Search for Hadronic Resonances at CMS

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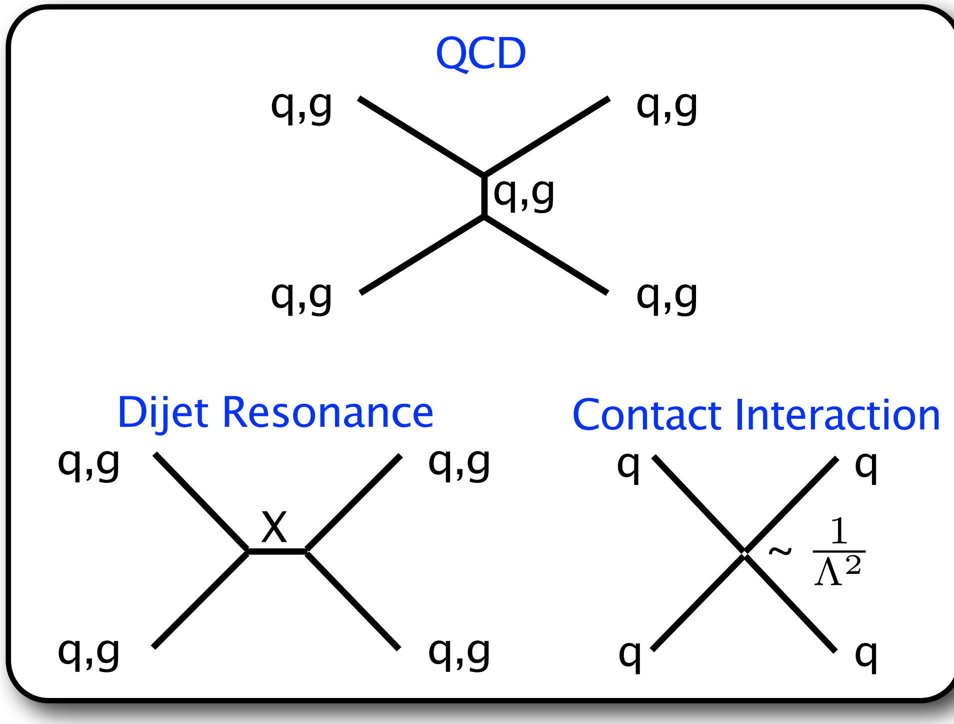
PLHC2011: Physics at LHC 2011, Perugia, Italy

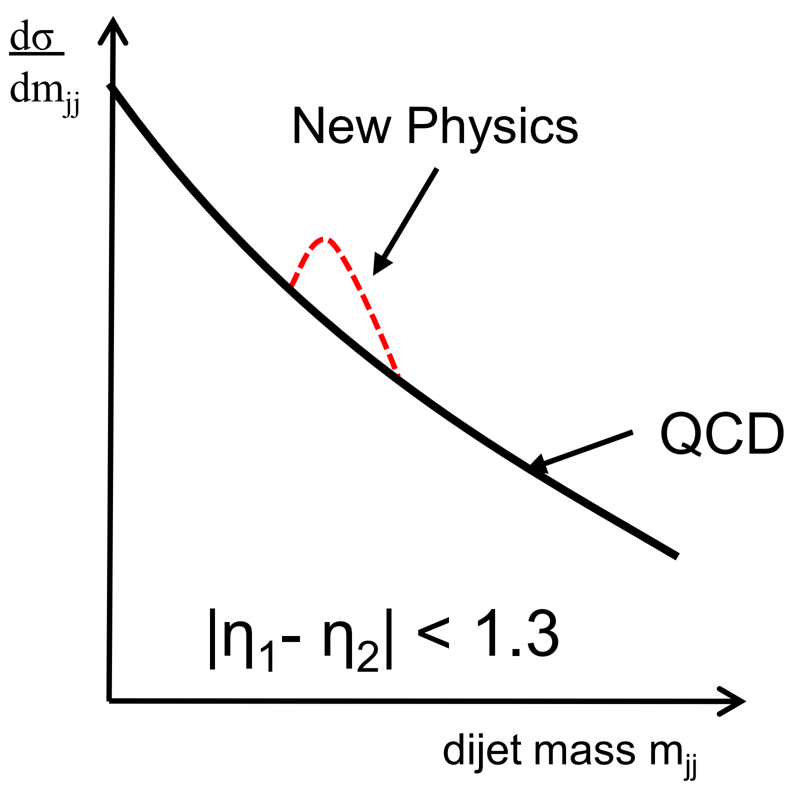
Outline

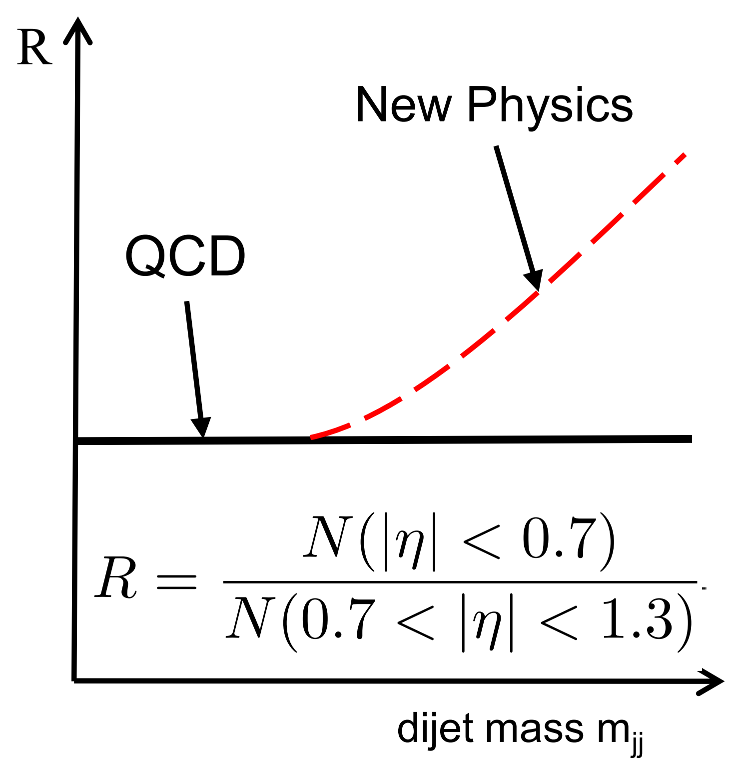
- Motivation
- The CMS Detector and Jet Reconstruction
- Dijet
  - Dijet Resonances
  - Dijet Centrality Ratio
  - Dijet Angular Distribution
- Multijet Resonances
- t-tbar Resonances
- Conclusion

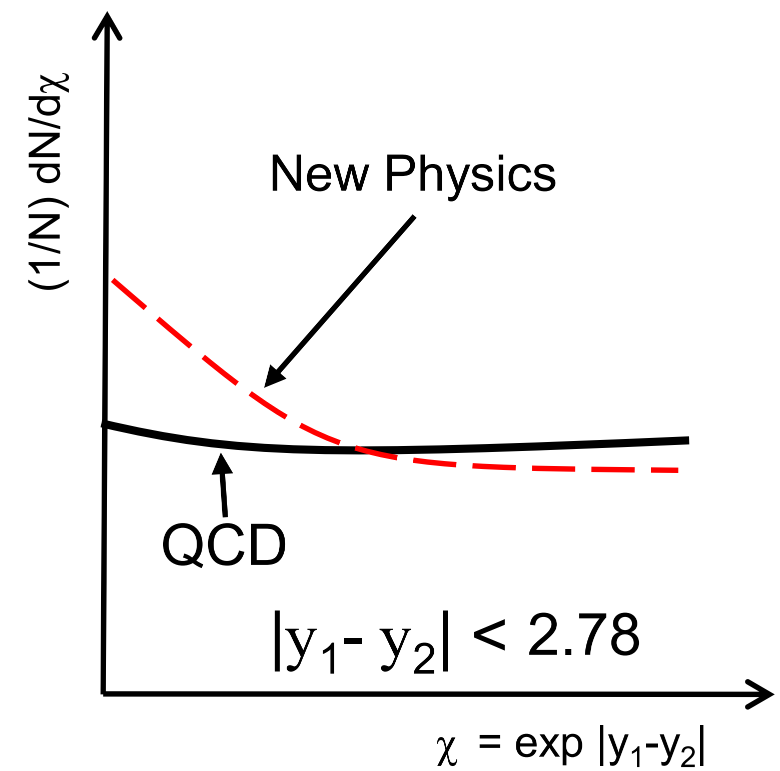
Motivation

- We search for new physics in hadronic final states.
- Dijet resonance in dijet mass (bump hunting).
  - String resonances, q*, axigluon, ...
- Dijet centrality ratio and Dijet angular distribution
  - Contact interaction.
  - Dijet centrality ratio also can confirm that a *"bump"* is not QCD fluctuation.
- In addition: RPV gluino in multijet channel and Z' in t-tbar channel.





