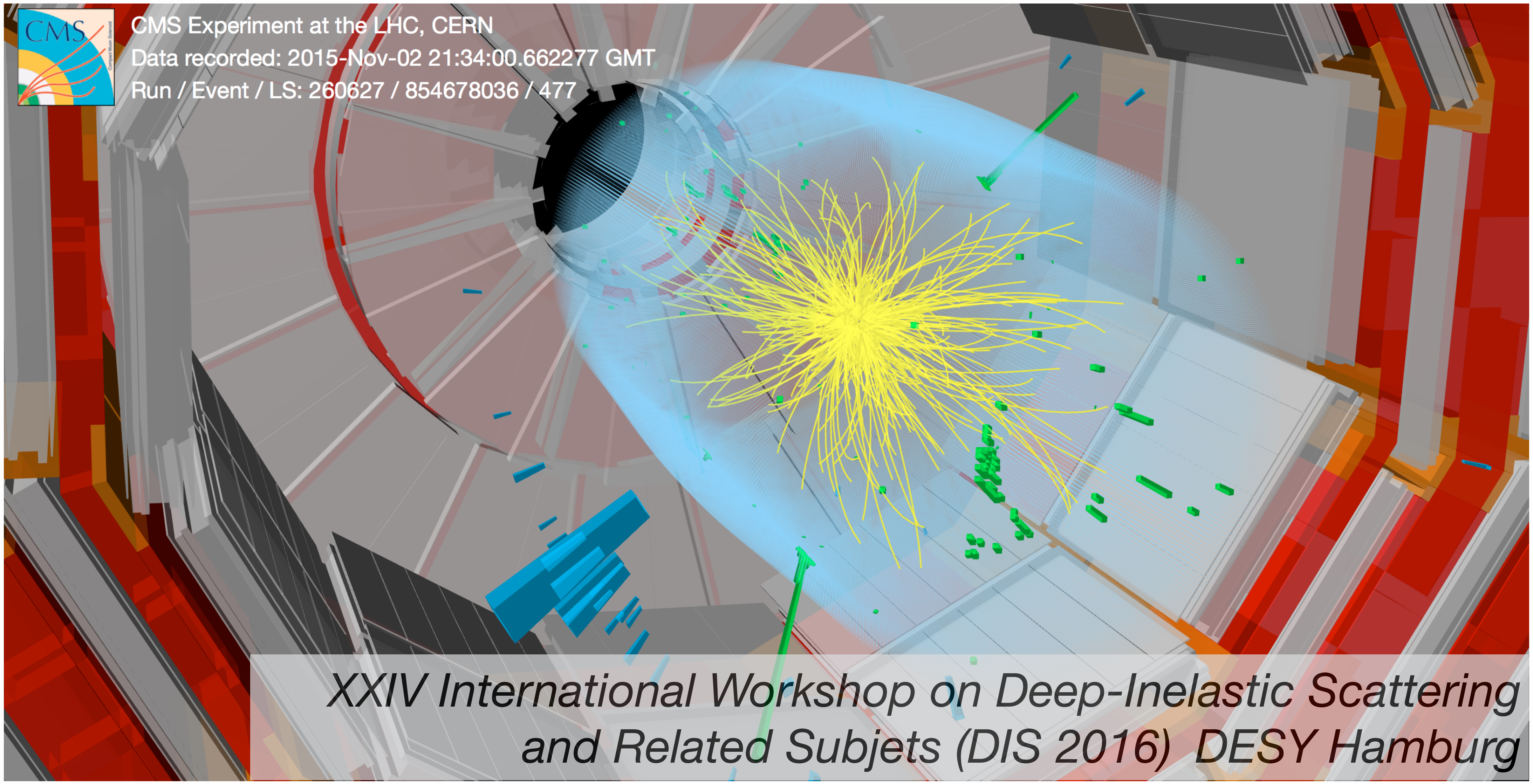
Searches for BSM physics in the diphoton final state at CMS



M. Quittnat (ETH Zurich)
on behalf of the CMS collaboration

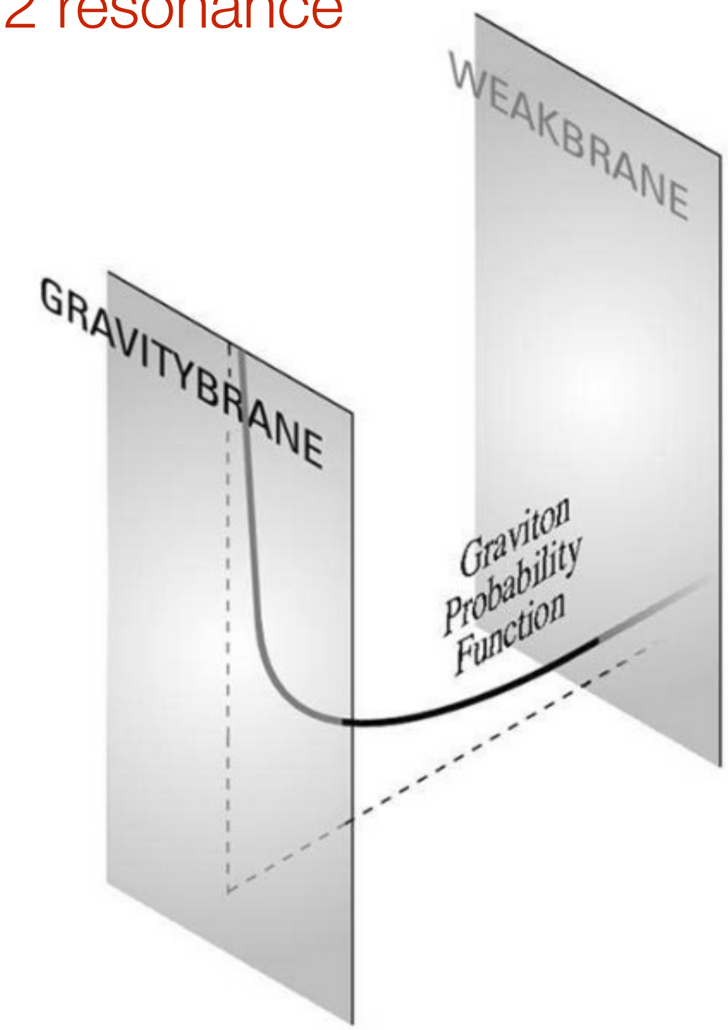
April 13th 2016

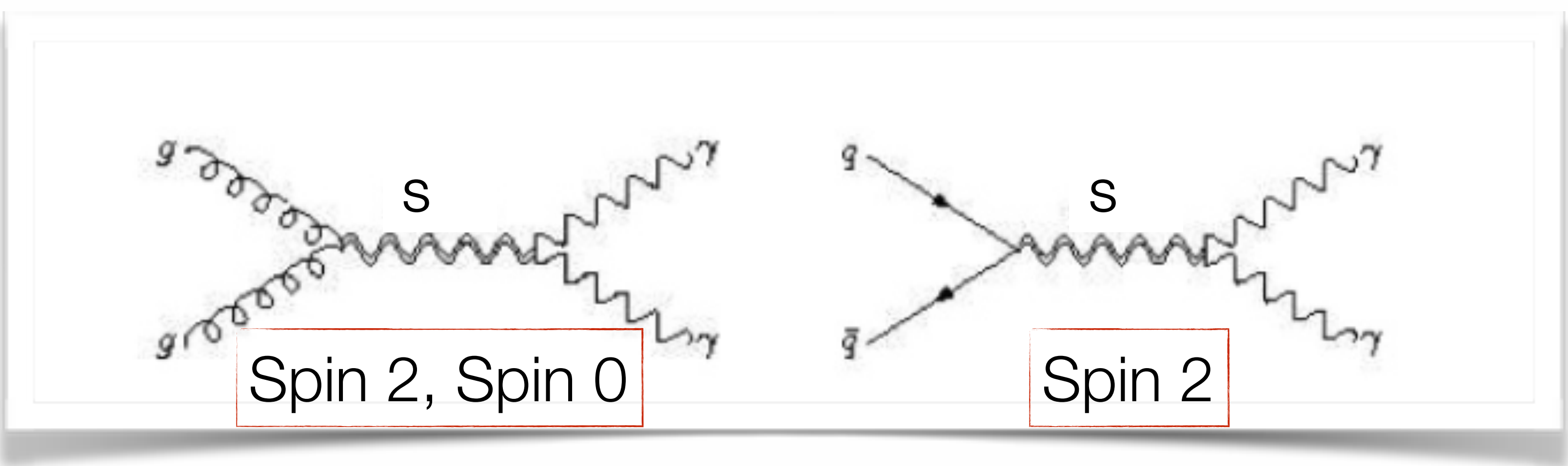
Motivation for the search

several models for physics beyond SM

benchmark models:

- extended Higgs sectors (2HDM) —> Spin 0 resonance
  - this analysis: assume gluon fusion production
- extra-dimensional models (Randall-Sundrum model) —> Spin 2 resonance
  - gravitons - Kaluza-Klein (KK) resonances: $M_{KK} \sim 1/R$
  - resonance wider with larger couplings:
    - $\Gamma_G/m_G = 1.4 * (\kappa/M_{Pl})^2$
- ….many more models according to arXiv



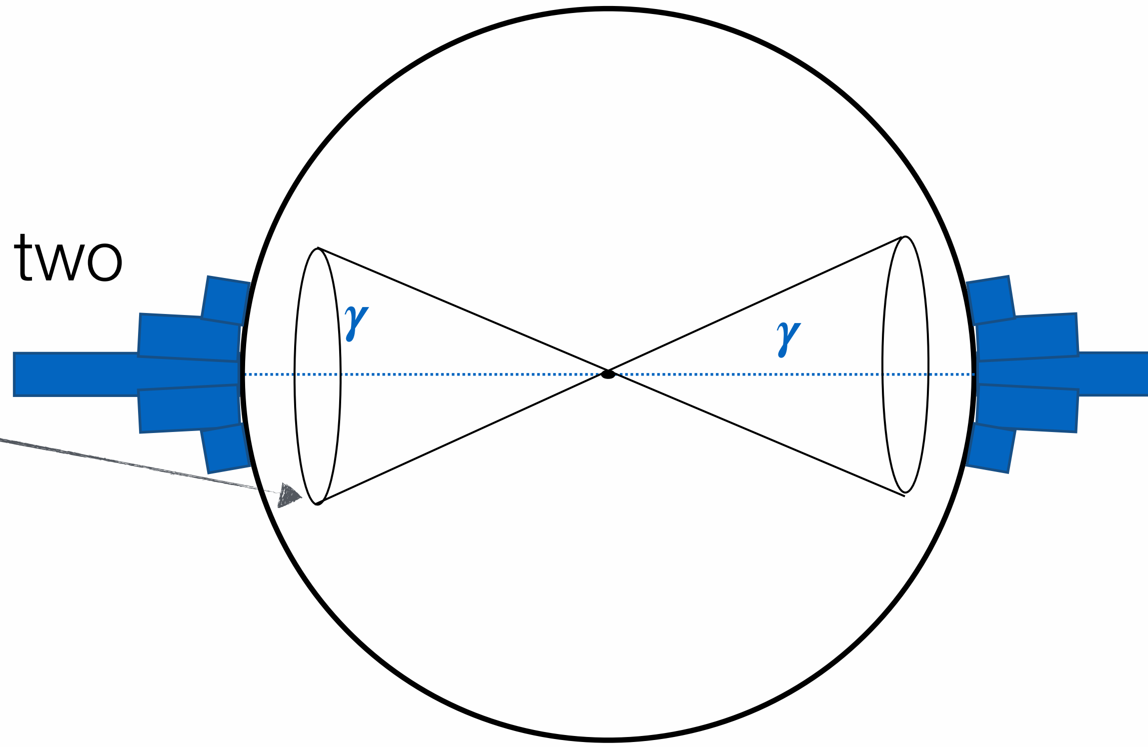


Experimental signature

clean final state

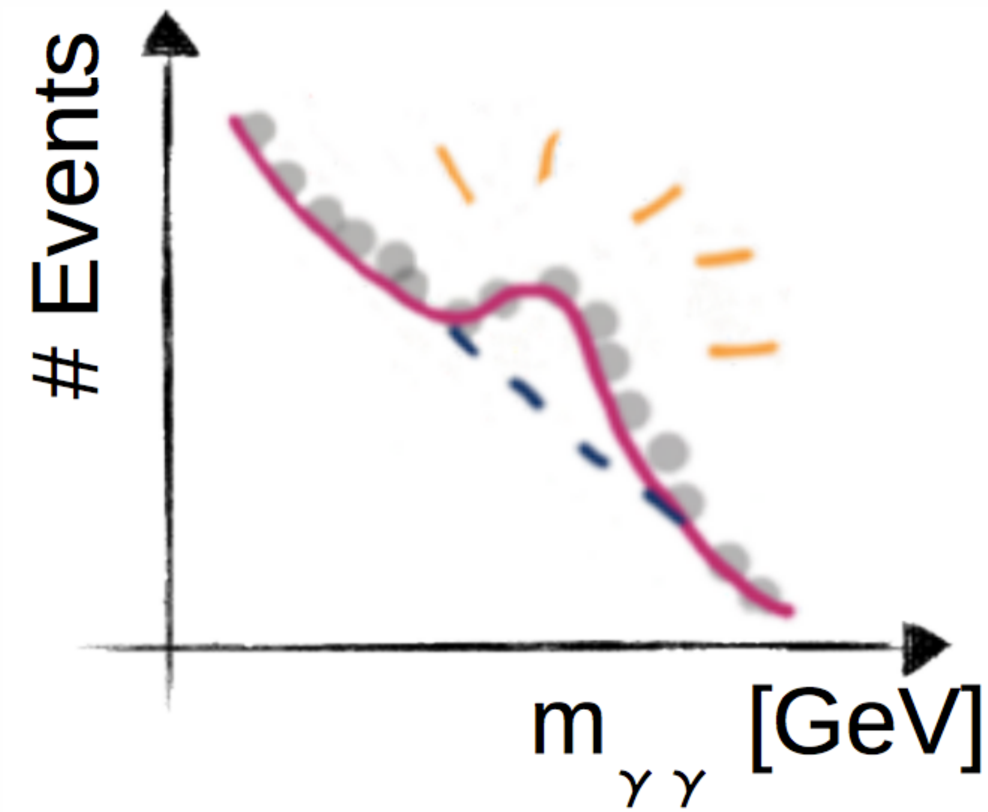
- **two high p_t photon candidates**

- **isolated**
  no additional activity in the direction of the two photon candidates



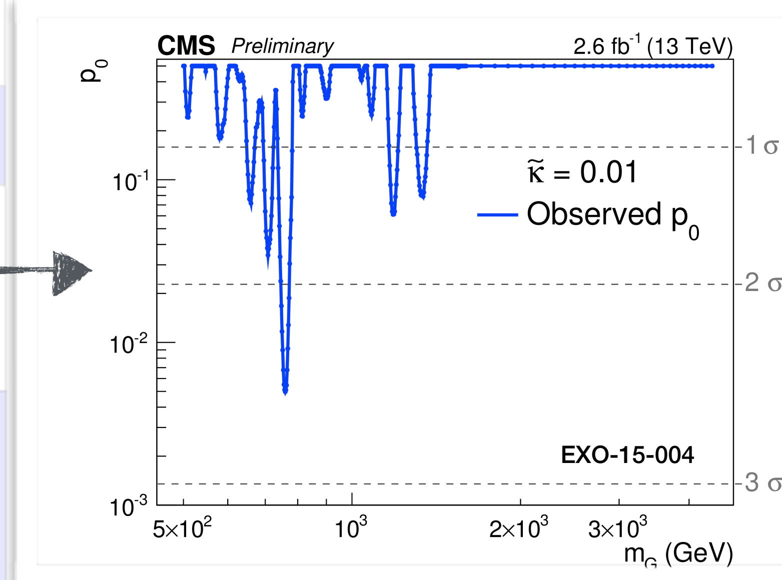
signature of resonant production:

- localised excess of events in diphoton invariant mass spectrum
- search region: $M_{\gamma\gamma} > 500$ GeV



Diphoton analyses @ 13 TeV

Ref	Title	M_X	interpreted as	
			spin-0	spin-2
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	x	yes
EXO-16-018 (new)	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	yes	yes



- **re-reconstruction** of dataset with L=2.7 fb^{-1}
- additional 0.6 fb^{-1} dataset, **recorded at B =0 T** (due to solenoid)
- analysed for search in diphoton final states

—> luminosity @ 13 TeV used in this analysis: **L_{tot}=3.3 fb^{-1}**

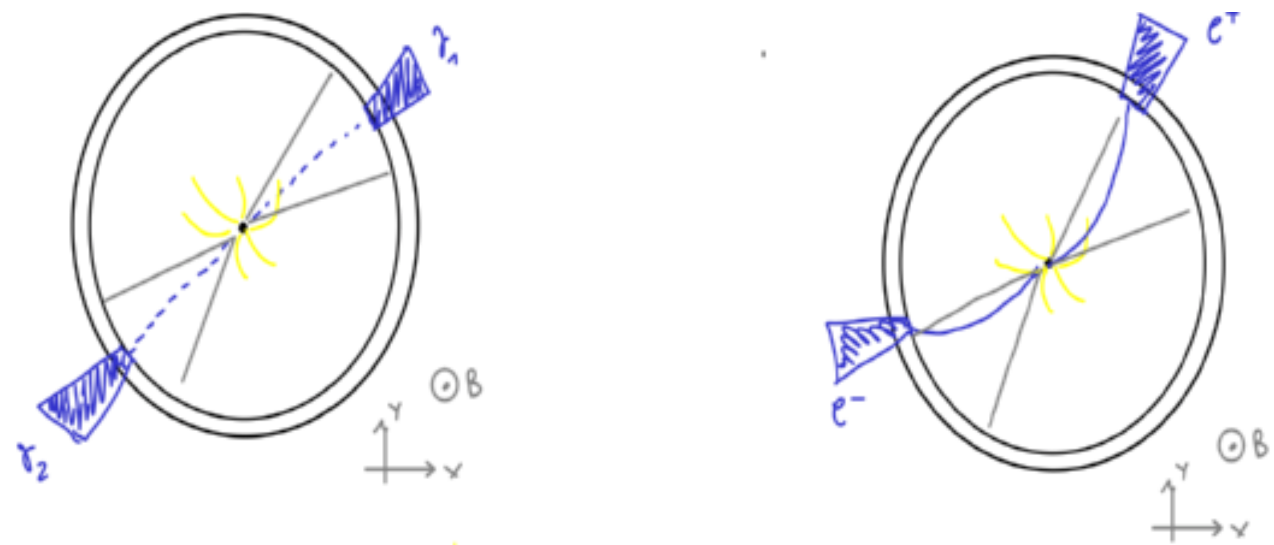
Analysis strategy

1. select diphoton pairs

- simple selection criteria

2. measure energy scale, resolution and efficiency scale factors in data

- using Z → ee and Z → llγ



3. parametrise background mass spectrum from data

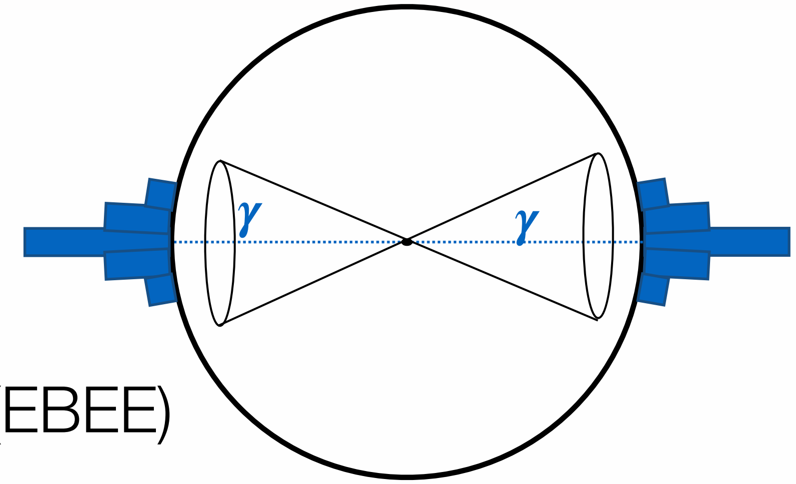
4. test compatibility of data with resonant diphoton production

blind analysis:

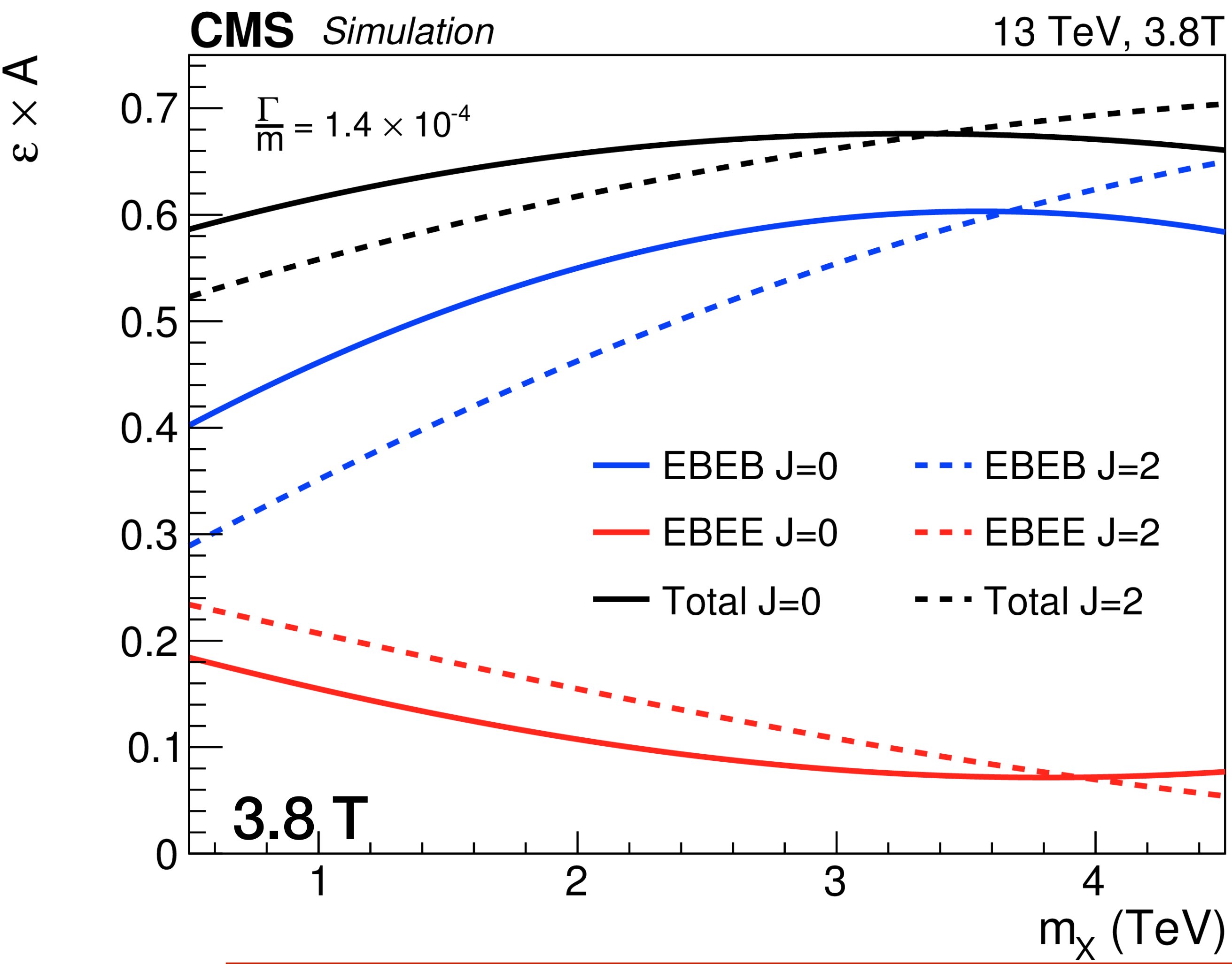
- selection criteria and signal width hypotheses fixed a-priori
- all analysis inputs (energy calibration, efficiency, etc..) checked before box-opening
- december dataset re-blinded to study analysis improvements

