

# Searches for Exotica at CMS

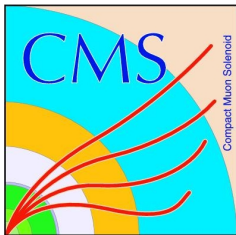


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(Centre for Cosmology, Particle Physics and Phenomenology)

*On behalf of the CMS Collaboration*



EPIPHANY, Kraków, 7-9 January 2016



- ✓ SM explains three types of fundamental interactions!
- ✓ There is a Higgs boson!

## Open Questions:

- Including gravitational force?
- Unification of forces?
- Hierarchy problem?
- Matter-antimatter asymmetry?
- Dark matter and energy?
- Neutrino mixing and masses?
- Origin of generations?
- ...

## CMS Exotica Searches:

- Heavy bosons
- Extra space dimensions
- Heavy fermions
- Black Holes
- Dark Matter
- Leptoquarks
- Exited fermions
- New phenomena
- ...

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**Early Run 2 results @ 13 TeV and Run 1 @ 8 TeV**



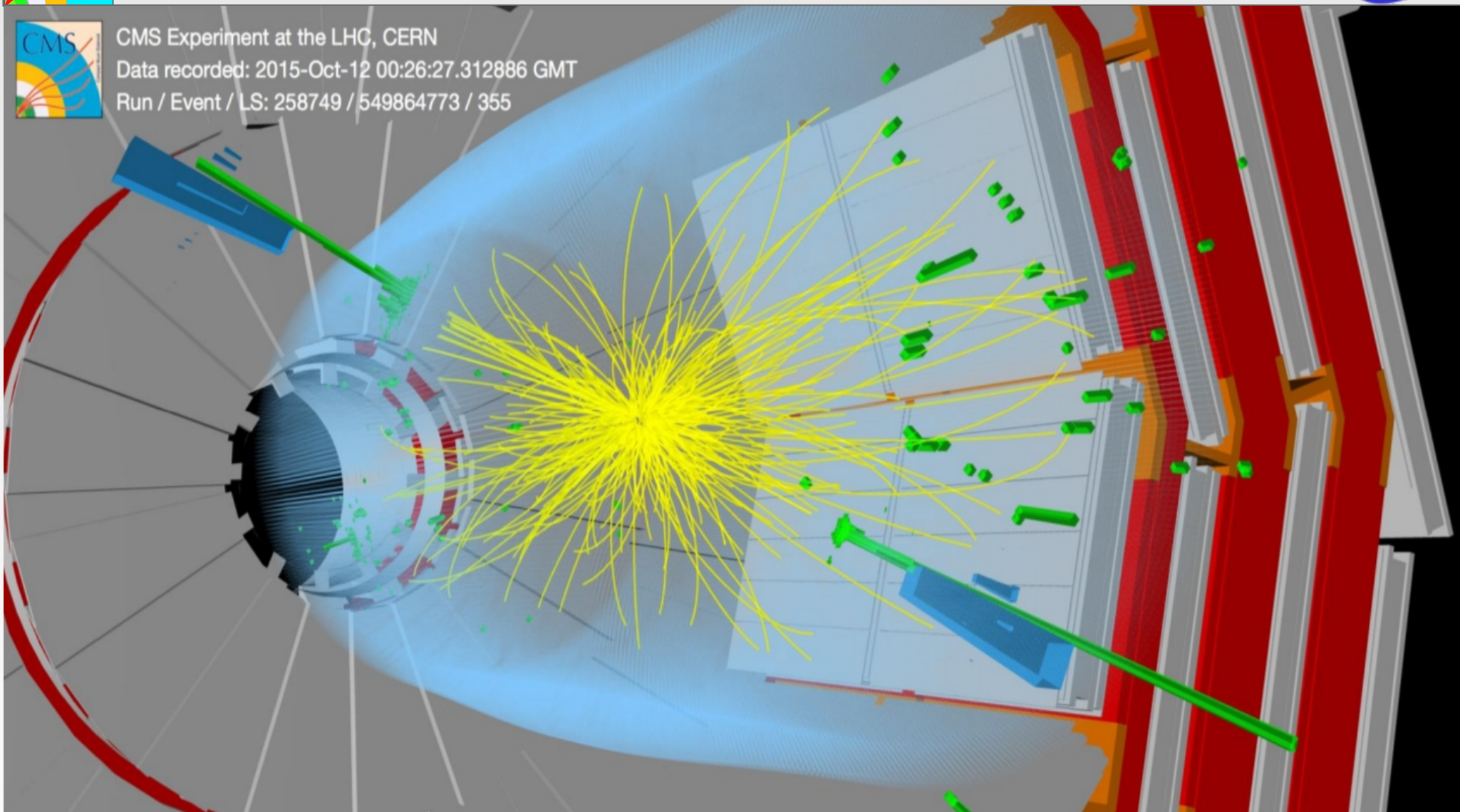
# Search for Dijet Resonances



CMS Experiment at the LHC, CERN

Data recorded: 2015-Oct-12 00:26:27.312886 GMT

Run / Event / LS: 258749 / 549864773 / 355



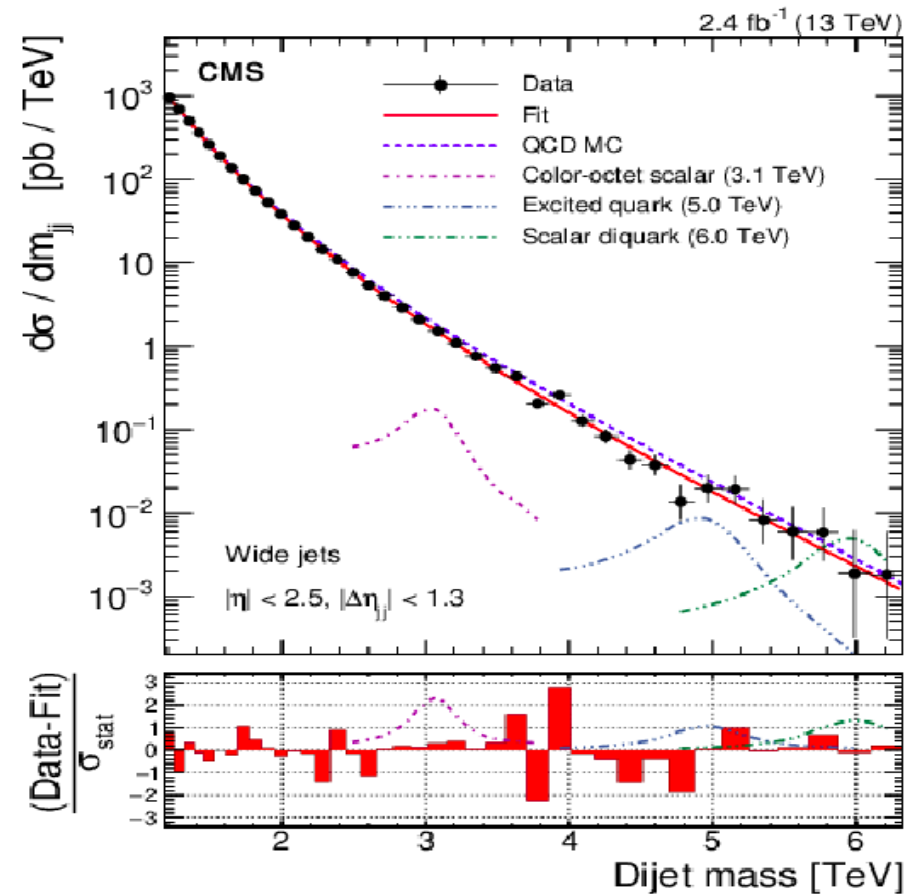
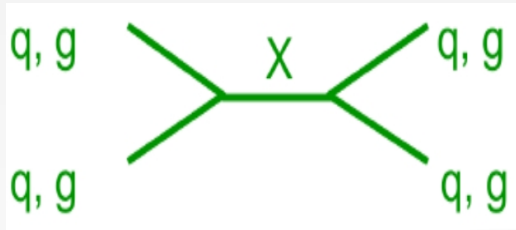
Event display highest dijet mass  $M_{jj} = 6.14 \text{ TeV}$



# Search for Dijet Resonances

EXO-15-001: arXiv:1512.01224

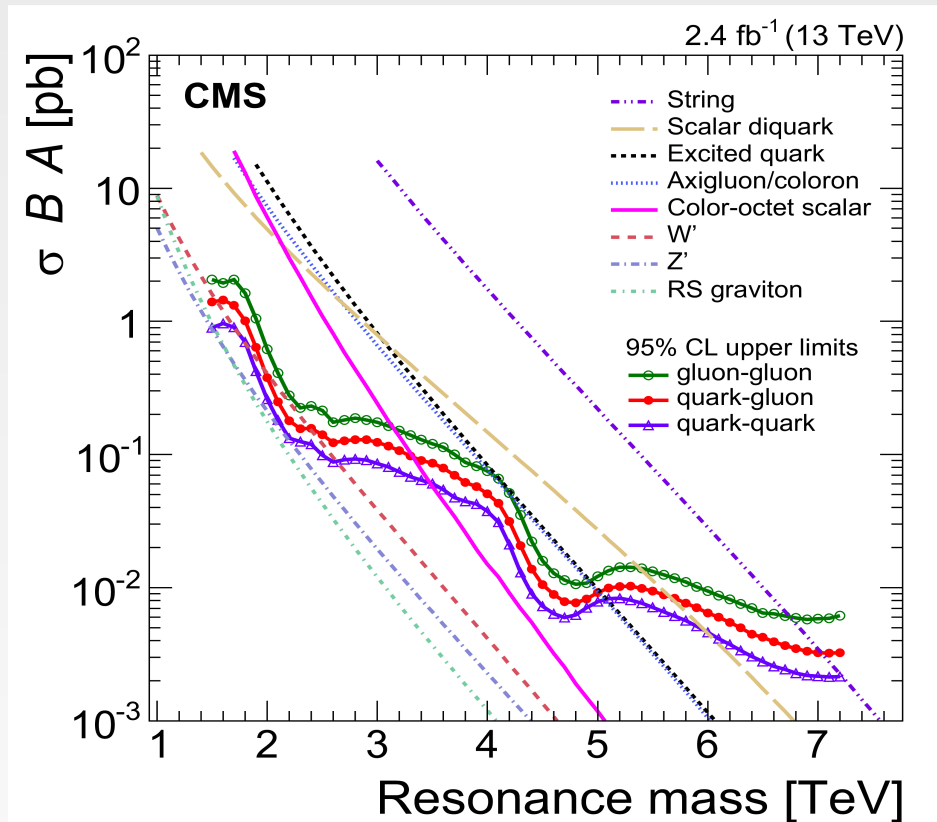
- Search for a bump in the smoothly falling dijet mass spectrum
- Sensitive to a wide range of models predicting dijet resonances
- qq, qg and gg final states



# Search for Dijet Resonances

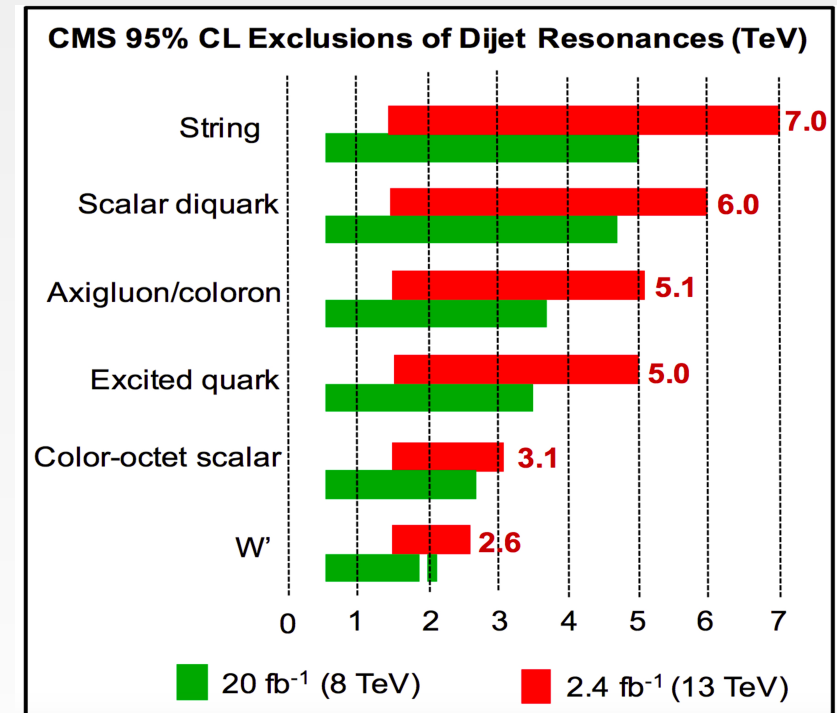
Observed limits @13 TeV

EXO-15-001: arXiv:1512.01224



Significantly better mass limits @ 13 TeV

Model	Final State	Obs. Mass Limit [TeV]	Exp. Mass Limit [TeV]
String	qg	7.0	6.9
Scalar diquark	qq	6.0	6.1
Axigluon/coloron	q $\bar{q}$	5.1	5.1
Excited quark (q*)	qg	5.0	4.8
Color-octet scalar	gg	3.1	3.3
Heavy PW (W')	q $\bar{q}$	2.6	2.3



- Expanding dijet analysis by exploiting the dijet angular distribution:

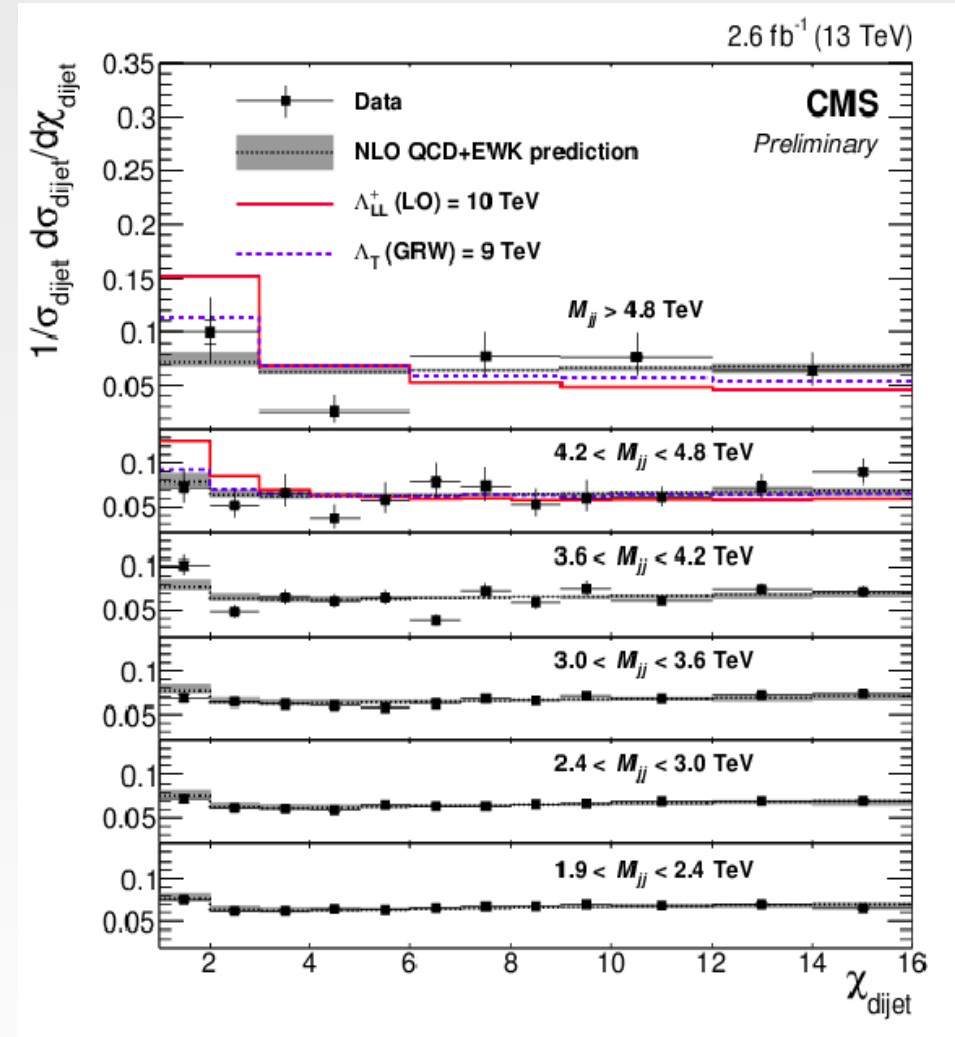
$$\chi = e^{2|y^*|} \xrightarrow{m \rightarrow 0} \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|}$$

