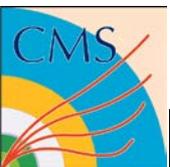


Searches for new heavy resonances in final states with leptons and photons

Riccardo Paramatti on behalf of CMS Collaboration
Sapienza Univ. and INFN Roma - Italy

7th International conference
on High Energy Physics
in the LHC Era
8-12 Jan 2018, Valparaiso





Outline

- CMS published results with 13 TeV data
 - 2015 and 2016 data
 - Analysis with 2017 data still in progress.
- Fully reconstructed final states:
 - Diphoton (with all the gory details)
 - Z' boson in dielectron and dimuon
 - Z +gamma (leptonic decay)
 - Electron-muon high mass resonances
- One example of non fully reconstructed final state:
 - W' boson in lepton plus missing transverse momentum
- Conclusions

[Motivation

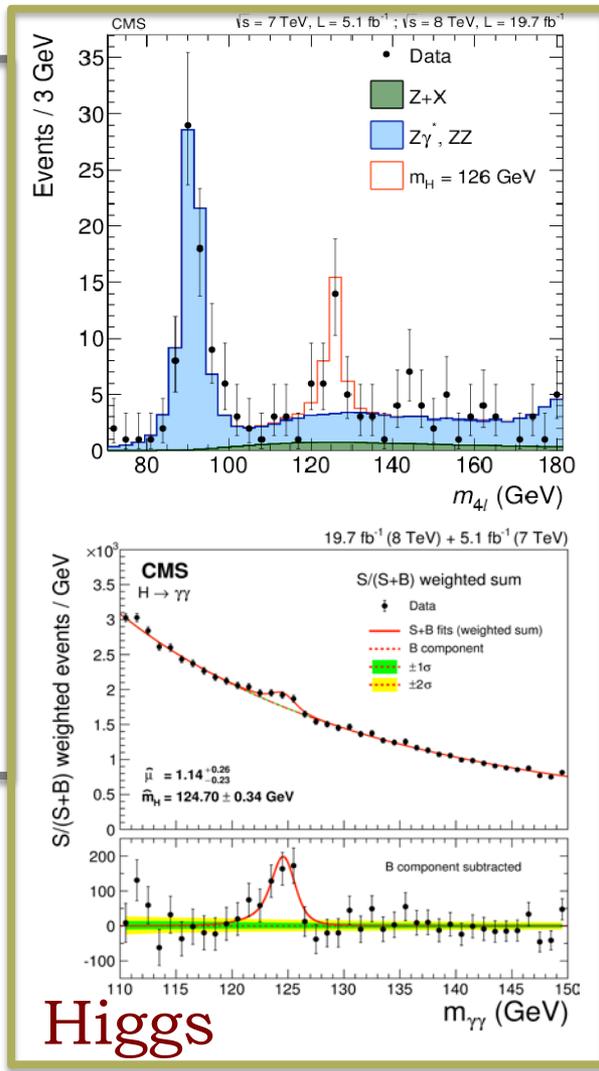
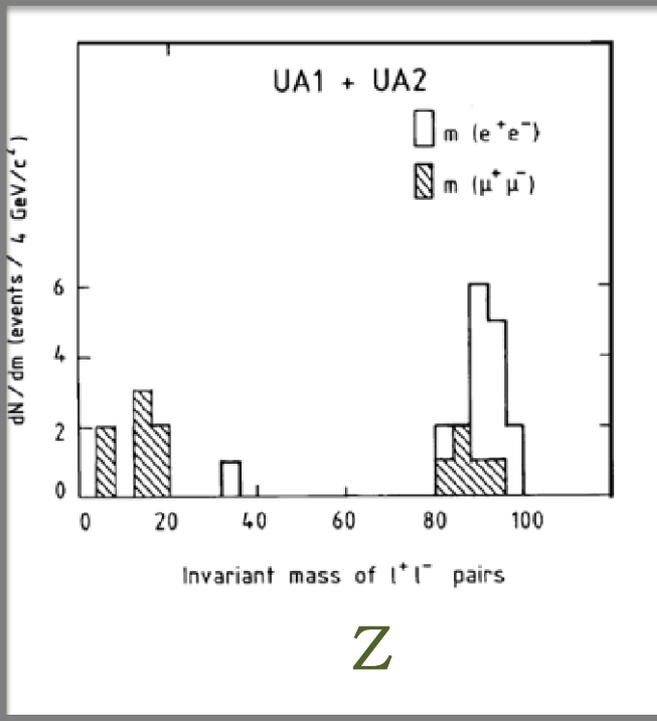
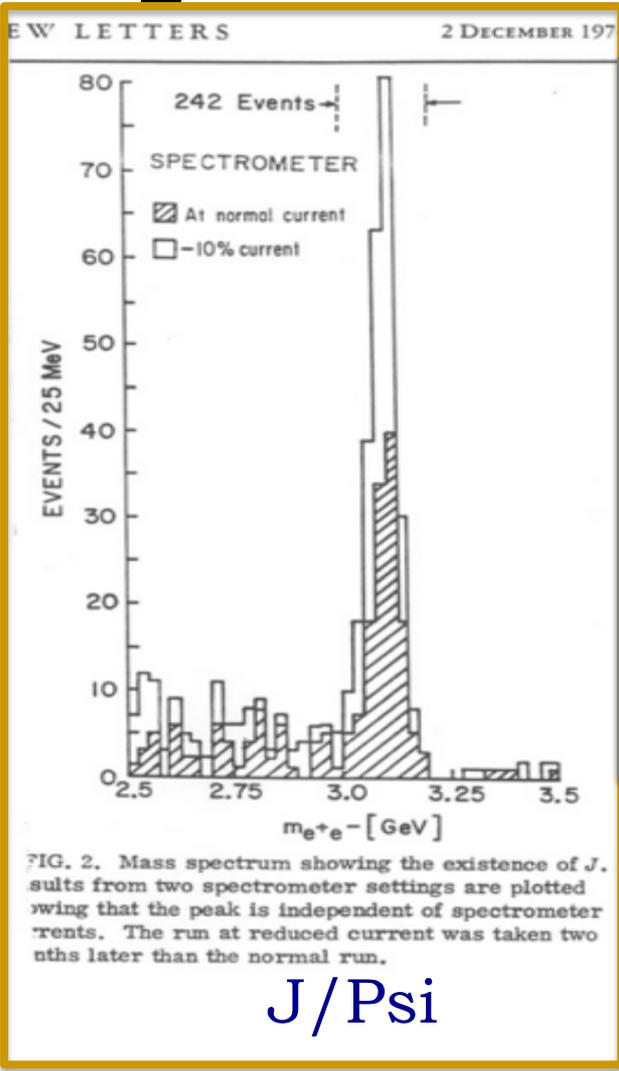
Fully reconstructed final state signatures at higher center-of-mass energy is the golden way to discover new particles and phenomena beyond the SM.

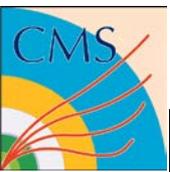
- LHC Run2: new data taken at $\sqrt{s} = 13$ TeV in 2015-2017(18).

Final states with leptons and photons \rightarrow good invariant mass resolution.

- Very clear signature: peak over a smooth background
- Experimentally robust
- Small systematic effects
- Model independent probe to new physics

Past discoveries

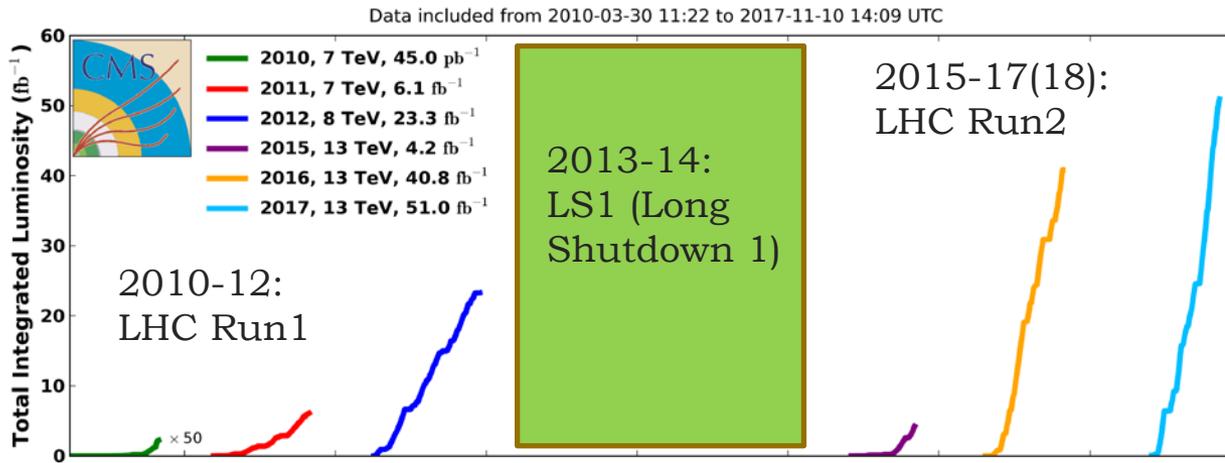




Large Hadron Collider performances (Run1-Run2)