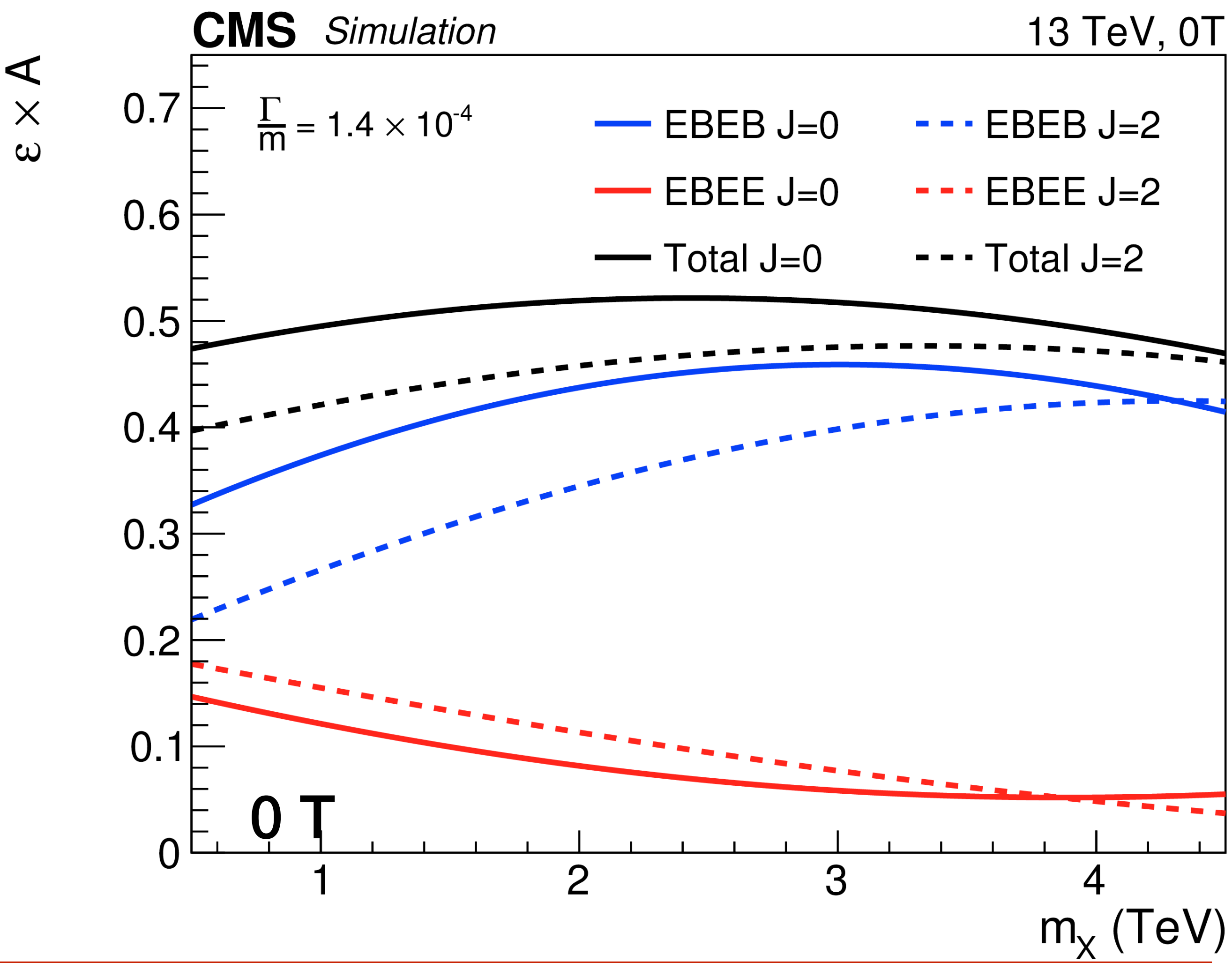
Photon identification

- diphoton trigger $p_t > 60$ (40) GeV for 3.8 (0)T
    - select two photons with $p_t > 75$ GeV
    - at least one in the barrel (EB) $|\eta| < 1.44$
- cut-based selection: shower shapes, isolation, electron-veto



- split events in categories: barrel-barrel (EBEB) and barrel-endcaps (EBEE)
- B= 3.8 T : 90% (EB)- 85 % (EE) per-photon-efficiency
- B= 0 T : 85%(EB) - 70 % (EE) per-photon-efficiency (less efficient electron-veto)



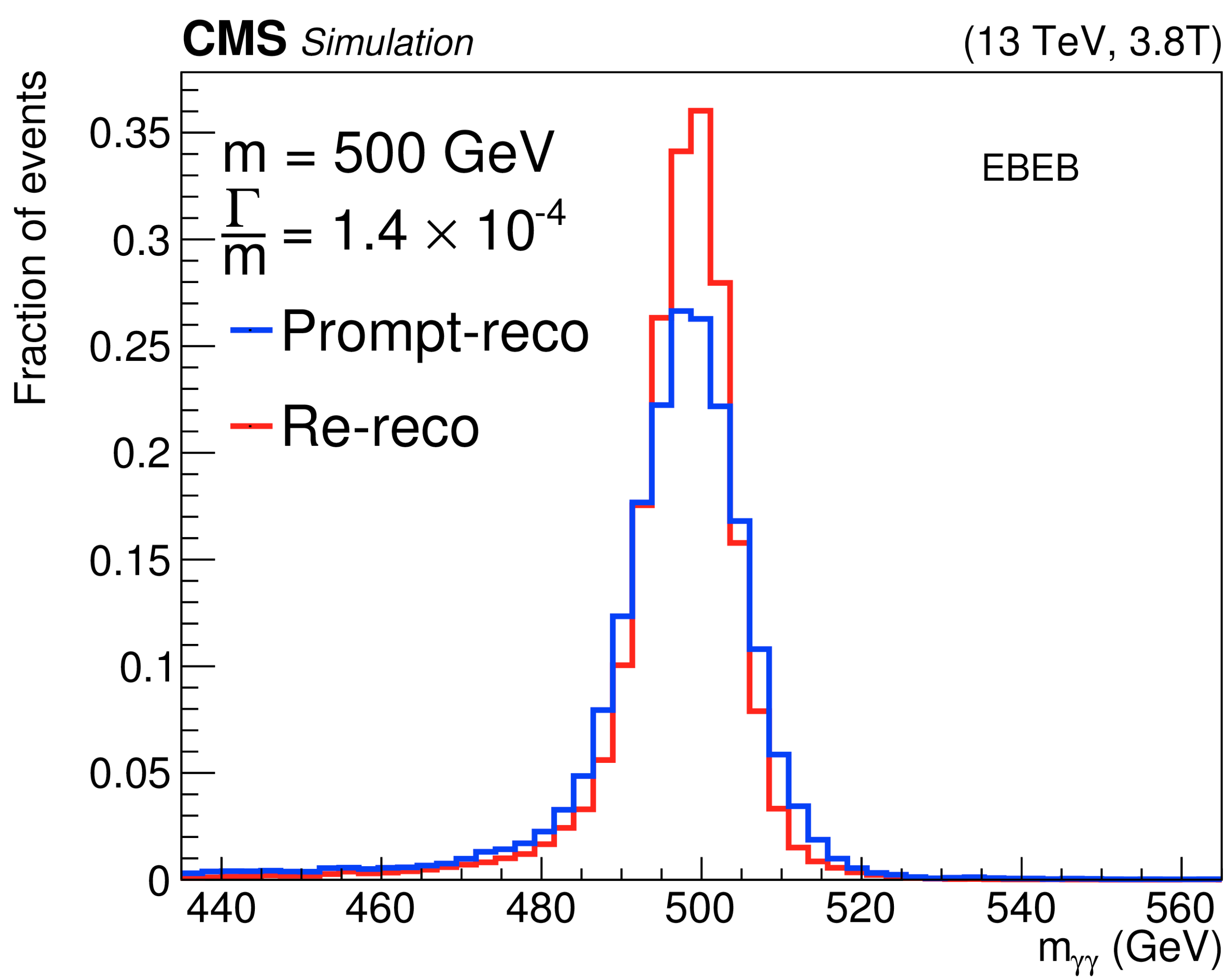


Efficiency x acceptance term parametrised as a function of the resonance mass

Benefits of re-reconstruction @ 3.8 T

data re-reconstruction provides:

- constants for **channel-to-channel calibration in ECAL** - using 2015 data



in high mass region: resolution improves by ~ 30%

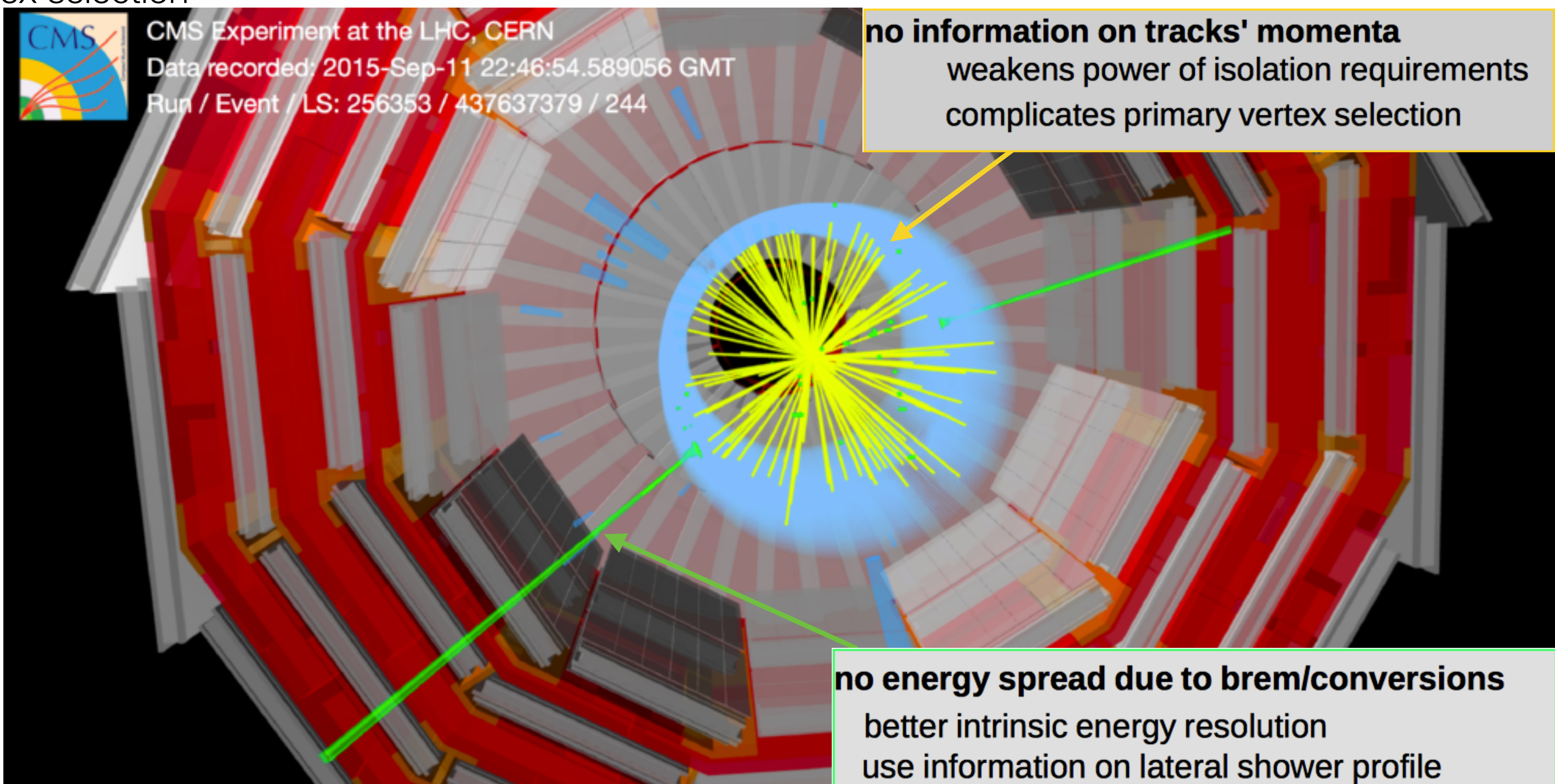
—> **10 % improvement in analysis sensitivity**

0 Tesla challenges

L=0.6 fb^{-1} recorded @ 0 T —> 10 % higher analysis sensitivity

conditions without magnetic field require dedicated…

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

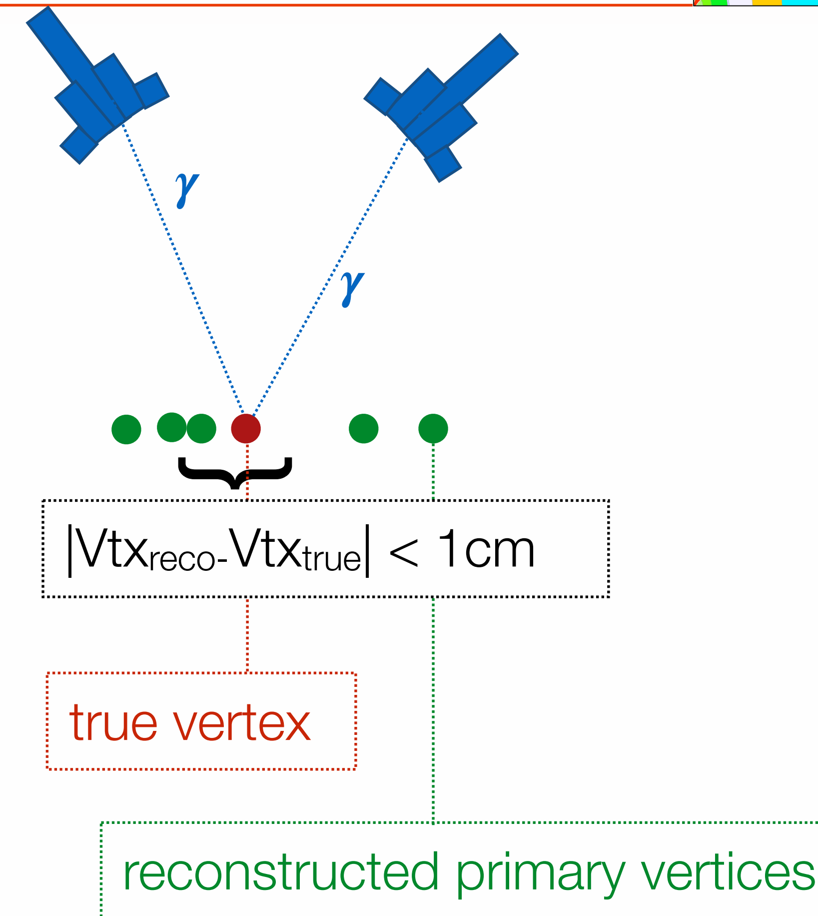


Vertex selection

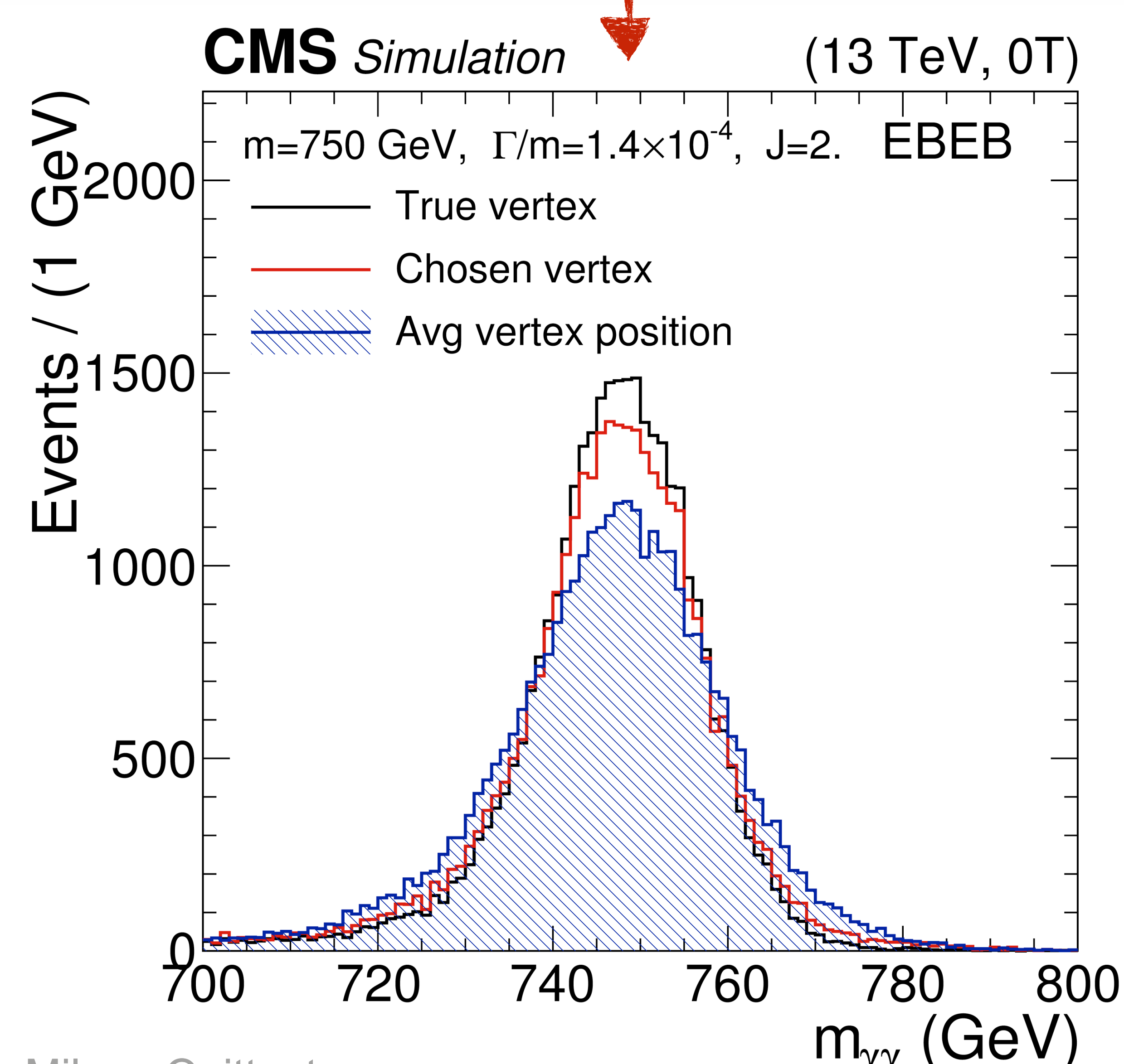
good mass resolution depends on vertex identification

- if $|Vtx_{reco} - Vtx_{true}| < 1$ cm

—> effect on mass resolution negligible



- 3.8 T: BDT trained for H->$\gamma\gamma$
- 0T: vertex with highest track multiplicity



$|Vtx_{reco} - Vtx_{true}| < 1$ cm for signal vertices:

- 90 % @ 3.8T
- 60 % at 0 T

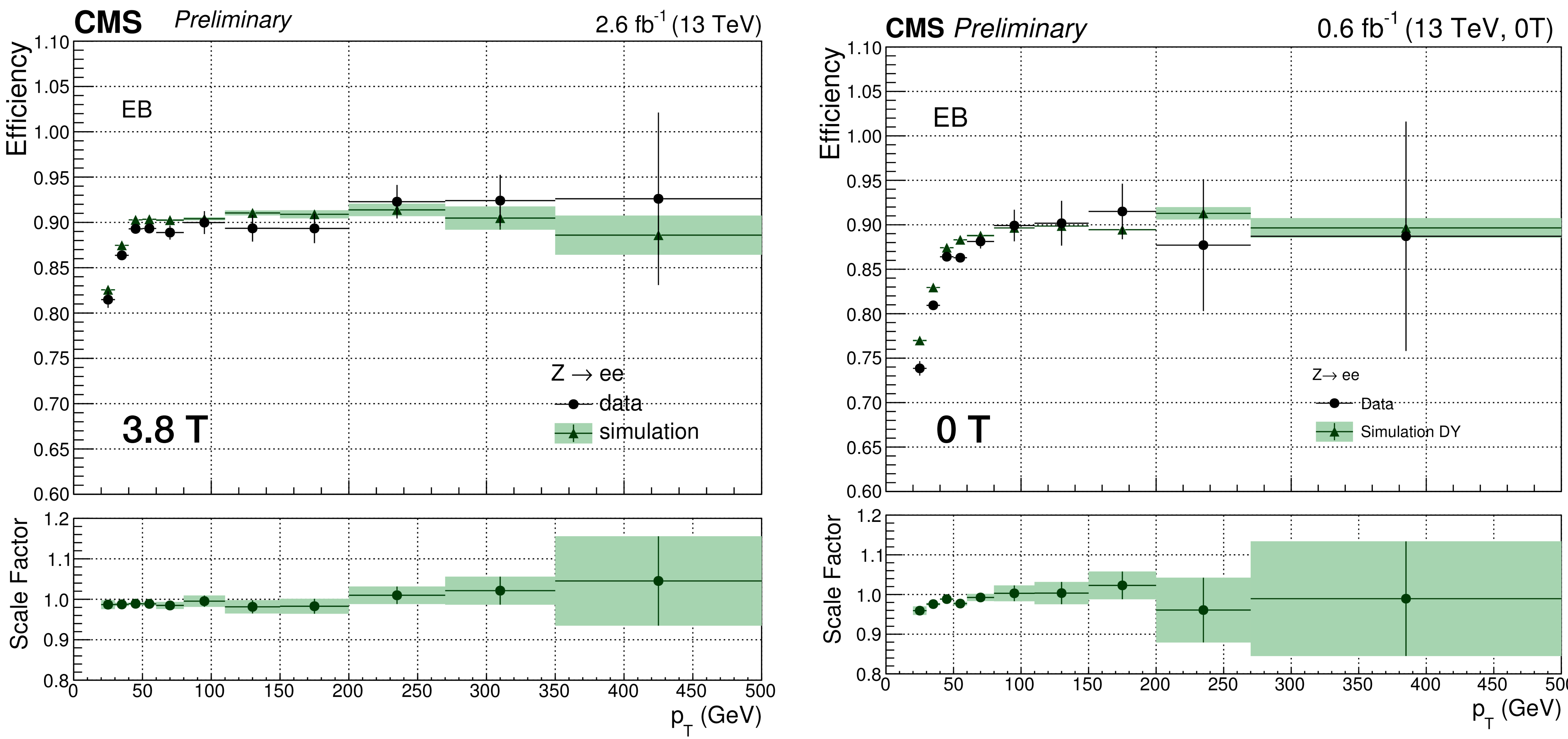
Photon identification efficiency

data-driven determination of selection efficiency to verify and correct MC predictions

