# THE 750-GEV EXCESS AT THE CMS EXPERIMENT

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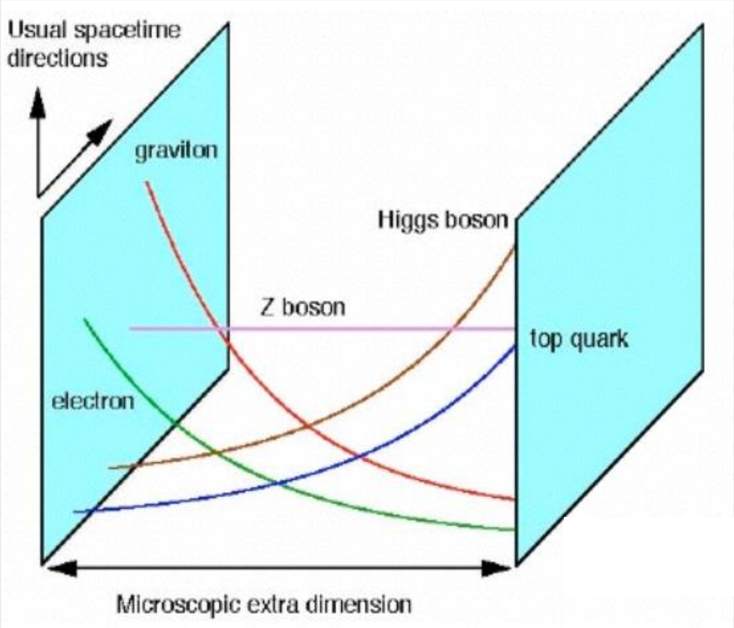
# HIGH-MASS SEARCHES AT CMS

- LHC is the ideal experimental setup to look for BSM resonances at high-mass
  - The addition of a second scalar doublet (2HDMs) is the most natural way to introduce high-mass spin-0 resonances
  - Other BSM models predict different types of neutral bosonic resonances, which may:
    - have spin of 1 or 2
    - have widths that are comparable, or negligible w.r.t. experimental resolutions («narrow»)
- Typical benchmark models:
  - Randall-Sundrum (RS) warped extra-dimension models — **Phys. Rev. Lett. 83 (1999) 3370**, **Phys. Rev. Lett. 83 (1999) 4690**
  - «Bulk-graviton» warped extra-dimension models — **Phys. Rev. D 76 (2007) 036006**, **JHEP 09 (2007) 013**, **Phys. Lett. B 666 (2008) 155**
  - Heavy vector triplet (HVT) model — **JHEP 09 (2014) 060**

# RS AND BULK GRAVITONS

- Hierarchy problem solved by adding one compactified («warped») extra dimension where just gravity can propagate → in ordinary space-time, gravitons appear as Kaluza-Klein (narrow) spin-2 resonances decaying to SM particles
- In the original RS model, two free parameters:
  - Mass of lightest KK resonance
  - Curvature radius ($\tilde{k} = c/M_{Pl}$)

  All masses/widths calculable (observable rates in ll and $\gamma\gamma$)
- «Bulk graviton»: explains unobserved $G^* \rightarrow ll$ by re-locating SM fields between the two branes → $G^*$ decays preferentially to heavy bosons and top



# THE HVT MODEL

- A simplified model based on the hypothesis of an additional triplet of heavy spin-1 bosons (Z', $W'^{\pm}$)
- A generic effective Lagrangian covers both the possible weak and strong couplings to SM

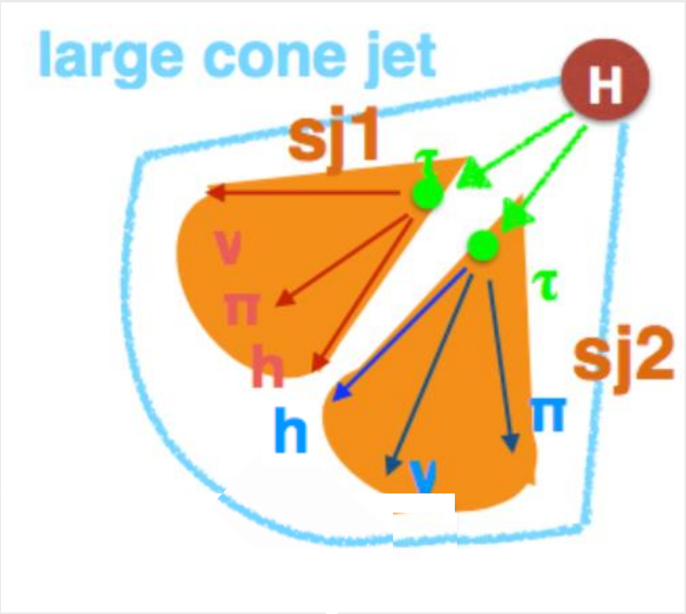
$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\,a} + i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\,a}_F$$