- Sensitive to many new physics (approximately flat for QCD, deviations at low values for new physics)

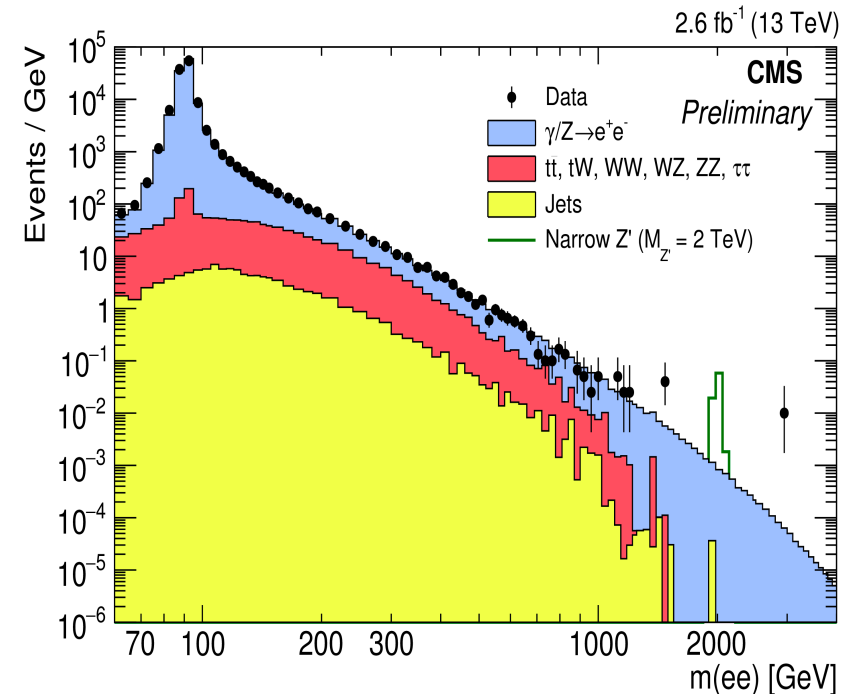
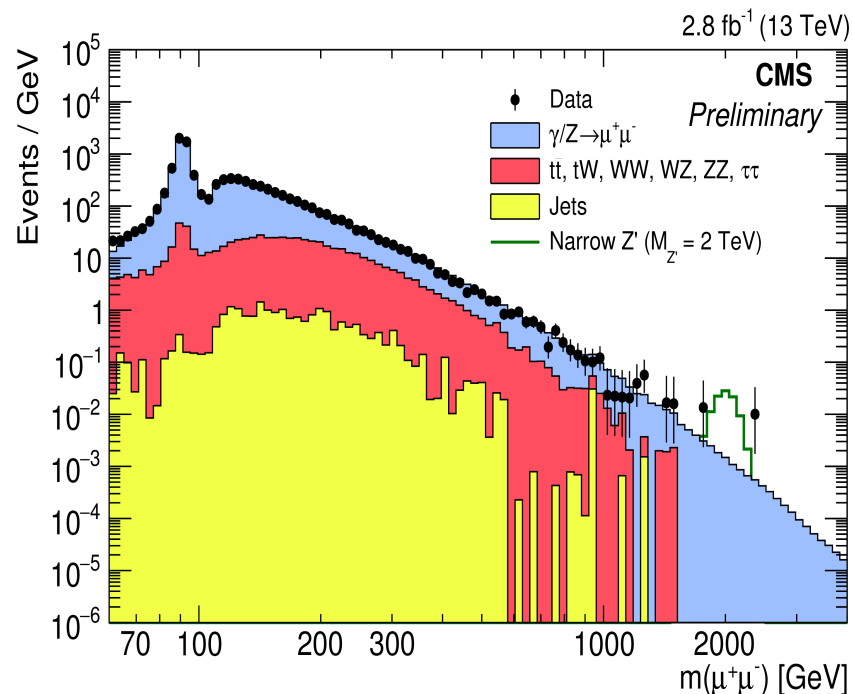
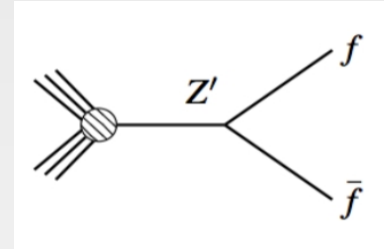
## Limits on contact interactions and Extra Dimensions at 13 TeV:

Compositeness model	Observed lower limit (TeV)	Expected lower limit (TeV)
$\Lambda_{LL/RR}^+$ (LO)	12.1	$12.0 \pm 1.1$
$\Lambda_{LL/RR}^-$ (LO)	16.3	$15.3 \pm 2.4$
ADD $\Lambda_T$ (GRW)	9.1	$9.0 \pm 0.7$
ADD $M_S$ (HLZ) $n_{ED} = 2$	9.7	$9.6 \pm 0.7$
ADD $M_S$ (HLZ) $n_{ED} = 3$	10.8	$10.7 \pm 0.8$
ADD $M_S$ (HLZ) $n_{ED} = 4$	9.2	$9.0 \pm 0.7$
ADD $M_S$ (HLZ) $n_{ED} = 5$	8.3	$8.1 \pm 0.6$
ADD $M_S$ (HLZ) $n_{ED} = 6$	7.7	$7.6 \pm 0.6$

## Most stringent limits on ADD models

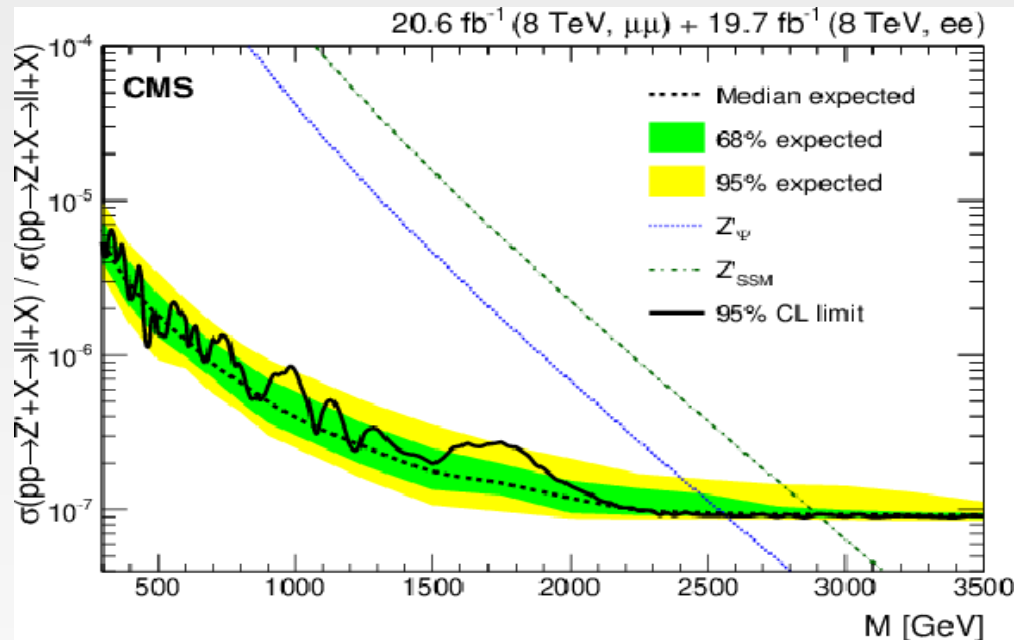


- Search for a heavy, narrow resonance in the dilepton invariant mass spectrum
- Analysis is sensitive to new heavy resonances e.g.  $Z'$  (SSM, String), extra space dimensions (RS, ADD Graviton) at high mass (low background)
- Reconstruction efficiency and mass resolution dominates

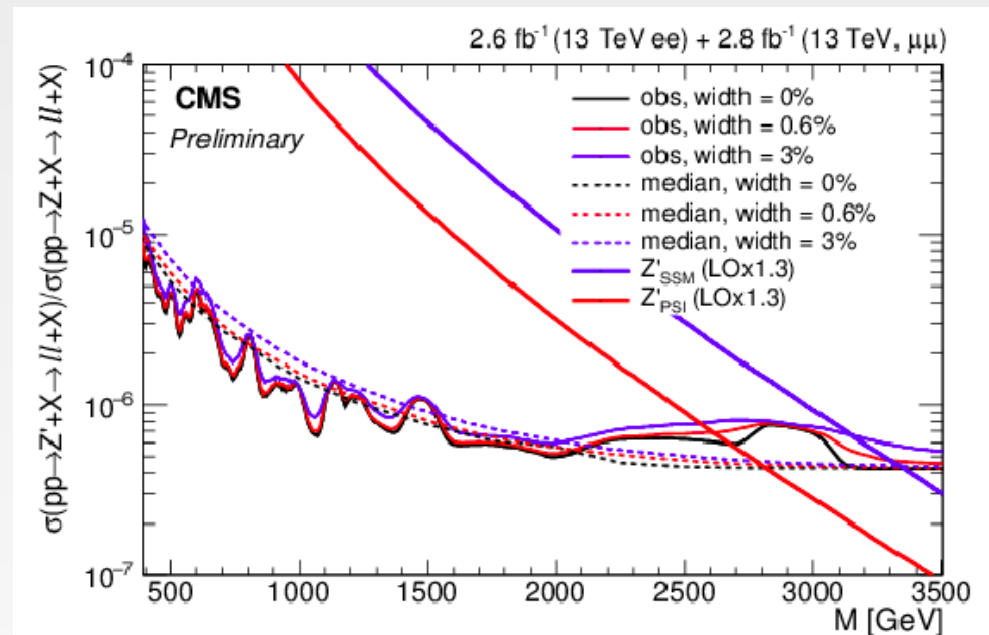


CMS-PAS-EXO-12-061, arXiv:1412.6302  
CMS-PAS-EXO-15-009

## Combined Limits @ 8 TeV



## Combined Limits @ 13 TeV



## Observed mass limits ( $Z'_\psi$ & $Z'_{SSM}$ )

Run-1 : 2.6, 2.9 TeV

Run-2 : 2.6, 3.2 TeV

channel	obs (TeV)	$Z'_\psi$	obs (TeV)	$Z'_{SSM}$
		expected (TeV)		expected (TeV)
$ee$	2.40	2.45	2.75	2.95
$\mu^+\mu^-$	2.40	2.55	3.00	3.05
$ee+\mu^+\mu^-$	2.60	2.80	3.15	3.35



## Matrix Element Method

For more info see my PhD Thesis (2015): <http://hdl.handle.net/2078.1/165868>

Uses the probability that an observed event in the experiment is the result of a given parton-level process, including the uncertainties on the measurements.

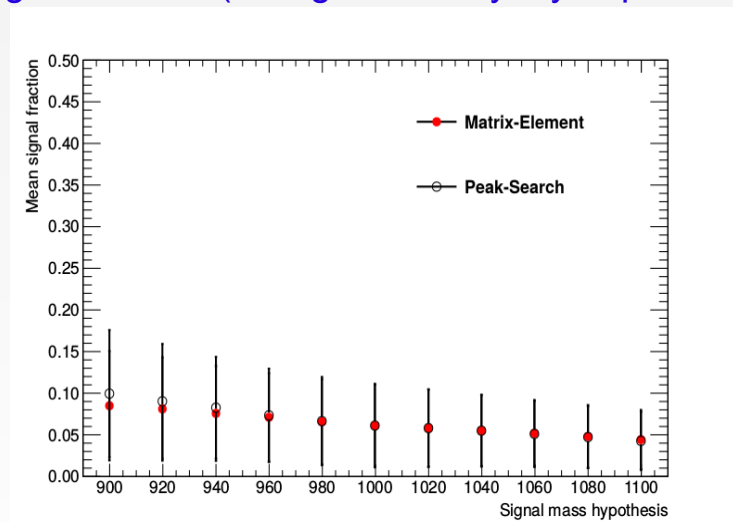
Takes into account

- all the information of all measured particles provided in an event
- change in detector resolution - particle by particle

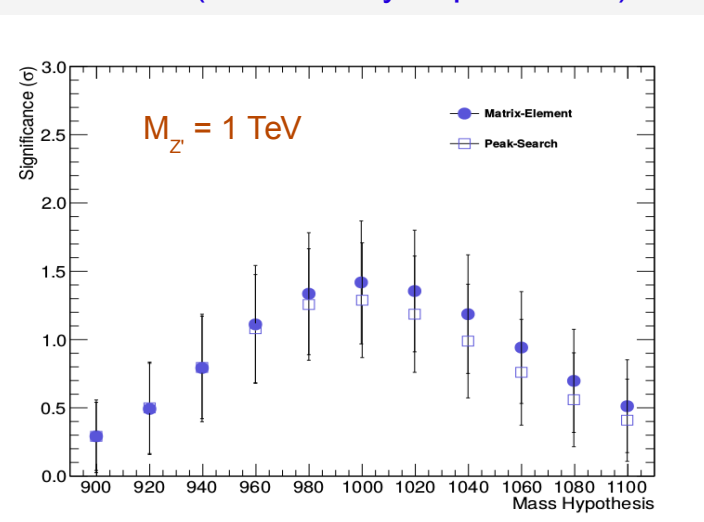
Likelihood function for underlying model parameters (M) taking into account detector setup and event selection

$$L(x|M) = pdf(x|M \text{ and } x \text{ in } X') = \frac{1}{\varepsilon' \sigma'} \int_{Y'} \frac{d\sigma_M}{dy} \varepsilon(y) w'(x|y) dy$$

Signal fraction (background-only toy-experiments)



Z-score (20B+5S toy-experiments)



