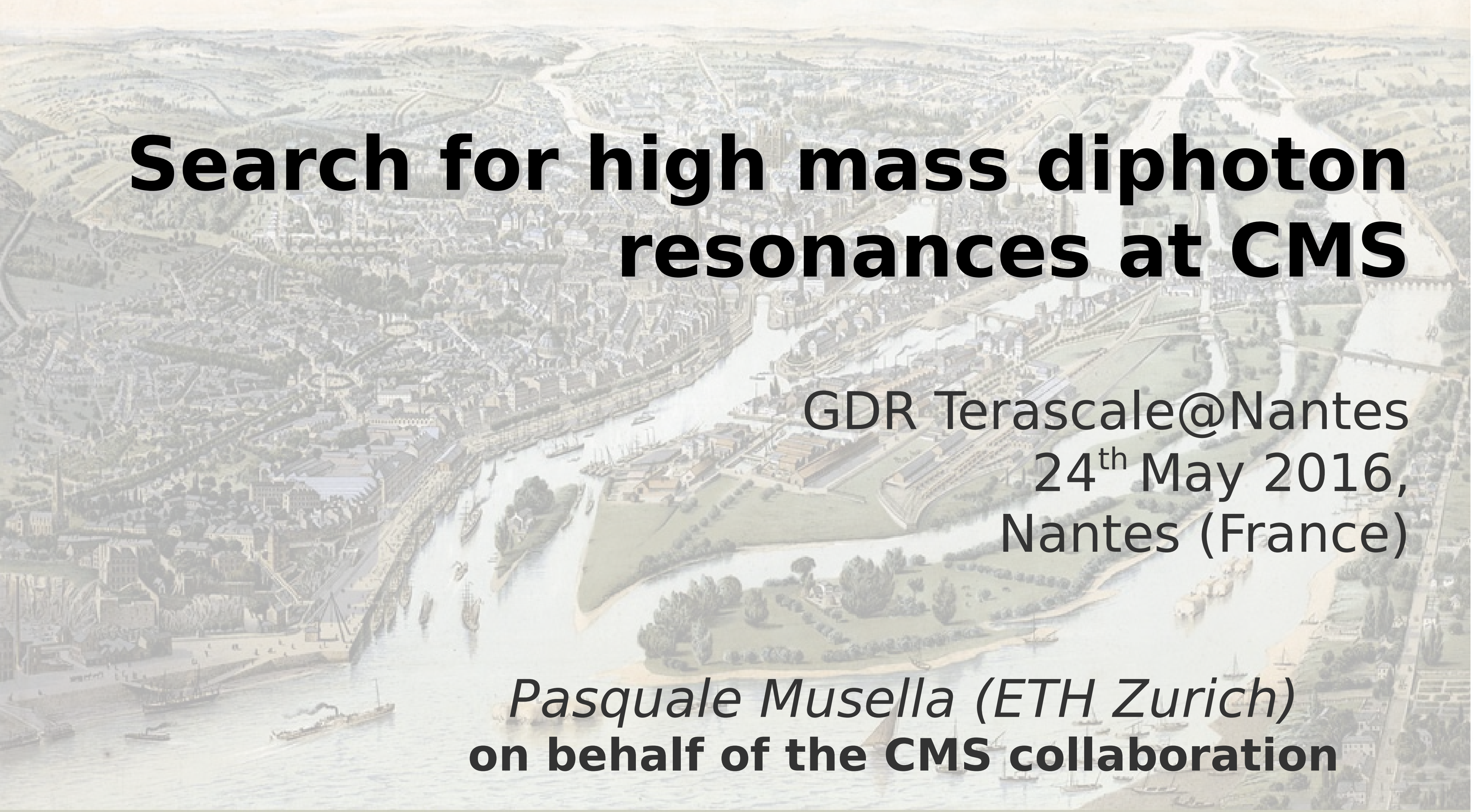

Search for high mass diphoton resonances at CMS

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24th May 2016,
Nantes (France)

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on behalf of the CMS collaboration

Ville de Nantes, Loire-Inférieure, 1888 (Alesi (d'), Hugo) / Collection du musée du château des ducs, Nantes

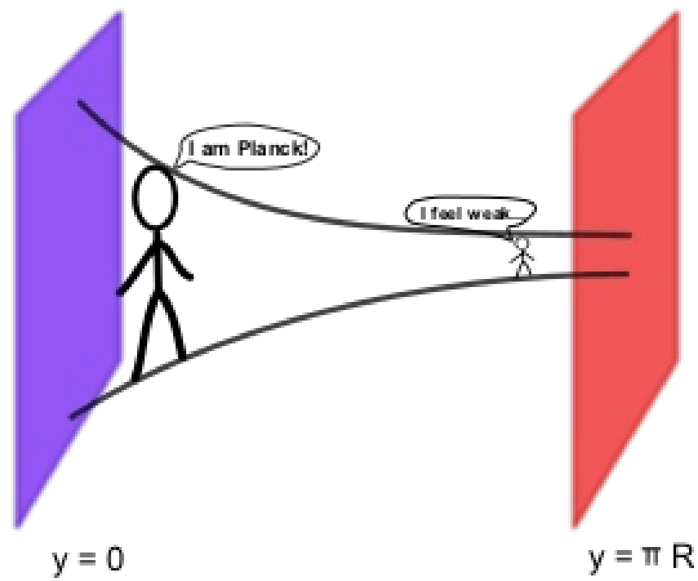
ETH Institute for Particle Physics

CMS
Compact Muon Solenoid

Motivation

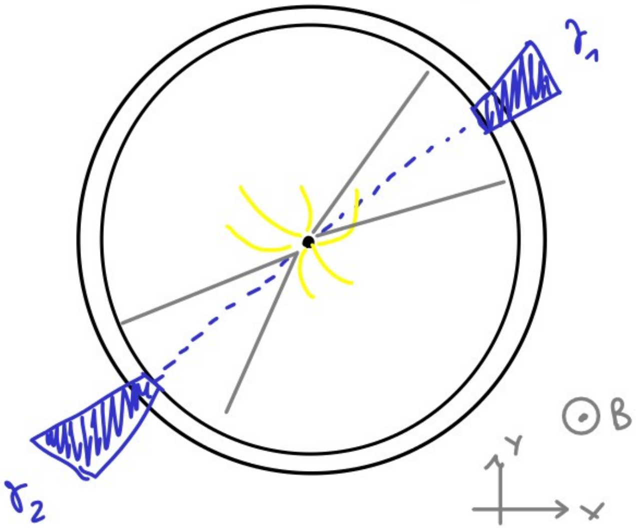
- Search for high mass diphoton resonances in proton-proton collisions motivated by several **models of physics beyond SM**.

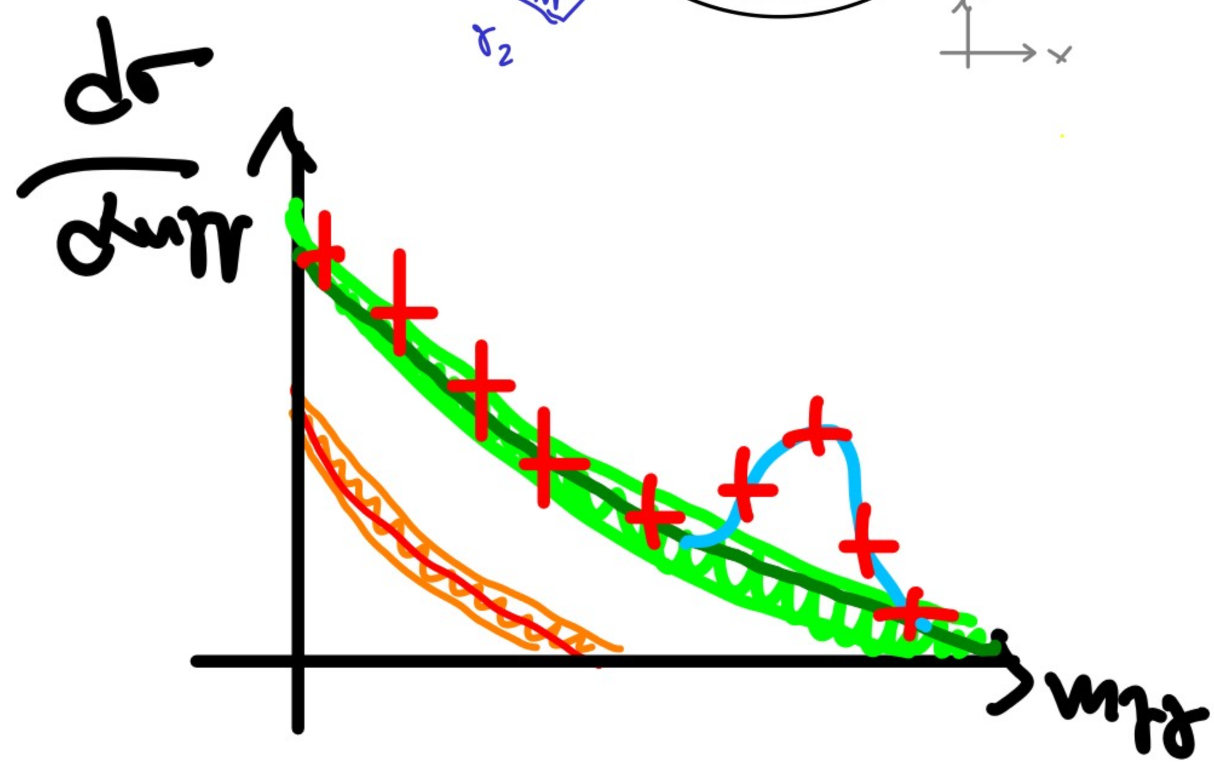
- For example:
  - Models with **extended Higgs sectors** predict appearance of **spin-0** resonances.
  - **Extra-dimensional** models predict appearance of **spin-2** resonances.
  - **Many more** models **than I thought** predict the appearance of diphoton resonance, given the recent number of phenomenological papers on arXiv.



Experimental signature

- Very clean final state:
  - Two **high p_T photon candidates**.
    Reconstructed as high energy deposits in EM calorimeters.
  - **Isolated**.
    No additional activity in the direction of the two photons candidates.
  - Signature of **resonant production**:
    localized **excess** of events in the diphoton **invariant mass spectrum**.





High mass diphoton searches at 8 and 13TeV

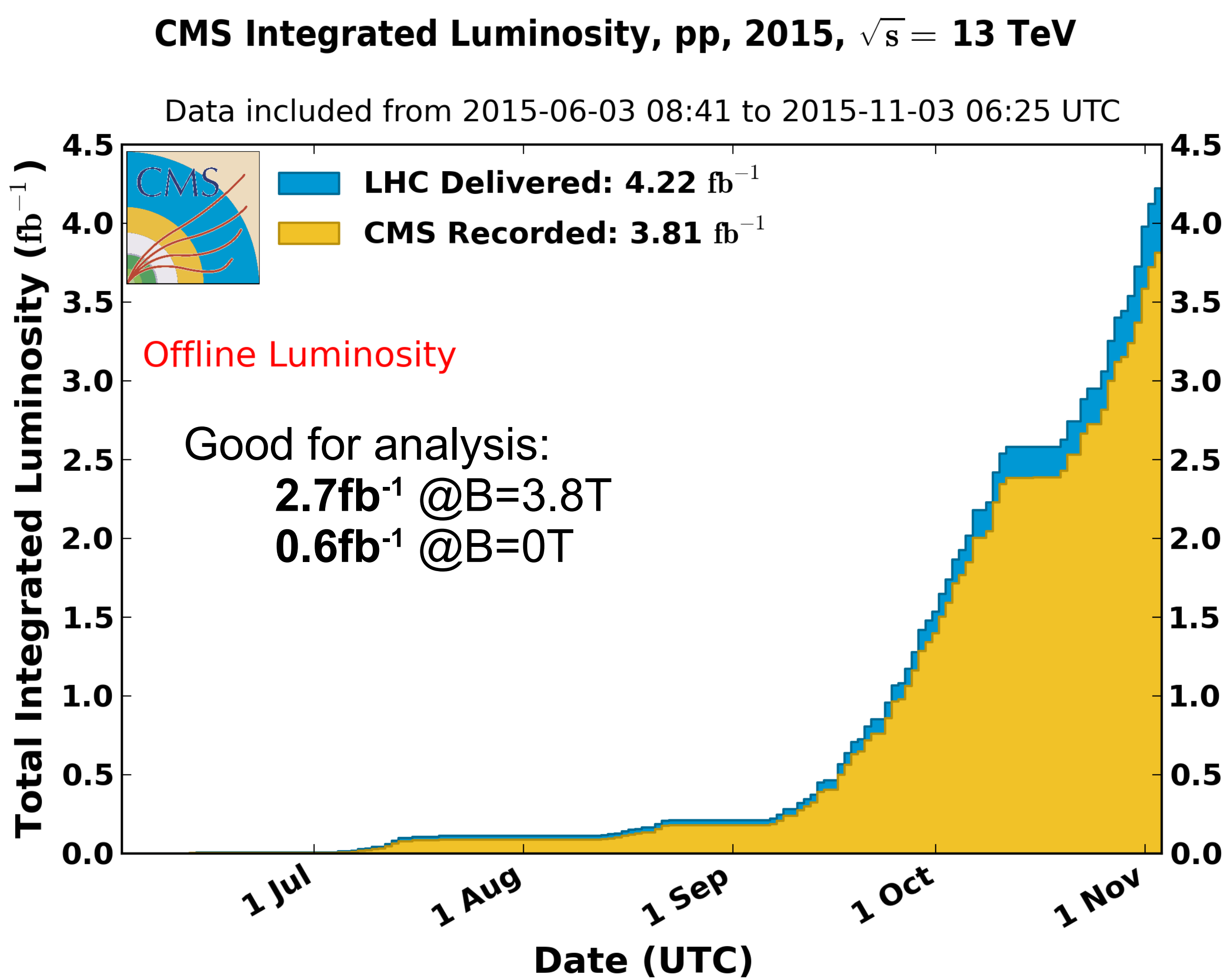
Ref	Title	M_x	interpreted as	
			spin-0	spin-2
PLB 750 (2015) 494	Search for diphoton resonances in the mass range from 150 to 850 GeV in pp collisions at √s = 8 TeV	150-850GeV	✔	✔
EXO-12-045	Search for High-Mass Diphoton Resonances in pp Collisions at √s = 8 TeV with the CMS Detector	0.5-3TeV	✘	✔
EXO-15-004 Dec'15	Search for new physics in high mass diphoton events in proton-proton collisions at √s = 13 TeV	0.5-4.5TeV	✘	✔
EXO-16-018 Moriond '16	Search for new physics in high mass diphoton events in **3.3 fb^{-1}** of proton-proton collisions at √s=13 TeV and combined interpretation of searches at √s=8 TeV and 13 TeV.	0.5-4.5TeV	✔	✔

Analysis strategy

- Select diphoton pairs and search for a **local excess** of events in the $\mathbf{m}_{\gamma\gamma}$ spectrum.
  - Simple selection criteria, categorize events according to S/B ratio to enhance sensitivity.
- **Measure** energy scale, resolution and efficiency **in data**.
  - Using $Z \rightarrow ee$ and $Z \rightarrow ll\gamma$
- Parametrize **background** mass spectrum **from data**.
- Test compatibility of data with resonant diphoton production.
- **Blind** analysis:
  - Selection **criteria** and **signal width hypotheses fixed a-priori**.
  - All analysis inputs (energy calibration, efficiency, etc..) checked before box-opening.
  - December dataset re-blinded to study analysis improvements.

2015 dataset

- Thanks to the nice performance of the LHC the CMS analysis could use 3.3fb^{-1}.



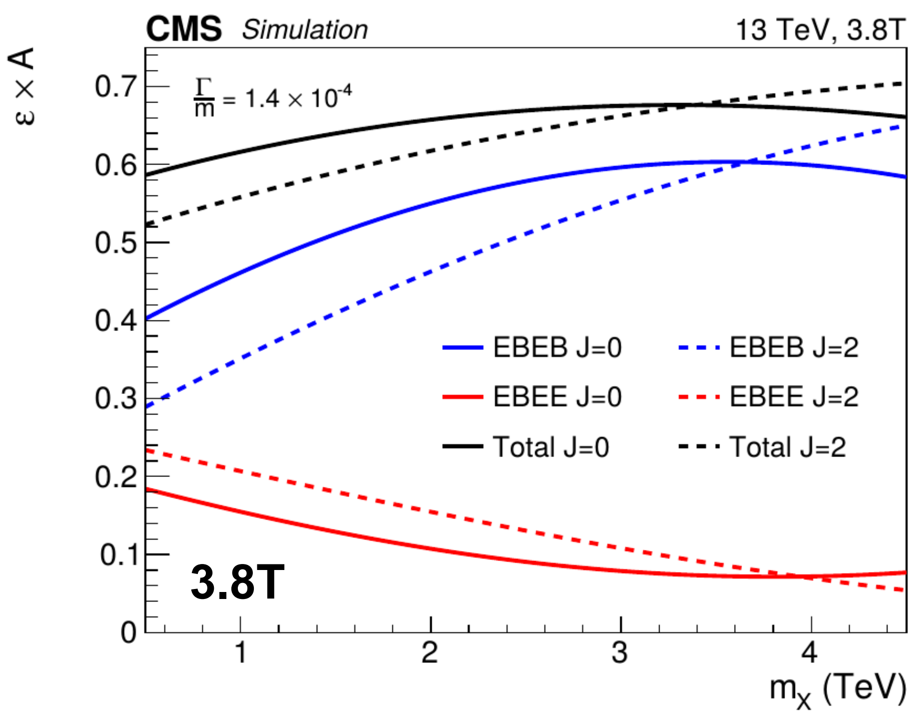
Event selection

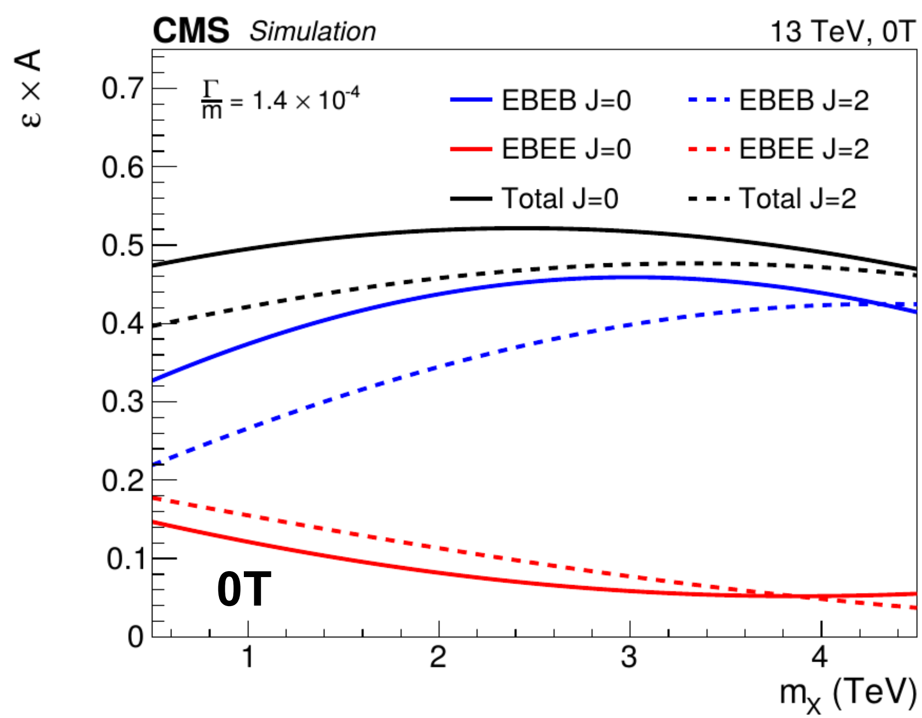
- Simple set of requirements.
  - **Fixed p_T cuts**, at least **one photon** in the barrel region (EB: **$|\eta|<1.45$**).
  - **Events categorized** in barrel-barrel (EBEB) and barrel-endcap (EBEE) configurations.

