Multi-jet Searches for New Physics at CMS

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(On behalf of CMS collaboration)

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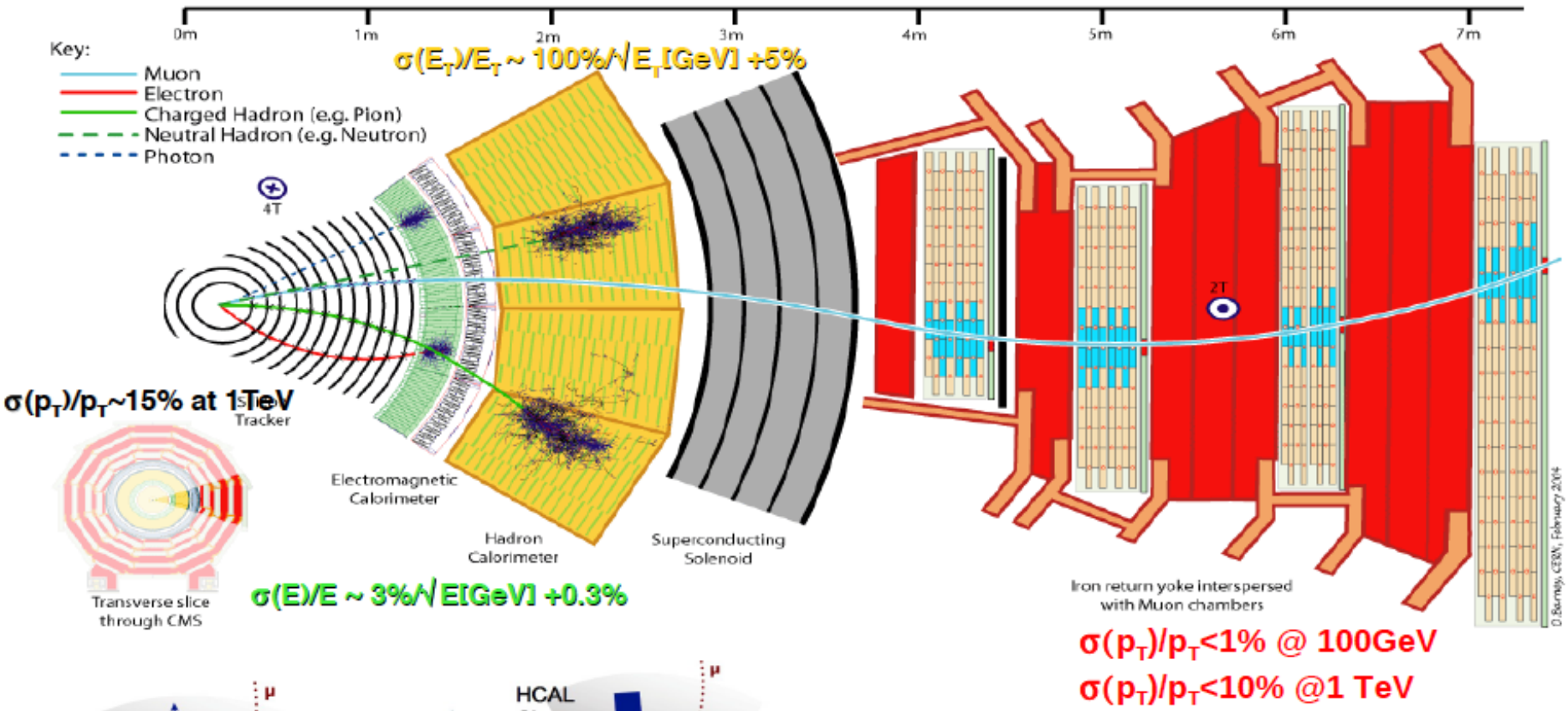
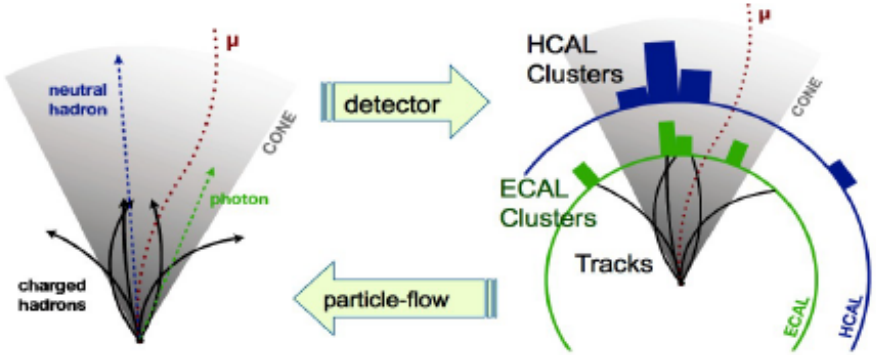
CMS: Physics Objects





Particle-Flow (PF) algorithms use:
e, μ, γ, charged & neutral hadrons
as building blocks for
jets, b-jets, τ's, ν (miss E_T), isolation

Why search for new physics with Jets?

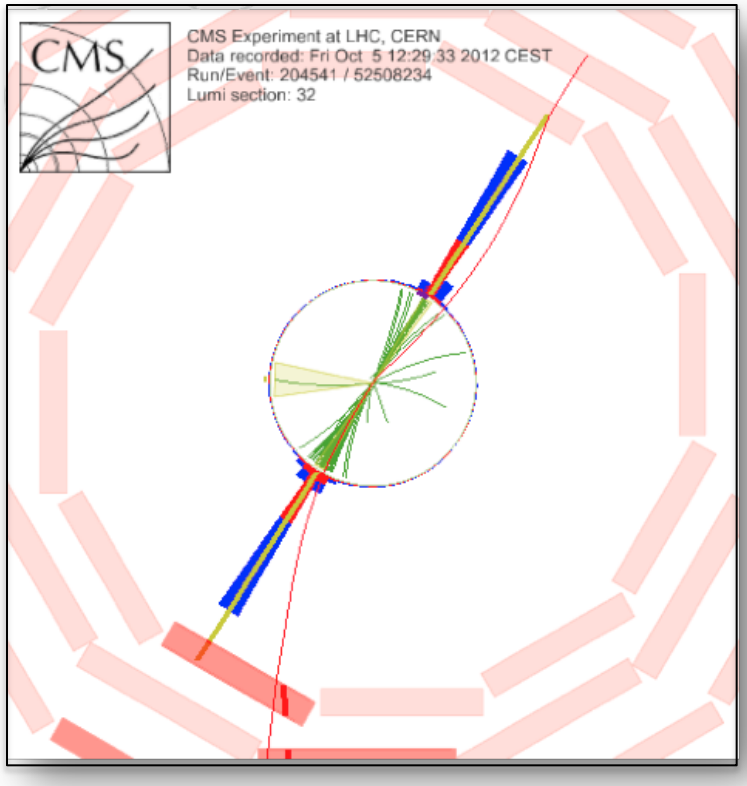
- We have a hierarchy problem if this is the Higgs and it is so light. The possible solutions from "new" physics:
  - SUSY: R-parity conserved and violated scenarios
  - Warped Extra Dimension
- We expect new physics if this is not the Higgs:
  - Need to find out a "Higgs"-like mechanism
  - Strong Dynamics?
- We need to find solution for Dark matter no matter what happens to Higgs
- Jets are everywhere, with several orders of magnitude higher cross section than other processes. Jets are either part of searching signal or background.

