Search for New Physics in the Dijet Mass Spectrum and Dijet Ratio in *pp* Collisions at $\sqrt{s} = 7$ TeV

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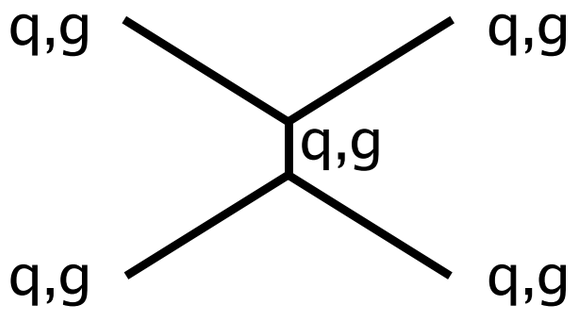
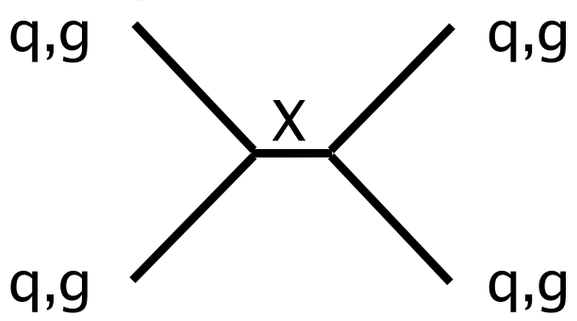
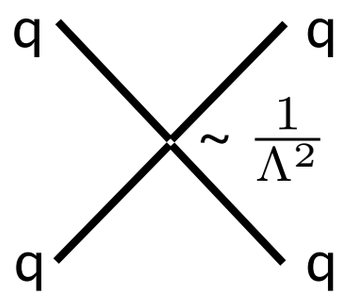
Motivation

- We study the inclusive dijet final state using the complementary dijet mass spectrum and dijet centrality ratio.
- These provide a test of QCD and sensitivity to new physics.

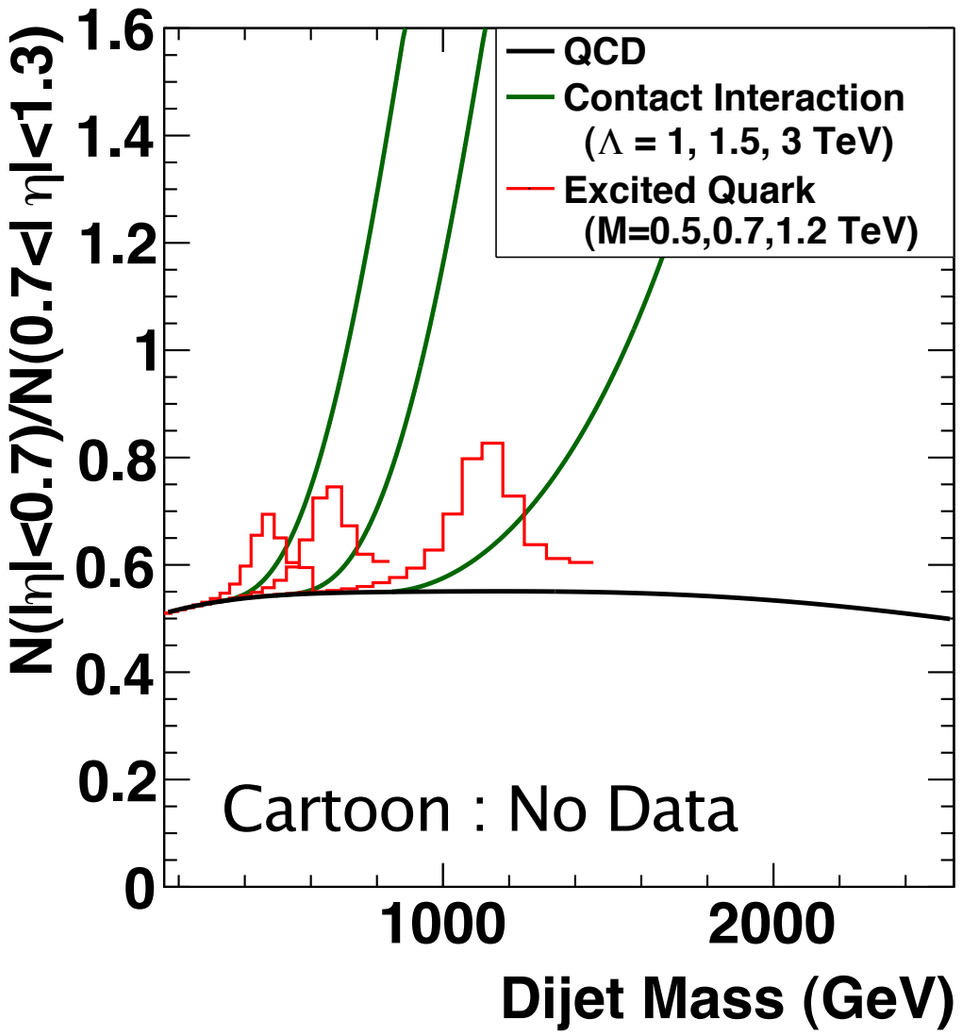
	Mass Spectrum	Centrality Ratio
QCD 	Test of cross section vs. dijet mass predictions from QCD and PDFs.	Test of QCD predictions for angular part of dynamics.
Dijet Resonance 	Most sensitive “bump” hunt for particles decaying to dijets.	Less sensitive to dijet resonances, but important confirmation that “bump” is real.
Contact Interaction 	Because of experimental uncertainties, mass spectrum is less sensitive to quark compositeness.	Sensitive search for quark compositeness.

The Dijet Centrality Ratio

- Quantifies the centrality of the dijet angular distribution at a given dijet mass.
- Many systematic uncertainties cancel in the ratio.

$$R = \frac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)} = \frac{N(\text{inner})}{N(\text{outer})}^{*}$$

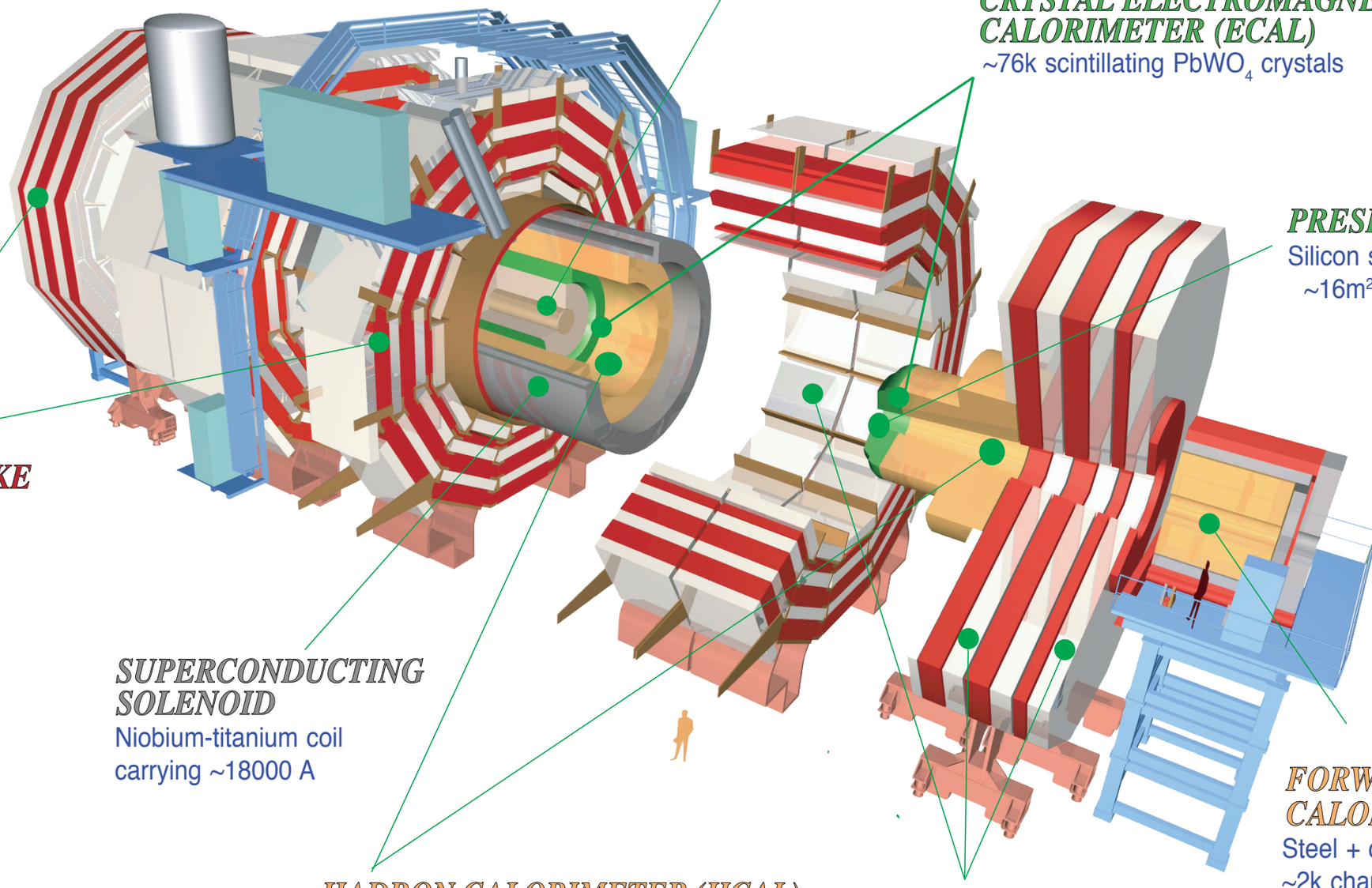
*Both jets inner or outer.



- Roughly flat vs. dijet mass for "t-channel" QCD.
- Rises vs. dijet mass for quark contact interactions.
- Bumps in dijet mass for "s-channel" dijet resonances.

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

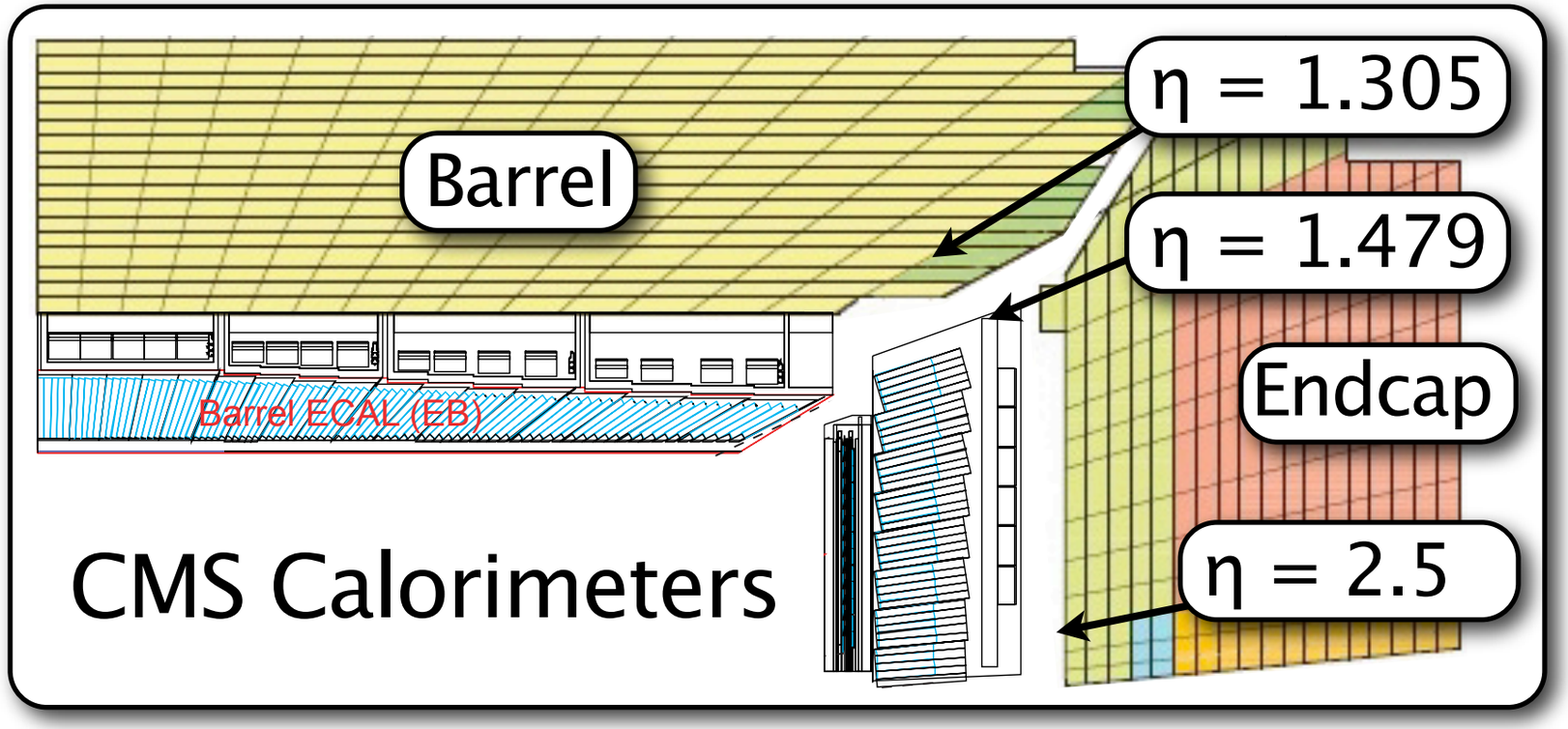
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

