Exotics Searches @ CMS

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for
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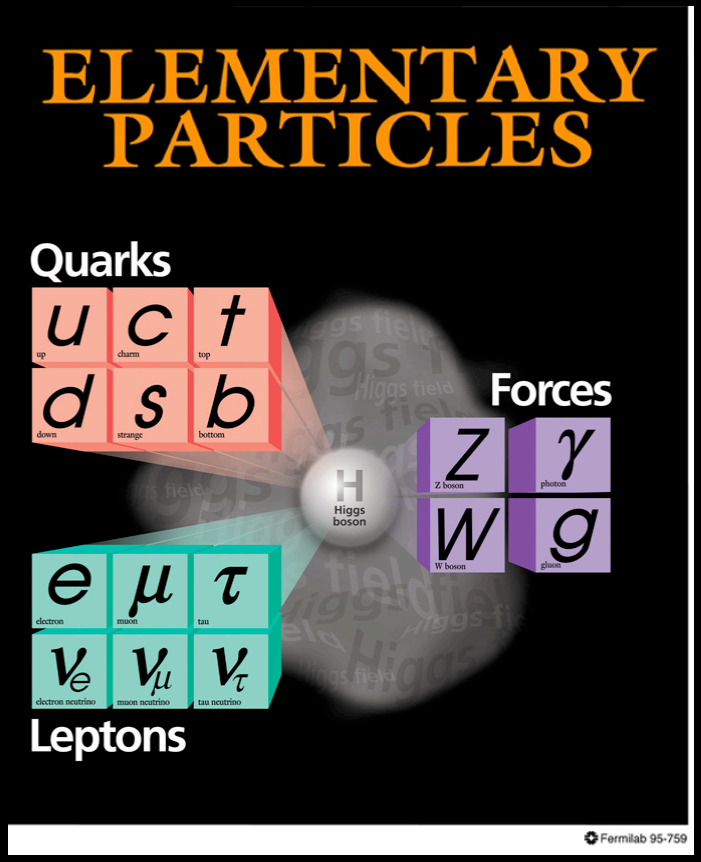
Particle Physics Today

The Standard Model has been successfully tested, but it is not the complete story

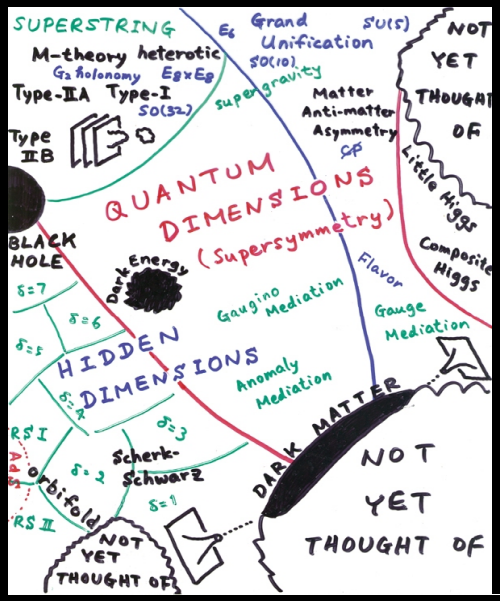


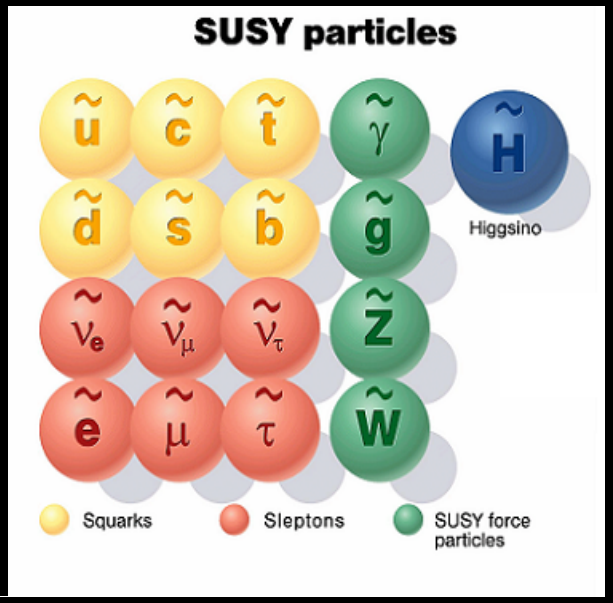
It still leave many important questions unanswered:

① hierarchy problem?
② dark matter?
③ grand unification?
④ number of generations?
⑤ matter antimatter asymmetry?, etc.

SUSY is the most widely accepted proposal to address the open questions of SM, but there are many other theoretical models that attempt to some of these questions

What can be non-SUSY BSM?
Many possibilities !
new symmetries, bosons, fermions, dimensions, or something completely different!





Schematic View of Particle Physics in the 21st Century

Roadmap: Beyond the S.M.

© McPherson (ICHEP'02), **Lee (APS'13)**

Heavy, Excited, Composite States

EWSB

$W_1\ W_2\ W_3$

B

H { $W^{\pm}$ Z γ }

$\begin{pmatrix} u \\ d \end{pmatrix}\ \begin{pmatrix} c \\ s \end{pmatrix}\ \begin{pmatrix} t \\ b \end{pmatrix}$

$\begin{pmatrix} \nu_e \\ e \end{pmatrix}\ \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}\ \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

MORE? → t' b' ν_L Z' W'

COMPOSITE? → q* l* ν* LQ

SUSY

$\tilde{\chi}^{\pm}\ \tilde{\chi}^0\ \tilde{\gamma}$

$\tilde{h}\ \tilde{H}\ \tilde{H}^{\pm}$

$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}\ \begin{pmatrix} \tilde{c} \\ \tilde{s} \end{pmatrix}\ \begin{pmatrix} \tilde{t} \\ \tilde{b} \end{pmatrix}$

$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e} \end{pmatrix}\ \begin{pmatrix} \tilde{\nu}_\mu \\ \tilde{\mu} \end{pmatrix}\ \begin{pmatrix} \tilde{\nu}_\tau \\ \tilde{\tau} \end{pmatrix}$

~~SUSY~~ → mSUGRA, GMSB, RPV, Split SUSY

Fine Tuning

2HDM

h H A $H^{\pm}$

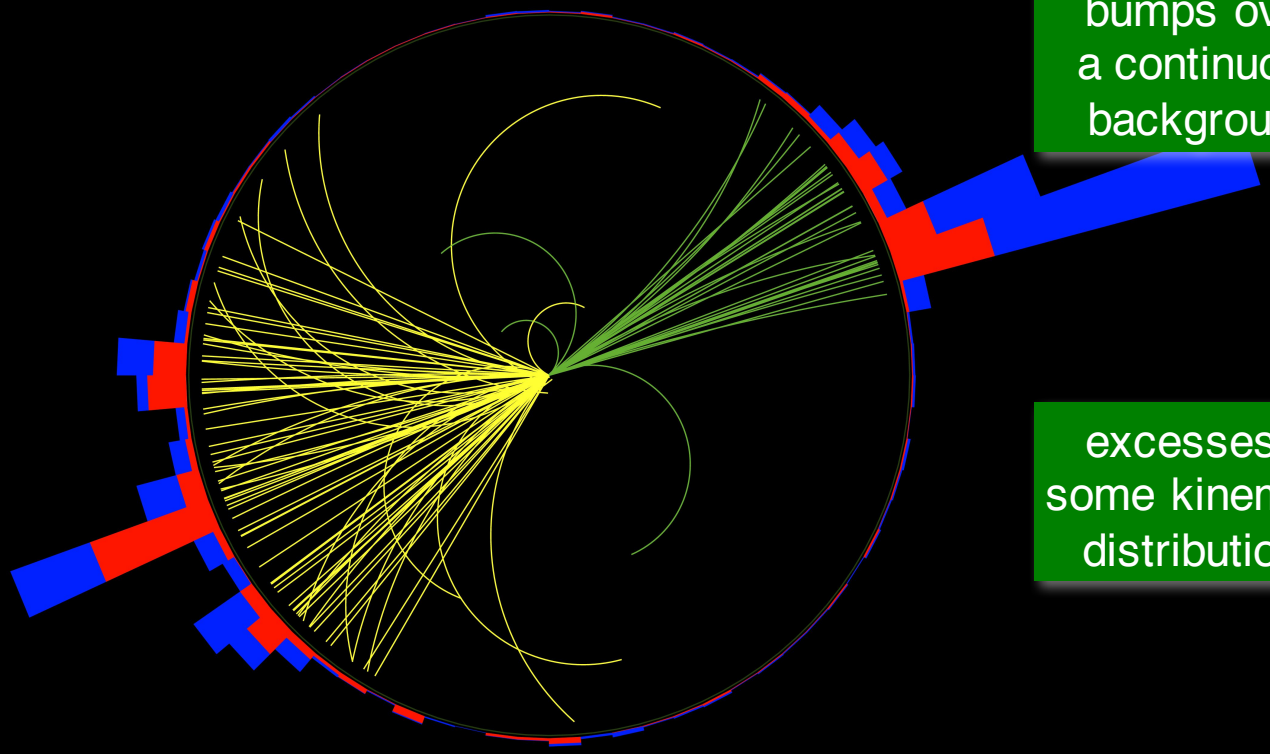
$H^{\pm\pm}$ (*eg:* **TRIPLET**)

Technicolor, Black Holes

Extra Dimensions → Large Extra Dimension (ADD); Warped Extra Dimension (RSG); Universal Extra Dimension

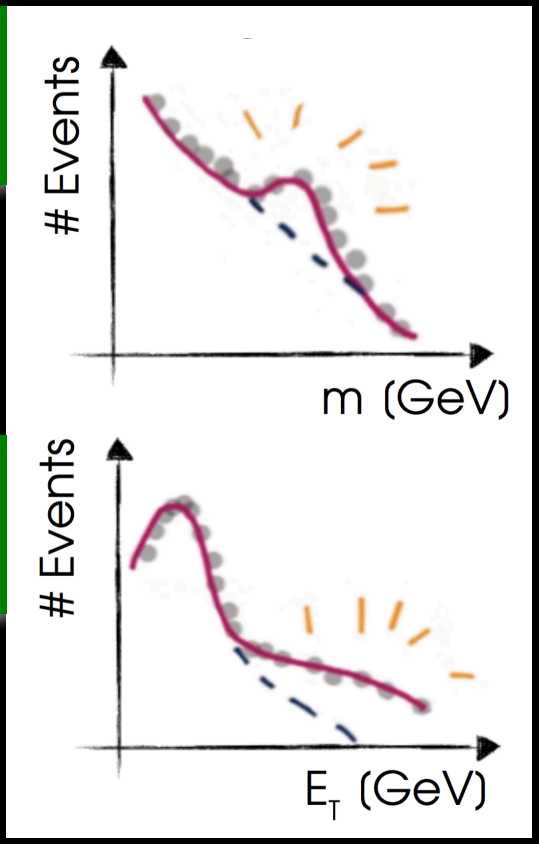
Unparticles, Hidden Valleys, Little Higgs, HSCP, DM, aGC, etc…

Exotics Searches @ CMS



bumps over a continuous background

excesses in some kinematic distributions



we are looking for signs of new physics in all possible directions

- look at interesting features in data: (non-)hadronic, L+J, LL, etc.
- look at all possible signatures for disagreement with expectations
- probe interesting new BSM models

Introduction

This talk will focus on

- some of the most recent "signature-based" searches we've performed using LHC Run 2 data (~2.4 fb^{-1}) @ 13 TeV
- some of the interesting BSM theories we've tested so far
  - heavy resonances, TeV scale gravity, 4th generations, etc.
    - SUSY: Claudio Campagnari's & Alfredo Gurrola's talks
    - BSM Higgs: Andrei Gritsan's & Luca Pernié's talks
    - DM: Steven Lowette's talk

These results are just fraction of our searches. More on the way.

Many 8 TeV results are published or submitted/accepted for publication.

