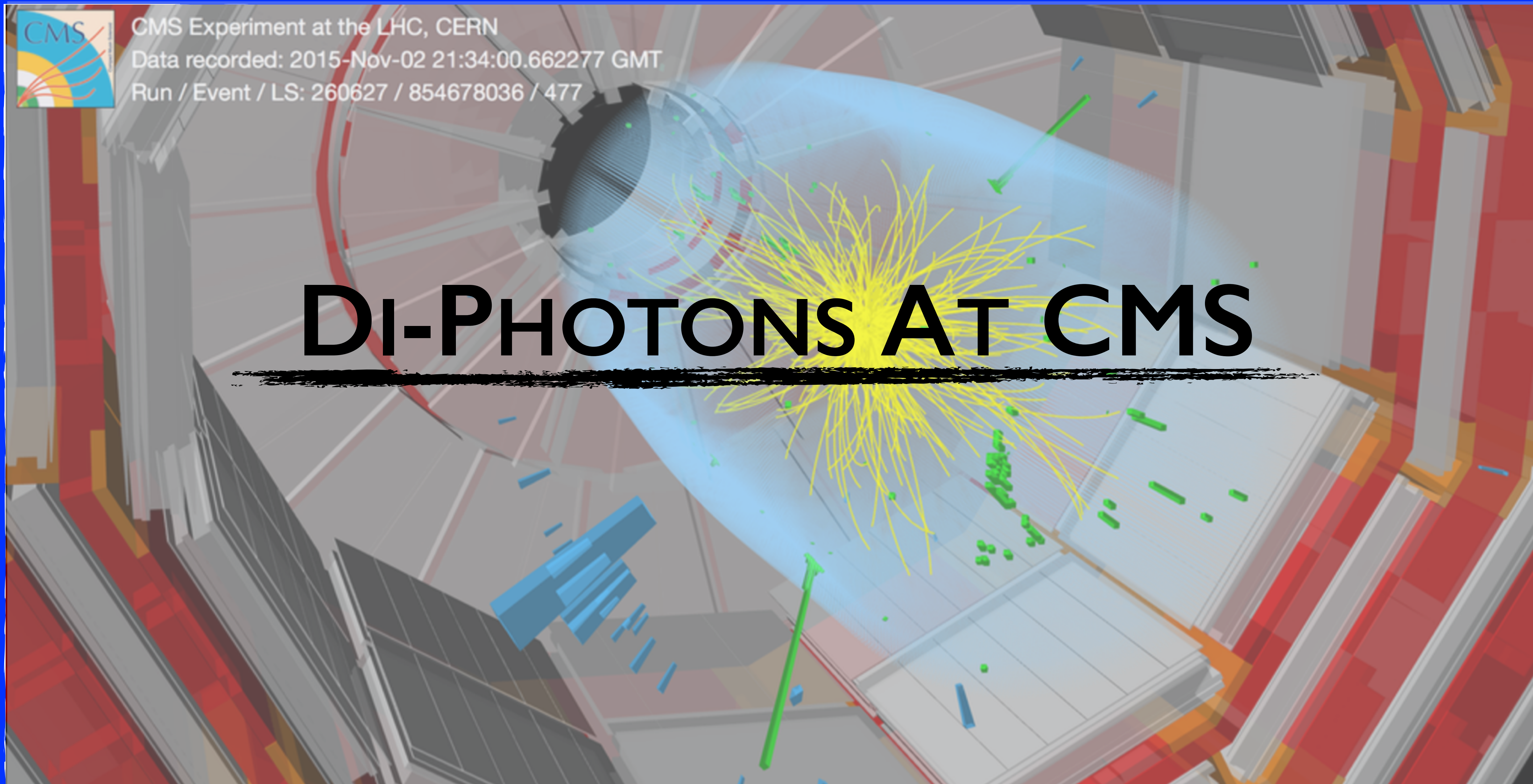


Di-Photons At CMS

P. Meridiani (INFN Roma)
on behalf of the CMS collaboration

16/5/2016

CALOR 2016
XVIIth International Conference on Calorimetry in Particle Physics
May 15 - 20, 2016, Daegu, Korea (South)

INFN Istituto Nazionale di Fisica Nucleare

INTRODUCTION

After the discovery of a particle compatible with the Higgs boson, the LHC program has 2 clear directions to look for new physics

Indirect: precision measurements of the Higgs properties

- Higgs couplings
- Higgs differential cross-sections
- …

Direct: look for new particles and rare final states

- new center of mass-of-mass energy 13 TeV significantly extends reach of Run I

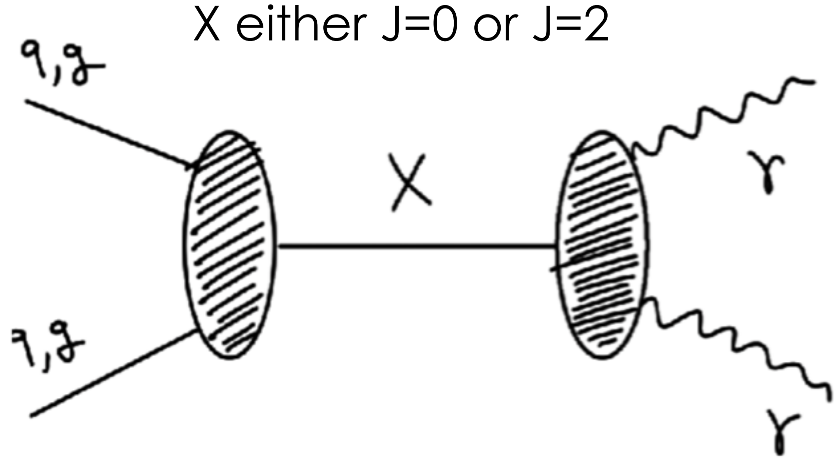
In either of these, di-photon final state plays a major role!

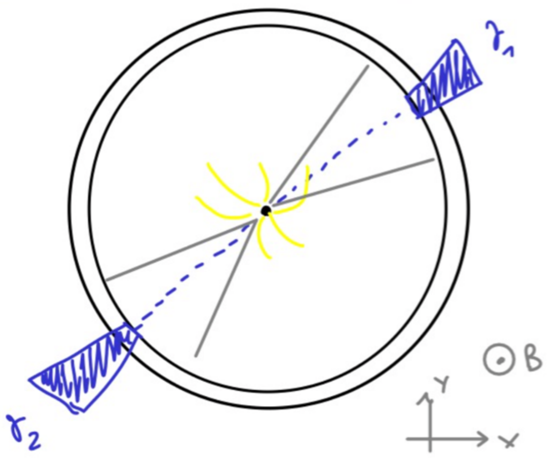
Di-Photon Searches

Di-photon is a clean experimental signature to look for new physics

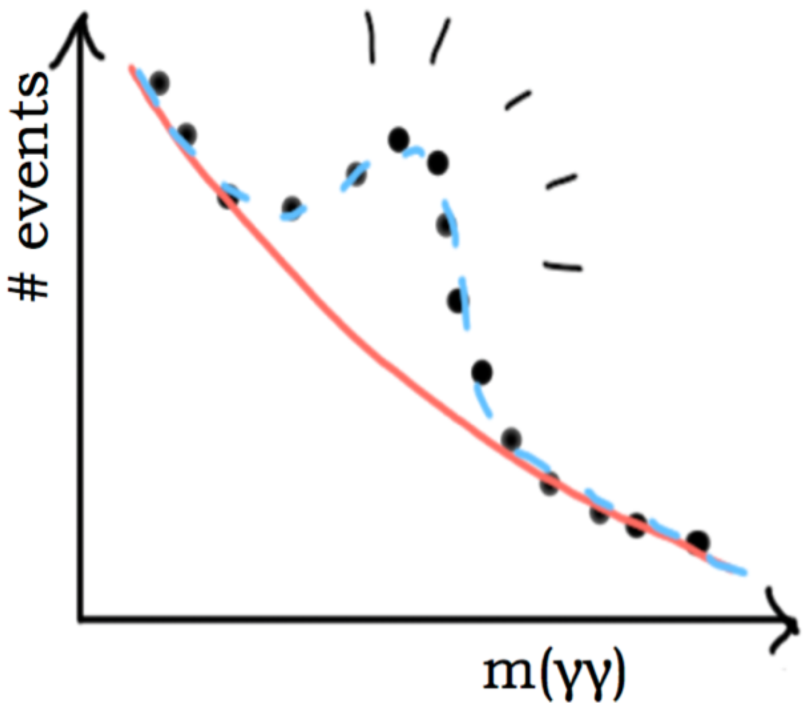
<u>fully reconstructed final state is a golden search mode for new particles</u>

Yang theorem:
X either J=0 or J=2

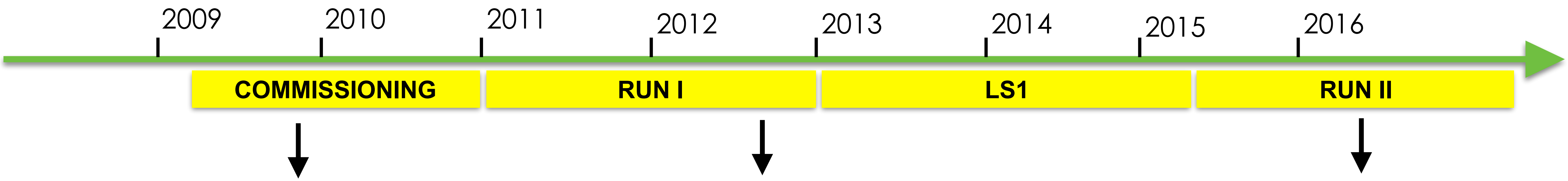


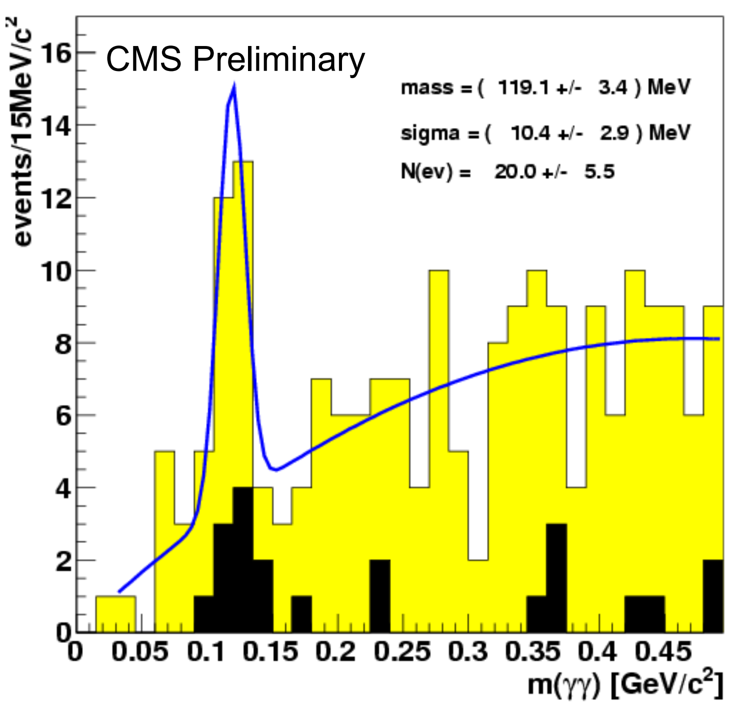


STEP	ISSUES
1) 2 isolated photons with high p_T	photon identification to reject QCD background
2) di-photon mass reconstruction $m_{\gamma\gamma} = \sqrt{2E_1E_2(1-cos\theta_{12})}$	energy scale and resolution vertex determination in presence of multiple interactions pile-up (PU)
3) signal extraction	background determination: can be estimated directly with a fit to the mass spectrum



Di-Photons @ CMS: Timeline

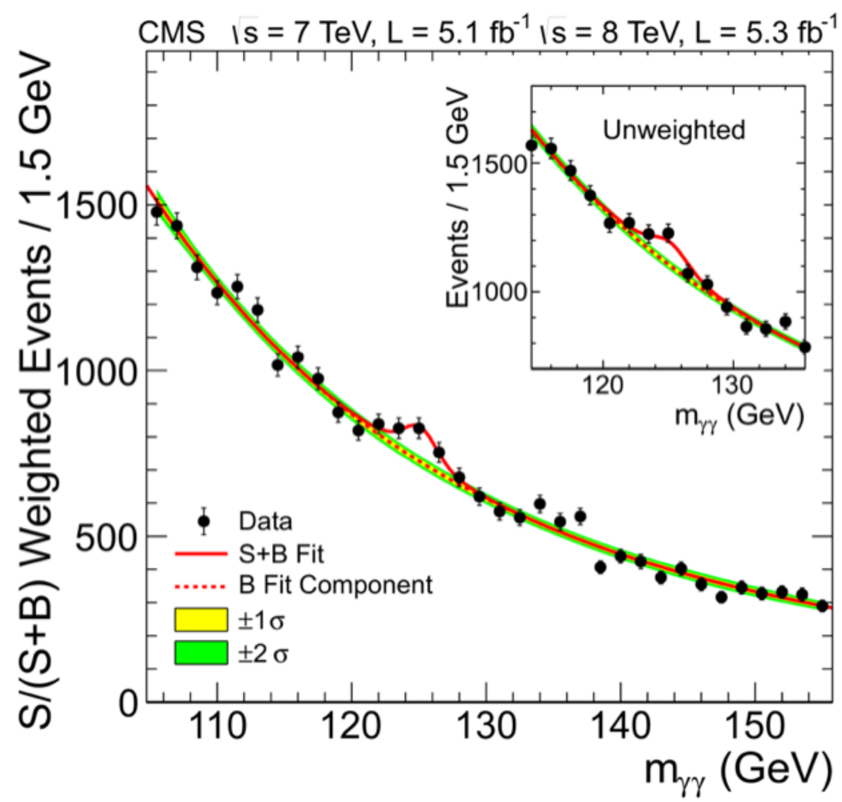




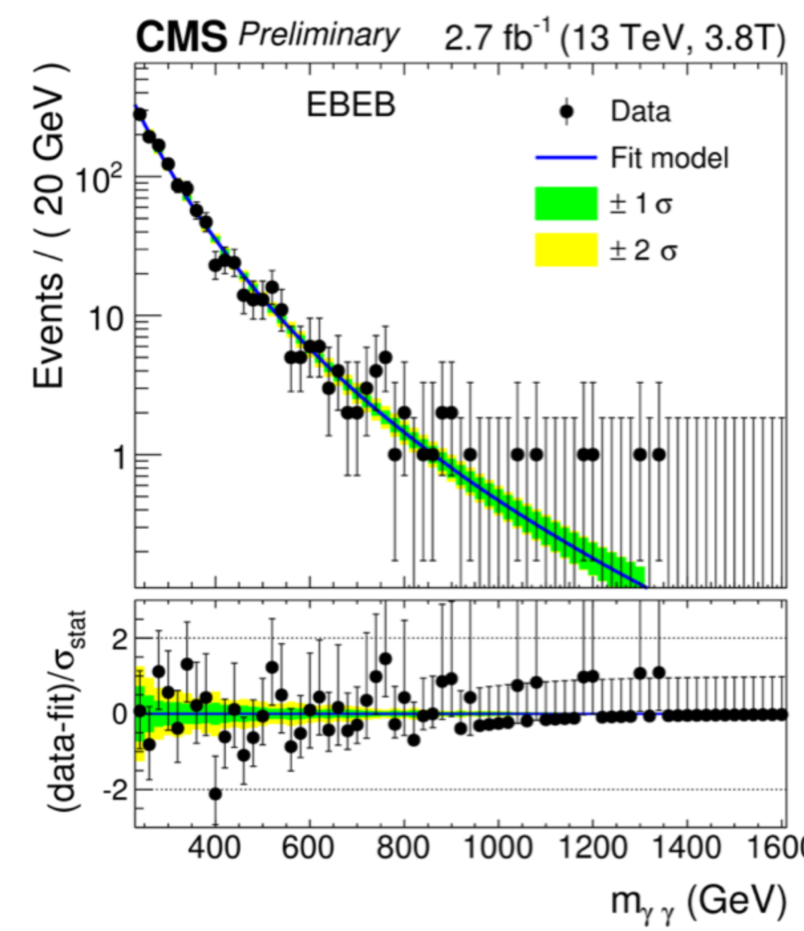
First di-photon distribution ever shown by CMS (Nov 2009)

First LHC collisions, √s=900 GeV, B=0T

Raw energy used (no energy corrections)



July 2012: Observation of a new boson at mass of 125 GeV (Phys. Lett. B 716 (2012) 30)