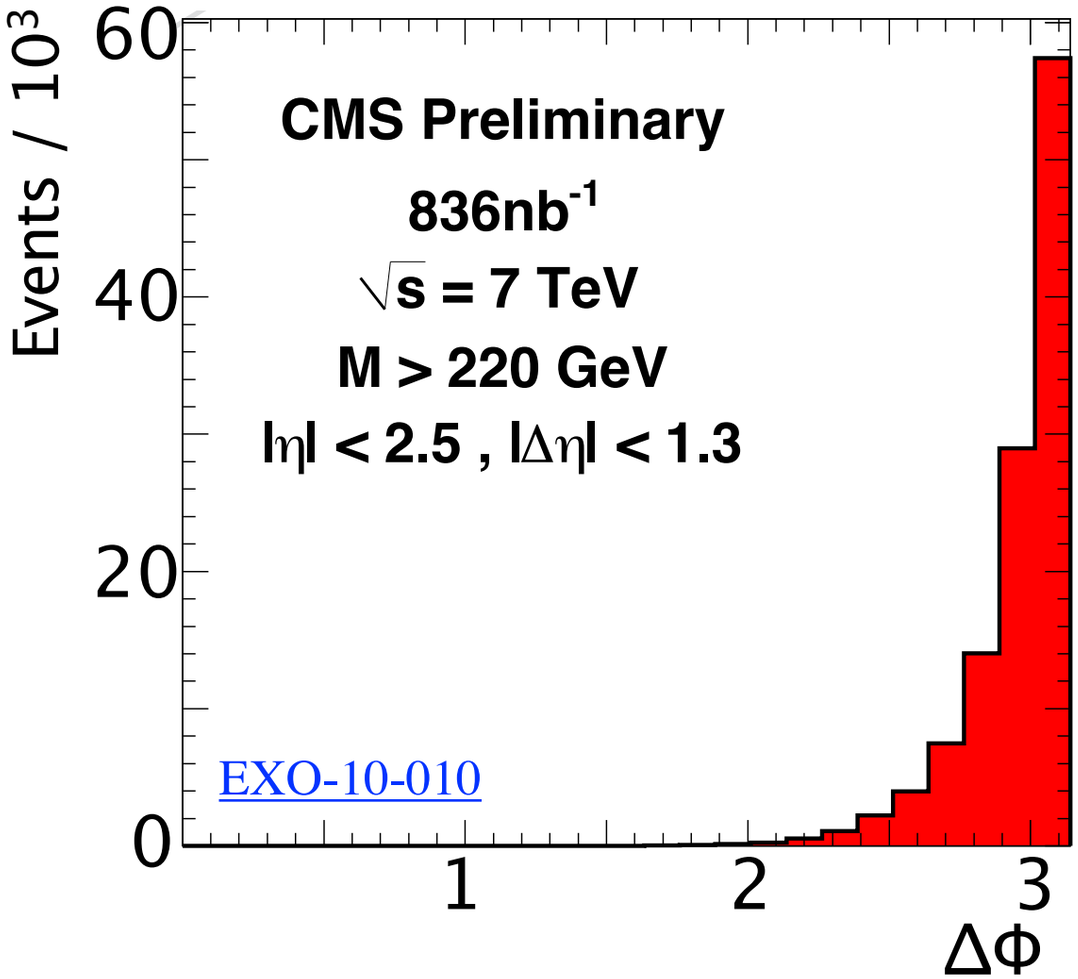
Jet Reconstruction

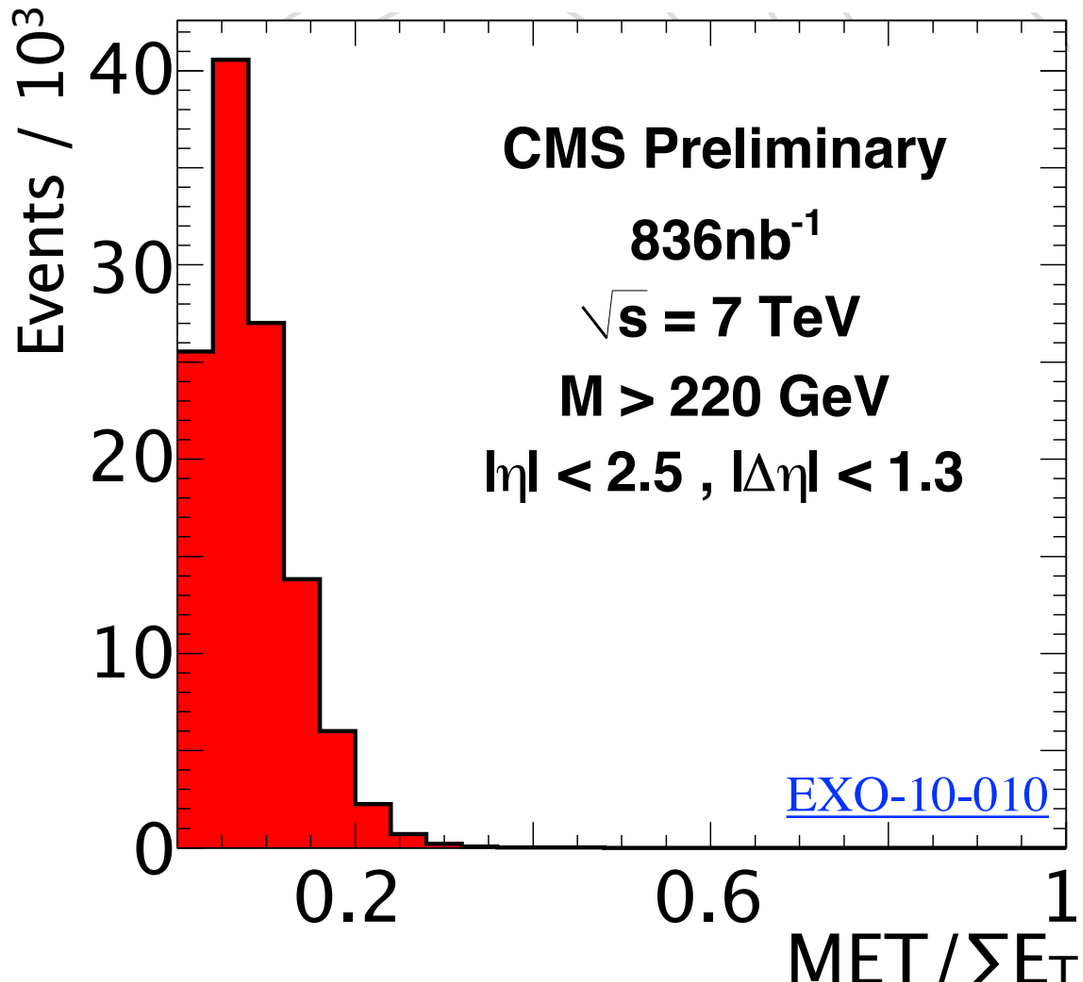
- Jets are reconstructed from energy deposits in the hadronic and electromagnetic calorimeters.



- Dijet ratio analysis requires $|\eta| < 1.3$ for both jets.
- Dijet mass analysis requires $|\eta| < 2.5$ for both jets and $|\eta_1 - \eta_2| < 1.3$.
- **Anti-k_T** clustering algorithm with distance parameter = **0.7**.
- Jet energy corrections are determined with MC, and verified with data.
  - Preliminary studies of photon+jet and single particle response indicate that uncertainty on jet energy scale is less than 10%.
- Jet energy resolution in data and MC agree.

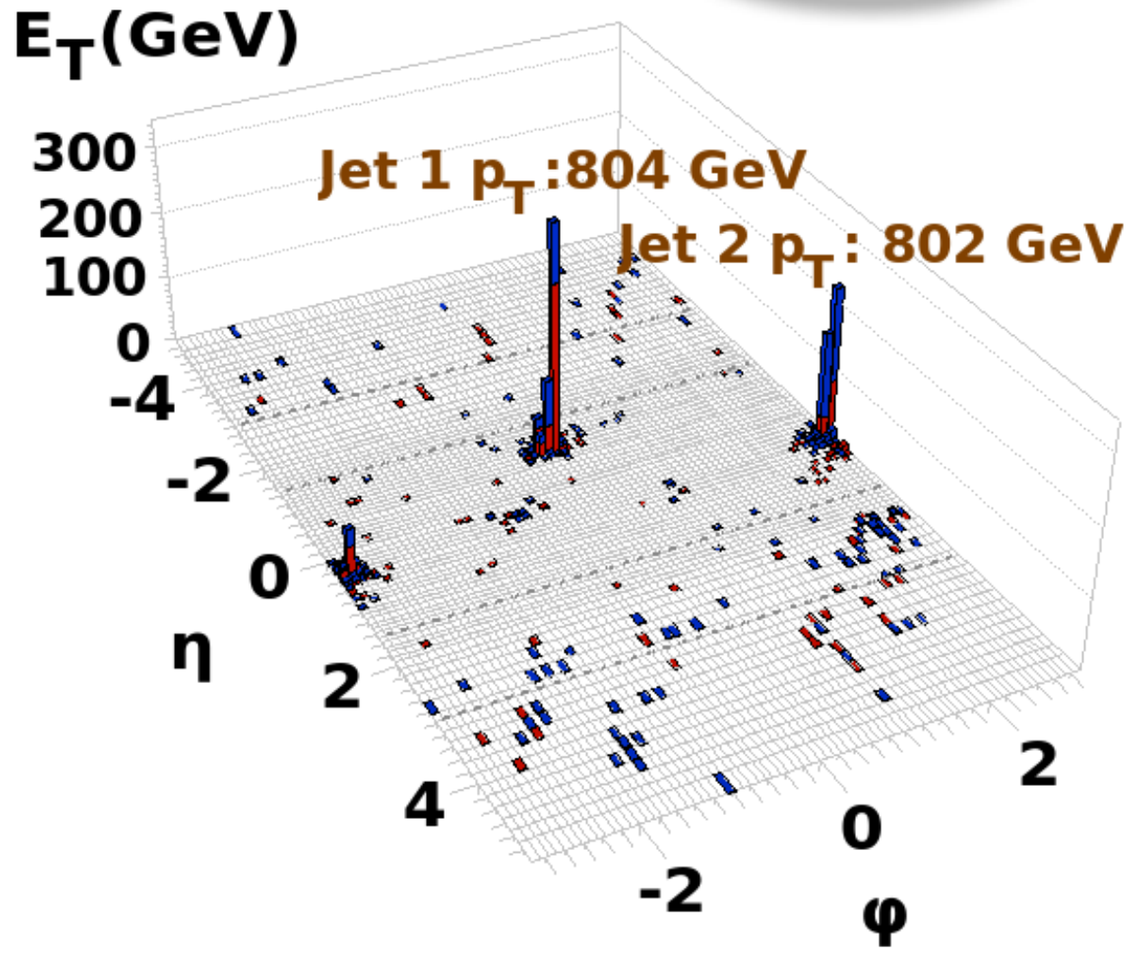
Dijet Topology

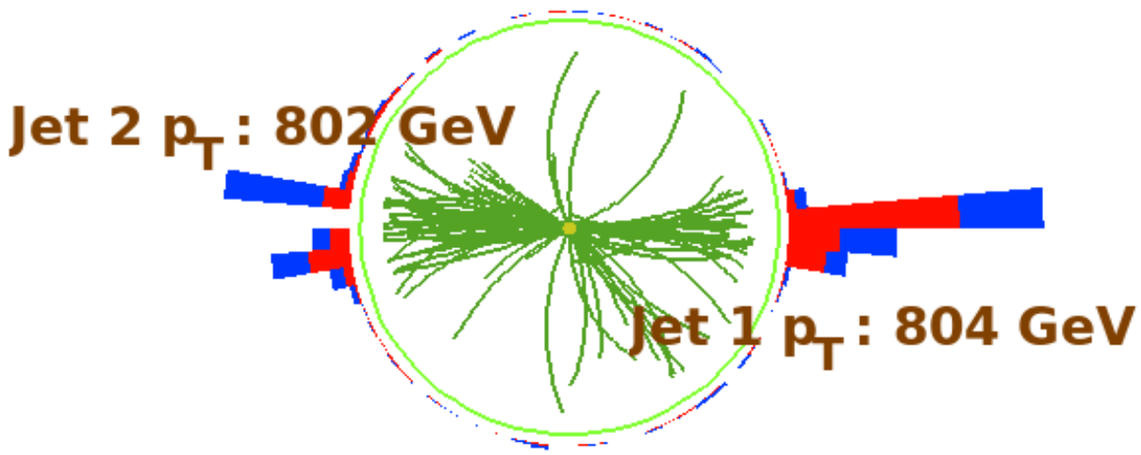




- ~116,000 events in 836 nb^{-1} for dijet mass analysis;
  ~11,000 events in 120 nb^{-1} for dijet ratio analysis.
- Events are well balanced, as expected from dijet topology.
- Low MET/∑E_T (non-zero due to finite jet resolution) consistent with real jets.
  - unphysical backgrounds would appear at MET/∑E_T near 1.
- Jets are back-to-back in Φ.
  - Events with low ΔΦ are real multijet events.

