First BSM results from Run2 of the LHC: Searches for $\gamma\gamma$ and $Z\gamma$ Resonances

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NEW PHYSICS KOREA INSTITUTE

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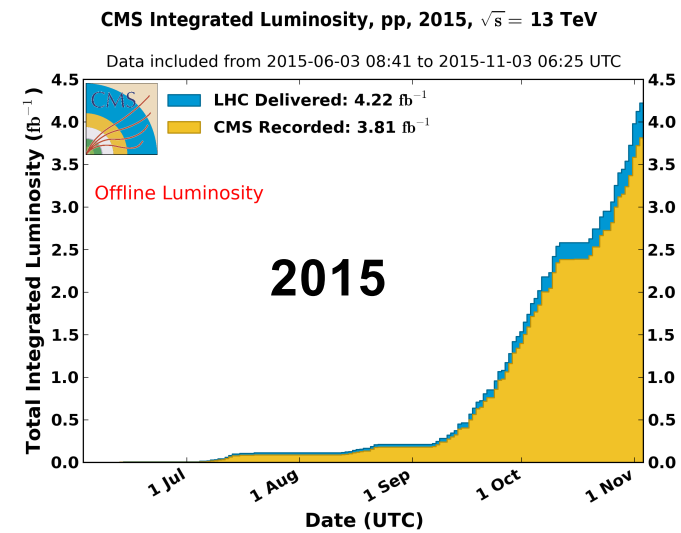
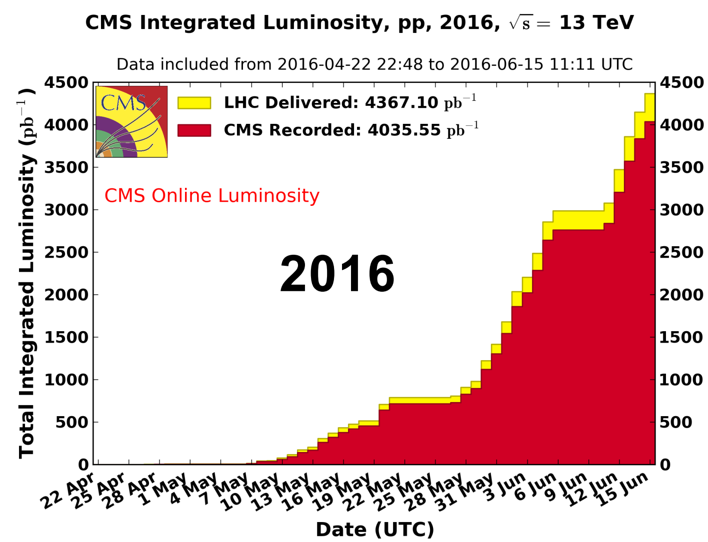
For the CMS Collaboration

Introduction

- I will focus on the following "exotic" searches:
  - Diphoton Resonances (most of talk)
  - Z + γ Resonances
- 2015 Dataset results only
  - 2.8 fb-1 w/ 3.8T
  - 0.6 fb-1 w/ 0T
- 2016 Run well underway!
  - No new results yet (but soon), so don't ask me.
- **All CMS new physics results can be found at:**

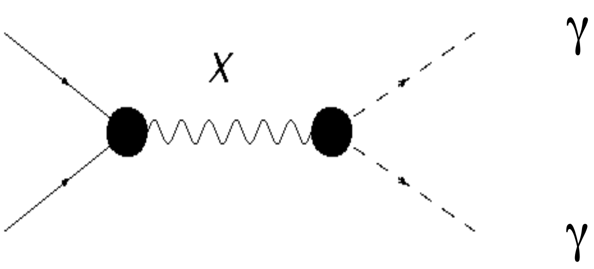
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO





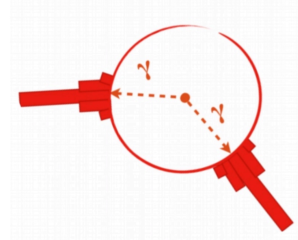
Motivation for Diphoton Resonances Search

- Search for excesses in invariant mass spectra (in this case $\gamma\gamma$)
  - Bump hunt
  - **Generic, powerful and track record for discovery in the past**



- Predicted by several BSM models with extended gauge symmetries, for example:
  1) Models with extended Higgs sectors
     - predict appearance of **spin-0 resonances**
  2) Extra-dimensional models
     - predict appearance of **spin-2 resonances**

Overview of Diphoton Searches from CMS

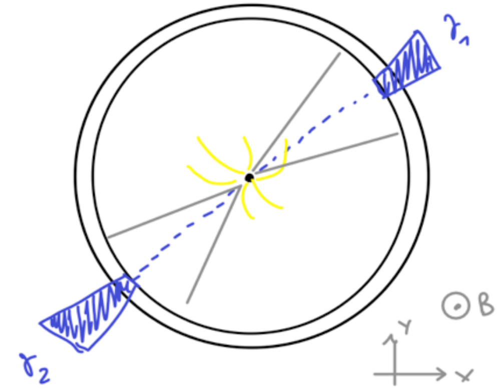


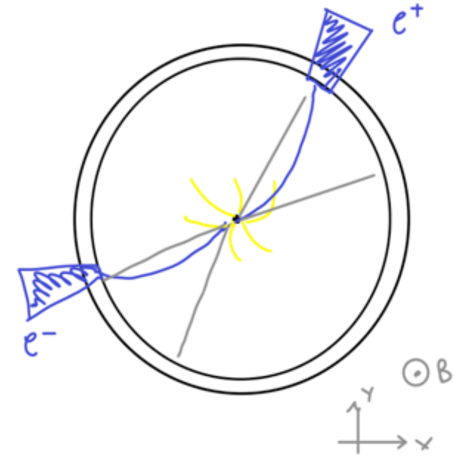
Ref	Title	M_X	Spin-0	Spin-2
PLB 750 (2015) 494	Search for diphoton resonances in the mass range from 150 to 850 GeV in pp collisions at √**s = 8 TeV**	150-850GeV	✔	✔
EXO-12-045	Search for High-Mass Diphoton Resonances in pp Collisions at √**s = 8 TeV** with the CMS Detector	0.5-3TeV	✗	✔
EXO-15-004 (Dec. 2015)	Search for new physics in high mass diphoton events in proton-proton collisions at √**s = 13 TeV**	0.5-4.5TeV	✗	✔
EXO-16-018 - **Mar. 2016, update of above** - **Jun. 2016 submitted to PRL (NEW!)**	Search for resonant production of high-mass photon pairs in pp collisions at √**s=8 TeV and 13 TeV**	0.5-4.5TeV	✔	✔

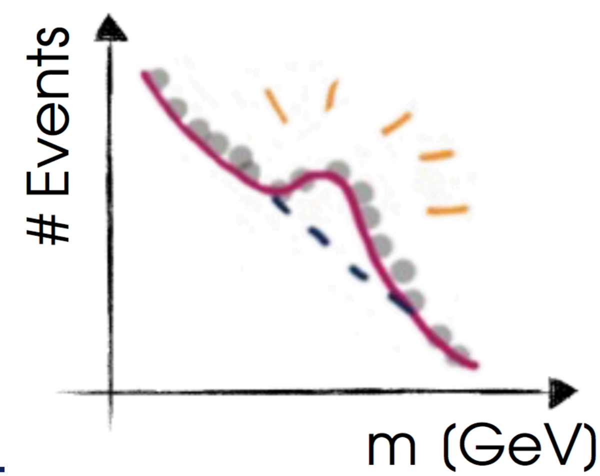
Diphoton Analysis Strategy

1) Select diphoton pairs and search for a local excess in $m_{\gamma\gamma}$ spectrum: **Simple and clean final state!**
   - Two high p_T photons
     - High energy deposits in EM calorimeter
     - Isolated: No additional activity nearby
     - Events are split into different categories to enhance sensitivity
2) Measure energy scale and resolution efficiency in the data
   - e.g. with Z→ ee events
3) Background model is a parameterized function obtained from data
4) Search for a localized excess in the invariant mass spectrum
   - Test compatibility of the data with resonant diphoton production

Performed as a "blind analysis"



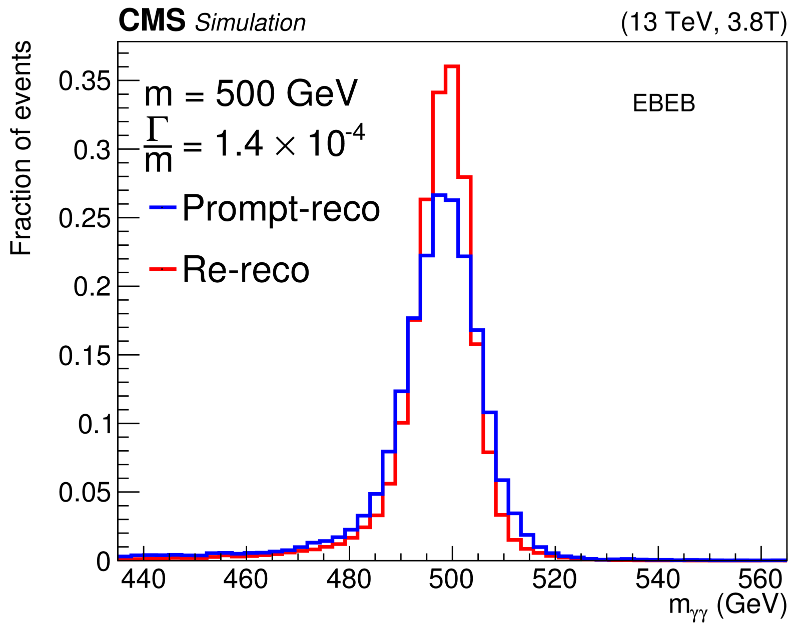




ECAL Channel-to-Channel Calibration

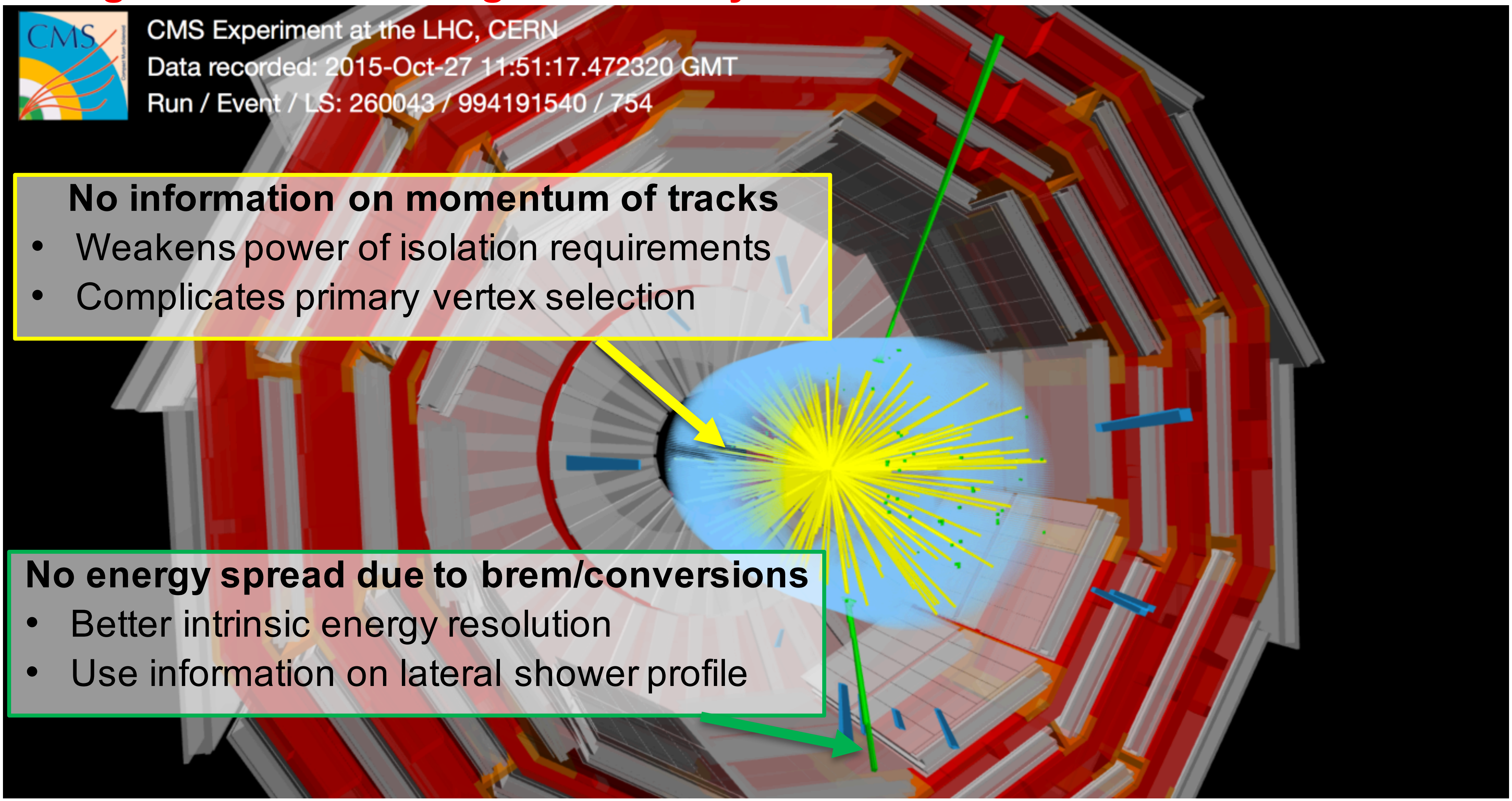
The ECAL calibration is crucial for the energy resolution

- For the updated results in EXO-16-018 the data were reprocessed using new channel-to-channel calibrations obtained from the 2015 dataset
  - 30% improvement in the mass resolution for $m_{\gamma\gamma}$>500 GeV (search region)!
  - 10% improvement in analysis sensitivity!