- using Z—> ee events (high p_t photon ID + inverted electron veto)
- for electron veto: separately using Z → $\mu\mu$(ee)γ events at 3.8(0)T

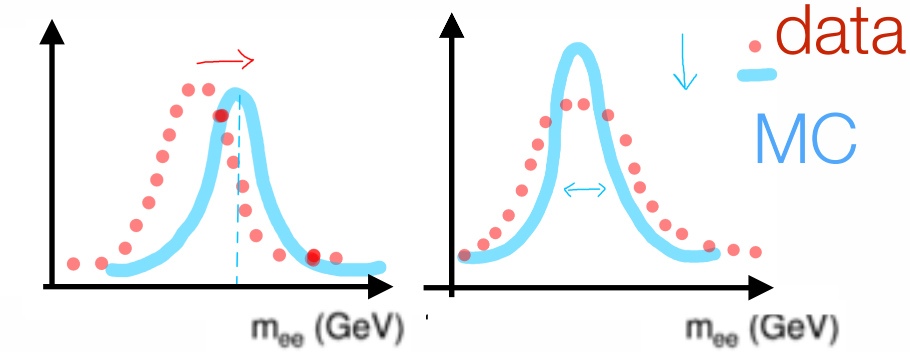
—> data/MC agree within a few percent

—> 8(16)% uncertainty for selection efficiency on signal normalisation at 3.8(0)T

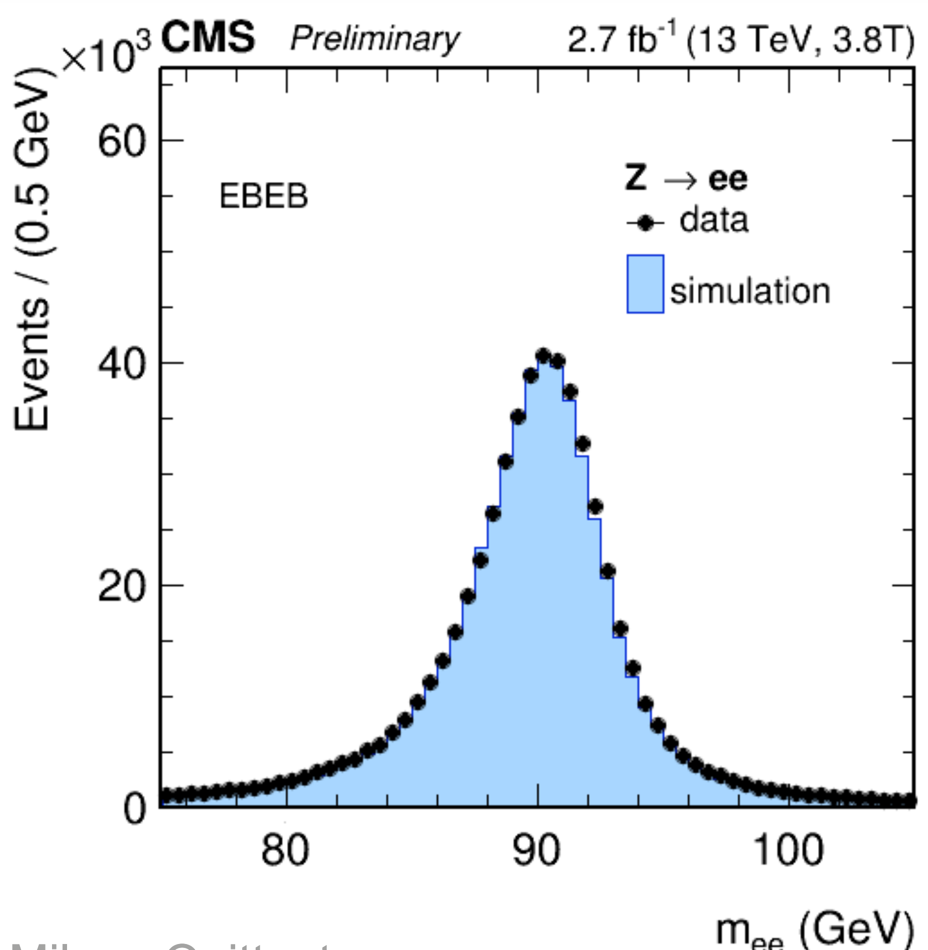


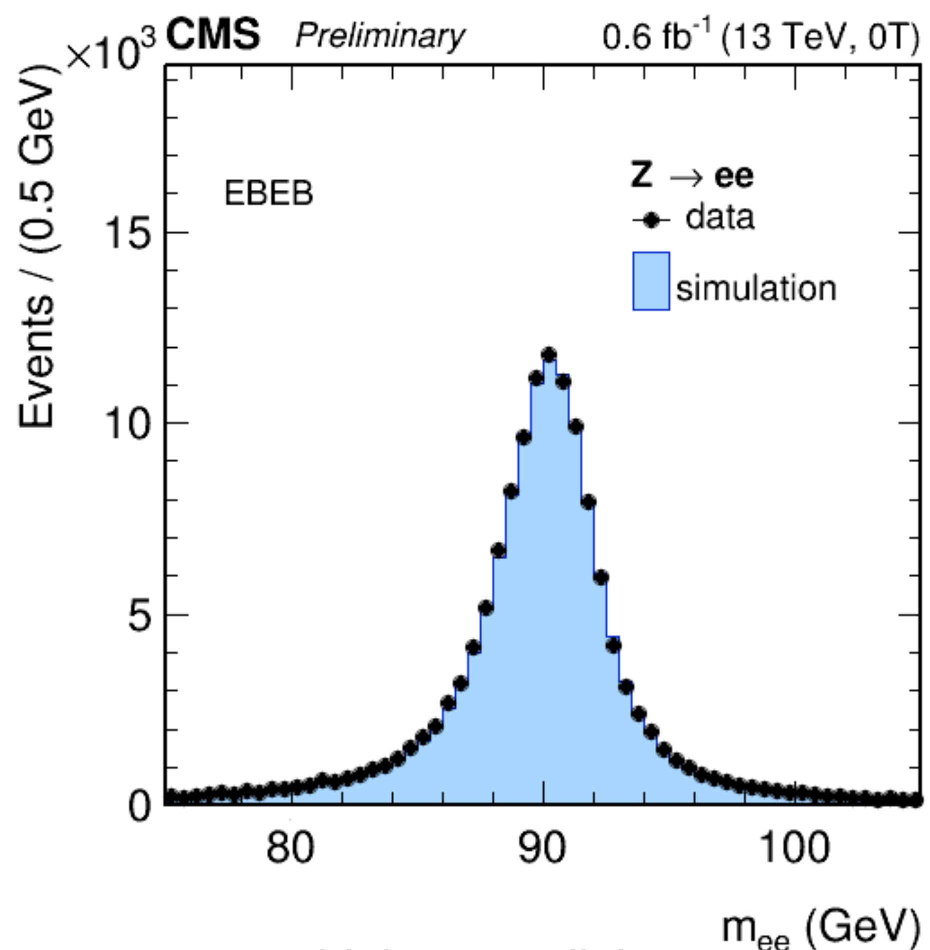
Energy corrections

correct energy scale and resolution using Z—> ee events



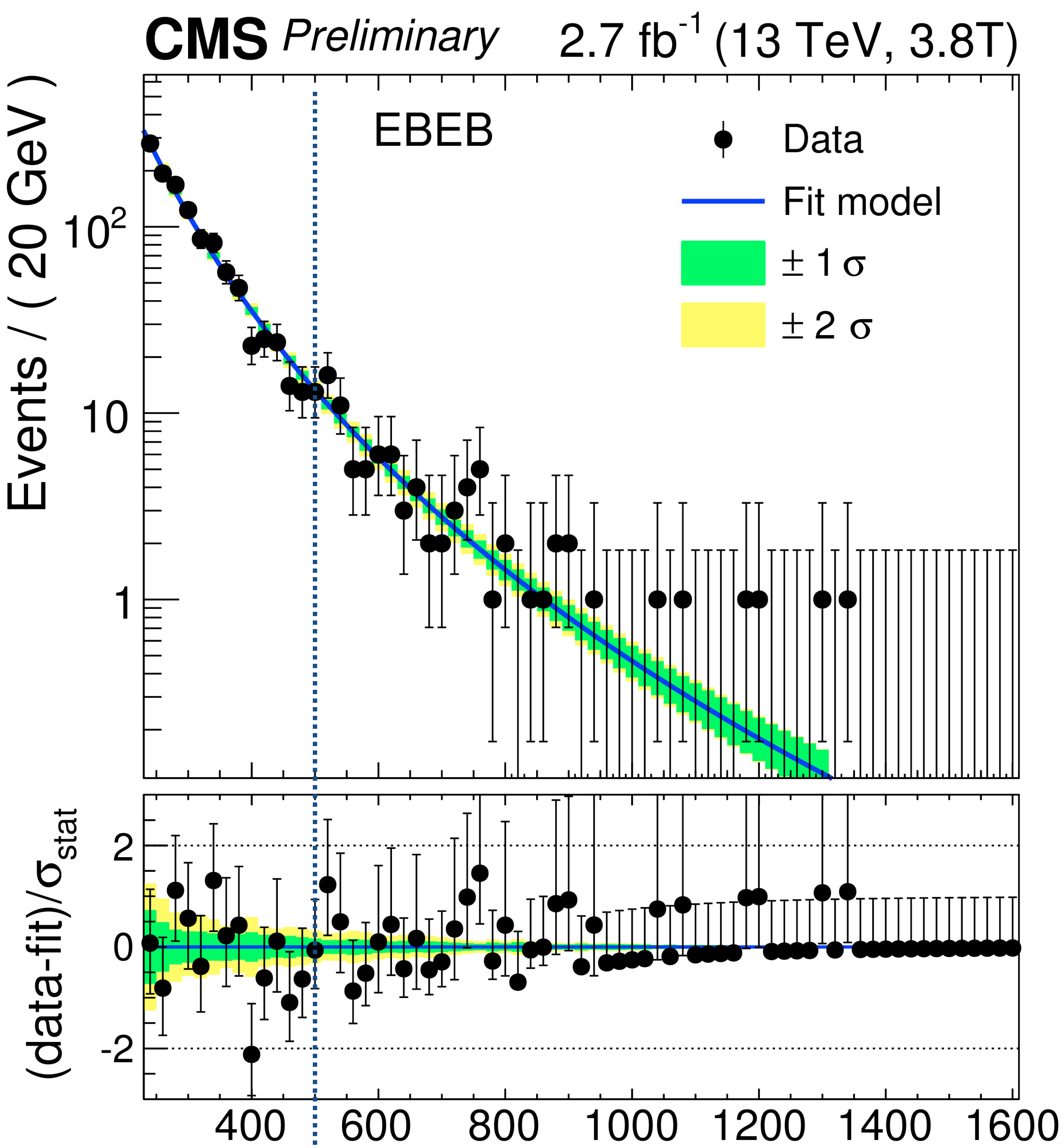
- stability vs $E_{T,e}$ checked with boosted events up to E_T~150 GeV
- for 3.8 T:
  - deviations within 0.5(0.7)% in EB (EE)
  - assigned 1% uncertainties to account for further extrapolation
- for 0 T:
  - data/MC scale corrections 1% larger than @ 3.8T
  - energy resolution corrections similar
  - assigned 1% uncertainty on knowledge of relative energy scale in analysis

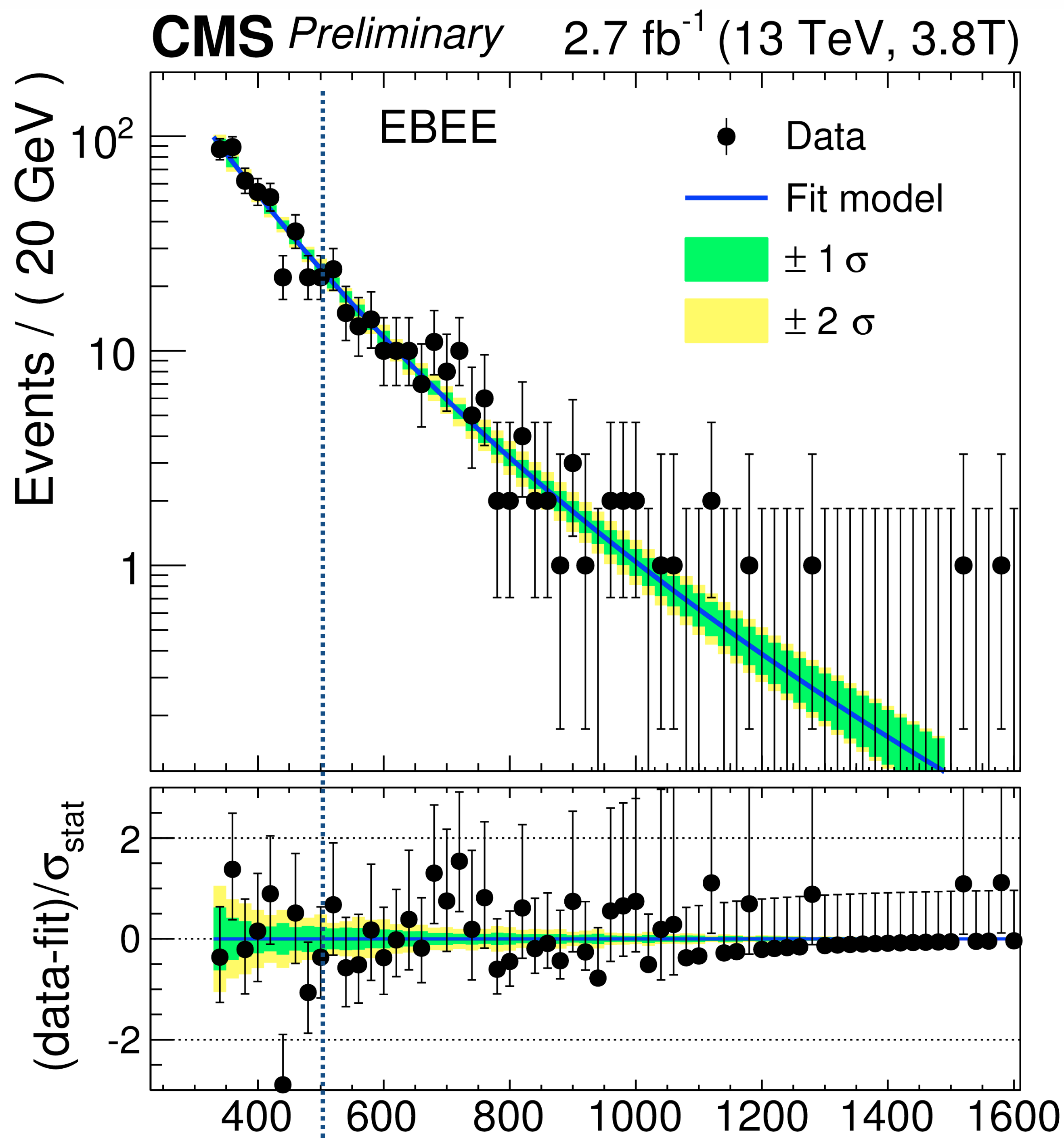




Mass spectra @ 3.8 T

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

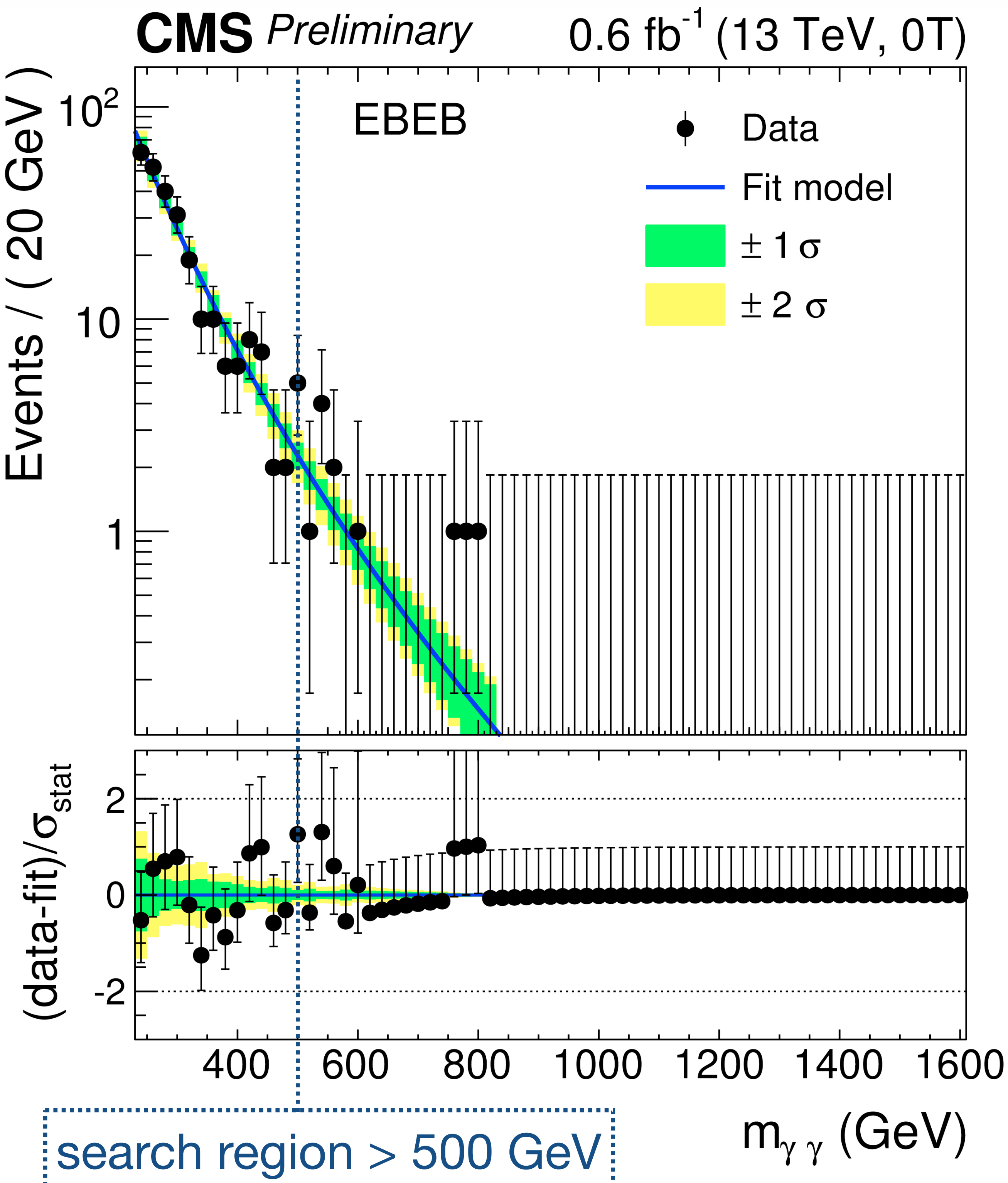


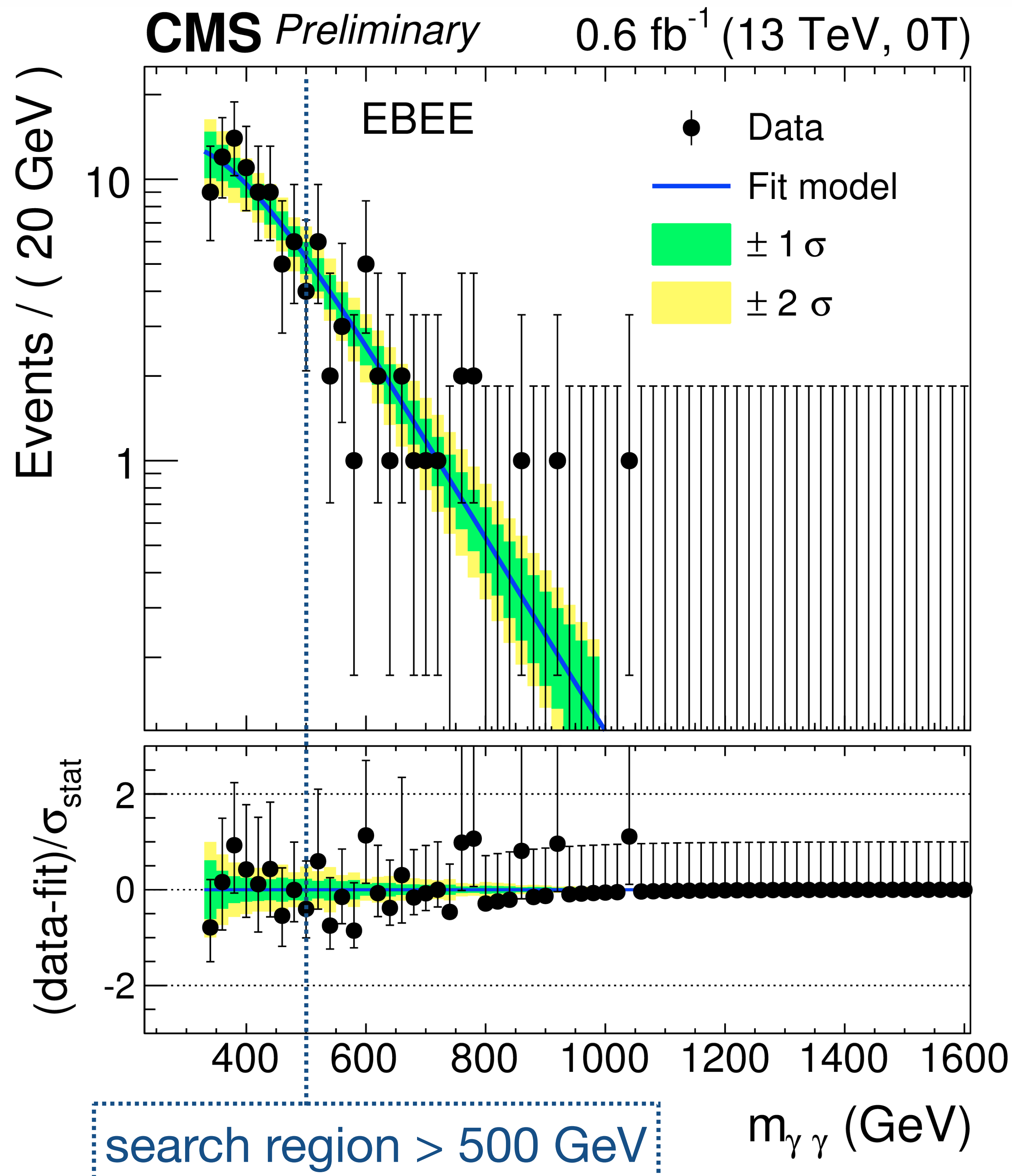


search region > 500 GeV

search region > 500 GeV

Mass spectra @ 0 T





Interpretation of results

- frequentists statistics using asymptotic formulas
- hypothesis test based on simultaneous unbinned likelihood fit to $m_{\gamma\gamma}$ in all four analysis categories (EB-EB, EB-EE) x (3.8 T, 0 T)