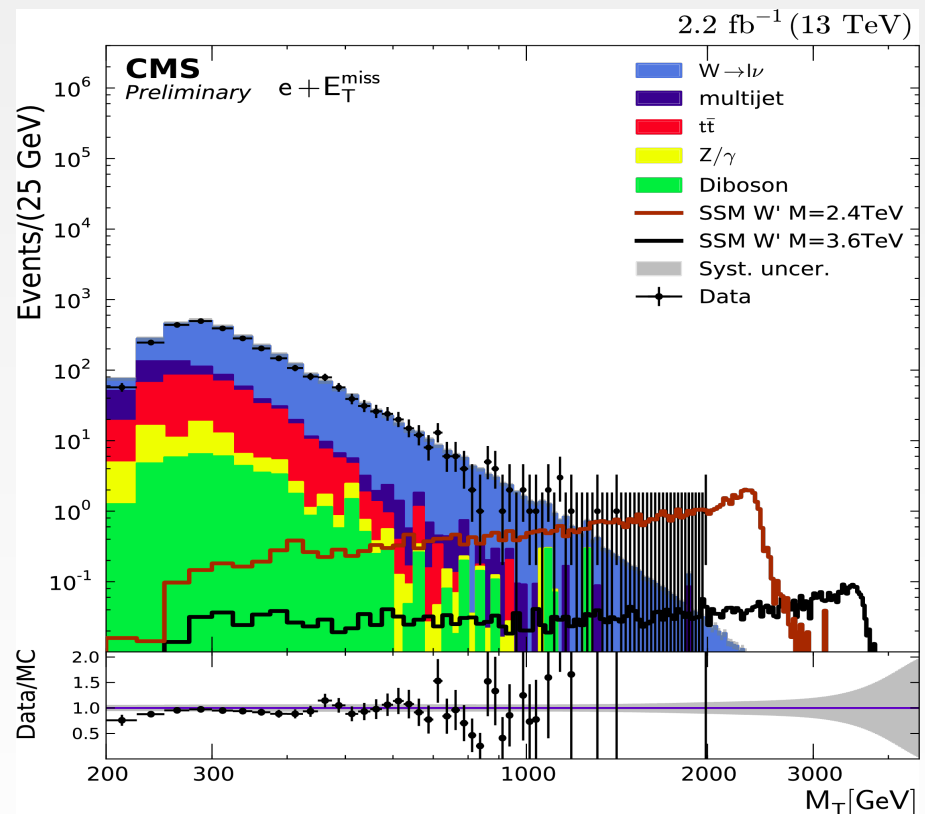
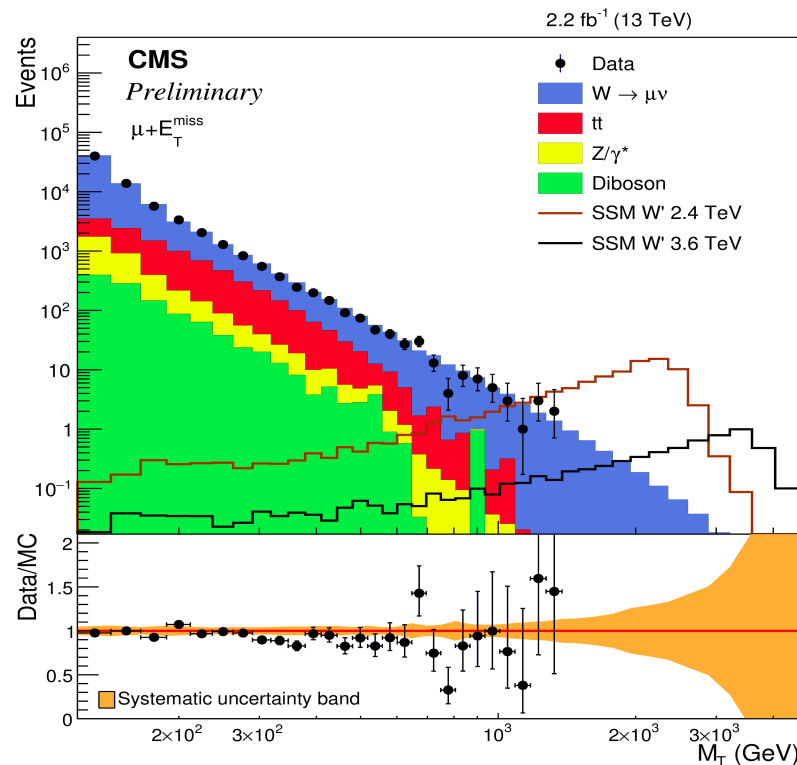
# Search for Heavy $W'$ with lepton+MET

CMS-PAS-EXO-15-006

- Search for a heavy  $W'$  resonance (SSM) decaying to a charged lepton and a neutrino
- Analysis is sensitive to new heavy resonances at the high mass
- Key aspects: lepton energy scale and resolution

Transverse mass discriminant:

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



# Search for Heavy $W'$ with lepton+MET

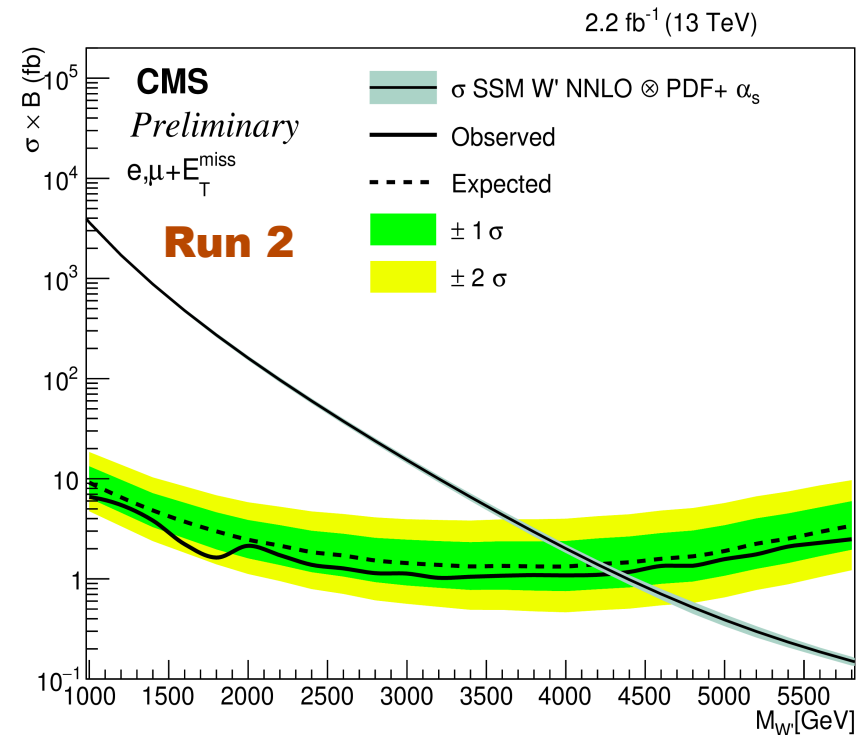
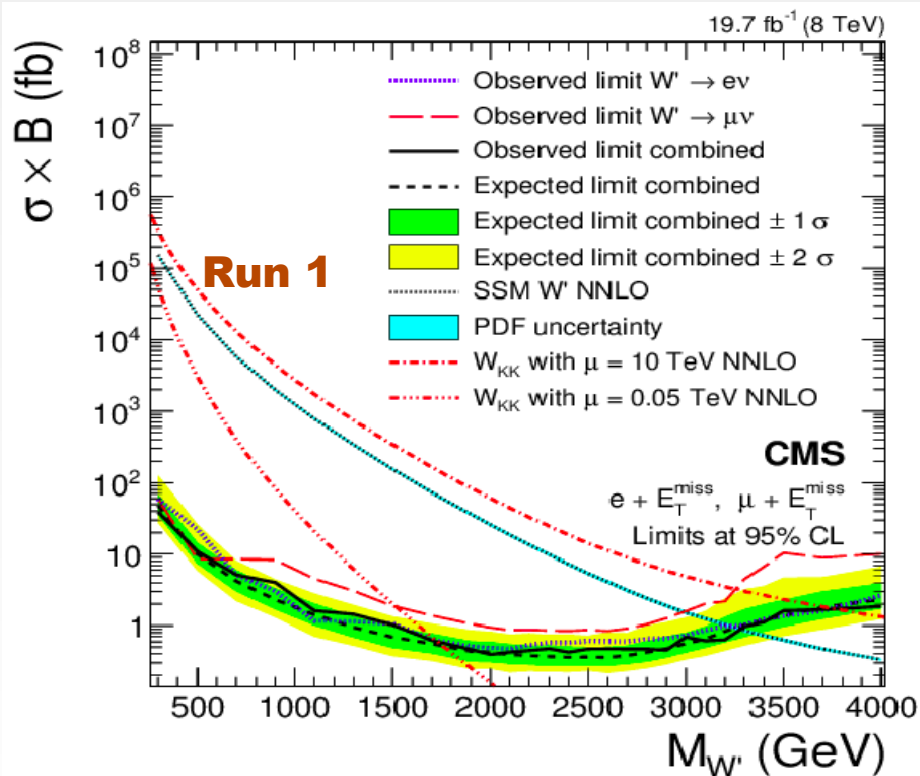
CMS-PAS-EXO-15-006

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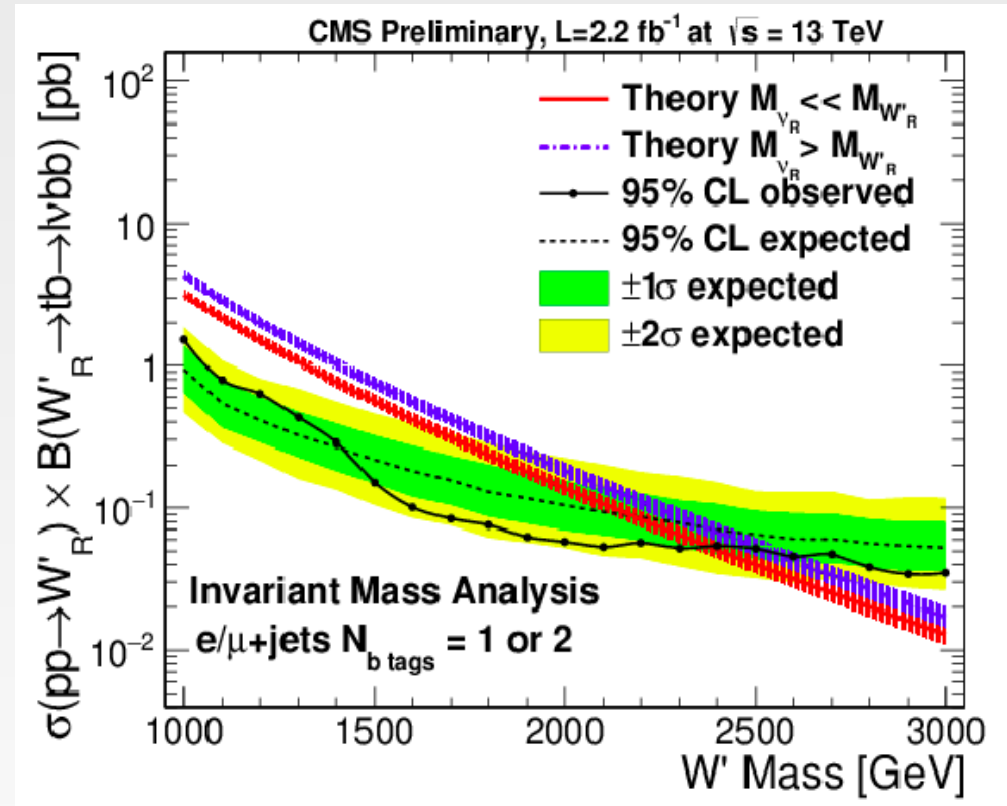
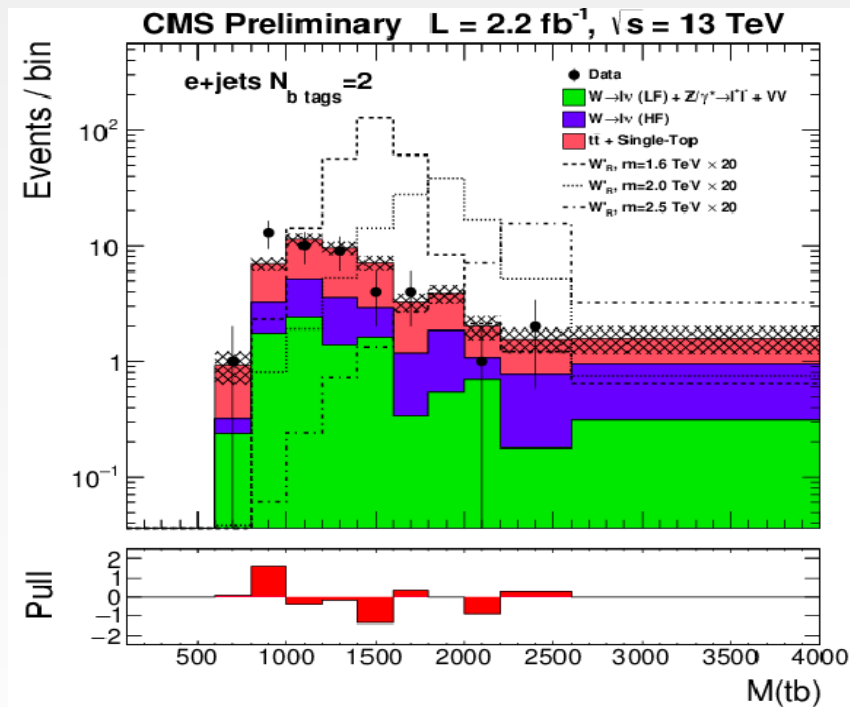
Mass limits improves  $\sim 1\text{TeV}$  @ Run2



# Search for Heavy $W'$ with $t+b$

CMS-PAS-B2G-15-004

- Search for a heavy  $W'$  decaying to a top and a bottom quark in leptonic final state
- Analysis is sensitive to new heavy resonances at high mass
- b-jet identification



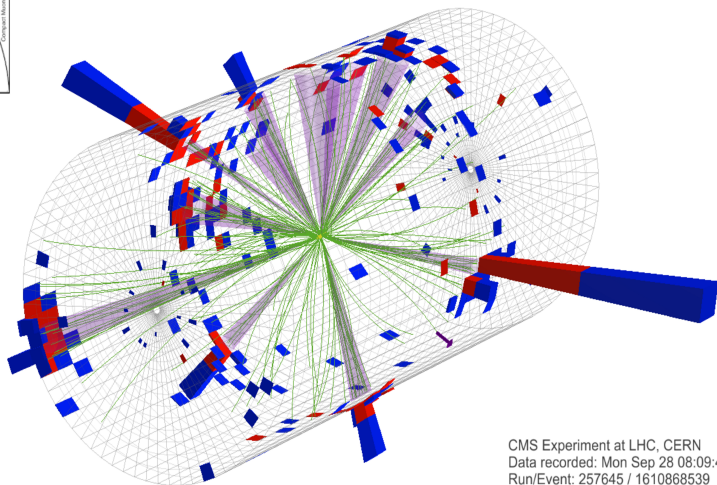
Mass limits (2.4TeV observed) already better than 8TeV

# Search for Black Holes

CMS-PAS-EXO-15-007

- Search for semi-classical and quantum Black Holes in highly energetic, high multiplicity decays
- Looking for a broad excess in the number of object multiplicity (N) and  $S_T$  shape
- Main background is QCD multijet