Highest Dijet Mass Event

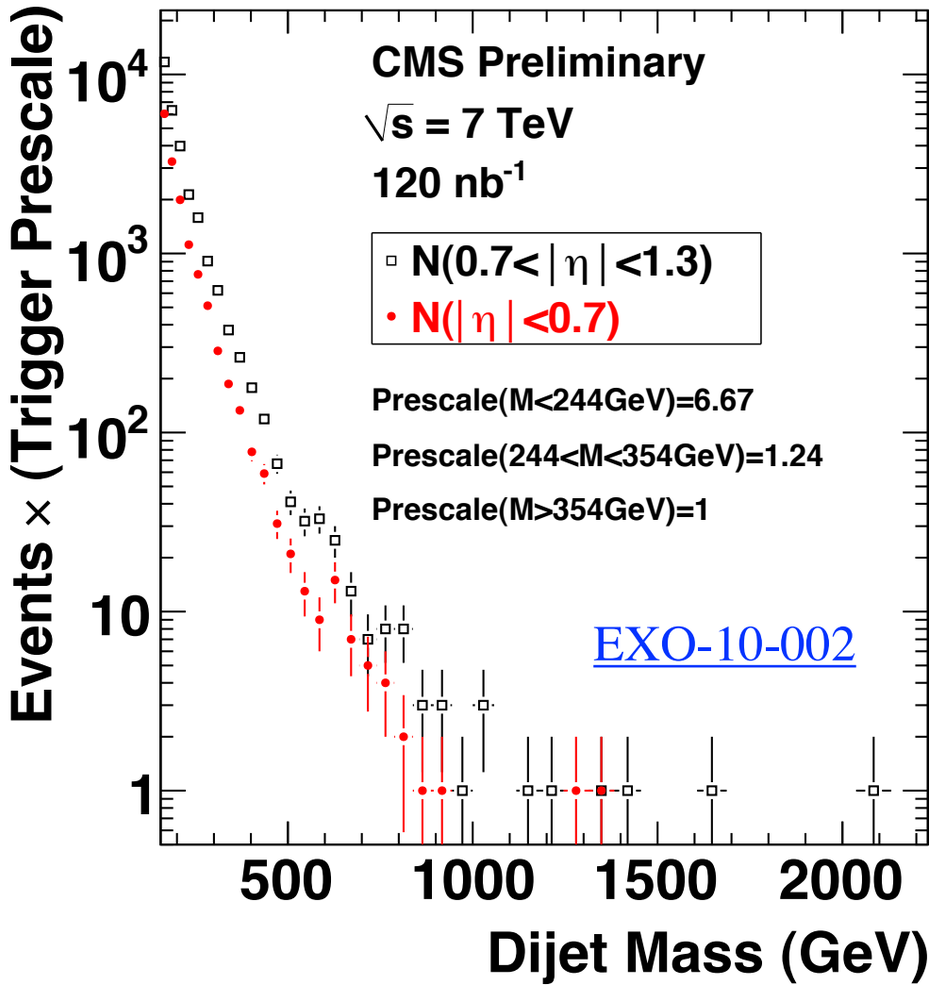


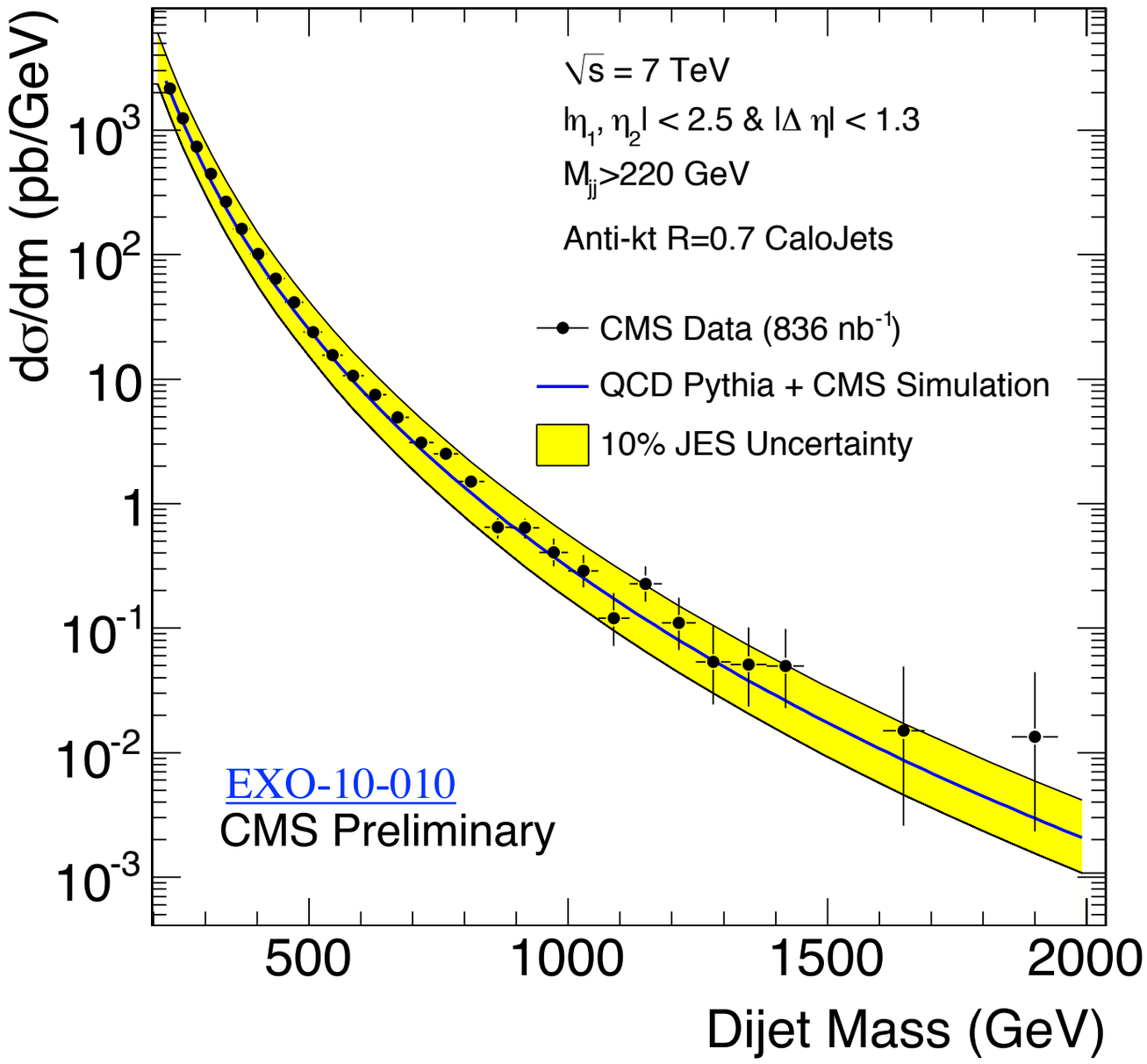


EXO-10-010

Dijet Mass Spectra in Data

- Data are in **good agreement with PYTHIA6** + CMS simulation.
- Spectrum extends to **1.9 TeV** (past Tevatron reach of 1.3 TeV).





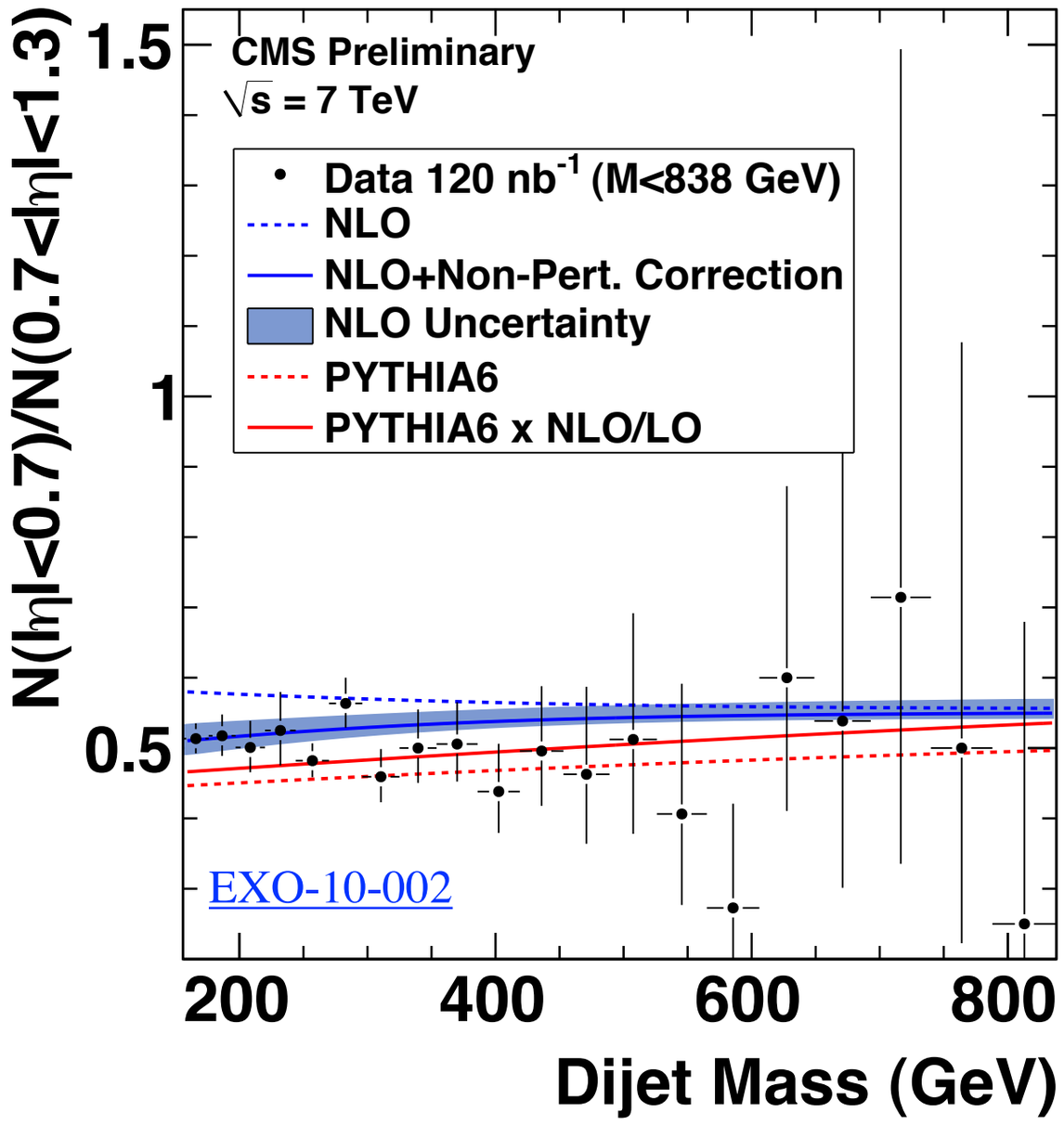
- Dijet ratio inputs are # of inner/outer events vs. dijet mass in 120 nb^{-1}.
- Spectra extend to 2.1 TeV without requirement on $|\eta_1-\eta_2|$.

Dijet Centrality Ratio in Data

- Compare data to:
  - NLO
  - NLO + non-perturbative corrections *
  - Pythia
  - Pythia × NLO/LO k-factor.

- **Data prefer NLO** + non-perturbative corrections (p-value = 0.8).

- The experimental systematic uncertainty is ~0.02 and < the stat. uncertainty on 1st data point.



