The Di-boson excitement at the LHC

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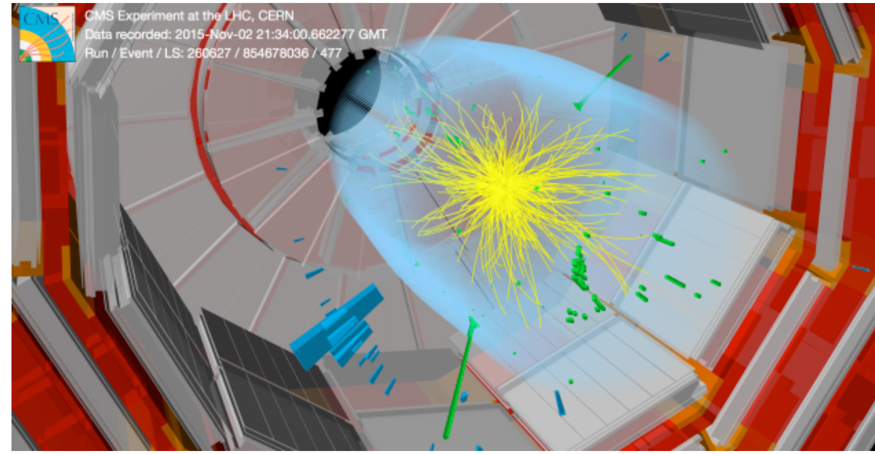
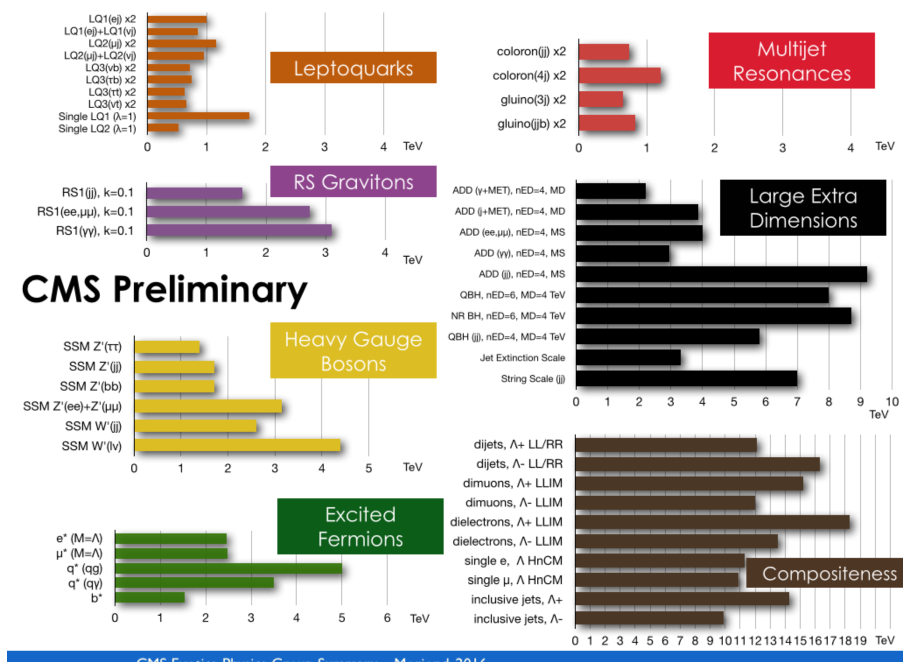
Meeting of the Belgian Inter-University Attraction Pole network on fundamental interactions, 2016

Overview

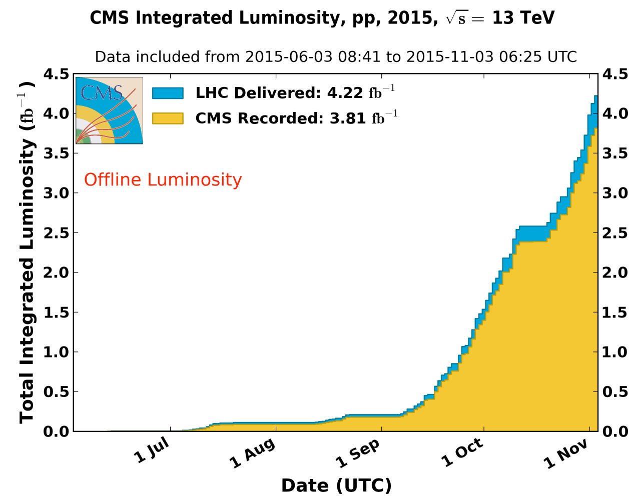
- Introduction and motivation
- Recent excitement in di-boson searches
- Diphoton resonance search with CMS
  - 13 TeV analysis with the magnet (B=3.8T)
  - 13 TeV analysis without the magnet (B=0T)
  - Combination with 8 TeV data
- Diphoton resonance search with ATLAS
- Zγ resonance searches with CMS
- Di-boson VV (V= W, Z, H) searches at 8 and 13 TeV

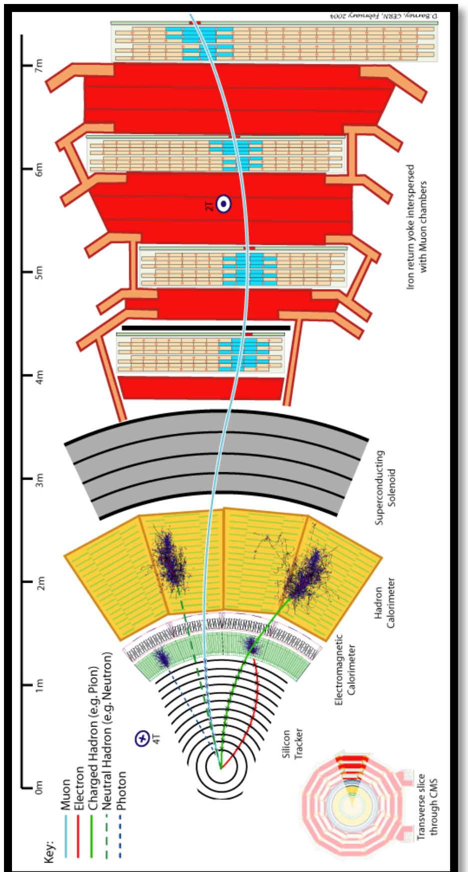


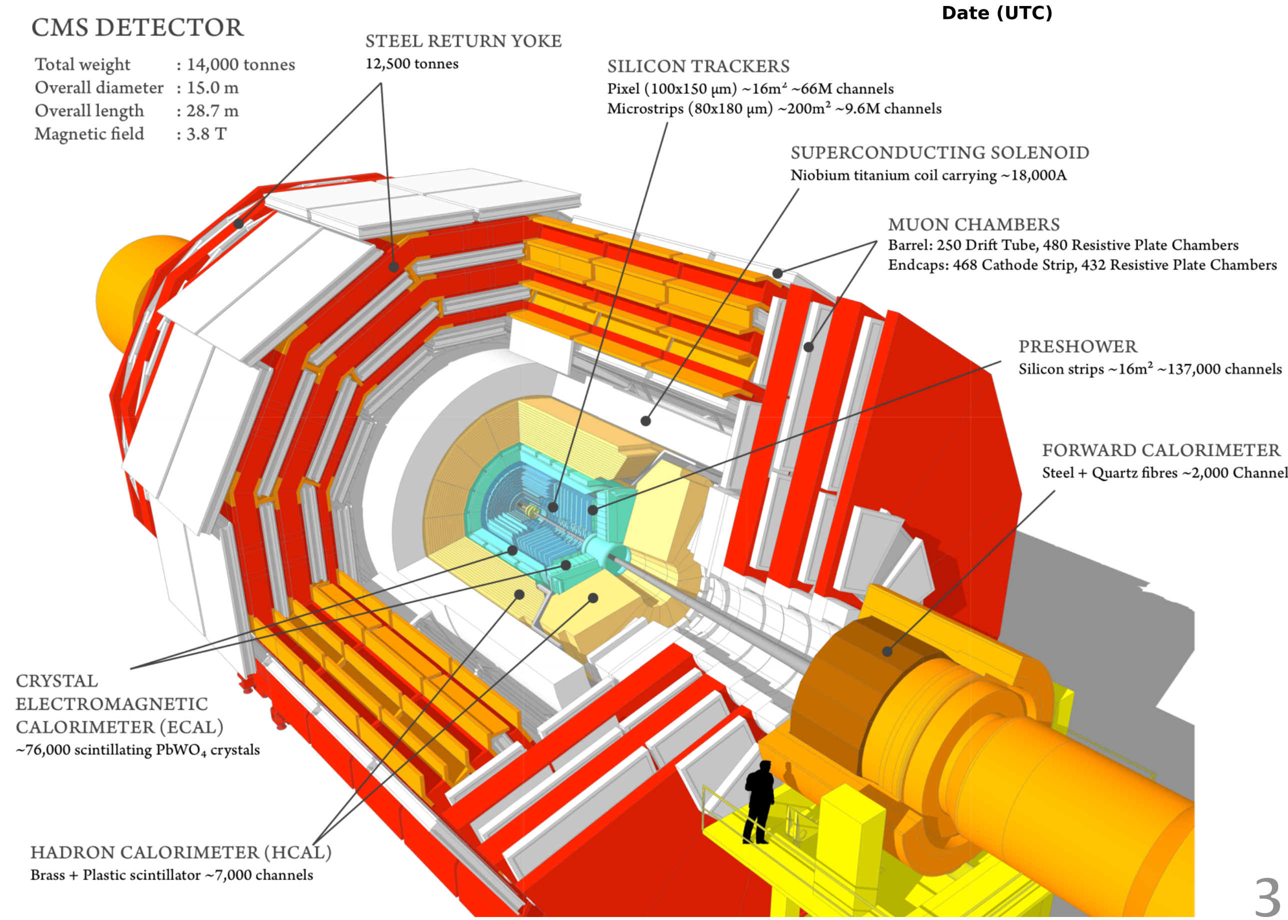


LHC and CMS

- The Large Hadron Collider (LHC) is a proton-proton collider.
- The LHC has been performing extremely well at 7, 8 and 13 TeV and CMS is efficiently taking data.

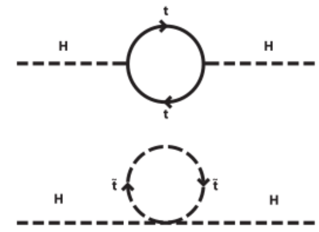


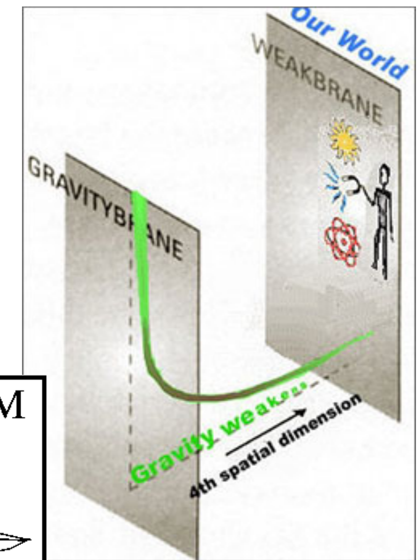


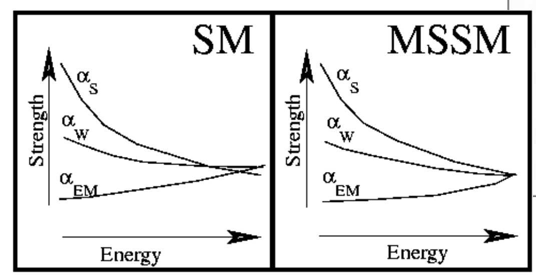


Introduction and motivation

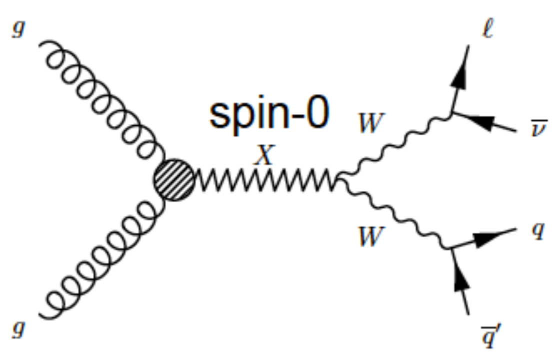
- There are several models that motivate the existence of heavy particles that decay to pair of bosons.
  - Extra dimensions
  - Compositeness
  - SUSY/2HDM
  - …
- These models aim to explain open questions of the SM models.
  - Hierarchy between the electroweak and Planck scale
  - Quantum corrections to the Higgs mass
  - Integration of gravity into the SM
  - …

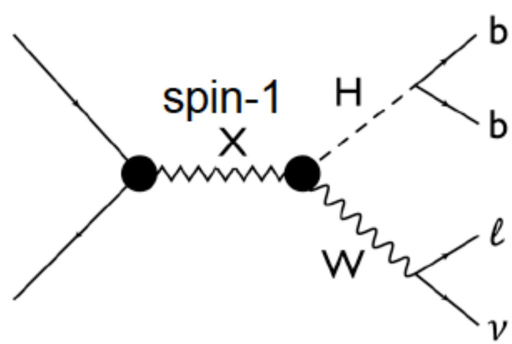


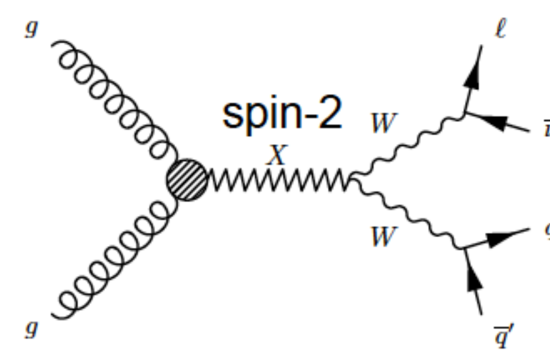




Predicted signature: heavy particle -> **VV** (V = W, Z, H), **γZ and , γγ**

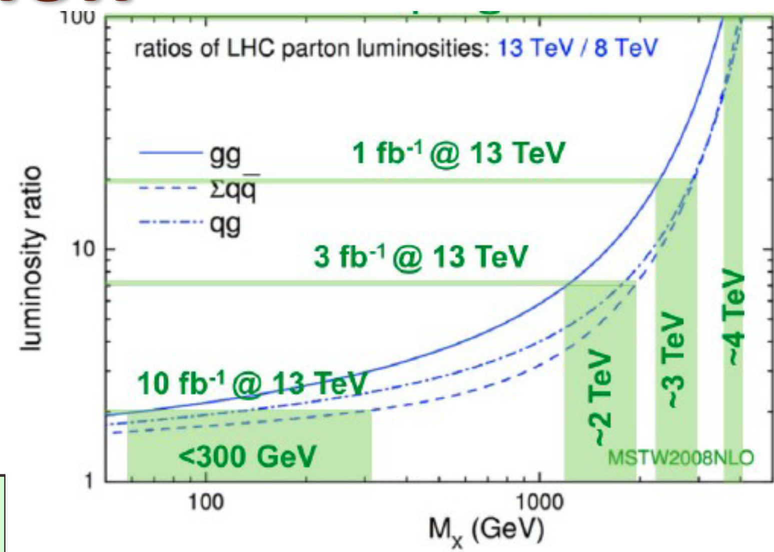






Introduction and motivation

- Heavy resonance searches benefit significantly from increase of √s from 8 to 13 TeV.
- Cross section at higher masses getting more from the √s increase.
- Dramatically increase discovery potential.



