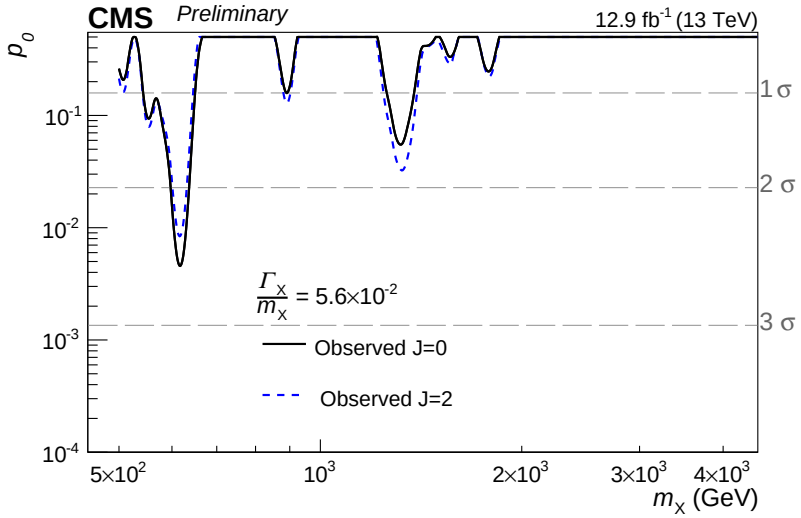
(b) EBEE

- Background fit with $g(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\log(m_{\gamma\gamma})}$ as previously

2016 Observed Significance



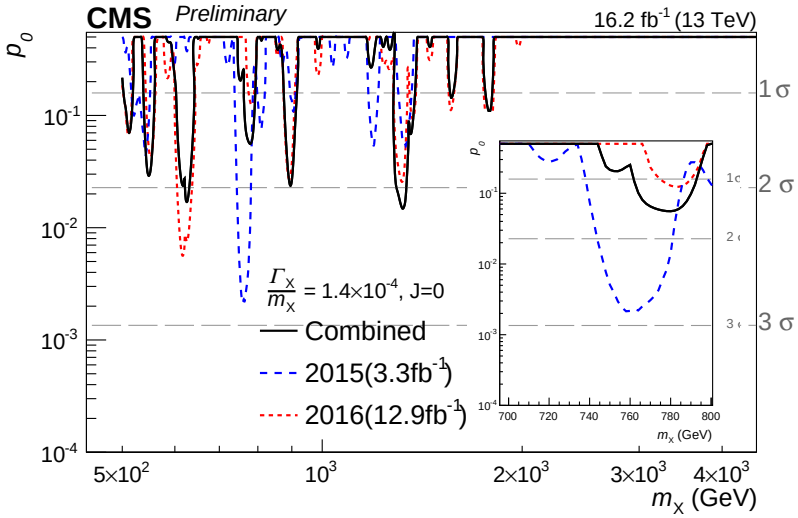
(a) Narrow



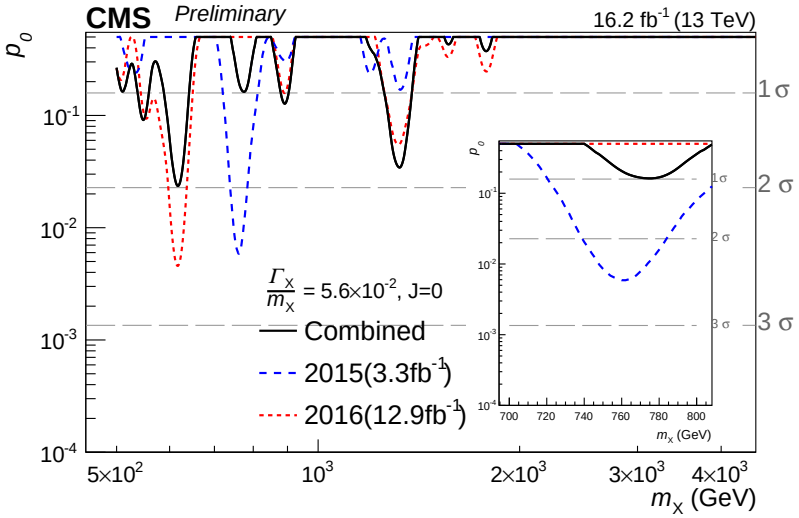
(b) Wide

- Excess of 2015 not confirmed
- Results well-consistent with background-only given LEE