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

Background model

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

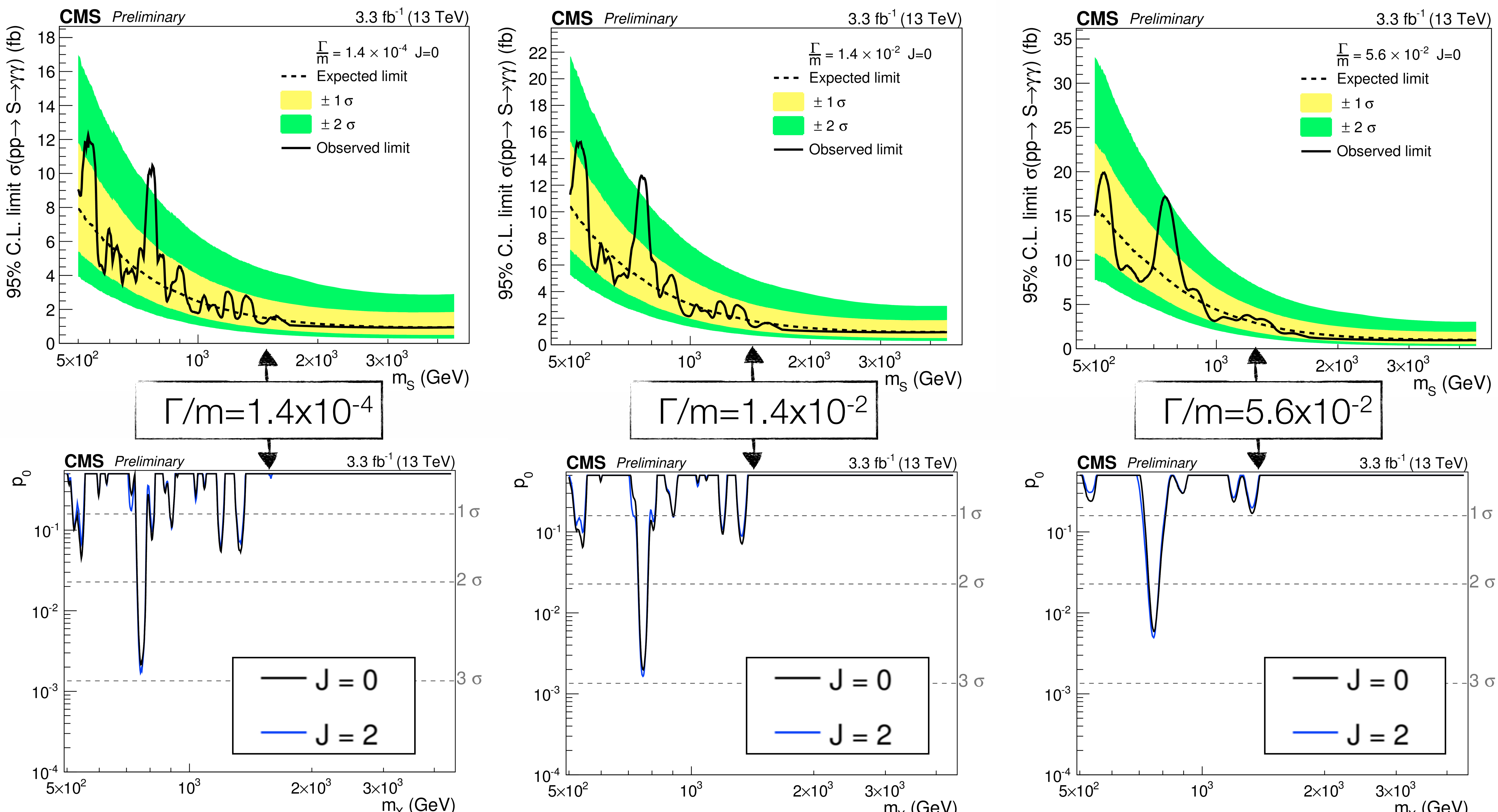
- independent shape for each of the category
- coefficients treated as unconstrained nuisance parameters
- possible mismodelling studied on simulation and explicit uncertainty added to the fit

Signal model

- signal shape: intrinsic width of resonance + ECAL response
- detector resolution model extracted from full simulation at fixed mass points
- interpolation of resonance width and ECAL resolution for each mass point
- search mass range: 0.5 - 4.5 TeV
- interpretation of results for three widths: $\Gamma/m=1.4\times10^{-4}, 1.4\times10^{-2}, 5.6\times10^{-2}$

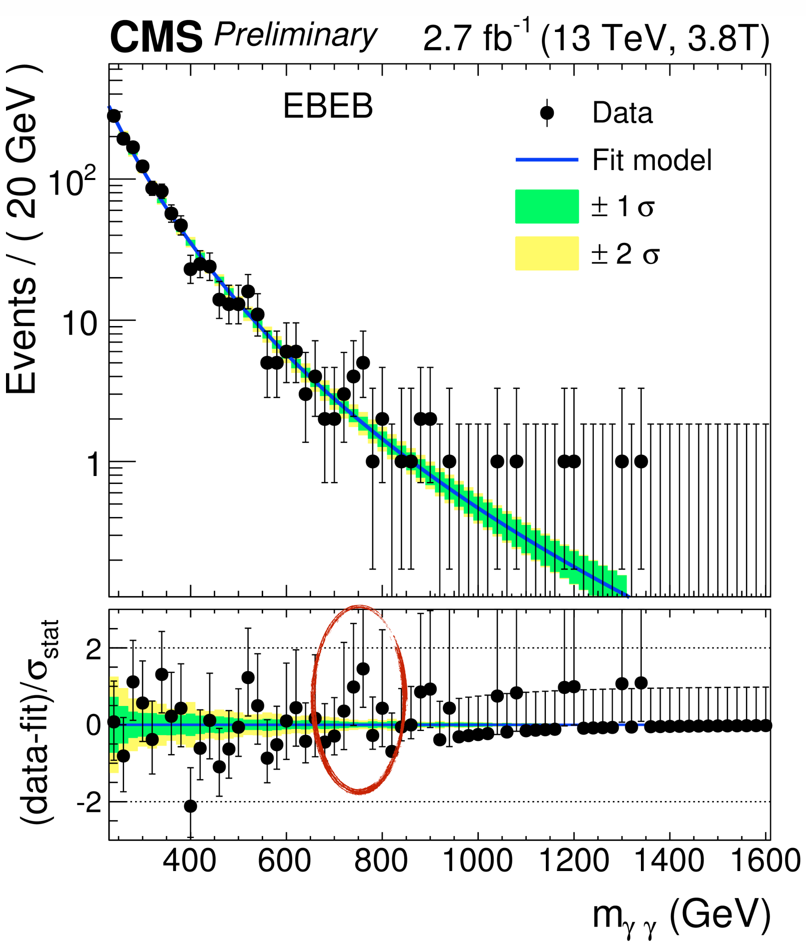
Limits and p-values @ 13 TeV

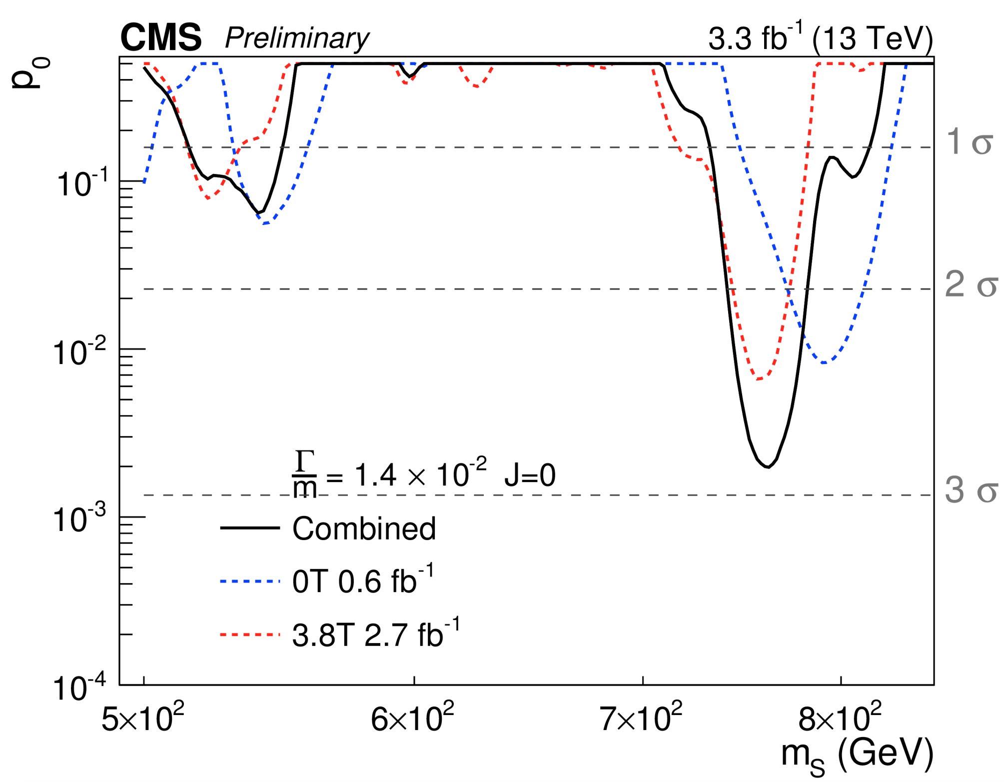
- upper limits shown for J=0, similar results for J=2
- J=0 and J=2 hypotheses have similar p-values
- highest significance for $\Gamma/m=1.4\times10^{-2}$ with 2.9 σ at 760 GeV
- significance decreases for larger width hypothesis

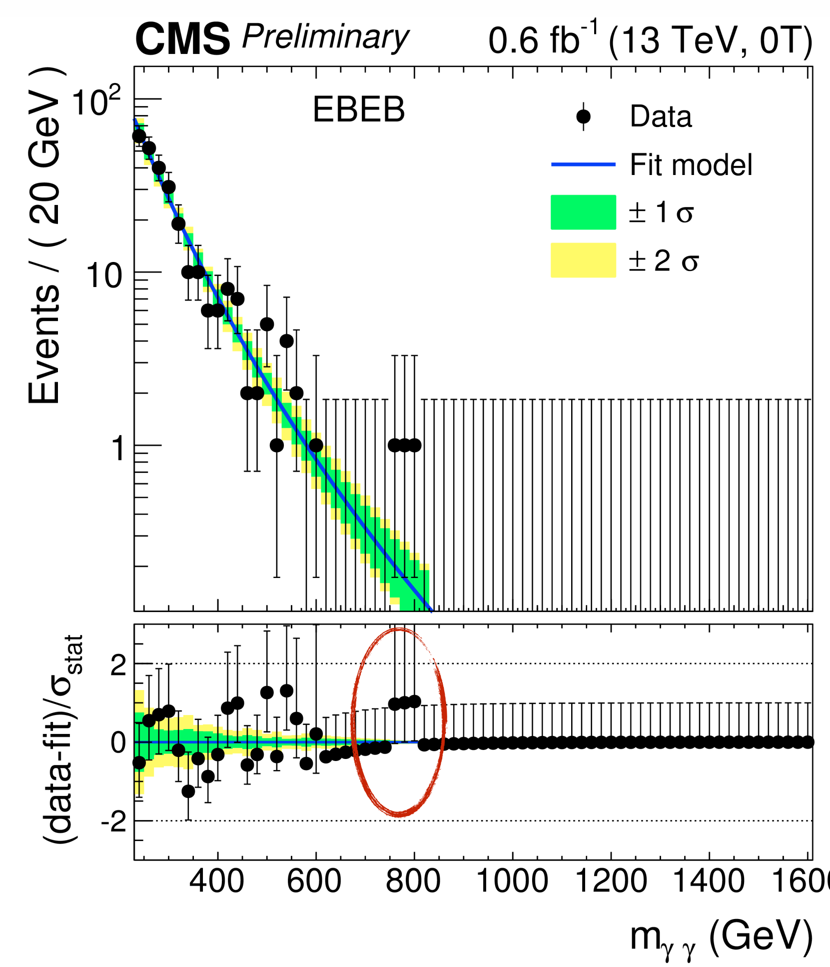


Significance of largest excess

- excess of 2.9σ @ 760GeV mostly from EBEB @ 3.8 T
- observed one event @ 0T dataset compatible with 3.8T excess
- “look elsewhere effect” for all spin & widths hypotheses
- global significance from observed excess < 1 σ





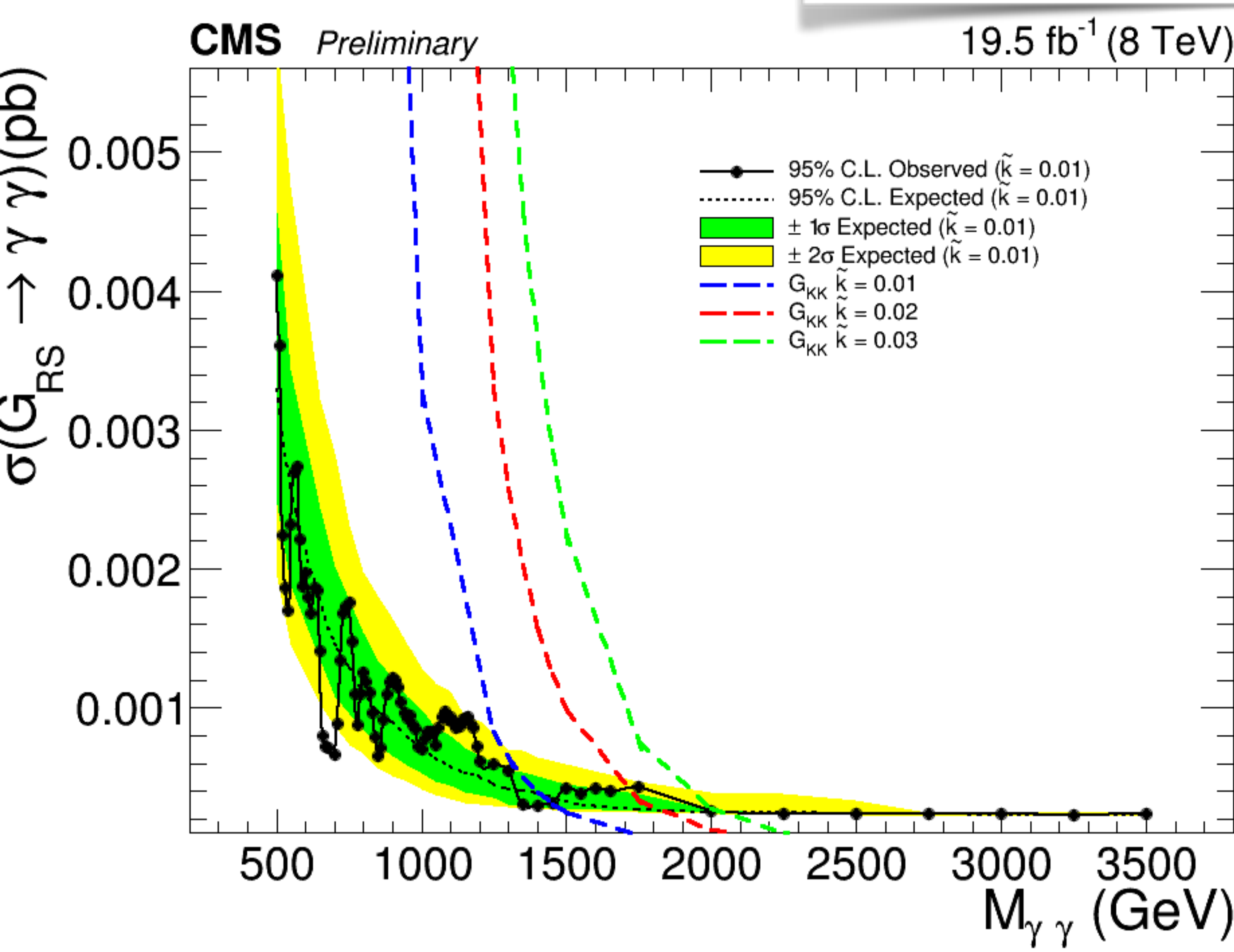


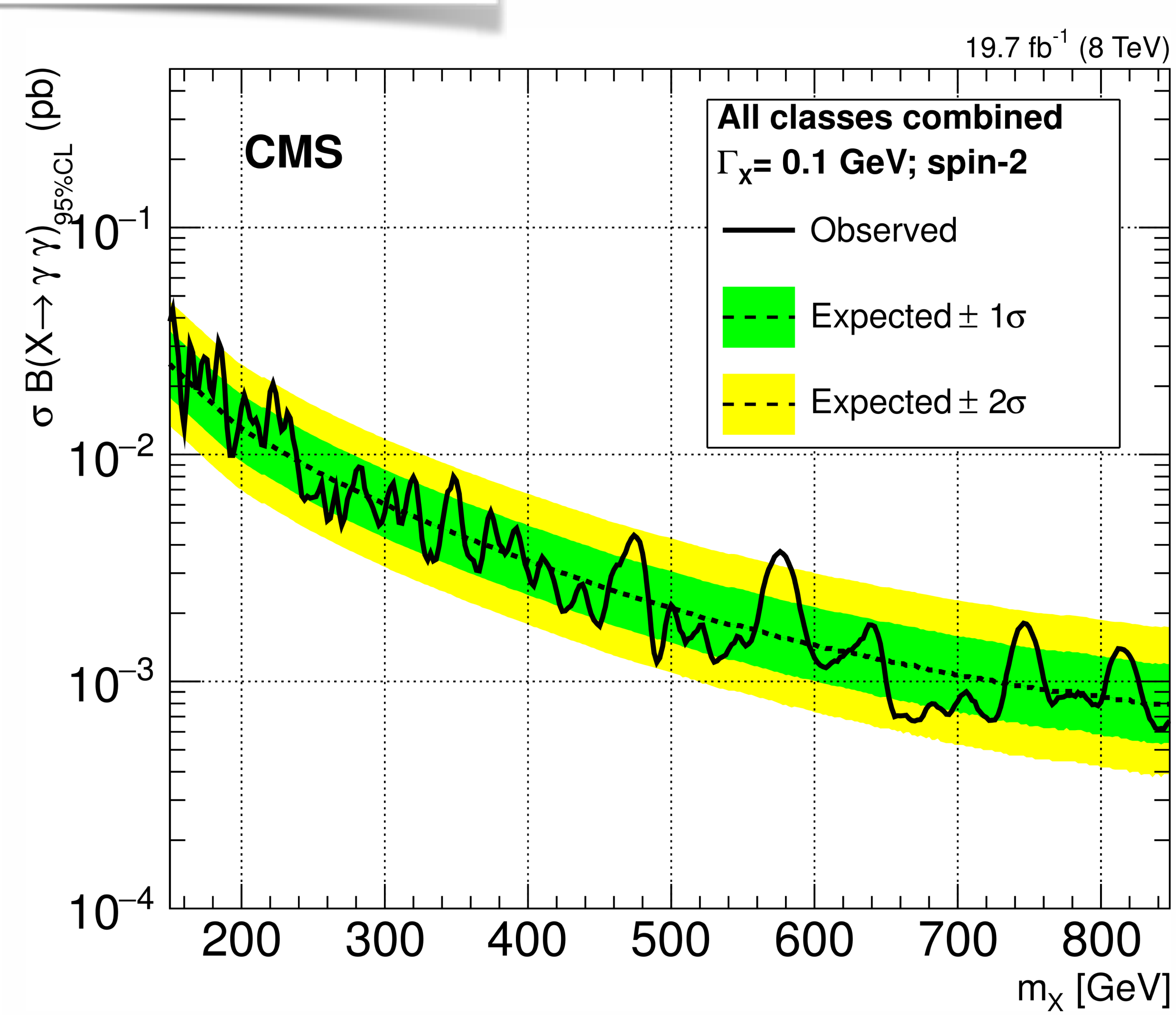
8 & 13 TeV combined

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 interpretation
- EXO-12-045: search range 500-3000GeV, spin-2 only interpretation
- combination in all 6 signal hypotheses tested at 13TeV

cross section ratios at 750GeV:
for spin 0 ($gg \rightarrow S$): $\sigma_{13TeV}/\sigma_{8TeV} = 4.7$
for spin 2 (GRS): $\sigma_{13TeV}/\sigma_{8TeV} = 4.2$