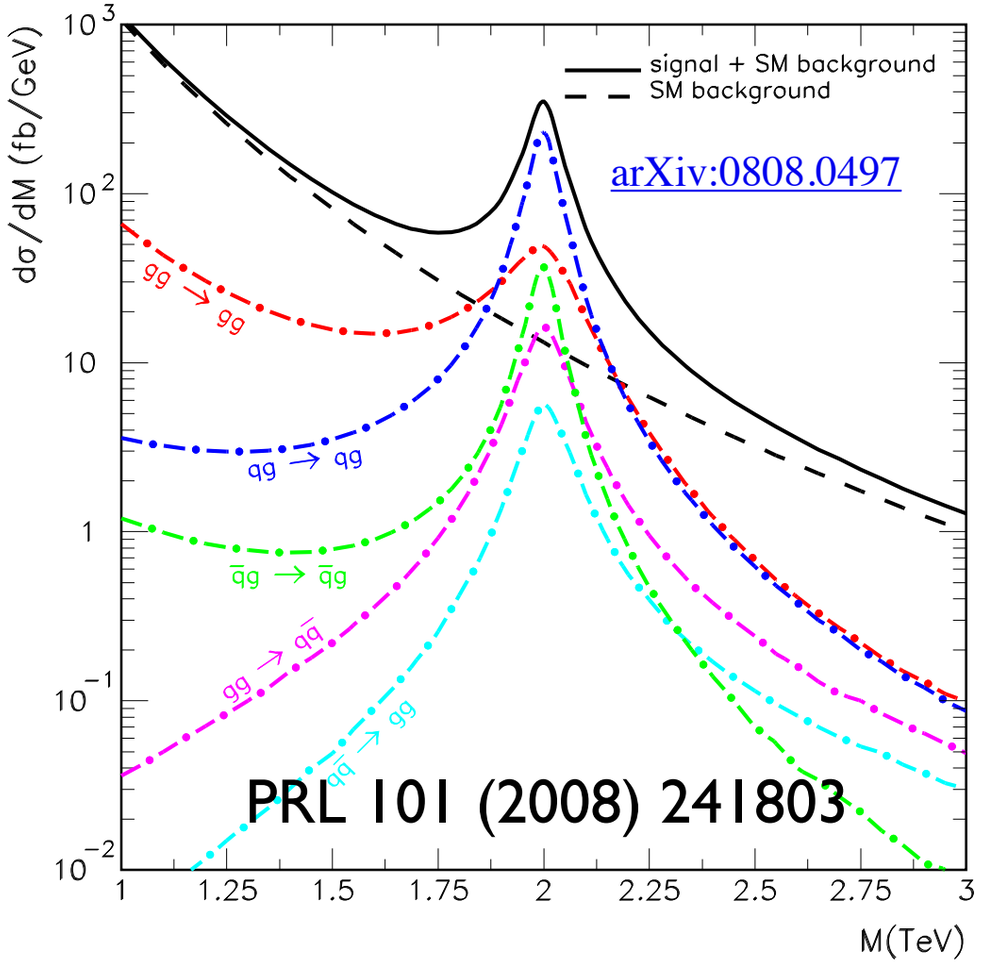
- "NLO Uncertainty" includes PDF, scale, and non-perturbative correction uncertainties.

*Corrections for hadronization & multiple parton interactions.

Dijet Resonance Models

- Parton resonances decaying to dijets are predicted by various models:

Model Name	X	Color	J^P	$\Gamma/(2M)$	Final-state Partons
String	S	mixed	mixed	0.003-0.037	$q\bar{q}$, qq, gg and qg
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
Excited Quark	q*	Triplet	$1/2^+$	0.02	qg
E_6 Diquark	D	Triplet	0^+	0.004	qq
RS Graviton	G	Singlet	2^+	0.01	$q\bar{q}$, gg
Heavy W	W′	Singlet	1^-	0.01	$q\bar{q}$
Heavy Z	Z′	Singlet	1^-	0.01	$q\bar{q}$



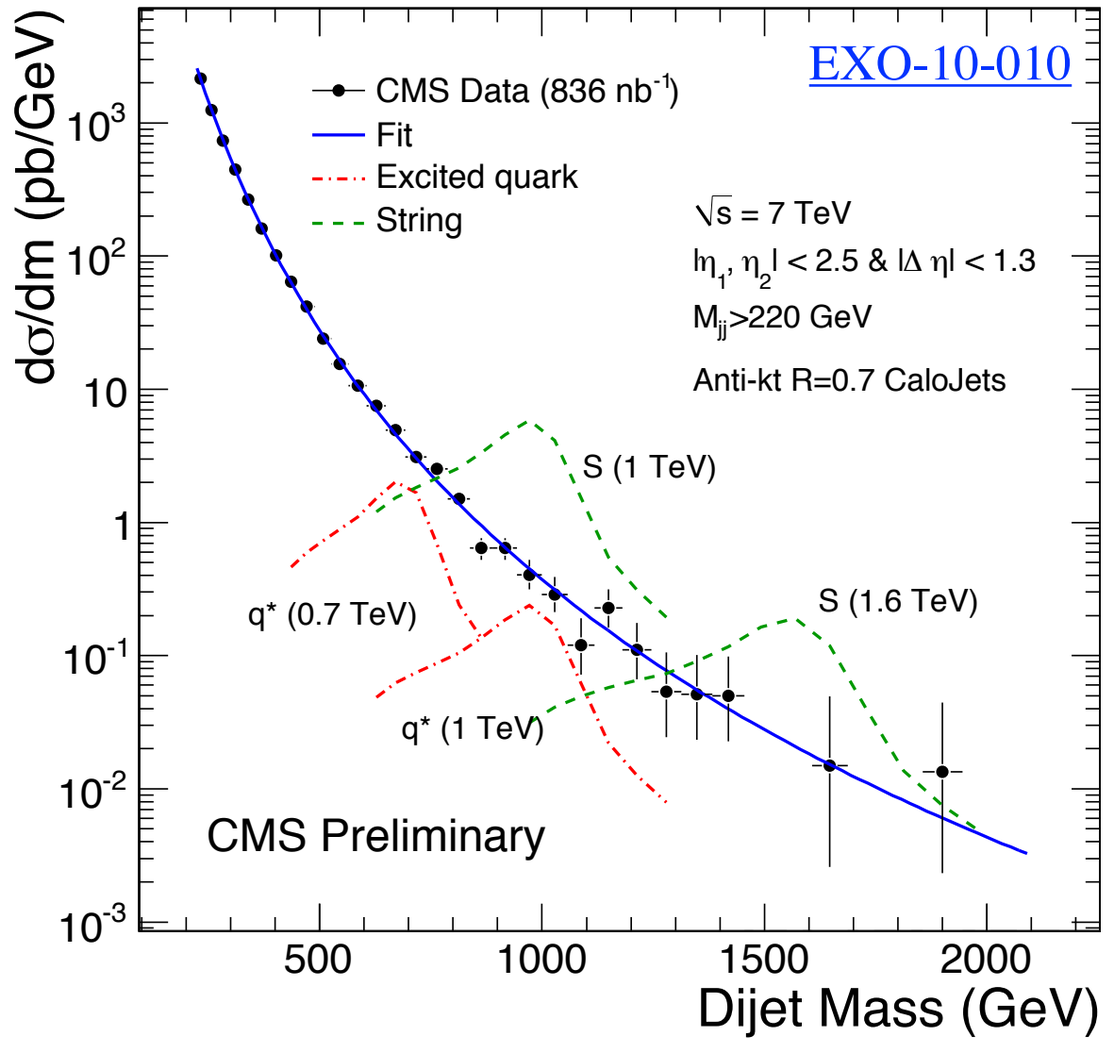
- Recent model: **string resonances**.
  - See “Strings at the LHC,” S. Stieberger, Monday, 23 Aug.
  - Regge excitation of quarks and gluons.
  - Cross section higher than excited quark models by factor 25 (due to color, spin, chirality effects).
  - **String resonances would produce a dramatic bump in the mass spectrum.**

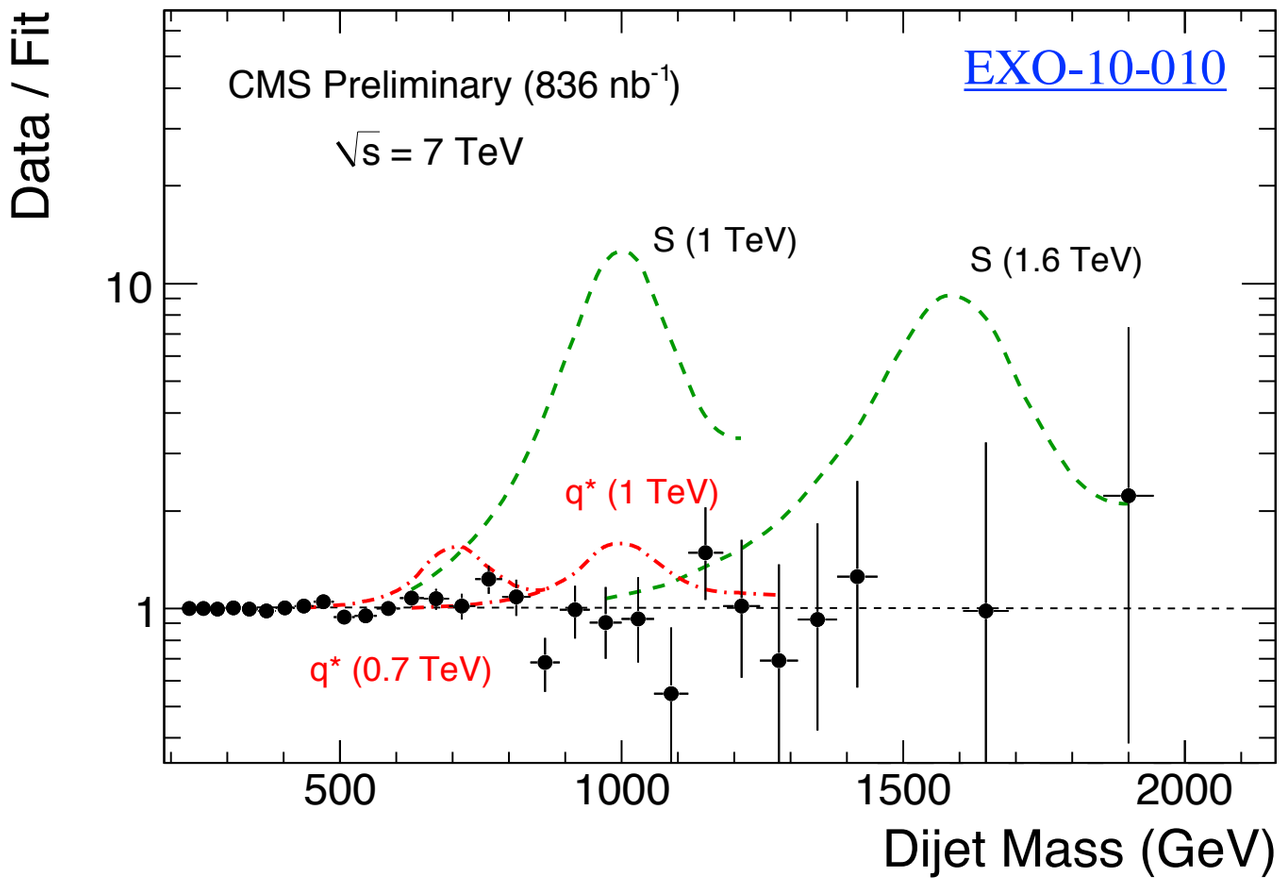
Smooth Fit of the Mass Spectrum

- Good fit (χ^2/ndof = 26/25) with 4 parameter function:

$$\frac{d\sigma}{dm} = p_0 \frac{\left(1 - \frac{m}{\sqrt{s}} + p_3\left(\frac{m}{\sqrt{s}}\right)^2\right)^{p_1}}{m^{p_2}}$$

- **No indication of new physics.**



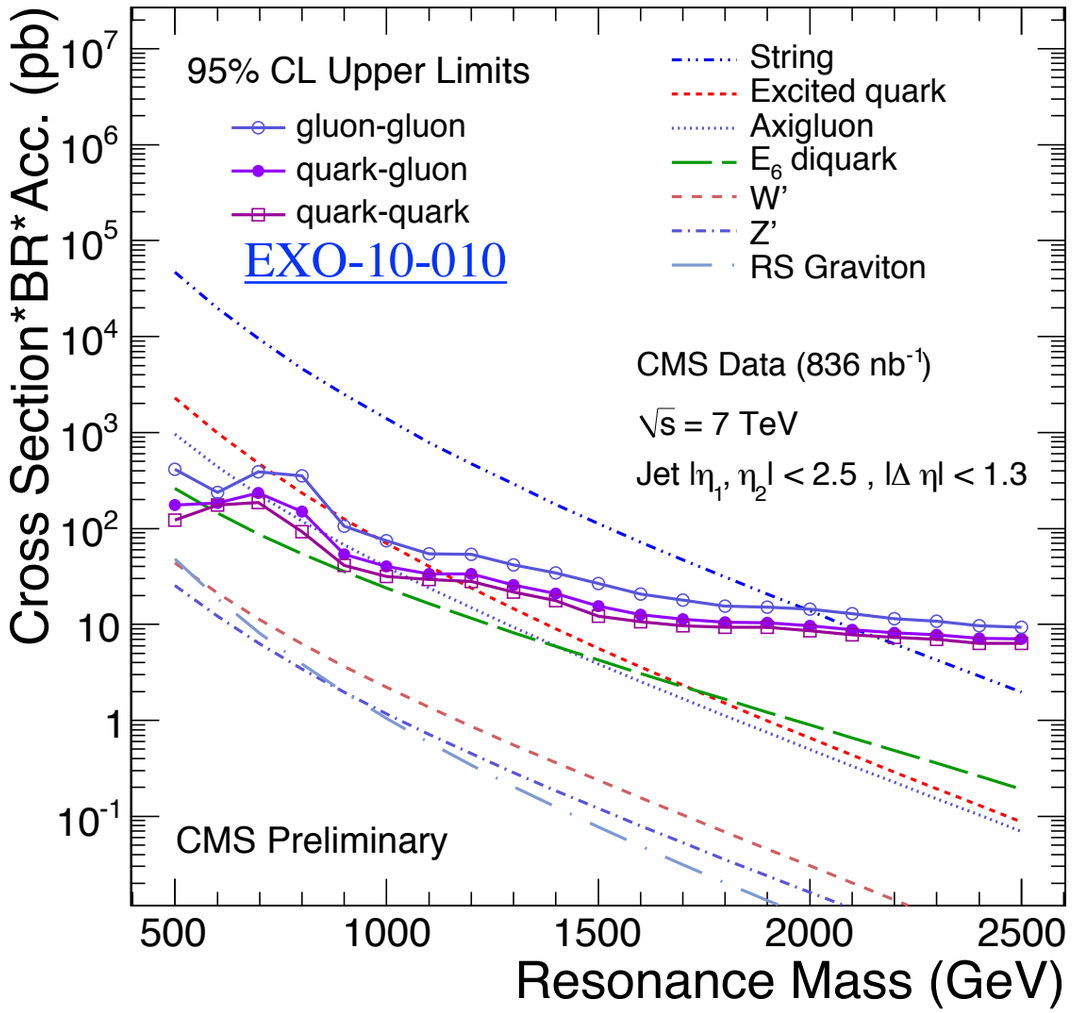


- **String resonances** have largest cross section and most search sensitivity.
  - Followed by **excited quarks**.