❖ **References for this talk:**

- Dijet mass 2012 [20 fb^{-1}] (EXO-12-059)
- Di-bjet resonance [20 fb^{-1}] (EXO-12-023)
- Search for W/Z tagged diet resonances [5 fb^{-1}] (EXO-11-095)
- Search for New Physics in the Paired Dijet Mass Spectrum [5 fb^{-1}] (EXO-11-016)
- Search for Multijet resonances [5 fb^{-1}] (EXO-11-060)
- Microscopic Black Holes [12 fb^{-1}] (EXO-12-009)
- Search for Jet Extinction in Inclusive Jet p_T Spectrum [10.7 fb^{-1}] [EXO-12-051]

Searches for Heavy Resonances

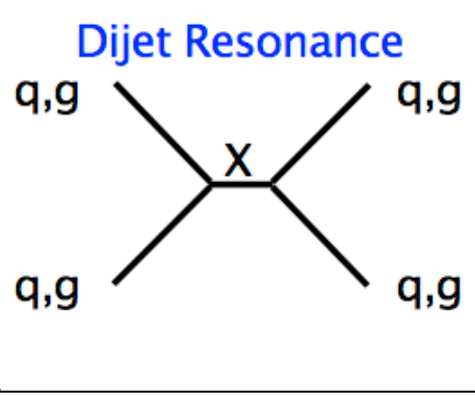
- Bump search in the dijet spectrum
- Bump search in di-bjet spectrum
- Bump search in W/Z tagged dijets
- Bump search in paired dijet mass
- Multijet resonance

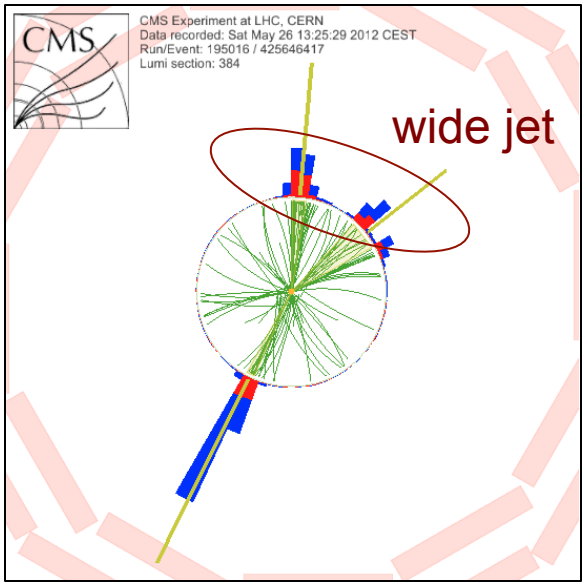


Dijet Mass Resonances - I

- The invariant mass spectrum of dijets is predicted to fall steeply and smoothly by Quantum Chromodynamics (QCD)
- Many extensions of the SM predict the existence of new massive objects that couple to quarks and gluons giving rise to resonances in the dijet mass spectrum
- Look for bumps in dijet mass spectrum

Model Name	X		Final-state Partons
String	S		$q\bar{q}$, qq, gg and qg
Axigluon	A		$q\bar{q}$
Coloron	C		$q\bar{q}$
Excited Quark	q^*		qg
E_6 Diquark	D		qq
RS Graviton	G		$q\bar{q}$, gg
Heavy W	W′		$q\bar{q}$
Heavy Z	Z′		$q\bar{q}$

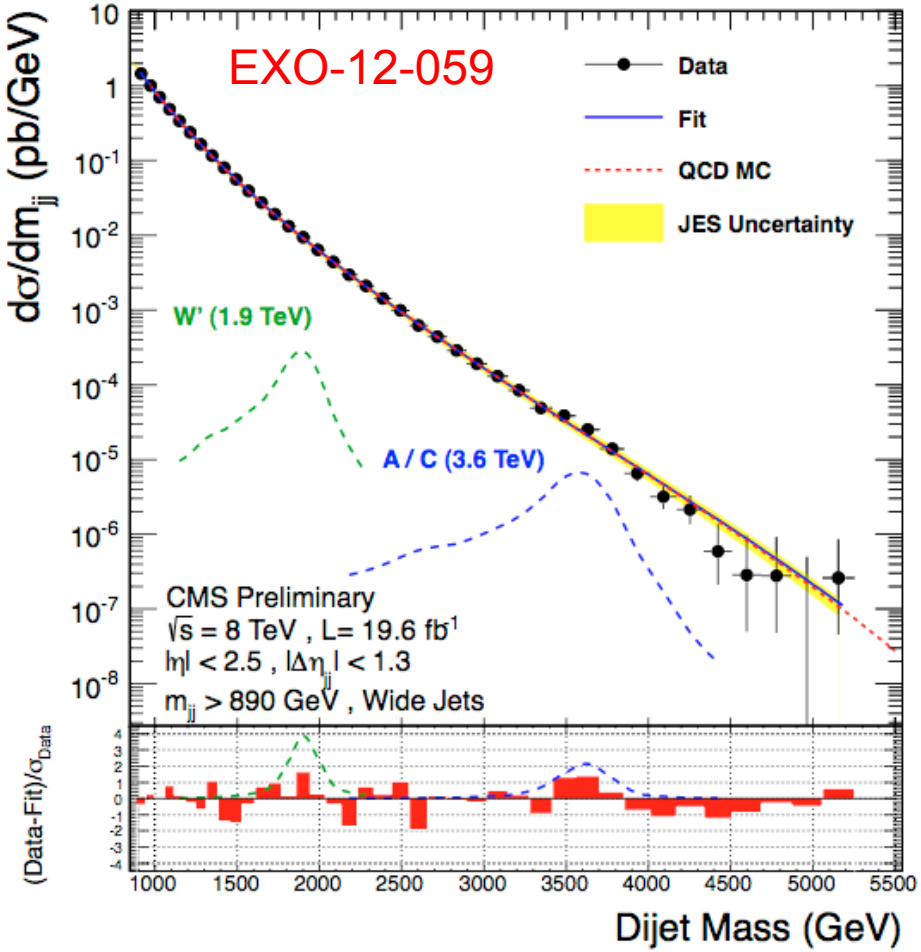




- Separate searches by final state **qq, qg, gg**

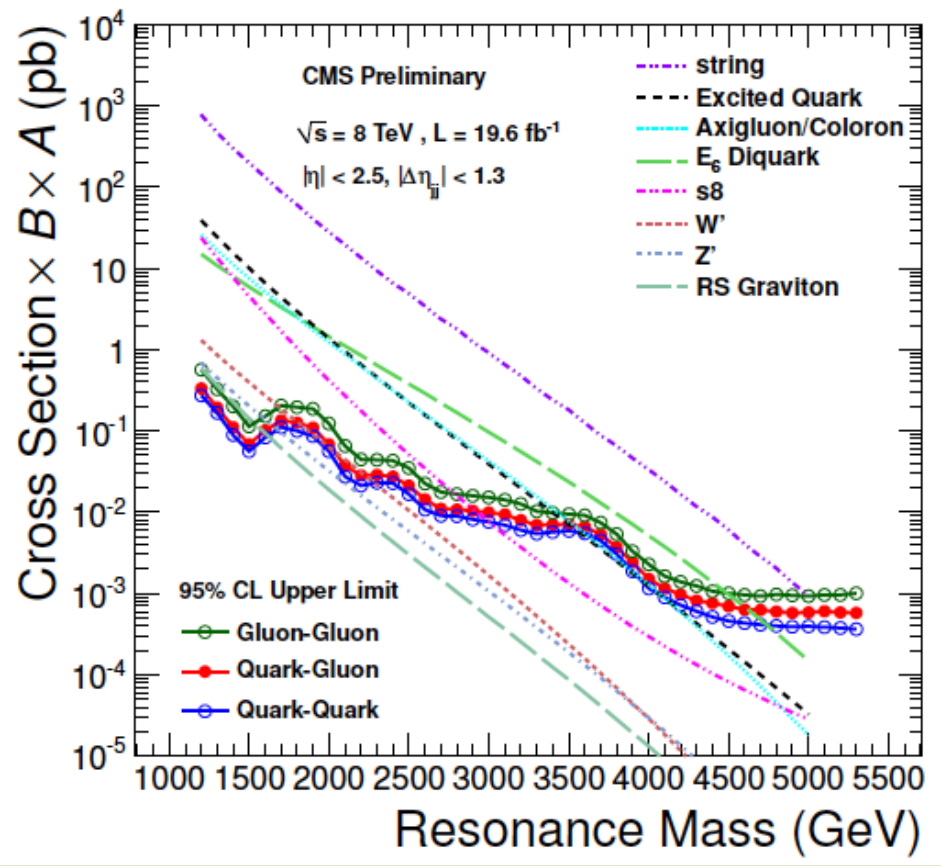
- "Wide jets" are used to reduce sensitivity to gluon radiation
  - Add all other jets closest to the leading two jets, within $\Delta R < R_{wide}$ (R_{wide}=1.1)
- Select two wide jets in event with $|\eta_1,\eta_2| < 2.5$ & $|\Delta\eta| < 1.3$

