Search for high mass diphoton resonances

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on behalf of the CMS and ATLAS collaborations

ETH Institute for Particle Physics

ATLAS

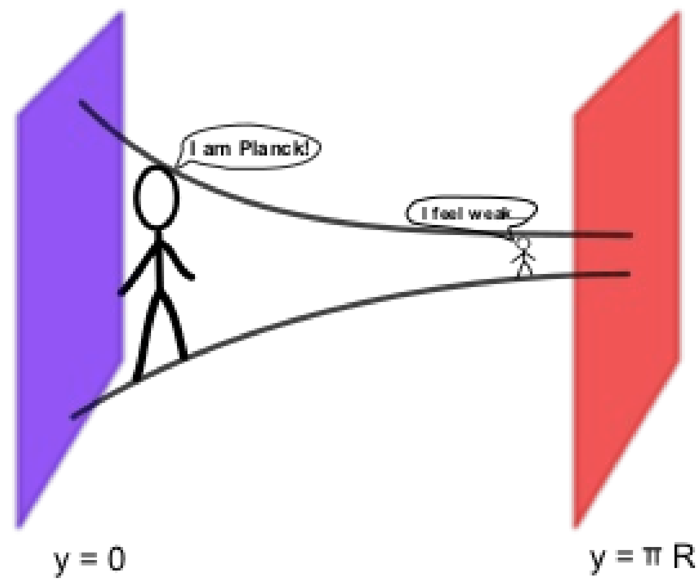
CMS

Compact Muon Solenoid

Motivation

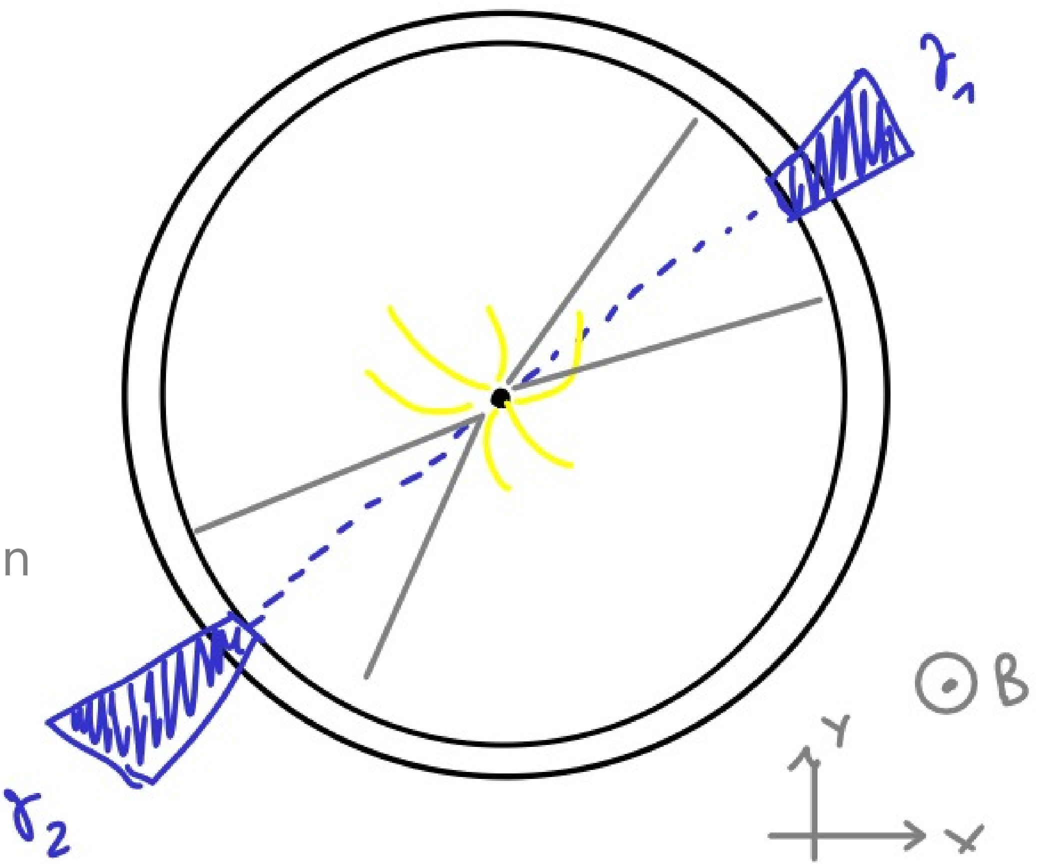
- Search for high mass diphoton resonances in proton-proton collisions motivated by several **models of physics beyond SM**.

- 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 though** predict the appearance of diphoton resonance, given the recent number of phenomenological papers on arXiv.



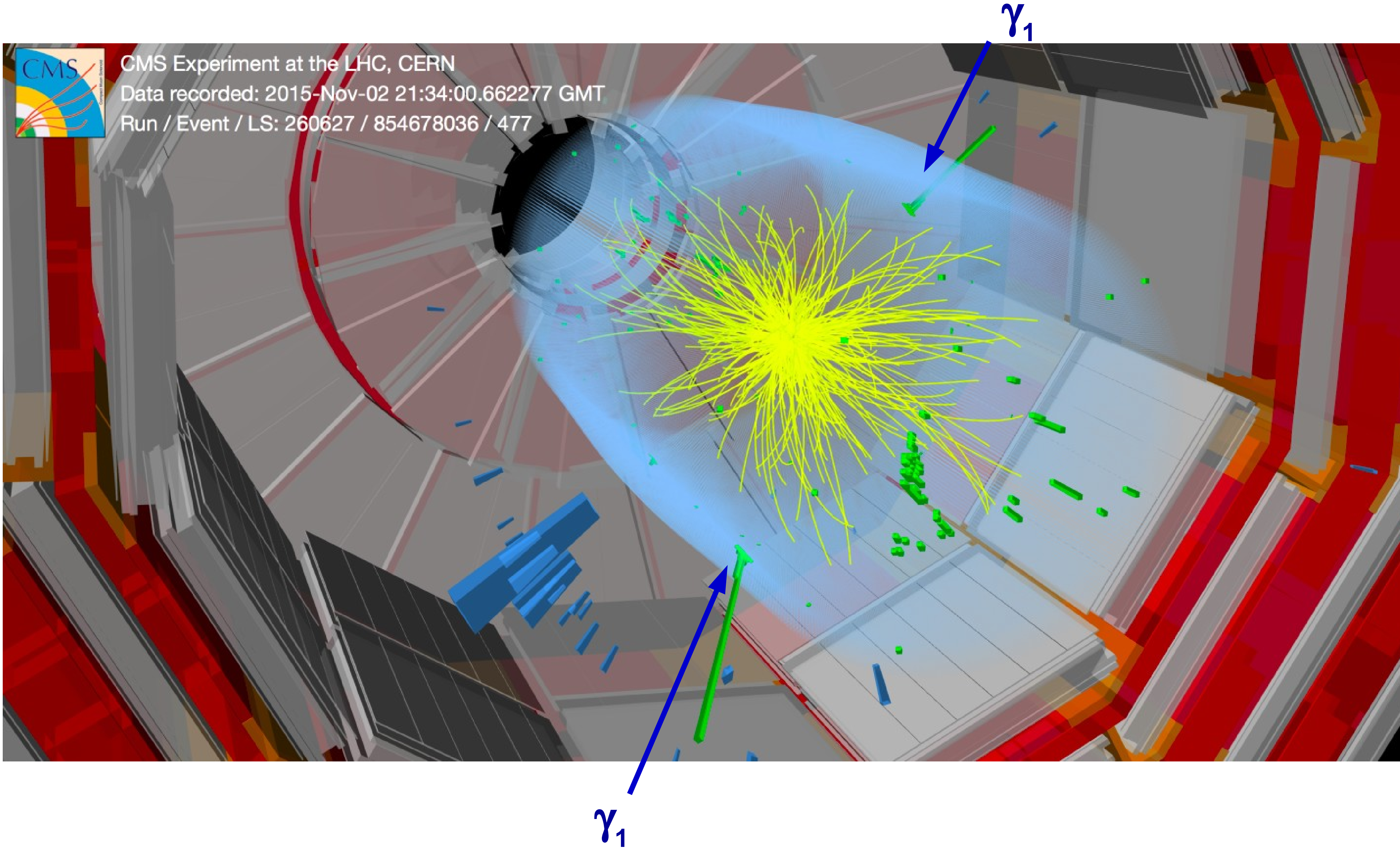
Experimental signature

- 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.



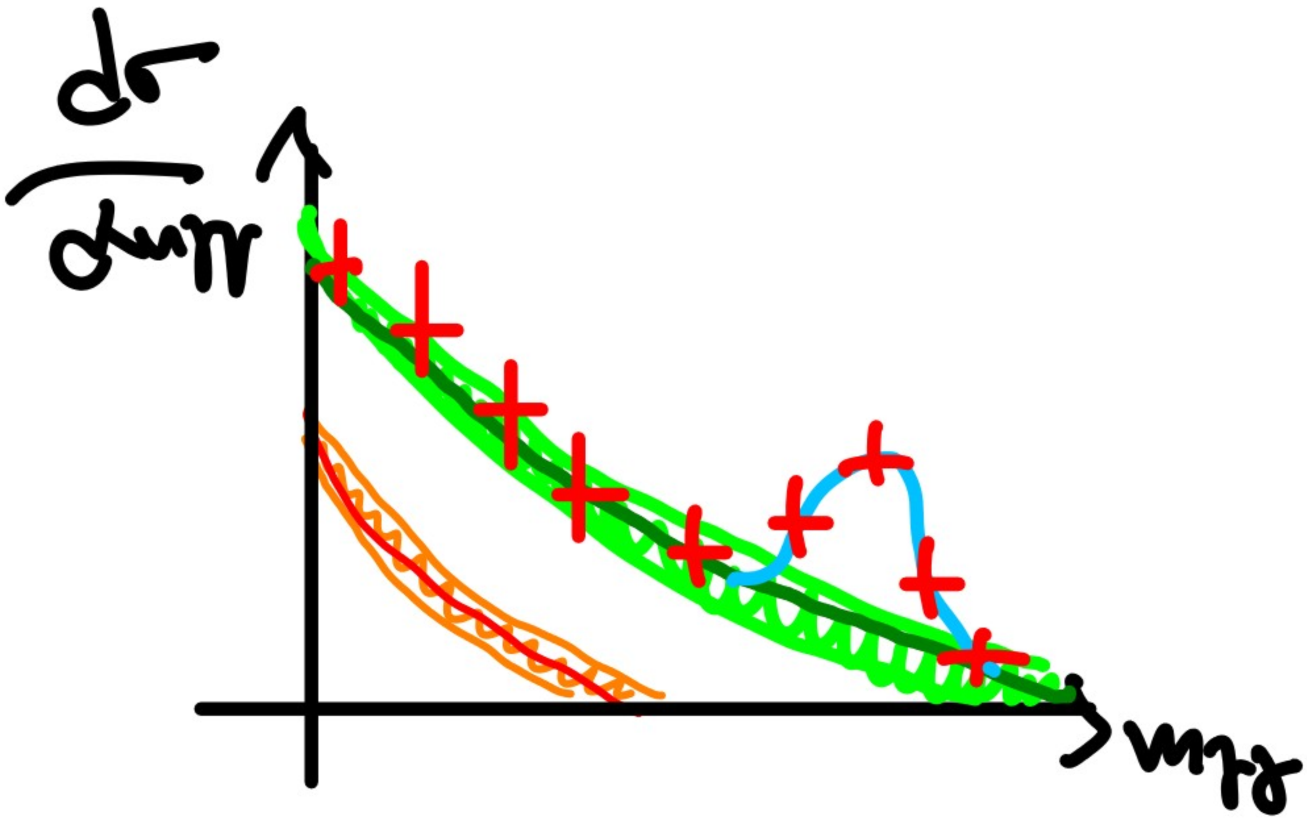
  - Signature of **resonant production**: localized **excess** of events in the diphoton **invariant mass spectrum**.

Experimental signature



Background processes

- In the SM, two kind of **background** processes can give raise to the same experimental signature.
  - **Irreducible** background: pp → γγ
  - **Reducible** backgrounds: pp → γj, pp → jj



- At large diphoton invariant masses, reducible backgrounds are small fraction (O(10%)).

High mass diphoton searches at the LHC.

Ref	Title	M_x	interpreted as	
			spin-0	spin-2
PRL 113 171801	Search for Scalar Diphoton Resonances in the Mass Range 65-600 GeV with the ATLAS Detector in pp Collision Data at √s = 8 TeV	65-600GeV	✔	✘
PRD92 (2015) 3 032004	Search for high-mass diphoton resonances in pp collisions at √s = 8 TeV with the ATLAS detector	0.5-2.8TeV	✘	✔
PLB750 (2015) 494–519	Search for diphoton resonances in the mass range from 150 to 850 GeV in pp collisions at √s = 8 TeV	150-850GeV	✔	✔
CMS-PAS-EXO-12-045	Search for High-Mass Diphoton Resonances in pp Collisions at √s = 8 TeV with the CMS Detector	0.5-3TeV	✘	✔
ATLAS-CONF-2015-081 NEW	Search for resonances decaying to photon pairs in 3.2 fb^{-1} of p p collisions at √s = 13 TeV with the ATLAS detector	0.2-2TeV	✔	✘
CMS-PAS-EXO-15-004 NEW	Search for new physics in high mass diphoton events in proton-proton collisions at √s = 13 TeV	0.5-4.5TeV	✘	✔

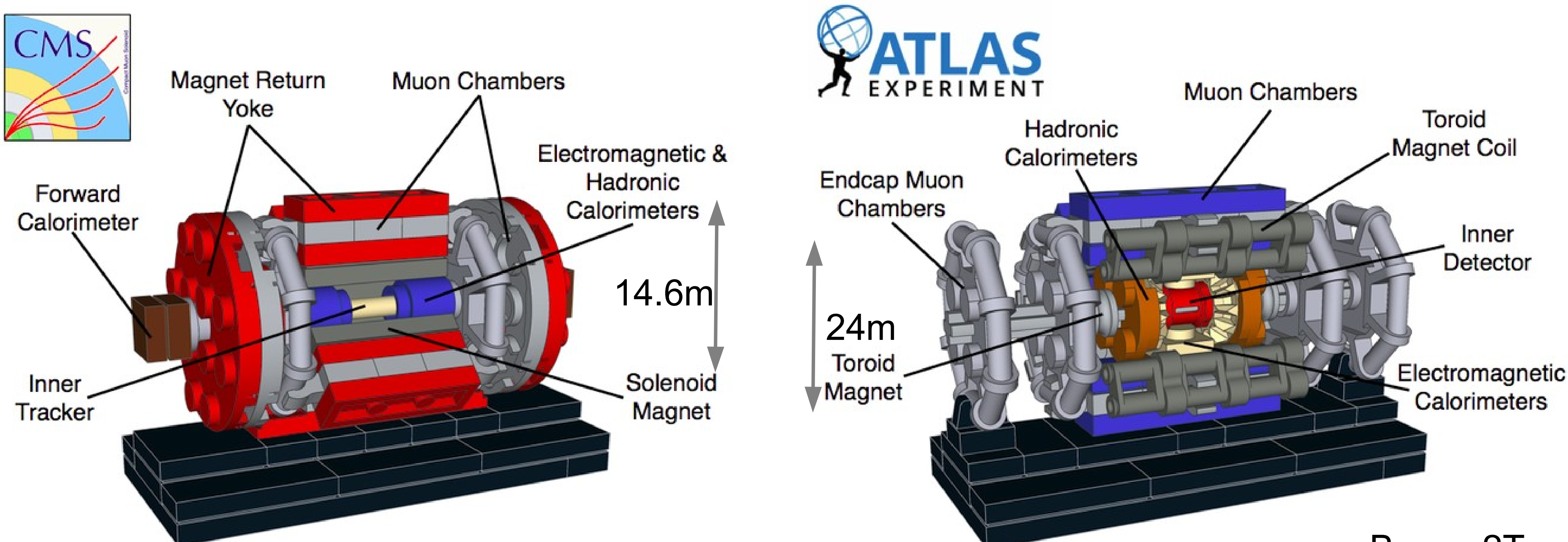
The recently presented searches from Run 2

- (As virtually anybody working on HEP knows)
  CMS and ATLAS recently presented the result of two searches for high mass resonances decaying to two photons.