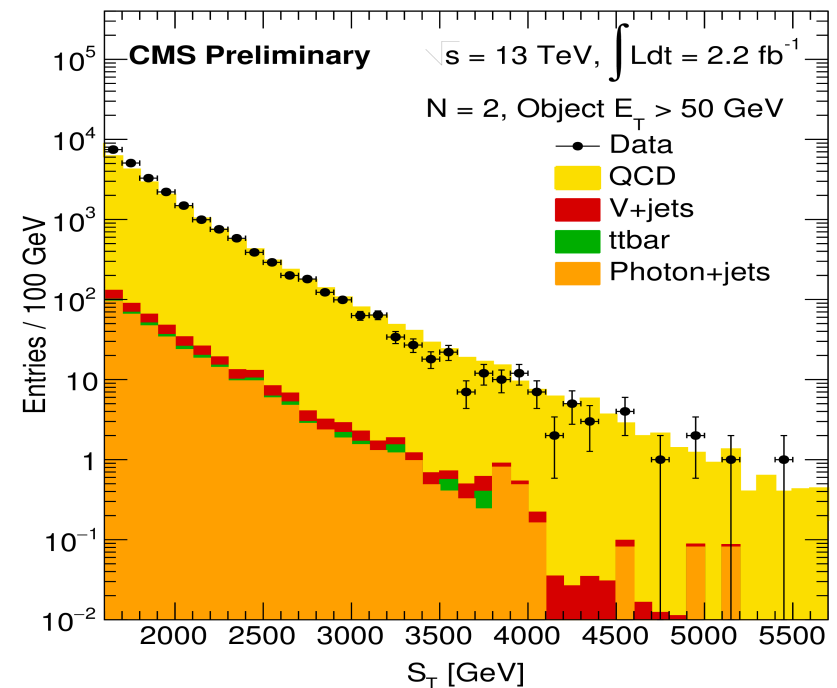
Event display for a black hole candidate  
N = 12,  $S_T = 5.48$  TeV



CMS Experiment at LHC, CERN  
Data recorded: Mon Sep 28 08:09:43 2015 CEST  
Run/Event: 257645 / 1610868539

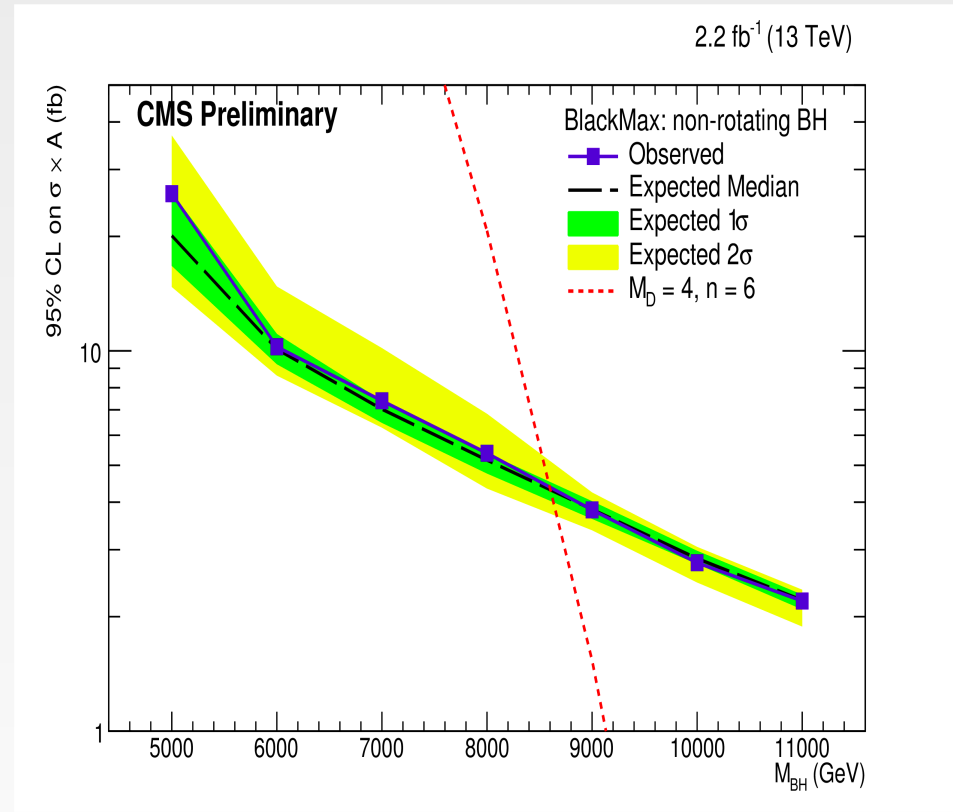
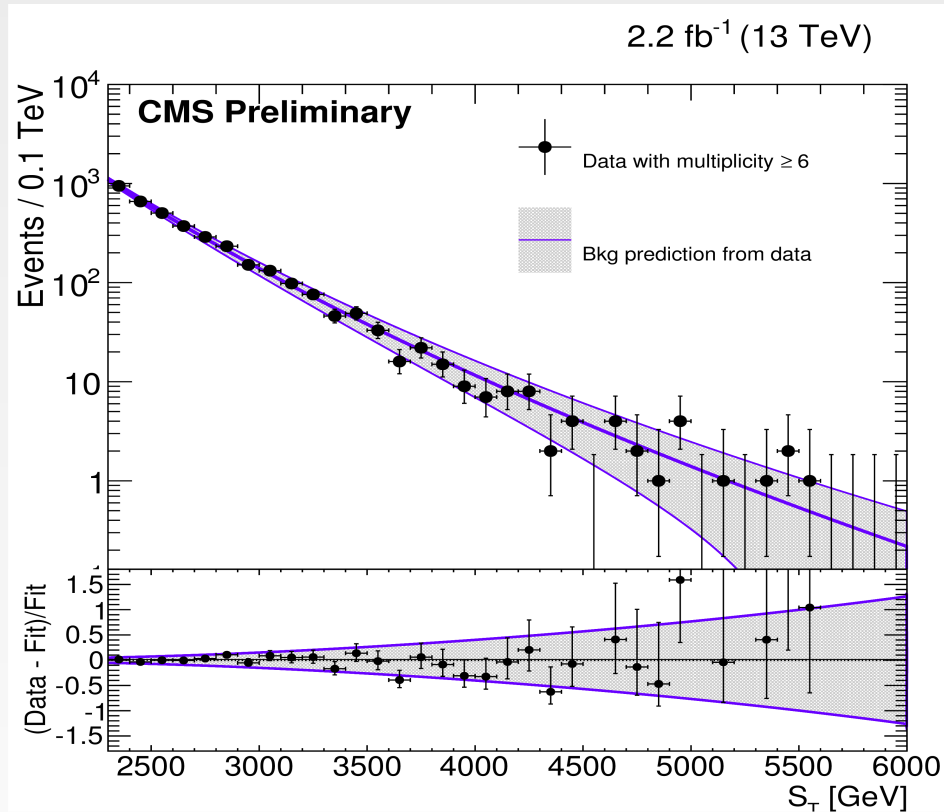
Key discriminant:

$$S_T = \sum_{j,e,\mu,\gamma}^N E_T \text{ (if } > 50 \text{ GeV)} + \text{MET (if } > 50 \text{ GeV)}$$





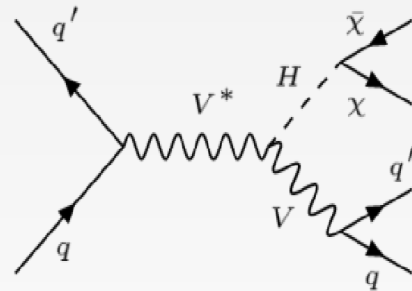
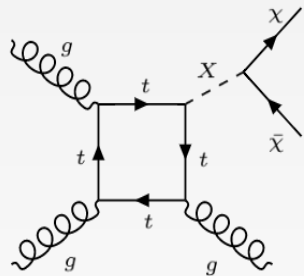
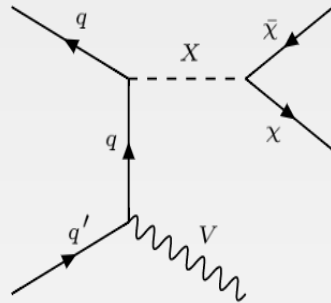
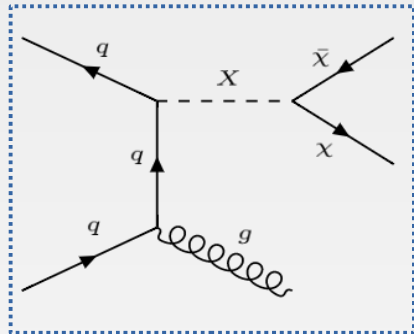
No significant excess is observed in binned  $N$  and  $S_T$  distributions



Run 2 mass limits : **8.0 TeV** (for QBH) and **8.7 TeV** (for semi-classical BH)

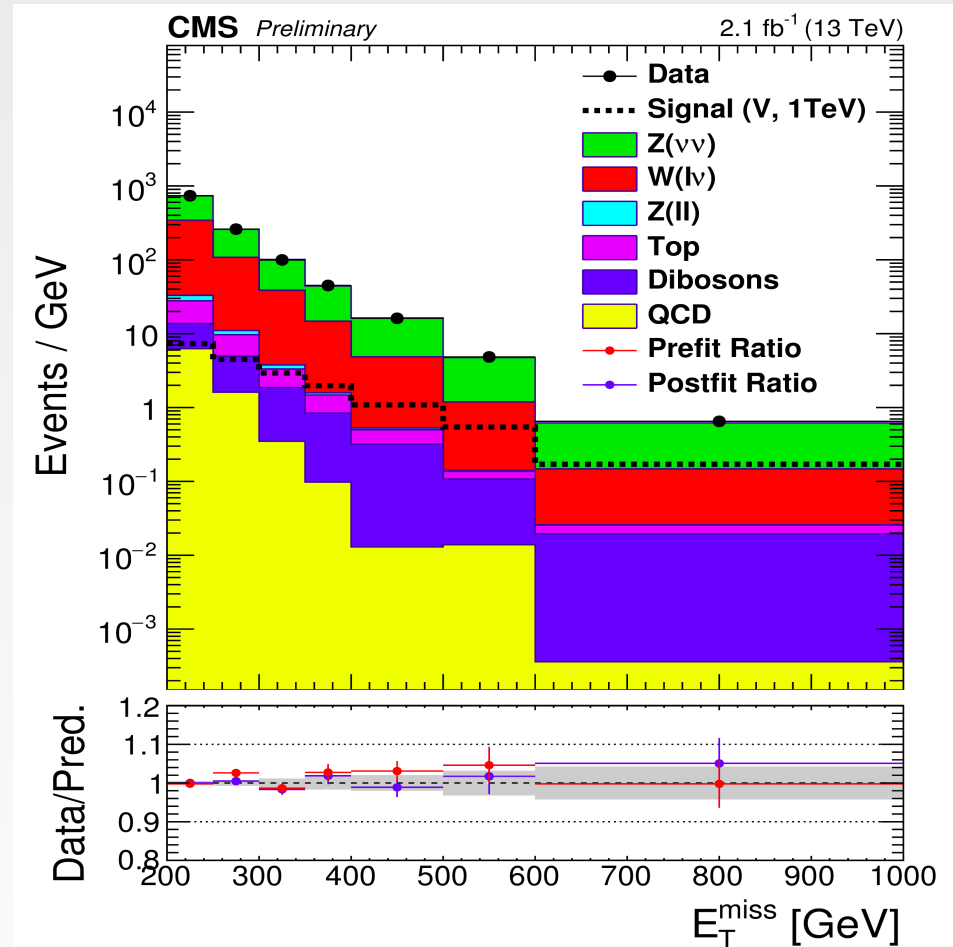
Run 1 mass limits : **5.5-6.0 TeV**

- Search for dark matter with jets and missing transverse energy (MET)
- DM pairs produced via mediator
  - Run-2: ISR jet
  - Run-1: ISR jet+ $V_{\text{had}}$  (V-tagging)

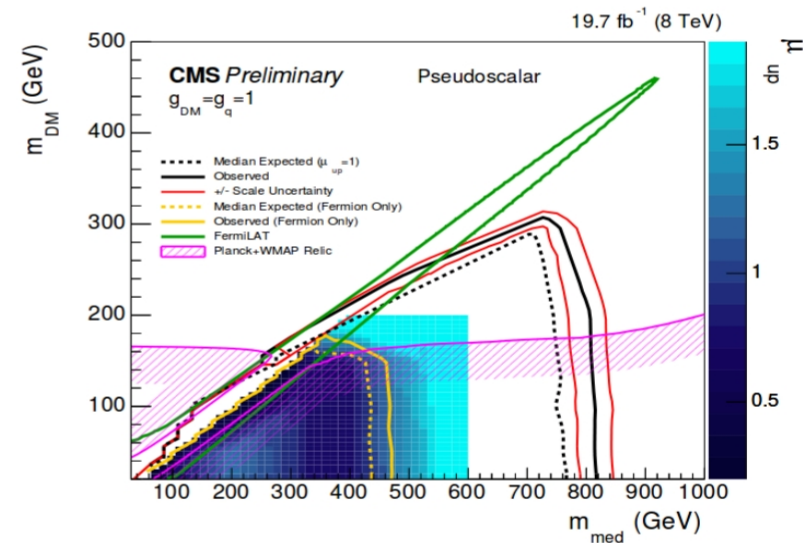
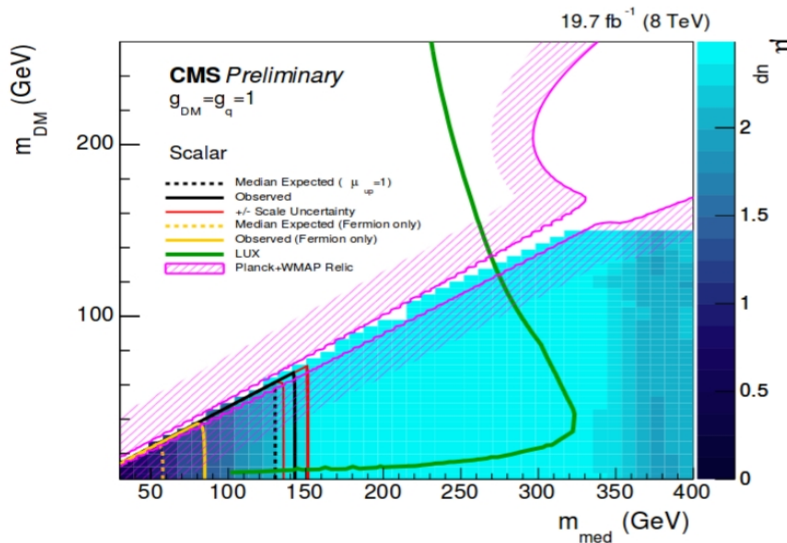
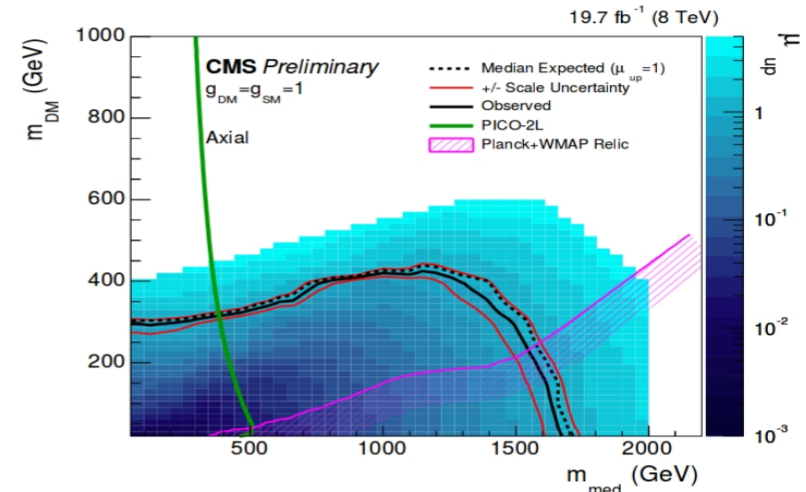
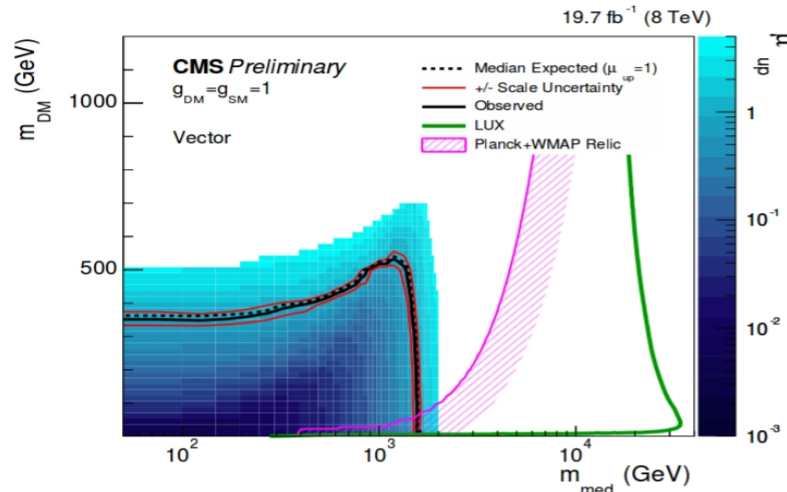