All CMS searches are detailed in:

CMS EXO http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/

CMS B2G http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/

EXO-15-004
EXO-16-018

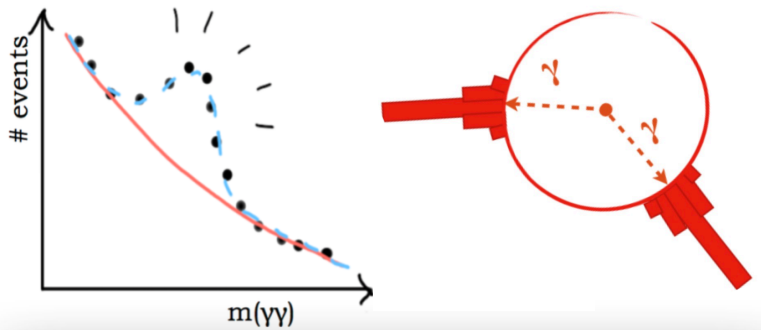
Diphoton Resonances

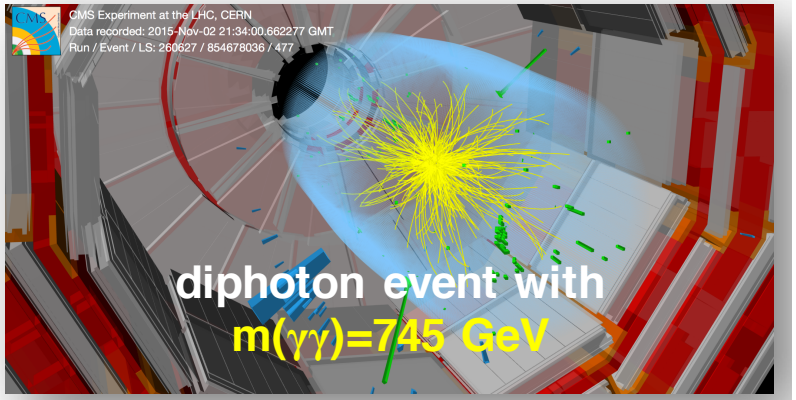
Look for bump in diphoton mass spectrum

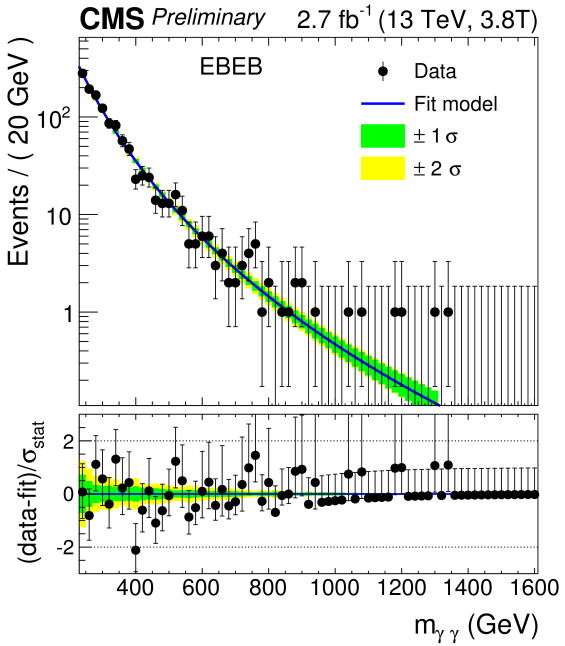
- generic signature of several BSM
  - J=0: extended Higgs sectors (2HDM)
  - J=2: extra-dimension (RS graviton)

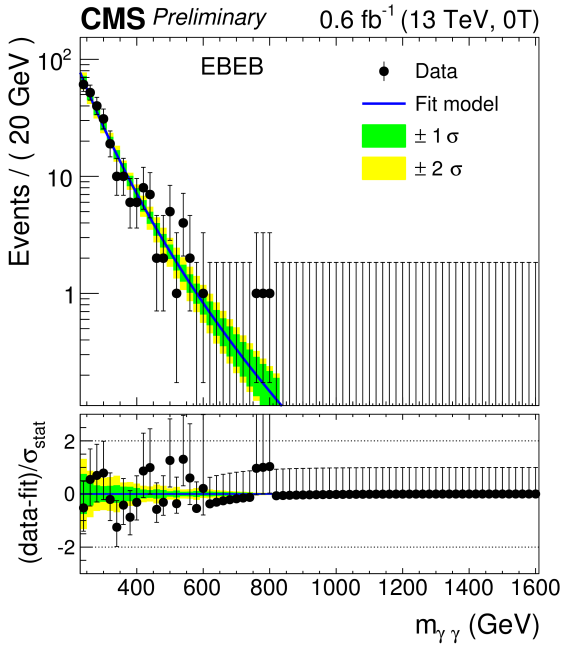
A clean experimental signature ☺

- localized excess of events in mass spectrum
- select diphoton in event with $p_T > 75$ GeV & at least one γ with $|\eta| < 1.44$
- split in barrel & endcap: EB-EB, EB-EE









Modest excess presented in Dec

Updated for Moriond New

① improved ECAL calib.

② use of 0.6 fb^{-1} 0T data

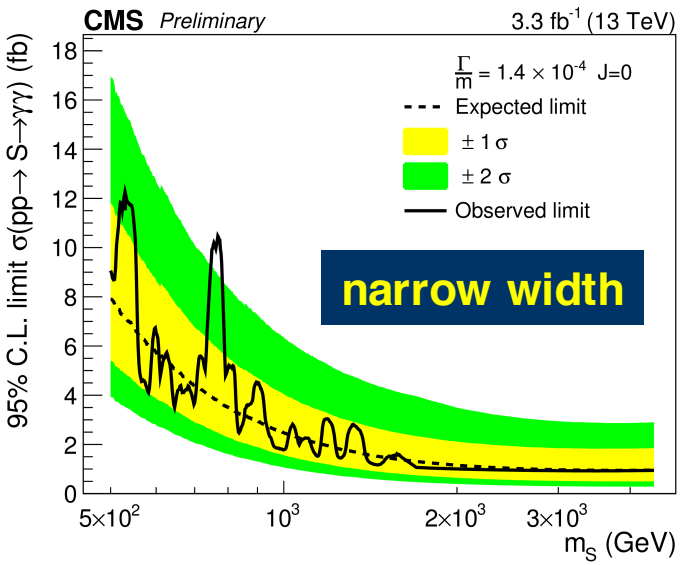
③ better background modelling

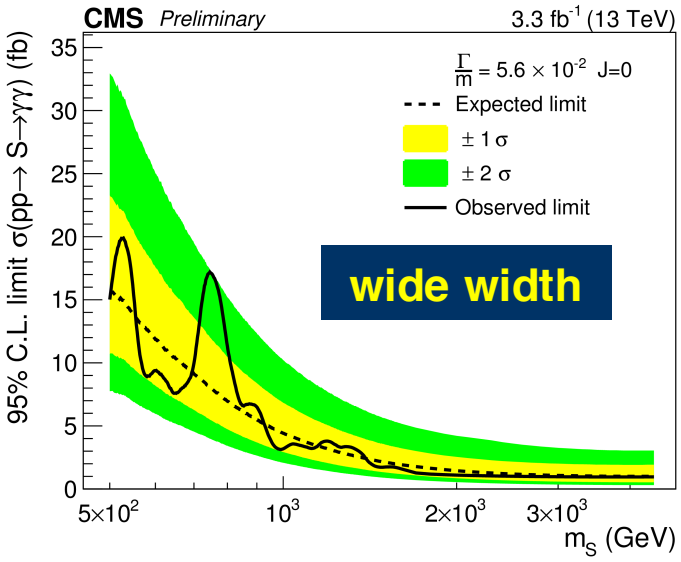
→ compared to previous result, improved sensitivity by > **20%**

EXO-16-018

Diphoton Resonances

Results then interpreted in terms of J=0 & 2 resonances, for 3 width hypotheses





largest excess @ 760 GeV for narrow width hypothesis

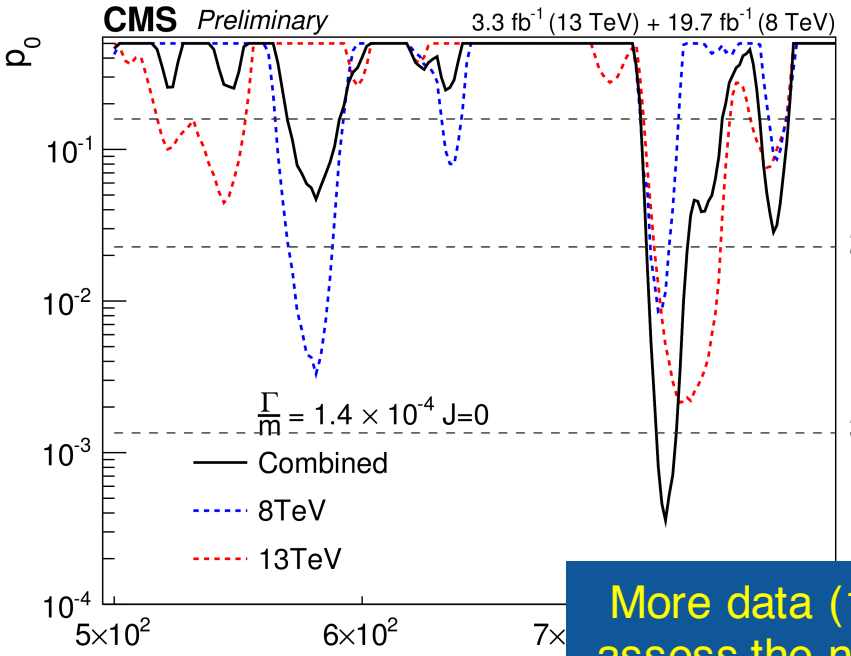
① local significance: 2.8-2.9σ depending spin hypothesis

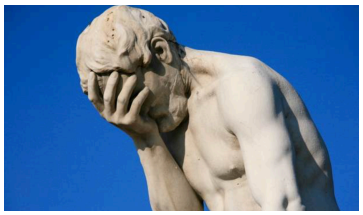
② global significance < 1σ

Combination with 8 TeV data

① local significance: 3.4σ for a mass of 750 GeV

② global significance < 1.6 σ





More data (10 fb-1) is needed to assess the nature of this excess

EXO-15-001
PRL 116, 071801 (2016)

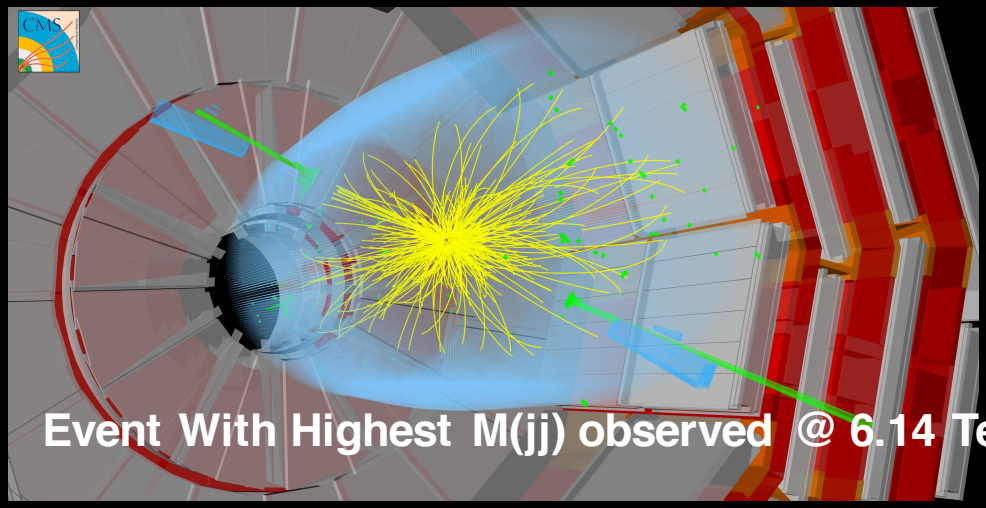
Dijet Resonances

Look for bump in dijet mass spectrum

- sensitive to the coupling of any new massive object to quarks and gluons
- separates searches by final state (qq, qg, gg)

Select dijet in event with $|\eta_1,\eta_2| < 2.5$ & $|\Delta\eta| < 1.3$

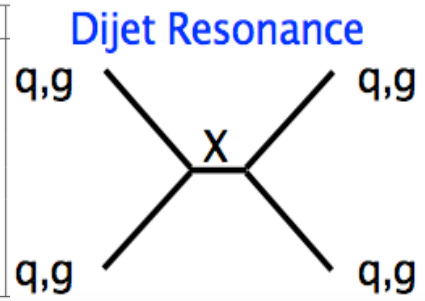
- CMS uses an FSR-recovery technique by combining anti-k_T 0.4 jets within $\Delta R < 1.1$