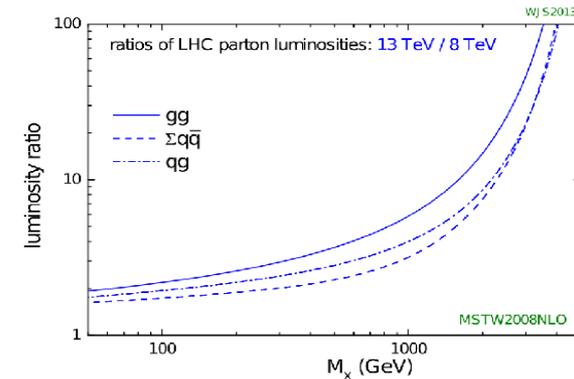


CMS Integrated Luminosity, pp

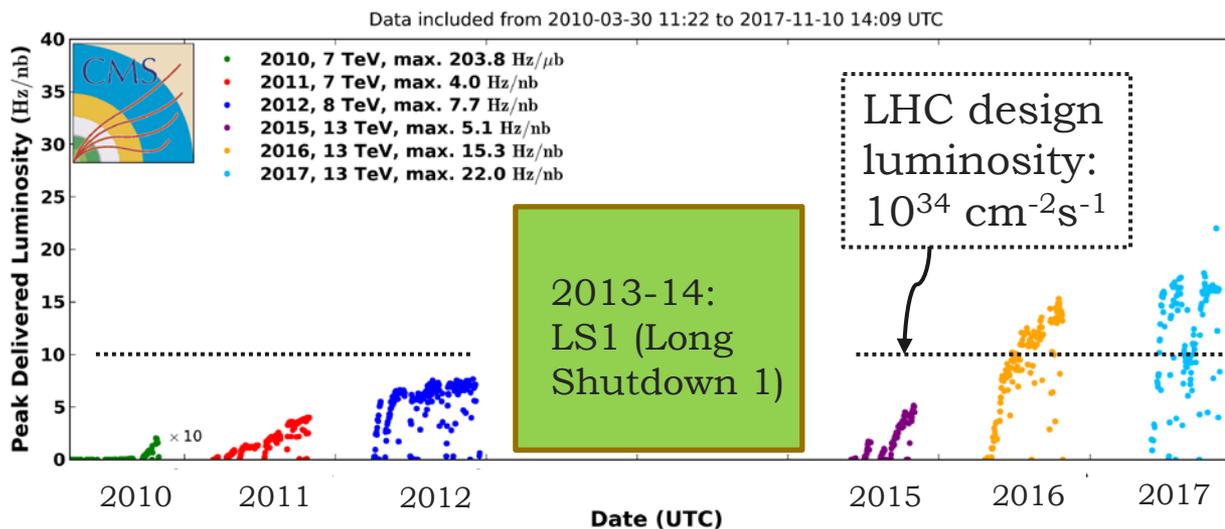


From Run1 to Run2

- 7/8 TeV → 13 TeV
- increasing \sqrt{s} extends the reach of Run1



CMS Peak Luminosity Per Day, pp



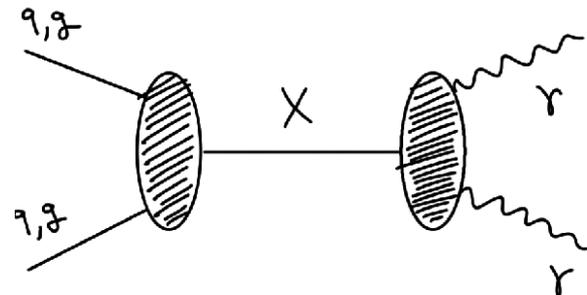
- Up to $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Higher event rate and larger PileUp; challenging for trigger and reconstruction.

High mass resonances in diphoton final state

PLB 767 (2017) 147

- Data sample: 12.9 fb^{-1} taken in 2016 at $\sqrt{s} = 13 \text{ TeV}$ combined with
 - 3.3 fb^{-1} taken in 2015 at $\sqrt{s} = 13 \text{ TeV}$
 - 19.7 fb^{-1} taken in 2012 at $\sqrt{s} = 8 \text{ TeV}$
- Analysis built on SM Higgs search experience
- Robust and model-independent cut based analysis

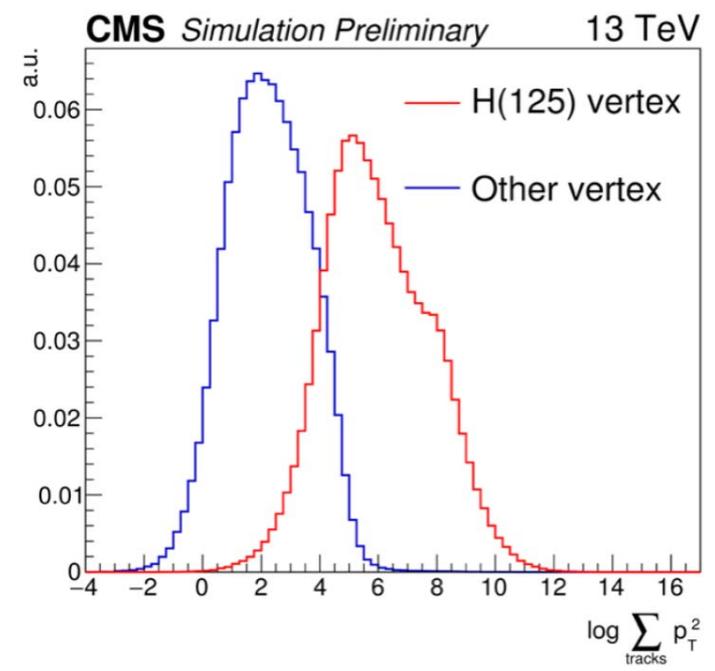
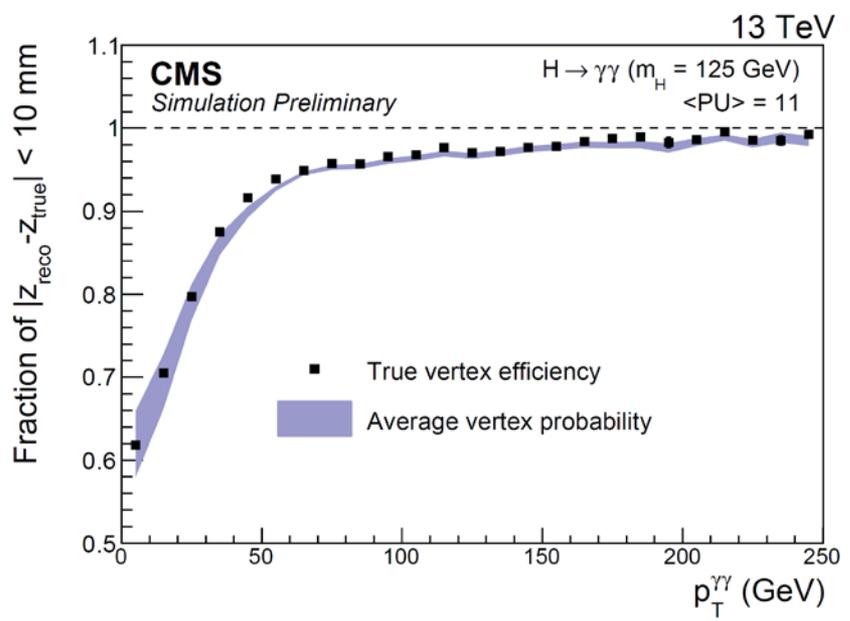


Benchmark models:

- **Spin-0 analysis:** extended Higgs sector (2HDM)
 - Scalar and/or pseudo-scalar can have sizable branching ratio to diphoton
- **Spin-2 analysis:** Randall-Sundrum graviton
 - Model predicts tower of Kaluza-Klein states with TeV mass scale; mass of the RS graviton is the mass lightest KK excitation

Diphoton vertex identification

- Spread of primary vertex position is ~ 5 cm in z
- If vertex is located within 1 cm, contribution to the mass resolution from angle negligible
- The vertex is selected using recoiling tracks (and reconstructed conversion when present)
- Multivariate approach for optimal performance
 $\Sigma p_T^2, p_T(\gamma\gamma)$ vs $p_T(\text{tracks}), z_{\text{conv}}$



- Average probability is \sim **90%**.
- Performance validated in data with $Z \rightarrow \mu\mu$ events

Event selection

Cut-based event selection (same selection for both benchmark models)

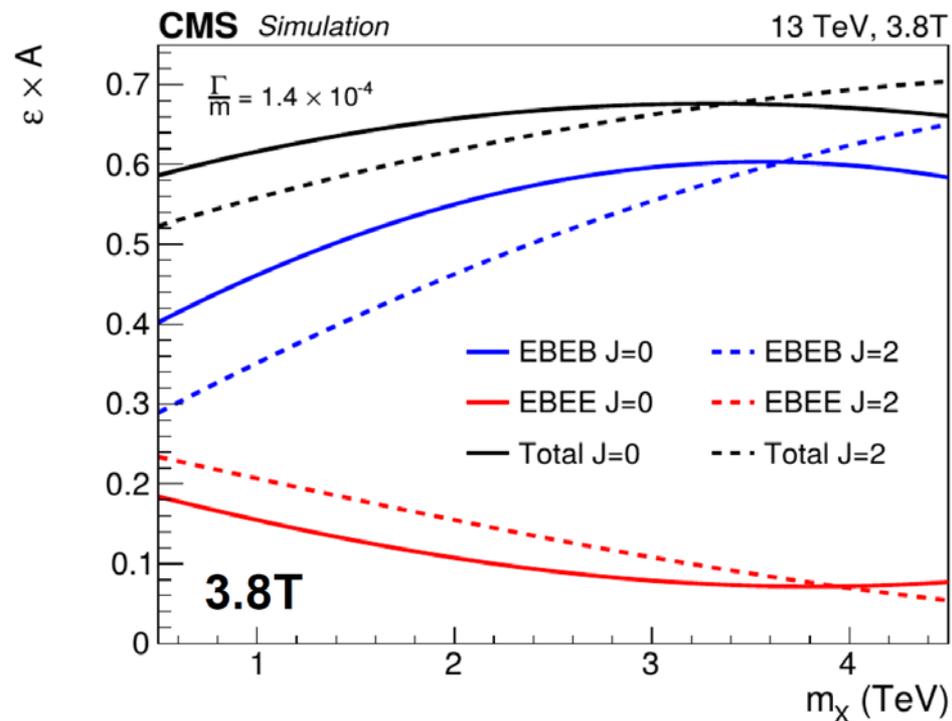
- ✓ HLT: 2 photons, $E_T > 60$ GeV
- ✓ Offline selection:
 - ✓ $E_T > 75$ GeV
 - ✓ ECAL fiducial region
 - ✓ dedicated photon selection (isolation, H/E, shower shape)
- ✓ 2 event categories:
 - ✓ EBEB: both γ in the barrel
 - ✓ EBEE: one γ in EB, one in EE

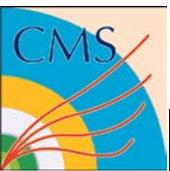
10-15% improvement from adding the barrel-endcap category

Per-photon efficiency in the barrel (endcaps): $\sim 90\%$ ($\sim 85\%$).