Combination with 2015



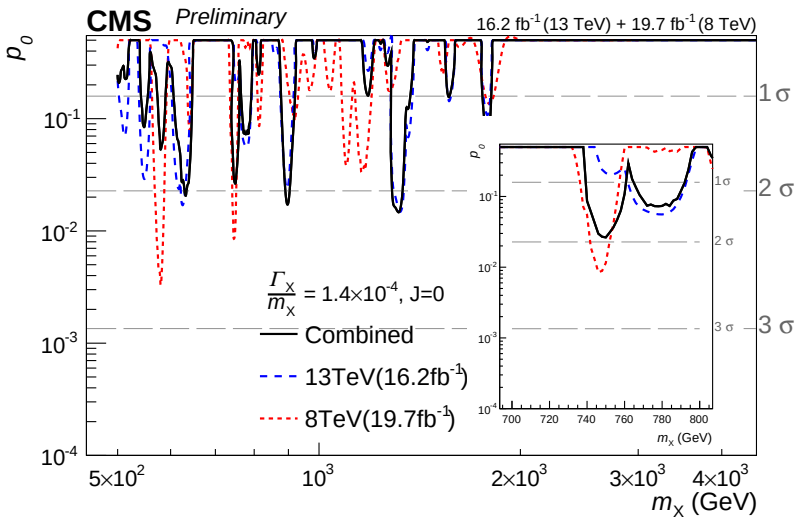
(a) Spin-0 Narrow



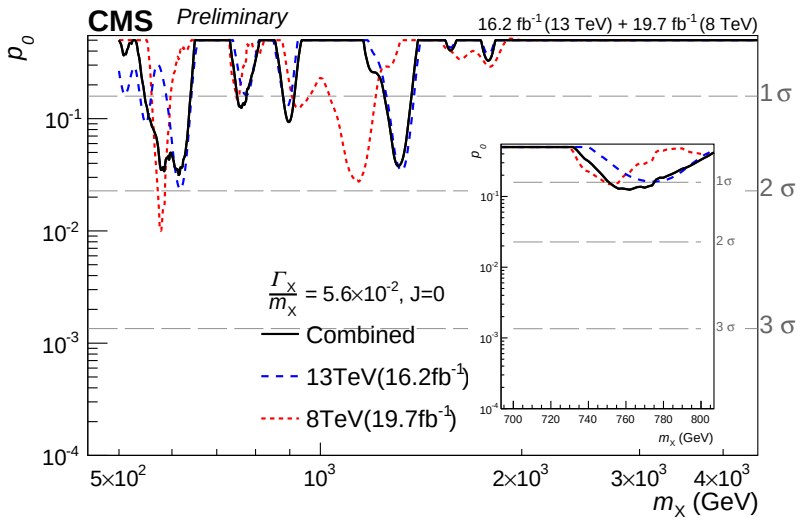
(b) Spin-0 Wide

- Excess of 2015 not confirmed
- Significance strongly diluted by combination with 2016 data

Combination with 2015+8 TeV



(a) Spin-0 Narrow

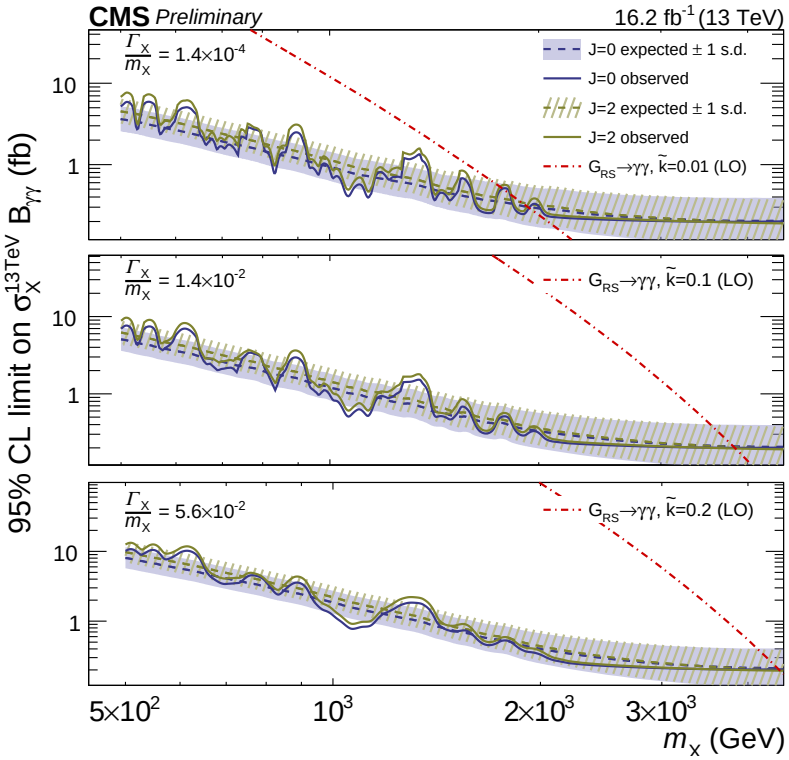


(b) Spin-0 Wide

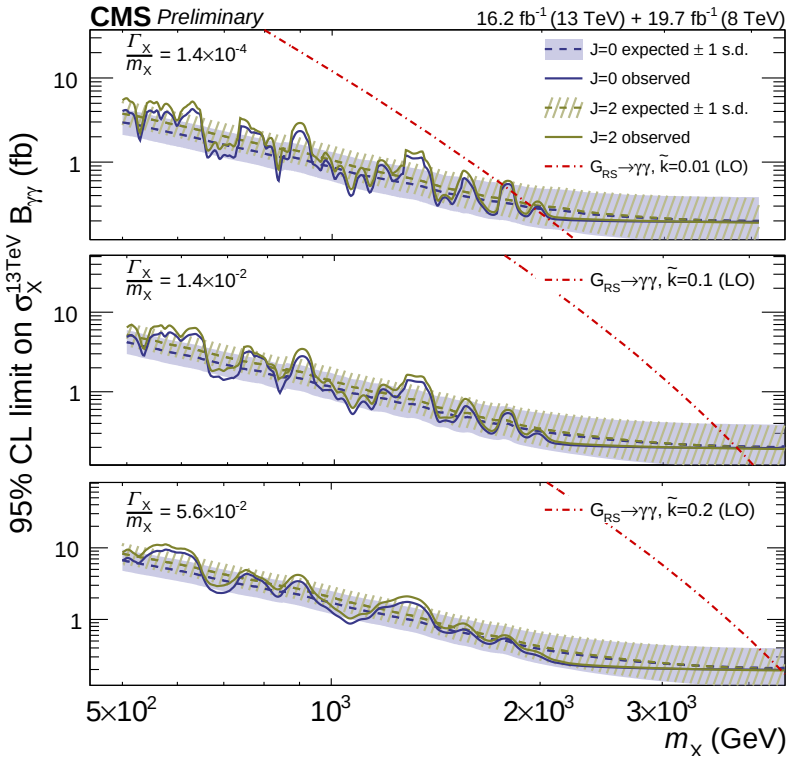
- Surviving excess in full combination of 8 TeV and 13 TeV data is fairly modest
- Will continue to shrink if further data is consistent with background on average