Model-Independent Cross Section Limits

- We obtain generic cross section limits on qq, qg, and gg resonances.

- Statistical method is Bayesian-inspired:
  - Likelihood from per bin Poisson probabilities in # of bkg. events and signal cross section σ.
  - Assuming uniform prior for cross section, normalized L(σ) = posterior PDF(σ).
  - Integrate PDF(σ) to obtain limit on σ.



- Compare limits with predicted cross sections for 7 resonance models to obtain 95% C.L. lower mass limits:

Mass Limits [TeV]	String	Excited Quark	Axigluon/ Coloron	E_6 Diquark
Observed	2.10	1.14	1.06	0.58
Expected	2.10	1.10	0.98	0.54

Resonance Mass Limits

Lower Mass Limits [TeV]	CMS observed (836/nb)	CMS expected (836/nb)	CDF [1] (1.13/fb)	ATLAS [2] observed (315/nb)	ATLAS [2] expected (315/nb)
String	**2.10**	2.10	1.4*	–	–
Excited Quark	**1.14**	1.10†	0.87	1.20	0.98
Axigluon/ Coloron	**1.06**	0.98	1.25	–	–
E_6 Diquark	**0.58**	0.54	0.63	–	–

- All results use CTEQ6L1 parton distribution functions.

†CMS expected limit with 315 nb^{-1} is 0.93 TeV.

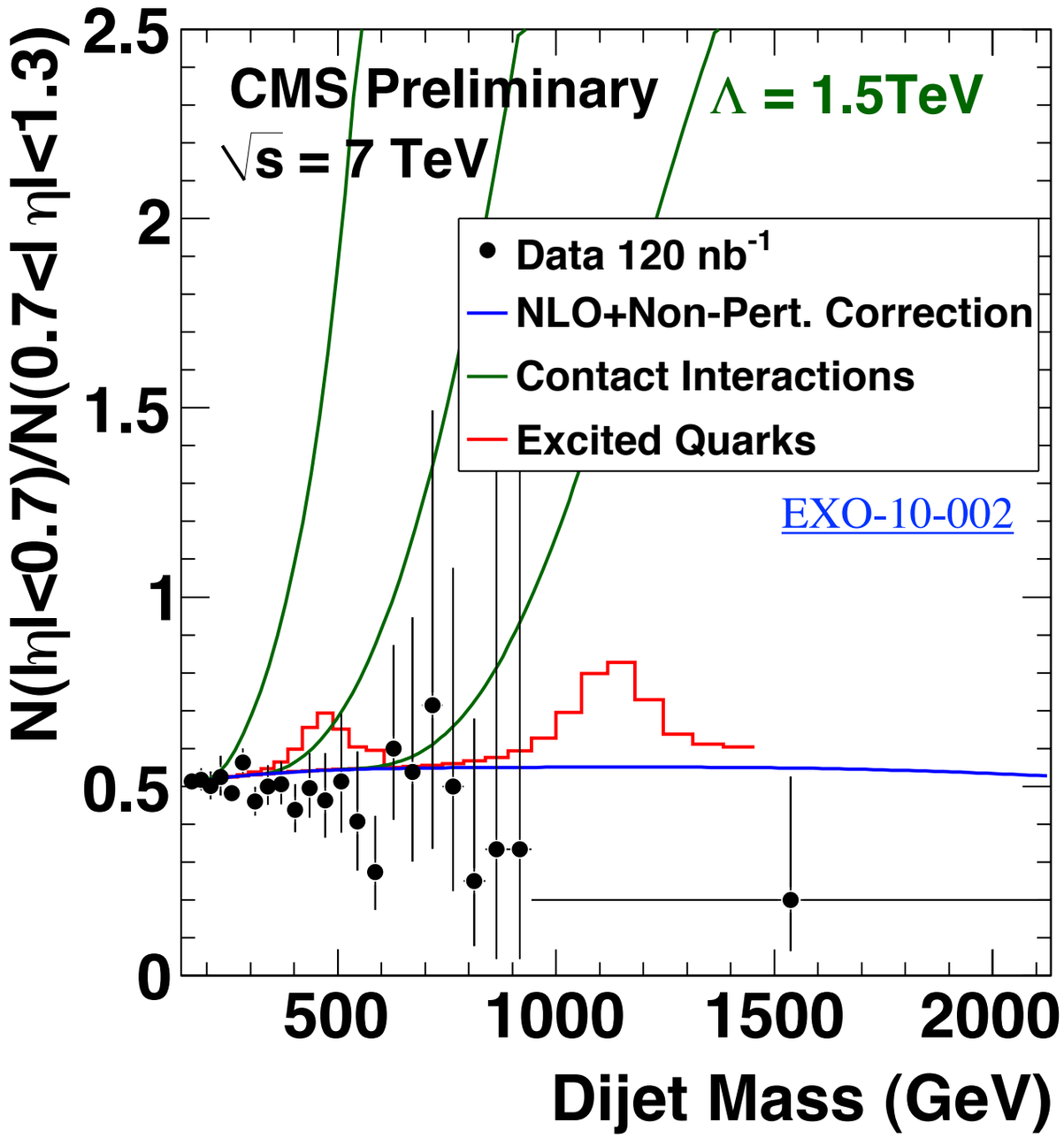
*CMS evaluation of string resonance cross section.

[1] CDF Collaboration, "Search for new particles decaying into dijets in proton- antiproton collisions at sqrt(s) = 1.96 TeV", Phys. Rev. D79 (2009) 112002; arXiv:0812.4036.

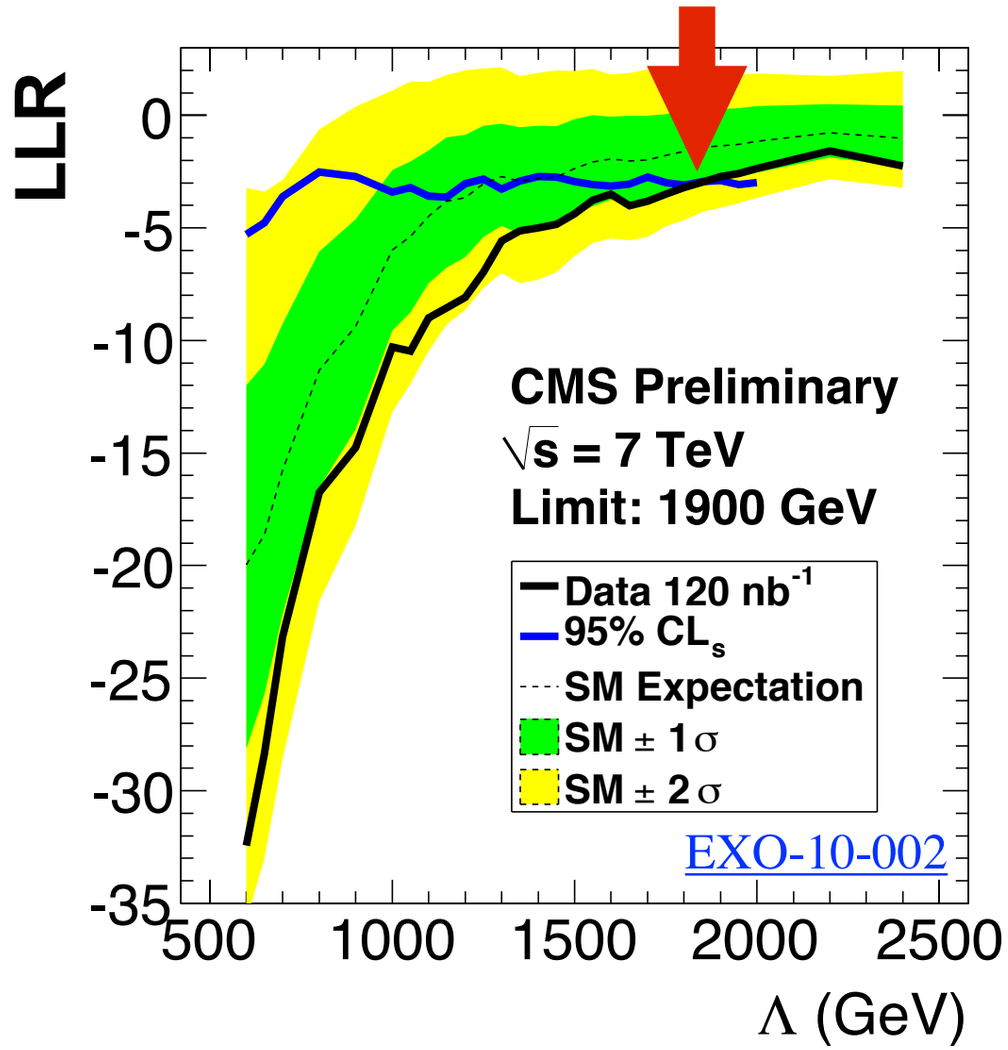
[2] ATLAS Collaboration, "Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC", arXiv:1008.2461.

New Physics Search with Dijet Ratio

- Comparison of data, QCD, contact interaction, q* models show **no sign of new physics.**

