CMS Searches Beyond SUSY

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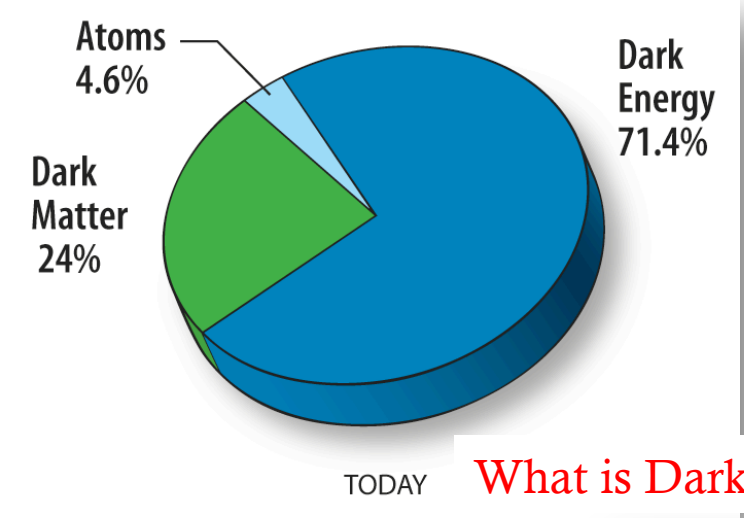
on behalf of the CMS Collaboration

Particle Physics on the Verge of Another Discovery?

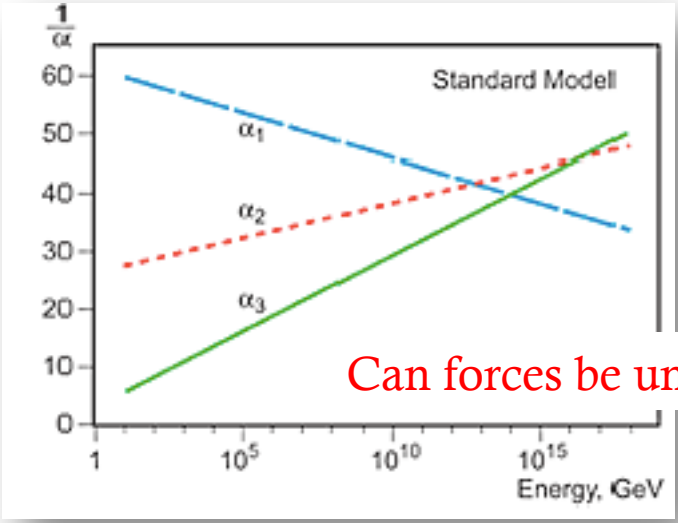
10-17 January, 2016

ASPEN CENTER FOR PHYSICS

- Higgs discovery was a triumph of Run 1 of LHC, but…

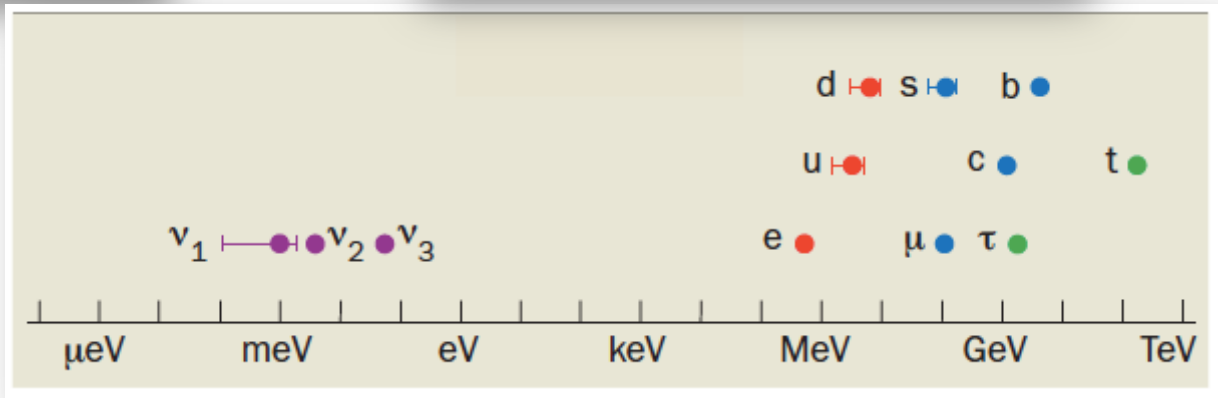


What is Dark Matter?



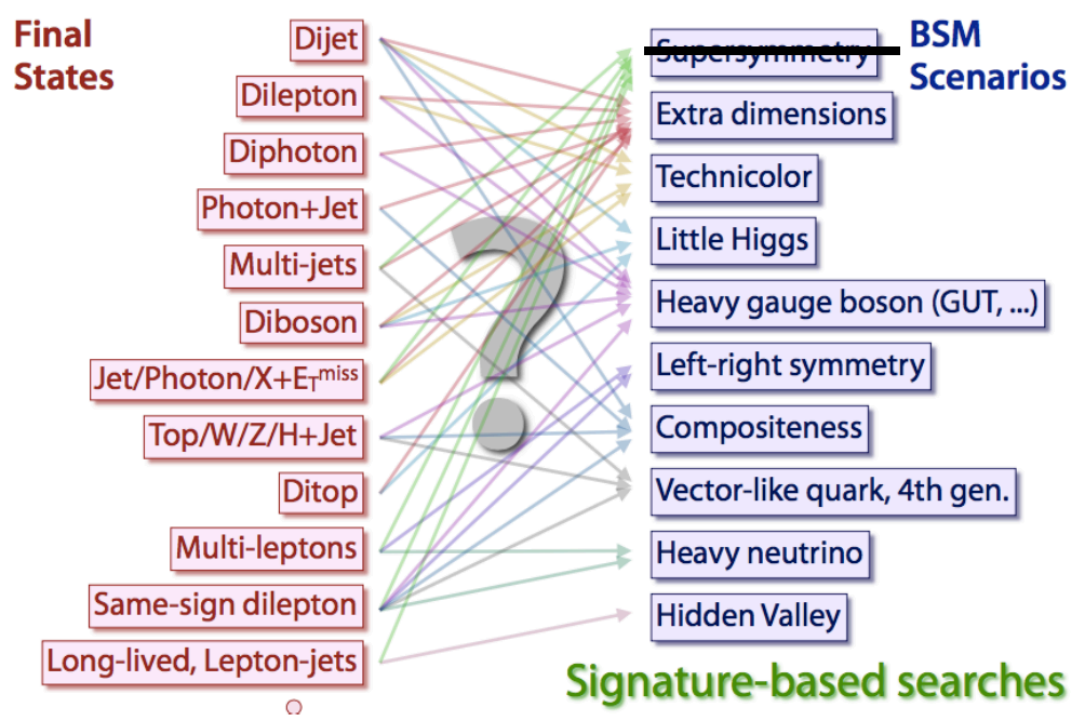
Can forces be unified?

Origin of fermion generation and neutrino mass?



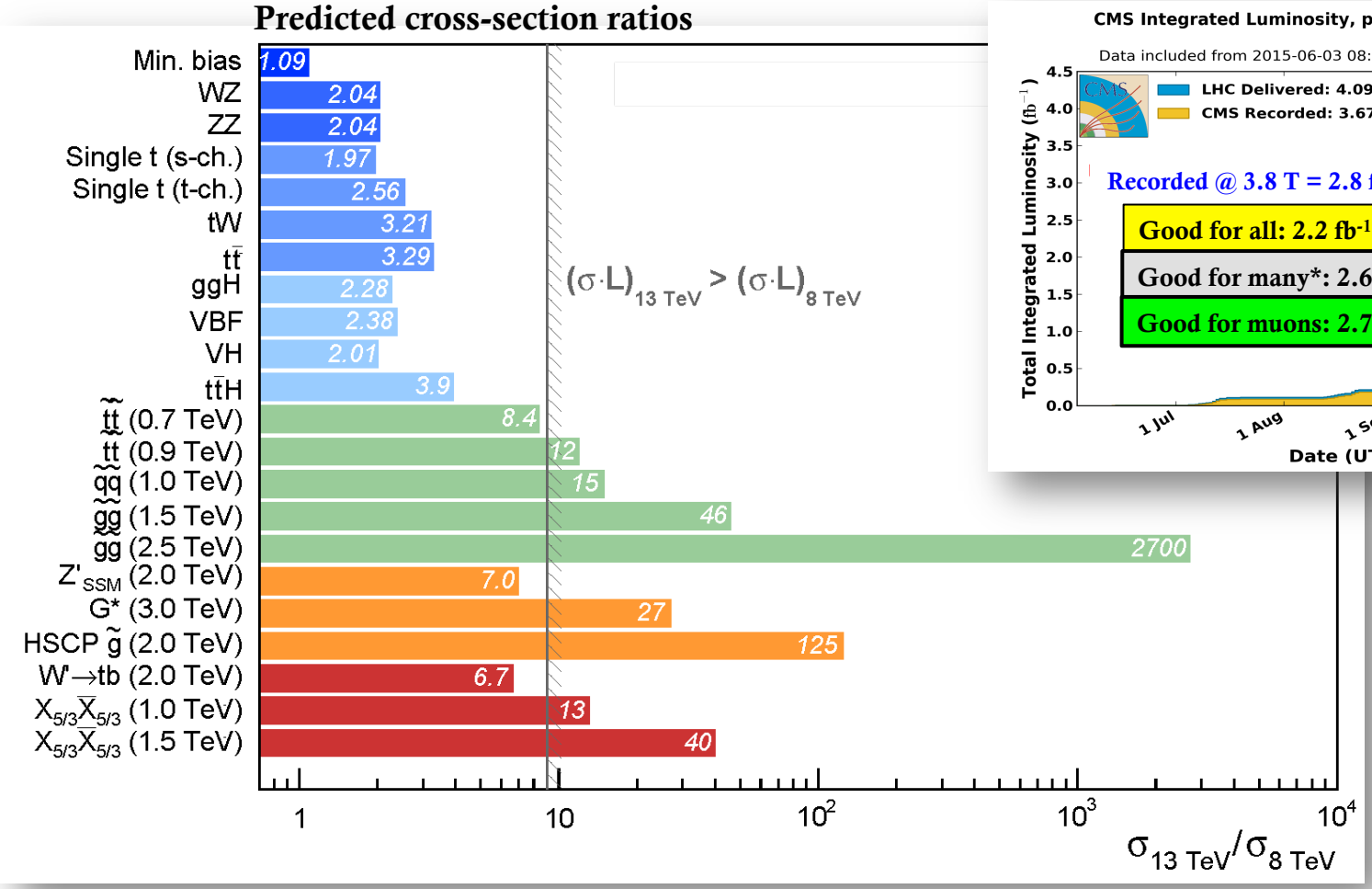
Non-SUSY Searches = ?

- Many interesting theories and interesting experimental signatures are explored at CMS
  - SUSY searches make only sub-set of a quest for new phenomena at CMS
  - EXOTICS and B2G groups at CMS pursue vibrant program for signature-based searches
    - Each signature provides a different window into BSM
    - Sometimes these also could have SUSY signal interpretations



Early Searches with Run 2 data

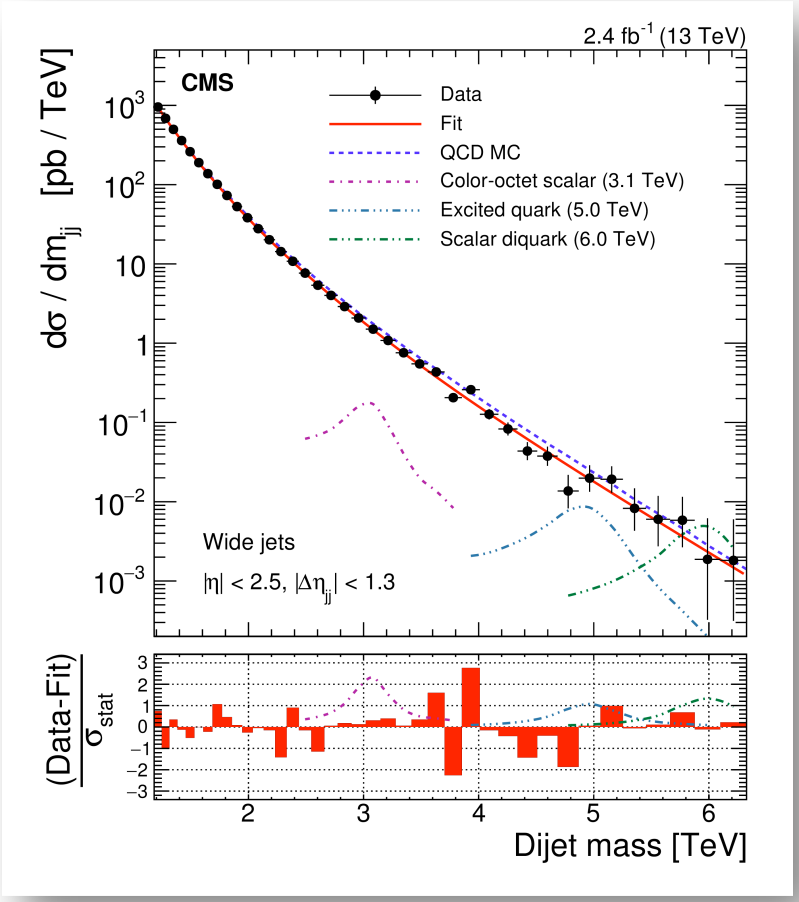
Cross section boost @ 13 TeV enhance discovery potential for massive particles