$p^{\gamma 1}_T$	75 GeV
$p^{\gamma 2}_T$	75 GeV
$\|\eta\|_{max}$	<2.5
$\|\eta\|_{min}$	<1.45
categorization	EB-EB EB-EE

Event selection

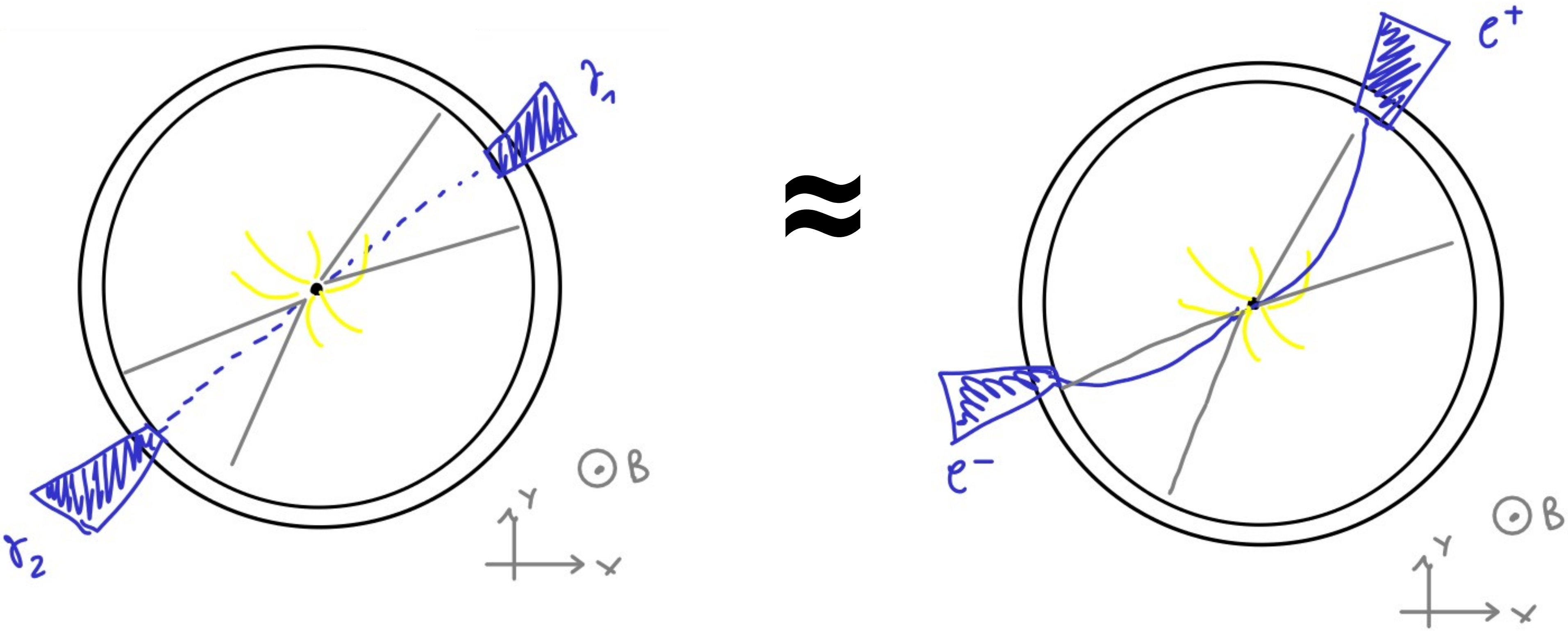
- Simple set of requirements.
  - **Efficient** cut-based photon **identification criteria**.
    - Per-photon efficiency in the barrel: 90(85)% at 3.8(0)T.
    - Per-photon efficiency in the endcaps: 85(70)% at 3.8(0)T.
  - Analysis **~equally sensitive to spin-0 and spin-2** resonances (up to an overall acceptance correction).





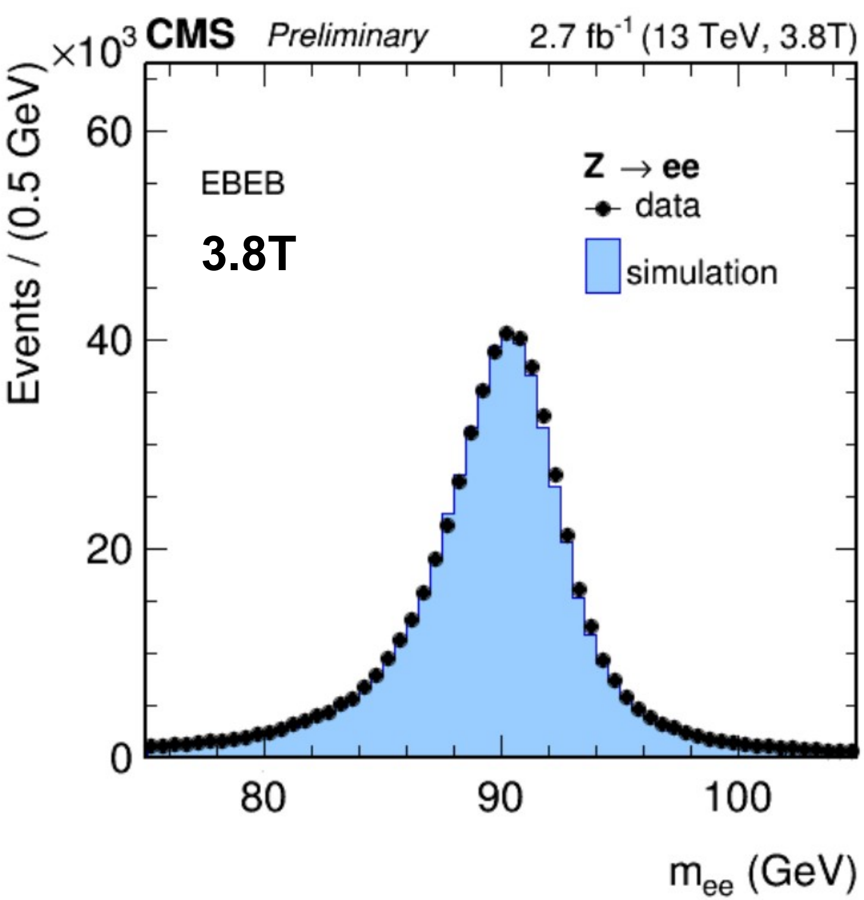
Understanding detector response to signal

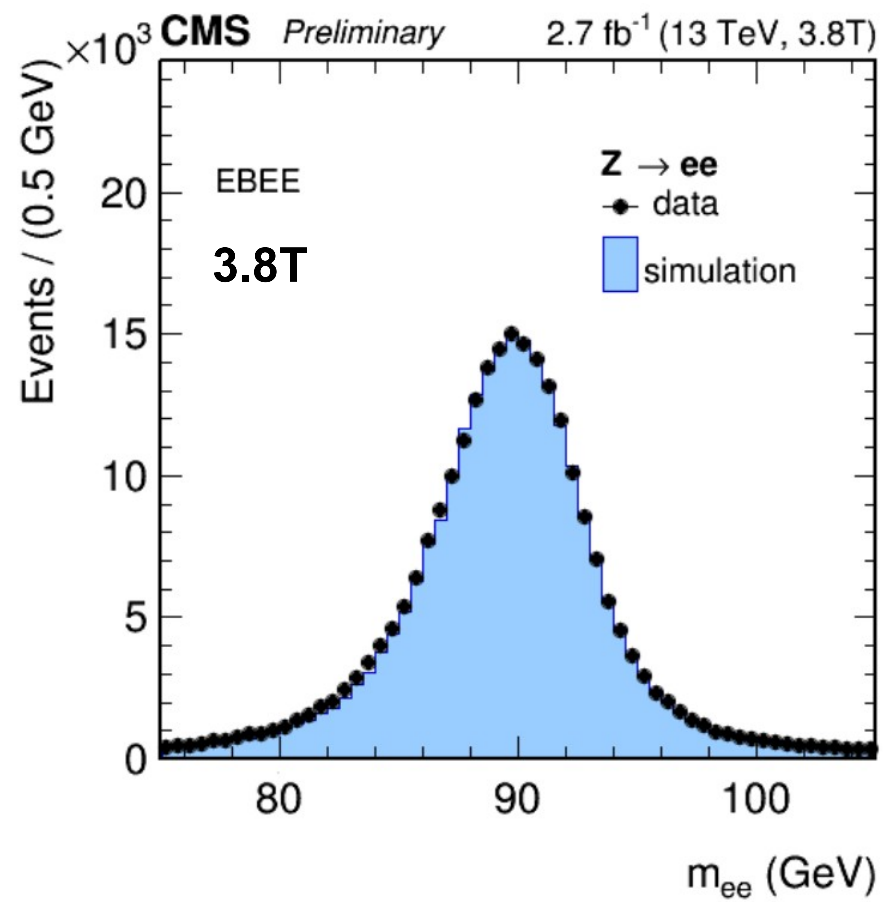
- **Detector response** to isolated photons assessed studying **di-electron events**.
  - Both at Z peak and in high mass Drell-Yan spectrum.
  - Allow to have precise measurement of **energy scale, resolution and selection efficiency**.



Energy scale calibration – 3.8T

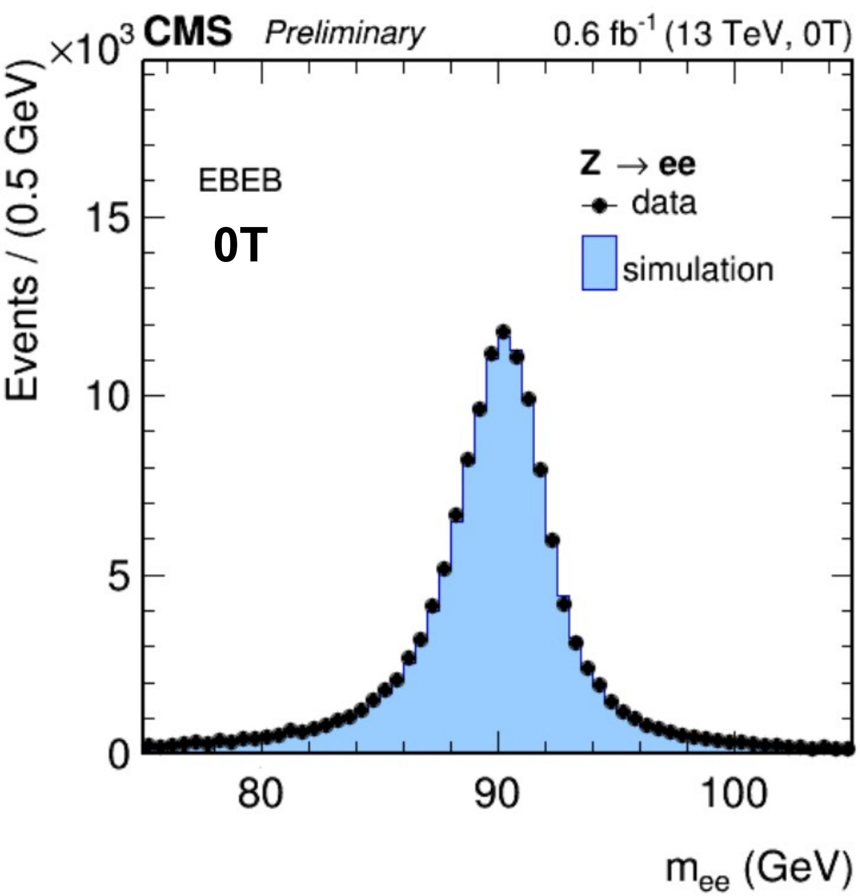
- Obtained **at the Z peak**.
  - Simultaneously **adjust energy scale and resolution** of electron candidates as a **function** of the **pseudo-rapidity** and **cluster shape** of the candidates.
- **Stability vs E_T** checked with boosted events up to ~150GeV.
  - Deviations within **0.5(0.7)%** in barrel (endcaps).
    Assigned 1% uncertainties to account for further extrapolation.

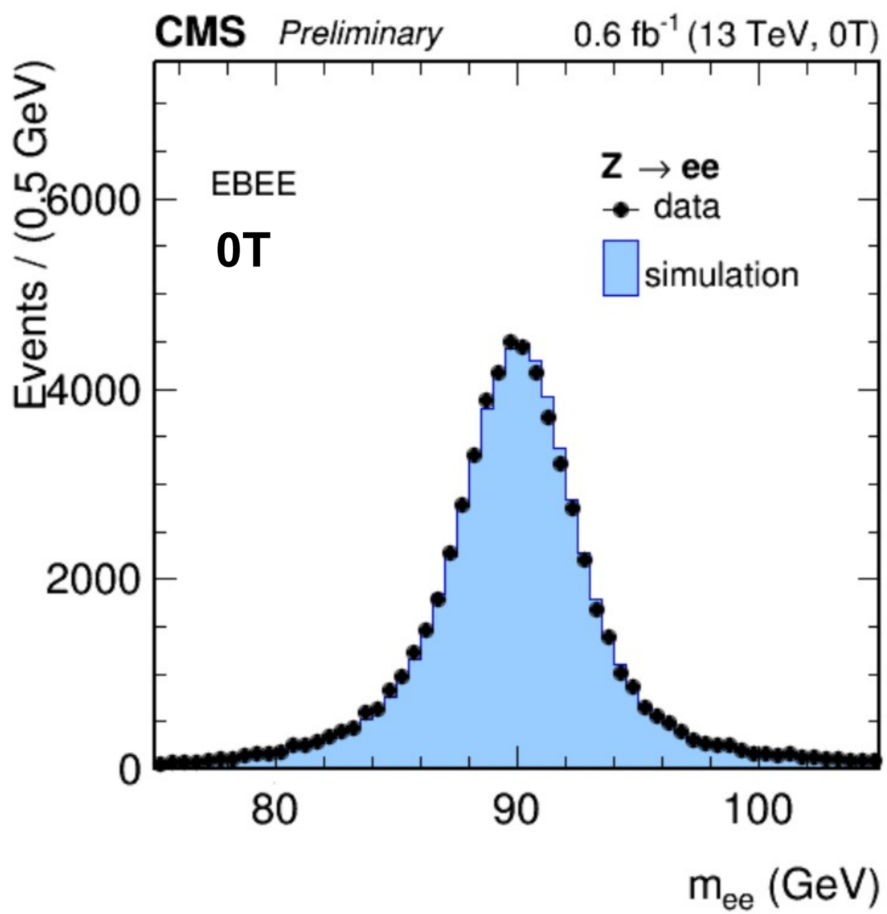




Energy scale calibration – 0T

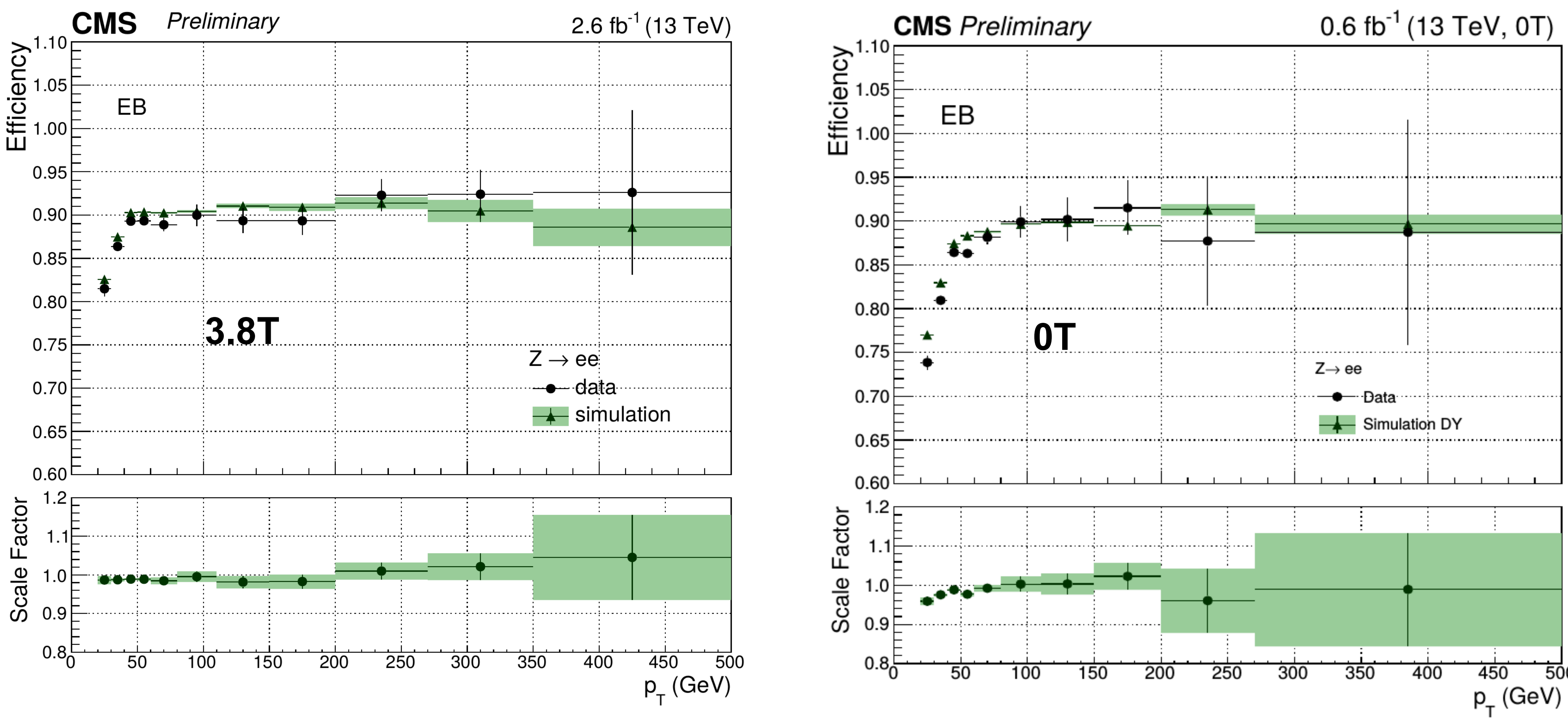
- Same procedure as for 3.8T but **no binning in cluster shape** (no radiative losses)
  - Data/MC **scale corrections** found to be **1% larger** than at 3.8T.
  - Energy **resolution** corrections **similar** at 0T and 3.8T.
  - Assigned 1% uncertainty on knowledge of the relative energy scale in the analysis
- Level of **stability** vs E_T ~**same** as for the 3.8T dataset.





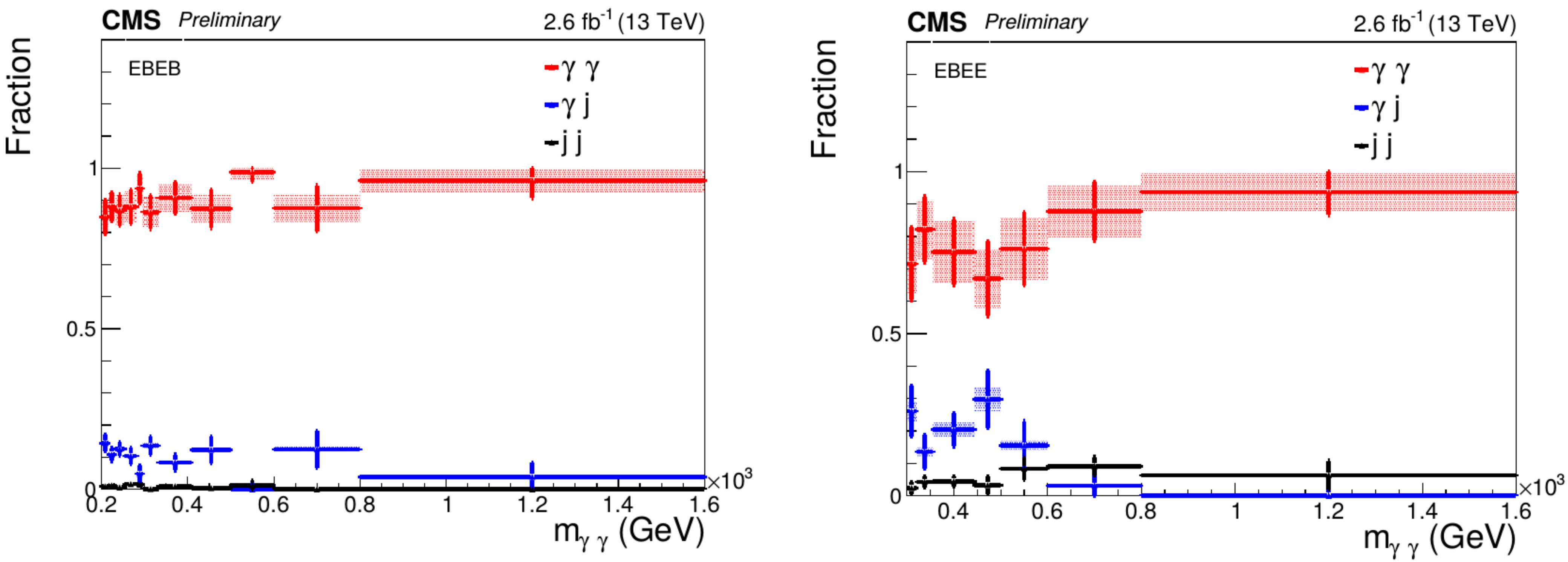
Photon identification efficiency

- Photon identification efficiency data/MC scale factor derived on **Z→ee** events.
  - The **electron veto** requirement is removed from the selection in this measurement and its efficiency is assessed separately using **Z → μμ(ee)γ** events at 3.8(0)T.



