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

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in the LHC Era
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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 → 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

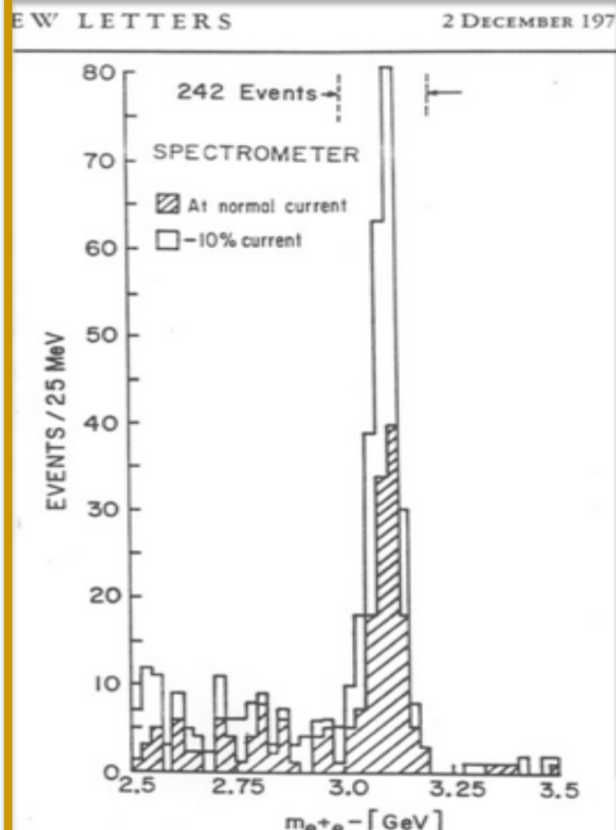
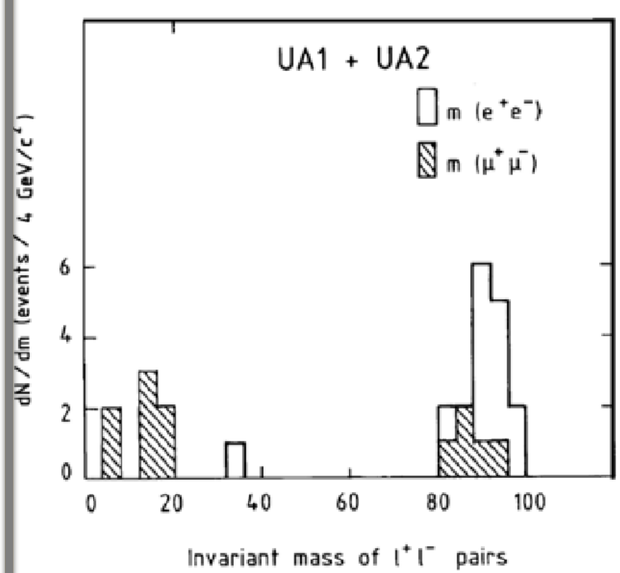
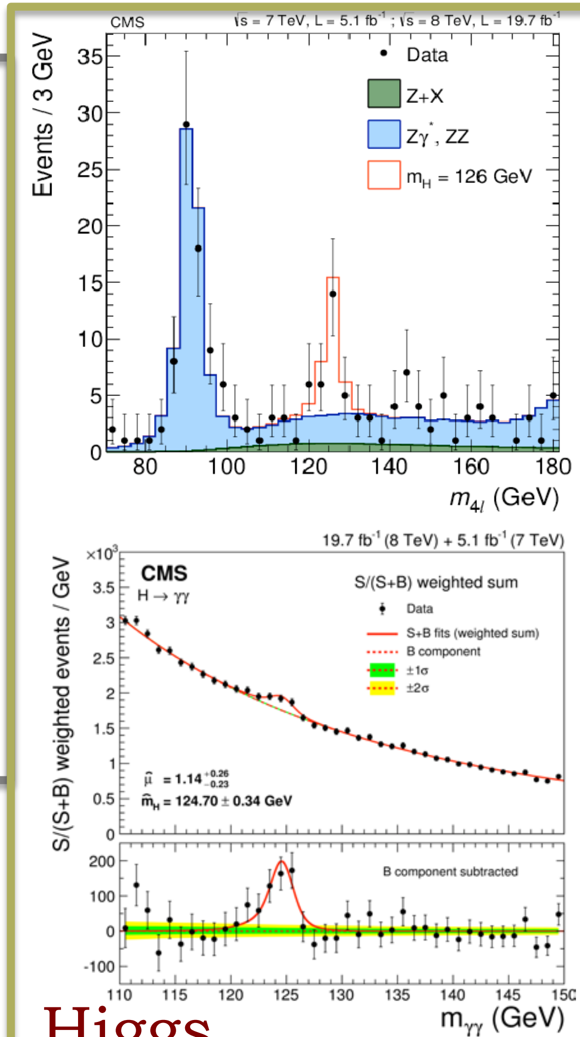


FIG. 2. Mass spectrum showing the existence of J. ...sults from two spectrometer settings are plotted ...wing that the peak is independent of spectrometer ...rents. The run at reduced current was taken two ...nths later than the normal run.

J/Psi

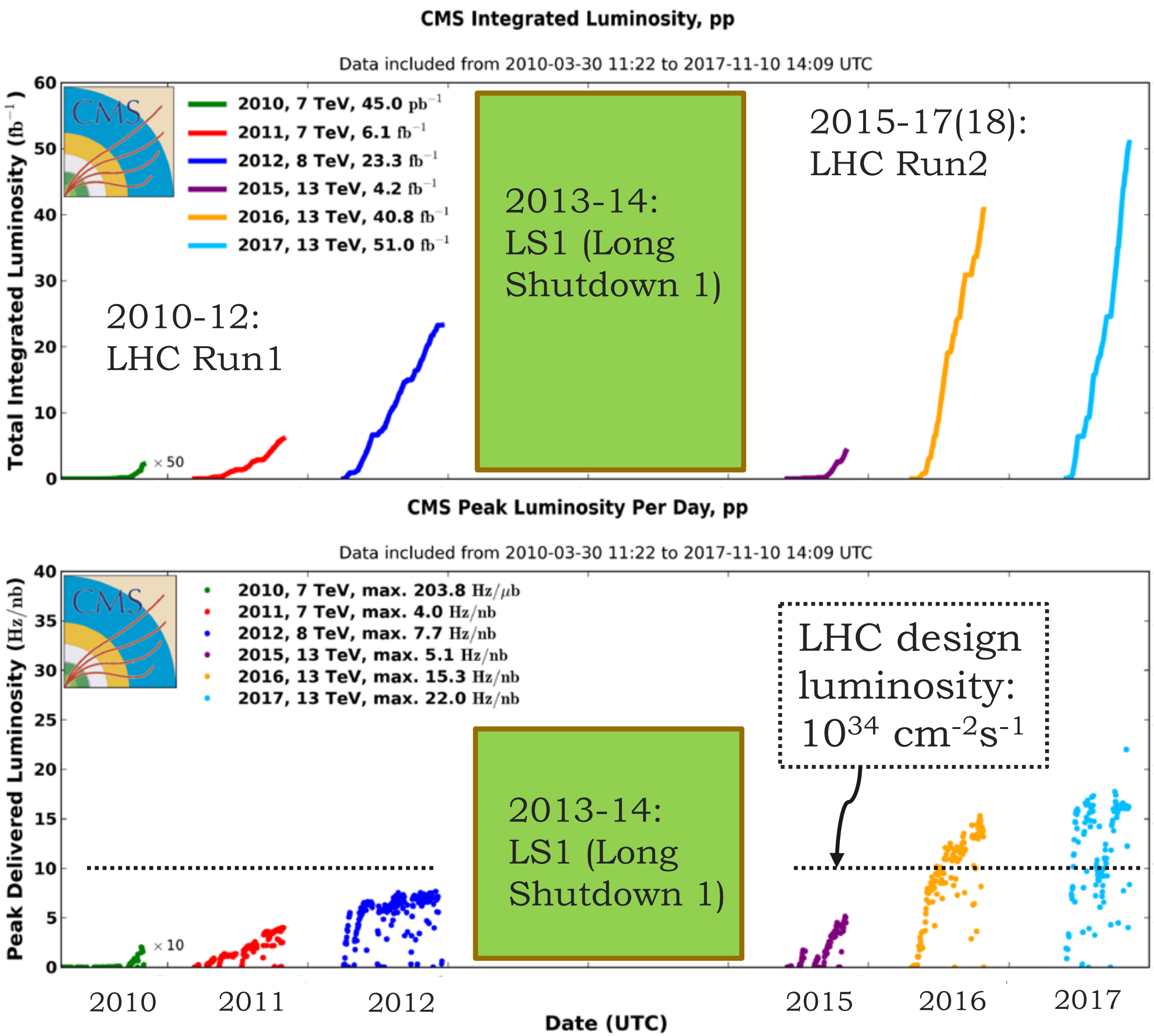


Z



Higgs

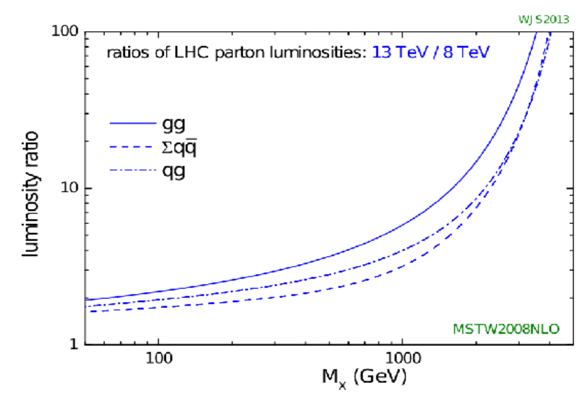
Large Hadron Collider performances (Run1-Run2)