Now: Looking for high mass resonances decaying in 2 photons in 13 TeV Collisions

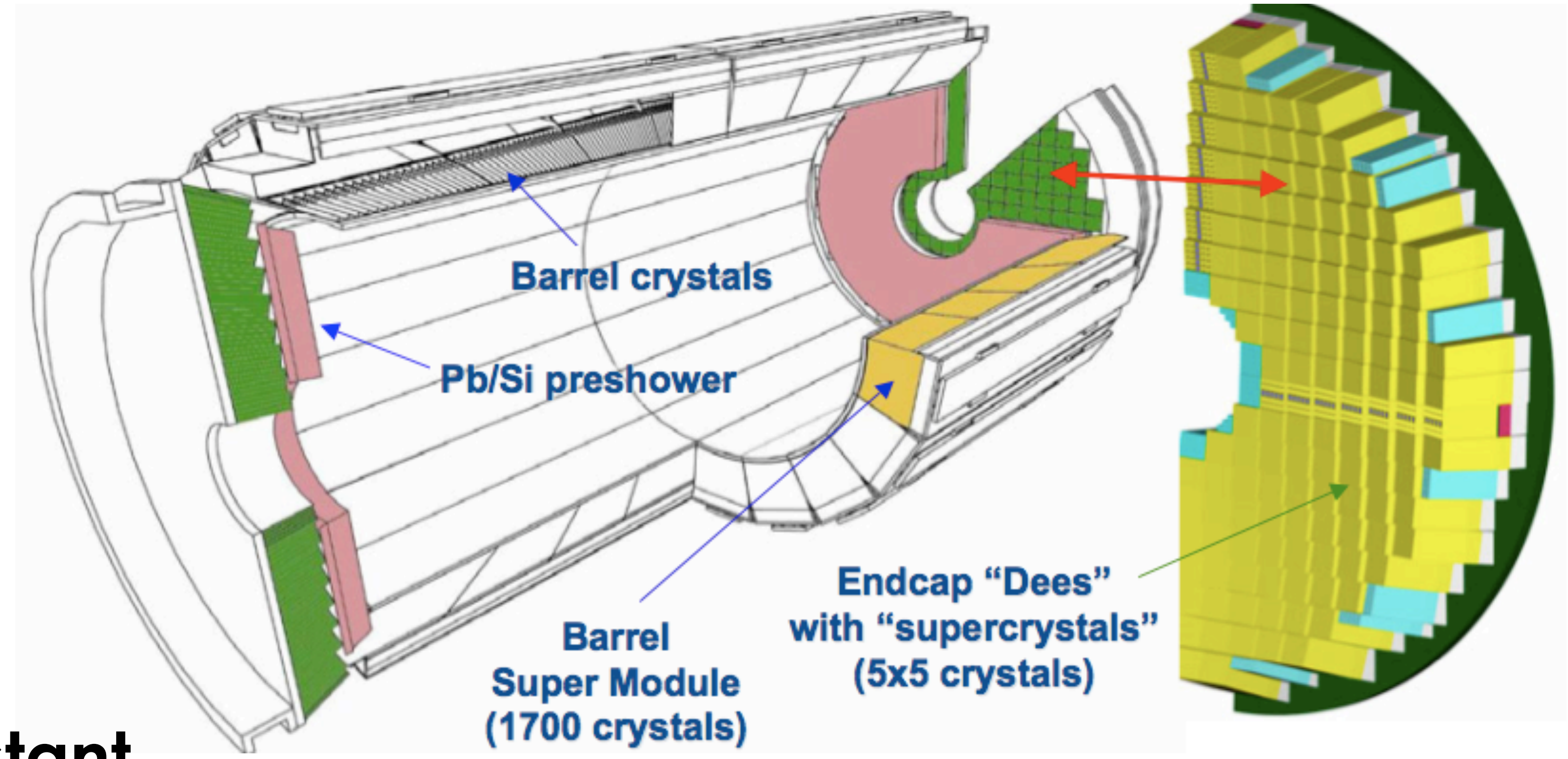
CMS ECAL

ECAL is THE crucial detector for di-photon analyses

CMS ECAL: Lead tungstate ($PbWO_4$) homogenous calorimeter

designed to discover the Higgs boson in the γγ final state: σ_E/E @ E>100 GeV ~0.5%

EB	**Barrel: $|\eta| < 1.48$** **36 Super Modules** **61200 crystals (2x2x23cm³) $26X_0$**
EE	**EndCaps: $1.48 < |\eta| < 3.0$** **4 Dees** **14648 crystals (3x3x22cm³) $24X_0$**
	Preshower: $1.65 < |\eta| < 2.6$ **$3X_0$ of Pb/Si strips** **1.90 × 61 mm² x-y view**



Most critical aspects (constant term of the energy resolution)

in-situ calibration

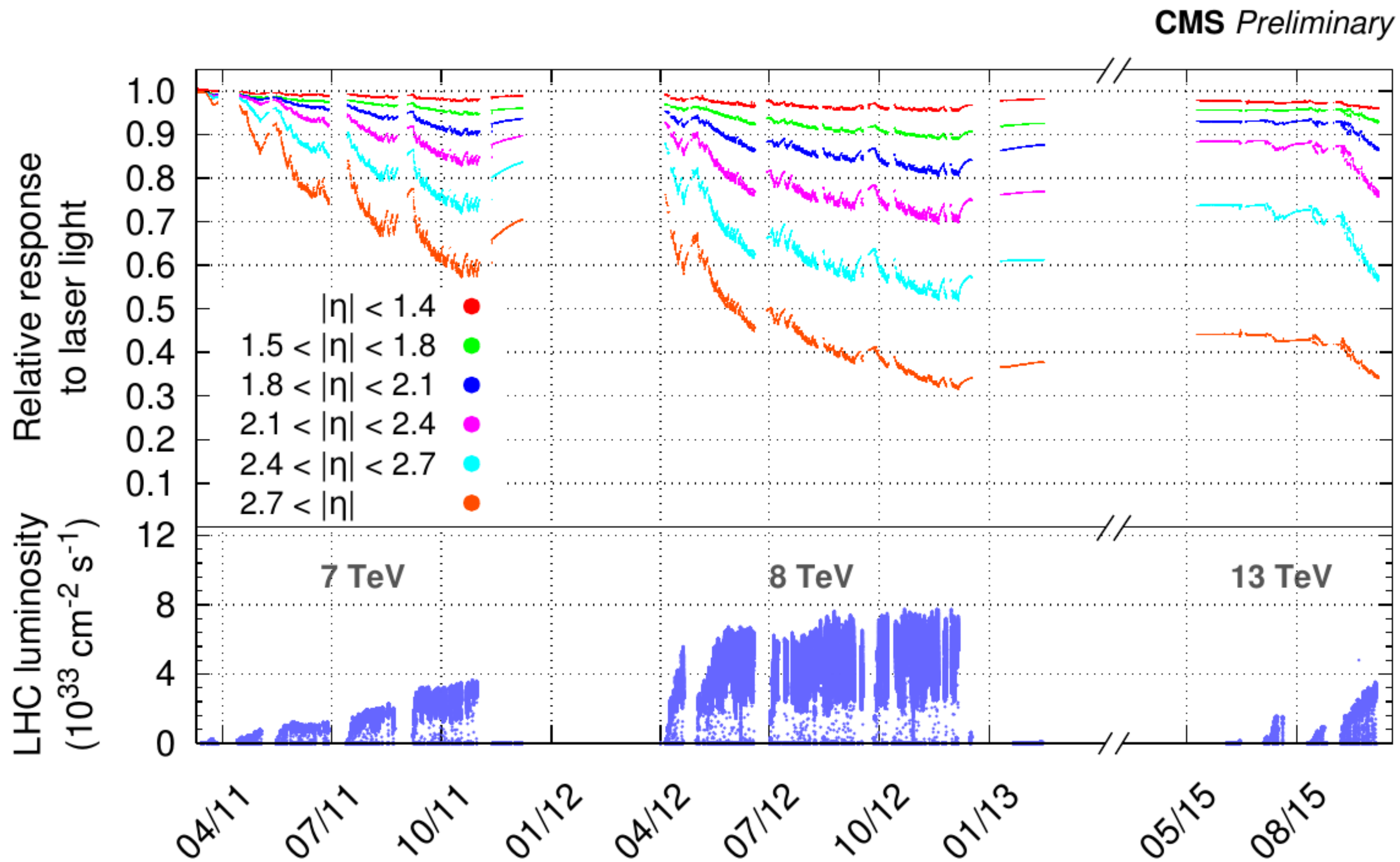
crystal transparency variations

More details in R. Teixeira De Lima's talk

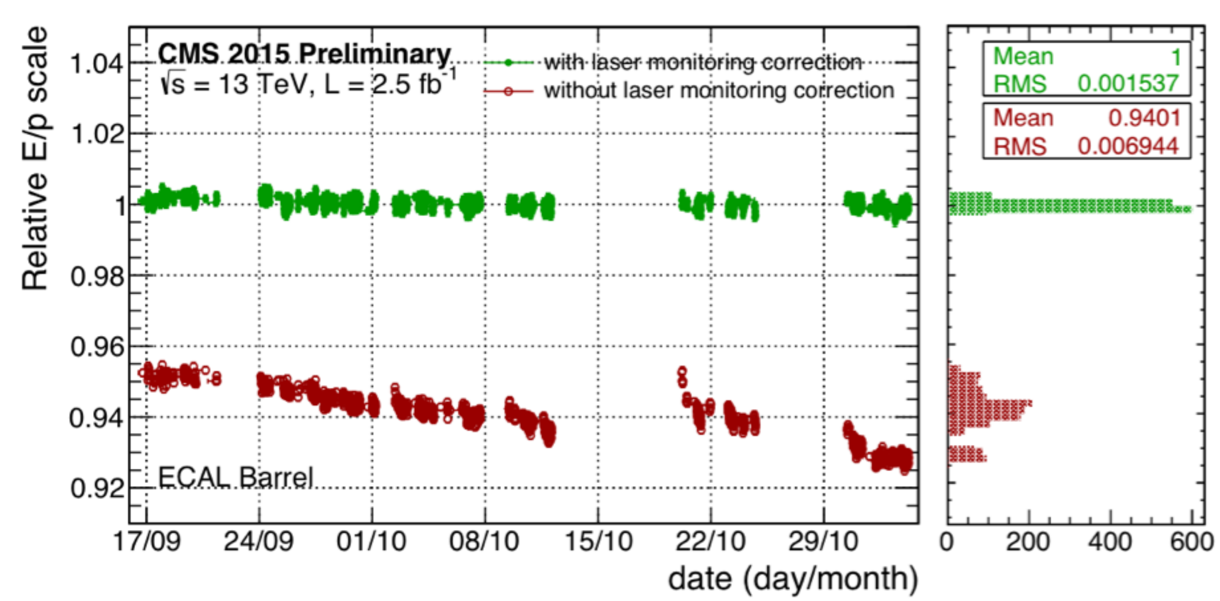
CMS ECAL Performance

Relative crystals response to laser light

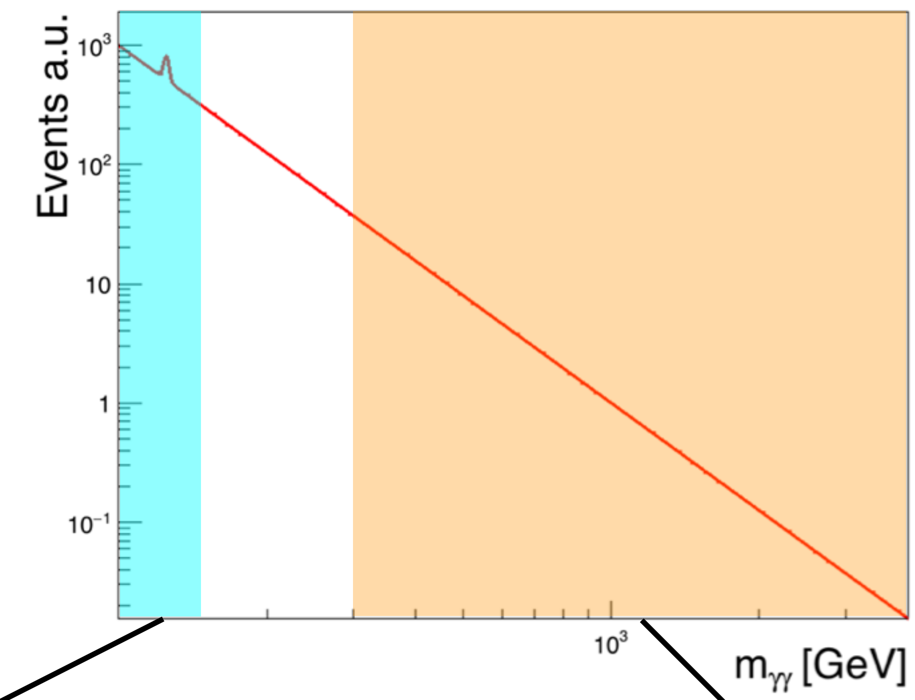
EB average signal loss ~6%



Energy scale stability at 0.15% level (EB) already in prompt reconstruction



DI-PHOTON ANALYSES IN CMS



H→γγ analysis

After discovery focus on measuring Higgs properties

couplings, mass, differential cross-section

Very optimised analysis: signal hypothesis well known (SM Higgs), systematics controlled with extrapolation from not so far Z→ee

X→γγ search (500<$m_{\gamma\gamma}$<4500)

Generic search for a high mass di-photon resonance as predicted in several BSM models:

- **Spin0:** e.g. heavy scalar in non minimal Higgs sector
- **Spin2:** e.g. graviton, as predicted in several extra-dimensions model (RS, ADD)