- The searches were performed using **similar strategies** (which in turn followed those employed for the $H \to \gamma\gamma$ analyses).

- Main difference:
  - **ATLAS** analysis **benchmark**: on **spin-0** resonances.
  - **CMS** analysis **benchmark**: on **spin-2** resonances.
  - Analyses are **sensitive to both spin hypotheses**.

- Main instrument to detect photons: electromagnetic calorimeter.



B = 3.8T

B_{inner} = 2T

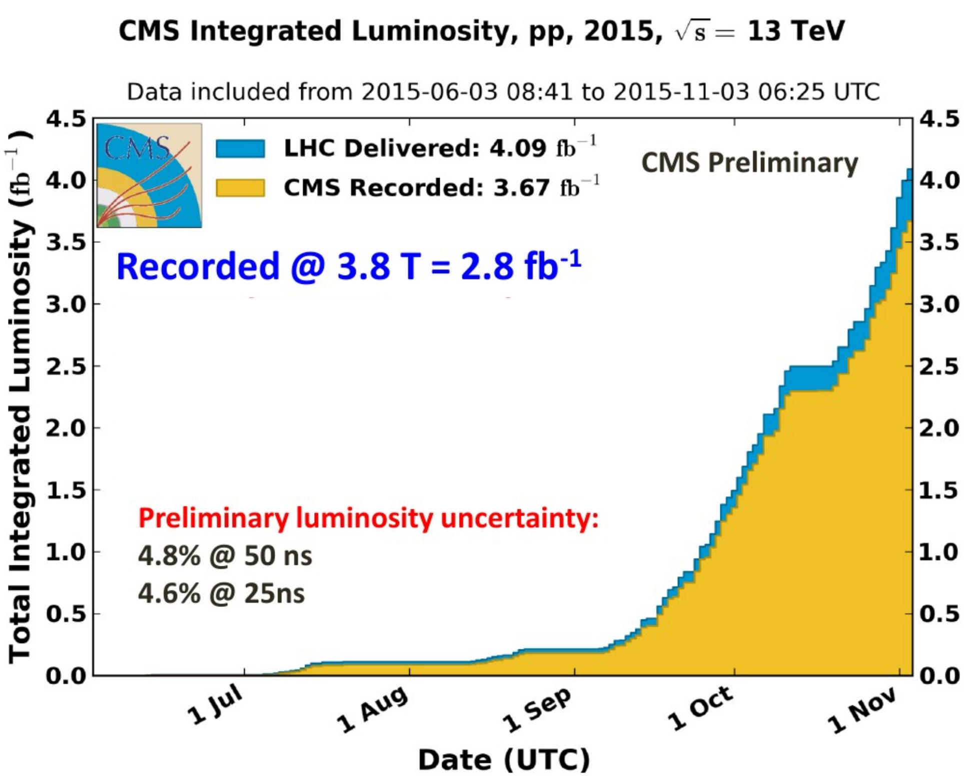
https://ideas.lego.com/projects/94885

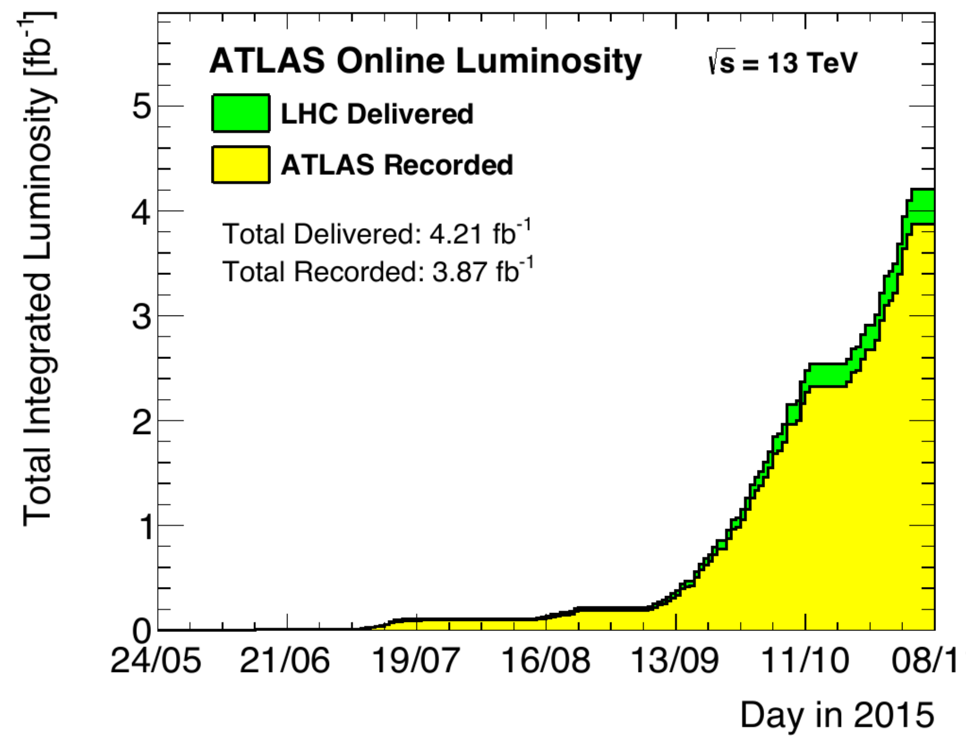
PWO homogeneous calorimeter.
Ideal energy resolution
@E_γ = 100GeV ~ 0.6%

LAr Longitudinally segmented calorimeter.
Ideal energy resolution
@E_γ = 100GeV ~ 1%

2015 dataset

- Thanks to the excellent performance of the LHC the CMS and ATLAS analyses could use 2.6fb^{-1} and 3.2fb^{-1} of data respectively.





Event selection

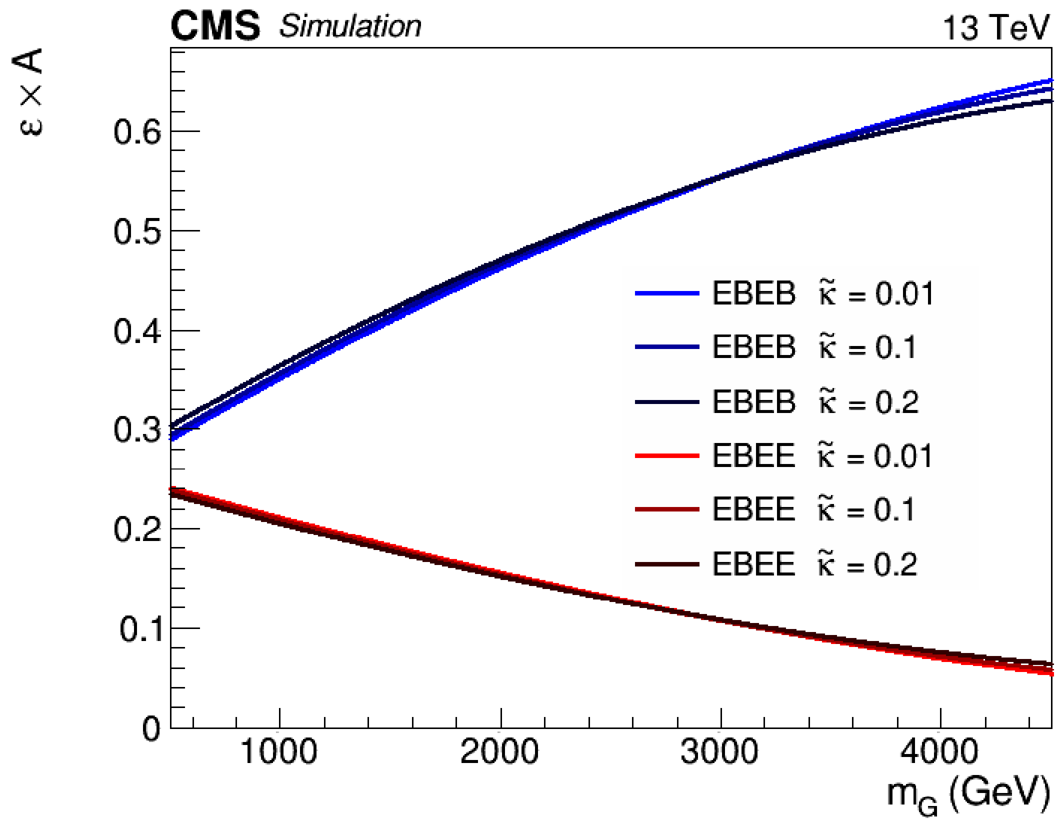
- Similar requirements for the two experiments.

	ATLAS	CMS
$p^{\gamma 1}_T$	$>0.4*m_{\gamma\gamma}$	75 GeV
$p^{\gamma 2}_T$	$>0.3*m_{\gamma\gamma}$	75 GeV
$\|\eta\|_{max}$	<2.37	<2.5
$\|\eta\|_{min}$	<2.37	<1.45
categorization	no	EB-EB EB-EE

- Main differences:
  - **ATLAS**: **scaling p_T cuts** → apply implicit cut on $|\eta_1-\eta_2|$.
  - **CMS: fixed p_T cuts**. At least one photon required to be in barrel region (EB: $|\eta|<1.45$).
    Events categorized in barrel-barrel (EBEB) and barrel-endcap (EBEE) configurations.
  - Isolation requirements not easy to compare (different definitions, cones, etc.), but not dramatically different.

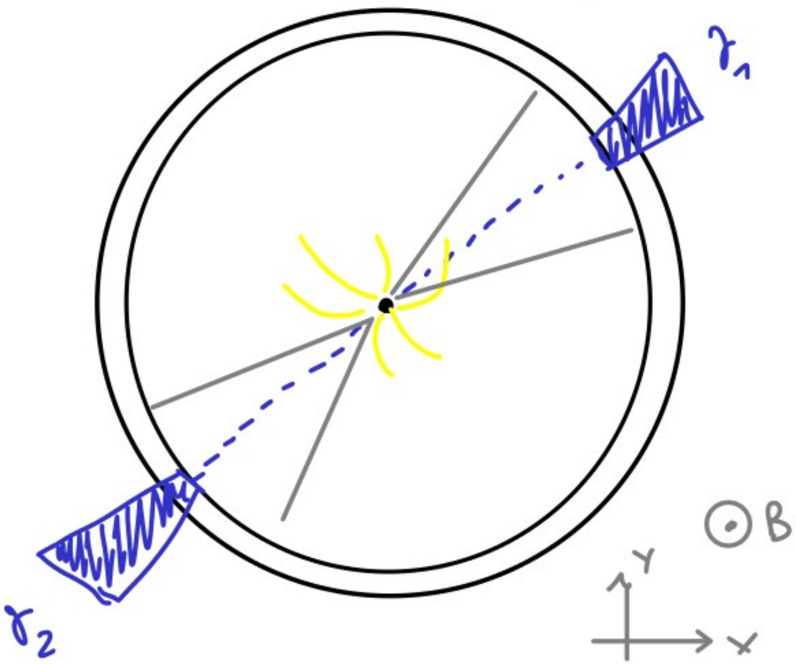
Event selection (2)

- Overall selection efficiency.
  - CMS: 0.55 for RS graviton of 750GeV.
  - ATLAS: 0.4 for gg → spin-0 → γγ (at 600GeV)
  - Note: acceptance for spin-2 resonances smaller than for spin-0 ones, but otherwise **analyses are not sensitive to spin hypothesis**.



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**.



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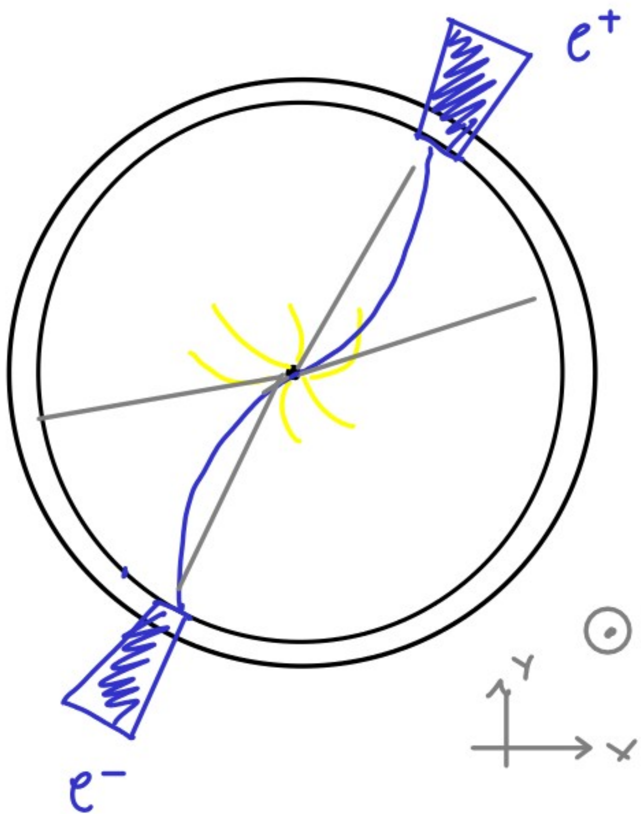
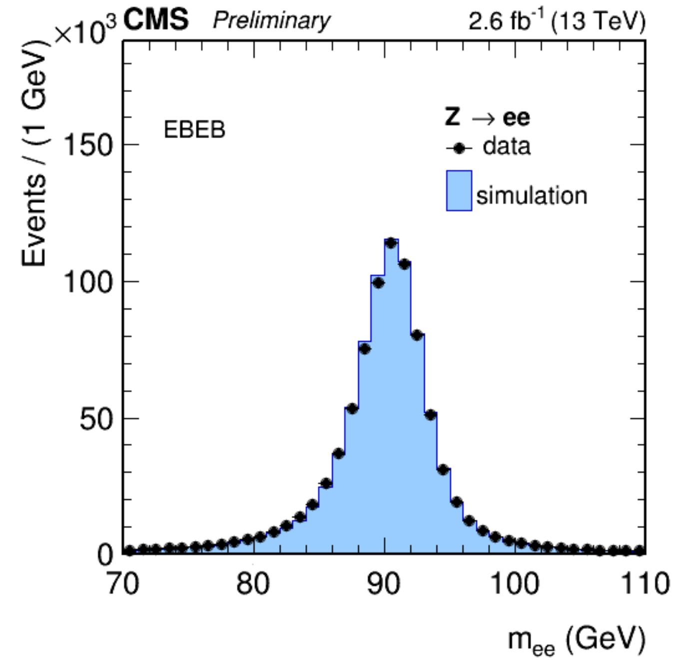
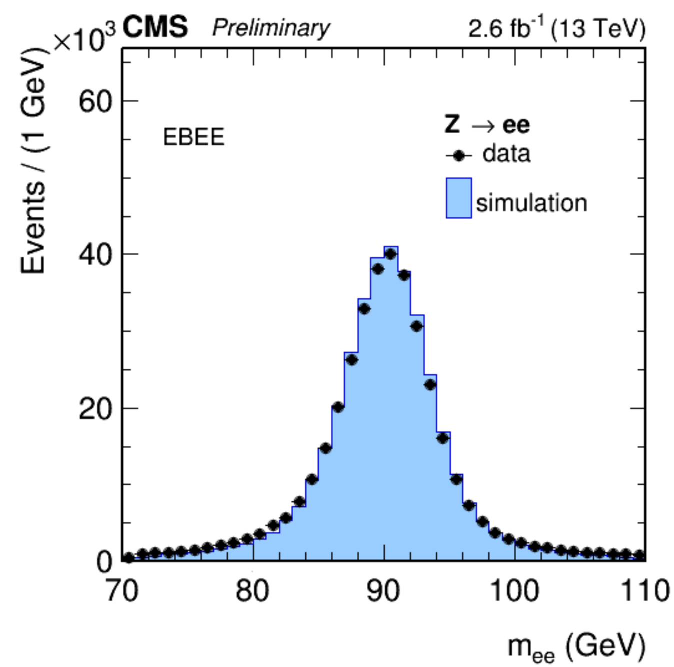