Zee to check efficiencies

- ✓ data/MC scale factors compatible with 1, constant at high p_T



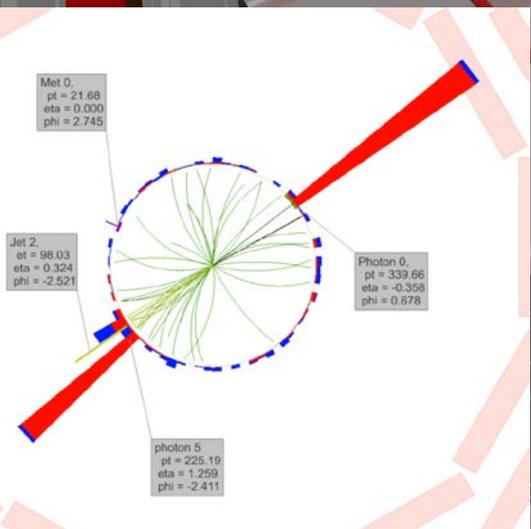
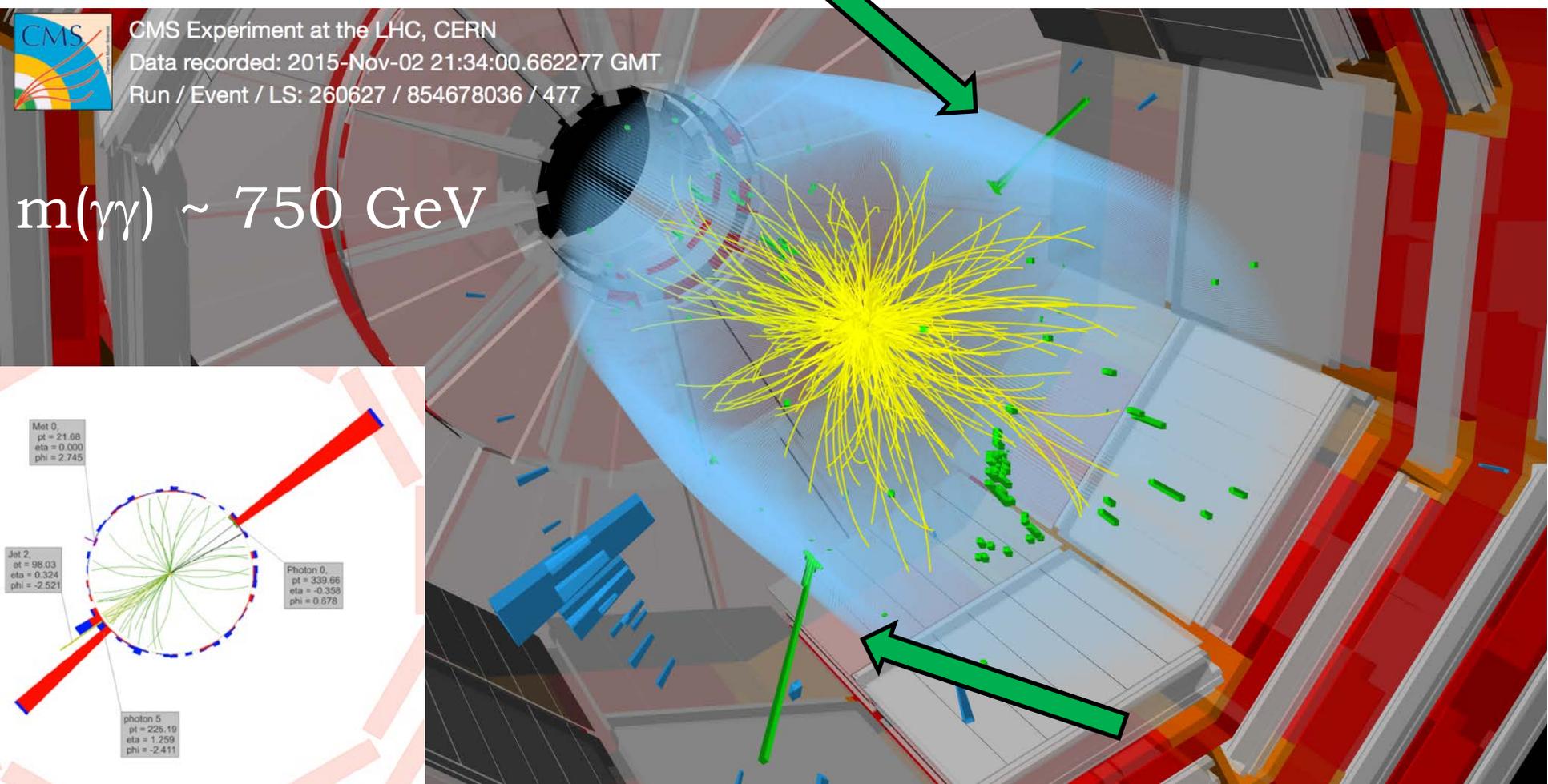


High mass resonances in diphoton final state



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

$m(\gamma\gamma) \sim 750 \text{ GeV}$



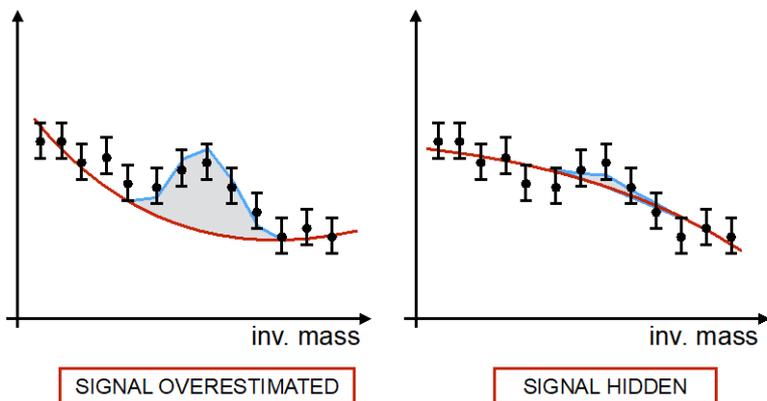
Signal and bg modelling

- Shape of the signal: combination of the intrinsic width of the resonance and the ECAL detector response.
- Detector response modeled on fully simulated signal sample with negligible intrinsic width

m (GeV)	$\sigma_{FWHM}^{3.8T} / m$	
	EBEB	EBEE
500	0.94×10^{-2}	1.5×10^{-2}
1000	0.94×10^{-2}	1.5×10^{-2}
2000	0.96×10^{-2}	1.4×10^{-2}
4500	1.11×10^{-2}	1.4×10^{-2}

Background $m_{\gamma\gamma}$ shape:

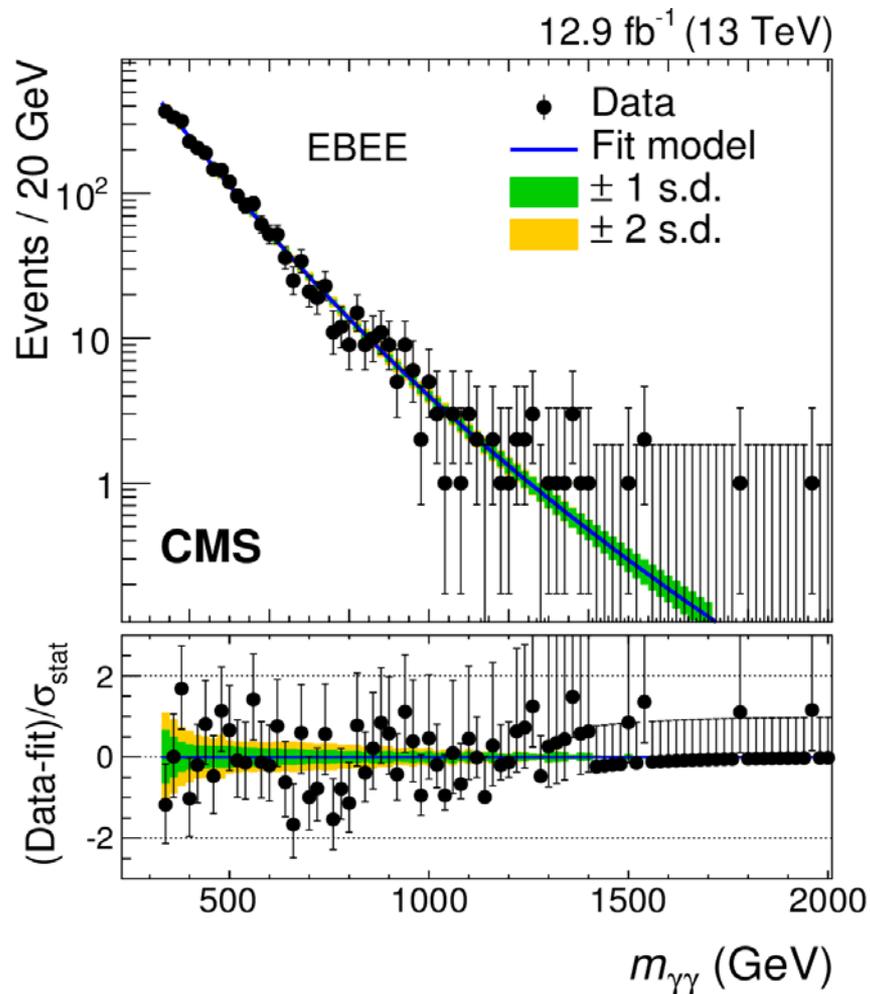
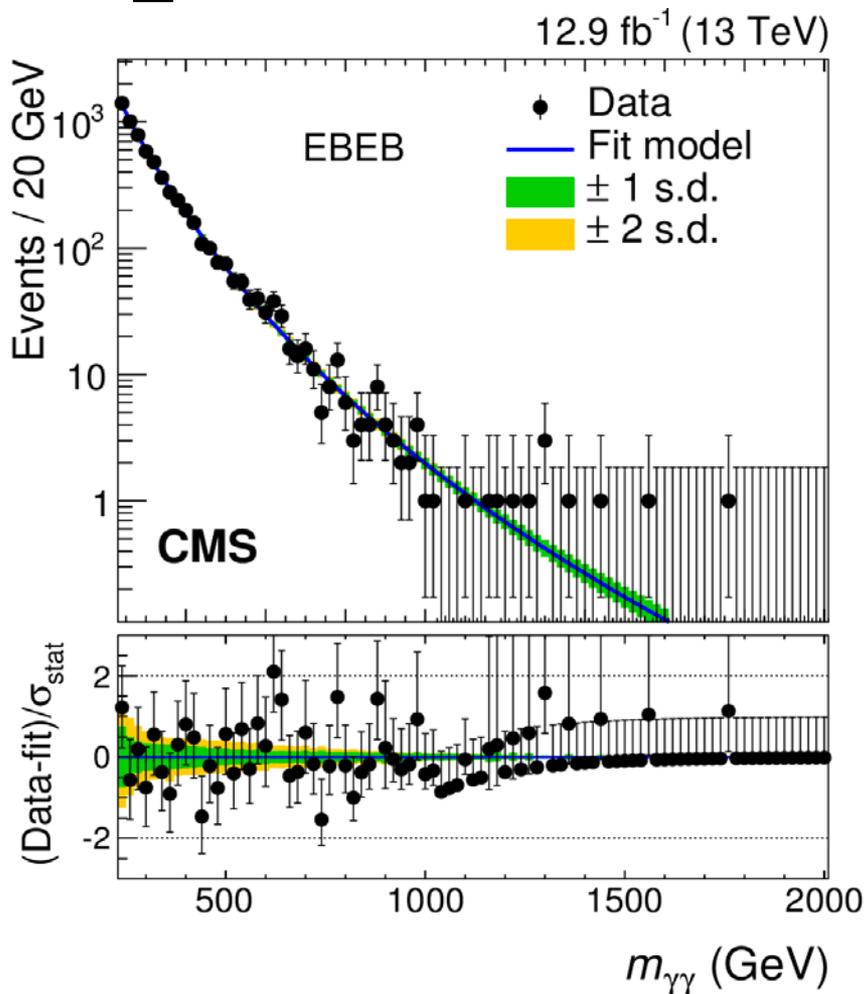
✓ parametric fit to data $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b \cdot \log(m_{\gamma\gamma})}$



Background composition is measured in data with template fits:

- Direct $\gamma\gamma$ SM production; two prompt photons \rightarrow irreducible. Dominant component (>80%)
- Dijets and γ +jets production \rightarrow reducible. (10-20%)