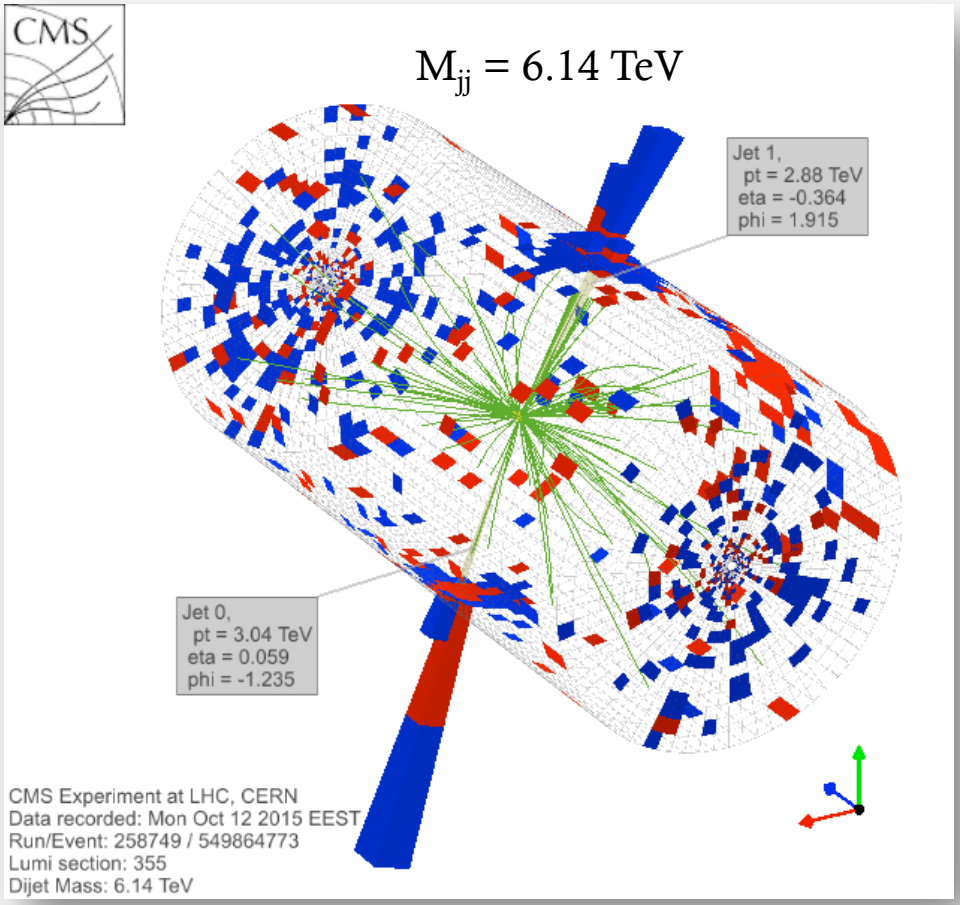
* $|\eta| < 3.0$ for jets and MET

Dijet Resonances

- Looking for a narrow bump above steeply falling M_{jj} spectrum

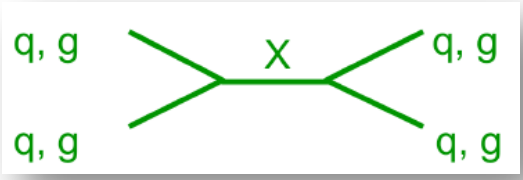


- di-jet event with highest invariant mass

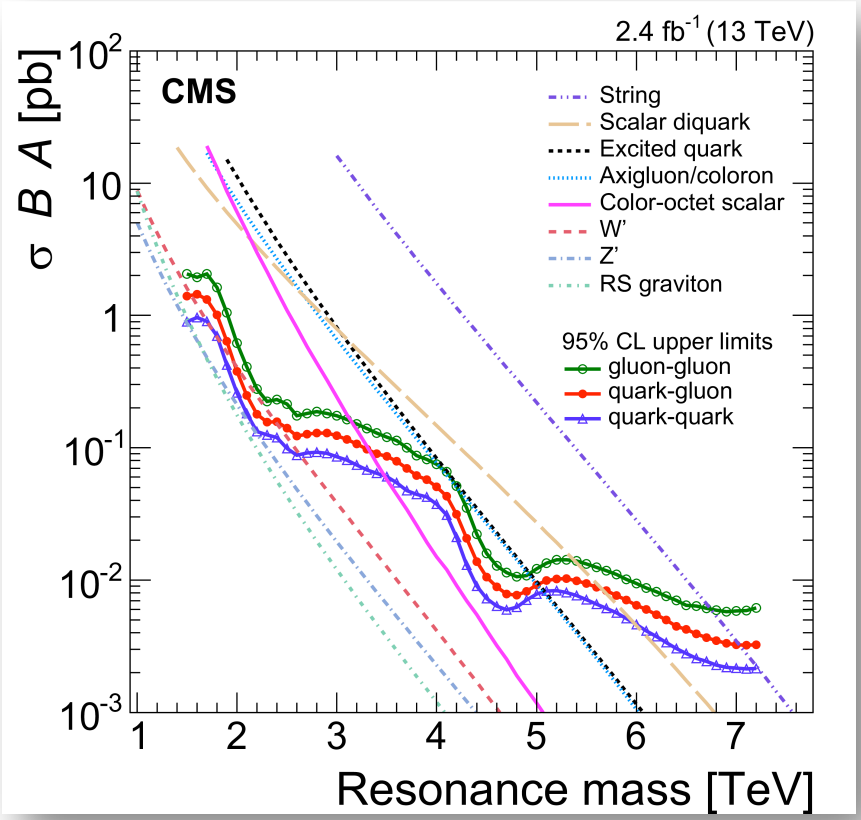


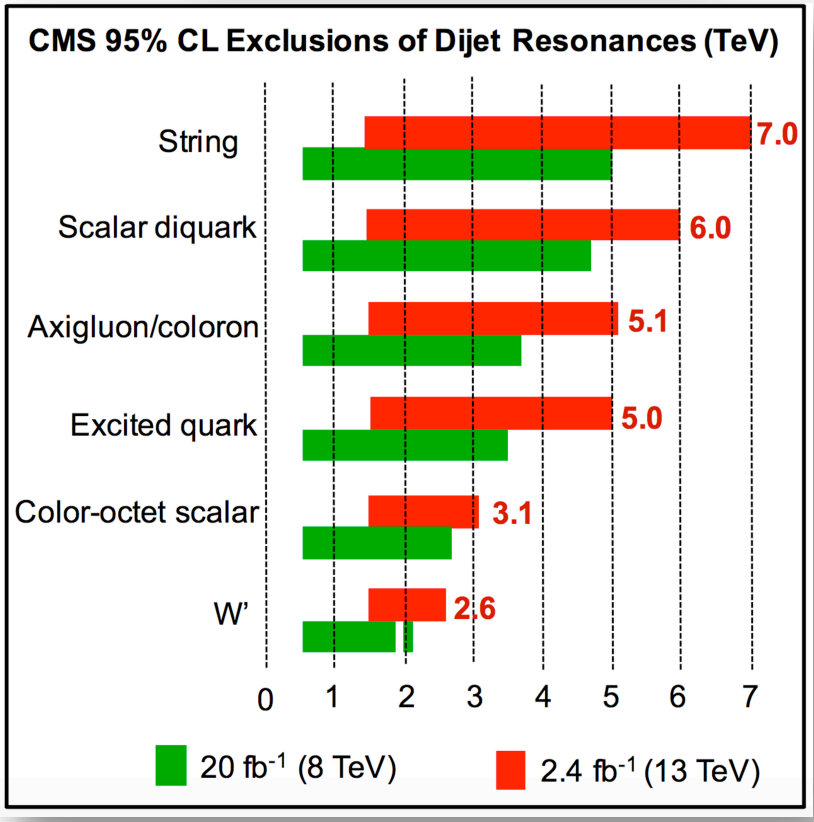
Dijet Resonances

- Probing s-channel production of new resonances



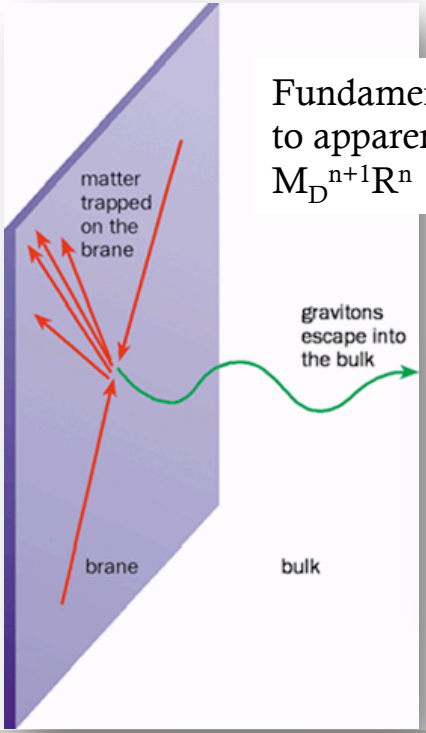
CERN-PH-EP-2015-317
CMS-PAS-EXO-15-001





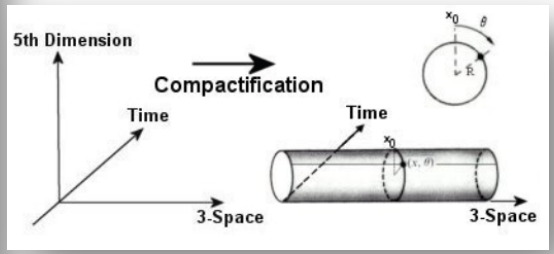
Black Holes

- Hierarchy problem: Why gravity is so weak compared to other forces?
  - Arkani-Hamed, Demopulos, Dvali (ADD) model – Gravity propagates through extra 4+n dim. making it appear weak in 4-dim.



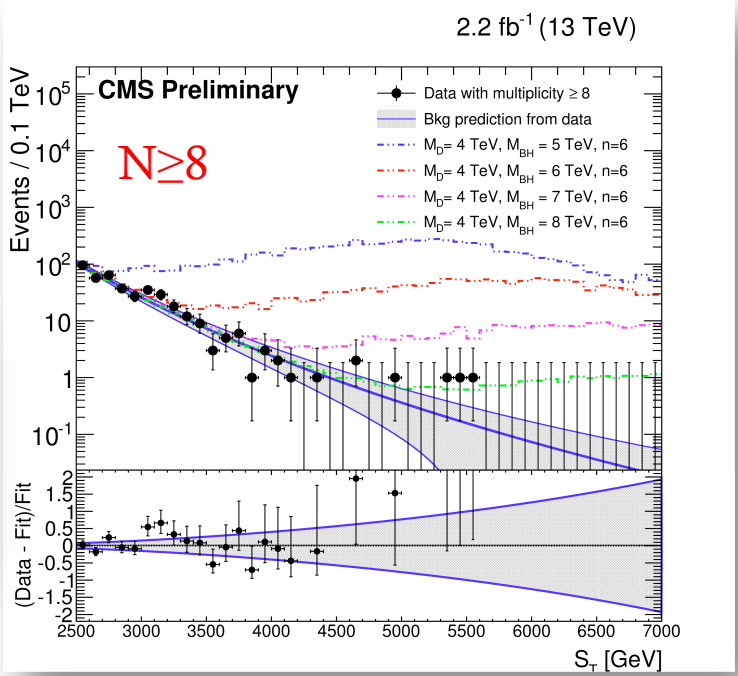
Fundamental Planck (M_D) scale relates to apparent Planck scale (M_{pl}) as $M_{pl} \sim M_D^{n+1}R^n$

Compactification radius constrained to small values, n>1



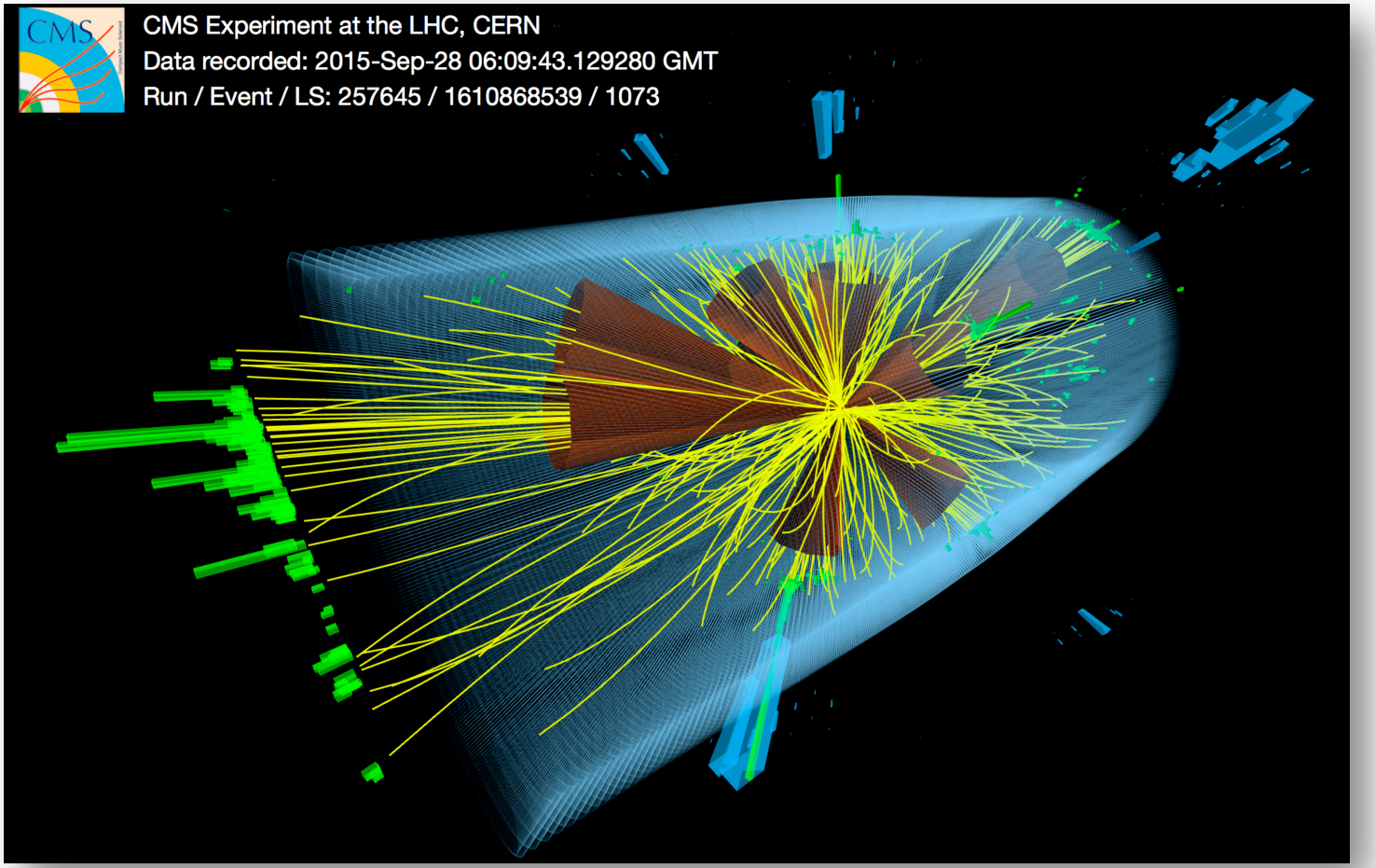
Run 1: M_D > 4 - 9 TeV

- Search for BHs decaying in all possible final states
  - ~75% of all are multijet or dijet events
  - Look for broad excess in S_T distribution
    - Jets, electrons, muons, photons, MET



Black Holes

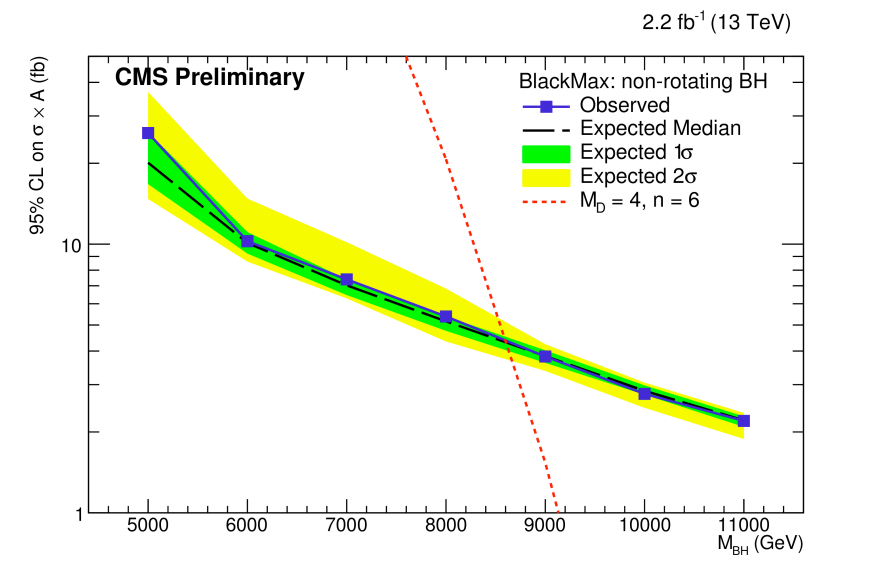
- Display of an event with 12 jets: ST = 5.48 TeV, MET = 120 GeV

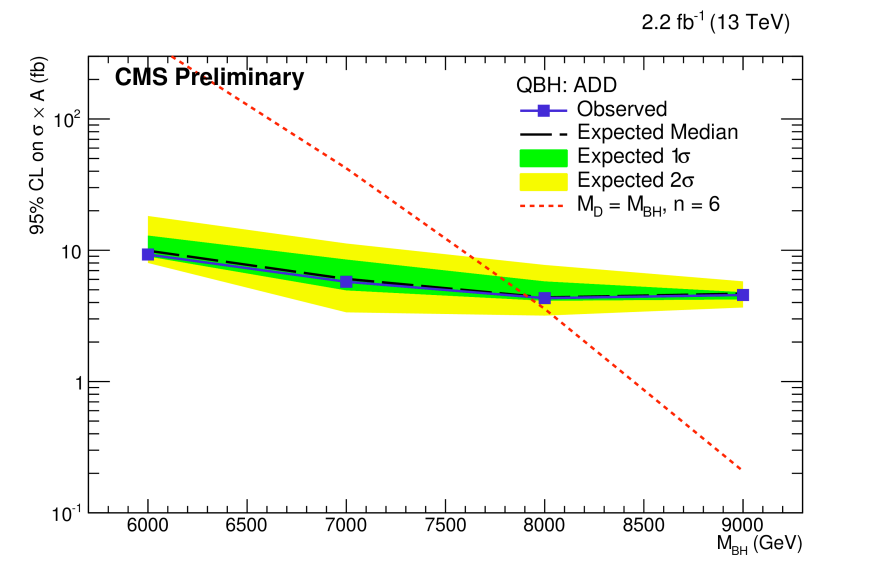


Black Holes

- Semiclassical black holes – $M_{BH} >> M_D$
  - M_D = 4 TeV, n = 6
  - M_{BH} > 8.7 TeV (Obs.)
- Quantum black holes – $M_{BH} >\sim M_D$
  - n = 6
  - M_{BH} > 8 TeV (Obs.)