Exclusion Limits

- "Having observed no statistically significant excess, we proceed to set limits"
- This is ultimately what remains as the physics result

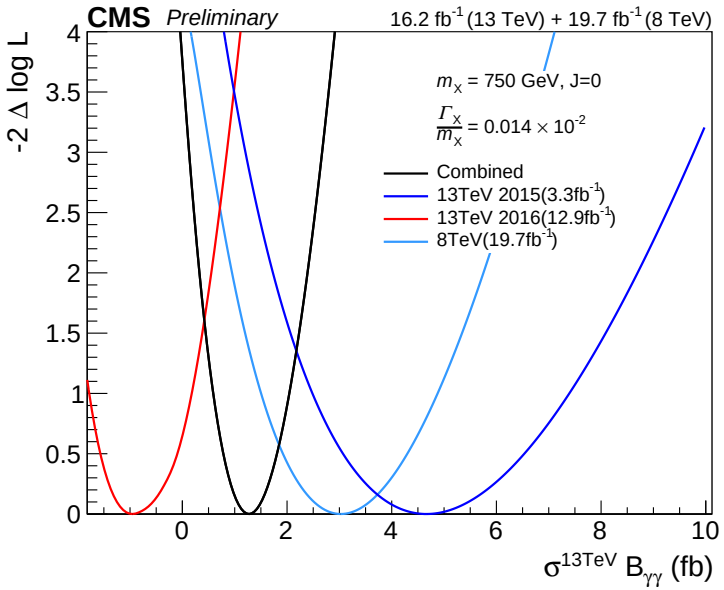


(a) 13 TeV



(b) 13 TeV + 8 TeV

Compatibility with previous results



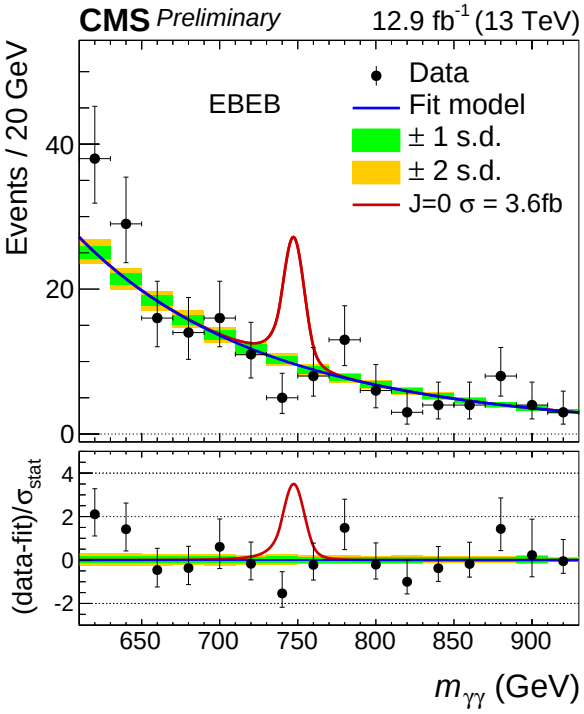
- Fitted signal cross sections compared in 2016 vs 2015 vs 8 TeV for a narrow spin-0 hypothesis with $m_X = 750$ GeV

- Compatibility estimated using profile likelihood ratio, assuming χ^2 distribution with $N-1$ degrees of freedom:
  - Two-way compatibility for 2016 vs 2015: 2.7σ
  - Three-way compatibility for 2016 vs 2015 vs 8 TeV: 2.4σ
- These numbers can be considered "local" compatibilities, and have a LEE associated with them similar to that of the search (effectively looking for least compatible point across the whole mass range)

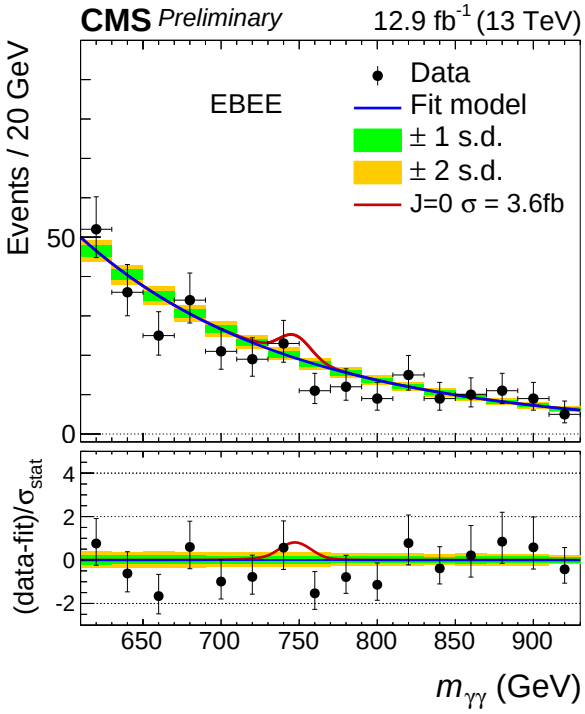
Conclusions

- Diphoton resonance search performed for 12.9 fb^{-1} of 13 TeV data from 2016
- Results compatible with background expectation
- Excess around 750 GeV from 2015 not confirmed
- Set exclusion limits for using both 13 TeV data and 13 TeV+8 TeV combination (8 TeV data now has negligible weight with assumed production cross section ratios)