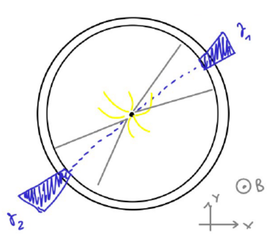
- Search for massive diboson resonances

Experimental advantages:
W/Z/H with well known mass → suppress backgrounds
Good kinematic reconstruction → reconstruct resonance mass

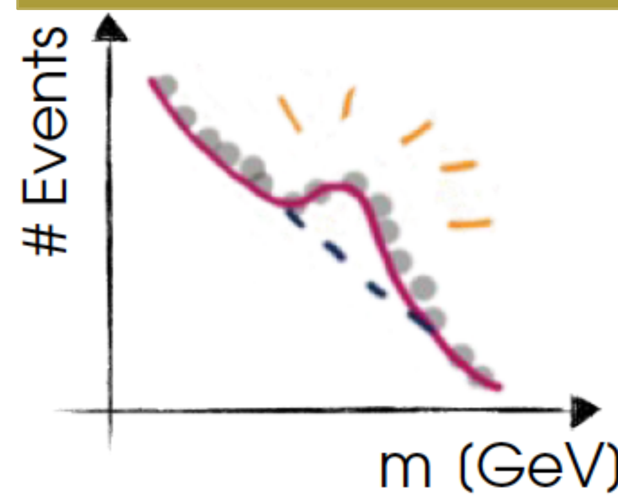
Experimental disadvantages:
Many different final states → lots of channels
Resolution suffers in final states with neutrinos

- Search for diphoton resonances

Very clean signature -> two high Pt isolated photons
excellent invariant mass resolution

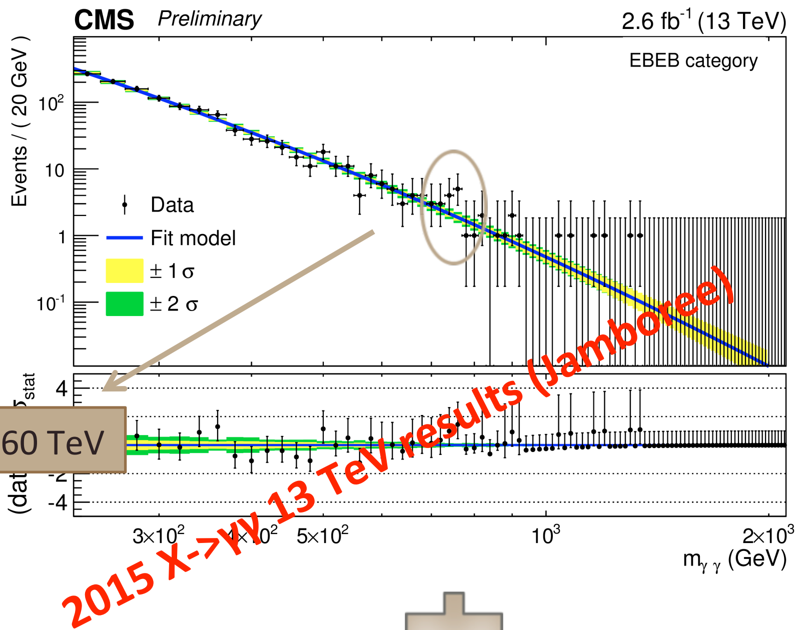


Experimental signature: bump over a continuous background



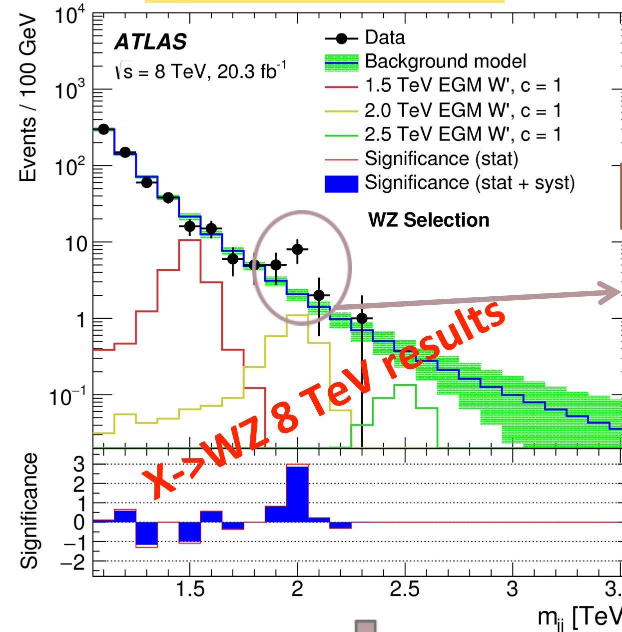
Recent excitement in di-boson searches

CMS-PAS-EXO-15-004



M_γγ =760 TeV

Phys. Lett. B 755 (2016) 285



M_WZ =2 TeV

ATLAS-CONF-2016-018

ATLAS: M_γγ =750 TeV

10.1140/epjc/s10052-016-4067-z

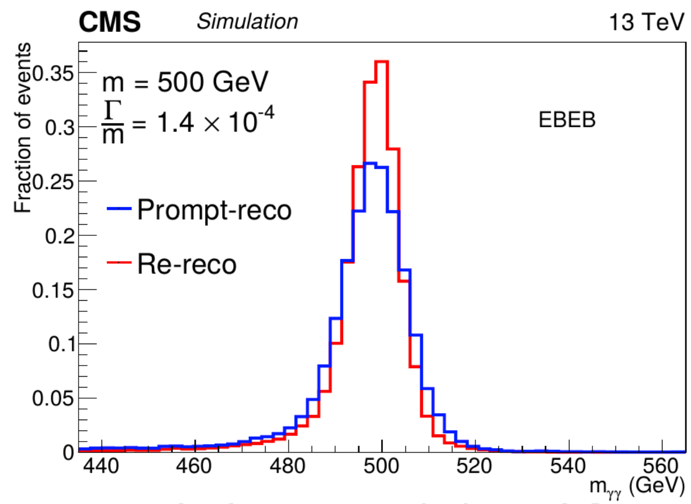
CMS : M_WH=1.8 TeV

- In this talk, new CMS and ATLAS results for searches in diboson final states motivated by previous observed excitements will be reviewed.
- Many complimentary final state are searched for the mentioned excesses.
- 8 and 13 TeV results are combined in some channels to reach better sensitivity.

From preliminary to final result

Ref	Title	M_x	interpreted as	
			spin-0	spin-2
Dec'15	events in proton-proton collisions at $\sqrt{s}$ = 13 TeV			
EXO-16-018 arXiv:1606.04093 NEW	Search for new physics in high mass diphoton events in **3.3 fb^{-1}** of proton-proton collisions at $\sqrt{s}$=13 TeV and combined interpretation of searches at $\sqrt{s}$=8 TeV and 13 TeV.	0.5-4.5TeV	✔	✔

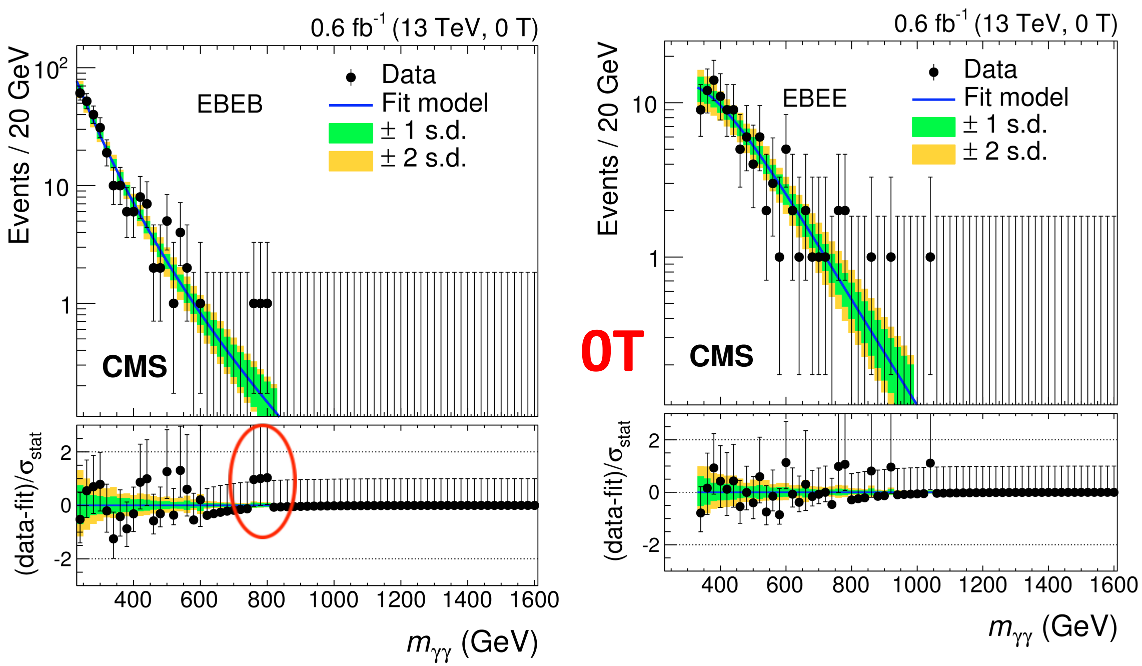
- Re-reconstruction of dataset with L=2.7 fb^{-1}
  - 10 % improvement in analysis sensitivity.
- Additional 0.6 fb^{-1} dataset, recorded at B =0 T (due to solenoid).
  - Lead to a further 10% improvement on top of the re-calibration.
  - There is no information on tracks momenta.
    - Dedicated photon identification.
    - Dedicated vertex selection.
- Results interpreted in terms of spin-0 and spin-2 resonances.

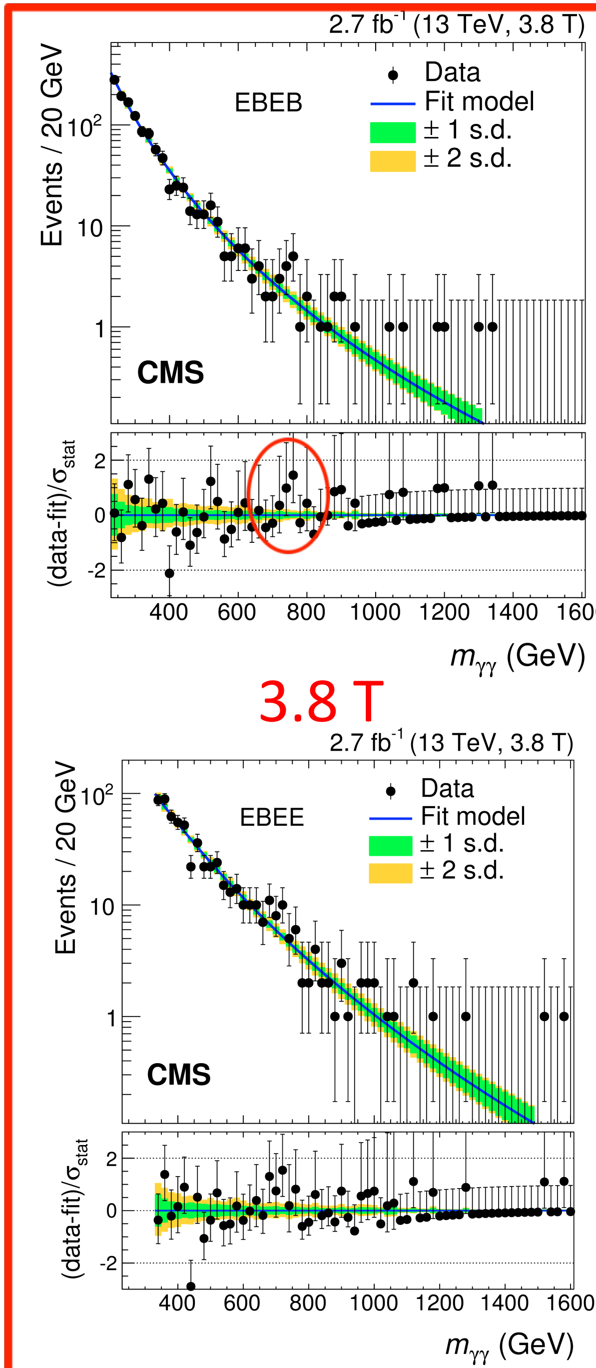


Diphoton mass spectrum

- Select events with two photons of pT> 75 GeV with dedicated ID for 0 and 3.8T.
- Split events in categories: (EB-EB, EB-EE) x (3.8 T, 0 T)
- Fit $M_{\gamma\gamma}$ in 0.5-4.5 TeV for the SM background

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



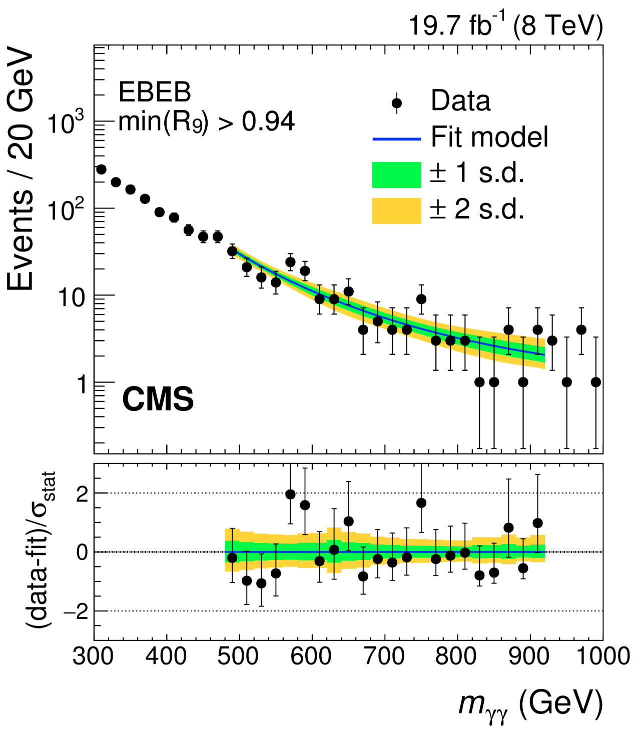


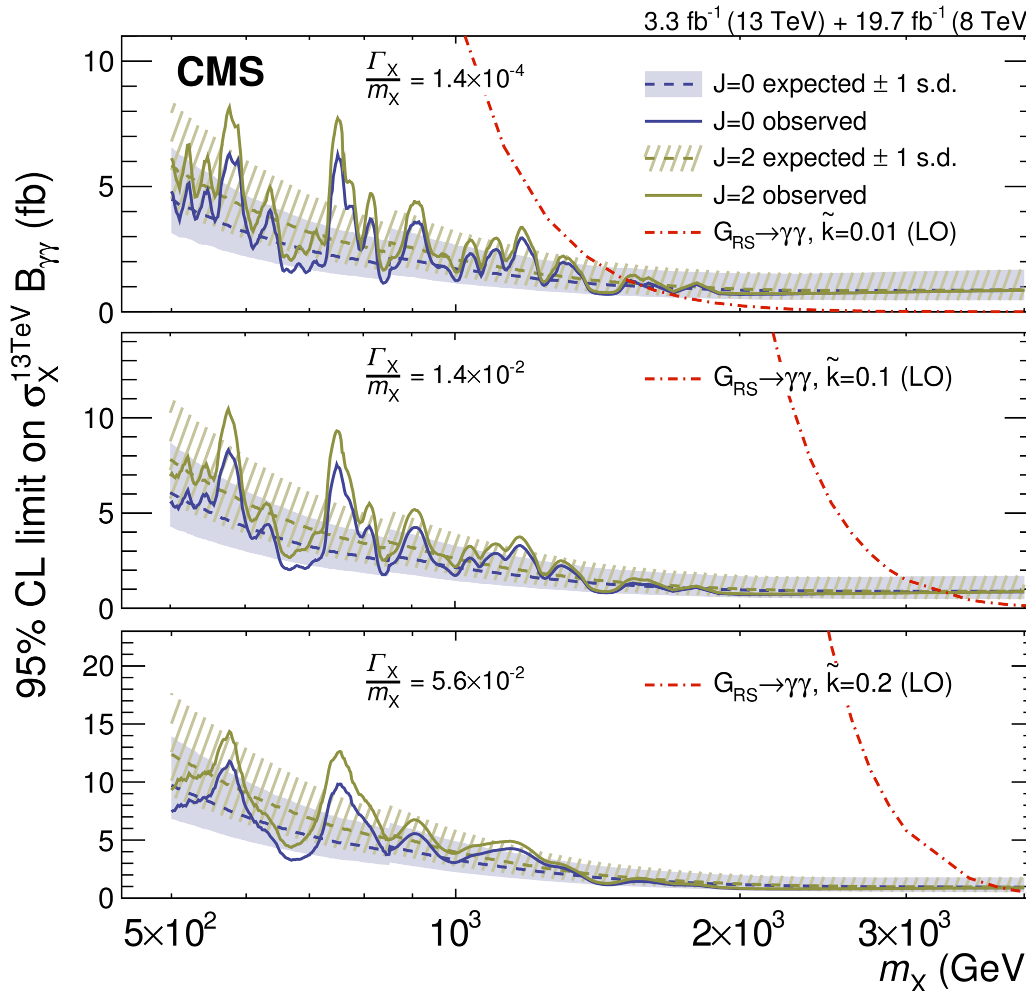
arXiv:1606.04093

CMS 8 and 13 TeV combination

- CMS presented two searches for diphoton resonances at
  - HIG-14-004(Phys. Lett. B 750(2015) 494): used in 500-850 GeV
  - EXO-12-045: used from 850 GeV, similar to 13 TeV analysis