CMS-PAS-EXO-15-007





Run 1: 4.3 – 6.2 TeV

More on dijet signatures

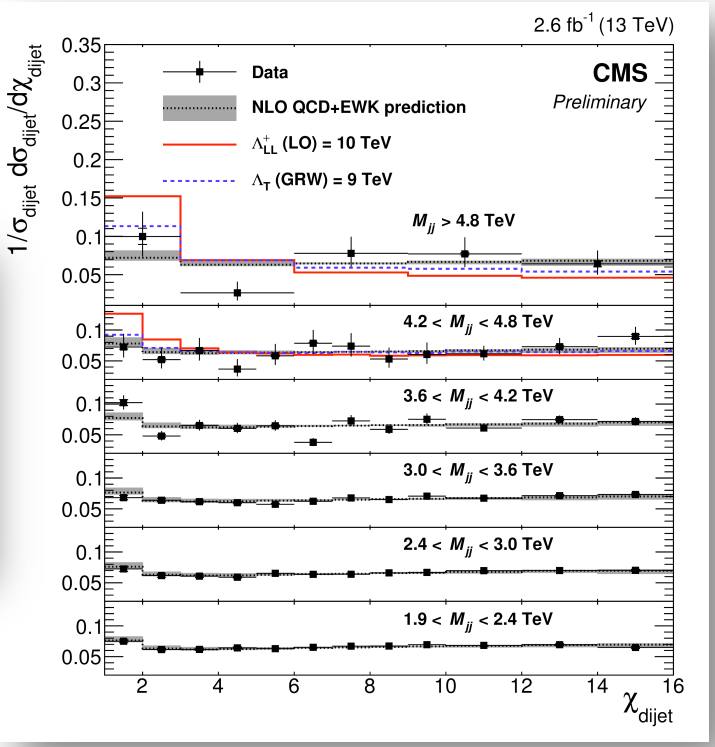
- Angular distribution of dijets allow to probe quark substructure and additional spatial dimensions
  - $\chi_{dijet} = \exp(|y_1 - y_2|)$, where $y = 1/2 \ln[(E+p_z)/(E-p_z)]$

CMS-PAS-EXO-15-009

Limits set on Λ CI scale and Λ_T and M_S ADD parameters; $M_S \sim M_D$

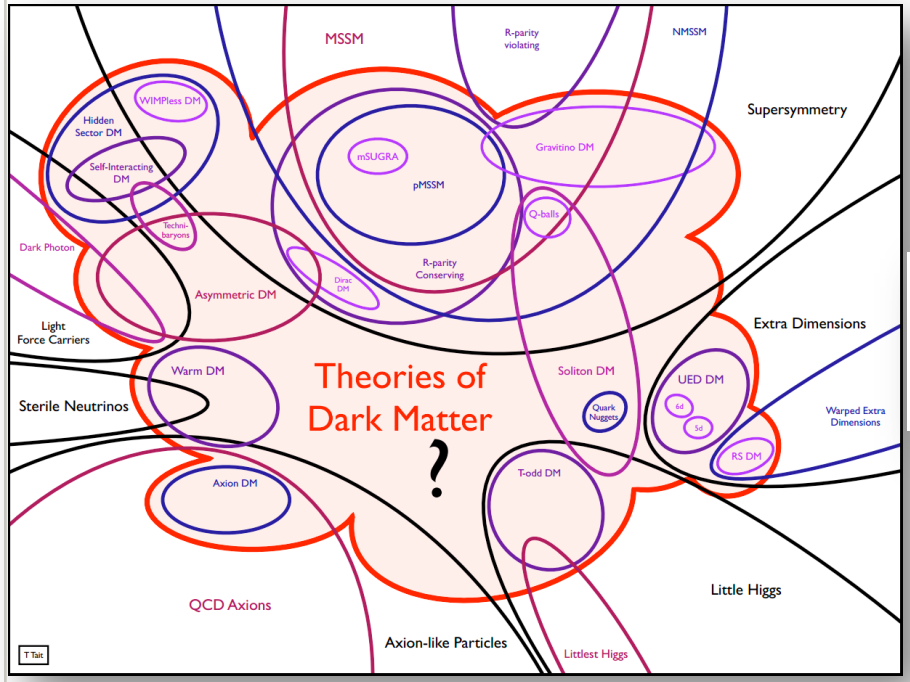
Compositeness model	Observed lower limit (TeV)	Expected lower limit (TeV)
$\Lambda^{+}_{LL/RR}$ (LO)	12.1	12.0 ± 1.1
$\Lambda^{-}_{LL/RR}$ (LO)	16.3	15.3 ± 2.4
ADD Λ_T (GRW)	9.1	9.0 ± 0.7
ADD M_S (HLZ) $n_{ED} = 2$	9.7	9.6 ± 0.7
ADD M_S (HLZ) $n_{ED} = 3$	10.8	10.7 ± 0.8
ADD M_S (HLZ) $n_{ED} = 4$	9.2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

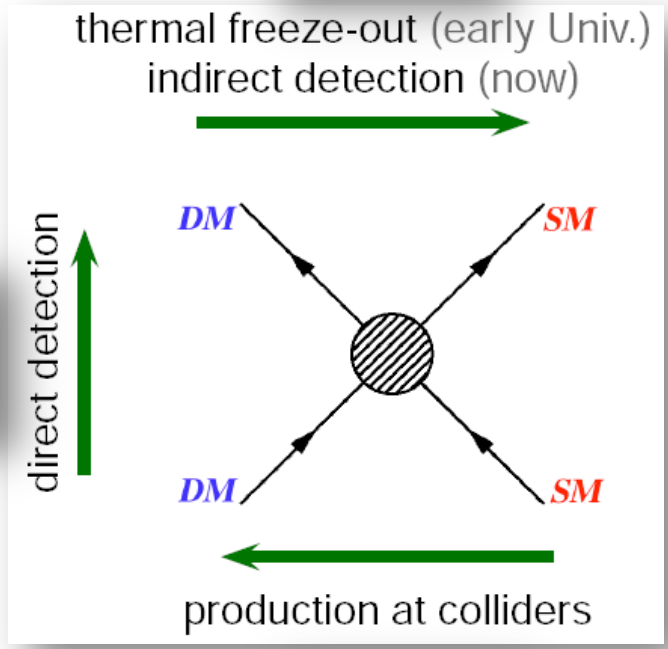
Run 1: $M_D > 4$ - 9 TeV



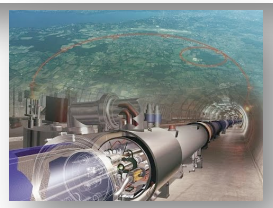
Dark Matter

- We know it is there…



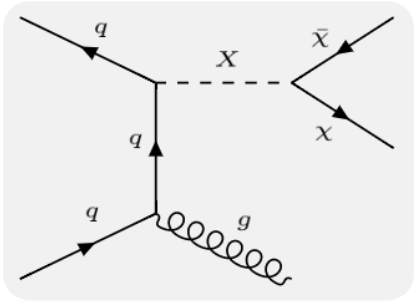


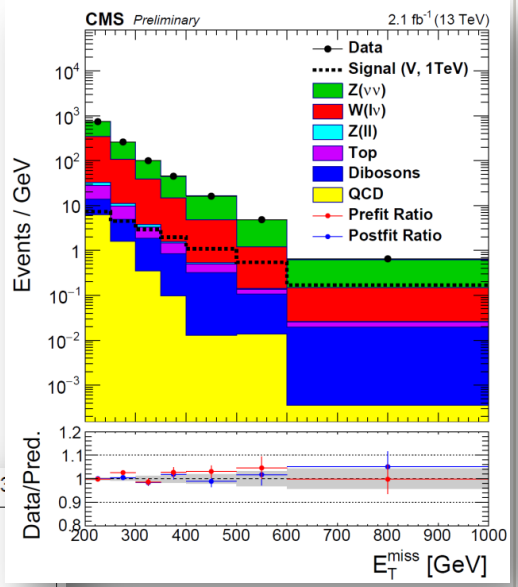
LHC can complement other detection methods

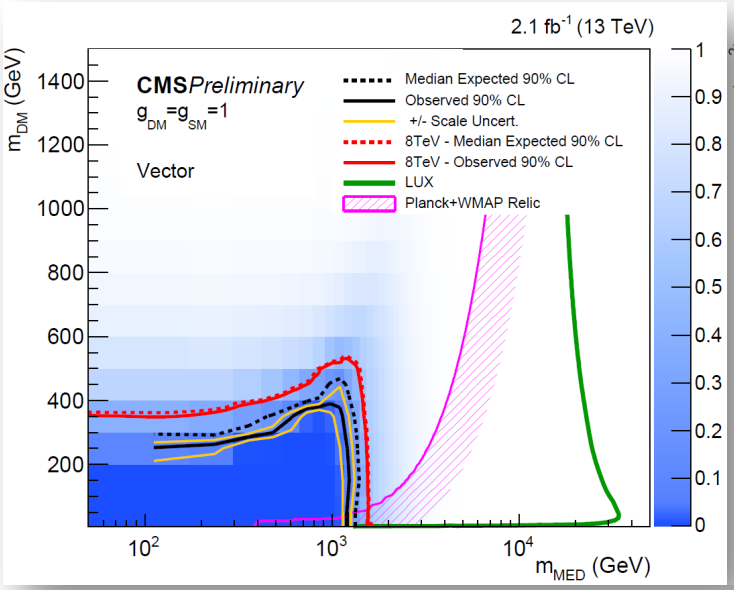


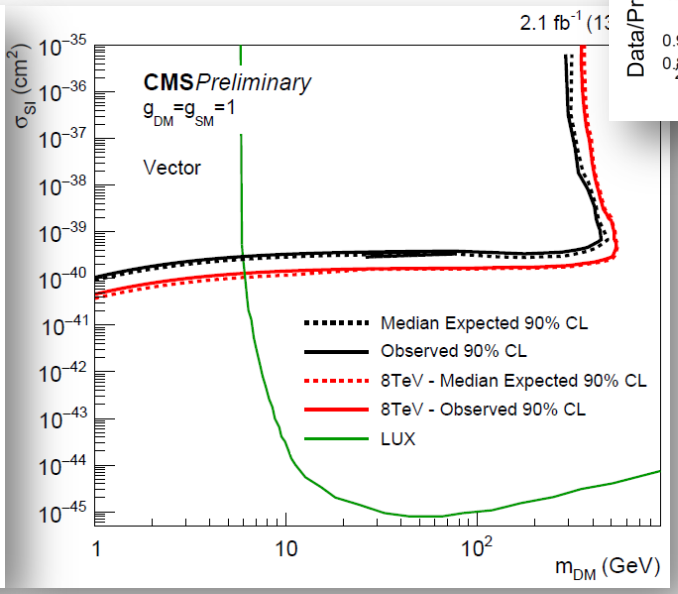
Dark Matter

- Search in final state with jet(s) and large transverse energy
  - Results interpreted in a scenario with a vector mediator
  - Current limits comparable to Run 1 exclusions







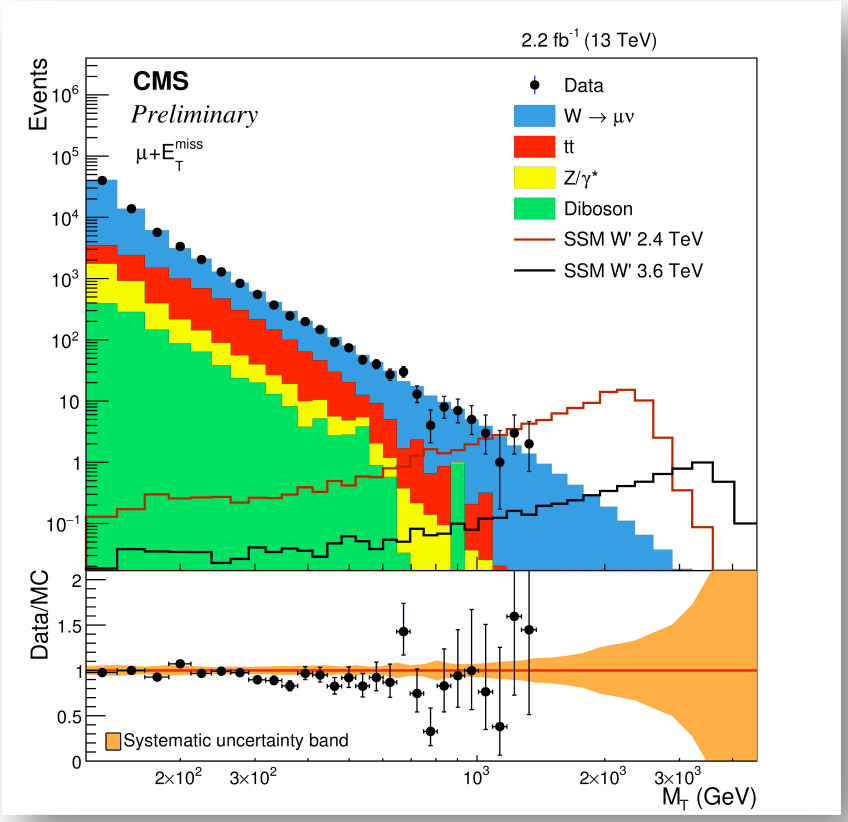


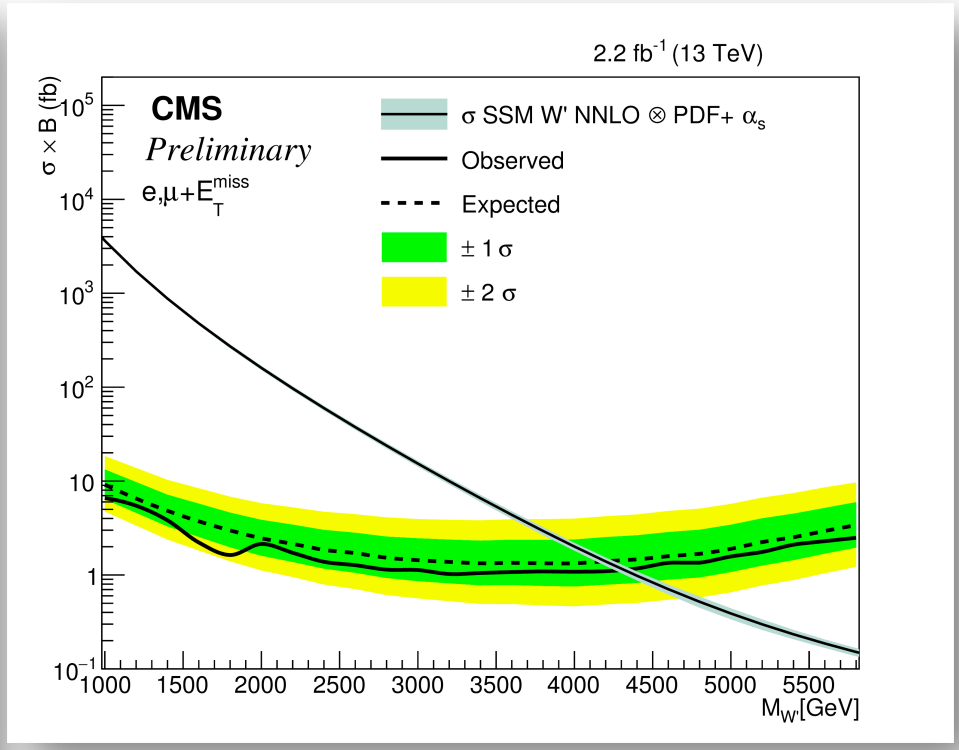
CMS-PAS-EXO-15-003

W'-> l+ν

- Search for SSM W' boson
  - Assuming SM-like couplings, decay to SM bosons suppressed, no interference with W boson
  - Electron/muon + large missing ET

CMS-PAS-EXO-15-006

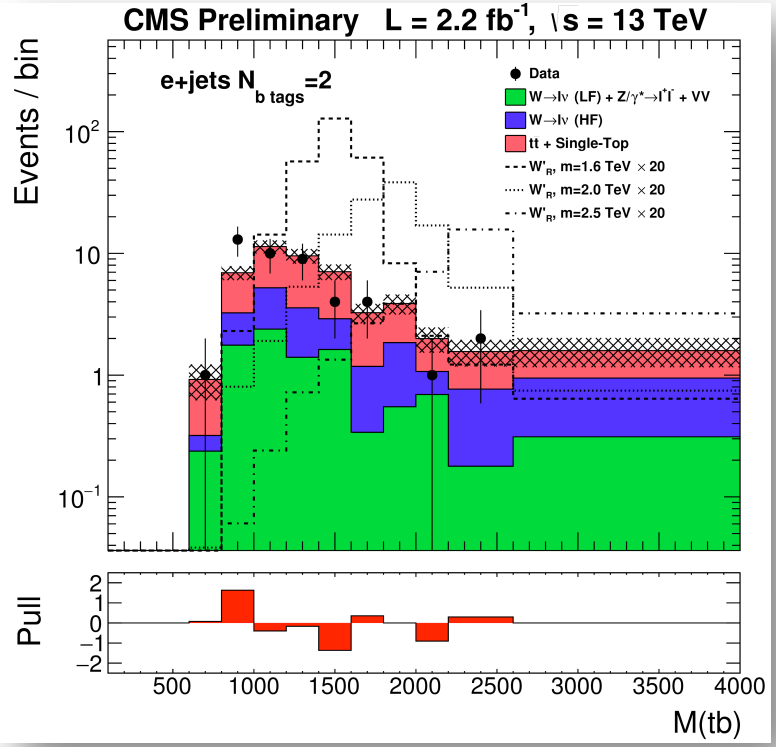




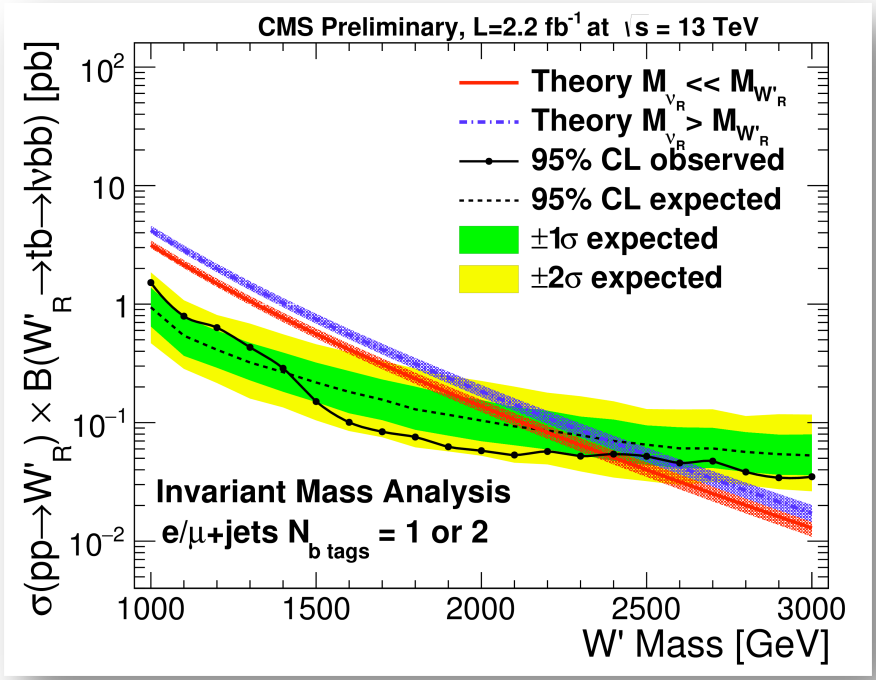
Run 1: ~3.3 TeV

W'->tb

- If W' is massive enough it decays to pair of top and bottom quarks
  - In some models coupling to third generation could be enhanced
  - Final states with single electron or muon and jets are considered: W'->bb+e/μ+MET
  - W' invariant mass is reconstructed by constraining neutrino p_z from W mass