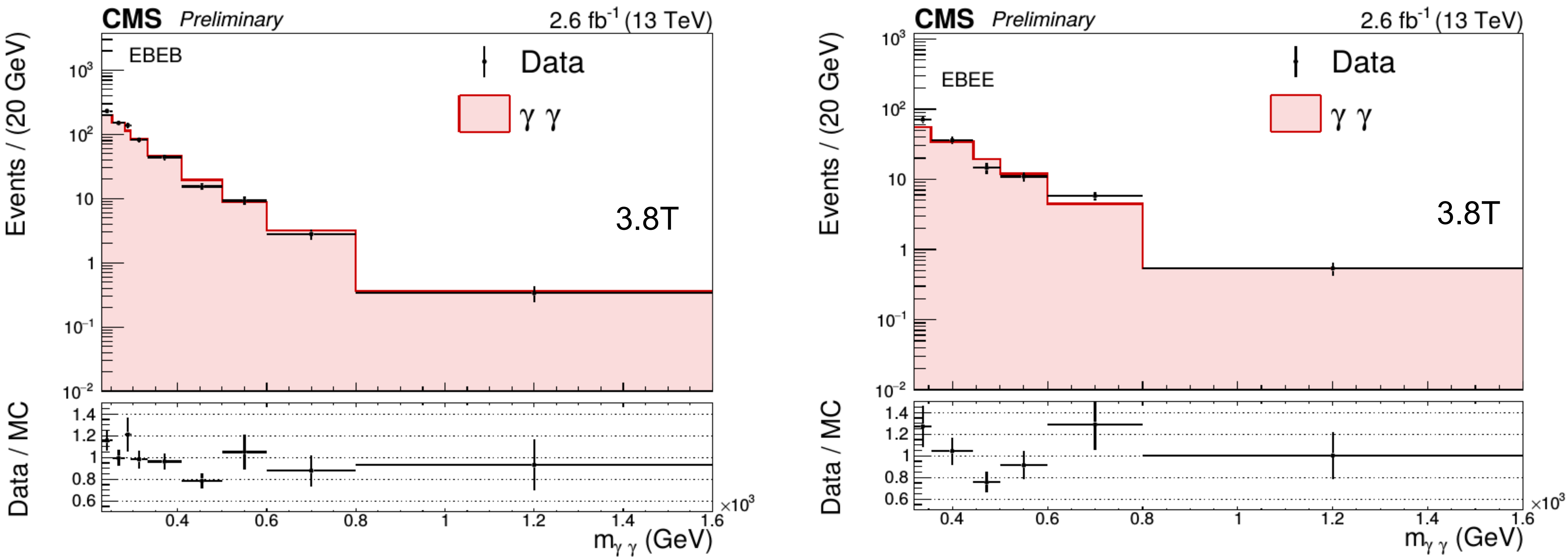
Background composition

- Measured in data using template fit (CMS) or ABCD method (ATLAS).
  - **Background dominated by irreducible component**.
    - CMS: $f_{\gamma\gamma}$>90(80)% for EBEB(EBEE) category.
    - ATLAS: $f_{\gamma\gamma}$>90%.
  - **Determination not used in hypothesis test.**

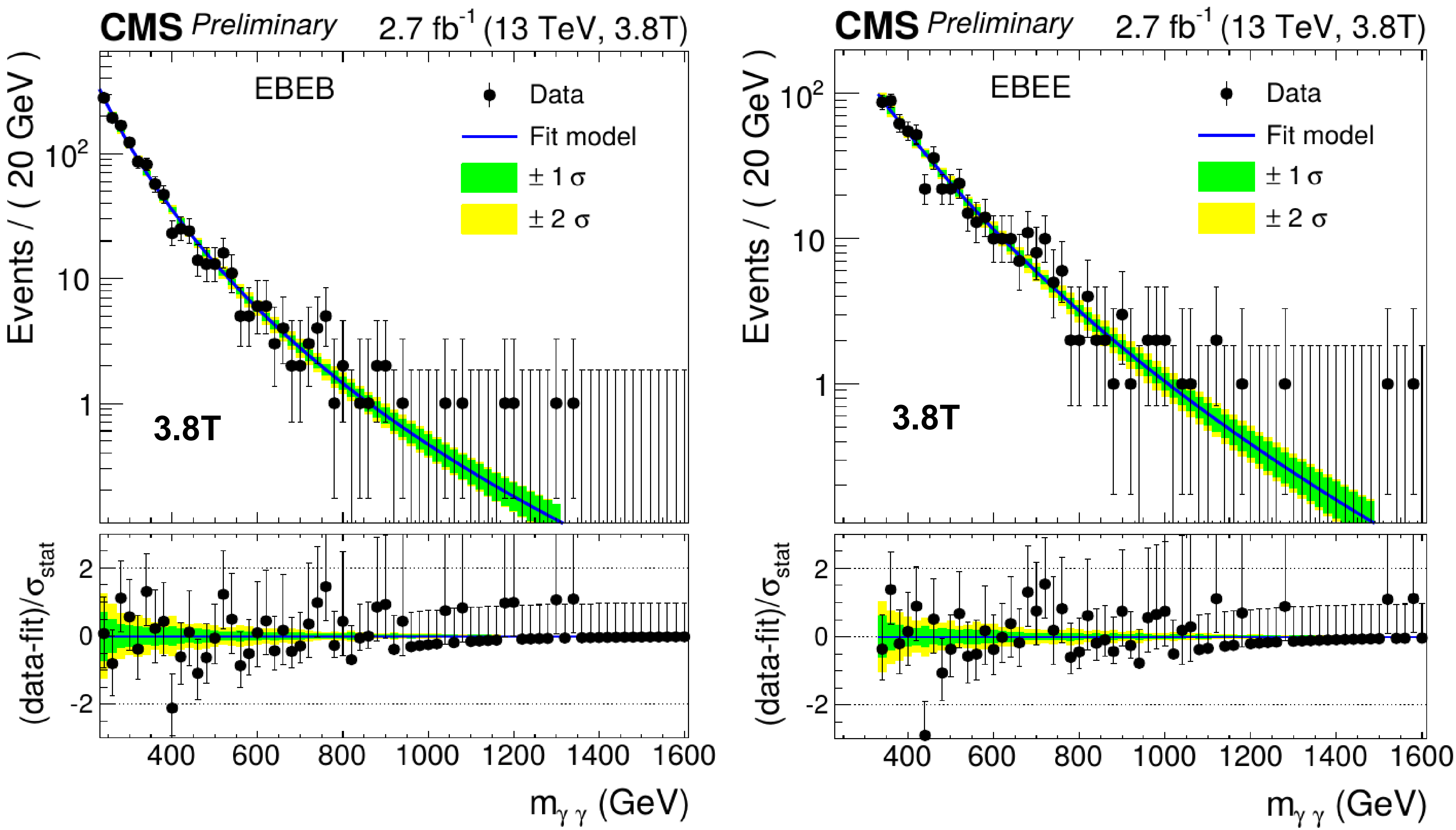


Background composition (2)

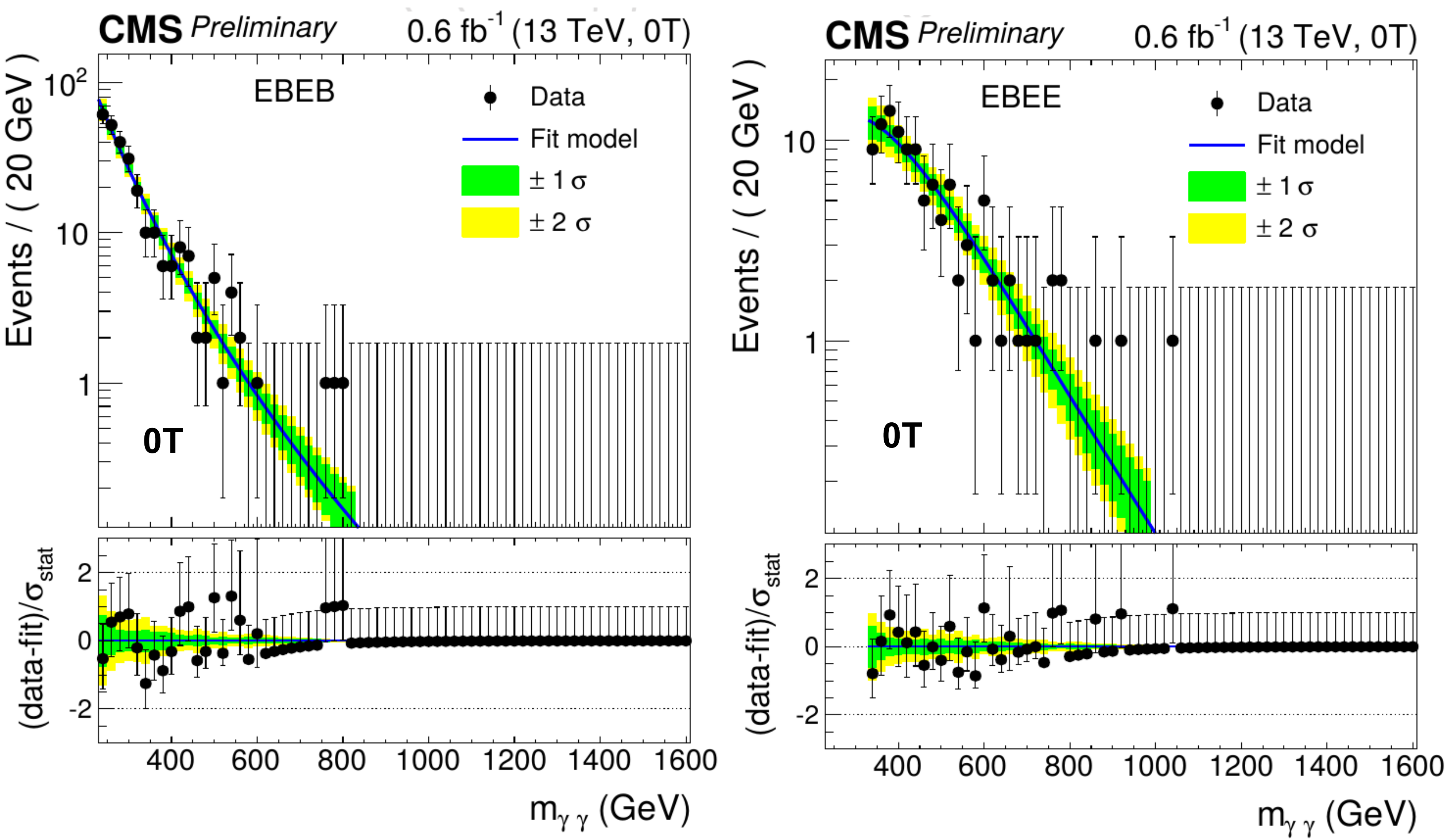
- In the case of CMS, prediction for $\gamma\gamma$ component checked against theory predictions.
  - Obtained using Sherpa-LO reweighted to 2γNNLO.
  - Observation in good agreement with model.



Mass spectra – 3.8T



Mass spectra – 0T



Interpretation of the results

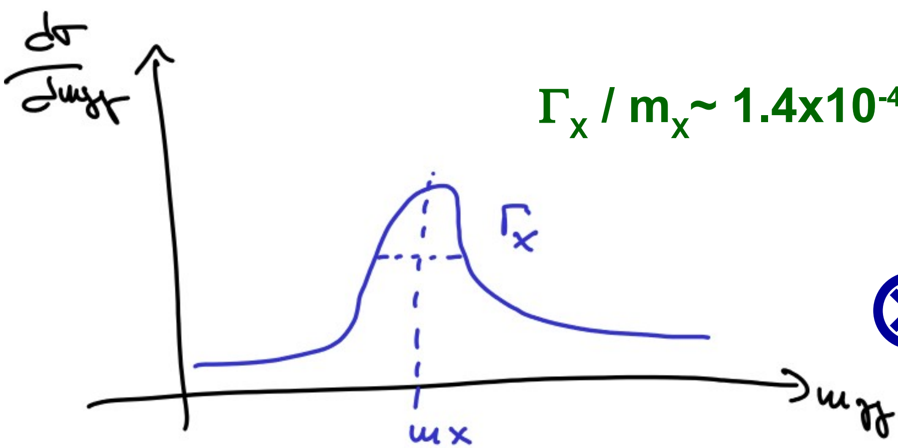
- Hypothesis test based on simultaneous unbinned likelihood fit to $m_{\gamma\gamma}$ in all four analysis categories.

$$L(\mu,\theta)=\prod_{i=1}^{N_{events}} \left[\ \mu S(m_i|\theta_S)\ +\ B(m_i|\theta_B)\ \right]\cdot Poisson(N_{events}|N_B+\mu N_S)$$

- Signal model.
  - Shape from convolution of detector response and intrinsic line-shape

$\Gamma_X / m_X \sim 1.4\mathrm{x}10^{-4} – 5.6\mathrm{x}10^{-2}$

$\sigma_{\gamma\gamma} / m_{\gamma\gamma} \sim 1\%$



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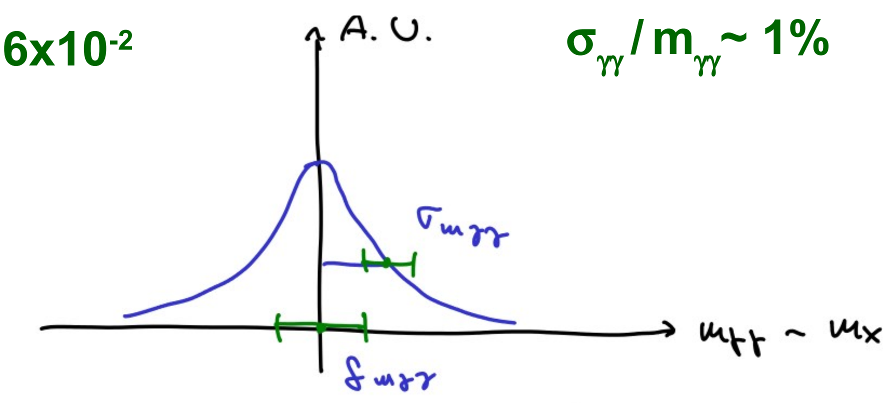


0.5 < m_X~ < 4.5TeV

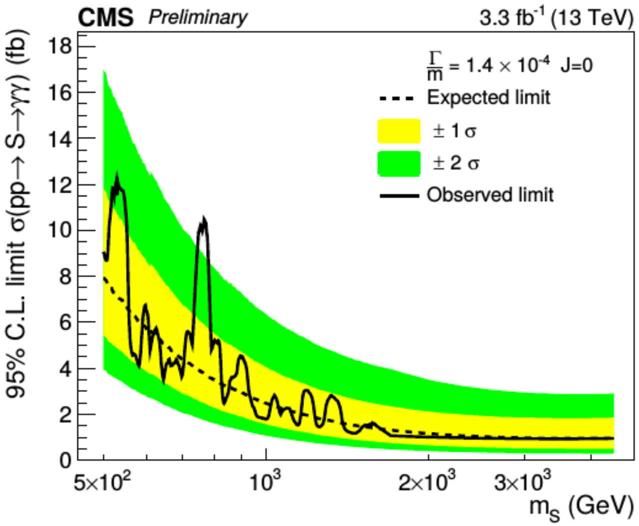
Interpretation of the results (2)

- Background model:
  - Parametric function of $m_{\gamma\gamma}$: $$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$$
  - Independent shape for each of the category.
    Coefficients treated as unconstrained nuisance parameters.
  - Possible mismodelling studied on simulation and explicit uncertainty added to the fit.

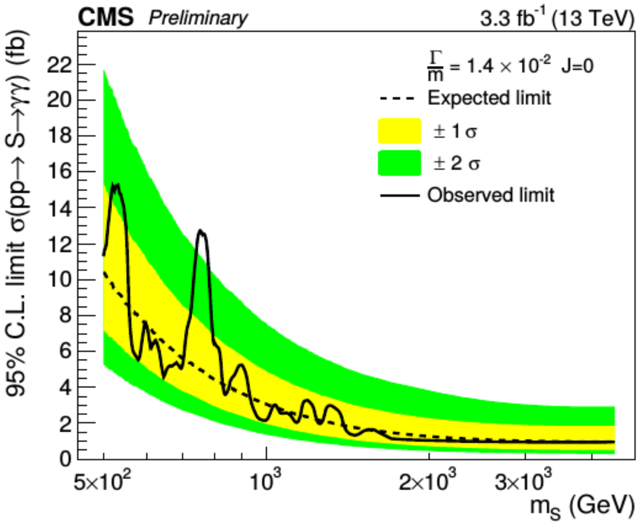
- Frequentist hypotheses tests.
  - Test statitics: based on LHC-type likelihood ratio.
  - Upper limits set based on CLs method.
  - Background hypothesis rejection evaluated through background-only p-value.
  - Asymptotic formulas used throughout
    (validity tested for a subset of the calculations using sampling distributions).

- Shown here for the spin-0 hypotheses
  - Spin-2 version gives equivalent message (and it's available in backup)

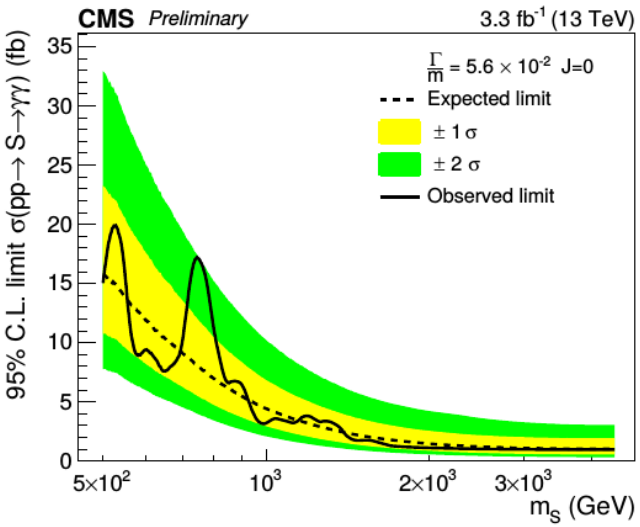
$\Gamma/m = 1.4x10^{-4}$



$\Gamma/m = 1.4x10^{-2}$



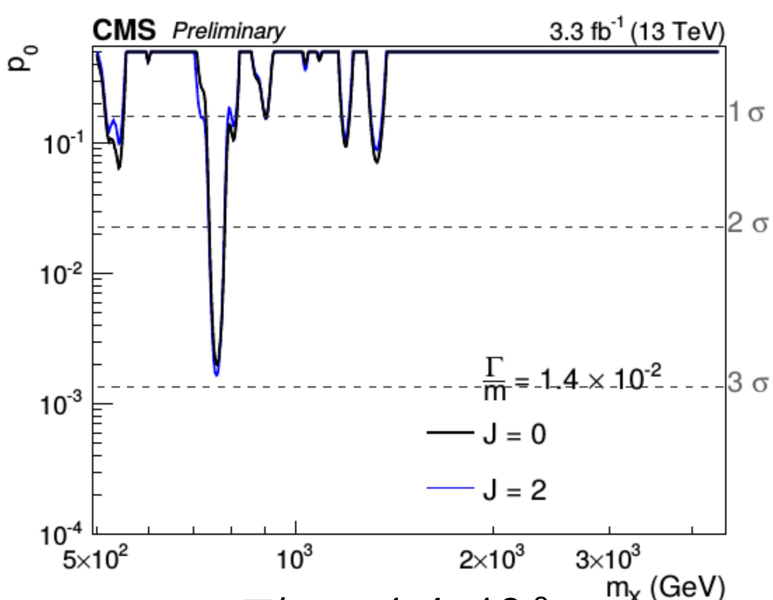
$\Gamma/m = 5.6x10^{-2}$



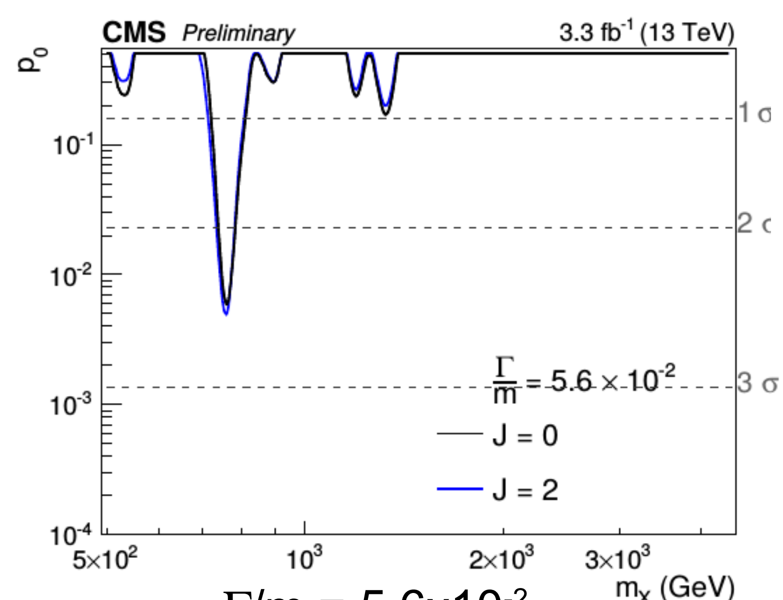
Spin 0

p-values

- Largest excess observed for **m_X = 760GeV** and **$\Gamma/m = 1.4\mathrm{x}10^{-2}$**.
  - **Local** significance: **2.8-2.9σ** depending on the spin hypothesis.
  - Similar significance for narrow-width hypothesis.
  - **Trial factors** estimated from **sampling distribution** of max(p_0), taking into account all the 6 signal hypotheses (spin and width).
  - **“Global”** significance **< 1σ**.