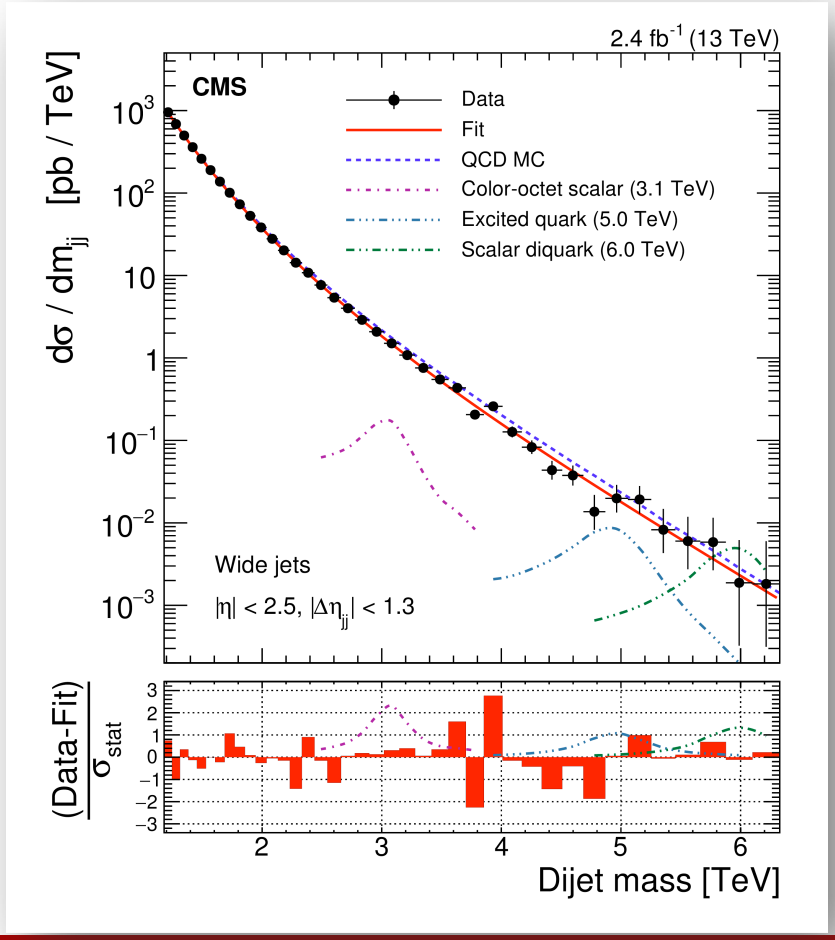


Data well fit to a smooth, steeply falling function

- no resonance signal observed
- set model-independent limits on several models

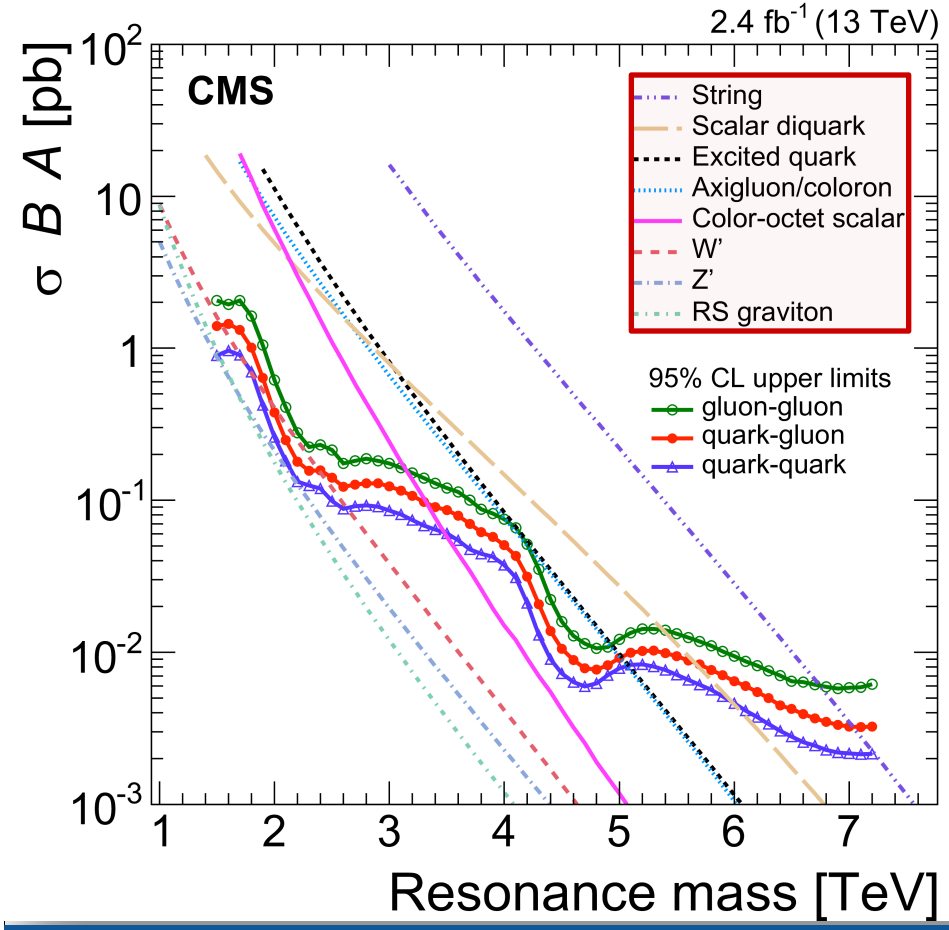
Model Name	Final-state Partons
String	$q\bar{q}$, qq, gg and qg
Axigluon	$q\bar{q}$
Coloron	$q\bar{q}$
Excited Quark	qg
E_6 Diquark	qq
RS Graviton	$q\bar{q}$, gg
Heavy W	$q\bar{q}$
Heavy Z	$q\bar{q}$



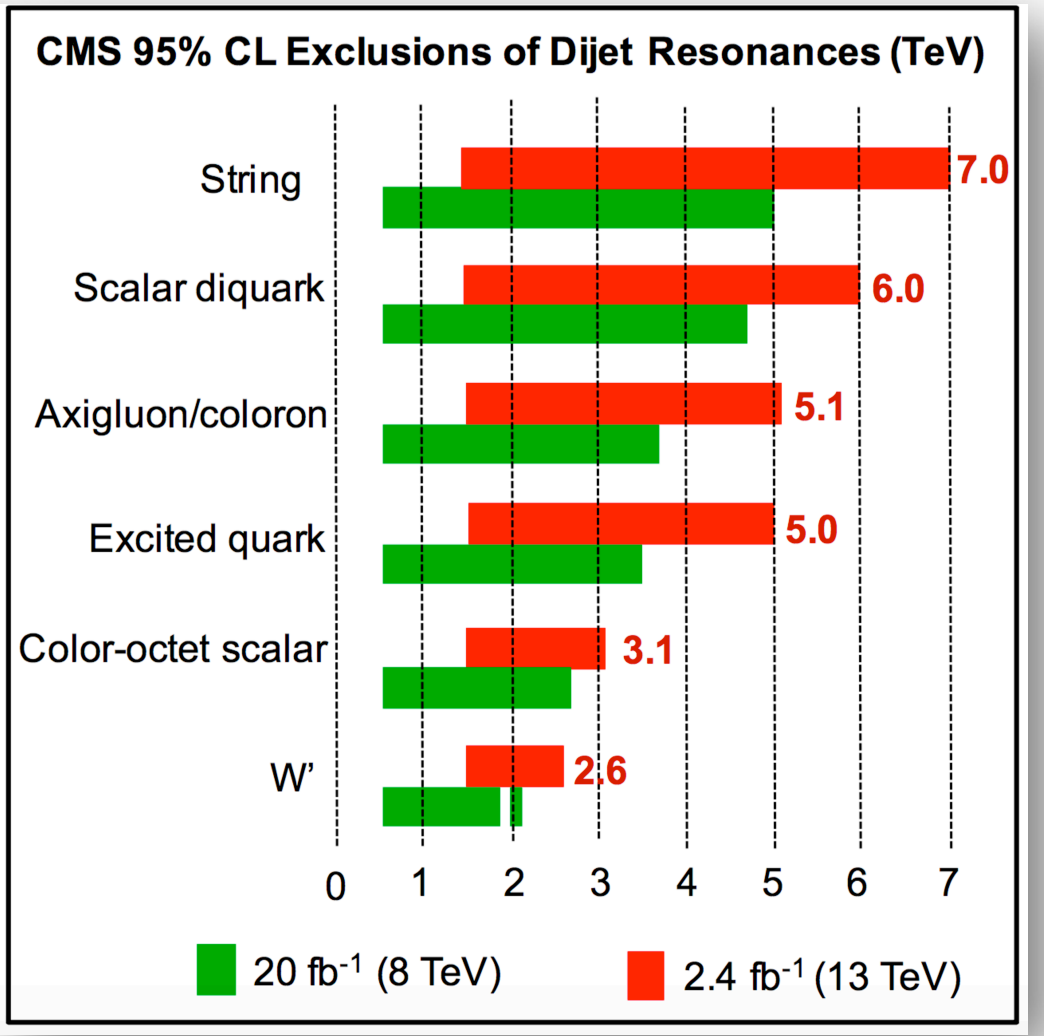


Dijet Resonances

We obtain generic cross section limits on qq, qg, gg resonances. The upper limits are compared to the expected cross section for 8 specific models.



2.4 fb^{-1} limits from 13 TeV already surpass the 20 fb^{-1} limits from 8 TeV



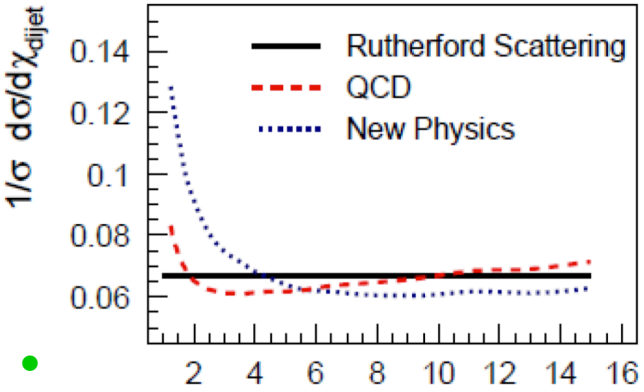
EXO-15-008 Dijet Angular Distribution

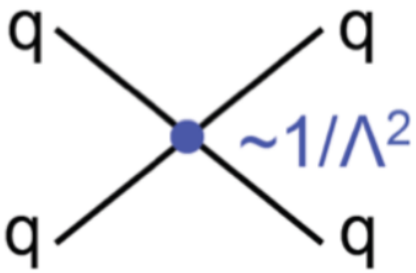
Look for dijet scattering angle θ^* via χ variable $\longrightarrow$

$$\chi_{\text{dijet}} = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

- χ flat LO QCD but sensitive to non-resonant (or wide width) phenomena at low χ & high mass
- quark contact interactions, large extra dimensions

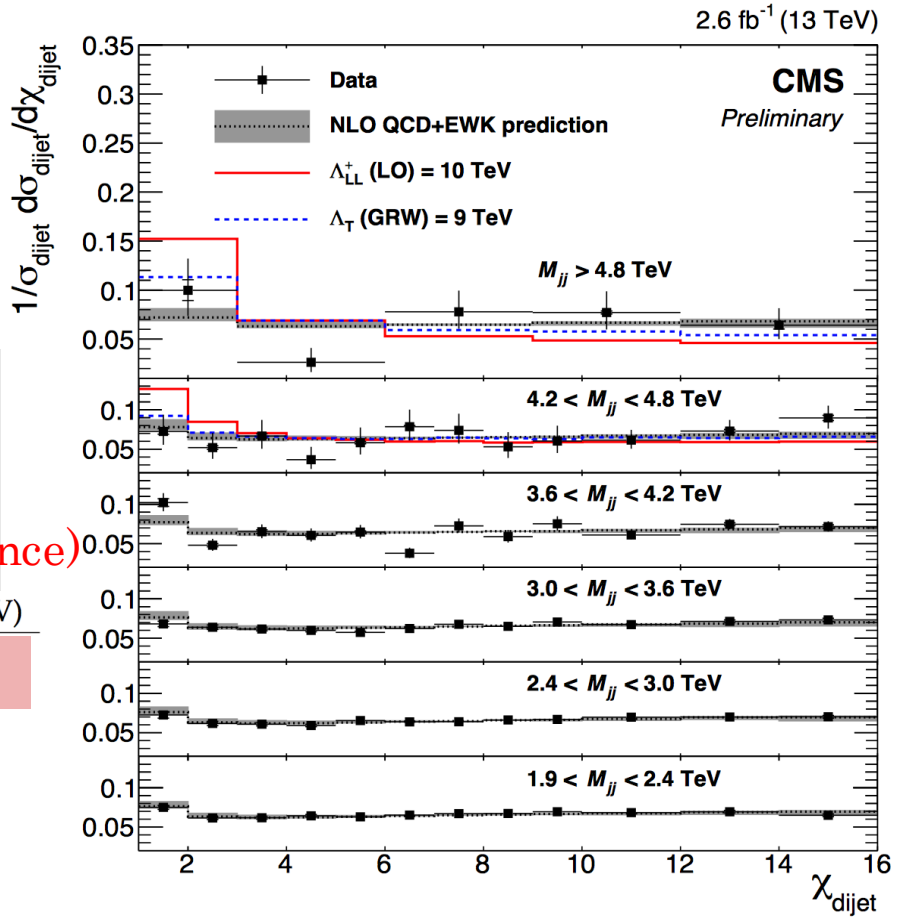
No evidence for substructure of quarks





- unfolded data in good agreement w/ NLO QCD+EW
- set limit on CI scale $\Lambda^+ > 12.1$ TeV (destructive interference) & $\Lambda^- > 16.3$ TeV (constructive interference)