Backup: 2016 Data vs 2015+8 TeV Signal



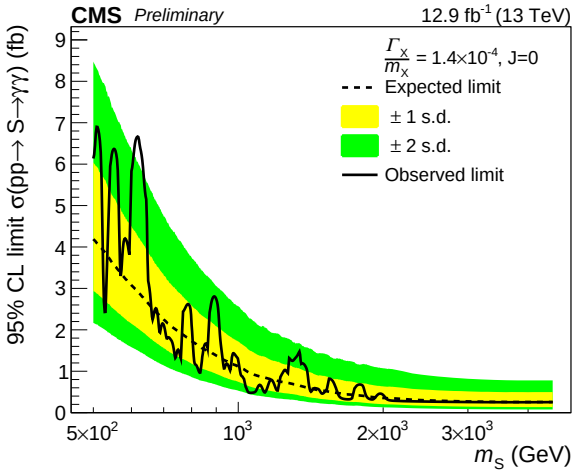
(a) EBEB



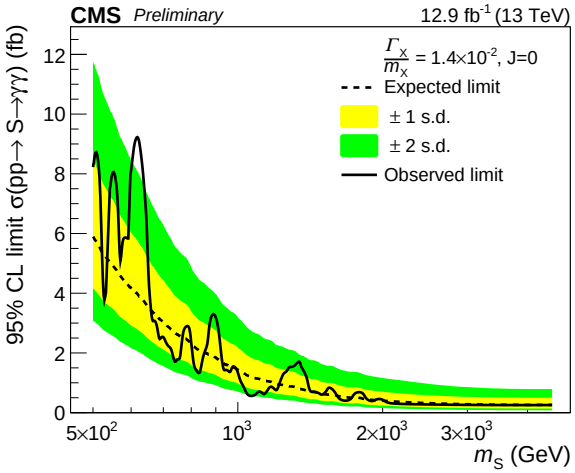
(b) EBEE

- 2016 data shown compared to plotted signal with $m_X = 750$ GeV and cross section fit from 2015+8 TeV combination
- Background fit and associated uncertainties shown integrated over data bins

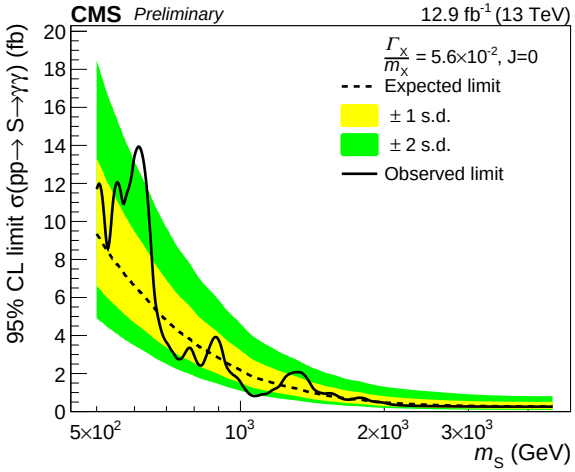
Backup: 2016 Exclusion Limits (Spin-0)