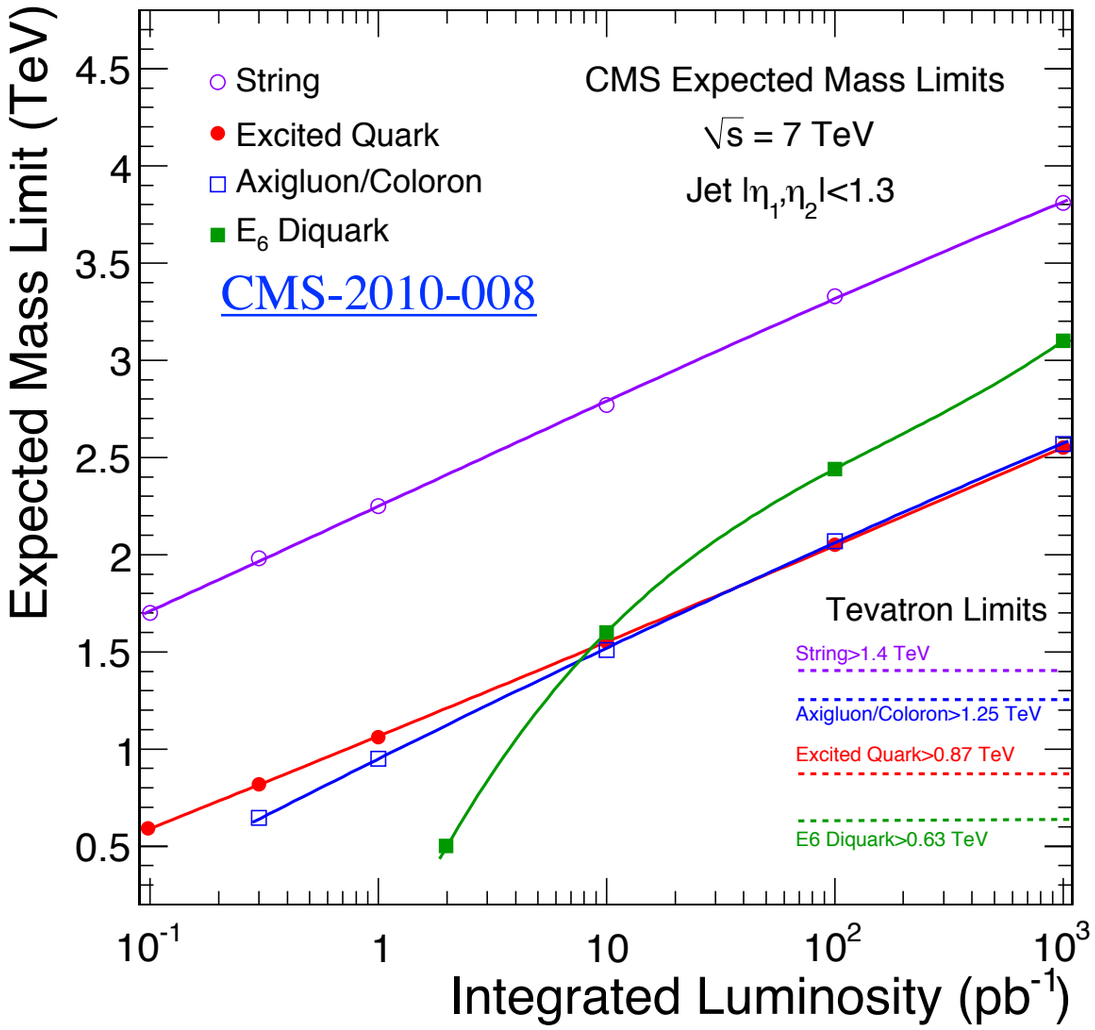


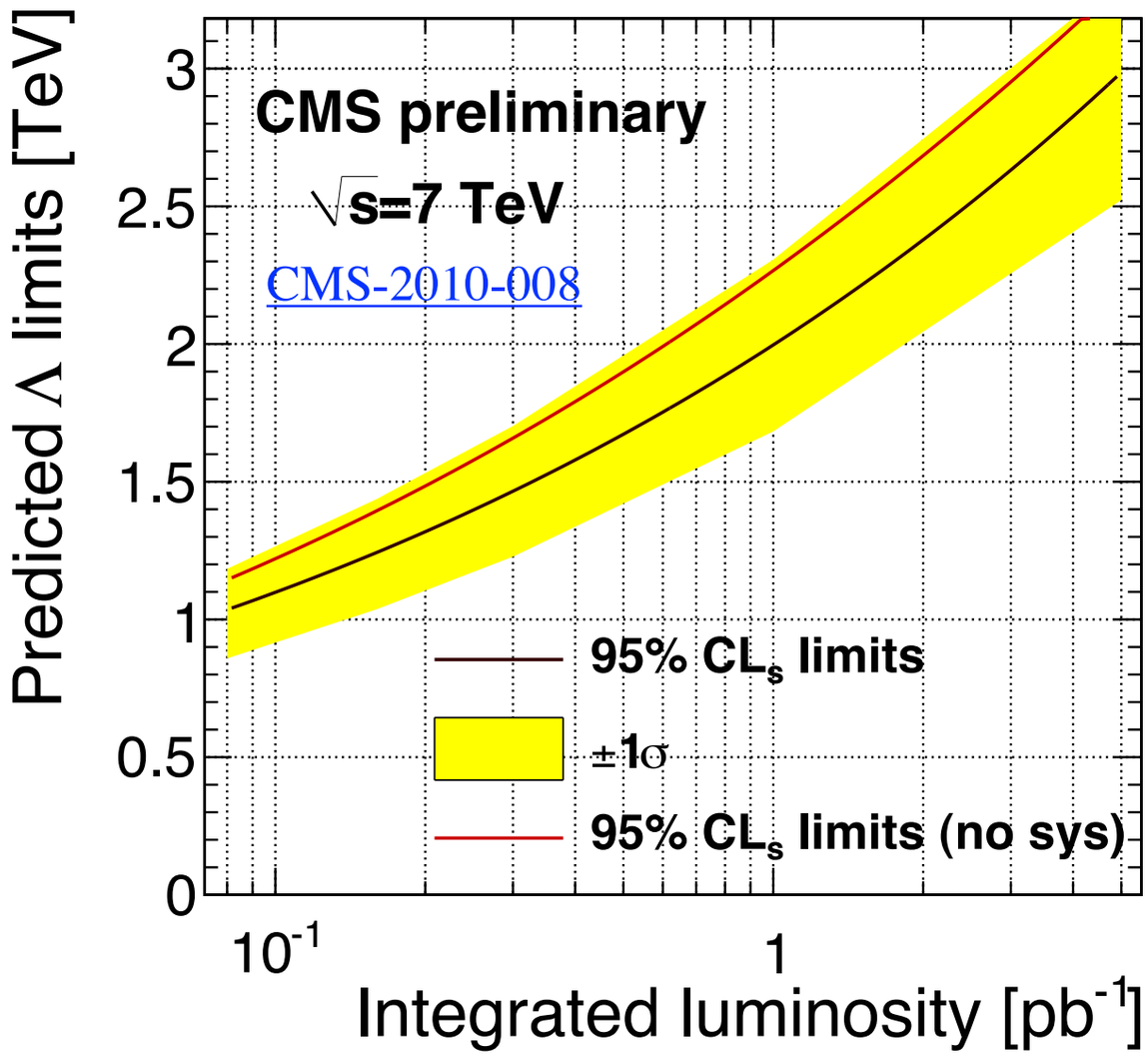
- Set limits with CL_S method; test statistic is log likelihood ratio for SM and SM+signal hypotheses.
- We **exclude Λ<1.9 TeV** at 95% C.L.
  - Tevatron exclusion is Λ<2.8 TeV.



Looking Forward

- Conservative expectations for 95% C.L. limits as function of integrated luminosity:





- CMS is exploring **new territory** beyond the Tevatron **string and q* resonance** mass limits.

- We expect to **surpass Tevatron limit** of $\Lambda > 2.8$ TeV at 95% C.L. with **4 pb^{-1}**.

Summary

- The dijet mass spectrum extends to 1.9 TeV with 836 nb^{-1} for $|\eta_{1,2}|<2.5$.
- The dijet mass spectrum is in good agreement with QCD from PYTHIA + full CMS simulation.
- The dijet centrality ratio is in good agreement with QCD from NLO calculations + non-perturbative corrections.
- We have used the data to set limits on the presence of new physics from five models:

New Physics Model	95% C.L. Limit [TeV]	Integrated Luminosity [nb^{-1}]
String Resonance	M > 2.10	836
Excited Quark	M > 1.14	836
Axigluon/Coloron	M > 1.06	836
E_6 Diquark	M > 0.58	836
Contact Interaction	Λ > 1.9	120

Extra Slides

CMS References

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

- CMS Collaboration, "Search for Dijet Resonances in the Dijet Mass Distribution in pp Collisions at $\sqrt{s} = 7$ TeV"," Physics Analysis Summary EXO-10-010
- CMS Collaboration, "Search for New Physics with the Dijet Centrality Ratio," Physics Analysis Summary EXO-10-002
- CMS Collaboration, "Jet Performance in pp Collisions at $\sqrt{s} = 7$ TeV," Physics Analysis Summary JME-10-003
- CMS Collaboration, "Single Particle Response in the CMS Calorimeters," Physics Analysis Summary JME-10-008
- CMS Collaboration, "The CMS physics reach for searches at 7 TeV", CMS NOTE 2010/008

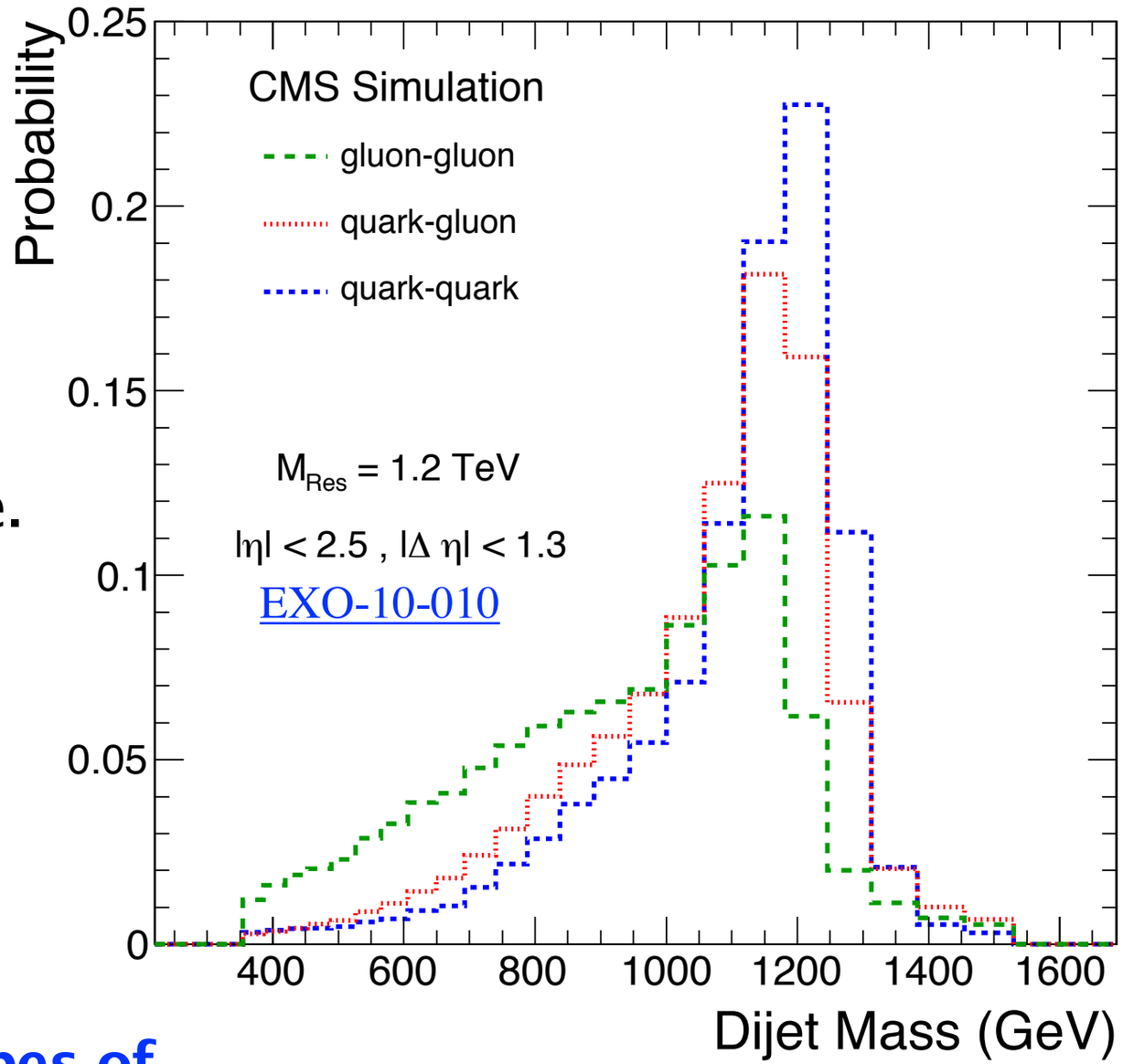
Model-Independent Lineshapes

- Resonance shapes from PYTHIA +CMS simulation.

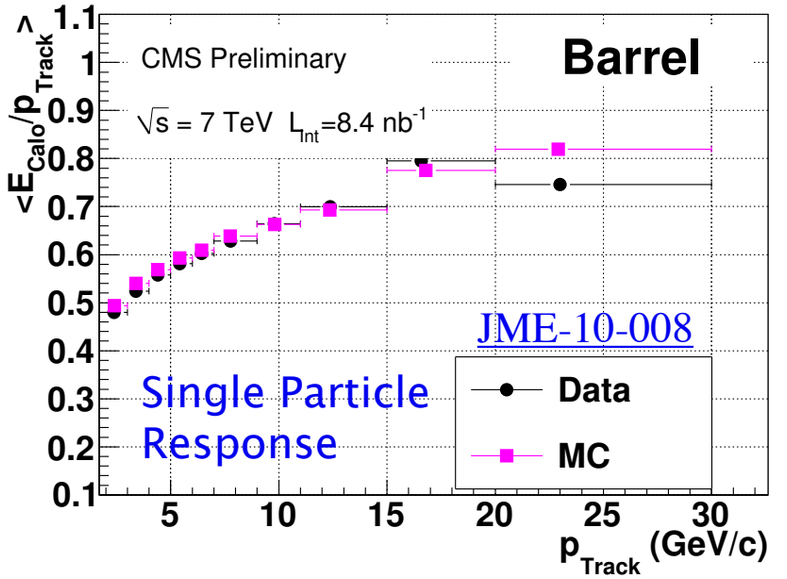
- Shape depends on parton content mostly because of FSR.
  - Gluons radiate more than quarks, broadening the shape.

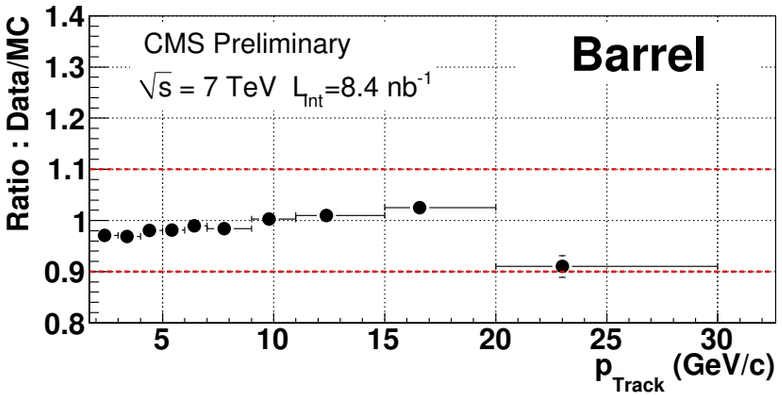
- Gaussian core of dijet mass resolution for qg resonances varies from 11% at 0.5 TeV to 6% at 2.5 TeV.