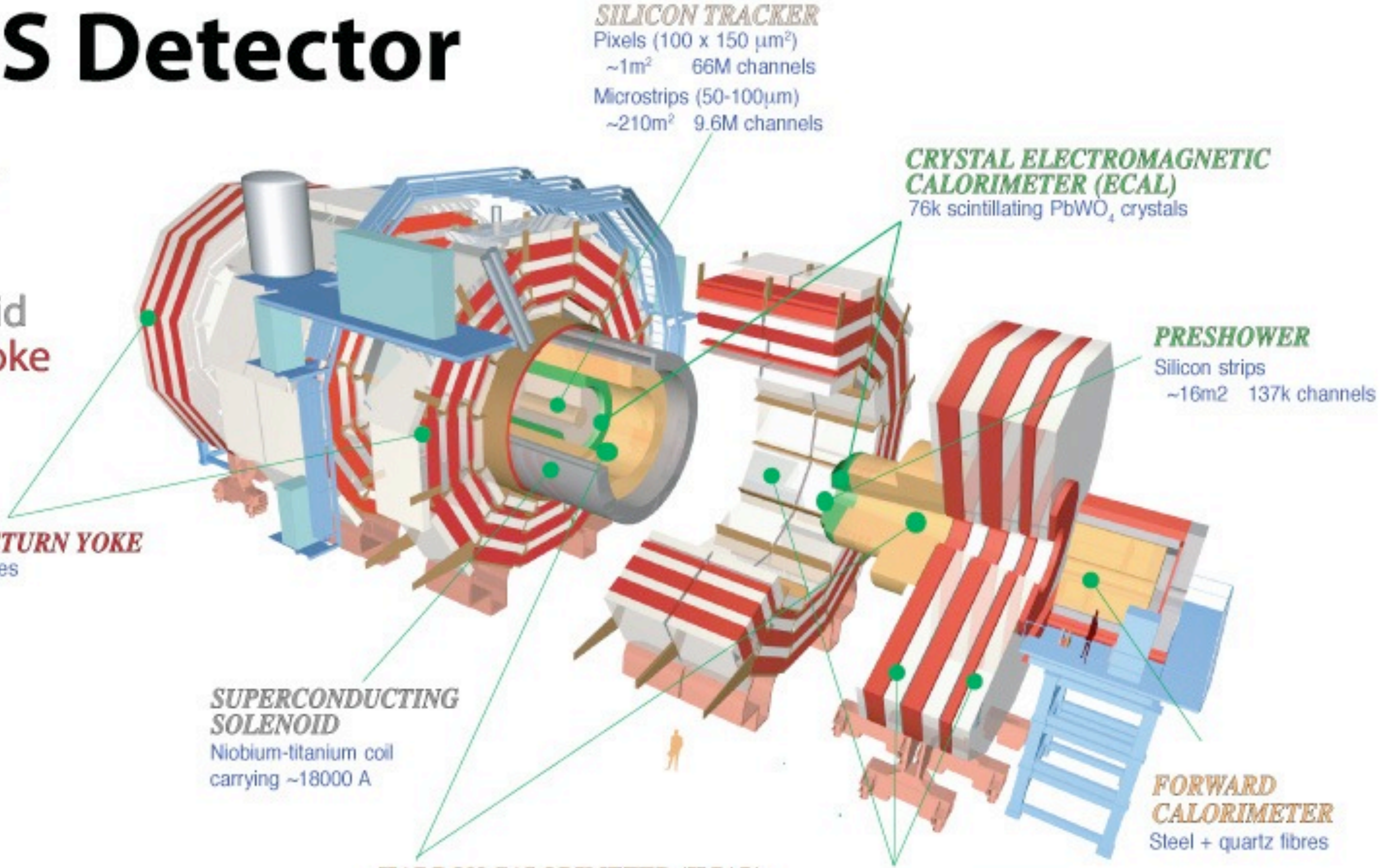




The CMS Detector

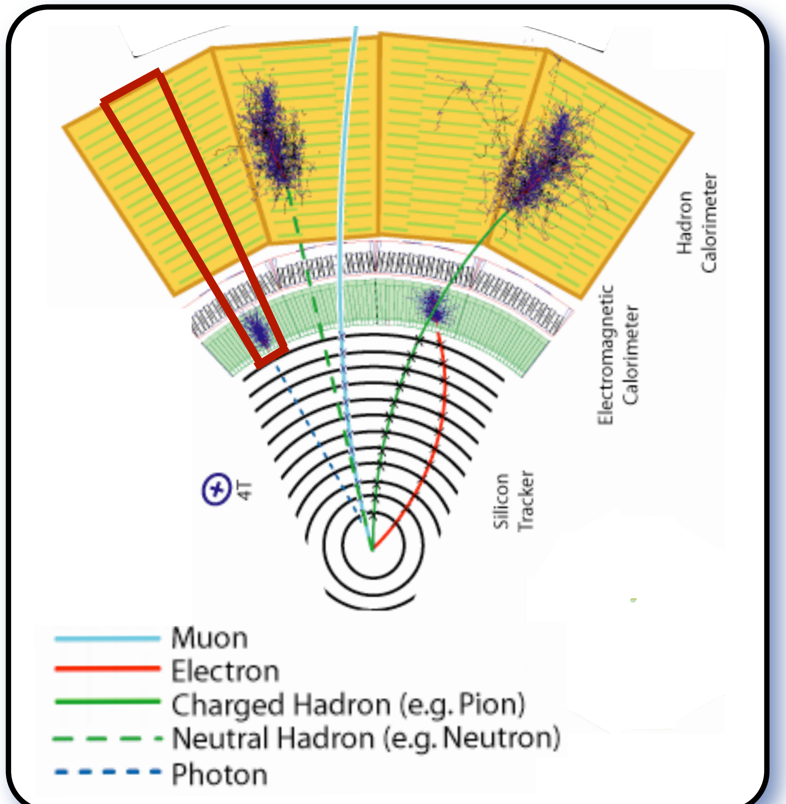
CMS Detector

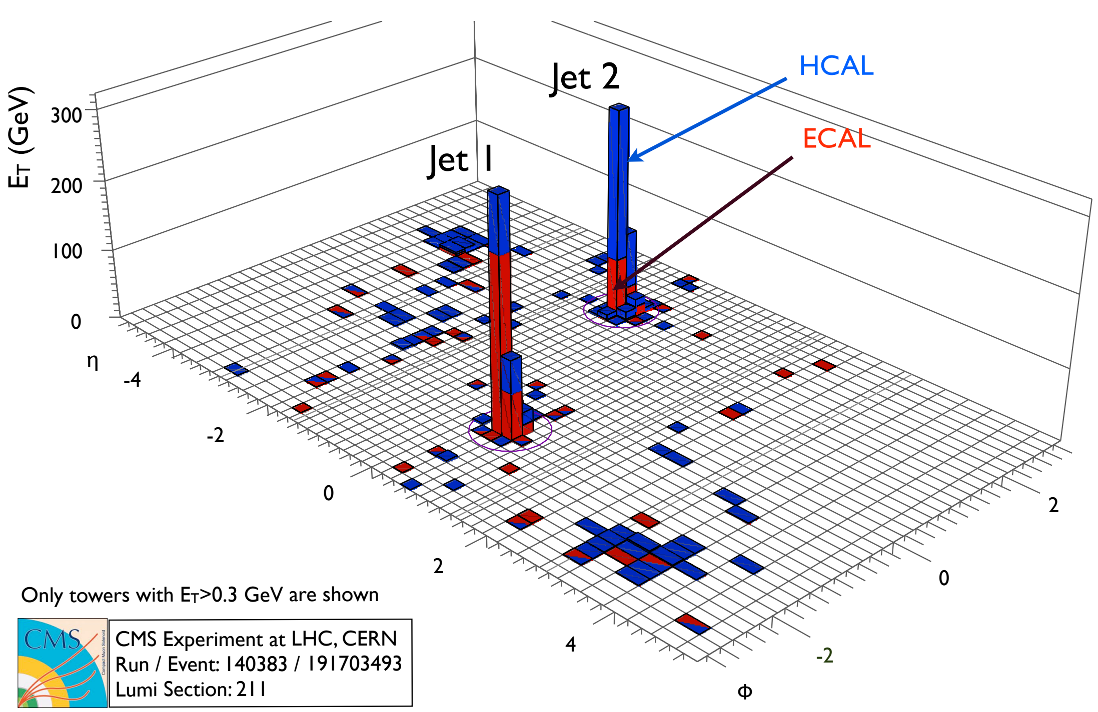
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



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

Jet Reconstruction



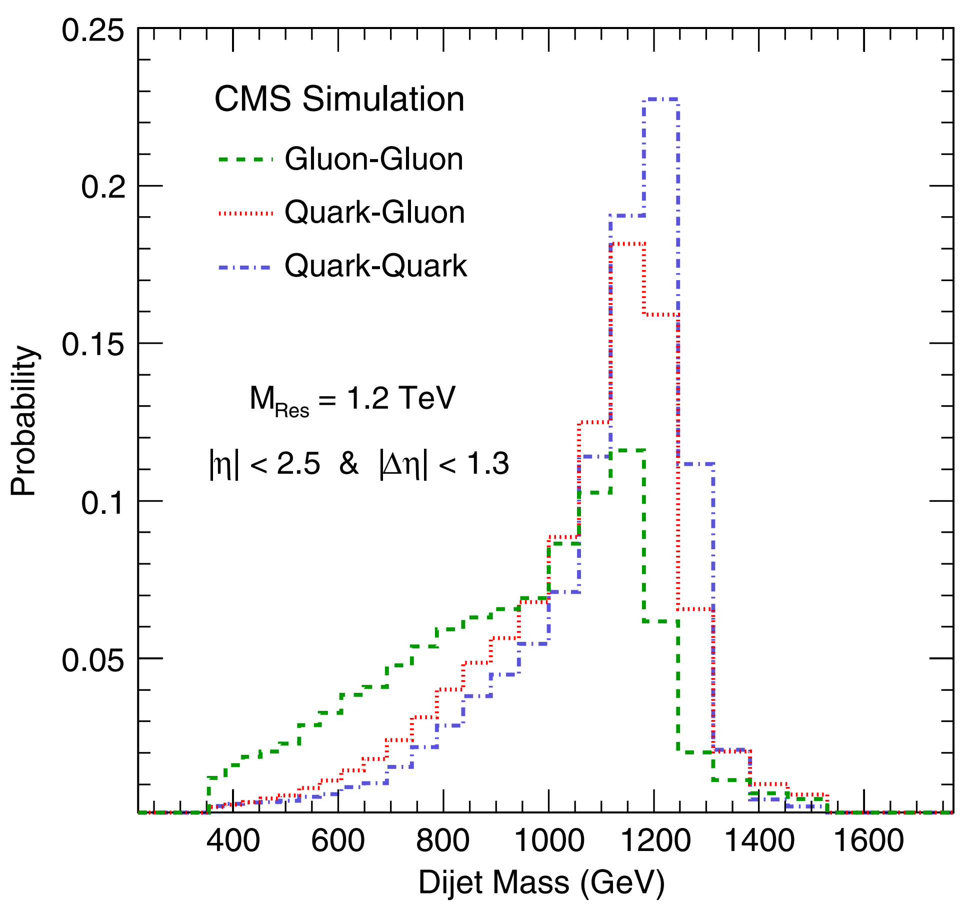


- Jet types:
  - Calorimeter Jets: reconstructed from energy deposits in the hadronic and electromagnetic calorimeters, grouped in projective calo towers.
  - Particle Flow (PF) Jets: Use all detector elements to reconstruct particles, then cluster to jets.
- Anti-kt clustering algorithm with cone size of 0.5 and 0.7.
  - infrared and collinear safe.
- Jet energy corrections are determined by using MC truth information and by employing data driven techniques.
  - Uncertainty on Jet energy scale is less than 5% .

Dijet Resonances Models

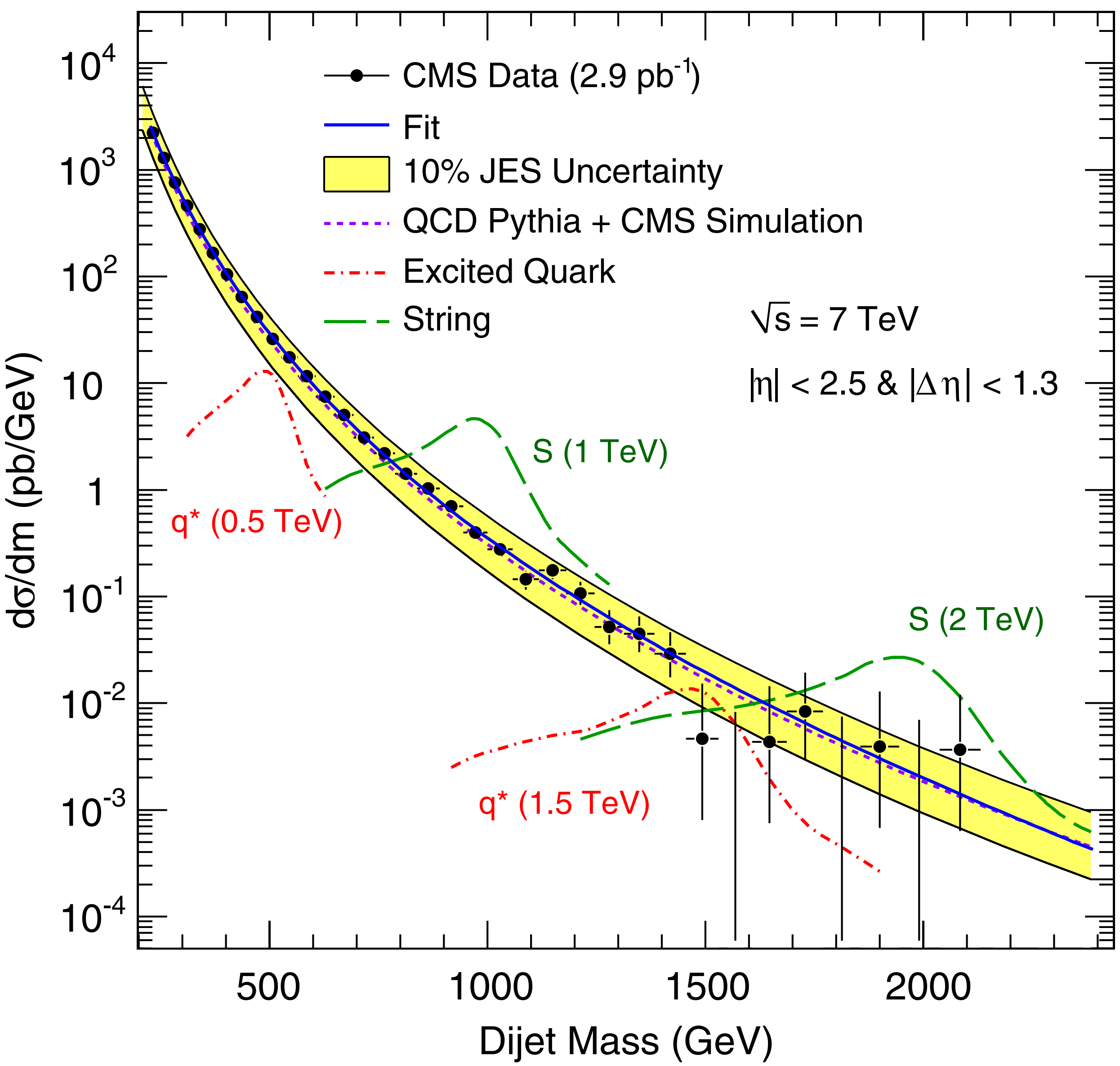
- Parton resonances decaying to dijets are predicted by various models:

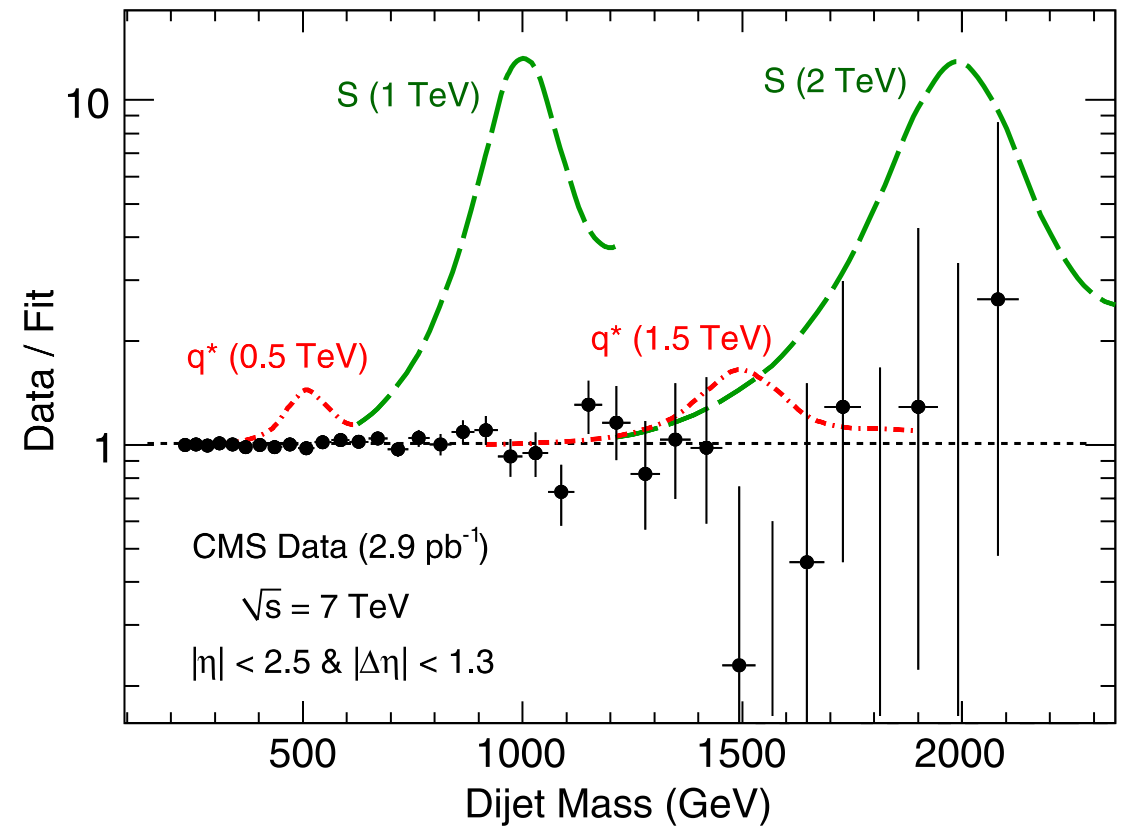
Model Name	X	Color	J^P	$\Gamma/(2M)$	Final-state Partons
String	S	mixed	mixed	0.003-0.037	qq, gg and qg
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
Excited Quark	q*	Triplet	$1/2^+$	0.02	qg
E_6 Diquark	D	Triplet	0^+	0.004	qq
RS Graviton	G	Singlet	2^+	0.01	$q\bar{q}$, gg
Heavy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



- We searched for 3 generic types of narrow dijet resonances in the data.
  - qq, qg and gg resonances
  - differences mainly due to FSR.
  - Gaussian core of dijet mass resolution for qg resonances varies from 11% at 0.5 TeV to 6% at 2.5 TeV

Dijet Resonances Search



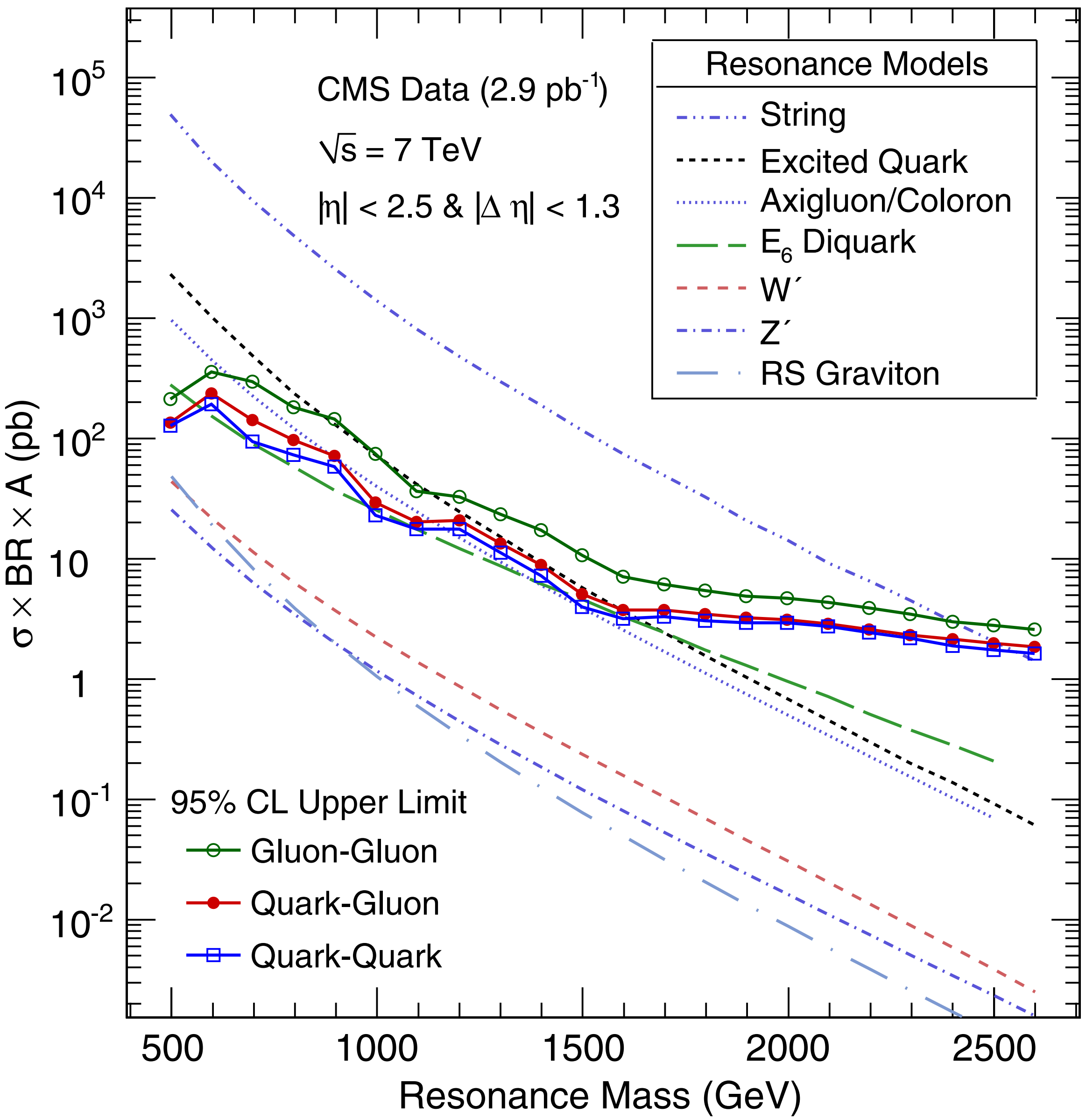


$$\frac{d\sigma}{dm} = p_0 \frac{(1-X)^{p_1}}{X^{p_2+p_3\ln(X)}} \qquad x = m_{jj}/\sqrt{s}$$

Phys. Rev. Lett. 105, 211801, 2010

- Anti-kt CaloJets with R=0.7, $|\eta|<2.5$ & $|\Delta\eta|<1.3$
- Good fit ($\chi 2/ndf = 32/31$) with 4 parameter function.
- The data is in good agreement with the full CMS simulation of QCD from PYTHIA.
- No indication of new physics.

Dijet Resonance Limits



Phys. Rev. Lett. 105, 211801, 2010

- We have **generic, cross-section upper limits** on quark-quark, quark-gluon and gluon- gluon resonances.
- Observed Bayesian(*) limit at 95% CL.