Dijet Mass Resonances - II



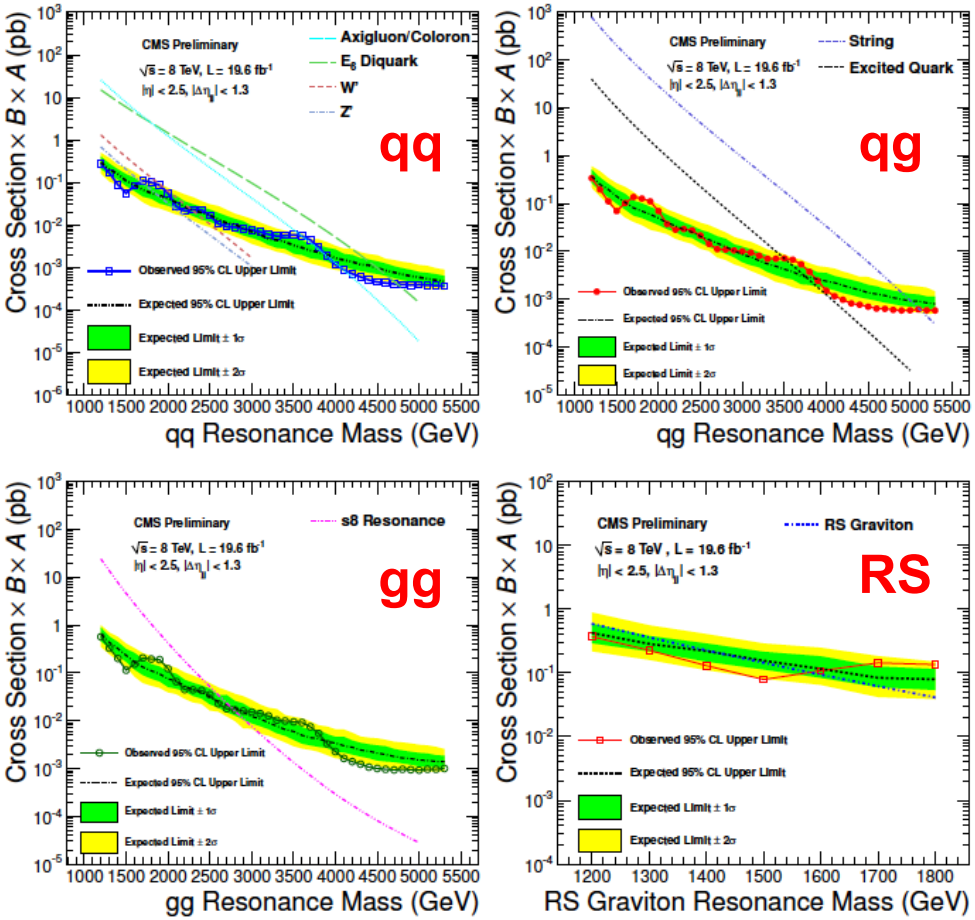
- Data well fit to a smooth, steeply falling function
- No resonance signal observed!

- Set model-independent limits on several models
- We obtain generic cross section upper limits on qq, qg, gg resonances.



Setting Limits to Various Resonance Models

- The lower mass limits reach up to 5.1 TeV, depending on the model, and extend previous exclusions from the dijet mass search technique
- The limits are compared to the expected cross section for 8 specific models



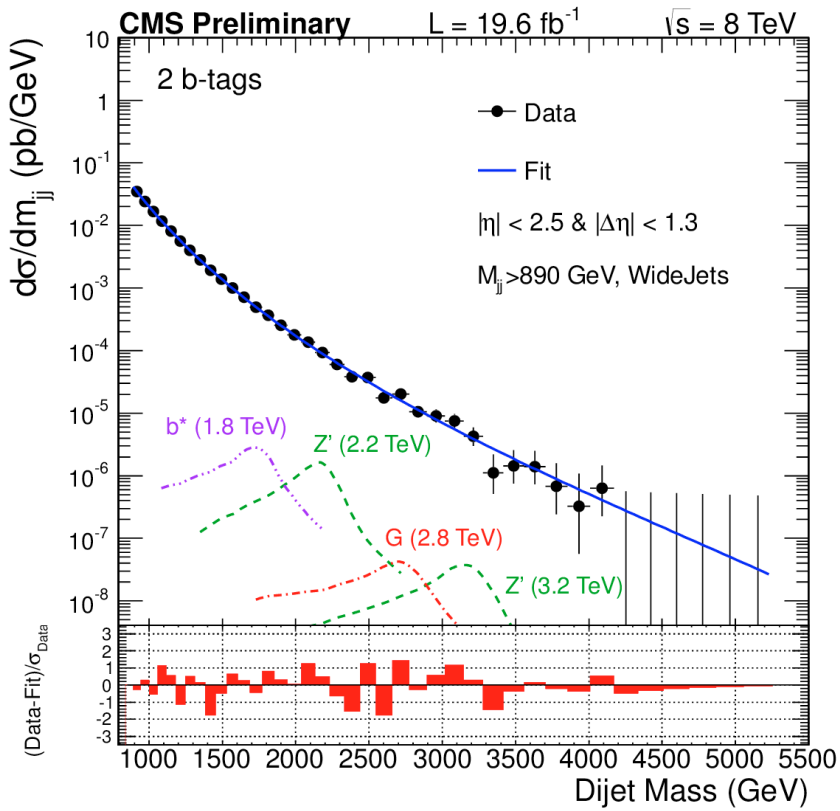
EXO-12-059

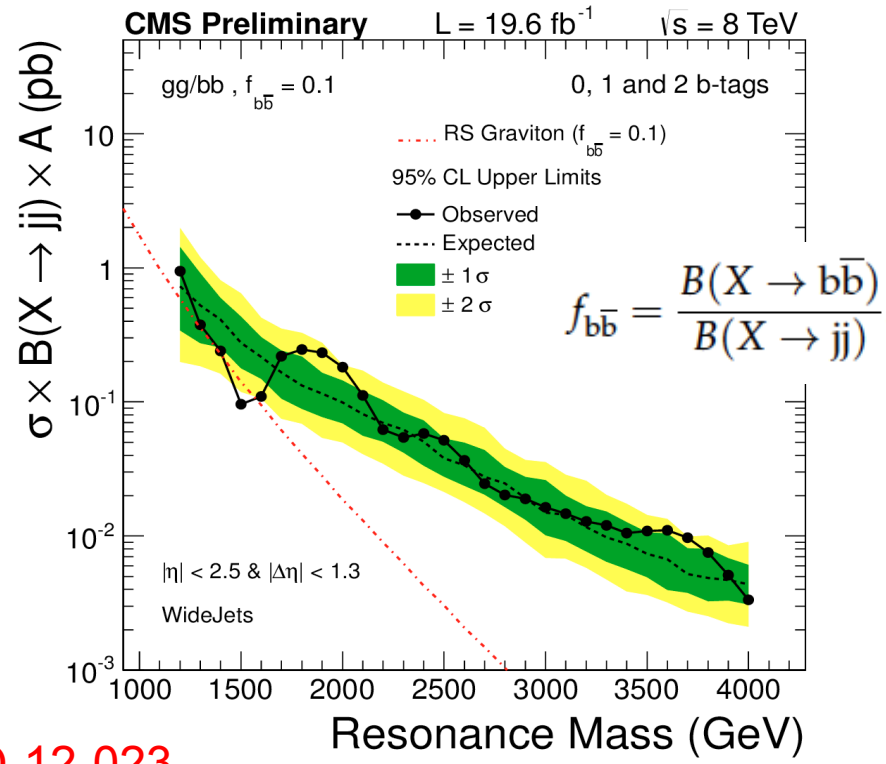
Model	Excluded Mass (TeV) ★	
	Observed	Expected
String Resonances	5.08	5.00
Excited Quarks	3.50	3.75
E_6 Diquarks	4.75	4.50
Axigluons/ Colorons	3.60	3.87
Color Octet Scalar	2.79	2.74
W' Bosons	2.29	2.28
Z' bosons	1.68	1.68
RS Graviton	1.58	1.58

★ lower limits on the excluded mass: eg. Mass(E_6)<4.75 TeV is excluded

Search for Di-bjet Resonances

- Extend inclusive dijet resonance searches by additionally considering information about the presence of secondary vertices within the jets -> jets resulted from b quarks
- Objects that decay preferentially into **bb** or **bg** final states will have <u>more stringent constraints</u> placed on their production