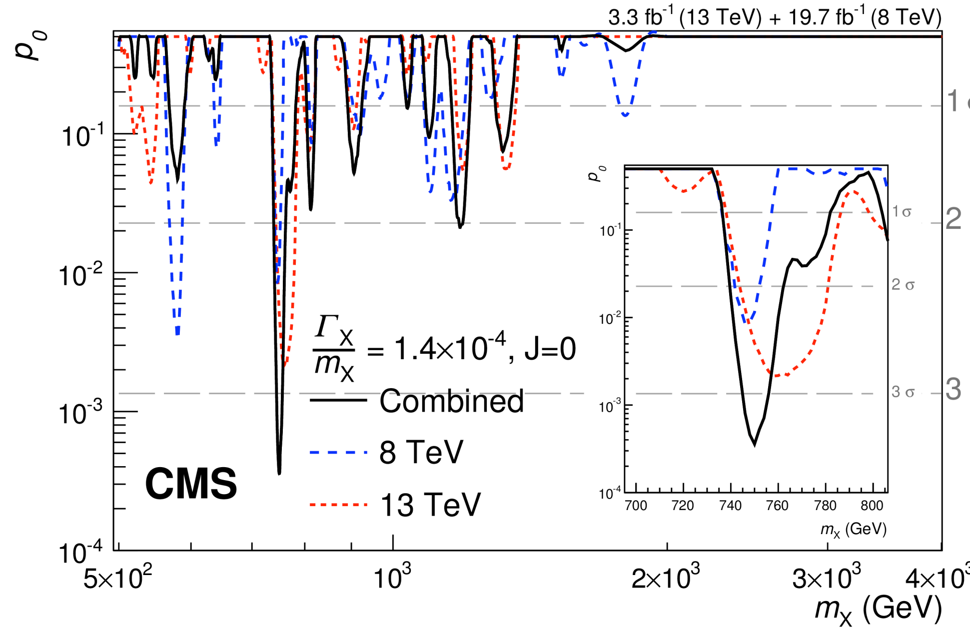
cross section ratios at 750GeV:
for spin 0 ($gg \rightarrow S$): $\sigma_{13TeV}/\sigma_{8TeV} = 4.7$
for spin 2 (GRS): $\sigma_{13TeV}/\sigma_{8TeV} = 4.2$

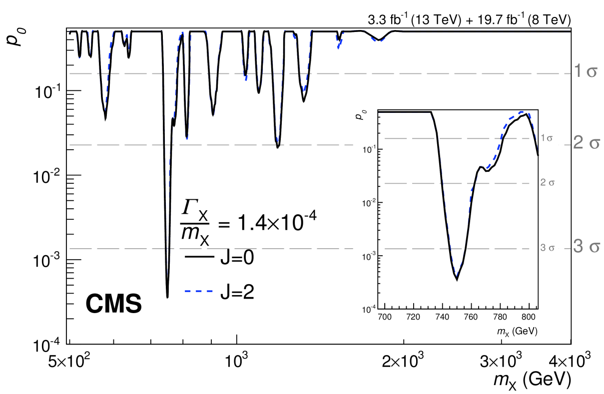


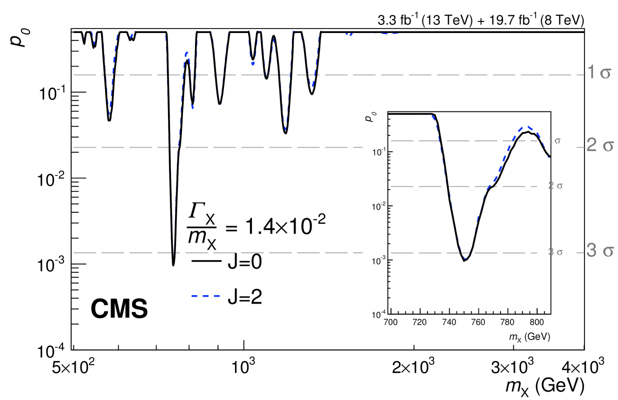


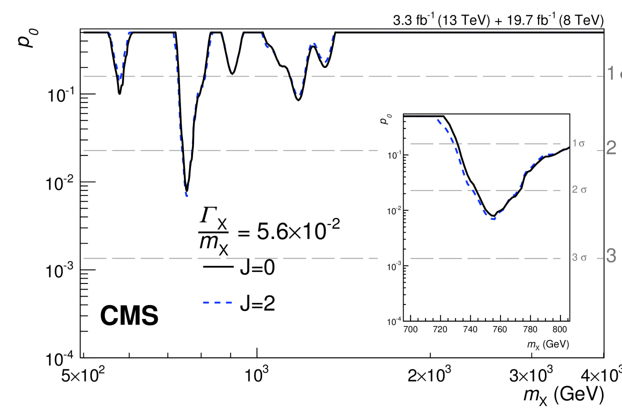
CMS exclusion limit (0T+3.8T)

- largest excess observed at m_X = 750 GeV and for narrow width —> local significance: 3.4σ
- global significance ~ 1.6σ
- J=0 and J=2 hypotheses have similar p-values
- significance decreases for larger width hypothesis





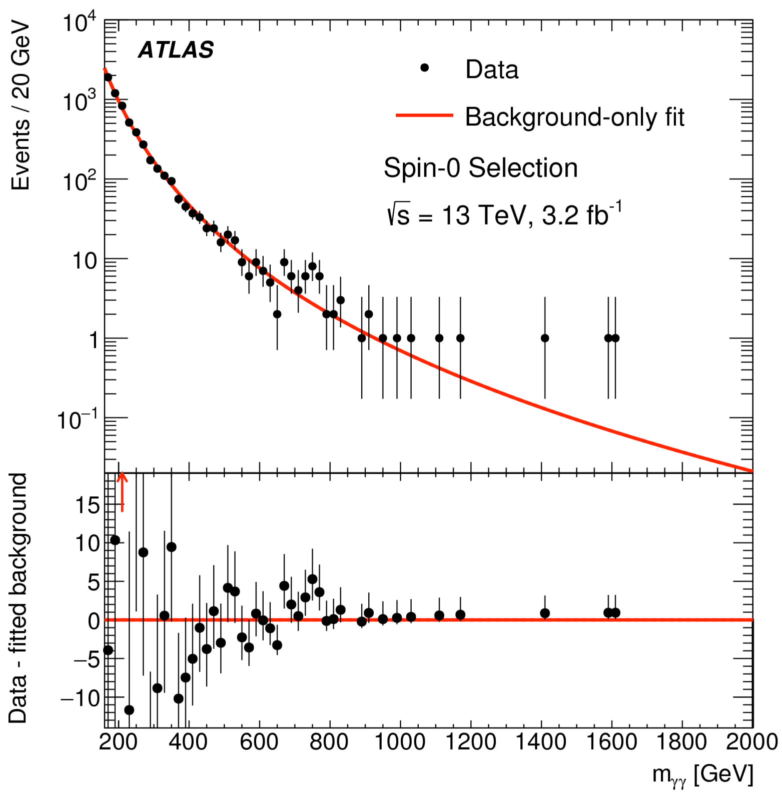


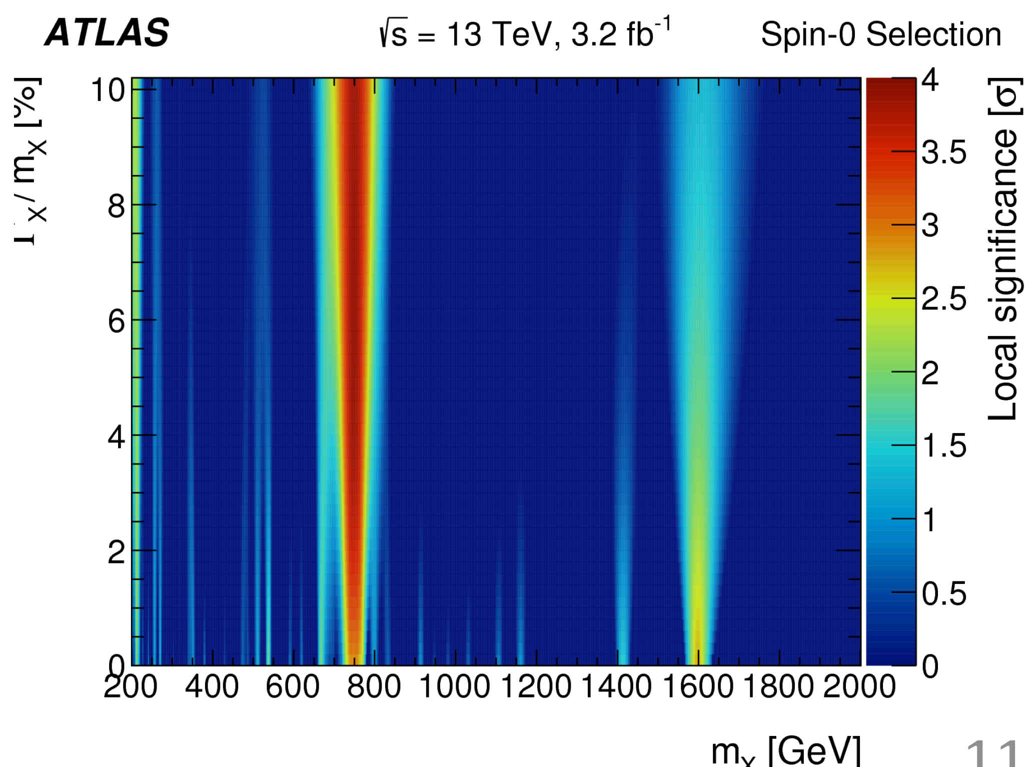


Narrow width → wide width

ATLAS diphoton search

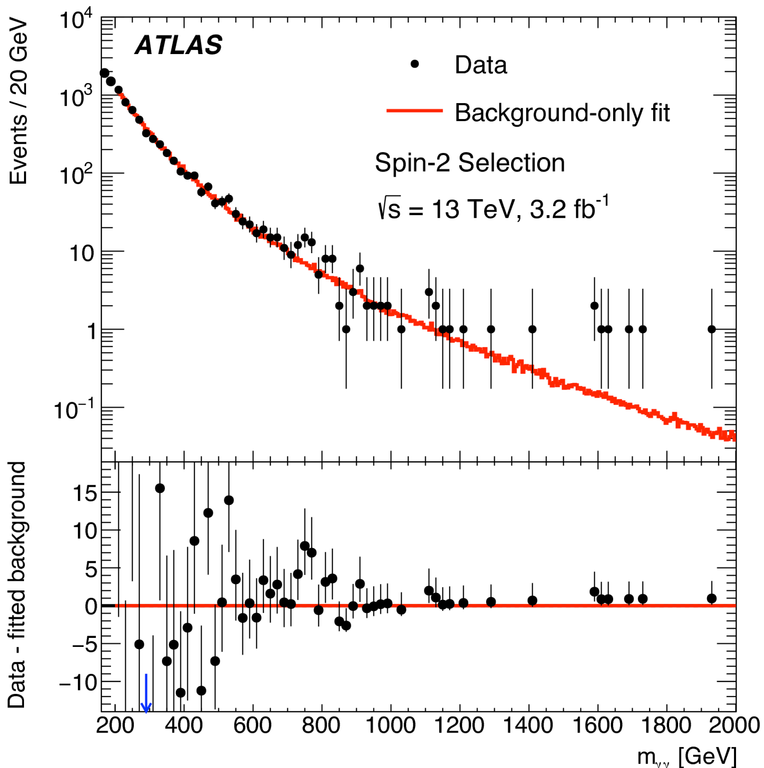
- **Spin-0 search**, extended Higgs sector
  - M->200 - 2000 GeV
  - widths up to 10% of hypothesized mass
  - two photons with E_T>40(30) GeV and >0.4(0.3)$m_{\gamma\gamma}$
- Best fit at 750 GeV for a width of 45GeV (Γ/m=6%) corresponds to 3.9σ local significance.
- 2.1 σ global significance.
- Assuming narrow width signal: 2.9σ local significance at 750 GeV
- small excess in the 8 TeV at 750 GeV (1.9σ)

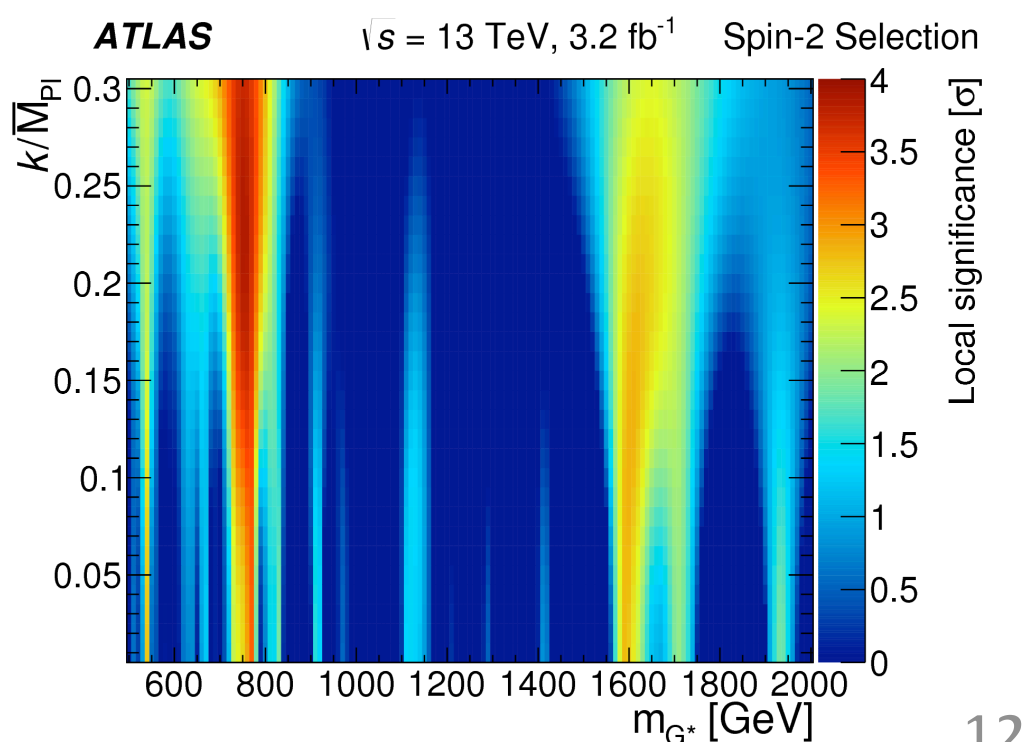




ATLAS diphoton search

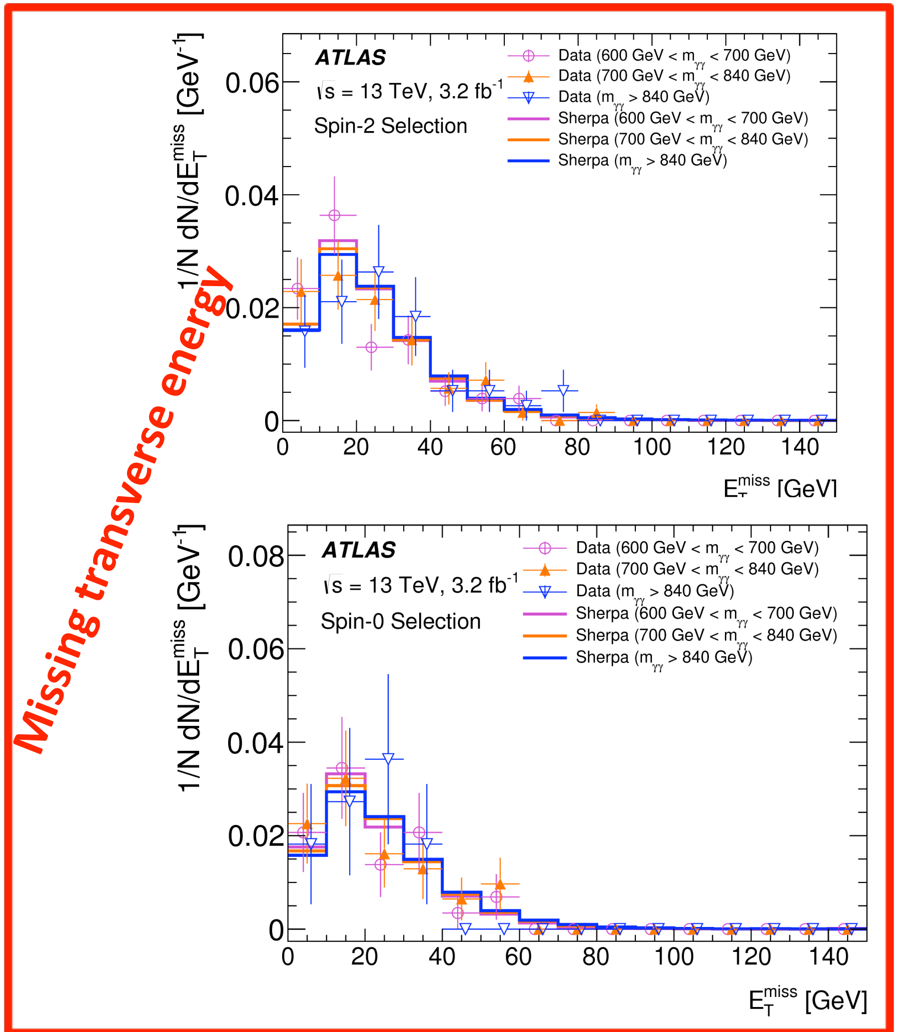
- **Spin-2 search**, Randall-Sundrum model with graviton excitation
  - M->500 - 5000 GeV
  - Dimensionless coupling k/M_{Pl} ranging from 0.01 to 0.3 $\Gamma_{G^*} = 1.44(k/\overline{M}_{Pl})^2 m_{G^*}$
  - two photons with E_T>55 GeV
- Best fit at 750 GeV for a width of 57GeV (Γ/m=8%, k/M_P=0.23) corresponds to 3.8σ local significance.
- 2.1 σ global significance.
- Assuming narrow width signal: 3.3σ local significance at 770 GeV
- no excess in the 8 TeV at 750 GeV