High mass resonances in diphoton final state



$m_{\gamma\gamma}$ spectra of selected events in the two categories

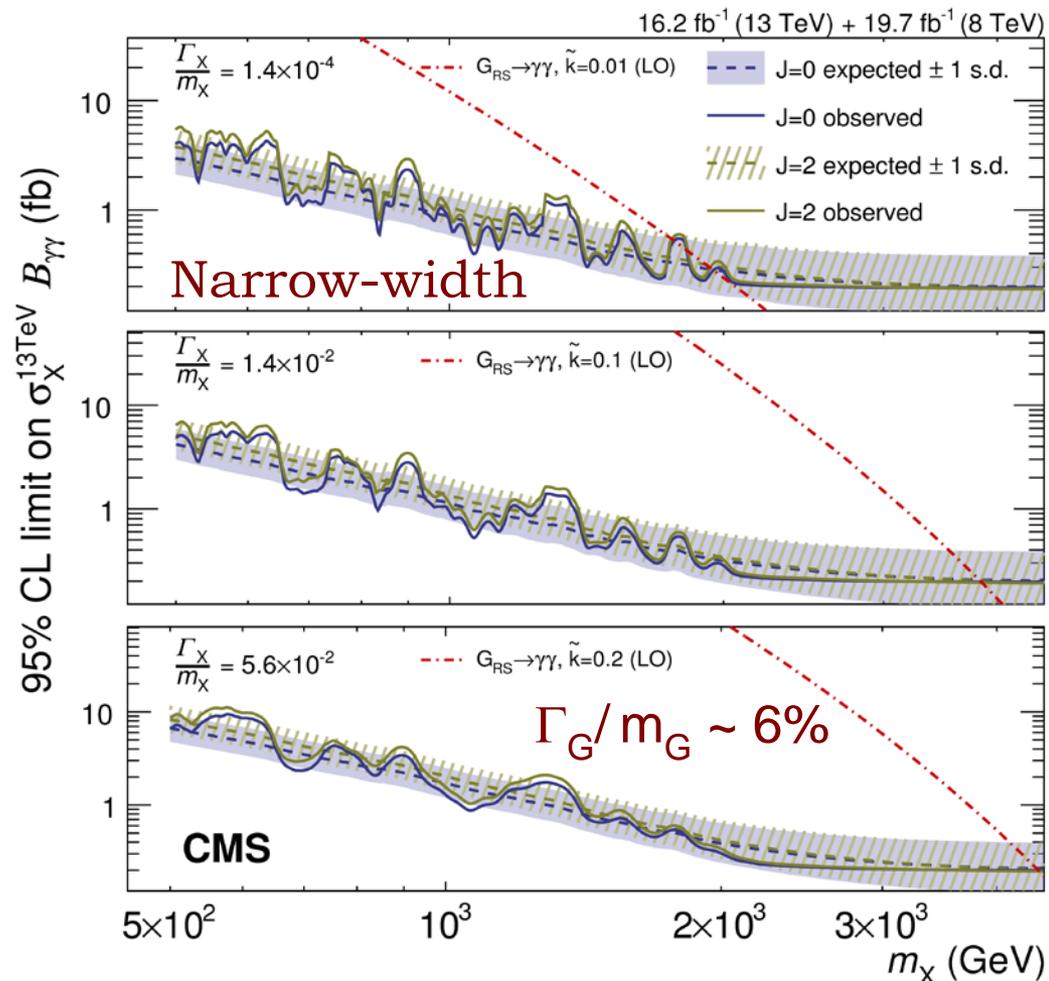
Interpretation: exclusion limits

Observed limits on Graviton cross section \times diphoton BR:

- $m_G < 1.95$ TeV excluded in the narrow-width scenario (detector resolution is dominant, $k = 0.01$)
- $m_G < 4.45$ TeV excluded in the broad scenario (intrinsic width is dominant, $k = 0.2$)

Most stringent limits on RS graviton production to date.

- Expected and observed limits in good agreement.
- Similar limits for spin-0 benchmark model.



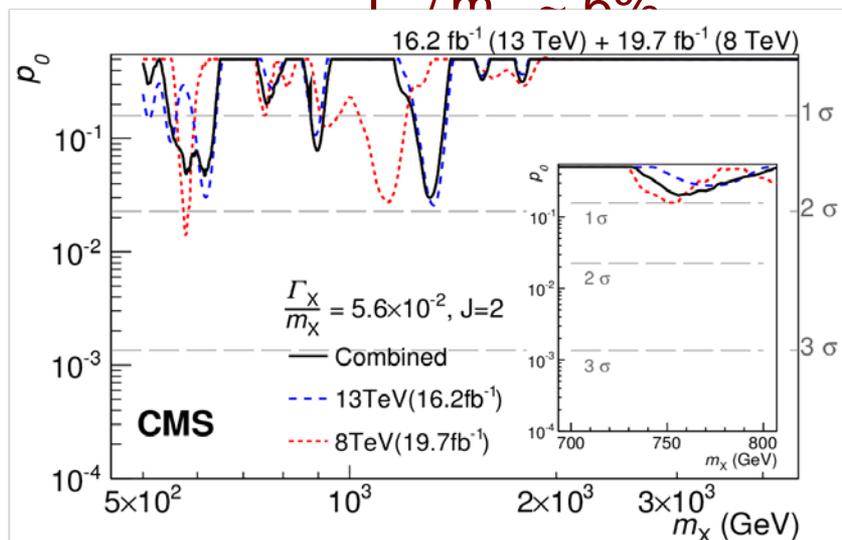
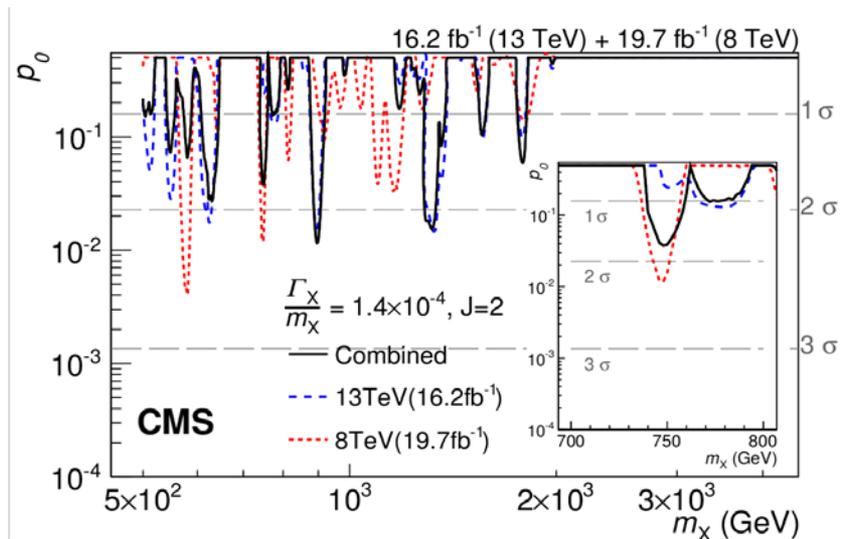
Interpretation: p value

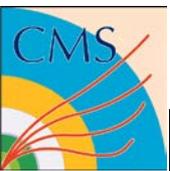
Excess observed by CMS and ATLAS at 750 GeV in 2015 data:

- Local significance was 3.4σ (CMS) and 3.9σ (ATLAS)

Excess not confirmed with 4 times more data analyzed in 2016.

- The largest excess in CMS dataset is at 0.9 TeV with a local significance of 2.2σ .
- The excess at 750 GeV is now reduced to 1.9σ .





High mass resonances in $Z(ee/\mu^+\mu^-)+\gamma$ final states

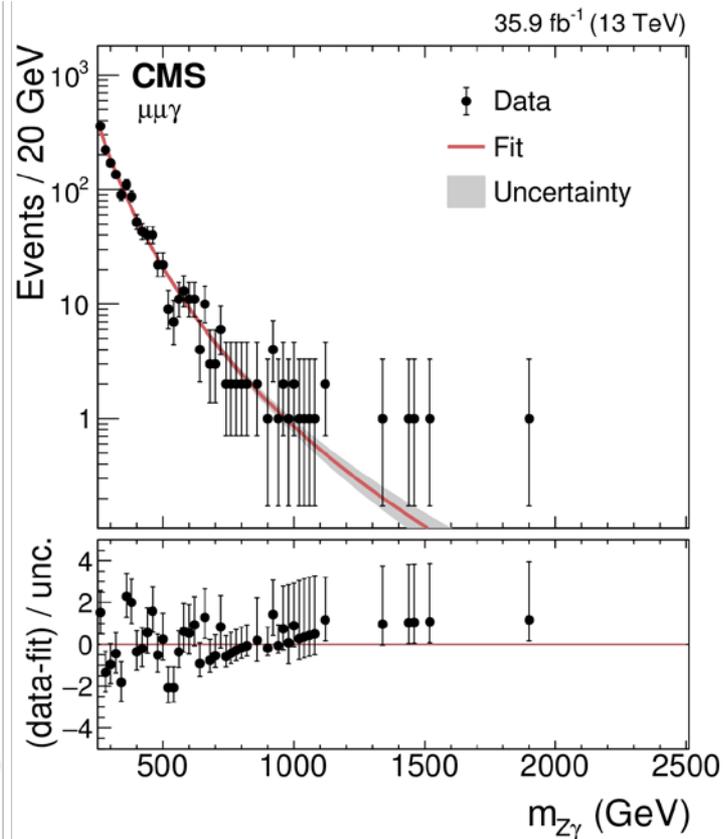
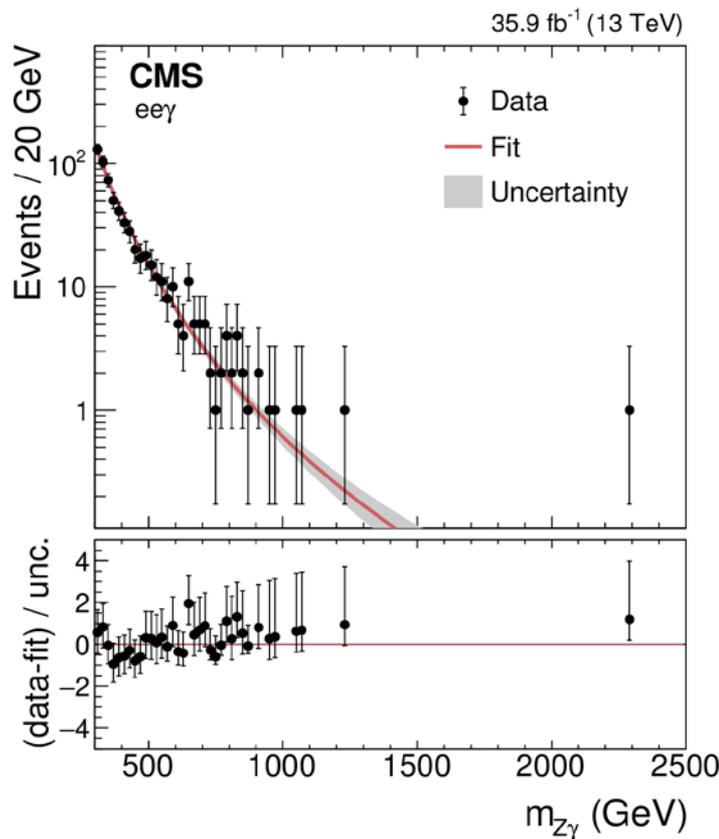


CMS PAS EXO-17-005 (arXiv:1712.03143 - submitted to JHEP)

Data sample: 35.9 fb^{-1} taken in 2016 at $\sqrt{s} = 13 \text{ TeV}$

- Two isolated electrons with $E_T > 65/10 \text{ GeV}$ and one photon with $E_T > 65 \text{ GeV}$ all in the acceptance $|\eta| < 2.5$
- Two isolated muons with opposite charge, $E_T > 52/10 \text{ GeV}$ and $|\eta| < 2.4$ and one photon with $E_T > 40 \text{ GeV}$ and $|\eta| < 2.5$
- Invariant mass of the dilepton system between 50 and 130 GeV.
- Dominant backgrounds:
 - continuum SM $Z\gamma$ production (irreducible)
 - leptonic decays of the Z boson with FSR and Z+jet with jet misidentified as photon (reducible)
- The photon is required to have a distance $\Delta R > 0.4$ from each of the two leptons, to minimize the effect of lepton FSR.
- Benchmark: narrow/broad spin-0 resonances (assuming no interference with SM non resonant $Z\gamma$ production)
- Signal acceptance depends weakly on the spin of the resonances.