Challenges with the 0T data

Significant re-thinking of the analysis needed to use data w/out B field

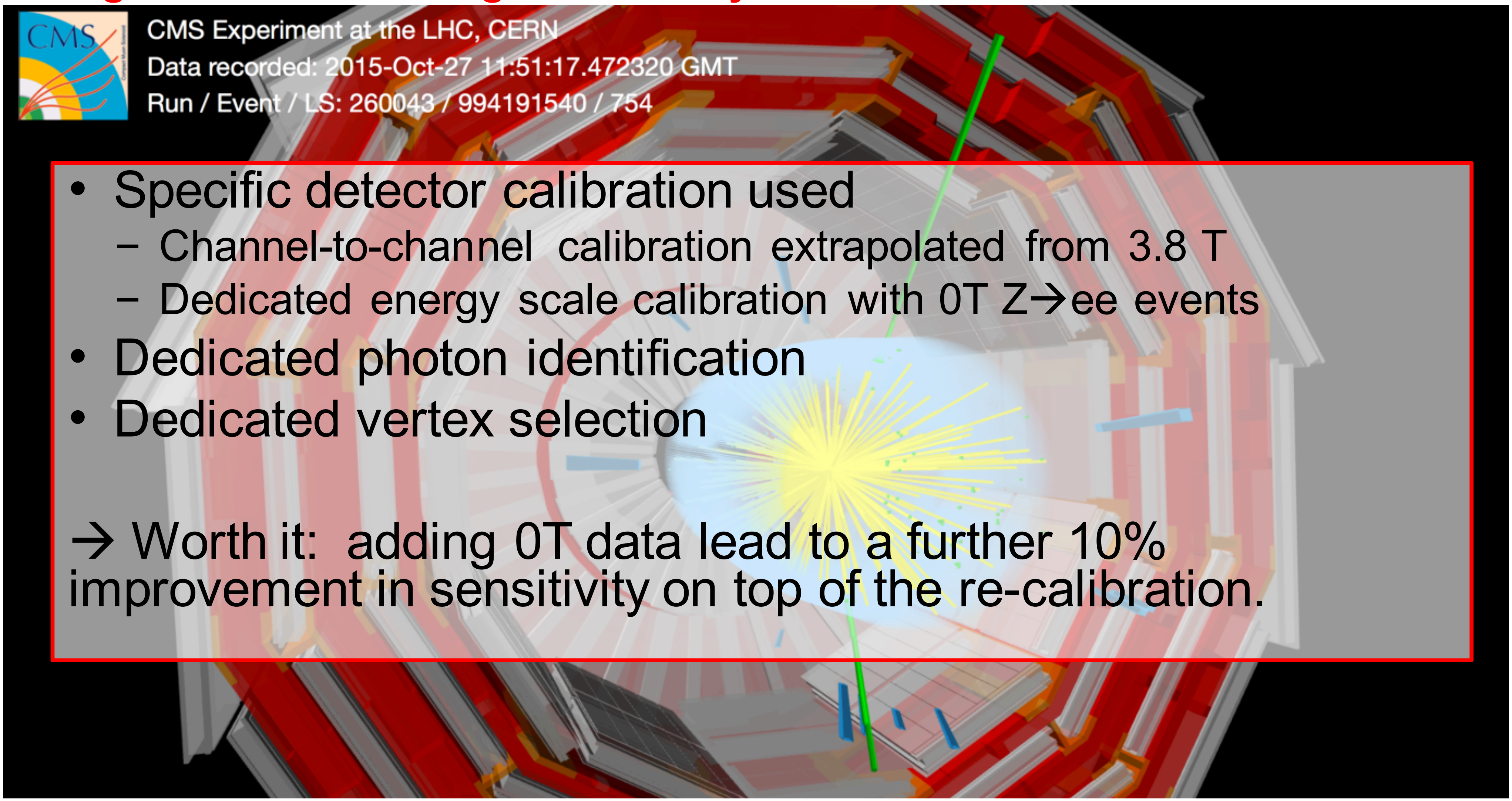


No information on momentum of tracks
- Weakens power of isolation requirements
- Complicates primary vertex selection

No energy spread due to brem/conversions
- Better intrinsic energy resolution
- Use information on lateral shower profile

Challenges with the 0T data

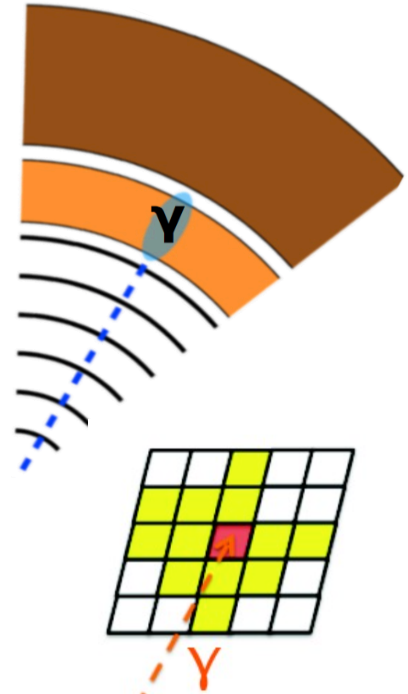
Significant re-thinking of the analysis needed to use data w/out B field



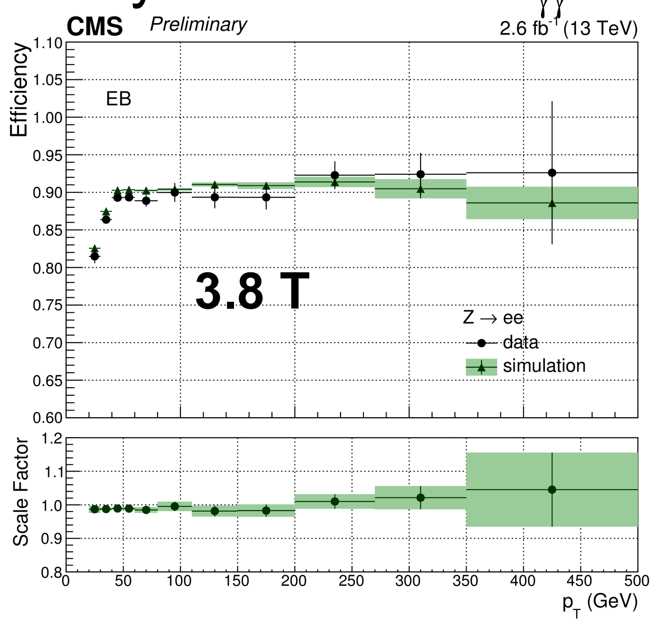
- Specific detector calibration used
  - Channel-to-channel calibration extrapolated from 3.8 T
  - Dedicated energy scale calibration with 0T Z→ee events
- Dedicated photon identification
- Dedicated vertex selection

→ Worth it: adding 0T data lead to a further 10% improvement in sensitivity on top of the re-calibration.

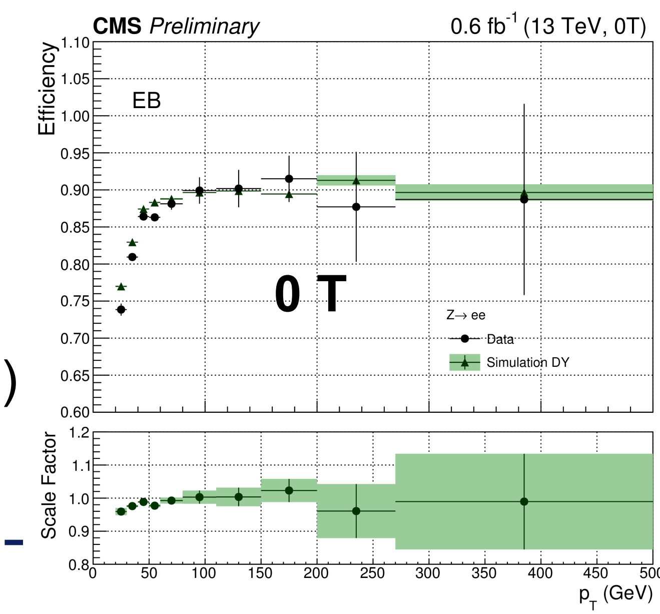
Photon Reconstruction and Trigger



- Photons:
  - Reconstructed from energy deposits in the ECAL, and grouped into “superclusters”
  - Require no associated tracks in the inner detectors
  - Dedicated photon ID for high-p_T objects
- Trigger:
  - Two photons with p_T>60(40) GeV for B=3.8T(0T)
  - Fully efficient for $m_{\gamma\gamma}$>500 GeV

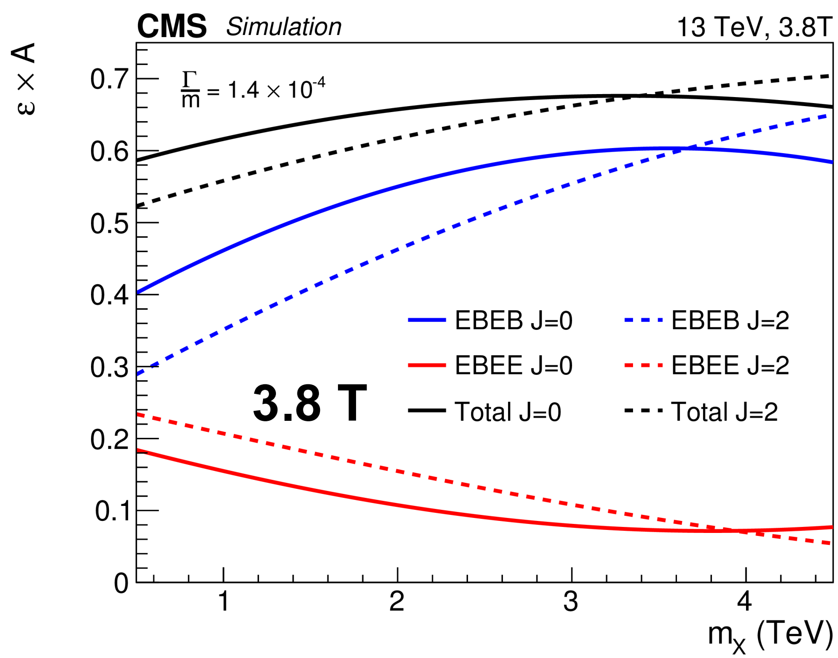


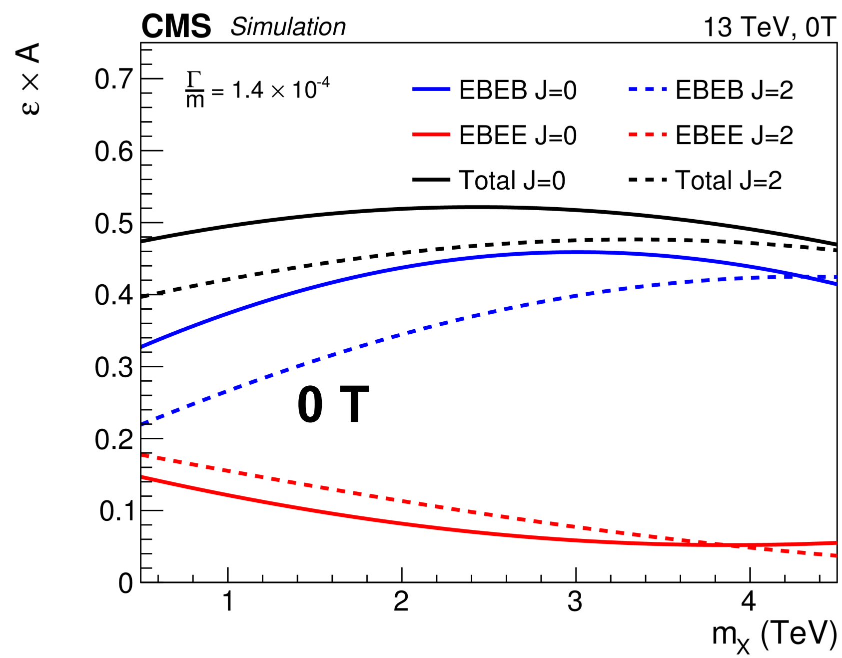
High p_T photon ID (derived with Z→ee events)



Diphoton Event Selection

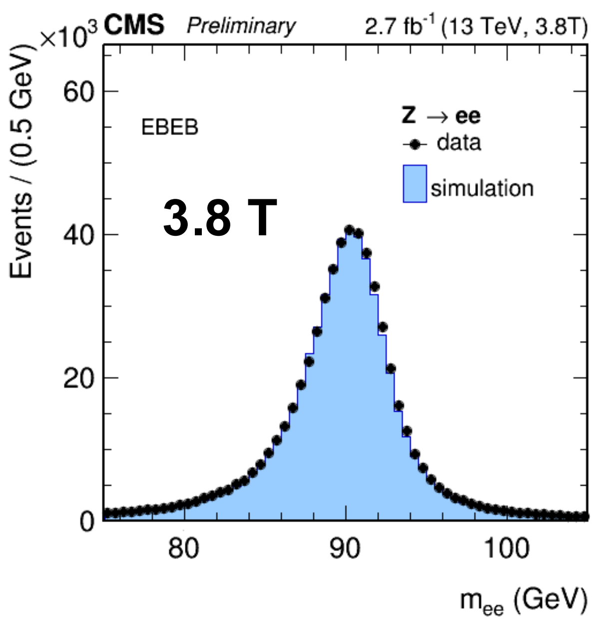
- **Two photons:** p_T >75 GeV. At least one in the barrel ($|\eta| < 1.44$)
- **Four event categories:** barrel-barrel (EBEB) and barrel-endcaps (EBEE), x (3.8 T and 0 T)
- **Search region:** $m_{\gamma\gamma}$> 500 GeV
- **Dedicated photon ID with isolation**
  - Per-photon efficiency in the barrel: 90 (85)% at 3.8 (0)T
  - Per-photon efficiency in the endcaps: 85 (70)% at 3.8 (0)T

