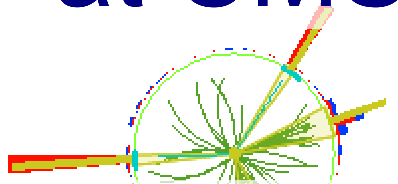
Hadronic Exotica Searches at CMS



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On behalf of the CMS Collaboration

SEARCH2012 Workshop

March 19, 2012

College Park, Maryland

Introduction and Overview

- Hadronic final states are sensitive to many extensions of the standard model
- Although experimentally challenging at hadron colliders, because of the strong production, hadronic final states provide an early discovery potential
- I will talk about the following hadronic Exotica searches at CMS (I will present the latest publicly available results)
  - Search for dijet resonances
  - Search for dijet resonances with the dijet angular ratio
  - Search for pair-produced dijet resonances
  - Search for three-jet resonances
  - Search for quark compositeness in dijet angular distributions

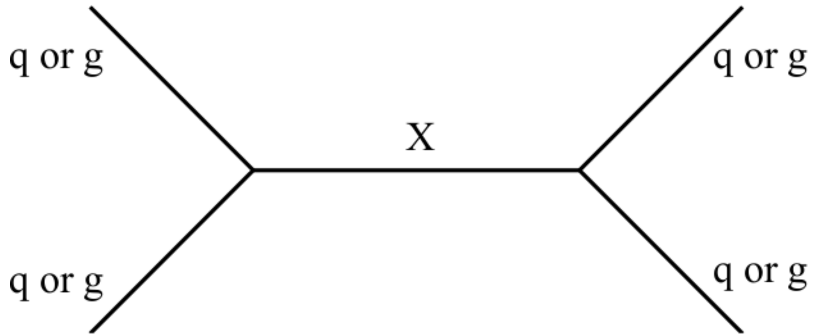
  All of the above searches dominated by a single source of background, the SM jet production
- I will not talk about
  - Search for boosted tops in fully hadronic final state (presented by Petar)
  - Search for black holes (presented by Alexey)

Search for Dijet Resonances (EXO-11-015)

- $\int L dt = 1\ fb^{-1}$
- Paper: Phys.Lett. B704 (2011) 123
- Preprint: arXiv:1107.4771
- Public TWiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11015

Dijet Resonances

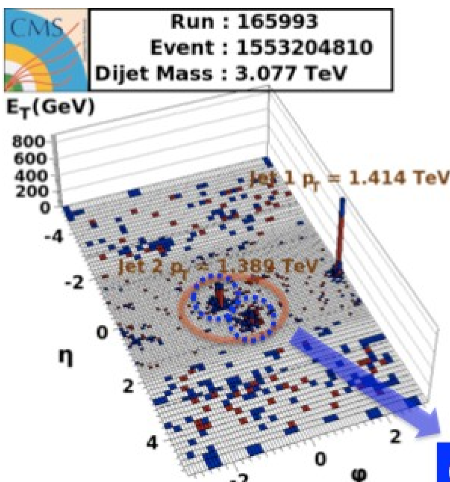
- QCD predicts a smooth, steeply falling dijet mass spectrum
- Many extensions of the SM predict new massive objects producing resonant structures (“bumps”) in the dijet mass spectrum

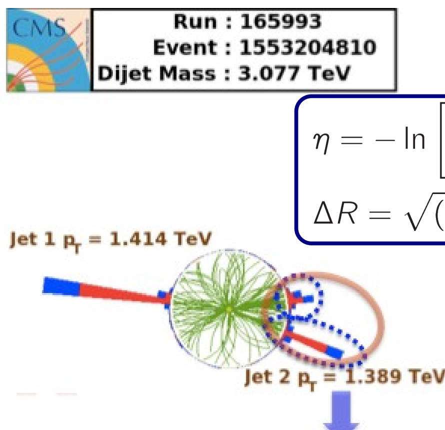


- The following specific models of *s*-channel resonances considered:
  - String resonances (S), E_6 diquarks (D), excited quarks (q*), axigluons (A), colorons (C), heavy gauge bosons (W' and Z'), RS gravitons (G)
- The main background for this search is the SM jet production

Dijet Resonances (cont'd)

- Trigger:
  - Using multijet H_T trigger ($H_T = \Sigma_i p_{T,i}$ for all jets with $p_T > 40$ GeV)
  - Requiring $H_T > 550$ GeV (99.9% efficient for $M_{jj} > 838$ GeV)
- Jet reconstruction:
  - Anti-k_T (R=0.5 and R=0.7) particle-flow jets (calorimeter jets used as a cross-check)
  - Energy-corrected AK5 PF jets combined into "wide jets" which are used to measure the dijet mass spectrum
  - Wide jets formed by adding all other AK5 jets with $p_T > 10$ GeV and $|\eta| < 2.5$ to the closest leading jet if within $\Delta R =< 1.1$

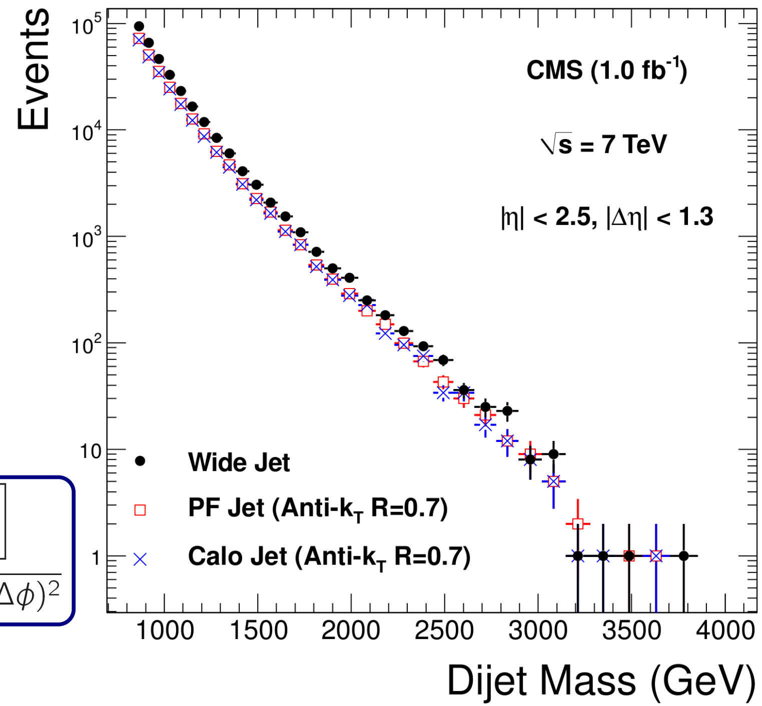




Combined into 1 Wide jet

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$



Wide jets collect more of the final-state radiation and improve the mass resolution

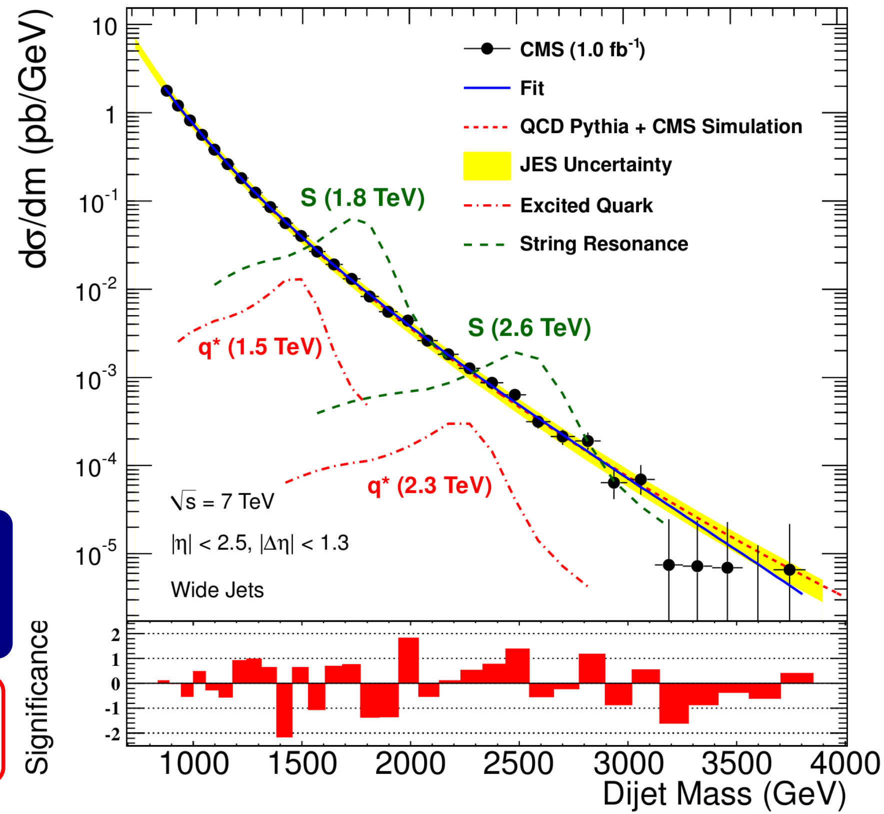
Dijet Resonances (cont'd)

- Event selection:
  - Two leading wide jets required to have $|\eta|<2.5$ and pseudorapidity separation $|\Delta\eta|<1.3$
    - Maximizes signal sensitivity for isotropic resonance decays in the presence of QCD background
  - $M_{jj}>838$ GeV (region with trigger efficiency ≥99.9%)
- Background modeling:
  - A smooth function is fitted to the data
  - No need for background Monte Carlo

Fit function:

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

χ^2/ndf=27.5/28

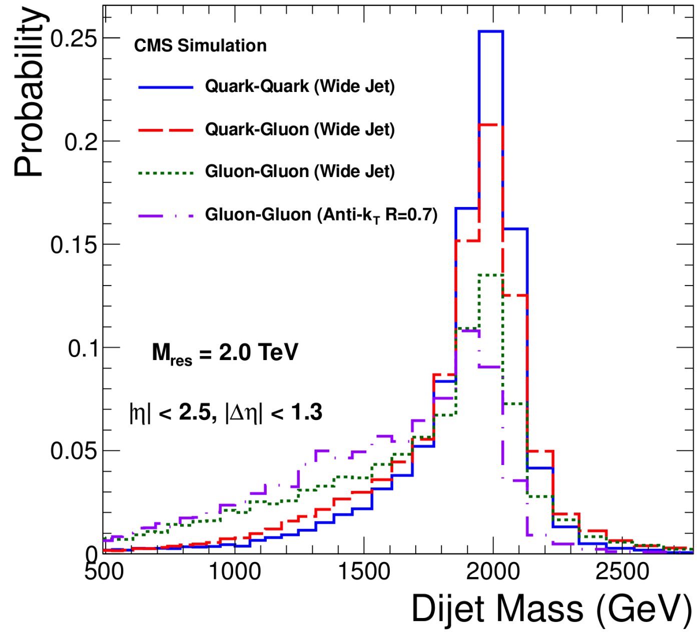


Inclusive dijet mass spectrum for pp→2 wide jets + X, where X can be anything. Bin widths approximately equal dijet mass resolution

Smoothly falling distribution.
No evidence for new particle production

Dijet Resonances (cont'd)