String Resonances

- ✓ **0.50<M(S)<2.50 TeV**
  - ➡ M(S)<1.40 from CDF (1 fb^{-1})

Excited Quark

- ✓ **0.50<M(q*)<1.58 TeV**
  - ➡ 0.60<M(q*)<2.15 from ATLAS (36 pb^{-1})

Axigluon / Coloron

- ✓ **0.50<M(A)<1.17 TeV & 1.47<M(A)<1.52 TeV**
  - ➡ 0.12<M(A)<2.60 TeV from ATLAS (36 pb^{-1})

E6 Diquark

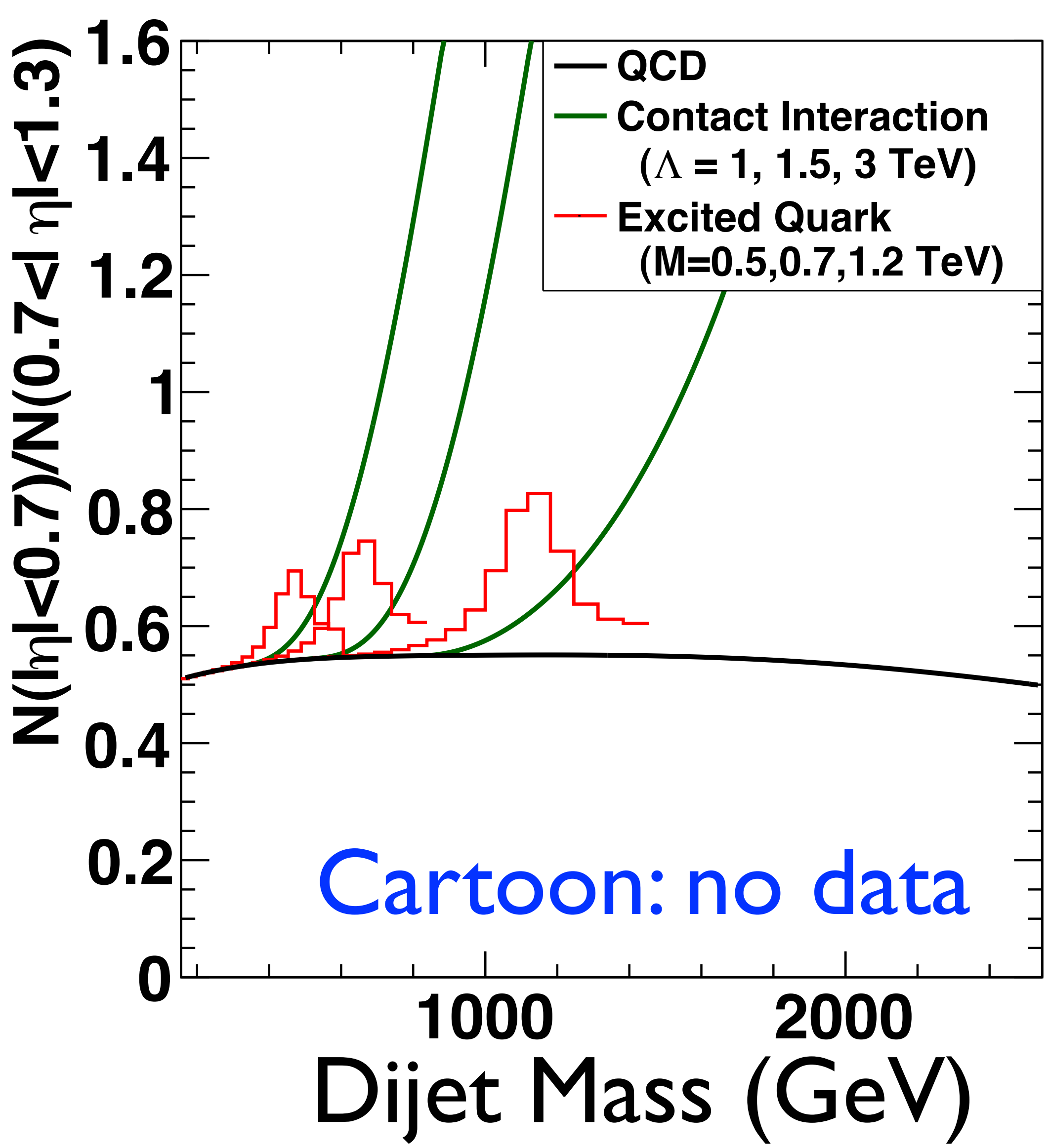
- ✓ **0.50<M(D)<0.58 TeV & 0.97<M(D)<1.08 TeV & 1.45<M(D)<1.60 TeV**
  - ➡ 0.29<M(D)<0.63 TeV from CDF (1 fb^{-1})

(*) with flat prior in signal strength.

Dijet Centrality Ratio

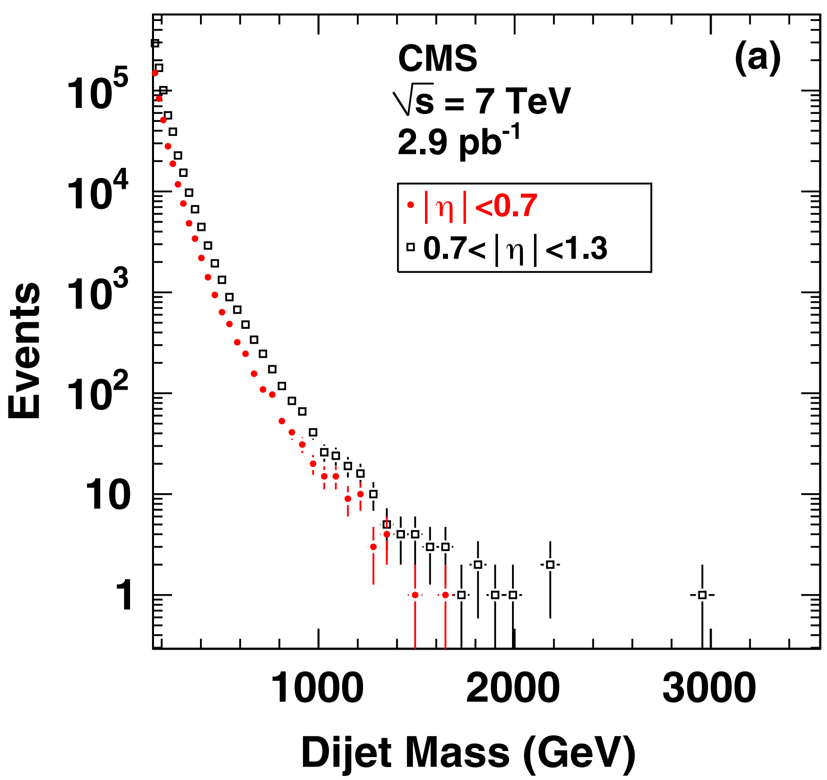
$$R = \frac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)} = \frac{N(\text{inner})}{N(\text{outer})}^{*}$$

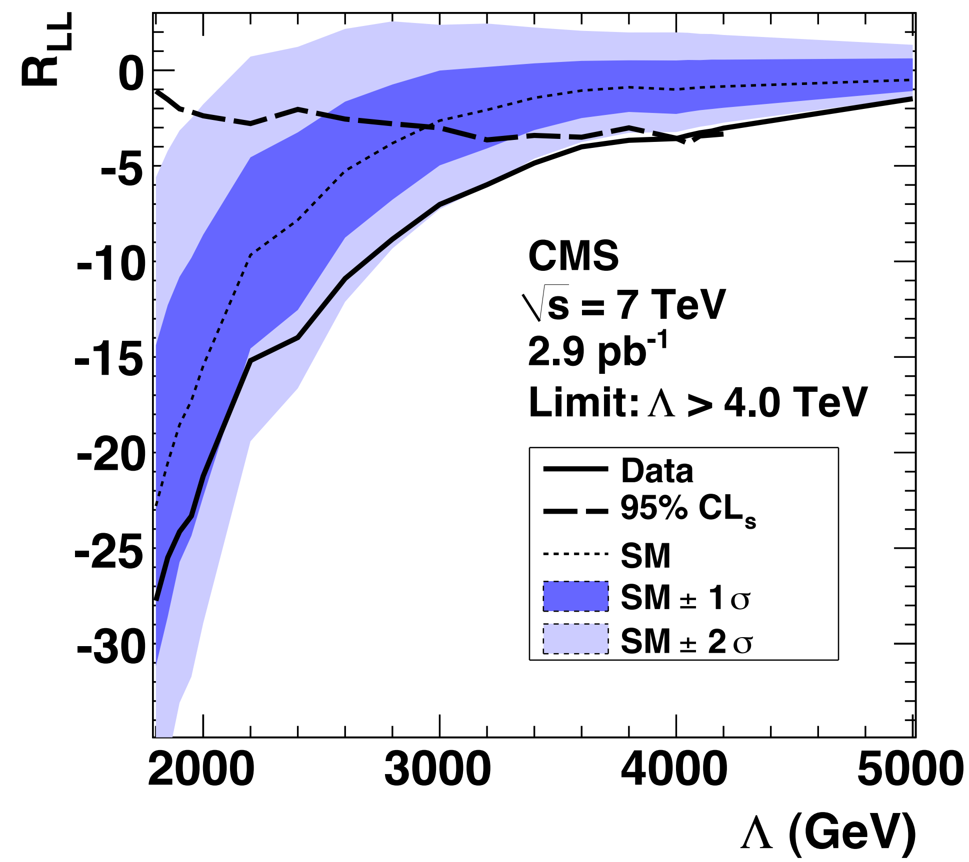
*Both jets inner or outer.

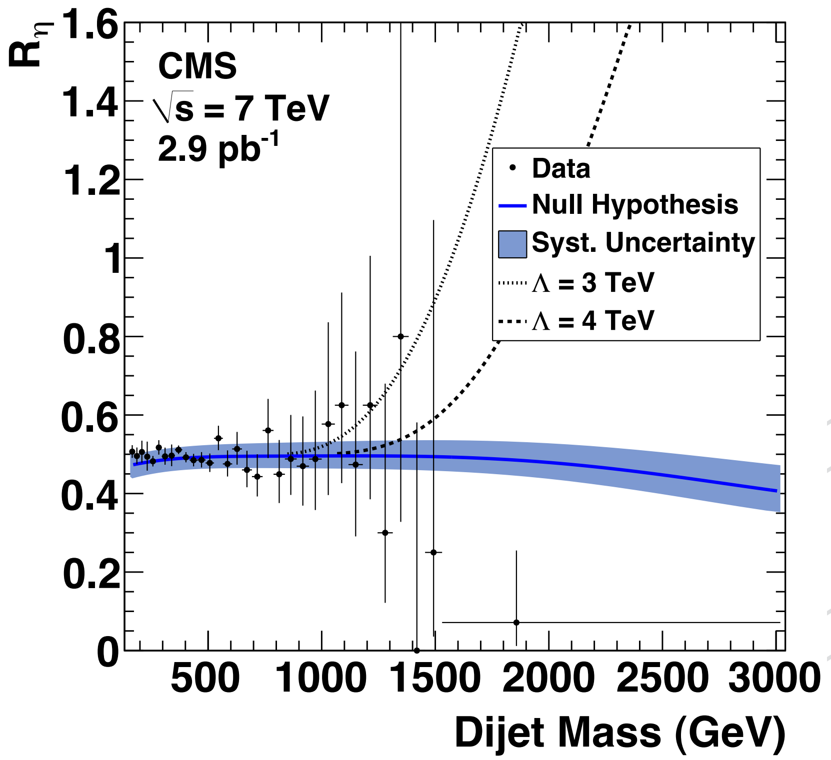


- Quantifies the centrality of the dijet angular distribution at a given dijet mass.
  - ✓ both leading jets are required to lie in the same η range.
- Important experimental uncertainties cancel because of the ratio (absolute jet energy scale, luminosity).
- “t-channel” scattering for QCD vs “s-channel” for most new Physics models
  - ✓ roughly flat vs dijet mass for QCD.
  - ✓ rises vs dijet mass for contact interactions.
  - ✓ “bumps” in dijet mass for dijet resonances.