- Mediators:  
Vector+Axial+Scalar+Pseudoscalar
- Atlas/CMS Dark Matter Forum  
arXiv:1507.00966

CMS PAS-EXO-12-055 @8TeV  
CMS-PAS-EXO-15-003 @13TeV

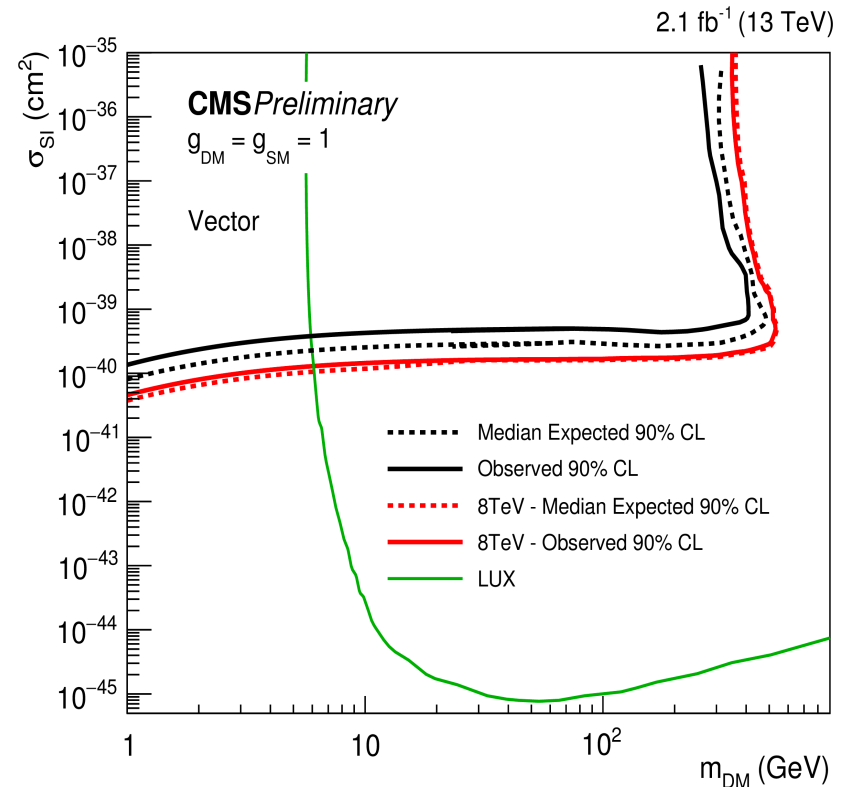
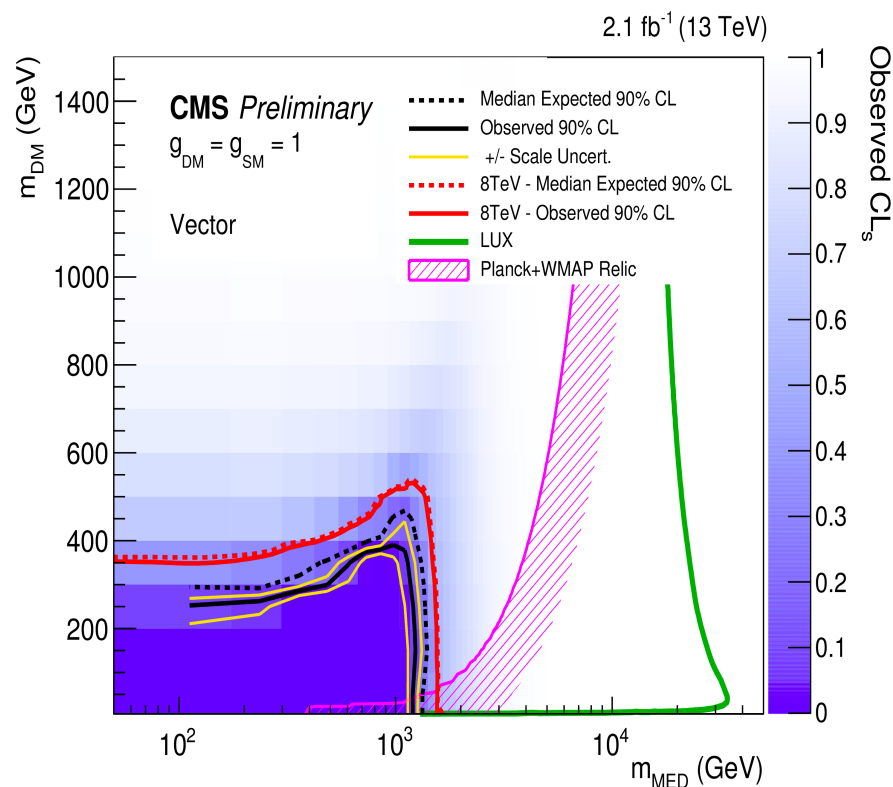


# Search for Dark Matter @ 8TeV



**Run 1 limits** in ( $m_{DM}, m_{med}$ ) plane, compare to **Direct Detection** and **Relic**  
 CMS most complementary for Axial and Psuedoscalar mediators

**Run 2** sensitivity comparable to **Run 1**  
(for Vector mediator and Direct Detection interpretation)

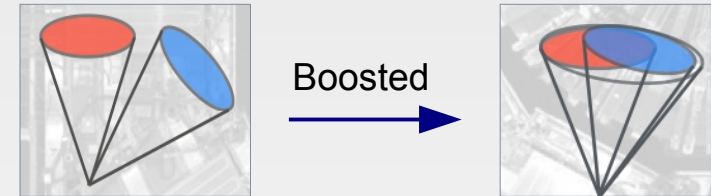


CMS contributes at low  $m_{DM}$

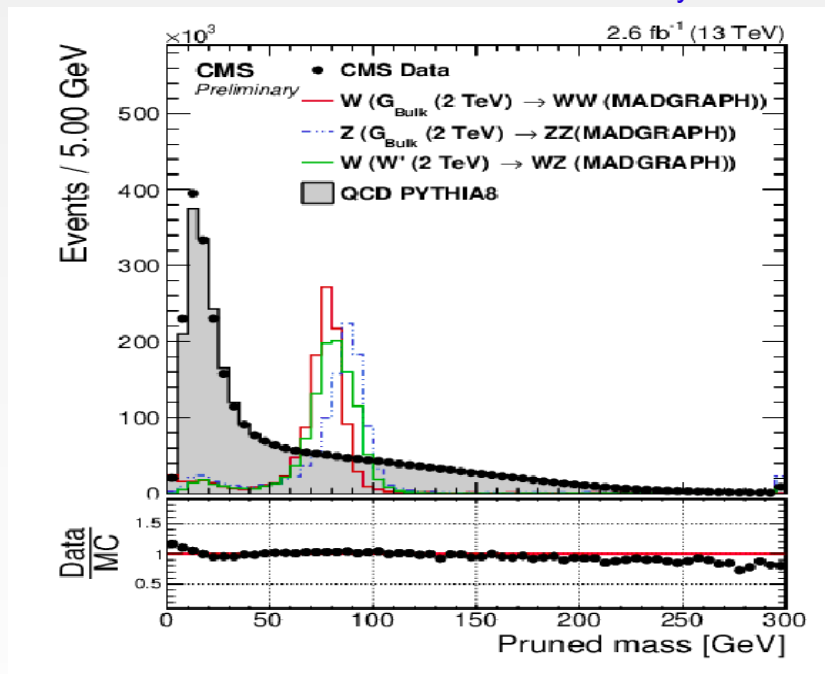
# Search for Diboson Resonances

CMS-PAS-EXO-15-002

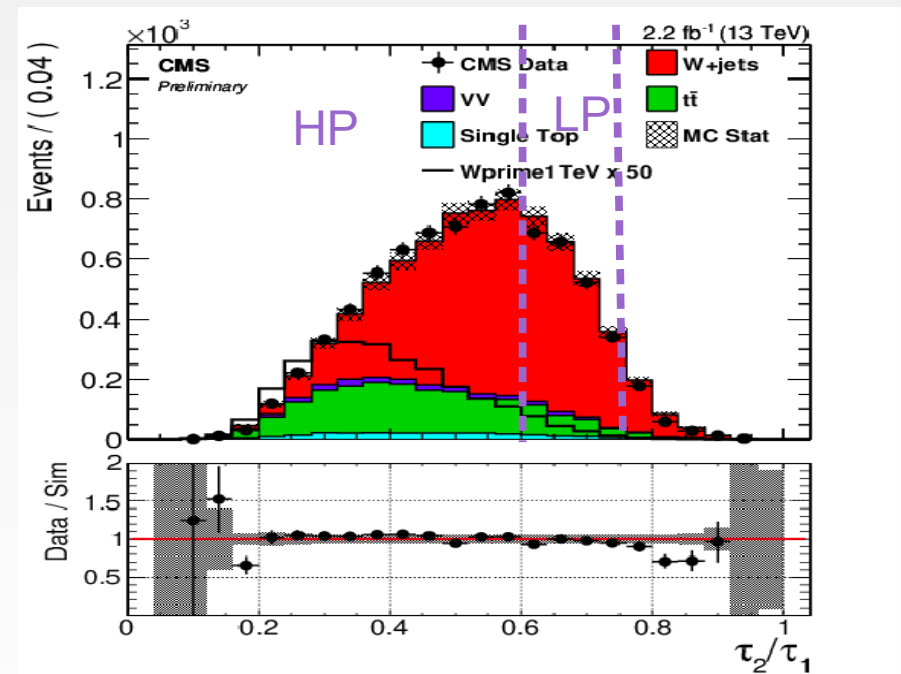
- Search for a resonance ( $W'$ ,  $Z'$  or Extra Dimensions) with boosted dibosons ( $VV$ ) in **semileptonic** and **fully hadronic** final states
- W/Z tagging is a key factor
  - ▶ V-jets pruned mass reconstruction ( $65 < m_{\text{jet}} < 105 \text{ GeV}$ )
  - ▶ N-Subjettiness ratio ( $\tau_{21} = \tau_2/\tau_1$ )
- Event categorization: Low-Purity and High-Purity
- **WZ**, **WW**, **ZZ** are presented



fully hadronic



semi leptonic

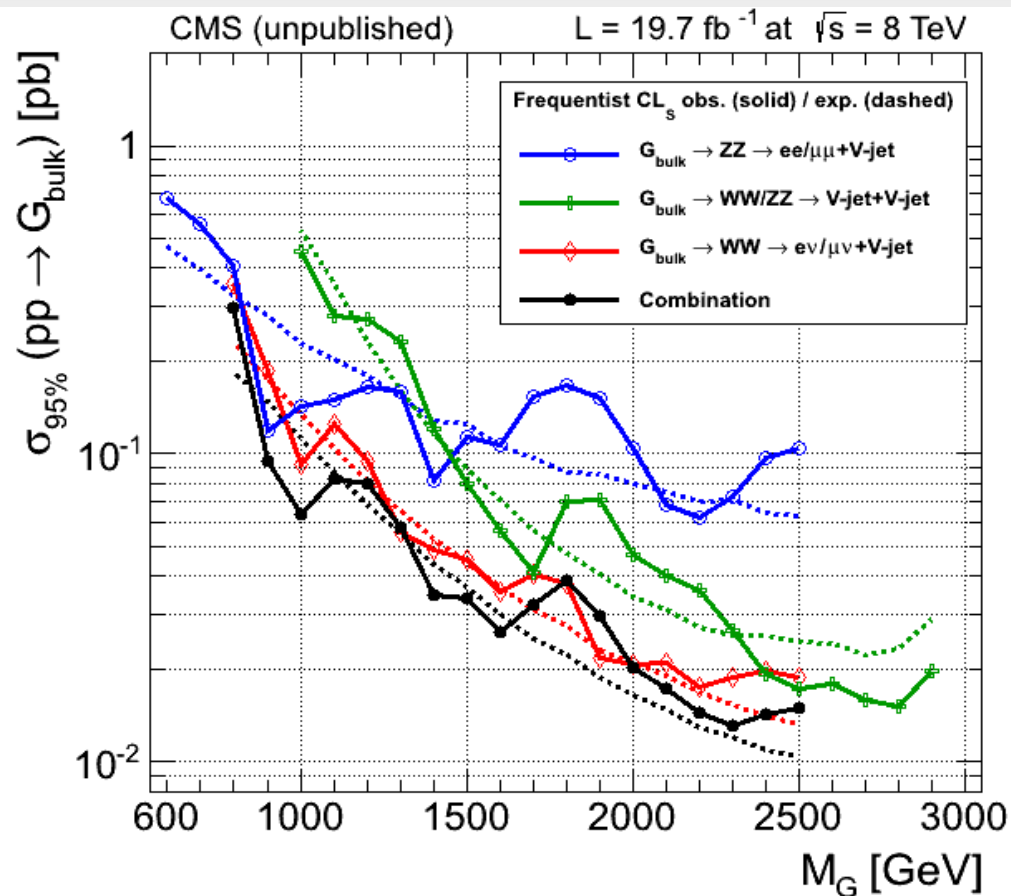
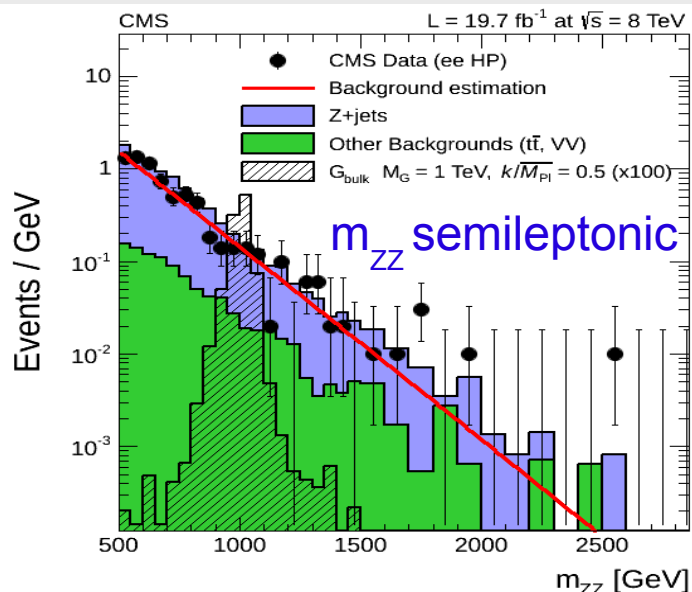