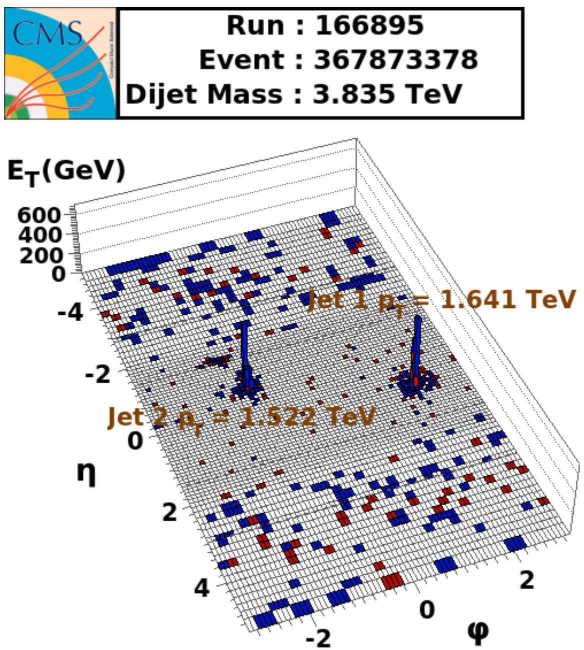
- Signal modeling:
  - Narrow resonances with the natural resonance width small compared to the CMS dijet mass resolution
  - Separate resonance shapes for 3 different parton pairings:
    - $q\bar{q}$ (or qq) (from PYTHIA6 G → $q\bar{q}$)
    - qg (from PYTHIA6 q* → qg)
    - gg (from PYTHIA6 G → gg)
  - These shapes together with the data and the background fit used to set limits
- Dominant sources of systematic uncertainty:
  - Jet energy scale
  - Jet energy resolution
  - Integrated luminosity
  - Statistical uncertainty on the background fit

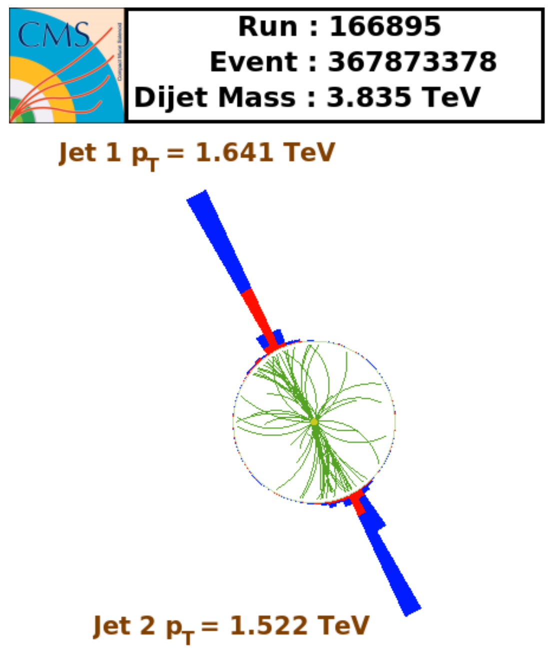


Gaussian core from jet energy resolution and low mass tail from QCD radiation

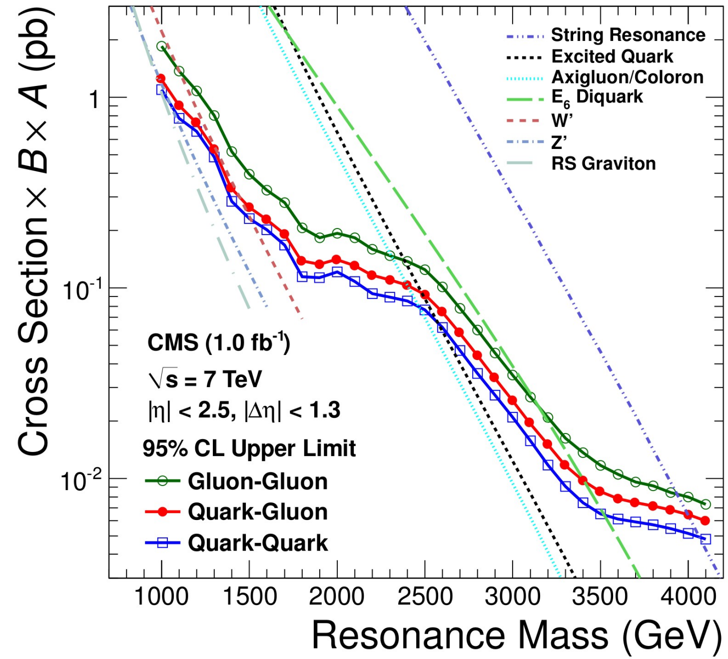
Dijet Resonances (cont'd)

- Generic 95% CL upper limits are set on σ×BR×A
  - Acceptance A refers to kinematic requirements $|\eta|<2.5$ and $|\Delta\eta|<1.3$ (for isotropic decays, A≈0.6)
- These limits can be compared to predictions of σ×BR×A at the parton level of any model of dijet resonance production





Highest dijet mass event



Mass limits for some of the benchmark models considered

Model	Excluded Mass (TeV) Observed	Excluded Mass (TeV) Expected
String Resonances	4.00	3.90
E_6 Diquarks	3.52	3.28
Excited Quarks	2.49	2.68
Axigluons/Colorons	2.47	2.66
W′ Bosons	1.51	1.40

Search for Resonances with the Dijet Angular Ratio (EXO-11-026)

- $\int L dt = 2.2 \text{ fb}^{-1}$
- Public PAS: https://cdsweb.cern.ch/record/1430651/files/EXO-11-026-pas.pdf
- Public TWiki: https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/PhysicsResultsEXO11026

Dijet Angular Ratio

- Angular distribution of the two jets with the largest p_T is sensitive to dijet resonances
  - QCD jets tend to be produced at forward angles (due to the *t*-channel pole in the scattering amplitude)
  - Most models predicting new massive resonances decaying into dijets give essentially isotropic angular distributions
- This search uses the dijet angular ratio

$$R = \frac{N(|\Delta\eta| < 1.3)}{N(1.3 < |\Delta\eta| < 3.0)}$$

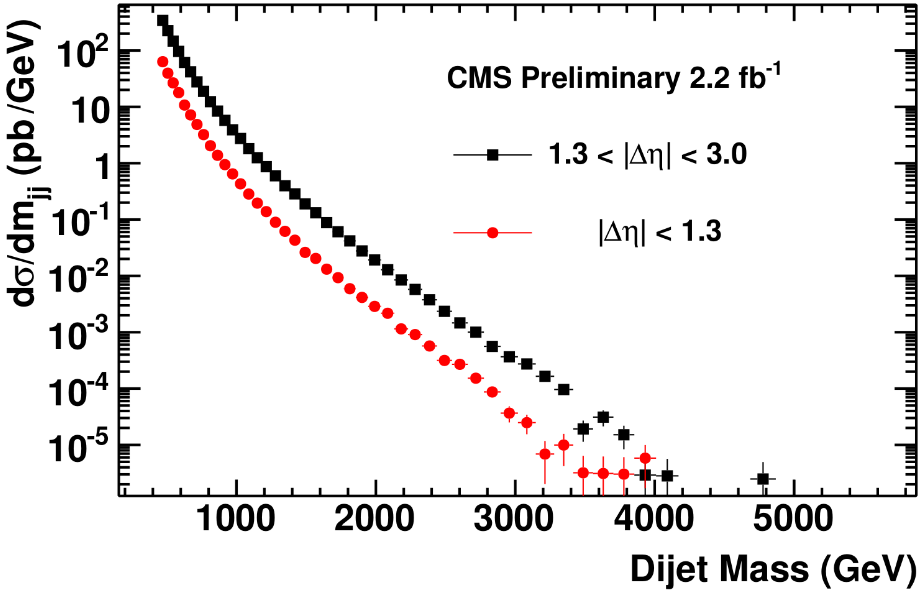
in different dijet mass bins to search for dijet resonances

  - Complementary to searches using only the dijet mass spectrum
- The main background is the SM jet production

Dijet Angular Ratio (cont'd)

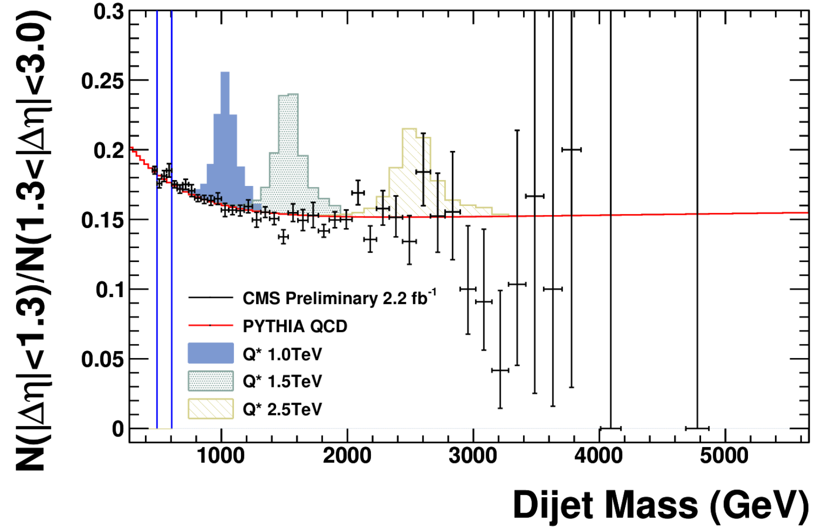
- Trigger:
  - Using single-jet triggers with varying thresholds on the jet p_T
  - For each trigger threshold, a value of the dijet mass at which the trigger becomes fully efficient is determined
- Jet reconstruction:
  - Anti-k_T (R=0.7) calorimeter jets with energy corrections applied

- Event selection:
  - Two leading jets required to have $|\eta|<2.5$
  - Selected event are classified as inner if the pseudorapidity separation of the two leading jets $|\Delta\eta|<1.3$, and outer if $1.3<|\Delta\eta|<3.0$

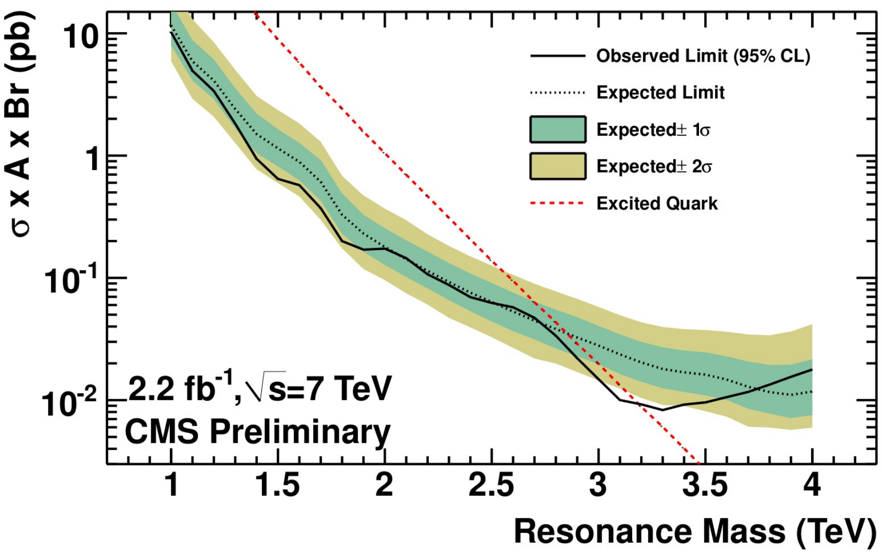


Dijet Angular Ratio (cont'd)