$\Gamma/m = 1.4\mathrm{x}10^{-2}$



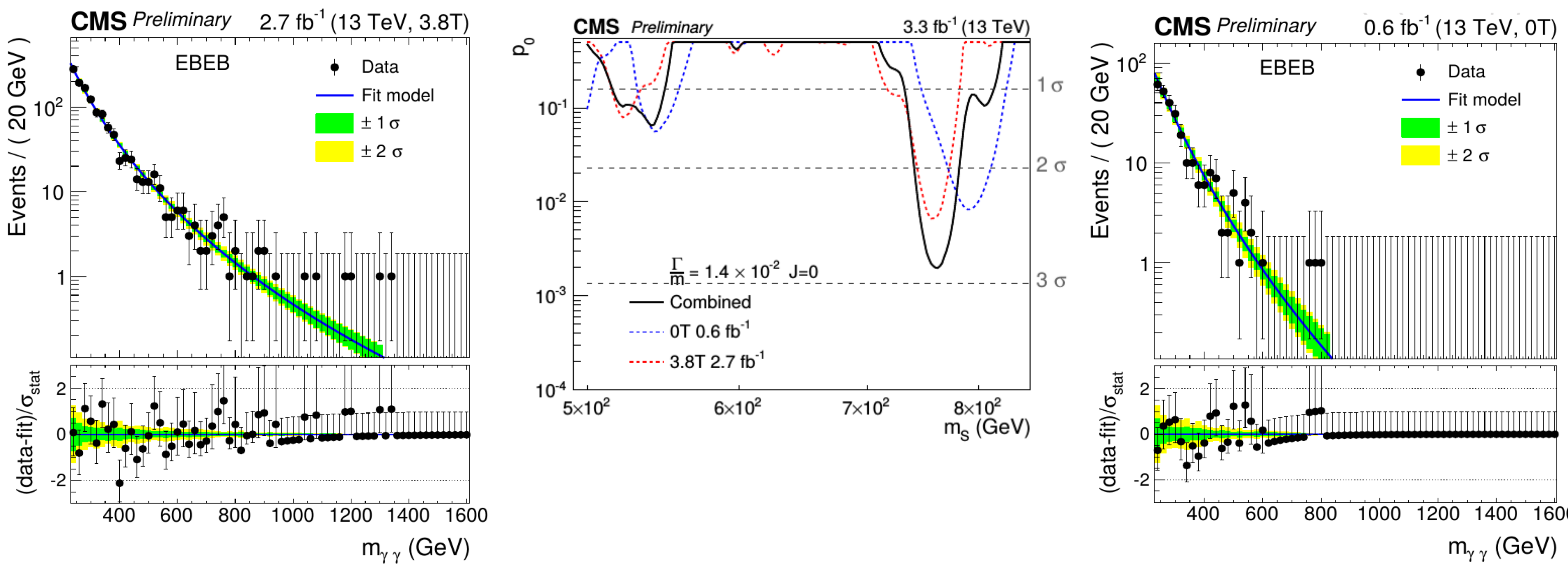
$\Gamma/m = 5.6\mathrm{x}10^{-2}$

Spin-0

Spin-2

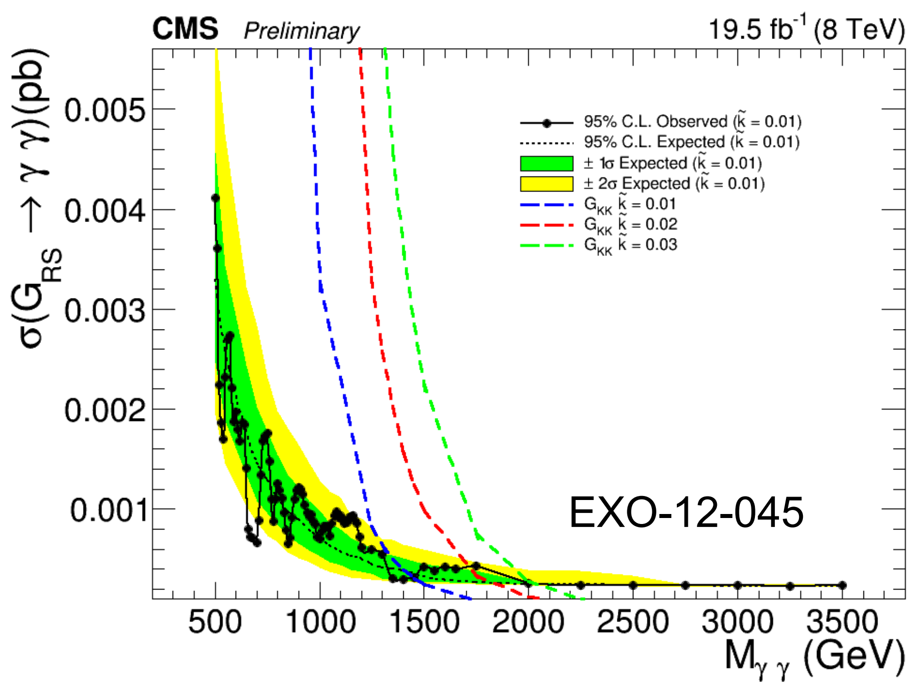
Breaking-down the contributions

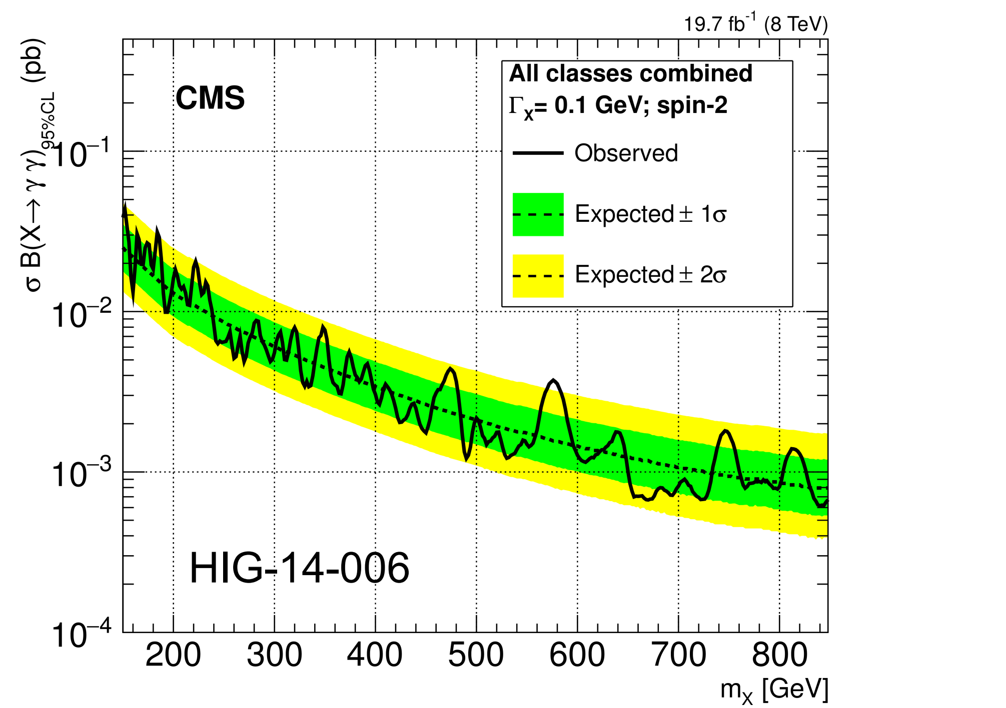
- Excess at 760GeV comes mostly from EBEB categories.
  - Driven by 3.8T category.
    (where the observed excess is ~unchanged w.r.t. the previous results).
  - Observed one event in the 0T dataset compatible with 3.8T excess.



Combined analysis of 8 and 13TeV data

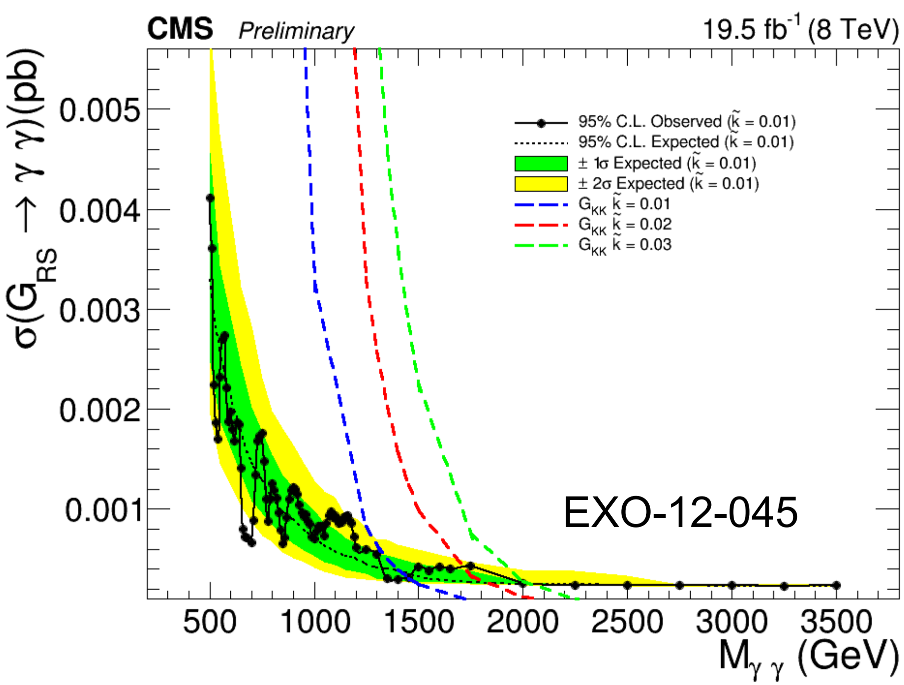
- CMS presented **two searches** for diphoton resonances at 8TeV.
  - **HIG-14-004**: (PLB 750 (2015) 494) search range 150-850GeV, spin-0 and spin-2 intepretation.
  - **EXO-12-045**: search range 500-3000GeV, spin-2 only interpretation.

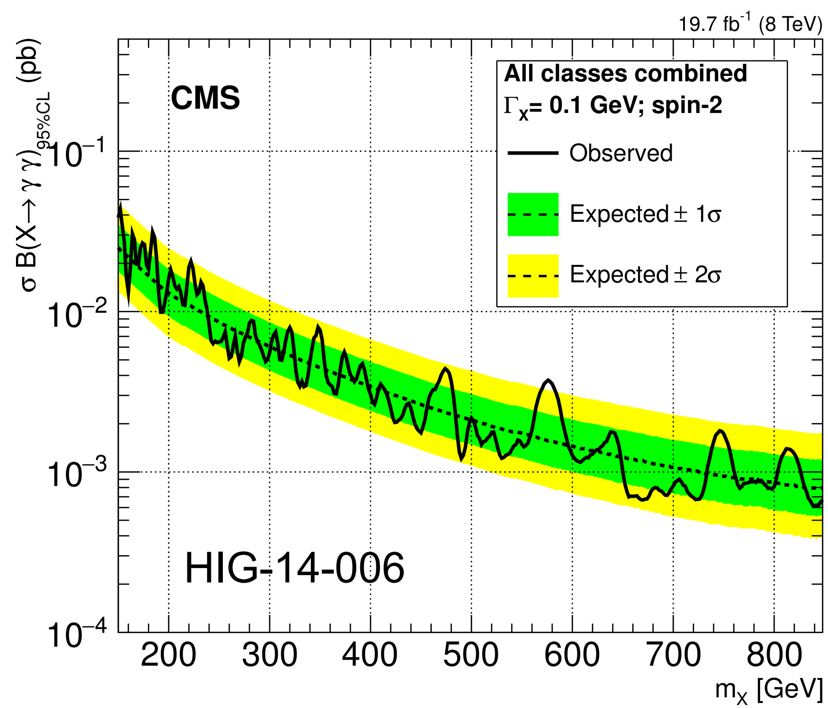




Combined analysis of 8 and 13TeV data

- Combination in all 6 signal hypotheses tested at 13TeV.
  - At **each mass**, **pick most sensitive** analysis: HIG-14-004 in 500-850GeV, EXO-12-045 otherwise.
  - **Cross section ratios** at 750GeV.
    - For spin 0 **(gg → S)**: σ(8eV)/σ(13TeV) = **0.22**
    - For spin 2 **(G_{RS})**: σ(8TeV)/σ(13TeV) = **0.24**

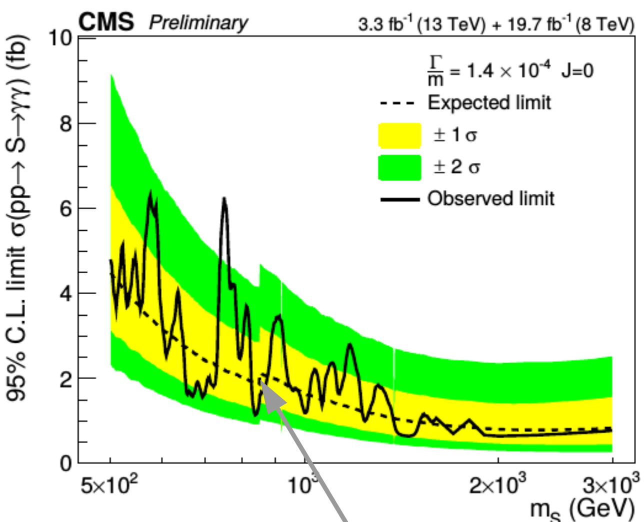




Upper limits (normalized to 13TeV x-sec)

- Compared to single analyses, sensitivity improved by 20-40%.

$\Gamma/m = 1.4\text{x}10^{-4}$



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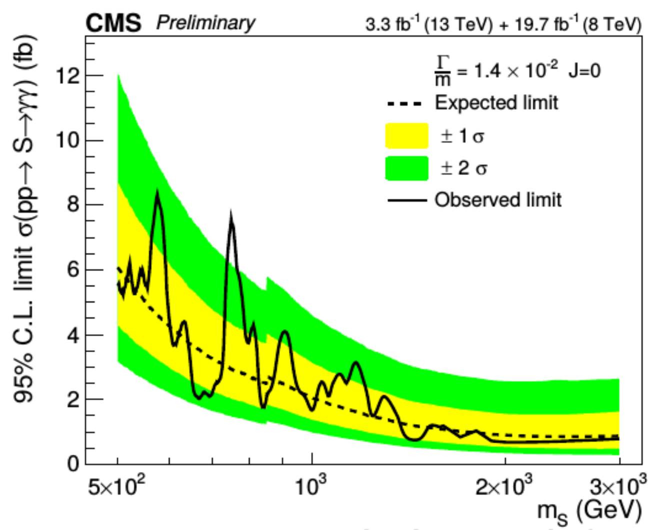
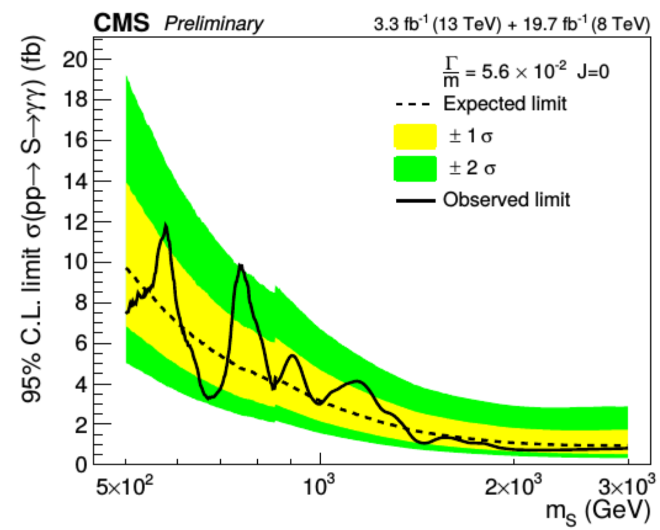


$\Gamma/m = 5.6\text{x}10^{-2}$

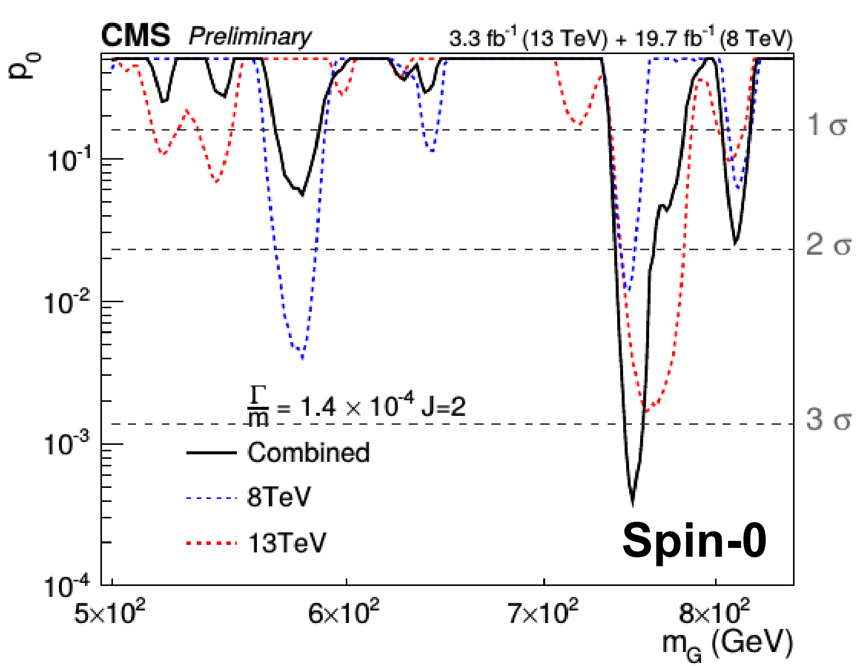


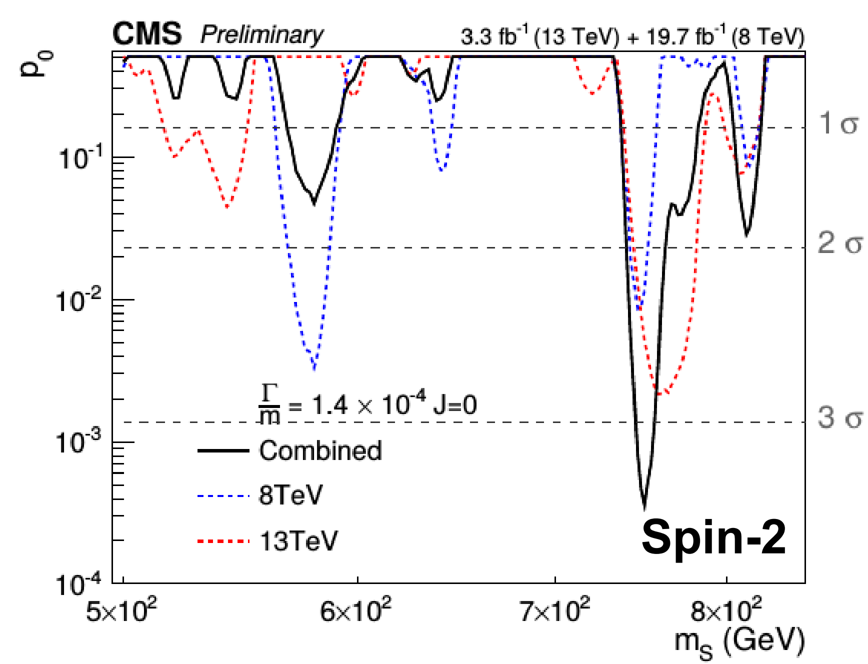
Spin 0

Switch between 8TeV analyses

p-values

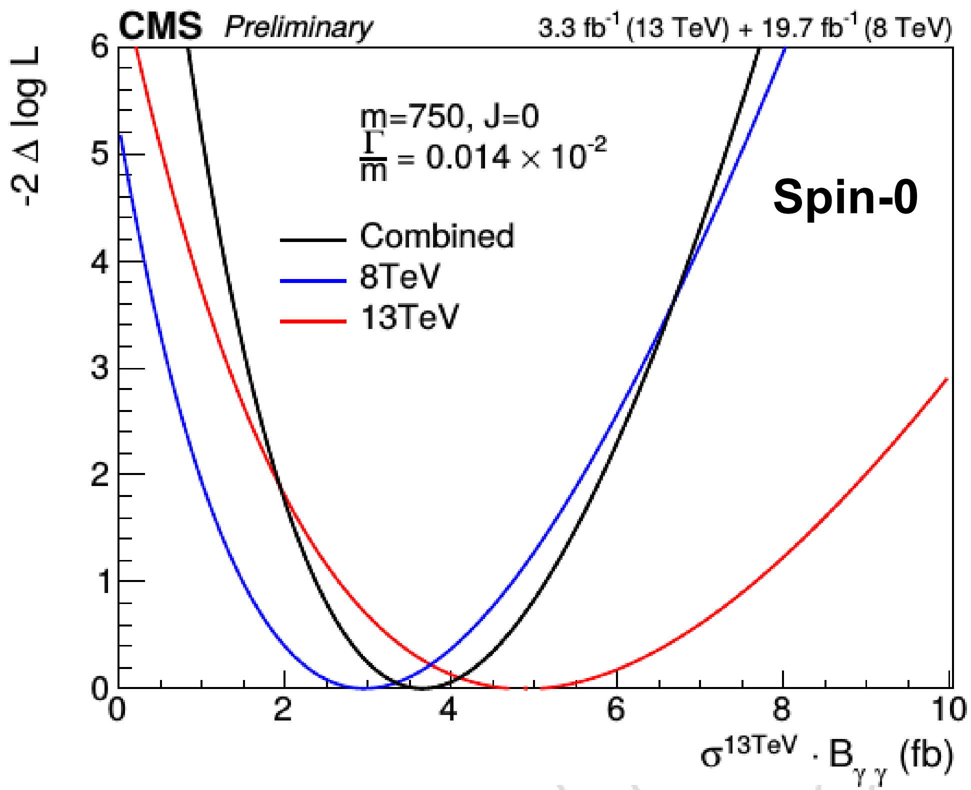
- Largest excess observed at **m_x = 750GeV** and for **narrow** width.
  - **Local** significance: **3.4σ**
  - Taking into account mass range 500-3500GeV (and all signal hypotheses), "**global**" significance becomes **1.6σ**