Closer look @ p- value for 8 & 13 TeV combination

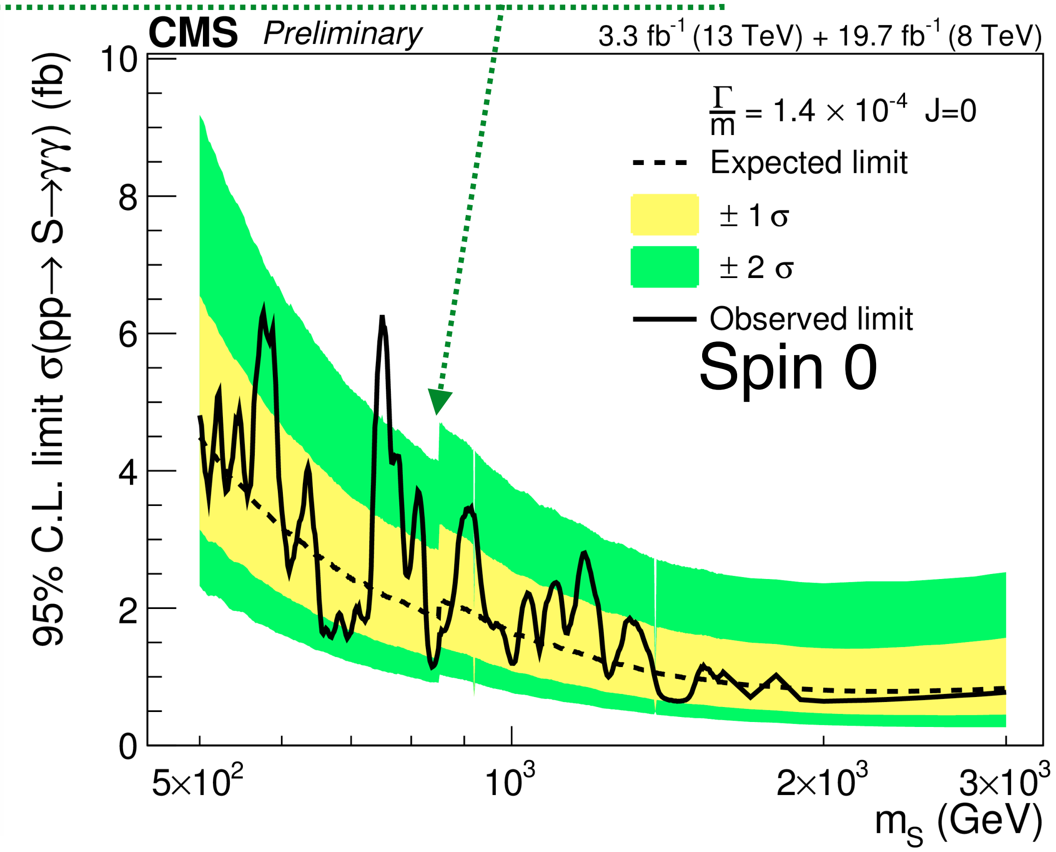
ETH Institute for Particle Physics

- pick most sensitive analysis: HIG-14-004 in 500-850GeV, EXO-12-045 otherwise

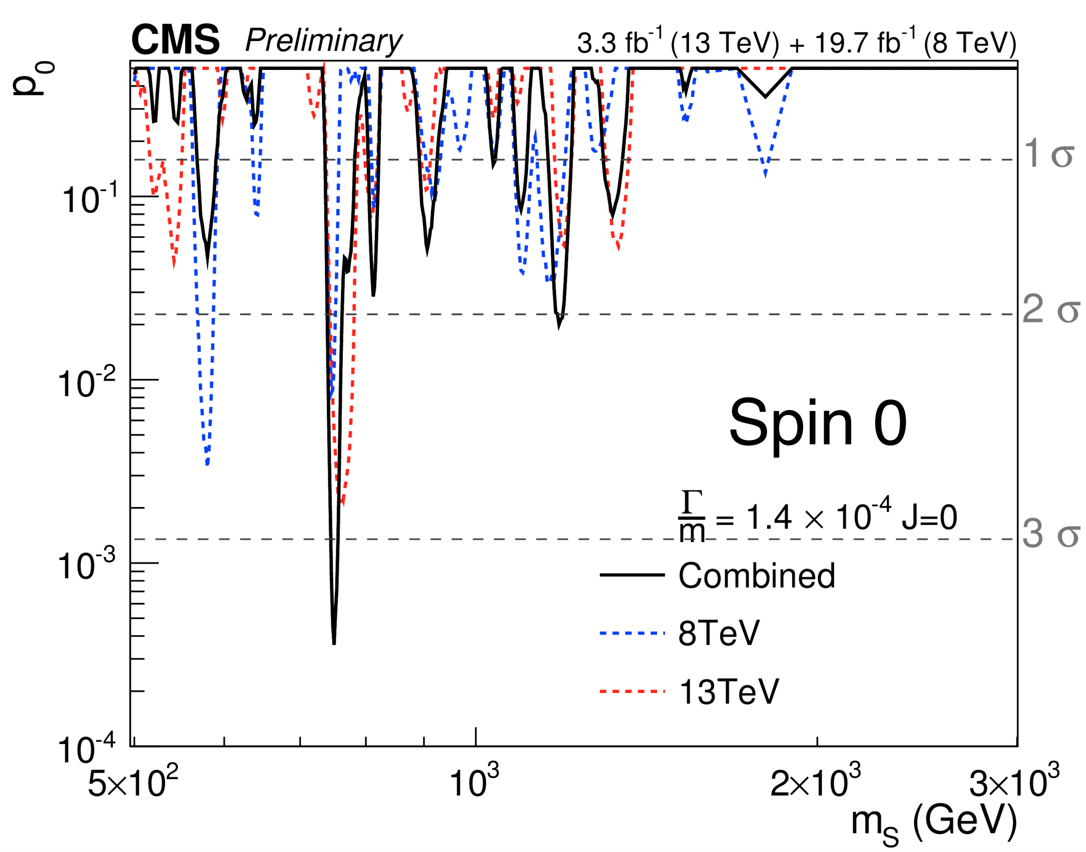
- compared to single analyses, sensitivity improved by 20-40%

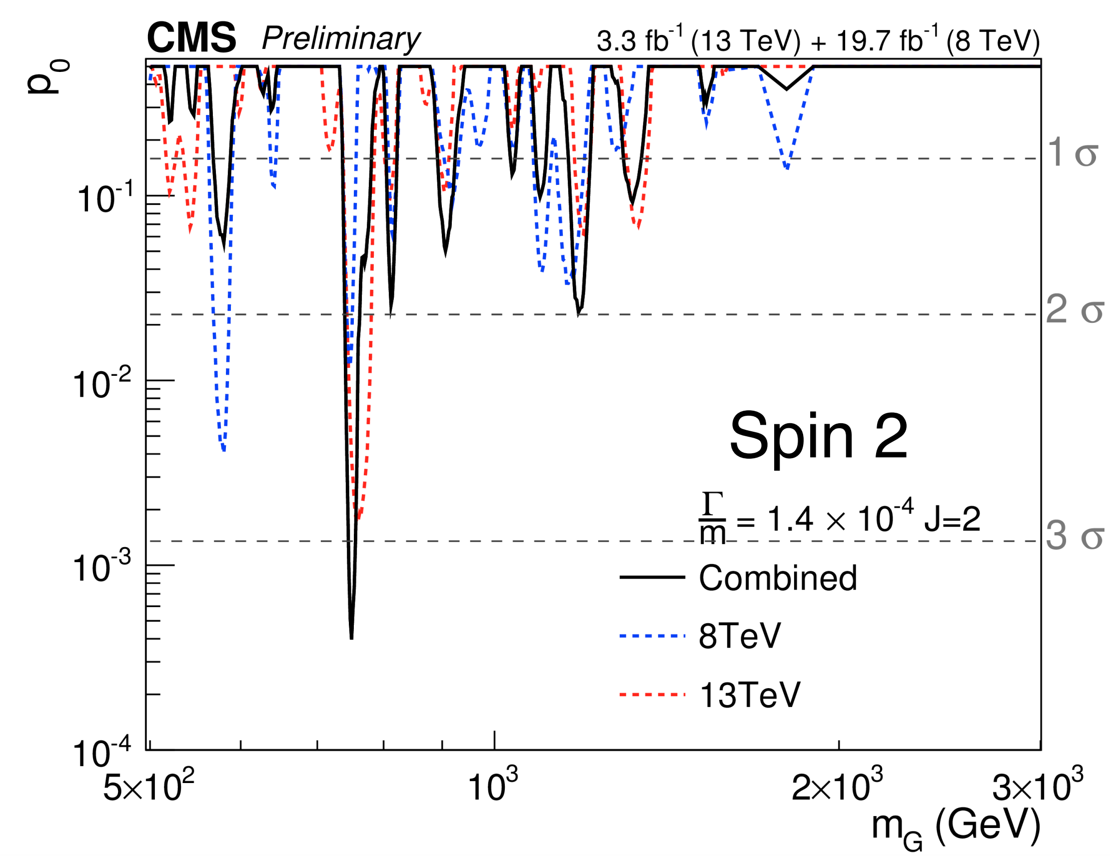
- largest excess observed at m_X = 750GeV and for narrow width —> local significance: 3.4σ
- mass range 0.5-3 TeV (and all signal hypotheses)

- "global" significance ~ 1.6σ



normalized to 13TeV x-sec





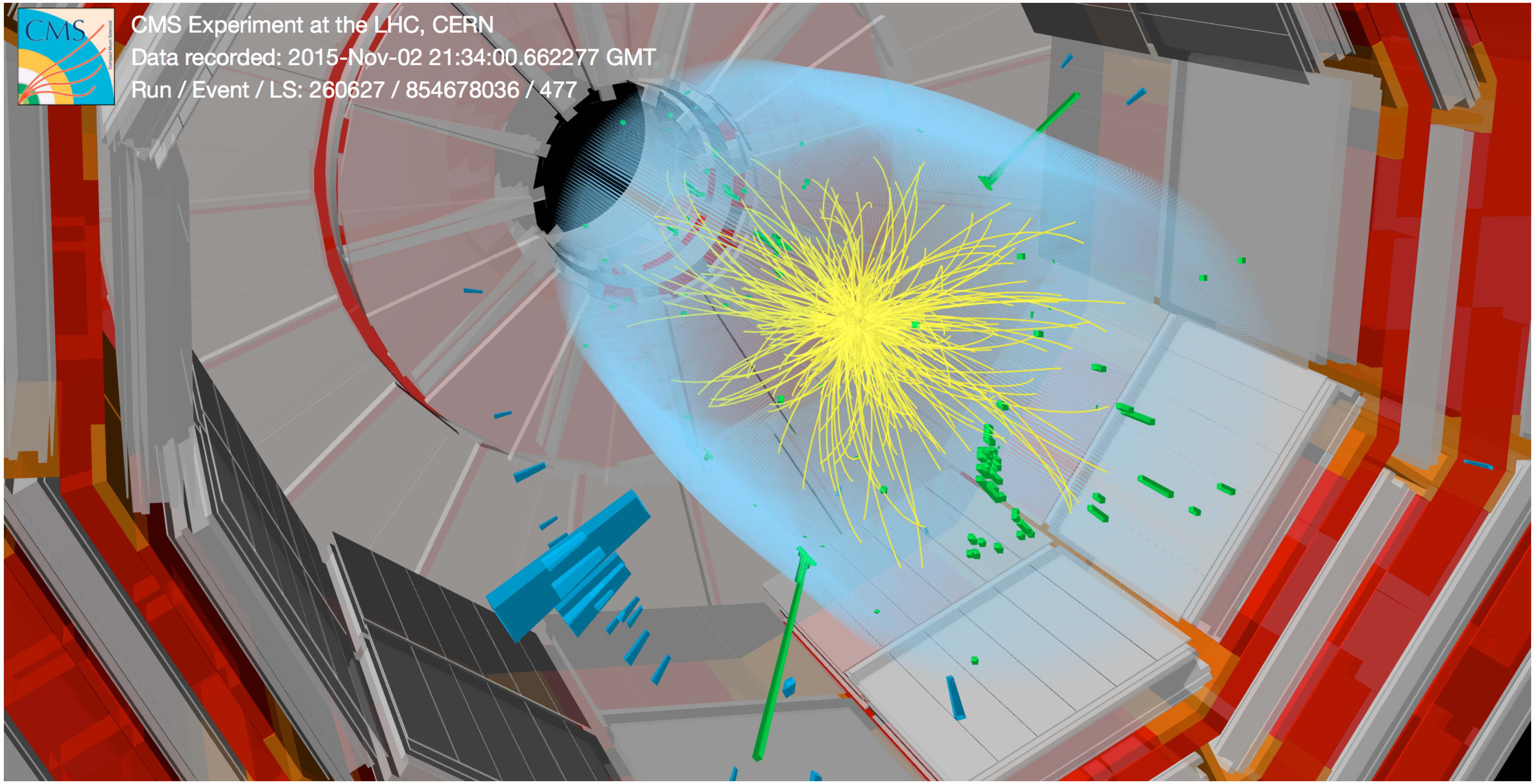
Summary

- presented the search for diphoton resonances with $m_{\gamma\gamma} > 500$ GeV at 8 and 13TeV

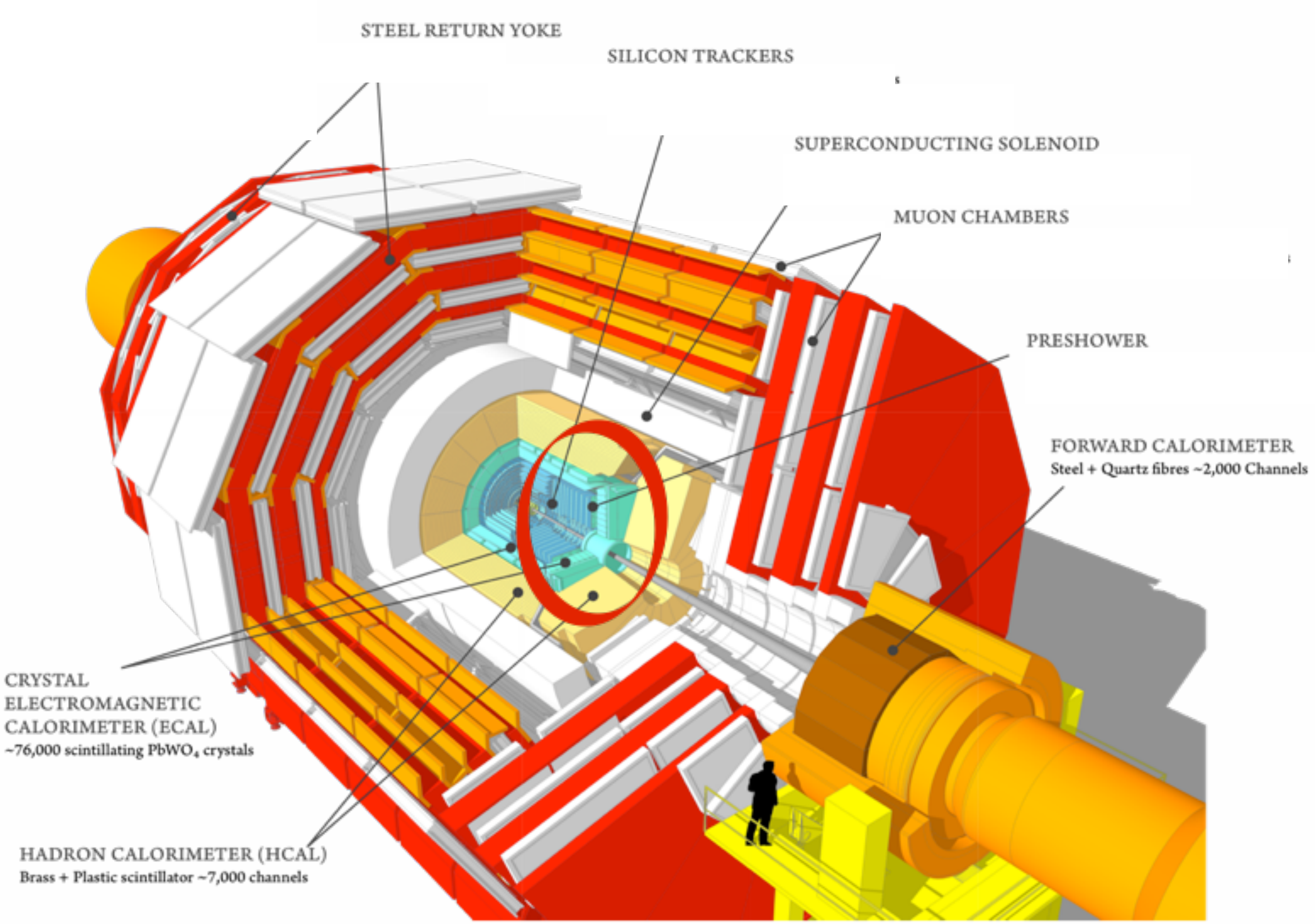
- simple and robust analysis strategy
- improved detector calibration @ 3.8 T
- analyzed dataset recorded @ 0T
- compared to previous results in Dec 15, 13TeV analysis improved sensitivity by more than 20%

- results interpreted in terms of scalar resonances & RS gravitons production for different widths
- modest excess of events observed at $m_{X=}$750(760)GeV for 8+13TeV(13TeV) dataset
- local significance is 3.4(2.9)σ, reduced to 1.6(<1)σ after accounting for look-elsewhere-effect

Backup

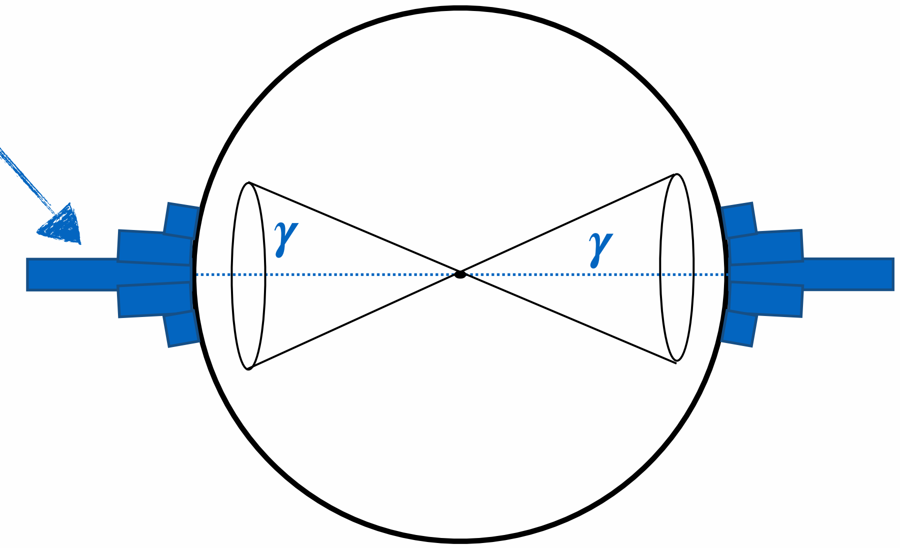

CMS Experiment at the LHC, CERN
Data recorded: 2015-Nov-02 21:34:00.662277 GMT
Run / Event / LS: 260627 / 854678036 / 477

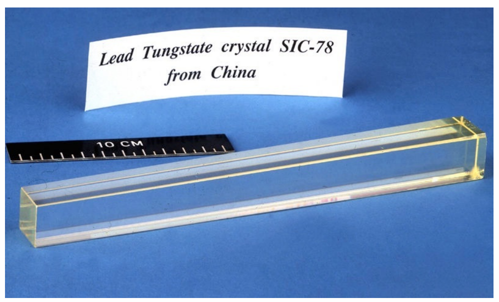
CMS at the LHC

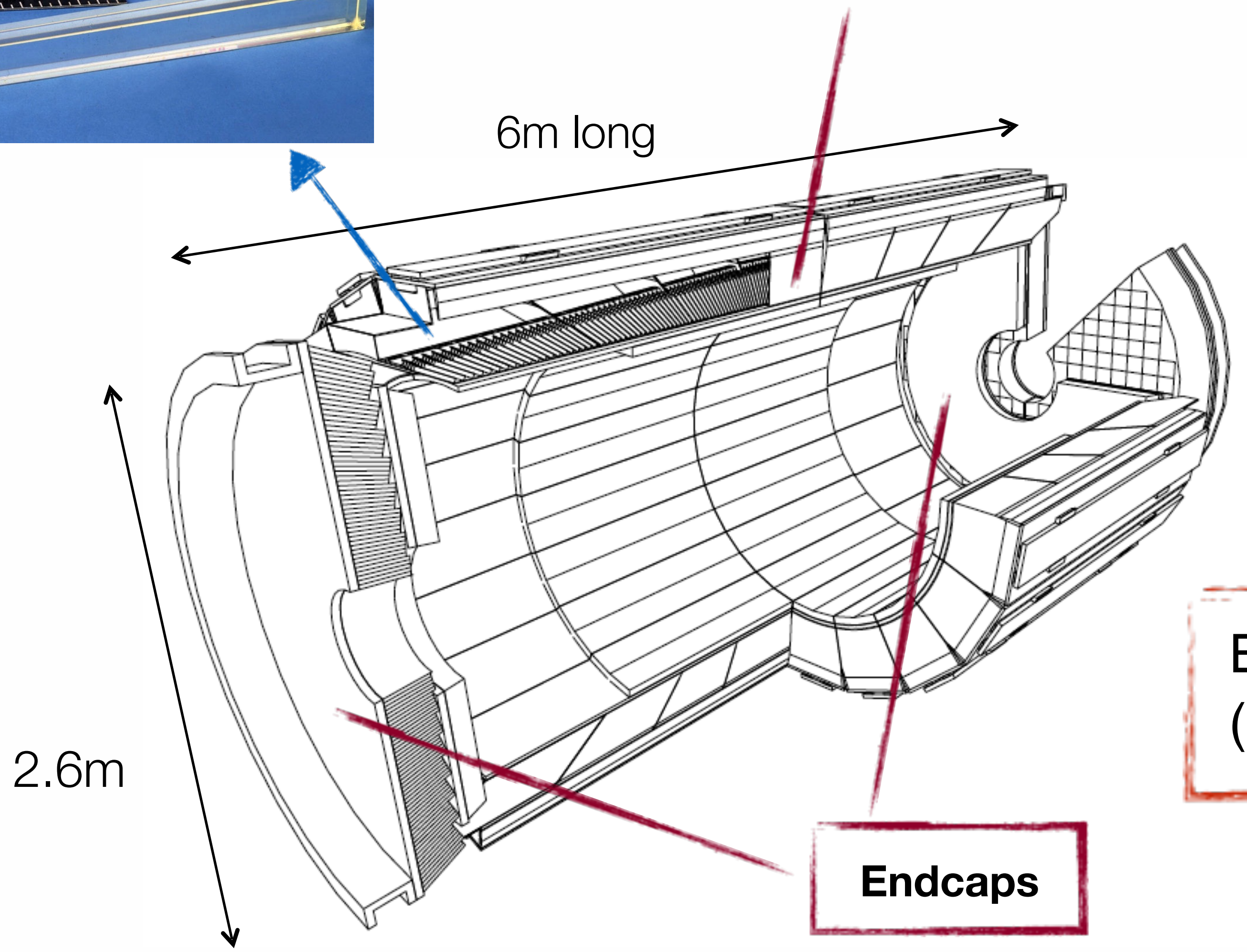


Electromagnetic calorimeter CMS

photon candidates from high energy deposits in em calorimeter (ECAL)







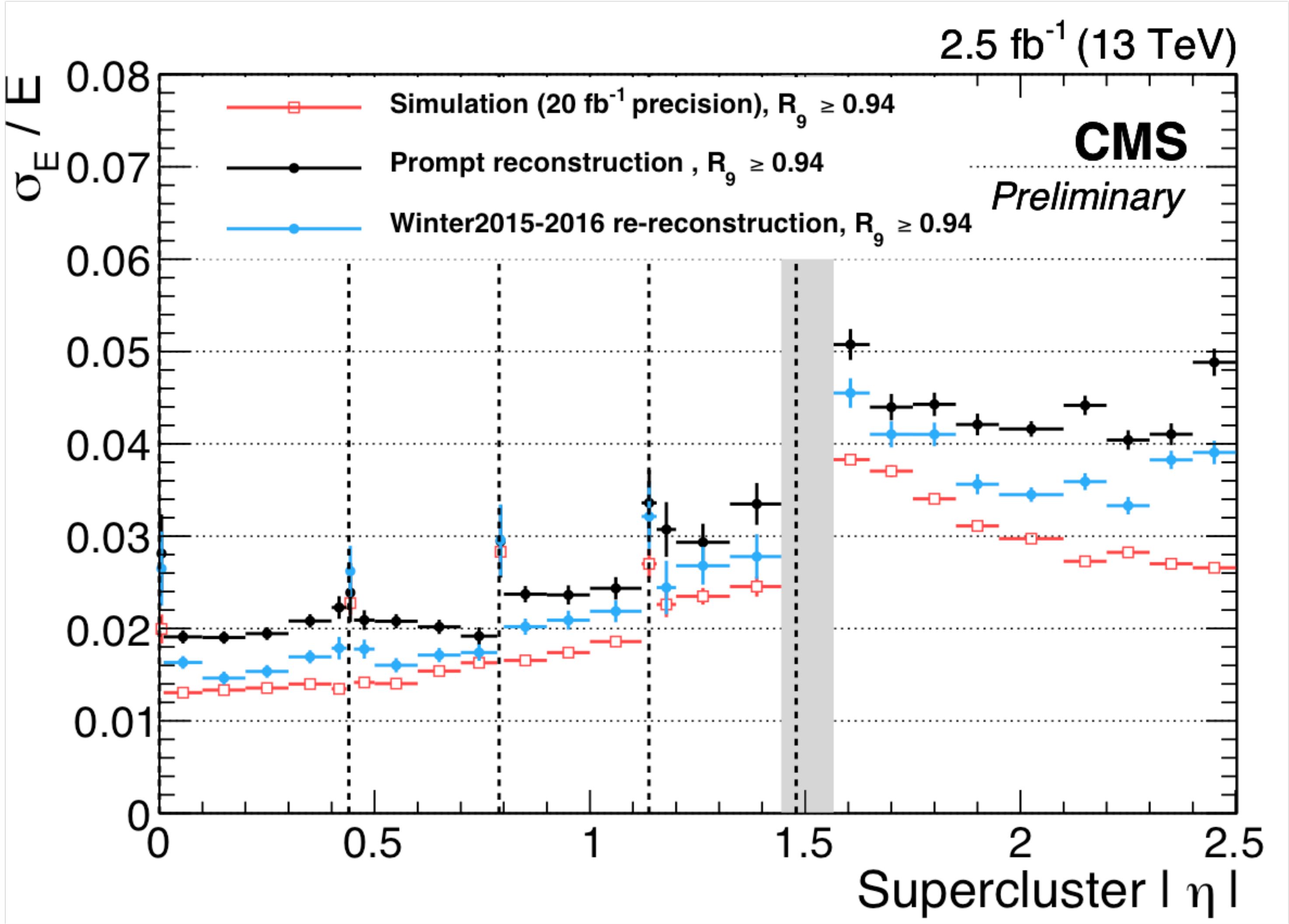
ECAL: excellent intrinsic diphoton energy resolution (~ 0.5% for masses above 100 GeV)