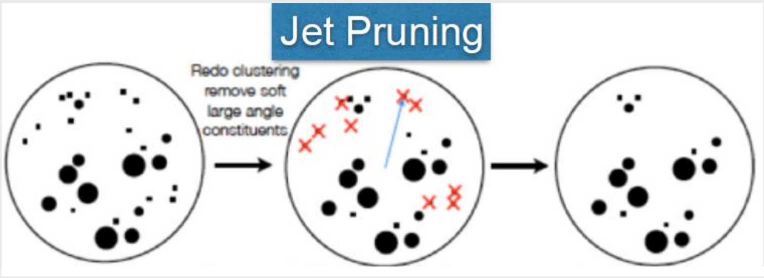
+ self-interaction terms

- General simplified-model results
  - New states almost degenerate in mass
  - Large decay rates to longitudinal SM dibosons ($\gamma\gamma$, ZZ forbidden but all other combinations of V and H possible) → BRs controlled by the parameter combinations $g_V c_H$ and $g^2 c_F/g_V$
  - Easy combination of charged vs. neutral final states

# HADRONIC BOSON DECAYS

- We will focus on high-mass resonance decays to SM bosons
  - While $\gamma$ is «easy», W/Z/H can produce several combinations of final states, each with its own experimental challenge
- $W/Z \to q\bar{q}$ and $H \to b\bar{b}$ are particularly affected by SM backgrounds
  - Exploit «boosted» topology
- If $\Delta R$ between the two quarks is:
  - $> 0.8$: the quarks from V decay hadronize in two $R = 0.4$ jets
  - $< 0.8$: the the quarks from V decay may hadronize in a single «fat» jet with $R = 0.8$ and large pruned mass
    - Subjet finding techniques help in finding smaller-radius jets within («subjettiness»), providing additional handles to clean up BSM signals



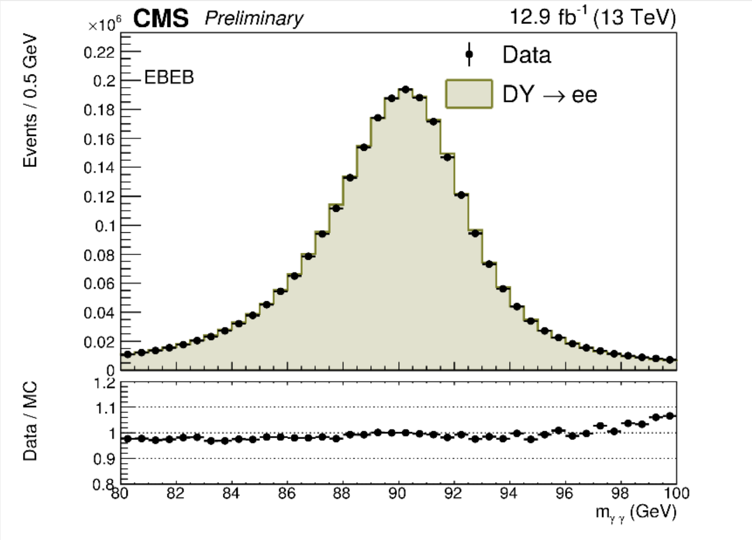
# $X \to \gamma\gamma$ (8 TEV AND 2015)

Phys. Rev. Lett. 117 (2016) 051802

- Simultaneous analysis of 8 TeV and early 13 TeV data
- Event selection
  - High-energy $\gamma$ (> 75 GeV)
  - Cut-based photon identification
  - Track and electromagnetic-energy isolation
- Di-photon candidates
  - Primary-vertex determination à la $H \to \gamma\gamma$
  - Two categories: both $\gamma$ in ECAL barrel (EBEB), or one in barrel/one in endcap (EBEE)
    - For 8 TeV data: further categorize events based on min($R_9$) variable (> or < 0.94)
- Selection efficiency
  - 50-70% depending on signal hypothesis