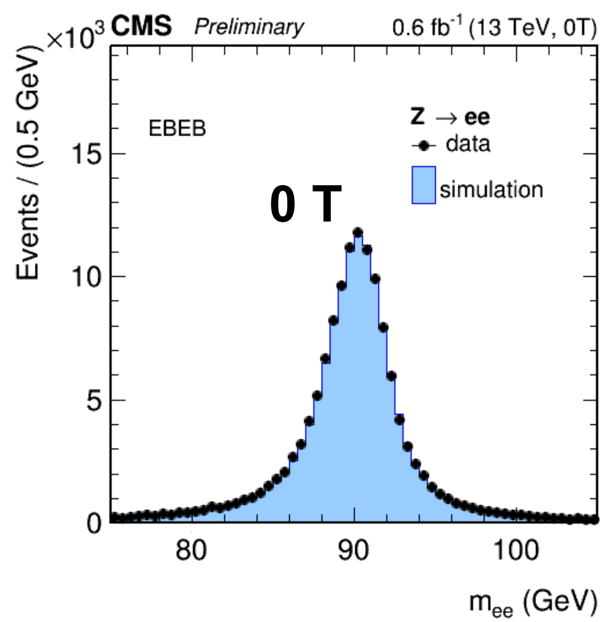




Energy Scale Calibration

- **Use the Z→ee peak:** simultaneously adjust energy scale (data) and resolution (MC), as a function of η and cluster shape of elec candidates
- **Stability vs. E_T:** checked with boosted events up to ~150 GeV
  - Deviations within 0.5 (0.7)% in barrel (endcaps)
- **Dedicated calibration for 0 T:** same procedure as for 3.8 T but no binning in cluster shape (no radiative losses)
  - Scale corrections ~1% larger than 3.8T. Resolution corrections similar to 3.8 T
  - Level of stability vs. E_T ~same as for 3.8 T

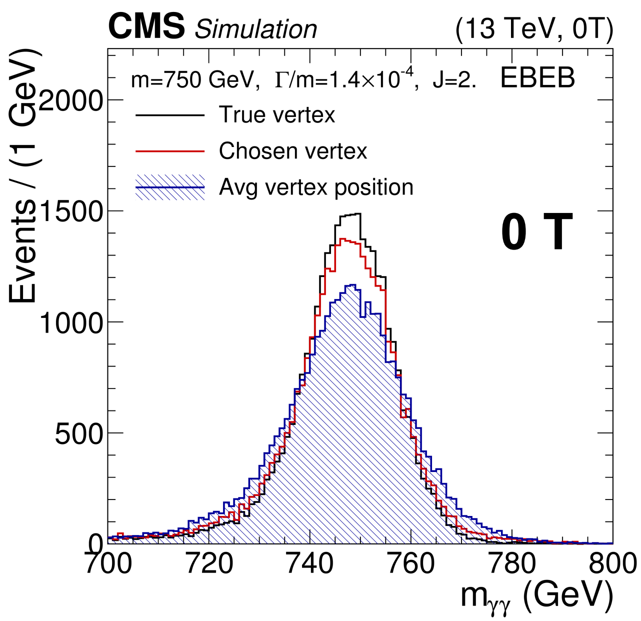


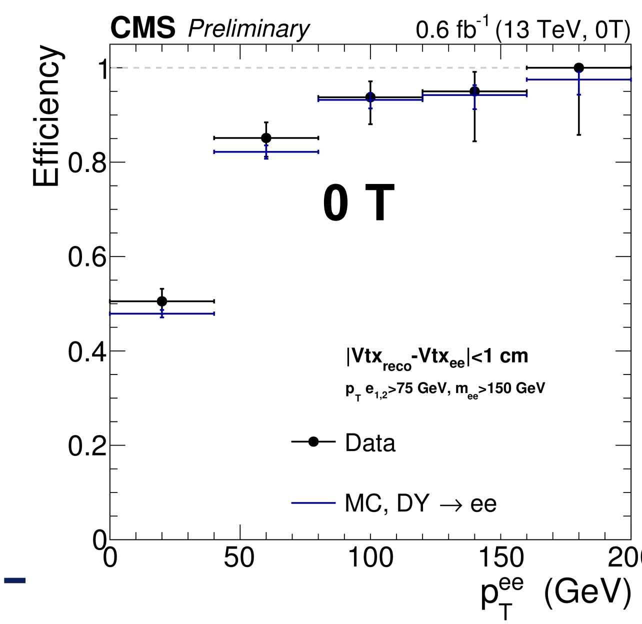


Vertex Identification

Vertex ID important for good mass resolution

- **For 3.8 T:** Multivariate method using recoil and tracks kinematics, trained for SM H→γγ
- **For 0 T:** Simpler algorithm based on track-counting. Vertex with the highest track multiplicity
- **Correct assignments:** 90% at 3.8T, 60% at 0T for $m_{\gamma\gamma}$>500 GeV
  - Modeling of correct vertex assignment tested in data
  - **3.8T:** use μμ and γ+jet events. **0T:** use ee events

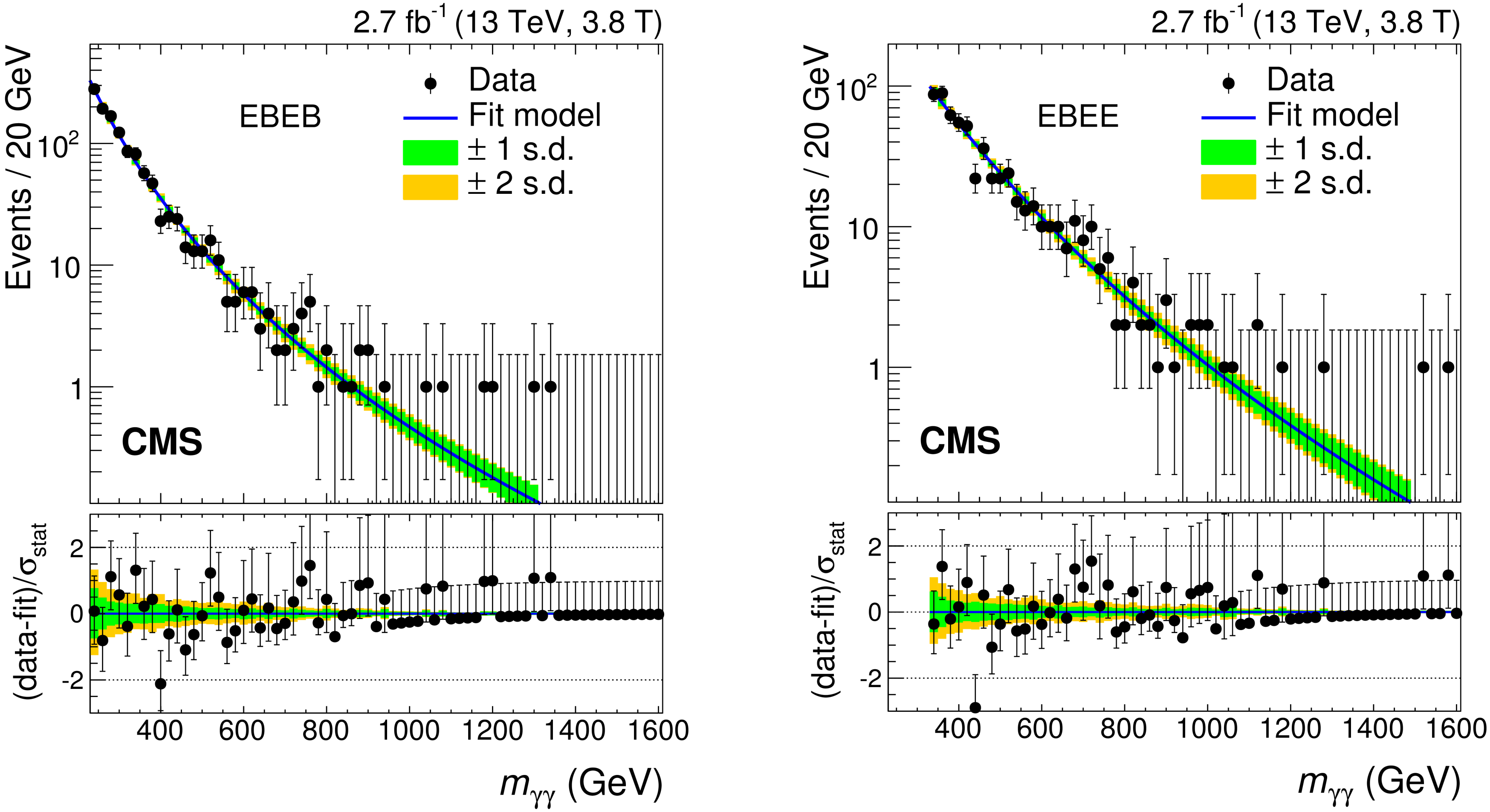




Diphoton Mass Spectra: 3.8 T

Fit $m_{\gamma\gamma}$ in range 0.5-4.5 TeV in 4 categories: (EBEB, EBEE)x(3.8T, 0T)

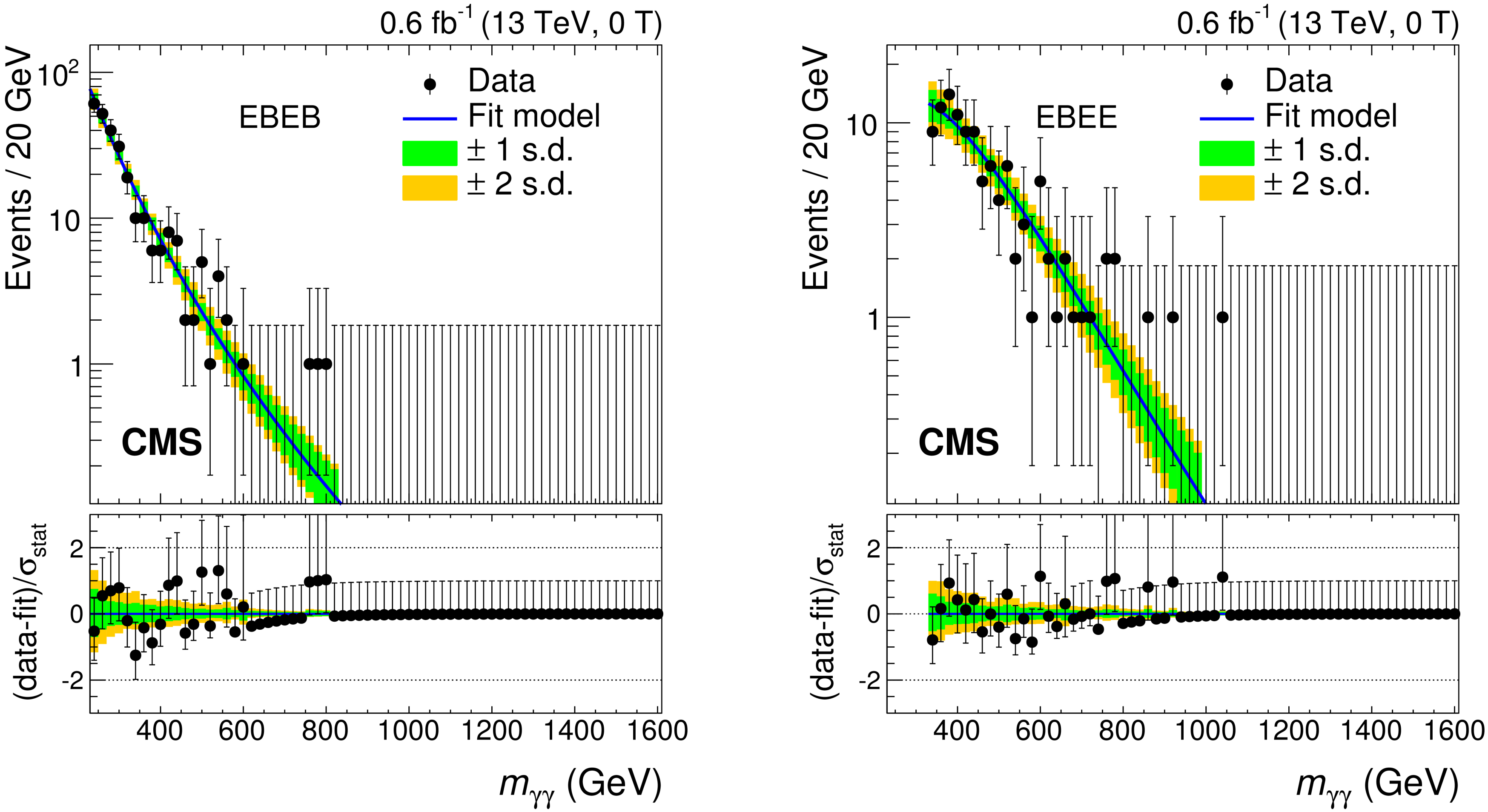
Background: parametric function: $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot log(m_{\gamma\gamma})}$



Diphoton Mass Spectra: 0 T

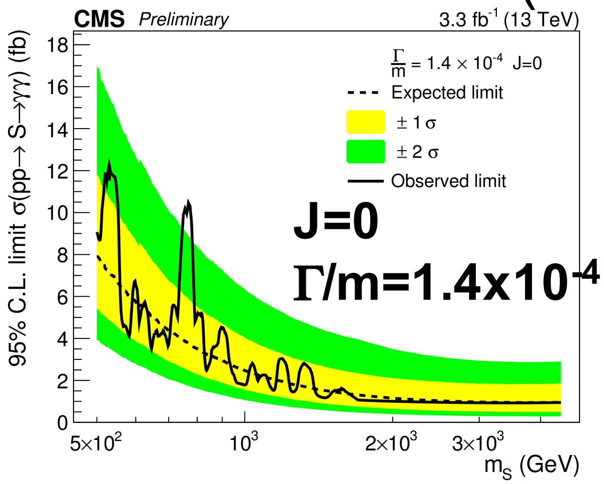
Fit $m_{\gamma\gamma}$ in range 0.5-4.5 TeV in 4 categories: (EBEB, EBEE)x(3.8T, 0T)

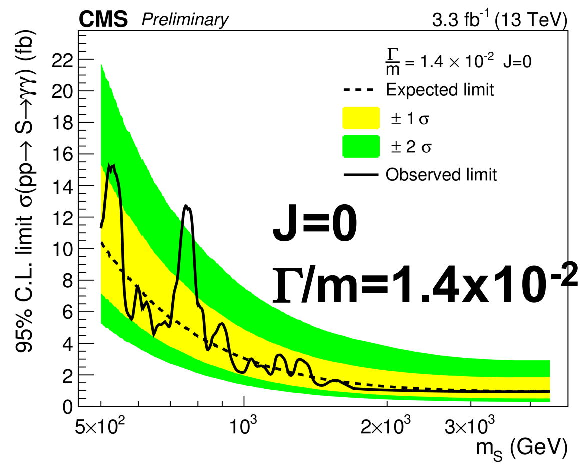
Background: parametric function: $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot log(m_{\gamma\gamma})}$