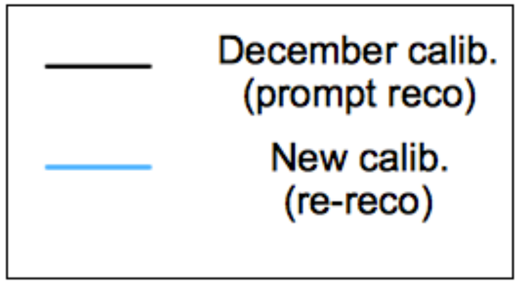
Benefits of re-reconstruction @ 3.8 T

data re-reconstruction provides:

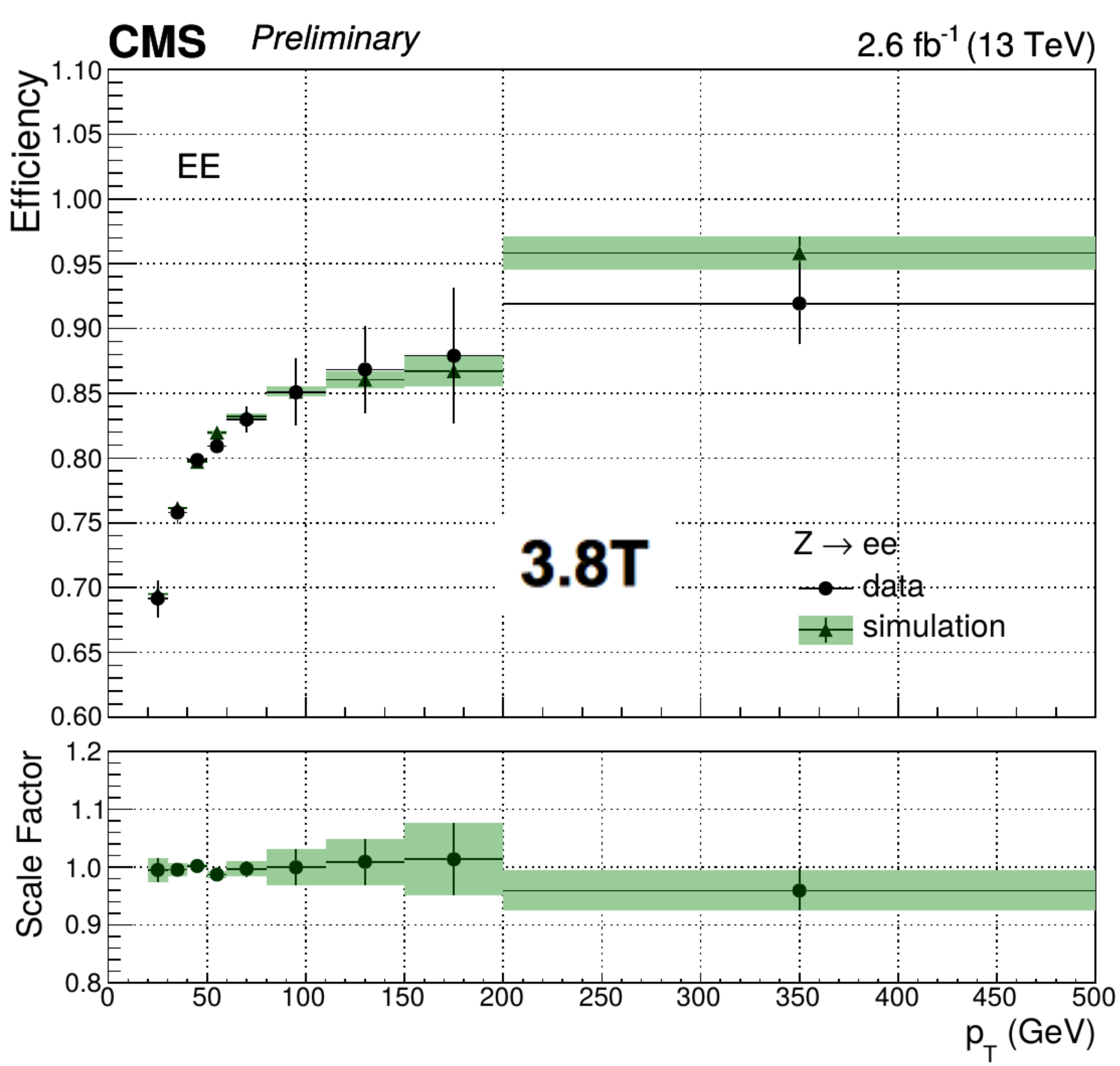
- constants for **channel-to-channel calibration in ECAL** - using 2015 data

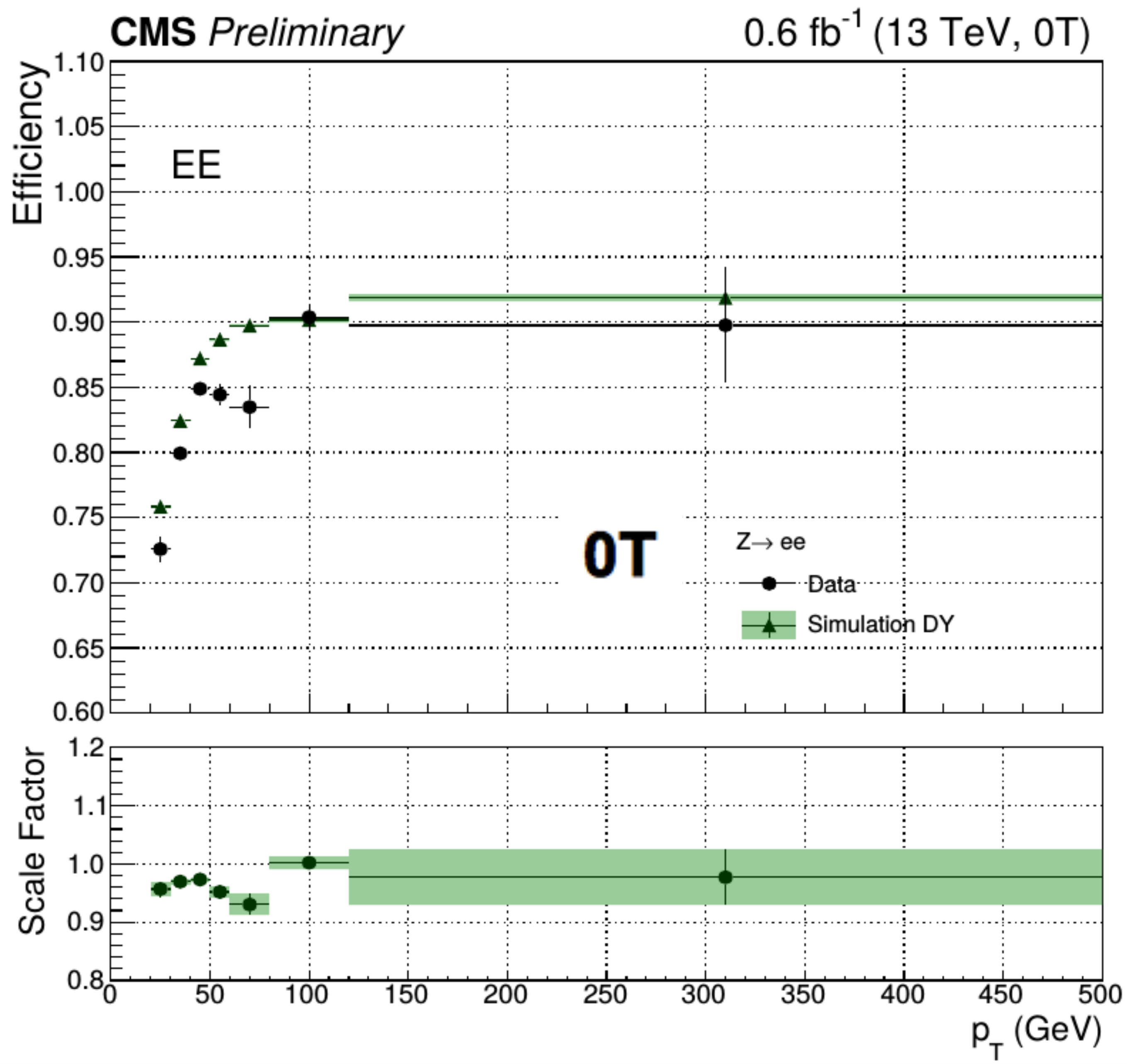
energy resolution for Z->ee electrons as a function of η



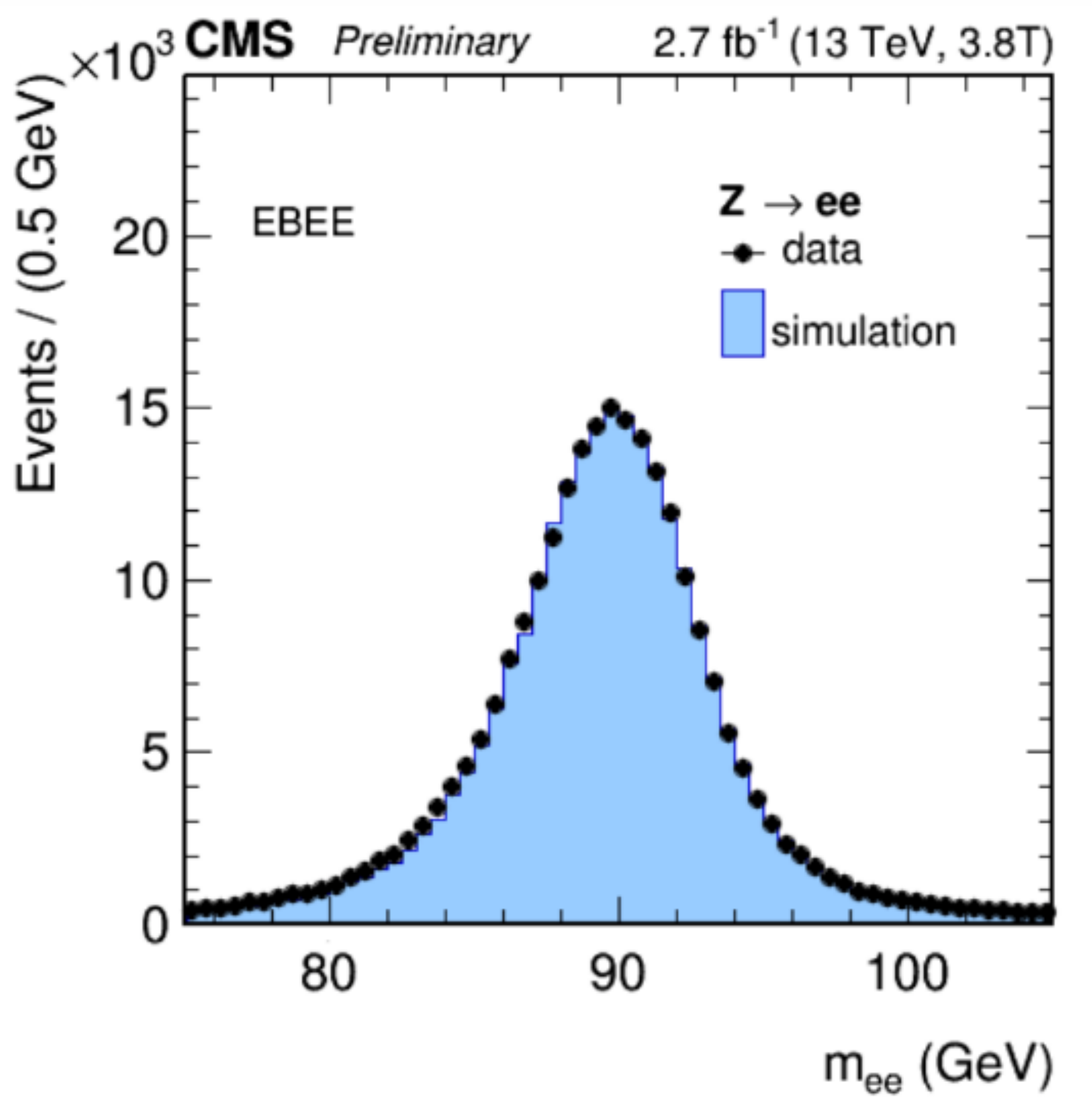


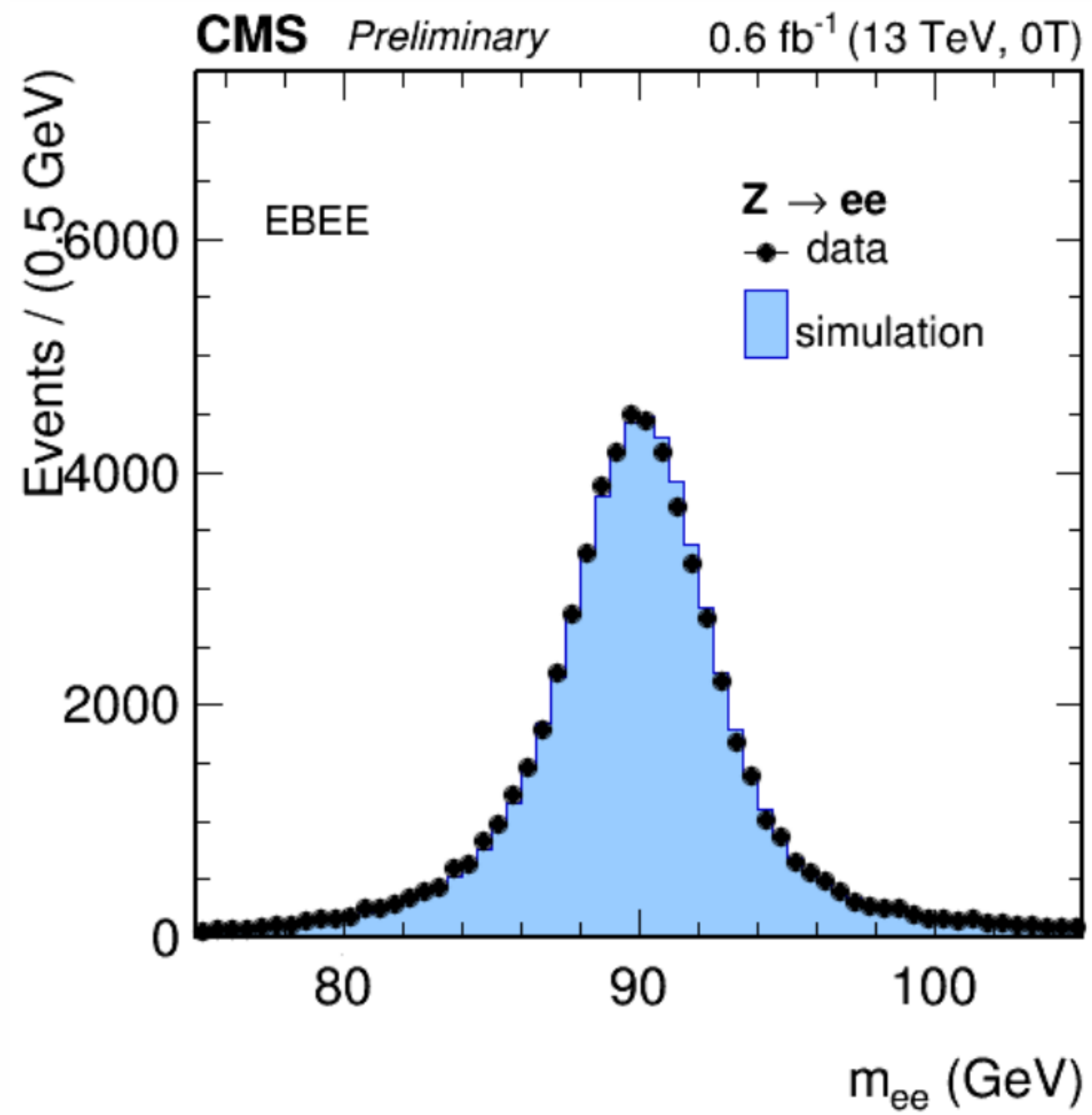
photon identification efficiency for endcap





Energy corrections for EBEE





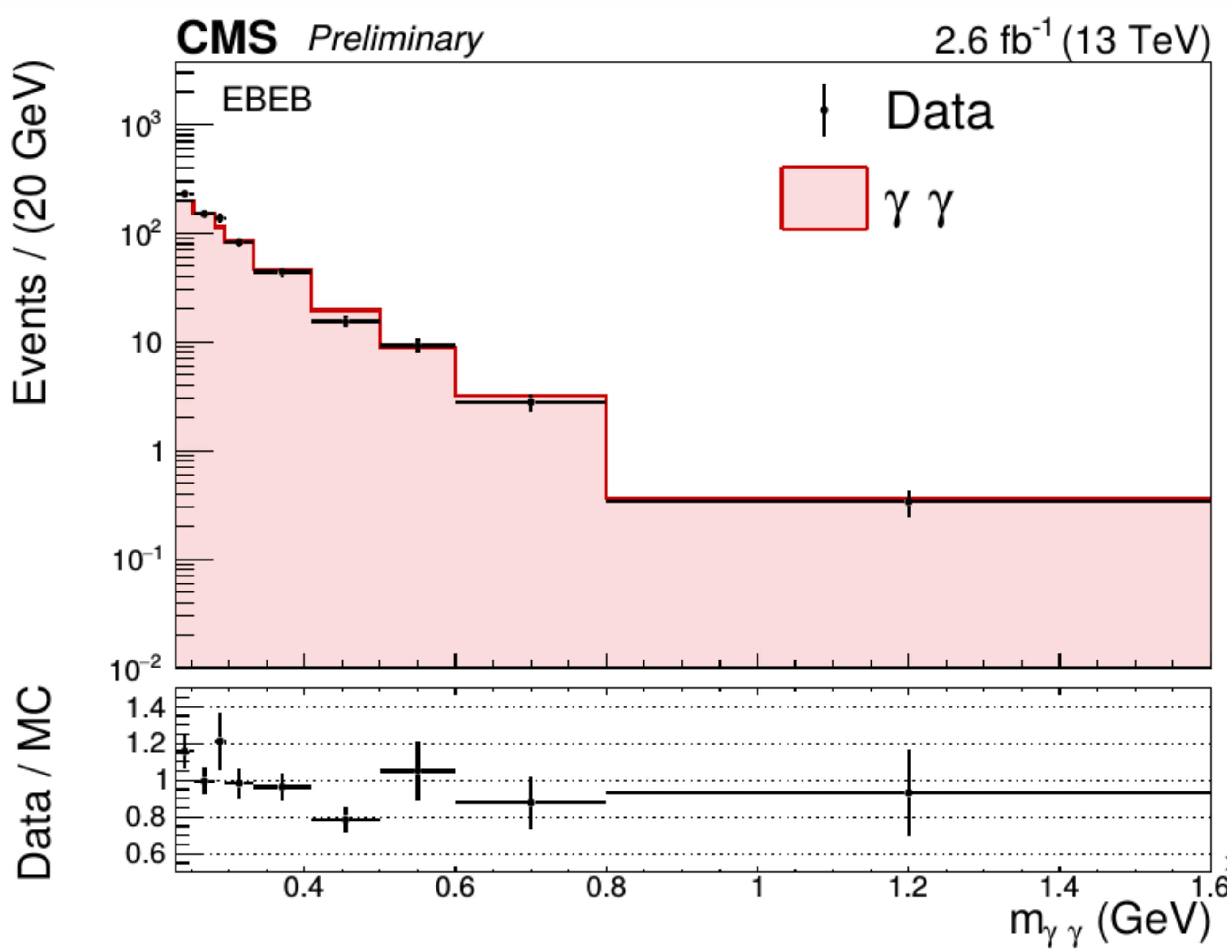
$\gamma\gamma$ bkg - measurement vs MC prediction