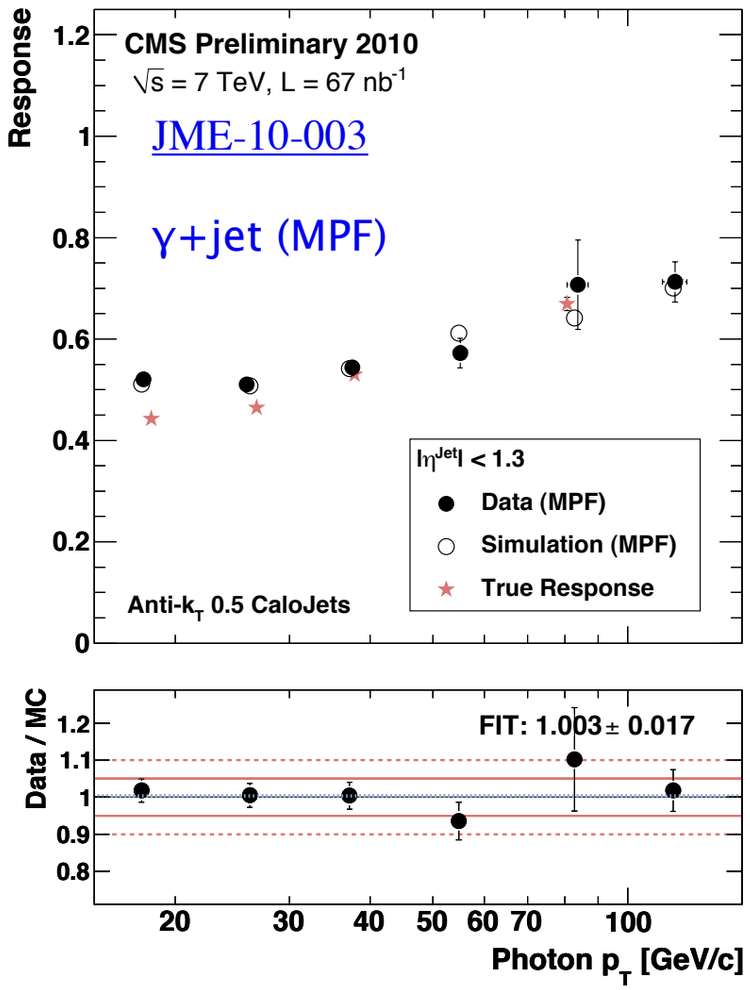
- **We search for these 3 generic types of narrow dijet resonances in the data.**

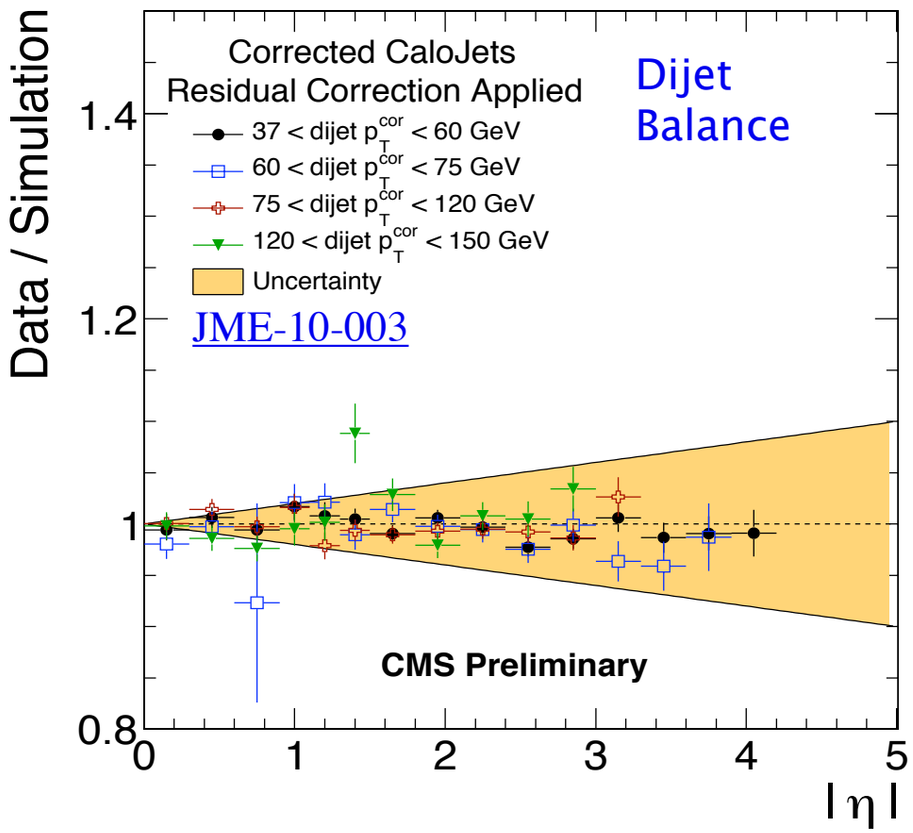


Jet Energy Scale









- Preliminary in situ measurement of **single particle response** indicates data/MC agreement better than 3% in barrel.
- Preliminary measurement of jet energy response (photon+jet, MPF method) shows good data/MC agreement.
- Direct measurement of the relative jet energy scale with **dijet p_T balance** shows that the uncertainty of the relative scale across η is less than 2%.

Anti-k_T Clustering Algorithm

- M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_T jet clustering algorithm", JHEP 0804:063 (2008); arXiv:0802.1189
- In family of **sequential recombination algorithms**:
  - Define: $d_{ij} = min(k_{Ti}^{2p}, k_{Tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$ ← Distance b/w entities i and j.

    $d_{iB} = k_{Ti}^{2p}$ ← Distance b/w entity i and beam.

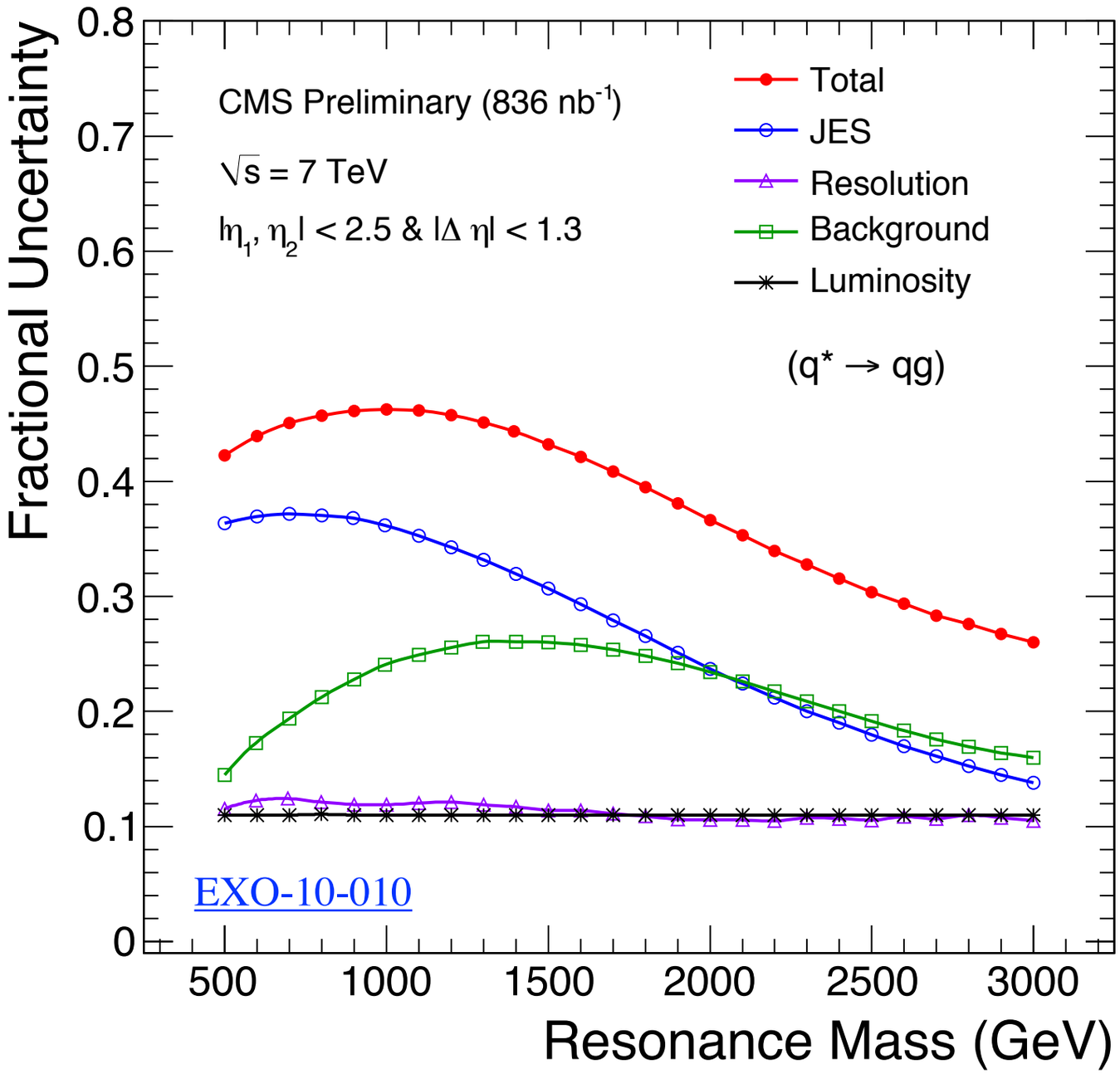
    $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$
    - Algorithm: If smallest *d* is d_{ij}, combine entities *i/j*; if smallest *d* is d_{iB}, call *i* a jet and remove from list of entities. Repeat until no entities left.
    - k_T p=1, Cambridge/Aachen p=0, **anti-k_T p=$^-$1**.
- Infrared and collinear safe.
- Soft-resilient boundaries yielding conical jets.

Systematic Uncertainties : Spectrum

- Posterior probabilities are convolved with Gaussian of width equal to systematic uncertainty -- conservative approach.

- Dominant source of uncertainty is jet energy scale.

- Systematic uncertainties increase cross section limits by 16-47% depending on resonance mass and parton content.