High mass resonances in $Z(ee/\mu^+\mu^-)+\gamma$ final states

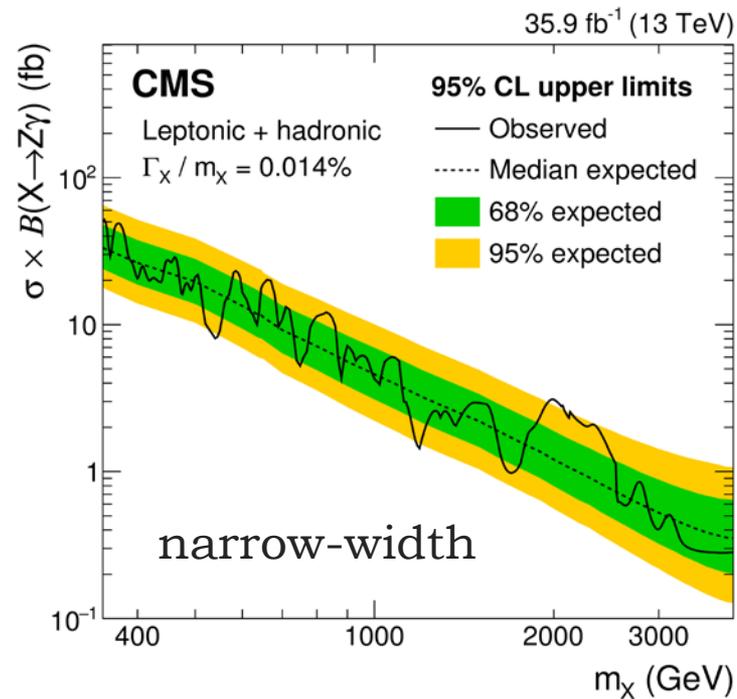
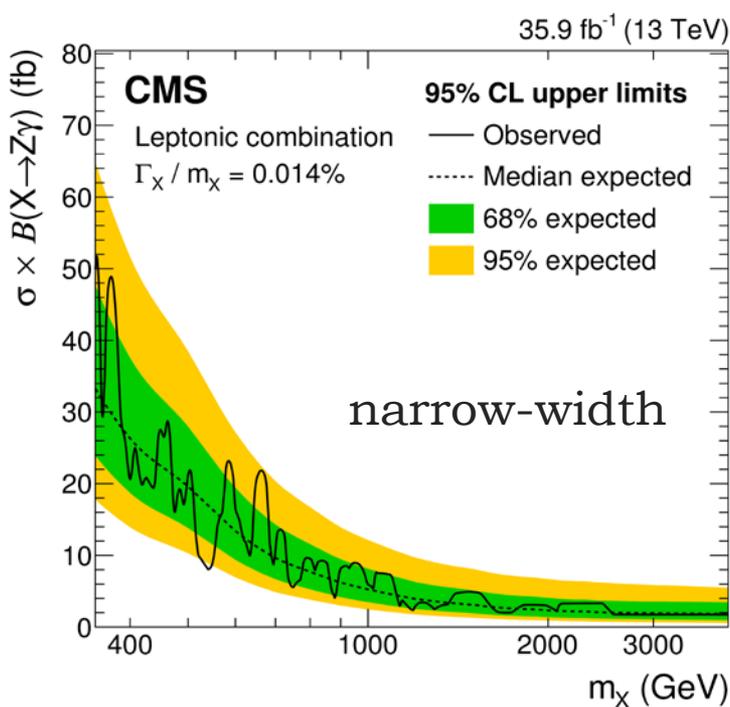


The SM background is described by the function $f(m_{Z\gamma}) = m_{Z\gamma}^{a+b \log m_{Z\gamma}}$ fitting directly on data events.

No significant excess over the background-only hypothesis.

High mass resonances in $Z(ee/\mu^+\mu^-)+\gamma$ final states

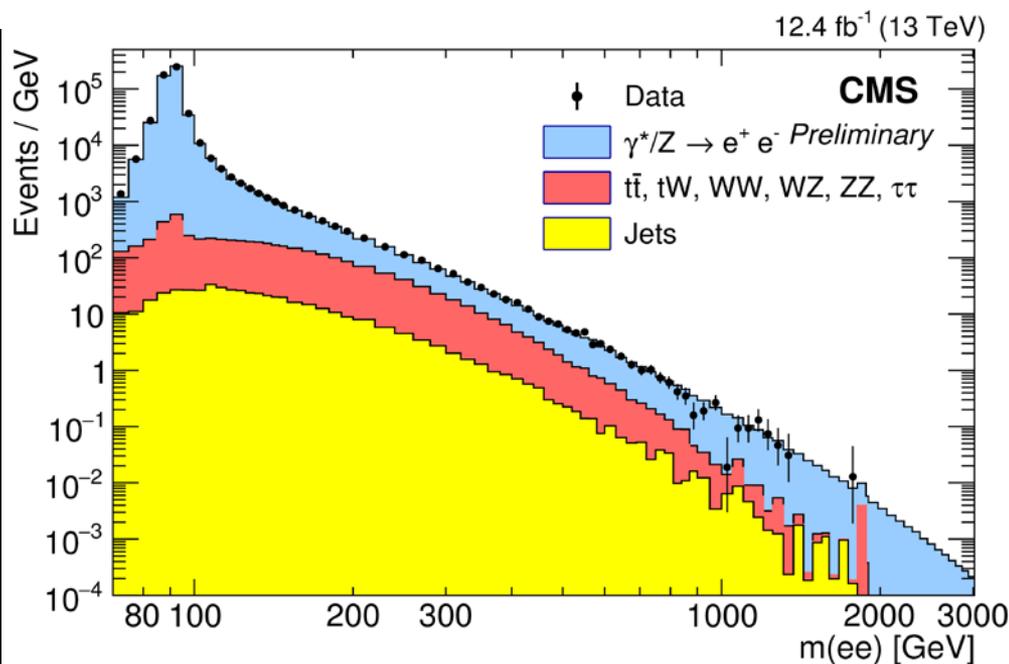
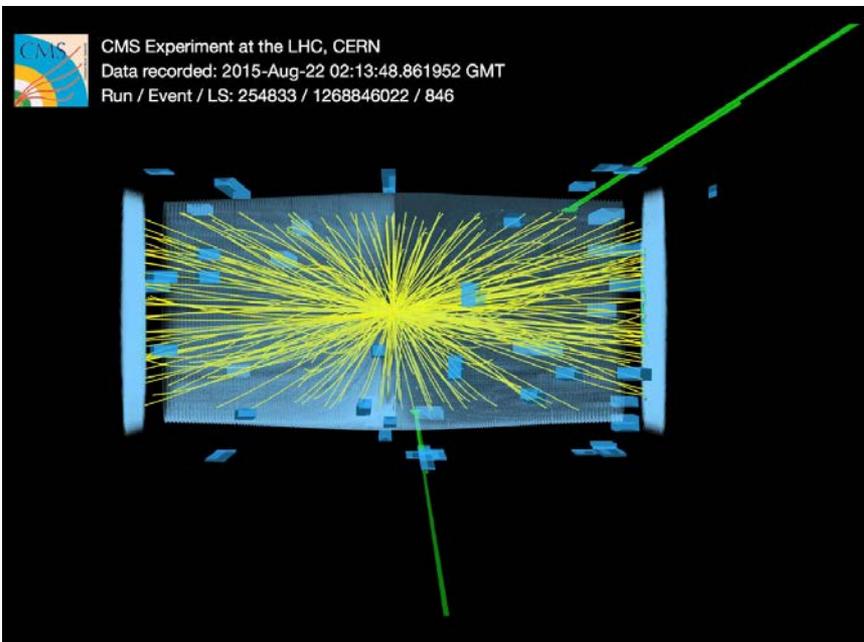
- The results from leptonic channels are combined with hadronic channel.
- The observed limits for narrow (broad) spin-0 resonances with masses between 0.35 and 4.0 TeV, ranging from 50 (100) to 0.3 (1.5) fb.
- These are the most stringent limits on such resonances to date.



High mass resonances in dielectron final state

CMS PAS EXO-16-031 - Data sample: 12.4 fb^{-1} taken in 2016 at $\sqrt{s} = 13 \text{ TeV}$

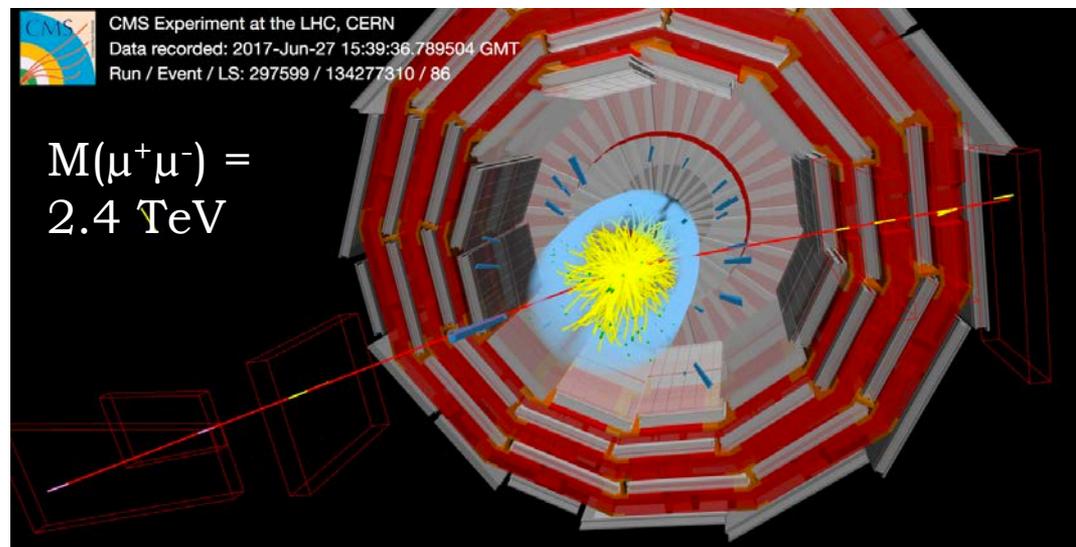
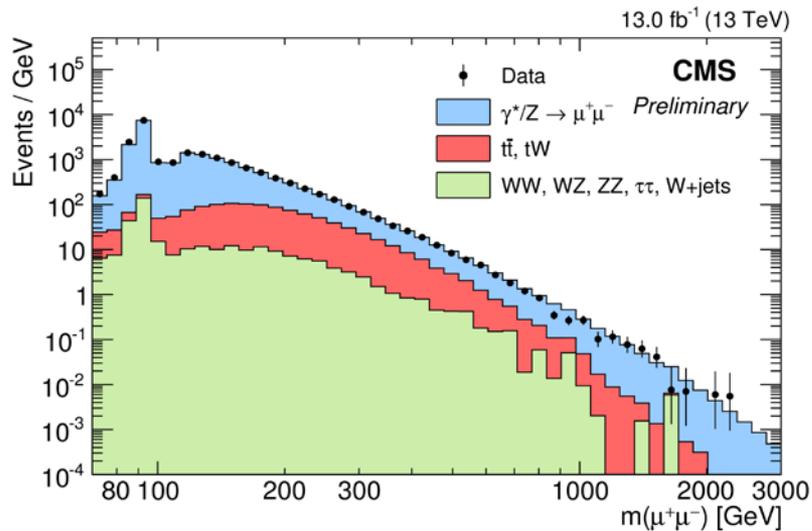
- Two isolated electrons with $E_T > 35 \text{ GeV}$ and at least one electron in the central region: $|\eta| < 1.44$ (CMS electron acceptance $|\eta| < 2.5$)
- Efficiency (reco+ID) of 1 TeV electron pair within the detector acceptance: BB $69 \pm 8\%$ and BE $66 \pm 10\%$