Energy scale and resolution

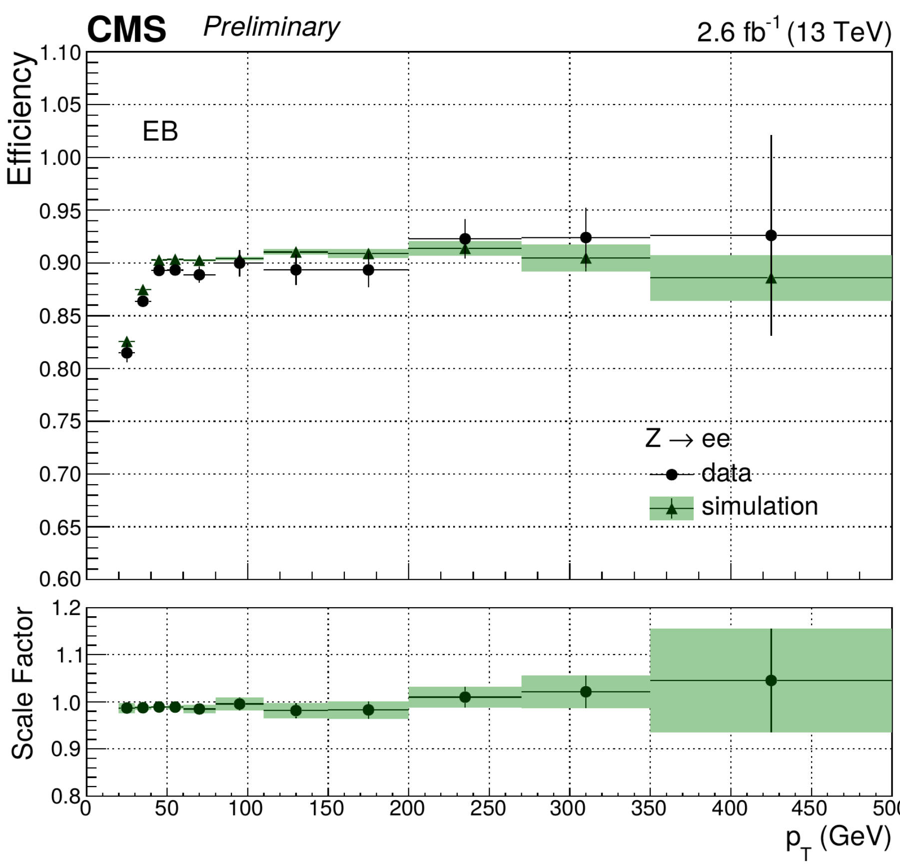
- Photon **energy** scale and resolution measured using **di-electron** events.
  - **ATLAS**: corrections from **8TeV Z→ee** (reconstructed with Run 2 conditions).
    - Systematic uncertainties on extrapolation to Run 2.
  - **CMS**: **in-situ** energy scale and resolution corrections using **13TeV Z→ee** sample.
    - **Extrapolation to high mass** checked with **high mass DY** events with a precision of **0.5%** (for m_{ee}>200GeV).
    - Note: photon resolution still worse than in Run 1.
      Channel-to-channel need update:
      new coefficients will be used for winter conferences.

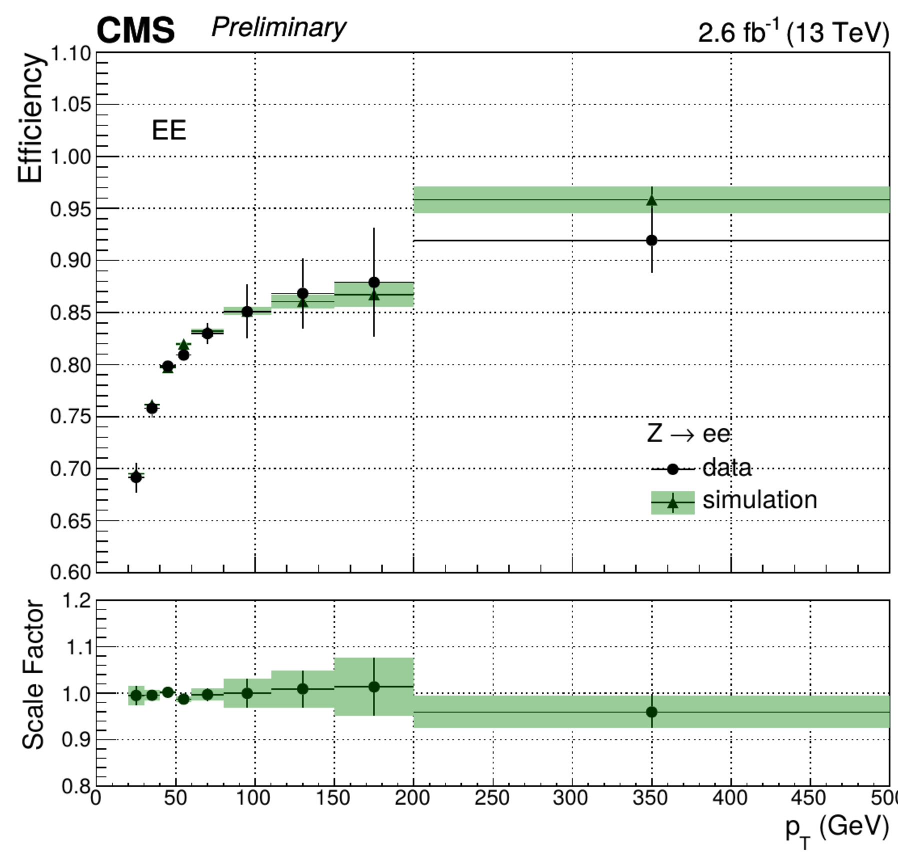




Signal efficiency measurement

- CMS: measurement of the photon identification efficiency in data and MC using 13TeV **Z→ee** events.
  - The **electron veto** requirement is removed from the selection in this measurement and its efficiency is assessed separately using **Z → μμγ** events.
- ATLAS: similar measurement, but on 8TeV data, reconstructed as in Run 2

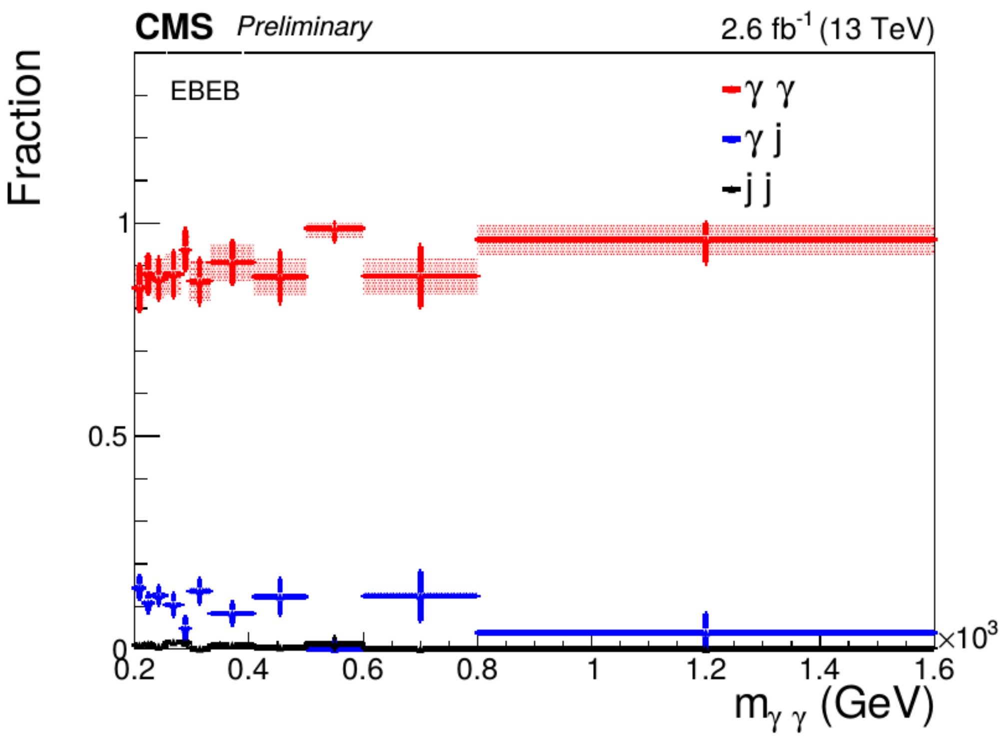


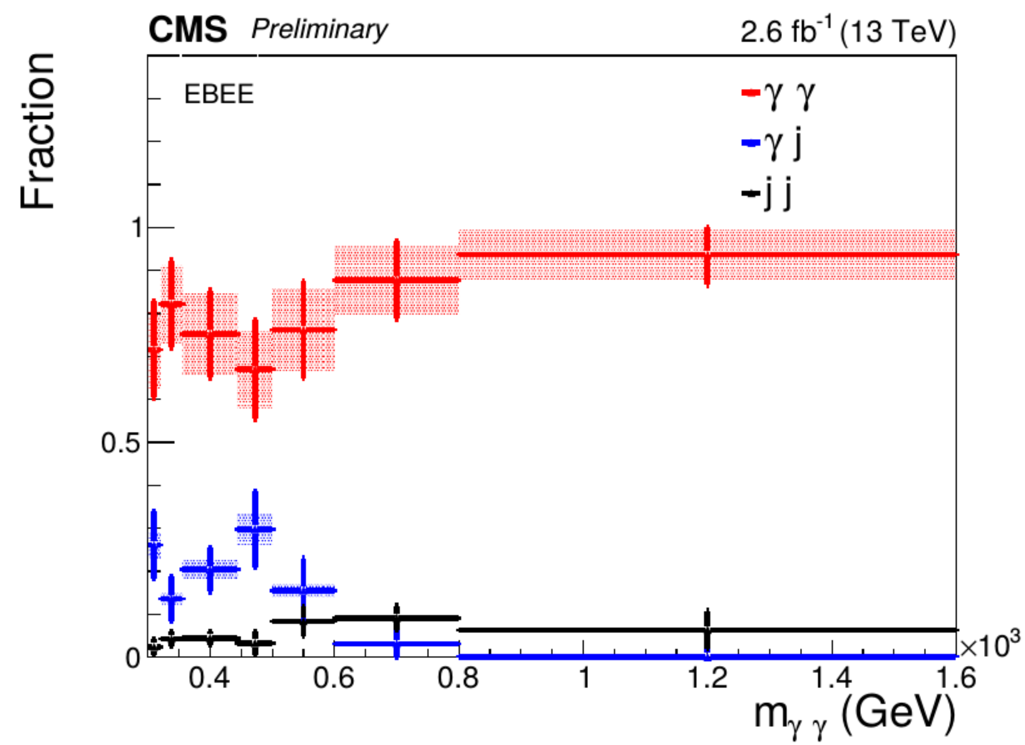


Understanding background processes

- 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.
- Background composition measured in data
  - Determination do not enter in search result, but very important to validate assumption that MC simulation are reliable.

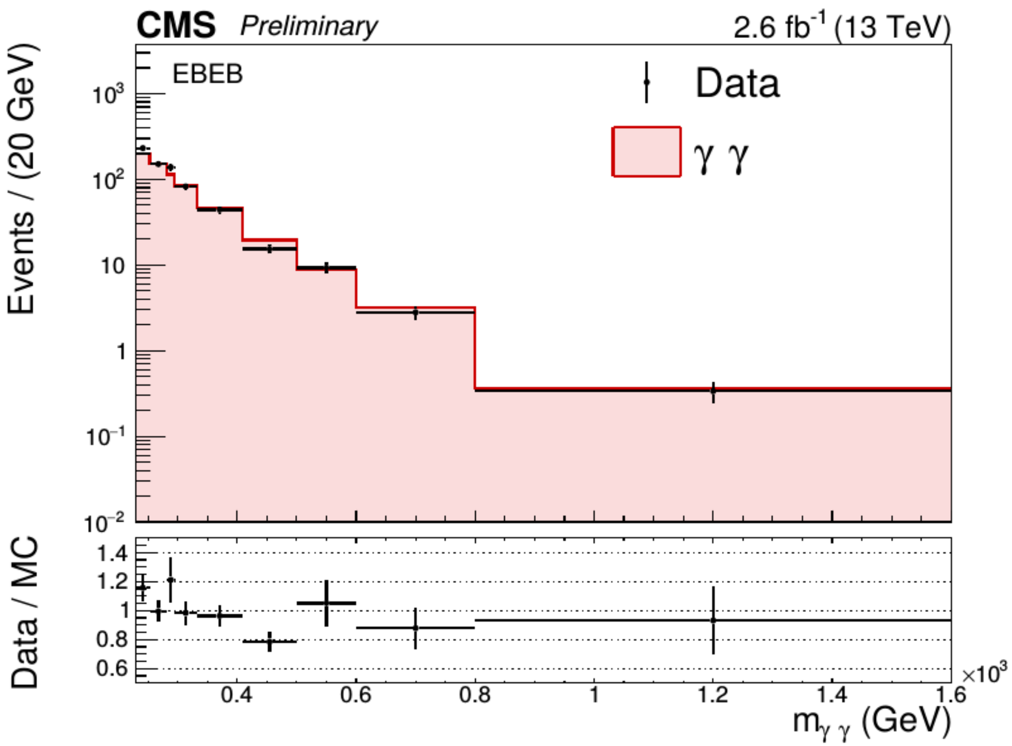
- Measured in data using template fit (CMS) or ABCD method (ATLAS).
  - **Background dominated by irreducible component**.
    - CMS: $f_{\gamma\gamma}$>90(80)% for EBEB(EBEE) category.
    - ATLAS: $f_{\gamma\gamma}$>90%.
  - **Determination not used in hypothesis test.**