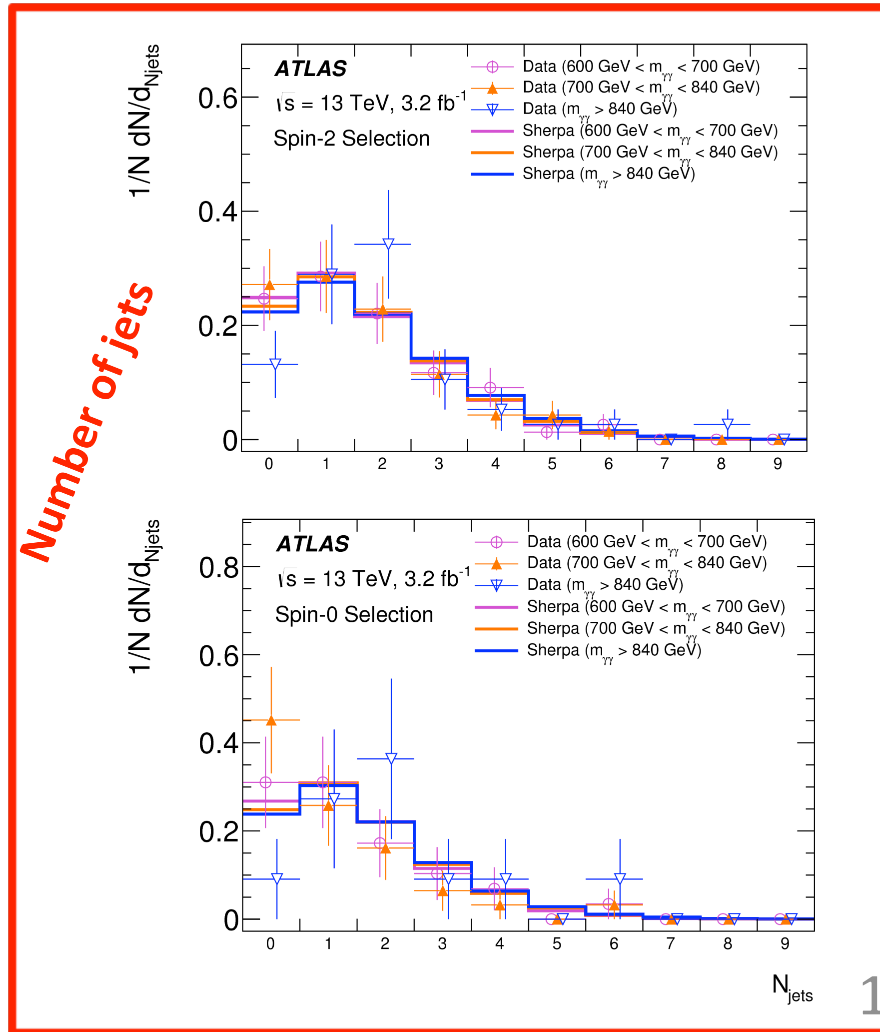




Kinematic distribution for events around bump

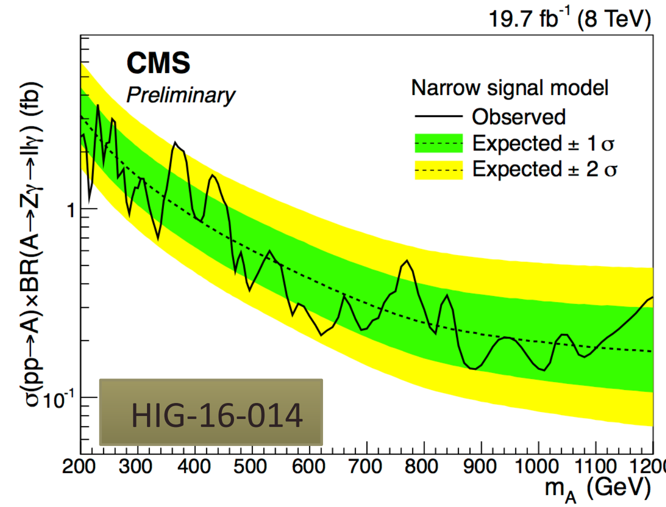
- ATLAS:comparison of events properties
  - 700<M<840
  - 600<M<700
  - M>840
- CMS: the multiplicity and kinematic distributions of the hadronic jets reconstructed in the events, do not exhibit significant deviations from the distributions expected for SM processes.



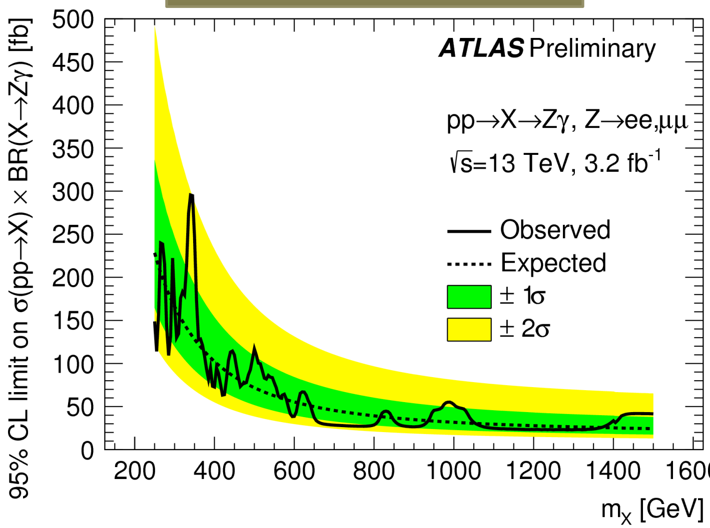


Z(ll) γ searches

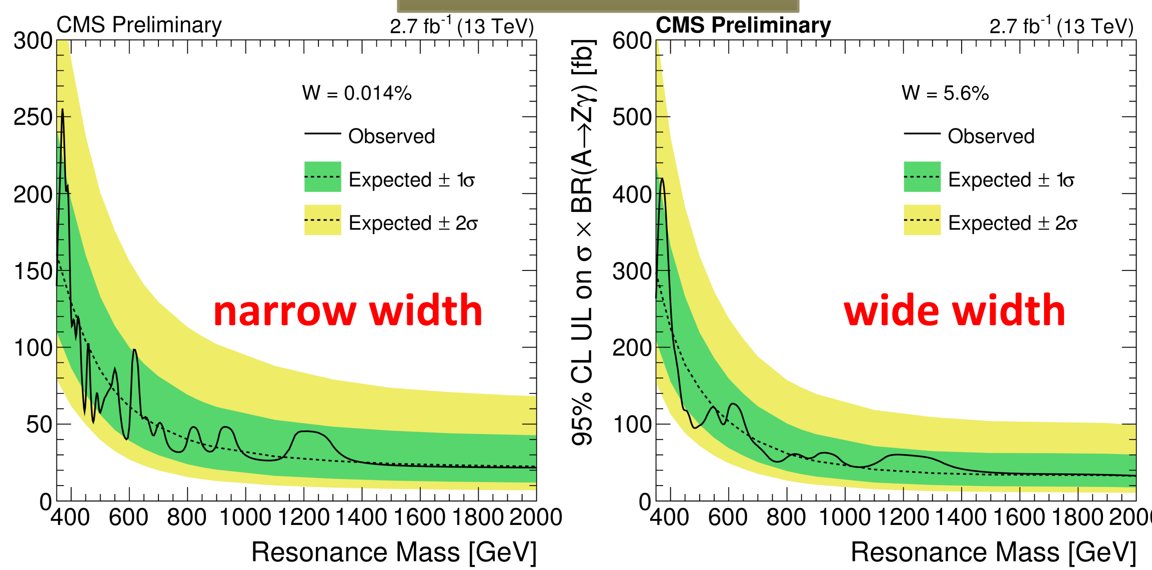
- low trigger threshold, less background->best at low mass
- Search at 8 TeV with no significant excess (~ 2σ fluctuation around 750 GeV)
- 13 TeV analysis: exactly two opposite-sign electrons or muons, and a photon
- Combining $ee\gamma/\mu\mu\gamma$
- No excess around 750 GeV



ATLAS-CONF-2016-010

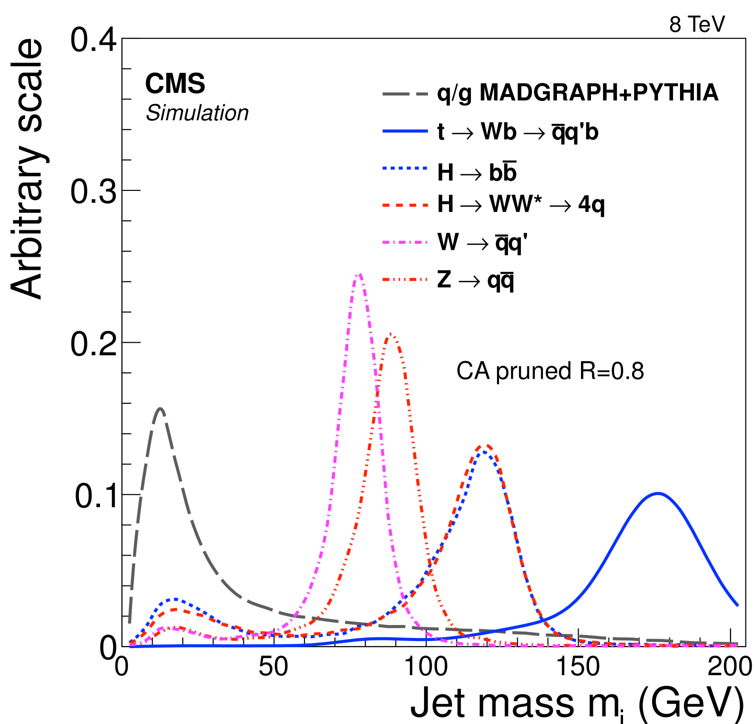


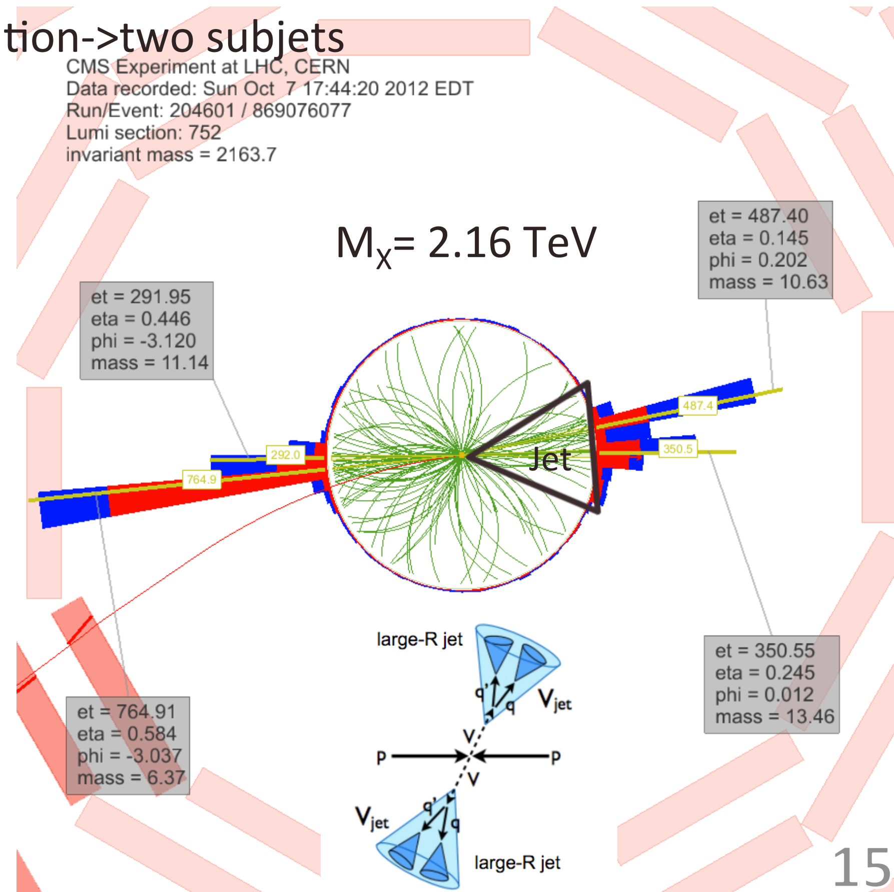
CMS-PAS-EXO-16-019



Reconstruction of boosted W/Z/H

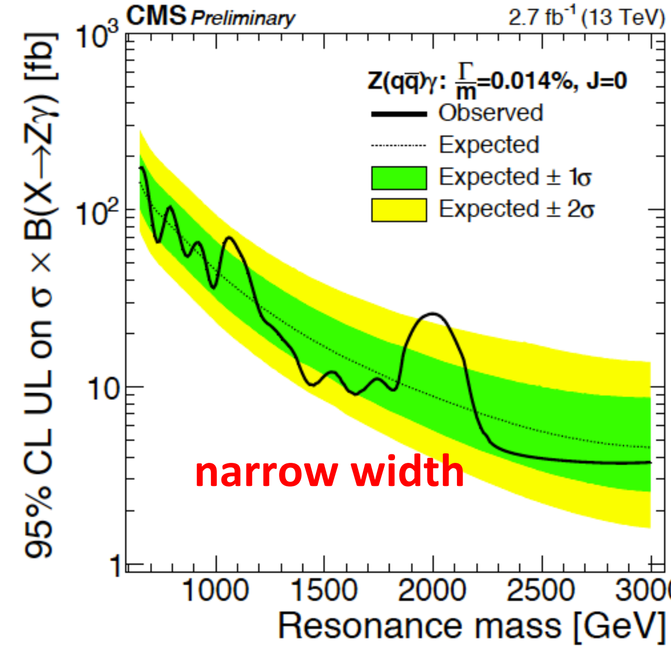
- Heavy resonances decay results in boosted di-bosons
- Hadronic decays enhancing the rates
- it is crucial to identify boosted V -> qq decays
- **Jet pruning** (arXiv:0903.5081, arXiv:0912.0033)
  - Recluster jet constituents, applying additional conditions at each recombination
  - Filter out soft and large angle QCD emissions
- **Mass Drop** (arXiv:0802.2470)
  - Decluster jet by stopping before last iteration->two subjets
- **N-subjettiness** (arXiv:1011.2268)