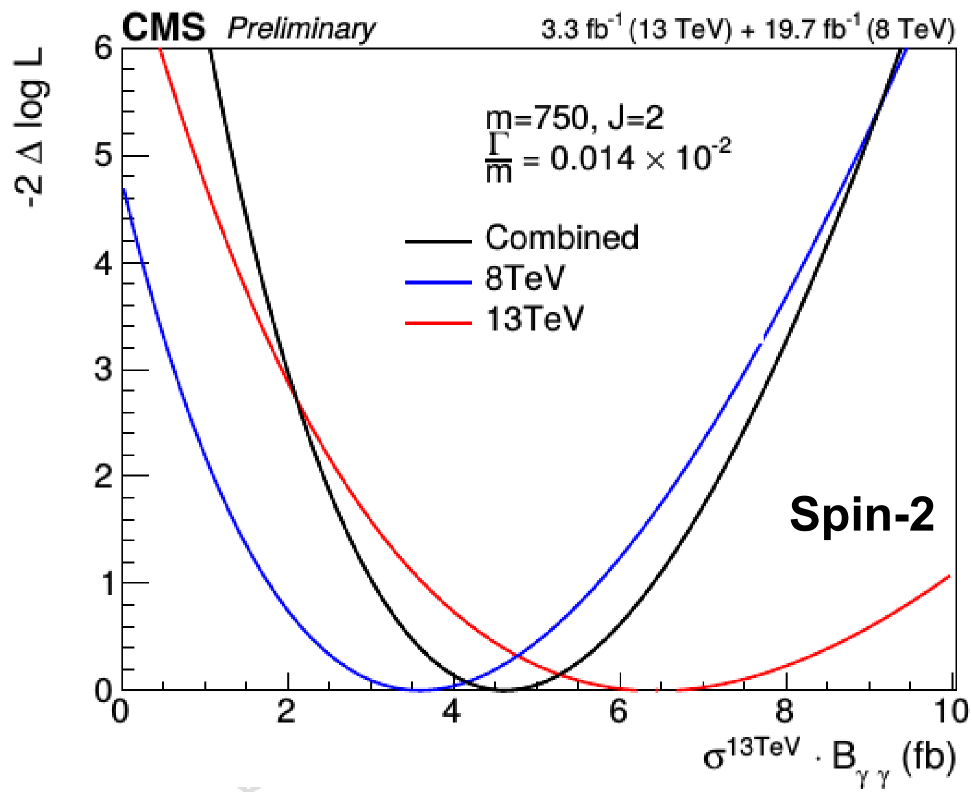




Consistency between 8 and 13TeV datasets

- Evaluated through likelihood scan vs equivalent 13TeV cross-section at m_X = 750GeV under both spin (narrow-width) hypotheses.
  - Compatible results observed in both datasets.



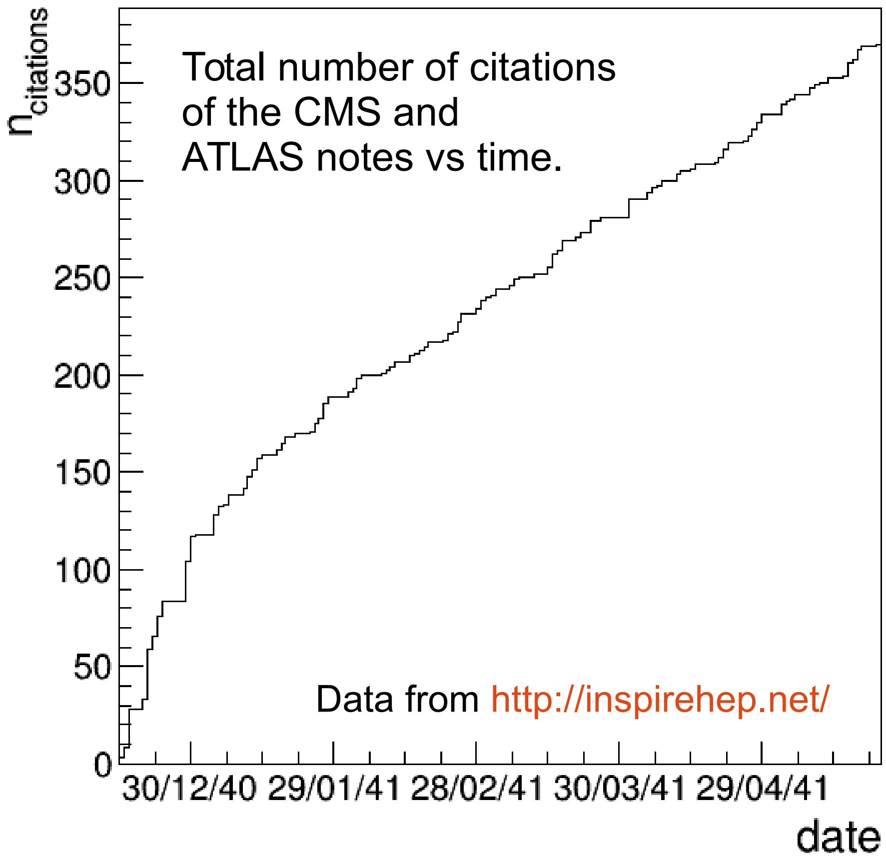


Additional checks

- Performed several checks for detector effects that could produce the observed patterns.
  - No pathology discovered.
- The region of the excesses have been checked in details.
  - Diphotons distributions compatible with what is expected from background.
  - Additional hadronic activity also compatible with background expectations.
  - Note: an s-channel-produced resonance would not be significantly different wrt the background at this level.

Is this the hint of a signal?

- (Disclaimer: this slide contains just my personal opinion.)
- Obviously, cannot say it with present data.
- It is surely interesting that both experiment observe an excess in the region around 750GeV.
  - Clearly, the theory community agrees with such a statement.
- On the other hand it will not be surprising if the excess is not confirmed with additional data.
  - As seen many times in recent and non-recent history.
- For sure, we should try not to over-interpret the data.
  - Keep in mind that the measured properties of early signals tends to be biased.
  - So do not take as given things like widths, cross sections, ….



Summary and perspectives

- Showed an **update on searches for diphoton resonances** in the mass range above 500GeV at 8 and 13TeV.
  - Used simple and robust analysis strategy.
- Results interpreted in terms of scalar resonances and RS gravitons production of different widths.
  - Observation generally consistent with SM expectations.
  - **Modest excess** of events observed at **m_X = 750(760)GeV** for the 8+13TeV(13TeV) dataset.
  - **Local** significance is **3.4(2.9)σ**, **reduced to 1.6(<1)σ** after accounting for look-elsewhere-effect.
- Looking forward to the 2016 LHC dataset.

Additional material

Improvements presented at Moriond'16

- Results presented at the CERN-LHC Seminar in December 2015 based on 2.6fb^{-1}
  (which became 2.7fb^{-1} due to an update in the luminosity measurement).
  - Based on channel-to-channel ECAL calibration extrapolated from Run 1 data.

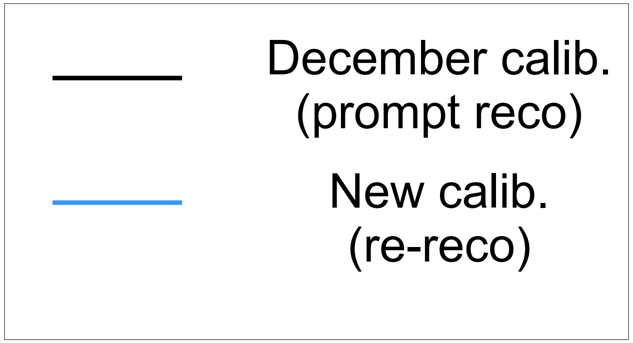
NEW

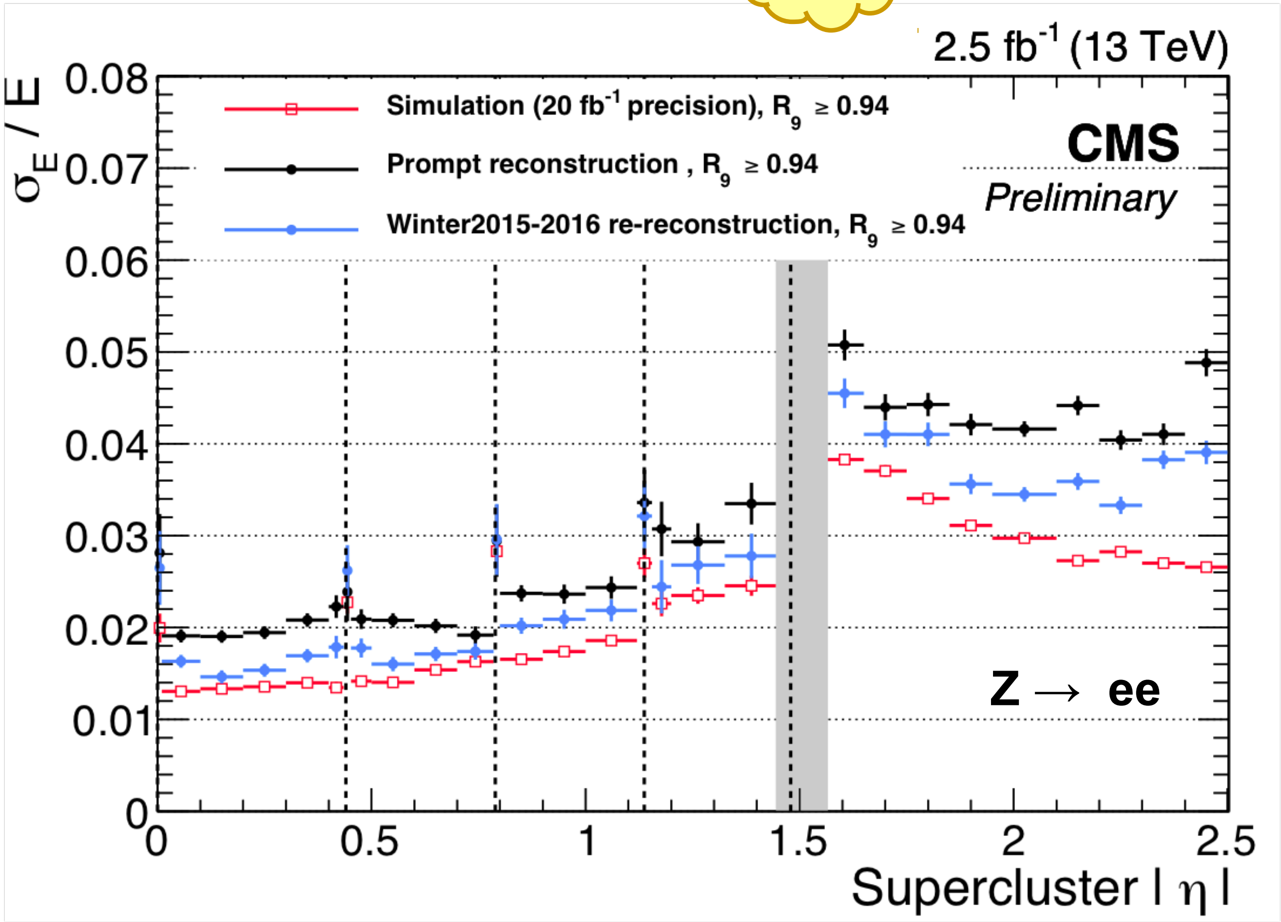
- **Data** re-reconstruction, using **updated channel-to-channel calibration,** completed over the winter shutdown.
  - Constants to equalize channel-to-channel response obtained on 2015 data.
  - In the high mass region, **resolution improved by ~30%**
    (leading to a ~10% improvement in analysis sensitivity).

New ECAL channel-to-channel calibration

- ECAL channel-to-channel calibration crucial for energy resolution.
  - Over the winter shutdown data were re-reconstructed using new channel-to-channel calibration obtained on the 2015 dataset.

NEW



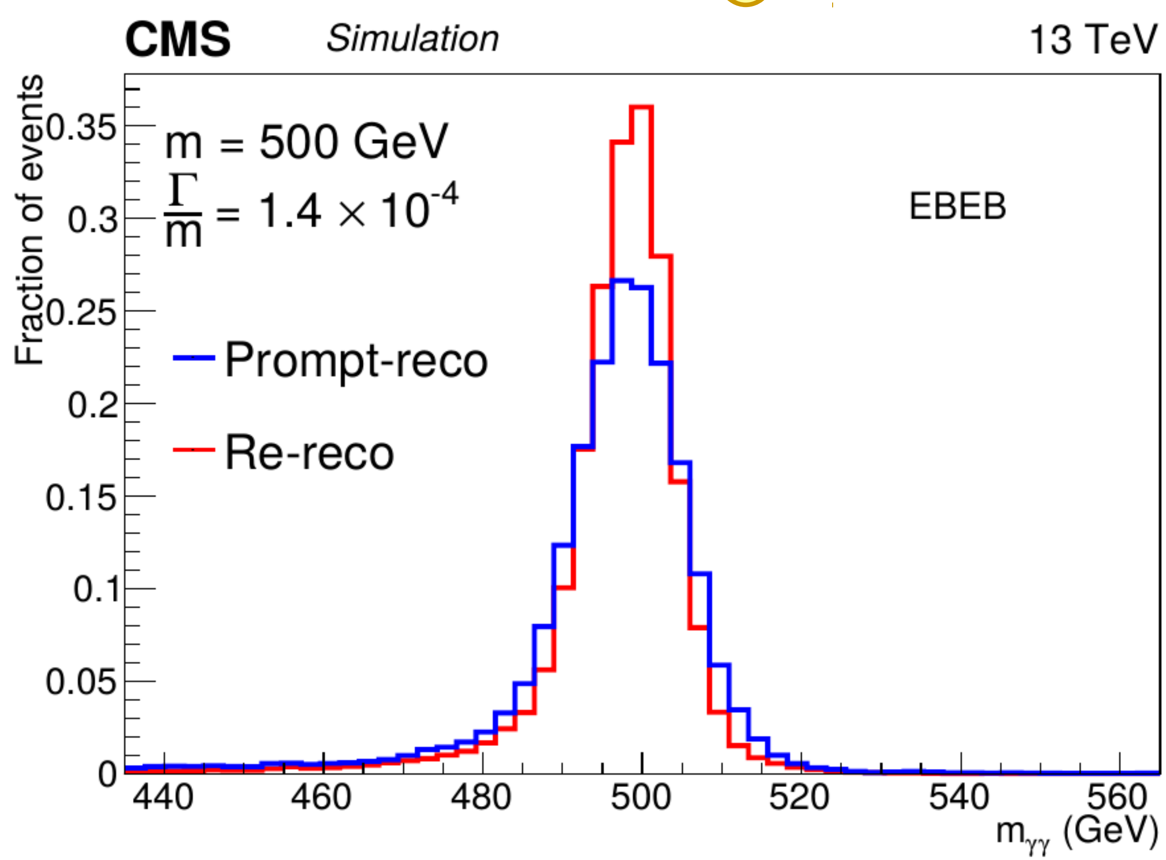


New ECAL channel-to-channel calibration

- ECAL channel-to-channel calibration crucial for energy resolution.
  - Over the winter shutdown data were re-reconstructed using new channel-to-channel calibration obtained on the 2015 dataset.

NEW

  - Lead to **30% improvement** in mass **resolution** above 500GeV.
  - Resolution correction assumed to be constant vs energy. (in run 1 observed decrease vs energy, but not possible to run fit in run 2 yet).



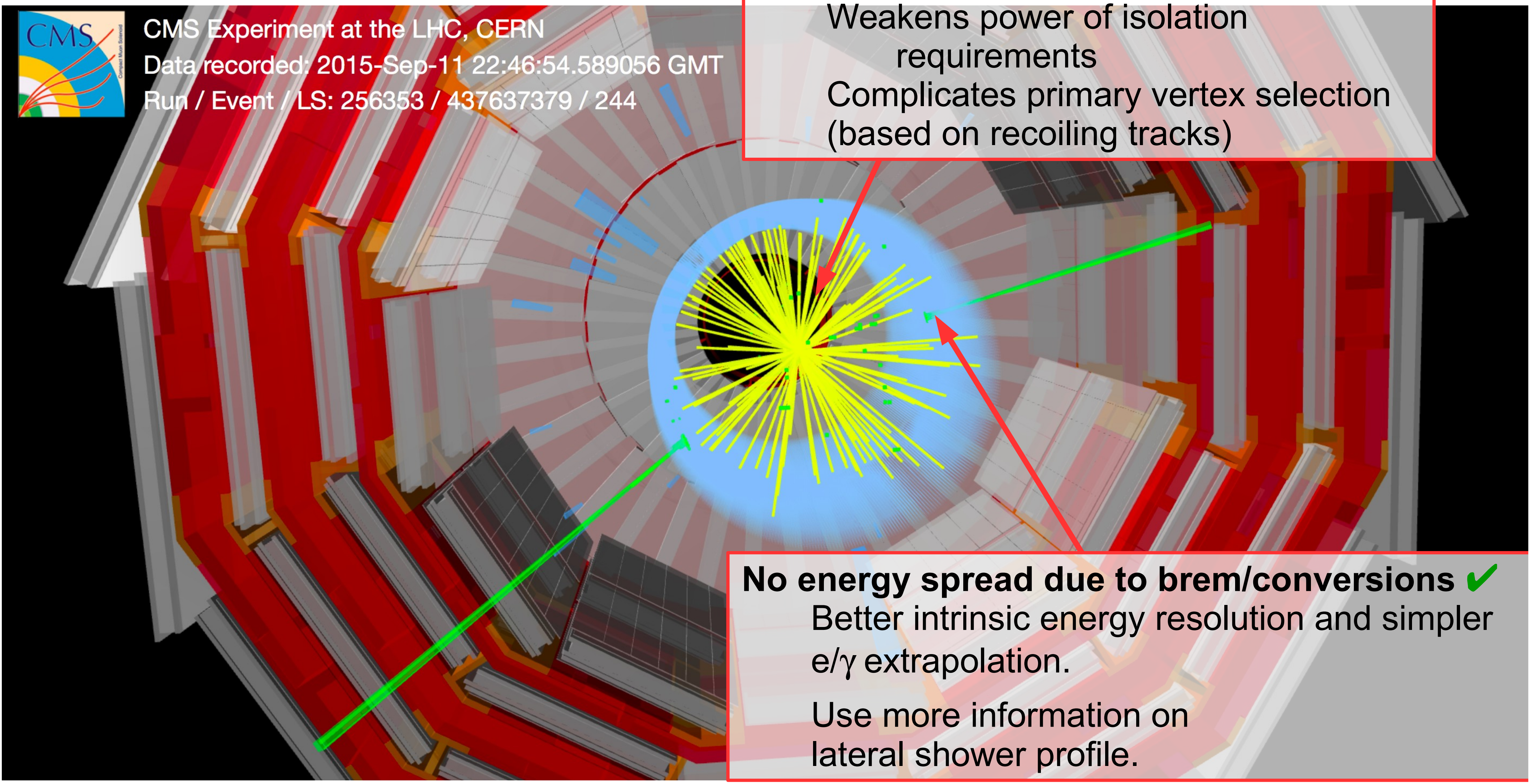
What's new?