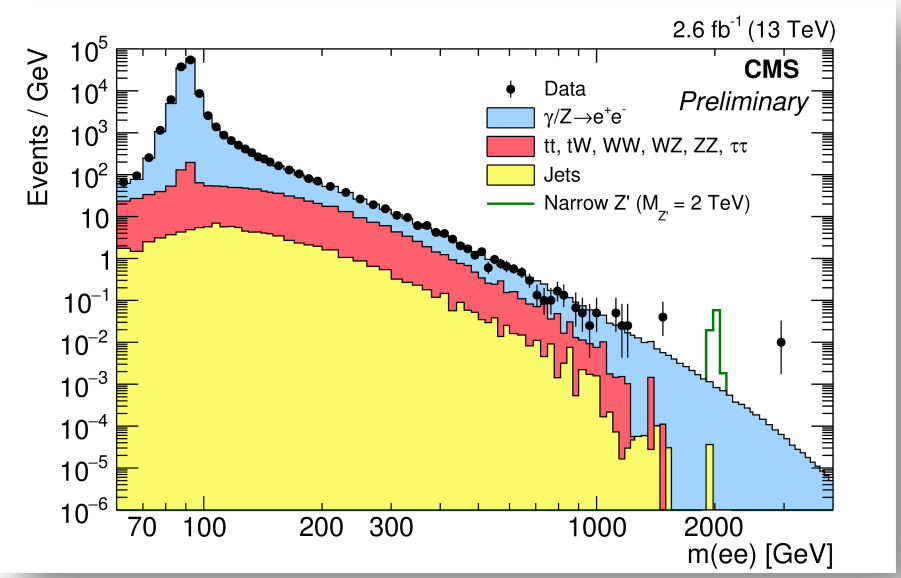


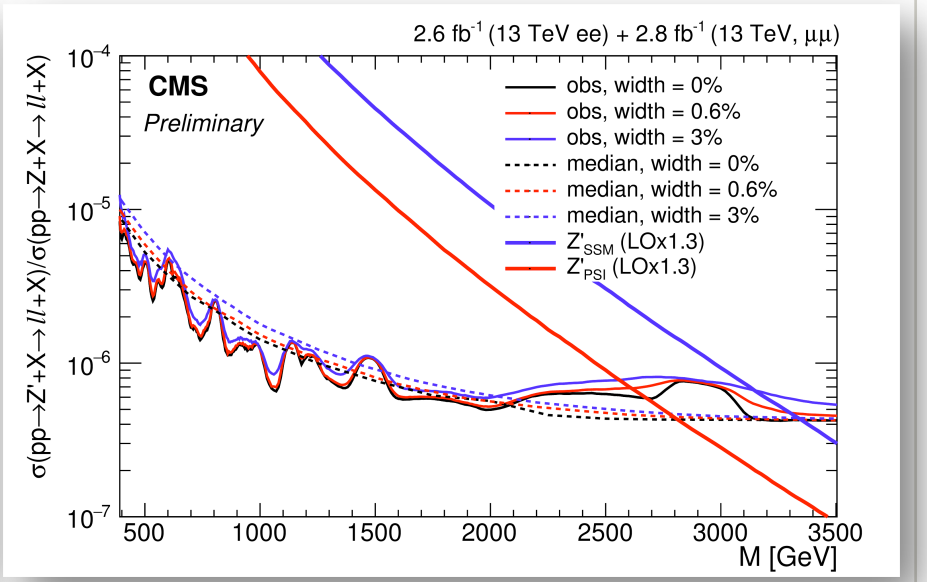
CMS-PAS-B2G-15-004



Dilepton Resonance

- Search for excess in dielectron/dimuon mass spectrum above very small background





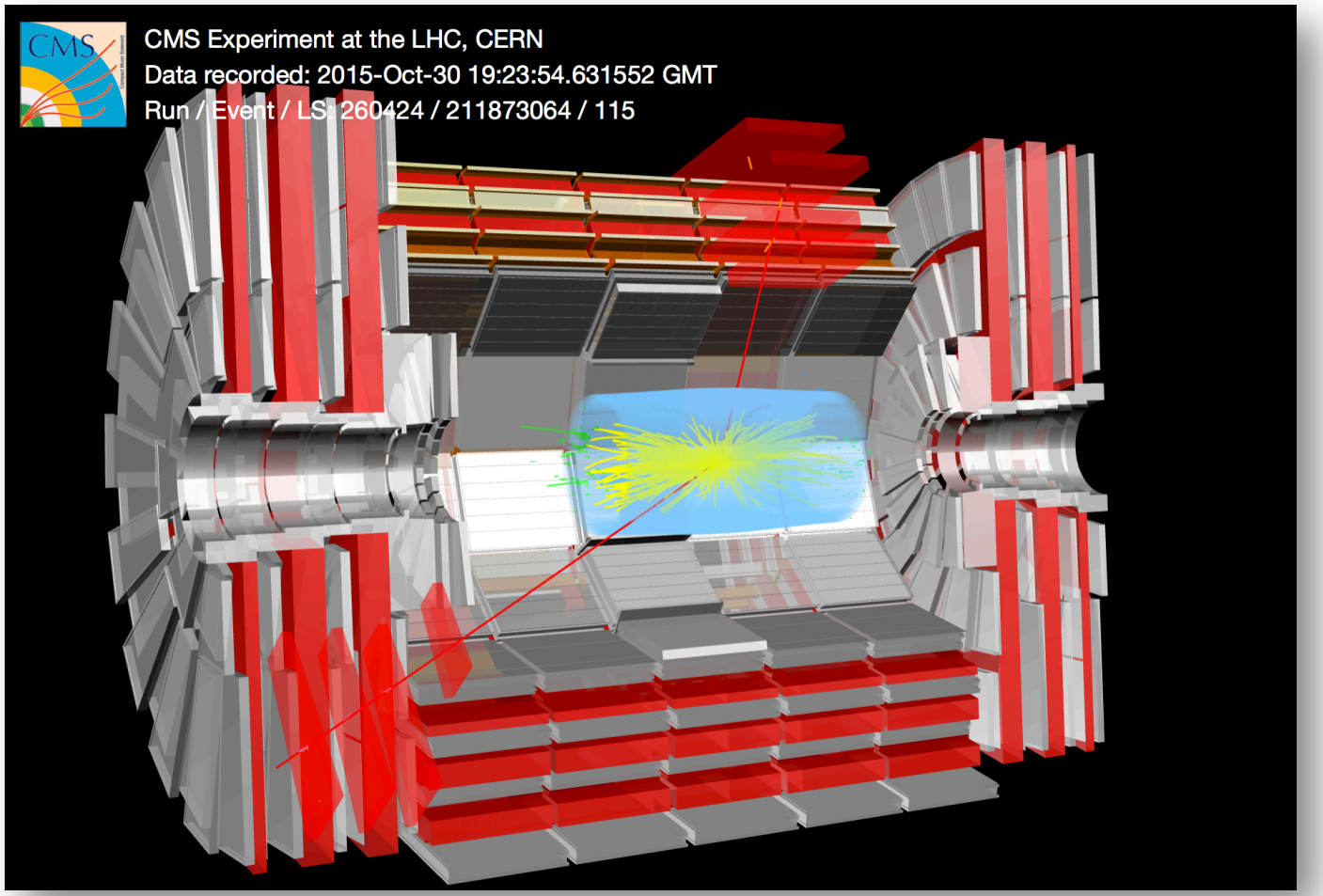
Run 1:
Z'_{SSM} ~2.9 TeV
Z'_{φ} ~2.5 TeV

channel	Z'_{ψ}		Z'_{SSM}	
	obs (TeV)	expected (TeV)	obs (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

CMS-PAS-EXO-15-005

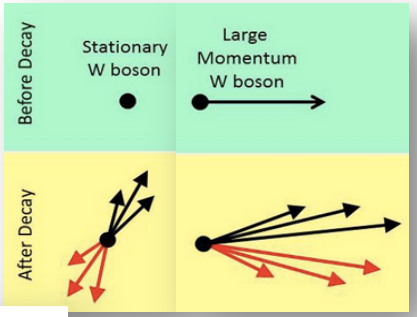
Dilepton Resonance

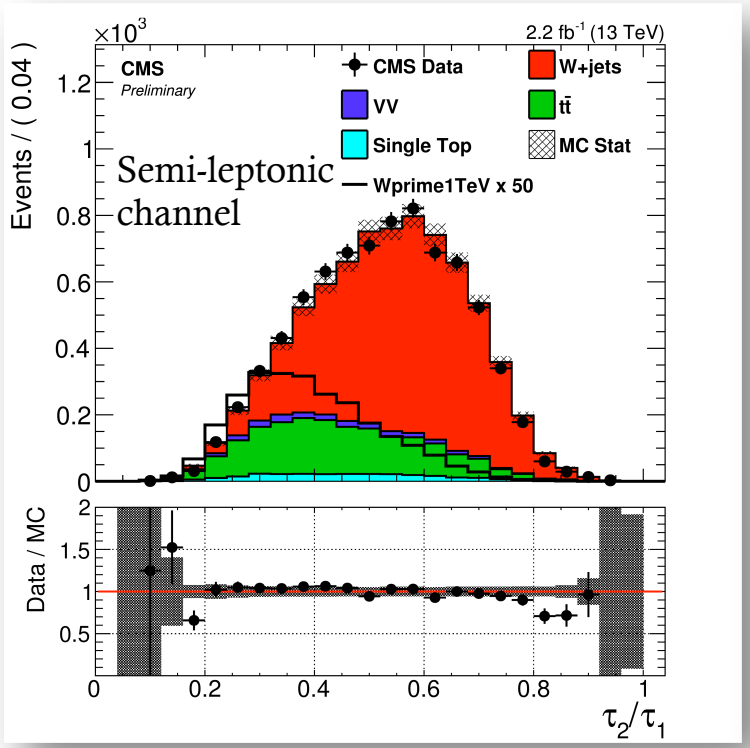
- Highest mass dimuon event: M = 2.4 TeV

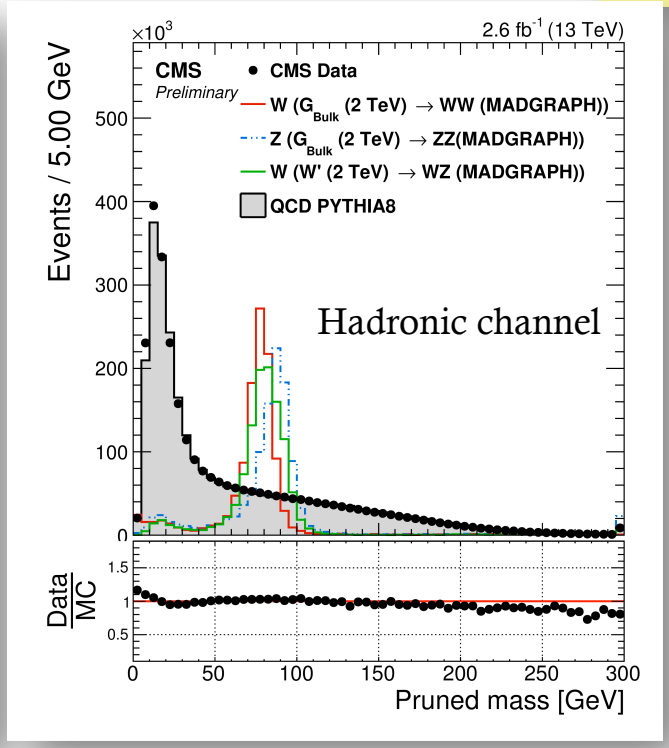


Diboson Resonances

- Vector boson pair production can probe RS extra dimensions or heavy vector triplet (HTV) models
  - Jet subsctructure is used to reconstruct boosted objects



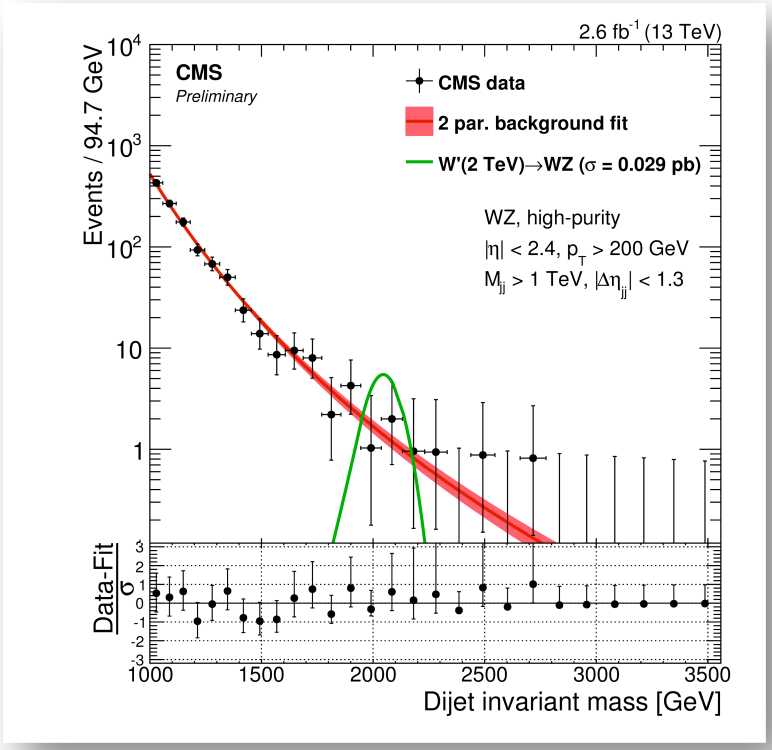




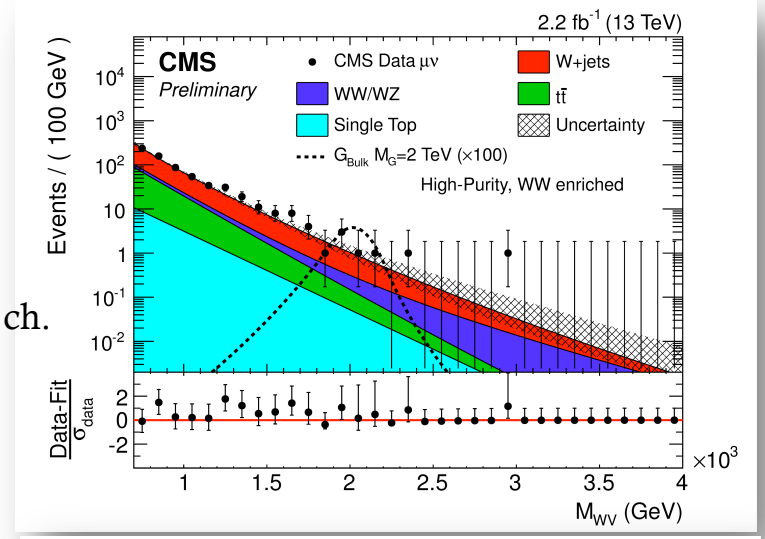
See more in talk by J. Dolen on Friday

Diboson Resonances

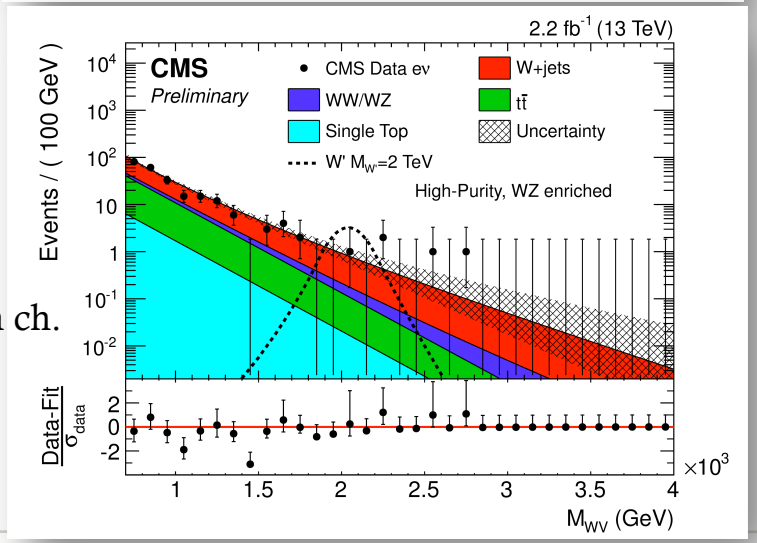
- Resonant structure on top of SM bkgs
  - X->VV-> JJ and X->WV-> lnJ, V=W or Z
  - Separate low and high purity regions
  - WW, WZ, ZZ treated as separate categories



Muon ch.



Electron ch.