From Run1 to Run2

- 7/8 TeV → 13 TeV

increasing √s extends the reach of Run1



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

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

High mass resonances in diphoton final state

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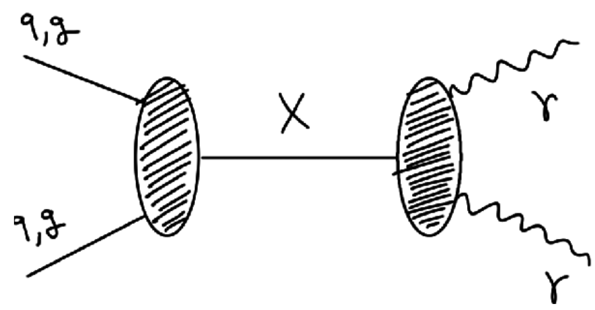
- Data sample: 12.9 fb^{-1} taken in 2016 at $\sqrt{s}$ = 13 TeV combined with
  - 3.3 fb^{-1} taken in 2015 at $\sqrt{s}$ = 13 TeV
  - 19.7 fb^{-1} taken in 2012 at $\sqrt{s}$ = 8 TeV
- Analysis built on SM Higgs search experience
- Robust and model-independent cut based analysis



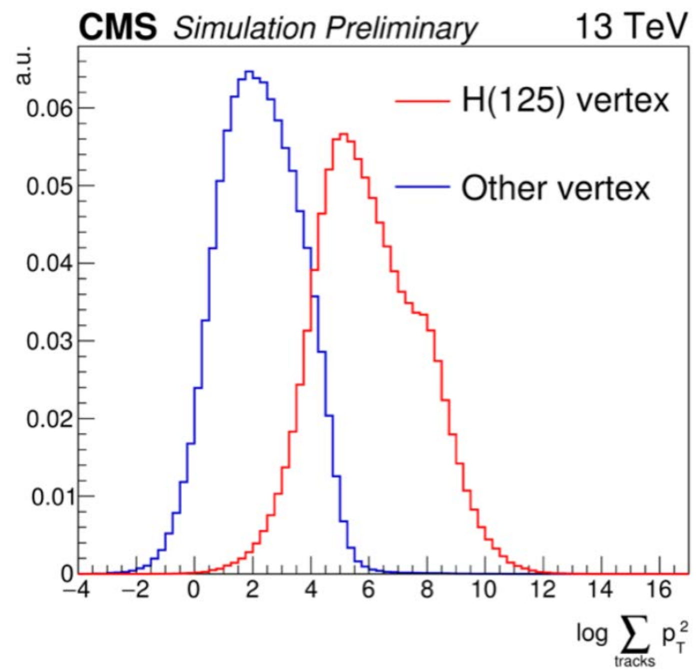
Benchmark models:

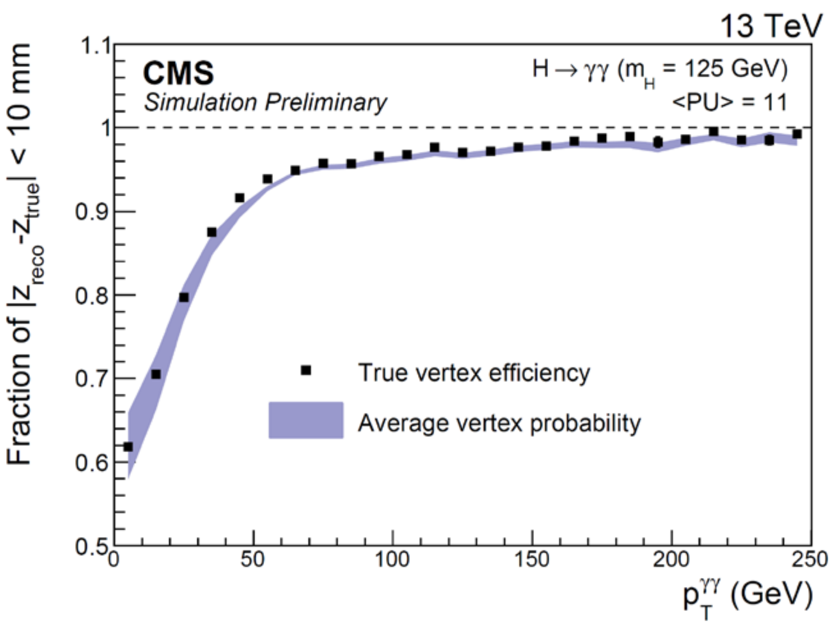
- **Spin-0 analysis**: extended Higgs sector (2HDM)
  - Scalar and/or pseudo-scalar can have sizable branching ratio to diphoton
- **Spin-2 analysis**: Randall-Sundrum graviton
  - Model predicts tower of Kaluza-Klein states with TeV mass scale; mass of the RS graviton is the mass lightest KK excitation

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

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





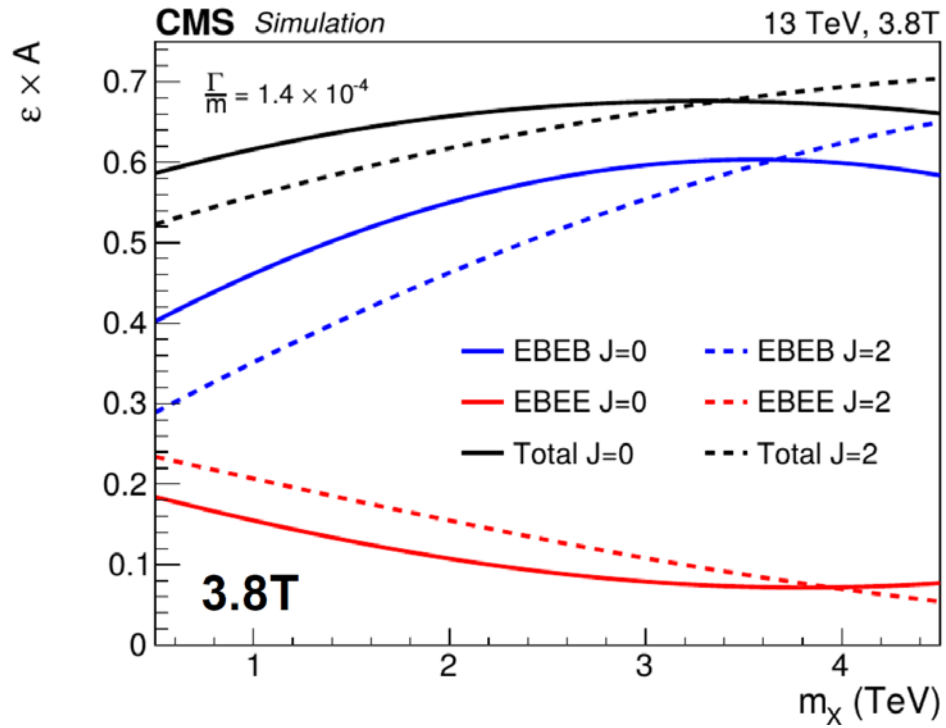
- Average probability is ~ **90%**.
- Performance validated in data with $Z \rightarrow \mu\mu$ events

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



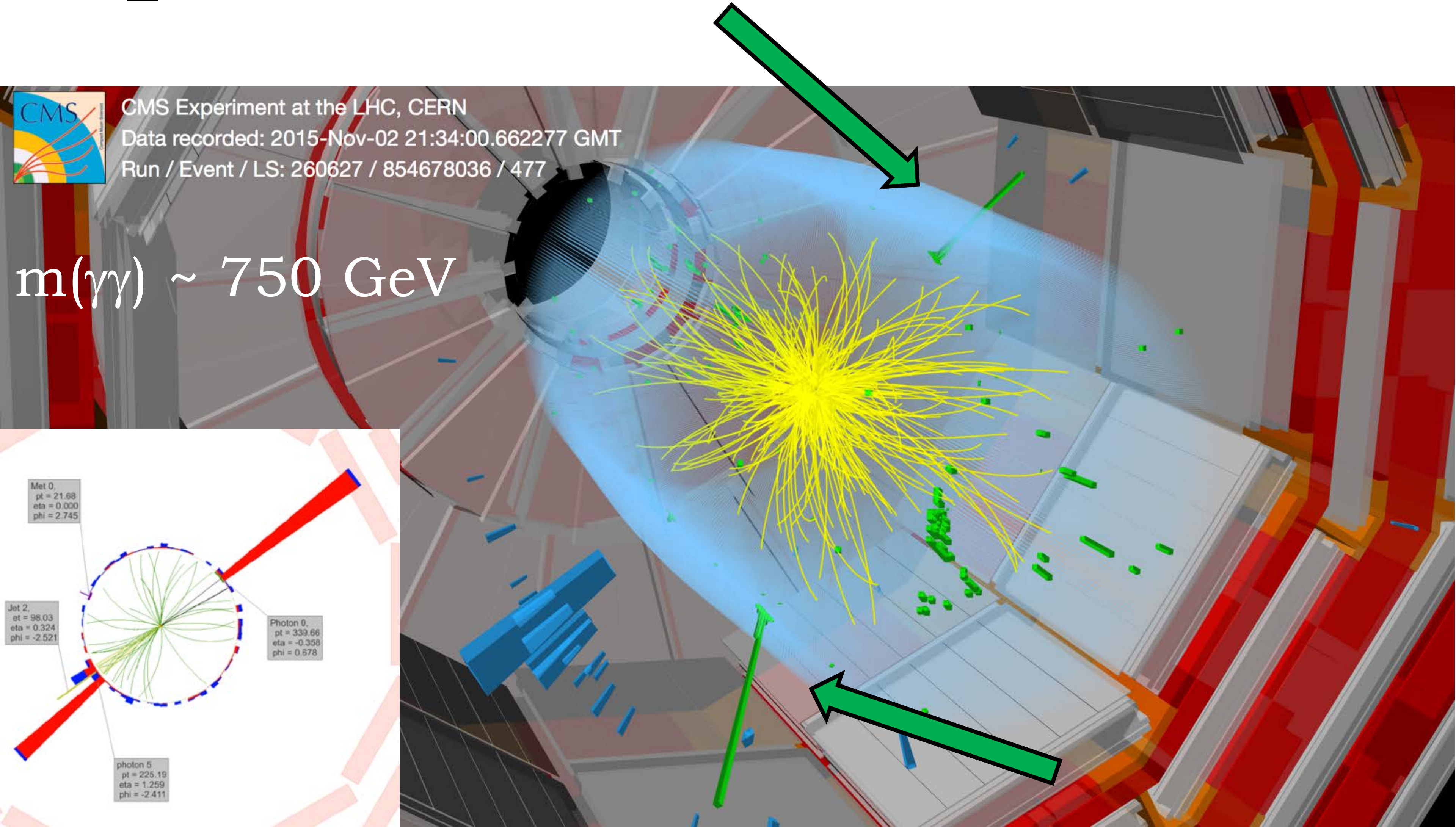
10-15% improvement from adding the barrel-endcap category