# $X \to \gamma\gamma$ (CONTINUED)

Phys. Rev. Lett. 117 (2016) 051802

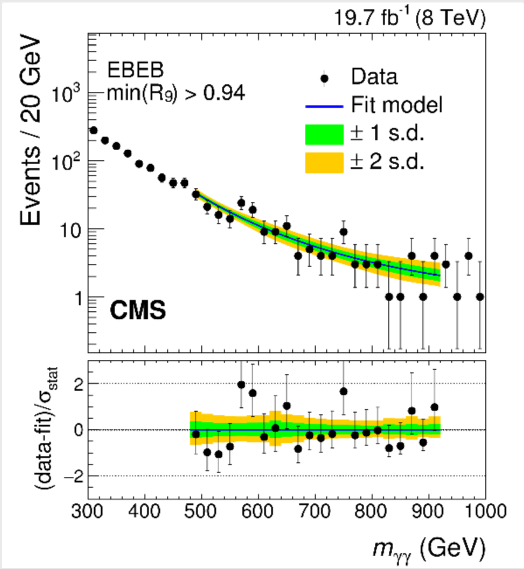


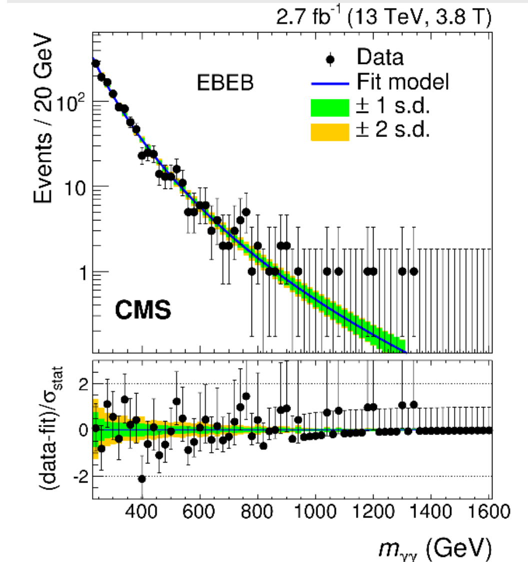

- Photon energy calibration
  - Use multivariate-regression technique and correct residual data/MC discrepancy on $Z \to ee$ events in bins of $R_9$ and $\eta_\gamma$
  - Final uncertainties on corrections: 0.5% (0.7%) for EBEB (EBEE) → larger at very high $\eta_\gamma$ and E > 500 GeV
  - Peak resolution:1.0% (1.5%) for EBEB (EBEE)
- For no-magnet data (~20% of 2015 13-TeV sample)
  - Simpler primary-vertex assignment (maximum $N_{tracks}$)
  - Remove track isolation and loosen ECAL isolation
  - Tighten requirements on shower shape and size
  - Selection efficiency reduced to 40-50%

# $X \to \gamma\gamma$ (8 TEV AND 2015)

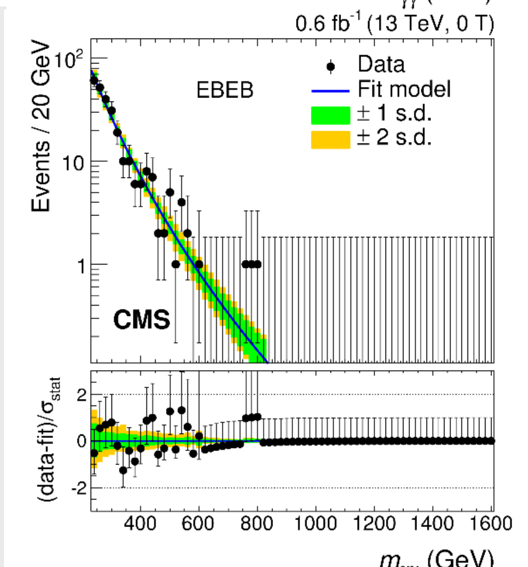
Phys. Rev. Lett. 117 (2016) 051802

- Modest excess around 750 GeV tested against 3 signal hypotheses (spin-0 and spin-2)
  - Narrow
  - Width similar to detector resolution ($\Gamma/m$ = 1.4%)
  - «Broad» ($\Gamma/m$ = 5.6%)
- Largest significance for narrow hypothesis (3.4$\sigma$ local, 1.6$\sigma$ with LEE)




$\sigma$(8 TeV)/$\sigma$(13 TeV) = 0.22 - 0.24



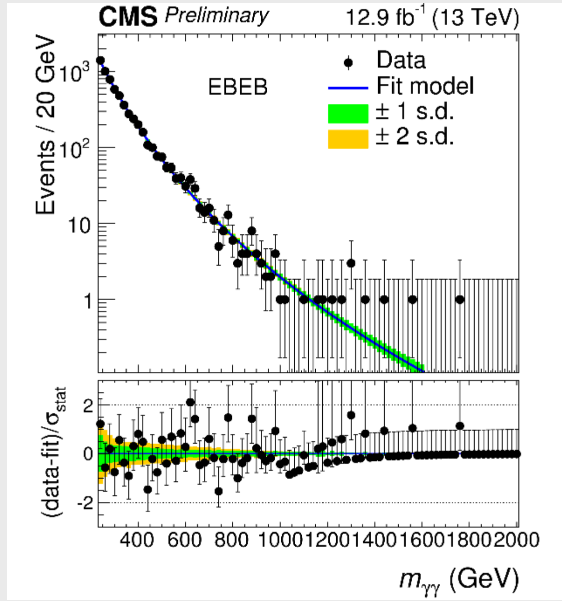

- Together with ATLAS result, triggered enormous theory speculation
  - Some «tension» found when accounting for small $\sigma$-ratio, likely gg production (no extra energetic particles observed in the events) and no observation in dijets