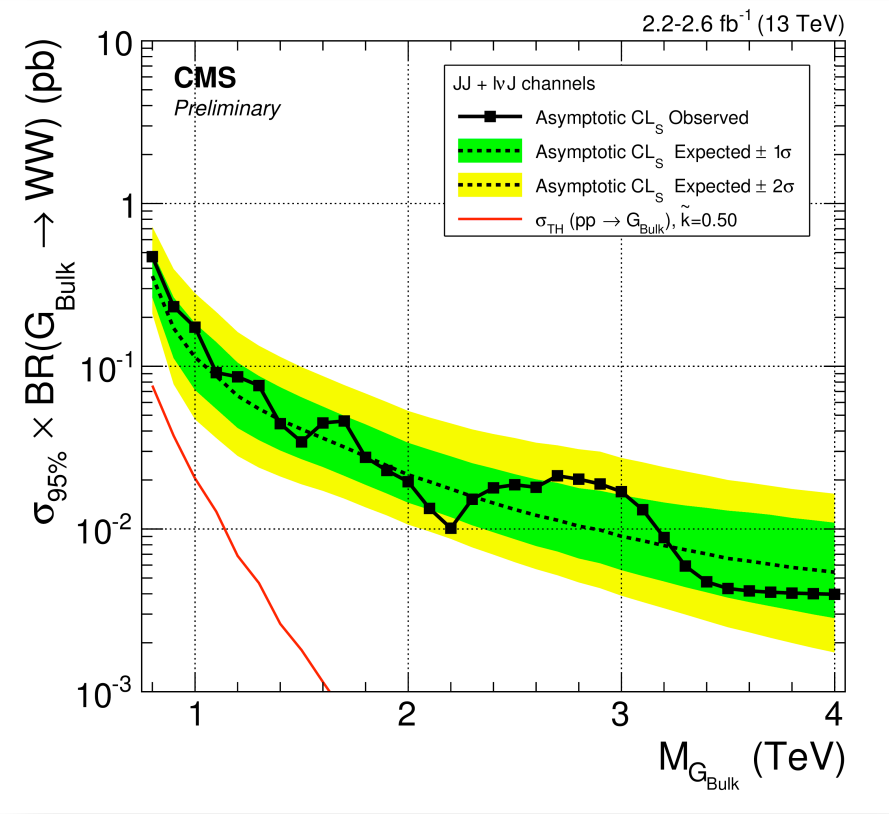


Diboson Resonances

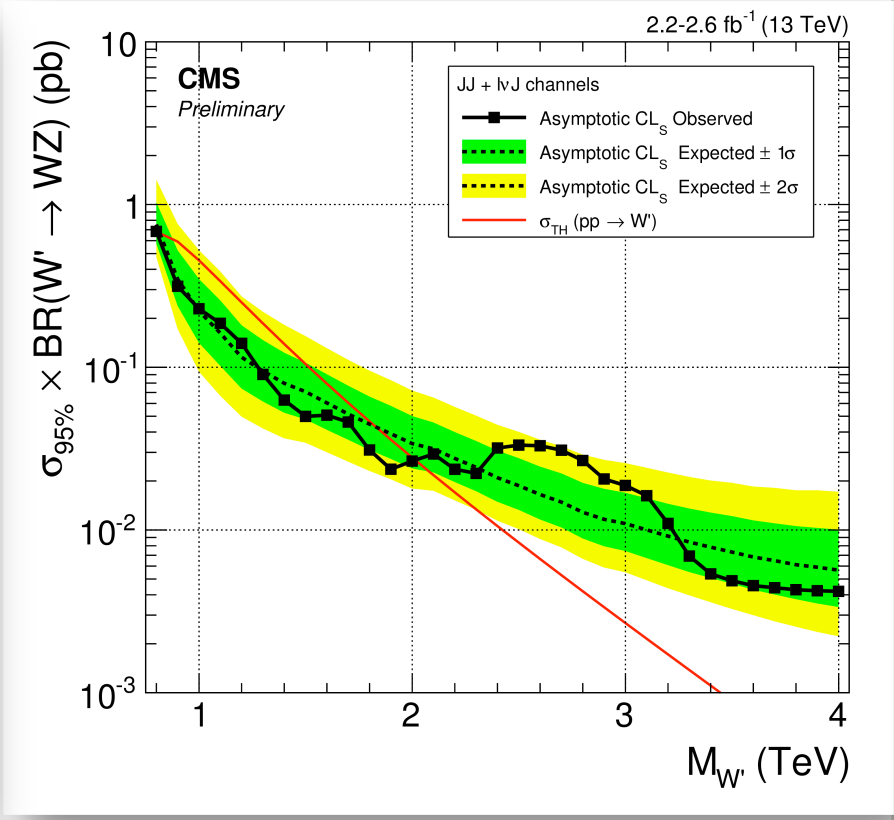
- VV and WZ channels can be combined

CMS-PAS-EXO-15-002

Limit on G_{bulk}

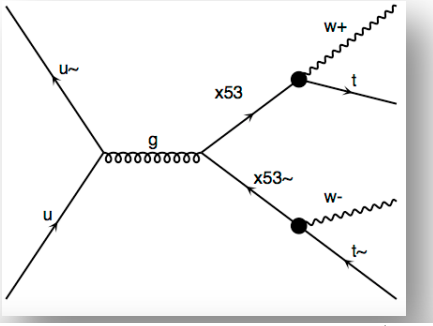


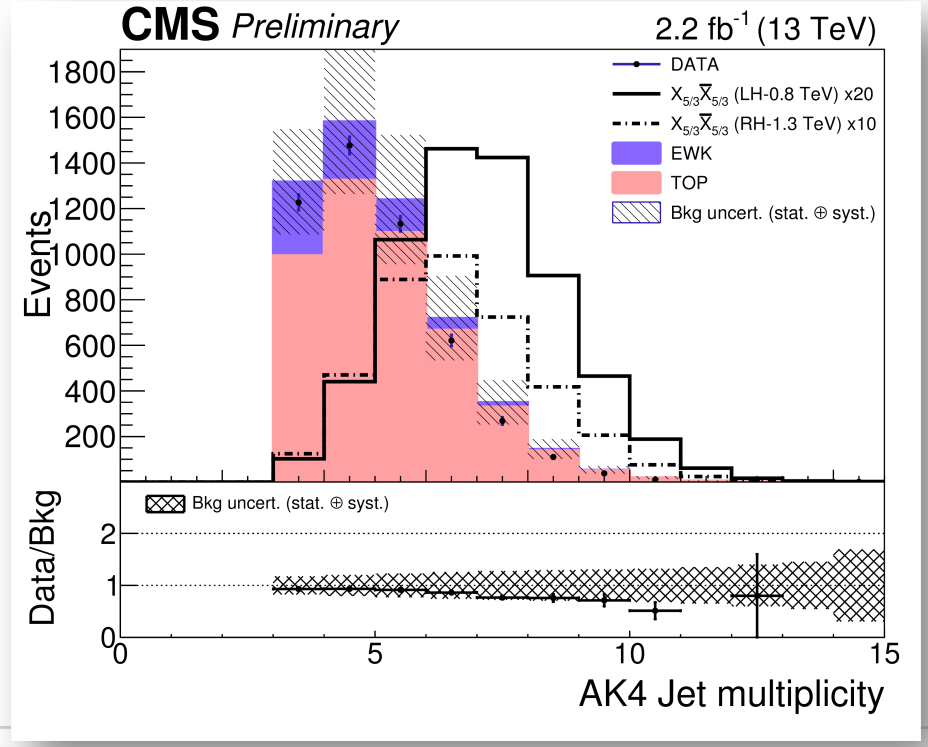
Limit on HVT

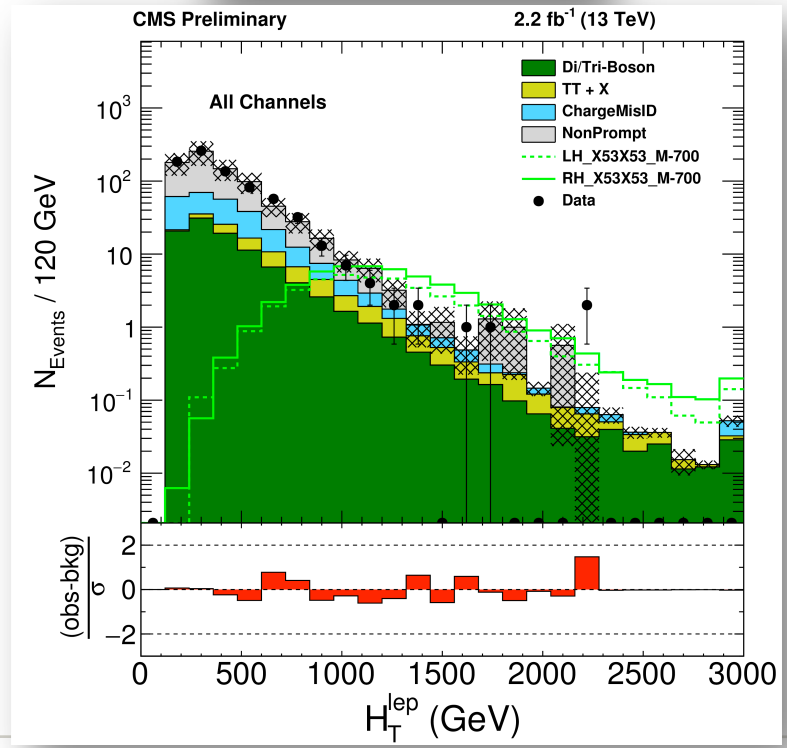


Top Quark Partners

- Heavy fermions with q=5e/3 predicted by composite Higgs models to address hierarchy problem
  - Consistent with the Higgs boson observation
  - High multiplicity events with high H_T
  - Consider dilepton and lepton+jets channels

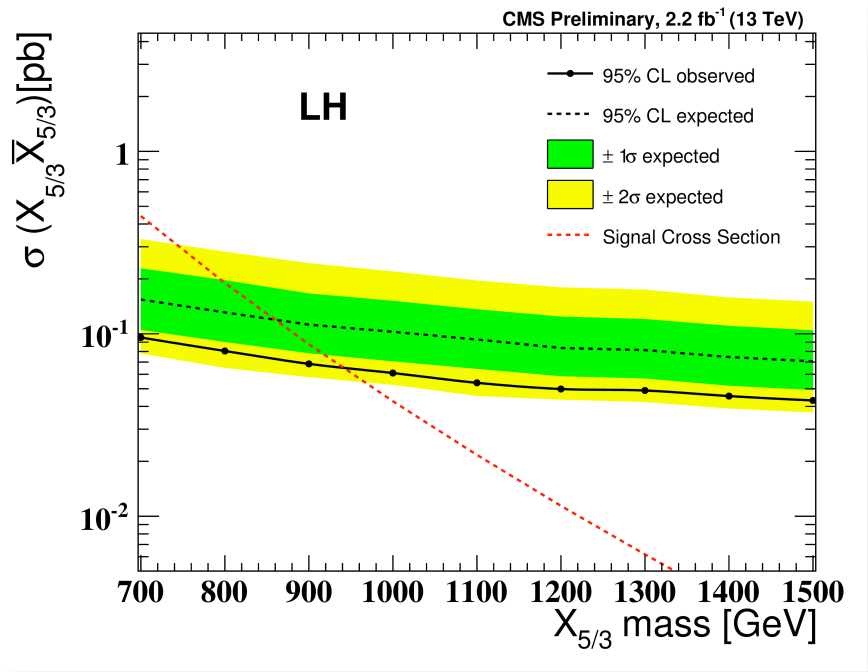


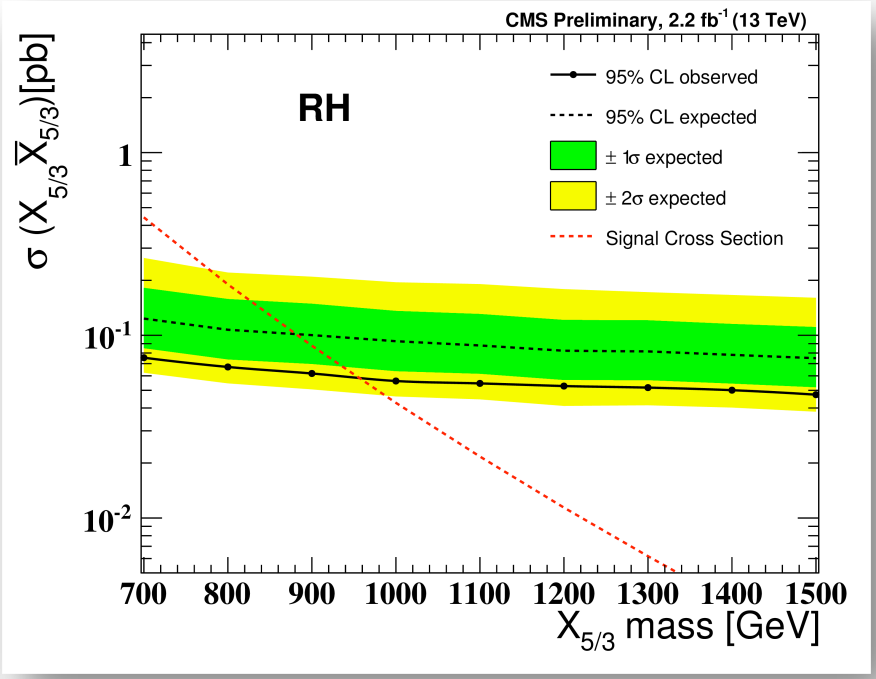




Top Quark Partners

- Different channels and categories are combined to set limits on left-handed and right-handed fermion hypotheses



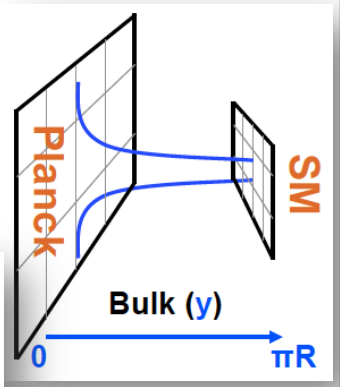


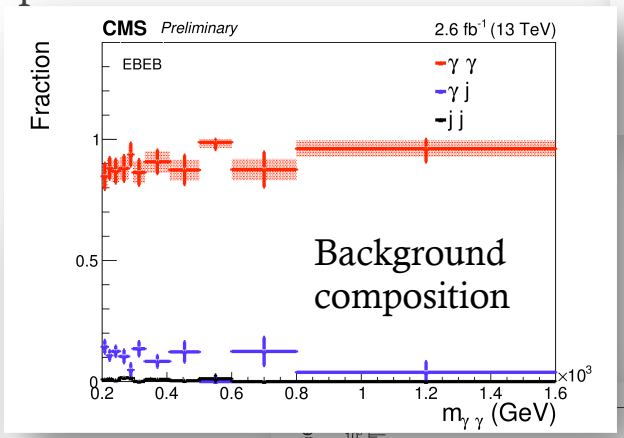
Run 1: ~800 GeV

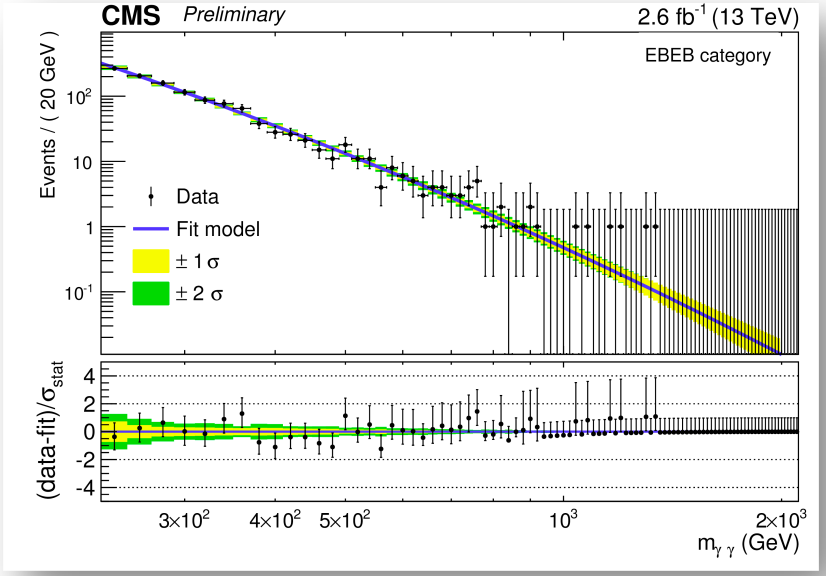
CMS-PAS-B2G-15-006

Diphoton Resonances

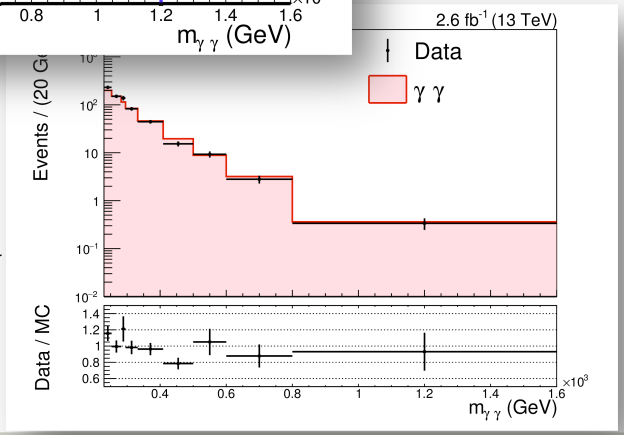
- Back to Extra Dimension models – Already talked about ADD
  - In Randall-Sundrum (RS) model one additional extra dimension joining two branes – Gravity is suppressed by wrap factor $\Lambda \sim M_{pl} e^{-kR\pi}$
  - Search for a resonance decaying to pair of photons
    - Extra dim. curvature scale (κ) 0.01–0.2
    - Graviton 0.5 – 4.5 TeV masses