Dijet Centrality Ratio



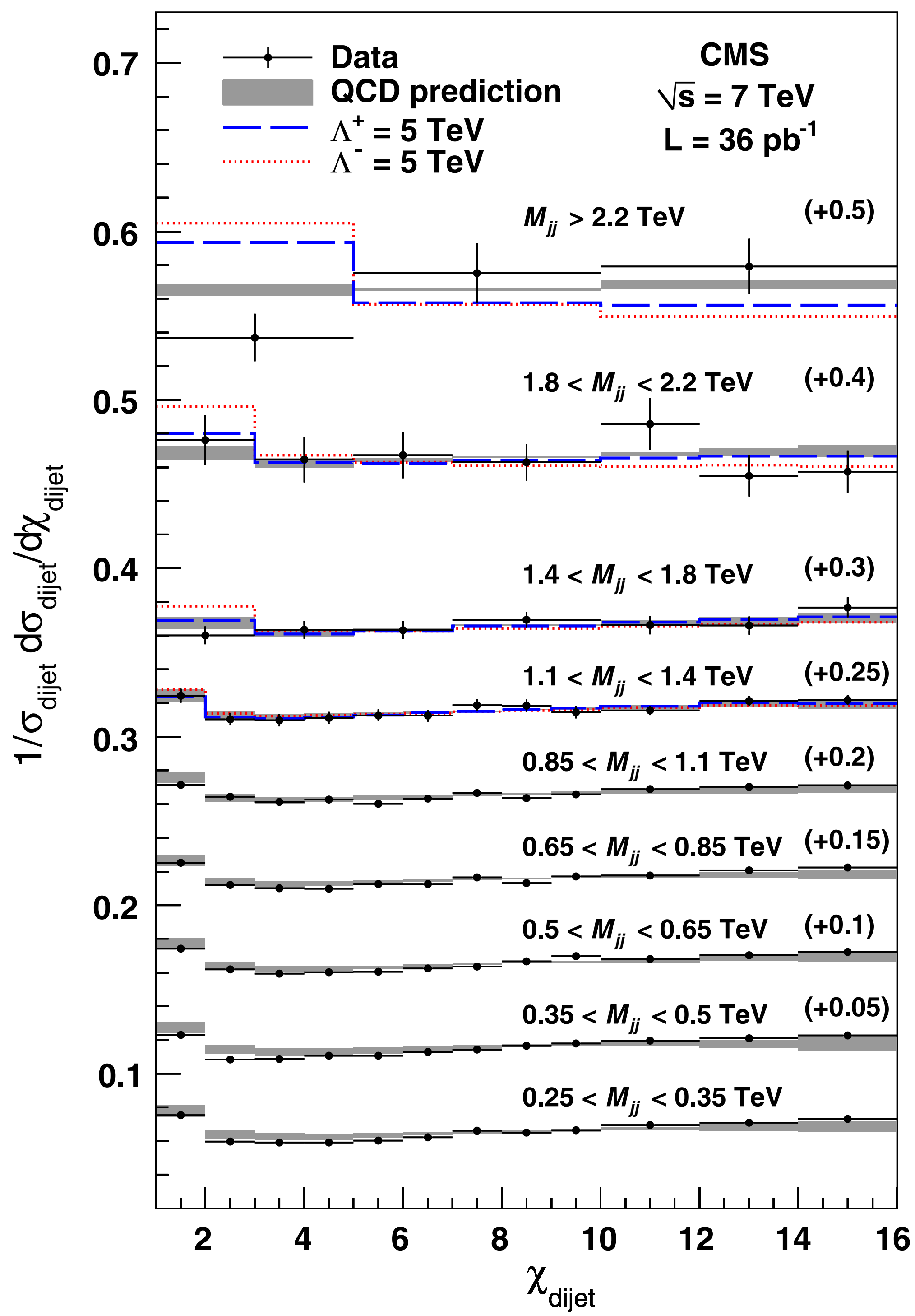


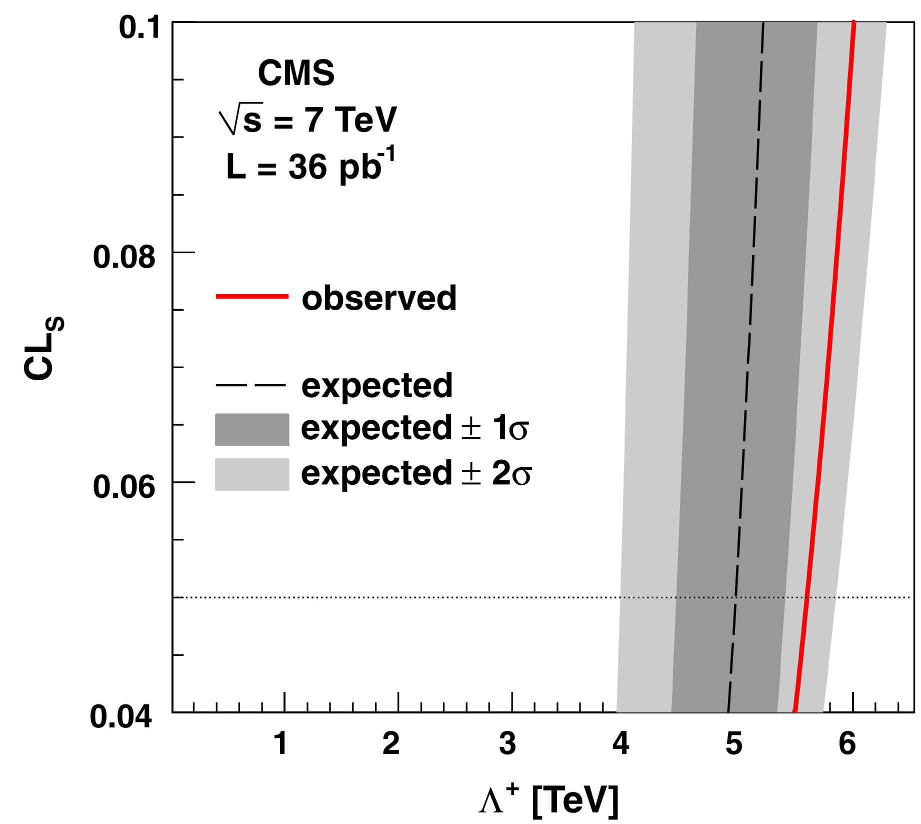


- Anti-kt CaloJets with R=0.7
- Data is agree with the predictions of the standard model.
- Ratio is flat, no sign of new physics.
- Set limit on contact interaction scale Λ with Modified frequentist approach (CLs) method.
- Contact interaction scale excluded for Λ<4.0 TeV at 95% CL.
  - Expected exclusion of Λ < 2.9 TeV.

Phys. Rev. Lett. 105, 262001 (2010)

Dijet Angular Distribution





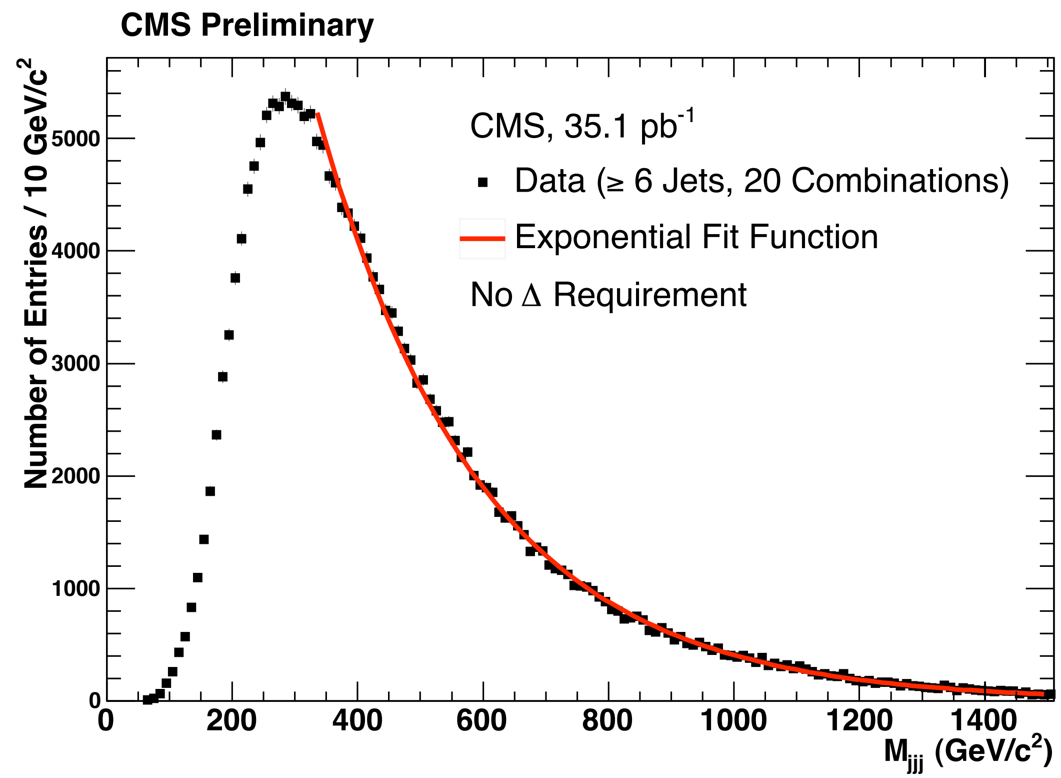
Phys.Rev.Lett.106:201804,2011

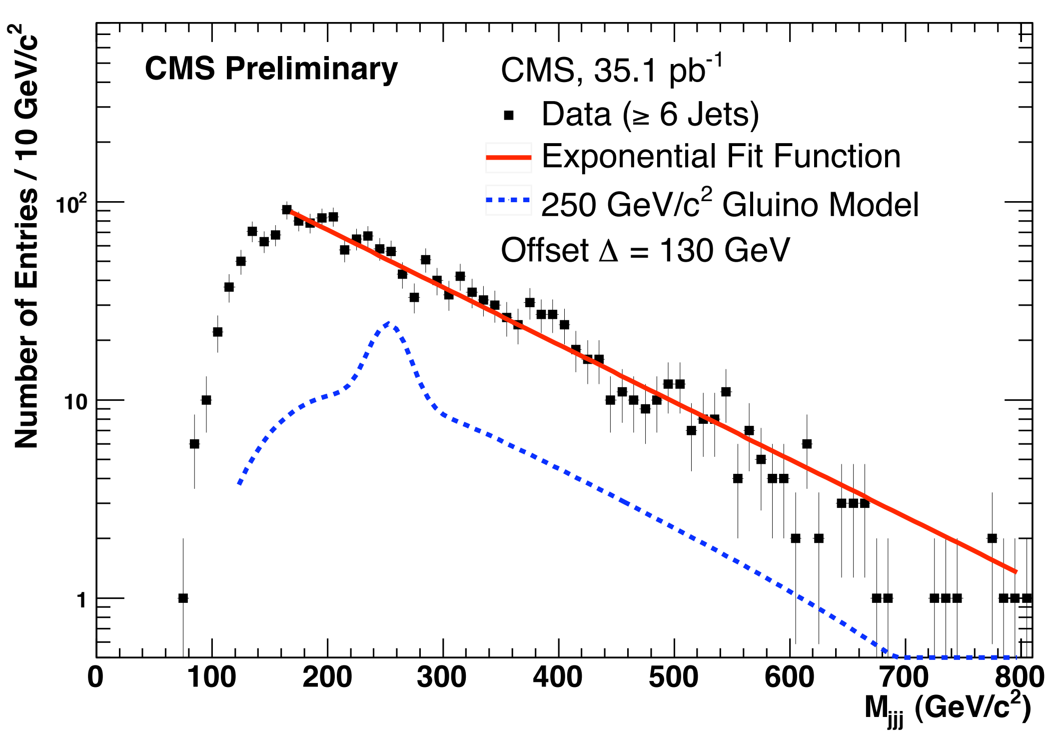
- ☑ Anti-kt PFJets with R=0.5.
- ☑ X range: 1< X<16 , 9 dijet mass bins ($\chi = e^{|y_1 - y_2|}$)
- ☑ Good agreement with NLO QCD predictions in 0.25 < Mjj < 2.2 TeV.
- ☑ Slight downward fluctuation at low χ in highest mass bin Mjj > 2.2 TeV.
- ☑ No evidence of quark substructure.
- ☑ Limit on Contact Interaction scale of Λ^+>5.6 TeV (Λ^->6.7 TeV) at 95% CL. (Λ^+>9.5 TeV from ATLAS with 36 pb^{-1})