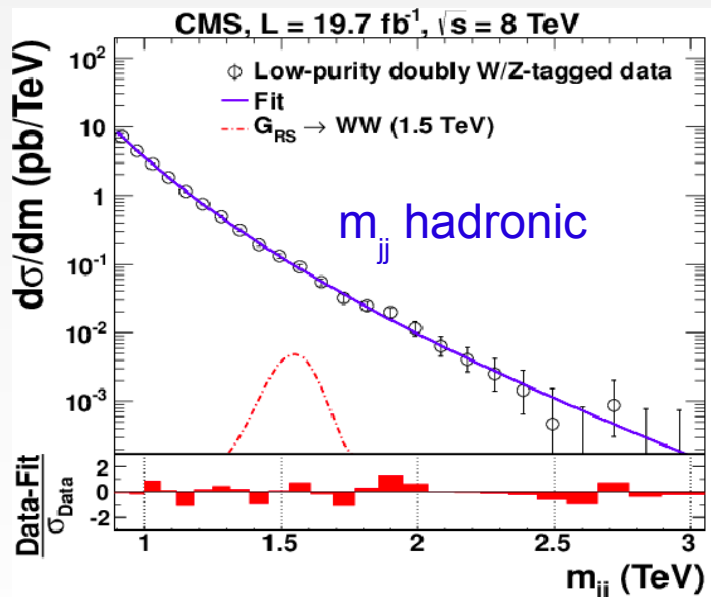
# Search for Diboson Resonances @ 8 TeV

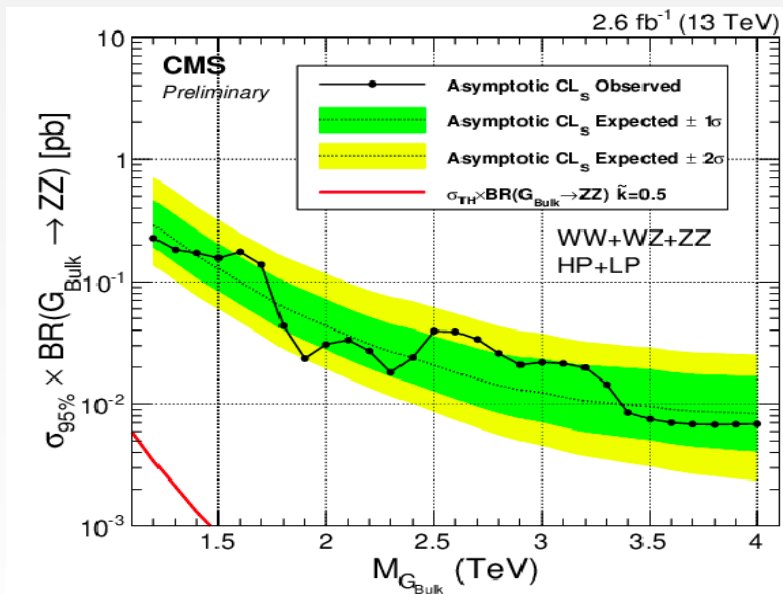
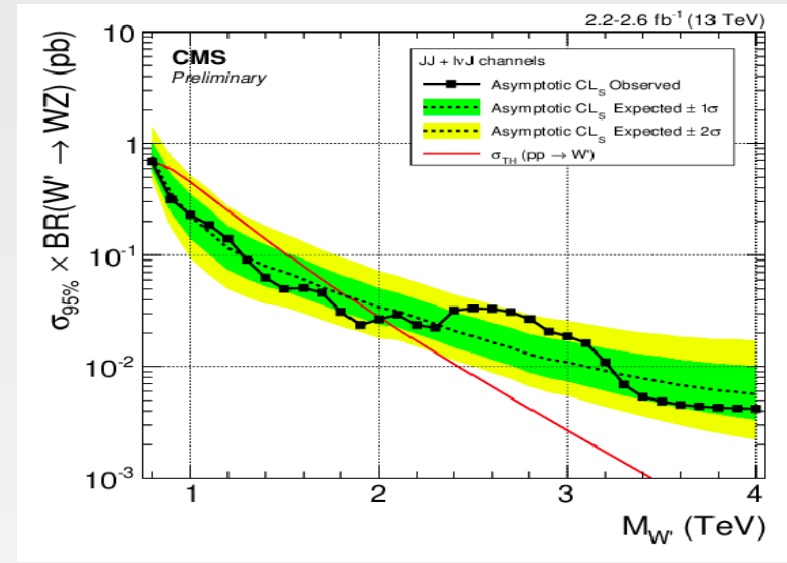
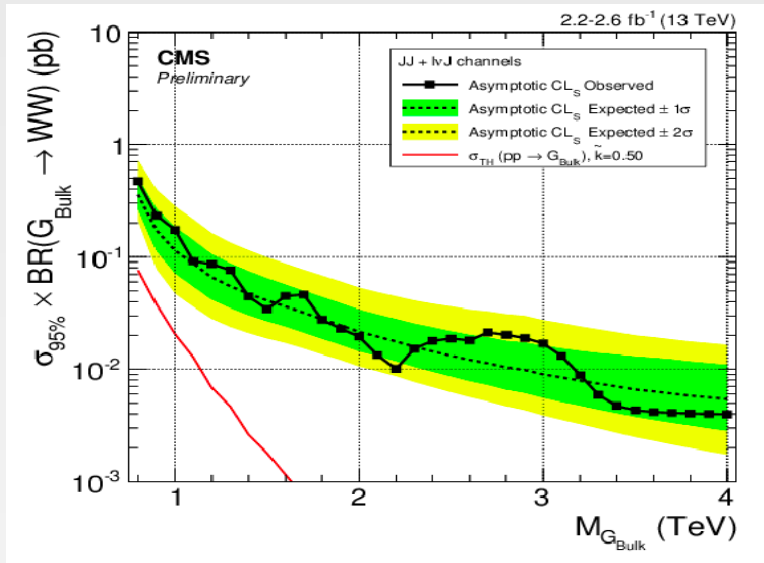
CMS-EXO-13-009, arXiv:1405.3447  
CMS-EXO-12-024, arXiv:1405.1994

## Combination semileptonic+hadronic



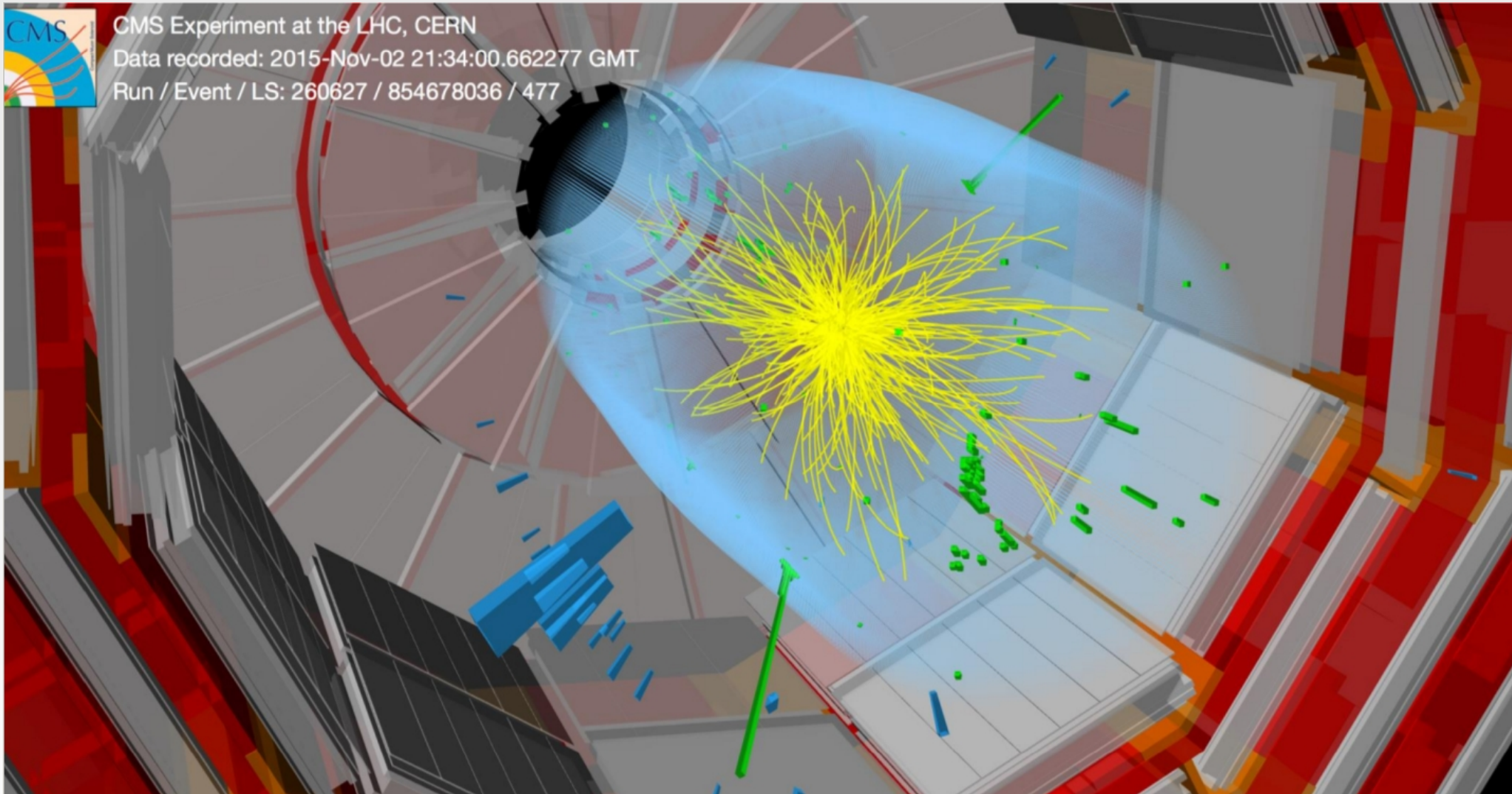
Run 1 excesses were seen ~1.8 TeV





- Hadronic (VV) + semileptonic (WV)
- No more excesses are observed ~1.8 TeV
- More stringent upper limits on the production  $\sigma \times \text{BR}$  are set for the models considered

# Search for Diphoton Resonances



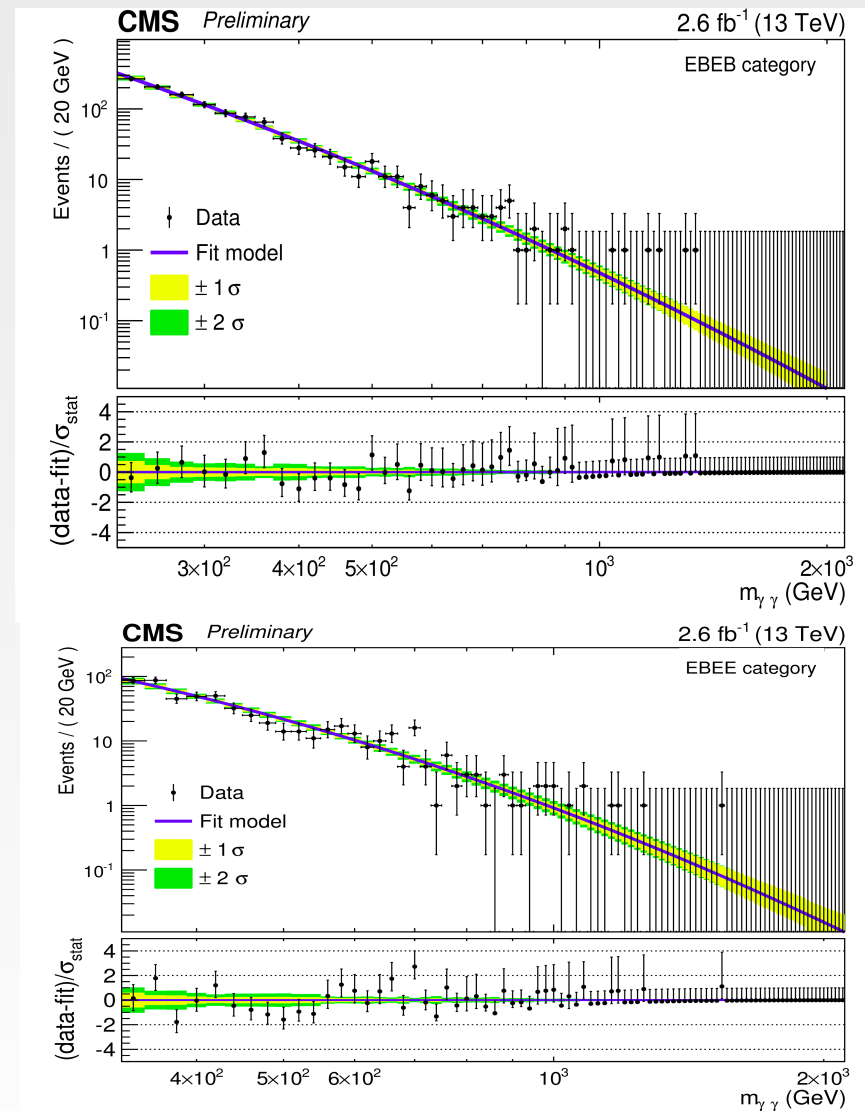
diphoton event display with a mass of 745 GeV

- Search for a bump in the diphoton invariant mass spectrum
- Sensitive to models of flat or warped Extra Dimension (Randall-Sundrum and ADD models)
- Two event categories of pairs of photons:
  - ▶ barrel-barrel (EBEB),
  - ▶ barrel-endcap (EBEE)
- RS gravitons are considered with three assumptions on effective coupling:

$$\tilde{k} = k / M_{Pl} = 0.01, 0.1, 0.2$$

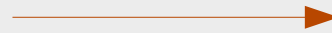
Background parametrization:

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

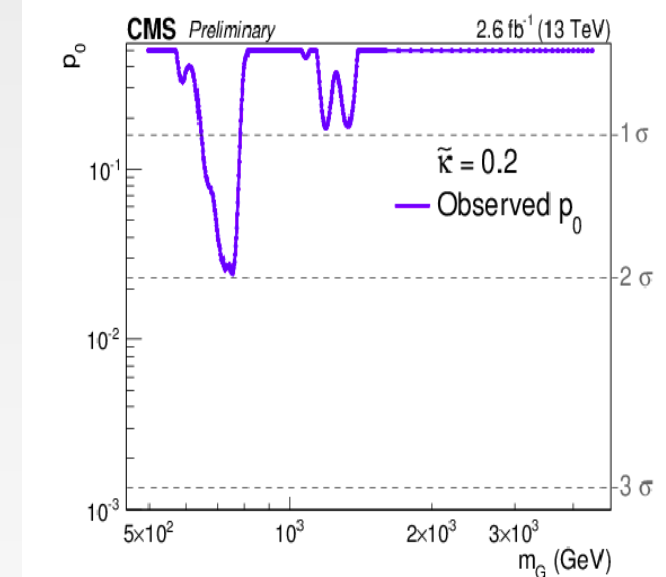
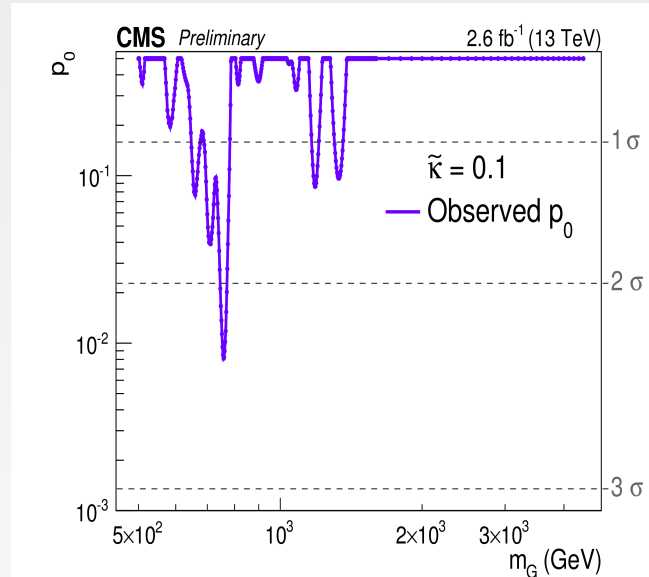
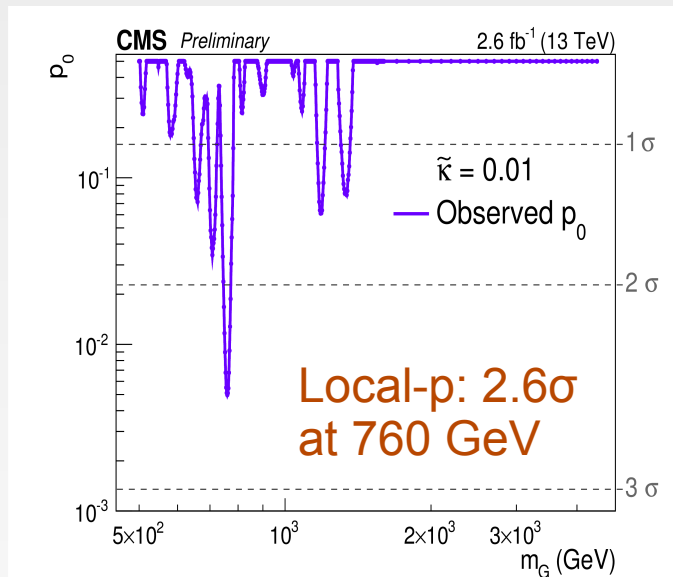


# Search for Diphoton Resonances

narrow width



wide width

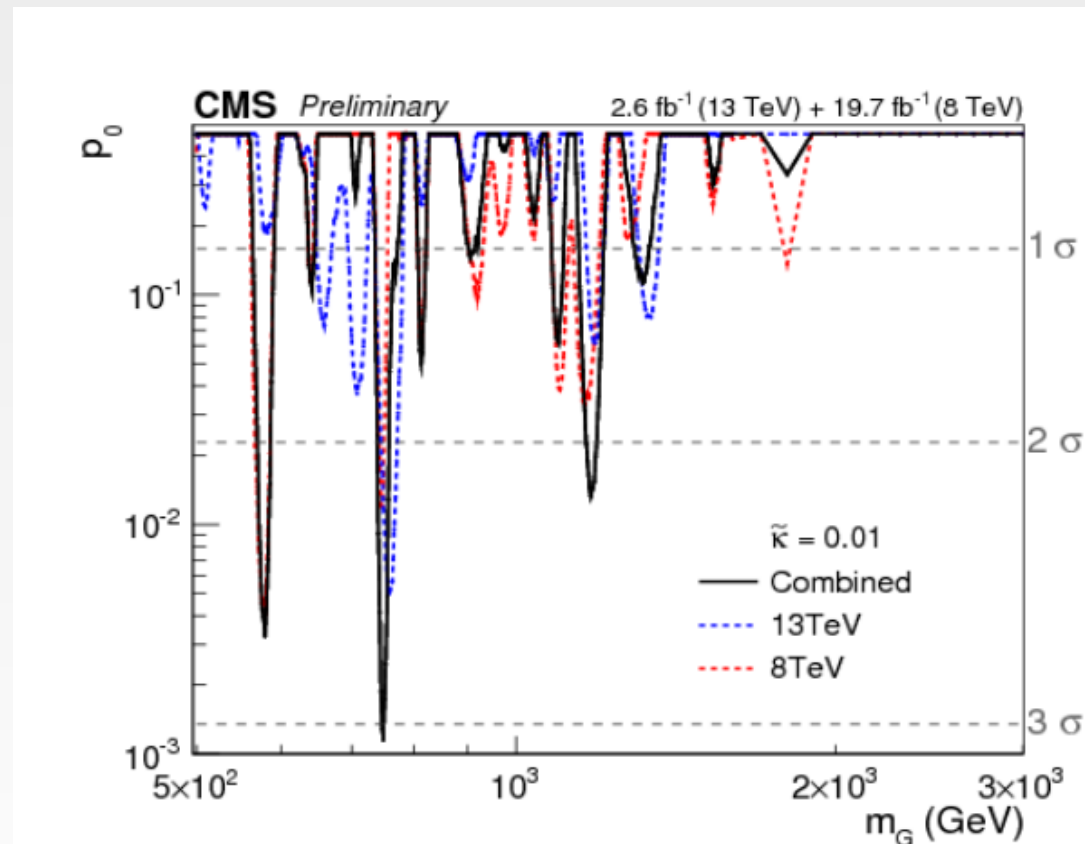


after LEE correction  $\rightarrow$  global p-value  $< 1.2\sigma$



# Diphoton Combination of Run 1 and Run 2

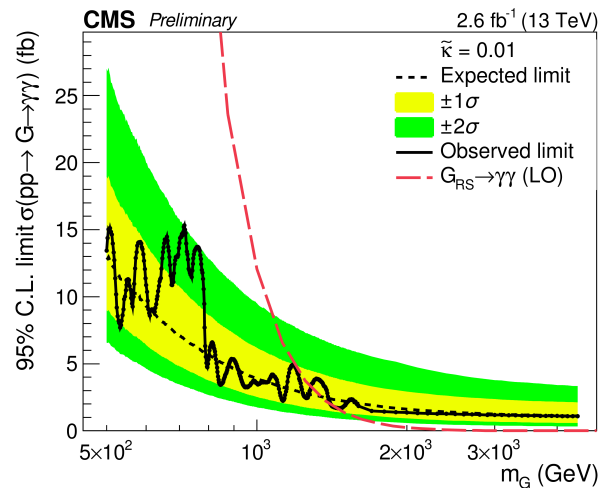
- Largest excess  $m_G = 750$  GeV with a local significance of  $3\sigma$
- Global significance  $< 1.7\sigma$



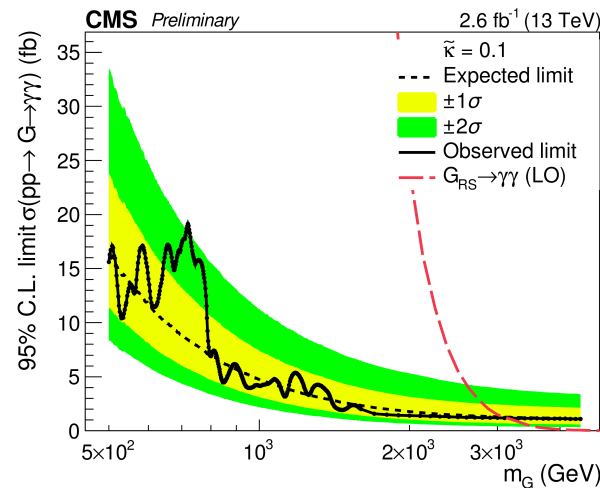
# Search for Diphoton Resonances

RS signal mass values lower than **1.3 TeV** ( $\tilde{k}=0.01$ ), **3.1 TeV** ( $\tilde{k}=0.1$ ) and **3.8 TeV** ( $\tilde{k}=0.2$ ) are excluded!

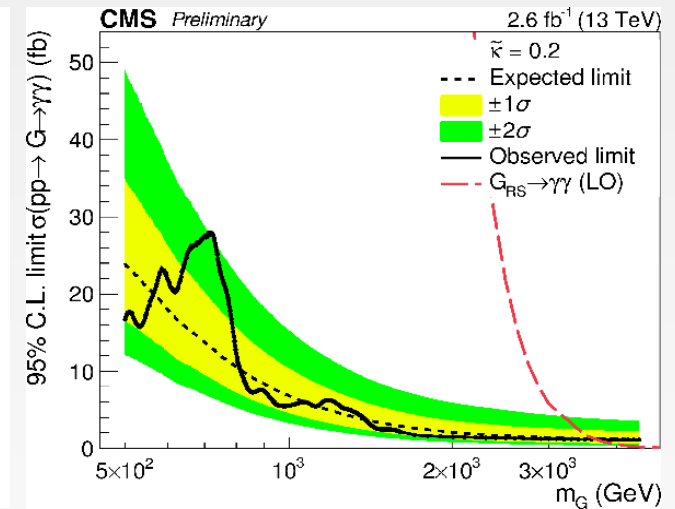
Run 1 mass limits: **1.4 TeV** ( $\tilde{k}=0.01$ ), **2.7 TeV** ( $\tilde{k}=0.1$ )



$\tilde{k}=0.01, m_G > 1.3 \text{ TeV}$



$\tilde{k}=0.1, m_G > 3.1 \text{ TeV}$



$\tilde{k}=0.2, m_G > 3.8 \text{ TeV}$

- 2015 data sample sufficient to reach or exceed Run 1 sensitivity for many analyses
- Exciting diboson excess at Run 1 does not appear at Run 2
- A new small excess in diphoton, more data needed!

CMS Physics Results @ 13 TeV: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LHC-Jamboree-2015.html>

Exotica Public Results: <http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html>

Exotica Preliminary Results: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html>

B2G LHC Jamboree Results: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LHC-Jamboree-2015/B2G.html>

- 2015 data sample sufficient to reach or exceed Run 1 sensitivity for many analyses
- Exciting diboson excess at Run 1 does not appear at Run 2
- A new small excess in diphoton, more data needed!
- **Analyses will be updated/improved...**



CMS Physics Results @ 13 TeV: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LHC-Jamboree-2015.html>

Exotica Public Results: <http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html>

Exotica Preliminary Results: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html>

B2G LHC Jamboree Results: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LHC-Jamboree-2015/B2G.html>