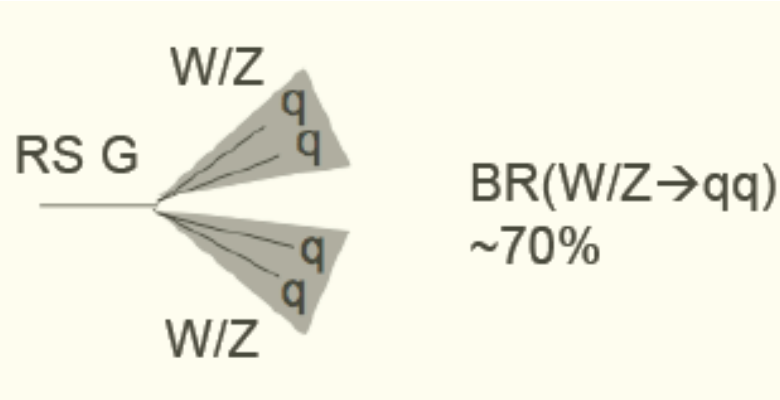




EXO-12-023

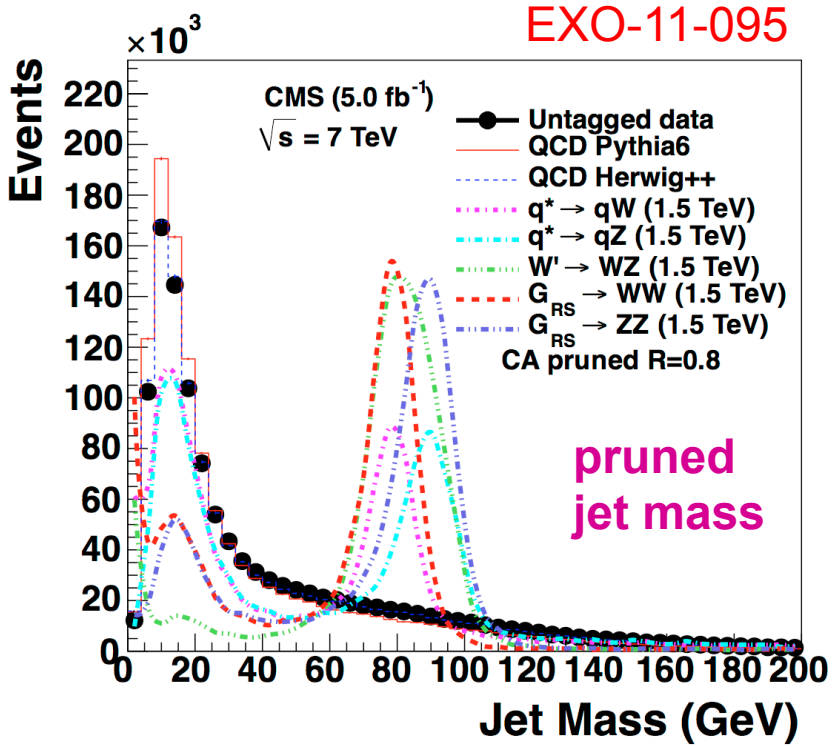
Model	Observed Mass Limits (TeV)
Z'	[1.20-1.68]
RS Gaviton	[1.42-1.56]
Excited b-quark	[1.36-1.53]

Search for W/Z tagged Dijet Resonance -I



- Look for new resonances coupling to pairs of vector bosons (ZZ,WZ, and WW)
- If M_X >~ 1TeV, boosted hadronic W/Z final states → "dijet" topology
- Use jet substructure techniques (jet mass, mass drop) to tag boosted hadronic W/Z bosons
- Data-driven background model with analytical functions

EXO-11-095



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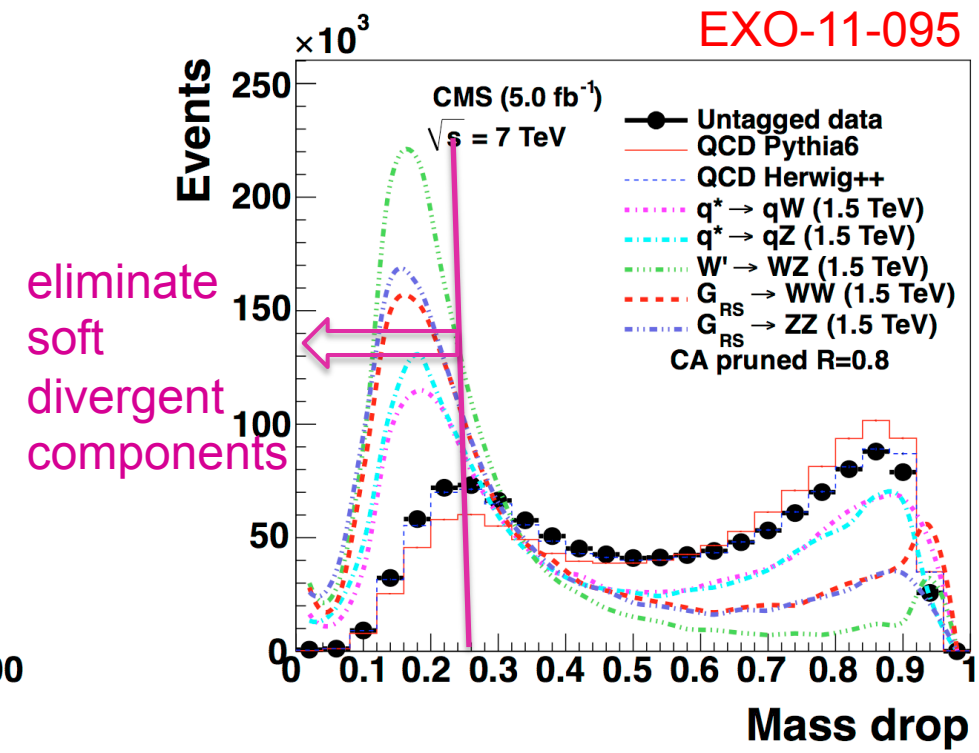
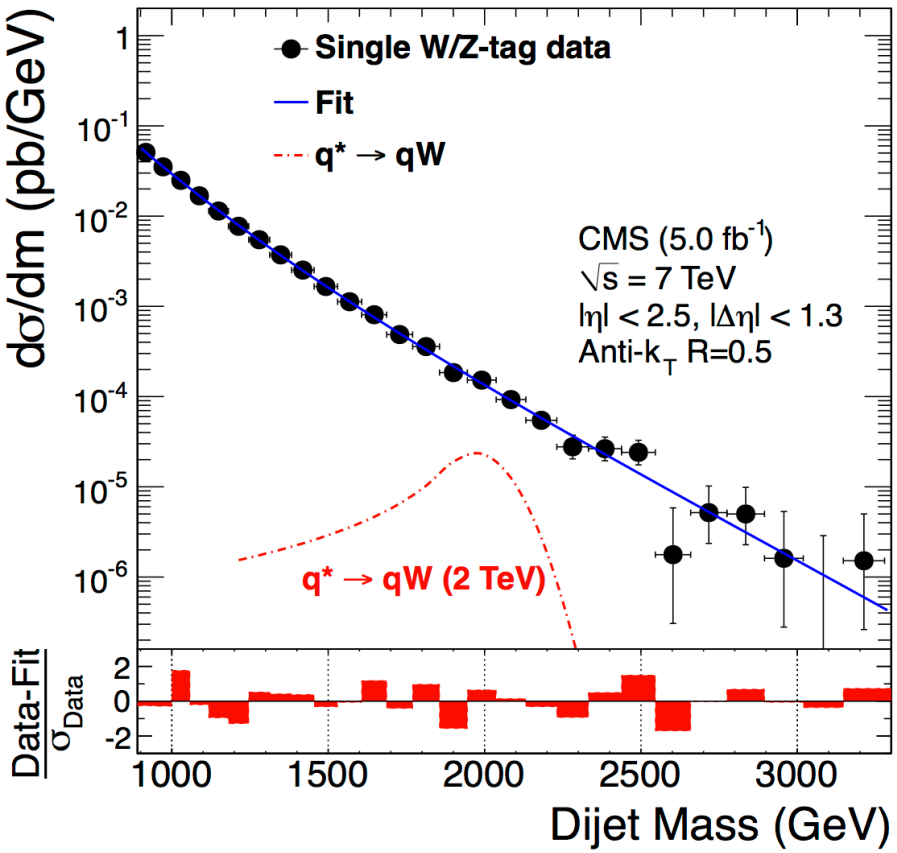