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



EXO-15-008

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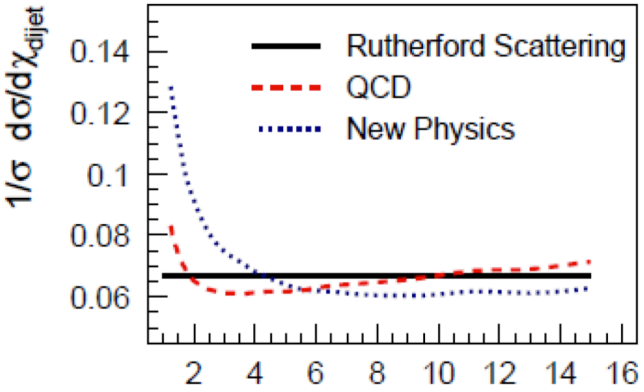

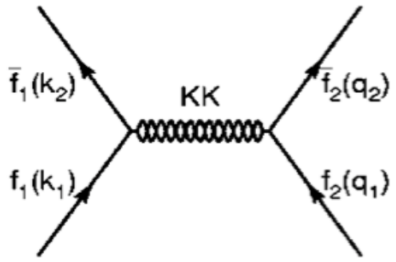

- unfolded data in good agreement w/ NLO QCD+EW
- set limit on C.I. scale $\Lambda^+ > 12.1$ TeV, $\Lambda^- > 16.3$ TeV
- set limit on ADD Λ_T(GRW)> 9.1 & M_S(HLZ)> 7.7 TeV

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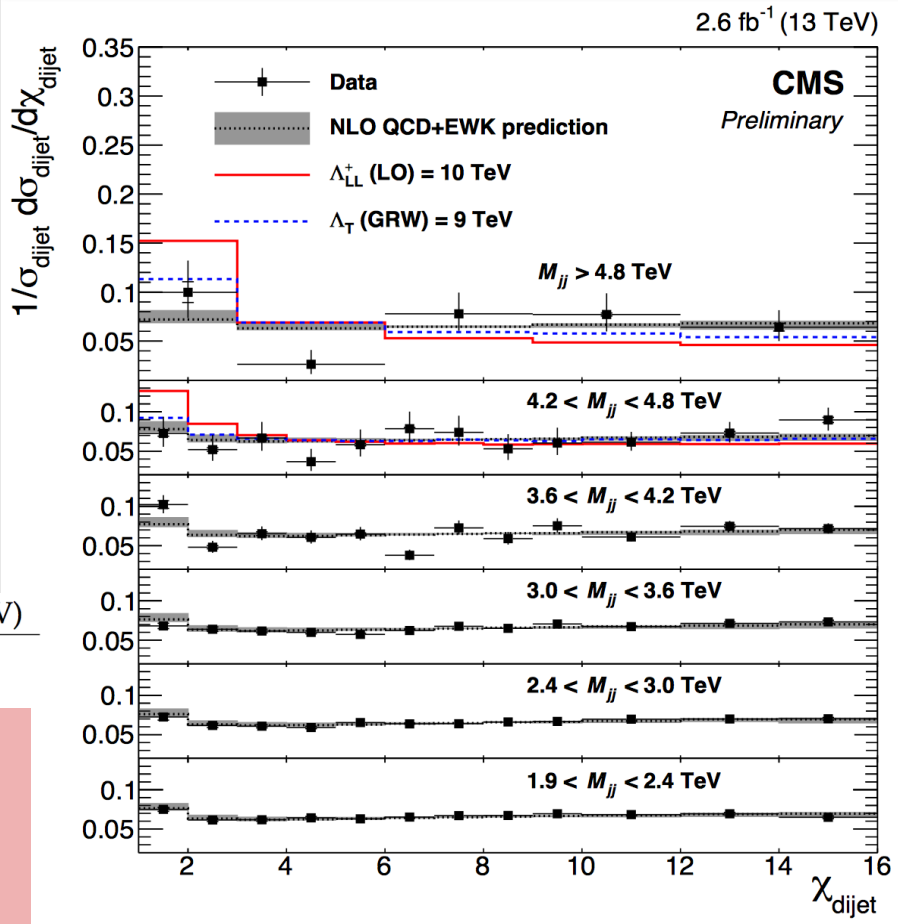
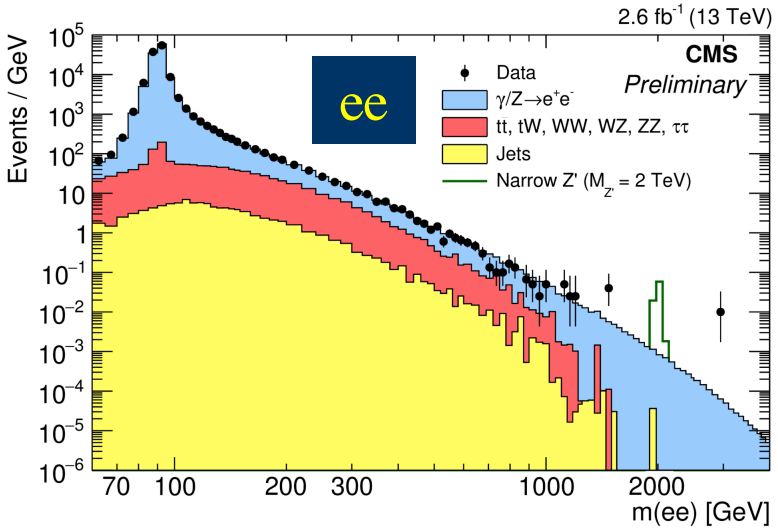
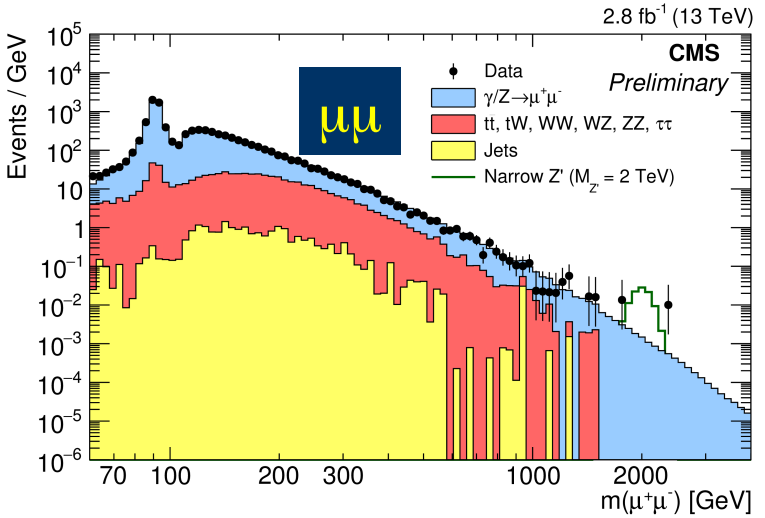


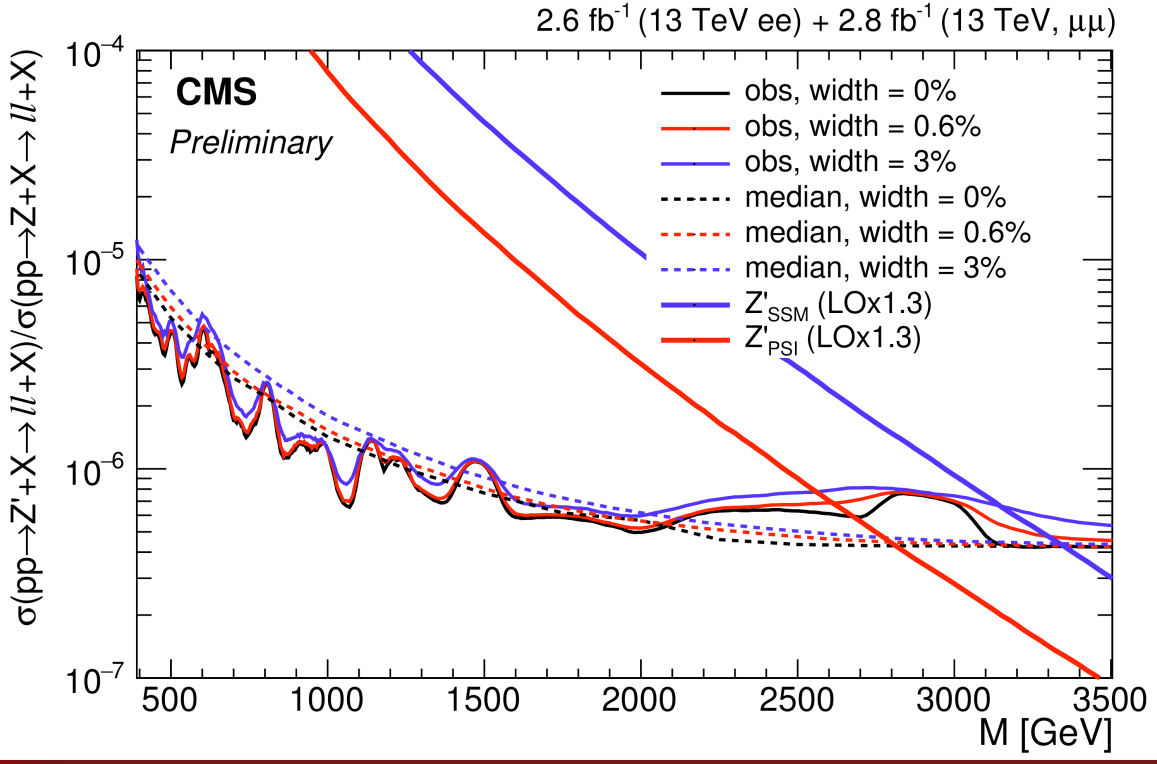
Dilepton Resonances

Look for bump in dilepton mass spectrum

- two high-p_T isolated leptons with same flavor (e,μ)
- background shape taken from MC and normalized to data in the mass side-band [60,120] GeV
- excellent data-SM agreement
- set limits on Z'_{SSM} & Z'_{PSI} by calculating σBr in mass; express limit as a ratio b/w σ(Z') to the SM σ(Z)





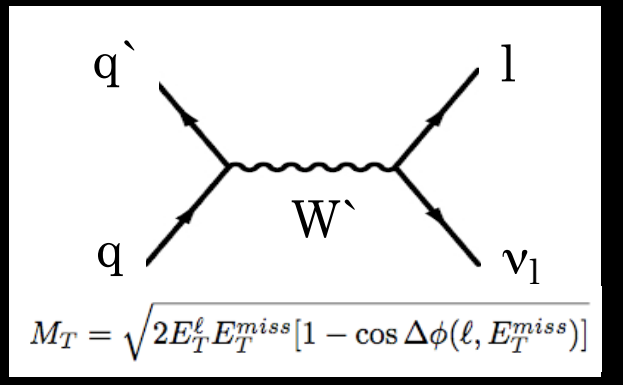


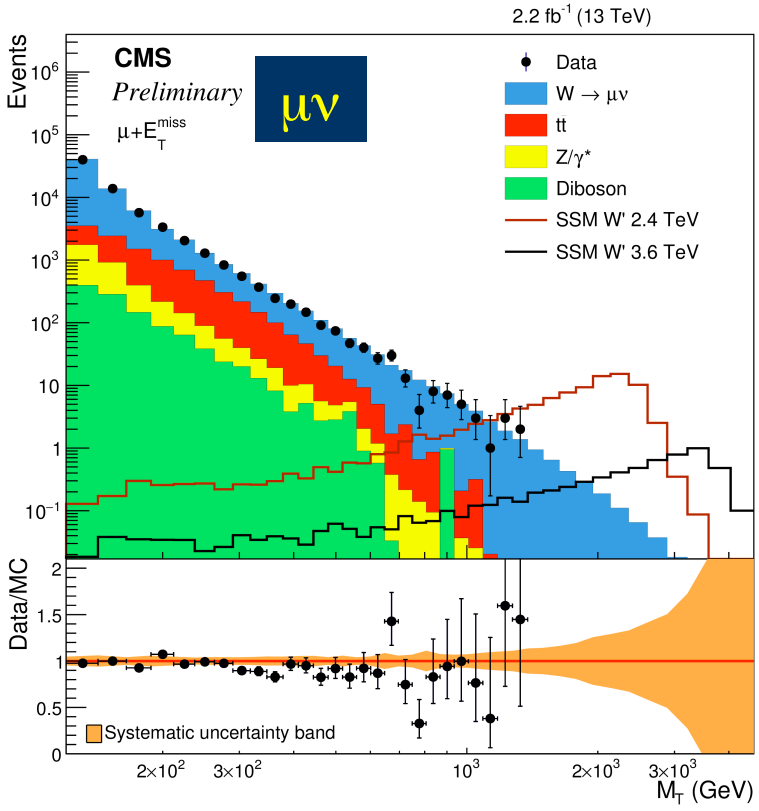
	Z'_{PSI}	Z'_{SSM}
combined	2.60	3.15
8 TeV	2.57	2.90