- Signal and background modeling:
  - Both signal and background modeled by PYTHIA6
  - Background prediction normalized to data in a low dijet mass sideband (500–600 GeV)
- Dominant sources of systematic uncertainty:
  - Jet energy scale (in particular relative jet energy scale), integrated luminosity, background modeling



Data consistent with background expectation



Results:

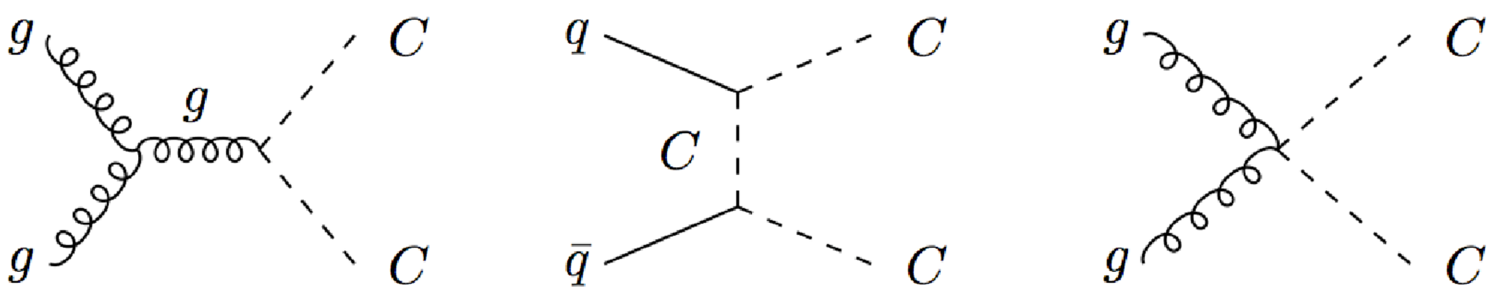
- Excited quarks with mass less than 3.2 TeV (2.85 TeV expected) excluded at 95% CL

Search for Pair-Produced Dijet Resonances (EXO-11-016)

- $\int L dt = 2.2\ fb^{-1}$
- Public PAS: http://cdsweb.cern.ch/record/1416058/files/EXO-11-016-pas.pdf
- Public TWiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11016

Pair-Produced Dijet Resonances

- Dijet resonance searches generally more sensitive to singly-produced new particles
- This search focuses on narrow colored resonances produced strongly in pairs and each decaying into a pair of jets
  - Search performed in a paired dijet mass spectrum in events with at least 4 jets
  - Paired dijet mass defined as the average of the two dijet masses
- Search results compared with a specific coloron model



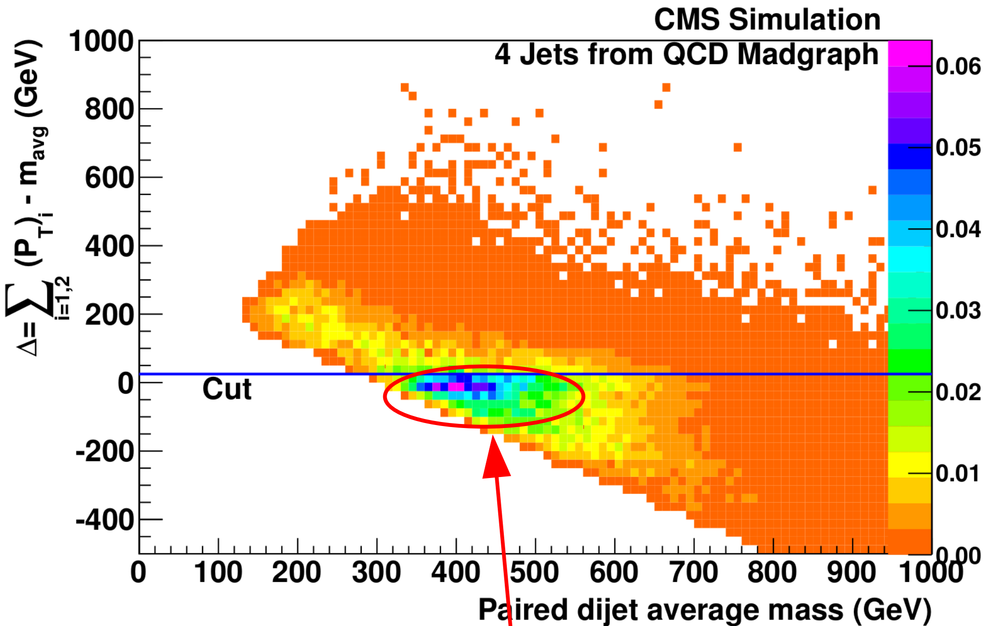
- As with the dijet resonances, the main background is the SM multijet production

Pair-Produced Dijet Resonances (cont'd)

- Trigger:
  - H_T>200 GeV (for 2010 data) and quadruple-jet trigger (for 2011 data) which requires 4 jets with p_T>70 GeV
  - Trigger fully efficient for events with 4 leading jets with p_T>140 GeV
- Jet reconstruction:
  - Anti-k_T (R=0.5) particle-flow jets with energy corrections applied
- Event selection:
  - ≥4 jets with $|\eta|<2.5$ and p_T>150 GeV
  - Create dijet combinations from the 4 leading jets by considering jet pairs with $\Delta R_{jj}>0.7$
  - Choose combination with the smallest $\Delta m/m_{avg}$
  - To additionally suppress QCD multijet background, require $\Delta m/m_{avg}<0.15$
  - To ensure a smoothly-falling paired dijet mass spectrum, require Δ>25 GeV (see next slide)

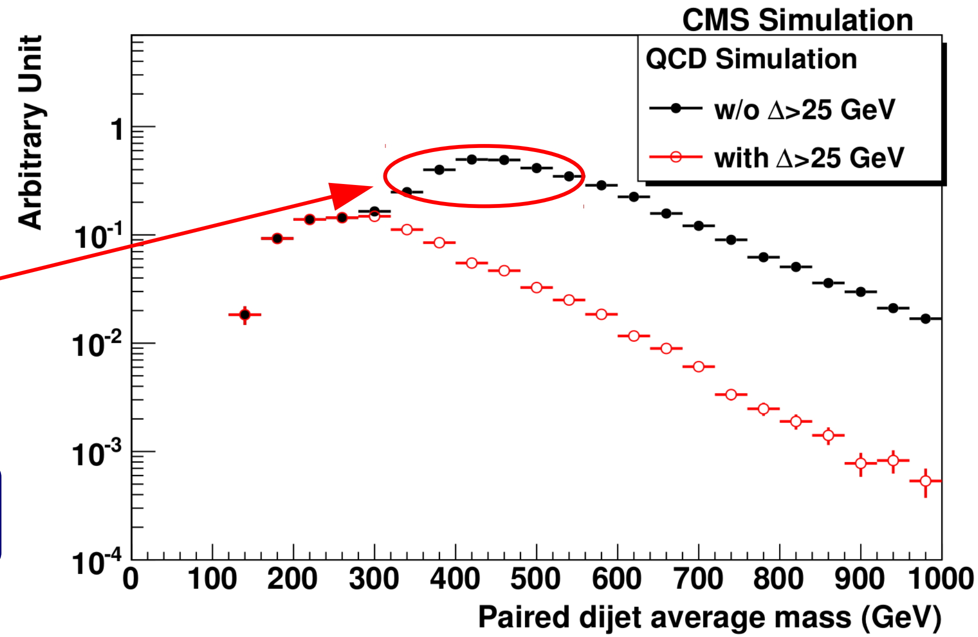
Pair-Produced Dijet Resonances (cont'd)

- Event selection (cont'd):



$$\Delta = \sum_{i=1,2} (P_T)_i - m_{avg}$$

$$\Delta > 25 \text{ GeV}$$

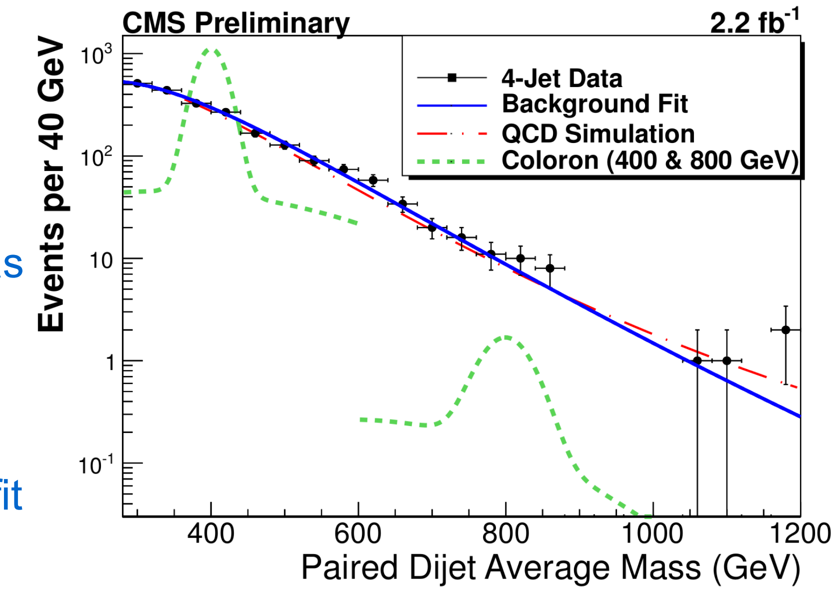


Broad structure caused by the applied selection cuts

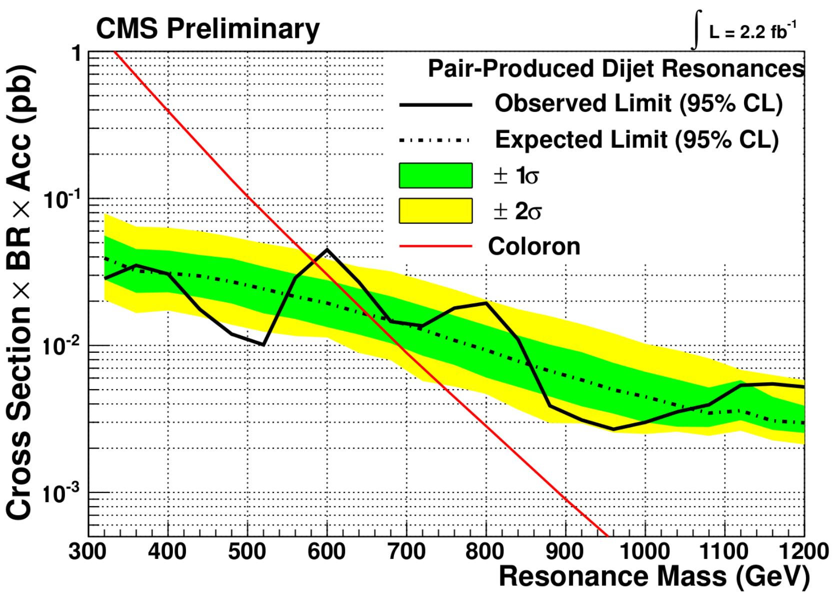
Acceptance varies from 3% for M(C)=300 GeV to 13% for M(C)=1000 GeV

Pair-Produced Dijet Resonances (cont'd)

- Signal and background modeling:
  - Signal samples produced using MadGraph with colorons modeled as narrow dijet resonances
  - Signal shape modeled by a double Gaussian
  - Background modeled by the same smooth function as in the dijet resonance search
- Dominant sources of systematic uncertainty:
  - Jet energy scale, jet energy resolution, integrated luminosity, statistical uncertainty on the background fit