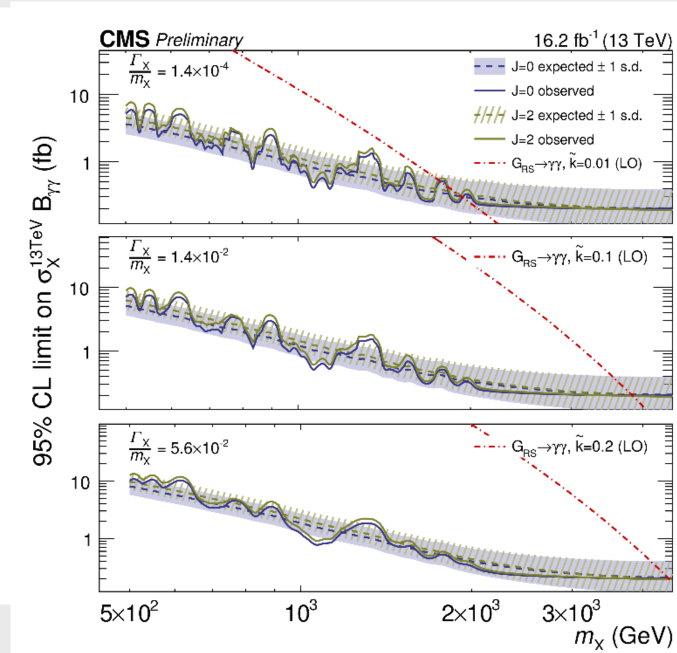
e.g. JHEP 03 (2016) 144

# $X \rightarrow \gamma\gamma$ (2016)

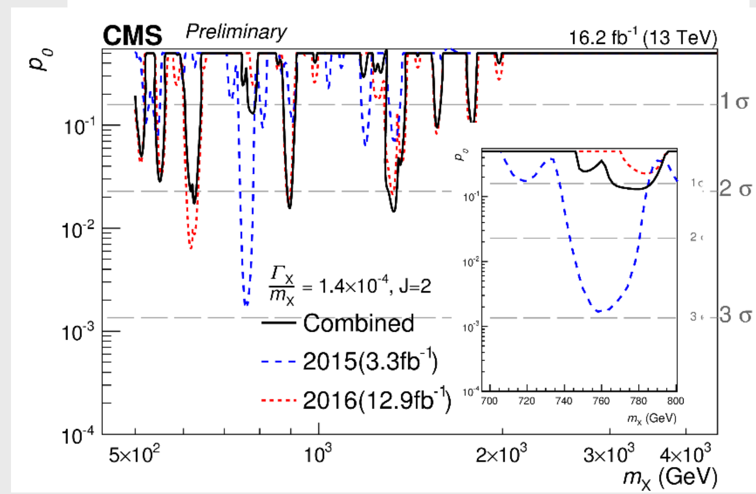
CMS-PAS EXO-16-027

- 2016 data are analyzed using exactly the same technique
  - No significant excess found



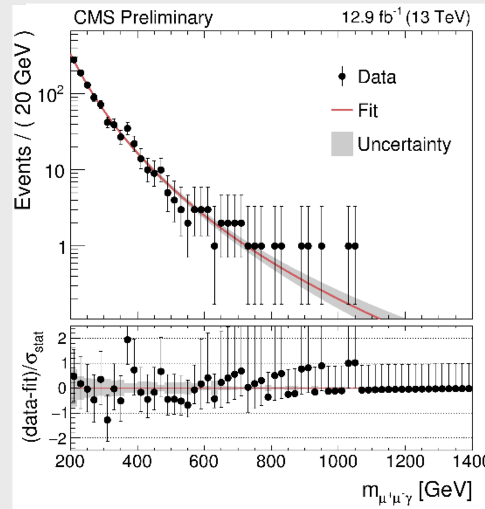

- Combining with previous results, 750 GeV is not the largest excess anymore
  - Limits on RS gravitons up to 1.95-4.5 TeV, depending on curvature parameter