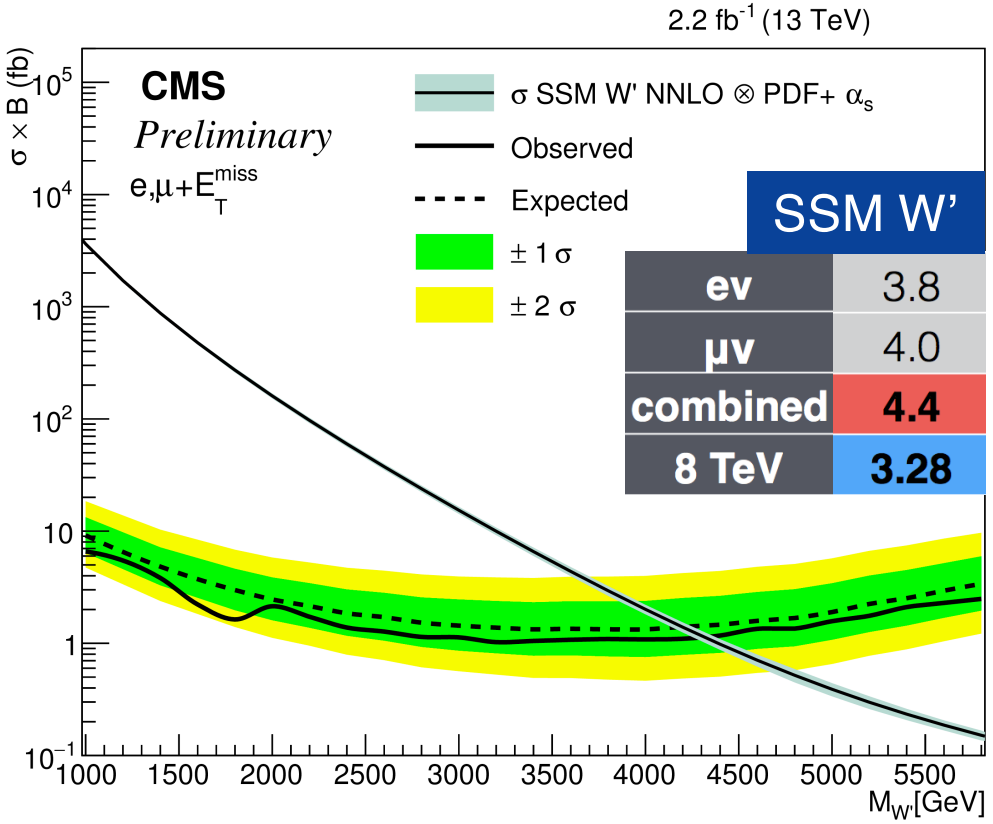
W'(→lν) Searches

Look for Jacobian peak in M_T(lν) distribution in tail

- a high p_T lepton + MET
- remove jet backgrounds with $0.4 < p_T/\text{MET} < 1.5$, $\Delta\phi > 0.8\pi$
- no significant deviation from SM expectation
- set the limit on SSM W': exclude W' with mass below 4.4 TeV





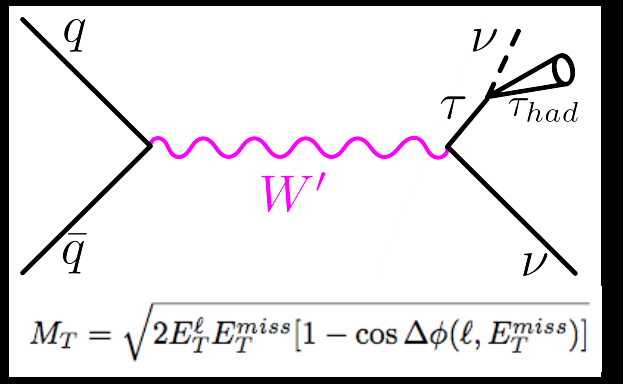


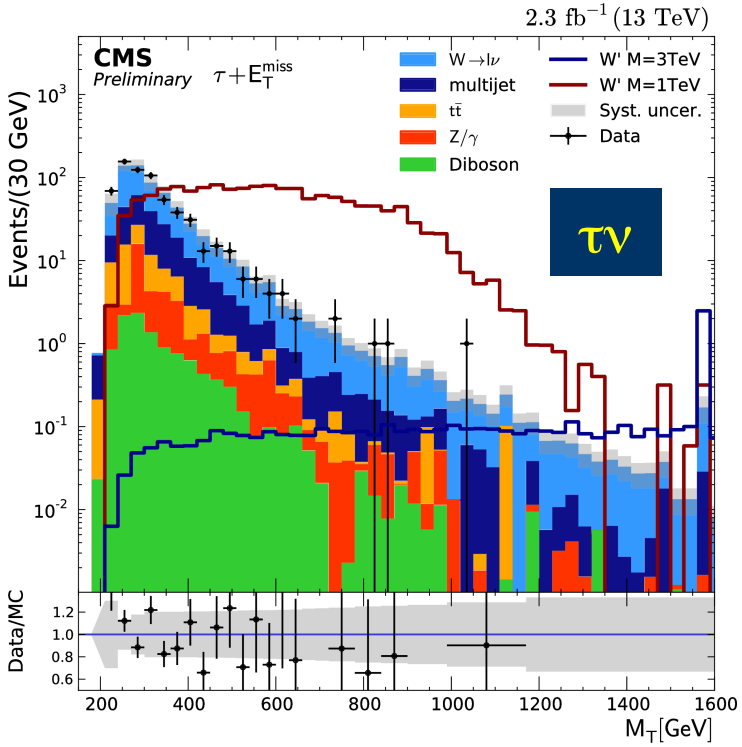
EXO-16-006

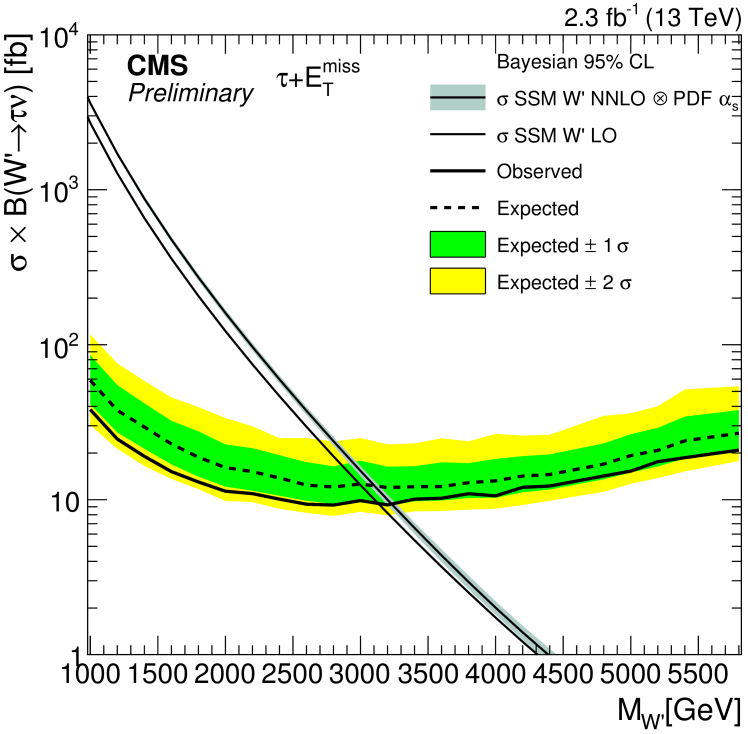
W'(→τν) Searches

Look for Jacobian peak in M_T(lν) distribution in tail

- also extend the searches looking at W'→ τν (BR=8.5%) with τ decaying hadronicllly;
- experimentally distinctive because of low charged hadron multiplicity w.r.t. QCD jets
- no significant deviation from SM expectation
- set the limit on SSM W': combined 8 & 13 TeV analyses exclude: 300 < $M_{W'}$ < 3.3 TeV







SSM W'

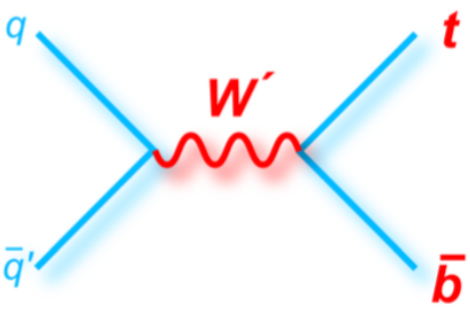
Run 1
$M_{W'}$ < 2.7 TeV

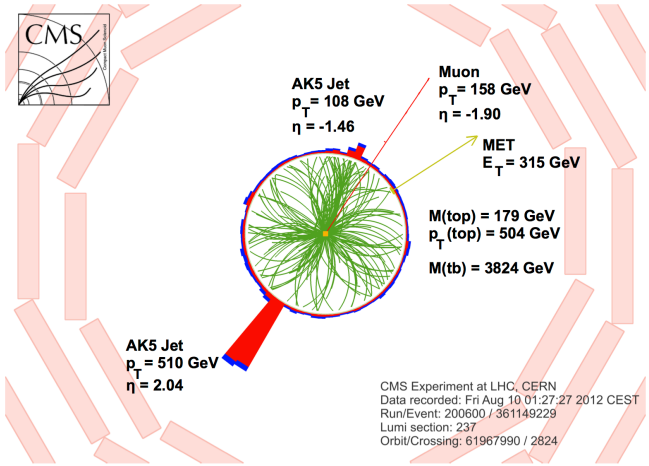
Run 2
$M_{W'}$ < 3.3 TeV

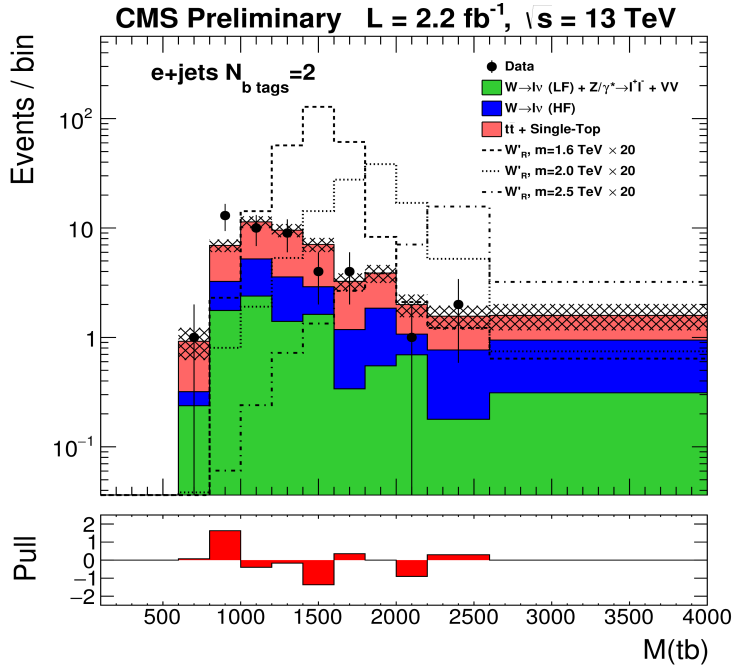
W'(→tb) Searches

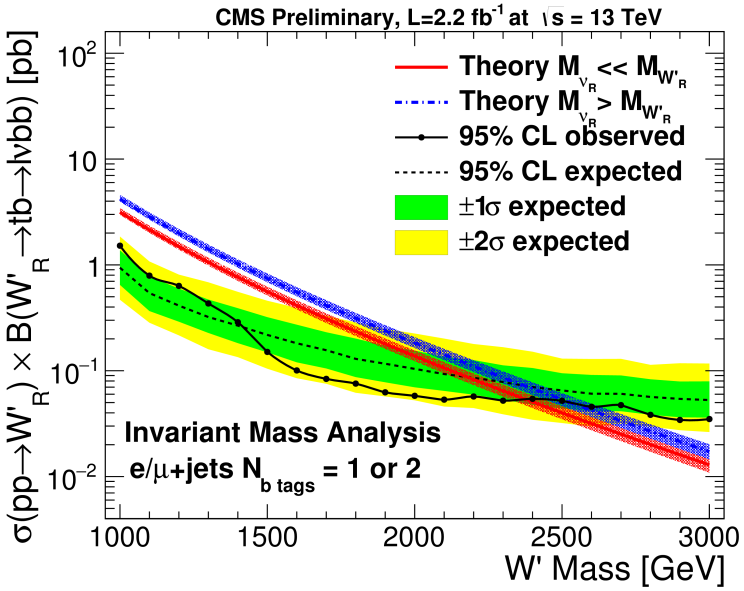
Also, search for W' decaying into t & b

- not as sensitive as e/μ, but W' can couple more strongly to 3rd gen
- select event with 1 lepton, 2 jets (>1 b-tag), MET
- reconstruct W' invariant mass, M(tb), by constraining neutrino p_z from W mass