Smoothly falling distribution.
No evidence for new particle production



Results:

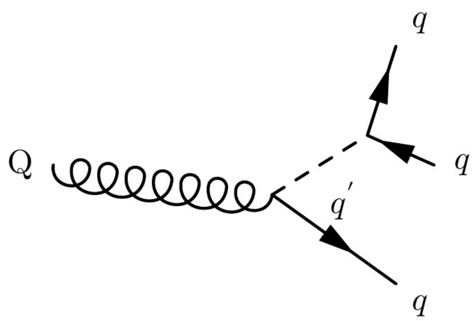
- Pair production of colorons with 320<M(C)<580 GeV (320<M(C)<650 GeV expected) excluded at 95% CL

Search for Three-Jet Resonances (EXO-11-001)

- $\int L dt = 35\ pb^{-1}$
- Paper: Phys.Rev.Lett. 107 (2011) 101801
- Preprint: arXiv:1107.3084
- Public TWiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11001

Three-Jet Resonances

- New physics could be hiding in final states with more than 4 high-p_T jets
- This search focuses on a pair production of massive colored resonances, each decaying into 3 jets, resulting in a 6-jet final state (pp → QQ → 3j 3j)



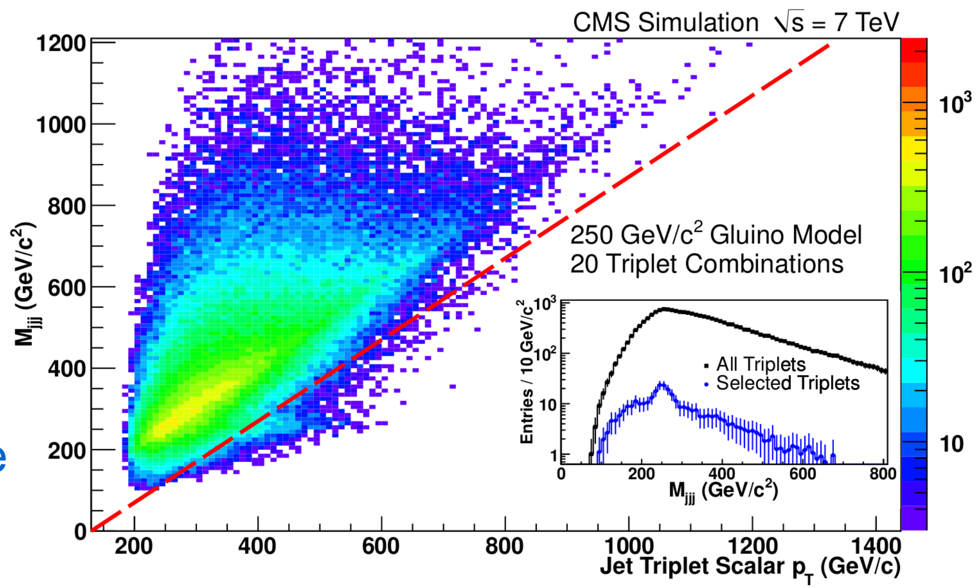
- One specific model of 3-jet resonances realized in RPV decays of supersymmetric gluinos to 3 quarks
  - Event selection criteria optimized in the context of this model but generic enough to provide a robust model-independent basis for searches for other models of new physics producing similar final states
- As in all cases up to now, the main background is the SM multijet production

Three-Jet Resonances (cont'd)

- Trigger:
  - H_T trigger with thresholds varying between 100 and 150 GeV, depending on the run period
- Jet reconstruction:
  - Anti-k_T (R=0.5) particle-flow jets with energy corrections applied
- Event selection:
  - ≥6 jets with H_T>425 GeV (this threshold ensures that the trigger is fully efficient)
  - Jet p_T>45 GeV and |η|<3.0
  - 6 leading jets combined into all possible unique triplet combinations → 20 combinations
  - To increase signal sensitivity and reduce combinatorial background, require

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

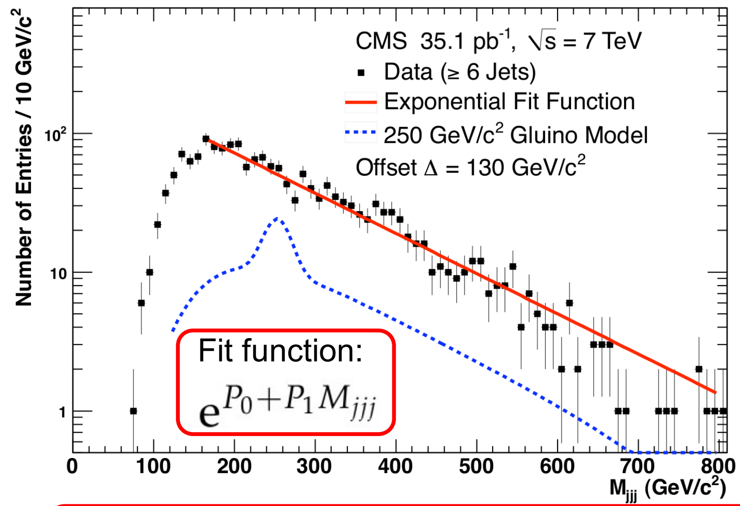
$$\Delta = 130 \text{ GeV}$$



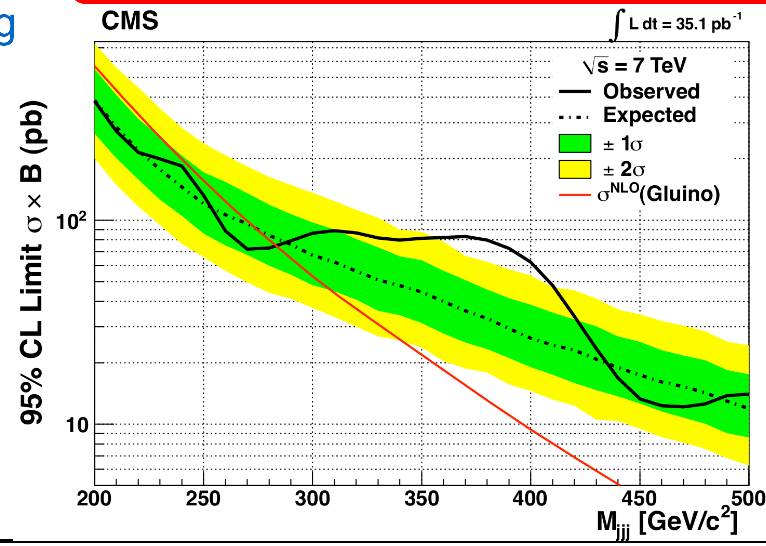
Acceptance varies from 0.4% for 300 GeV gluino to 5% for 1000 GeV gluino

Three-Jet Resonances (cont'd)

- Background modeling:
  - Shape of the triplet mass distribution largely unchanged between events with N_{jet}=4 (or N_{jet}=5) and $N_{jet}\geq6$
  - $N_{jet}\geq6$ triplet mass distribution described by an exponential function with the slope parameter P_1 constrained by the N_{jet}=4 triplet mass distribution
- Signal modeling:
  - Signal samples simulated using PYTHIA6
  - Gluinos modeled as narrow resonances and set to decay to 3 quarks through the λ_{uds} quark RPV coupling with BR(g~→qqq)=100%
- Dominant sources of systematic uncertainty:
  - Jet energy scale, ISR/FSR, pile-up, choice of PDFs, integrated luminosity



Data consistent with background expectation



Results:

- Gluino masses in the range 200 to 280 GeV (200 to 270 GeV expected) excluded at 95% CL

Search for Quark Compositeness in Dijet Angular Distributions (EXO-11-017)

- $\int L dt = 2.2\ \mathrm{fb}^{-1}$
- Preprint: arXiv:1202.5535
- Public TWiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11017

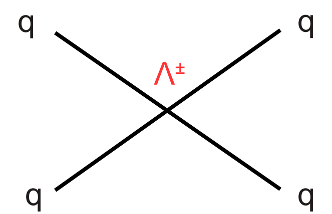
Dijet Angular Distributions

- In certain models of BSM physics, quarks are proposed to be composite objects
- At energies well bellow the compositeness scale Λ, compositeness manifested as a four-fermion contact interaction (CI)

$$L_{qq} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)\right]$$

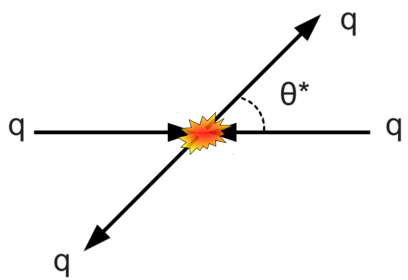
  - The following CI scenarios investigated

$$\Lambda = \Lambda^{\pm}_{LL} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (\pm1,0,0)$$
$$\Lambda = \Lambda^{\pm}_{RR} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (0,\pm1,0)$$
$$\Lambda = \Lambda^{\pm}_{VV} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (\pm1,\pm1,\pm1)$$
$$\Lambda = \Lambda^{\pm}_{AA} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (\pm1,\pm1,\mp1)$$
$$\Lambda = \Lambda^{\pm}_{(V-A)} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (0,0,\pm1)$$



$\Lambda^+ \rightarrow$ Destructive interference between CI and QCD
$\Lambda^- \rightarrow$ Constructive interference between CI and QCD

- Contact interactions resulting from the quark compositeness affect the angular distribution of the scattered partons



$$\text{Angular distribution} \equiv \frac{1}{\sigma_{\text{dijet}}}\frac{d\sigma_{\text{dijet}}}{d\chi_{\text{dijet}}}$$

Flat for Rutherford scattering, approximately flat for QCD, peaking at low values of χ_{dijet} for CI models

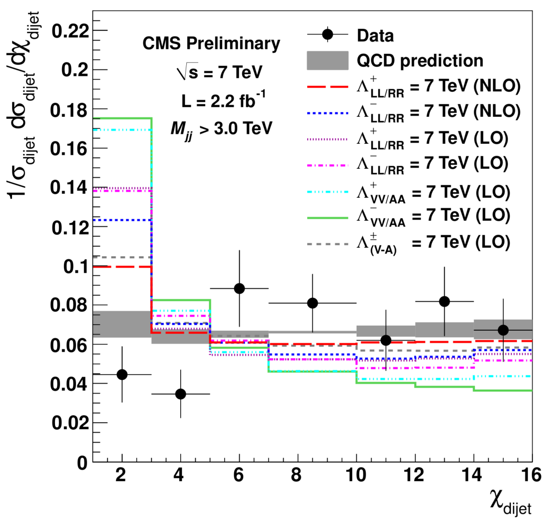
$$\chi_{\text{dijet}} = e^{|y_1-y_2|} \xrightarrow[m\to0]{} \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|},\ y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-Pz}\right),\ y_{\text{boost}} = \frac{1}{2}(y_1+y_2)$$

Dijet Angular Distributions (cont'd)