Search for W/Z tagged Dijet Resonance - II

EXO-11-095



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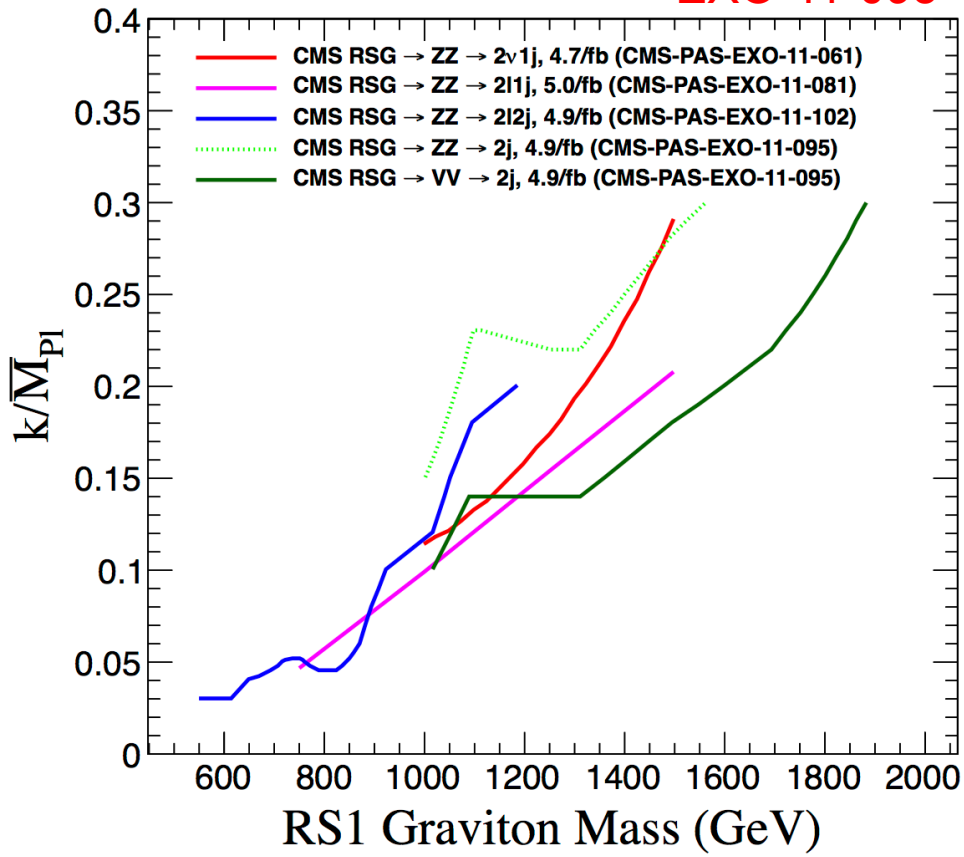
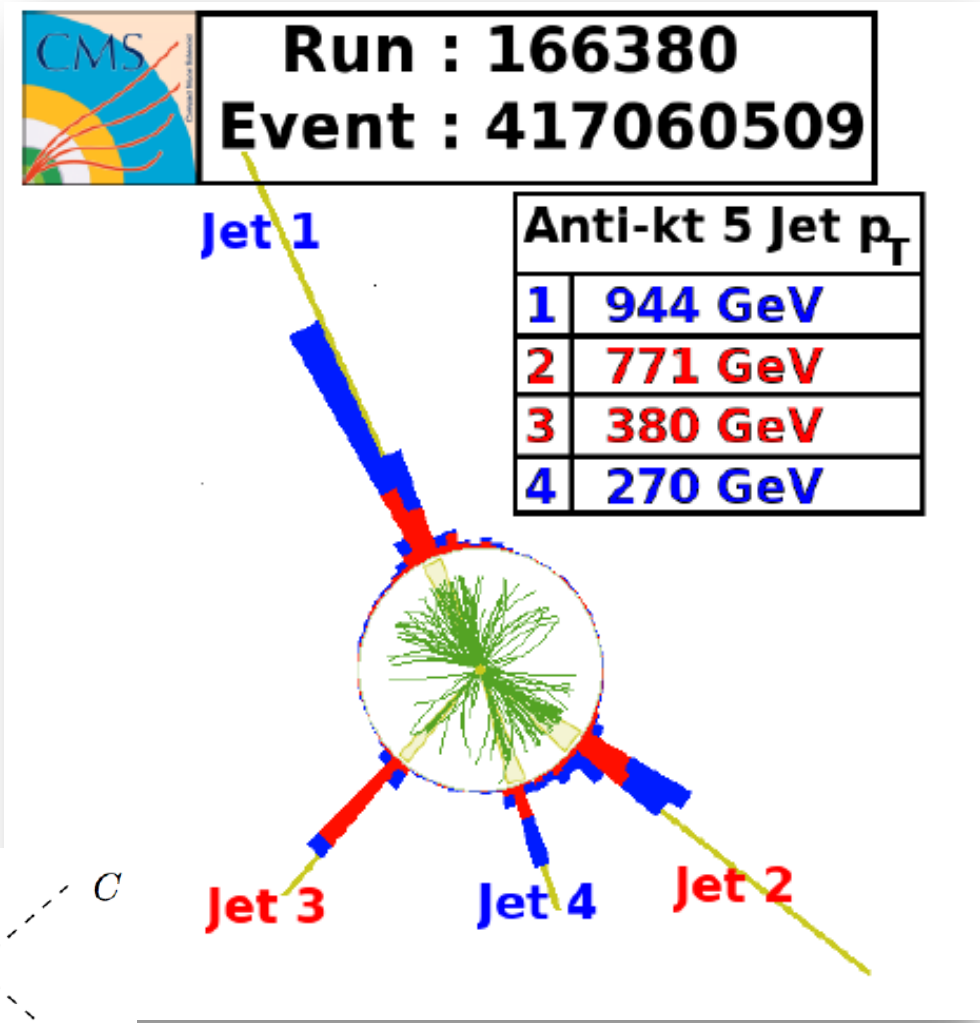
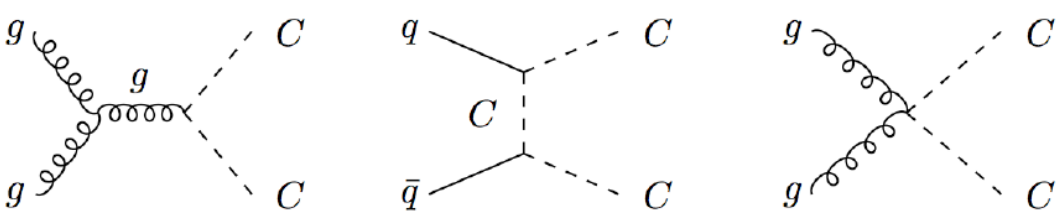


- ❑ No evidence of narrow VV resonances, set limits
- Excited quark resonances decaying into qW is excluded at 2.32 TeV
- Excited quark resonances decaying into qZ is excluded at 2.04 TeV
- Randall-Sundrum model, graviton resonances with masses in the range 750 – 880 (800) GeV at NLO (LO) are excluded for $k/M_{Pl} = 0.05$

Search for Resonances in Paired Dijet Mass

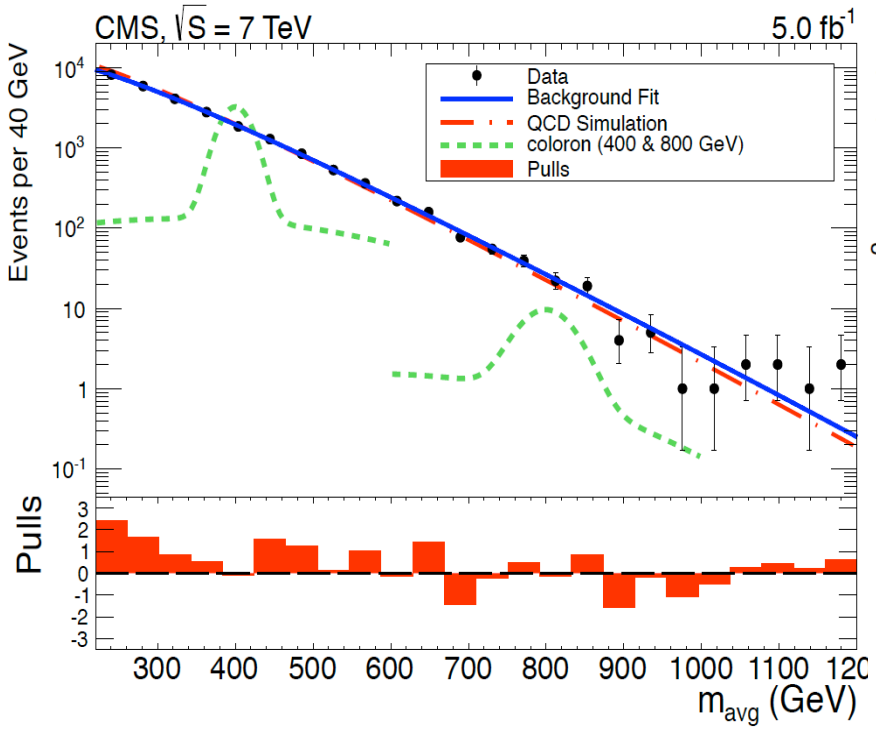
- Focus on physics signals from new colored particles, produced strongly in pairs, that decay hadronically to dijets
- Search for pair-produced narrow resonances each decaying into a pair of jets, using the paired dijet mass spectrum in four-jet final states
- Benchmark model: pair production of Colorons [Phys. Lett. **B670**, 119 (2008)] which decay to quark anti-quark pairs ($q\bar{q}$, gg -> CC -> $q\bar{q}\,q\bar{q}$)