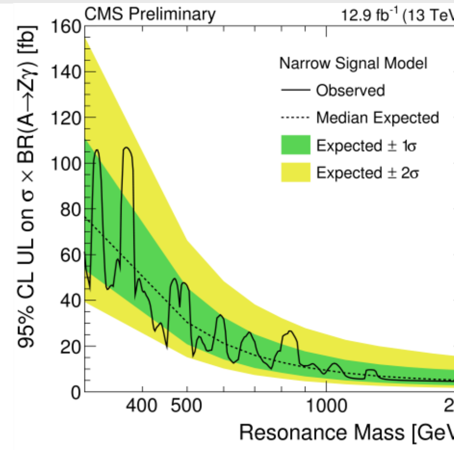


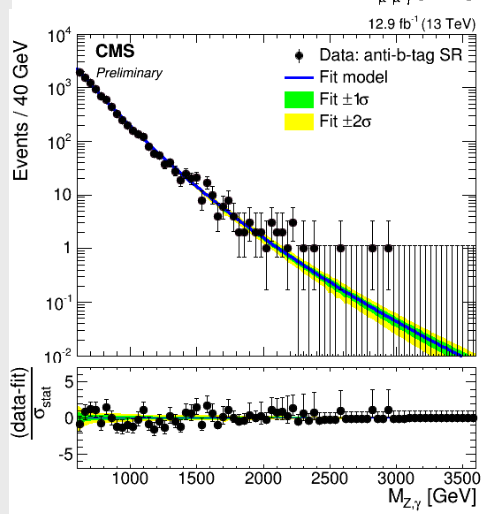
# $X \rightarrow Z\gamma$ (2016)

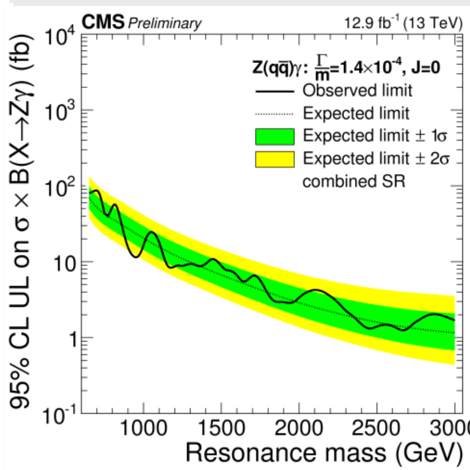
**CMS-PAS EXO-16-034 / EXO-16-035**

- An effort towards cross-check of 750-GeV excess started in many other channels
- $Z\gamma$ searches for spin-0 narrow and broad resonances (same width hypotheses as in $\gamma\gamma$)
  - Leptonic Z
    - down to low resonance mass, mainly irreducible background
  - Boosted hadronic Z
    - only high mass, background dominated by $\gamma$+jet
    - Exploits b-tagging of subjets to define a purer category
  - Leptonic more sensitive in overlap regions