Requires robust analysis tools, since performed over a large mass range

more difficult to extrapolate from Z→ee

Common Ingredients For Di-Photon Analyses

Photon reconstruction

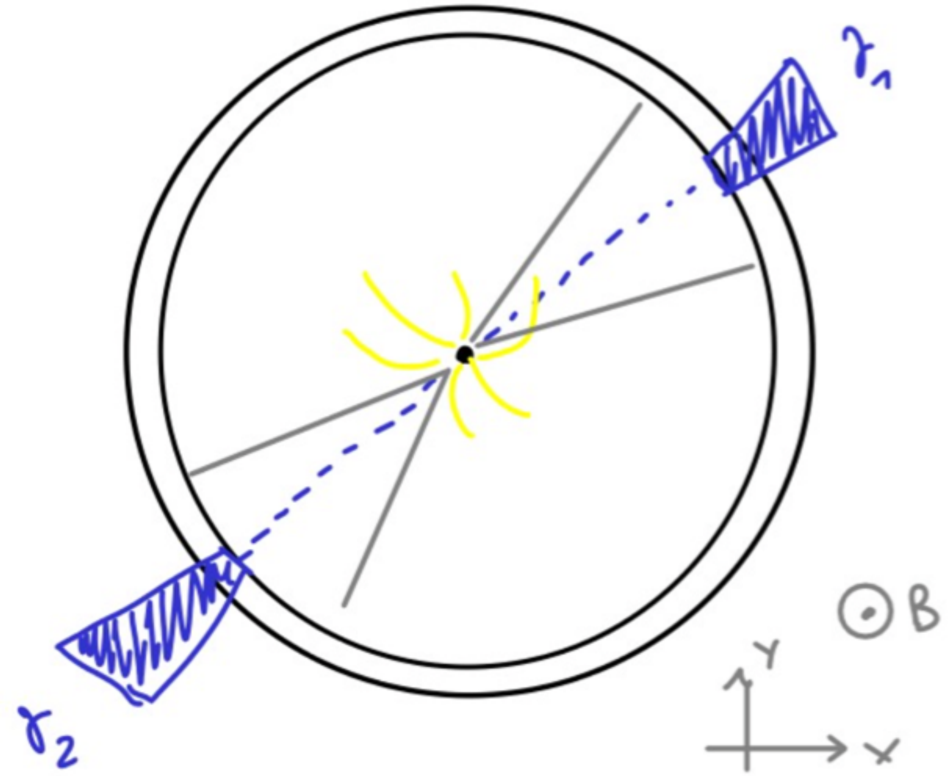
ECAL clustering

Energy reconstruction and corrections

Photon identification

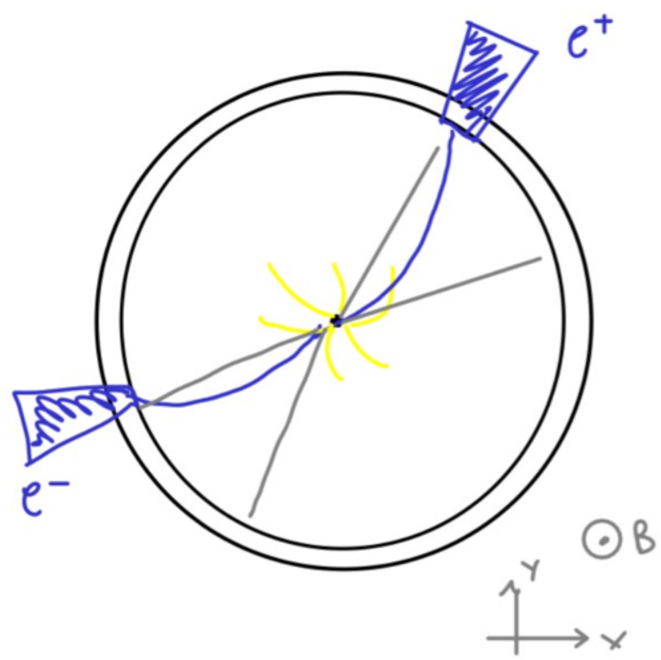
Cut based or multivariate

Vertex identification

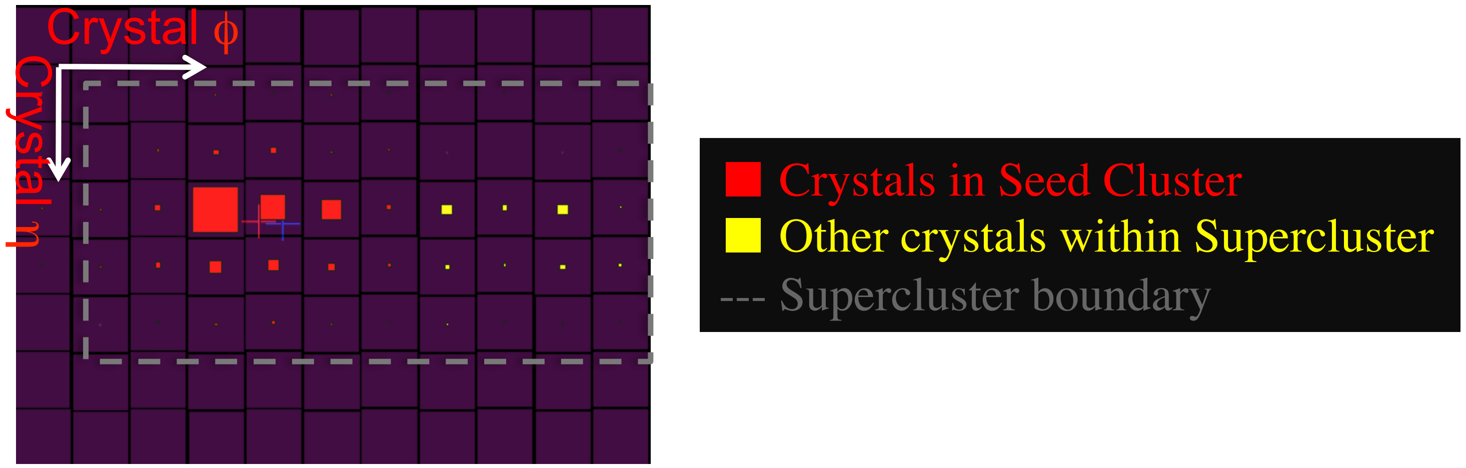


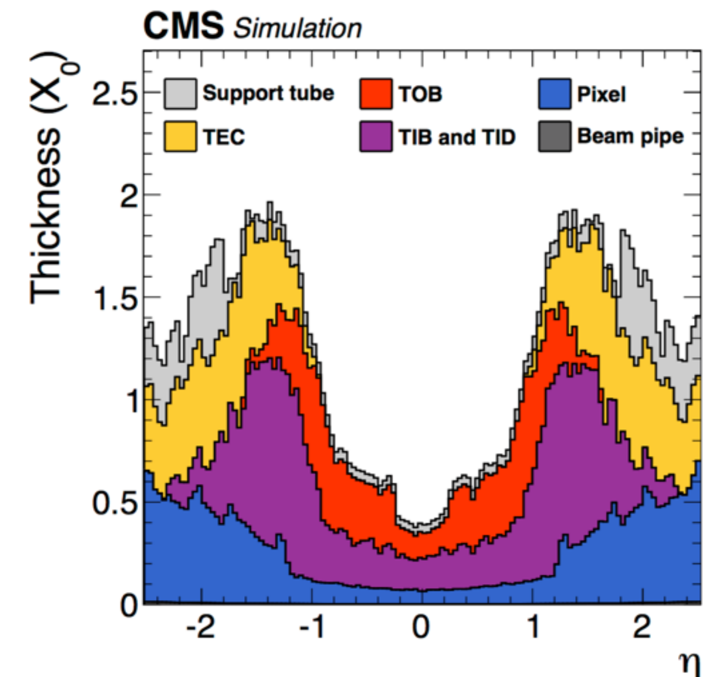
Data driven approach to measure energy scale, resolution and efficiency

main control samples: Z→ee and Z→llɣ



PHOTON RECONSTRUCTION



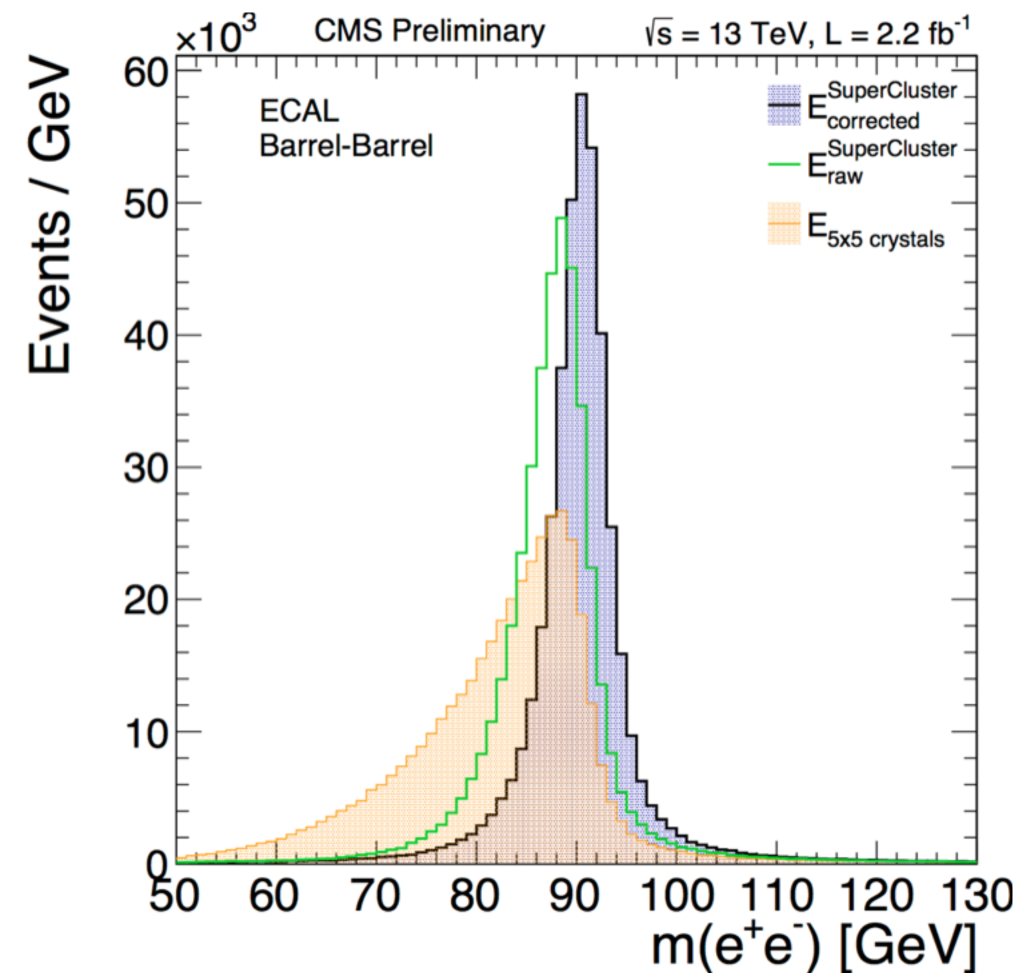


ECAL clustering optimised to collect energy radiated from conversions and bremsstrahlung (tracker material up to $2X_0$)

- dynamic "Supercluster" algorithm recollects additional energy along ϕ
- material effects are smaller at high p_T (>100 GeV)

Energy estimate from a MC trained multivariate regression

- further correct material effects, gaps, PU contamination
- can provide also a per photon resolution estimate



More details in J. Bendavid's talk

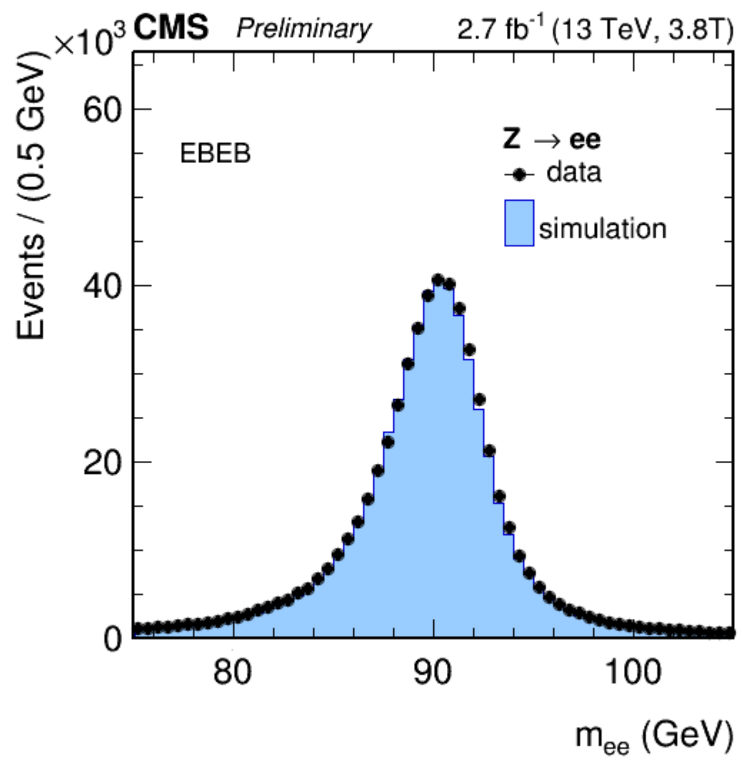
PHOTON RECONSTRUCTION: PERFORMANCE

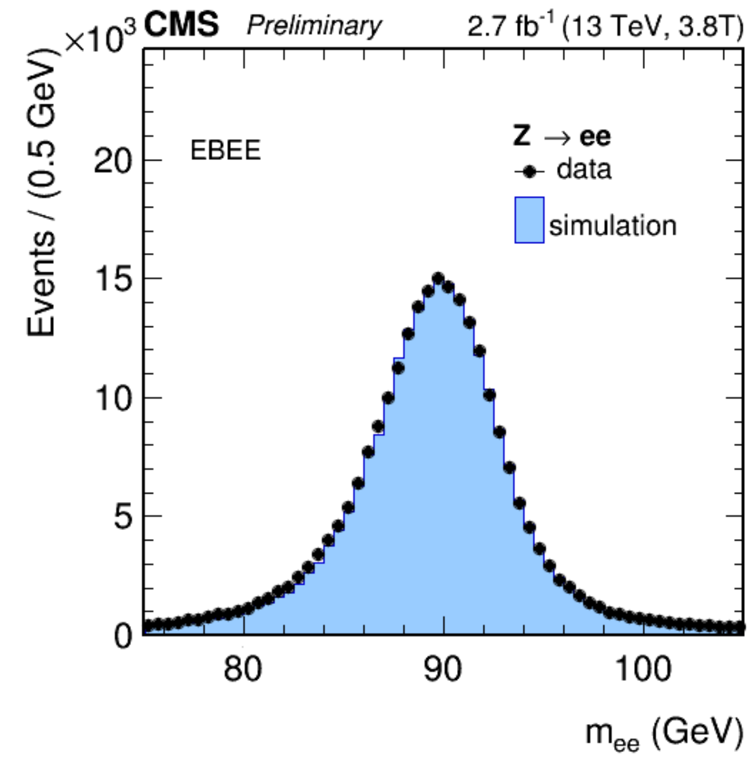
Energy scale and resolution measured in data at O(0.1%) level

- MC used as a template to fit the data $E_{MC} * Gauss(1+\Delta P, \Delta\sigma)$
- fit performed in bins of η and cluster shape

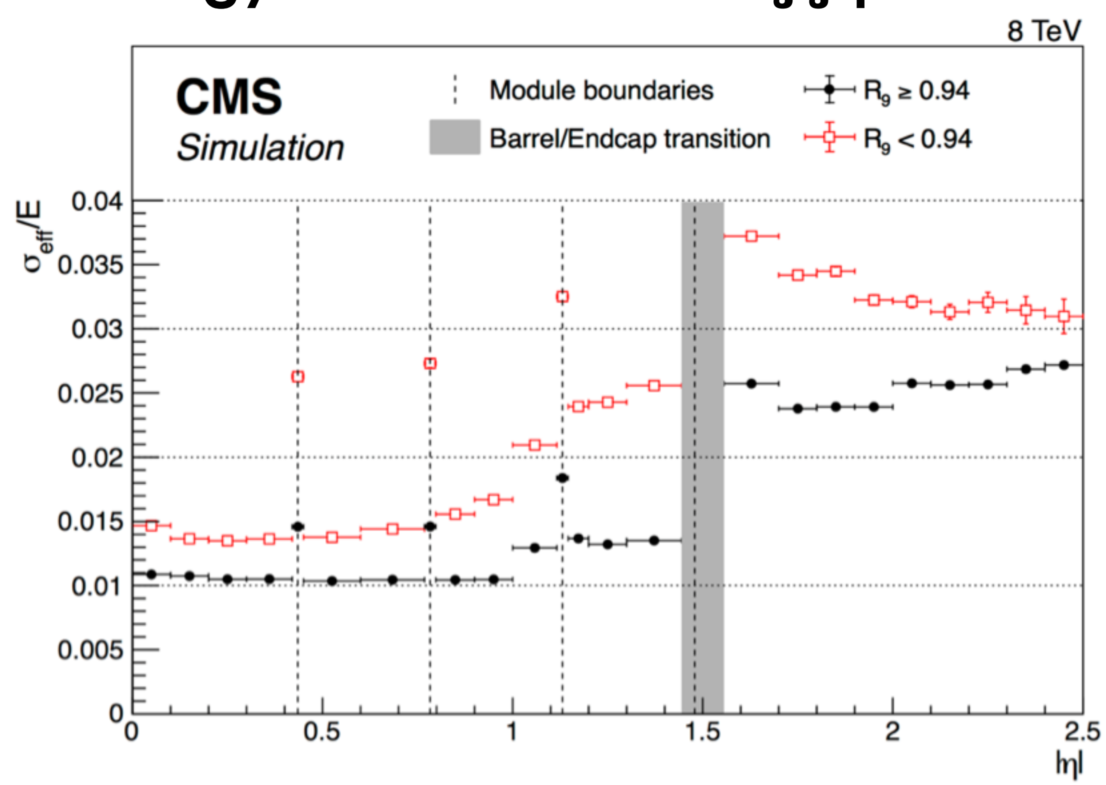
Linearity checked with boosted Z→ ee up to $p_T \sim$ 200 GeV

- deviations within 0.5%(0.7%) in barrel(endcap)





Energy resolution for H→γγ photons

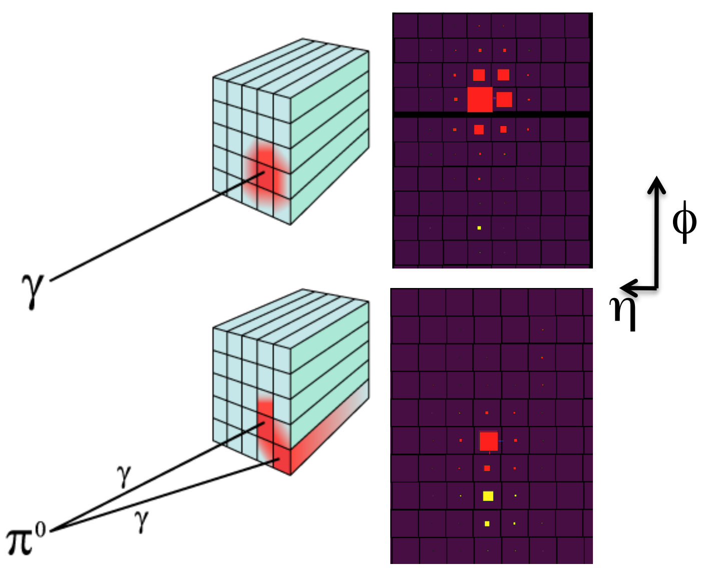


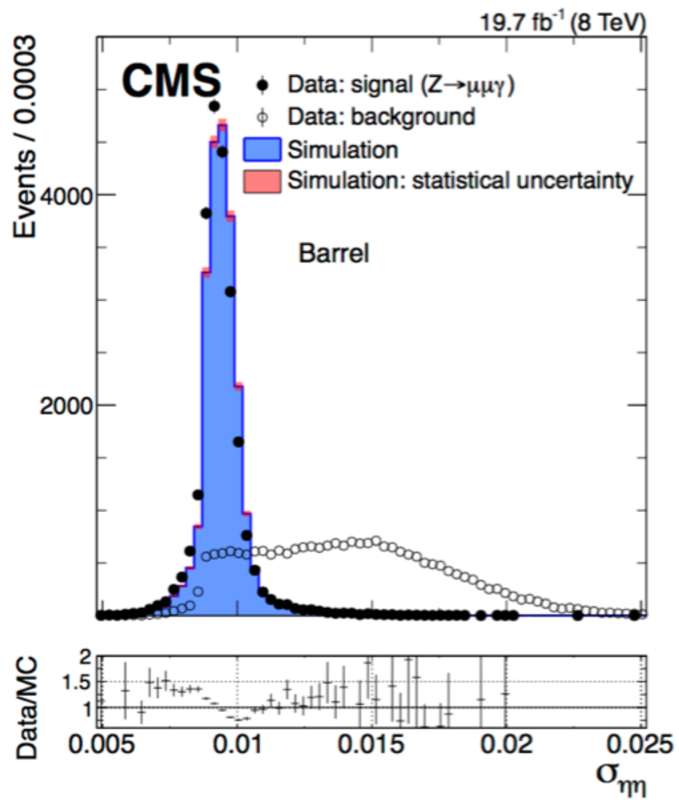
Energy resolution ~1% for uncoverted photons

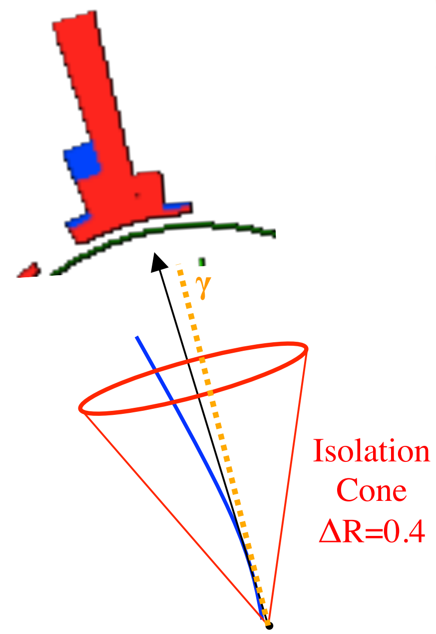
R9=$E_{3x3}/E_{SuperCluster}$
measures the spread in φ of the energy deposition