Per-photon efficiency in the barrel (endcaps): ~90%(~85%).

Zee to check efficiencies

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

High mass resonances in diphoton final state



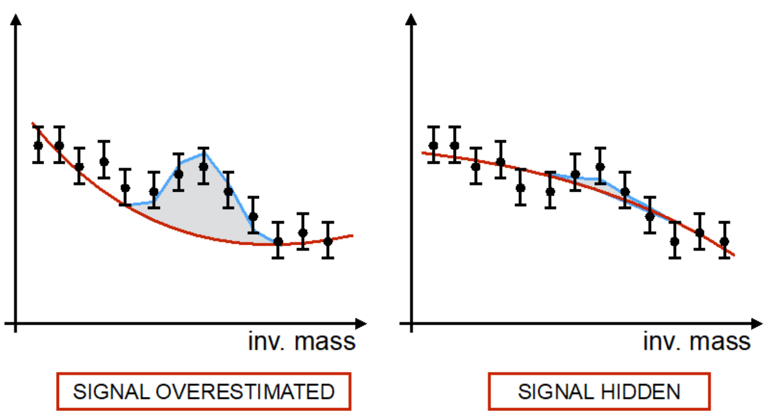
Signal and bg modelling

- 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)	$\sigma^{3.8T}_{FWHM}/m$	
	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:

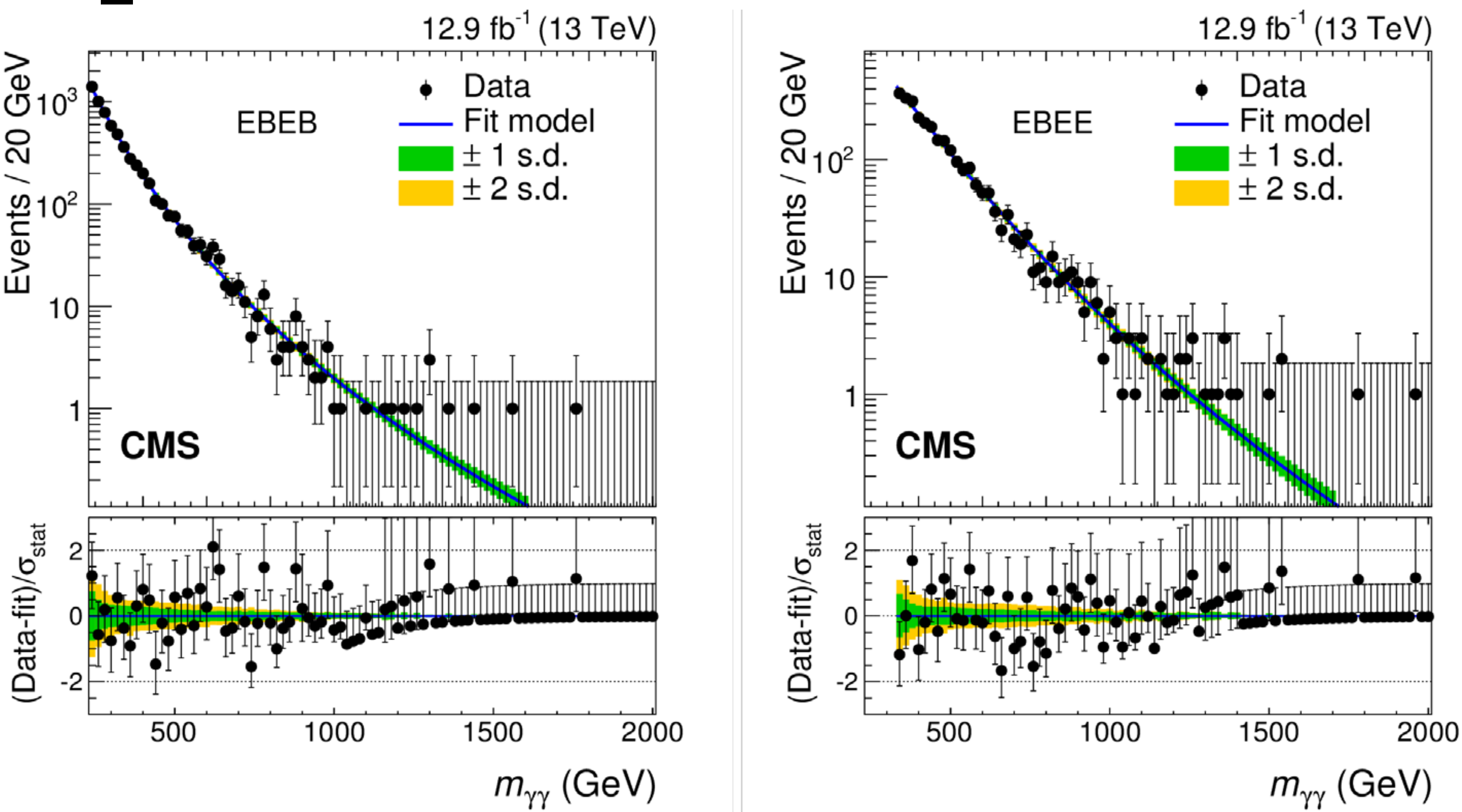
✓ parametric fit to data $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$



Background composition is measured in data with template fits:

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

High mass resonances in diphoton final state

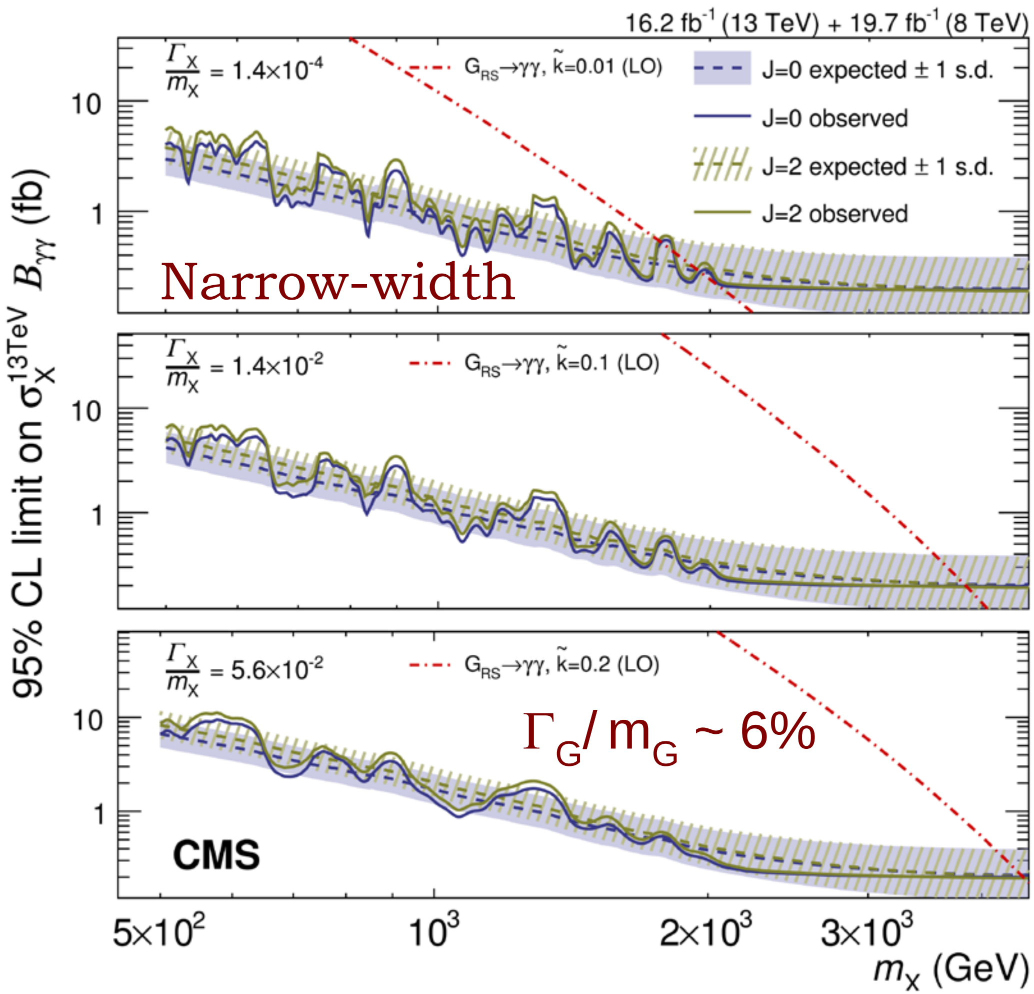


$m_{\gamma\gamma}$ spectra of selected events in the two categories

Interpretation: exclusion limits

Observed limits on Graviton cross section x 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)