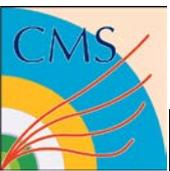


High mass resonances in dimuon final state

CMS PAS EXO-16-031 - Data sample: 13.0 fb^{-1} taken in 2016 at $\sqrt{s} = 13 \text{ TeV}$

- Two isolated muons with opposite charge, $E_T > 53 \text{ GeV}$ and $|\eta| < 2.4$ coming from the same vertex and not perfectly back-to-back (to reject cosmic rays)
- Dimuon pair invariant mass resolution at 2 TeV is $\sim 5\%$ with both muons in the central region ($< 2\%$ for dielectron pair).





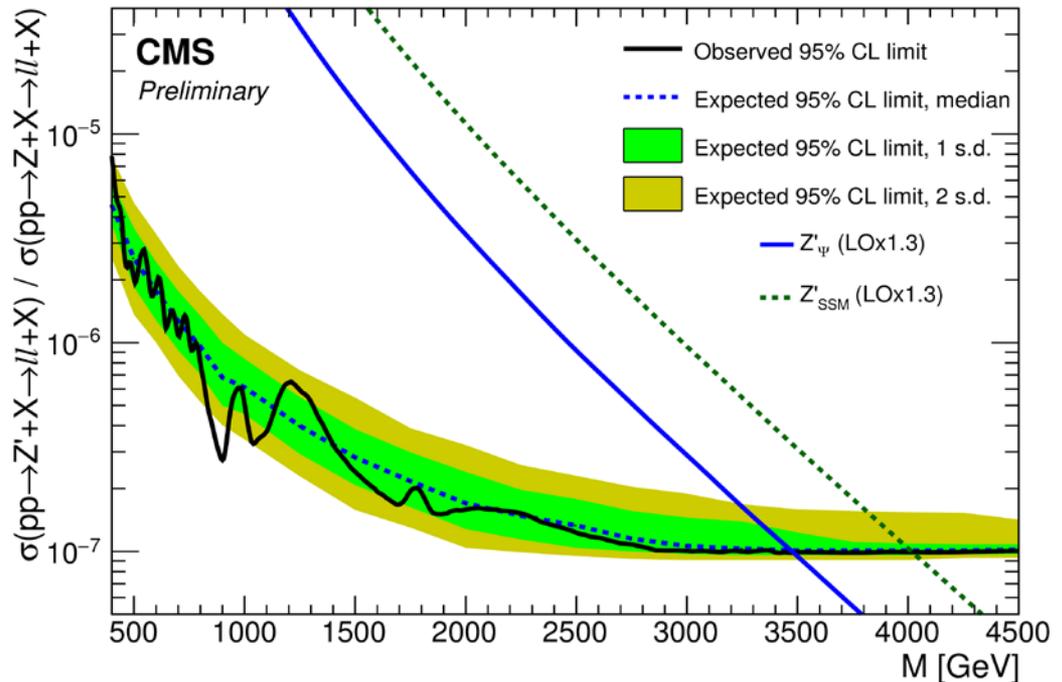
High mass resonances in $ee/\mu^+\mu^-$ final states

- Search for a new spin 1 neutral narrow resonance: intrinsic width negligible w.r.t. experimental resolution.
- Signal model: Breit-Wigner convoluted with a Gaussian.
- Observations consistent with SM expectations.

Upper limits at 95% of CL on:
 - Sequential Standard Model (additional U(1) symmetries)
 - GUT inspired models with a Z'_ψ boson with narrow width

Channel	Z'_{SSM} Obs. (TeV)	Z'_ψ Obs. (TeV)
ee	3.65	3.10
$\mu^+\mu^-$	3.75	3.20
$ee + \mu^+\mu^-$	4.0	3.50

12.4 fb⁻¹ (13 TeV, ee) + 13.0 fb⁻¹ (13 TeV, $\mu\mu$)



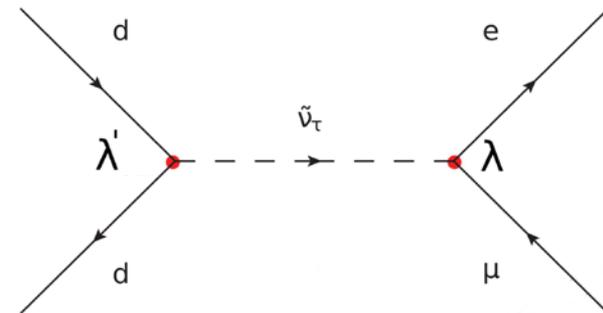
High mass resonances in LFV $e\mu$ final states

CMS PAS EXO-16-058 - Data sample: 35.9 fb^{-1} taken in 2016 at $\sqrt{s} = 13 \text{ TeV}$

- One isolated electron with $E_T > 35 \text{ GeV}$, $|\eta| < 2.5$ and one isolated muon with $E_T > 53 \text{ GeV}$, $|\eta| < 2.4$
- Signal efficiency ranges from 55% to 66% for different benchmark and resonance mass of 1-4 TeV.

Benchmark models:

- tau sneutrino: the Lightest Supersymmetric Particle in R-parity violating (RPV) SUSY
 - limits on λ (coupling with $e\mu$ pair) and λ' (coupling with $d\bar{d}$ pair)
- Z' gauge boson in LFV models
 - Assuming BR = 10% for LFV decay and width/mass = 0.03
- QBH: spin-0, colourless, neutral quantum black holes



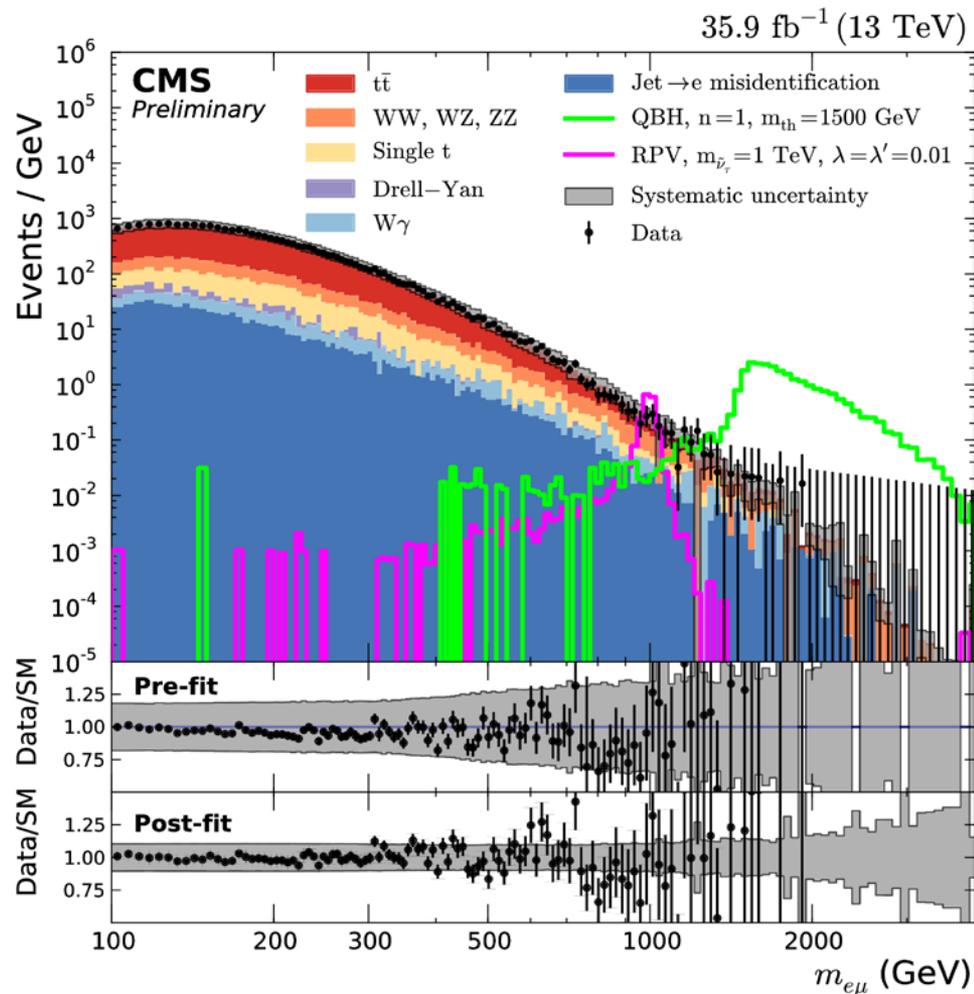
High mass resonances in LFV $e\mu$ final states

Data consistent with SM expectation in the whole mass range.

- Four events observed with invariant mass > 1.5 TeV.
- SM expectation:
 $4.2 \pm 0.35(\text{stat.}) \pm 0.91(\text{syst.})$

Invariant mass resolution:
 2.2% (3.1%) at 200 GeV (3 TeV)

QBH signal is a broad distribution with a threshold mass smeared out by the detector resolution.