(a) Narrow

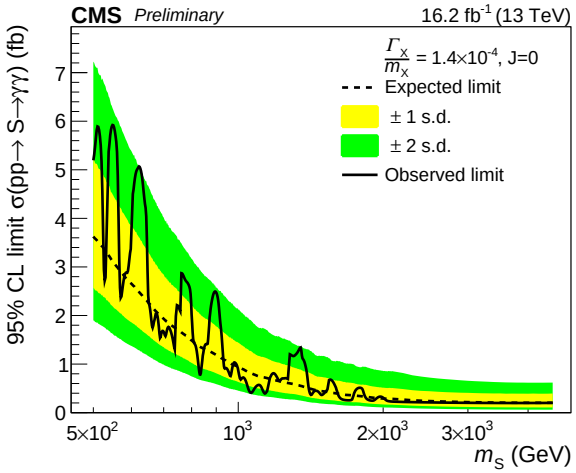


(b) Medium

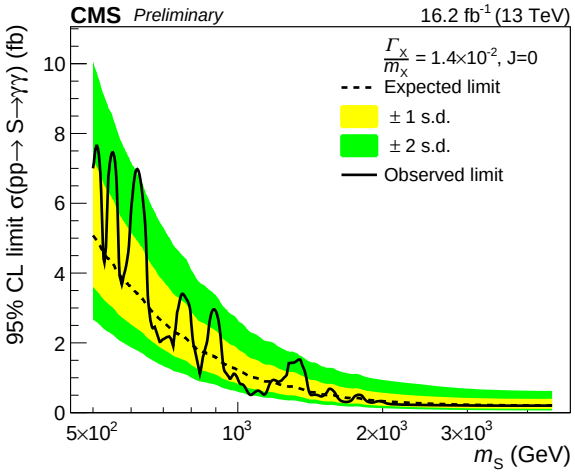


(c) Wide

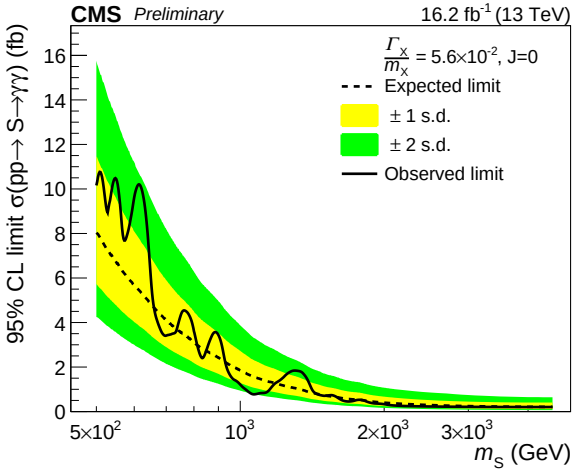
Backup: 13 TeV (2015+2016) Exclusion Limits (Spin-0)



(a) Narrow

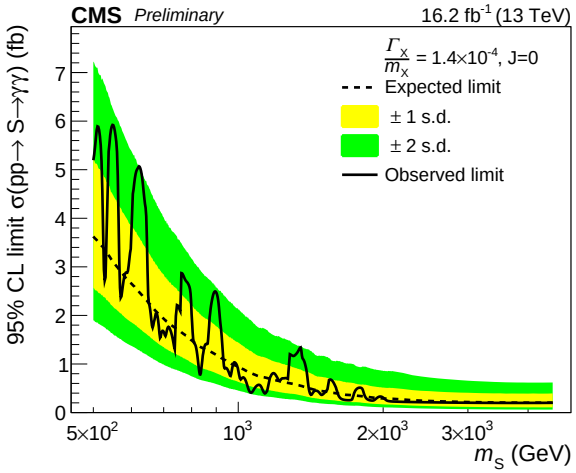


(b) Medium

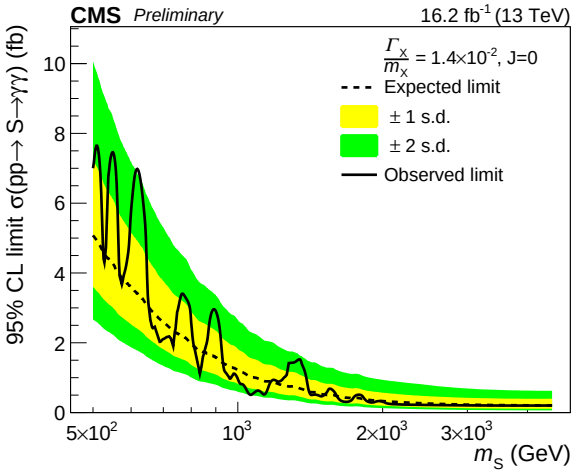


(c) Wide

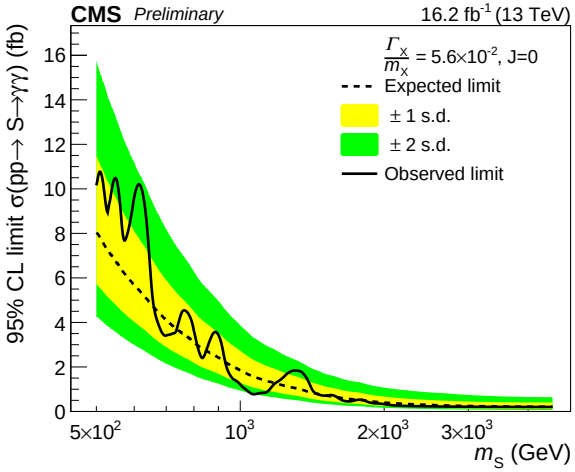
Backup: 13 TeV + 8 TeV (2015+2016+8 TeV) Exclusion Limits (Spin-0)