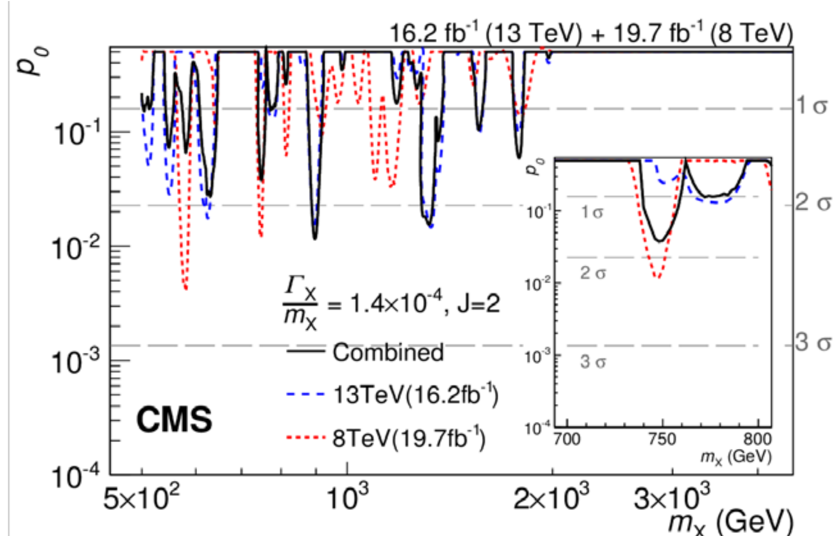
<u>Most stringent limits on RS graviton production to date.</u>

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

Interpretation: p value

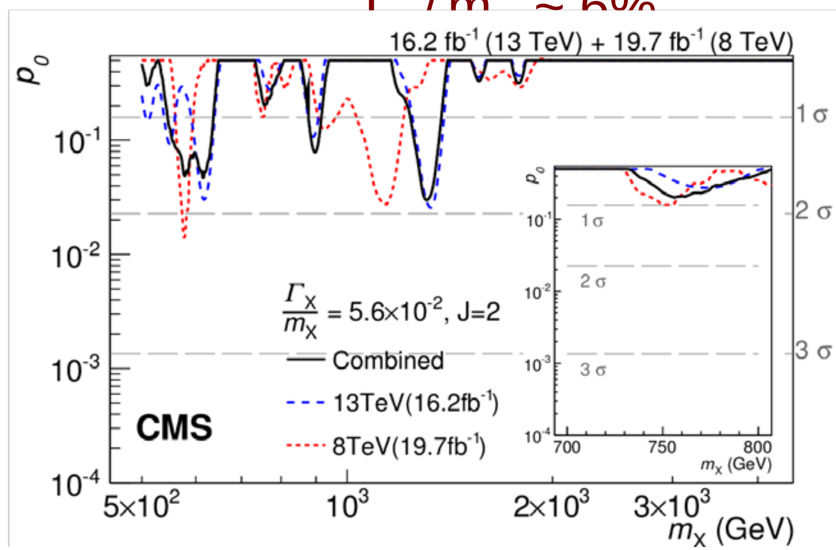
Excess observed by CMS and ATLAS at 750 GeV in 2015 data:

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



<u>Excess not confirmed with 4 times more data analyzed in 2016.</u>

- 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

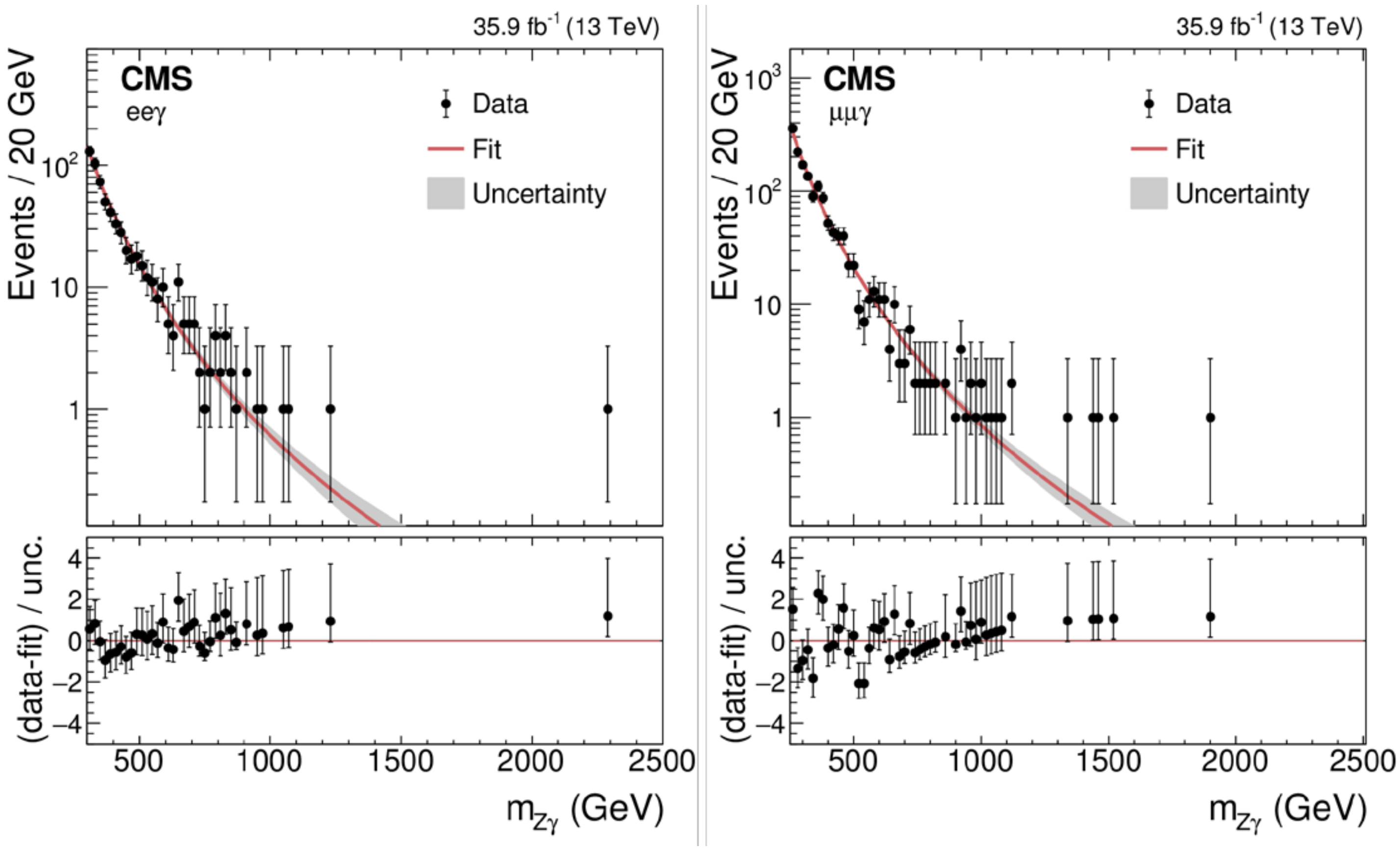
CMS PAS EXO-17-005 (arXiv:1712.03143 - submitted to JHEP)

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

- Two isolated electrons with $E_T > 65/10$ GeV and one photon with $E_T > 65$ GeV all in the acceptance $|\eta| < 2.5$
- Two isolated muons with opposite charge, $E_T > 52/10$ GeV and $|\eta| < 2.4$ and one photon with $E_T > 40$ 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