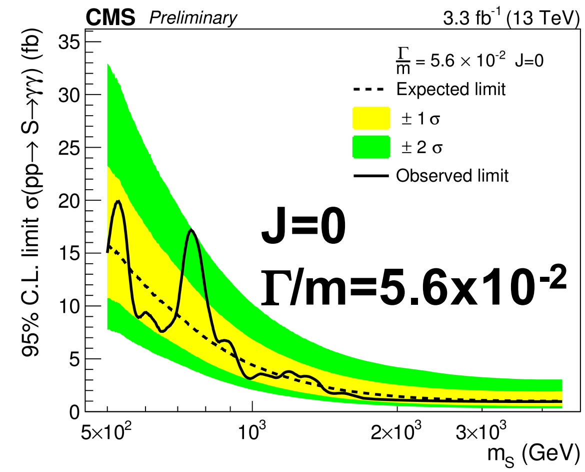


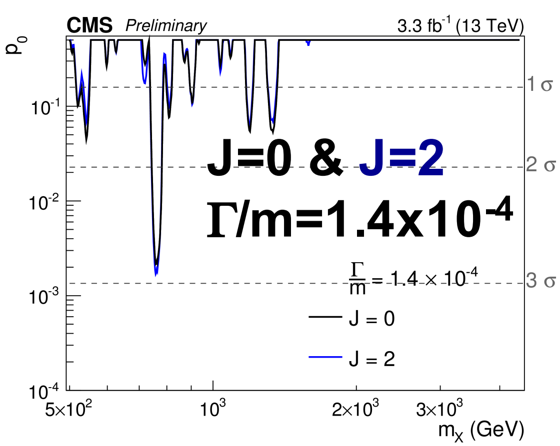
Diphoton Upper Limits and P-values

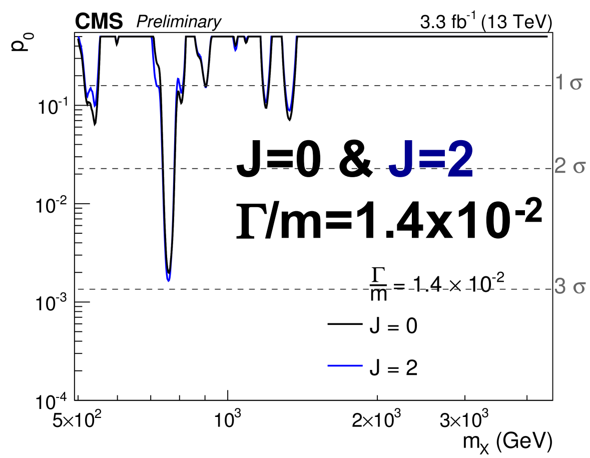
- Combined fit of all 4 categories
- **Spin-0** (gluon-fusion) and **Spin-2** (RS-graviton) interpretations. **Three widths** ($\Gamma/m=1.4\text{x}10^{-4}$, $1.4\text{x}10^{-2}$, $5.6\text{x}10^{-2}$)

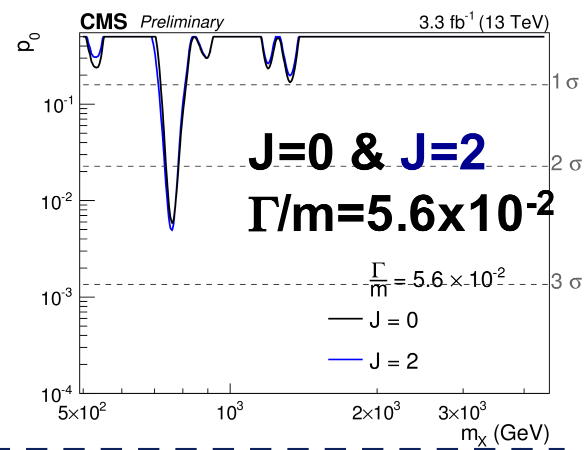






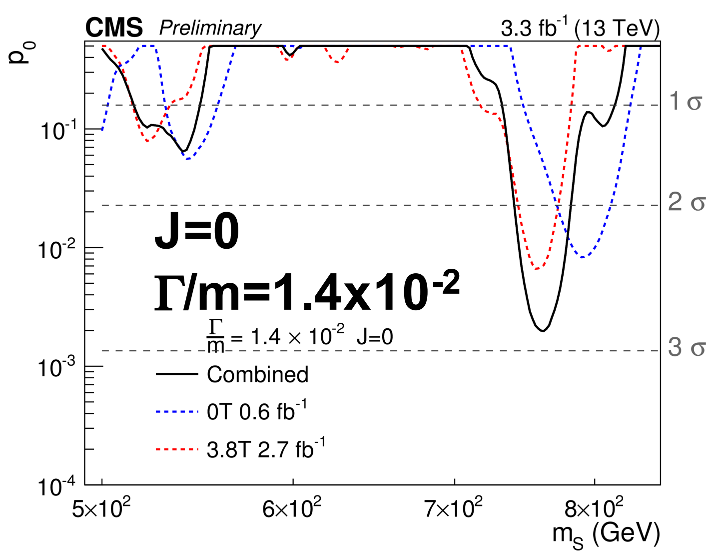


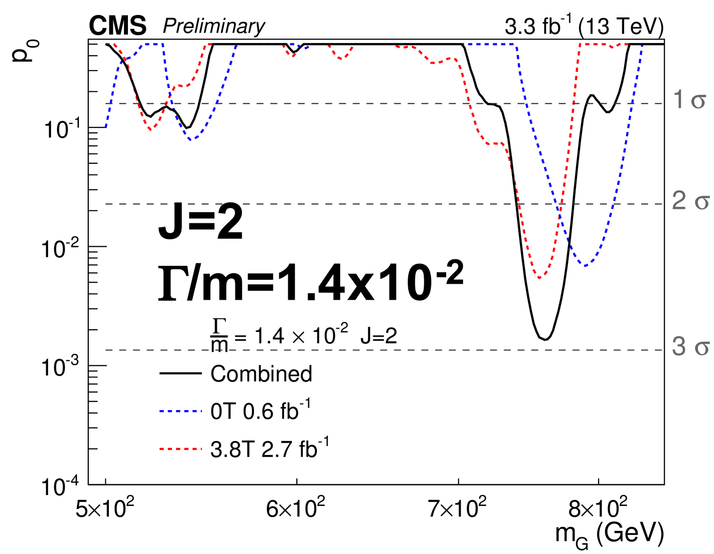




Significance of Largest Excess

- Largest excess observed for **$m_{\gamma\gamma}$ = 760GeV and Γ/m 1.4x10^{-2}**
- **Local significance: 2.8-2.9σ** depending on the spin hypothesis.
- Trial factors from sampling distribution of max(p_0), considering all the 6 signal hypotheses (spin and width).
- **"Global" significance < 1σ**
- Excess mostly driven by EBEB, 3.8T category.

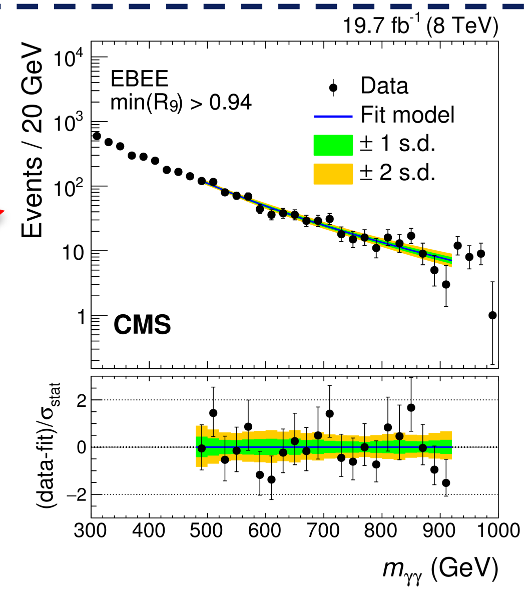




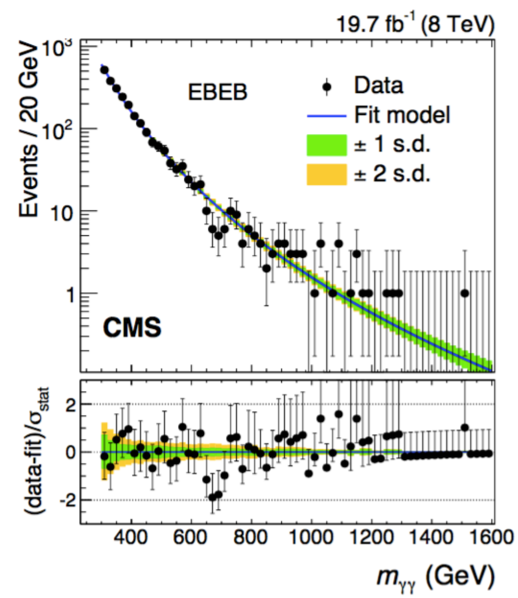
Diphoton Combination of 8TeV and 13TeV

CMS performed two searches for diphoton resonances at 8TeV

- **$m_X \leq 850$ GeV**: (*PLB 750 (2015) 494*)
  - Further categorized according to cluster energy shape variable (R9)
  - Different bkg parameterization used (yields similar levels of uncertainty)



- **$m_X > 850$ GeV**:
  - Extended 8TeV search
  - Similar analysis to 13 TeV



- Combination in all 6 signal hypotheses (widths and spins) tested at 13TeV

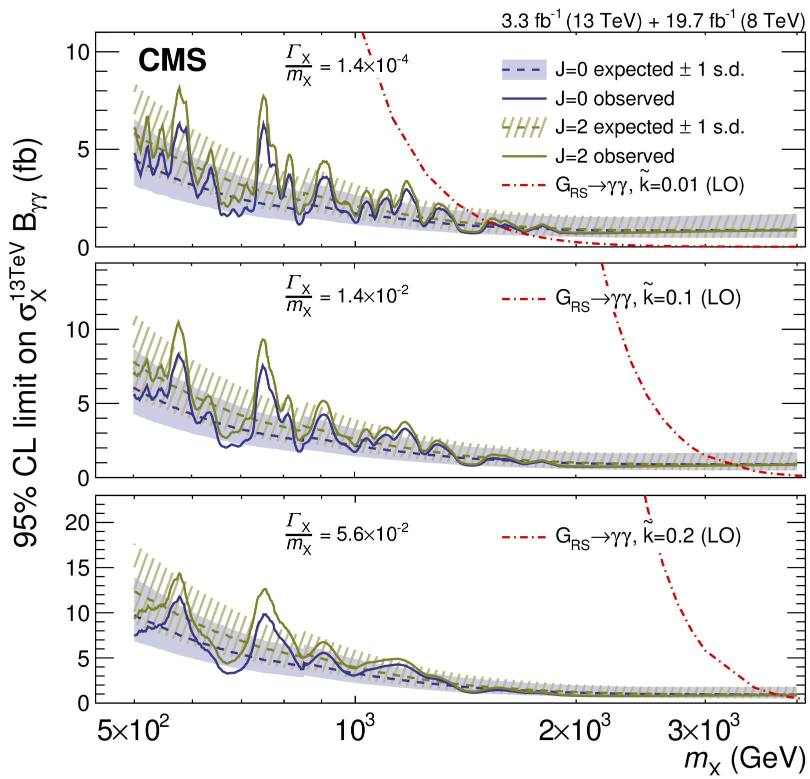
Diphoton Combined 8+13TeV Results: Normalized to 13TeV x-section

- Sensitivity improved by **20-40%**
- Largest excess observed at **$m_{\gamma\gamma}$ = 750 GeV** and for narrow width.
  - **Local significance: 3.4σ**
  - Taking into account mass range 500-3500GeV and all signal hypotheses, **"global" significance** becomes **1.6σ**