- Results presented at the December Jamboree based on 2.6fb^{-1} (which became 2.7 due to an update in the luminosity measurement).
  - Based on channel-to-channel calibration extrapolated from Run 1 data.
- **Data** re-reconstruction, using **updated channel-to-channel calibration**, completed over the winter shutdown. NEW
  - Constants to equalize channel-to-channel response obtained on 2015 data.
  - In the high mass region, **resolution improved by ~30%** (leading to a ~10% improvement in analysis sensitivity).
- An **additional 0.6fb^{-1}** dataset, recorded at **B=0T** was analyzed.
  - Lead to a further 10% improvement on top of the re-calibration. NEW

Analyzing B=0T data

NEW

- Significant re-thinking of the analysis needed to use data without magnetic field.



No information on tracks momenta ✗

Weakens power of isolation requirements

Complicates primary vertex selection (based on recoiling tracks)

No energy spread due to brem/conversions ✔

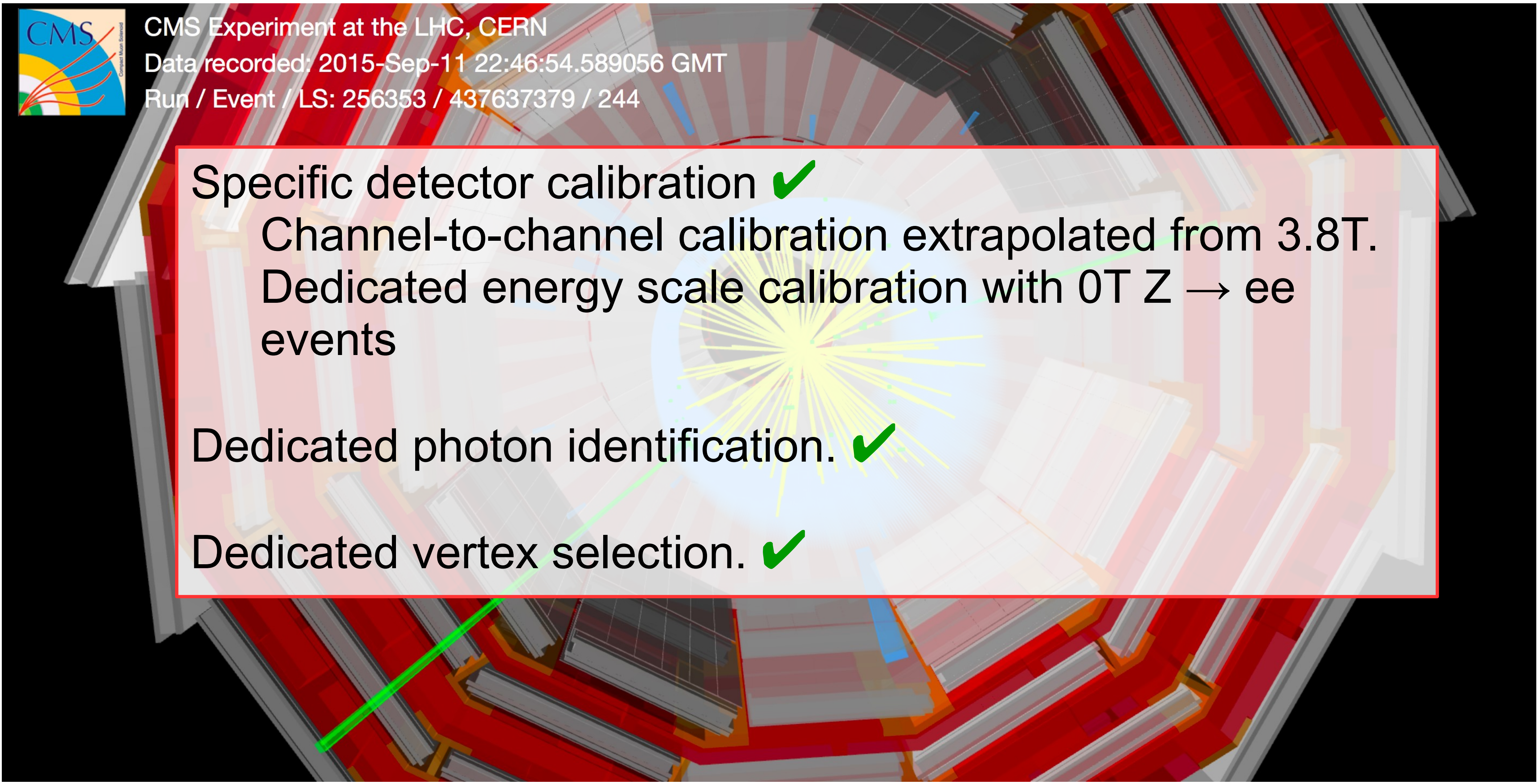
Better intrinsic energy resolution and simpler e/γ extrapolation.

Use more information on lateral shower profile.

Analyzing B=0T data

NEW

- Major re-thinking of the analysis needed to use data without magnetic field.



Specific detector calibration ✔

- Channel-to-channel calibration extrapolated from 3.8T.
- Dedicated energy scale calibration with 0T $Z \rightarrow ee$ events

Dedicated photon identification. ✔

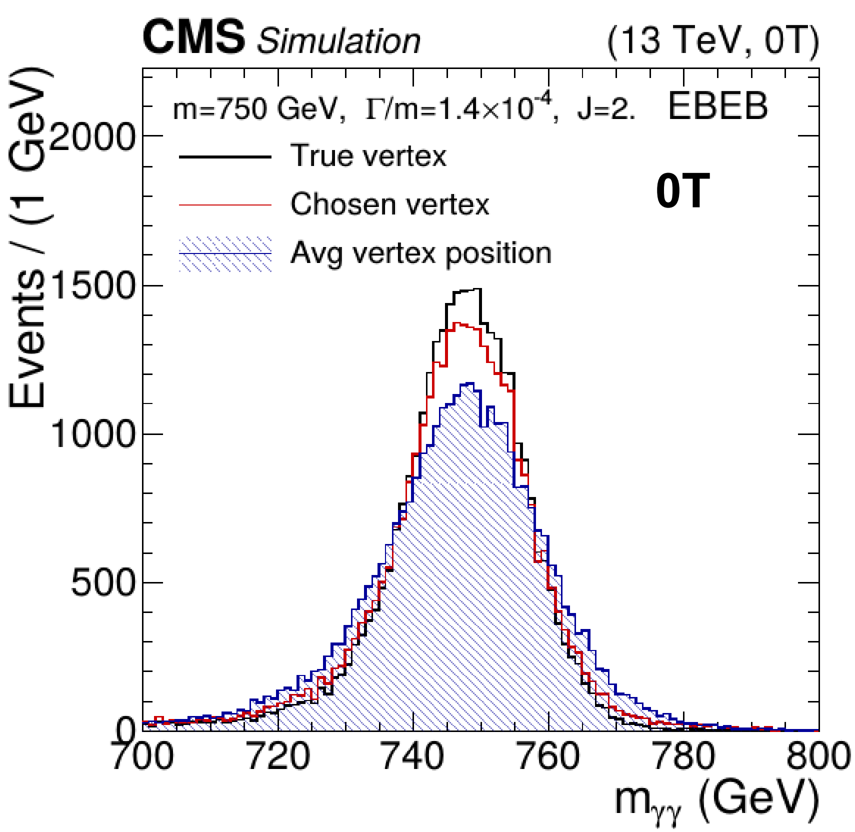
Dedicated vertex selection. ✔

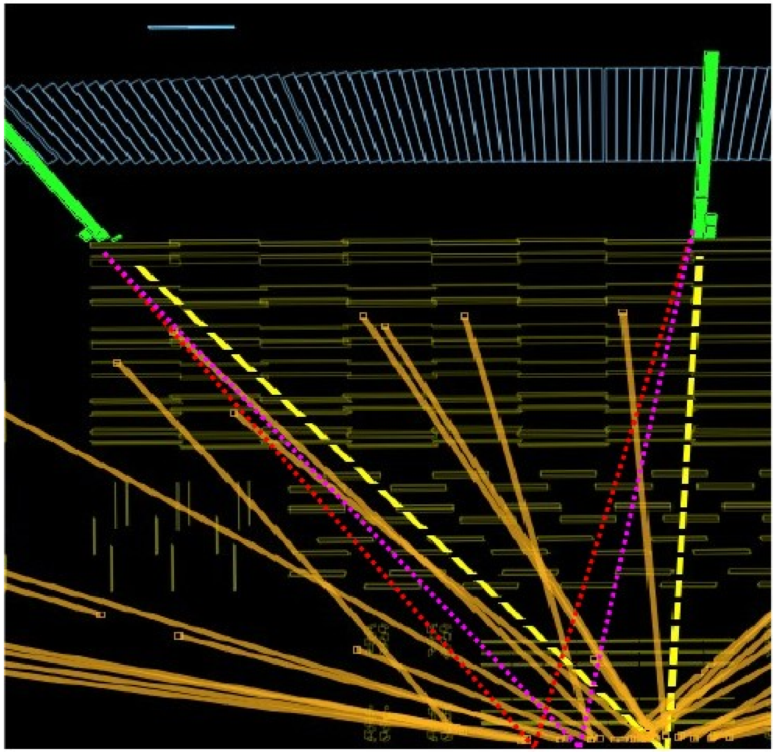
What's new?

- Results presented at the December Jamboree based on 2.6fb^{-1} (which became 2.7 due to an update in the luminosity measurement).
  - Based on channel-to-channel calibration extrapolated from Run 1 data.
- **Data** re-reconstruction, using **updated channel-to-channel calibration**, completed over the winter shutdown. NEW
  - Constants to equalize channel-to-channel response obtained on 2015 data.
  - In the high mass region, **resolution improved by ~30%** (leading to a ~10% improvement in analysis sensitivity).
- An **additional 0.6fb^{-1}** dataset, recorded at **B=0T** was analyzed.
  - Lead to a further 10% improvement on top of the re-calibration. NEW
- Results **interpreted** in terms of **spin-0** and **spin-2** resonances.
  - J=0: assumed gluon-fusion produciton, J=2: RS-graviton NEW
  - **Three widths** (Γ/m=1.4x10^{-4}, 1.4x10^{-2}, 5.6x10^{-2})

Vertex identification

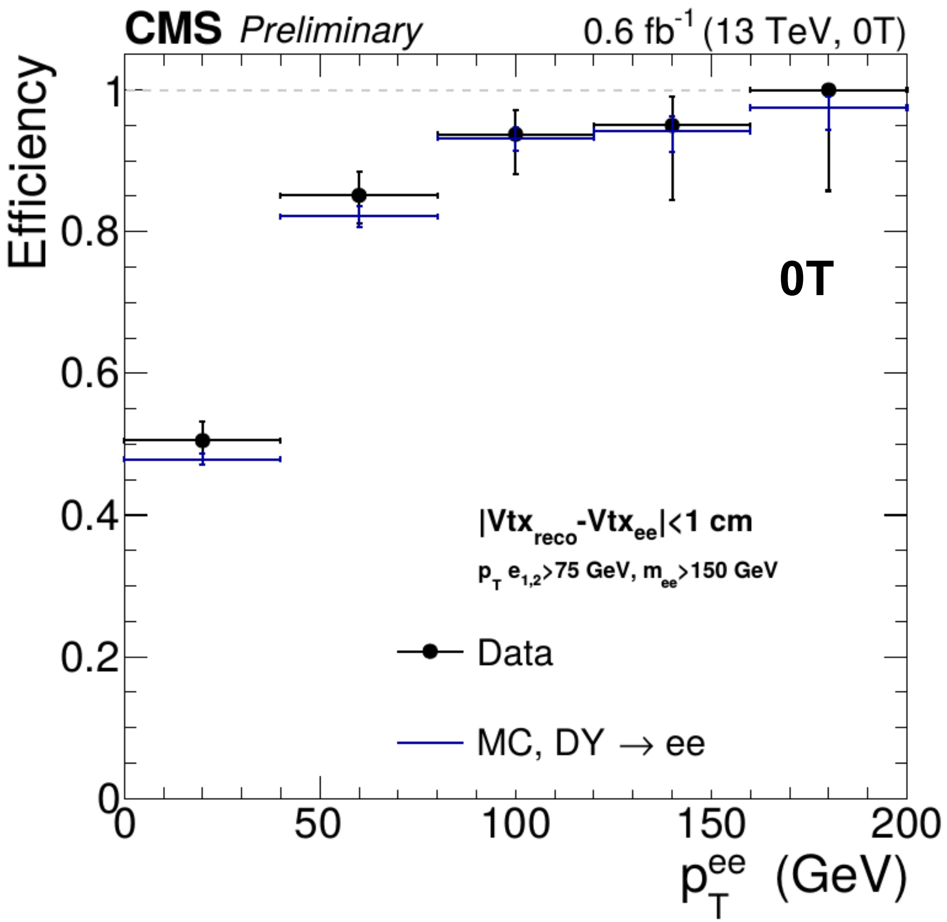
- Vertex identification important to maintain good mass resolution.
  - For 3.8T: use BDT (using recoil and tracks p_T) trained for $H \rightarrow \gamma\gamma$. ***(see I.Kucker in Wed. YSF)***.
  - For **0T:** simpler algorithm based on **track-counting**.
  - **Correct** assignments: **90% at 3.8T**, **60% at 0T**





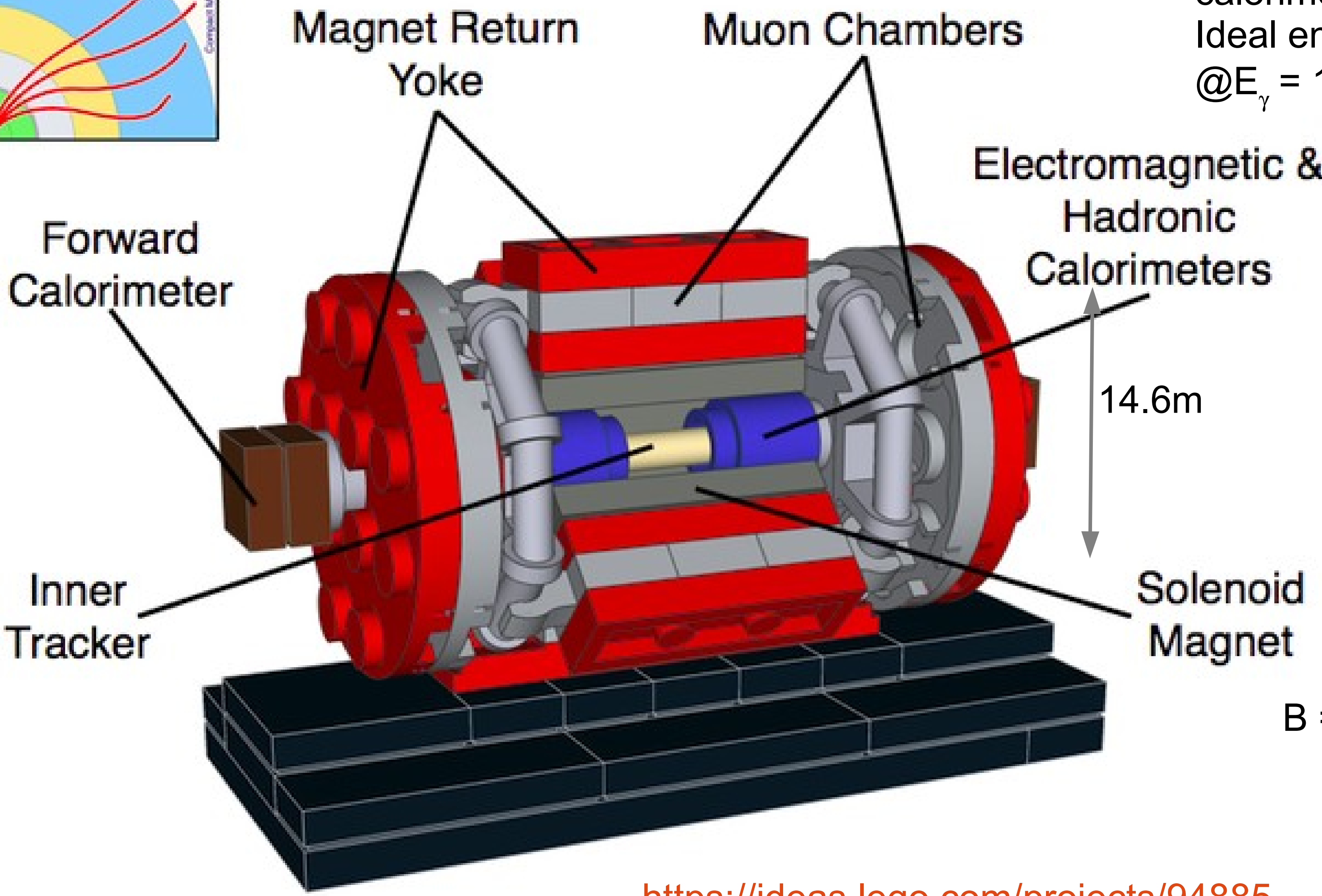
Vertex identification validation

- Modeling of correct vertex assignment tested in data.
  - Using di-muon and g+jet events for 3.8T. *(see Inna's talk for more details)*
  - Using di-electron events 0T.
  - *(Lepton and jets tracks remove from events)*



The CMS detector

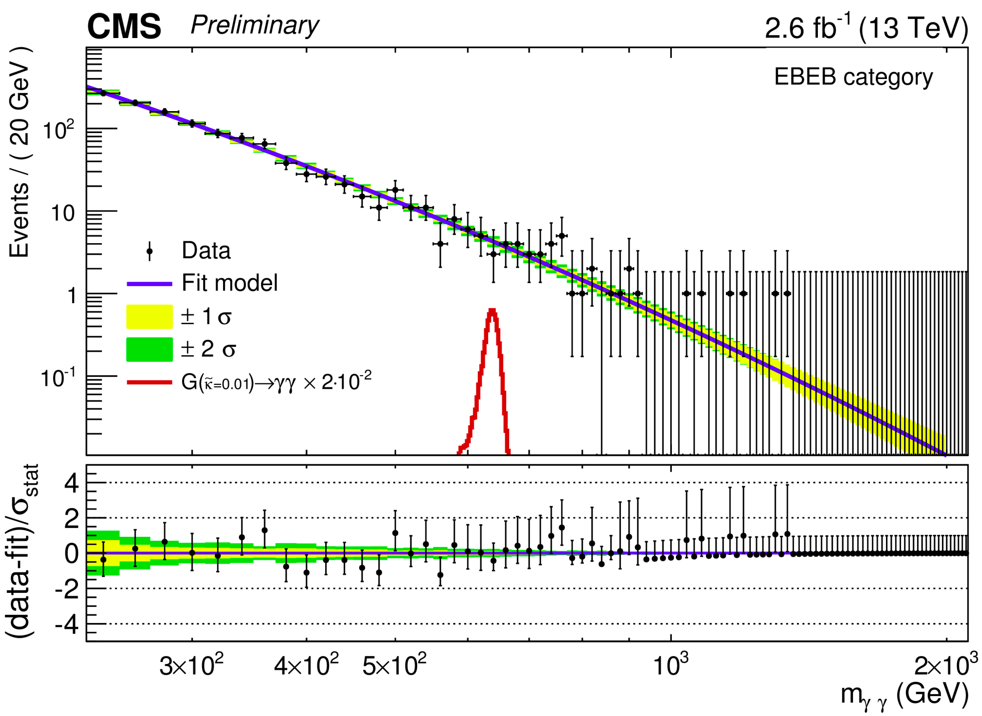
PWO homogeneous calorimeter.
Ideal energy resolution $@E_{\gamma}$ = 100GeV ~ 0.6%