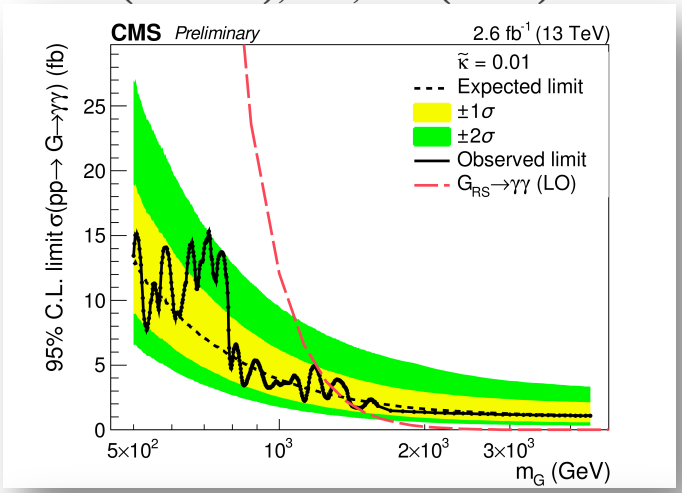
Major background

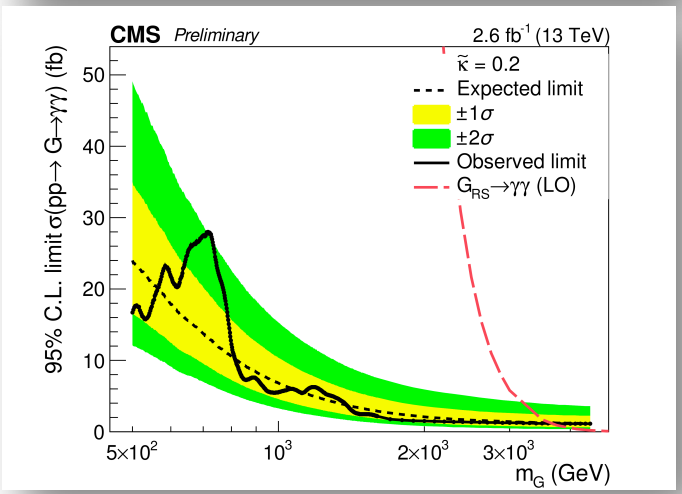


Diphoton Resonances

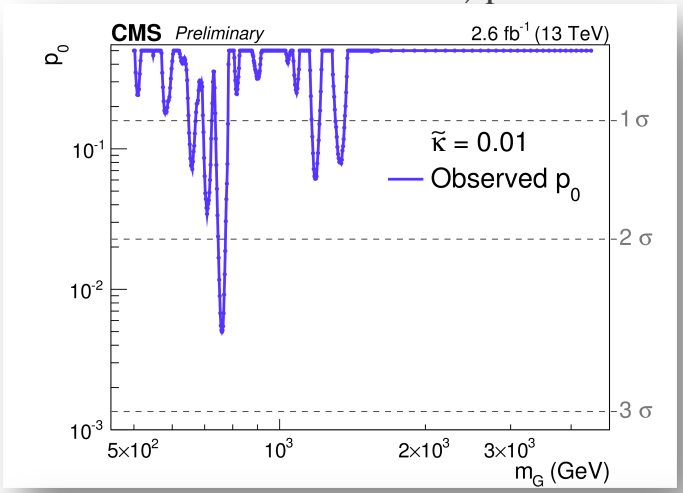
- κ = 0.01 (narrow), 0.1, 0.2 (wide)

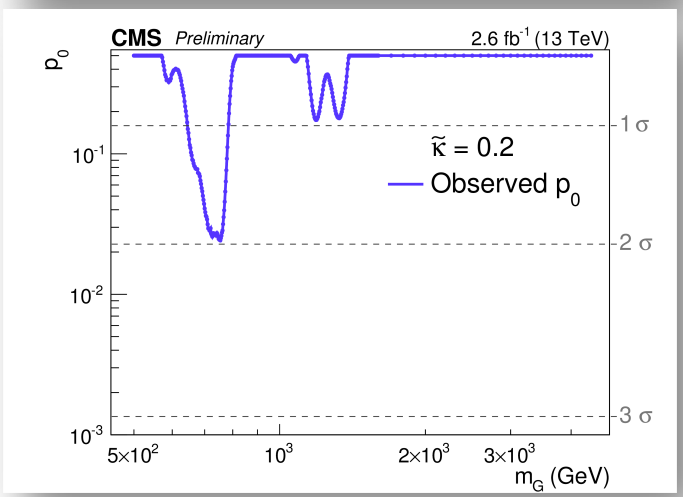
CMS-PAS-B2G-15-004





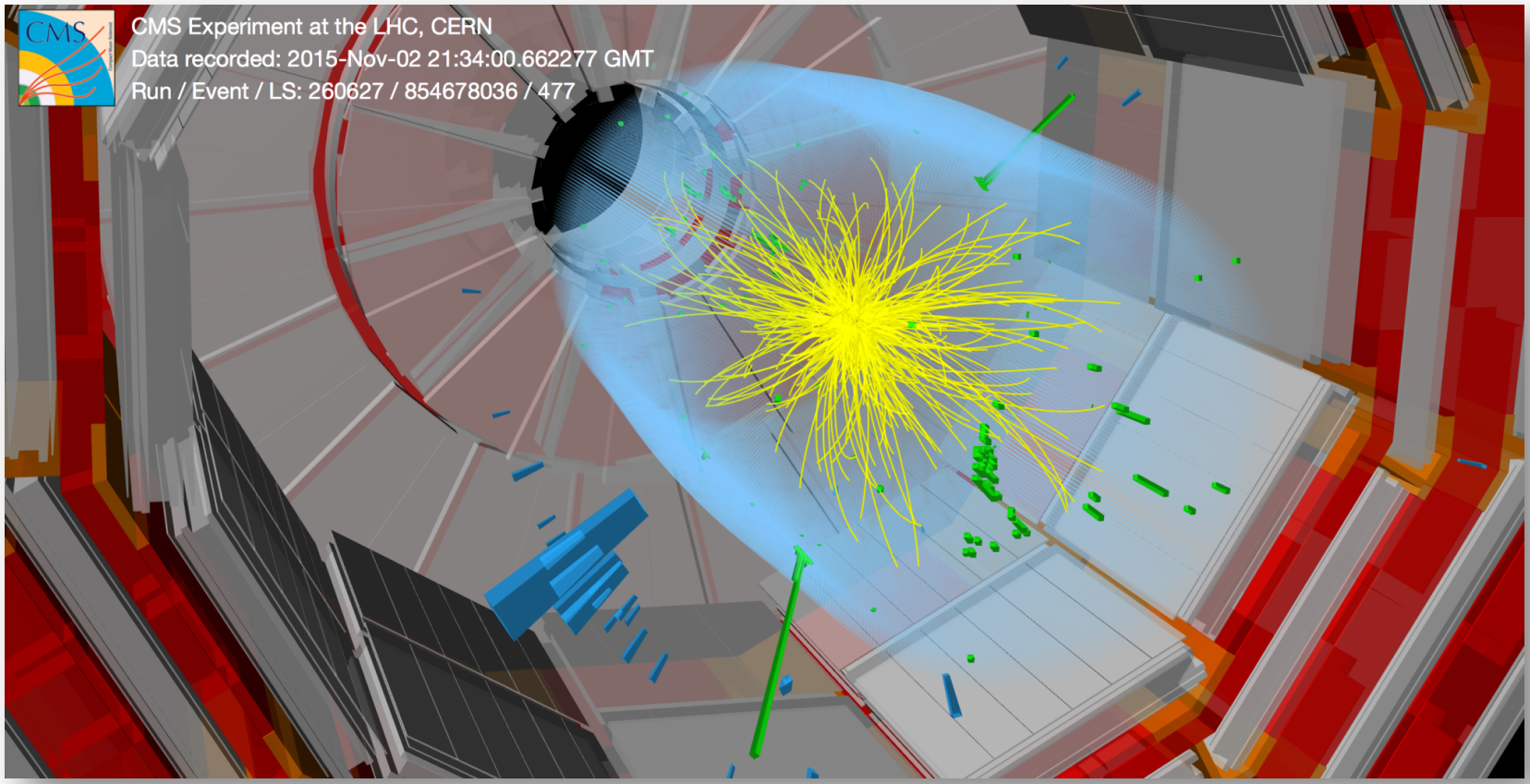
- With LLE and narrow wid., p-value < 1.2 σ





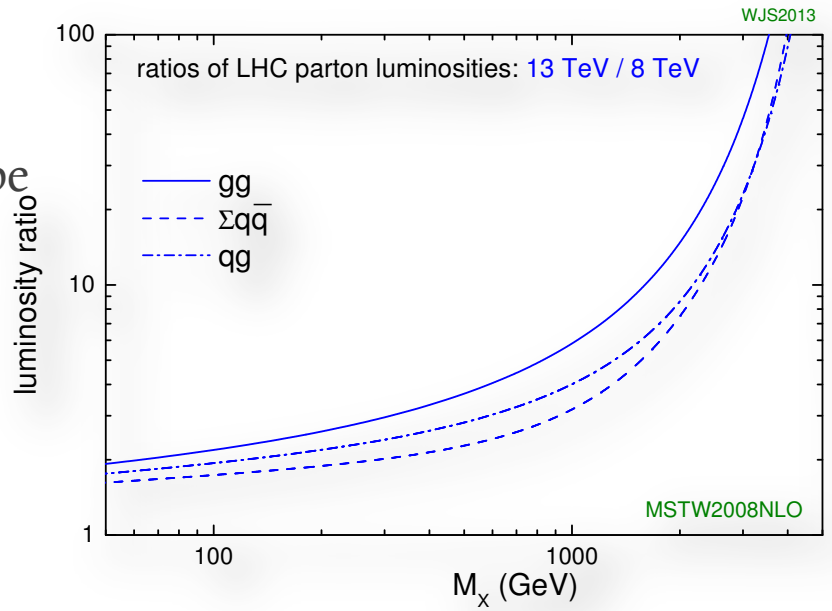
Diphoton Resonance

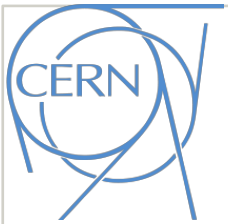
- Diphoton event with $M_{\gamma\gamma}$ = 745 GeV

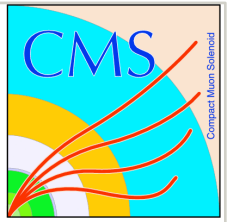


Summary

- A successful year at CMS
  - The first long shutdown was completed
  - ~90% of 13 TeV data was recorded by CMS (~75% with magnetic field)
  - Various improvements in reconstruction and analysis techniques
- Higher energy boosts sensitivity to new physics searches
  - Already 2.2 – 2.7 fb^{-1} data allows to probe new phase space of BSM models
  - Small but exciting excess in diphoton final state is seen
- These results are only overture to long quest for all possible BSM signatures based on more Run 2 data!



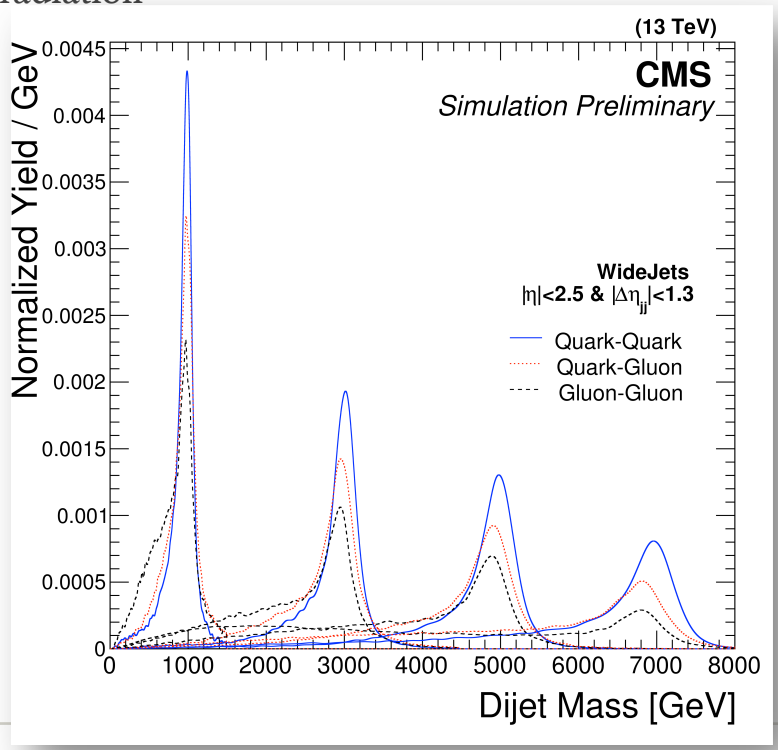




Additional Material

Dijet Resonances

- Narrow gg/gq/qq resonance
  - Trigger: HT > 800 GeV or p_T^{jet} > 500 GeV – 100% efficient for m_{jj} > 1.2 TeV
  - $p_T^{jet} > 30$ GeV and $|\eta^{jet}| < 2.5$
  - Two wide jets are constructed to reduce sensitivity to gluon radiation
- Background from t-channel dijet production is reduced by $|\Delta\eta^{jet}| < 1.3$
  - Pythia8(205), tune CUETP8M1, NNPDF2.3LO
- Separate limit is derived for each resonance model due to dependence on mass shape



CERN-PH-EP-2015-317
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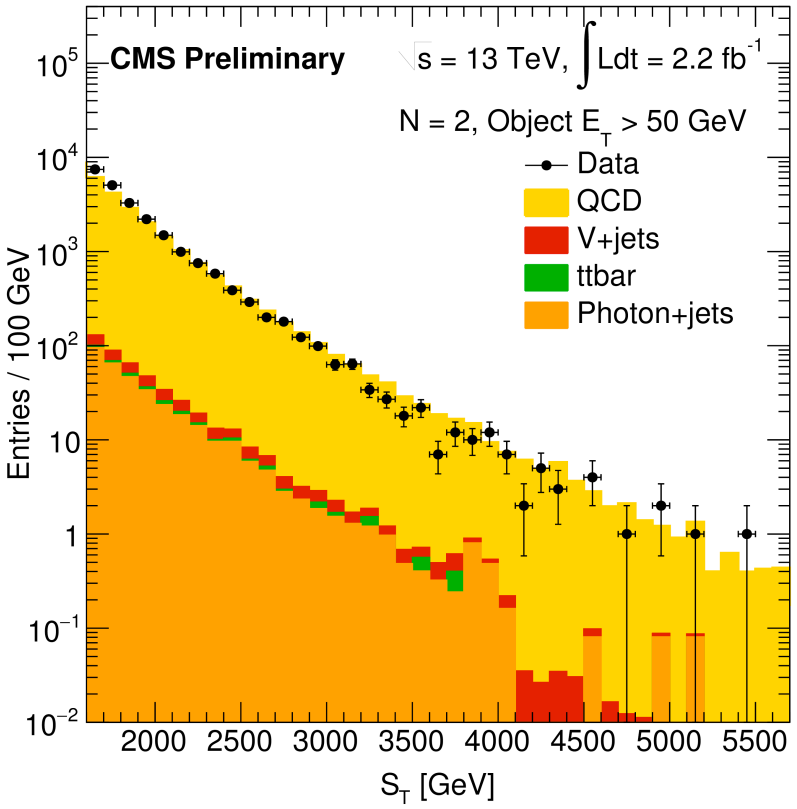
Black Holes

- Inclusive search with all types of objects in final state
  - Less sensitive to evaporation model
  - Sensitive to different models predicting enhanced emission of gravitons or weakly interacting BH remnants

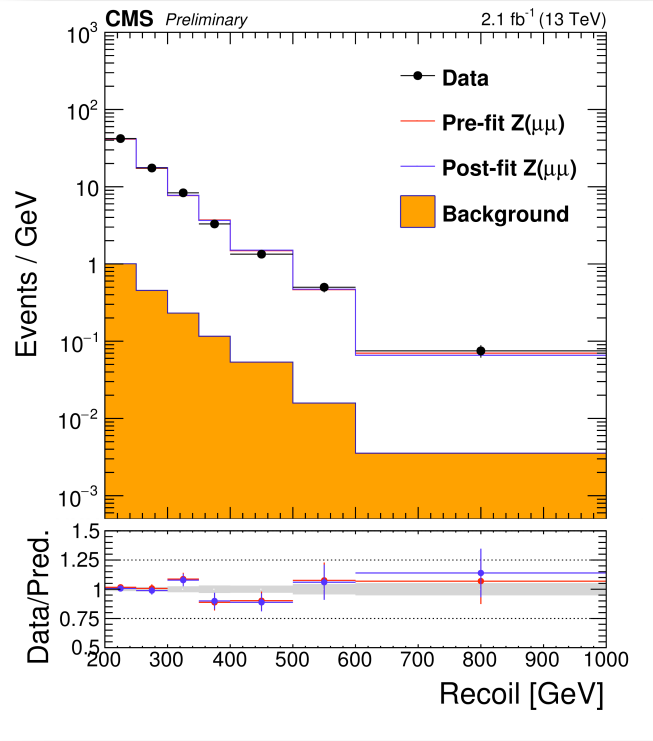
$$S_T = \left(\sum_{i=1}^{N} E_{T,i}\right) + (E_T^{miss} > 50\ GeV)$$