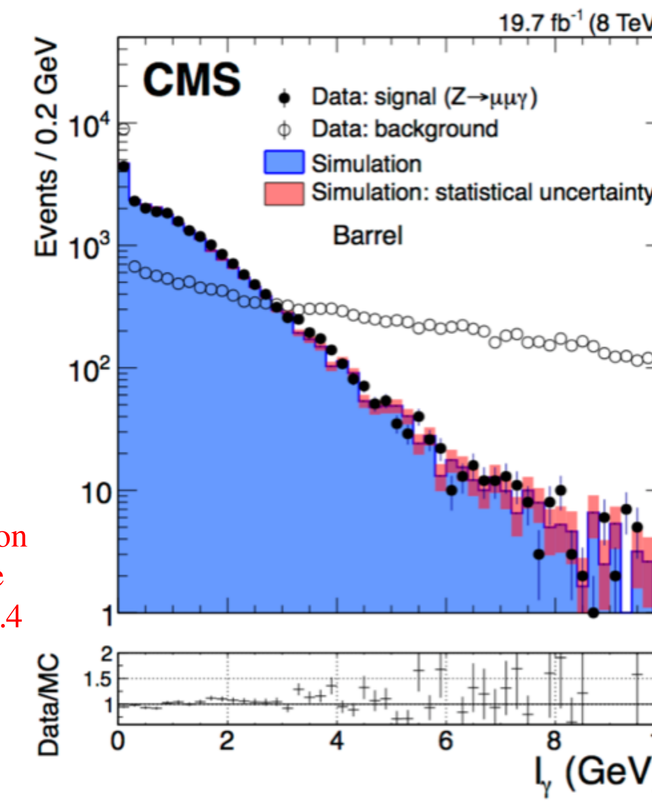
- discriminate unconverted/ converted photons

Photon Identification





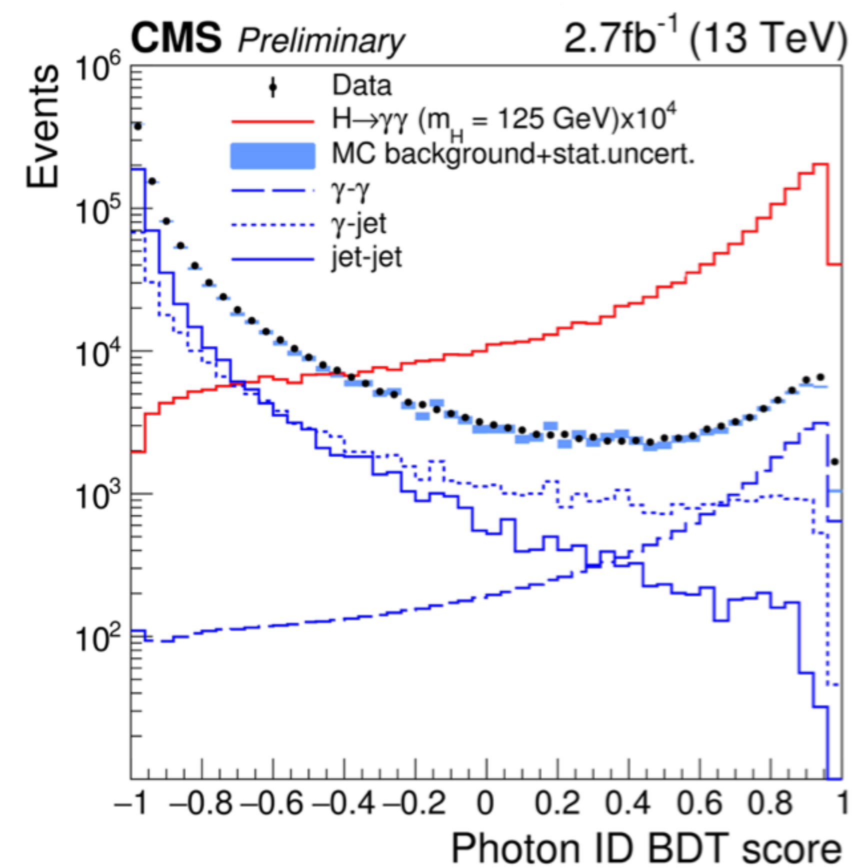




Isolated photons can be distinguished from jets by means of shower shape and isolation variables

- cut-based selection (more robust for high p_T photons) used for high mass search
- multivariate techniques (BDT) to exploit correlation among several variables used in $H\to\gamma\gamma$ analysis

Electron rejection: veto EM cluster with matching prompt electron, keeping reconstructed conversions

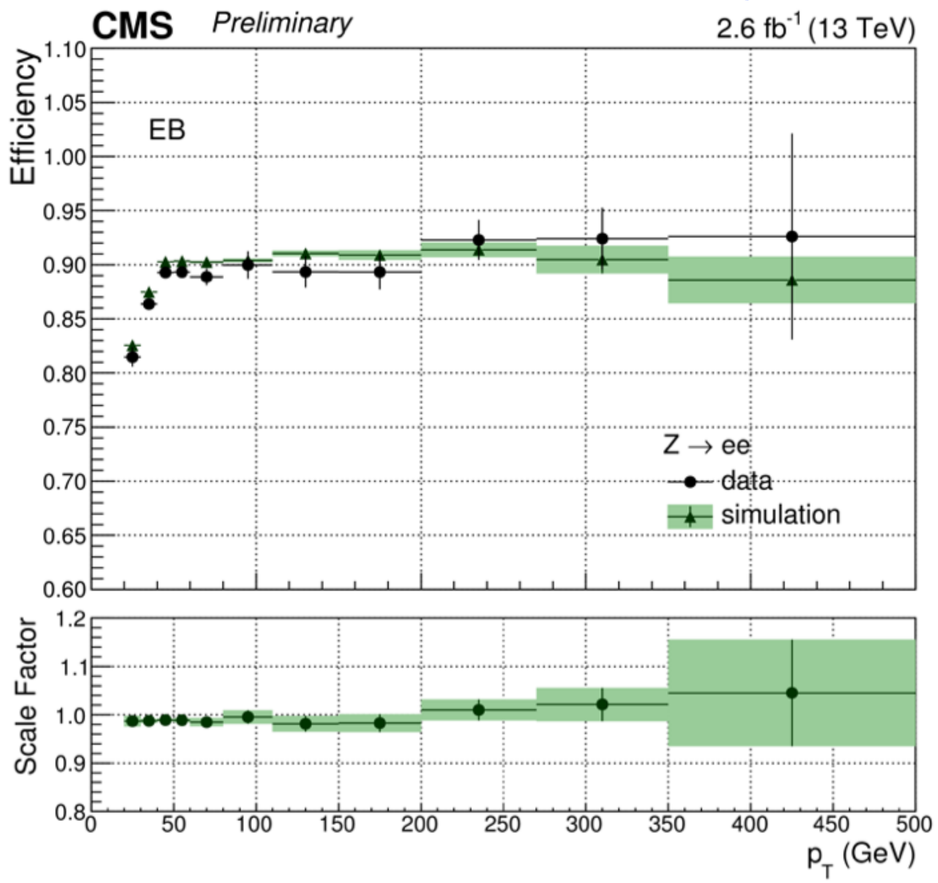


PHOTON ID: PERFORMANCE

Cut based selection adopted in X→γγ search has ~90% efficiency for p_T>100 GeV

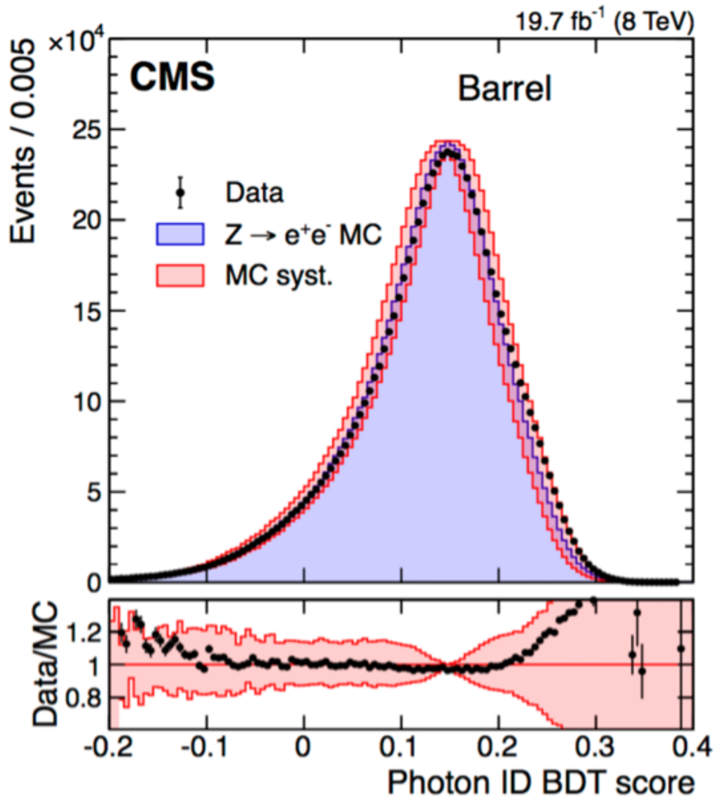
efficiency checked in data (Z→ee)

Electron veto efficiency measured with Z→μμγ

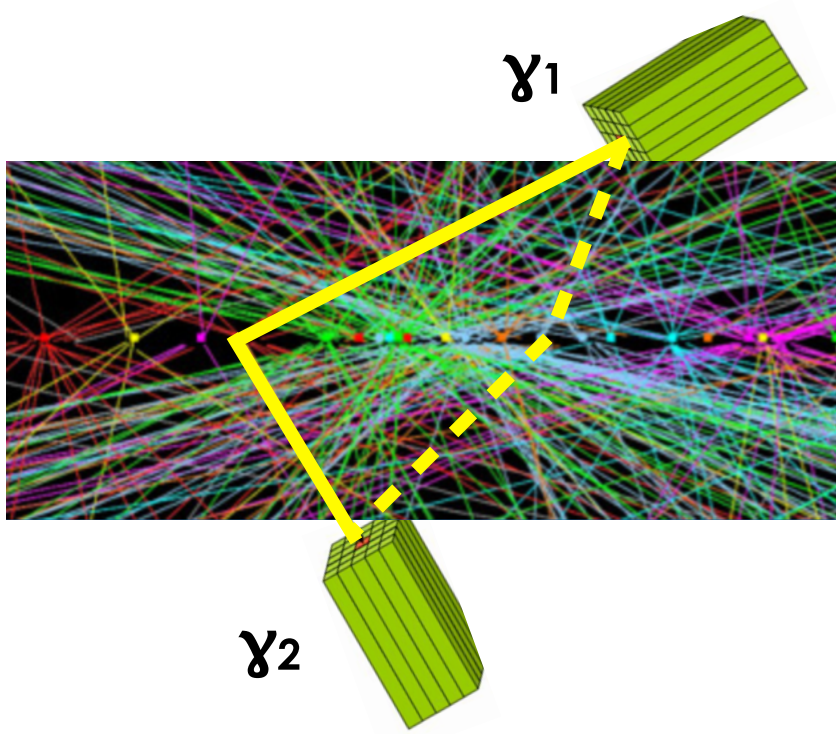


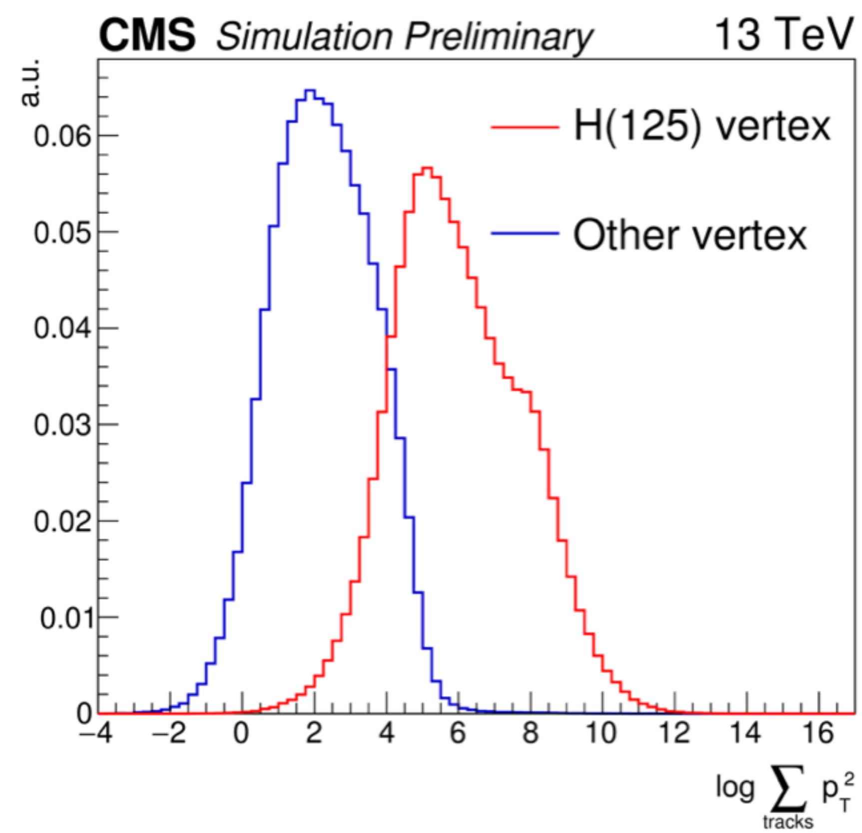
Shower shape variables, isolation variables and their correlations are well reproduced by the MC

nice data/MC agreement on the BDT output on Z→ee and Z→μμγ events



Vertex Identification





Mass reconstruction depends on the position of the primary vertex

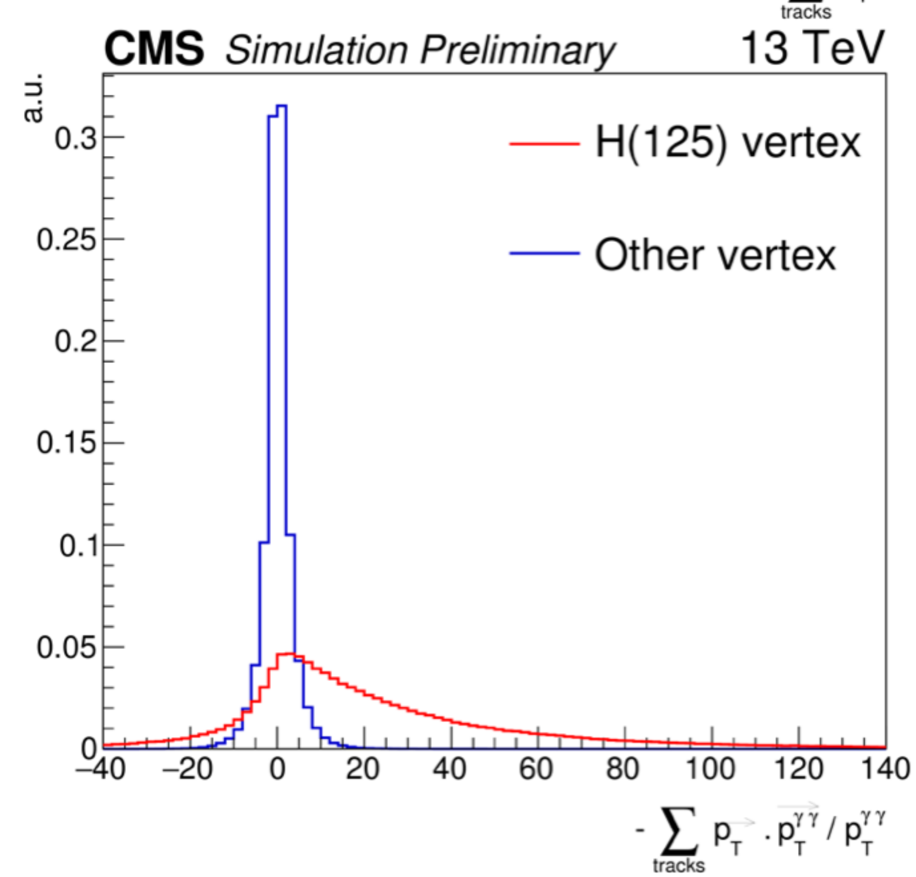
in current pile-up conditions the di-photon production vertex has to be selected among ~20 vertices

Interaction vertex identified using recoiling tracks (and reconstructed conversions when present)