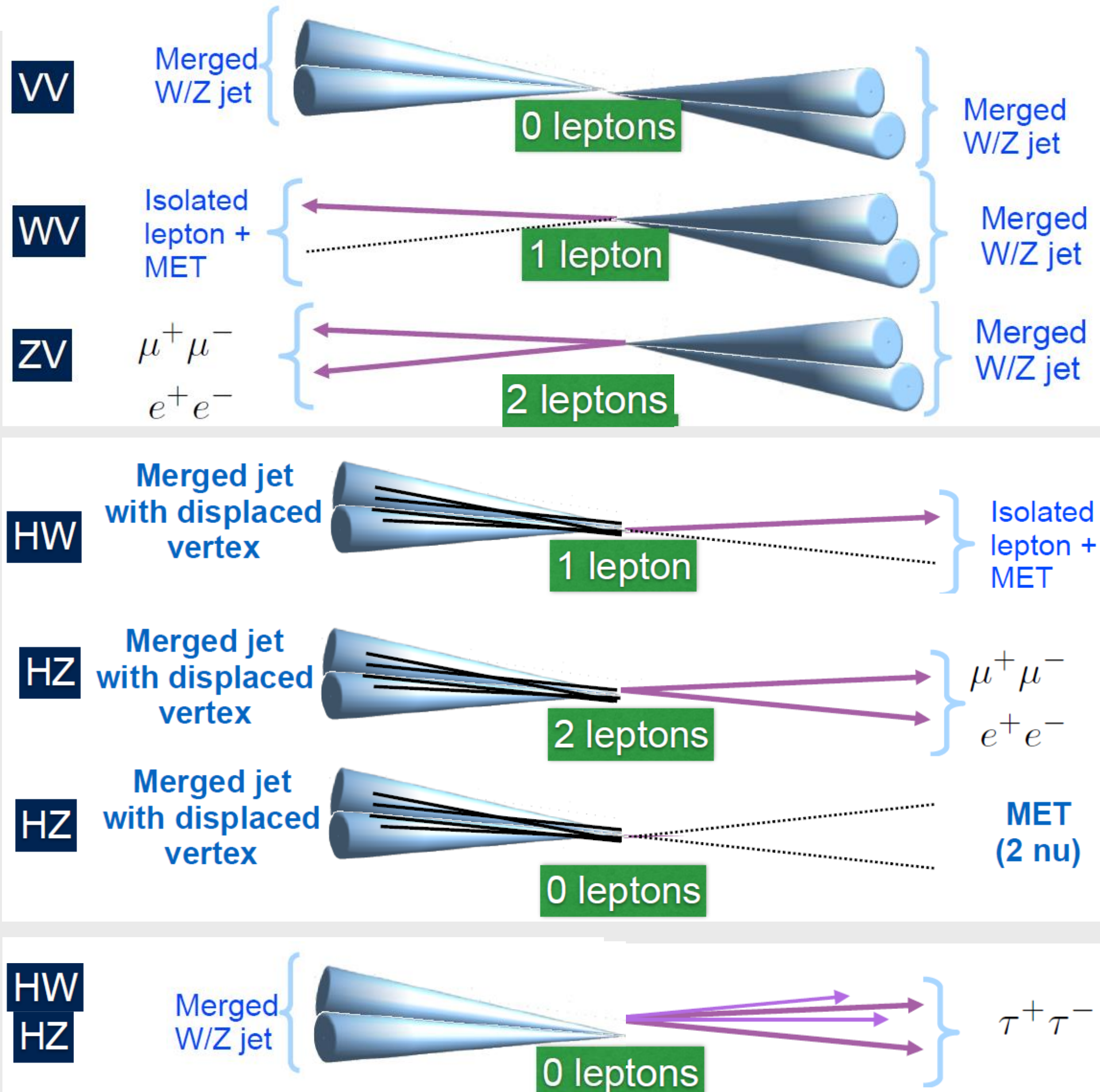


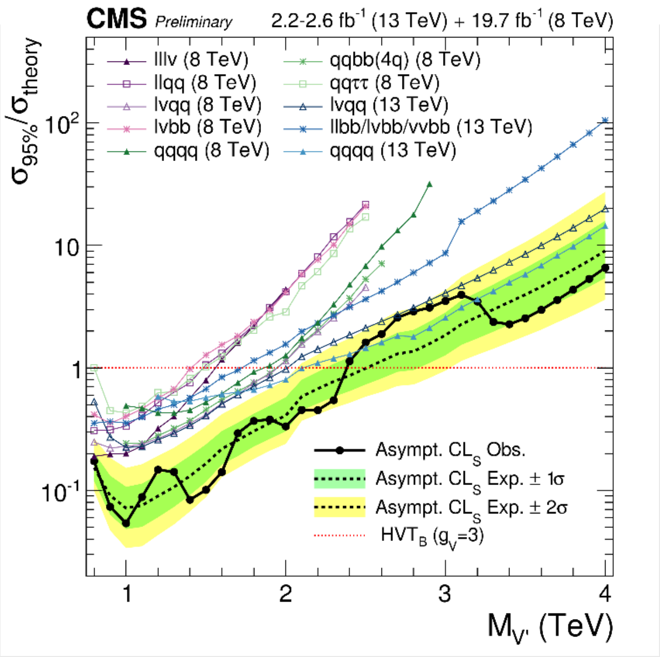



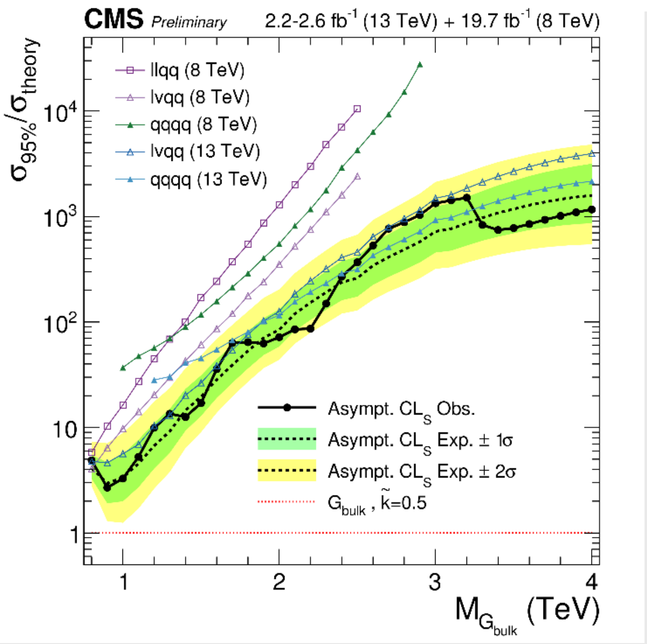
# X → VV/VH FINAL STATES




- Several different analyses targeting in general narrow or almost-narrow resonances with very high mass (≥ 0.8 TeV)
  - VV «golden channels» for bulk-graviton model
  - WZ/WW/VH «golden channels» for HVT model