Γ/m=1.4 x10^{-4}

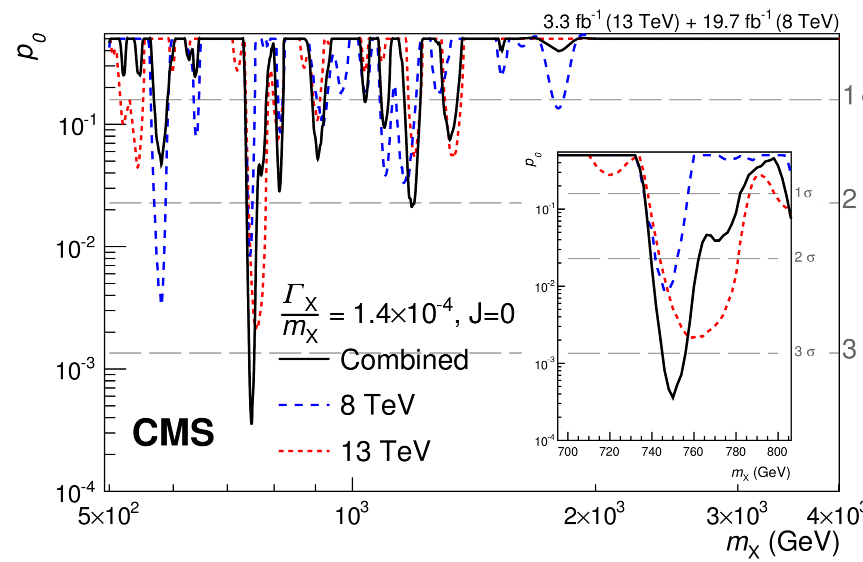
Γ/m=1.4 x10^{-2}

Γ/m=5.6 x10^{-2}



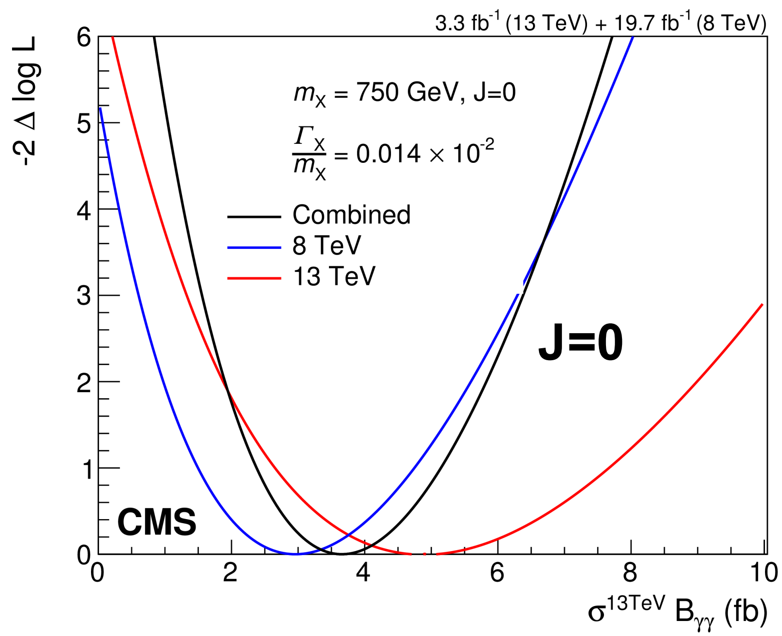
J=0
Γ/m=1.4x10^{-4}

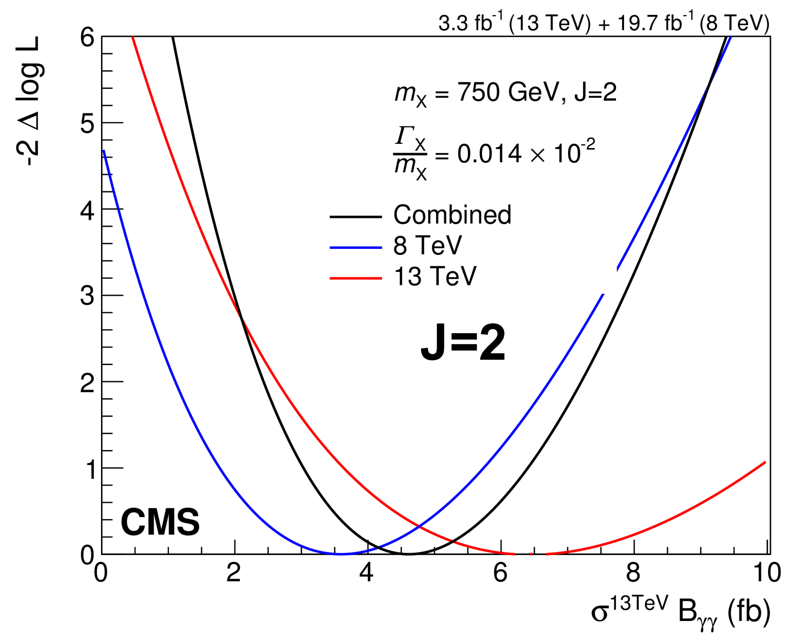
Similar results for J=2



Consistency between 8TeV and 13TeV

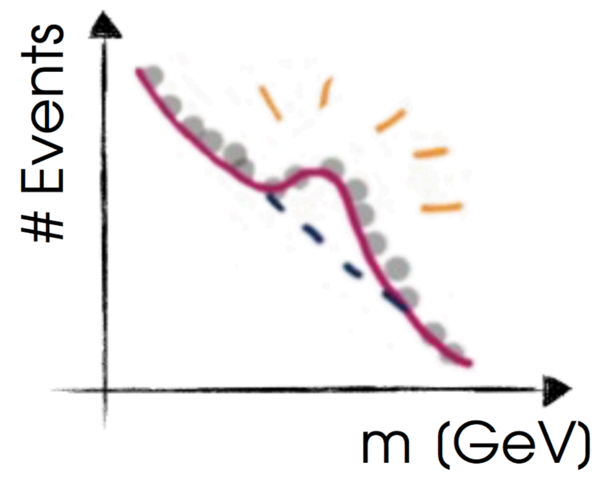
- Evaluated through likelihood scan vs equivalent σ_{13TeV} at m_X = 750GeV under both spin (narrow width) hypotheses
- Cross section ratios at 750GeV:
  - For spin 0 (gg→ S): $\sigma_{8TeV}/\sigma_{13TeV}$ = 0.22
  - For spin 2 (RS graviton): $\sigma_{8TeV}/\sigma_{13TeV}$= 0.24
- **Compatible results observed in both datasets**





Motivation for Zγ Resonances

- If diphoton excess is real, expect additional decays to WW, ZZ and Zγ from SU(2) x U(1) symmetry.
  - **Zγ particularly important if new resonance couples preferentially to hyper-charge**.
- Therefore, a search for new resonances decaying to Zγ could shed more light (pun intended!) on the 750 GeV excess
- Similar signature as in diphoton analysis
  - Search strategy measures the non-resonant background directly and looks for localized excesses



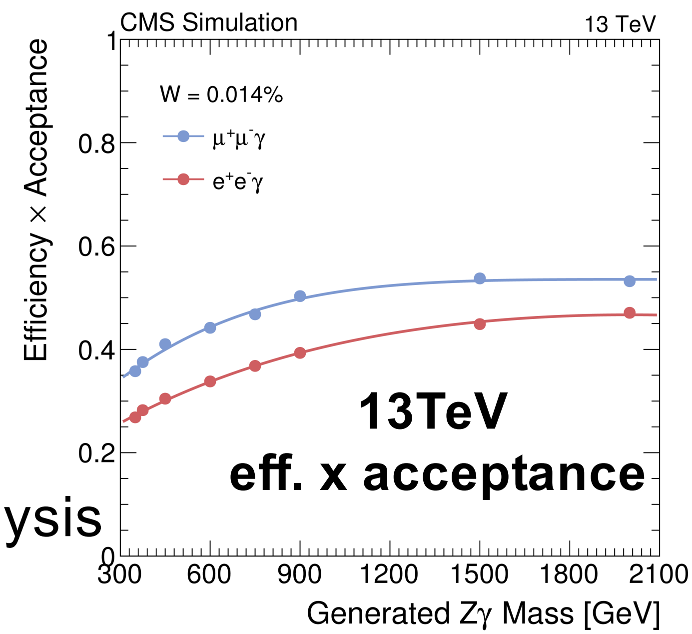
Z(→$\ell\ell$)γ Resonance Search

Search for Z+γ resonance, with either Z→ee or Z→μμ

- 8 TeV (HIG-16-014) and 13 TeV (EXO-16-019) searches
- Dedicated event selection:
  - $p_T(\ell)$ > 20,10 GeV [8TeV] and > 25,20 GeV [13 TeV]
  - modified isolation cone for high p_T leptons
  - $p_T(\gamma)$ > 40 GeV and ΔR > 0.4 from leptons
  - suppress backgrounds with:

$$p_T(\gamma) > \frac{40}{150} \cdot m_{Z\gamma}$$

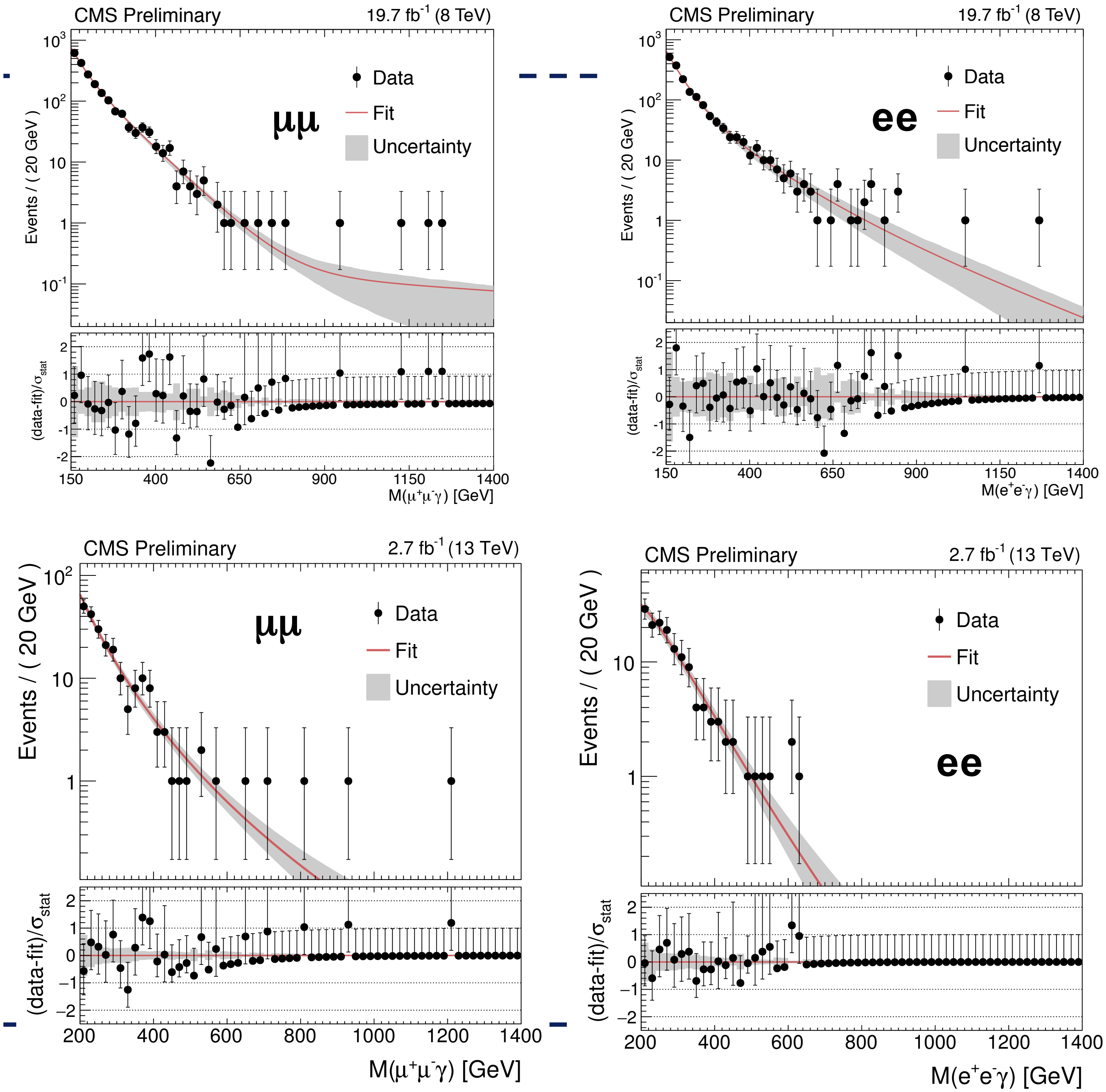
  - $M_{\ell\ell}$ > 50 GeV [8TeV] and $M_{\ell\ell}$ 50-130 GeV [13 TeV]
- Fit background to smoothly falling fuction
  - 13 TeV: similar function as in diphoton analysis
  - 8 TeV: sum of exponentials
- Fit for resonant signal production
  - $M_{Z\gamma}$>150 GeV [8TeV] and > 200 GeV [13TeV]



Zγ Mass Spectra

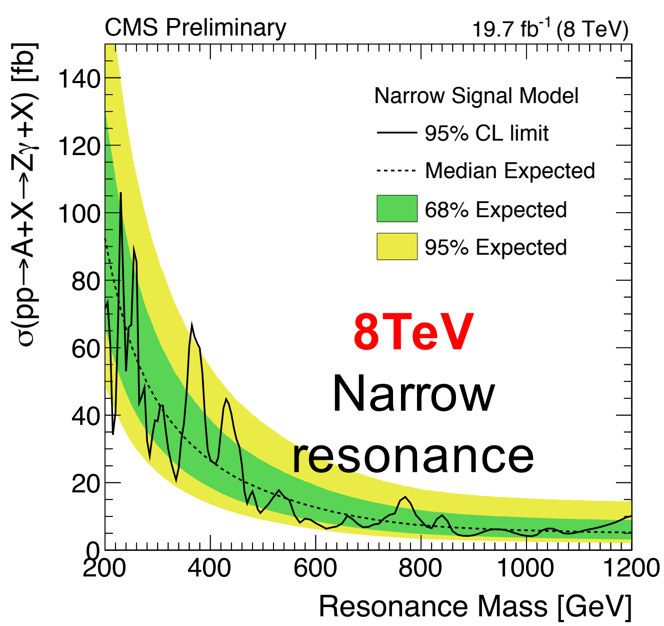
8TeV

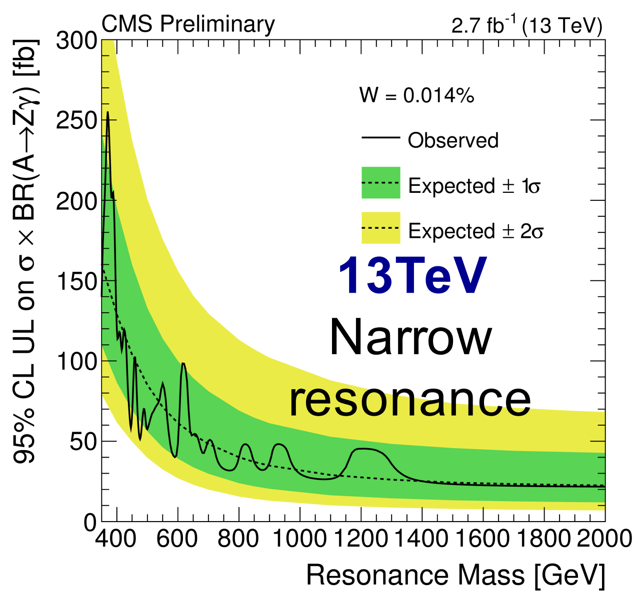
13TeV

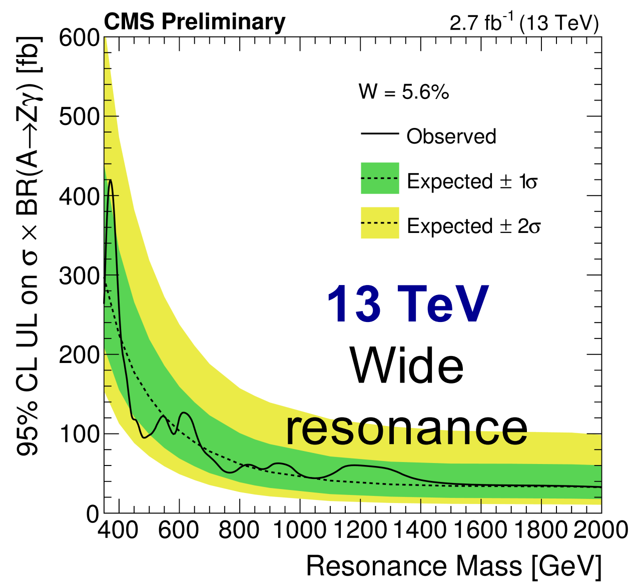


Zγ Results

- **8TeV:** only narrow resonance considered
  - Probe masses between 200-1200 GeV
- **13TeV:** both narrow and wide resonances
  - Probe masses between 350-2000 GeV