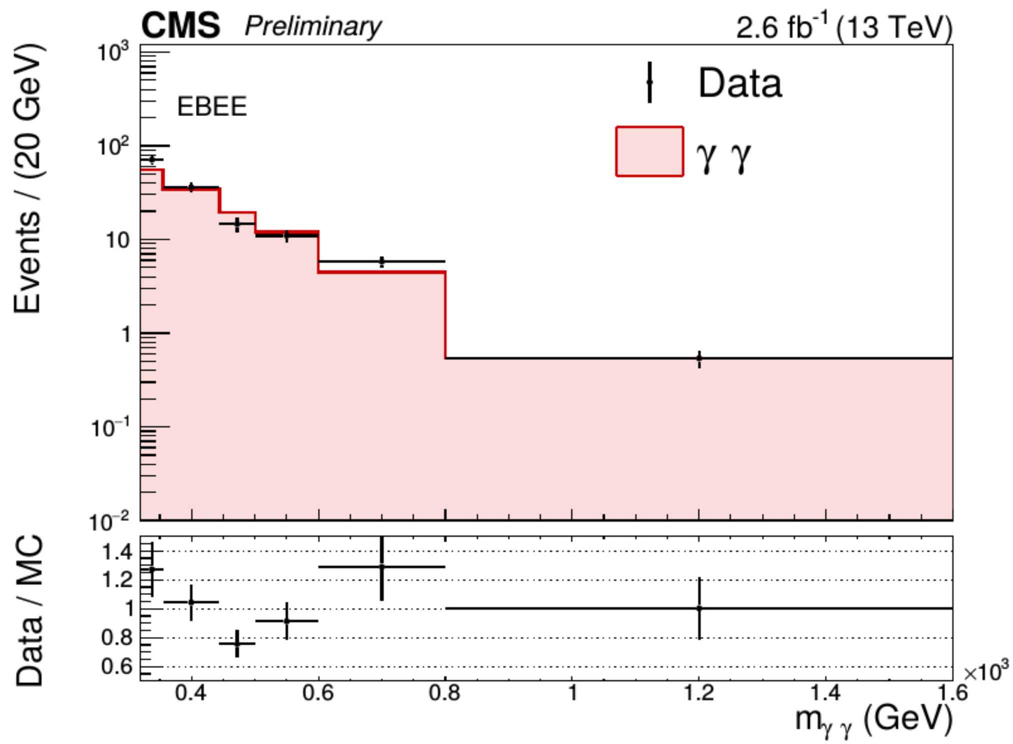




Background composition (2)

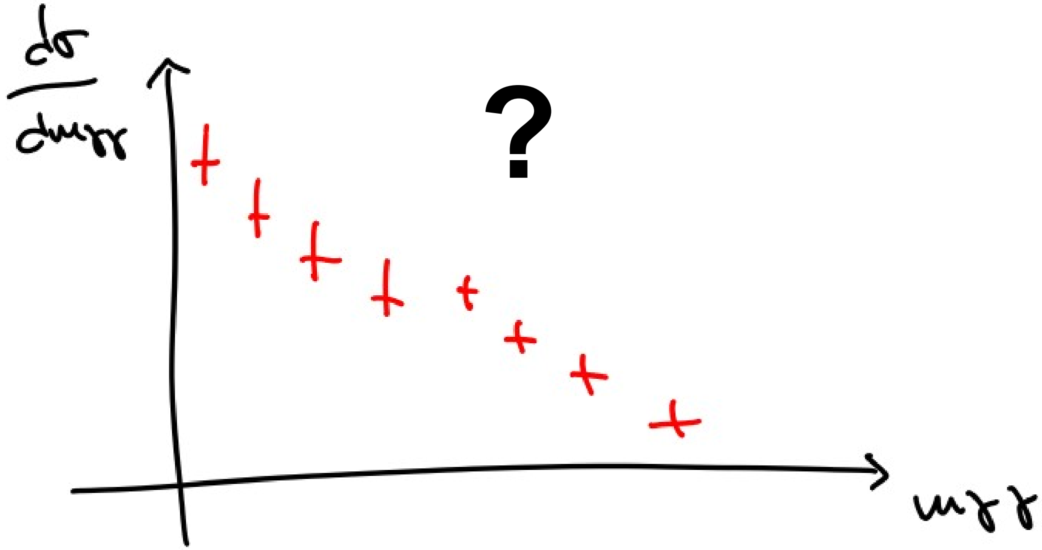
- In the case of CMS, prediction for $\gamma\gamma$ component checked against theory predictions.
  - Obtained using Sherpa-LO reweighted to 2γNNLO.
  - Observation in good agreement with model.





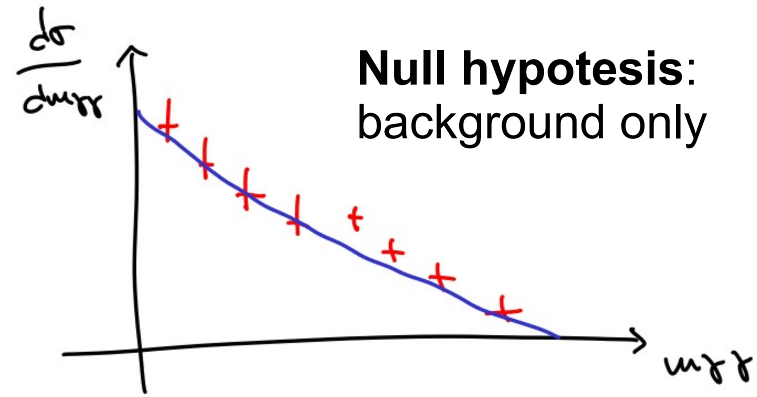
Interpreting the observations

- Goal of the analysis: determine (in-)consistency of data with resonant production of two photons.

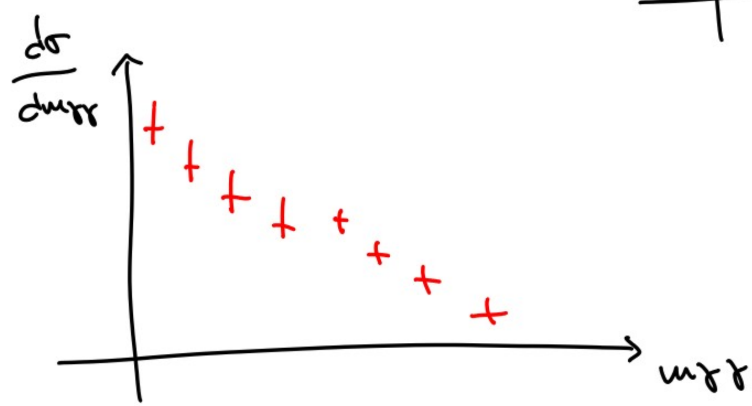


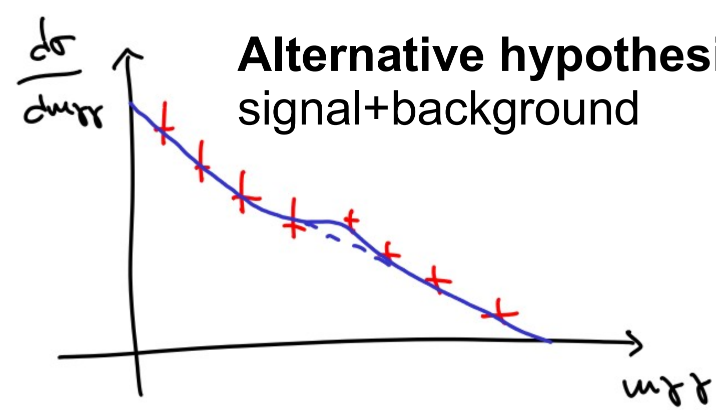
Interpreting the observations

- Mathematically phrased in terms of a (frequentist) composite hypothesis test.



Null hypotesis: background only

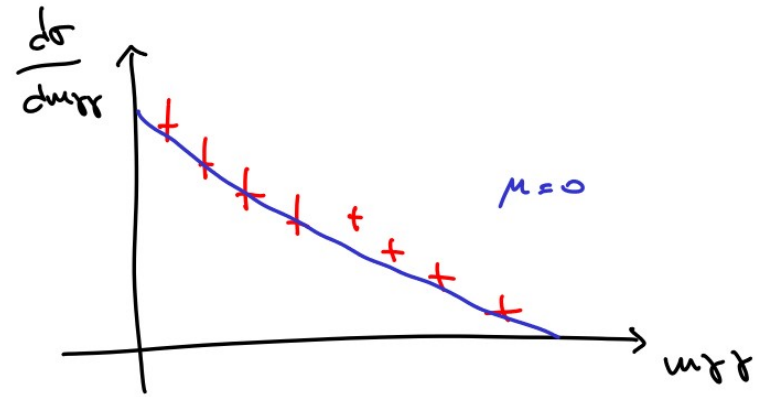




Alternative hypothesis: signal+background

Interpreting the observations

- Test statistics based on (profile) likelihood ratio.



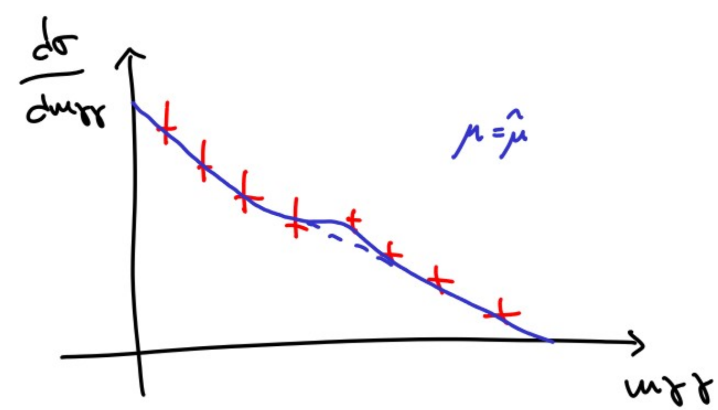
$$x(\mu) = -2\log\left[\frac{L(\mu,\hat{\theta}_\mu)}{L(\hat{\mu},\hat{\theta})}\right]$$

- (Trivially) need two ingredients:
  - Signal and background models.

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

Signal strength

Nuisance parameters (model syst. uncertainies)



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.

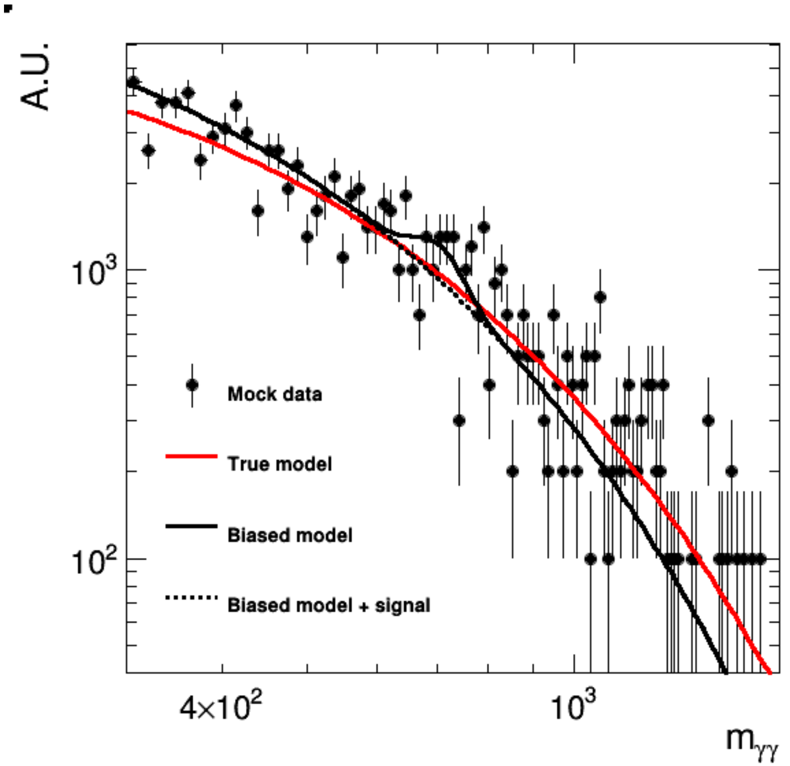
- ATLAS: $f_{(k)}(x; b, \{a_k\}) = (1 - x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j}$ $x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$
  - Order of the function (k) chosen as 0 using F-test in data.

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

Background modelling

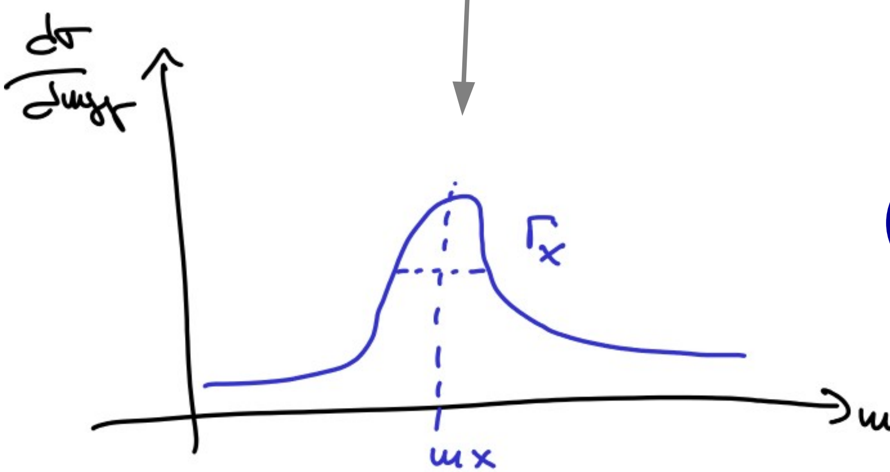
- Background modelled using **parametric fit** to data.
  - Model **coefficients** treated as unconstrained **nuisance parameters** in hypothesis test.

- 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**.
  - CMS: mismodelling required to be < ½ of the background stat. uncertainty.
  - ATLAS: mismodelling required to be < 1/5 of the stat. uncertainty on signal stength.



Signal modelling

- Two components in signal model.
  - Intrinsic line shape and detector response.



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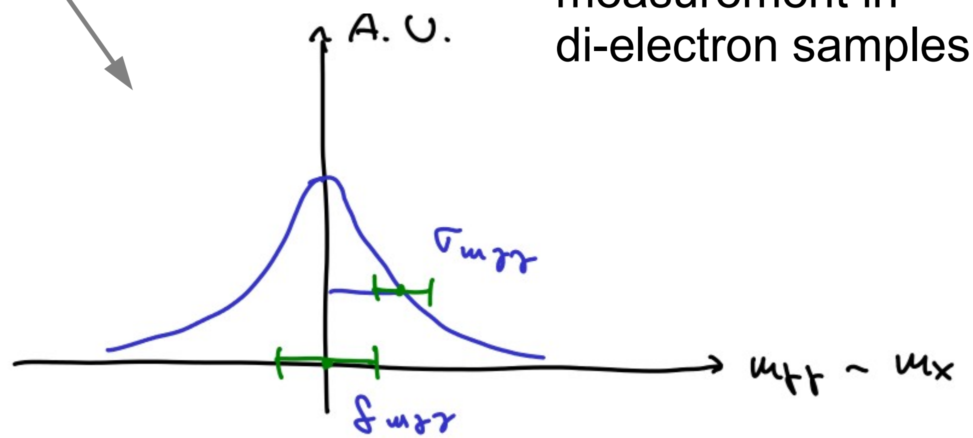


From MC simulation,
Corrected for
measurement in
di-electron samples.