Σp_T^2 , $p_T(\gamma\gamma)$ vs p_T(tracks), z_{conv}

variables combined in a BDT

probability to assign the correct vertex also determined using a BDT

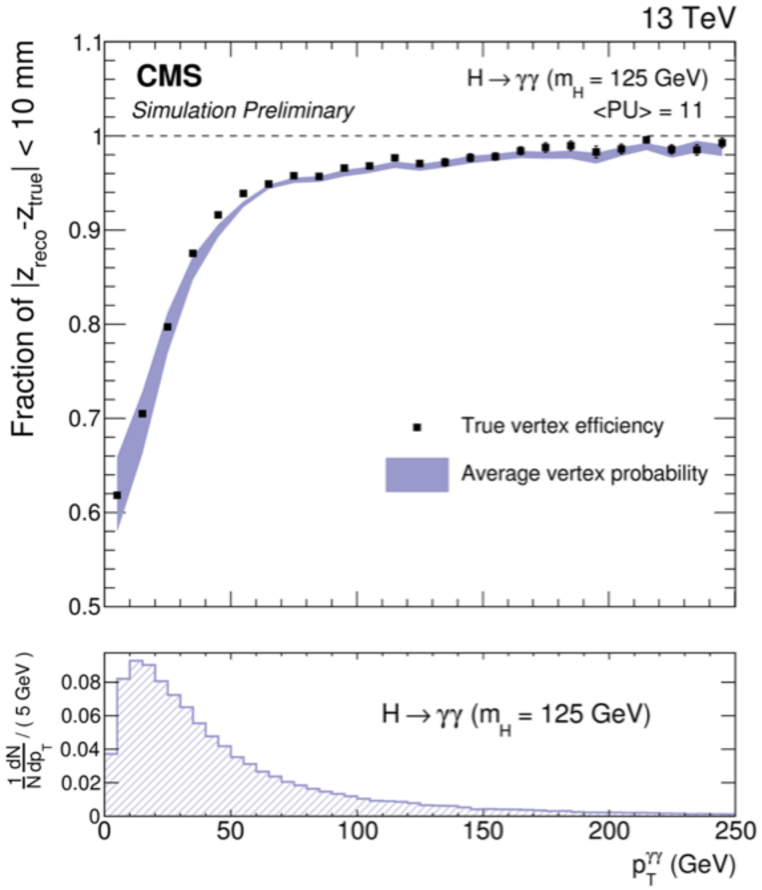


Vertex ID: Performance

Probability to assign the correct vertex depends on the $p_T(\gamma\gamma)$

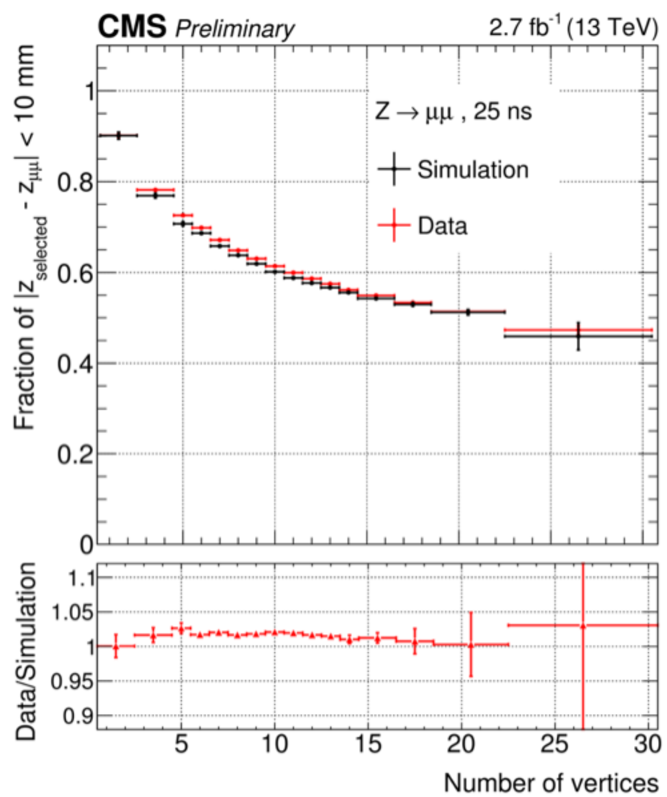
for H→γγ efficiency to find correct vertex within 1cm ~80%

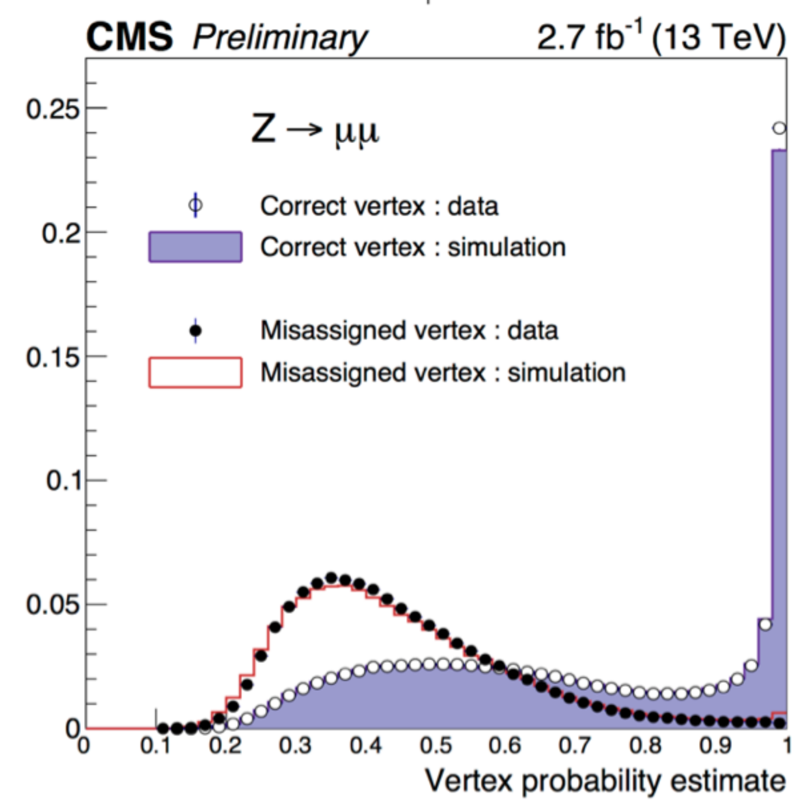
for X→γγ efficiency is ~90%



BDT output validated using Z→μμ

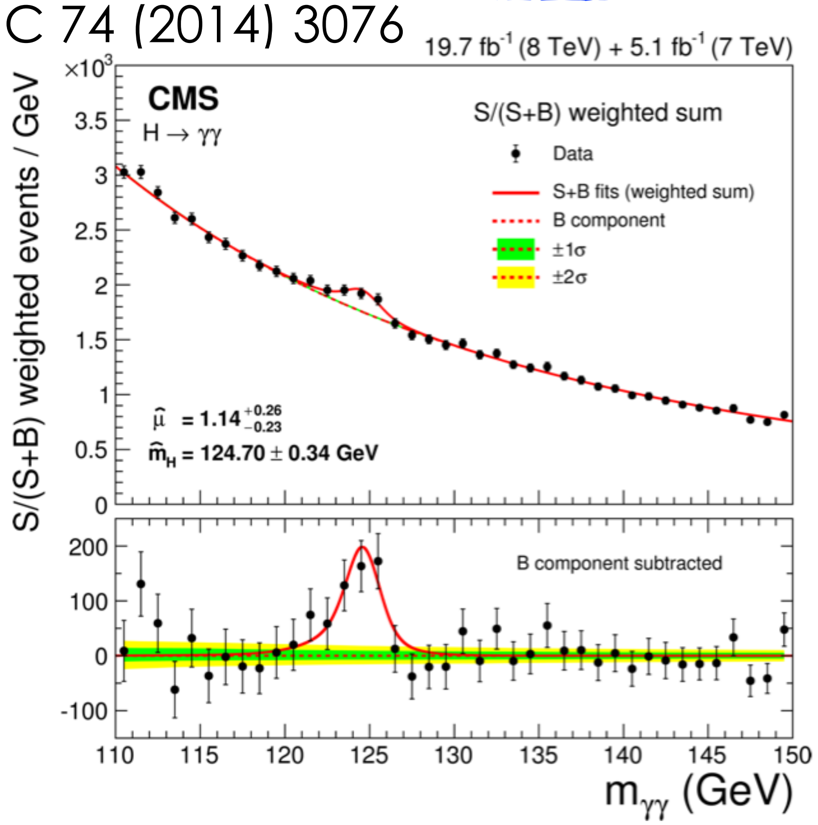
γ+jets events used for events with a conversion



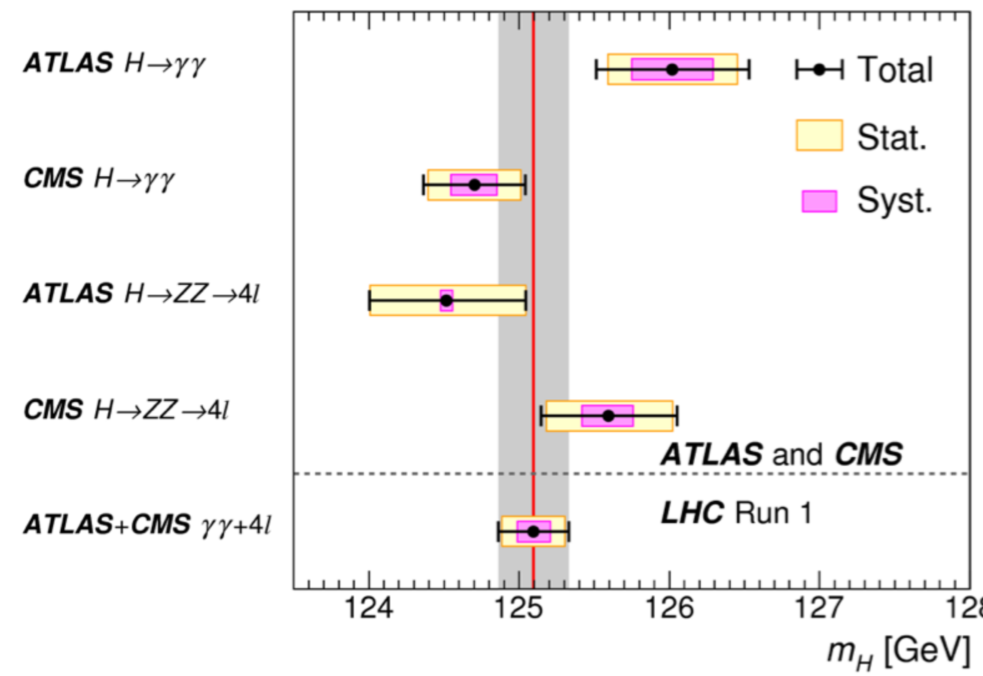


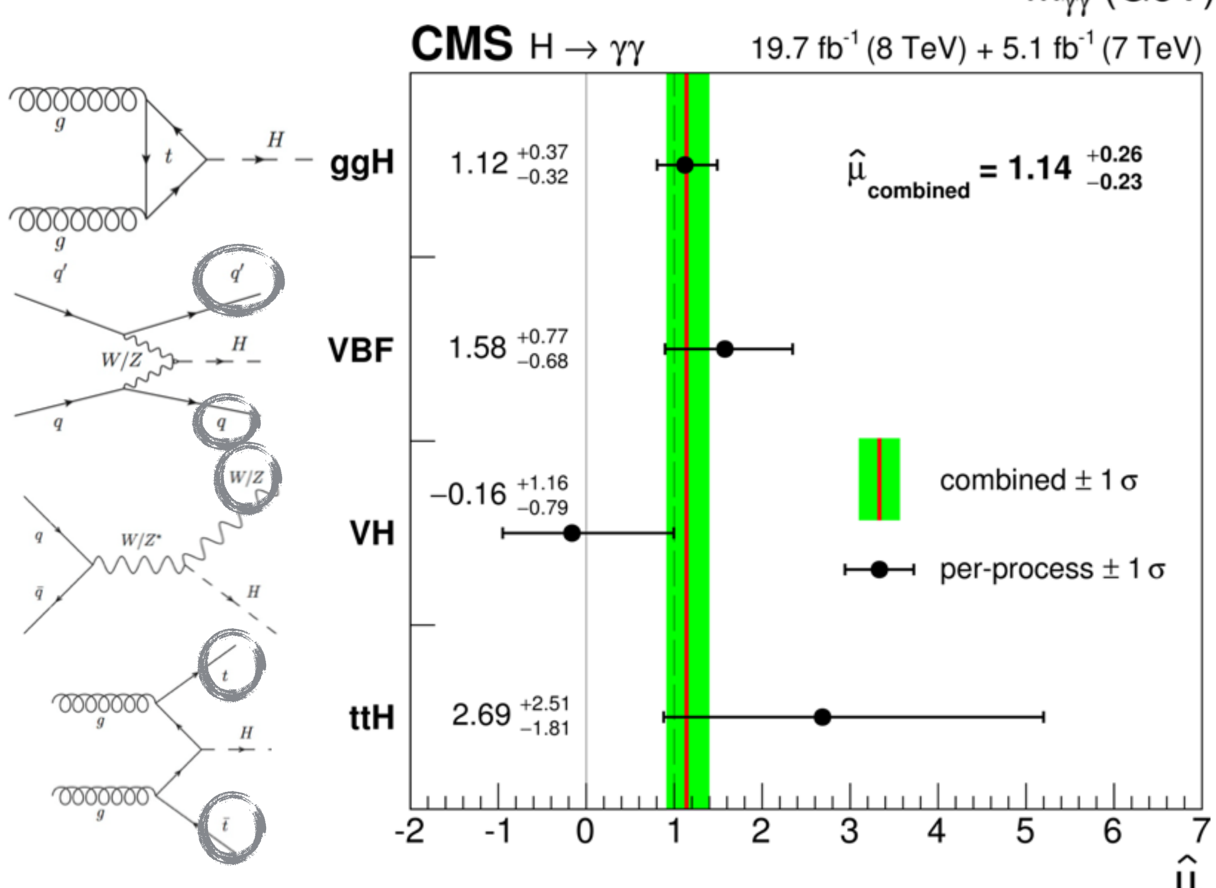
SELECTED H→γγ RESULTS

EPJC 74 (2014) 3076



PRL 114 (2015) 191803





Events split in 11(7 TeV) + 14(8TeV) categories

H→γγ can measure each Higgs production mode

- special event categories to tag associated production with jets, lepton, MET

CMS H→γγ mass measure is the single most precise (340 MeV)

- extrapolation from Z→ee allows to control photon energy scale systematics at 0.1-0.2% (150 MeV)

HIGH MASS DI-PHOTON SEARCHES

	Title	m_X range [GeV]	interpretation			
			spin0	spin2	narrow width	large width
PLB 750 (2015) 494	Search for diphoton resonances in mass range 150 to 850 GeV in pp collisions at √**s=8 TeV**	150-850	✔	✔	✔	✔
EXO-12-045	Search for diphoton resonances in mass range 150 to 850 GeV in pp collisions at √**s=8 TeV**	500-3000	✗	✔	✔	✔
EXO-15-004	Search for new physics in high mass diphoton events in pp collisions at √**s=13 TeV**	500-4500	✗	✔	✔	✔
Mar`16 **EXO-16-008**	Search for new physics in high mass diphoton events in 3.3fb^{-1} of pp collisions at √**s=13 TeV** and combined interpretation of searches at √**s=8 TeV** and √**s=13 TeV**	500-4500	✔	✔	✔	✔

Highlights Of Most Recent High Mass Analysis

New result (EXO-16-008) based on full 13 TeV luminosity 3.3 fb^{-1}

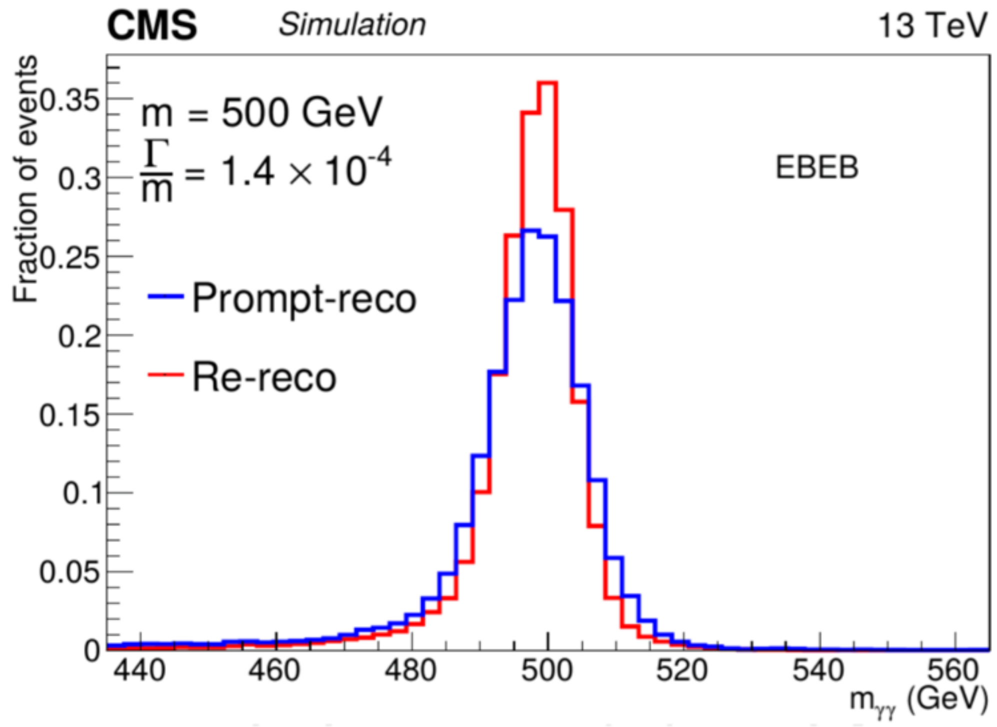
includes 0.6 fb^{-1} of additional data recorded at 13 TeV at B=0T

analysis sensitivity improves by 10%

data reconstruction with improved ECAL inter-calibration completed over winter shutdown