# COMBINATION AFTER 2015



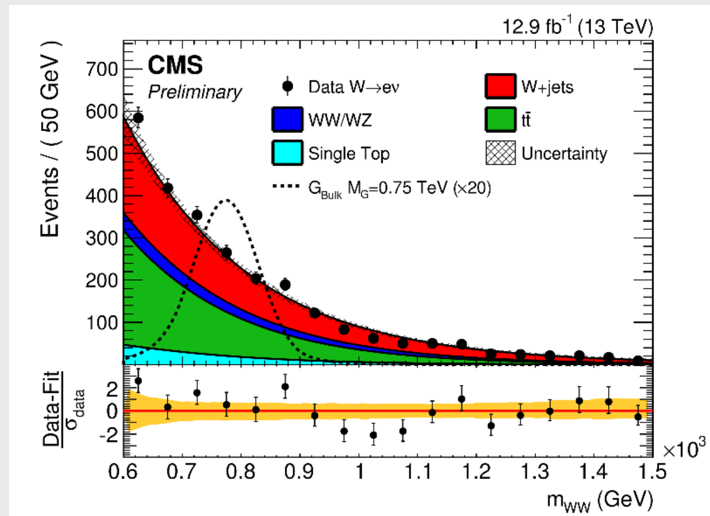

- 12 analyses combined at 8 and 13 TeV
  - All-hadronic final states generally more sensitive at very large mass, between 1 and 2.5 TeV all analyses contribute with similar sensitivity (smaller backgrounds balance smaller BRs)
  - HVT (strongly coupled) excluded at 95% CL for $M_{V'} < 2.4$ TeV
  - Still open room for bulk-G* even with moderate $\tilde{k}$