- no evidence for W' boson production ☹
- treat 1 and 2 b-tag categories separately and then combine to set limits on the production x-section.
  - exclude RH W' bosons < 2.38 TeV
  - better than Run 1! (2.05 TeV)

tt Resonance Searches

Several BSM predict massive gauge bosons decaying into final states with top pair

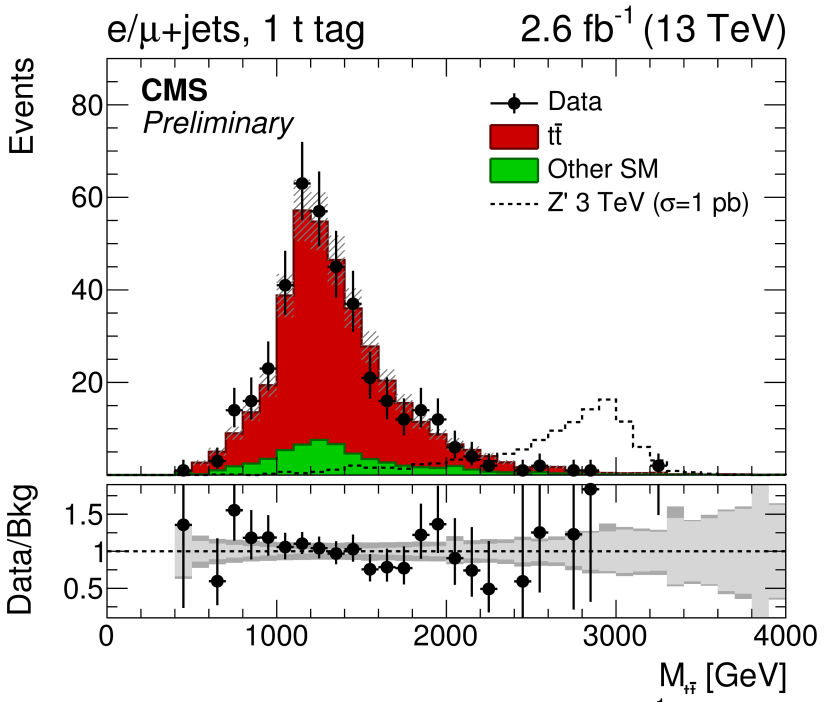
- e.g. Z', KK excitations, heavy Higgs, etc…
- analysis targets the semi-leptonic final state
- final event categorization based on # of b-tagged & t-tagged jets:

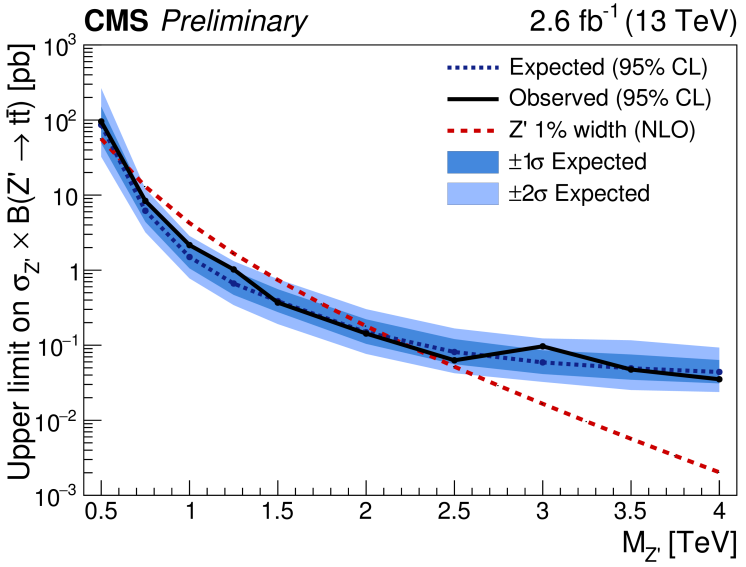
$$e/\mu \text{ channel} \otimes \begin{matrix} 1\ t\text{-tag} \\ 0\ t\text{-tag}\ \&\ 1\ b\text{-tag} \\ 0\ t\text{-tag}\ \&\ 0\ b\text{-tag} \end{matrix}$$

- reconstruct M(tt)
- no significant deviation from the SM prediction
  ⇒ limits extracted for different BSM scenarios

signal	excluded mass regions [TeV] μ + jets observed (expected)	e + jets observed (expected)	combination observed (expected)
Z' (1% width)	0.5 – 1.8 (0.6 – 1.9)	1.0 – 1.1, 1.3 – 2.2 (0.9 – 1.7)	0.6 – 2.3 (0.6 – 2.1)
Z' (10% width)	0.5 – 3.2 (0.5 – 3.3)	0.5 – 3.2 (0.5 – 3.2)	0.5 – 3.4 (0.5 – 3.5)
Z' (30% width)	0.5 – 3.9 (0.5 – 4.0)	0.5 – 3.8 (0.5 – 3.8)	0.5 – 4.0 (0.5 – 4.0)
KK gluon	0.5 – 2.7 (0.5 – 2.8)	0.6 – 2.7 (0.6 – 2.5)	0.5 – 2.9 (0.5 – 2.9)

competitive with Run 1!





EXO-15-002

Diboson Resonances

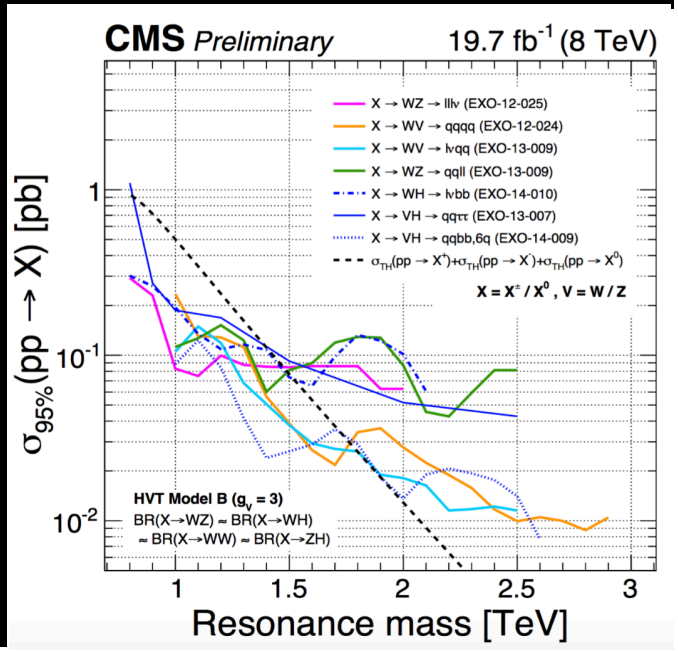
Many BSM predict heavy resonances decaying into diboson final states

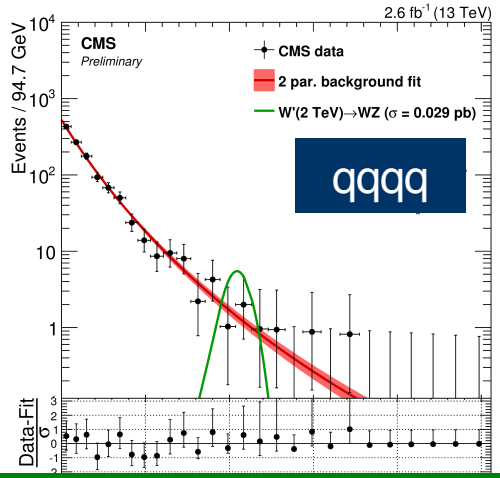
CMS performed comprehensive set of diboson searches in Run 1

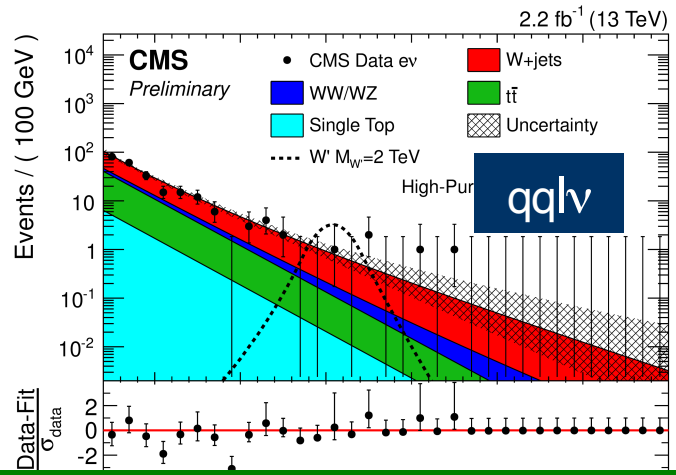
- cover many different final states
- cover different theoretical interpretations: RSG, WED, HVT_B
- observed modest excess(2σ) near 1.8-2.0 TeV
- use jet mass & substructure to identify boosted V→qq

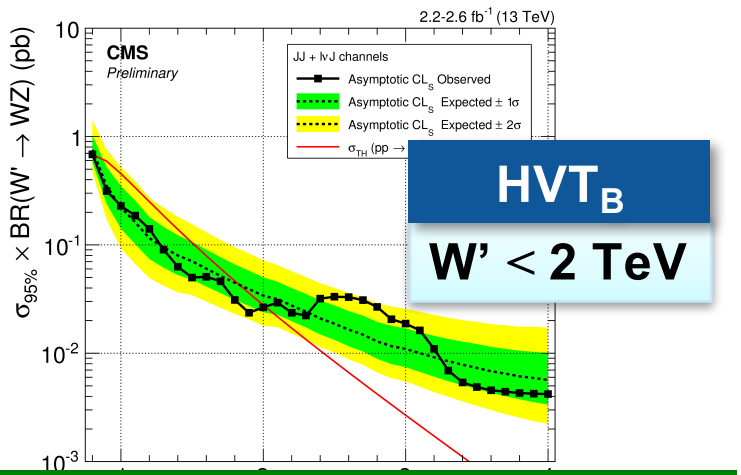
- Run 2: repeat the search using the most sensitive channels;
- The analysis is categorized in dijet mass for optimal sensitivity to WW, WZ, ZZ signals: reconstruct VV masses

JJ, lνJ









No particular enhancement around 2 TeV in the 2015 data so far!... more data needed to exclude it