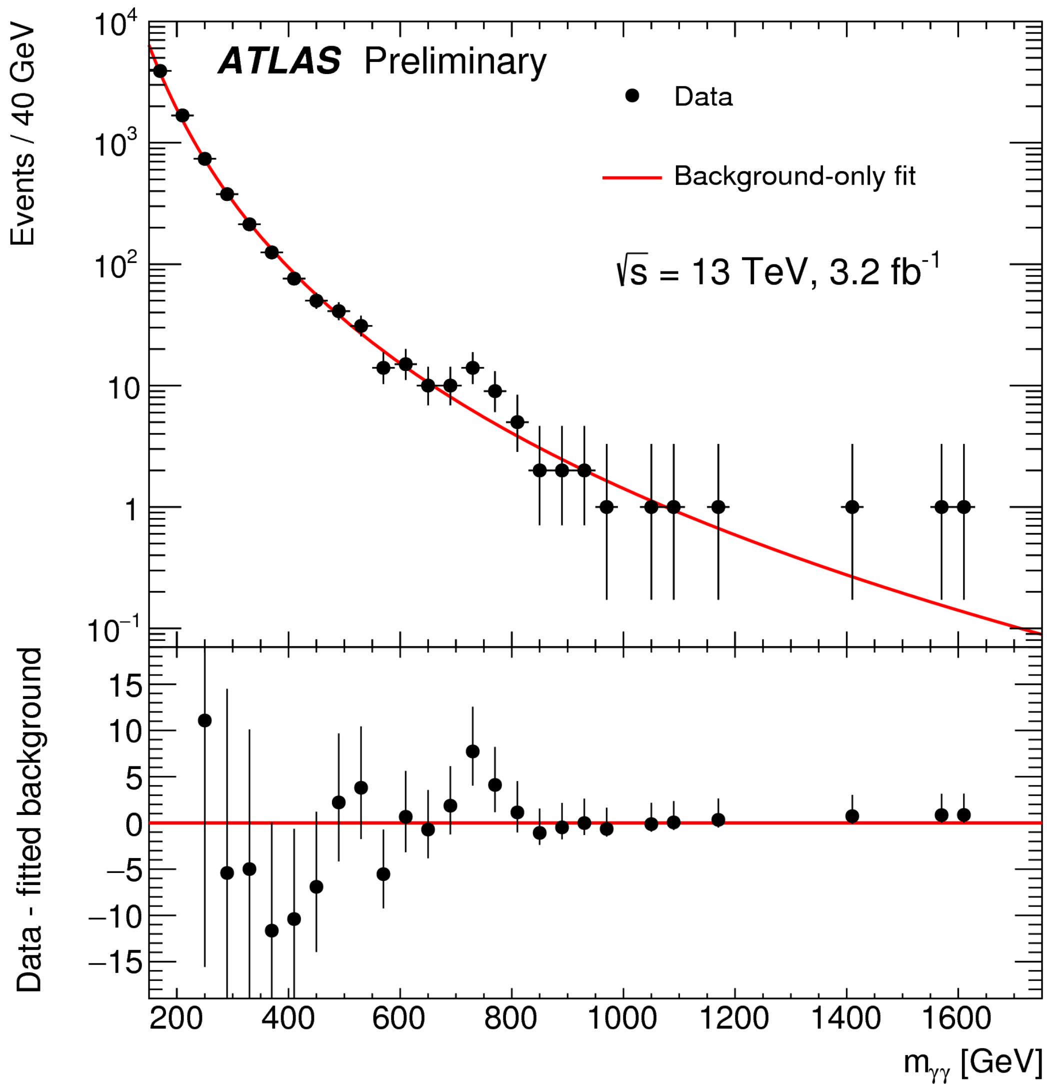
Several mass and width hypotheses
tested.

Tested signal hypotheses

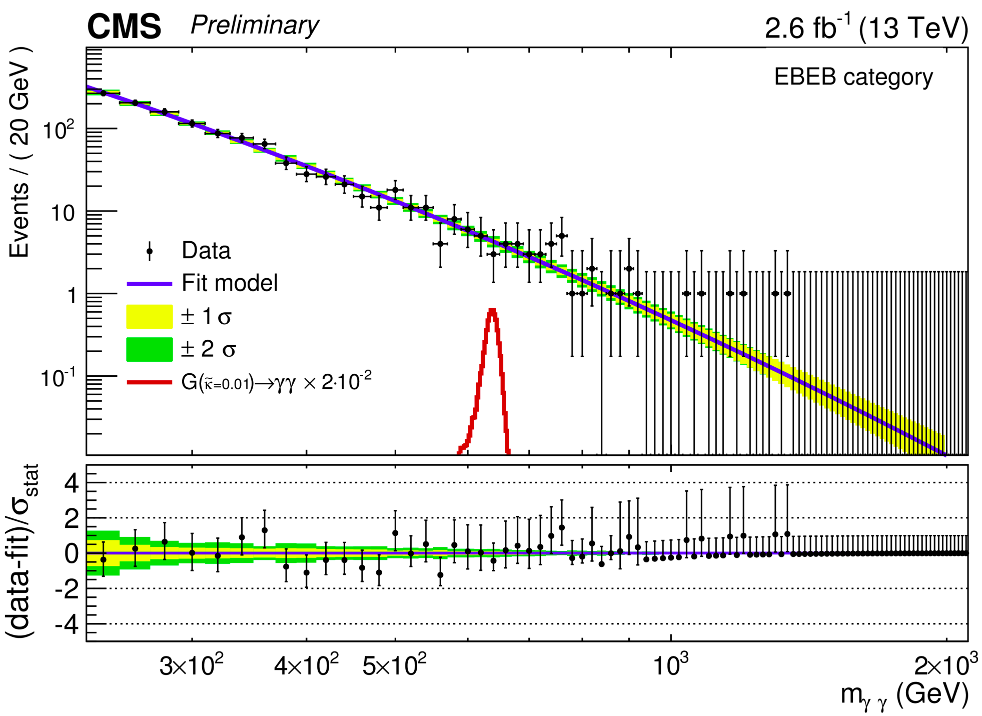
- ATLAS:
  - Spin-0 **narrow width** resonance.
  - **A-posteriori also** tested **wider** resonances.
  - Signal $m_{\gamma\gamma}$ shape modelled as double-sided crystal-ball (DSCB) function. Verified that DSCB can model also wider resonances.

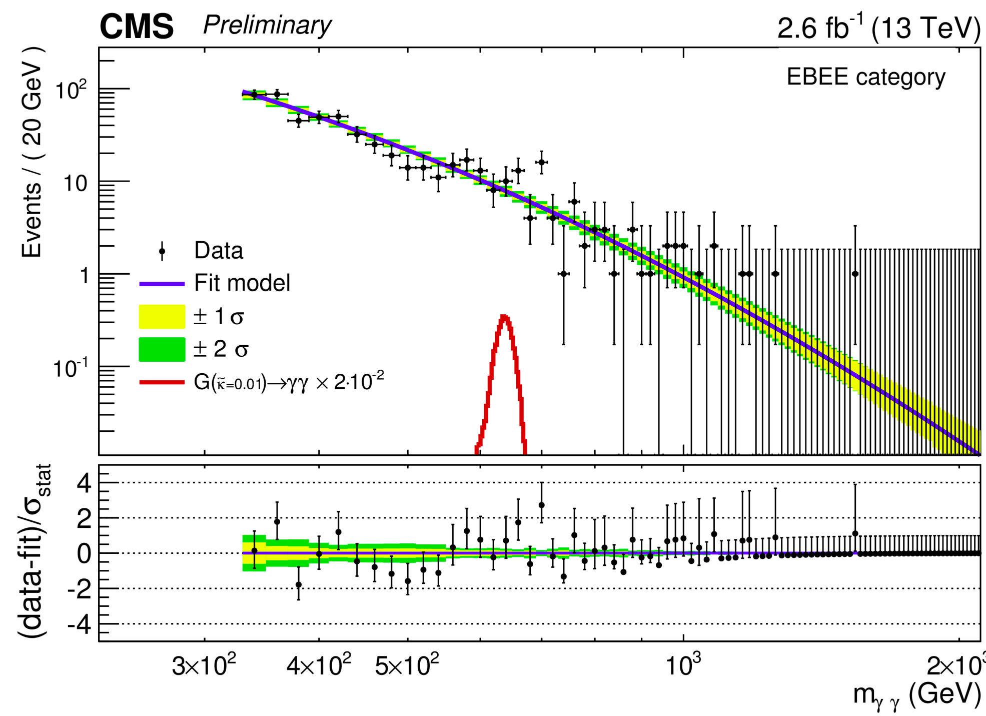
- CMS:
  - **RS graviton spin-2** resonances.
  - Width parametrized as $\Gamma_G / m_G = 1.4\, k^2$;
    Largest **width set a priori**: $k_{max} = 0.2 \rightarrow \boldsymbol{\Gamma_G / m_G \sim 6\%}$
  - Signal $m_{\gamma\gamma}$ shape modelled by convolution of gen-level mass shape from PYTHIA and detector resolution. Dependence on m_G accounted though semi-parametric interpolation.

Selected mass spectra: ATLAS



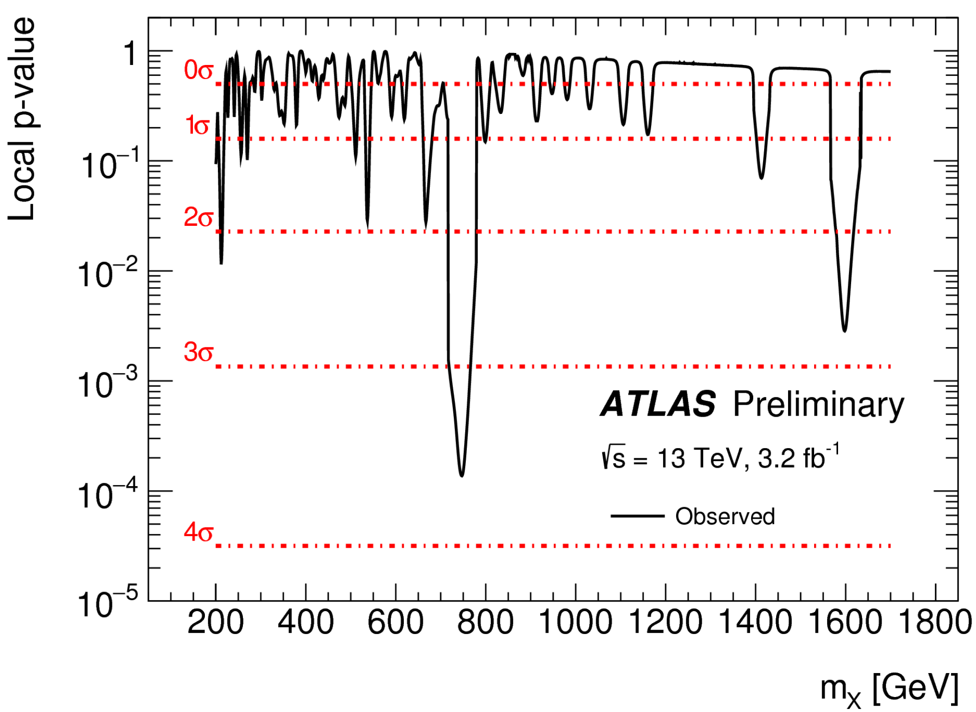
Selected mass spectra: CMS

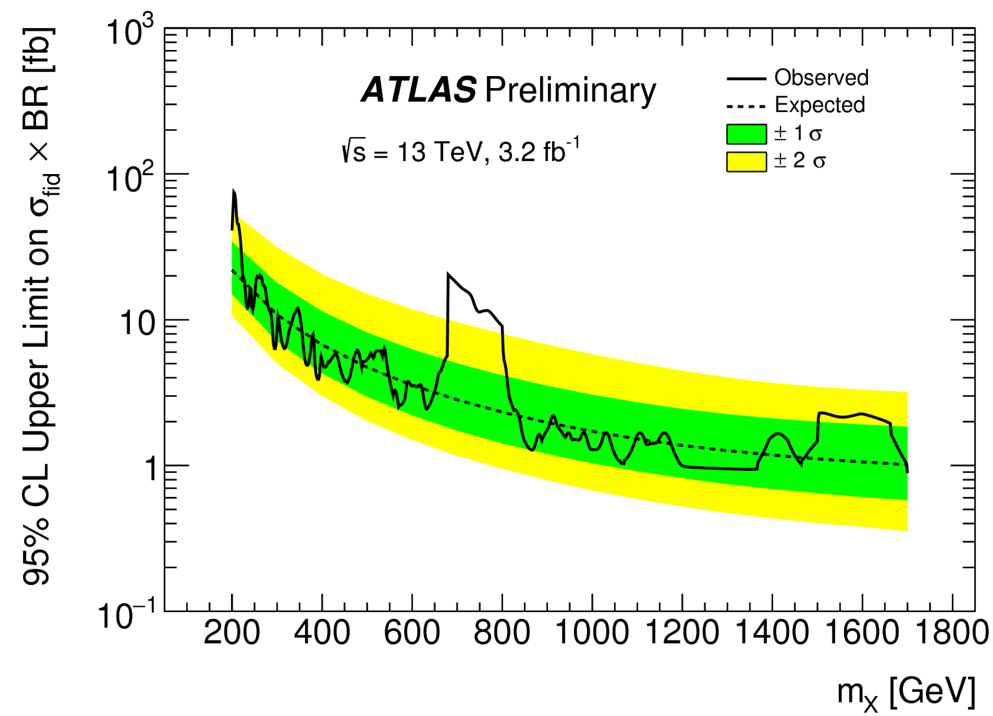




Interpretation: ATLAS

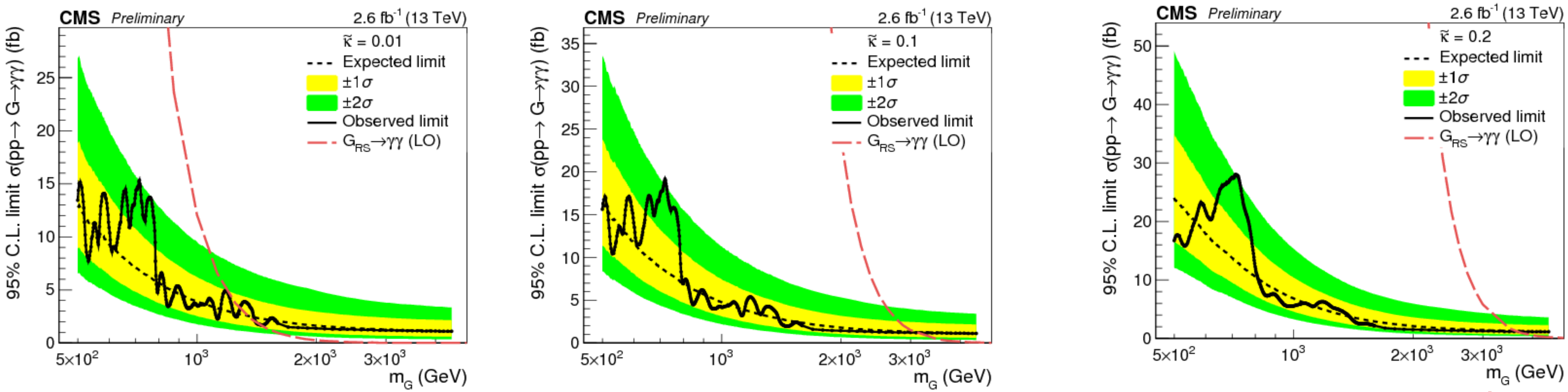
- In the narrow width hypothesis **largest excess** observed for **m_X=750GeV**.
  - **Local significance: 3.6σ**, reduced to **2.0σ after** accounting for **LEE**.
  - Resolution parameters in signal model pulled by ~1.5σ.
  - A-posteriori, best-fit width found to be ~6%.
    - Local significance 3.9σ, reduced to 2.3σ after accounting for LEE (including widths up to 10%).