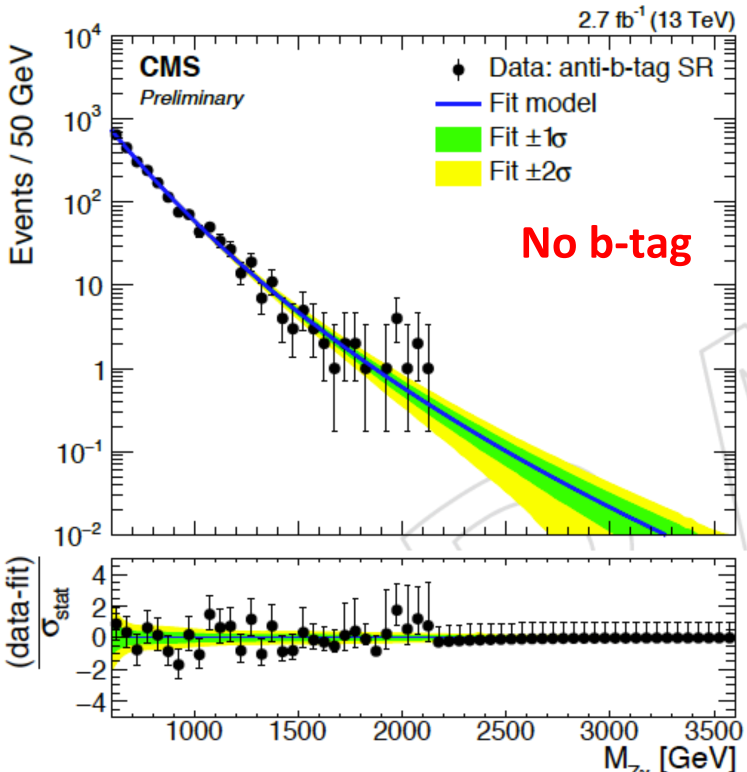


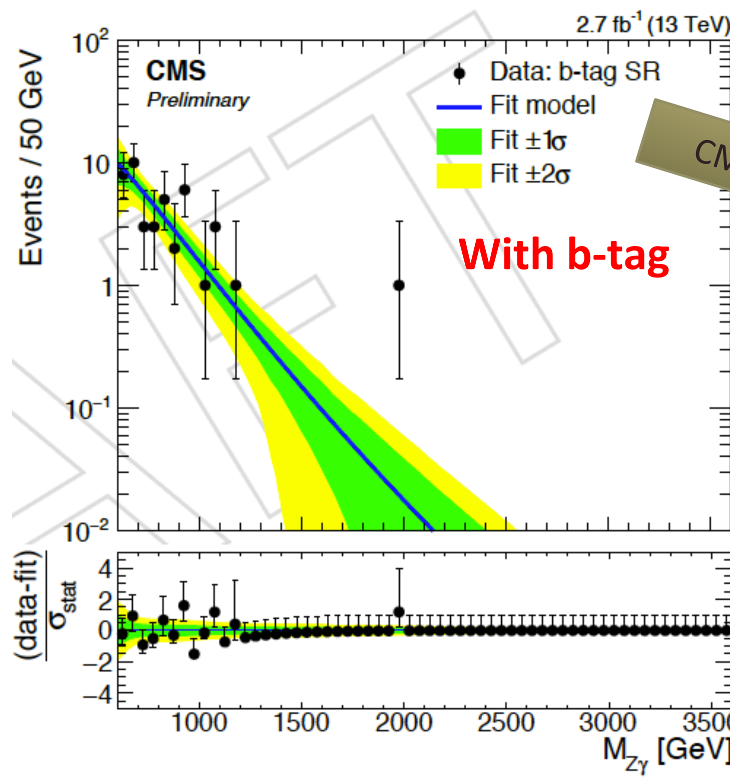


Z(qq) γ searches

- higher acceptance compared to leptonic channel-> best at high mass
- Event selection: Photon p_T> 180, AK8 jet p_T> 200, $m_{J\gamma}$> 600 GeV
- Sub-jet b-tagging: Two categories (anti-b-tagged and b-tagged)
- No significant excess observed
- ATLAS 13 TeV analysis gives the similar result (ATLAS-CONF-2016-010)





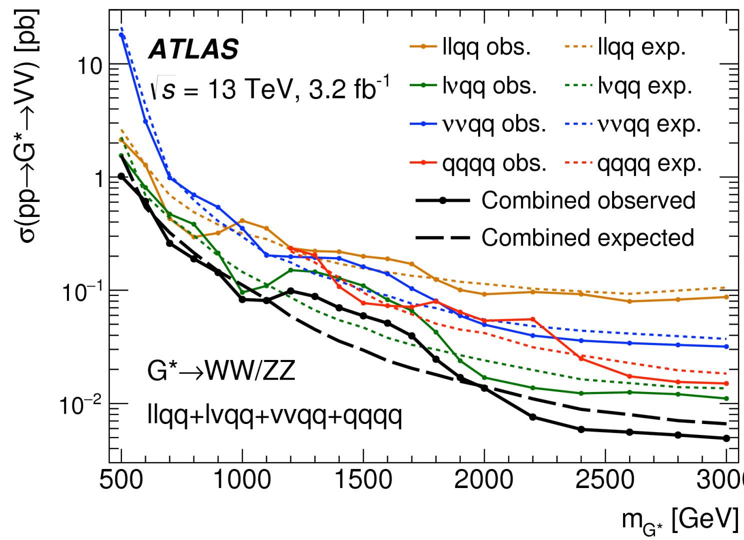


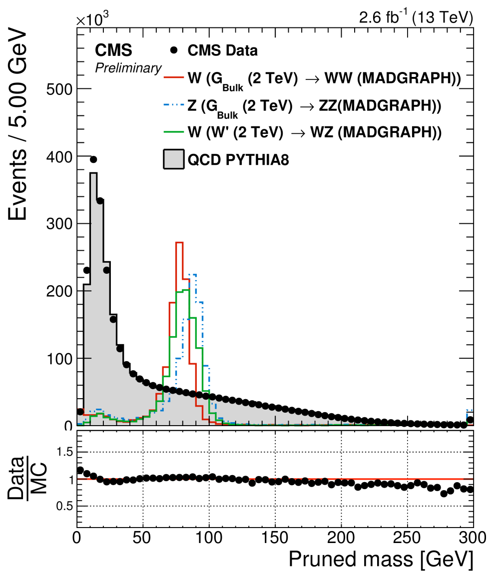
CMS-PAS-EXO-16-020

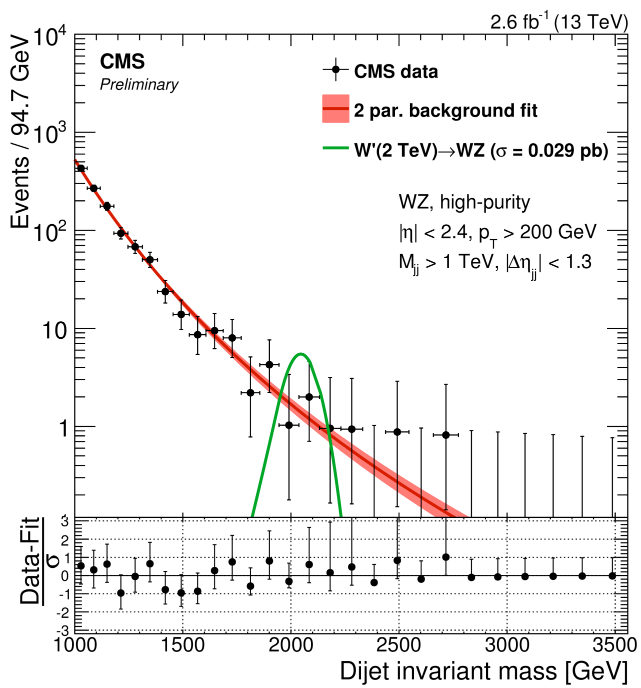
WW / WZ / ZZ @ 13 TeV

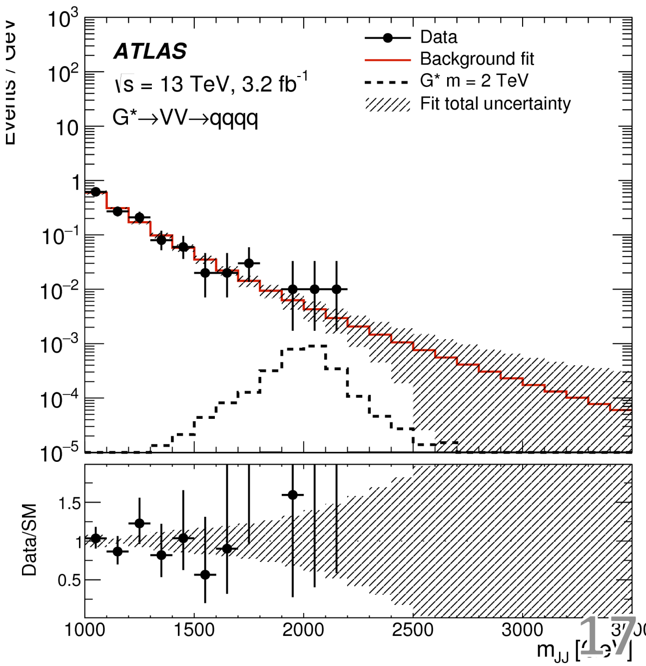
CMS-PAS-EXO-15-002
ATLAS-CONF-2015-068
ATLAS-CONF-2015-075
ATLAS-CONF-2015-071
CMS-EXO-PAS-15-002
CMS-PAS-B2G-16-004

- 13 TeV data is analyzed in both ATLAS and CMS with most of the possible final states
  - WW/WZ/ZZ->qqqq
  - WW/WZ/ZZ->υυqq/lvqq/llqq
- Reconstructed jet masses in hadronic final states are used to define different sensitive signal region
- $65<m_{pruned}<105$ GeV
- No excesses observed by CMS and ATLAS
- Better limits than in Run 1





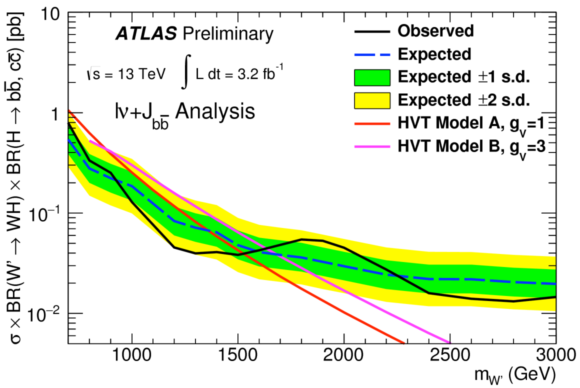


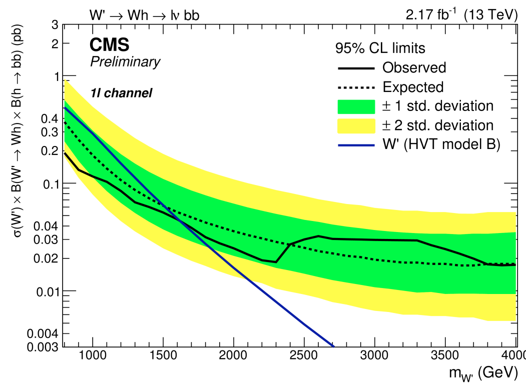


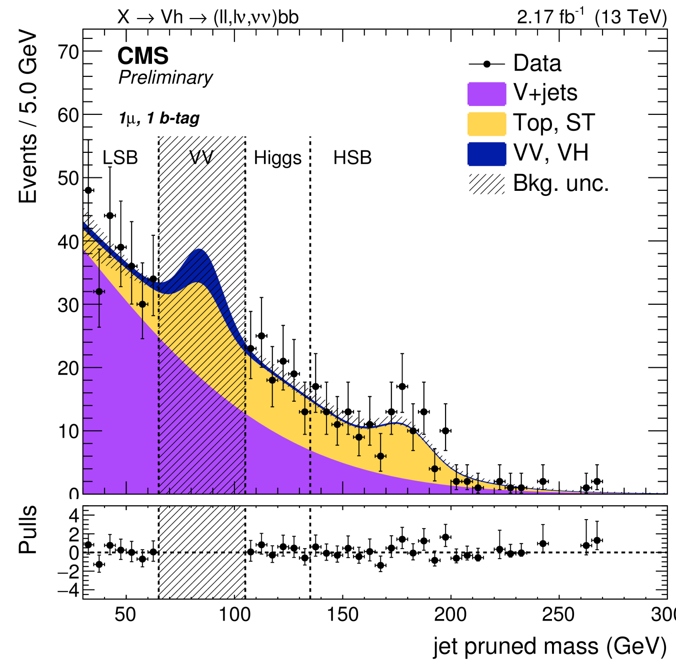
VH

ATLAS-CONF-2015-074
CMS-PAS-B2G-16-003
CMS-PAS-B2G-16-007

- Higgs identification: $105<m_J<135$
- Same conclusions from ATLAS and CMS: No significant excess observed over background

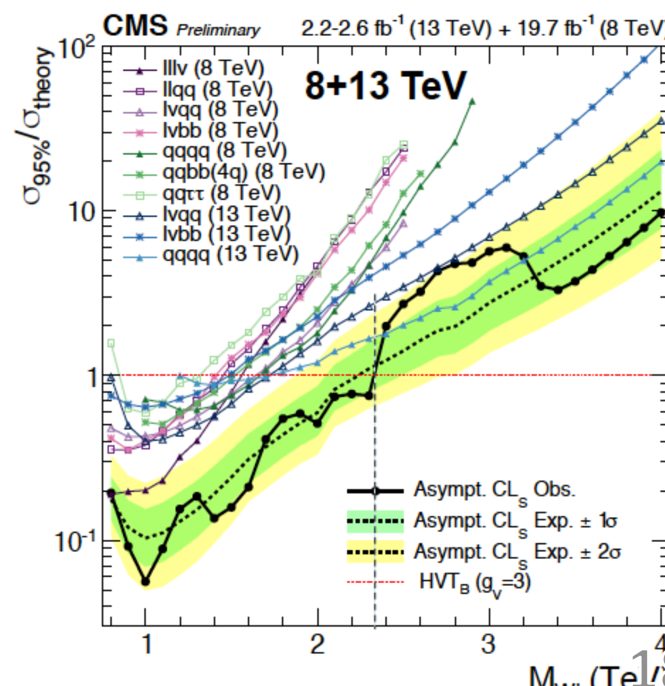






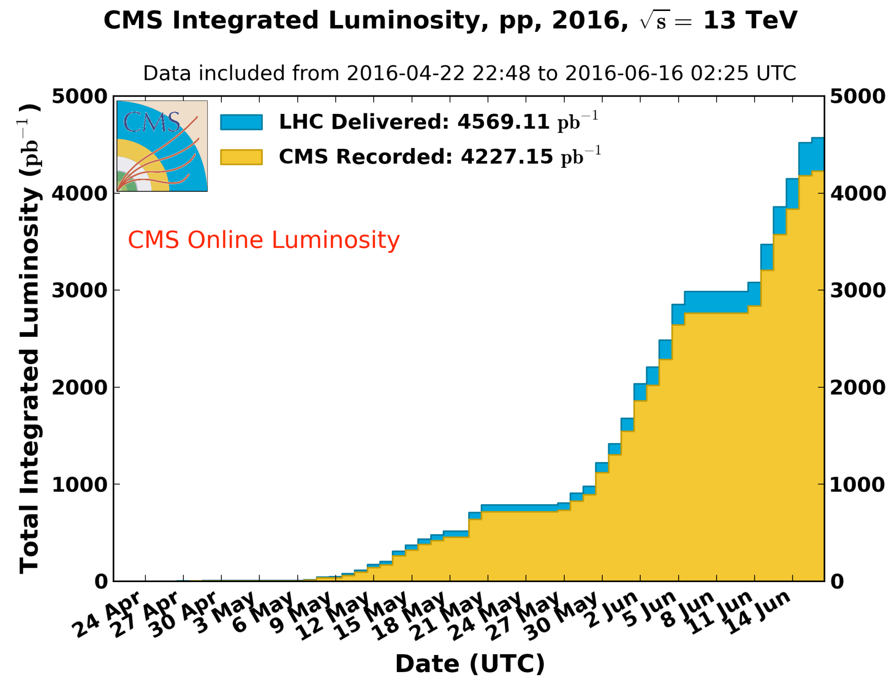
WH and WZ combination

- Most significant excess from Run 1 in CMS: 2.2σ local for W'->WH@ 1.8 TeV
- Combining all 8 TeV VV+VH searches: remains 2.2σ in W' hypothesis
- Combining all 8+13 TeV VV+VH searches: reduced to 0.9σ in W' hypothesis