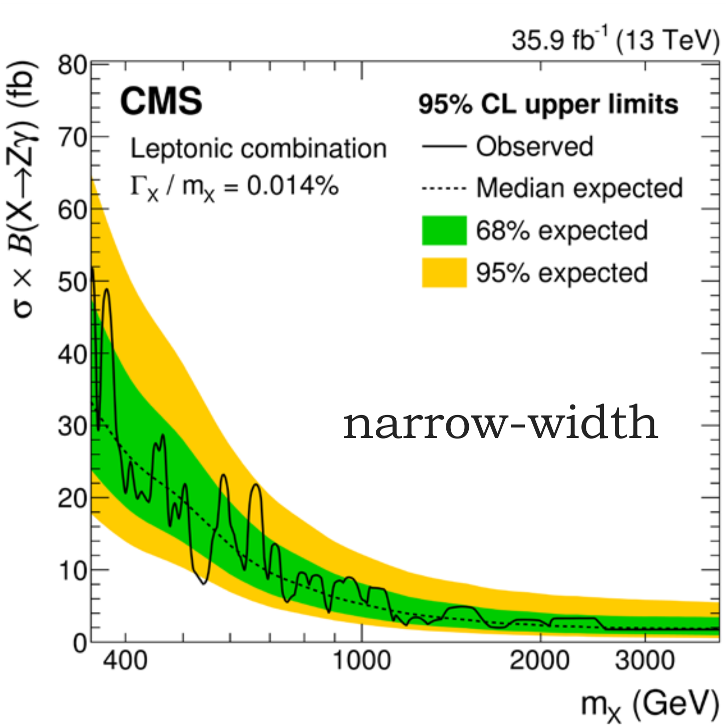


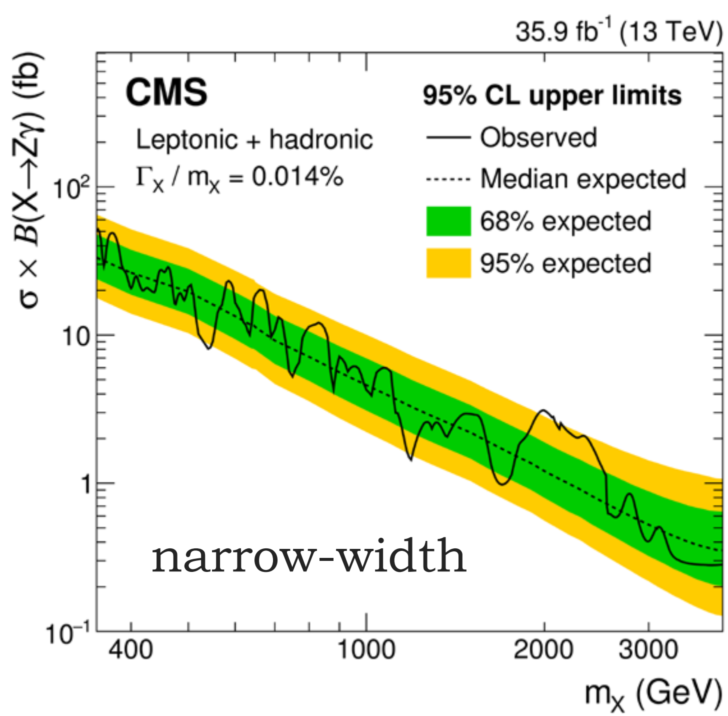
The SM background is described by the function $f(m_{Z\gamma}) = m_{Z\gamma}^{a+b\log m_{Z\gamma}}$ fitting directly on data events.

<u>No significant excess over the background-only hypothesis.</u>

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.

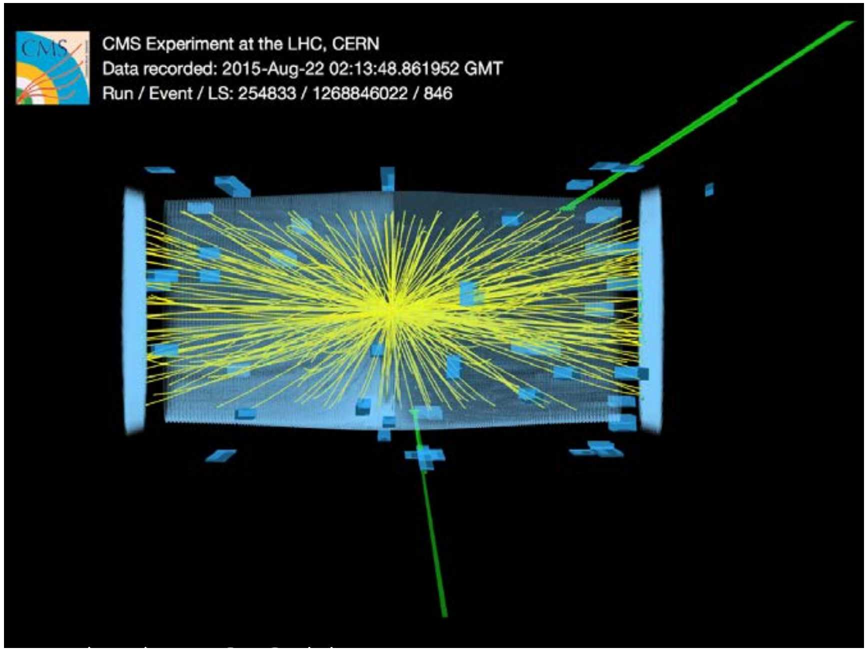


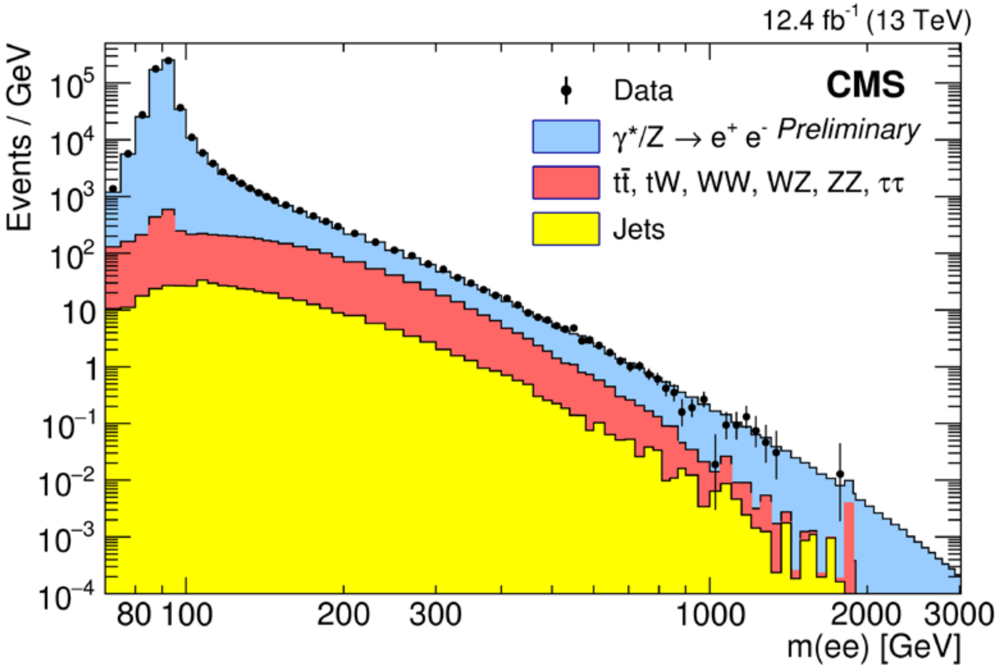


High mass resonances in dielectron final state

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

- Two isolated electrons with E_T > 35 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±8% and BE 66±10%

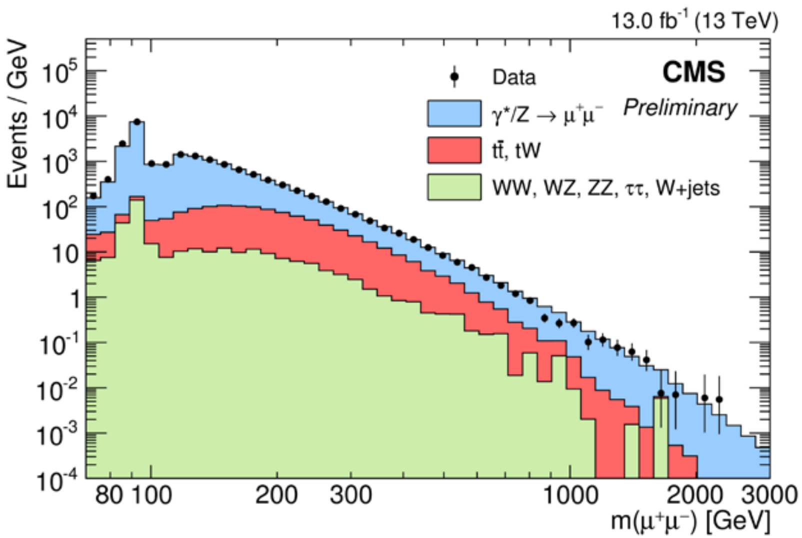


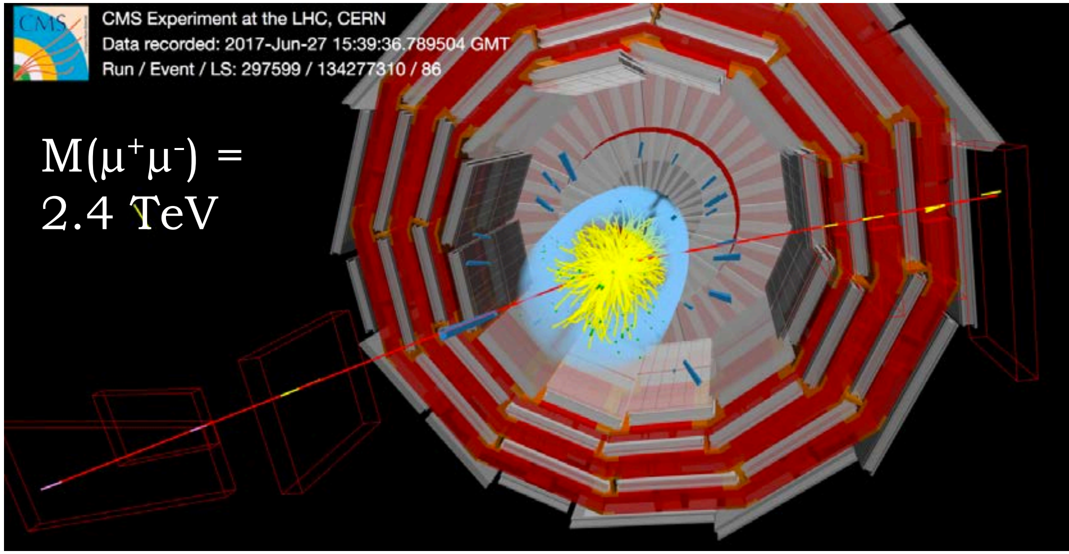


High mass resonances in dimuon final state

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

- Two isolated muons with opposite charge, E_T > 53 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 ~5% with both muons in the central region (<2% for dielectron pair).