30% improvement in mass resolution for a narrow resonance m_X>500 GeV

10% improvement in analysis sensitivity



Results interpreted in terms of spin0 and spin2 resonances

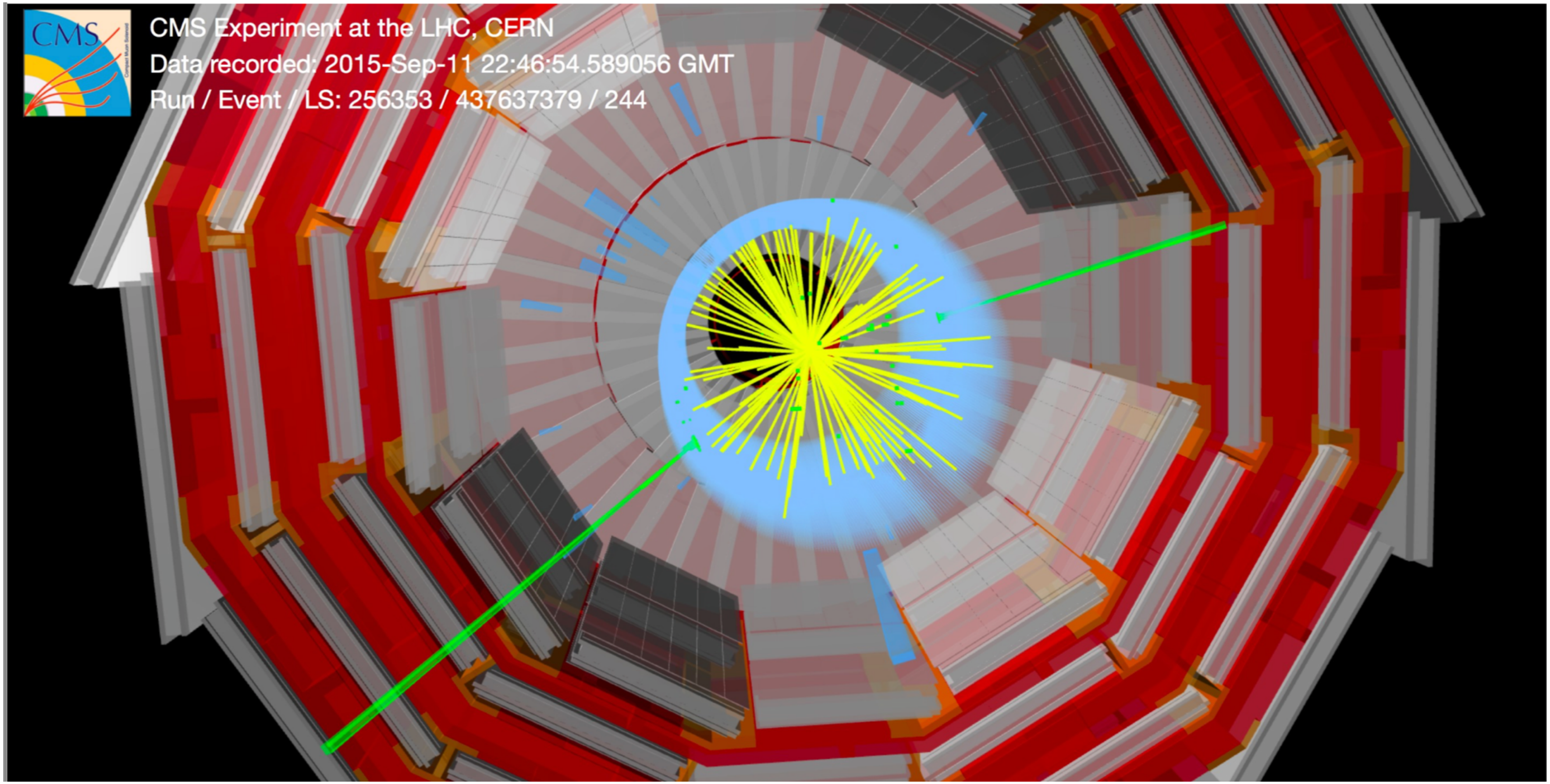
J=0 gluon fusion production, J=2 RS-graviton

3 widths considered: Γ/m=1.4E-4, 1.4E-2, 5.6E-2

combination with 8 TeV results

DI-PHOTONS @ 0T CHALLENGES

All analysis ingredients had to be re-thought to use data without magnetic field



Di-Photons @ 0T Challenges

All analysis ingredients had to be re-thought to use data without magnetic field

No informations on tracks momenta ☹

- weakens isolation power
- more difficult to identify correct vertex

Energy spread for conversions/brem reduced ☻

- better energy resolution, easier e/ɣ extrapolation
- shower shape discrimination more powerful

Dedicated channel inter-calibration

Dedicated photon identification

- photon identification efficiency in EB~80% (less efficient ele-veto)

Dedicated vertex identification

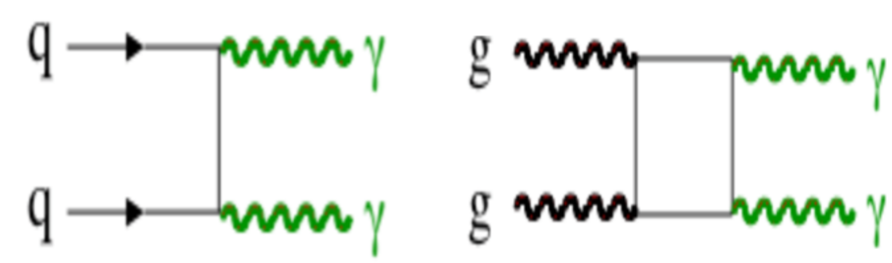
- probability to find correct vertex ~60% (only track count can be used)

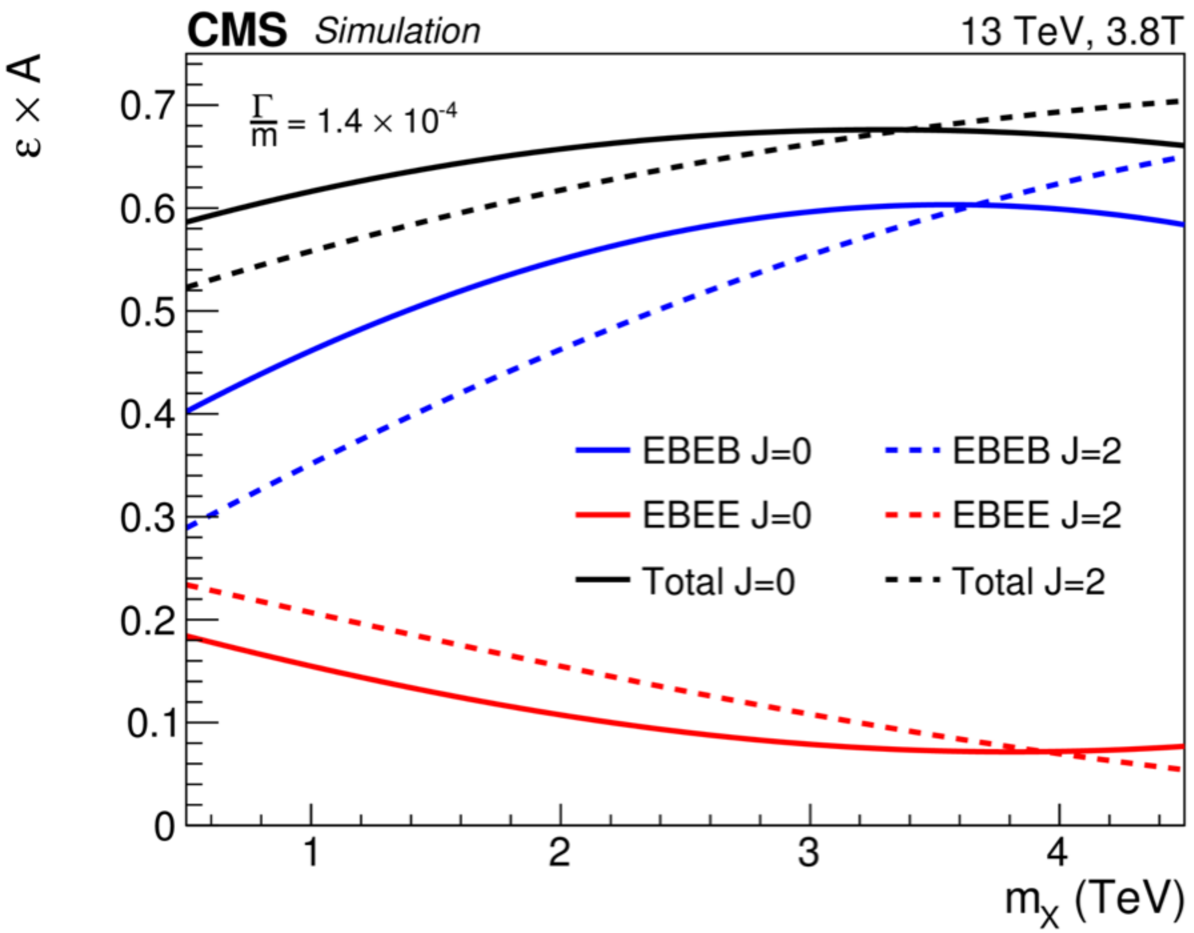
EVENT SELECTION

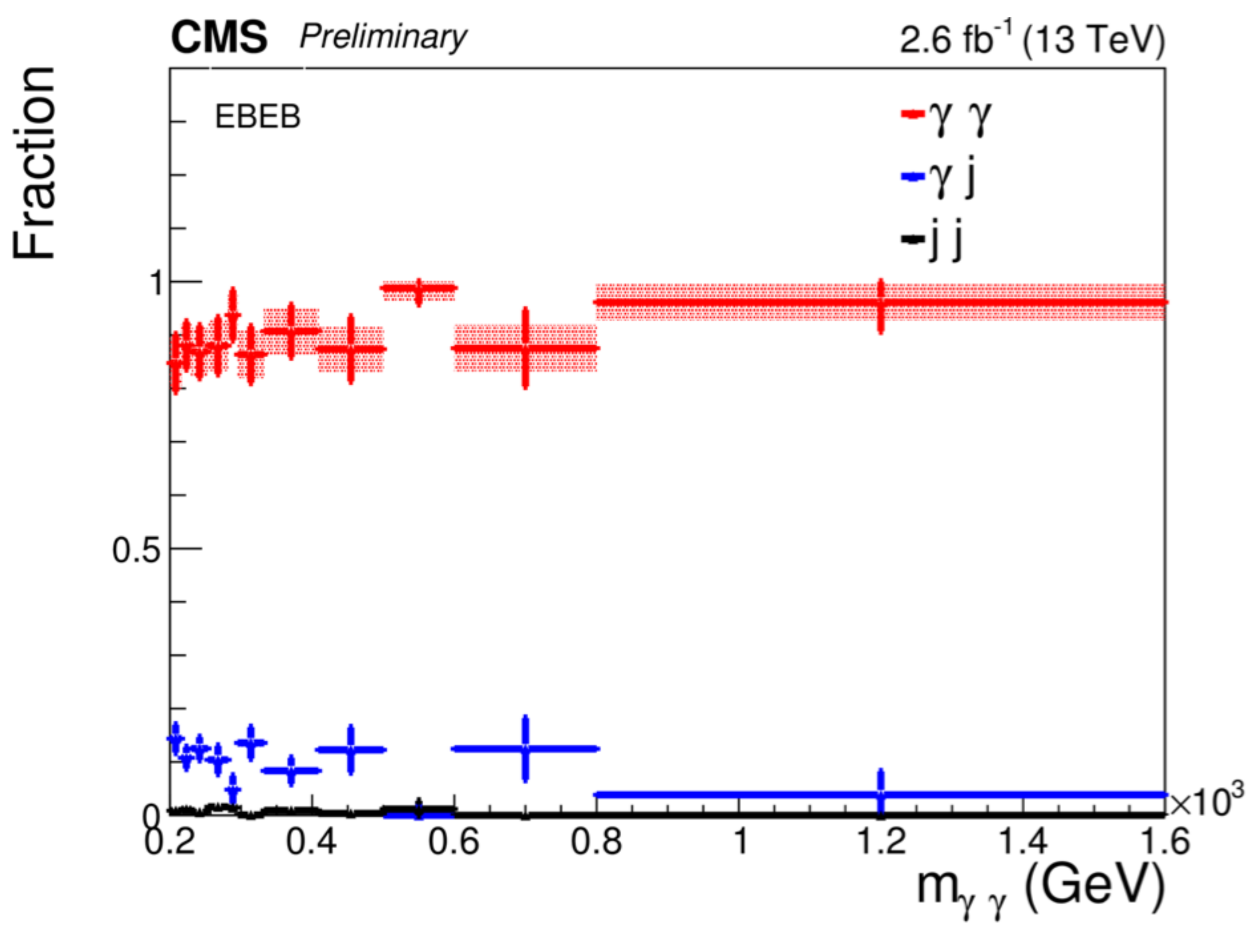
Simple and robust selection

- 2 isolated photons, **p_T>75 GeV**
- Split events into **(EB-EB,EB-EE)x(3.8T,0T)**
- **Background composition** (measured in data with template fits) **dominated by irreducible SM γγ production**: ~90%