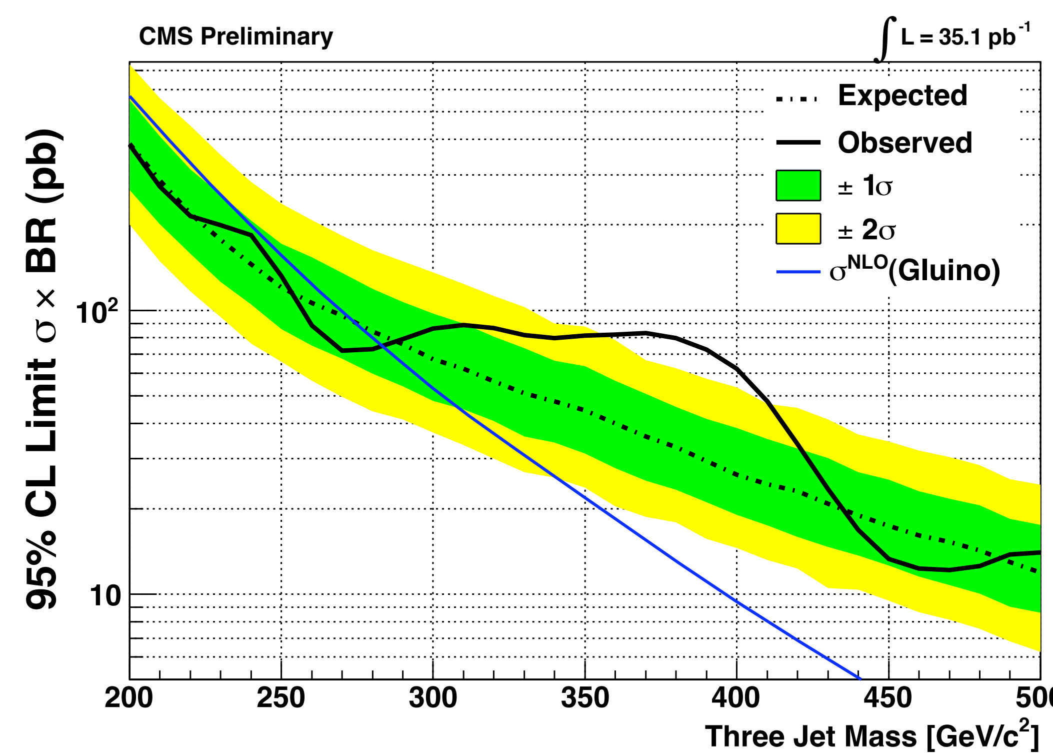
Multijet Resonances

CMS-PAS-EXO-11-001

- Studying pp → QQ → 3j + 3j = 6 jets
  - R-Parity violating Supersymmetric (RPV) gluino (No Missing ET)
- $M_{jjj} < \sum_{i=1}^{3} |p_T^{\rm jet}|_i - \Delta$
  - to reduce background and optimize signal sensitivity
- Good agreement between the data and the expected QCD background.
- Excluded mass limit of RPV gluino at Bayesian 95% CL is between 200 GeV and 280 GeV
  - the highest limit on date and the first limit from pp collisions.

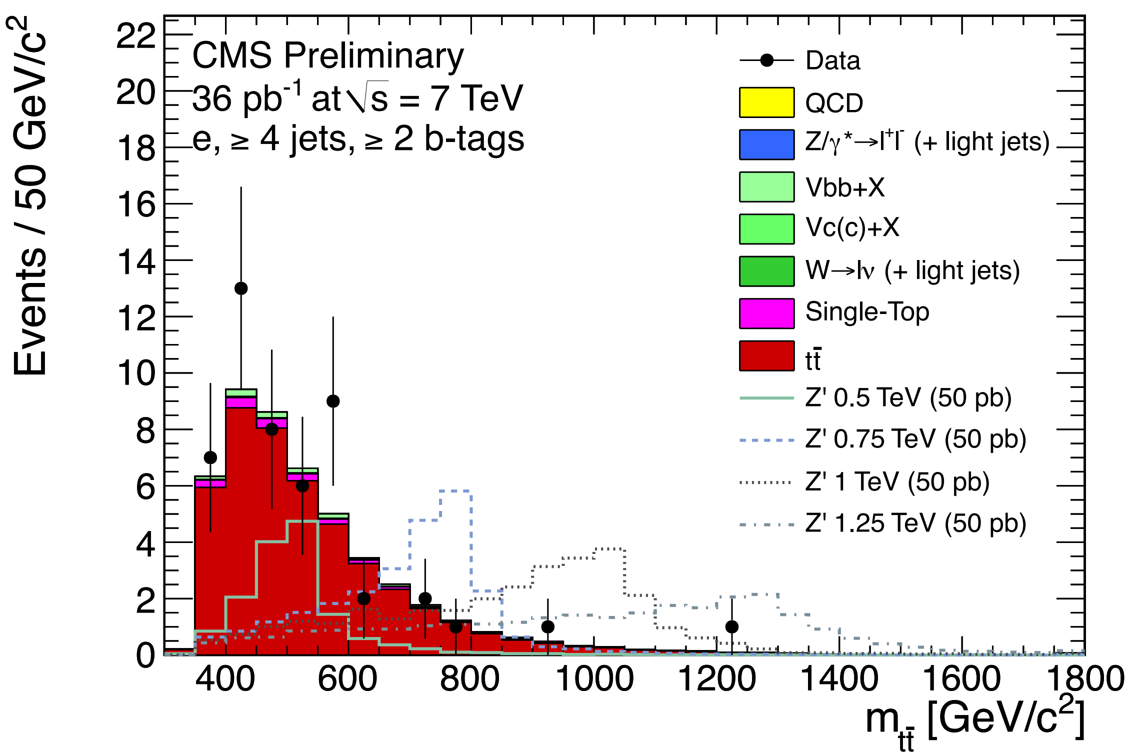


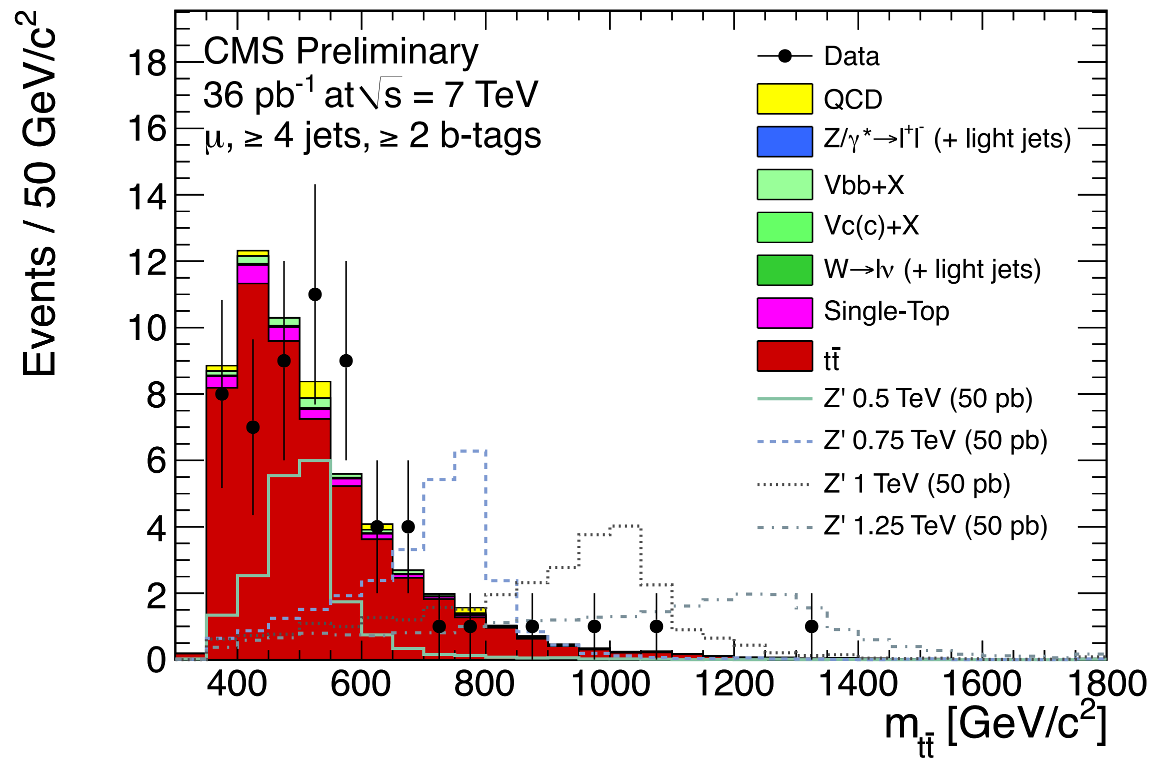




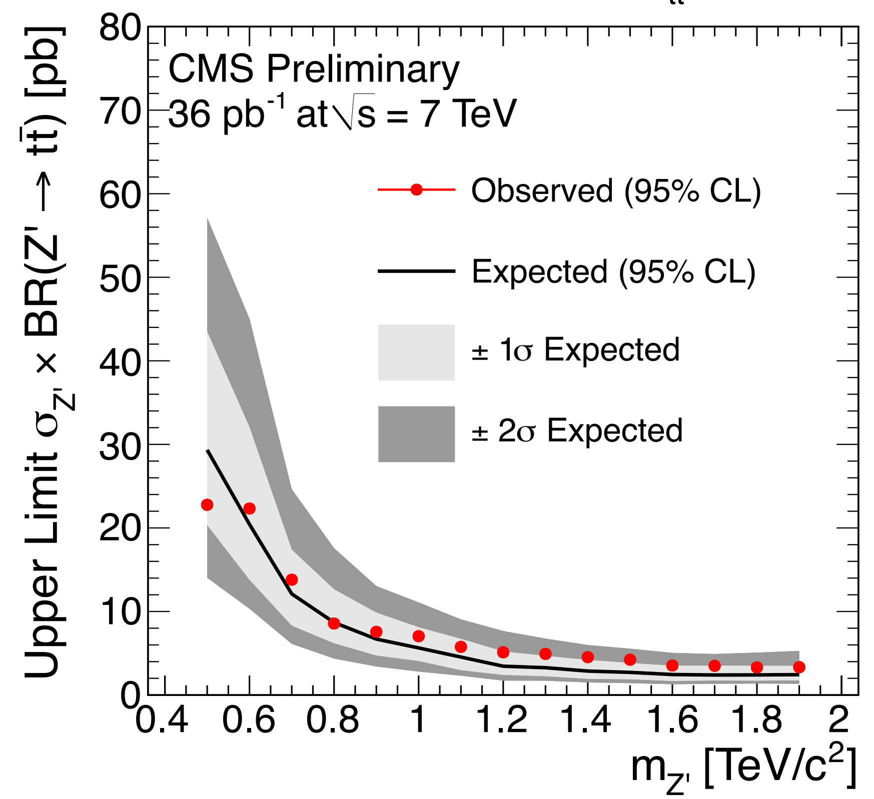
t-tbar Resonances

CMS-PAS-EXO-10-023





- ☑ Generic search for narrow width new particles decaying to top quark pairs
  - ✓ Benchmark model: Narrow-width Z'
- ☑ Semi-leptonic top-pair decays
  - ✓ Lepton+Jet channels (Electron and muon)
  - ✓ 8 event categories
- ☑ No evidence for new physics.
- ☑ 95% CL generic upper limits on the production cross section.
  - ✓ These limits are competitive with those from the Tevatron