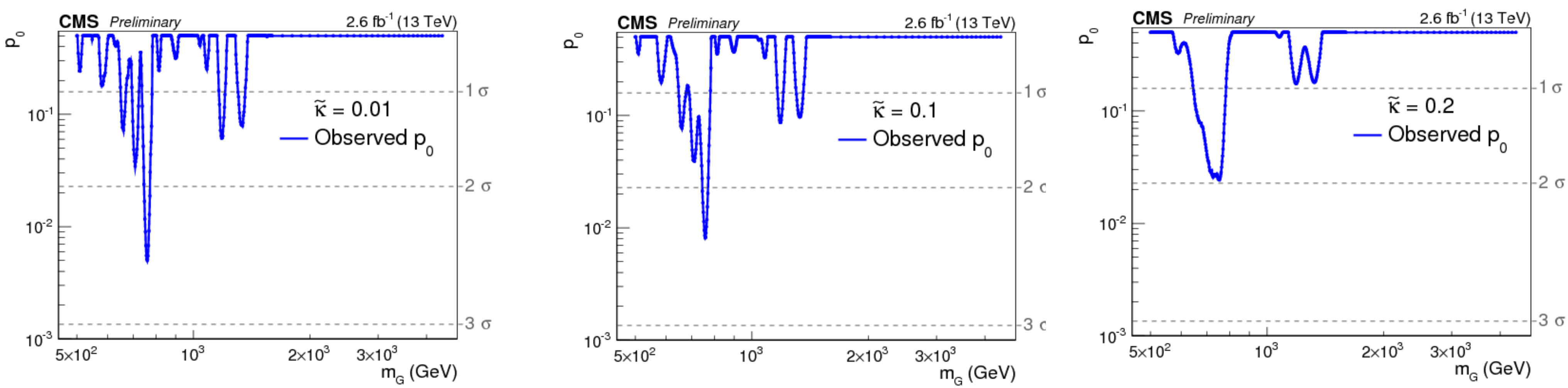


Interpretation: CMS

- **Largest excess** for **m_G=760GeV** in the **narrow width hypothesis**
  - **Local significance: 2.6σ**, reduced to **1.2σ** when accounting for **LEE** in **m_G**. Would be **reduced even more** once accounting for **LEE** in **k**.



Narrow-width → **$\Gamma_{G\,a}/m_G \sim 6\%$**



Consistency with data at lower √s

- Both collaboration searched for diphoton resonances at lower centre-of-mass energies.
  - Most sensitive searches preformed at 8TeV.

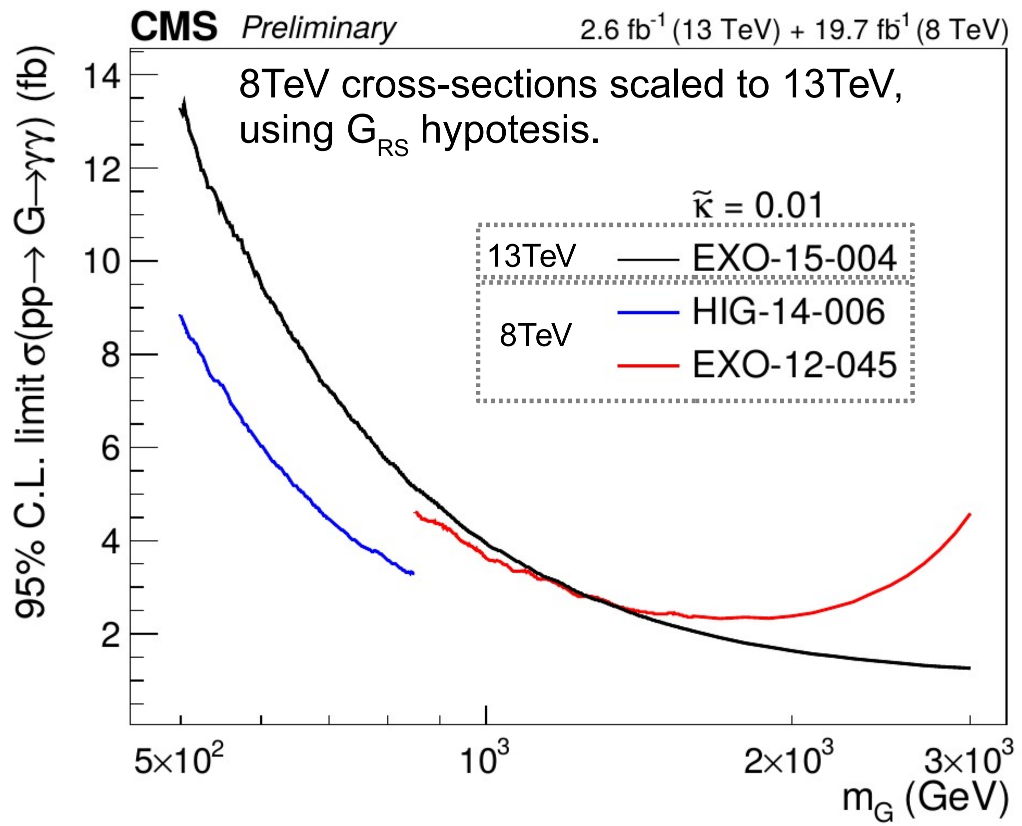
- Consistency with those results can be assessed under different signal hypothesis.
  - Main parameter to be fixed: σ(13TeV)/σ(8TeV).
  - σ(13TeV)/σ(8TeV) ($gg \rightarrow X$) = 4.7
  - σ(13TeV)/σ(8TeV) (G_{RS}) = 4.2

Consistency with 8TeV data

- **ATLAS**:
  - m_X=750GeV not tested for spin-0 resonances in the published analysis.
  - Analysed the 8TeV dataset consistently with what done at 13TeV, under the hypothesis of a **spin-0** resonance produced in **gluon-fusion**.
  - Under the narrow-width hypotheses observations at 8 and 13TeV compatible at 2.2σ level. Compatibility at 1.4σ level for Γ/m = 6%.

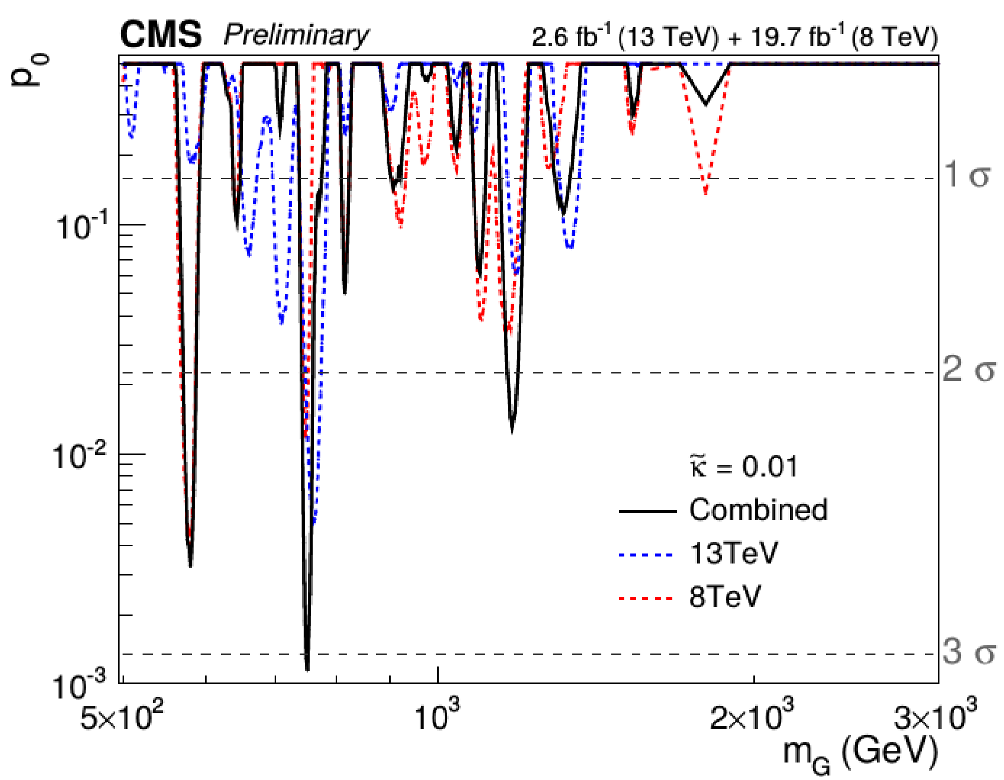
Consistency with 8TeV data

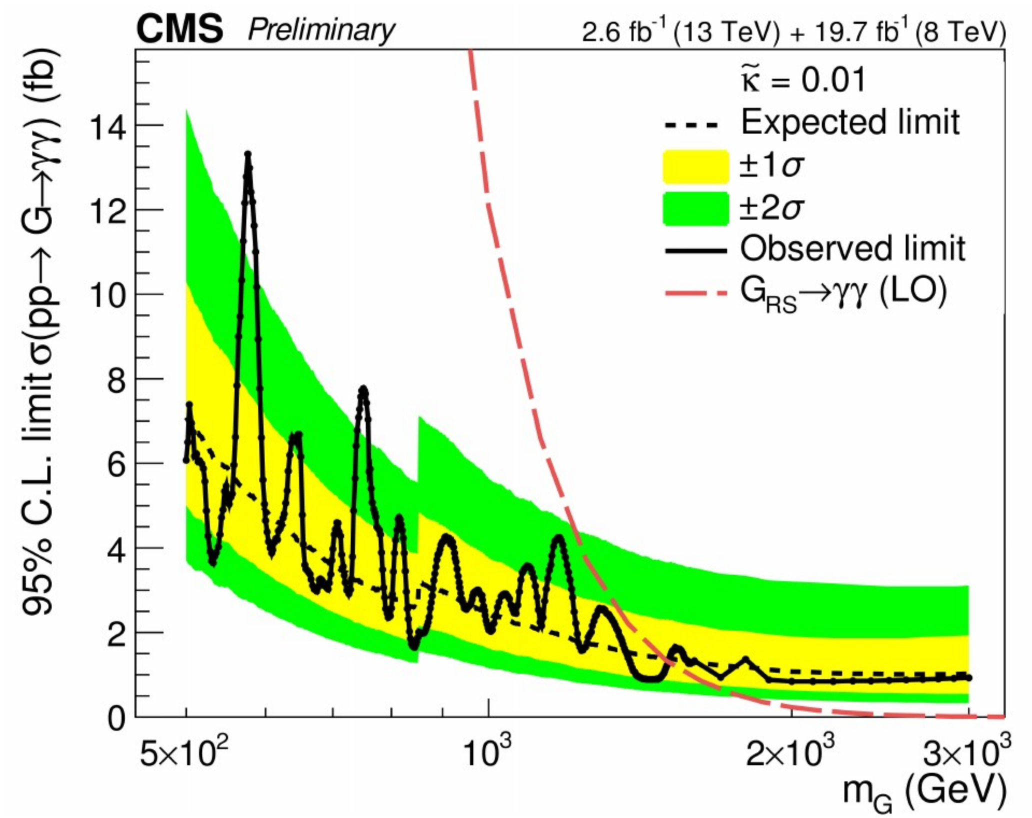
- **CMS**:
  - At 8TeV m_G=750GeV tested under spin-0 and spin-2 hypoteses (in the latter case
by two different analyses).
  - Combination of the results had been planned for winter/spring 2016.
  - Anticipated combination of **narrow G_{RS} hypothesis.** Choosen most sensitive 8TeV analysis at each m_G.



CMS: combined 8+13TeV results

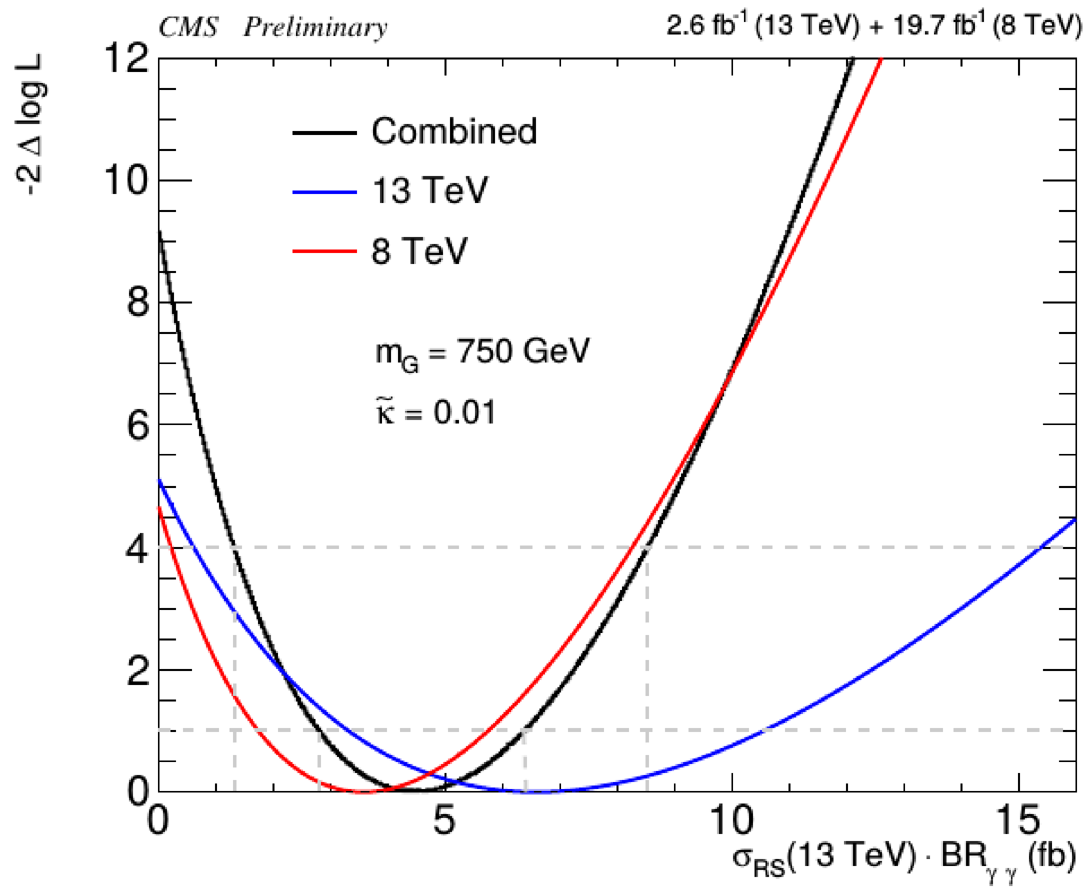
- Combined limit improves single analyses sensitivity by 20-30%.
  - **Largest excess: m_G=750GeV**, **local** significance **3.05σ**, reduced to **<1.7σ after** accounting for **LEE**.





CMS: combined 8+13TeV likelihood

- At m_G=750GeV 8 and 13TeV results compatible within uncertainties.

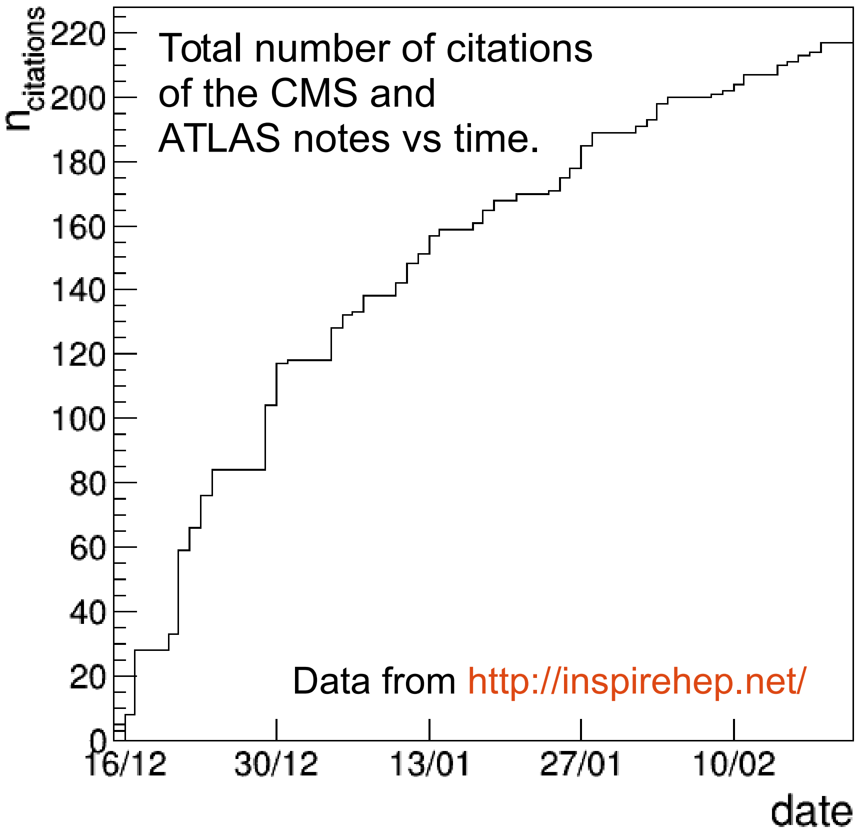


Additional checks

- Both collaboration 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.