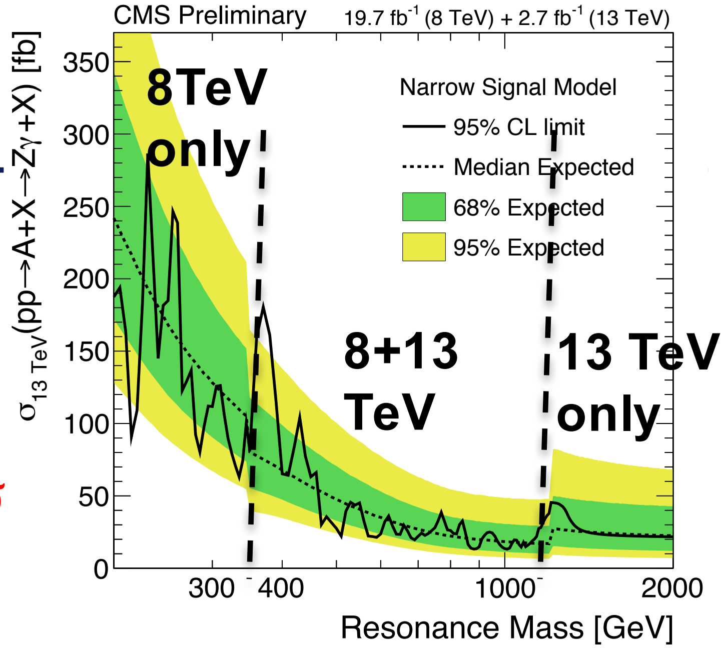




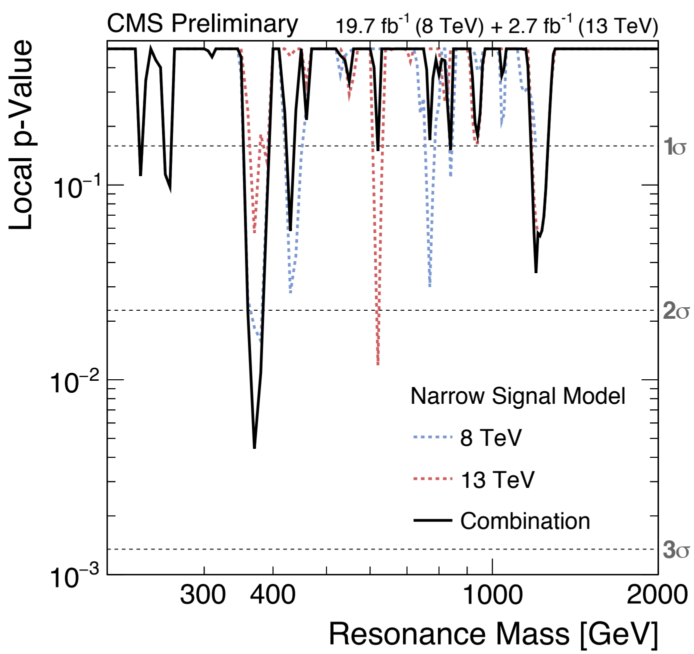


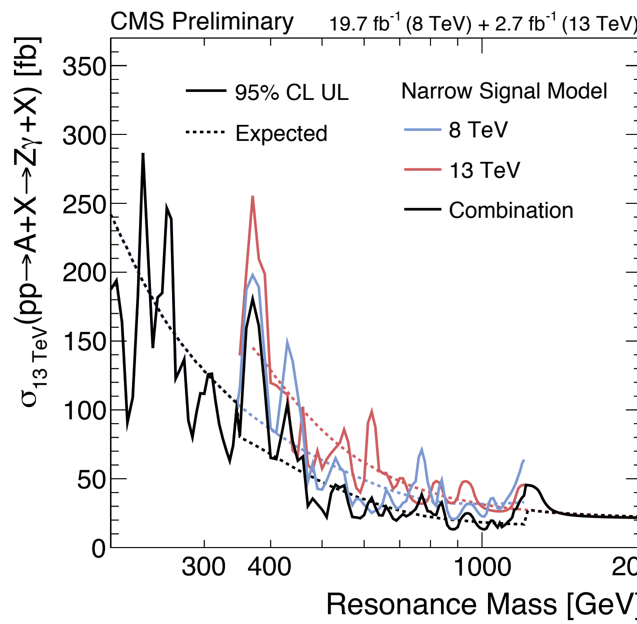
Zγ 8+13 TeV Combination

- Combination of results take into account parton luminosity ratios
  - $\sigma_{13TeV}/\sigma_{8TeV}$ = 4.3 @ 750 GeV
- Local significance @370 GeV is 2.6 σ
  - Global significance < 1σ



NEW!

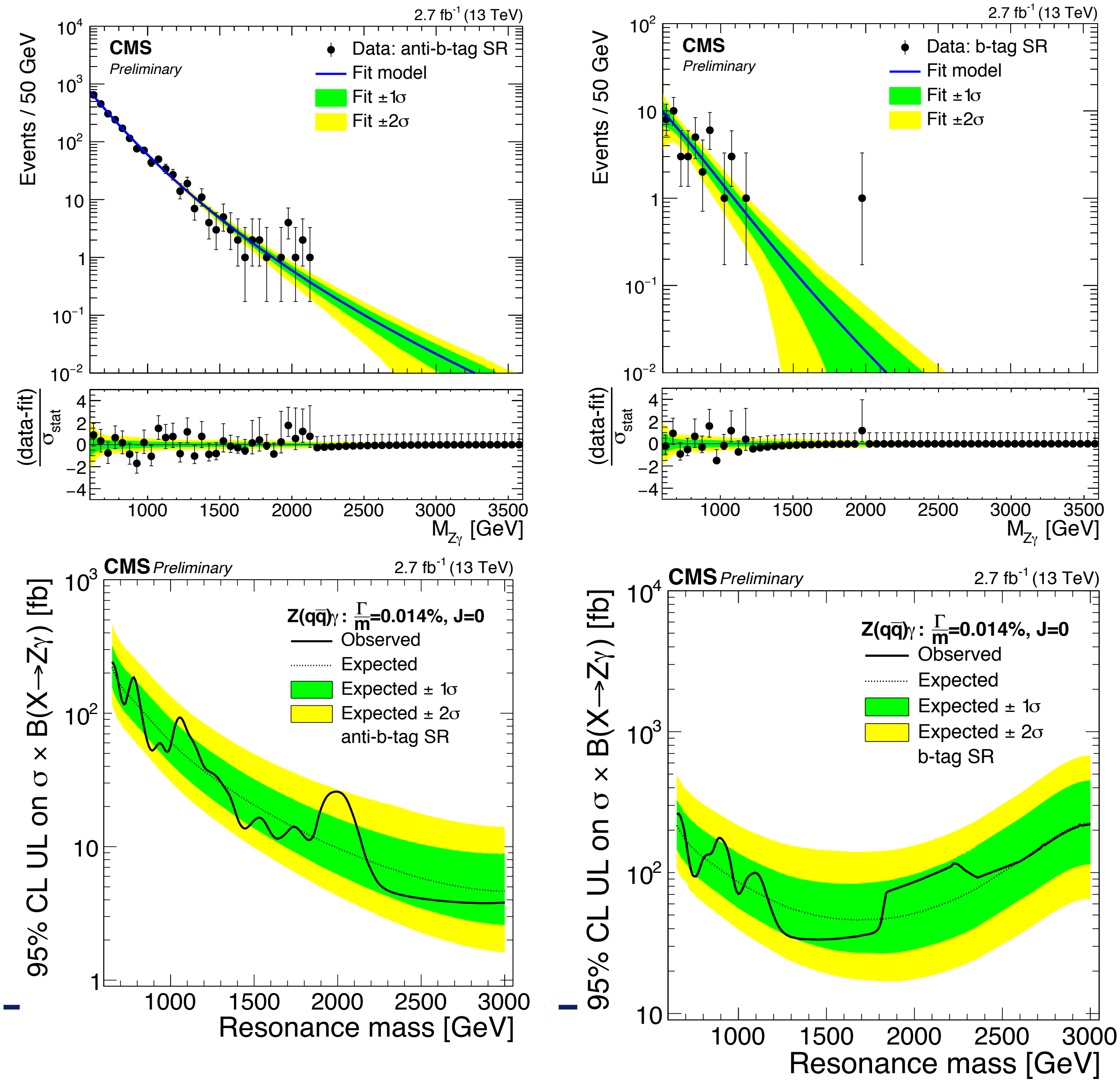




Zγ in hadronic channel (NEW!)

Hot off the press!

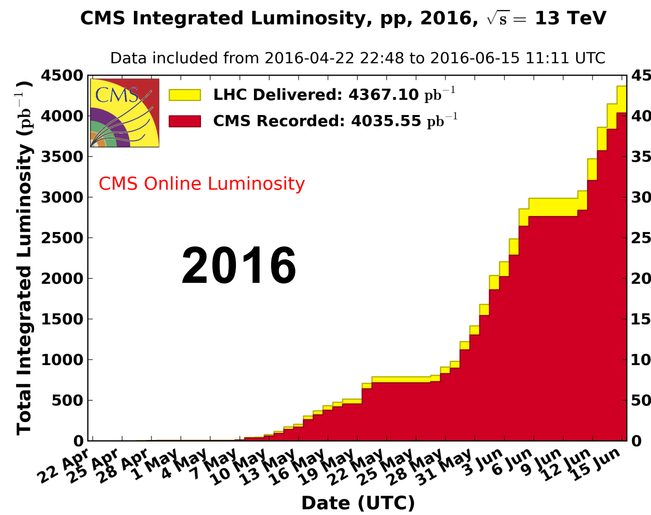
CMS-PAS-EXO-16-020



Summary and Outlook

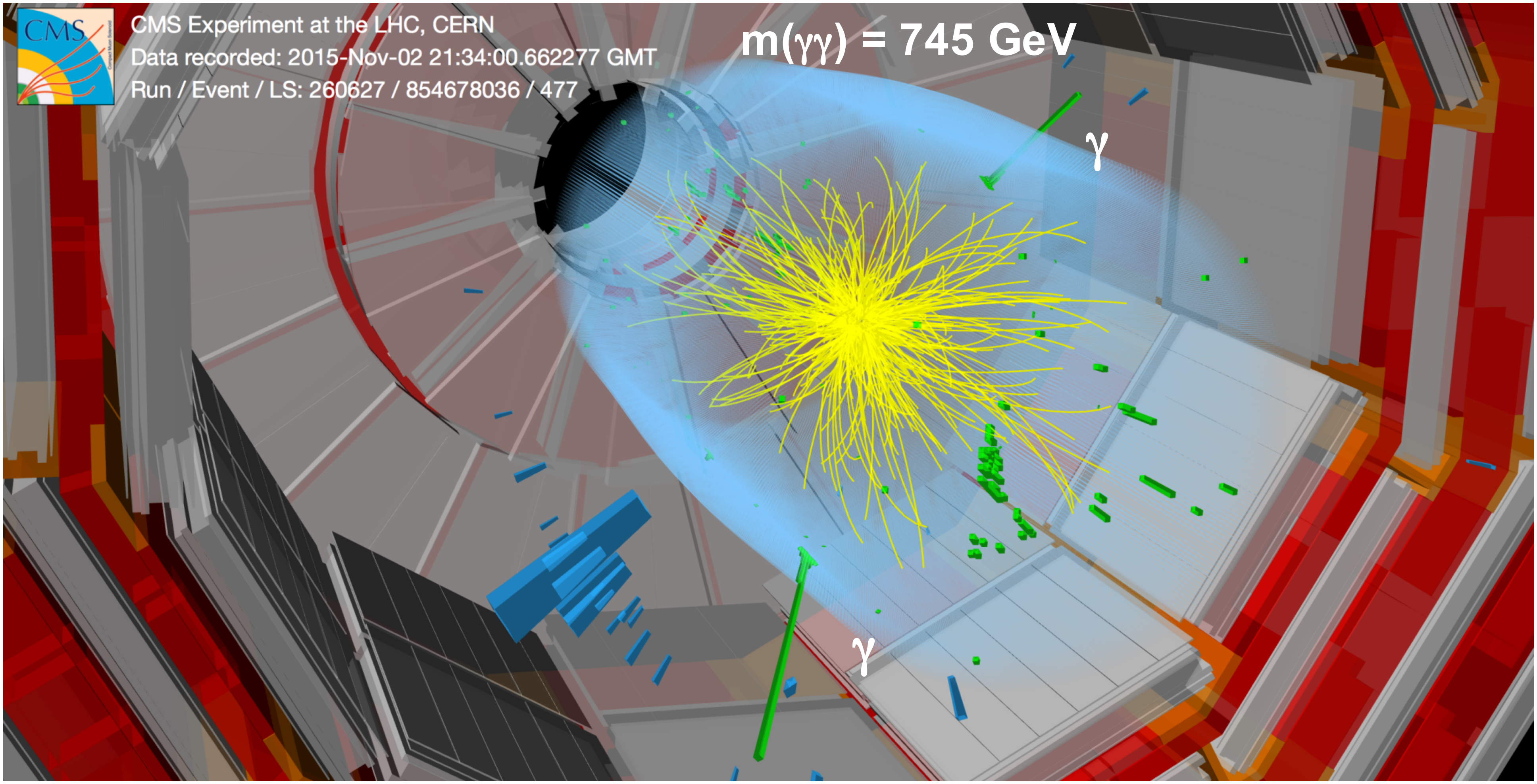
- **Diphoton resonances search offer a powerful way to probe BSM physics**
- Low significance excesses seen in diphoton channel around a mass of 750 GeV and narrow natural width
  - **Local (global) significance of the excess: 3.4 (1.6) σ**
- Analyzing the new data and investigating new aspects of the resonance:
  - width and spin measurements
  - correlated final states (WW, tt, VV, Zγ, YY>γγγγ, jj)

shown today



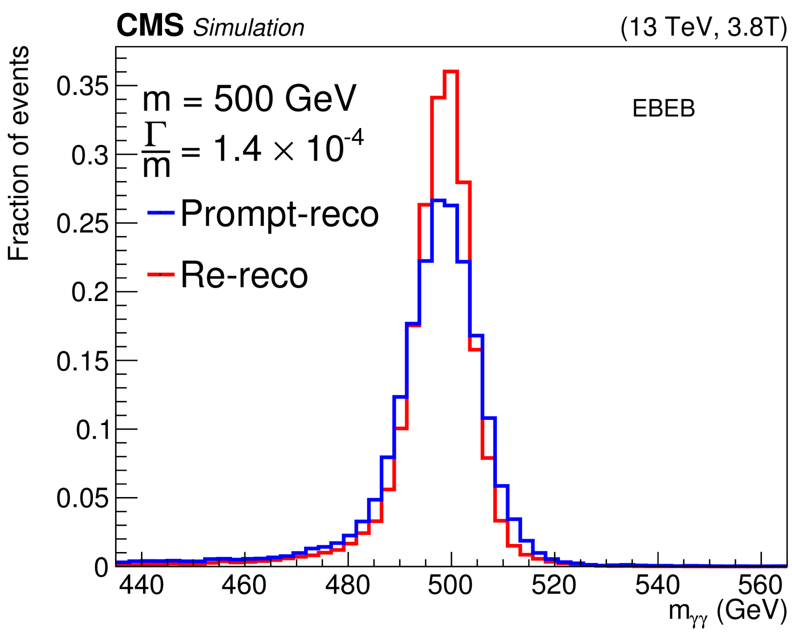
- A lot more data needs to be taken before we can make any definitive statements about the 750 GeV excess
- We should know a lot more by the end of the year, if not earlier