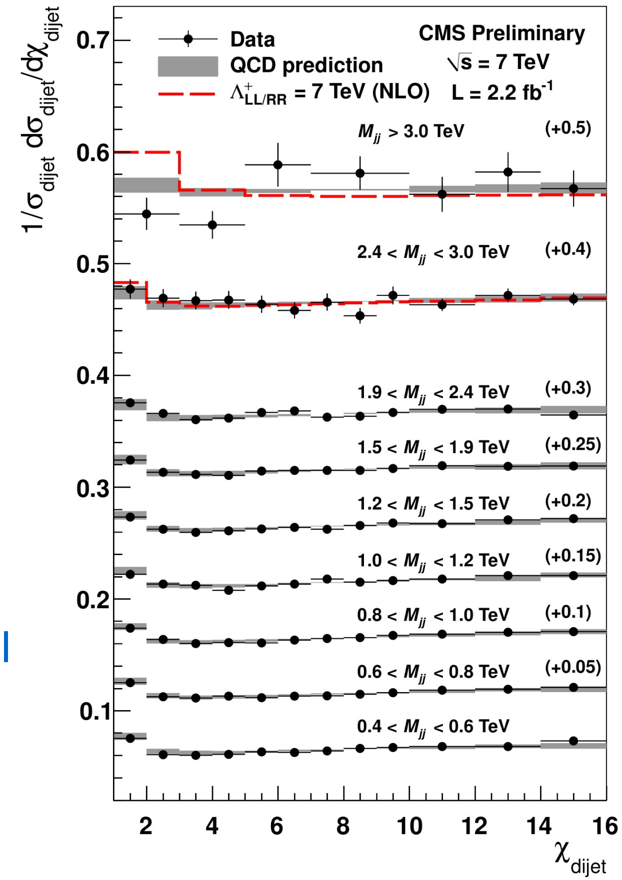
- Trigger:
  - Single-jet triggers with different p_T thresholds (60, 80, 110, 150, 190, 240, and 300 GeV). All except the last one prescaled
- Jet reconstruction:
  - Anti-k_T (R=0.5) particle-flow jets with energy corrections applied
- Event selection:
  - Require ≥2 jets with χ_{dijet}<16 and $|y_{boost}|$<1.11 (effectively restricts $|y_1|$ and $|y_2|$ to <2.5)
  - Angular distribution measured in multiple dijet mass bins with lower edges chosen such that the trigger efficiency exceeds 99% (0.4, 0.6, 0.8, 1.0, 1.2, 1.5, 1.9, 2.4, and 3.0 TeV)
    - The first 5 bins correspond to 0.77, 5.9, 32, 108, and 371 pb^{-1}. Only the last 4 bins correspond to the full integrated luminosity of 2.2 fb^{-1}

Dijet Angular Distributions (cont'd)

- Background modeling:
  - Predictions at NLO obtained with NLOJET++ 2.0.1
  - Correction factors applied to account for nonperturbative effects (obtained from PYTHIA6 and HERWIG++)
- Signal modeling:
  - Using LO (as implemented in PYTHIA8) and NLO predictions
  - Correction factors applied to account for nonperturbative effects

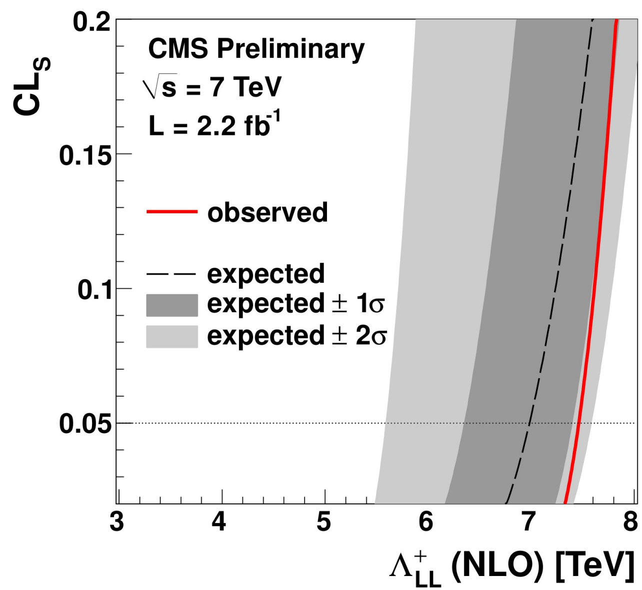


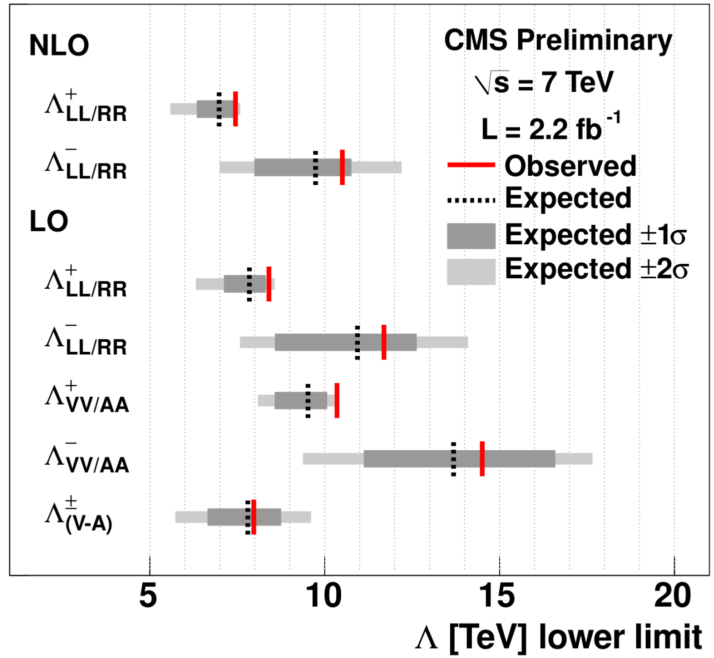
- Data unfolding:
  - Data corrected for instrumental effects
  - Unfolding correction factors obtained from PYTHIA6 and HERWIG++



Dijet Angular Distributions (cont'd)

- 95% CL limits on Λ:





CI model	Observed limit (TeV)	Expected limit (TeV)
NLO $\Lambda^{+}_{LL/RR}$	7.5	$7.0^{+0.4}_{-0.6}$
NLO $\Lambda^{-}_{LL/RR}$	10.5	$9.7^{+1.0}_{-1.7}$
LO $\Lambda^{+}_{LL/RR}$	8.4	$7.9^{+0.5}_{-0.7}$
LO $\Lambda^{-}_{LL/RR}$	11.7	$10.9^{+1.7}_{-2.4}$
LO $\Lambda^{+}_{VV/AA}$	10.4	$9.5^{+0.5}_{-1.0}$
LO $\Lambda^{-}_{VV/AA}$	14.5	$13.7^{+2.9}_{-2.6}$
LO $\Lambda^{\pm}_{(V-A)}$	8.0	$7.8^{+1.0}_{-1.1}$

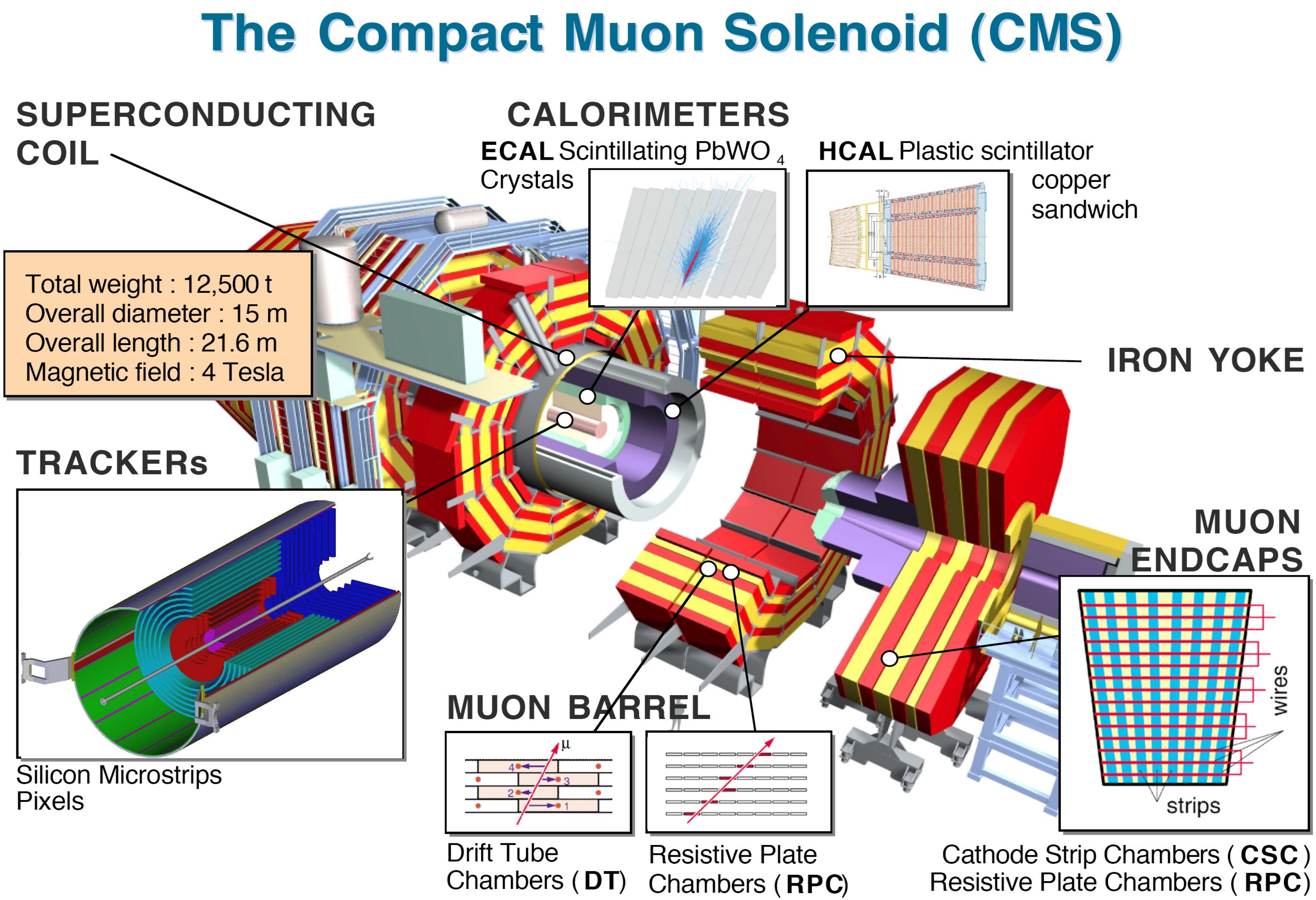
Observed limits slightly higher than the expected ones because of a downward fluctuation at low χ_{dijet} for M_{jj}>3.0 TeV

Summary and Outlook

- Hadronic final states proved to be a fertile ground for searches for new physics
- Many results already made public, many new and updated results in the pipeline
- Despite our best efforts, the standard model is still alive and well
  - Excluded a wide range of mass scales where new physics could have been hiding
- An exciting year ahead of us
  - Higher center-of-mass energy (8 TeV) → sensitivity to higher mass scales
  - Expect at least 3 times more data than in 2011 → more stringent cross section limits
- Stay tuned!