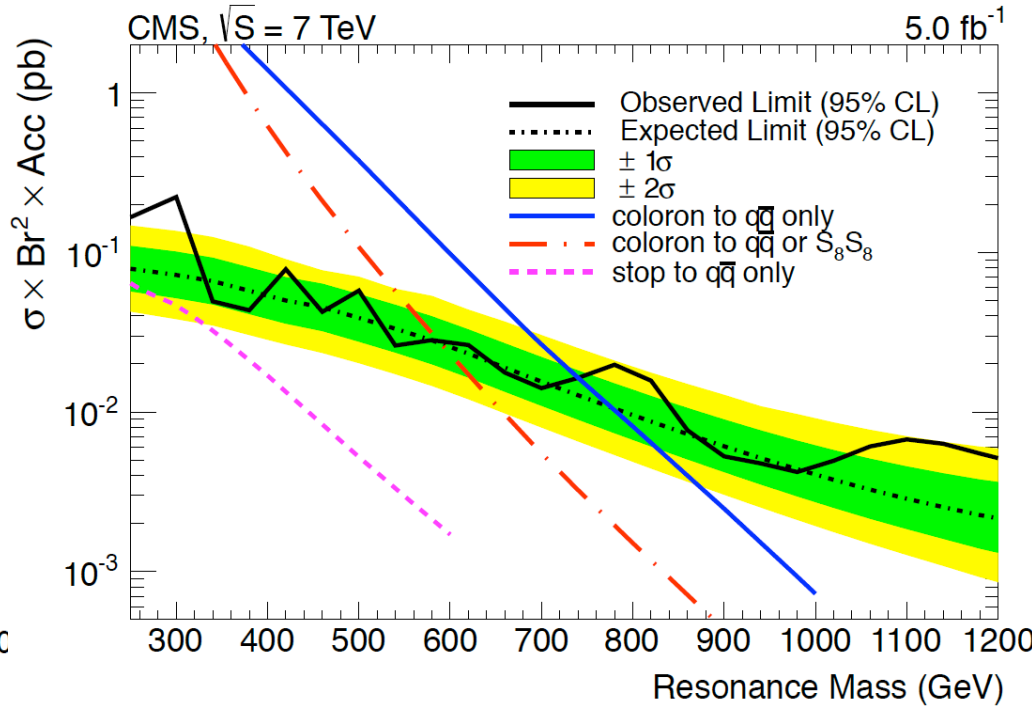


Limit to Colorons

$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}}$$



PRL **110**, 141802 **(2013)**



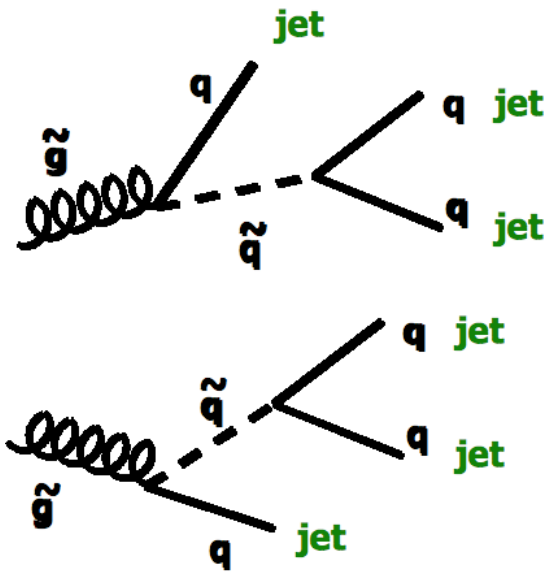
- 4-parameter parameterization as in Dijet Resonance search (blue solid).
- Both model the data well
- No evidence for new physics
- Clearly excluded at low resonance mass

❑ We exclude pair production of colorons with mass between 250 and 740 GeV at 95% C.L.

Search for Multijet Resonances

❖ **What if New Physics has color?**

- Q = g = $SU(3)_C$ Adjoint Majorana Fermion
- R-Parity violating (No Missing ET)
- Modeled as RPV (uds Yukawa) gluino (negligible intrinsic width)



❑ Studying pp → QQ → 3j + 3j = 6 jets

- Constructing ensembles:
  In the 6 jet scenario, there are 20 unique combinations of jet triplets
- The challenge:
  Separating the good ensembles (resonances) from everything else!

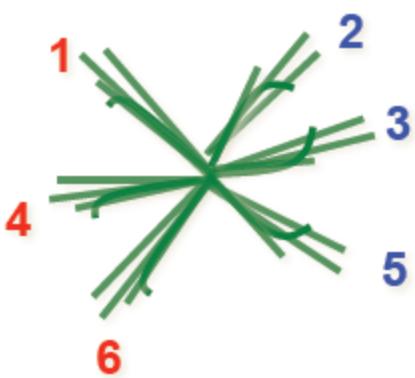
❑ Use established data-driven techniques
❑ Model-independent approach
❑ To improve sensitivity to the presence of a three-jet resonance:

$$M_{jjj} < \sum_{i=1}^{3} c|p_T|_i - \Delta$$

Triplet Mass

scalar sum of jet p_T

offset



6 highest pt jets

Q= g̃

pp → QQ → j j j, j j j

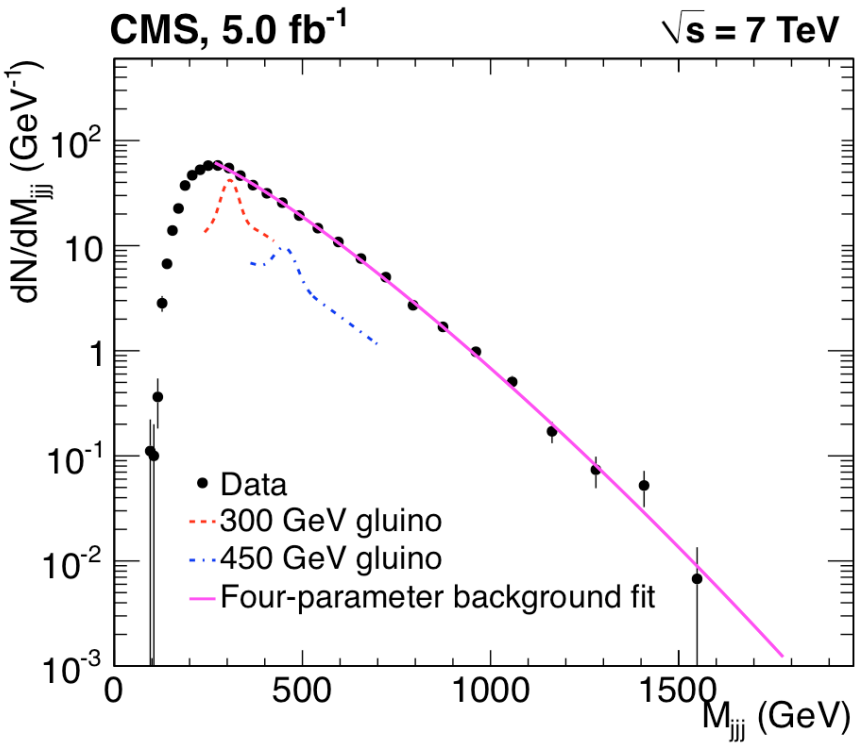
Limit to RPV gluinos

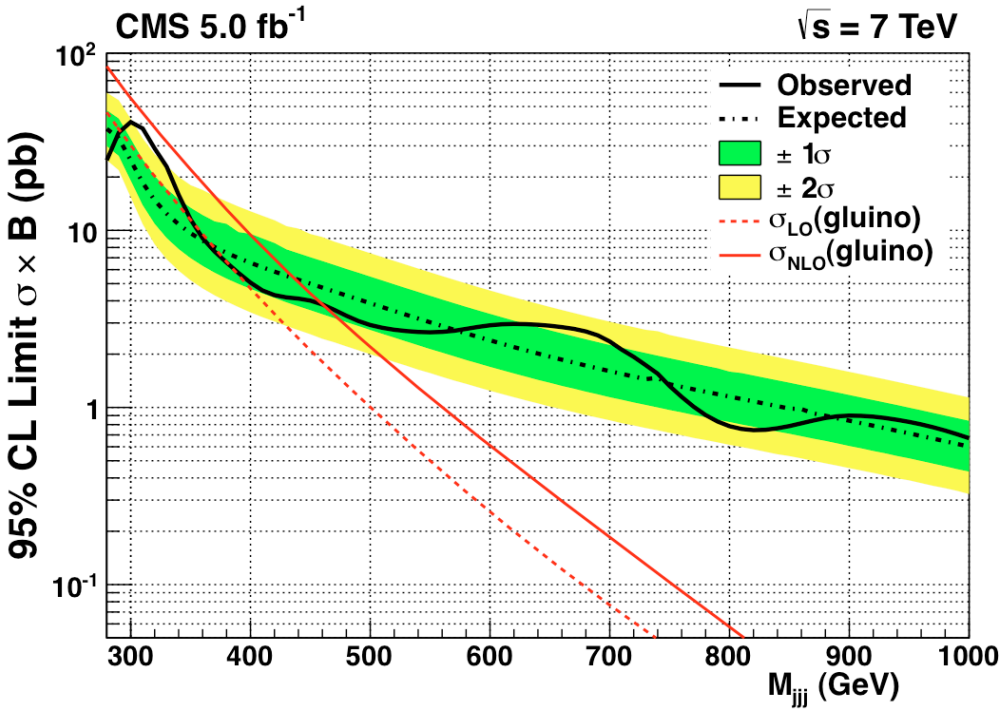
- Parametrized triplet mass:

$$\frac{d\sigma}{dM_{jjj}} = \frac{P_0(1 - M_{jjj}/\sqrt{s})^{P_1}}{(M_{jjj}/\sqrt{s})^{P_2+P_3\ln(M_{jjj}/\sqrt{s})}}$$

- Benchmark signal model: Pair produced gluinos
  - Production and decay are simulated in PYTHIA
  - Each gluino decays through Λ_{uds} quark RPV coupling, with a 100% branching fraction to three light-flavored jets

PLB **718** (2012) 329-347

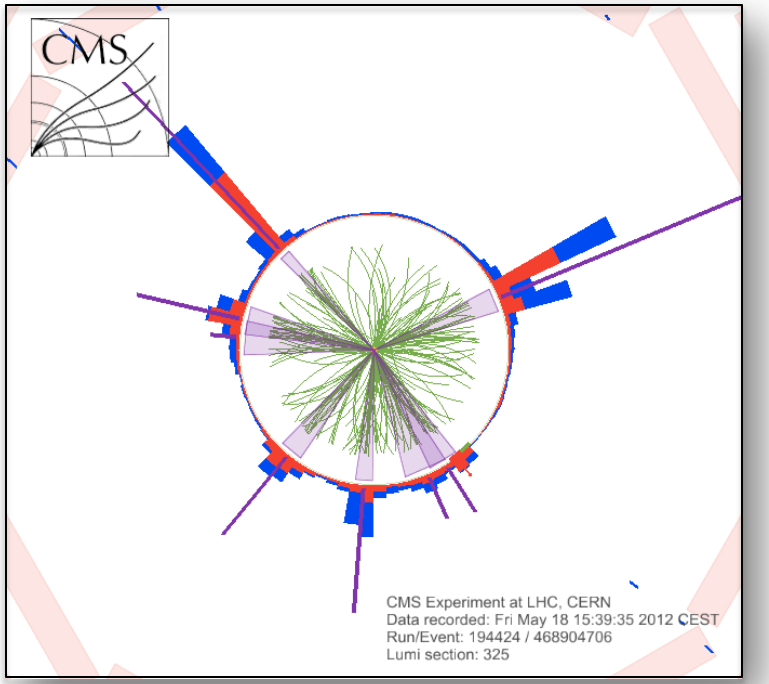




- Gluinos decaying through R-parity violating coupling is excluded for masses below **460 GeV** at 95% CL

Searches for
TeV Scale Gravity & Dark Matter

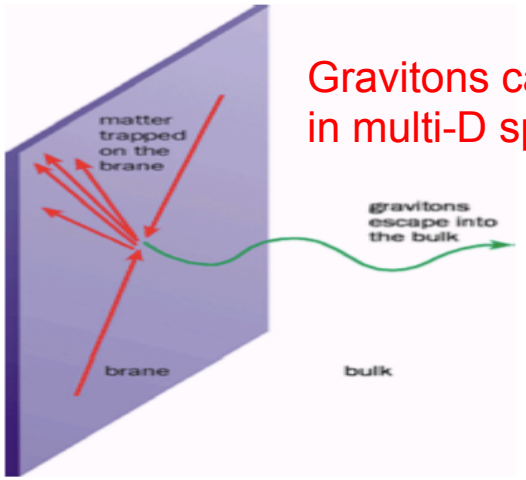
- Extra Dimensions *
- Microscopic Black Holes
- Dark Matter *
- Jet Extinction



** refer to S Malik's talk (Tue, 14:30, DM II session)*

Black Holes

- ADD (Arkani-Hamed, Dimopoulos and Dvali) model proposed to solve the hierarchy problem (M_{Pl}~10^{19} GeV, M_{EW}~10^{2} GeV)
- By introducing n extra dimensions in space, compactified on an n-dimensional torus or sphere with radius **r**
- Only gravity can propagate in extra dimensions
- Gravitation coupling enhanced at distances smaller than **r**
- "True" Planck scale in 4+n dimensions (M_D) can be lowered to the EWK scale
  - Scale for new physics given in terms of multi-dimensional Planck scale M_D



Gravitons can propagate in multi-D space

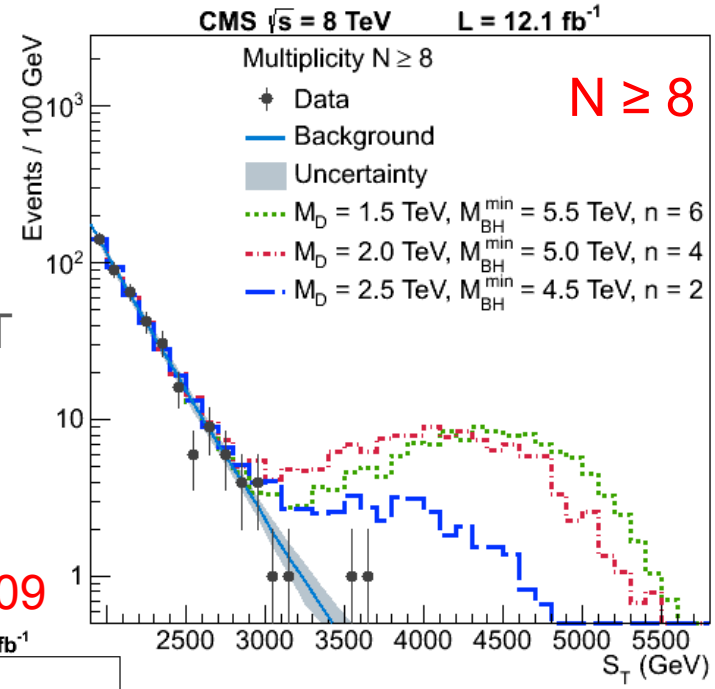
$$M_D^{n+2} = M_{Pl}^2 / (8\pi \cdot r^n)$$

Democratic BH decay via Hawking radiation to all SM degrees of freedom (mostly quarks and gluons)

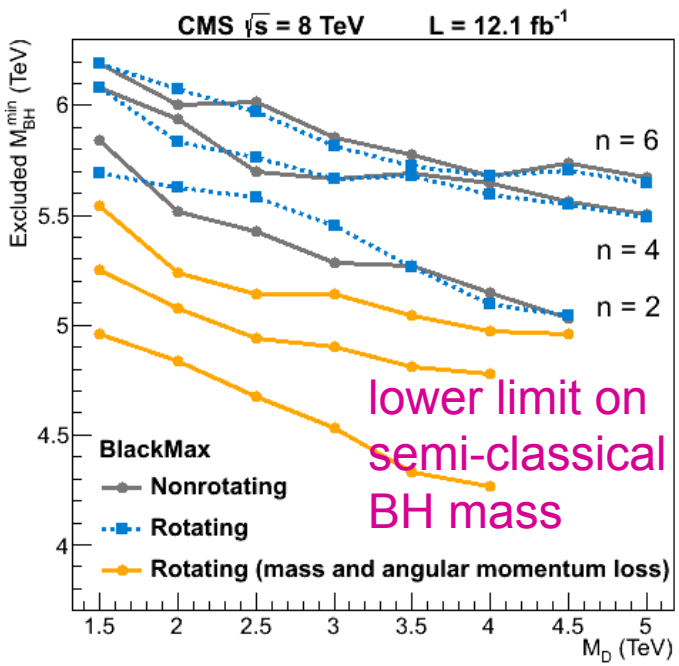
- One prediction is the formation of microscopic Black Holes
  - Spectacular signature with large number (N) of energetic particles (75% jets, 25% W/Z/γ/leptons)