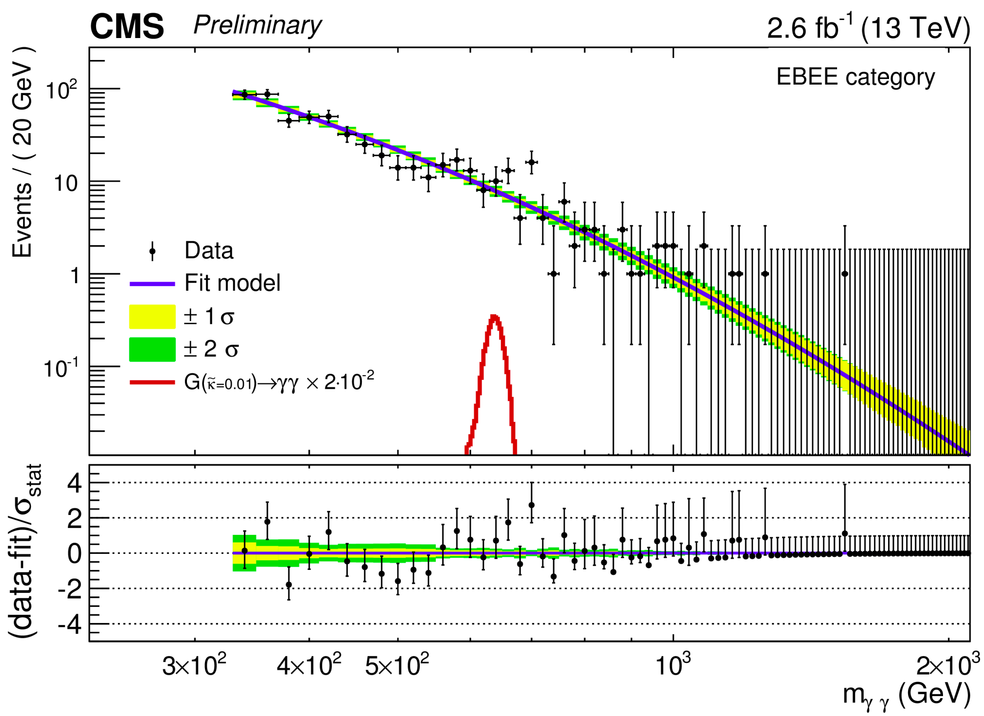


B = 3.8T

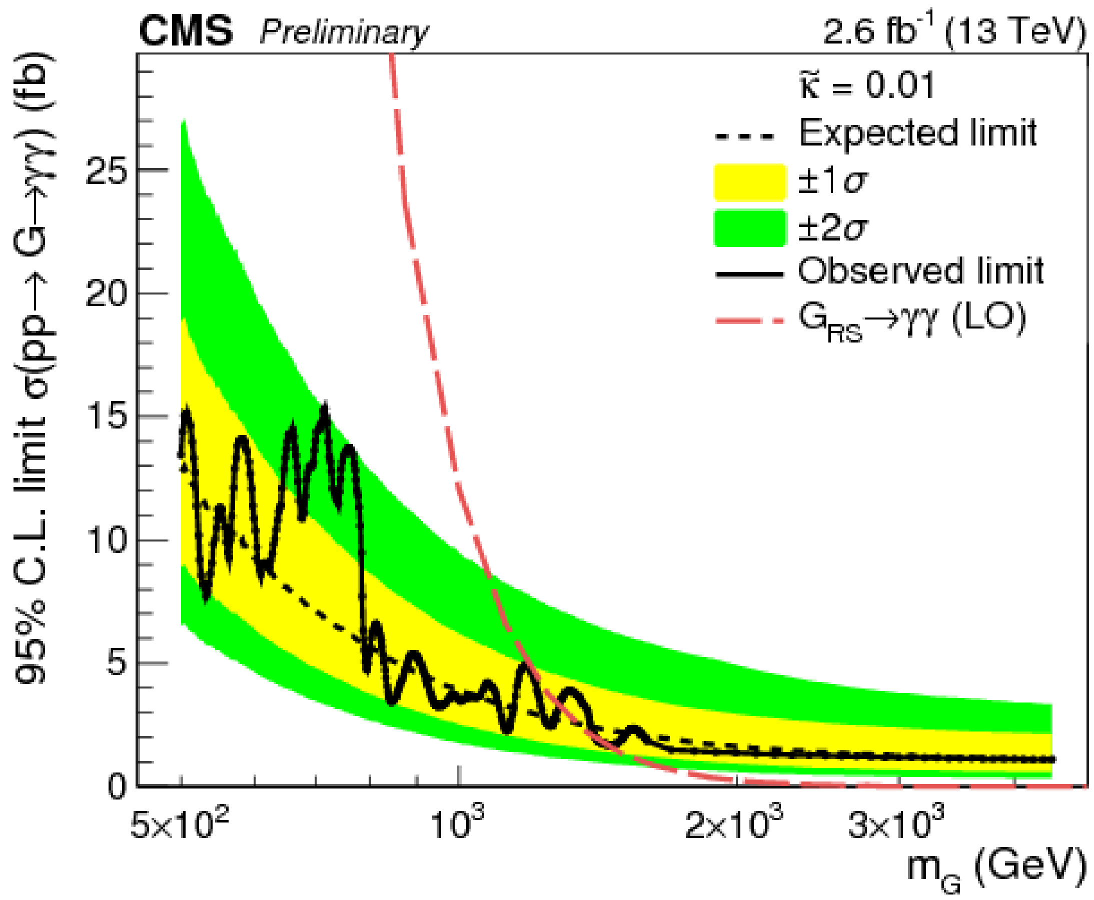
https://ideas.lego.com/projects/94885

December results – mass spectra

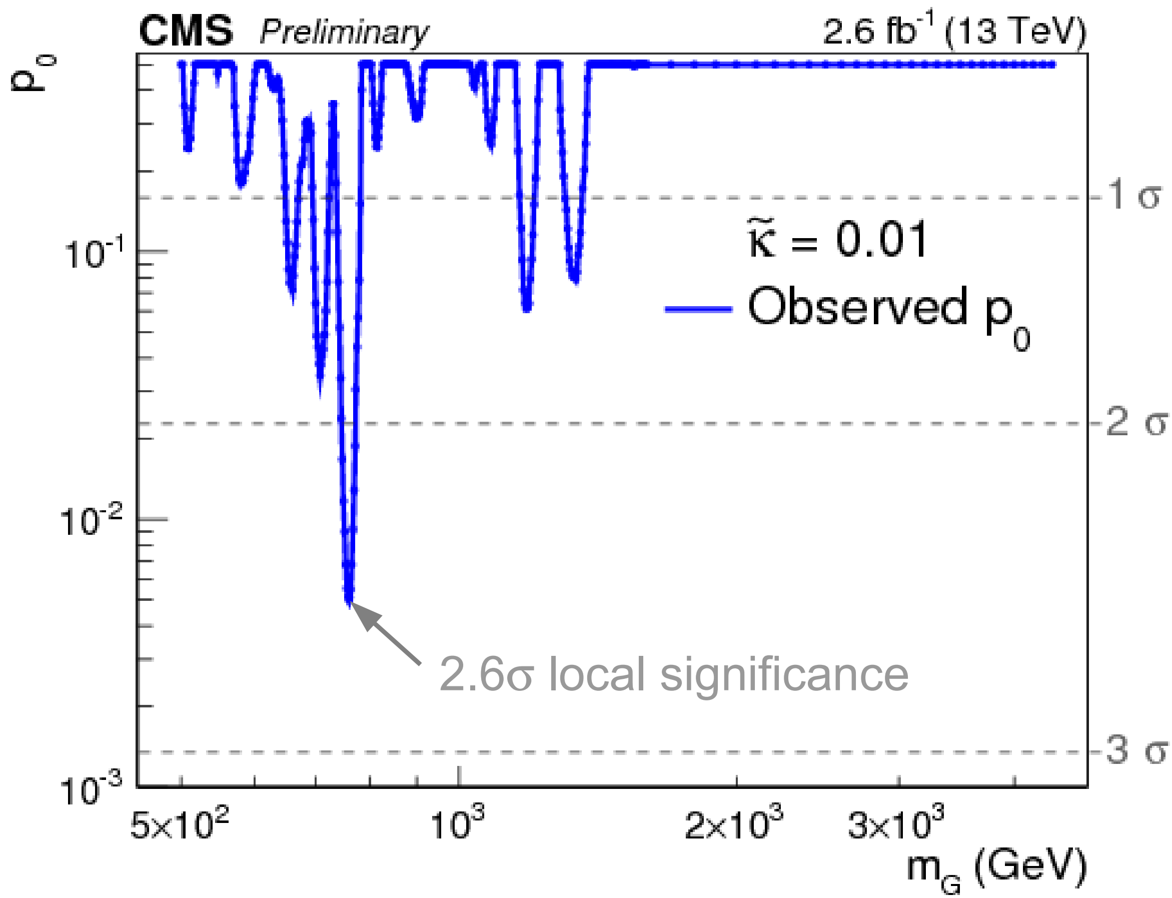




December results - limits



December results - pvalues

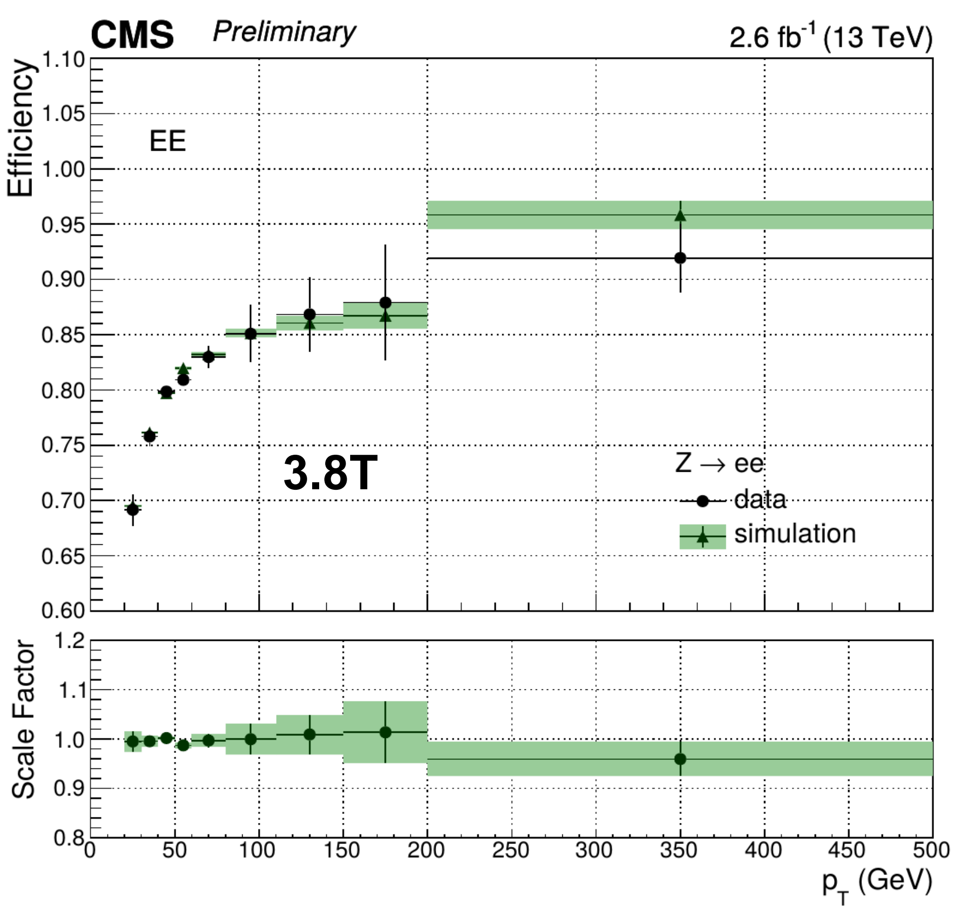


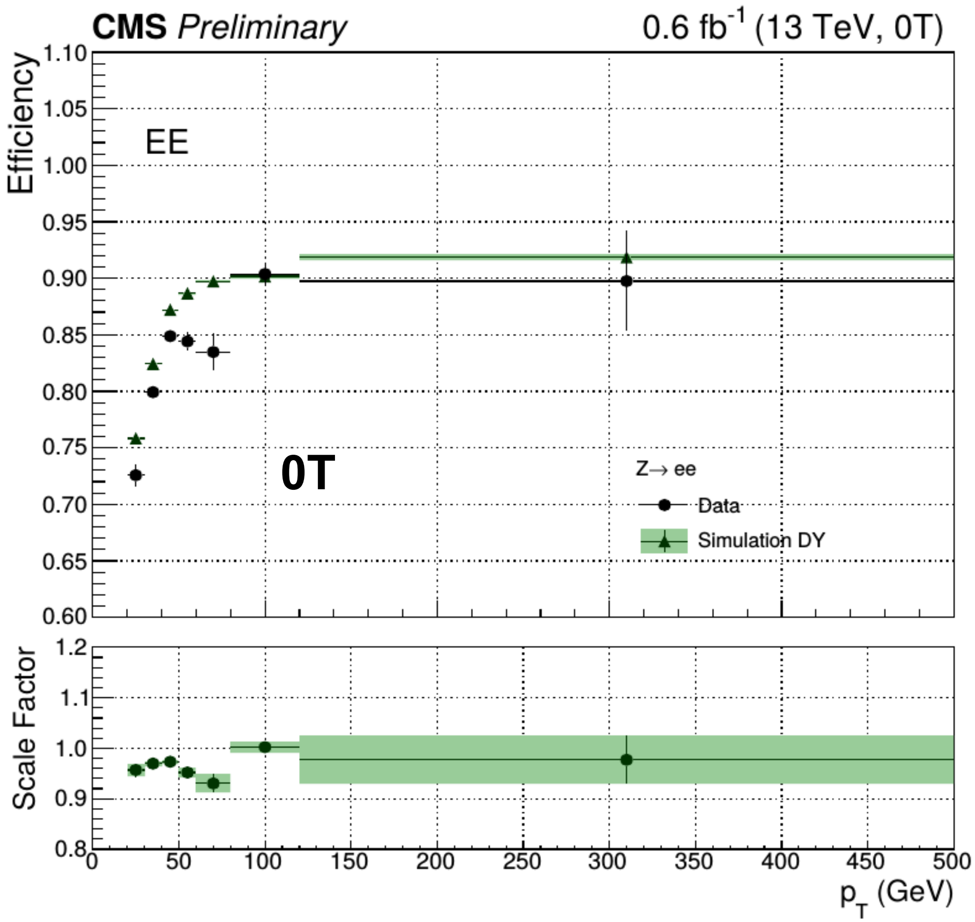
Background composition

- Analyses estimate background process extrapolating from side-bands in $m_{\gamma\gamma}$ spectrum.
  - Do not rely on precise prediction of background processes from MC simulation.
  - MC simulations used only to determine functional form used.

- At 3.8T, background composition measured in data
  - Determination do not enter in search result, but important to validate assumption that MC simulation are reliable.
  - Irreducible background accounts for 90(80)% of the events in the EBEB(EBEE) category.

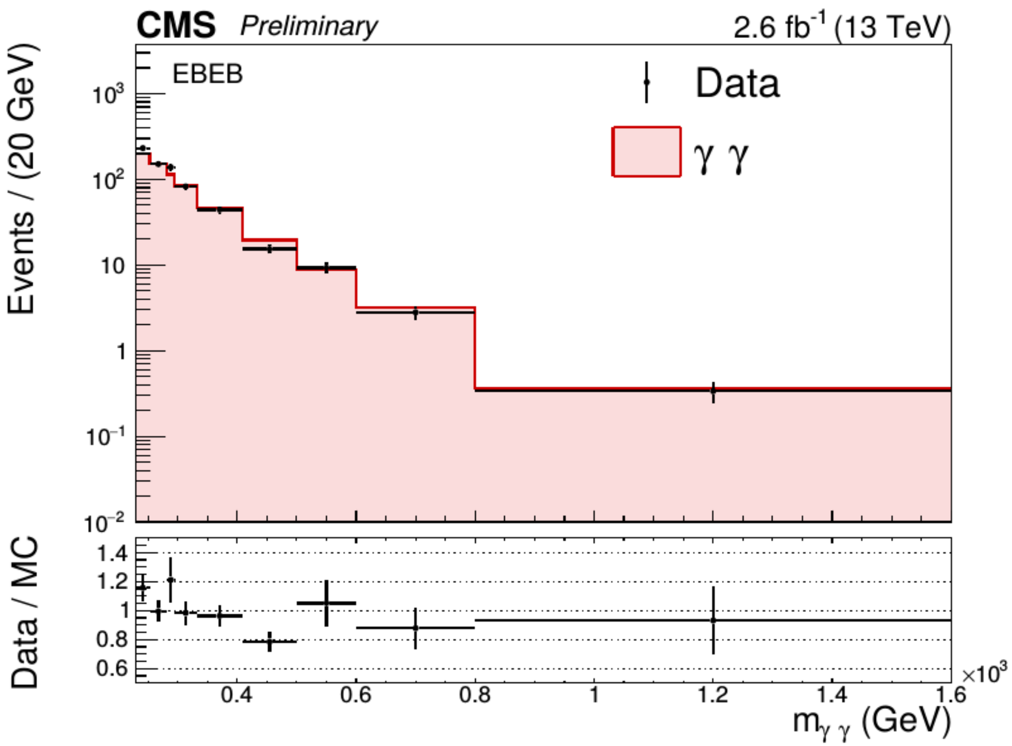
Photon identification efficiency for endcap photons.

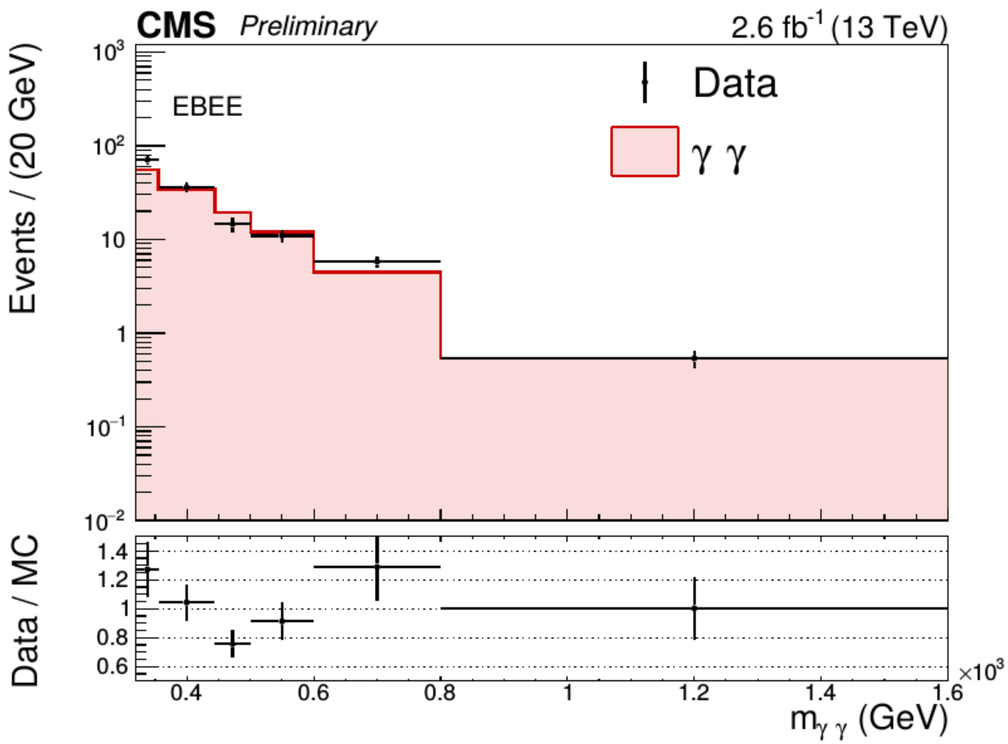




Background composition (2)

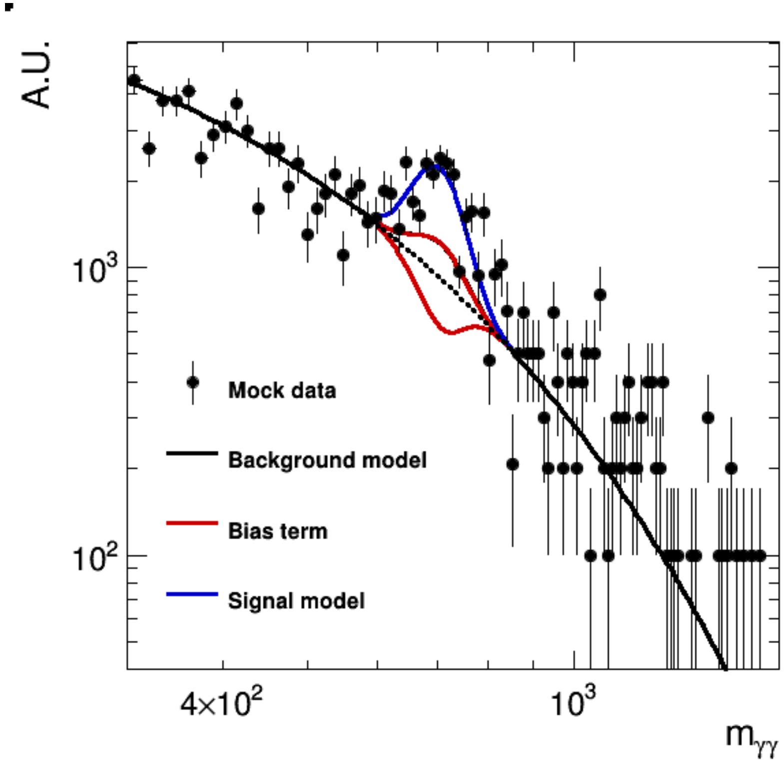
- Prediction for $\gamma\gamma$ component checked against theory predictions.
  - Obtained using Sherpa-LO reweighted to 2γNNLO.
  - Observation in good agreement with model.