B2G-16-004

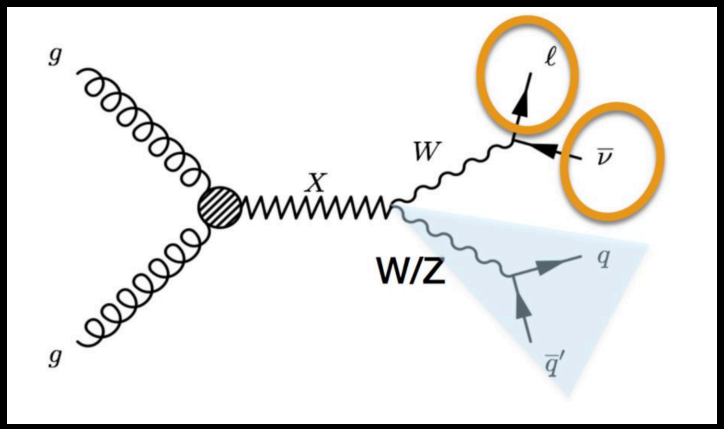
Diboson Resonances

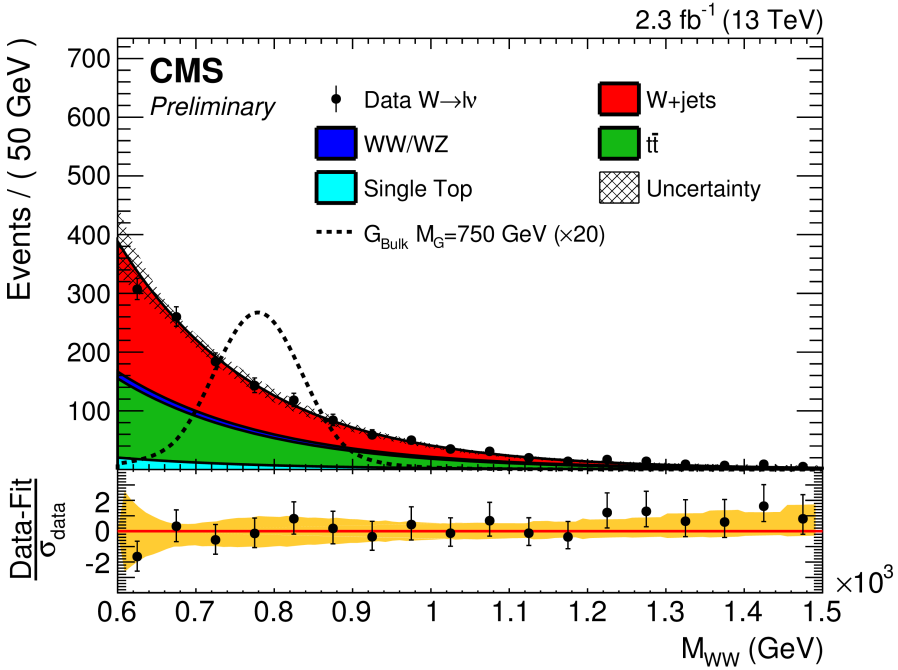
Extension of the X→VW→lνqq analysis to "low mass"

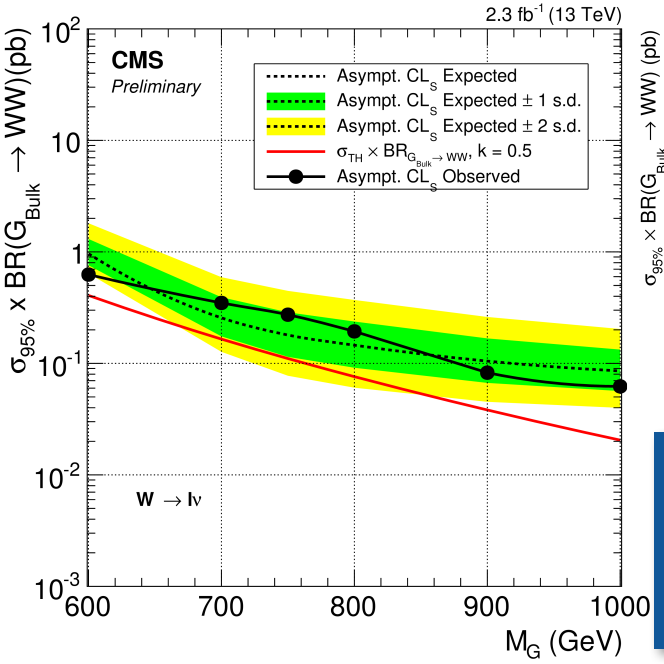
- i.e. 600 – 1000 GeV and optimized for X→WW
- probes region of di-photon excess
- signal modelling: narrow resonance approximation, bulk graviton as benchmark

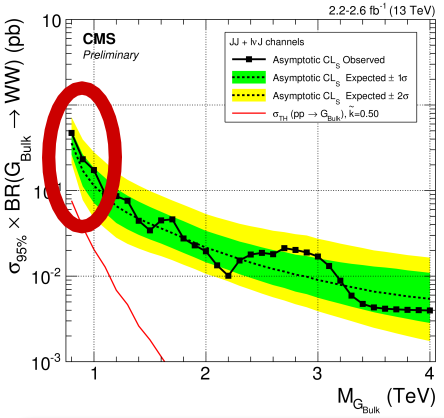
Resonance search is performed using the W^+W^- peak

- no significant deviation from SM expectation
- set the limit on x-sec ranges from 623 to 63 fb









Improves over high-mass analysis in the common range (800-1000 GeV)

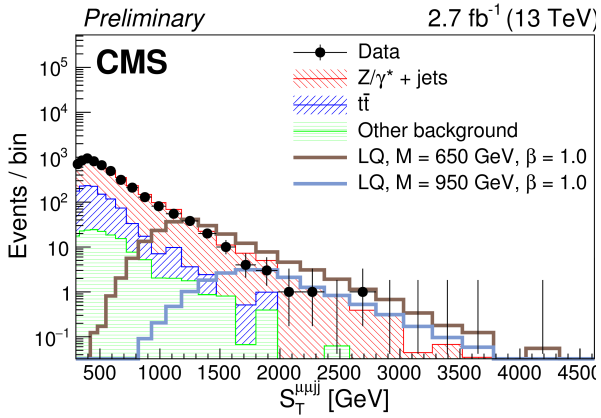
EXO-16-007

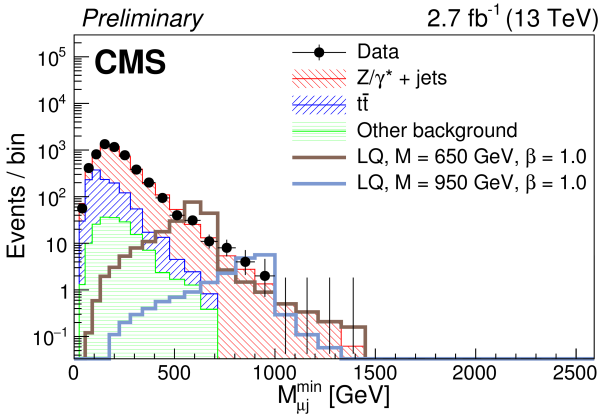
LQ Searches

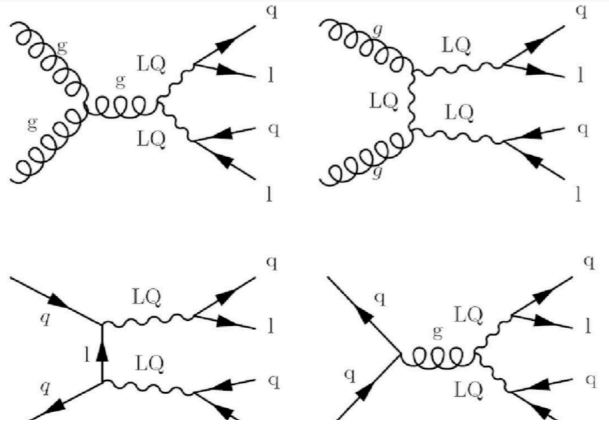
Many extensions of SM like GUTs, technicolor, compositeness predict the existence of LQ.

- search utilizes events with, at least, 2 muons & 2 jets, imposing criteria on $M_{\mu\mu}$, S_T, M(μ,jet)

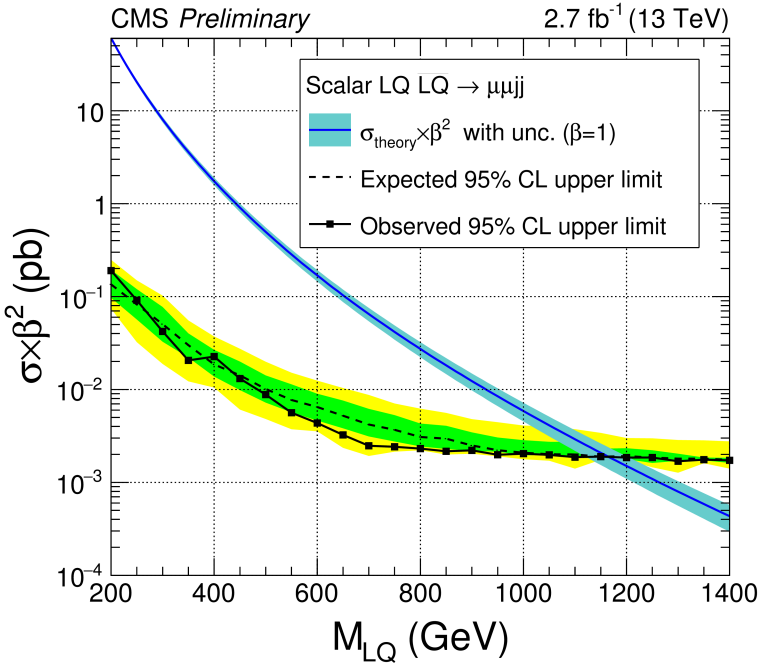
LQ carry both baryon & lepton numbers, fractional charge







- no evidence for 2nd generation LQ production ☹
- set limits on the production cross-section.
  - $M_{LQ} < 1165$ (960) GeV for β = 1 (0.5)
  - CMS 8 TeV results (19.7 fb^{-1}): $M_{LQ} < 1080$ (800) GeV for β = 1 (0.5)



EXO-15-007

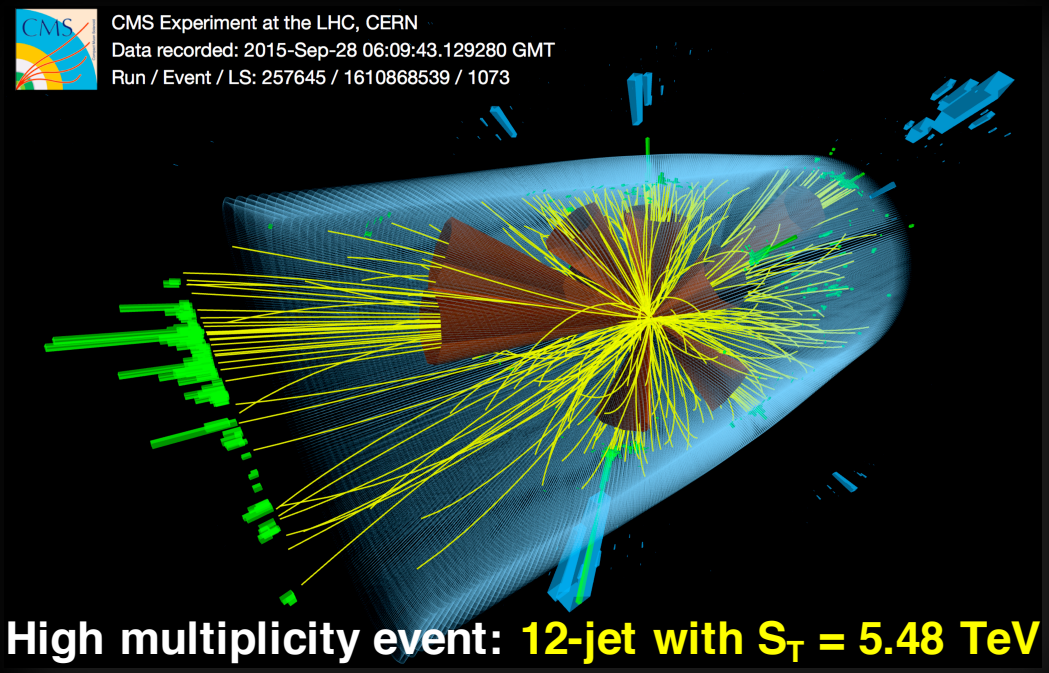
Black Holes

Smoking gun signature of TeV scale quantum gravity

- BH produce large number of energetic objects

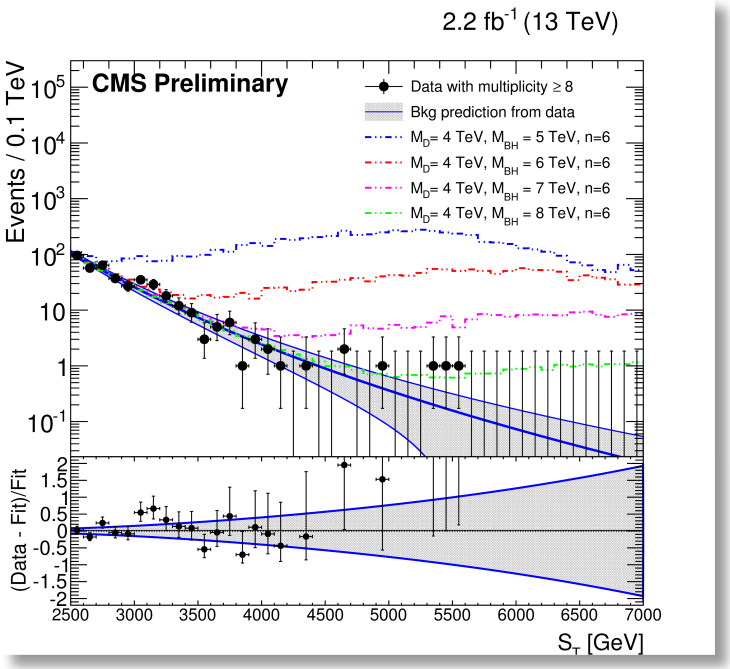
Search for deviation in S_T distribution in bins of object multiplicity (n; at least > 2)