Summary and Conclusions

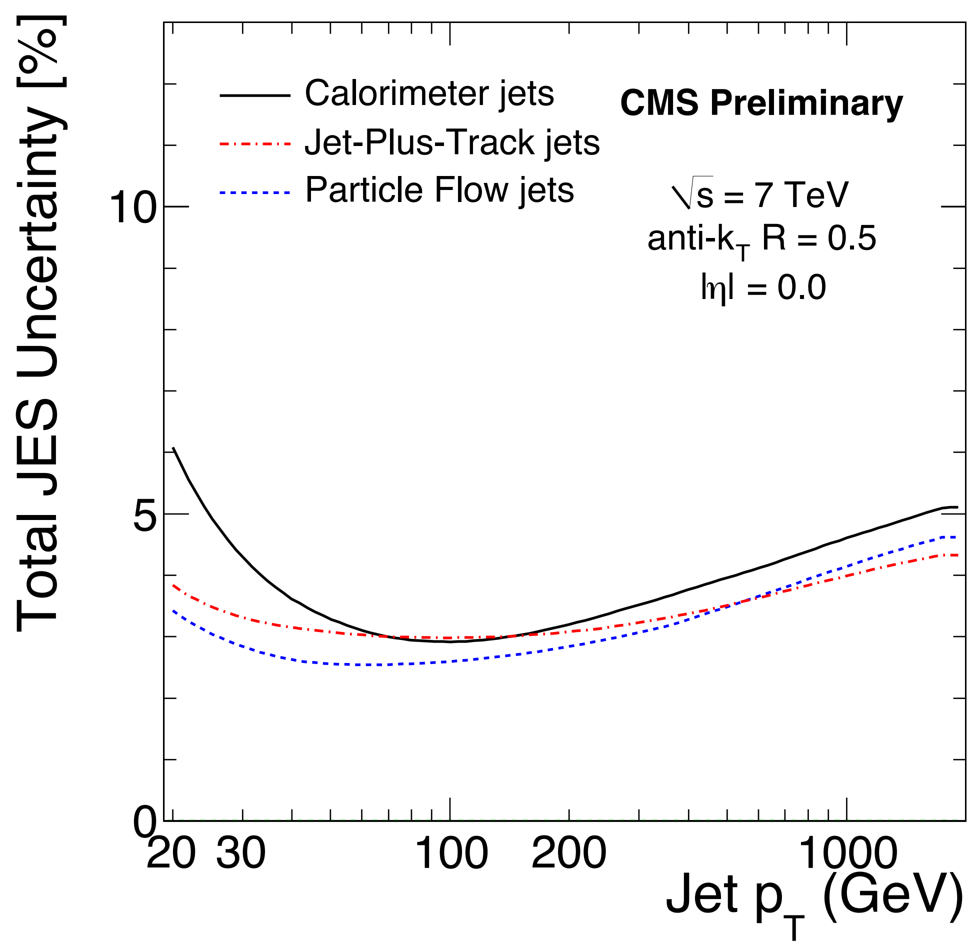
- CMS hadronic resonance searches have been presented based on 2010 data.
- The CMS analysis have been performed to search for new physics in hadronic final states.
  - Most of them have been published.
- No evidence for new physics yet.
- Many Tevatron results superseded.
- 2011 data expected to quick supersede 2010 results, leaving ample space for discoveries.

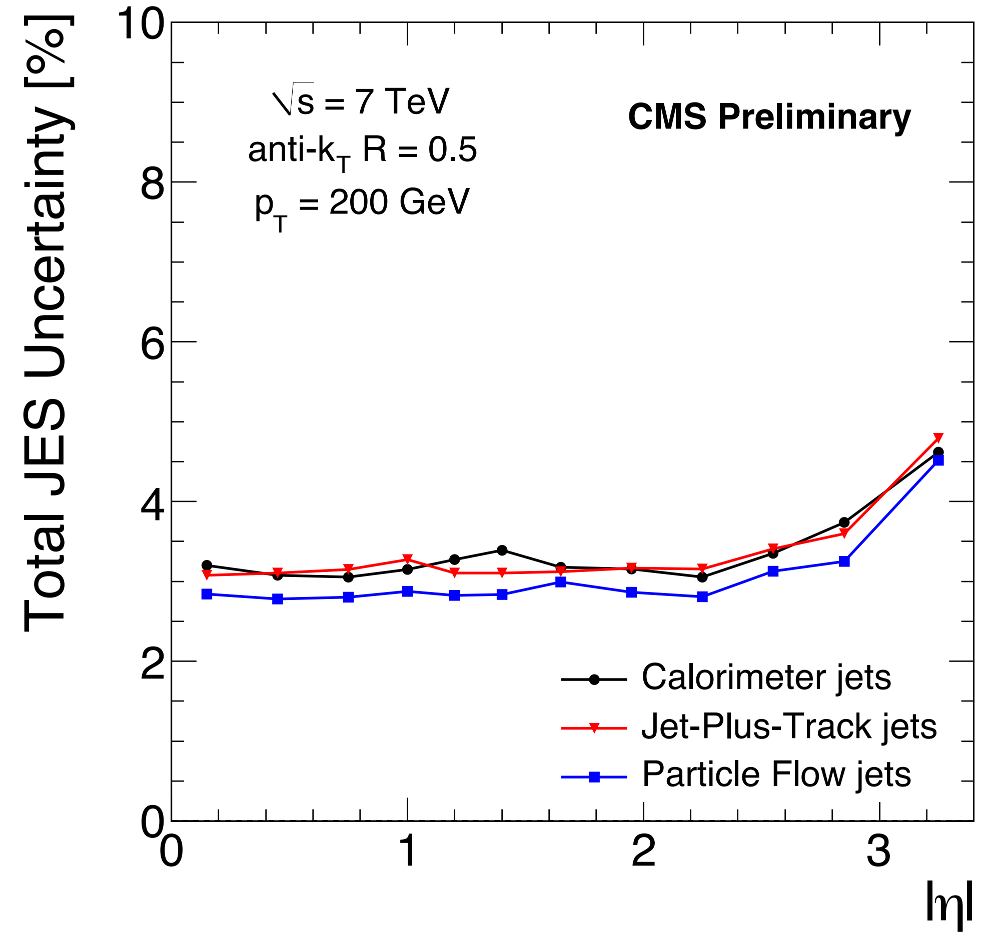
References

- Search for Dijet Resonances in 7 TeV pp Collisions at CMS, Phys. Rev. Lett. 105, 211801, 2010
- Search for Quark Compositeness with the Dijet Centrality Ratio in pp Collisions at 7 TeV, Phys. Rev. Lett. 105, 262001, 2010
- Measurement of Dijet Angular Distributions and Search for Quark Compositeness in pp Collisions at 7 TeV, Phys. Rev. Lett. 106, 201804, 2011
- Search for Multijet Resonances in pp Collisions at 7 TeV, CMS-PAS-EXO-11-001
- Search for narrow resonances decaying to top quark pairs, CMS-PAS-EXO-10-023

Backup

Jet Energy Scale

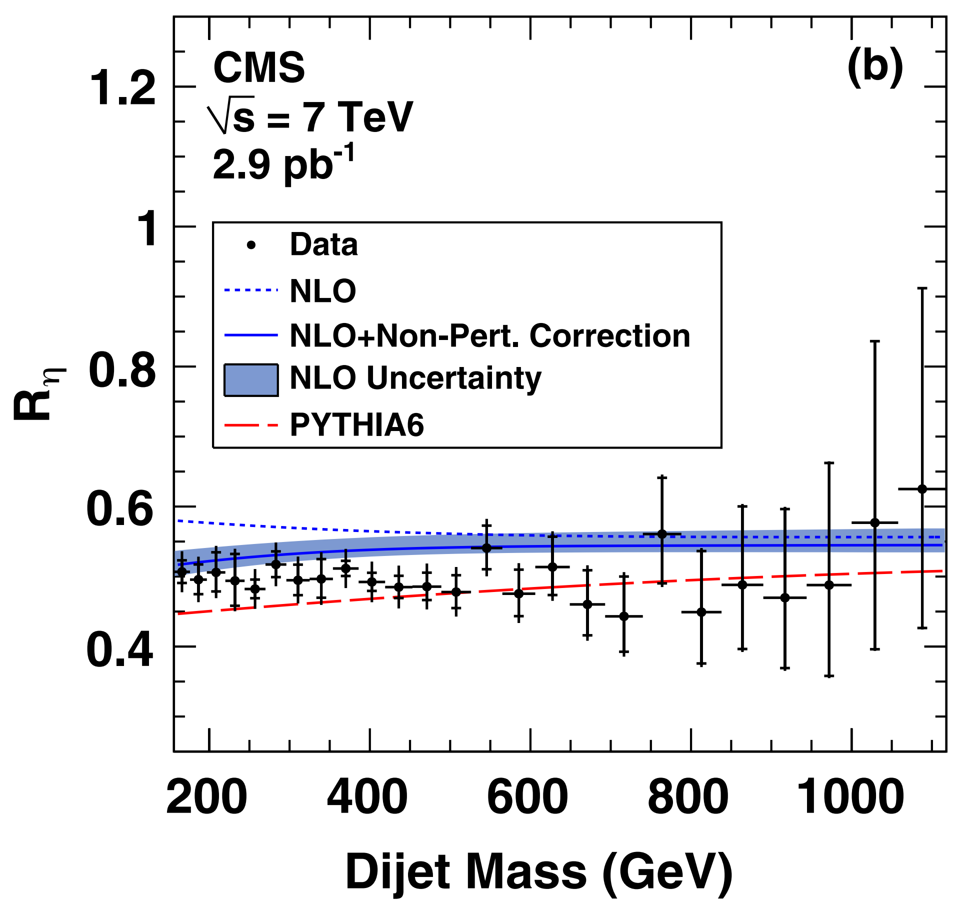




- Total jet energy scale uncertainty varies 3-5% for all jet types.
  - Estimated with the first 3 pb^{-1} of data.
  - Uncertainty dominated by the high pt extrapolation.

Dijet Centrality Ratio

- Compared data to:
  - NLO
  - NLO + non-perturbative corrections
  - Pythia
- Data prefer NLO + non-perturbative corrections (p-value = 0.8)
- "NLO Uncertainty" includes PDF, scale, and non-perturbative correction uncertainties.