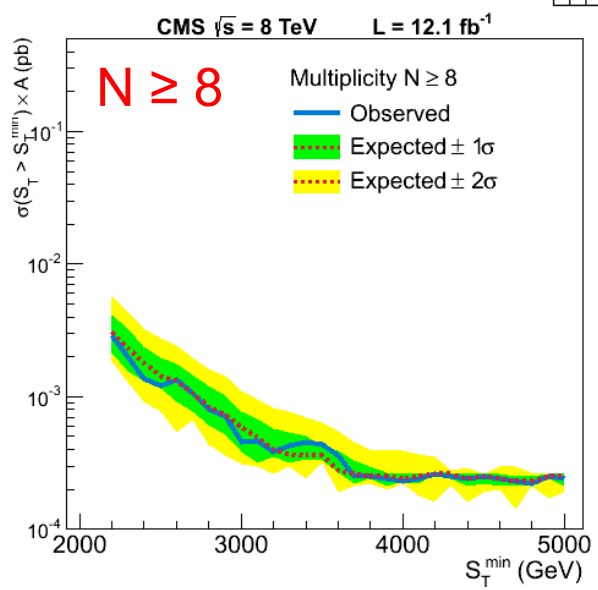
Microscopic Black Holes

- 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 in final state (N at least > 2)
- S_T = scalar sum of all objects with p_T>50 GeV+MET
- Use S_T spectrum from N=2 to predict QCD background at N≥3,4,5,6,7,8,9,10 where signal would be present



EXO-12-009



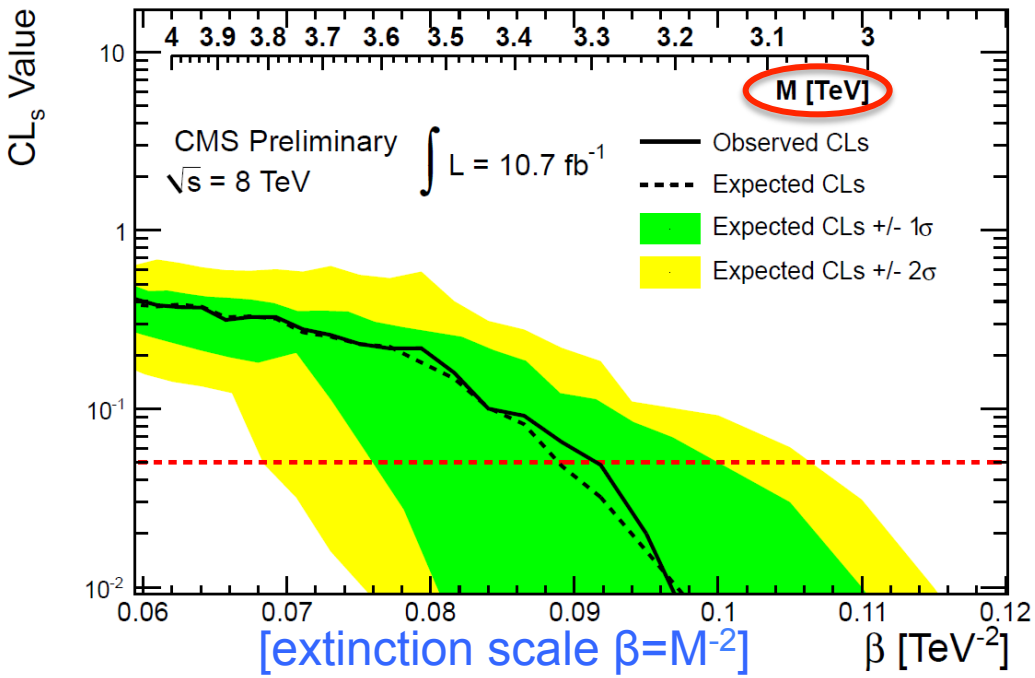


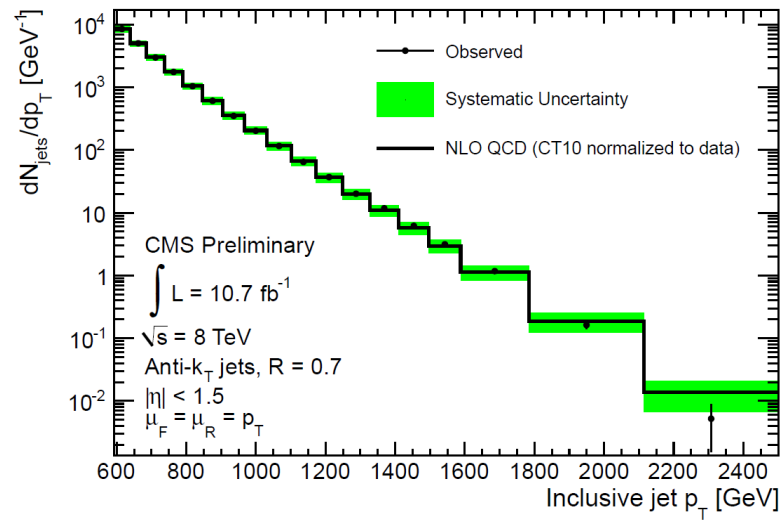
- No excess observed in data
- Set model independent upper limit on the minimum BH mass of 4.3 – 6.2 TeV

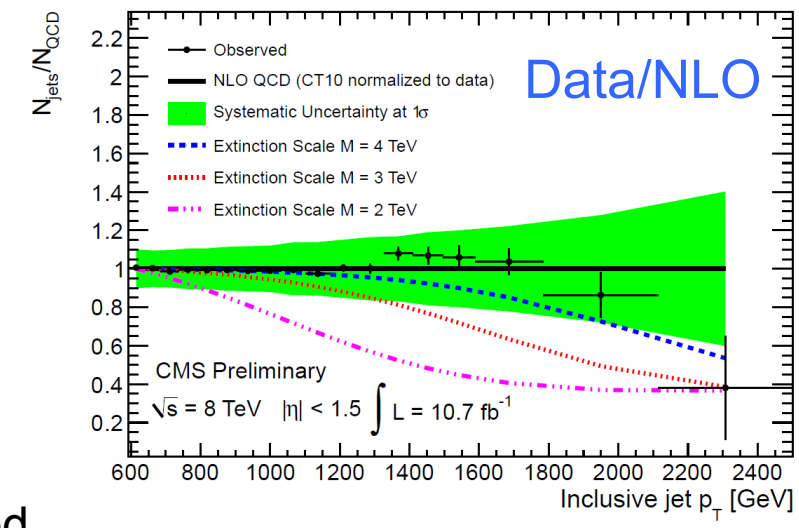
Search for Jet Extinction in Inclusive Jet p_T Spectrum

- Motivation: Search for signatures of Terascale gravity at the LHC
- Extinction signatures manifest as an attenuation of SM processes → Beyond some scale, expected σ drops rapidly to zero

EXO-12-051







- ❑ No Evidence of an extinction effect is observed with respect to an MSTW or CT10 background prediction
- ❑ A limit of 3.3 TeV is set on the extinction scale given CT10 (3.6 TeV for MSTW)

Conclusions and Outlook

- Searches for evidence of different models of new physics beyond SM in final state with jets remain crucial in CMS
- No signals of the new physics BSM has been found in data yet
- CMS has already set the most stringent limits on many BSM scenarios using multi-jets in the final state
- Only recent/selected 8 TeV results shown here today, and many more new results to arrive in the coming months
- For more results:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

- Interest continue on searches for heavy resonances in diboson final states
  - High resonance mass -> boosted topologies (i.e. jet substructure)
  - Start searching for new particles decaying to ~125 GeV "Higgs"
- SUSY particles might be long-lived
  - Try to be model-independent and exploit all the different detection techniques
    - dE/dX in trackers, TOF in muon detectors, timing in calorimeters
- **Stay tuned!**