SM irreducible γγ background



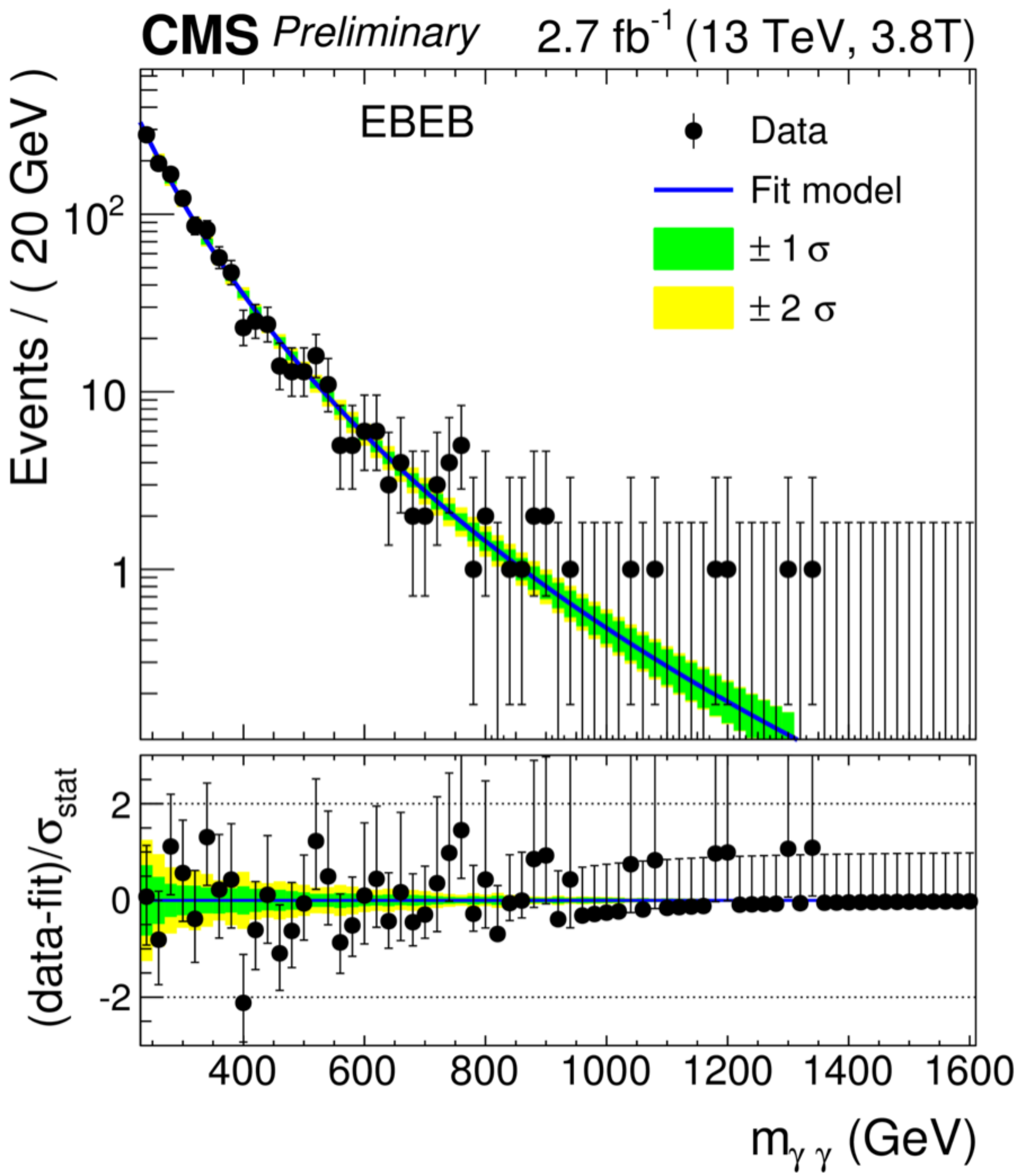




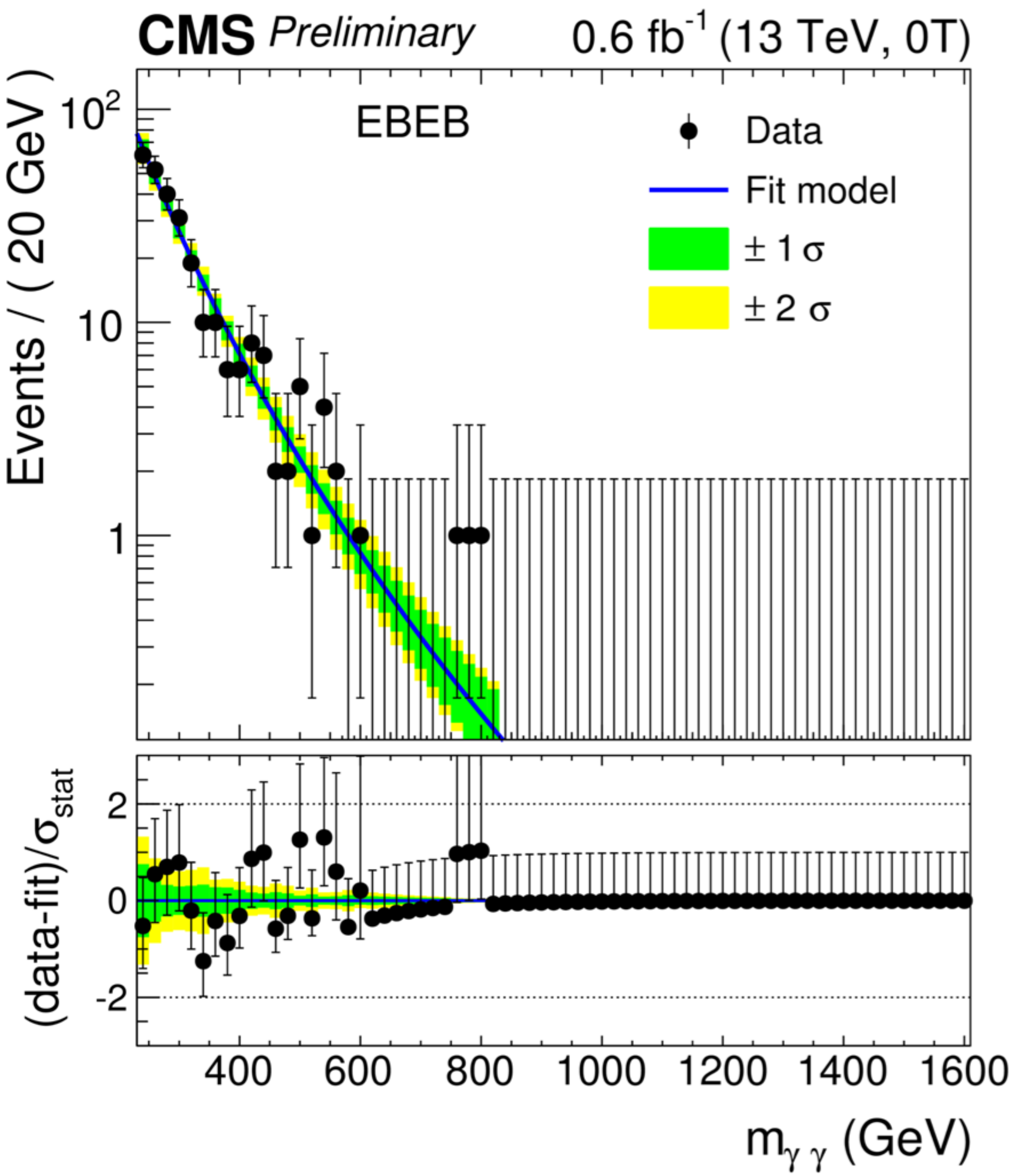
MASS SPECTRA

EB-EB categories at 3.8T and 0T

B=3.8T



B=0T

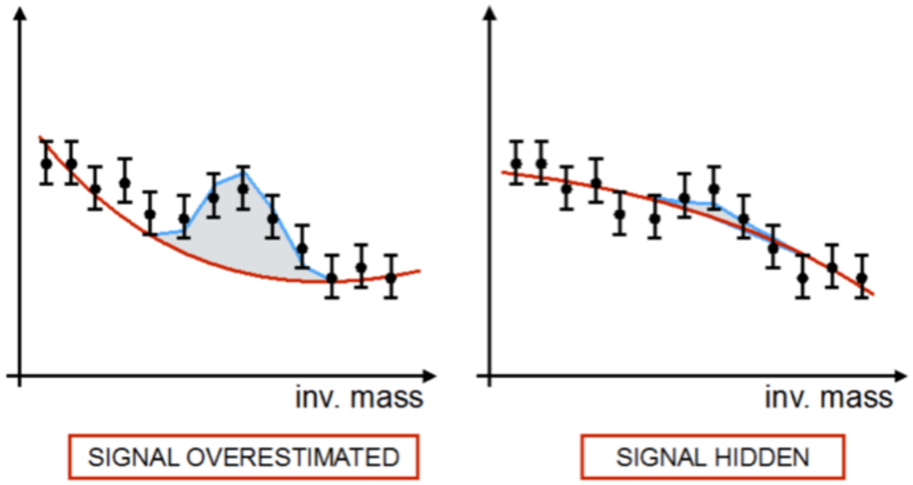


INTERPRETATION

Statistical interpretation from simultaneous fit to $m_{\gamma\gamma}$ distribution
0.5-4.5TeV in the 4 analysis categories **(EB-EB,EB-EE)x(3.8T,0T)**

Background model: parametric fit to the data with empirical function $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$

- possible mis-modelling assessed with MC and included as a "bias-term"



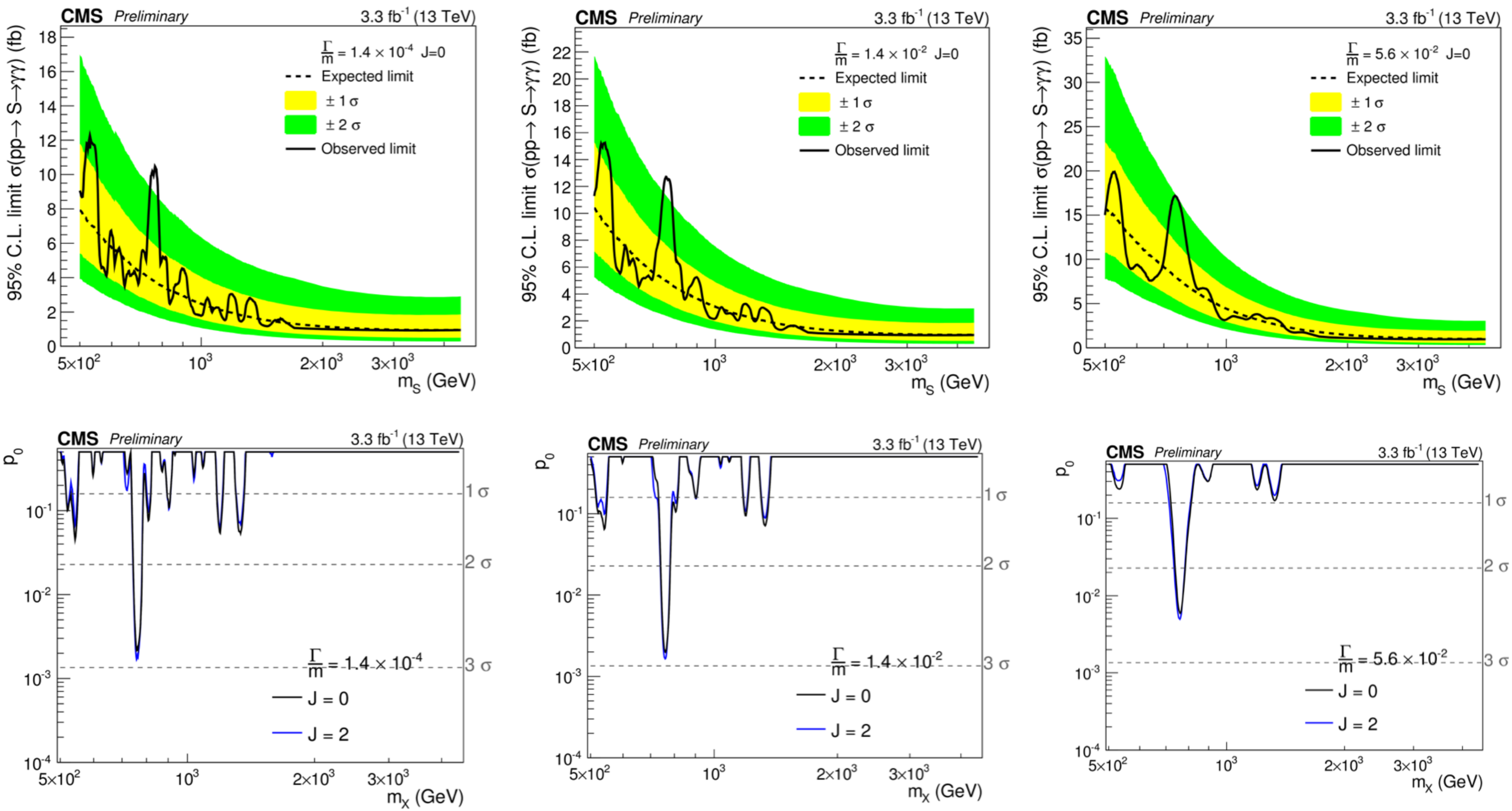
Signal model: MC prediction including energy resolution corrections interpolated between several mass points

- **(Spin0,Spin2)x(3 widths) signal hypotheses**

UPPER LIMITS AND P-VALUES

Combination of 13 TeV 3.8T and 0T dataset

Γ/m=1.4E-4 Γ/m=1.4E-2 Γ/m=5.6E-2



THE "HOT" TOPIC

Largest excess observed for **m_X=760 GeV Γ/m=1.4E-2**

Local significance: 2.8-2.9σ depending on spin hypothesis

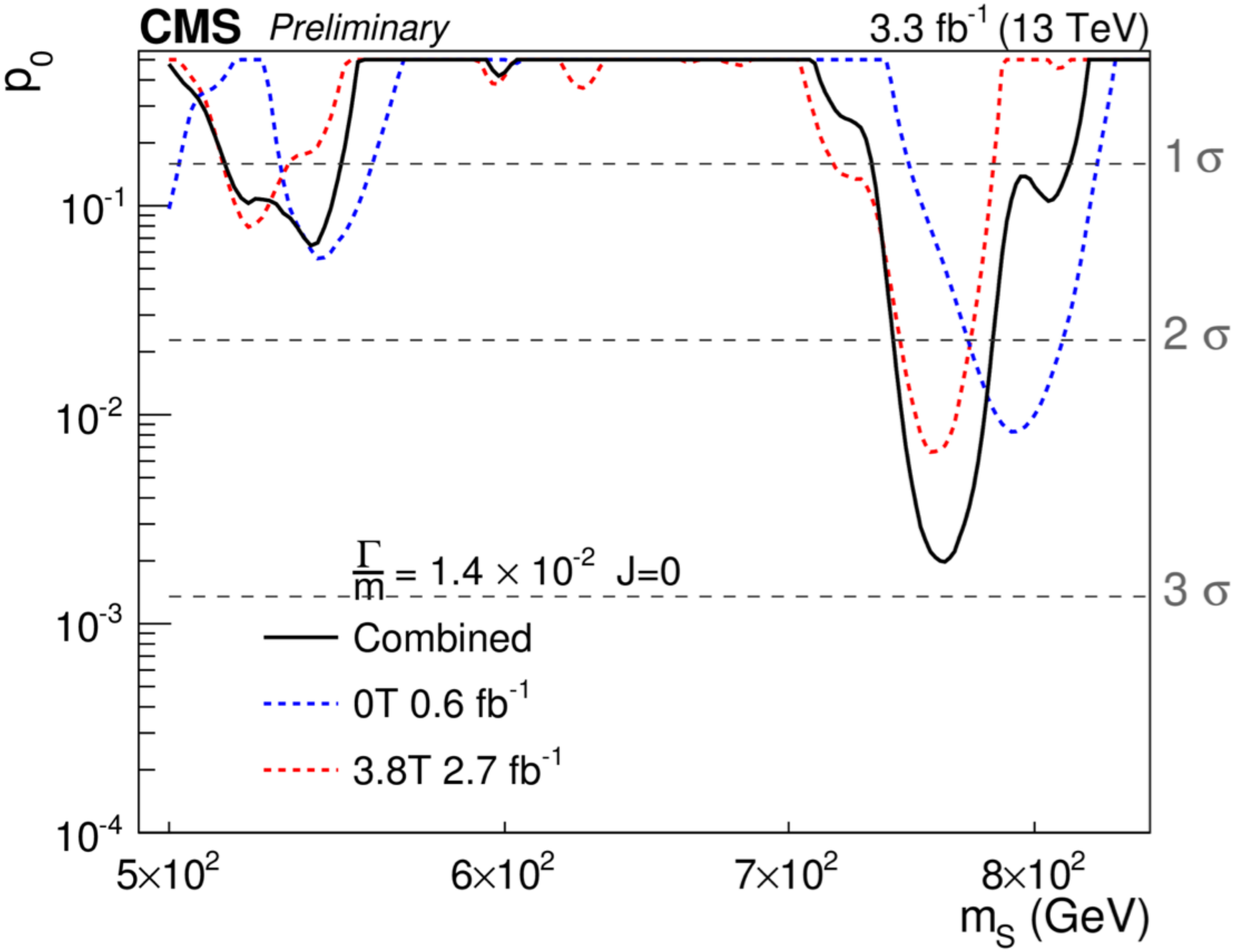
similar significance for narrow width

Global significance <1σ

trial factors obtained considering all 6 signal hypotheses (spin x width) in the 500-4500 GeV mass range

Excess mostly driven by EBEB 3.8T category

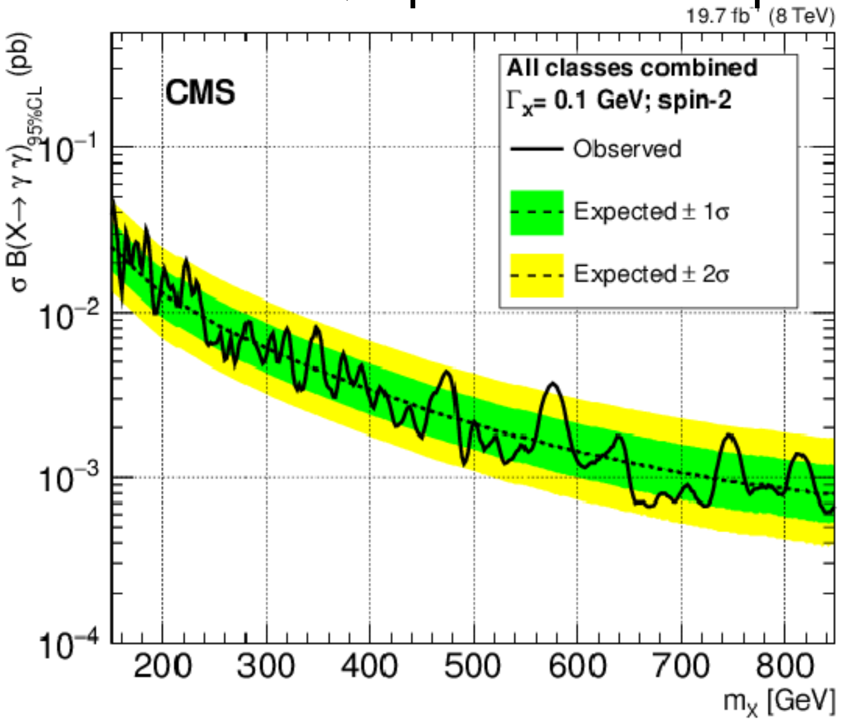
One event in the 0T dataset compatible with 3.8T excess