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, ….



Consistency with searches in other channels?

- Answer is obviously model dependent.
  - Better answered by a theorist.

- Searches for s-channel production of resonances performed in many other channels.
  - Most of the searches are available only for the 8TeV run at the moment.
  - Many searches are being updated using 13TeV data.

- I tried to compile a summary of the available informations.
  - Only considered $X \to YY$, no associated production.

Searches in other channels (2)

Channel	ATLAS	CMS	interpreted as spin-0	spin-1	spin-2	Rough limit (@m_x=750GeV)
ee μμ	PRD 90, 052005 (2014) ATLAS-CONF-2015-070	JHEP 04 (2015) 025 CMS-PAS-EXO-15-005	✘	✔	✔ (8TeV only)	~1fb(@8TeV) few fb(@13TeV)
ττ		JHEP 10 (2014) 160	✔	✘	✘	~20fb(@8TeV)
ttbar	JHEP08 (2015) 148	PRL 112 119903 (2014) PRD 93(2016) 012001	✔ (ATL only)	✔	✔ (ATL only)	~1pb (@8TeV)
VV	arXiv:1512.05099 arXiv:1507.05930	arXiv:1504.00936	✔	✘	✔ (ATL only)	~20-30fb (@8TeV)
Zγ	Phys.Lett. B738 (2014) 428-447		✔	✘	✘	~200fb (@8TeV)
HH	PRD 92, 092004	PLB749 (2015) 560-582 CMS-PAS-HIG-13-032	✔	✘	✔ (CMS only)	~20fb (@8TeV)
jj	PRD 91, 052007 (2015)	CMS-PAS-EXO-14-005	✔	✔	✔	few pb (@8TeV)

Summary

- Presented the recent **searches of high mass diphoton resonances** by the CMS and ATLAS collaborations.
  - A total integrated lumiosity of **2.6fb^{-1}** and **3.2fb^{-1}** of **13TeV** pp collisions was analysed by CMS and ATLAS respectively.
  - **Simple** and **robust** analysis strategies were put in place by both collaborations.
  - The ATLAS search benchmark is a spin-0 resonance, while the CMS one a spin-2 one. Both analyses are nevertheless sensitive to both spin hypotheses.

Summary

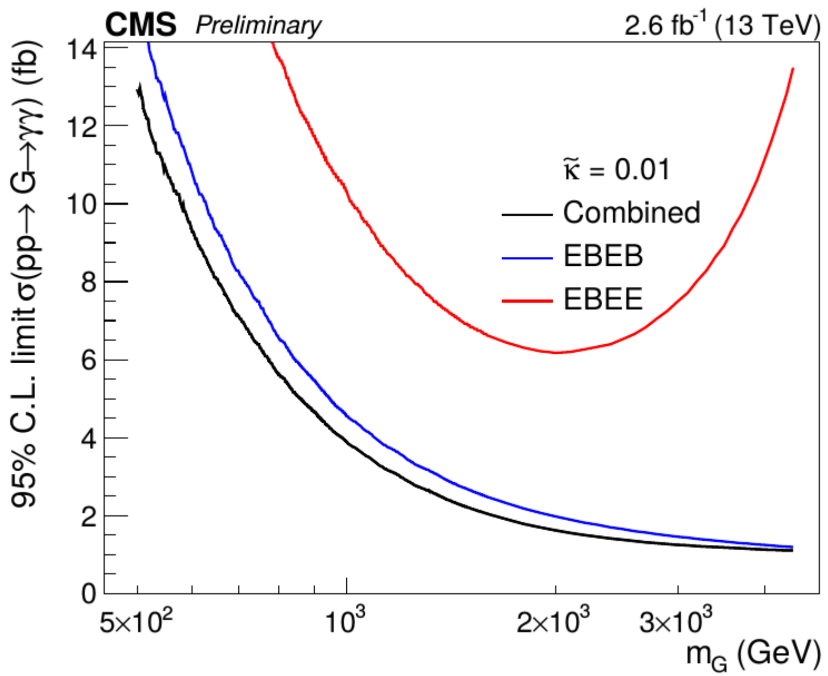
- The **results** are **generally** well **compatible** with the **Standard Model** expectations.
  - **Modest excesses of events** was observed by both collaborations at a **mass** of roughly **750GeV**.
  - The observed excesses **not in contradiction** with what observed at **lower √s**.
  - **More data are needed** to **determine** if the excesses are generated by a statistical fluctuations in the **background-only** SM hypothesis **or** if they are a manifestation of **something else**.

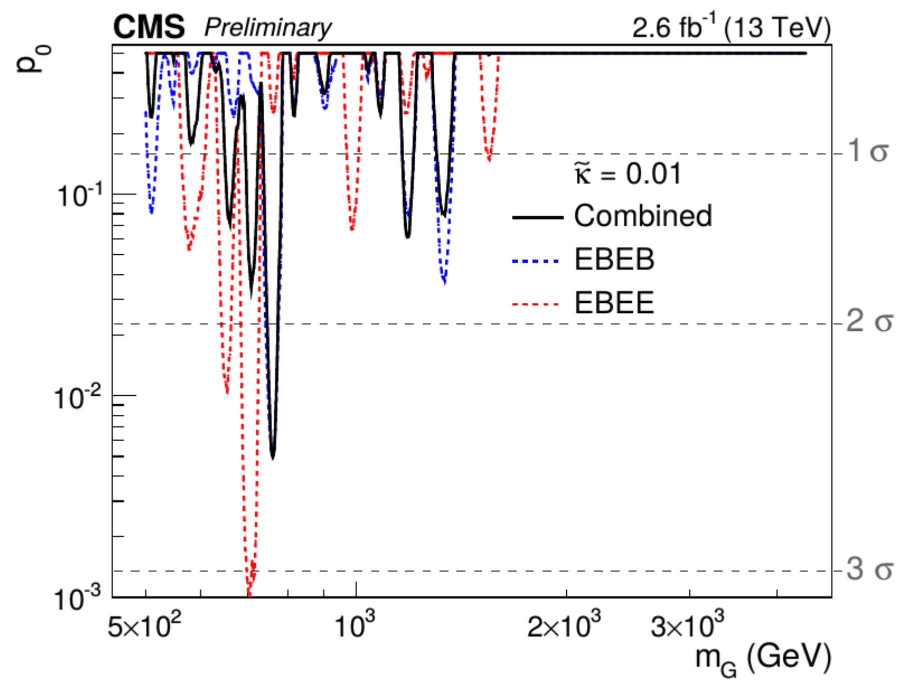
… for your attention!
Do you have any question?

Additional material

CMS: analysis categories

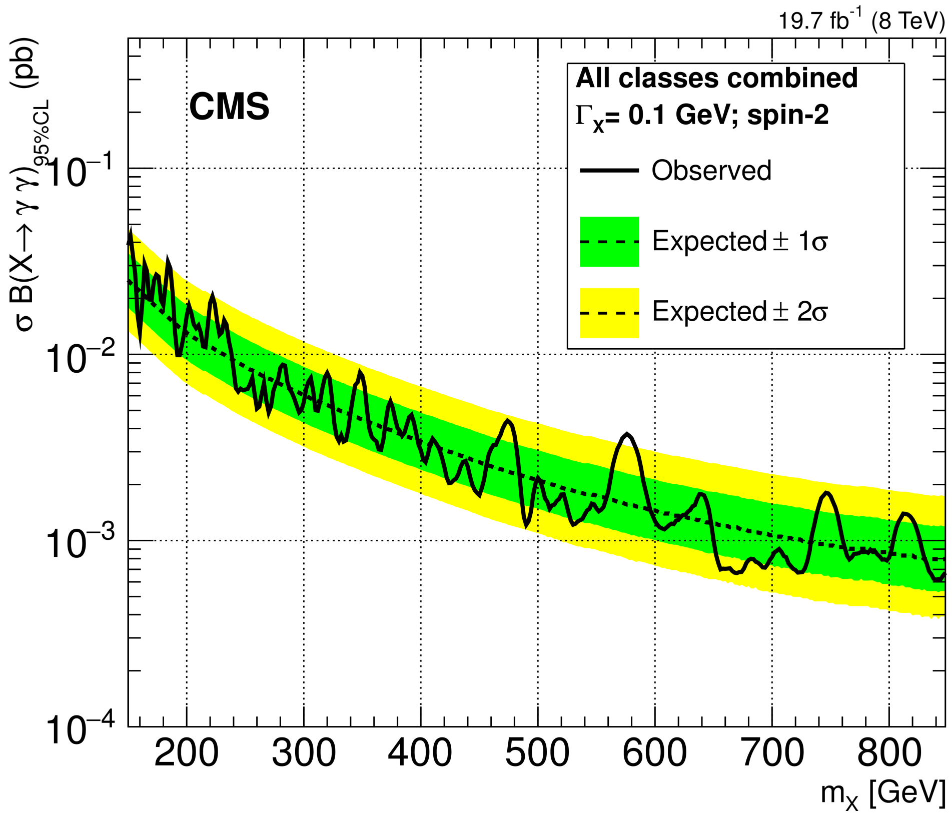
- Events split into EBEB and EBEE category.
  - Acceptance of EEEE negligeably small.
- Fraction of signal events in the EBEE category varies between 10 and 45%.
  - Including the EBEE category in the analysis improves the sensitivity by 10-15%.
  - Excess around 750GeV dominated by EBEB category.

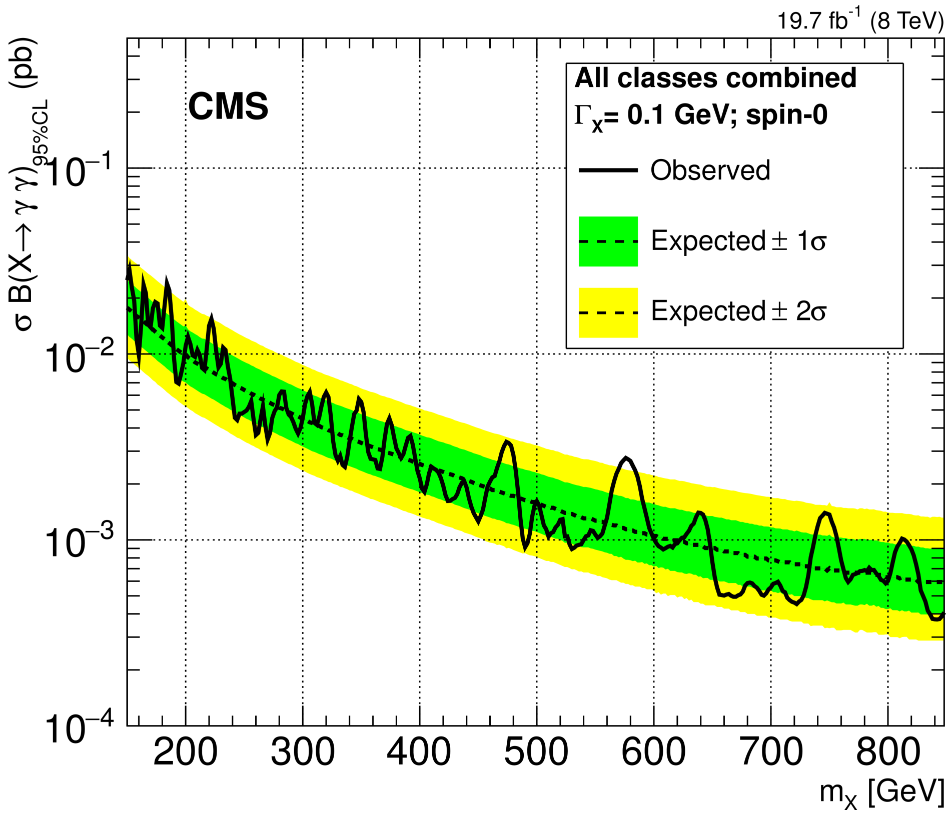




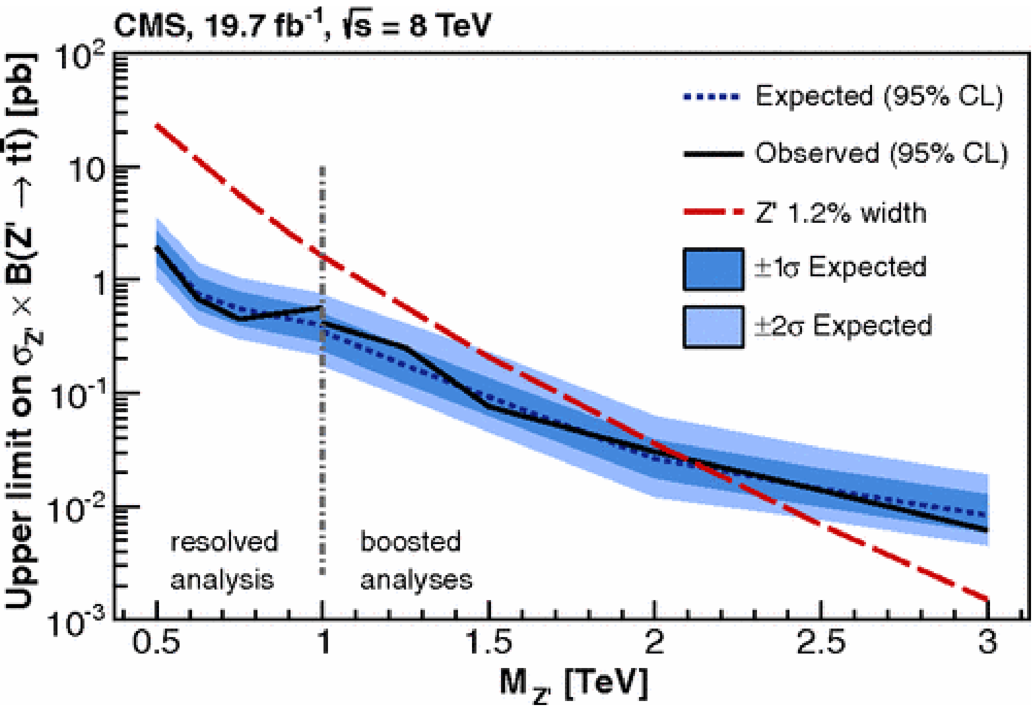
How different are the spin-0 and spin-2 interpratations?