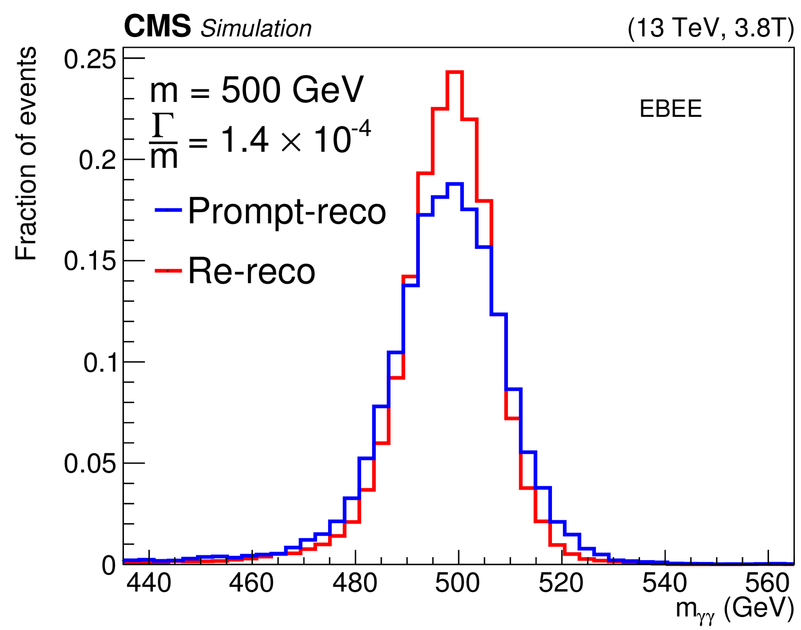
Stay Tuned!