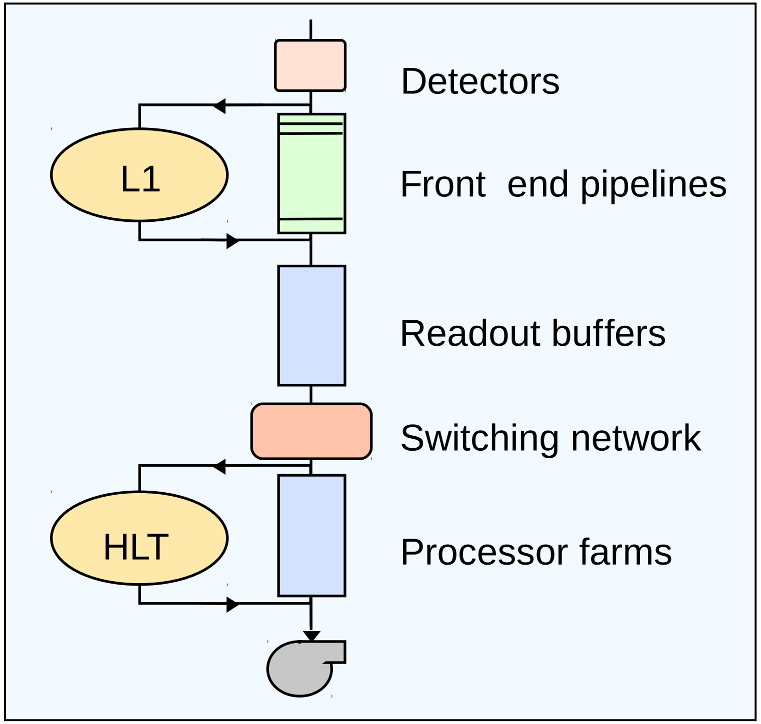
Backup Slides

CMS Detector

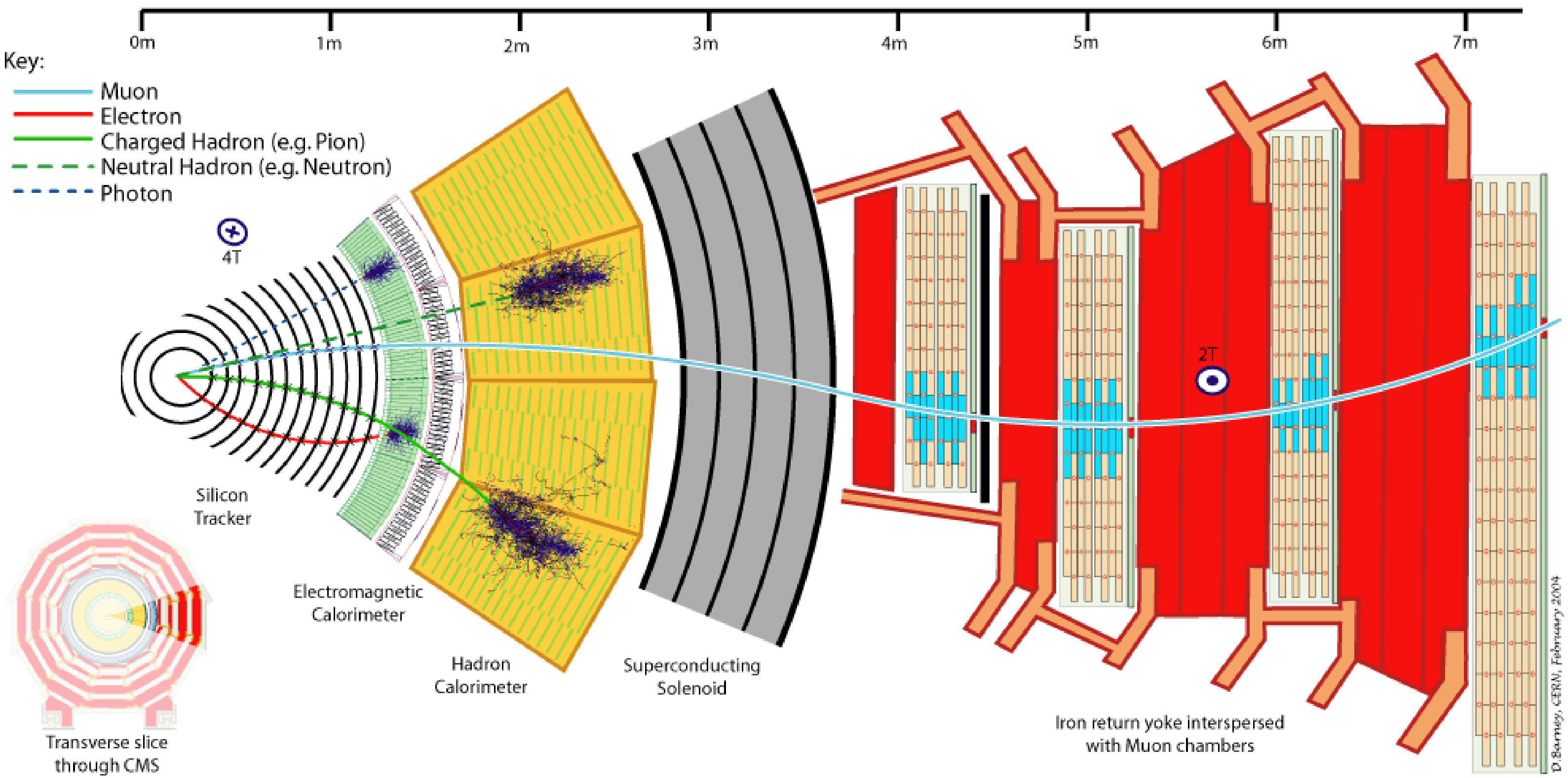


CMS Trigger System

- CMS has a two-tiered trigger system:
  - Level-1 (L1) trigger:
    - Consists of custom-designed fast electronics
    - Reduces event rate from 40 MHz to 100 kHz
  - High-Level Trigger (HLT):
    - Consists of a farm of commercially available CPUs running reconstruction code optimized for fast processing
    - Reduces event rate from 100 kHz to *O*(100) Hz



Particle-flow Reconstruction



- Particle-flow algorithm reconstructs all stable particles by combining information from all subdetectors
- Particles categorized into the following 5 types:
  - Muons, electrons (with associated bremsstrahlung photons), photons (including conversion in the tracker volume), charged hadrons, neutral hadrons

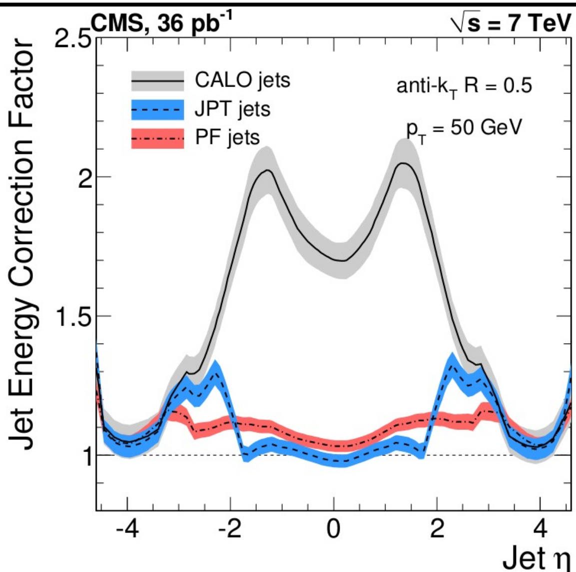
Noise Cleanup

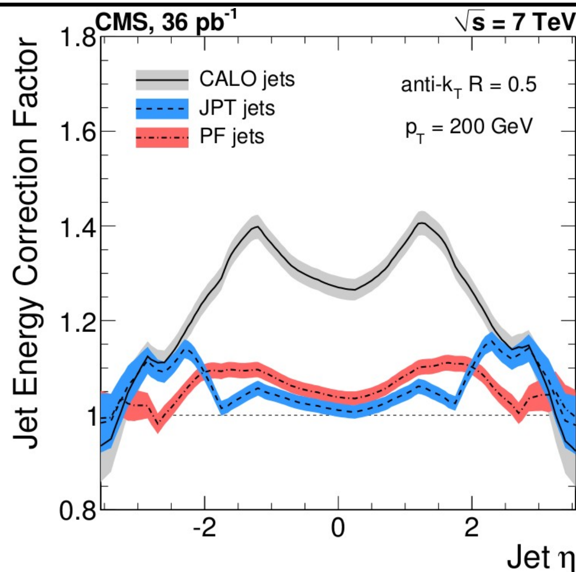
- To remove possible instrumental and non-collision backgrounds, events required
  - To have a reconstructed primary vertex within |z|<24 cm and r<2 cm
  - Jets passing identification criteria that is fully efficient for signal
  - In paired dijet resonance analysis, events also required to pass HCAL noise cleanup criteria

Jet Identification Criteria

- Calorimeter loose jet ID:
  - jet electromagnetic fraction (EMF) > 0.01 if jet $|\eta| < 2.6$
  - number of rechits carrying 90% of the jet energy (n90hits) > 1
  - fraction of energy contributed by the hottest HPD (fHPD) < 0.98
- Particle-flow loose jet ID:
  - Neutral Hadron Fraction < 0.99
  - Neutral Electromagnetic Fraction < 0.99
  - Number of Constituents > 1
  - Charged Hadron Fraction > 0 if jet $|\eta| < 2.4$
  - Charged Electromagnetic Fraction < 0.99 if jet $|\eta| < 2.4$
  - Charged Hardron Multiplicity > 0 if jet $|\eta| < 2.4$

Jet Energy Corrections





$$p_{\mu}^{\mathrm{cor}} = \mathcal{C}\cdot{}^{\mathrm{raw}}_{\mu}$$

$$\mathcal{C} = C_{\mathrm{offset}}(p_{\mathrm{T}}^{\mathrm{raw}}) \cdot C_{\mathrm{MC}}(p'_{\mathrm{T}}, \eta) \cdot C_{\mathrm{rel}}(\eta) \cdot C_{\mathrm{abs}}(p''_{\mathrm{T}})$$

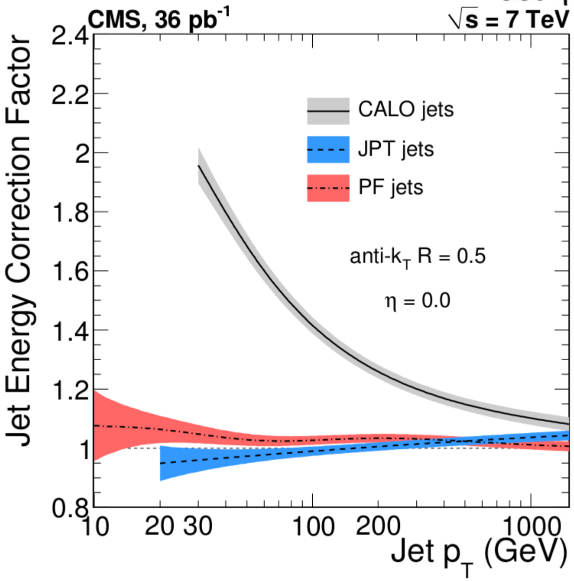
$\mathcal{C}$ - Overall correction factor