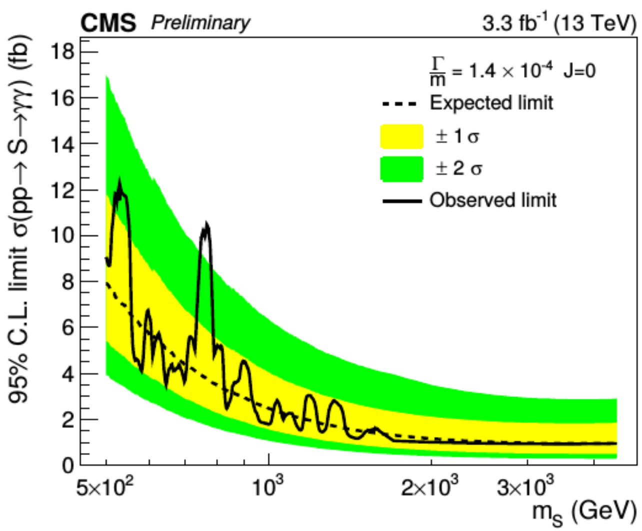


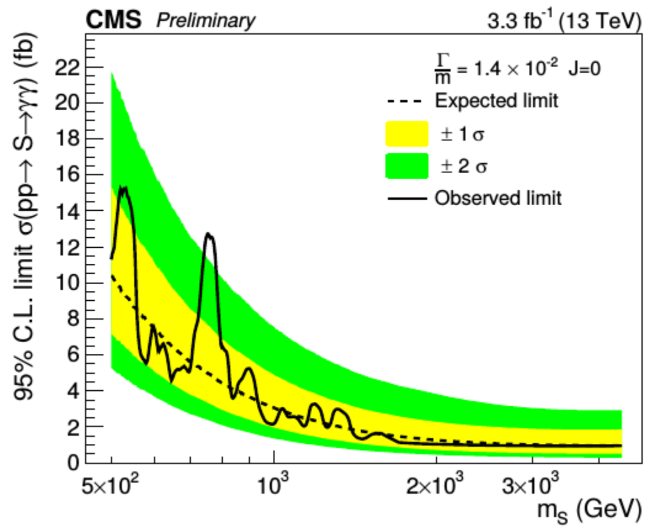
Background modelling

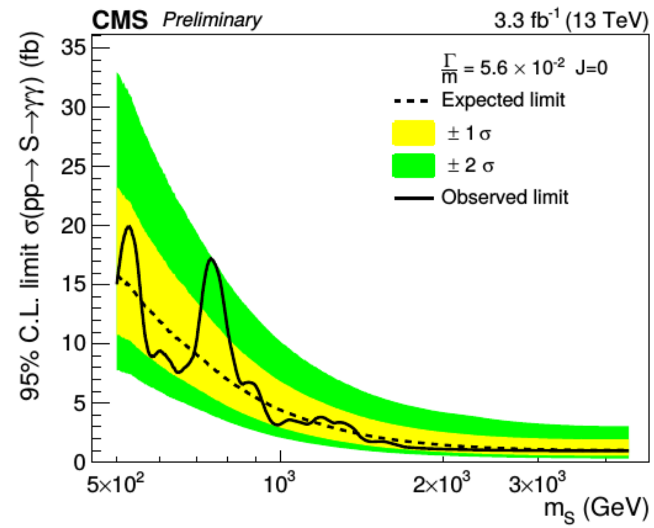
- Background modelled using **parametric fit** to data.
  - Model **coefficients** treated as unconstrained **nuisance parameters** in hypothesis test.
- Choice of background parametrization is arbitrary a-priori.
- Requirement: should not lead to false positives or negatives.
  - Fulfilled making sure that the **bias on** the predicted **background** is **small compared** to the **statistical uncertaines**.
  - Mismodelling required to be < ½ of the background stat. uncertainty.
  - Extra uncertainty added if condition not fulfilled, modelled as signal-like background component (“bias term”).



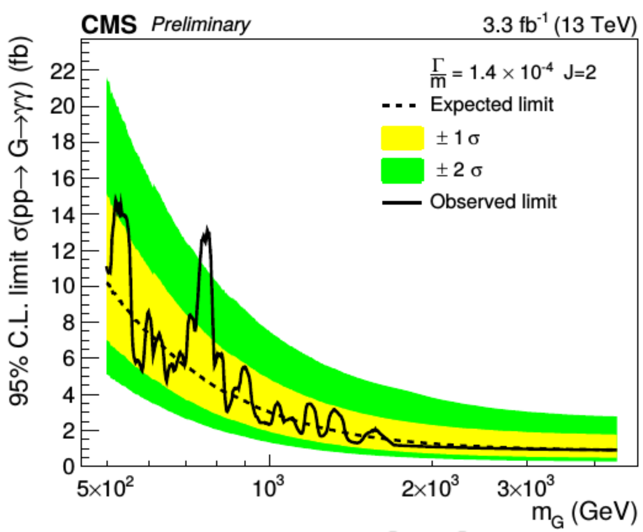
Upper limits - 13TeV

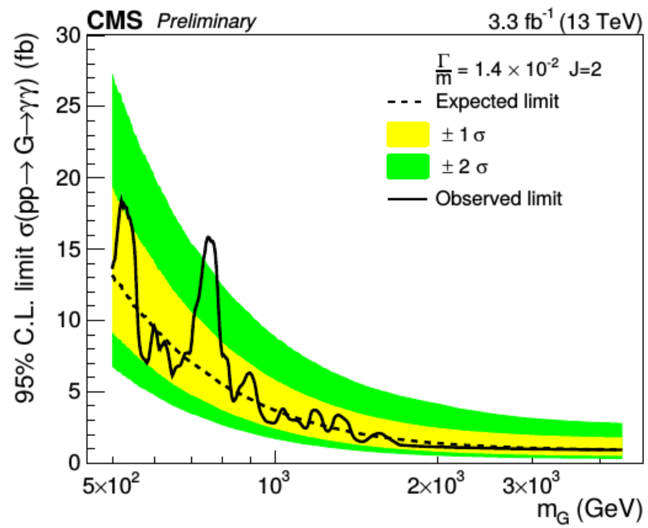


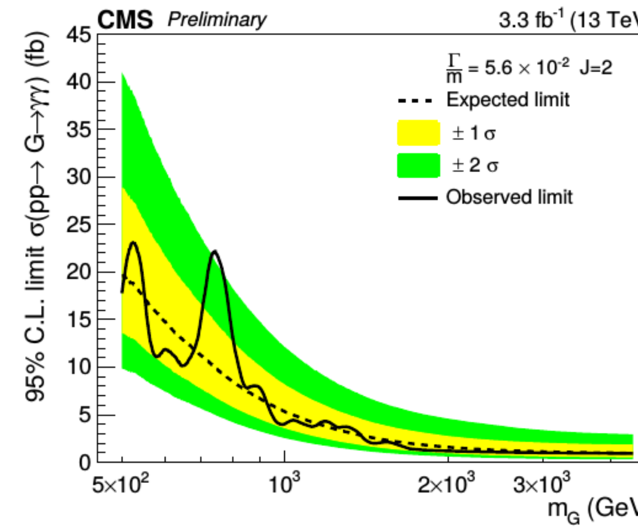




Spin 0





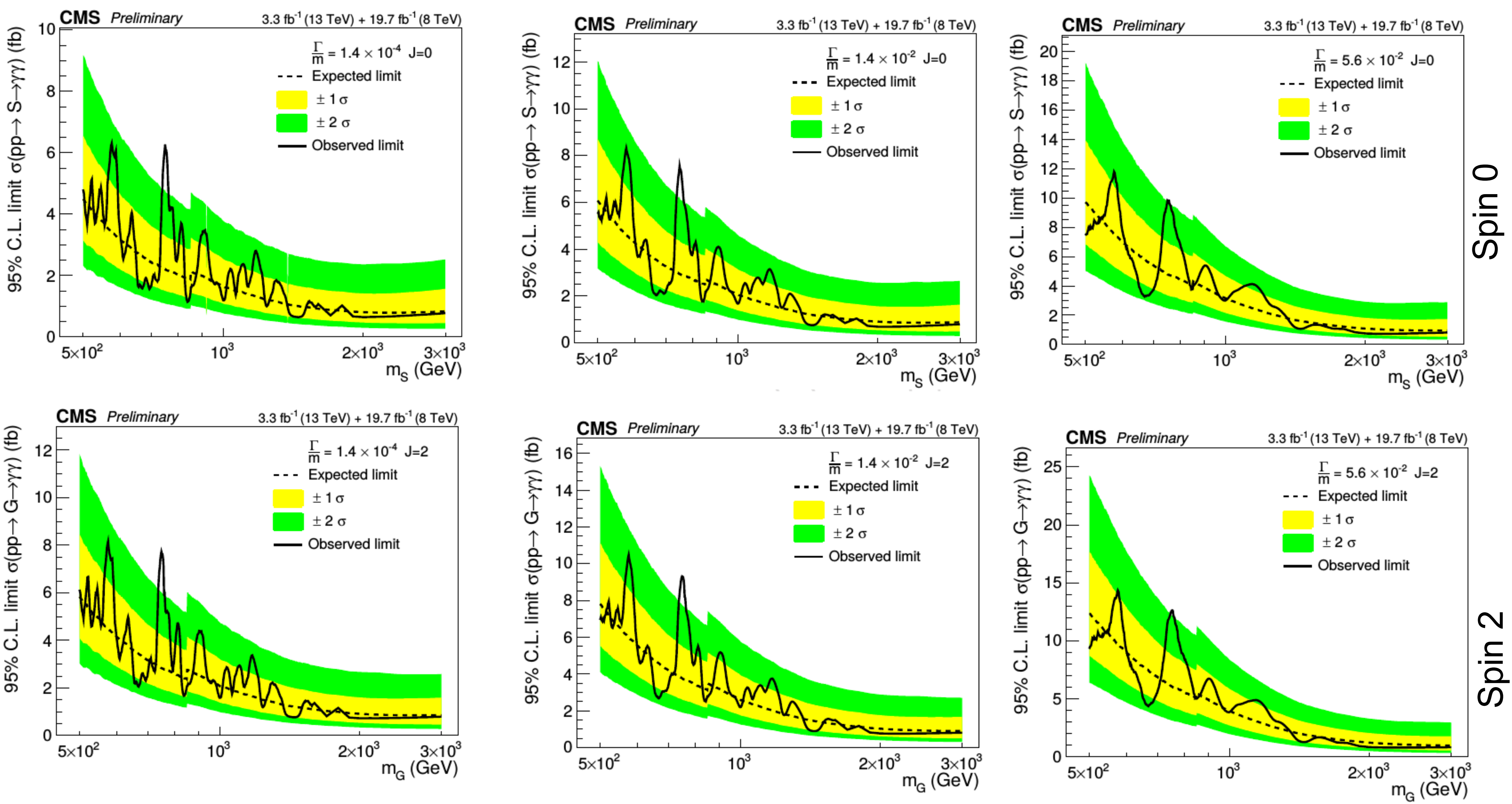


Spin 2

$\Gamma/m = 1.4\times10^{-4}$ $\Gamma/m = 1.4\times10^{-2}$ $\Gamma/m = 5.6\times10^{-2}$

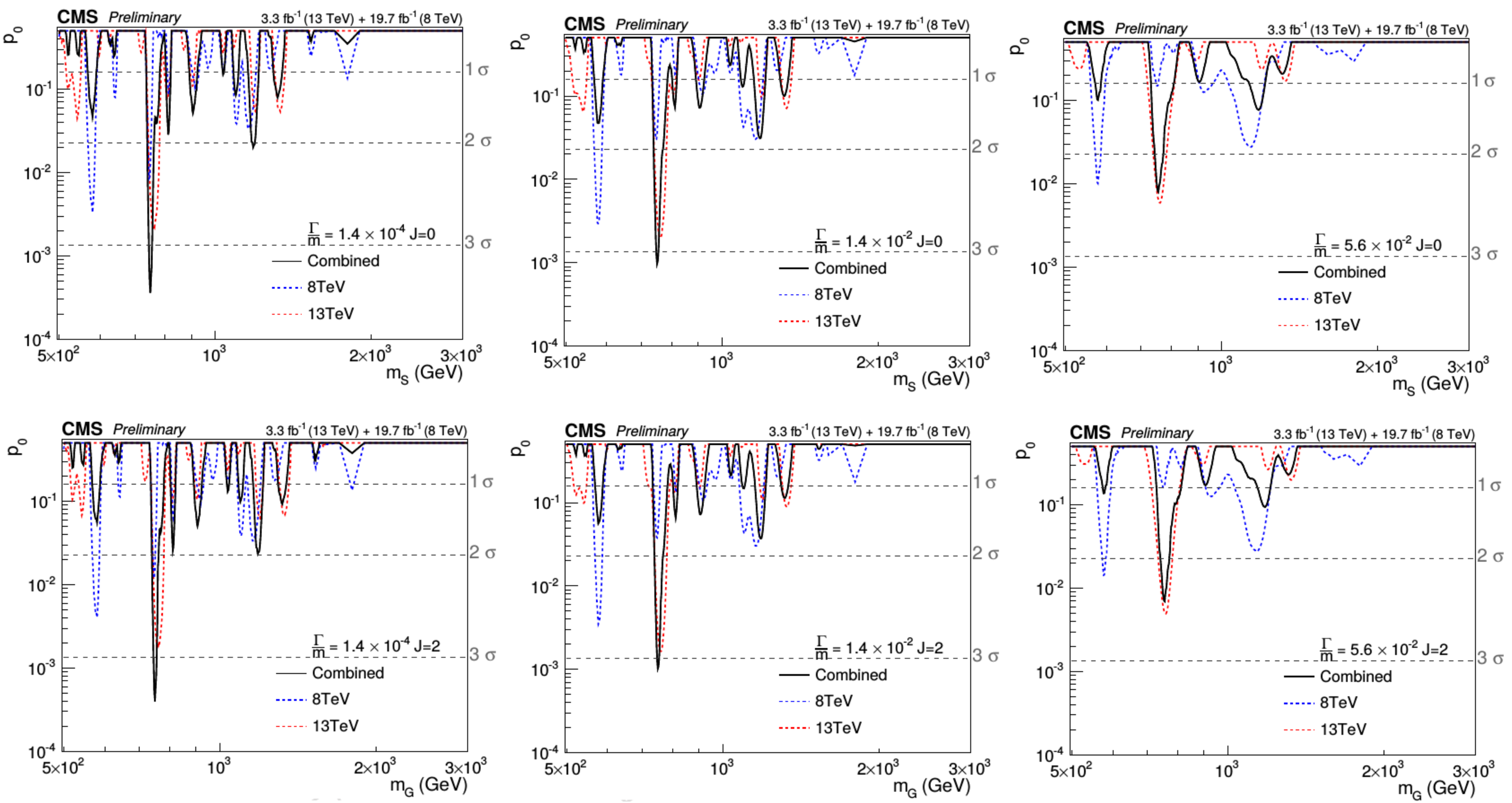
Upper limits (normalized to 13TeV x-sec)

8+13TeV

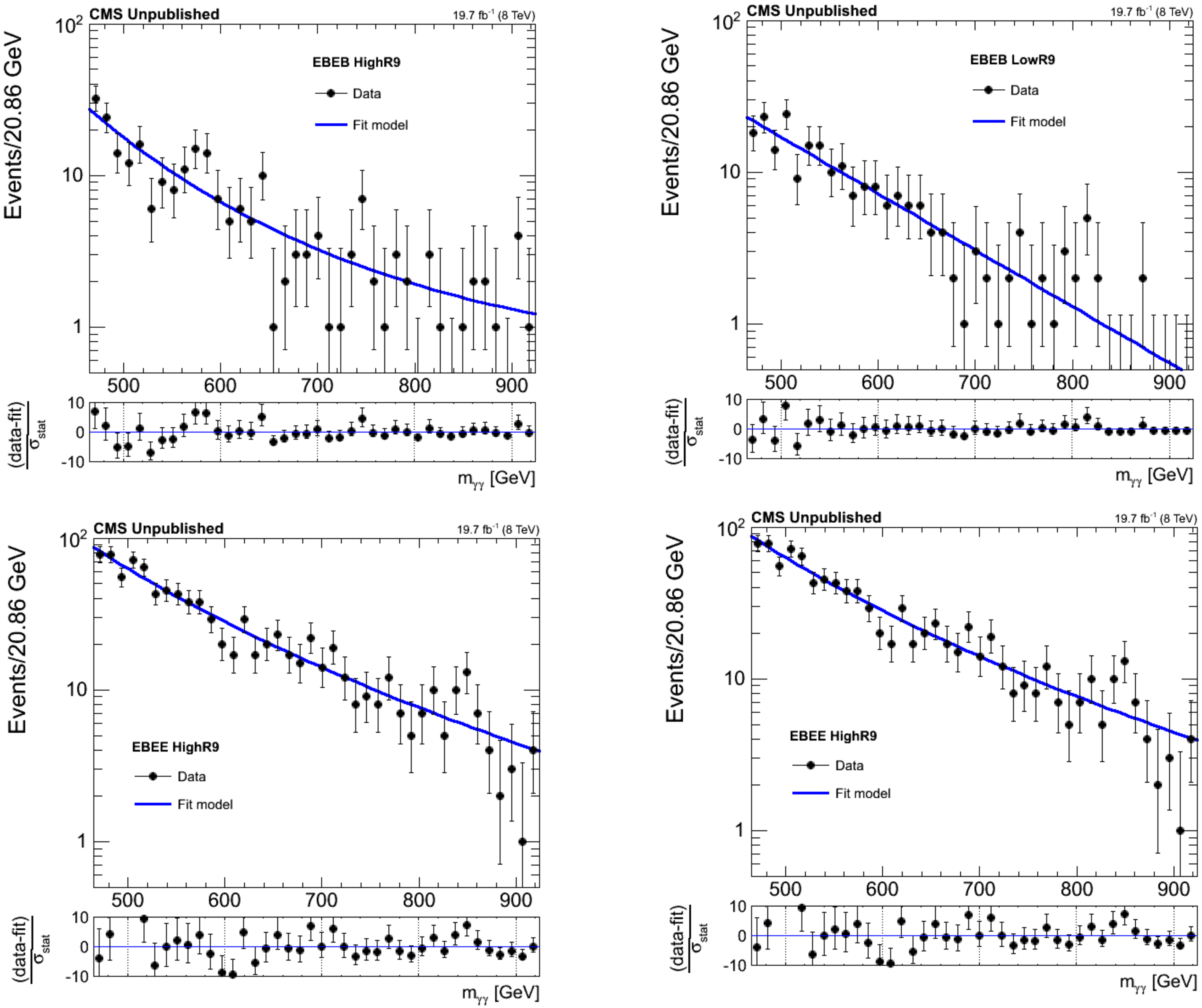


$\Gamma/m = 1.4\mathrm{x}10^{-4}$ $\Gamma/m = 1.4\mathrm{x}10^{-2}$ $\Gamma/m = 5.6\mathrm{x}10^{-2}$

P-values – all signal hypotheses



8TeV data


CMS Unpublished
19.7 fb^{-1} (8 TeV)
EBEB HighR9
Data
Fit model
Events/20.86 GeV
(data-fit)/σ_stat
m_γγ [GeV]
CMS Unpublished
19.7 fb^{-1} (8 TeV)
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