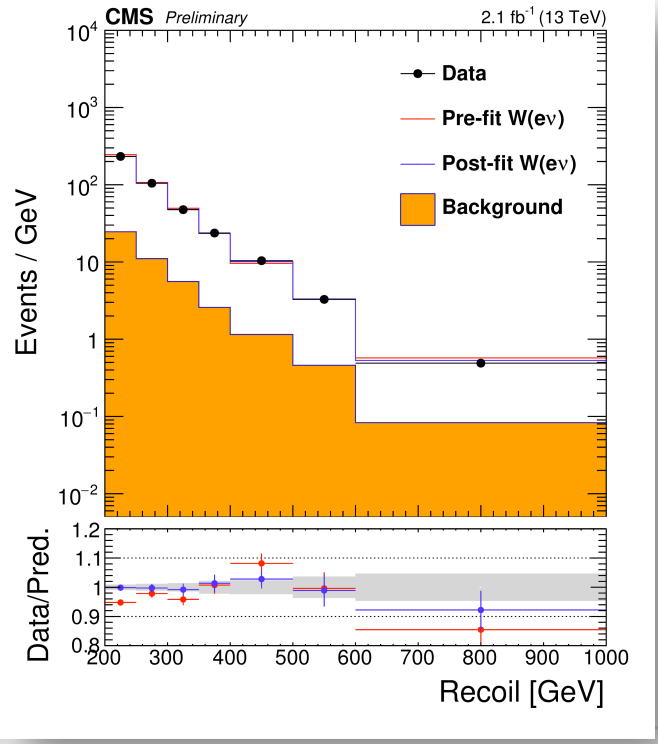
- Very robust data-driven description of multijet background
  - Use low multiplicity to predict shape in high multiplicity events N ≥ 2, 3
  - Use low ST region for normalization 1400 – 1200 GeV



Dark Matter

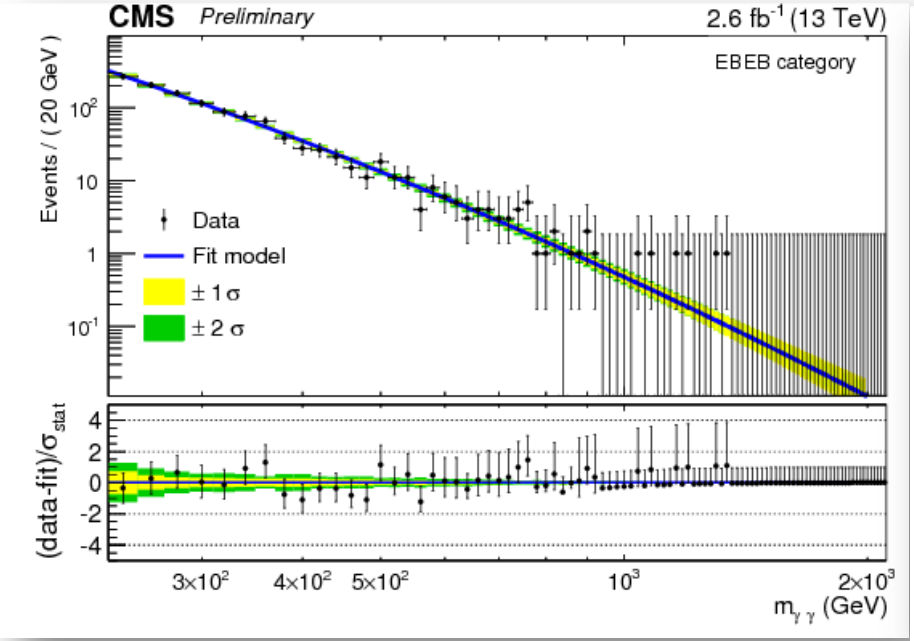
- Event selection
  - Trigger: MET > 90 GeV or miss-HT > 90 GeV – 100% efficient for MET>200 GeV
  - $p_T^{jet} > 100$ GeV and $|\eta^{jet}| < 2.5$
  - $\Delta\phi^{jets,met} > 0.5$ – reduce fake MET
- Backgrounds
  - Veto events with b-jet – ttbar bkg
  - Veto events with $e/\mu/\tau/\gamma$ -- V+jets bkg.
  - Using dilepton, single lepton, and γ+jets to predict MET distirbution in signal region for major bkgs $Z(\nu\nu)/W(l\nu)$ + jets

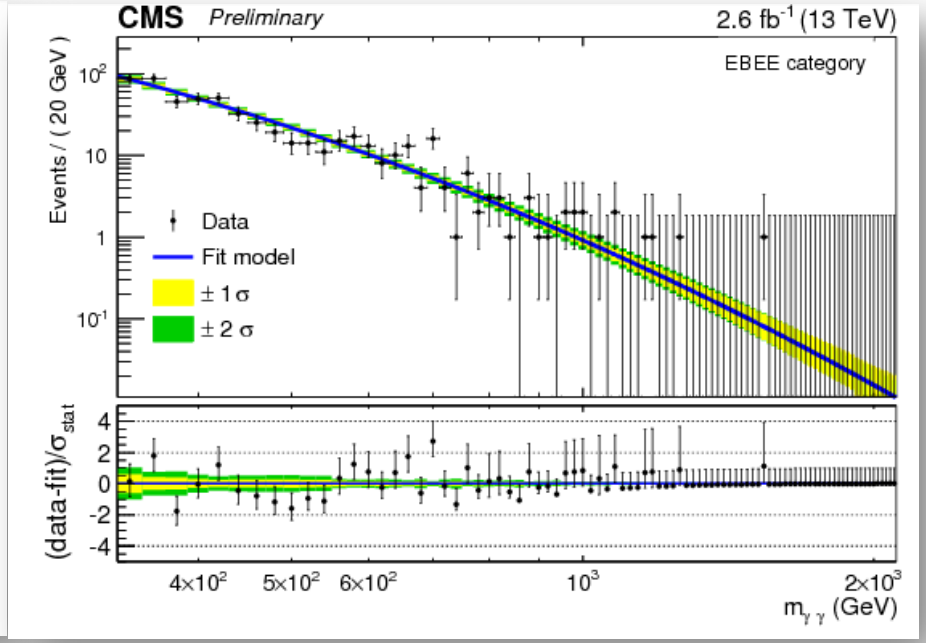




Diphoton Resonances

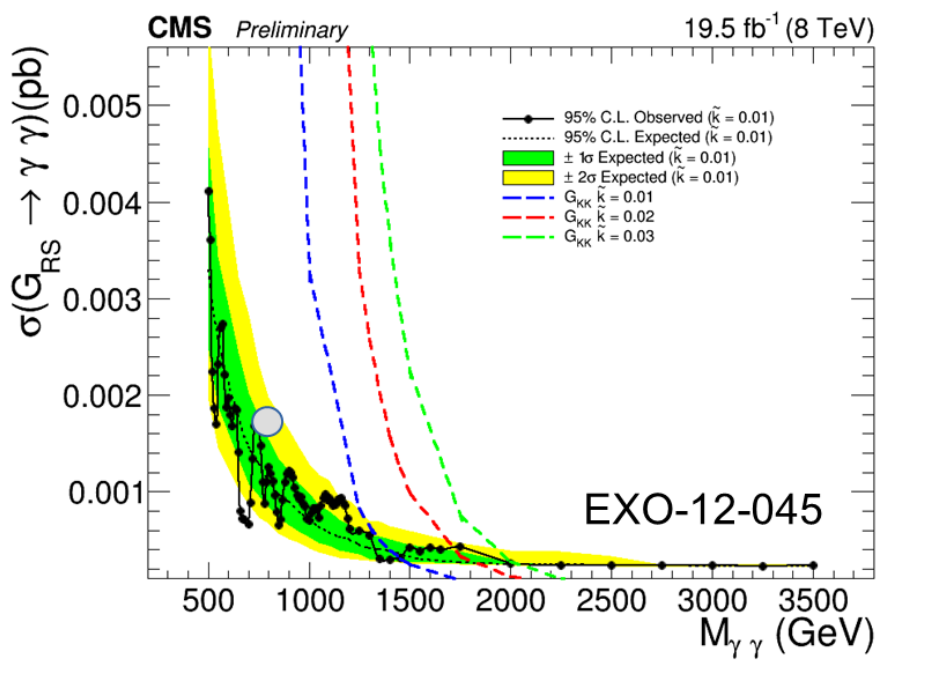
- Two categories: Barrel-Barrel and Barrel-Endcap
- pT(photon) > 75 GeV, Isolated
- Efficiency, scale and resolution calibrated in Z(ee) and high mass DY events

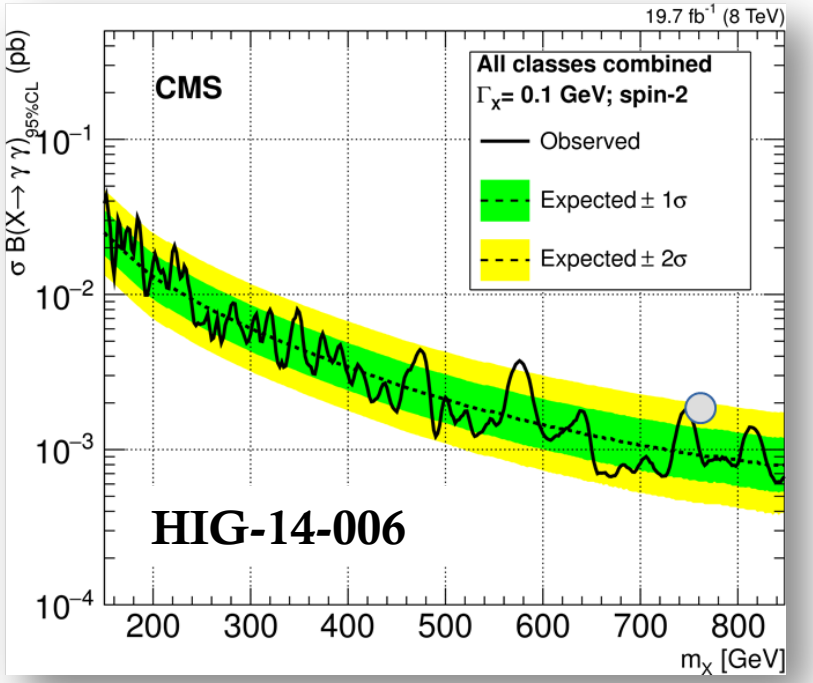




Diphoton Resonances I

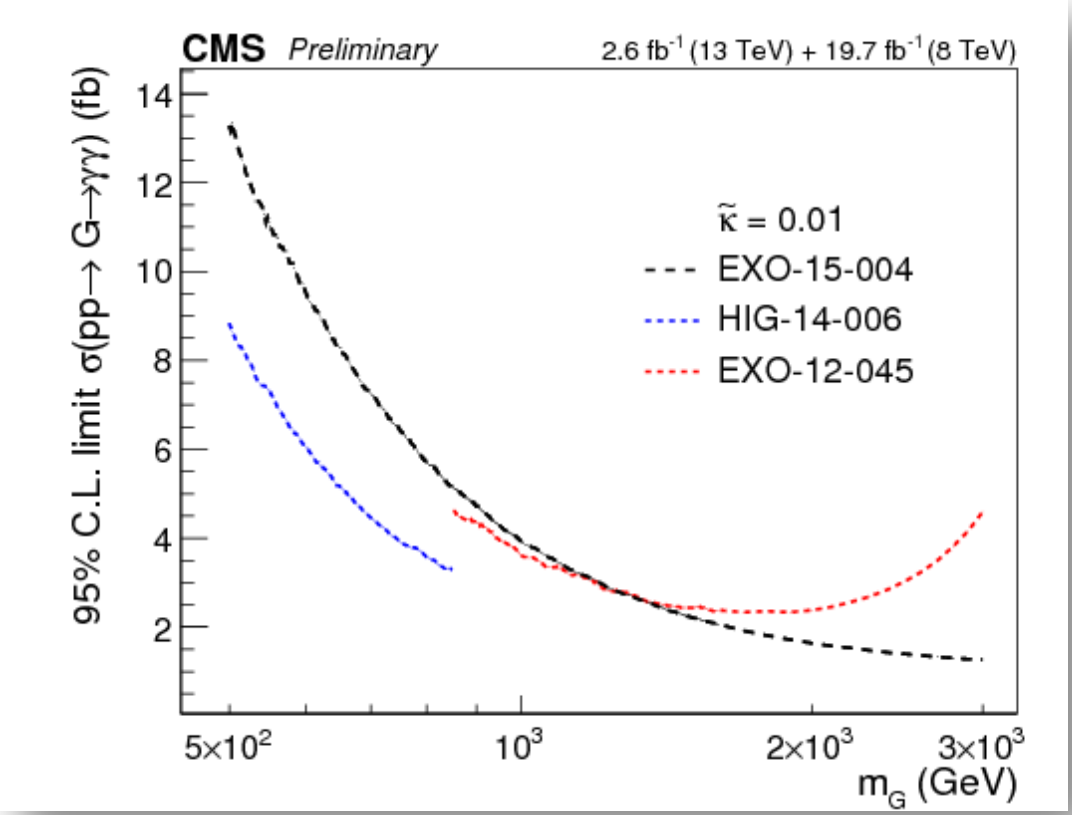
- Excess not excluded by Run 1 searches





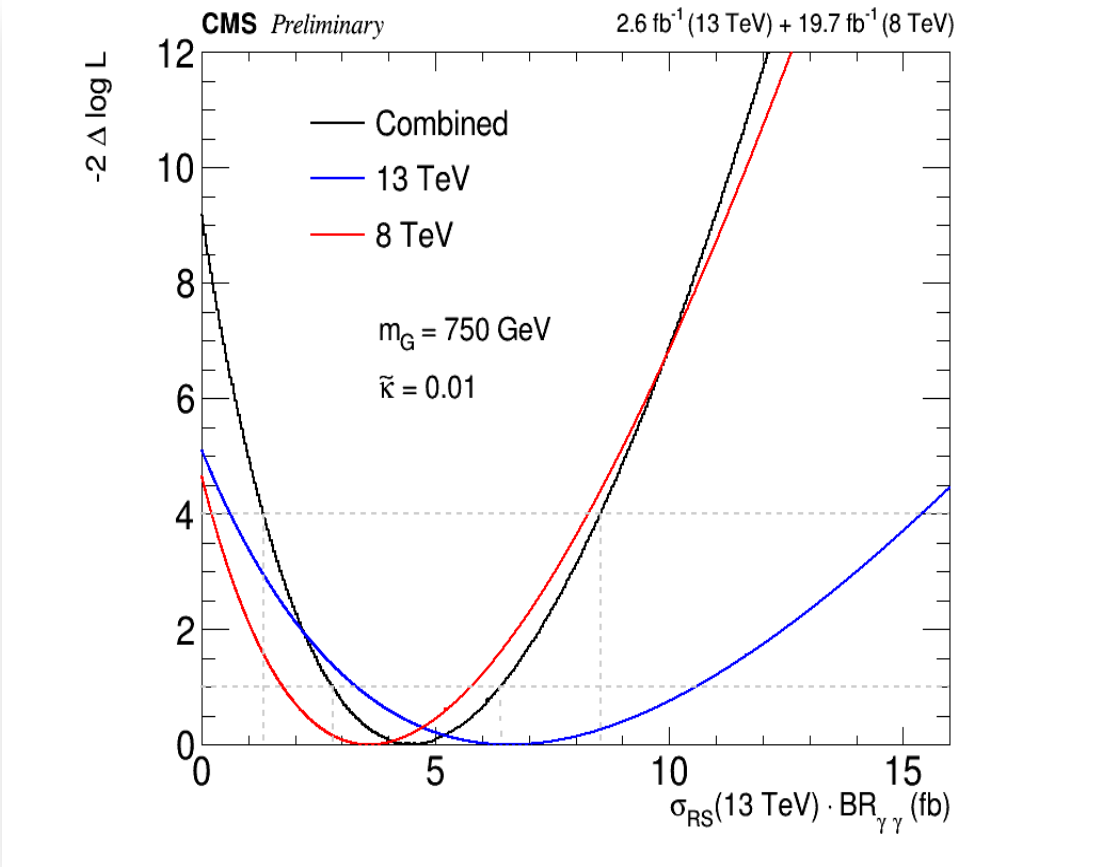
Diphoton Resonances II

- Combination is performed assuming narrow RS graviton
  - Results expressed in terms of equivalent 13TeV cross sections
  - Among two analyses at 8 TeV, HIG-14-006 is more sensitive