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

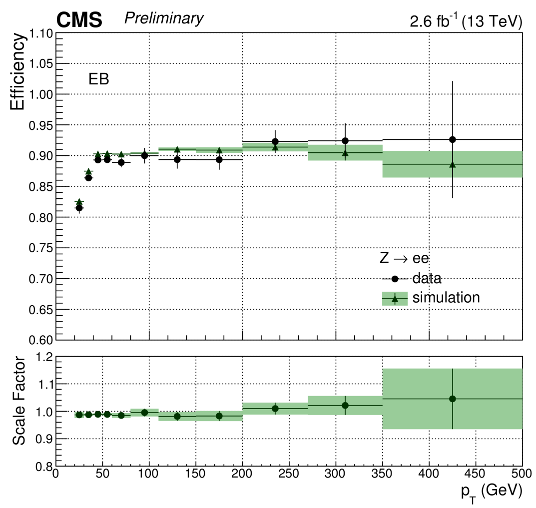
Backup

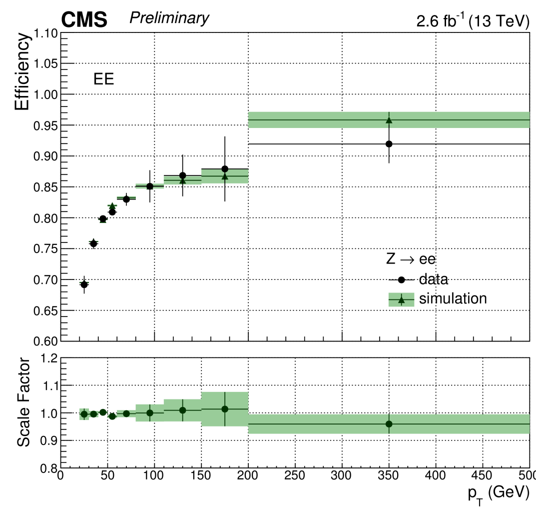
Channel-to-Channel Calibration

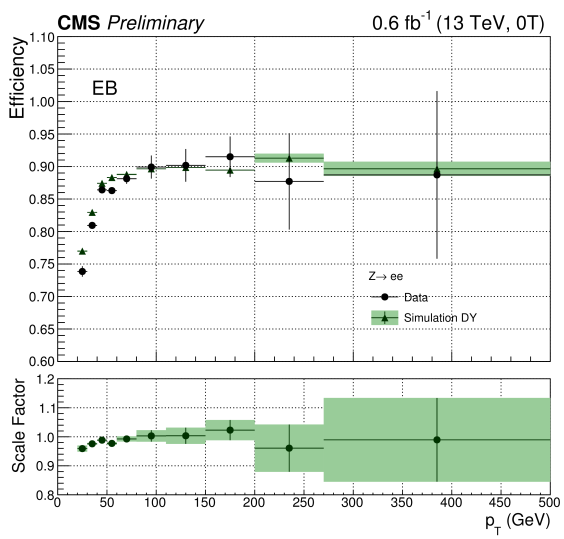


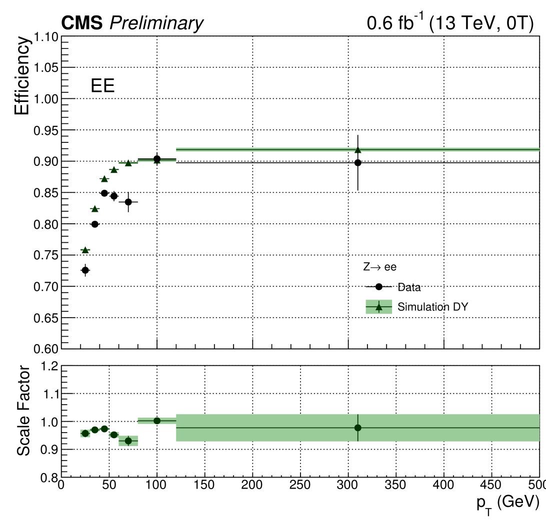


Photon Efficiencies

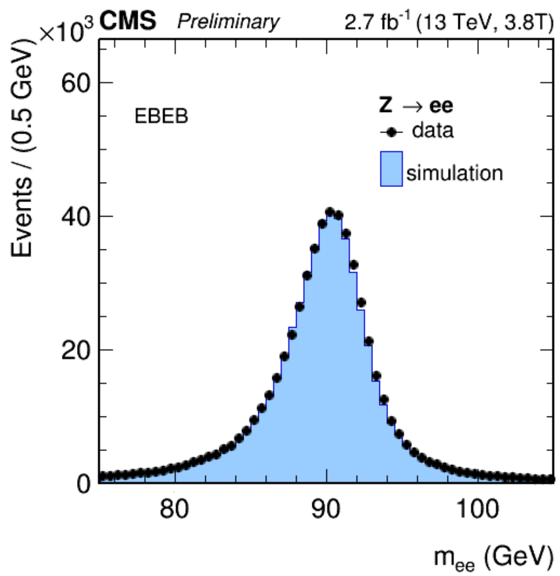


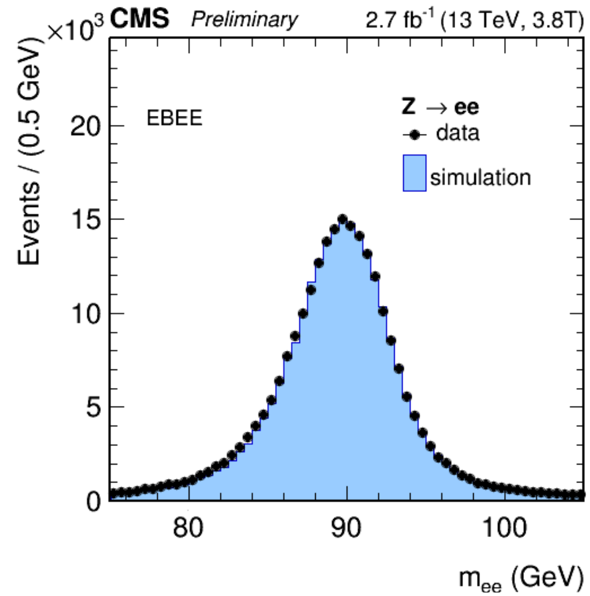


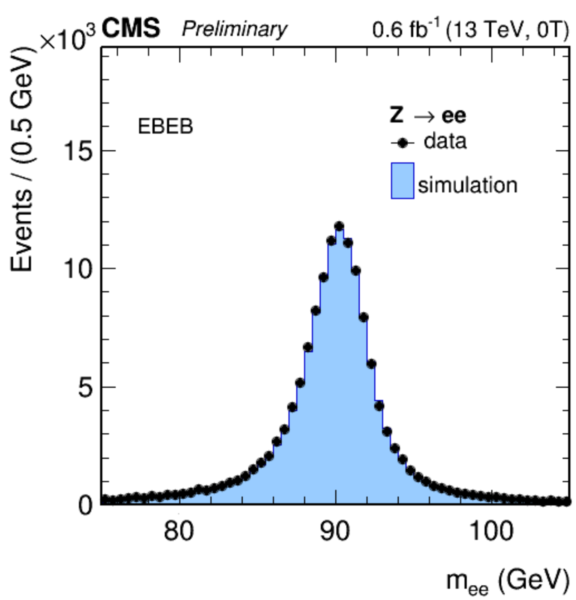


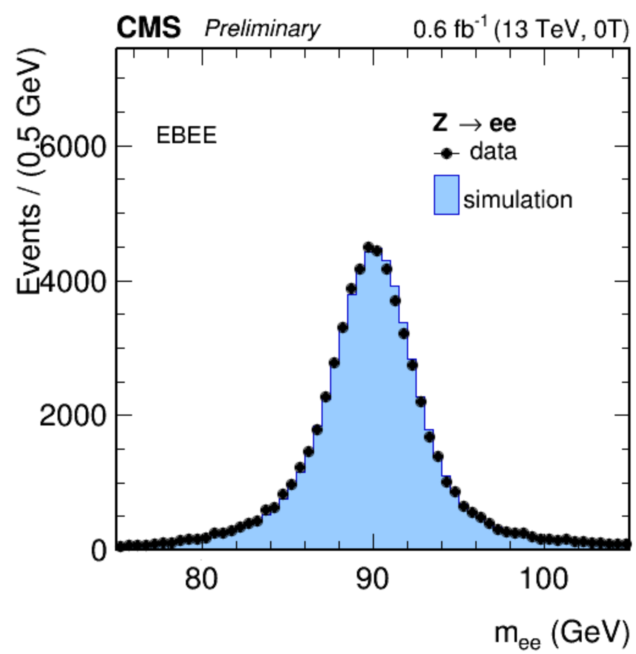


Energy Scale Calibrations

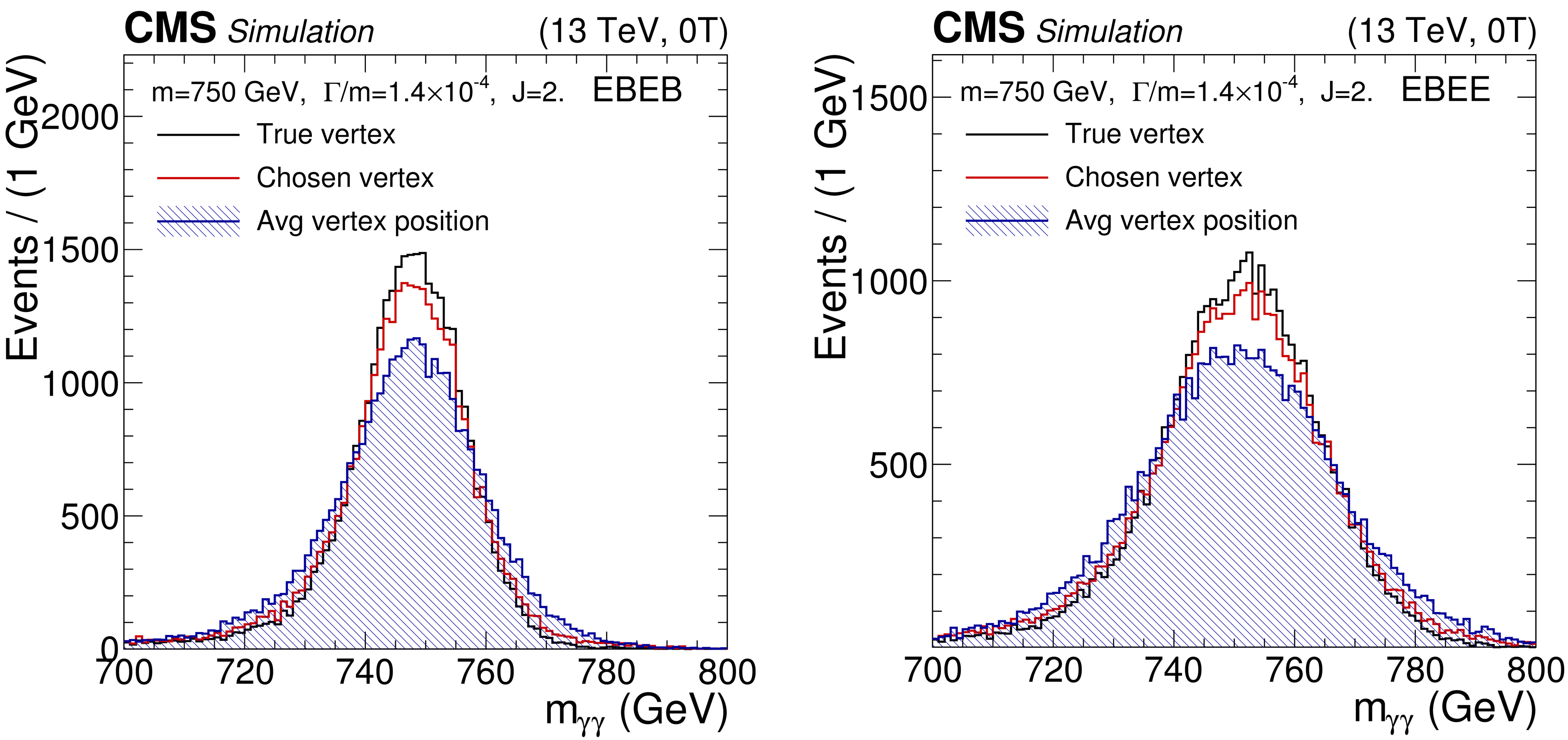








Vertex ID

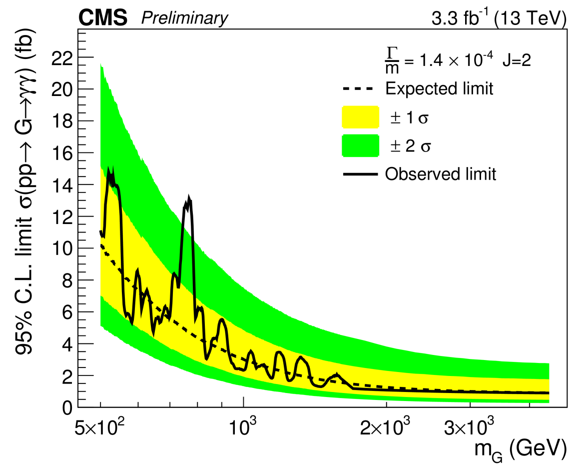

CMS Simulation
(13 TeV, 0T)
m=750 GeV, Γ/m=1.4×10^-4, J=2.
EBEB
True vertex
Chosen vertex
Avg vertex position
Events / (1 GeV)
0
500
1000
1500
2000
700
720
740
760
780
800
mγγ (GeV)
CMS Simulation
(13 TeV, 0T)
m=750 GeV, Γ/m=1.4×10^-4, J=2.
EBEE
True vertex
Chosen vertex
Avg vertex position
Events / (1 GeV)
500
1000
1500
700
720
740
760
780
800
mγγ (GeV)

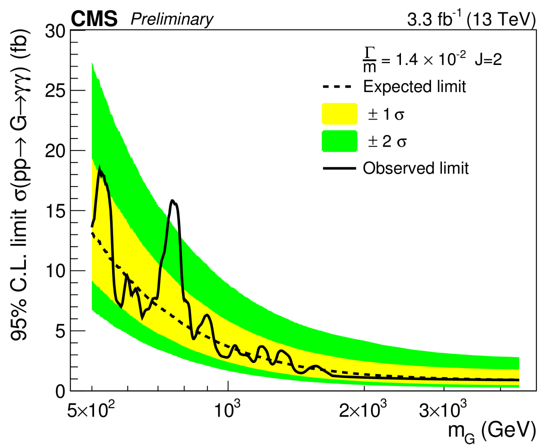
Diphoton Systematics

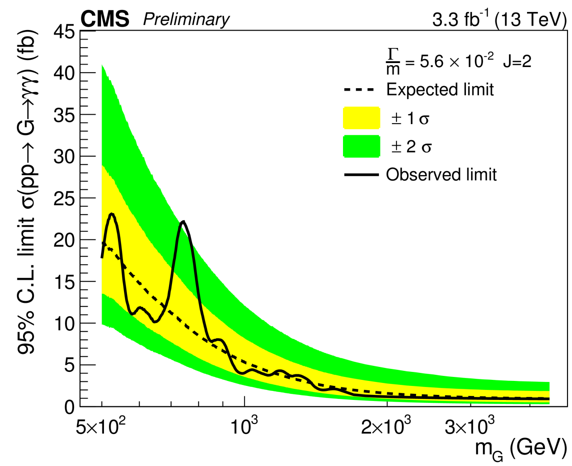
Source	3.8T	0T	Correlation
Luminosity	2.7%	12%	0
Selection eff.	8%	16%	0
PDFs	6%	6%	1
g energy scale	1%	1% $\oplus$ 1%	1, 0
g energy res.	0.5%	0.5%	0

Source	13 TeV	8 TeV	Correlation
γ energy scale EBEB	1%	0.5%	0.5
γ energy scale EBEE	1%	2%	0.5
γ energy res.	0.5%	0.5%	0

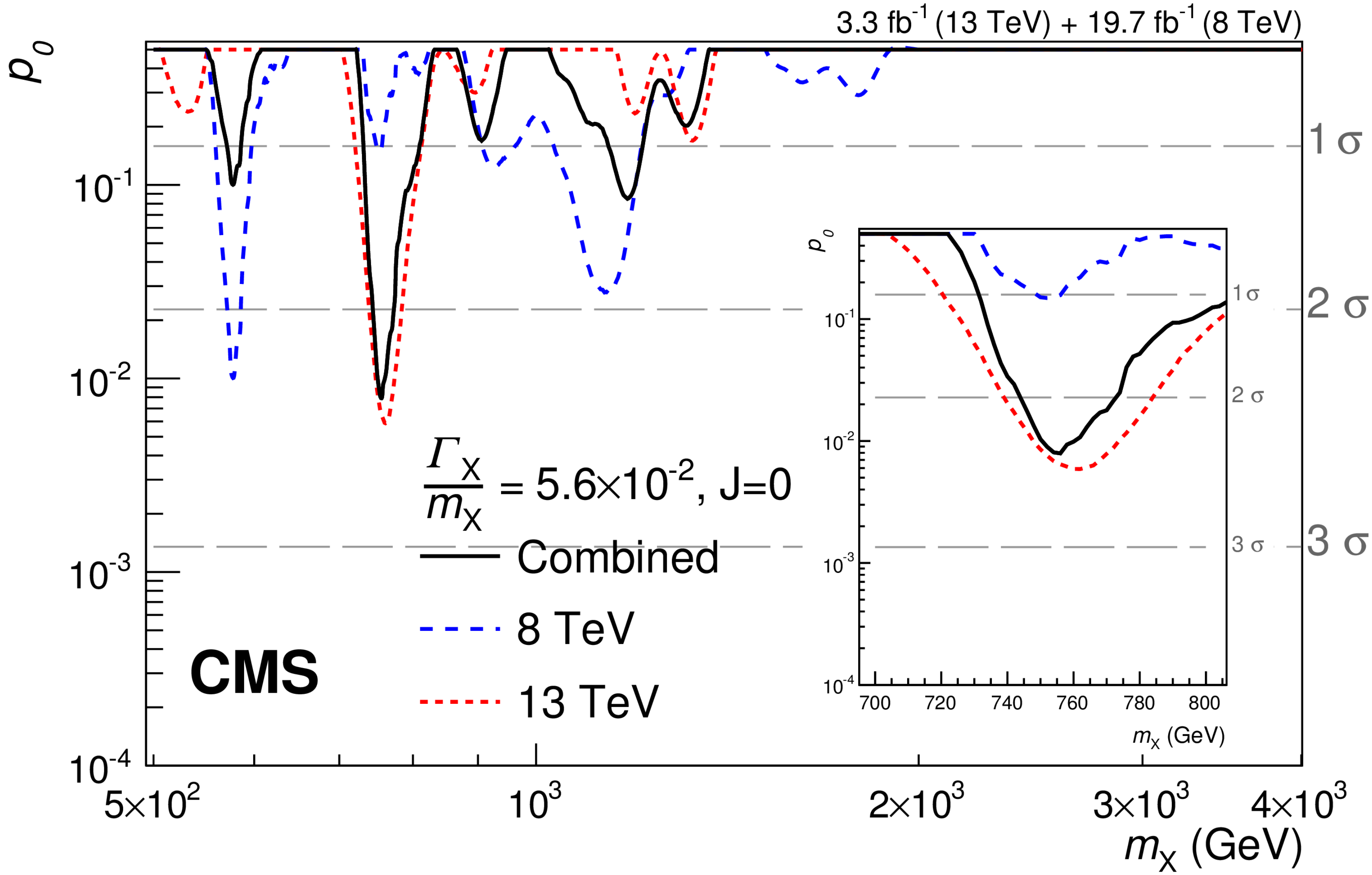
Diphoton Limits J=2



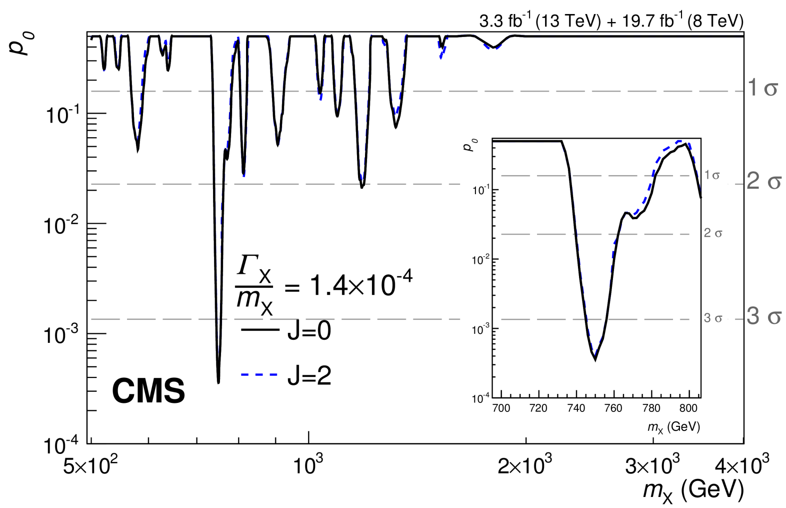


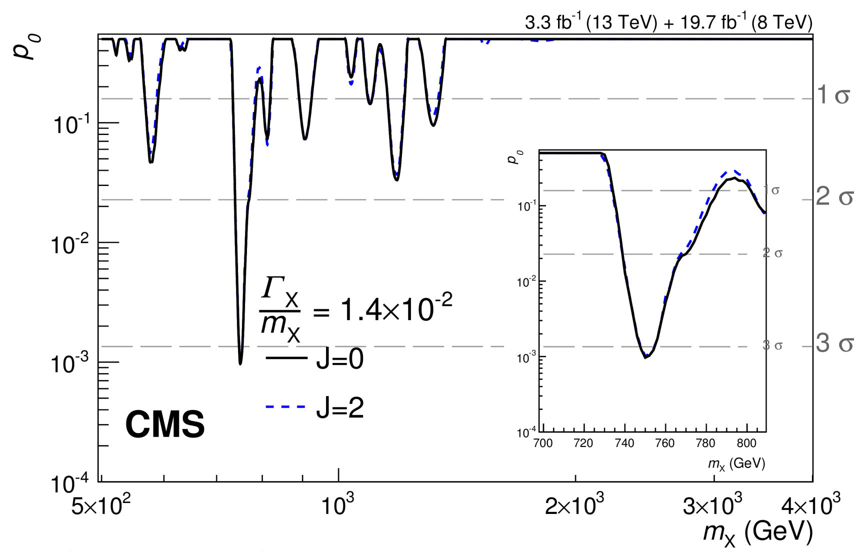


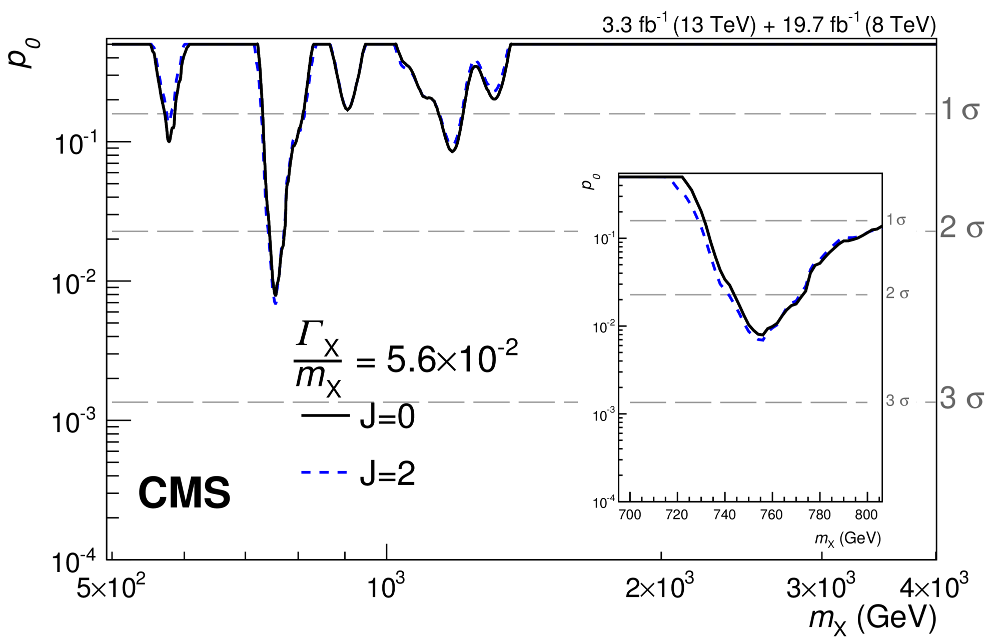
Diphoton p-values



Diphoton p-values







Zγ Systematics

Table 1: Summary of considered systematic uncertainties on signal.

Source	8 TeV	13 TeV
Luminosity	2.6%	2.7%
PDF	1 %	1%
Lepton Efficiency	5%	5%
Trigger Efficiency	2–3%	2–3%
Photon Efficiency	1–2.6%	5%
Mass Scale/Resolution	1–10%	1–5%