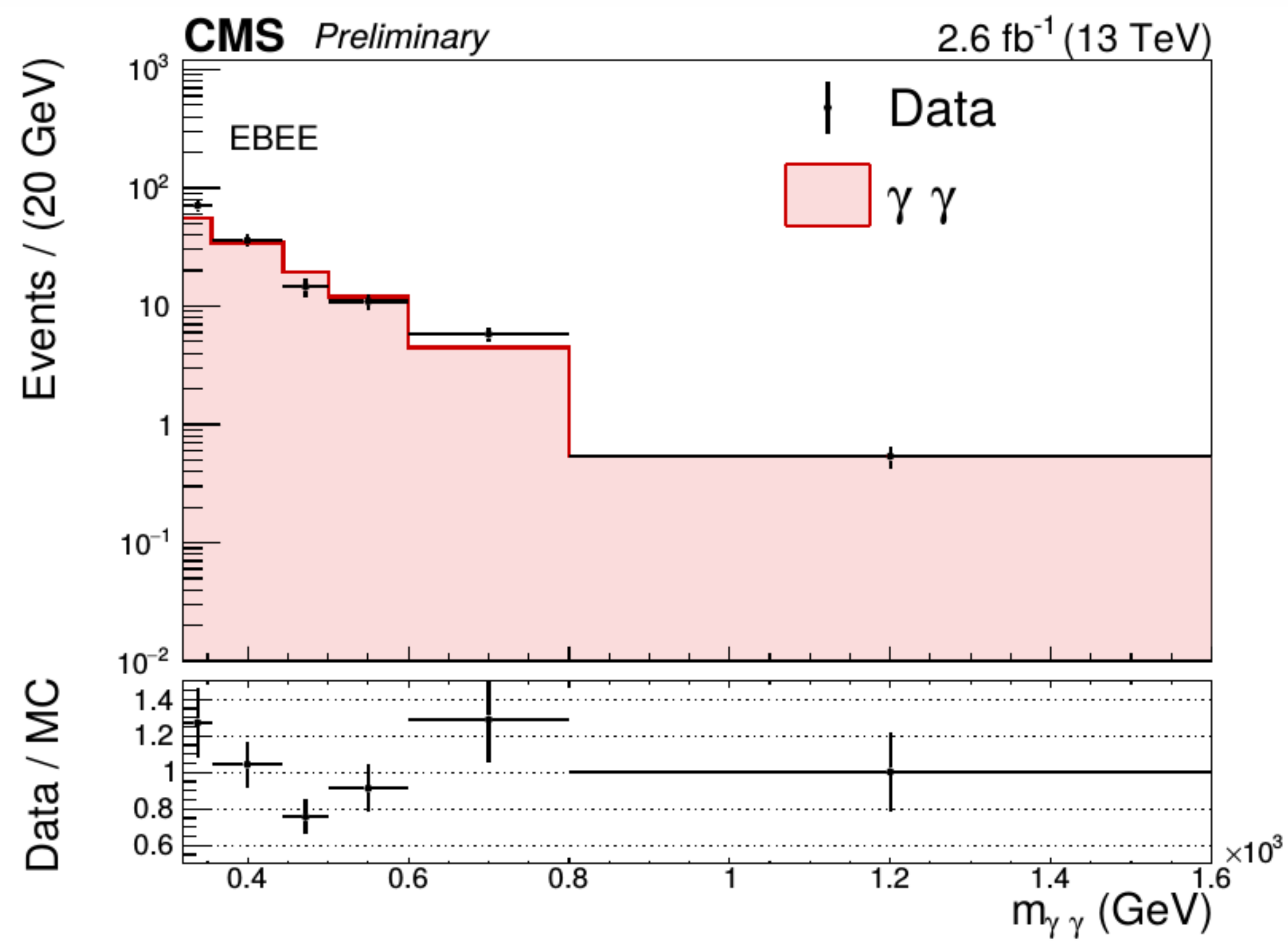
prediction for γγ component checked against theory prediction

$$N_{data}^{\gamma\gamma}(bin) = f_{\gamma\gamma}(bin) \cdot N_{data}(bin)$$

obtained using Sherpa-LO reweighted to 2γNNLO

observation in good agreement with model.





background shape accuracy

- possible mis-modelling in MC and accounted as “bias term“

- study pull of mean number of bkg events in several mass windows →

$$p_i^j = \frac{N_{\hat{g}_i}^{w_j} - N_h^{w_j}}{\sigma(N_{\hat{g}_i}^{w_j})}$$

- accept if b = |median(p)| <0.5 for all windows
  - difference max. 0.5 of total uncertainty
  - b= 0.5 underestimates error by max 10 %

- if not increase error by “bias term”

$$\tilde{p}_j^i = \frac{N_{\hat{g}_i}^{w_j} - N_h^{w_j}}{\sqrt{\sigma^2(N_{\hat{g}_i}^{w_j}) + \beta_I^2(w_j)}}$$

modelling of the bias term in the search

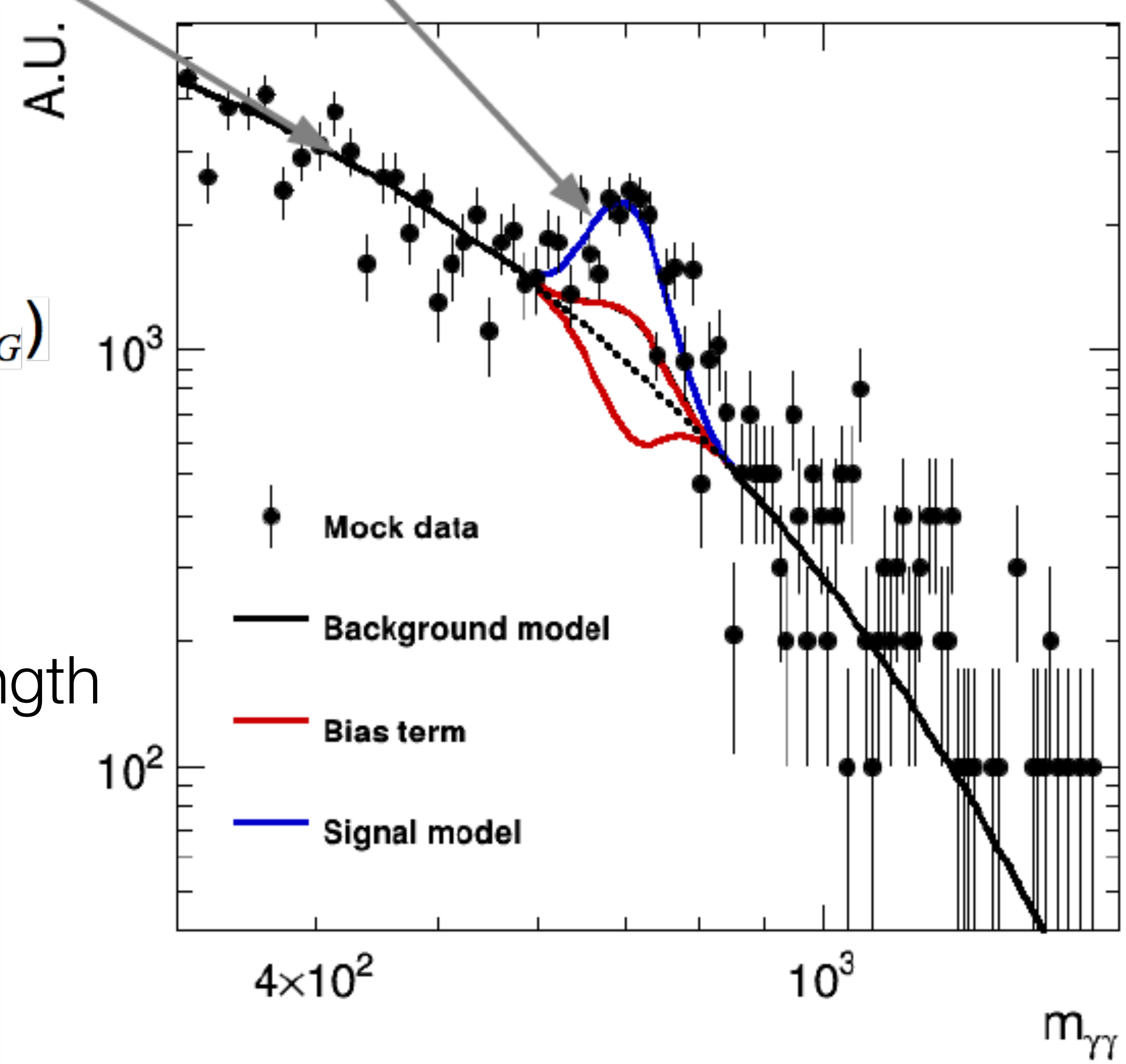
- bias term included in hypothesis test adding a signal-like component to the background model

$$bkg(m_{\gamma\gamma}|\theta_{bias}) = N_{bkg}\cdot\left(\frac{N_{bkg}-\theta_{bias}}{N_{bkg}} bkg(m_{\gamma\gamma}) + \frac{\theta_{bias}}{N_{bkg}} sig(m_{\gamma\gamma})\right)\cdot Gaus(\theta_{bias}|0, N_{bias})$$

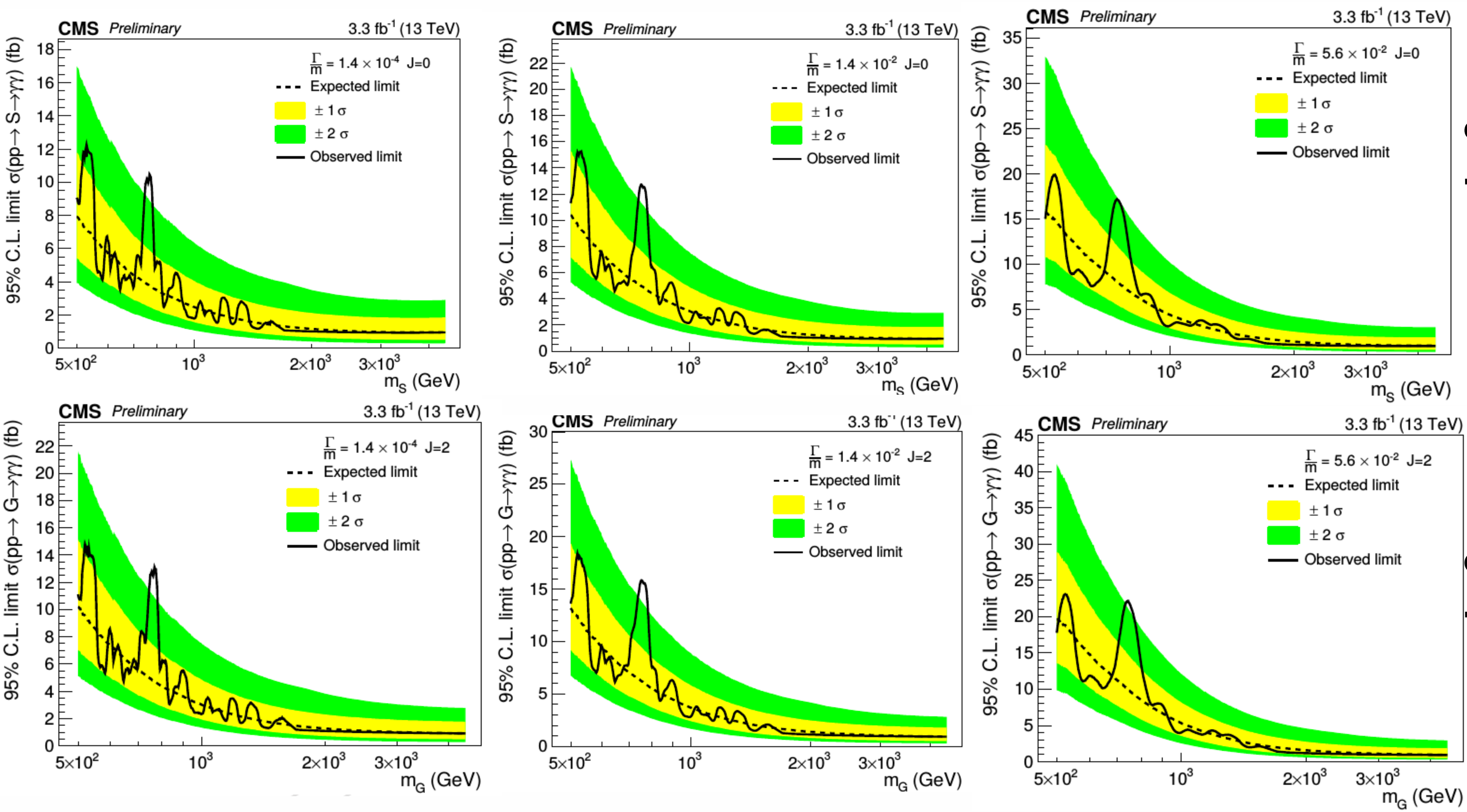
- normalisation of signal-like component constrained from result of bias study

$$N_{bias} = \int sig(m_{\gamma\gamma})\beta(m_{\gamma\gamma}) \sim FWMH(sig)\cdot\beta(m_G)$$

- effect on sensitivity:
  - to quantify the effect, look at signal strength which would give raise to a 3σ excess
  - effect is below 5-10% everywhere