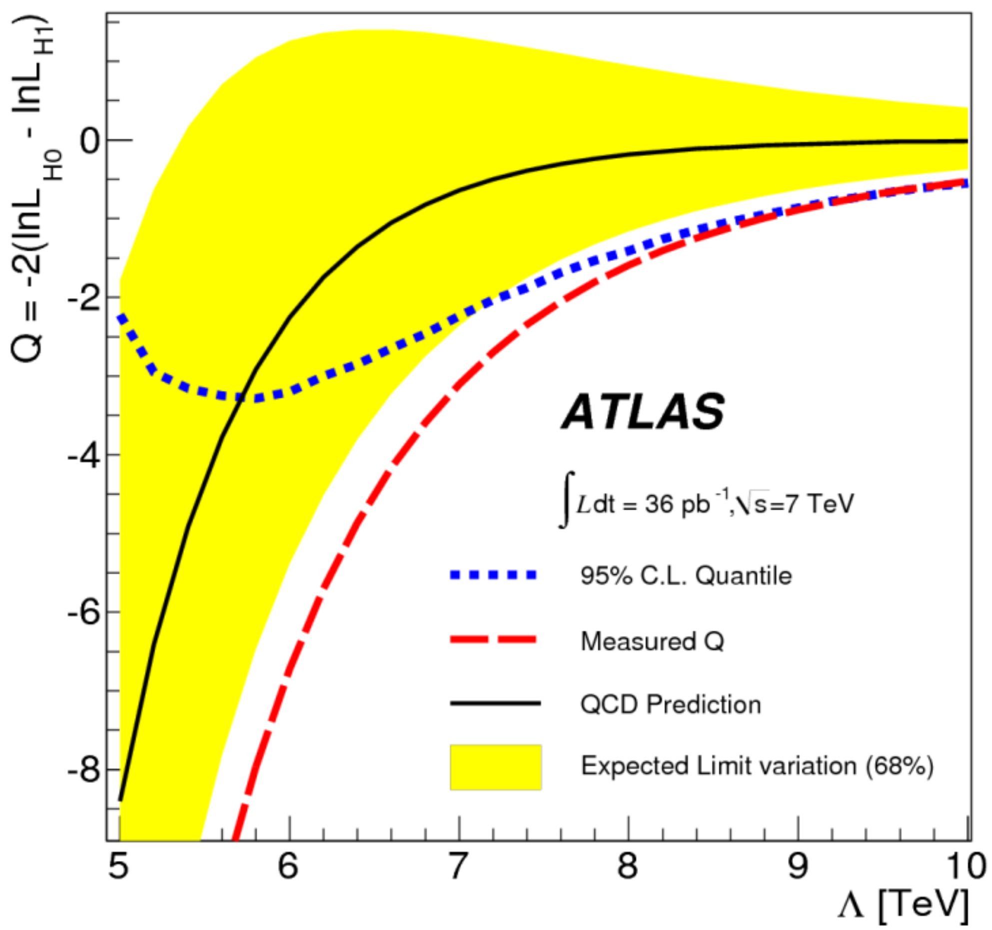


Systematic Uncertainties

TABLE I. Systematic uncertainties on R_η related to the measurement of R_η (detector uncertainties) and to the QCD model (model uncertainties). For each source of uncertainty, we show the range of values over the entire m_{jj} range and at a representative point in the signal region.

Source	Full range	m_{jj} = 1.6 TeV
Detector uncertainty		
Relative JES	0.02–0.05	0.032
Absolute JES	0.00–0.03	0.003
Jet energy resolution	0.003	0.003
Other	0.01	0.010
Total detector	0.02–0.05	0.034
Model uncertainty		
PYTHIA6–NLO	0.00–0.05	0.032
Offset	0.021	0.021
Scale	$^{+(0.01-0.05)}_{-(0.01-0.02)}$	$^{+0.029}_{-0.011}$
PDF	$^{+(0.002-0.004)}_{-(0.002-0.007)}$	$^{+0.002}_{-0.003}$
MC statistics	0.005	0.005
Nonpert. corr.	0.002–0.014	0.002
Total model	$^{+(0.02-0.07)}_{-(0.01-0.05)}$	$^{+0.044}_{-0.034}$
Total	$^{+(0.03-0.09)}_{-(0.03-0.08)}$	$^{+0.055}_{-0.048}$

Dijet Angular Distribution from ATLAS

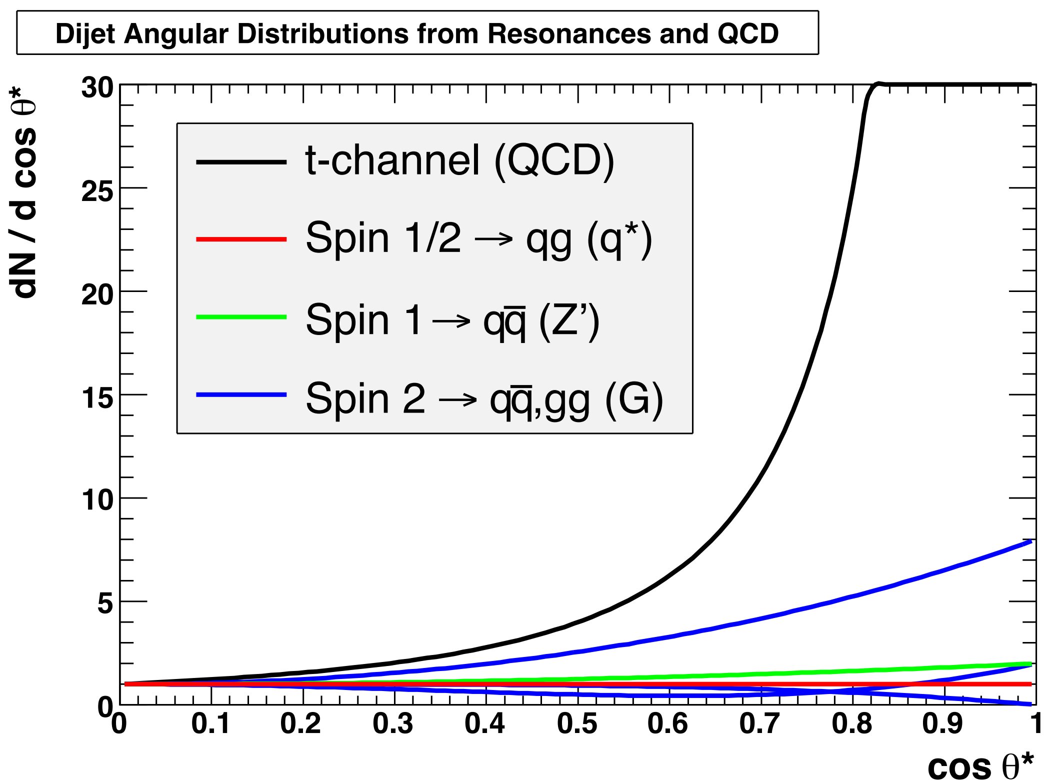


Effective Lagrangian

$$\mathcal{L}_{qqqq}(\Lambda) = \frac{\eta g^2}{2(\Lambda^{+}_{LL})^2_q} \bar{\Psi}^L_q \gamma^\mu \Psi^L_q \bar{\Psi}^L_q \gamma^\mu \Psi^L_q$$

- Limit setting approach
  - ✓ Frequentist CL_{s+b} using LEP likelihood ratio $Q=-2(\ln L(H_0)-\ln L(H_1))$
  - ✓ Limit on contact interaction scale of Λ>9.5 TeV at 95% CL.
  - ✓ unconstrained limit setting approach.

Dijet Angular Distribution



Resonance or contact interaction would show deviation from QCD at large scattering angles.

$$\chi = e^{|y_1 - y_2|} \approx \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

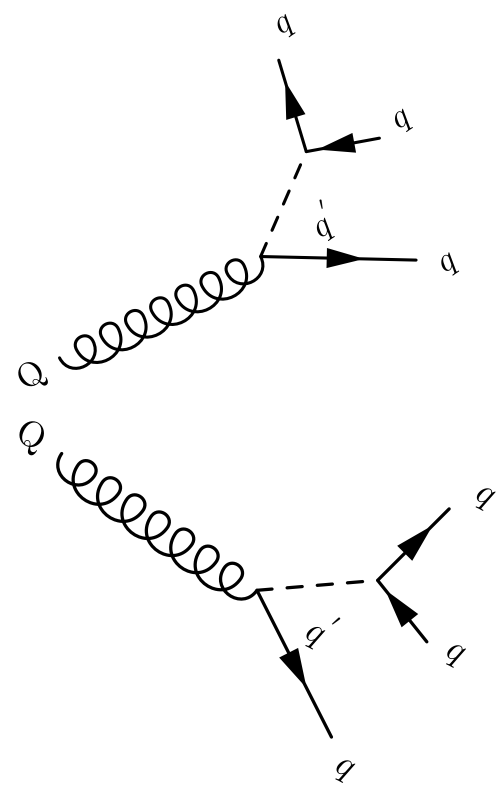
- Experimental Uncertainties
  - Insensitive to many systematic effects (absolute JES, luminosity)
  - Relative JES vs y, resolution
- Theory Uncertainties
  - Scale uncertainty dominates (5-9%)
  - non-perturbative correction uncertainty (up to 4%)
  - insensitive to PDFs
- Signal: PYTHIA6

$$\mathcal{L}_{qq} = \eta_0 (2\pi/\Lambda^2)(\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L)$$

η_0 = +1 destructive interference

η_0 = -1 constructive interference

Multijet Resonances



Signal Generation

- ☑ PYTHIA6
- ☑ Cross section include NLO k-factors

Event Selection

- ☑ Anti-kt PFJets with R=0.5
- ☑ $N_{jets} \geq 6$, Pt>45 GeV, $|\eta|<3$
- ☑ $\sum^{Njets}$ Pt>425 GeV
- ☑ Mjjj < $\sum_{i=1}^{3} |p_T^{jet}|_i$ - 130 GeV

Systematic Uncertainties

- ☑ JEC Uncertainty (7-16%)
- ☑ Acceptance (1-6%)
- ☑ Pile-up Effects (2-4%)
- ☑ PDF Uncertainties (4%)
- ☑ Luminosity (4%)
- ☑ Total (10-19%)

t-tbar Resonances

- Rate Changing
  - Influence specific or subset of samples
  - Also affect shape of total MC background
  - Most important: Luminosity, top pair cross section and heavy flavour ratio
- Shape Changing
  - Repeat full at ±1σ variations of considered quantity and calculate distribution
  - Most important: top pair modeling, , JES, b-tag efficiency, Q^2 scale for W/Z

Uncertainty	Variation	Type
Luminosity	4%	rate
Electron efficiency (trigger + ID + isolation)	5%	rate
Muon efficiency (trigger + ID + isolation)	5%	rate
$t\bar{t}$ cross section	20%	rate
Single top cross section	30%	rate
W+jets cross section	50%	rate
Ratio Drell-Yan to W cross section	30%	rate
Ratio W/Z+HF to σ(W)	100%	rate
Muon QCD yield	100%	rate
Electron QCD yield	100%	rate
Jet energy scale	p_T,η dependent	shape
Jet energy resolution	10%	shape
Unclustered energy	10%	shape
b tagging efficiency (b jets)	15%	shape
b tagging efficiency (c jets)	30%	shape
Q^2 scale for W and Drell-Yan events	$\pm 1\sigma$ generator parameters	shape
$t\bar{t}$ modelling	$\pm 1\sigma$ generator differences	shape
Q^2 scale for $t\bar{t}$ events	$\pm 1\sigma$ generator parameters	shape
Amount of ISR/FSR for $t\bar{t}$ events	$\pm 1\sigma$ generator parameters	shape
Matching scale for $t\bar{t}$ events	$\pm 1\sigma$ generator parameters	shape