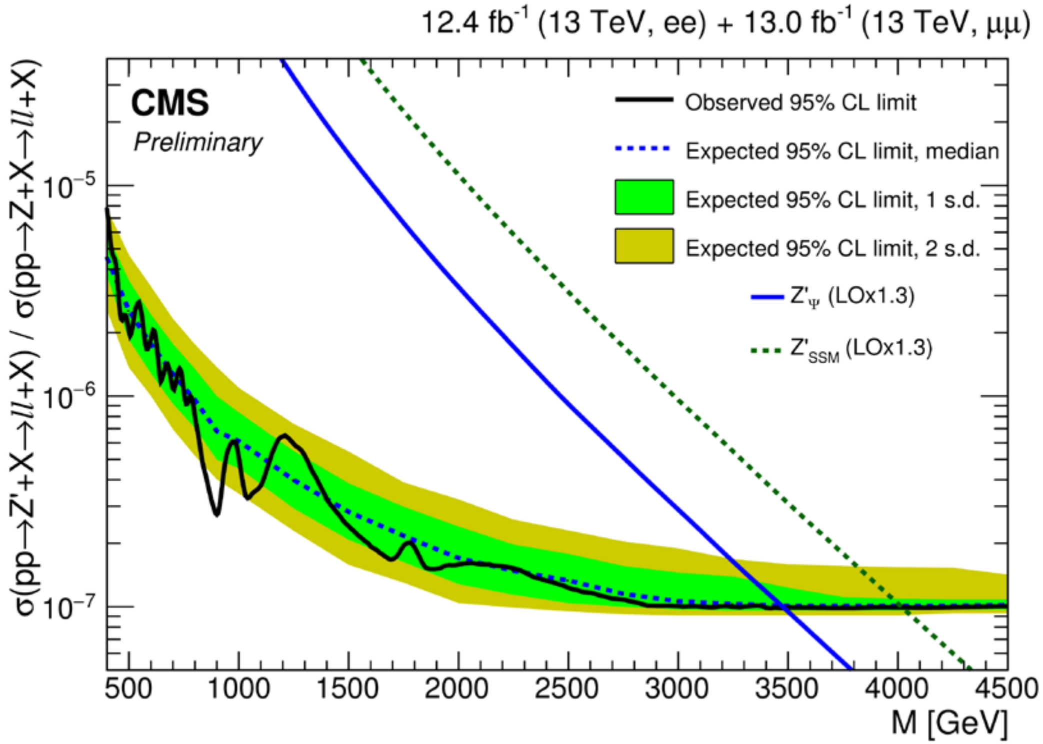


High mass resonances in $ee/\mu^+\mu^-$ final states

- 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



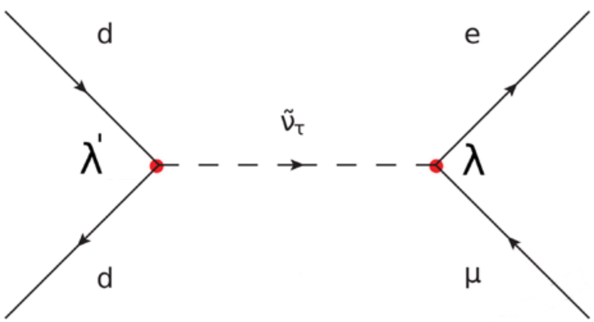
High mass resonances in LFV eμ final states

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

- One isolated electron with E_T > 35 GeV, $|\eta|$ < 2.5 and one isolated muon with E_T > 53 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 eμ pair) and λ' (coupling with ddbar 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 eμ final states

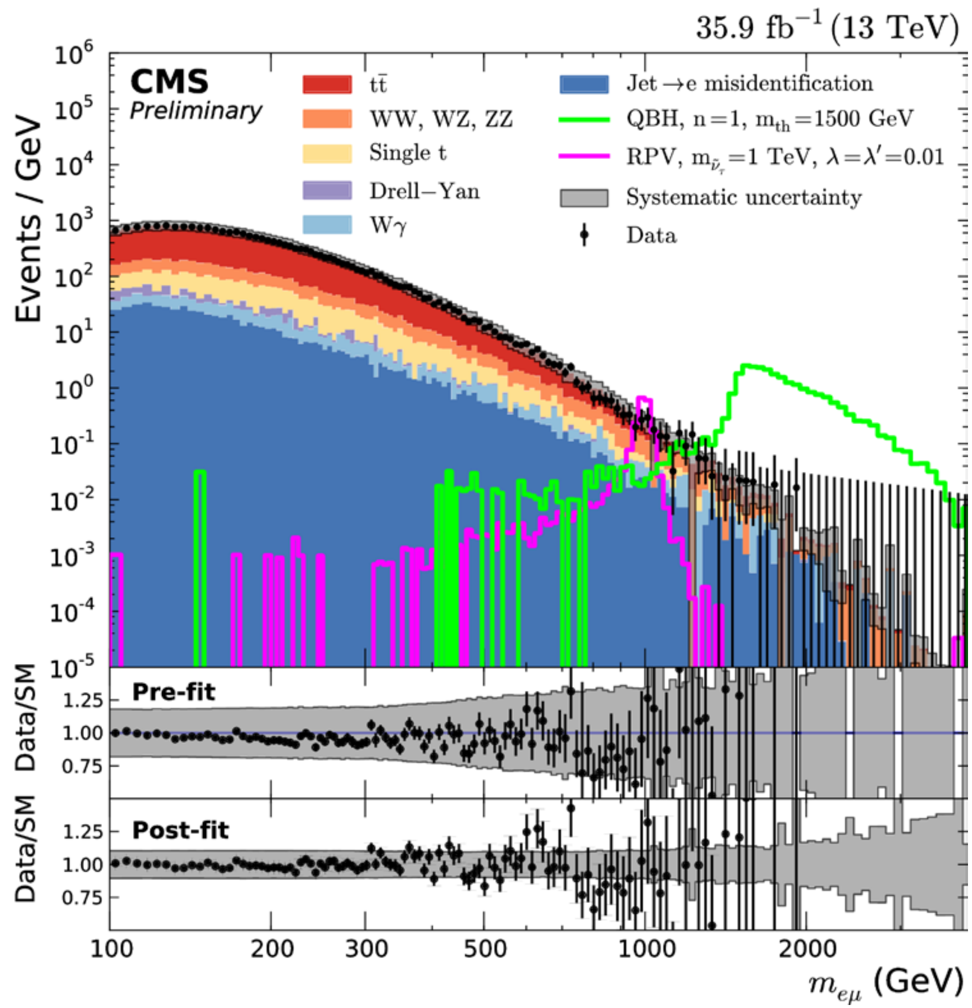
Data consistent with SM expectation in the whole mass range.

- Four events observed with invariant mass > 1.5 TeV.
- SM expectation:
  4.2 ± 0.35(stat.) ± 0.91(syst.)

Invariant mass resolution:

2.2% (3.1%) at 200 GeV (3 TeV)

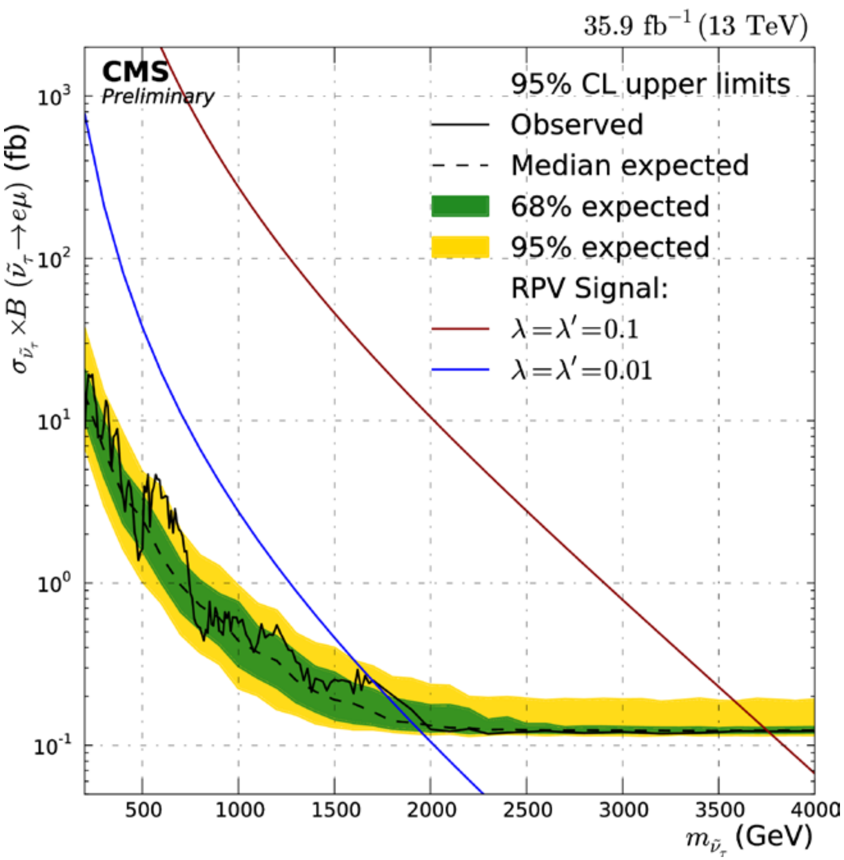
QBH signal is a broad distribution with a threshold mass smeared out by the detector resolution.