upper limits for 13 TeV



spin 0

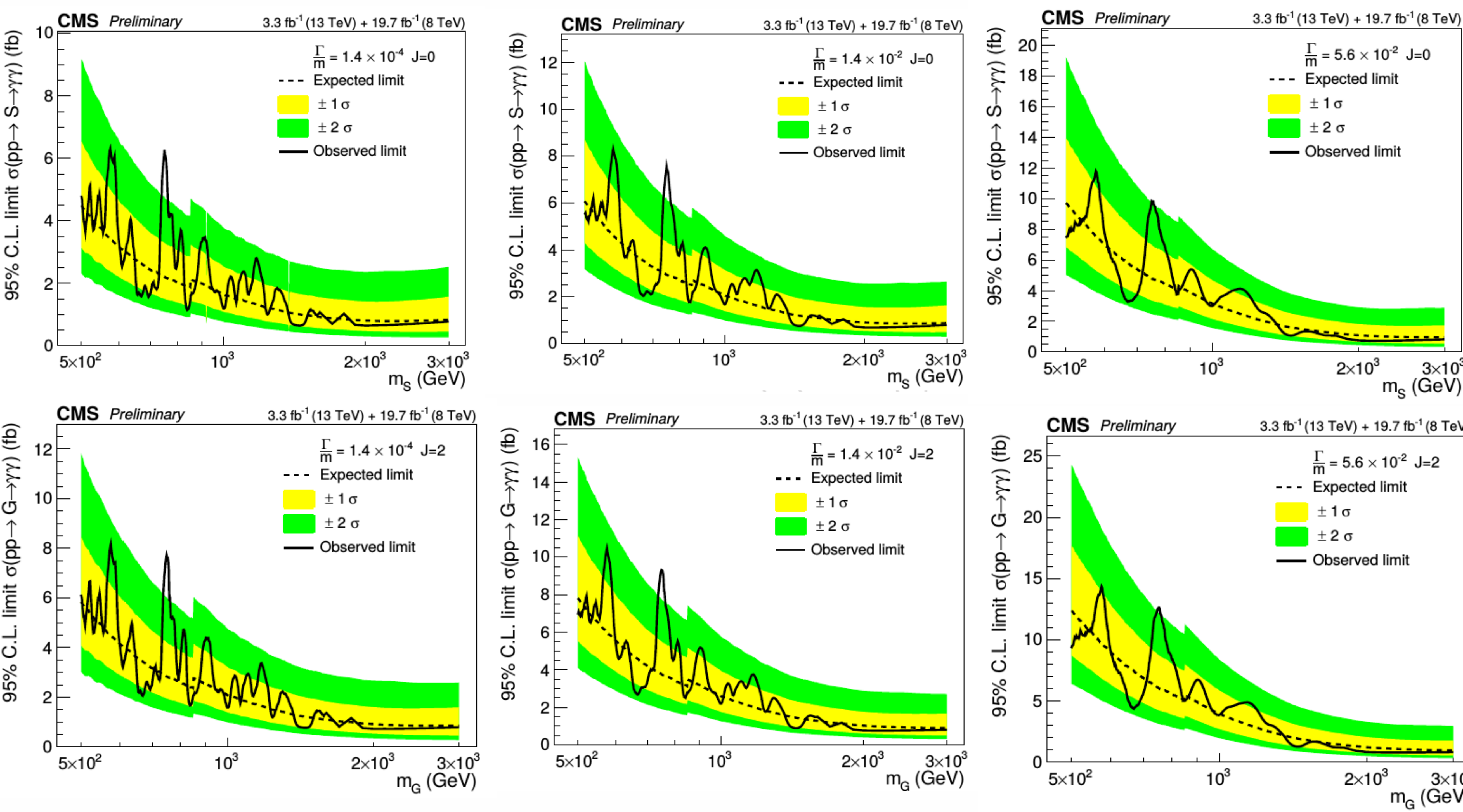
spin 2

G/m = 1.4x10⁻⁴ | G/m = 1.4x10⁻² | G/m = 5.6x10⁻²

ETH Institute for Particle Physics

upper limits for 8 & 13 TeV combination

- normalised to 13 TeV cross section

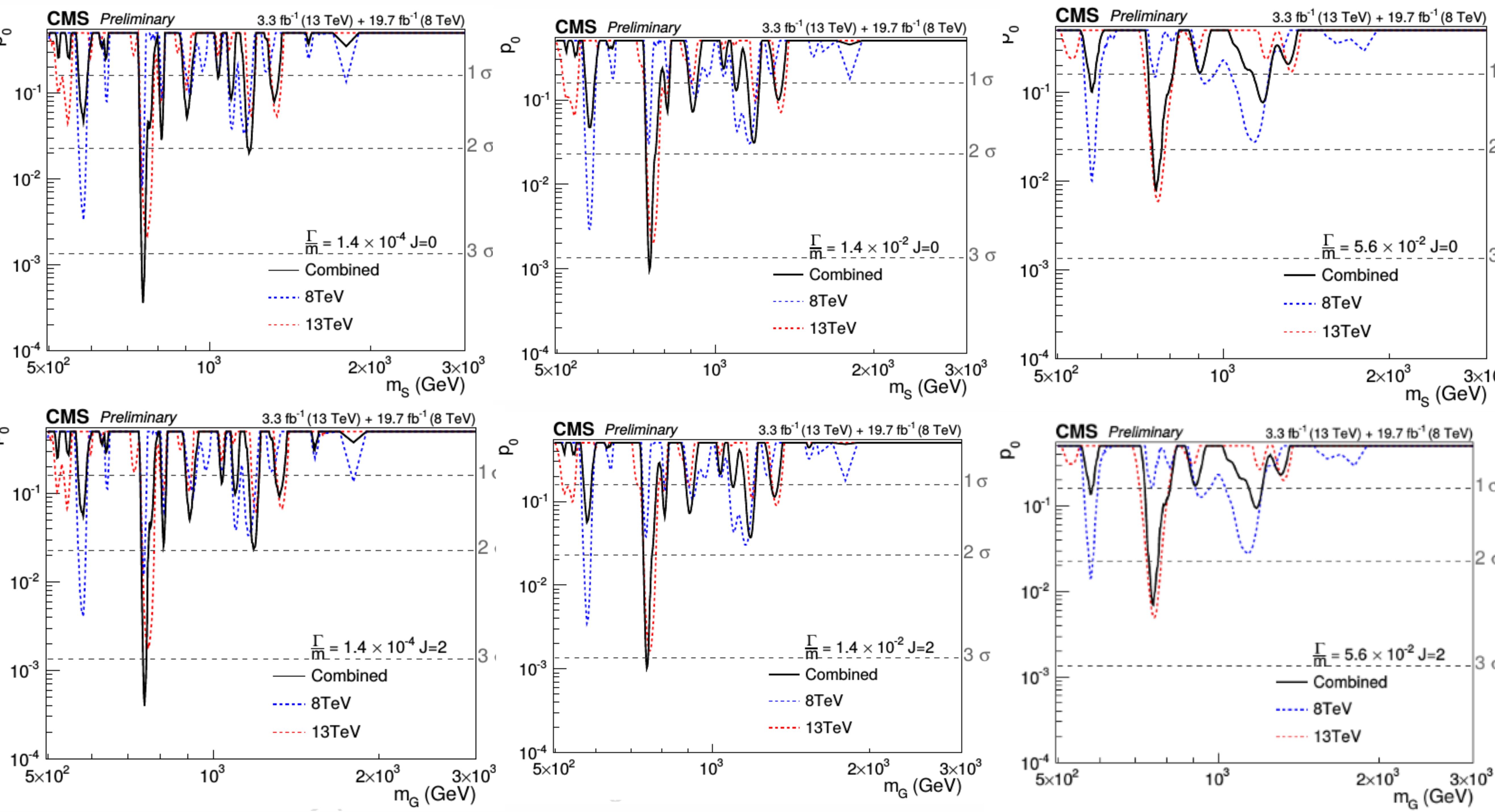


spin 0

spin 2

G/m = 1.4x10^{-4} **G/m = 1.4x10^{-2}** **G/m = 5.6x10^{-2}**

p-values all signal hypotheses

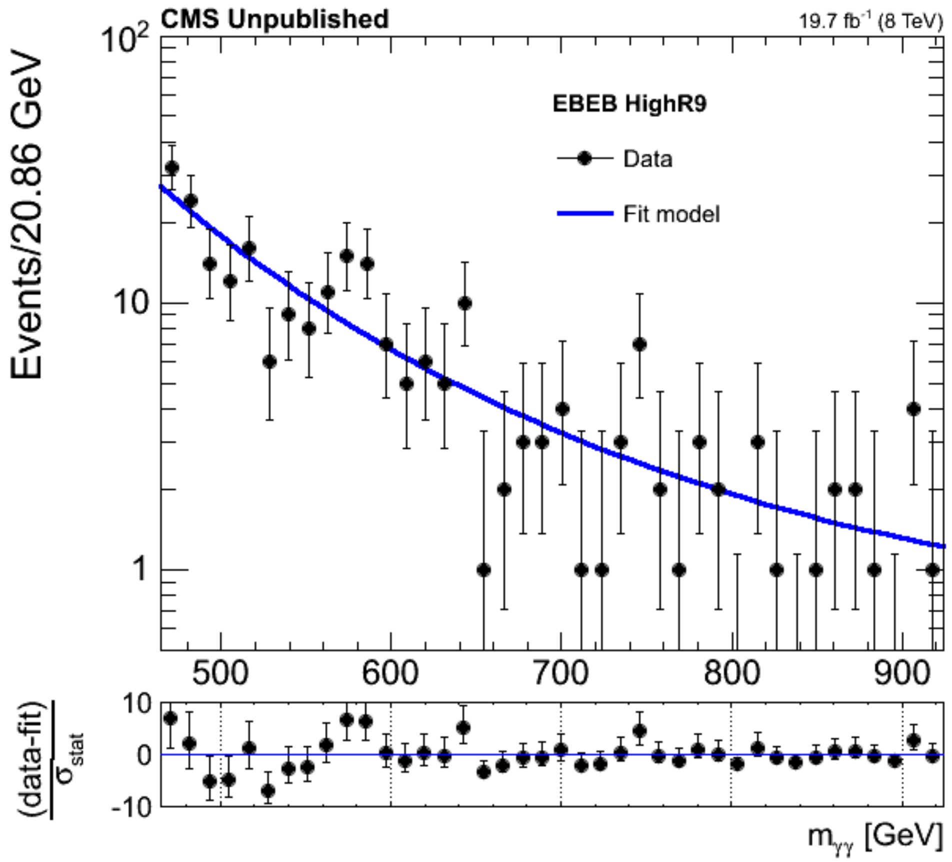


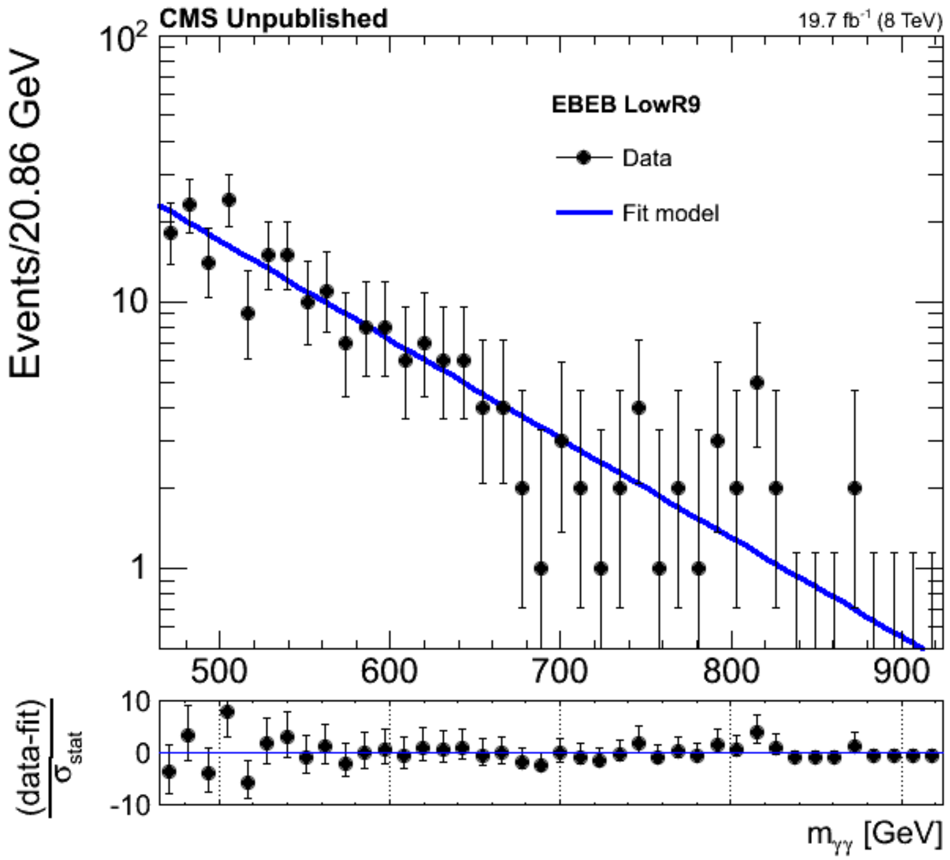
spin 0

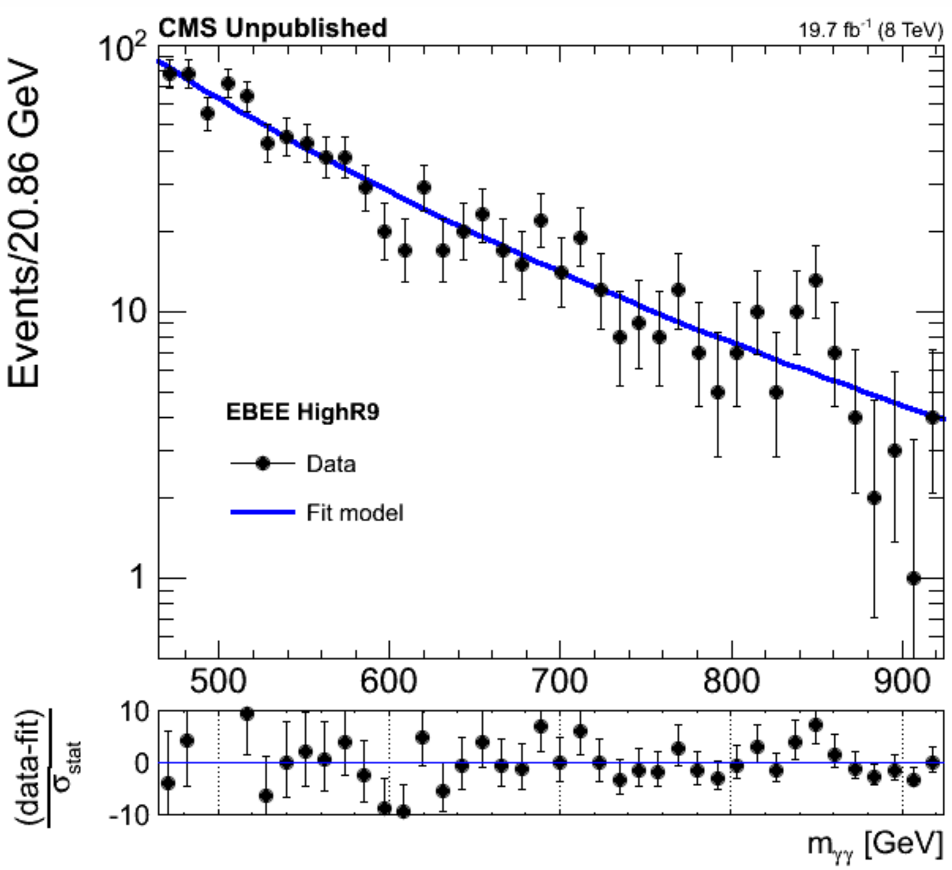
spin 2

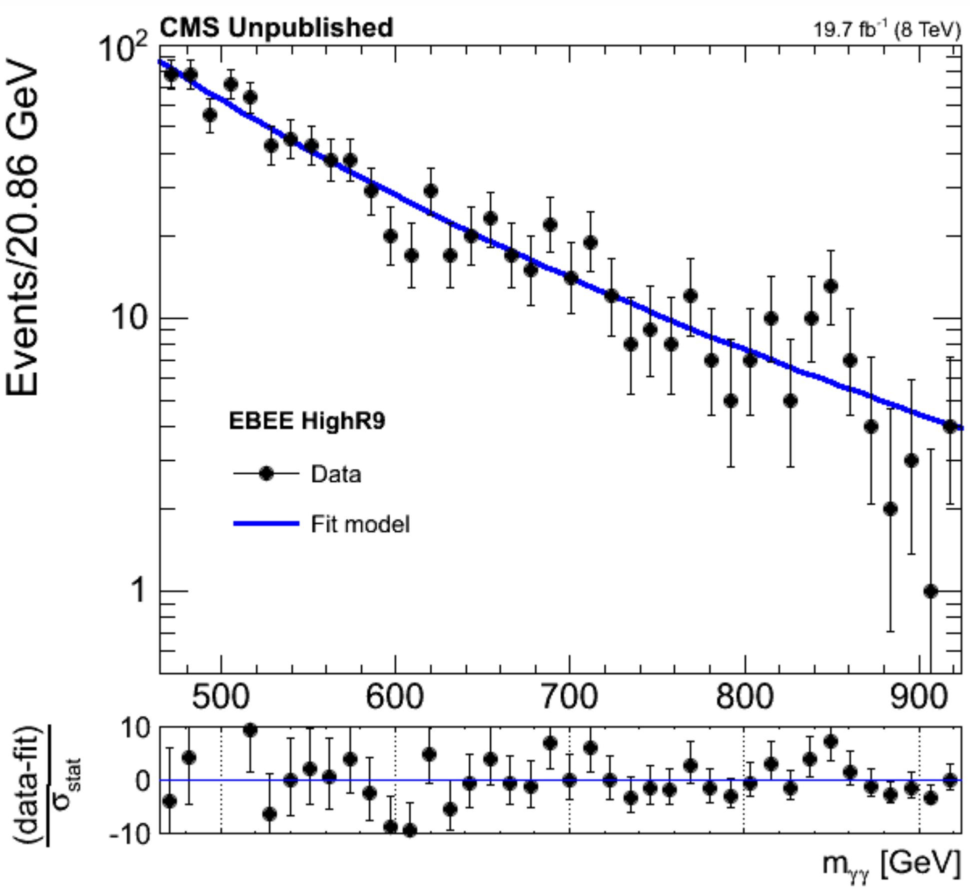
G/m = 1.4×10^{-4} | **G/m = 1.4×10^{-2}** | **G/m = 5.6×10^{-2}**

8 TeV data

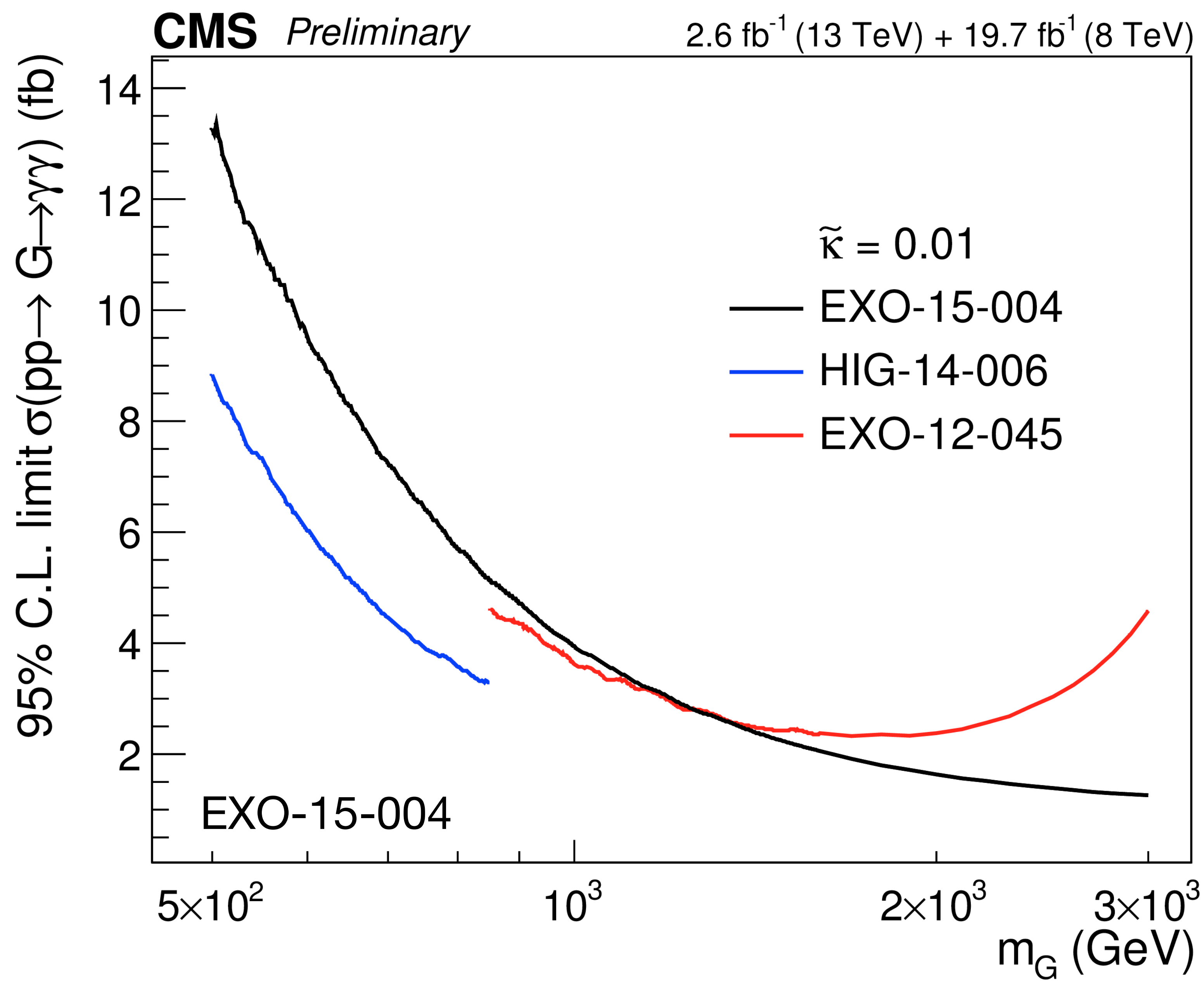

CMS Unpublished
19.7 fb⁻¹ (8 TeV)
EBEB HighR9
Data
Fit model
Events/20.86 GeV
(data-fit)/σstat
mγγ [GeV]


CMS Unpublished
19.7 fb⁻¹ (8 TeV)
EBEB LowR9
Data
Fit model
Events/20.86 GeV
(data-fit)/σstat
mγγ [GeV]


CMS Unpublished
19.7 fb⁻¹ (8 TeV)
EBEE HighR9
Data
Fit model
Events/20.86 GeV
(data-fit)/σstat
mγγ [GeV]


CMS Unpublished
19.7 fb⁻¹ (8 TeV)
EBEE HighR9
Data
Fit model
Events/20.86 GeV
(data-fit)/σstat
mγγ [GeV]

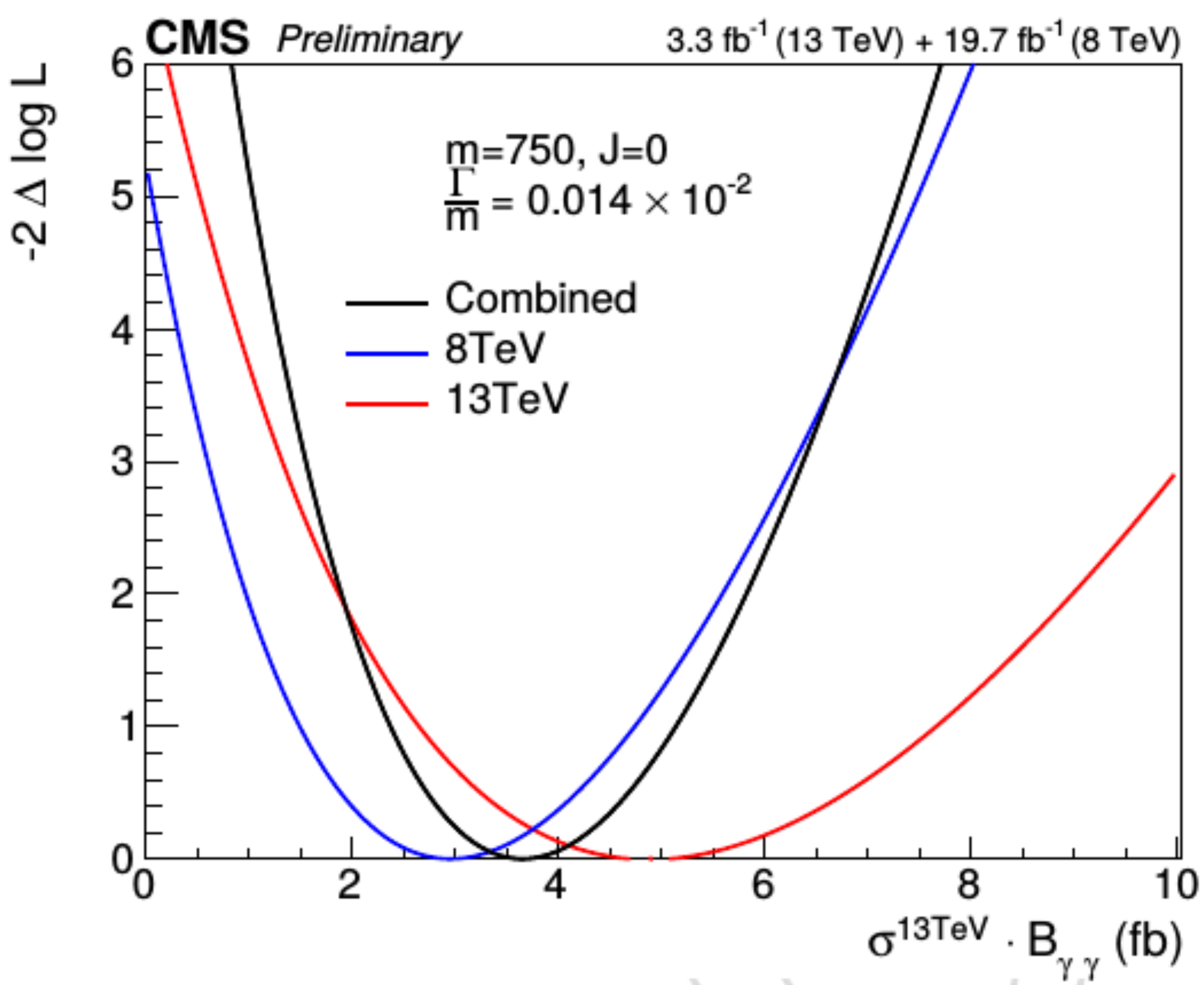
8 and 13 TeV combination

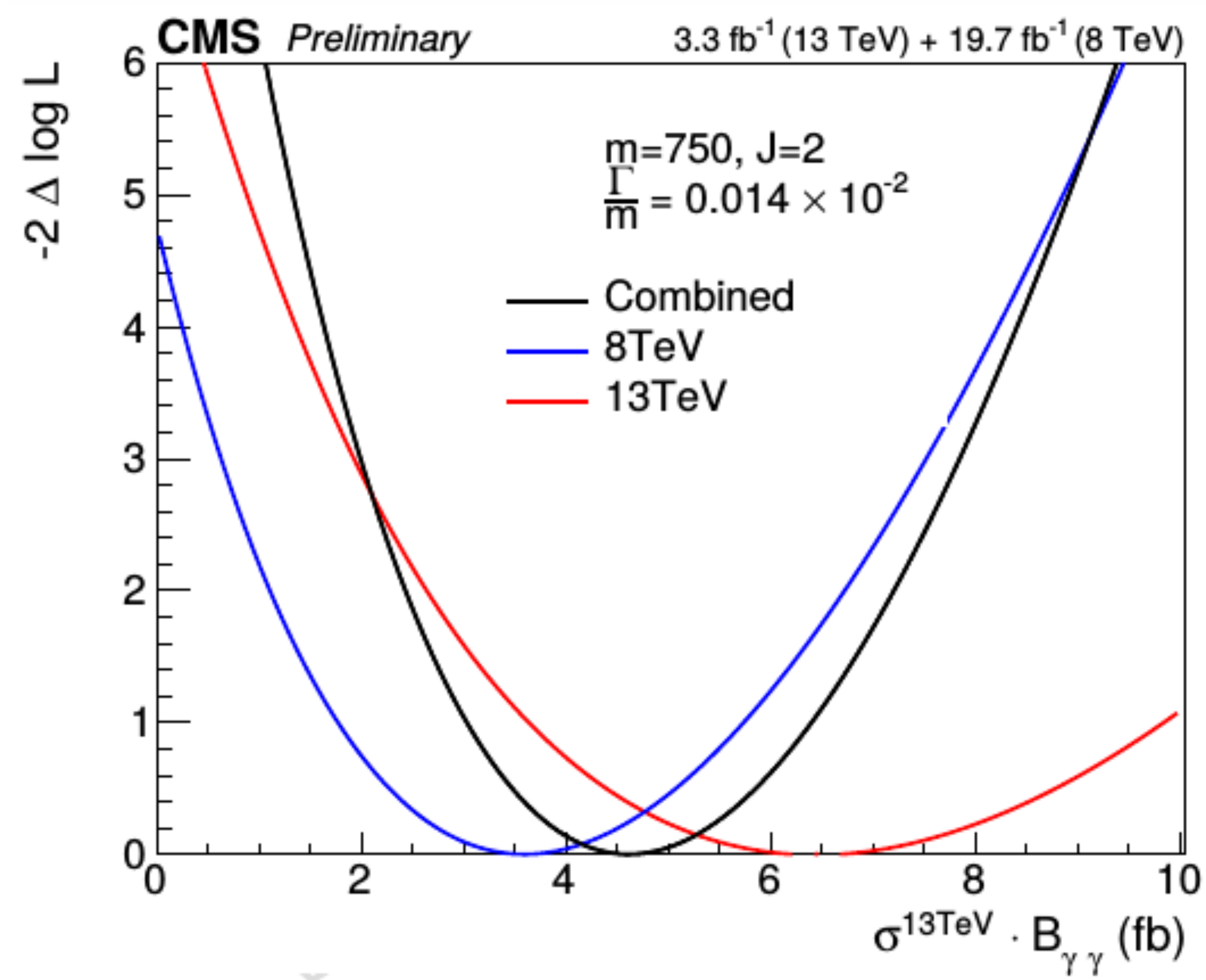


- comparison of the median expected upper limits of the analyses entering the combination
- the 8 TeV results are scaled by the expected ratio of cross sections predicted for an RS graviton

Consistency 8 & 13 TeV combined

- 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





ETH Institute for Particle Physics

global significance for 8 & 13 TeV combination

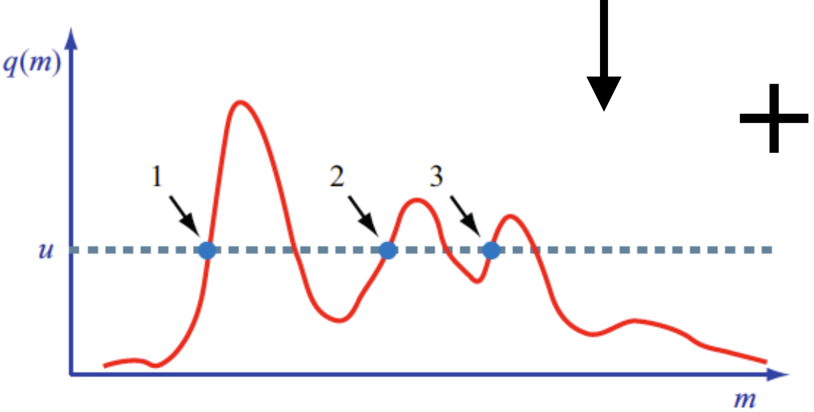
problem: @ 8 TeV sliding window for mass fit —> cannot throw correlated toy experiments

trial factor: P(excess @ m_0)/P(excess in signal region)

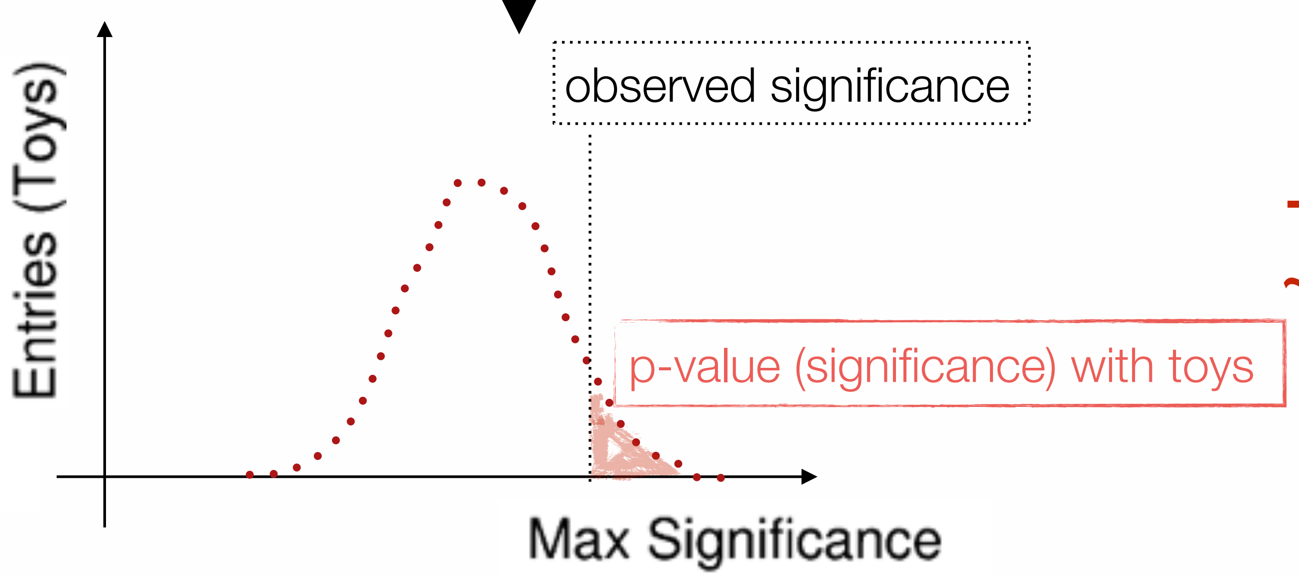
approximation:
trails factor = trails factor(mass) x trails factor(Γ, J |Mass)

asymptotic formulas (crossings)
(~100)

from toys @ 13 TeV
~1.3



+



—> global p-value
~ 1.6 σ

ratio of LHC parton luminosities