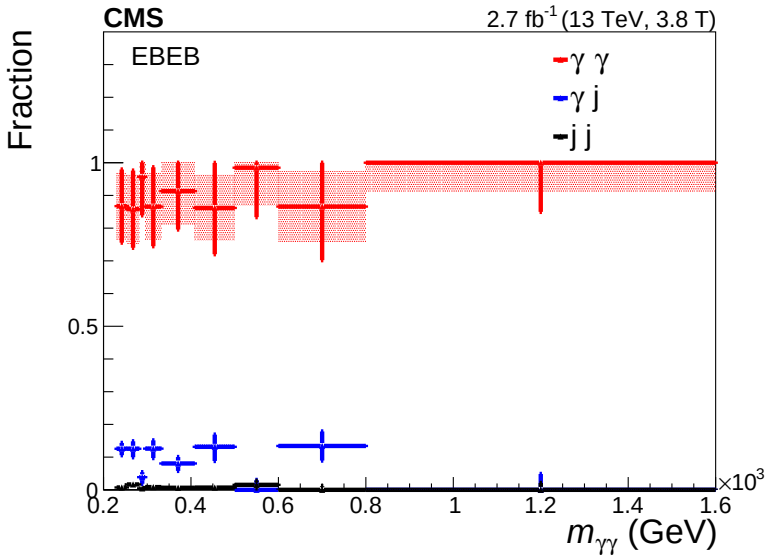
(a) Narrow



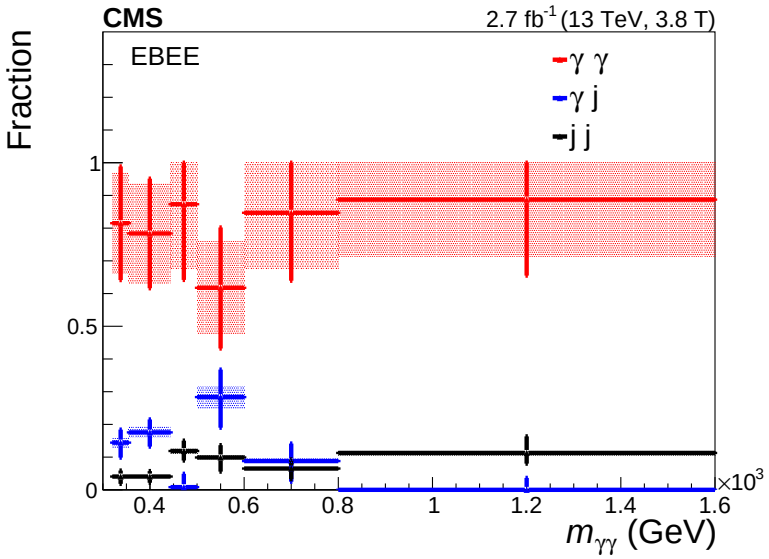
(b) Medium



Backup: Background Composition (2015)

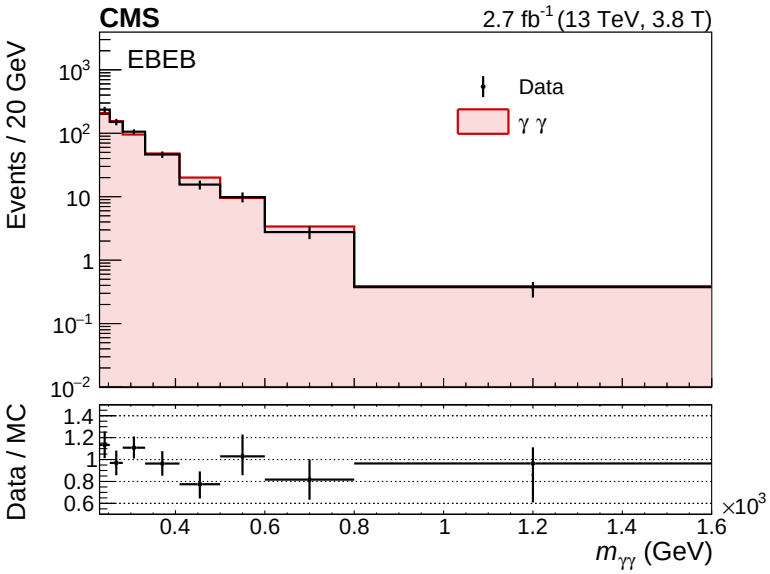


(a) EBEB

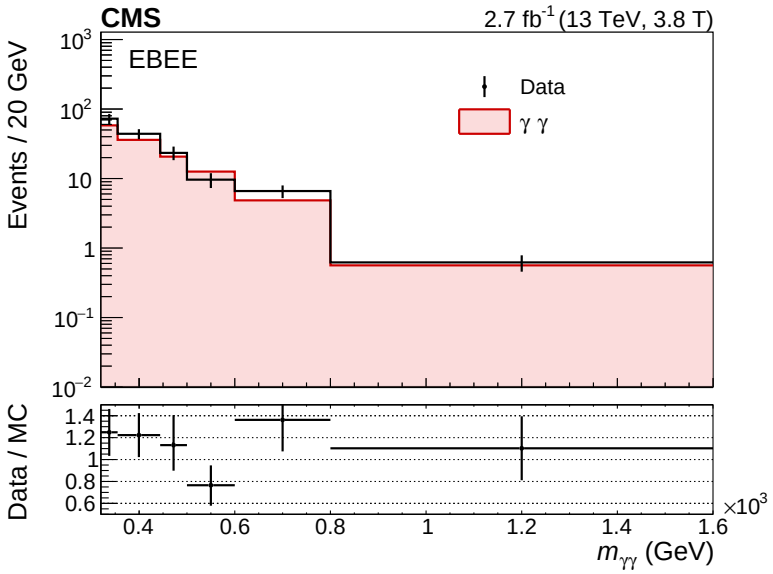


(b) EBEE

Backup: Background Data vs MC (2015 $\gamma\gamma$ component)