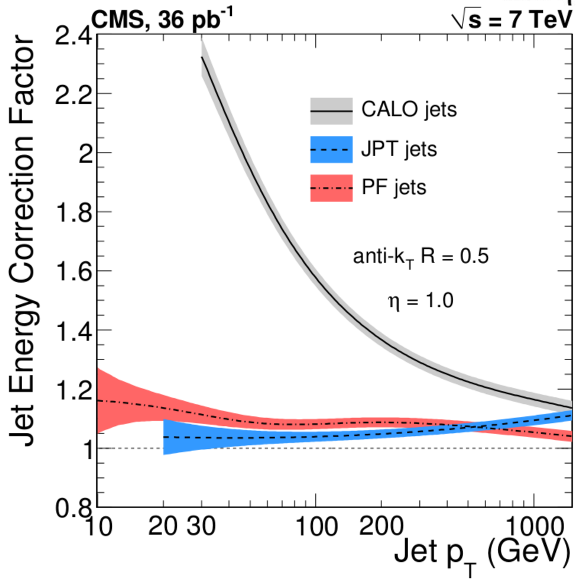
C_{offset} - Offset correction factor

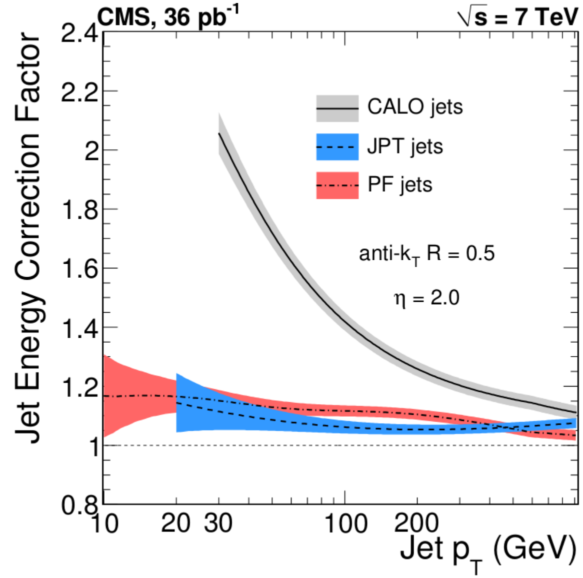
C_{MC} - MC calibration factor

C_{rel} - Residual relative calibration factor

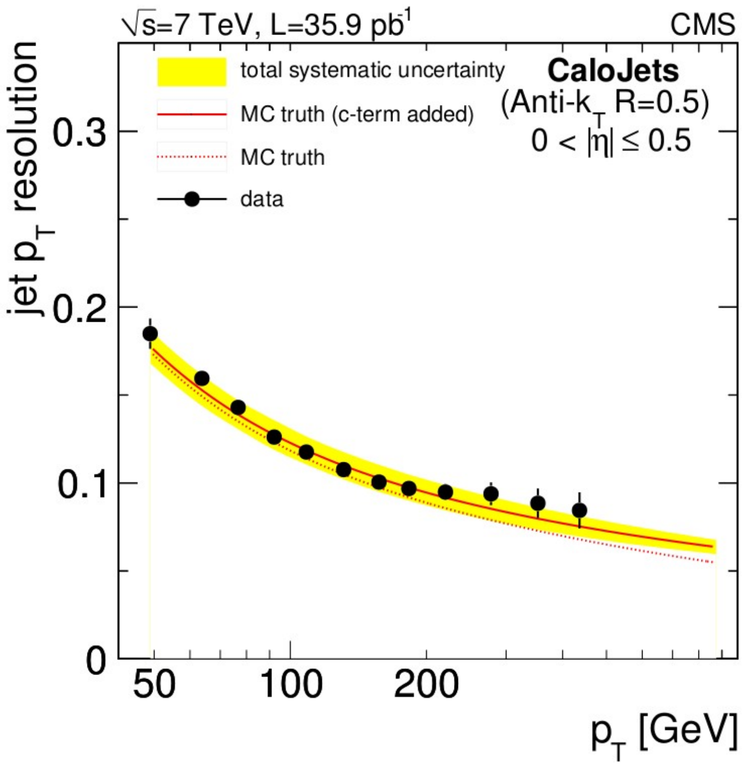
C_{abs} - Residual absolute calibration factor

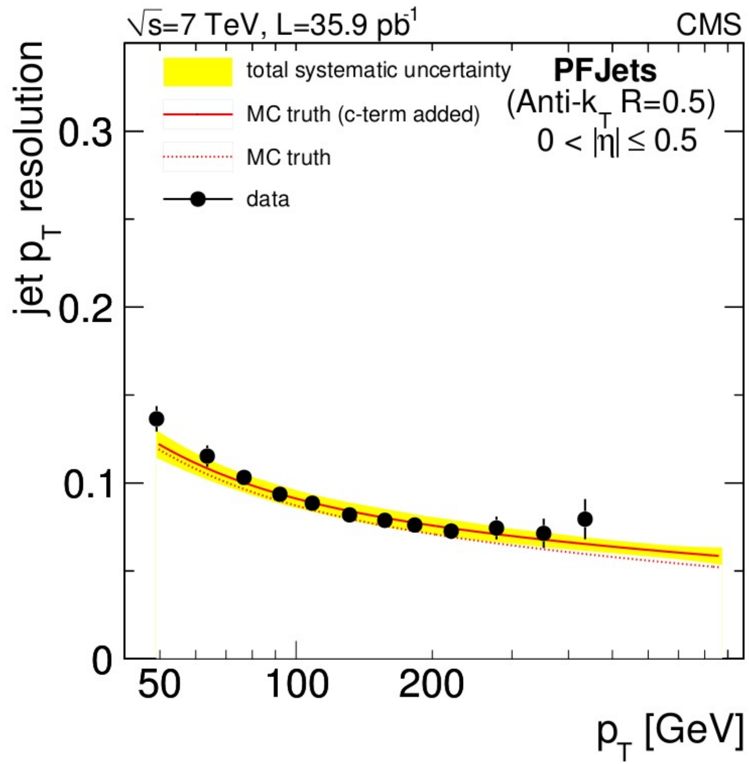






Jet p_T Resolution





$$\frac{\sigma(p_T)}{p_T} = \sqrt{\mathrm{sgn}(N)\cdot\left(\frac{N}{p_T}\right)^2 + S^2\cdot p_T^{(M-1)} + C^2}$$

N - Noise term

S - Stochastic term

C - Constant term

Dijet Resonances

Properties of some resonance models

Model Name	X	Color	J^P	$\Gamma/(2M)$	Chan
Excited Quark	q*	Triplet	$1/2^+$	0.02	qg
E_6 Diquark	D	Triplet	0^+	0.004	qq
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
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	$q\bar{q}$
String	S	mixed	mixed	0.003 – 0.037	qg, $q\bar{q}$, gg

CMS dijet mass resolution (wide jets):

qq :

$$\frac{\sigma}{M} = \frac{1.31}{\sqrt{M[GeV]}} + 0.018$$

$\approx 8\%\,(M = 0.5$ TeV$), \approx 4\%\,(M = 2.5$ TeV$)$

qg :

$$\frac{\sigma}{M} = \frac{1.56}{\sqrt{M[GeV]}} + 0.027$$

$\approx 10\%\,(M = 0.5$ TeV$), \approx 6\%\,(M = 2.5$ TeV$)$

gg :

$$\frac{\sigma}{M} = \frac{2.09}{\sqrt{M[GeV]}} + 0.015$$

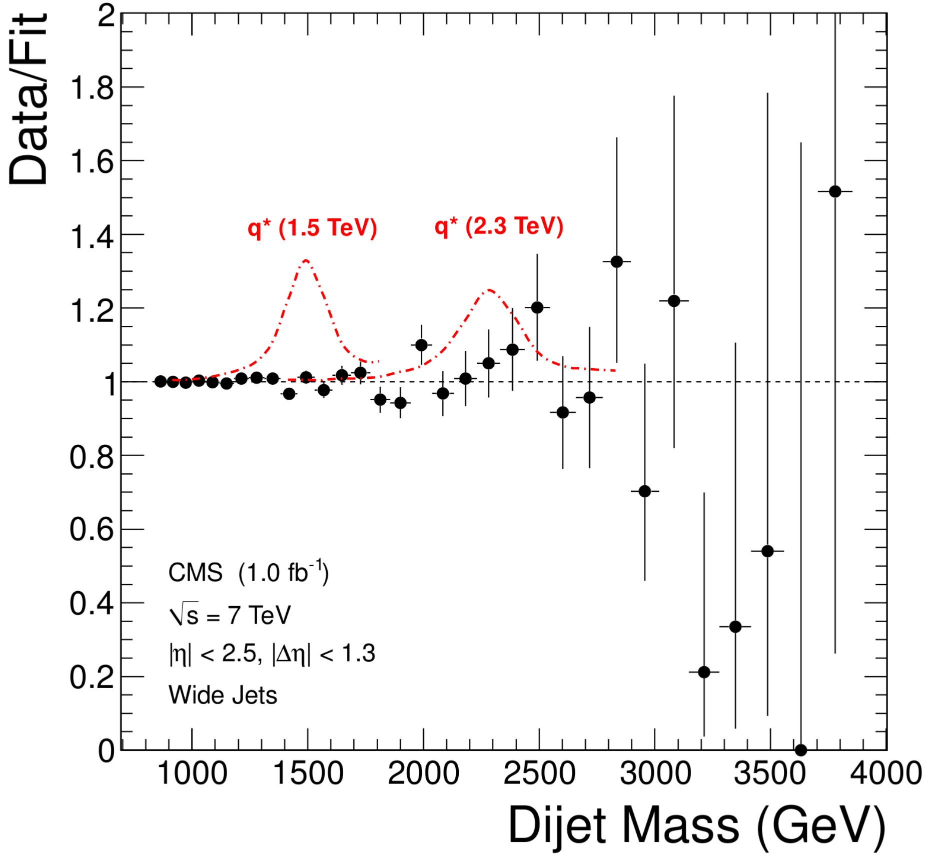
$\approx 11\%\,(M = 0.5$ TeV$), \approx 6\%\,(M = 2.5$ TeV$)$

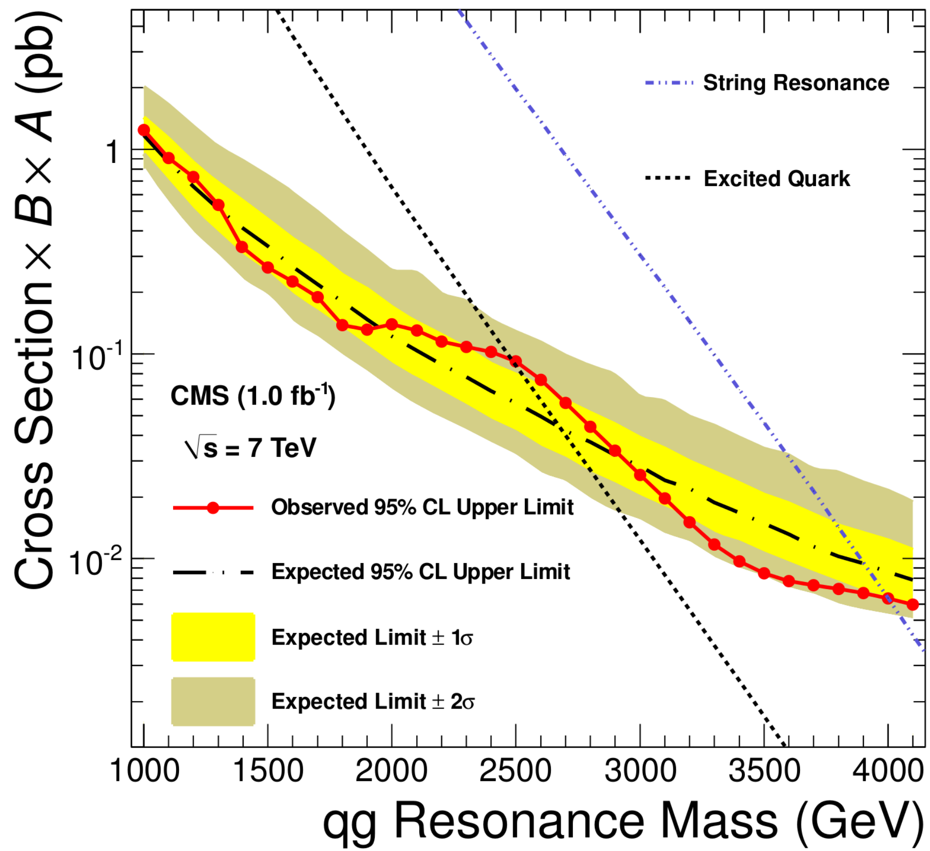
$F(\cos\theta^*) \equiv d\hat{\sigma}/d\cos\theta^*$