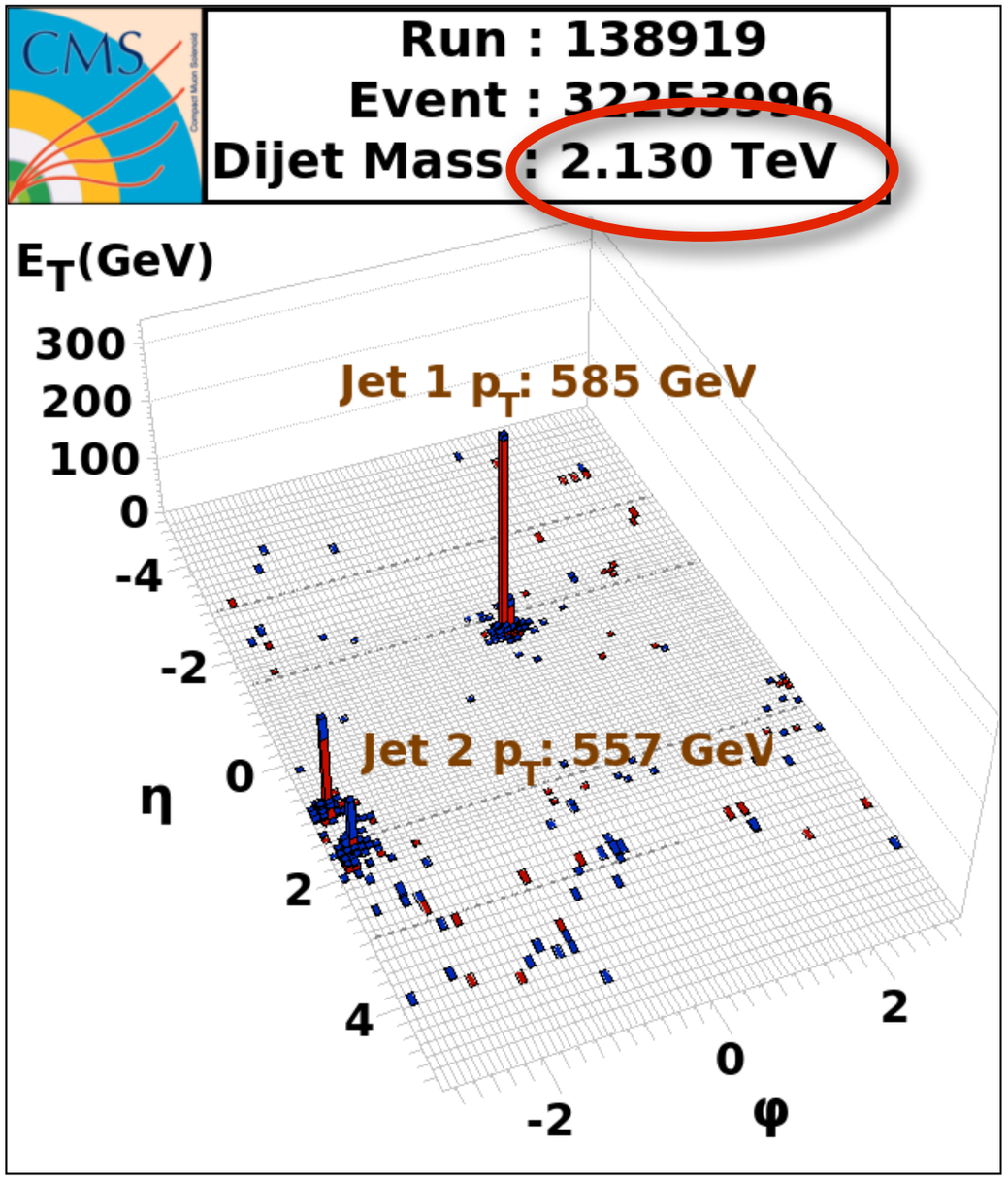


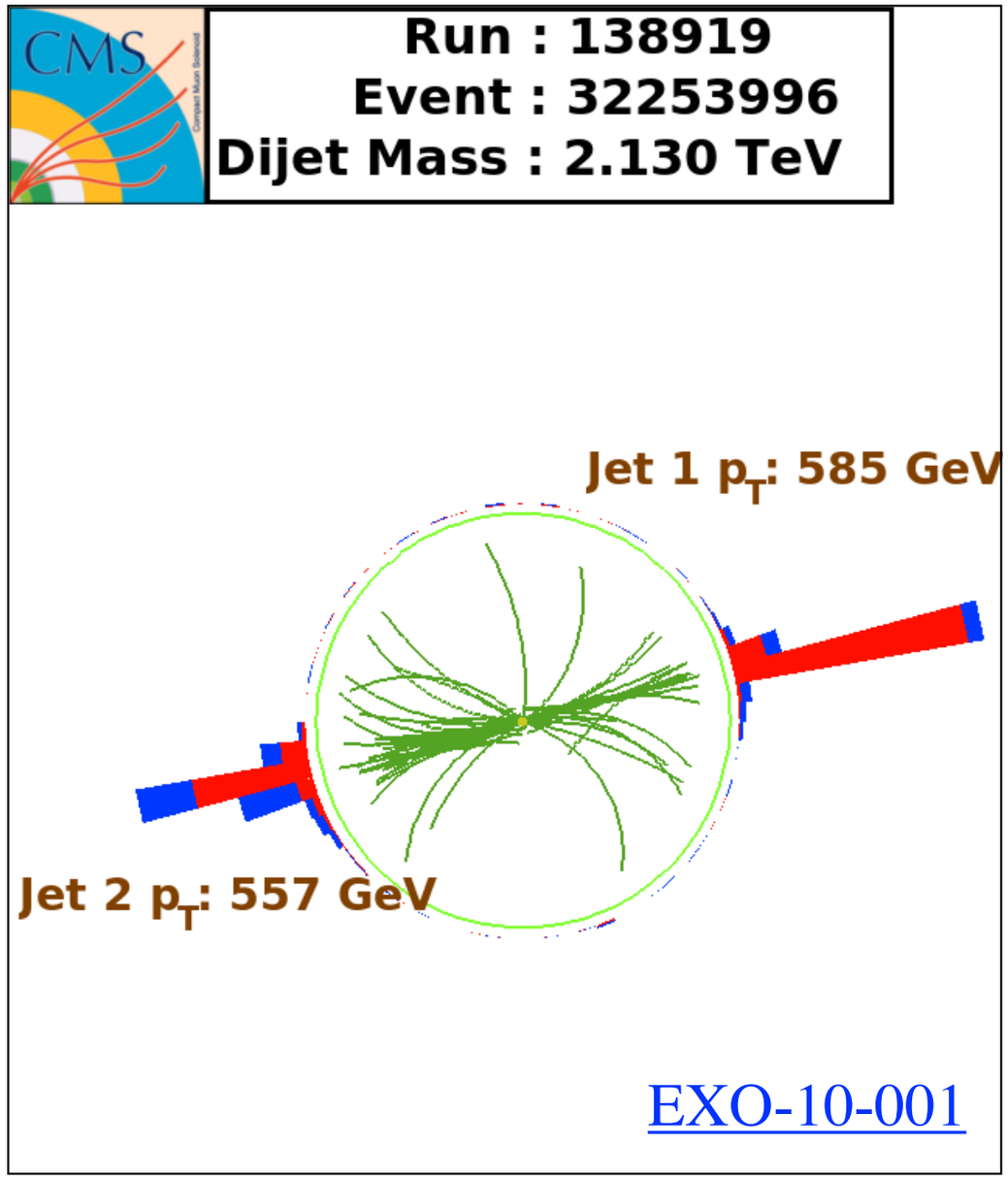
Systematic Uncertainties : Dijet Ratio

- Included in limit setting with Cousins–Highland method.
    - Uncertainties are represented by nuisance parameters which affect the number of inner and outer events in pseudodatasets.
- Dominant sources of uncertainty are circled in red.

Source of Uncertainty	NLO QCD (Units of Ratio)	NLO QCD (%)	Contact Interactions (%)
Detector Uncertainty			
Absolute JES	0.002 - 0.004	0.3 - 0.8	5 - 30
Relative JES	0.02 - 0.03	3.9 - 5.3	2
Other	0.01	2.0	–
Jet Energy Resolution	0.003	0.6	–
Total Detector	0.02 - 0.03	4.5 - 5.8	5 - 30
Model Uncertainty			
Scale	$+(0.014 - 0.023)$ $-(0.005 - 0.008)$	$+(2.7 - 4.4)$ $-(0.9 - 1.6)$	–
Offset	0.02	3.9	–
Fit	0.005	1.0	2 - 5
PDF	0.002	0.3	–
Total Model	$+(0.024 - 0.030)$ $-(0.021 - 0.022)$	$+(4.8 - 5.9)$ $-(4.0 - 4.3)$	2 - 5
Total	$+(0.034 - 0.042)$ $-(0.031 - 0.037)$	$+(6.6 - 8.3)$ $-(6.1 - 7.2)$	6 - 30

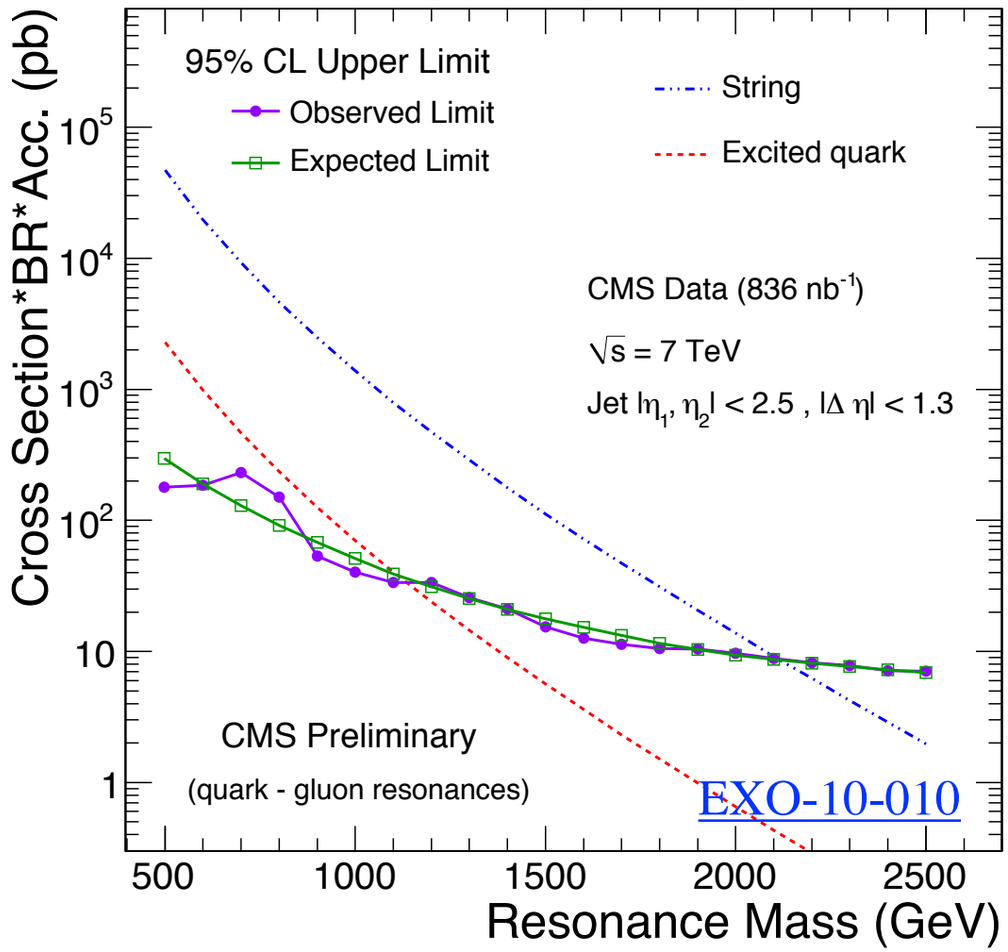
Previous Highest Dijet Mass Event

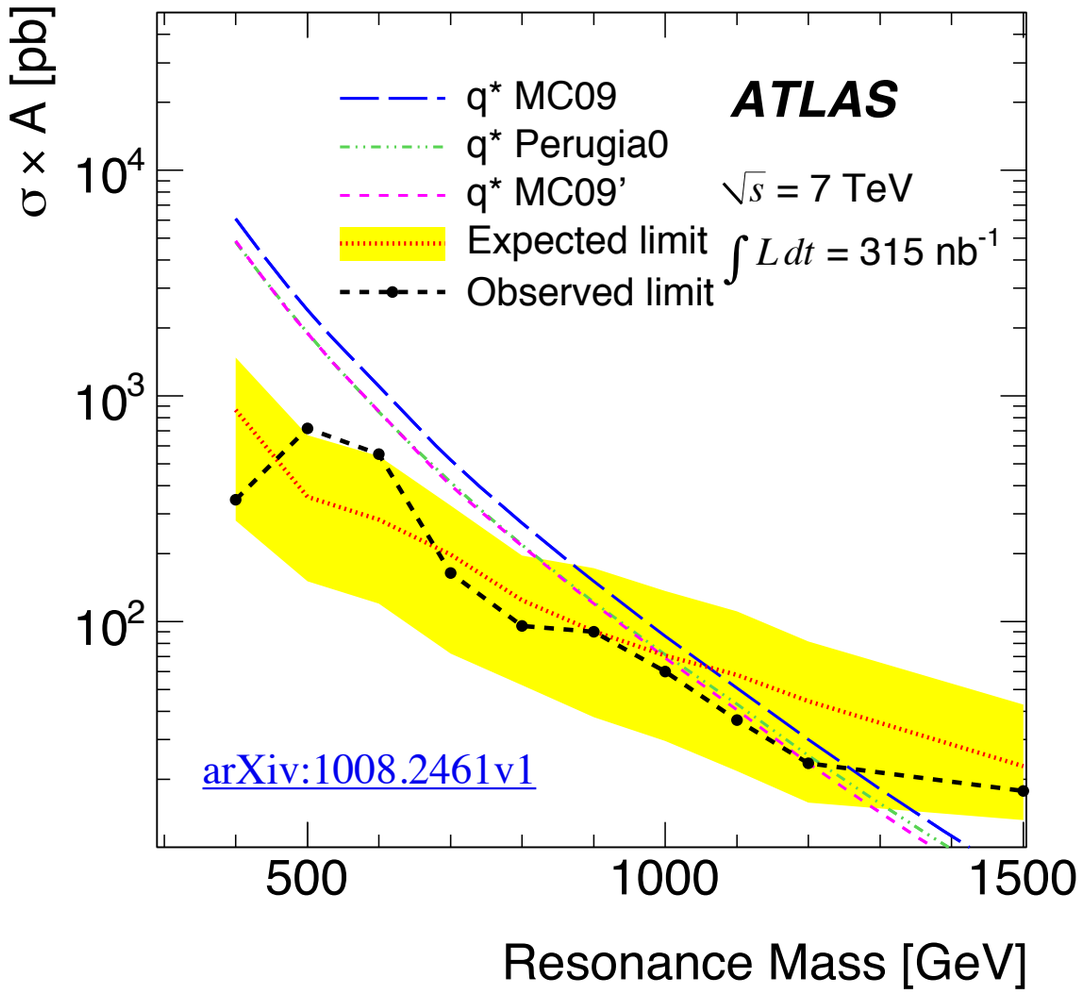




- In EXO-10-001, we reported an event with dijet mass = 2.1 TeV.
- In the EXO-10-010 analysis, this event fails the $|\eta_1-\eta_2|<1.3$ requirement.

ATLAS vs. CMS





Mass Limits [TeV]	95% CL Mass Limit on q* (TeV)			
	CMS CTEQ6L1 (836 nb^{-1})	CMS CTEQ6L1 (315 nb^{-1})	ATLAS CTEQ6L1 (315 nb^{-1})	ATLAS MRST07 (315 nb^{-1})
Observed	1.14	–	1.20	1.26
Expected	1.10	**0.93**	**0.99**	1.06