# Thank you!



*Krakow Epiphany 2016*

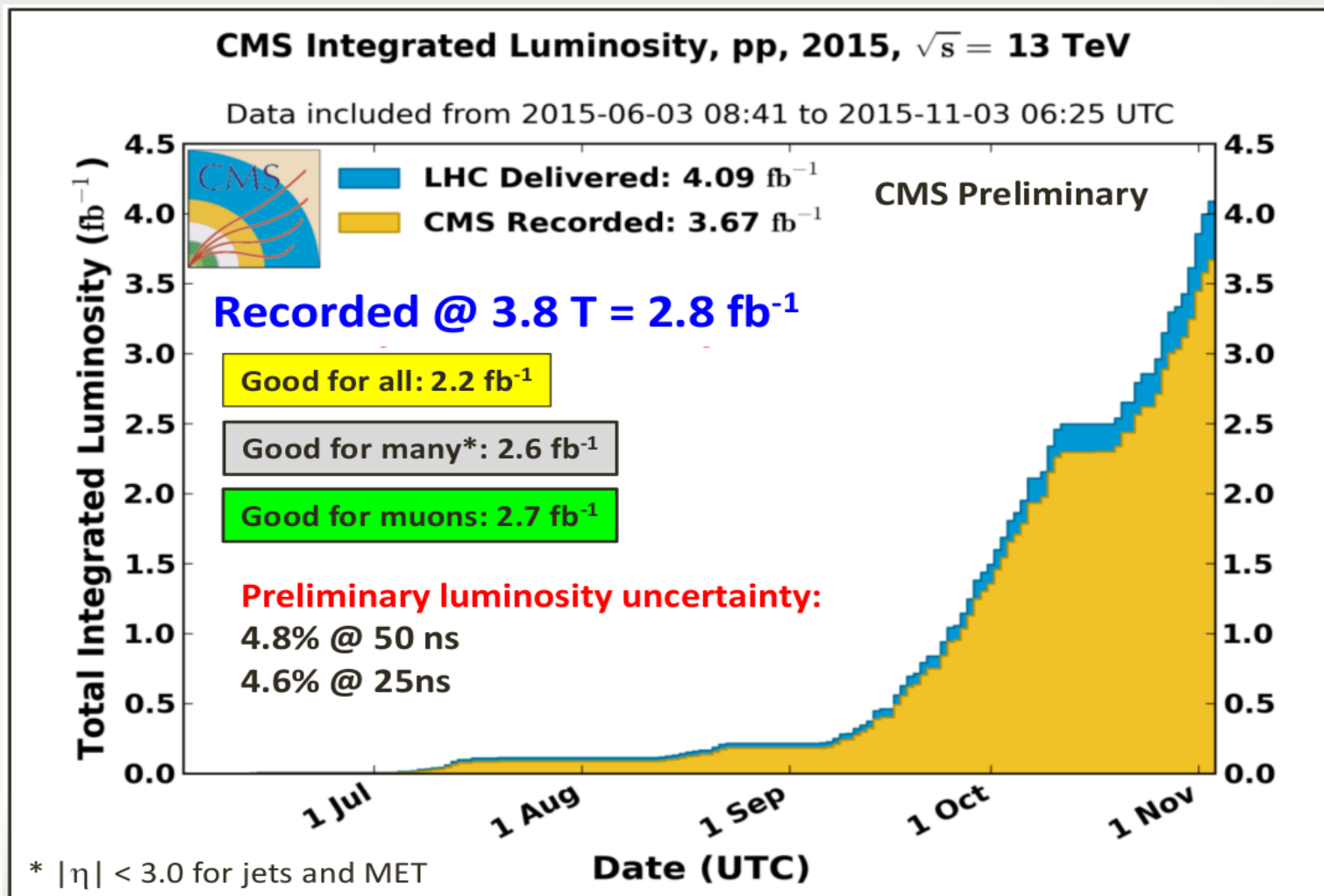


# Back-Up

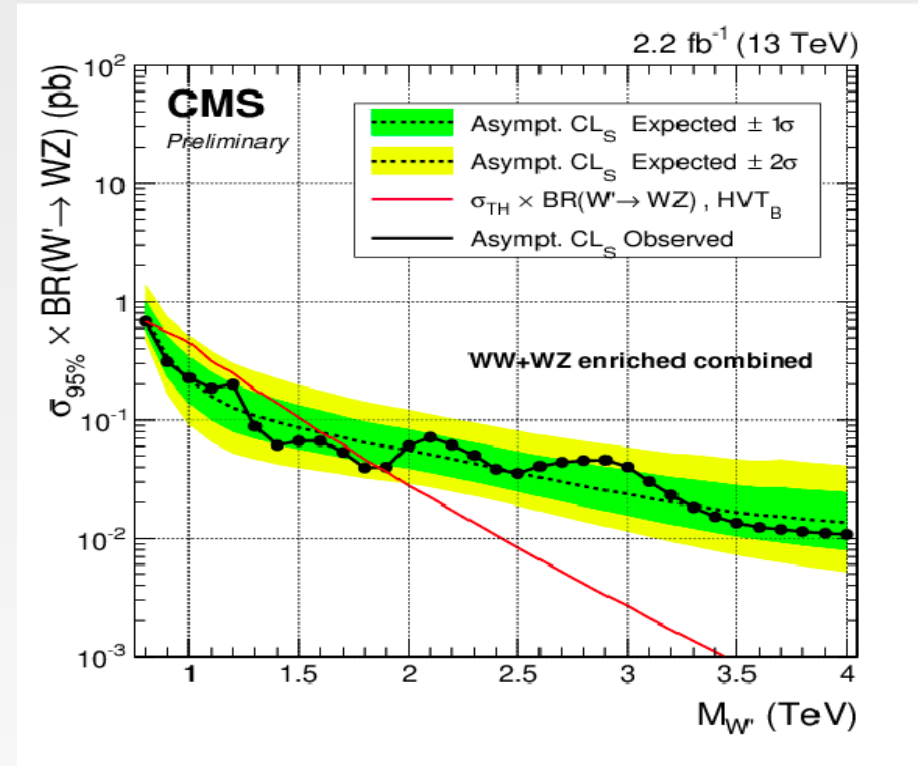
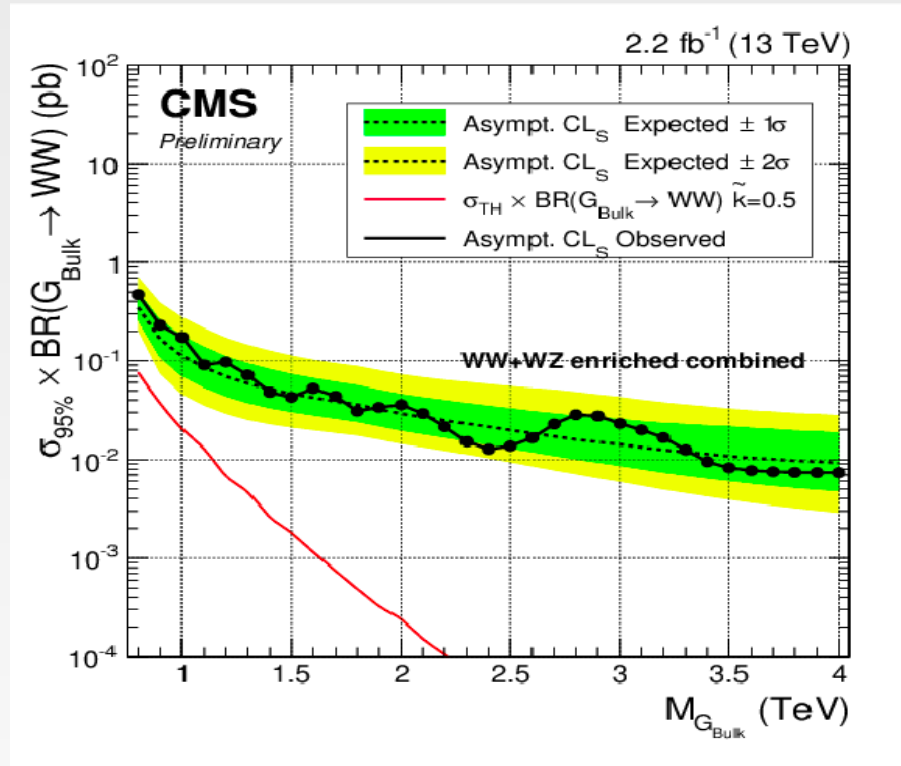


Back-Up

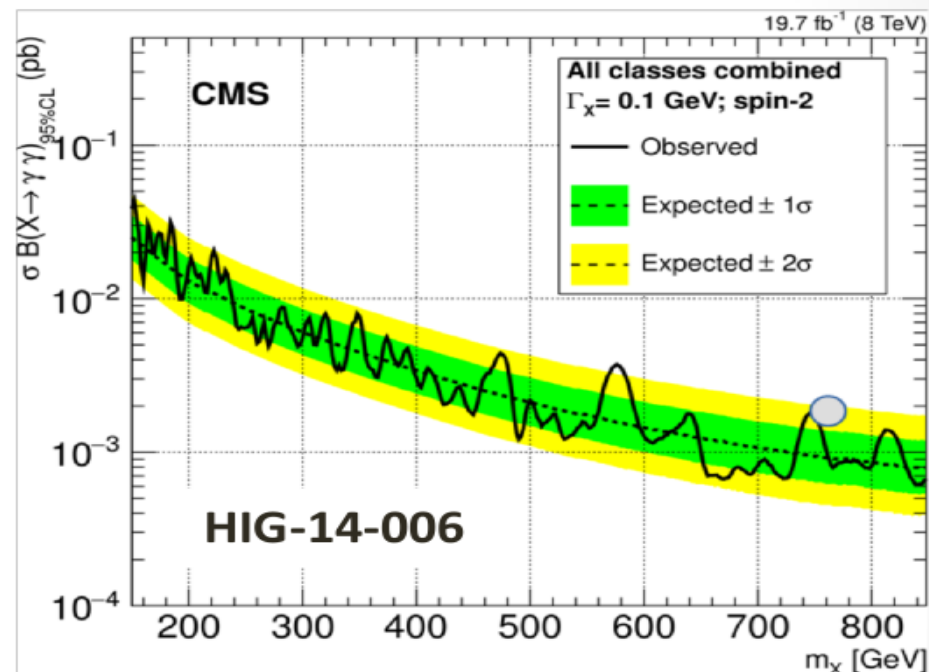
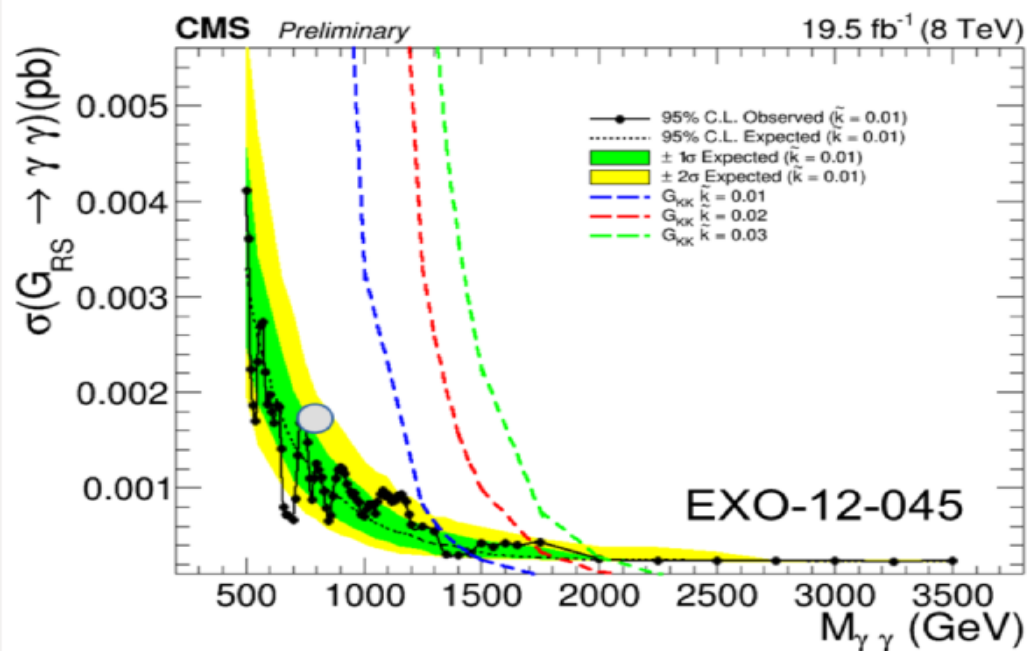




# Searches with Dibosons: Semi-leptonic



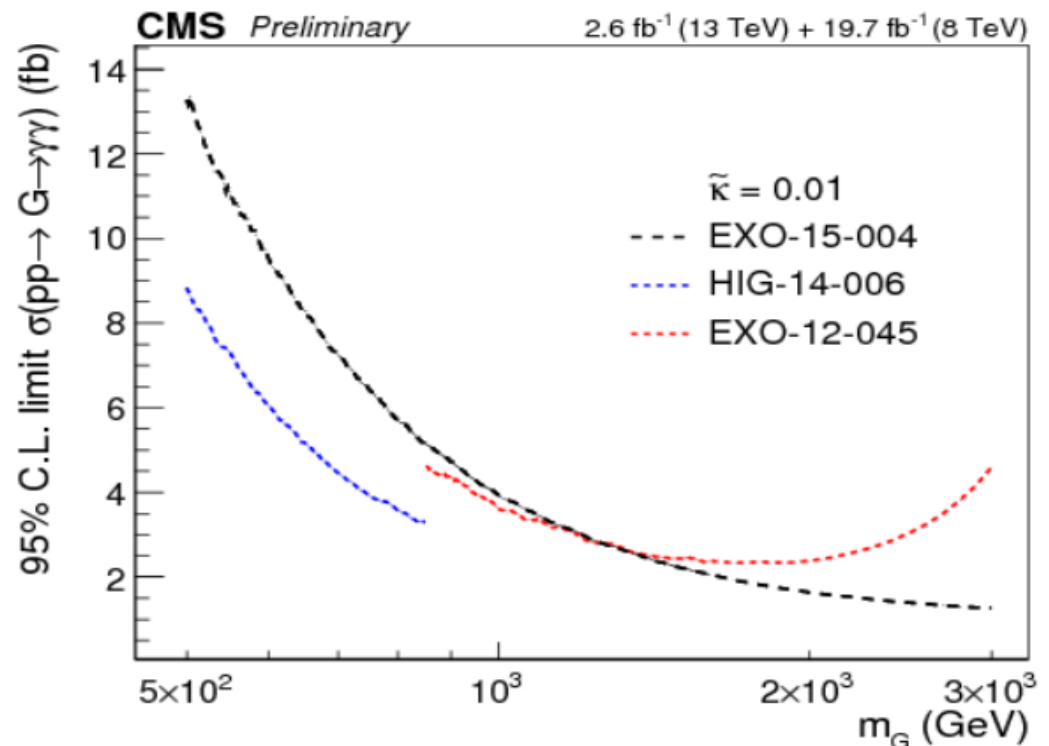
## Compatibility with Run 1



Excess not excluded by Run 1 searches

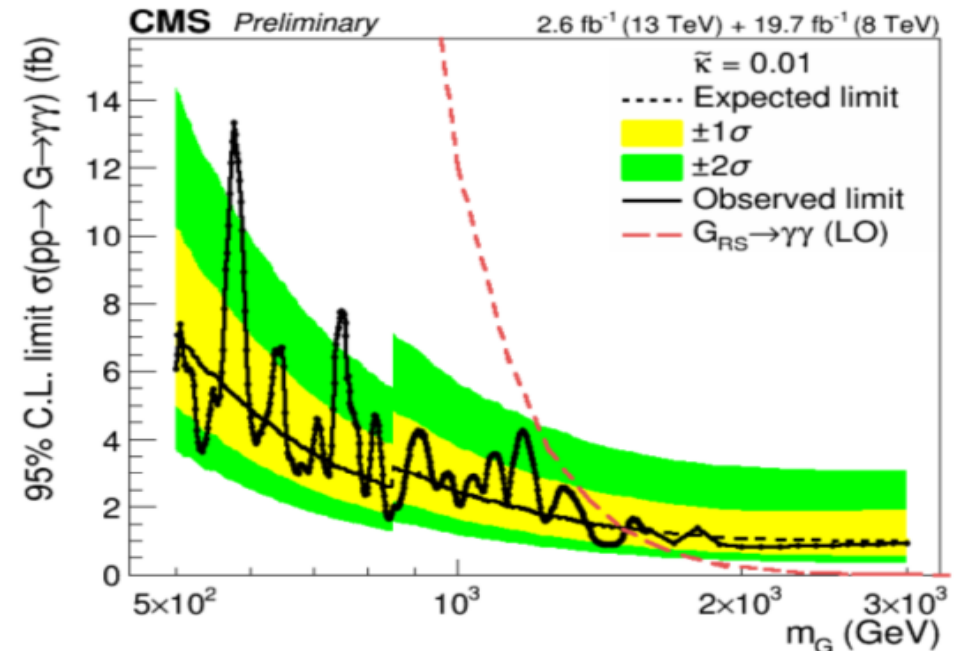
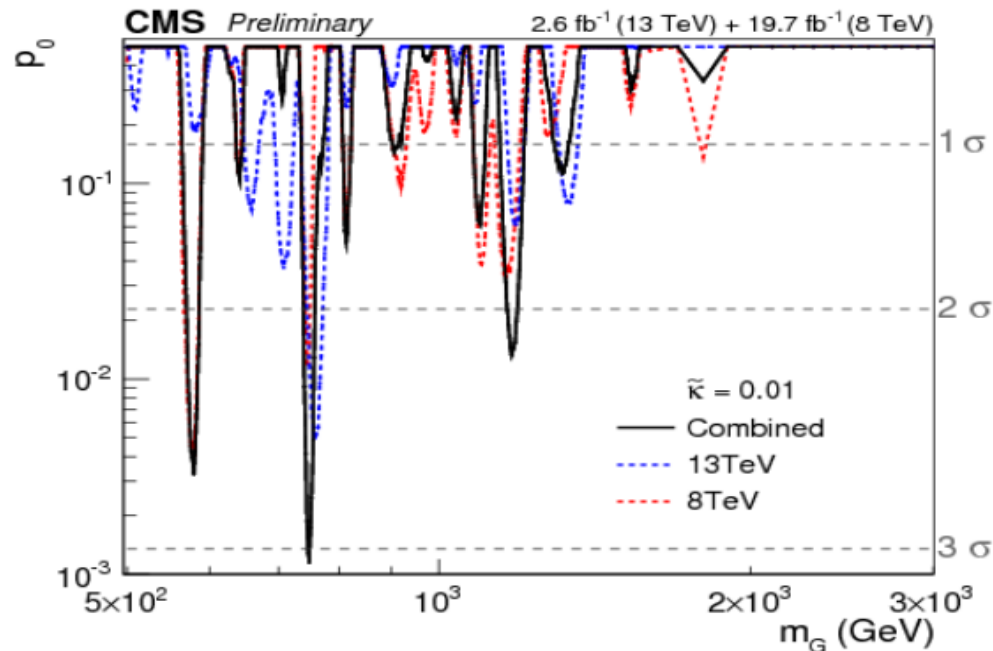
## Combination of 8TeV and 13TeV results

- Combination performed assuming narrow RS graviton hypothesis.
  - Results expressed in terms of equivalent 13TeV cross sections.
- Two analyses at 8TeV.
  - HIG-14-006 and EXO-12-045
  - HIG-14-006 is the most sensitive in the covered range (larger acceptance, plus categorization).



## Combined limits and p-values

- Combined limit improves single analyses sensitivity by 20-30%.
  - Largest excess:  $M_G = 750 \text{ GeV}$ , local significance  $3\sigma$
  - global significance  $< 1.7\sigma$



Jim Olsen, LHC Jamboree 2015: [https://indico.cern.ch/event/442432/contribution/0/attachments/1205563/1756687/CMS\\_13\\_TeV\\_results\\_public.pdf](https://indico.cern.ch/event/442432/contribution/0/attachments/1205563/1756687/CMS_13_TeV_results_public.pdf)