Summary

- Combining 8 and 13 TeV data, CMS +ATLAS conclude a solid "maybe" on the 750 GeV bump.
- LHC already delivered more than 4.5/fb in 2016 in the last few weeks -> we will get further understanding soon!
- Di-boson resonance masses >TeV explored in all final states by CMS+ATLAS



- Analyses with 13 TeV data supersede 8 TeV searches at >TeV masses and put most stringent mass limits on W'/Z'/G* resonances
- Combination of 8+13 TeV VV+VH searches disfavor bump at 2 TeV, Final confirmation with 2016 data

Thanks for your attention

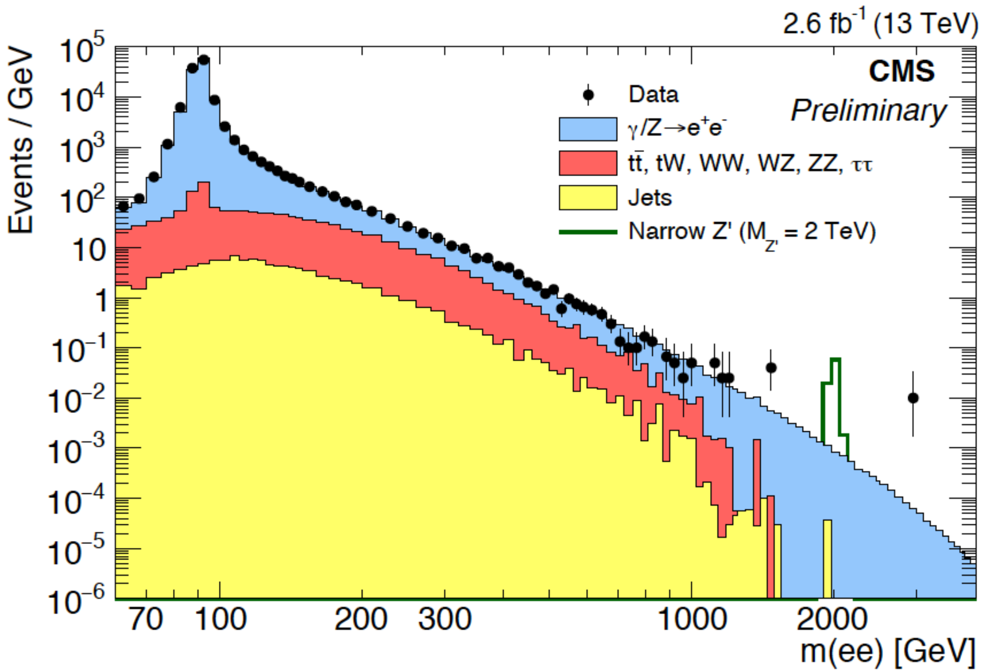
Backup

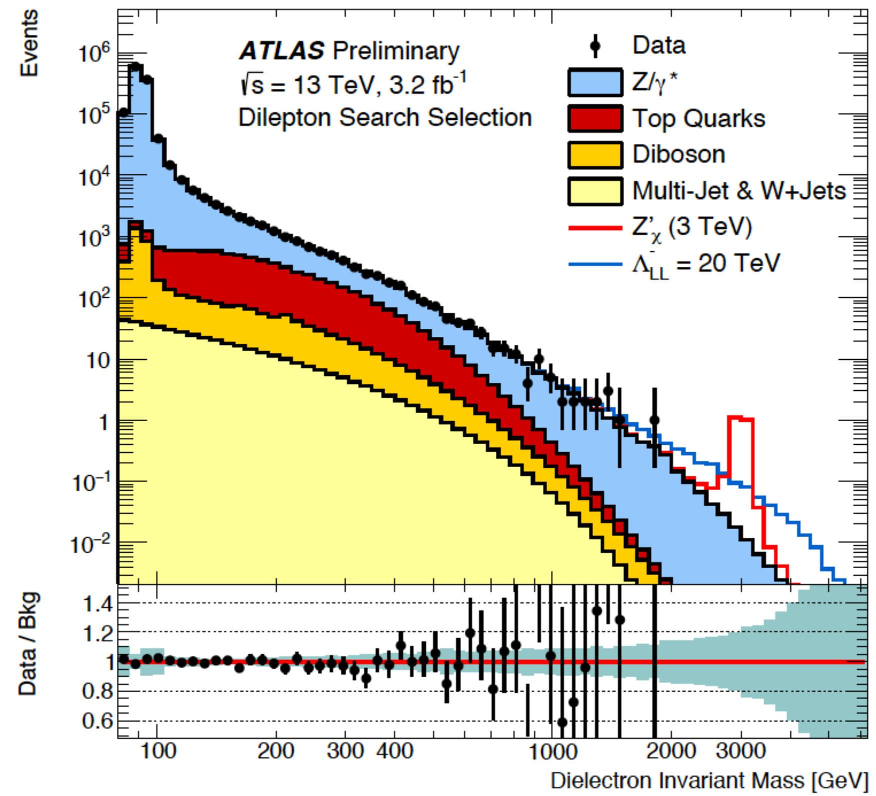
dilepton resonances

[ATLAS-CONF-2015-070]
[CMS-PAS-EXO-15-005]

experimental challenges:

- lepton reconstruction at high momenta
- efficiency and fake rate calibration (extrapolation from low to high momenta)
- background estimation (extrapolation)





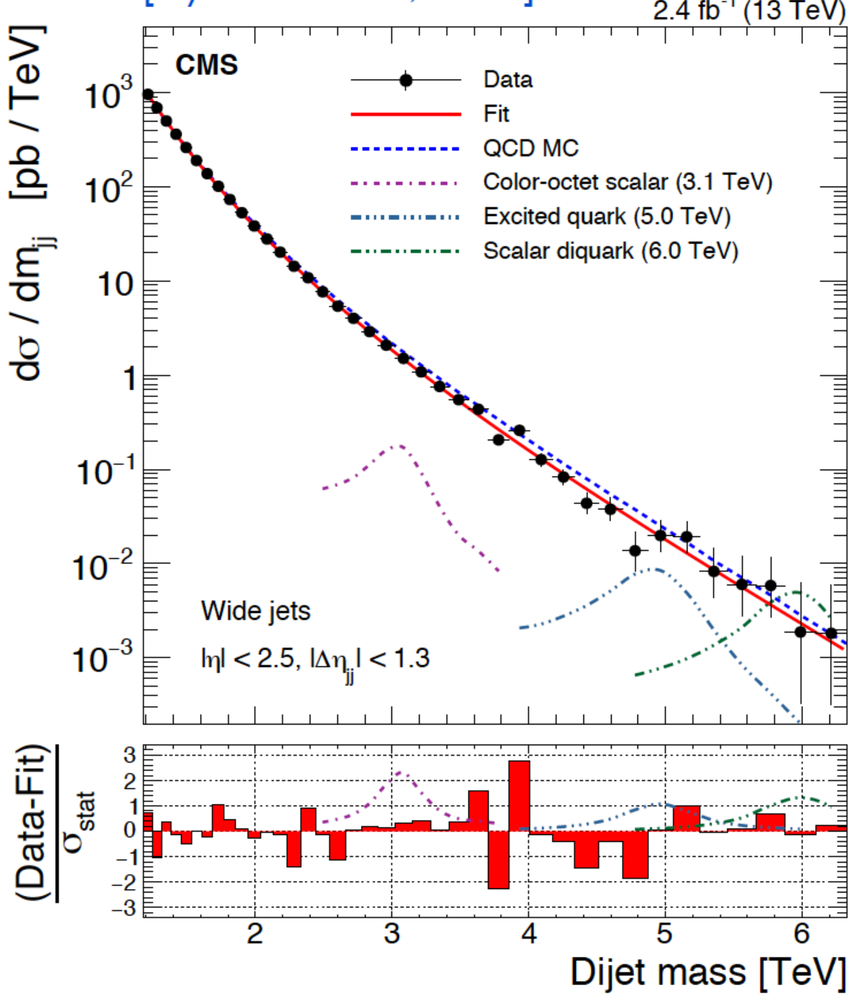
- highest mass event: m_{ee}=2.9 TeV

  (0.3 events expected above 2 TeV)

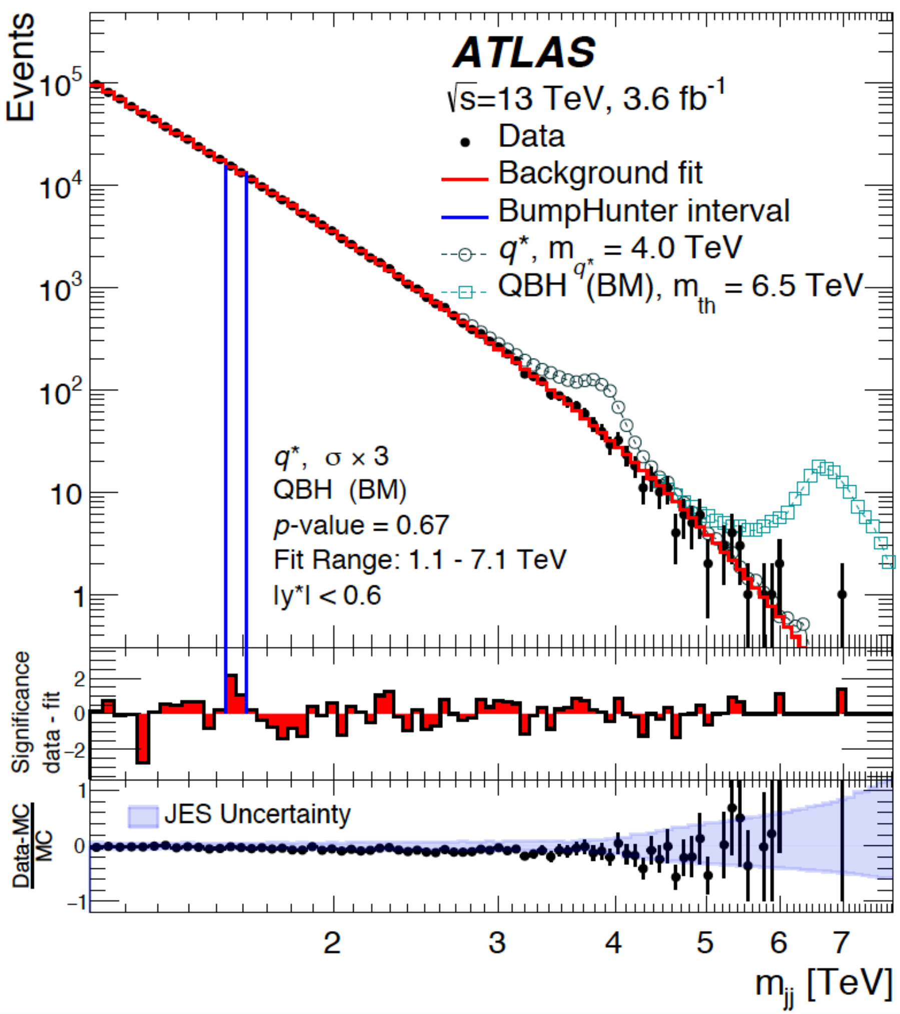
  (0.08 events expected above 2.5 TeV)

high-mass dijet resonances

[Phys. Rev. Lett. 116, 071801]



[Phys. Lett. B 754, 302]



low-mass dijet resonances

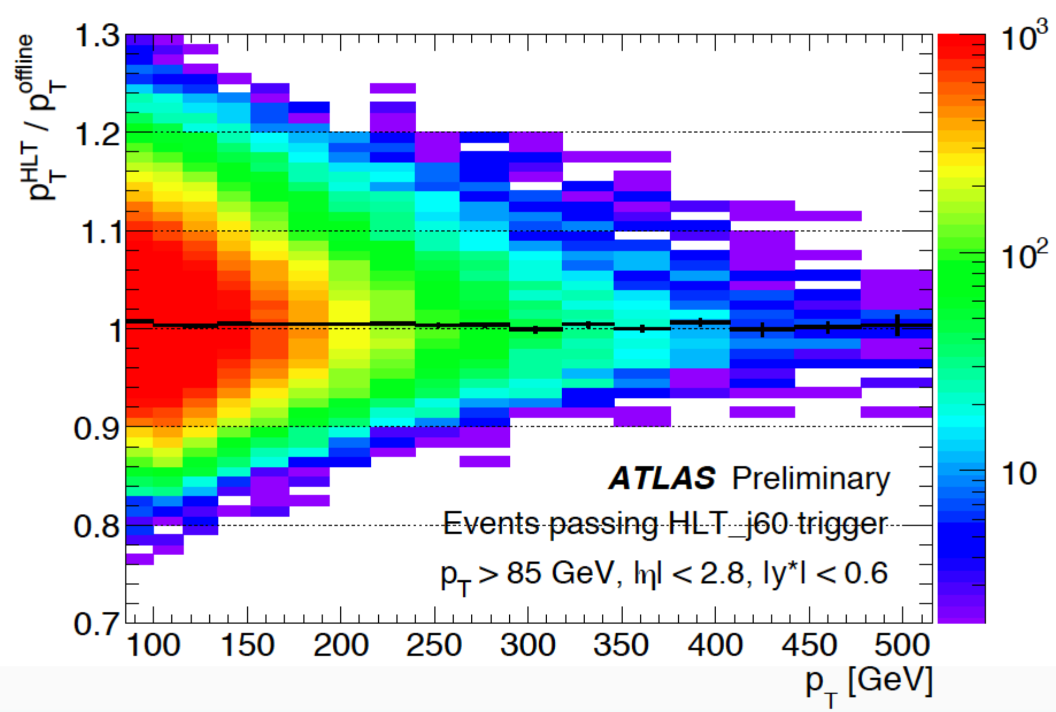
[ATLAS-CONF-2016-030]

NEW

hot from the press:

- data scouting (trigger-object-level) search in mass region 450 - 900 GeV
- avoids high trigger pre-scales for full analysis

- dedicated trigger-level jet calibration



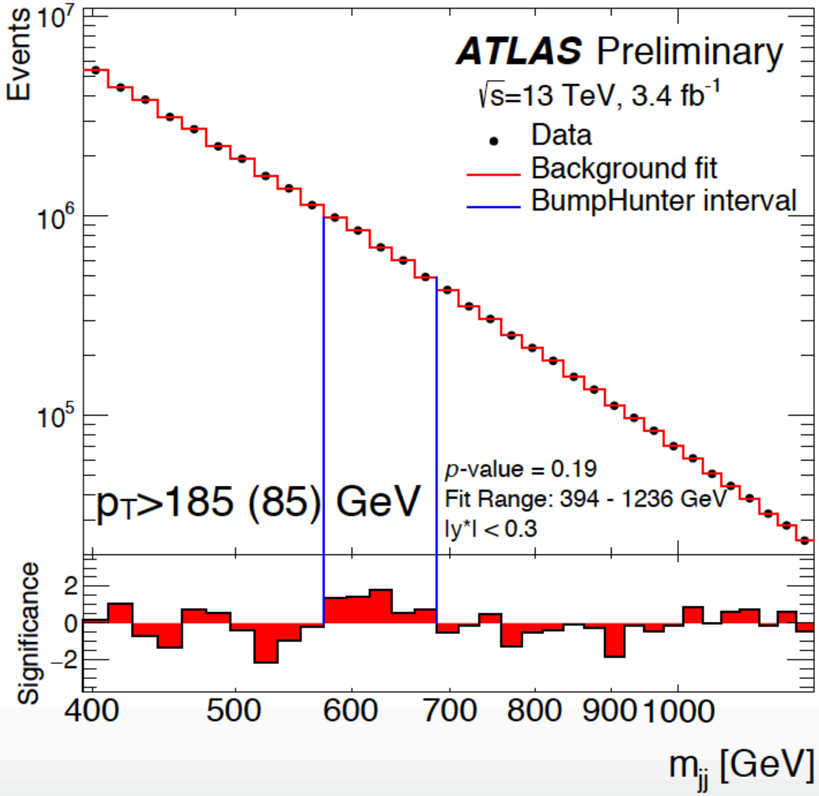
low-mass dijet resonances

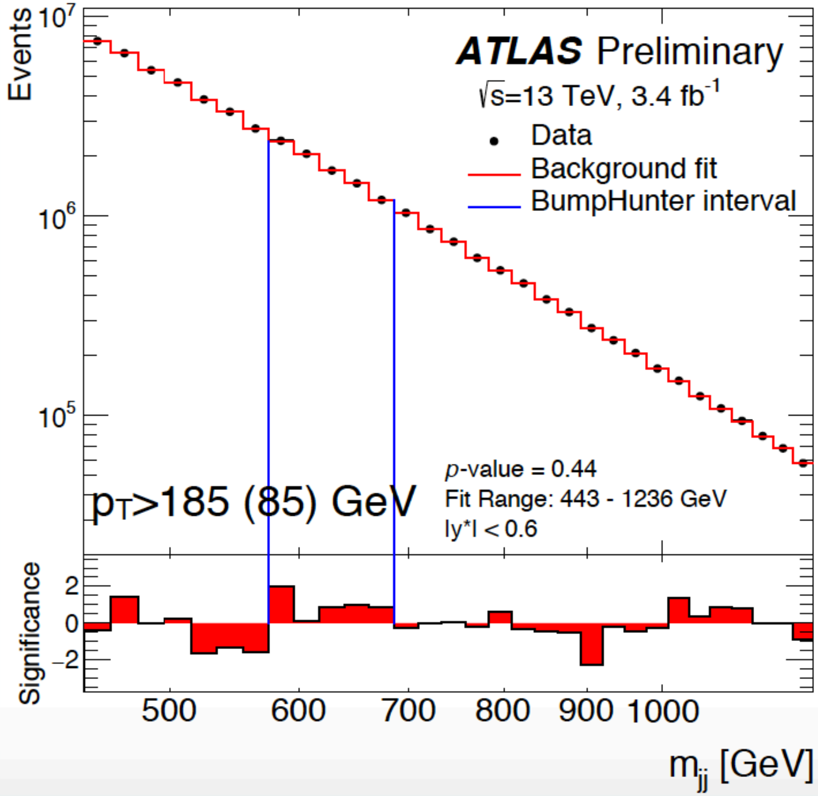
[ATLAS-CONF-2016-030]