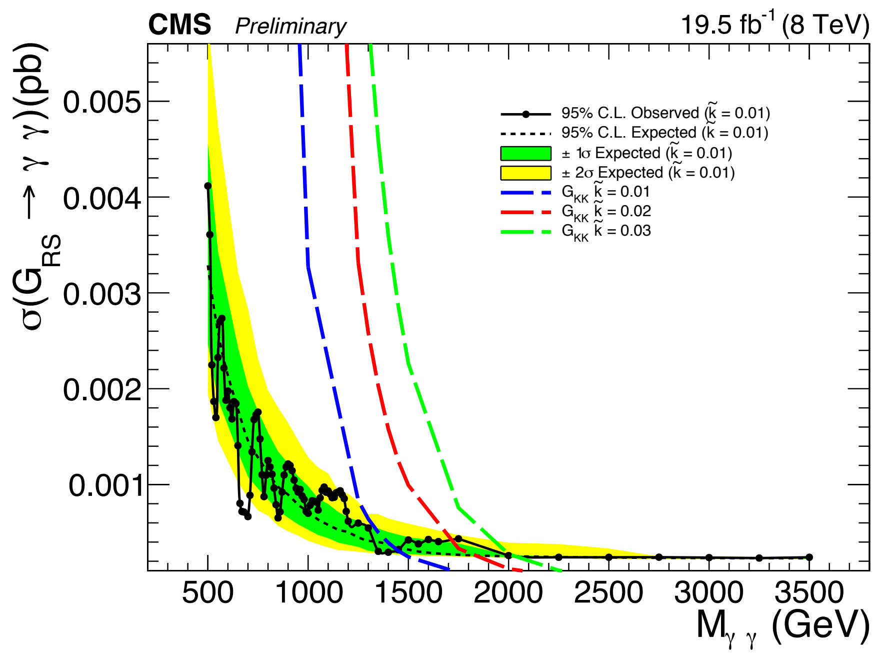
COMBINATION WITH 8 TEV

2 analyses performed on 8 TeV data

HIG-14-006 (PLB 750(2015) 494):
150-850 GeV, spin0 and spin2



EXO-12-045:
500-3000 GeV, spin2 only



Combination in all 6 signal hypotheses with 13 TeV

pick most sensitive analysis: 500-850 GeV HIG-14-006, EXO-12-005 otherwise

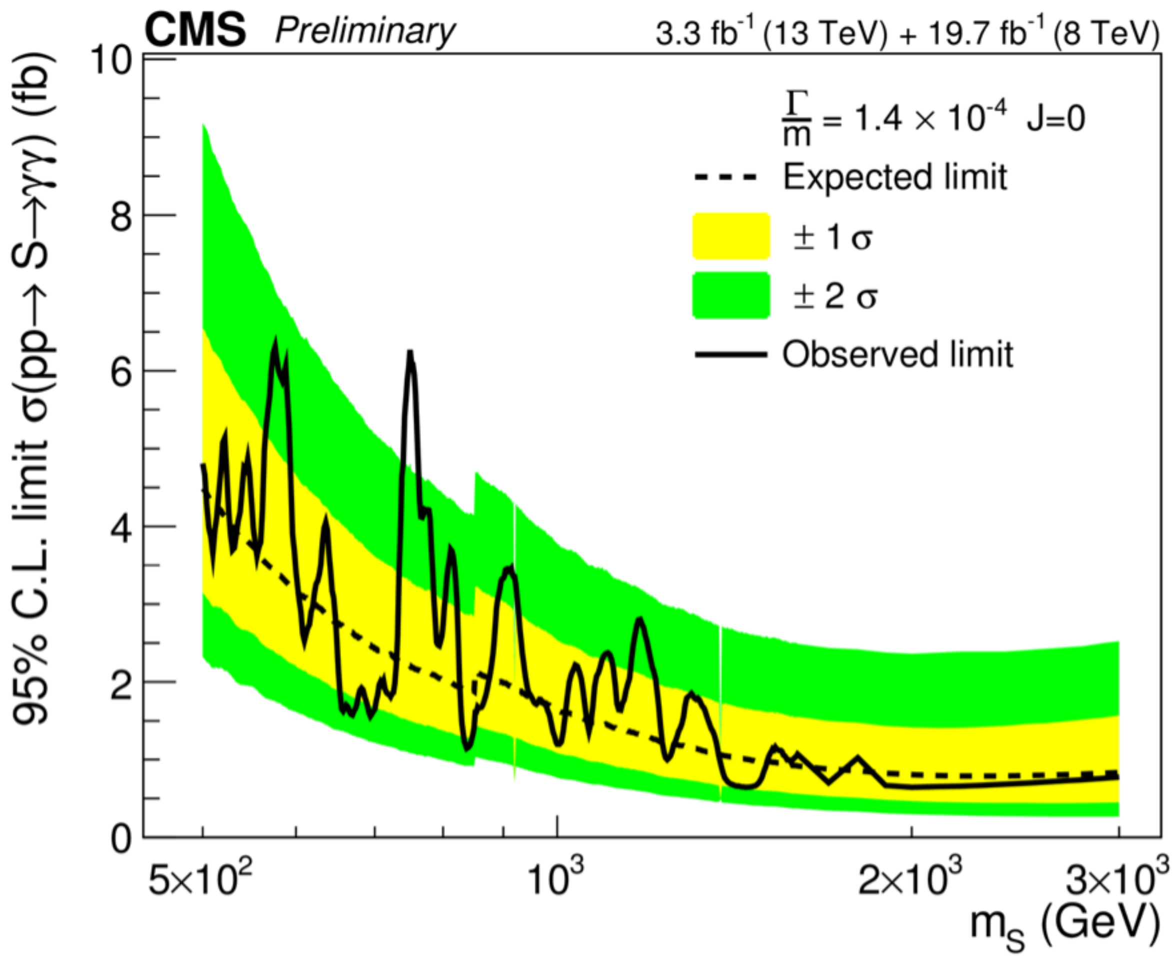
Cross section ratios:

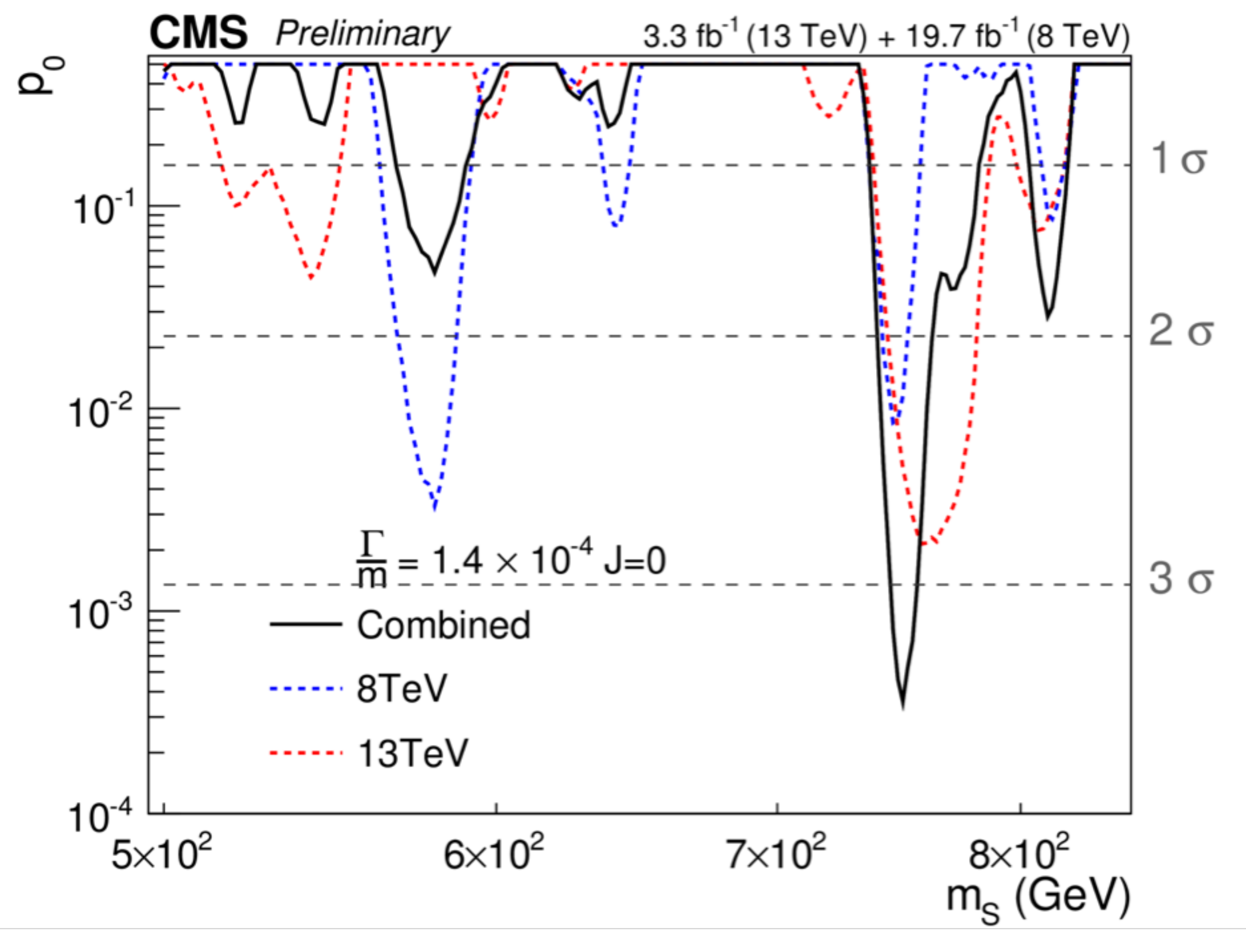
spin0 (gg→S): $\sigma_{13\ TeV}/\sigma_{8\ TeV}$=4.7

spin2 (RS): $\sigma_{13\ TeV}/\sigma_{8\ TeV}$=4.2

COMBINATION WITH 8 TEV

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





Largest excess observed at m_X=750 GeV for narrow width

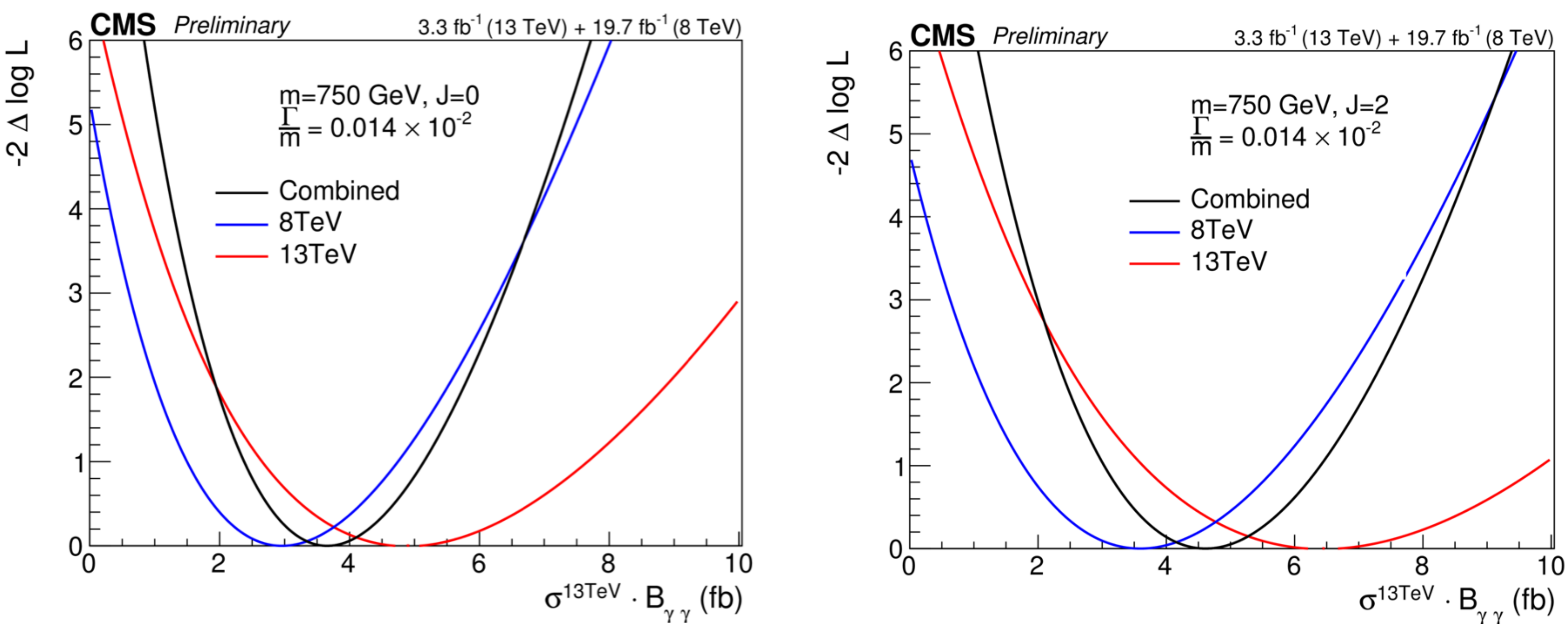
Local significance: 3.4σ

Global significance 1.6σ, considering all signal hypotheses in 500-3500 GeV mass range

Consistency Between 8 TeV and 13 TeV

Evaluated looking at likelihood profile for equivalent $\sigma_{13\ TeV}$ at 750 GeV for both spin hypotheses

Excess is compatible between the 2 datasets



CONCLUSIONS

Di-photon is a robust and powerful final state to look for new physics and explore the Higgs boson properties

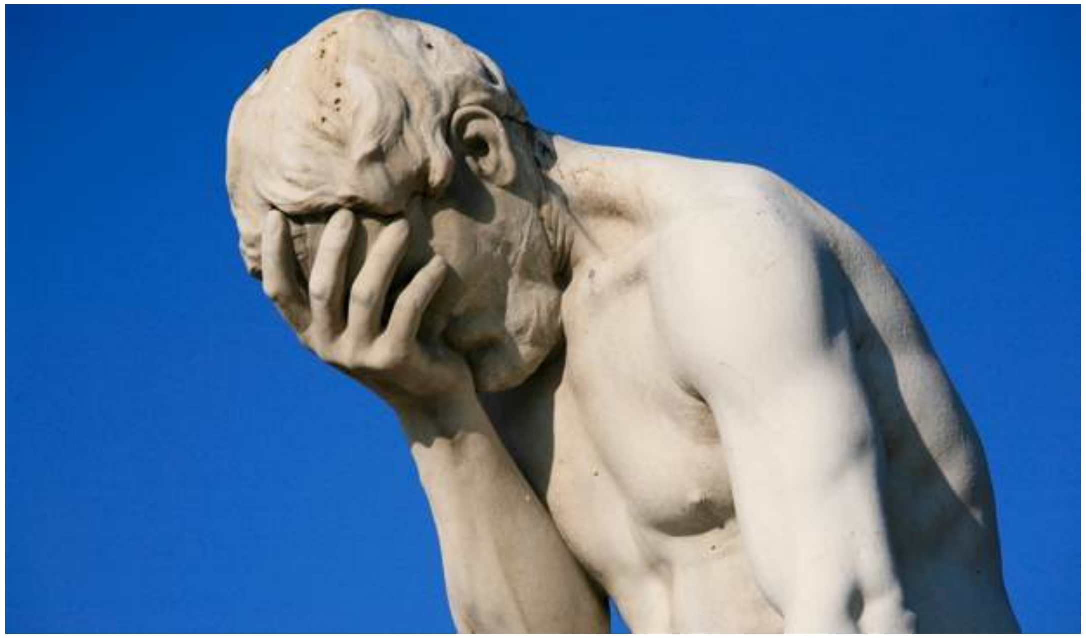
relies heavily on excellent CMS ECAL performance

13 TeV center-of-mass energy is a new unexplored territory

not only limits, a modest excess has been observed at mass ~ 750 GeV

10 fb^{-1} at 13 TeV are required to assess the nature of this excess

statistical fluctuation | new physics



OR

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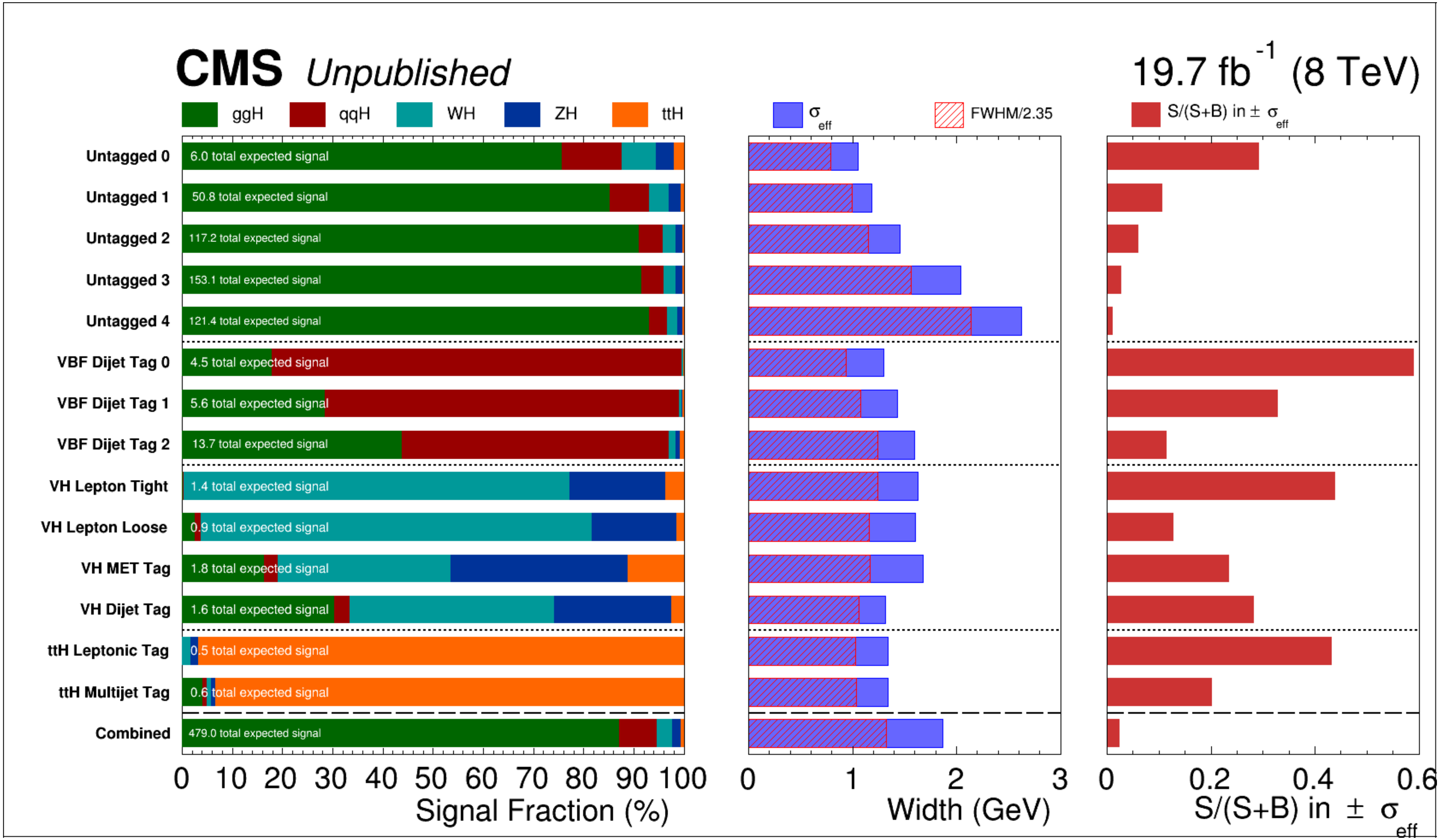
BACKUP

H→γγ Event Categories



H→γγ Event Categories