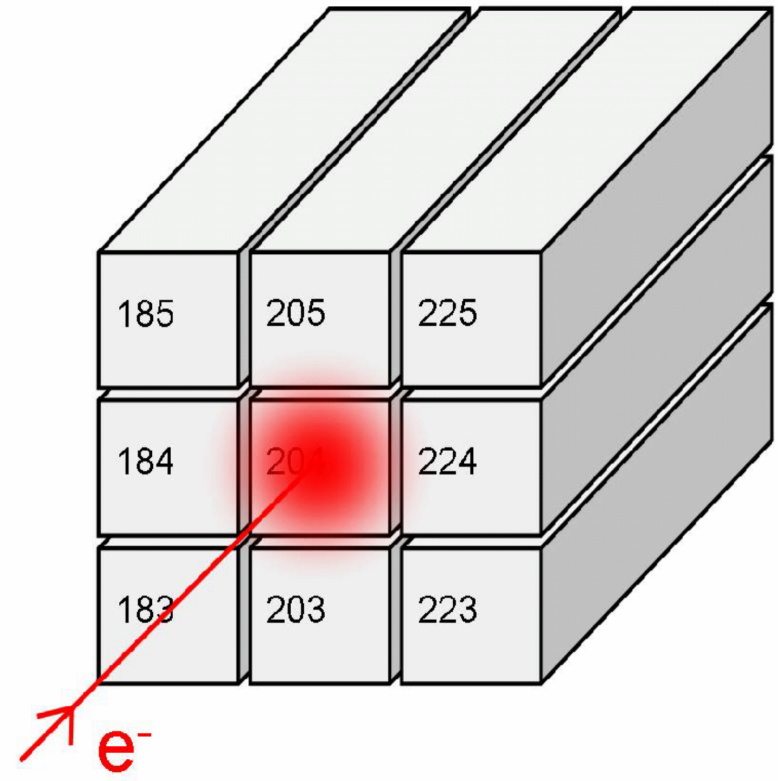


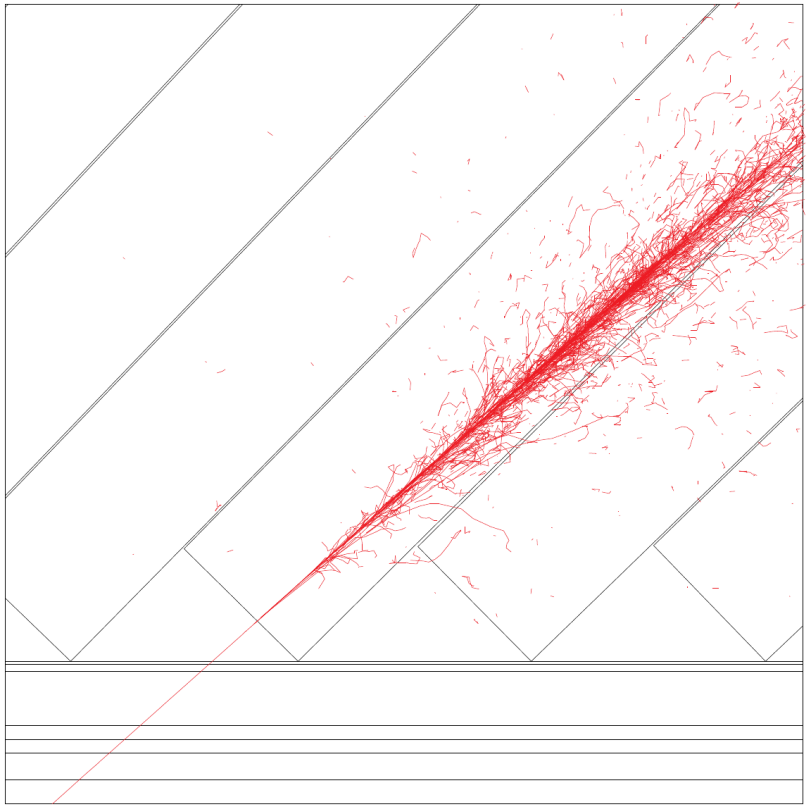
(a) EBEB



(b) EBEE

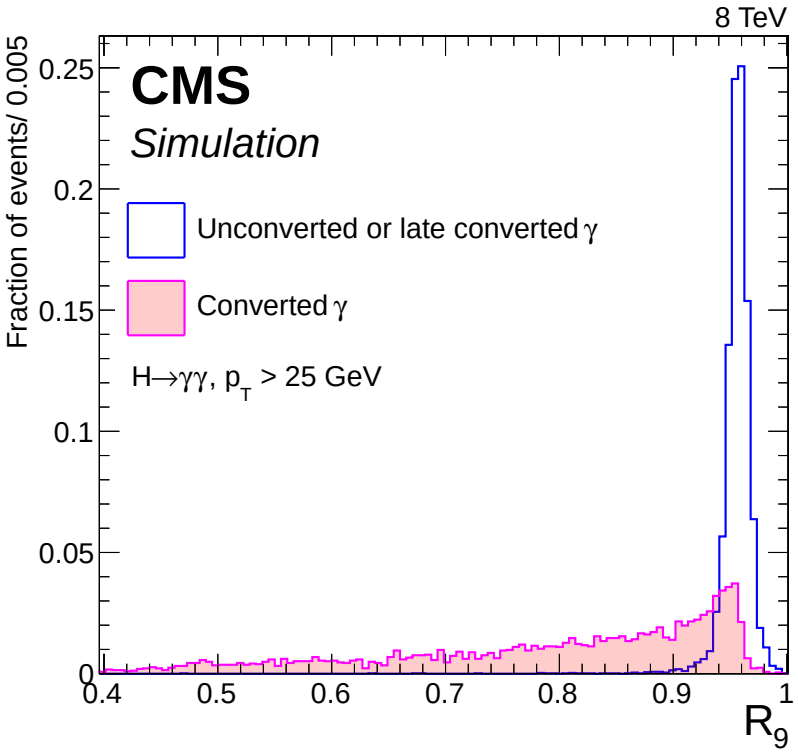
Backup: Electromagnetic shower in ECAL

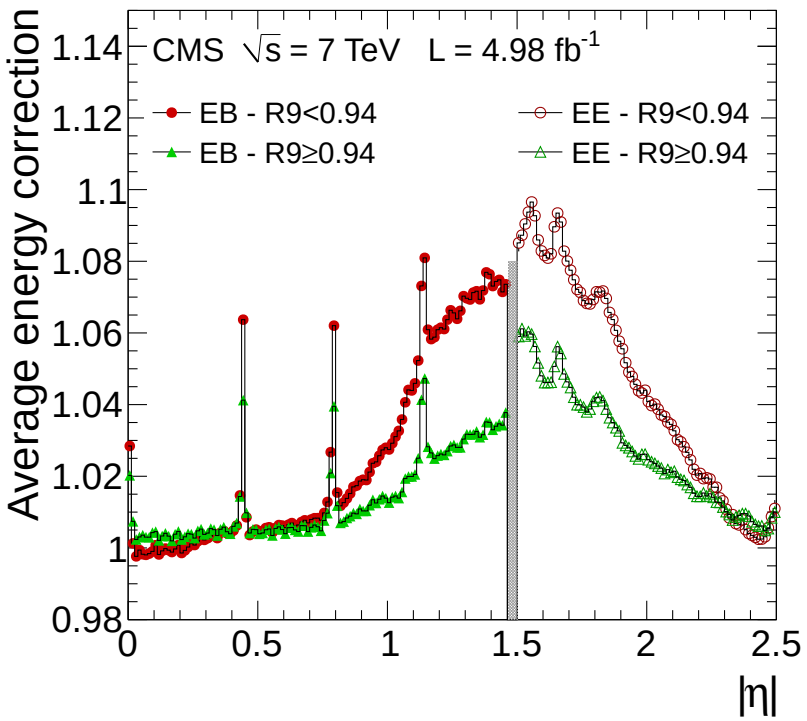




- Crystals are approximately $1R_M^2$ at front face $\rightarrow\sim$ 95% containment in 3x3 grid, $>$ 99% in 5x5 grid

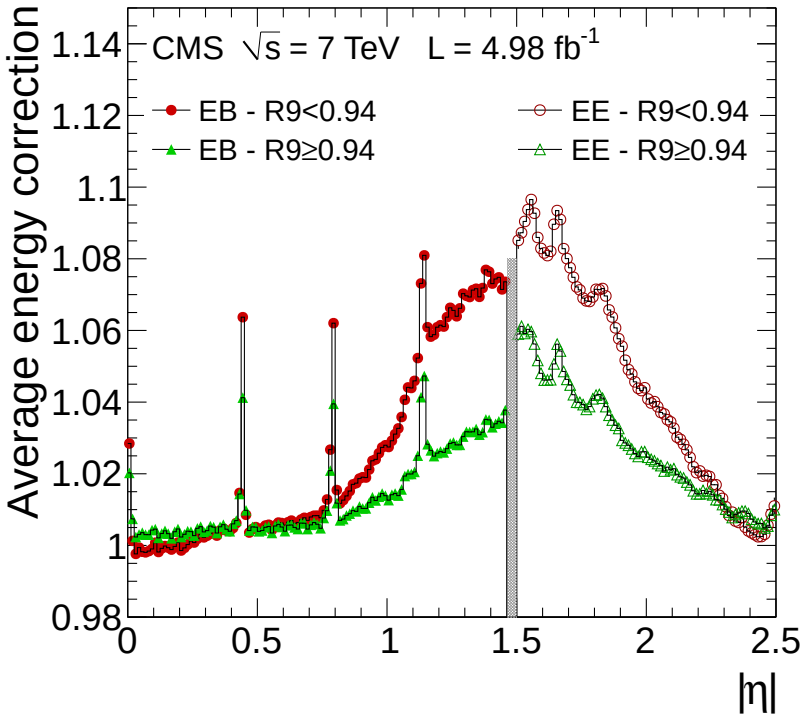
Backup: Inside the corrections



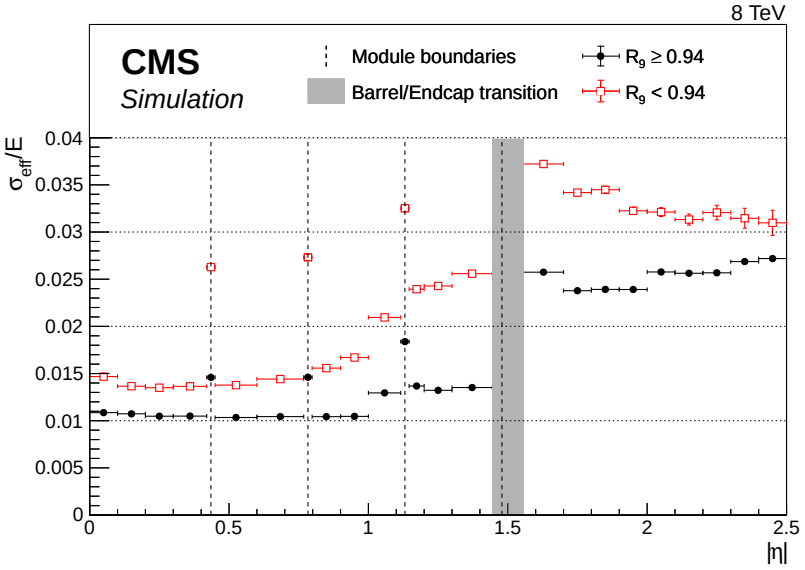


- $R_9 = E_{3x3}/E_{SC}$ is an effective, but not 100% pure conversion tagging variable (electrons and photons treated separately, no explicit converted vs unconverted distinction)
- Correction vs η has a non-trivial correlation with R_9 (and other shower profile variables)

Backup: Per-photon Resolution Estimate



(c) Correction



(d) post-correction resolution

- Strong, but non-trivial relationship between size of correction and post-correction resolution (size of effect vs photon-to-photon fluctuations)
- Per-photon resolution estimate mapped with the full granularity of the multidimensional space used to derive the corrections