arXiv:1110.5302

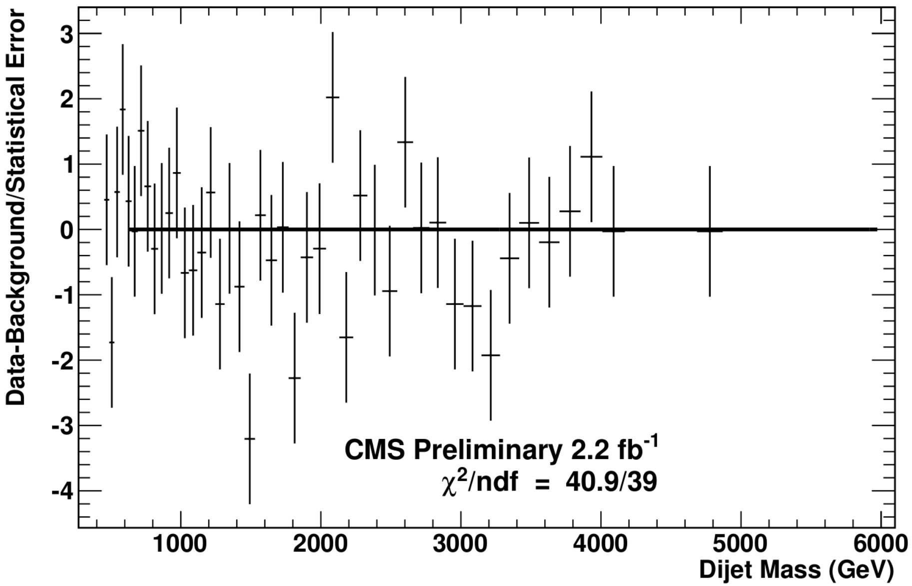
- *E_6 diquark, color octet scalars:* $F(\cos\theta^*) = \text{const.}$
- *excited quark:* $F(\cos\theta^*) \sim 1 + \cos\theta^*$, which becomes $F(|\cos\theta^*|) = \text{const.}$ (odd in $\cos\theta^*$).
- *axigluon, coloron, W', Z':* $F(\cos\theta^*) \sim 1 + \cos^2\theta^*$.
- *RS gravitons:* $F(gg \to G \to q\bar{q}) = F(q\bar{q} \to G \to gg) \sim 1 - \cos^4\theta^*$, $F(gg \to G \to gg) \sim 1 + 6\cos^2\theta^* + \cos^4\theta^*$, and $F(q\bar{q} \to G \to q\bar{q}) \sim 1 - 3\cos^2\theta^* + 4\cos^4\theta^*$

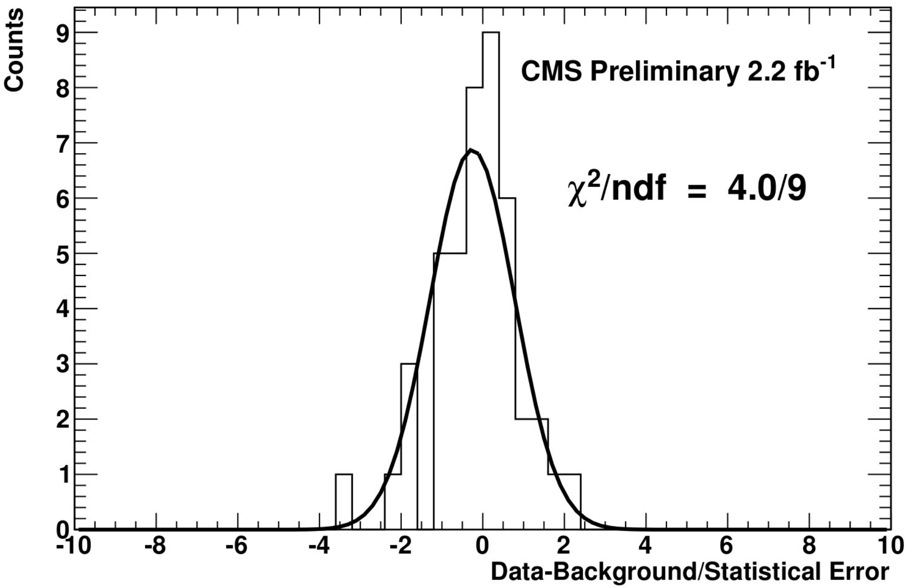
Dijet Resonances (cont'd)



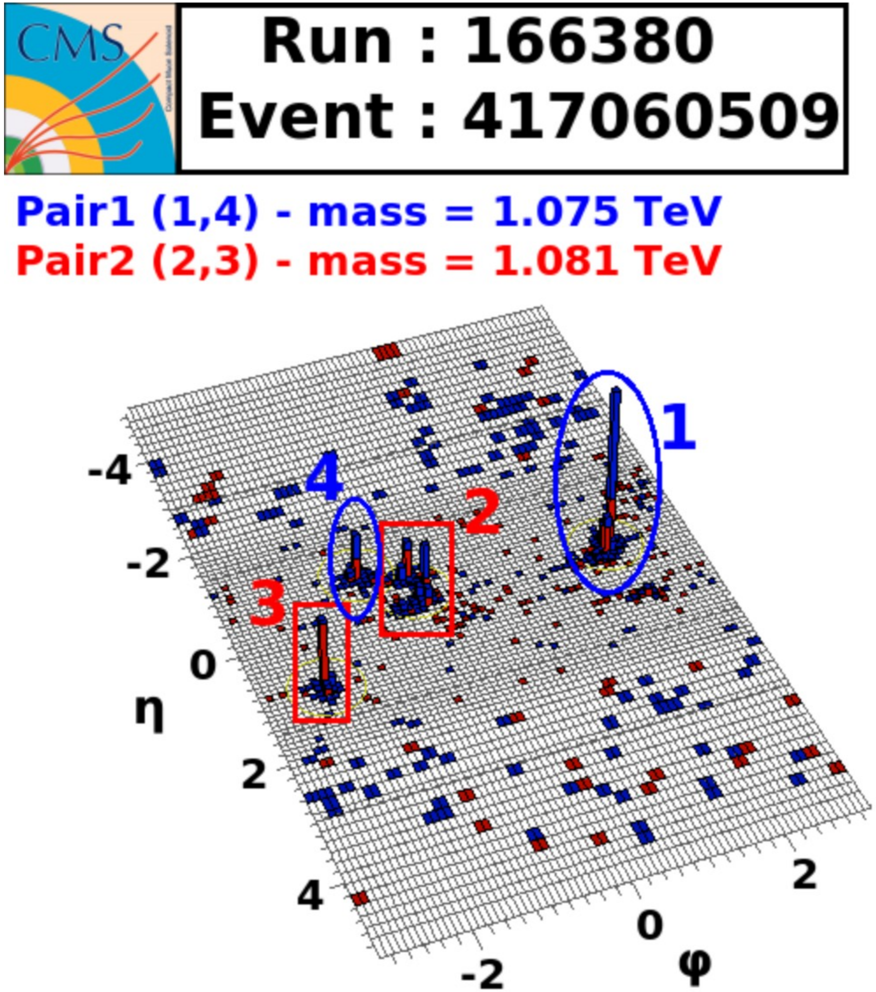


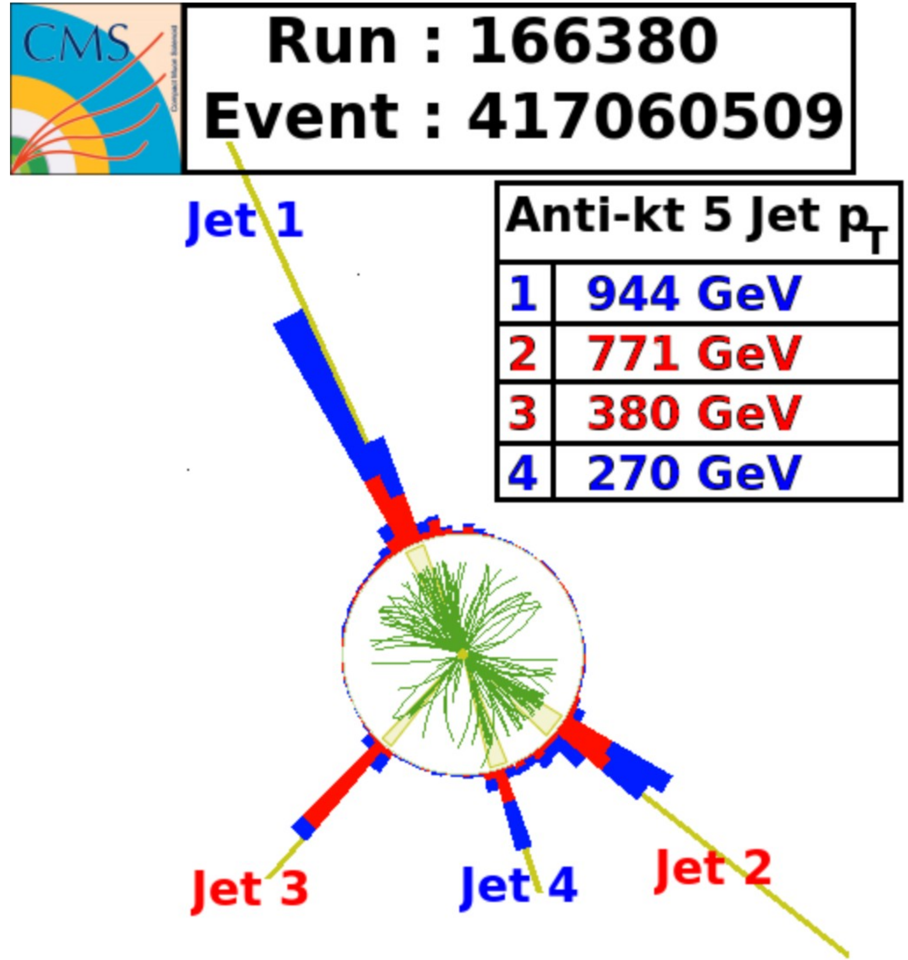
Dijet Angular Ratio





Pair-Produced Dijet Resonances





Energetic 4-jet event passing event selection

Dijet Angular Distributions

Source of Uncertainty	$0.4 < M_{jj} < 0.6$ TeV (%)	$M_{jj} > 3$ TeV (%)
Jet energy scale	1.0	0.3
Jet energy resolution	0.2	0.6
Jet energy resolution tails	0.5	4.6
Unfolding, MC modeling	0.2	4.9
Unfolding, detector simulation	1.3	2.0
Total experimental systematic uncertainty	1.7	7.0
Statistical uncertainty	2.5	31.6
μ_r and μ_f scales	5.6	14.9
PDF (CTEQ6.6)	0.5	0.7
Non-perturbative corrections	1.7	1.1
Total theoretical systematic uncertainty	5.9	15.0