High mass resonances in LFV eμ final states

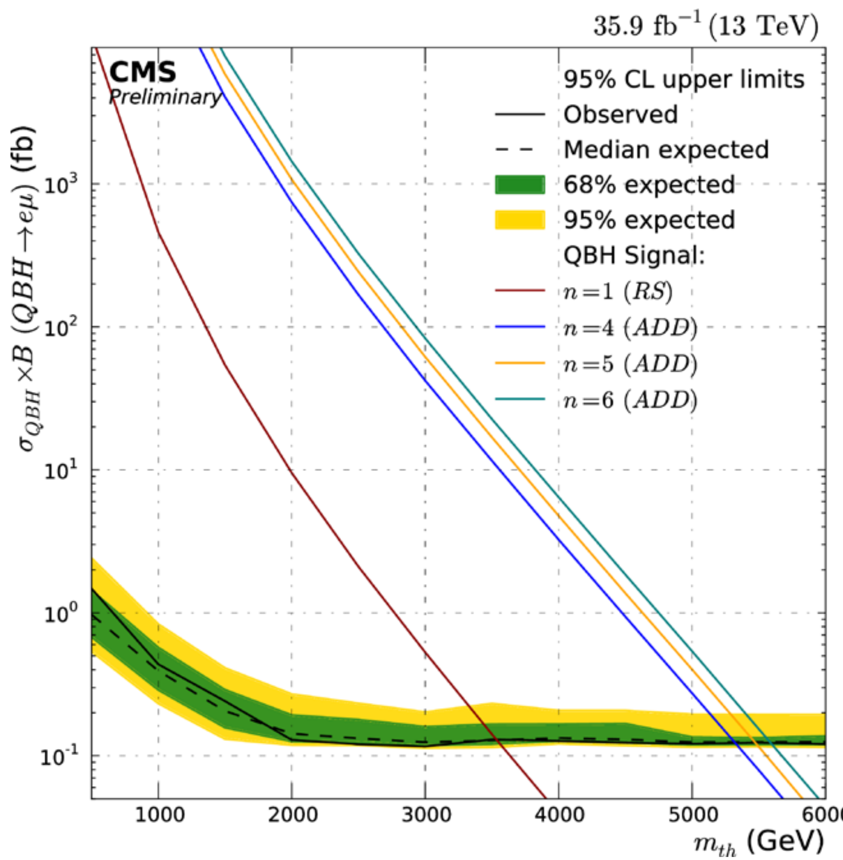
LFV tau sneutrino mass limit:

1.7 TeV to 3.8 TeV for different couplings.



Z' mass limit: 4.4 TeV

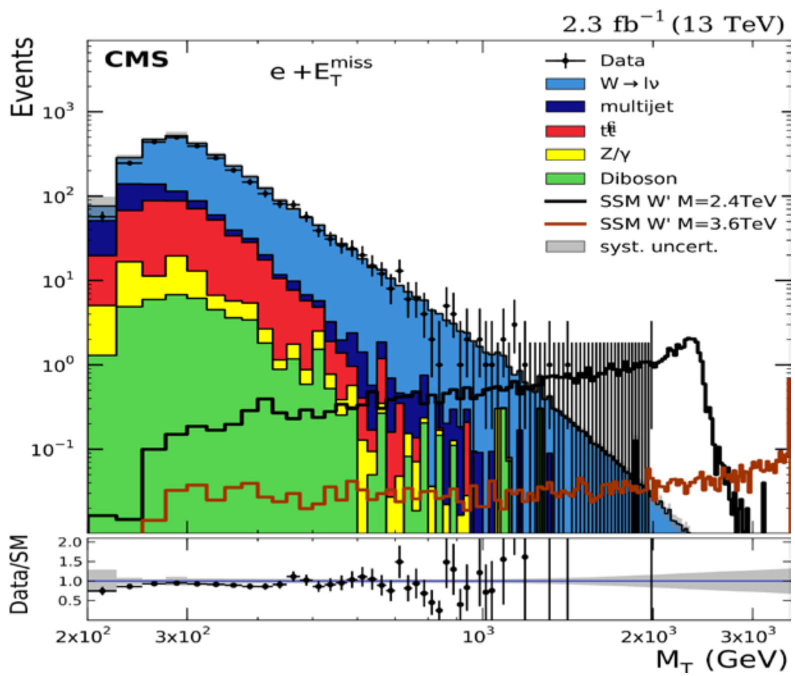
QBH threshold mass limit: 3.6 TeV (one extra-dim.) to 5.6 TeV (n=6)

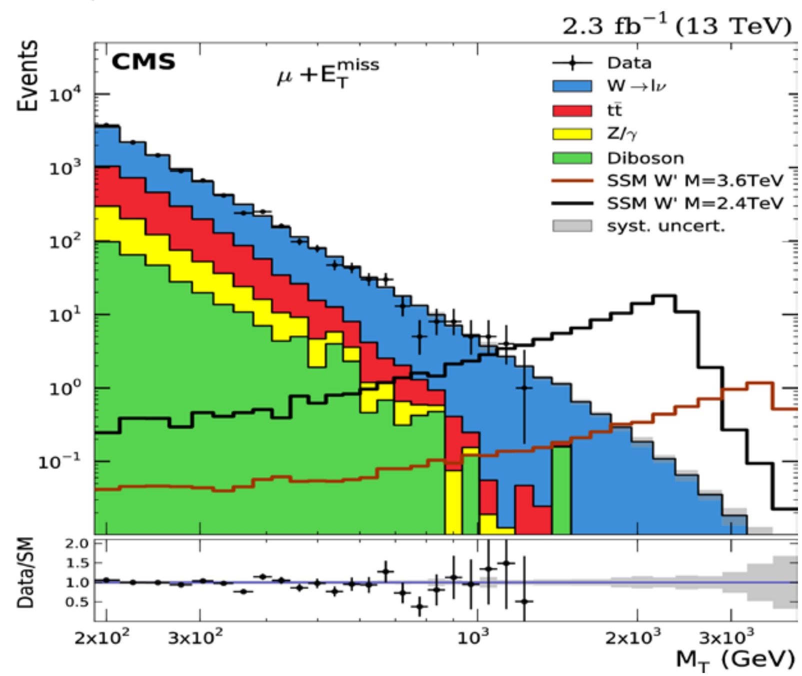


W' gauge boson in lepton plus missing transverse momentum.

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

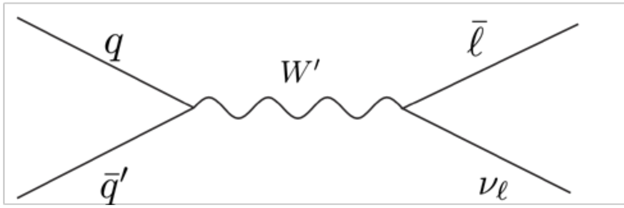
- Large missing transverse momentum and one isolated electron (E_T > 130 GeV to suppress non-prompt electrons and misidentified jets and $|\eta|$ < 2.5) or one isolated muon (E_T > 53 GeV and $|\eta|$ < 2.4).
- Two additional requirements in the selection are: $|\Delta\phi(\vec{p}_T^{\,\ell}, \vec{p}_T^{\,miss})| > 2.5$ and $0.4 < p_T^{\ell}/E_T^{miss} < 1.5$
- The main discriminating variable is: $$M_T = \sqrt{2 p_T^{\ell} E_T^{miss} (1 - \cos[\Delta\phi(\vec{p}_T^{\,\ell}, \vec{p}_T^{\,miss})])}$$

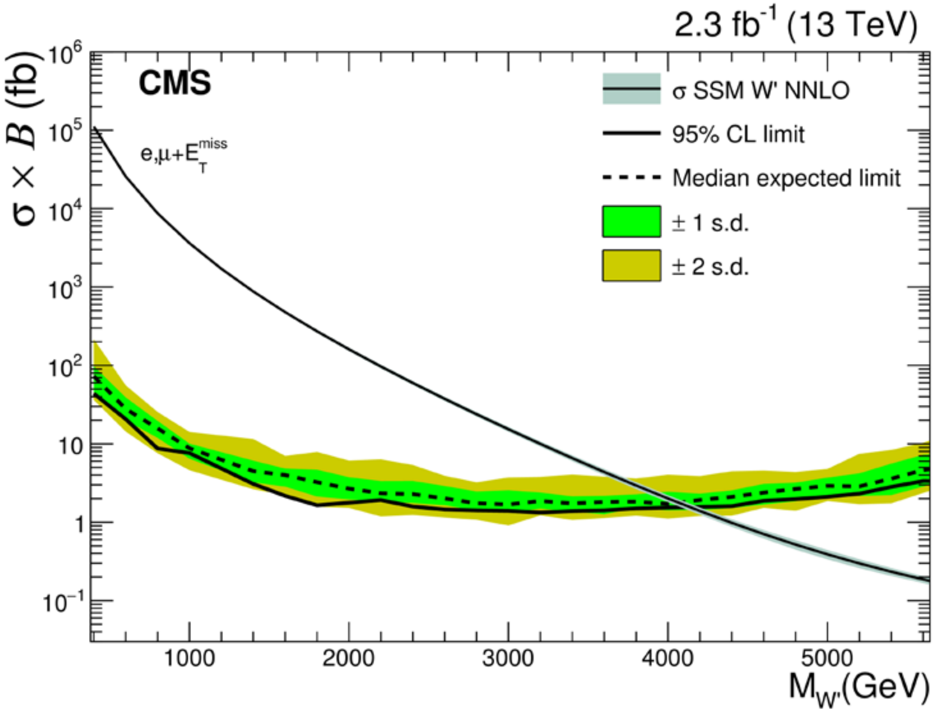




W' gauge boson in lepton plus missing transverse momentum.