- S_T = scalar sum of all objects with p_T > 50 GeV

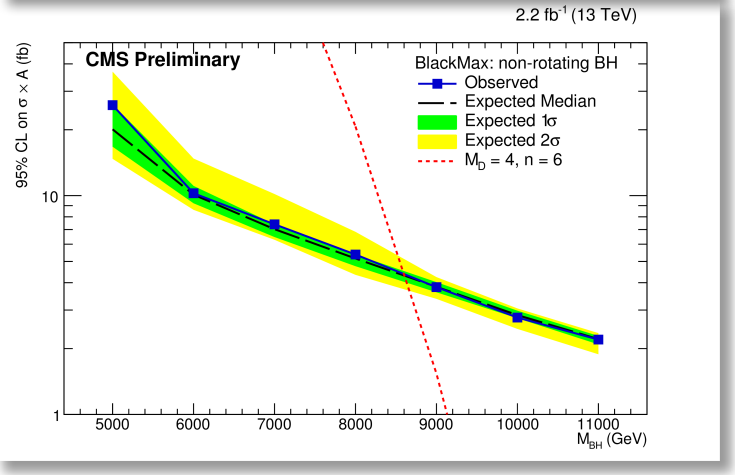


High multiplicity event: 12-jet with S_T = 5.48 TeV

BH mass excluded in range below ~8-9 TeV depending on assumptions: semi-classical BH & quantum BH



No excess observed in data



B2G-15-006

Top Partner Search

Many BSM include heavy partners to the top quark

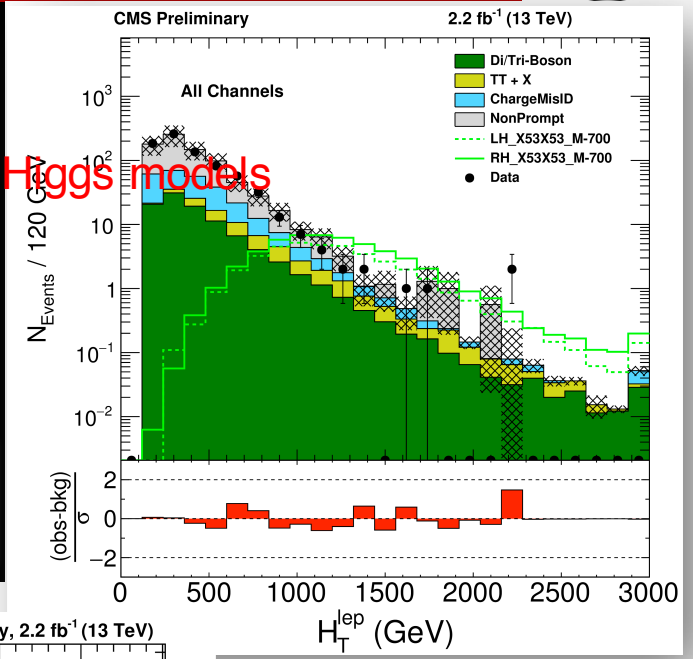
- ✦ simple extension of SM to 4th generation
- ✦ exotic top partner $X_{5/3}$ (w/ charge 5/3e) predicted by composite Higgs models

Search for pair-production of $X_{5/3}$ decaying 100% to Wt

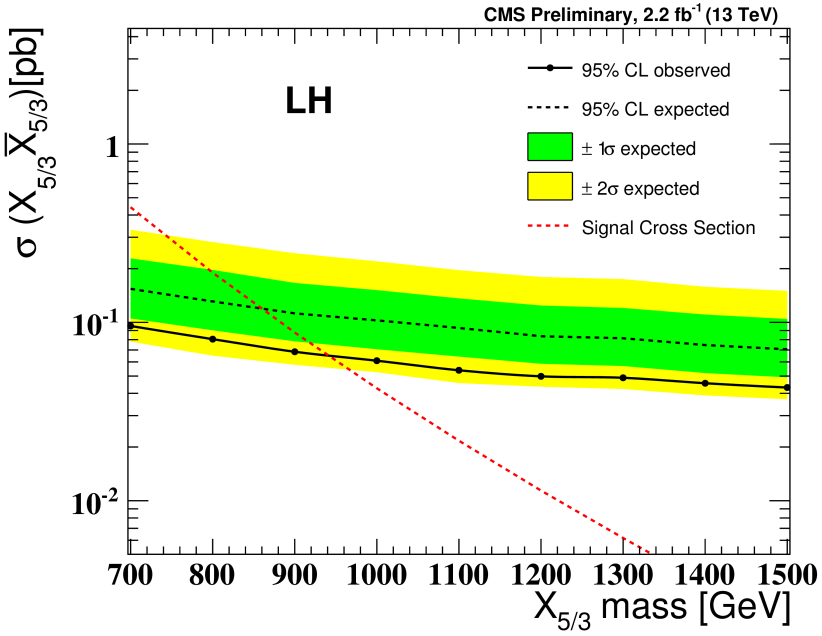
① consider SS dilepton & semi-leptonic channels

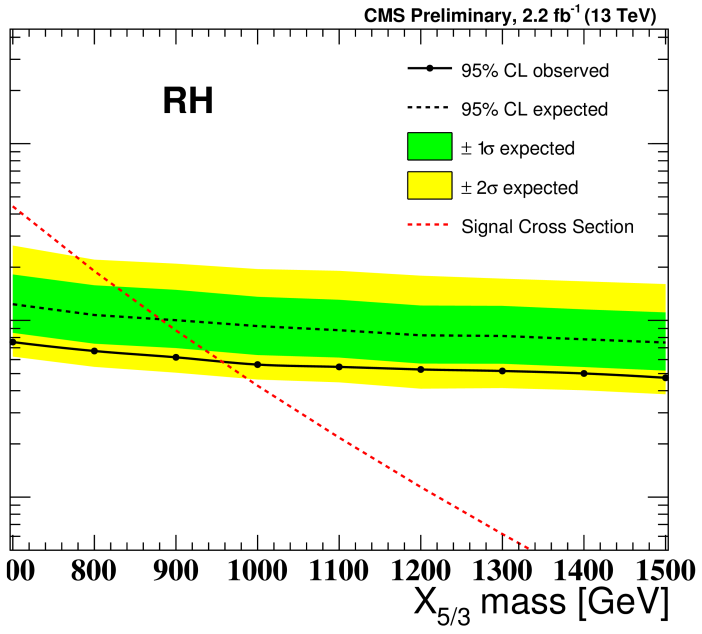
② require high multiplicity events with high H_T

- different channels and categories are combined to set limits on left-handed(LH) and right-handed(RH) fermion hypotheses



Reconstructed $X_{5/3}$ mass in all channels combined





combined RH
$M_{X(5/3)} < 960$ GeV

combined LH
$M_{X(5/3)} < 940$ GeV

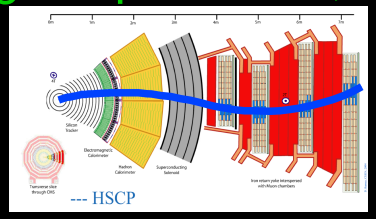
Run I: ~800 GeV
[Better than Run1]

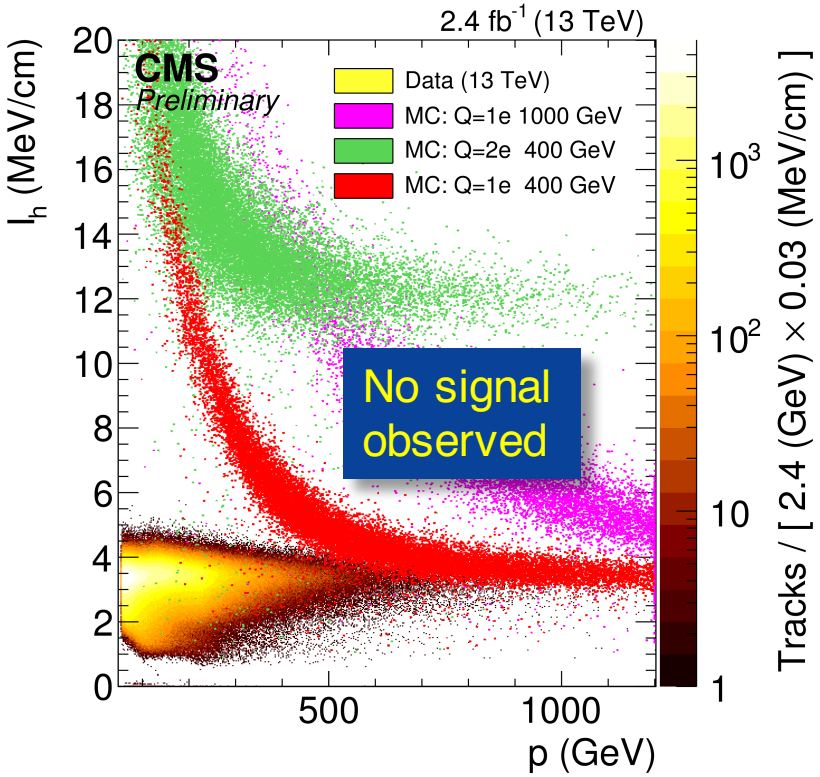
EXO-15-010

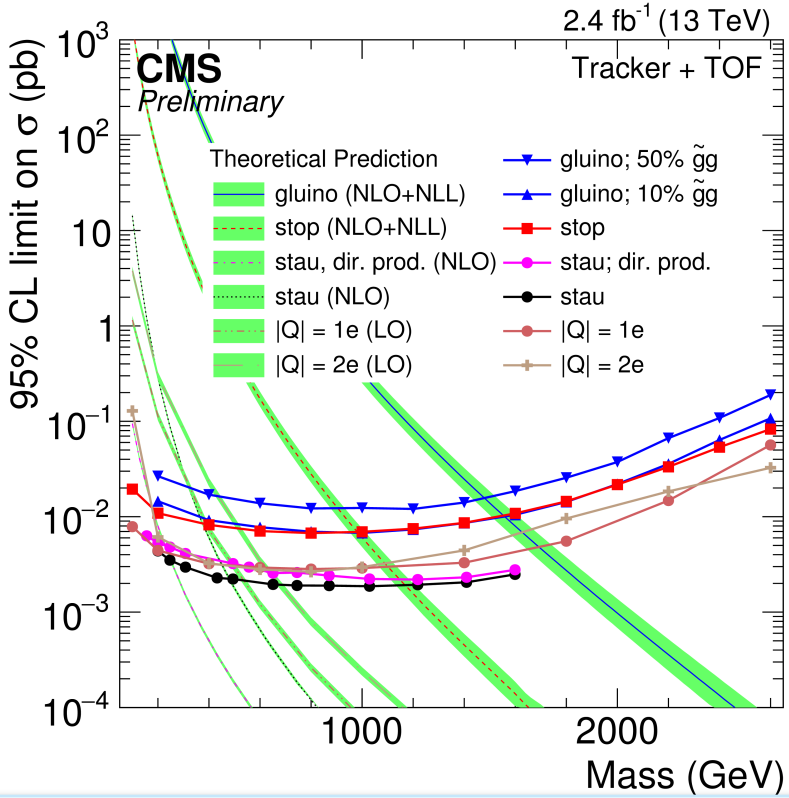
HSCP Searches

Heavy Stable Charged Particles appear in many BSM (e.g. $\tilde{g}$ in split SUSY, GMSB)

- since massive, HSCPs often travel considerably slower (<0.9c).
- signature: tracks with high p_T, high dE/dx, long TOF from IP to the muon system
- CMS has performed searches for 2 distinctive signature: **tracker-only & (Tracker+TOF)**







CMS has ruled out gluinos with a mass of up to 1.6 TeV, which was 1.3 TeV in Run 1.

Conclusions

- CMS is searching for evidence of different models of new physics beyond SM in many different channels/final state.
- No signals of the new physics BSM has been found in Run 2 data yet.
- Only recent/selected 13 TeV results shown here today, and many new results to arrive in the coming months.
- CMS has just begun exploring the full Run 2 13 TeV dataset. Stay tuned!

2016 and Beyond …

Looking forward to see more of these events…