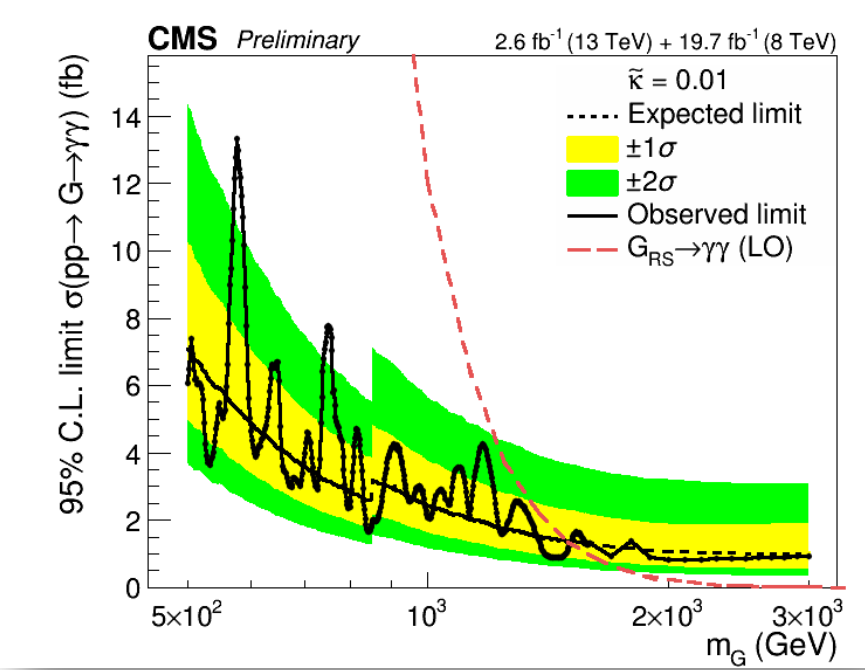
Diphoton Resonances III

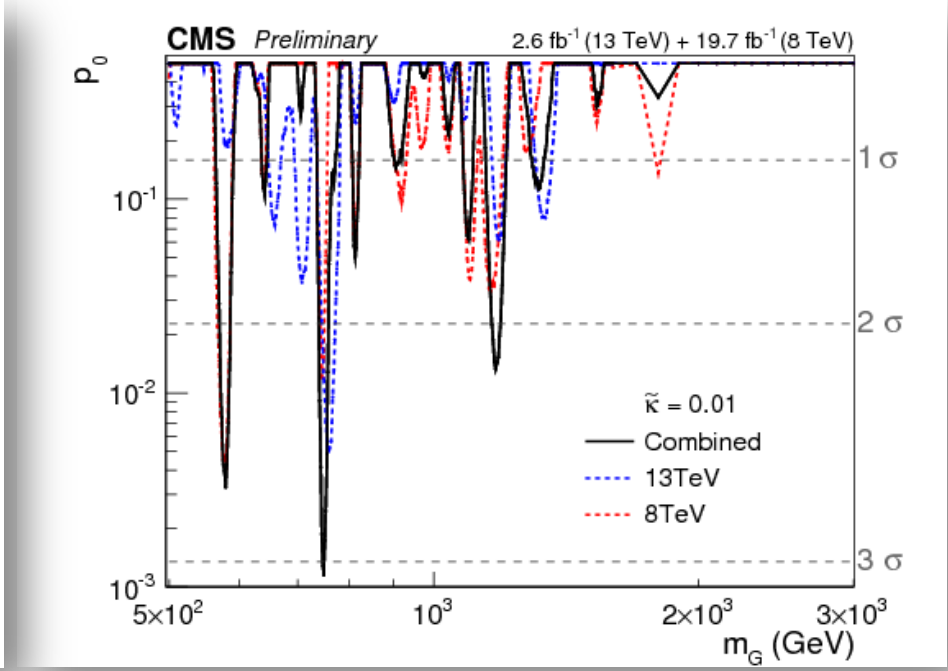
- Log-likelihood scan at 750 GeV
  - Results are expressed in terms of equivalent 13TeV cross sections



Diphoton Resonances IV

- Combined limit improves single analyses sensitivity by 20-30%.
  - Largest excess: M_G=750GeV, local significance 3σ
  - global significance < 1.7σ





Diboson Resonances

- VV channel
  - AK8 Jet pT>30 GeV, $|\eta| < 3$
  - $|\Delta\eta_{jj}| < 3$
  - $M_{jj} > 1000$ GeV
  - Definition of low and high purity regions:

- high-purity (HP) category: $\tau_{21} \leq 0.45$;
- low-purity (LP) category: $0.45 < \tau_{21} < 0.75$.

- Totally 6 categories:
  - V-jet mass category (WW,WZ,ZZ)
  - LP and HP

- VW channel
  - Lepton pT(e/μ) > 120 GeV / 53 GeV
  - MET (e/μ) > 80 GeV / 40 GeV
  - Data-driven method in sideband of jet mass distribution
  - $\Delta R(l,J) > \pi/2$, $\Delta\phi(l,J) > 2$, $\Delta\phi(MET,J) > 2$
  - Veto events with b-jets
  - Definition of high and low purity regions:

- high-purity (HP) category: $\tau_{21} \leq 0.6$;
- low-purity (LP) category: $0.6 < \tau_{21} < 0.75$,

- Totally 8 categories:
  - Electron and muon channel
  - V-jet mass category (WW,WZ,ZZ)
  - LP and HP

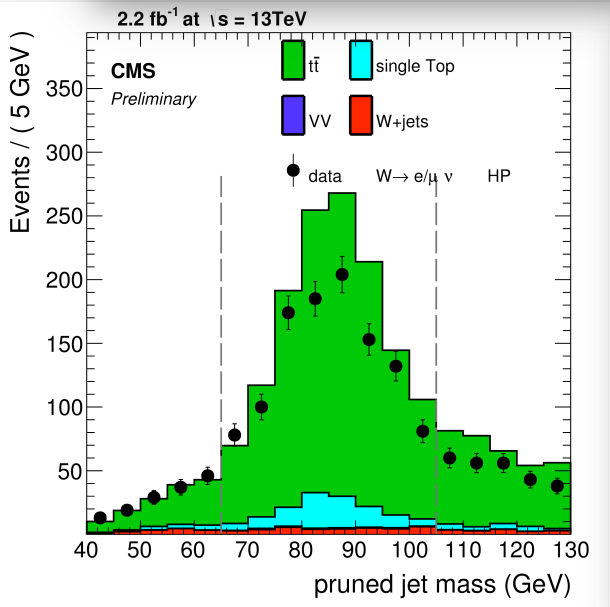
Events with M_{jj} in a range 105 – 135 GeV are excluded from this analysis

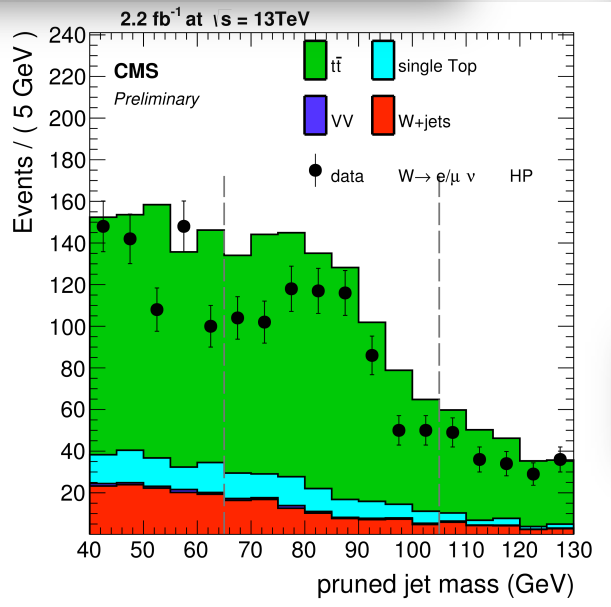
Diboson Searches

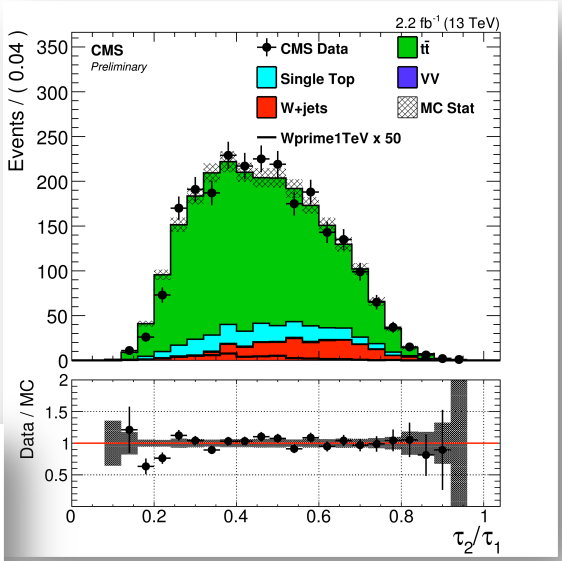
- W-tagging modeling in top-quark enriched sample

Scale factors

Category	Definition	W scale factor
Dijet channel HP	$(\tau_{21} < 0.45)$	0.69 ± 0.14
Dijet channel LP	$(0.45 < \tau_{21} < 0.75)$	1.46 ± 0.38
$\ell\nu$+jet channel HP	$(\tau_{21} < 0.6)$	1.03 ± 0.13
$\ell\nu$+jet channel LP	$(0.6 < \tau_{21} < 0.75)$	0.88 ± 0.49







W-jet mass peak position and resolution

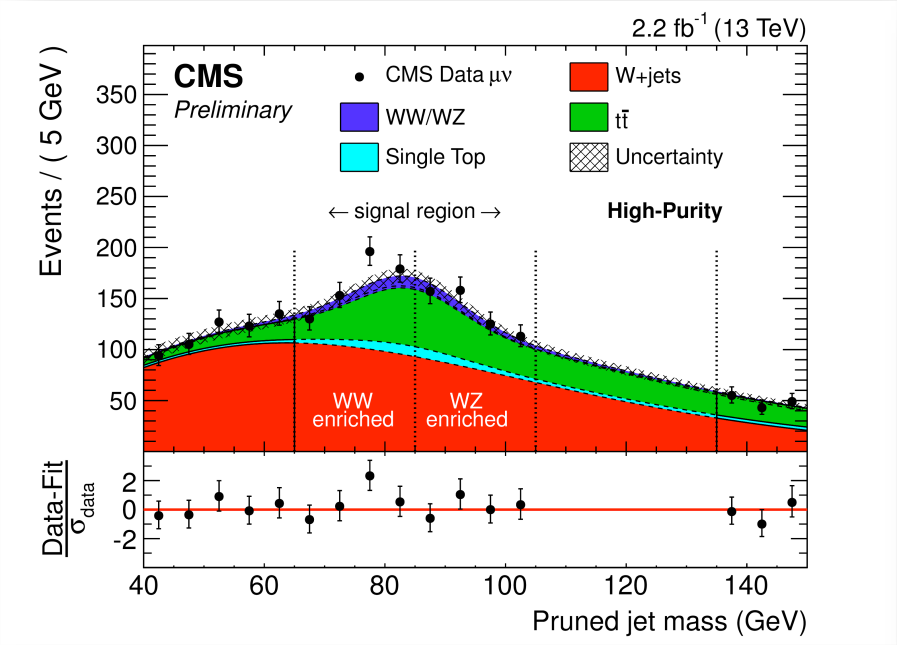
$\tau_{21} < 0.45$	m [GeV]	σ [GeV]
Data	84.7 ± 0.4 GeV	8.2 ± 0.5 GeV
Simulation	85.3 ± 0.4 GeV	7.3 ± 0.4 GeV

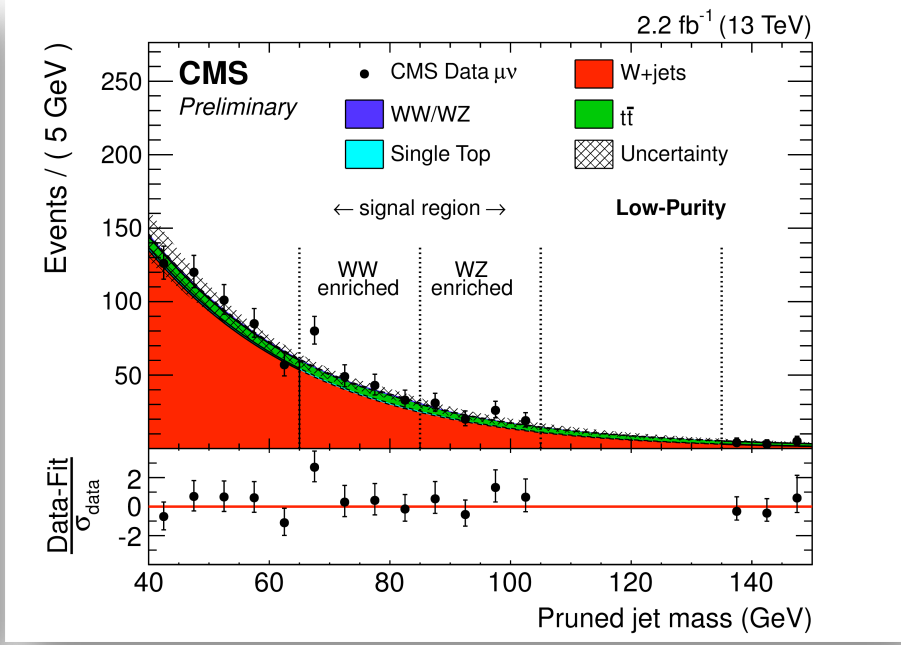
Same corrections used for Z-tagging.

Diboson Searches

- Background estimation is based on Alpha Ratio method
  - Data events in side-band region are rescaled by factor to predict V+jets background in signal region

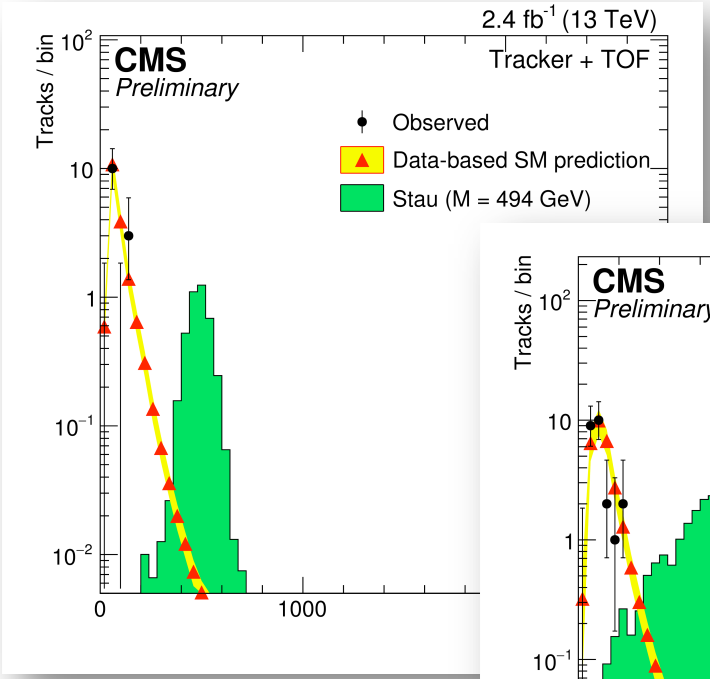
$$\alpha_{MC}(m_{VV}) = \frac{F^{V+jets}_{MC,SR}(m_{VV})}{F^{V+jets}_{MC,SB}(m_{VV})}$$

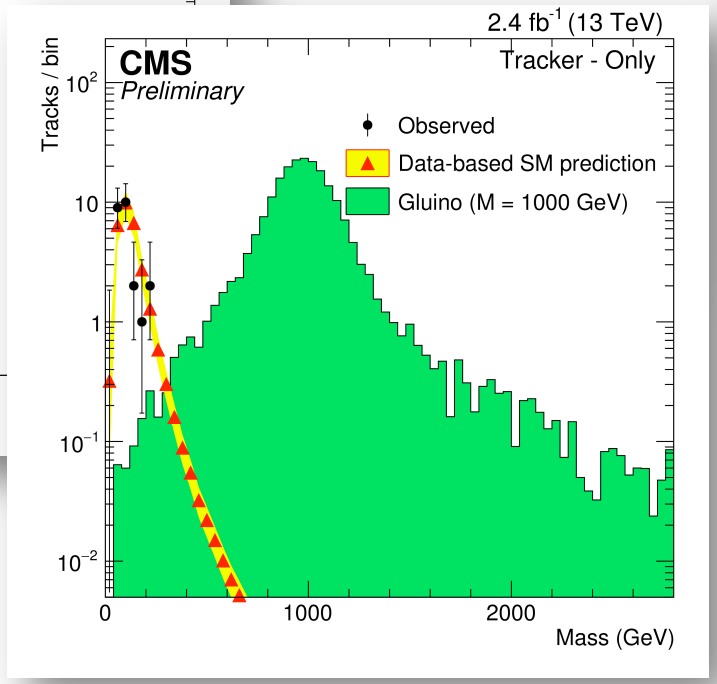


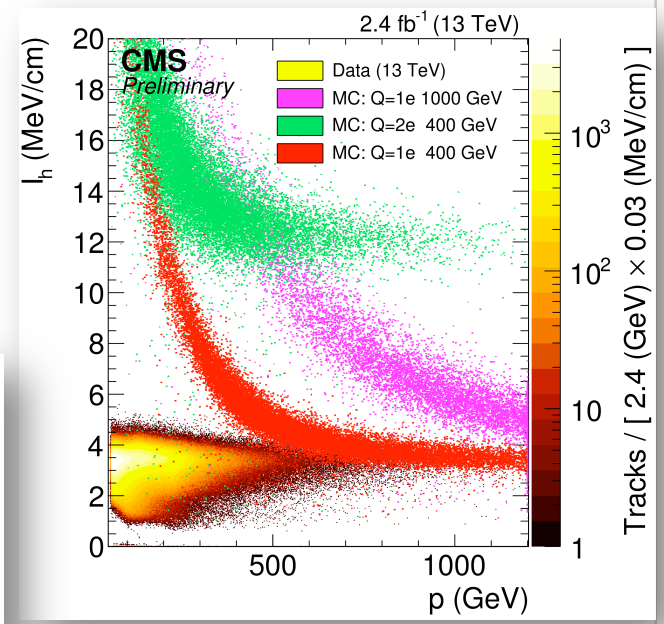


Heavy Stable Charged Particle

- Signature: tracks with high pT and dE/dx and long TOF from IP to Muon System







Heavy Stable Charged Particle

- Limits set on several HSCP models
  - Gluinos and stops under Split SUSY scenario
  - Lepton-like particles from mGSMB scenario
  - Modified Drell-Yan production of lepton-like fermions

CMS-PAS-EXO-15-010