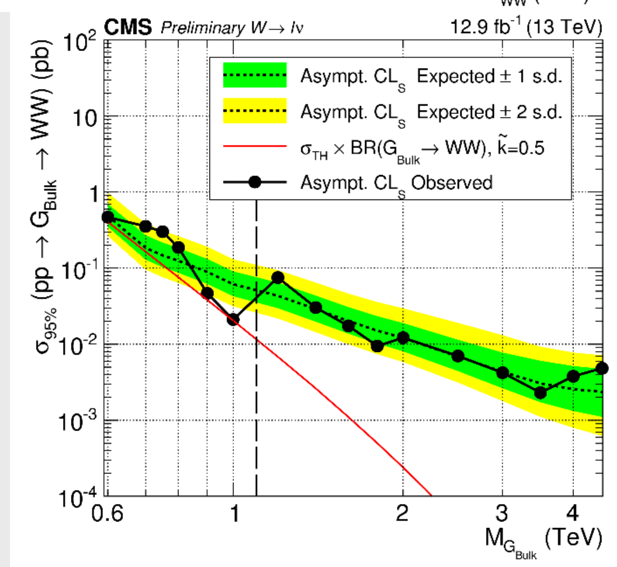
**CMS-PAS B2G-16-007**

# $X \to WV$ (2016)

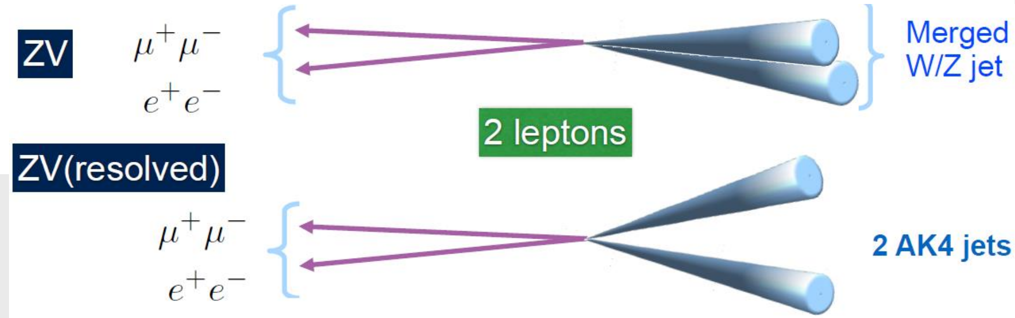

- Target narrow resonance (charged and neutral)
  - 0.6-1 TeV region separately opimized in order to test low-mass excesses
- Main backgrounds after kinematic cuts:
  - W+jet with misidentified jet (use «subjettiness» variable $\tau_{21}$ to suppress)
  - $t\bar{t}$ with 2 genuine W's (use b-tag veto)
- Inverted b-tag veto sample is used to estimate:
  - Amount of $t\bar{t}$ peaking background
  - W-signal efficiency of $\tau_{21}$ cut
- Sensitivities start to approach $\tilde{k}$ = 0.5 bulk-G predictions

CMS-PAS B2G-16-020



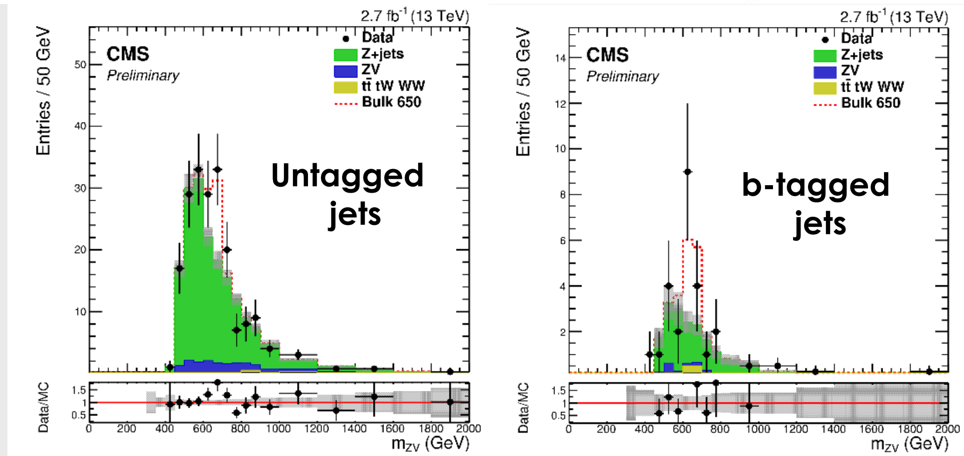



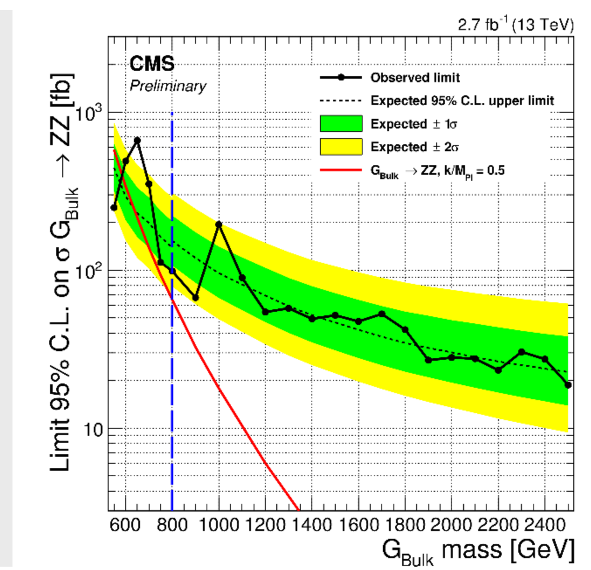
# $X \to ZV$ (2015)




CMS-PAS B2G-16-010

- Analysis optimized more aggressively in the 0.6-1 TeV region by adding 2-jet final state when no merged jet is found
- Signal extraction
  - Merged-jet selection: similar to WV
  - Resolved-jet selection: use Z+jets MC, normalized to $m_{jj}$ or $m_J$ sidebands
- Modest excess observed at 650 GeV (3.4σ, 2.9σ with low-mass LEE)
  - To be tested with 2016 data



# CONCLUSIONS

- Several BSM models predict boson resonances which have negligible or comparable width w.r.t. CMS resolution
- Hint of a narrow $\gamma\gamma$ resonance at 750 GeV has not stood the test of time, but it triggered interesting ideas:
  - From theory: simple phenomenological extrapolations from previous LHC results provide guidance on when/where an excess can be expected
  - In CMS: renewed effort in extending existing searches to mass regions not investigated before ($Z\gamma$, VV, VH etc.) → cross-section limits already superseding 8-TeV results
- 650-GeV «younger brother» doomed already?
  - A lot to learn from full-2016 and future LHC datasets

# BACKUP