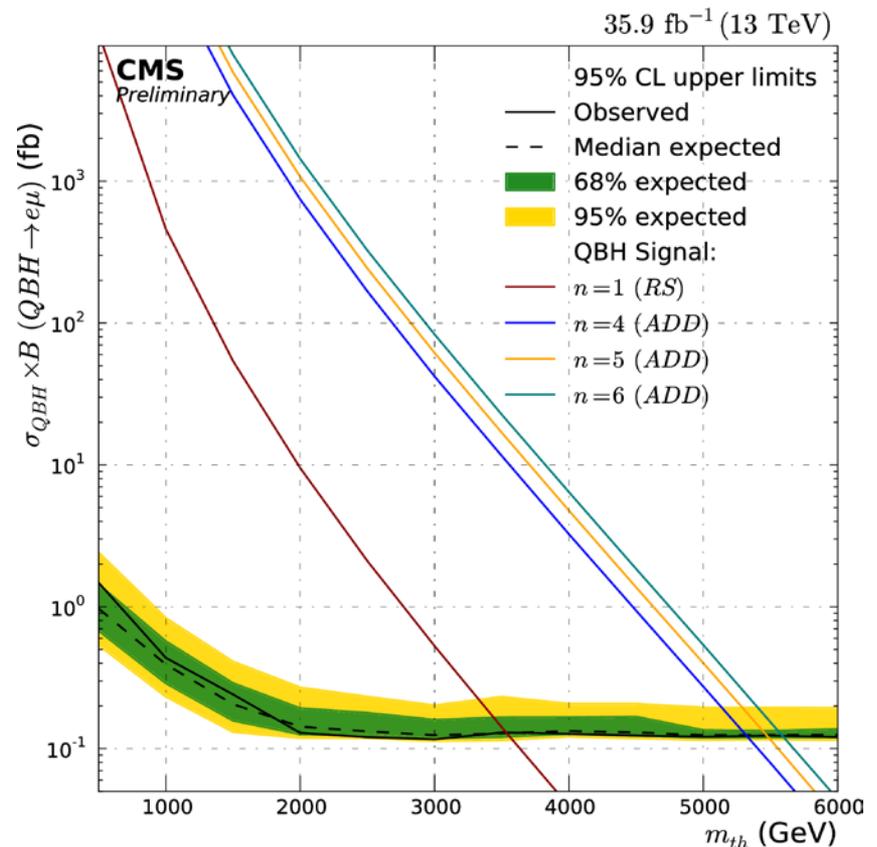
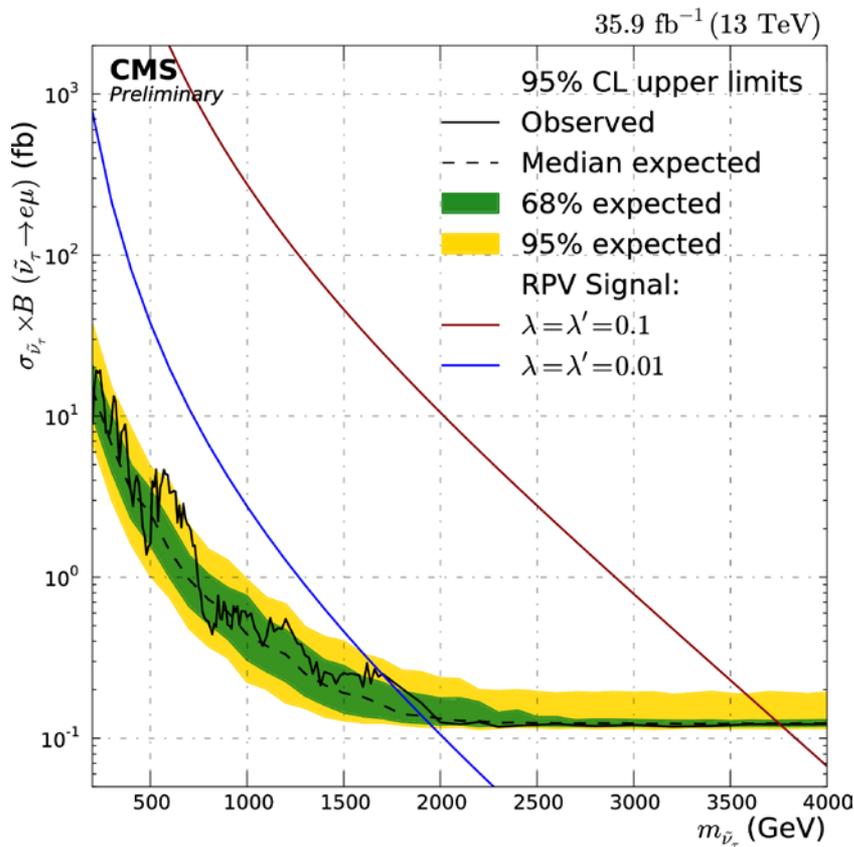
High mass resonances in LFV $e\mu$ final states



LFV tau sneutrino mass limit:
1.7 TeV to 3.8 TeV for different couplings.

Z' mass limit: 4.4 TeV

QBH threshold mass limit: 3.6 TeV (one extra-dim.) to 5.6 TeV ($n=6$)

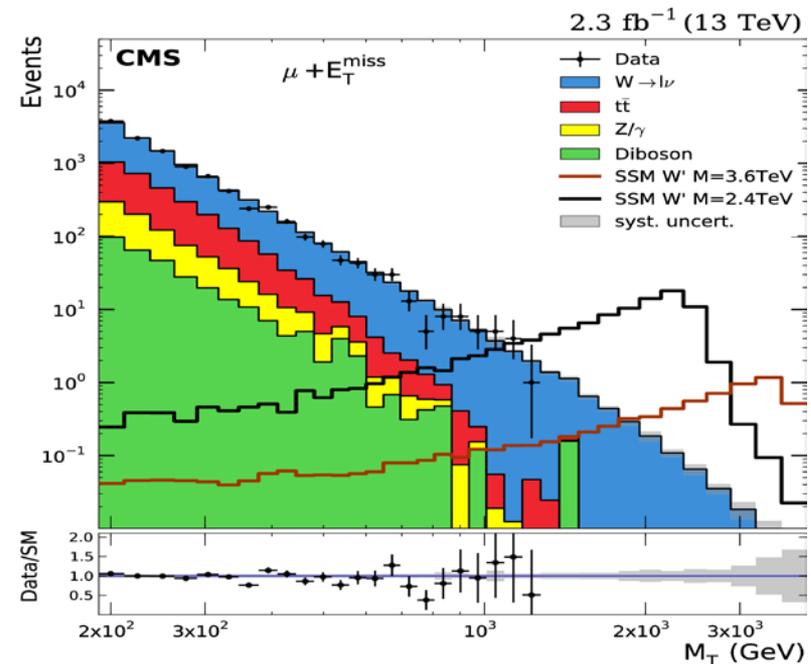
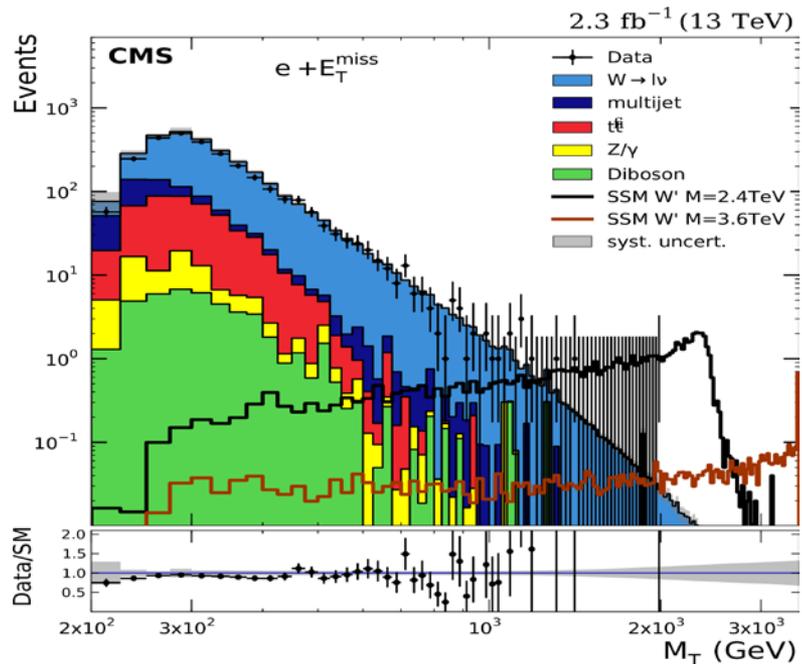


W' gauge boson in lepton plus missing transverse momentum.

PLB 770 (2017) 278 - Data sample: 2.3 fb^{-1} taken in 2015 at $\sqrt{s} = 13 \text{ TeV}$

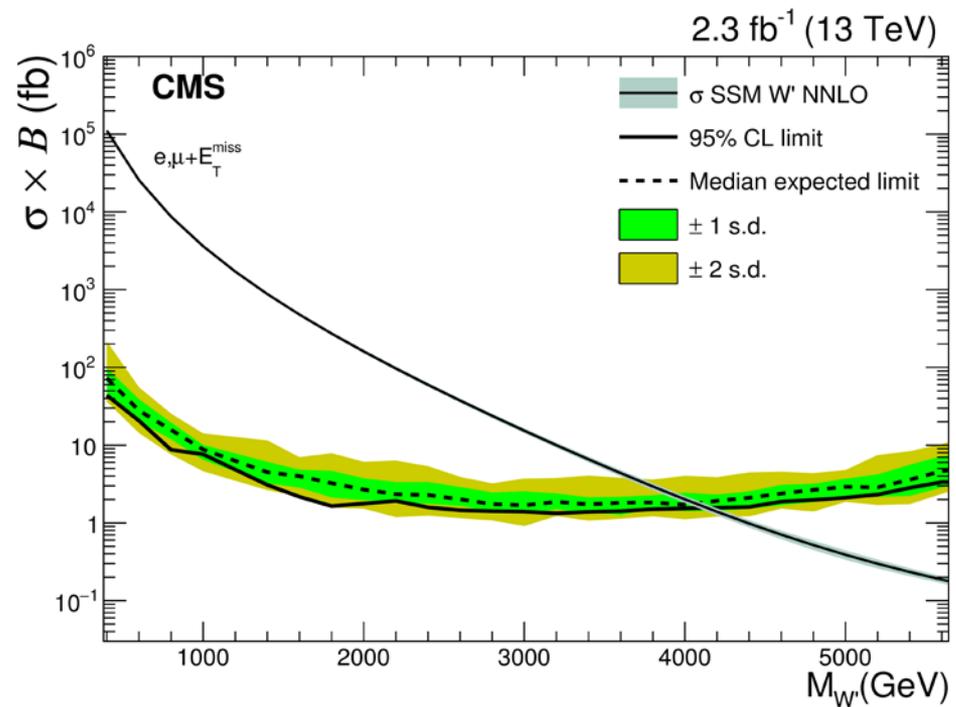
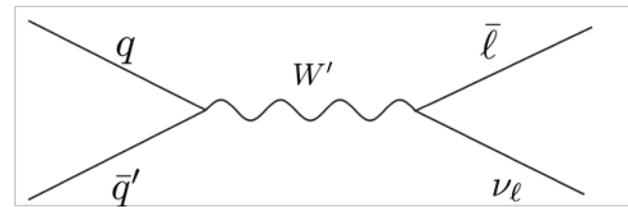
- Large missing transverse momentum and one isolated electron ($E_T > 130 \text{ GeV}$ to suppress non-prompt electrons and misidentified jets and $|\eta| < 2.5$) or one isolated muon ($E_T > 53 \text{ GeV}$ and $|\eta| < 2.4$).
- Two additional requirements in the selection are: $|\Delta\phi(\vec{p}_T^\ell, \vec{p}_T^{\text{miss}})| > 2.5$ and $0.4 < p_T^\ell/E_T^{\text{miss}} < 1.5$
- The main discriminating variable is:

$$M_T = \sqrt{2p_T^\ell E_T^{\text{miss}} (1 - \cos[\Delta\phi(\vec{p}_T^\ell, \vec{p}_T^{\text{miss}})])}$$



W' gauge boson in lepton plus missing transverse momentum.