- Sequential standard model (SSM): new massive boson with same couplings as the SM W boson. The decay channel W'→tb is also allowed.
- Exclusion limits are also set for the production of generic W' boson using a model-independent approach.





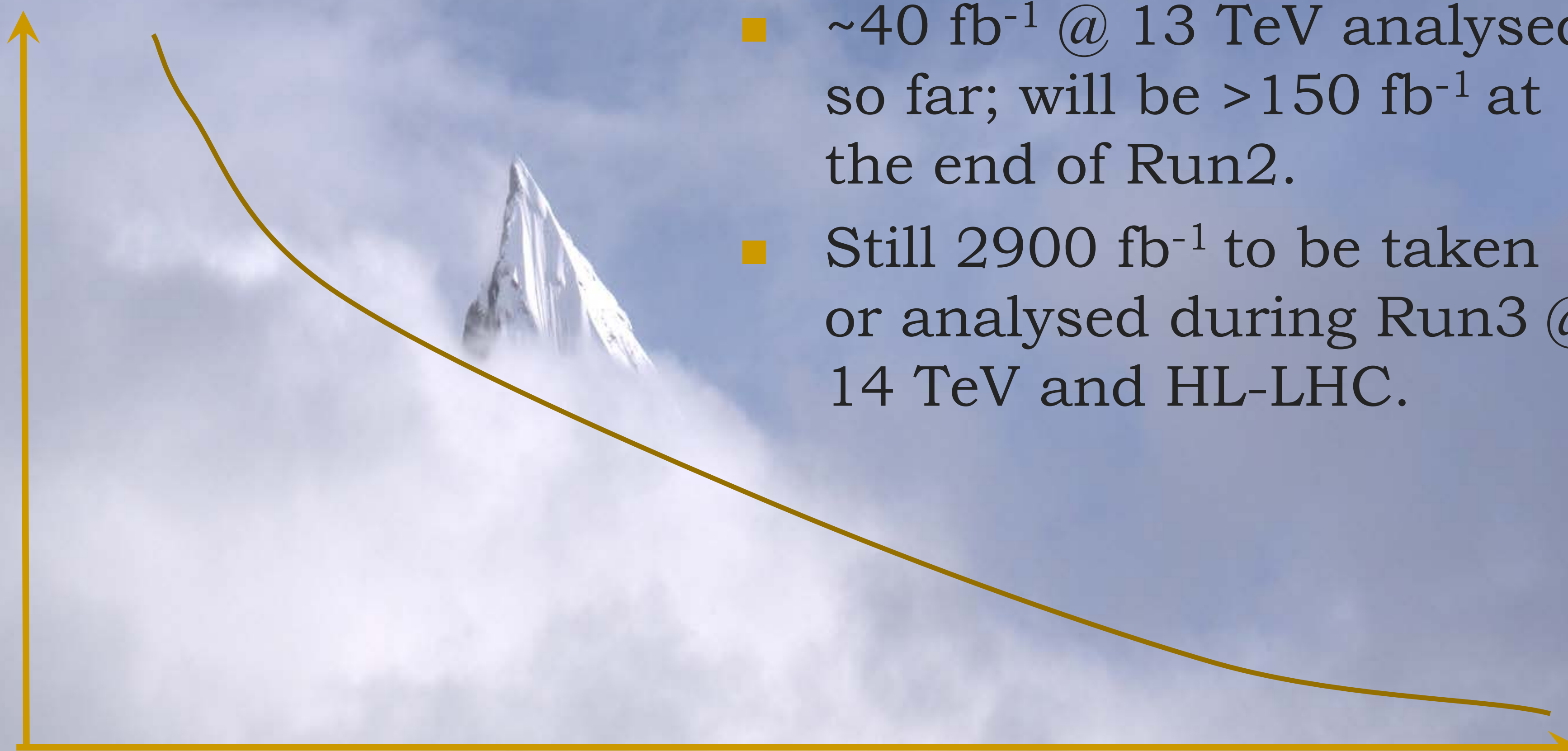
95% CL limit on SSM W' mass:

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

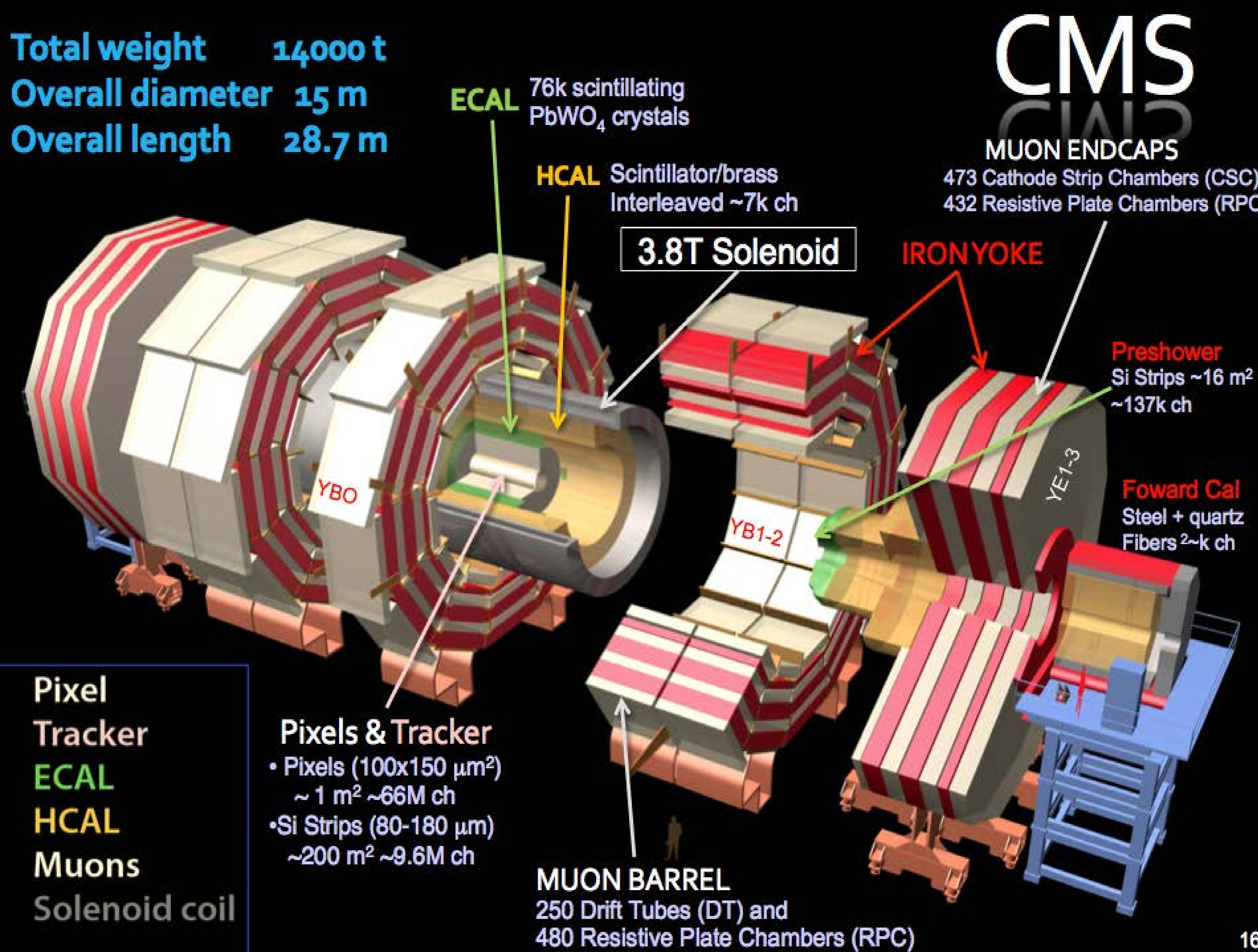
Tighter limits than those obtained from Run 1 data.

Conclusions

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



Backup


Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL 76k scintillating $PbWO_4$ crystals
HCAL Scintillator/brass Interleaved ~7k ch
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
3.8T Solenoid
IRON YOKE
Preshower
Si Strips ~16 m²
~137k ch
YE1-3
Foward Cal
Steel + quartz
Fibers 2~k ch
YBO
YB1-2
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²)
~ 1 m² ~66M ch
•Si Strips (80-180 μm)
~200 m² ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

CL limit procedure

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

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

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

$$1-p_b \;=\; P(\,\tilde{q}_\mu \geq \tilde{q}_\mu^{obs}\,|\,\mathrm{background\text{-}only}) \;=\; \int_{q_0^{\mathrm{obs}}}^{\infty} f(\tilde{q}_\mu|0,\hat{\theta}_0^{\mathrm{obs}})\,d\tilde{q}_\mu$$

and calculate $\mathrm{CL_s}(\mu)$ 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***