NEW

results:

- empirical function to fit the background spectrum
- analyse all possible mass intervals for excess
- most discrepant interval 574-685 GeV (0.8 σ)
- excludes gaussian excess with cross sections 3 pb (450 GeV) to 0.7 pb (900 GeV)





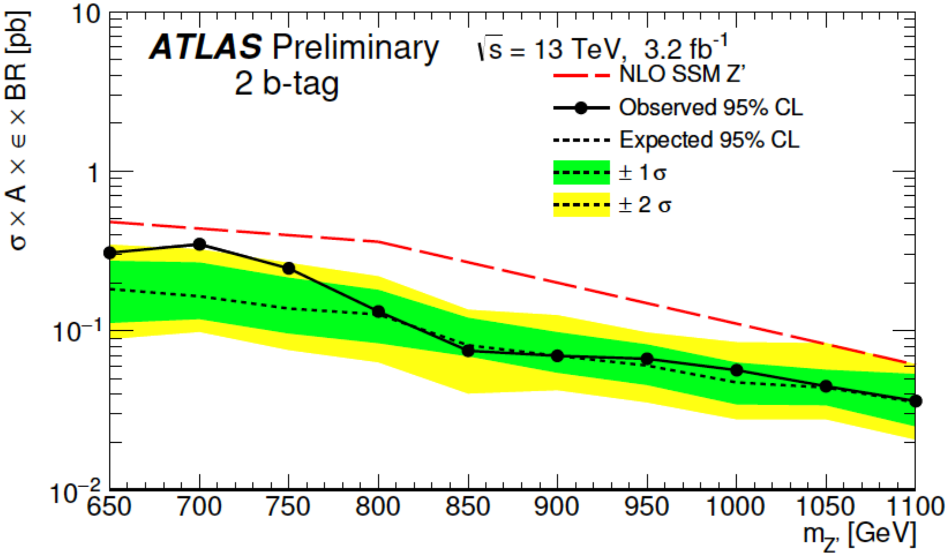
low-mass di-b-jet resonances

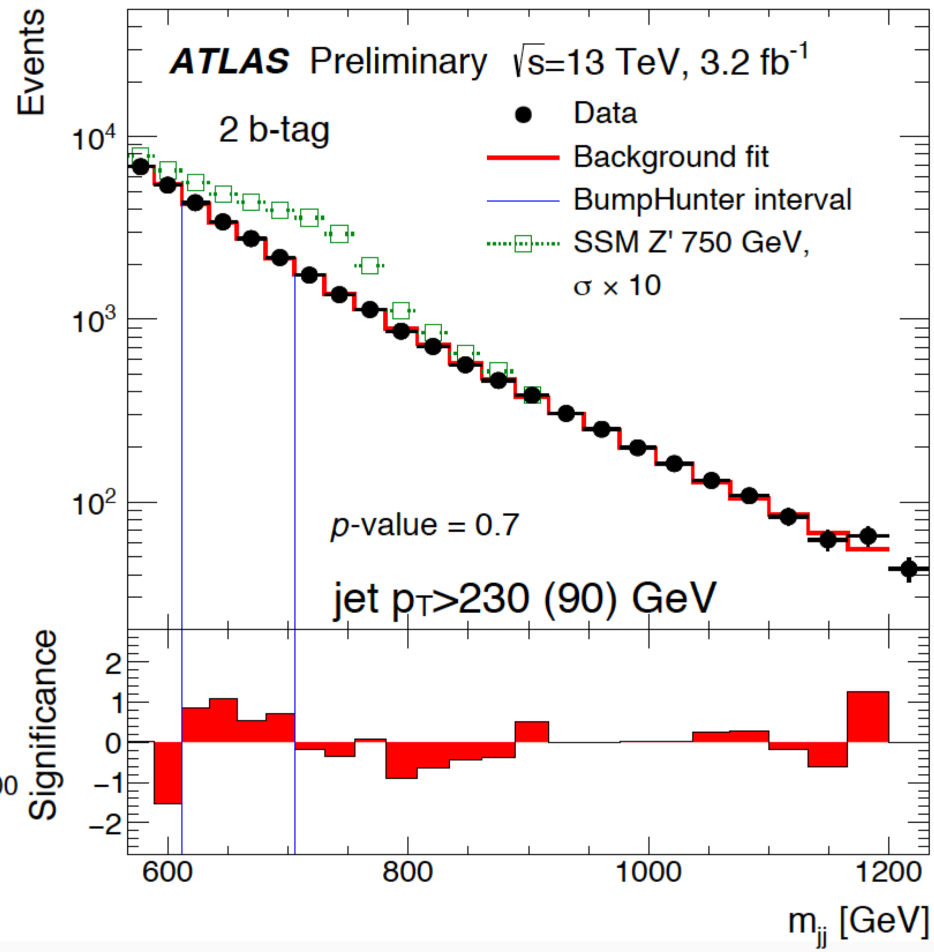
[ATLAS-CONF-2016-031]

NEW

hot from the press:

- search in mass region 570 - 1200 GeV
- b-tagged triggers → full offline analysis





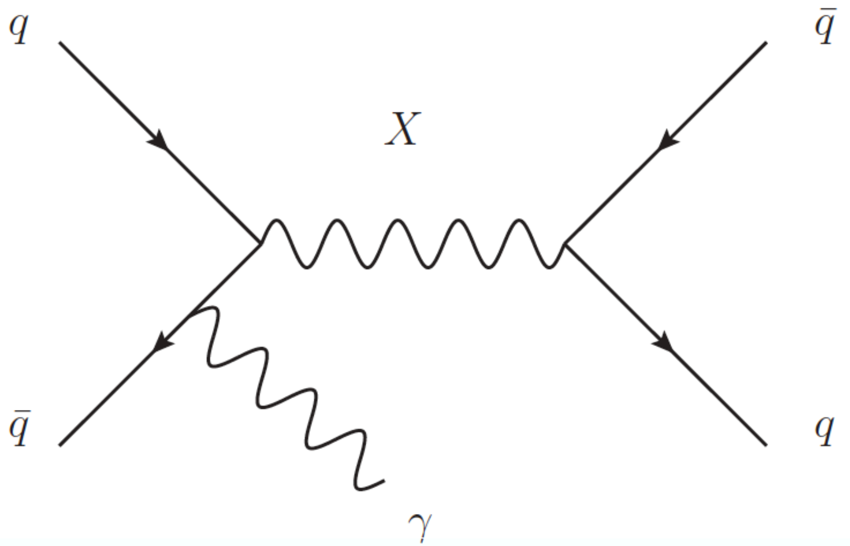
low-mass dijet resonances

[ATLAS-CONF-2016-029]

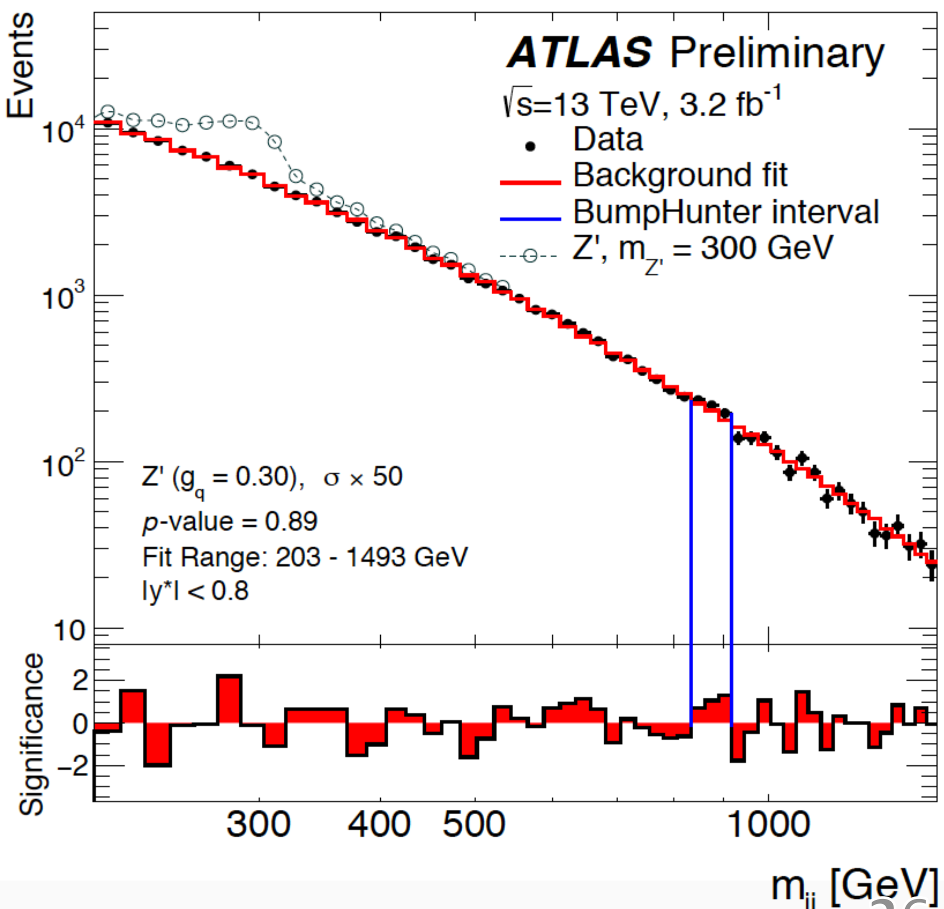
NEW

alternative approach:

- exploit initial state photon for triggering dijets (isolated photon p_T>120 GeV)



- excludes gaussian excess with cross sections 100 fb (250 GeV) to 10-20 fb (1200 GeV)



Signal modelling (from MC)

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$m_{\gamma\gamma}$ spread = intrinsic decay width convoluted with the experimental resolution

NWA -

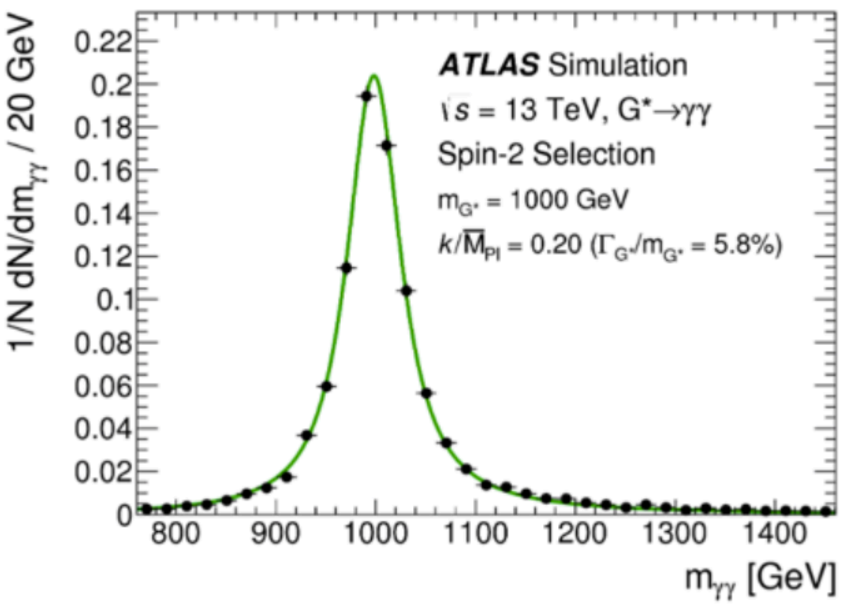
Gaussian core σ_{CB} describes the detector resolution effects

$m_{\gamma\gamma}$ resolution is 2 GeV at 200 GeV and 13 GeV at 2 TeV

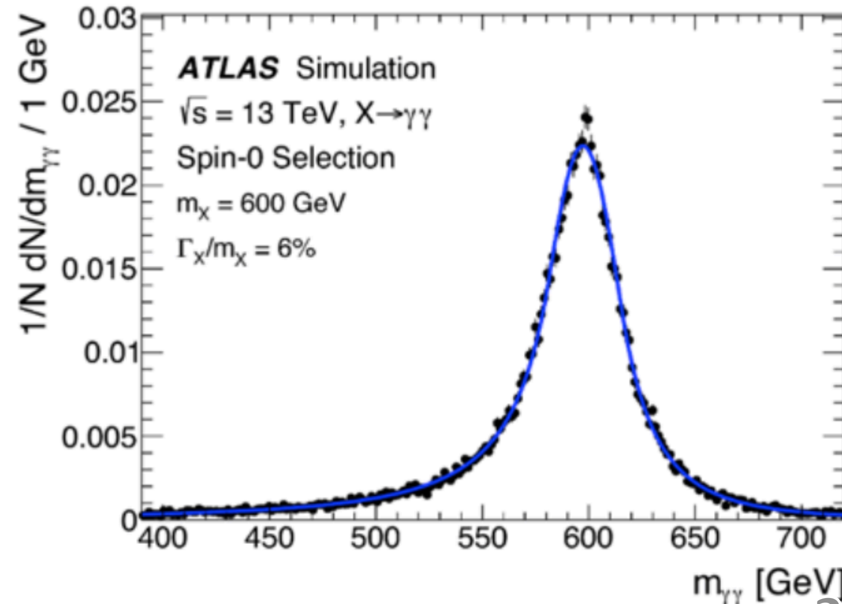
modelled by double sided Crystal Ball (DSCB)

Large Width (LW)

spin-2 - theoretical line shape from Breit-Wigner distribution (+ ME and parton luminosity) + detector resolution from DSCB - Pythia



spin-0 - theoretical line shape and detector resolution predicted from DSCB in Powheg-Box



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Background modelling

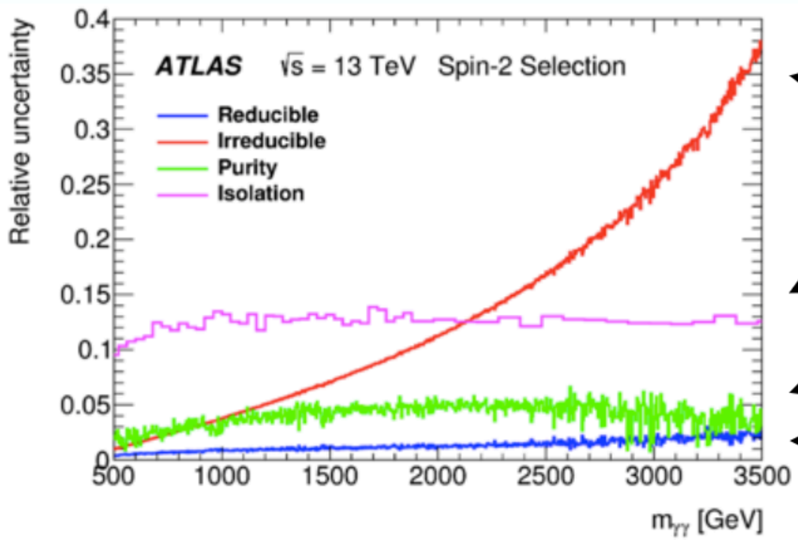
spin-2 - MC extrapolation (not enough data events at high mass)

irreducible γγ - fully simulated Sherpa LO $m_{\gamma\gamma}$ spectrum reweighted to DIPHOX (NLO) - variations up to 20%

reducible γj/jj - control sample with non-tight ID photons; $m_{\gamma\gamma}$ shape from functional form; shape uncertainties from varying ID requirements