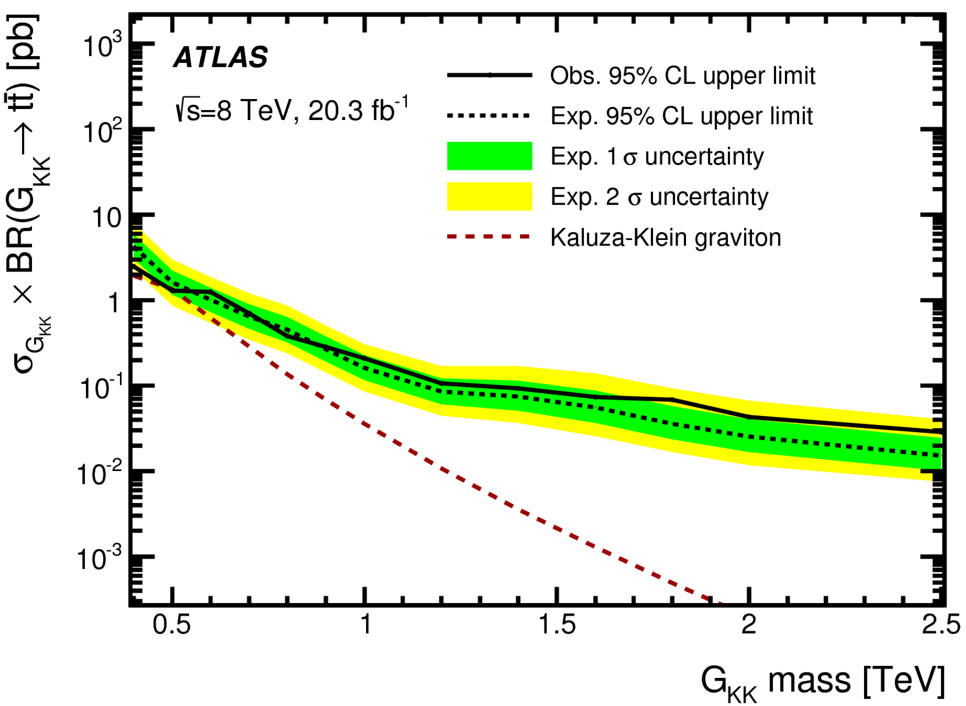
- In the case of the ATLAS analysis, it mostly changes the overall acceptance.
- In the case of CMS it also changes the weight of each category.
  - In the 8TeV analysis (which uses even more event categories), the actual difference in the shape of the observed limit is quite small.



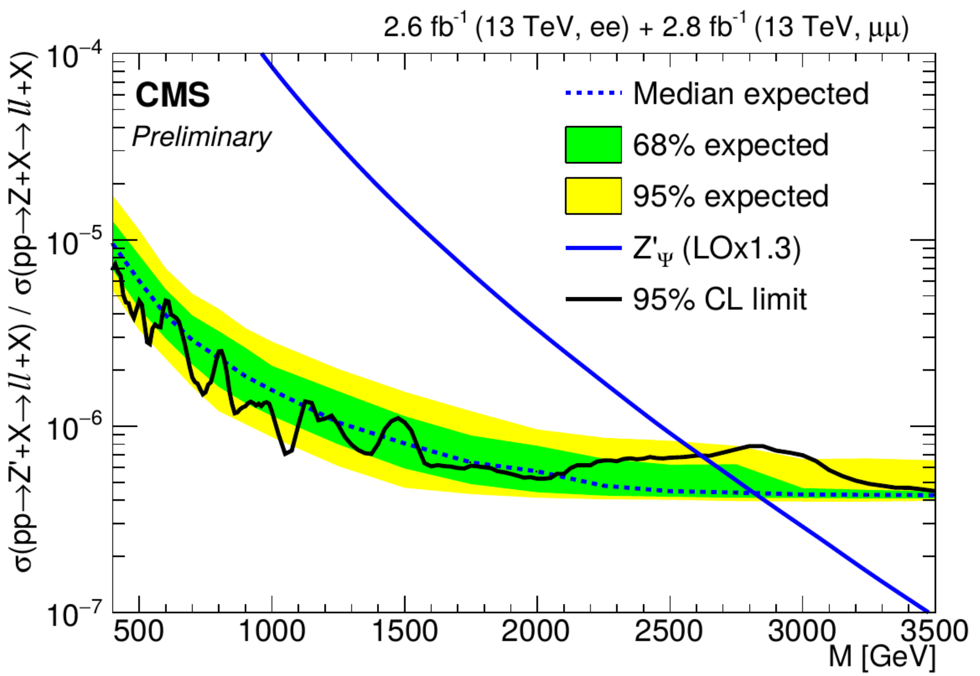


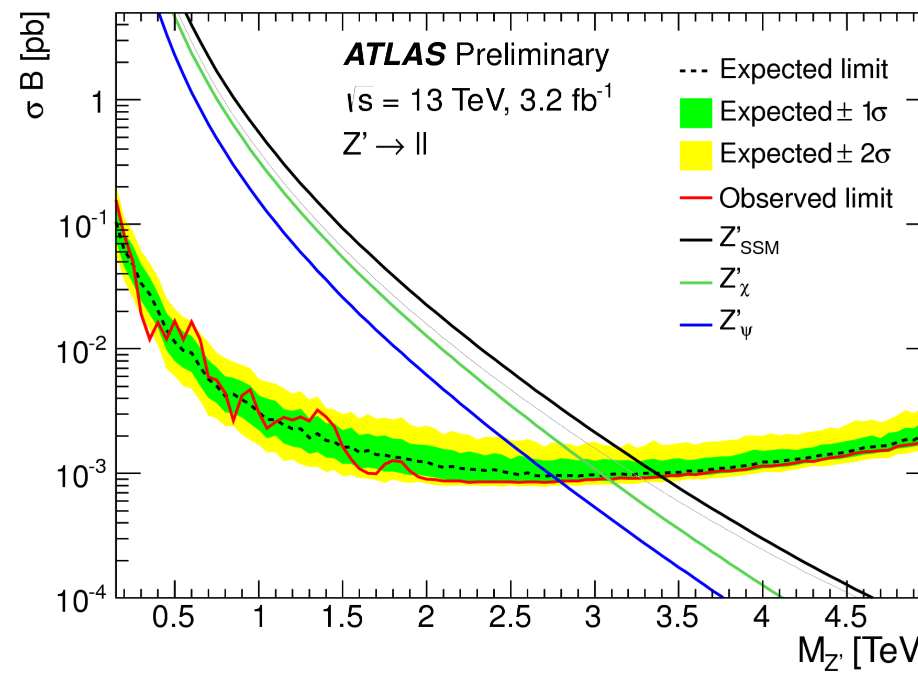
Ttbar resonances



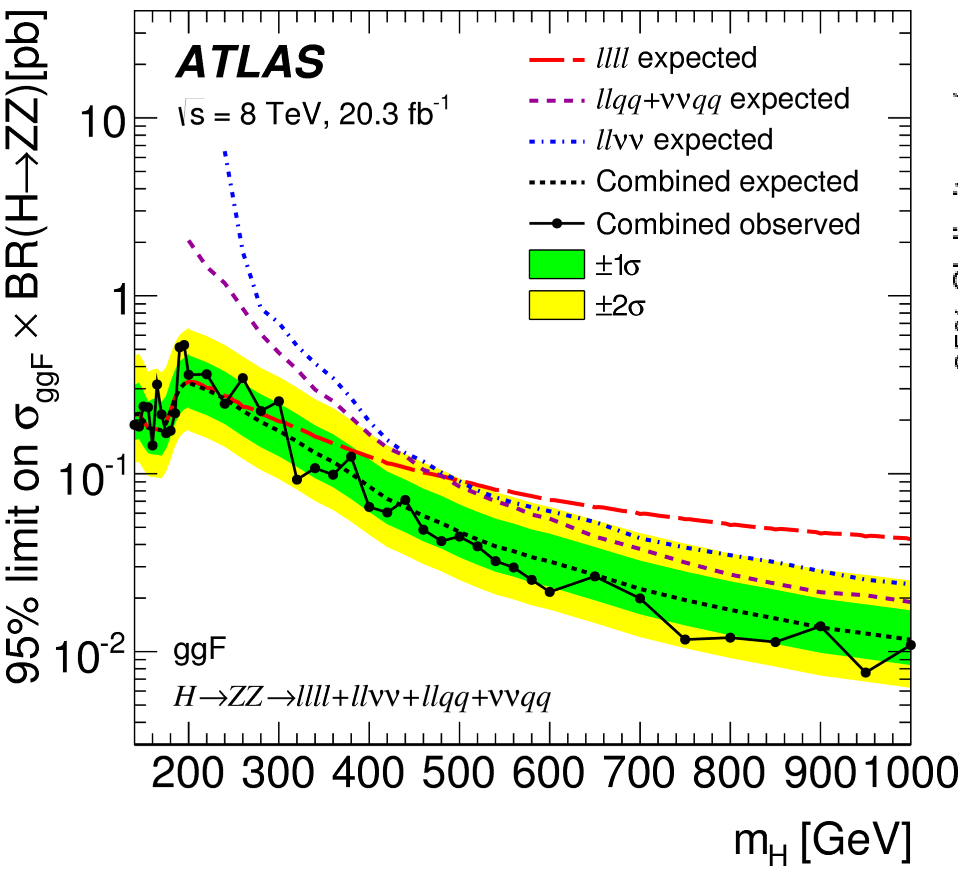


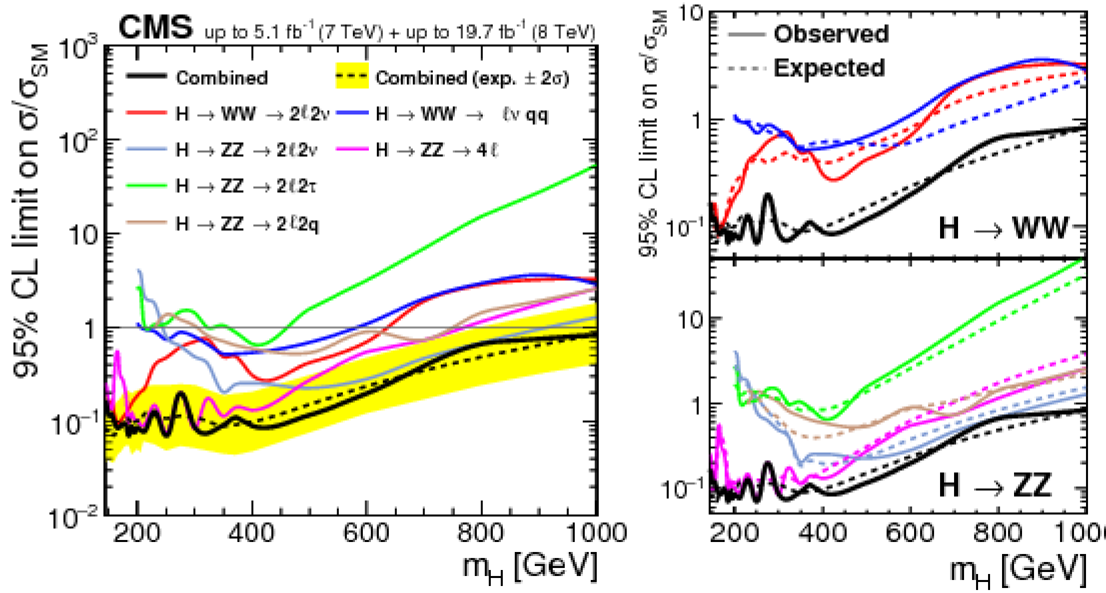
Dilepton resonances



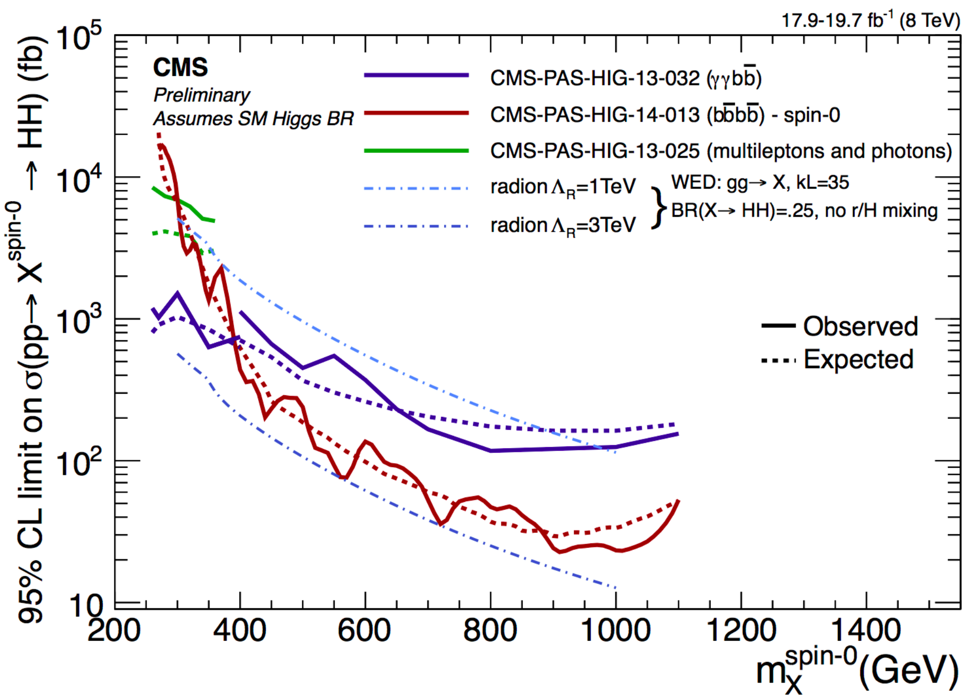


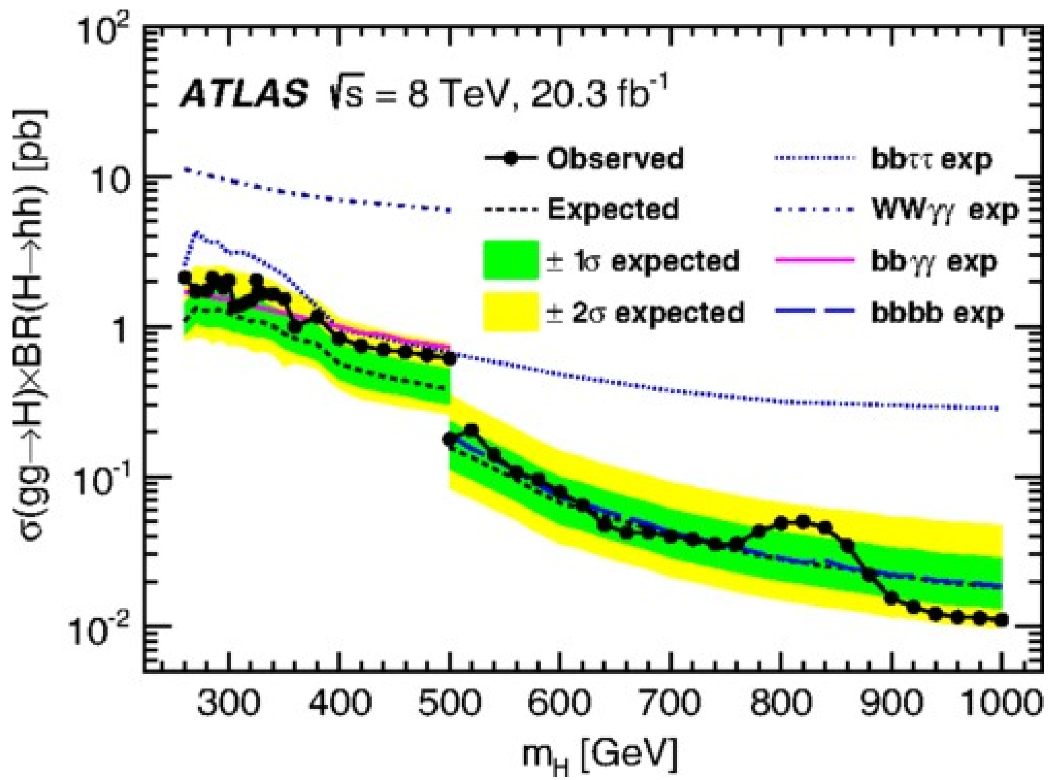
VV resonances





HH resonances





Dijet resonances