- Sequential standard model (SSM): new massive boson with same couplings as the SM W boson. The decay channel $W' \rightarrow t\bar{b}$ is also allowed.
- Exclusion limits are also set for the production of generic W' boson using a model-independent approach.



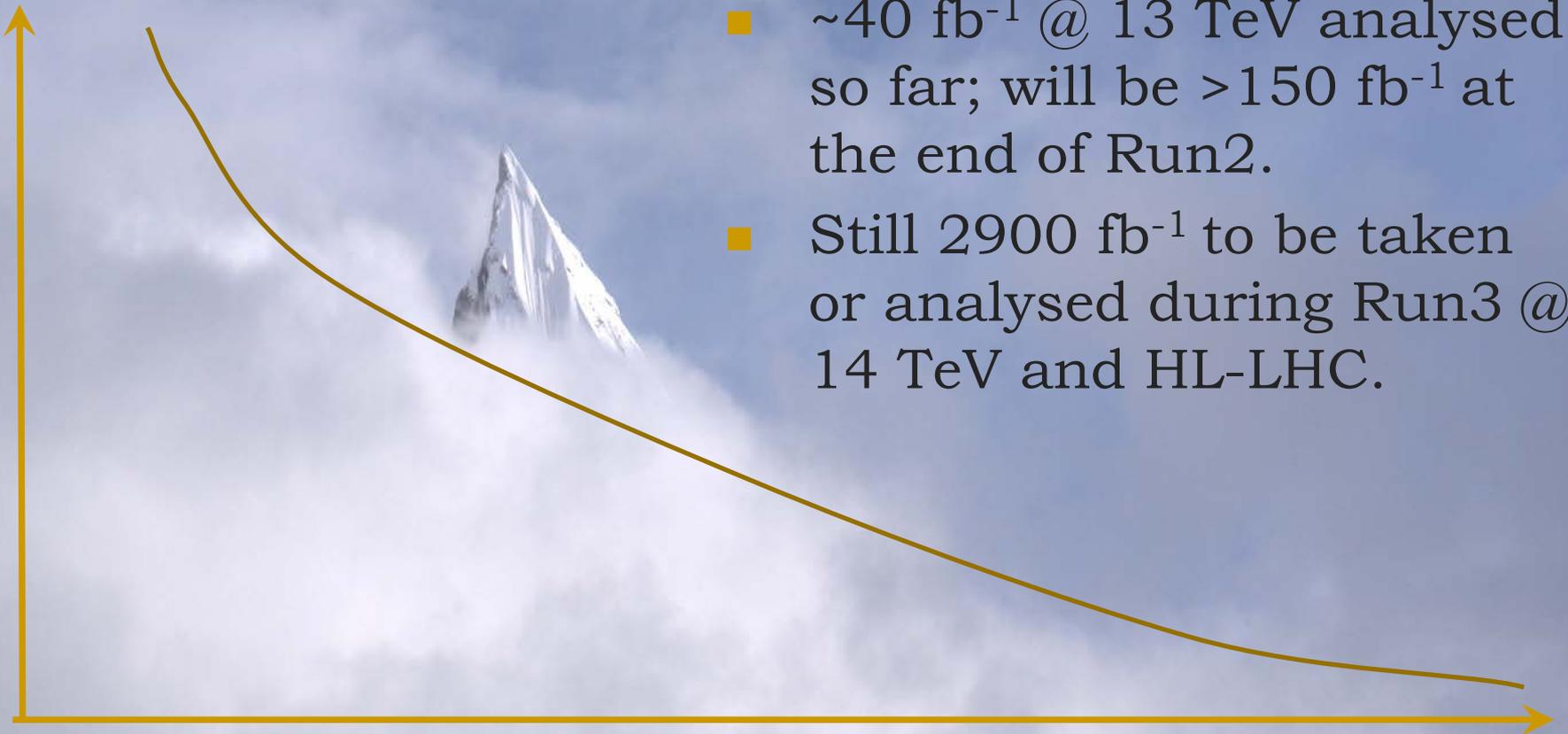
95% CL limit on SSM W' mass:

- electron channel 3.6 TeV
- muon channel 3.9 TeV
- combined 4.1 TeV (4.0 TeV expected)

Tighter limits than those obtained from Run 1 data.

Conclusions

- No sign of new heavy resonances in the very first 13 TeV data.
- CMS (with ATLAS) is setting stringent limits on BSM scenarios.
- $\sim 40 \text{ fb}^{-1}$ @ 13 TeV analysed so far; will be $> 150 \text{ fb}^{-1}$ at the end of Run2.
- Still 2900 fb^{-1} to be taken or analysed during Run3 @ 14 TeV and HL-LHC.





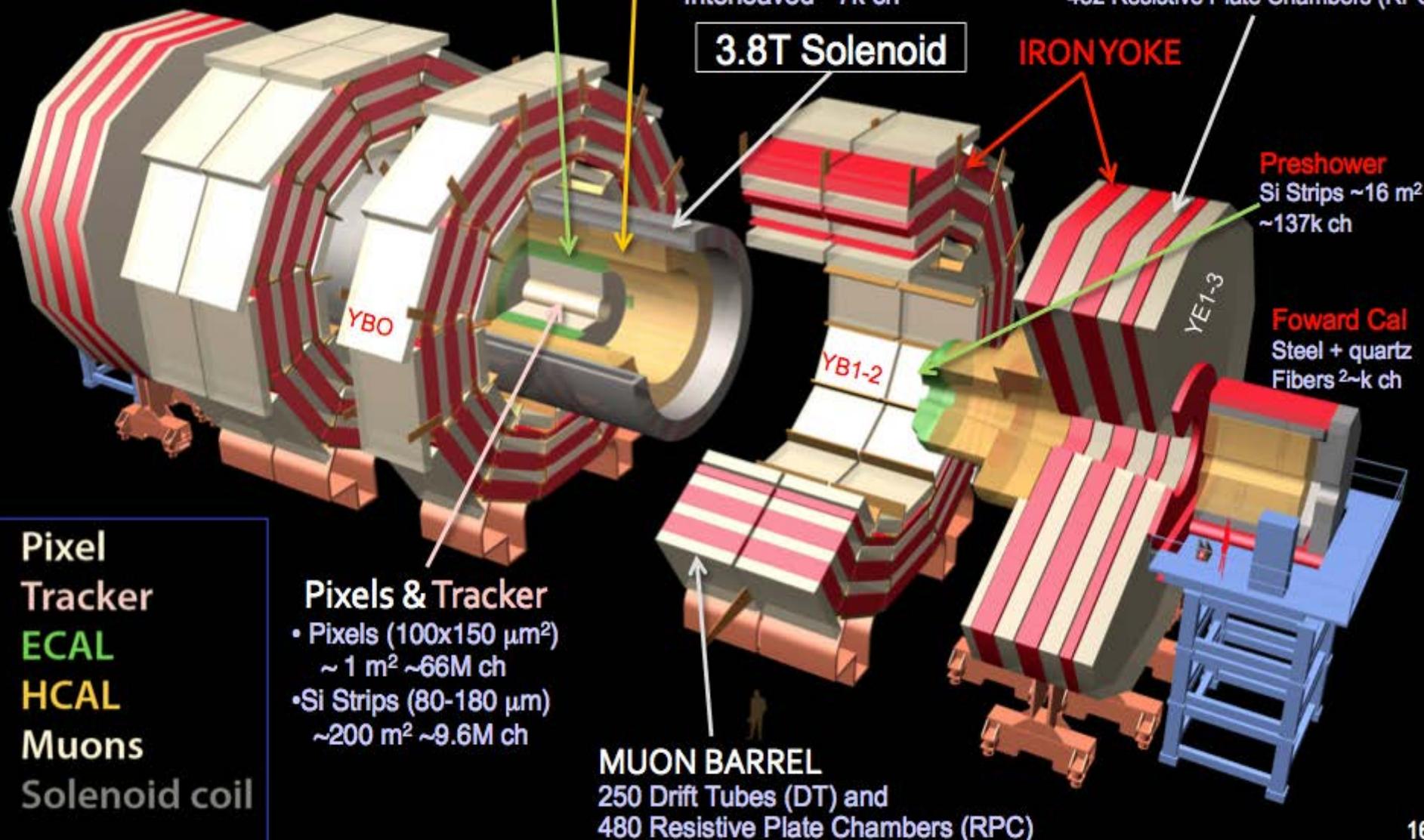
Backup

CMS

Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m

MUON ENDCAPS

473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)



[CL limit procedure]

$$\mathcal{L}(\text{data} | \mu, \theta) = \text{Poisson}(\text{data} | \mu \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta} | \theta).$$

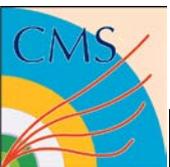
$$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(\text{data} | \mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data} | \hat{\mu}, \hat{\theta})}$$

$$p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} | \text{signal+background}) = \int_{\tilde{q}_\mu^{\text{obs}}}^{\infty} f(\tilde{q}_\mu | \mu, \hat{\theta}_\mu^{\text{obs}}) d\tilde{q}_\mu$$

$$1 - p_b = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} | \text{background-only}) = \int_{\tilde{q}_0^{\text{obs}}}^{\infty} f(\tilde{q}_\mu | 0, \hat{\theta}_0^{\text{obs}}) d\tilde{q}_\mu$$

and calculate $CL_s(\mu)$ as a ratio of these two probabilities ¹

$$CL_s(\mu) = \frac{p_\mu}{1 - p_b}$$



Systematic errors in diphoton analysis



Signal model:

- ✓ Luminosity: 6.2% on signal normalization
- ✓ Trigger and photon selection: 6% on signal normalization
- ✓ Photon energy scale: 1%
- ✓ Photon energy resolution: 0.5%
- ✓ PDF: 6% on signal normalization

Background model:

- ✓ Bias term only
- ✓ Parameter coefficients: unconstrained nuisance parameters contribute to statistical error

Comparison to 8 TeV search

- Combination with 8 TeV results in narrow width hypothesis
- ✓ different acceptance and categorizations
- ✓ most sensitive 8 TeV analysis in each mass range considered

Likelihood of fits to S+B hypothesis vs 13 TeV equivalent cross-section:

- ✓ 8 TeV limits scaled by xsec ratio
- ✓ S=RS Graviton, $m_G=750$ GeV, $k=0.01$
 - ✓ production: 90% gg, 10% qqbar
 - ✓ $xsec(8TeV)/xsec(13TeV)=1/4.2=0.24$

- **Compatible equivalent cross-sections within uncertainties**
- **13 TeV result not in contradiction with 8 TeV**