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

- PDF eigenvector variations (up to 40% at 3.5 TeV)
- PDF choice (up to 5%)
- photon isolation (up to 10%)
- QCD scale (up to 5%)



Pre-fit $m_{\gamma\gamma}$ shape uncertainties:

- **irreducible** - NLO γγ computations (dominated by PDFs)
- **isolation** - choice of parton-level isolation cut in DIPHOX
- **purity** - relative normalization between γγ and γj/jj
- **reducible** - $m_{\gamma\gamma}$ shape

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Background modelling

spin-0 - functional form adapted from di-jet searches

$m_{\gamma\gamma}$ shape - family of functions: $f_{(k)}(x; b, \{a_k\}) = N(1 - x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j}$ $x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$

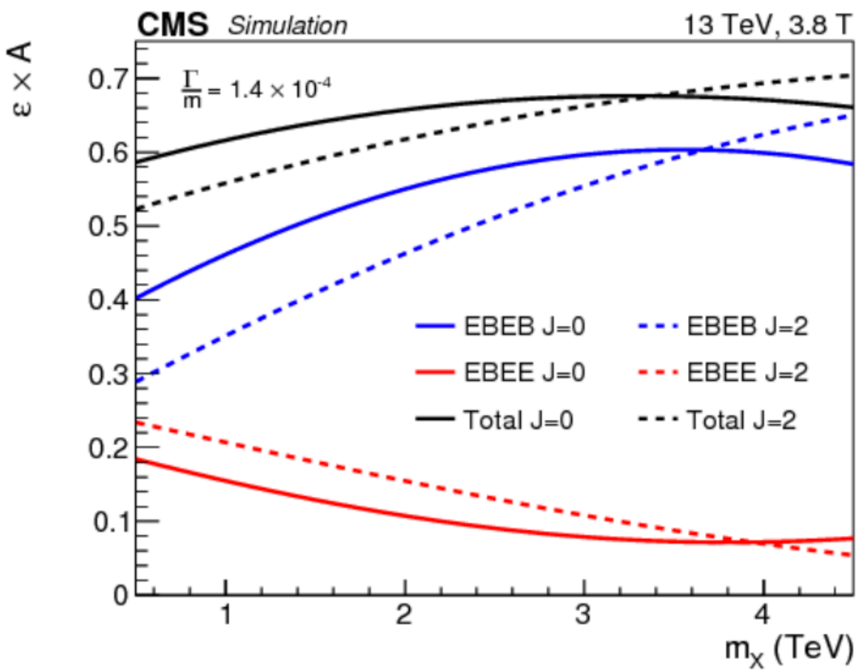
k+2 free parameters - choice of k=0 was made based on the constraints on spurious signal (< 20% of the statistical uncertainty on the fitted signal yield) - S+B fit to the background template only built using high statistics γγ Sherpa MC, and γj/jj from data from a control sample (smoothen with a fit function and fractions determined using the sample decomposition studies); F-test was performed to ensure that a more complex (larger value of k) function is not needed to model the data

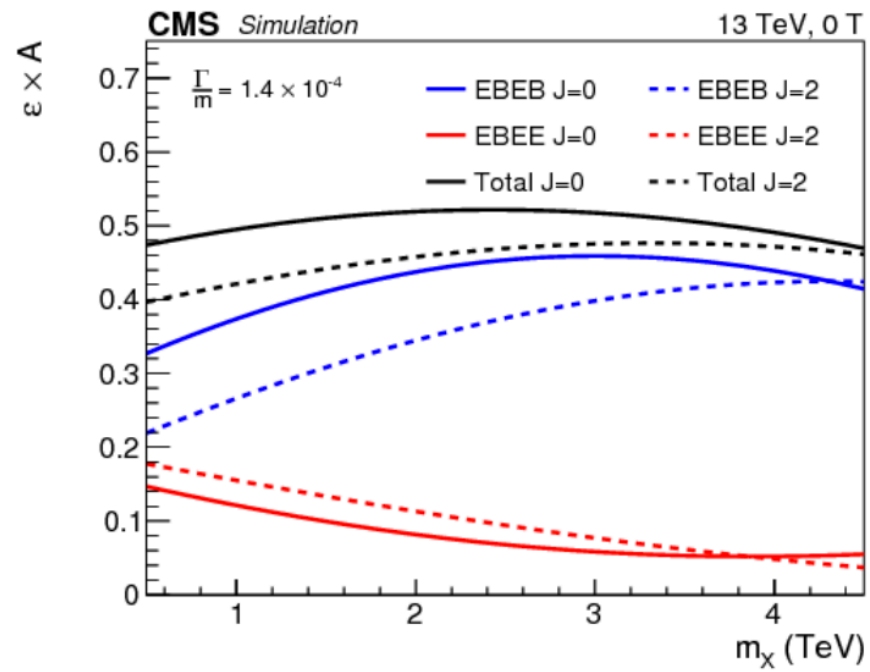
uncertainties - 7 to 0.006 events from 0.2 to 2 TeV (NWA), 20 to 0.04 events from 0.2 to 2 TeV (Γ/m=6%)

Analysis strategy

- Select events with two photons of **p_T> 75 GeV**
- Photons are required to pass two dedicated photon ID:
  - B= 3.8 T **L=2.7 fb^{-1}**: 90% efficiency
  - B= 0T **L=0.6 fb^{-1}** : 80% (EB) – 70% (EE) efficiency

- Split events in categories: **(EB-EB, EB-EE) x (3.8 T, 0 T)**
- Search region: **Mγγ > 500 GeV**
- Results interpreted for 3 widths and 2 spin hypothesis





CMS

Vertex selection

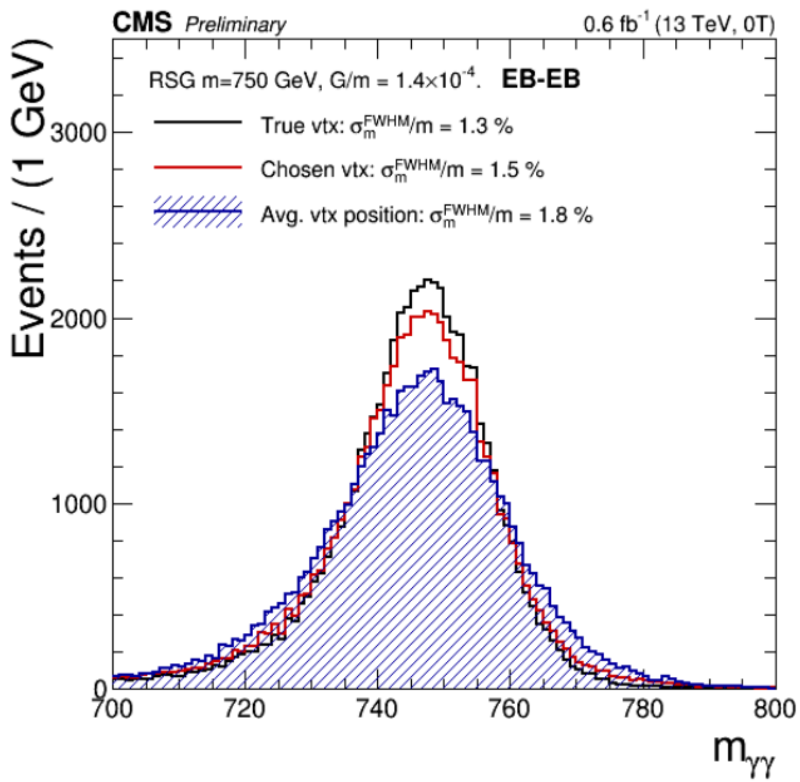
@ 3.8 T:

- **Multivariate approach** using recoil and track kinematics, trained for $H \rightarrow \gamma\gamma$

@ 0 T:

New algorithm needed

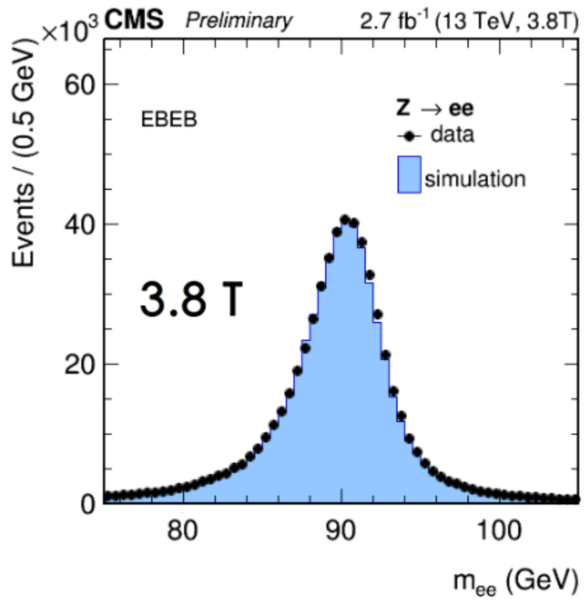
- Vertex selected with the highest track multiplicity (simple and robust approach)

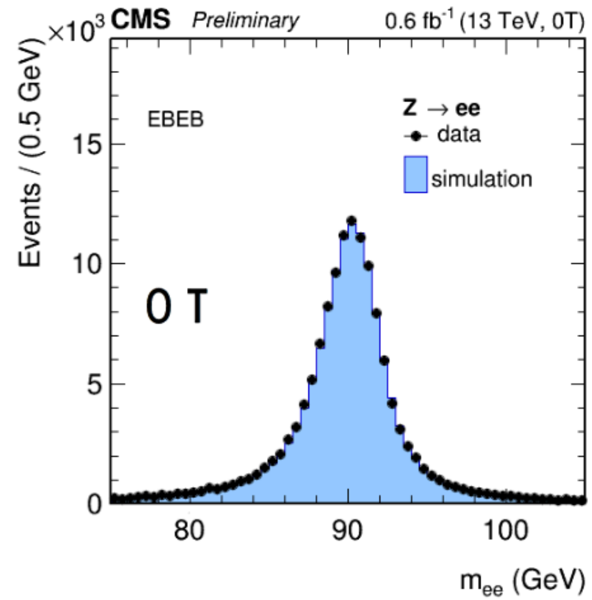


CMS

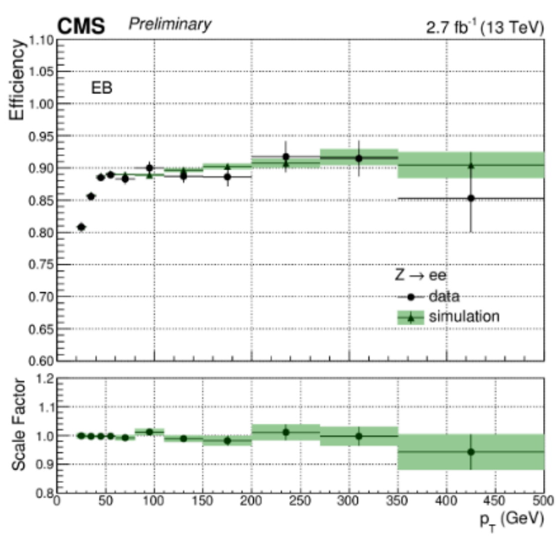
Data driven inputs

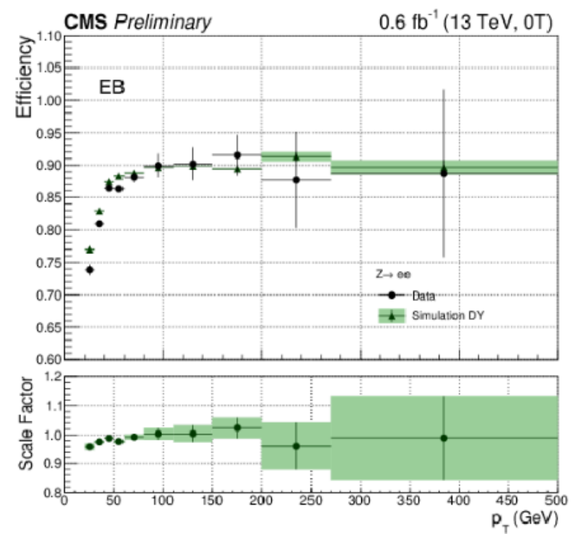
- **Energy scale and resolution** corrections (MC used as a template to fit the data)





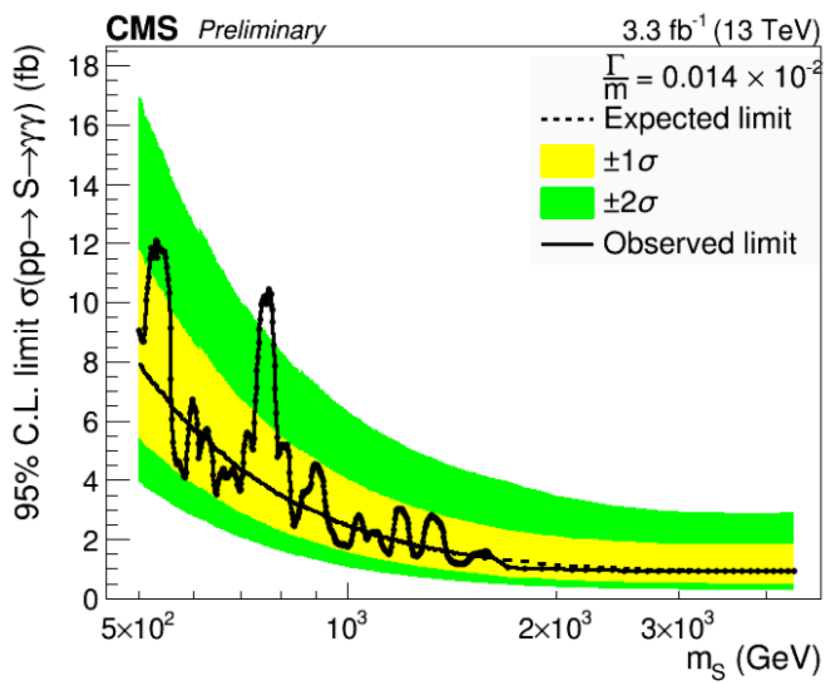
- **Efficiency scale factors** from Z → ee with TP technique



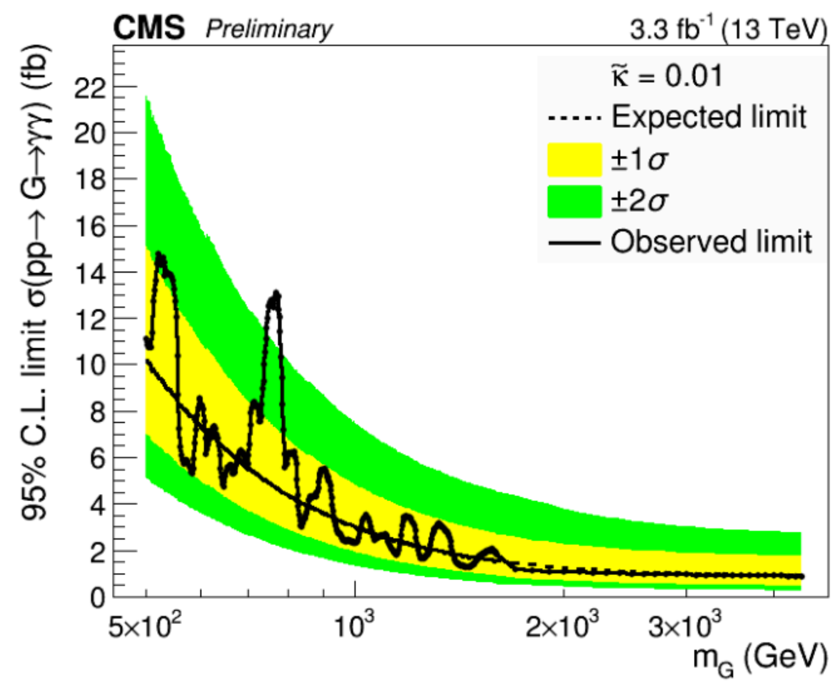


Exclusion Limits: (3.8 T + 0 T)

- 10% improvement in sensitivity adding 0T



Spin 0; Narrow width



Spin 2; Narrow width