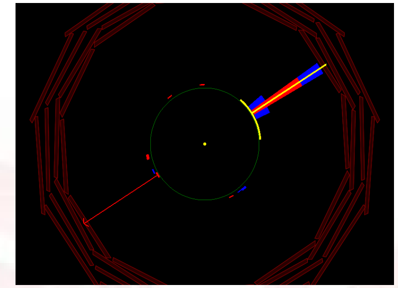
Extra Dimensions and other Exotic Searches with Jets in CMS

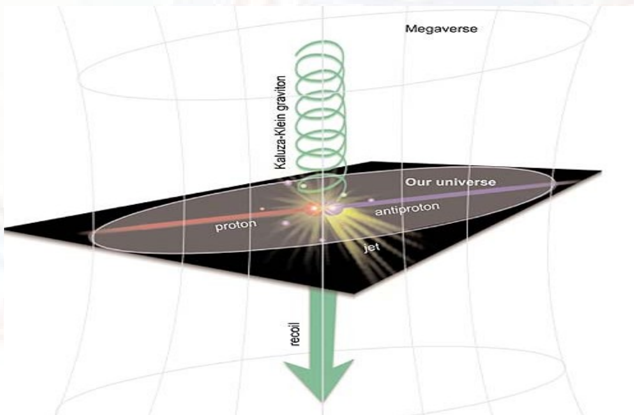
Marco CARDACI
Universiteit Antwerpen

02/10/09 Bruxelles, Belgium

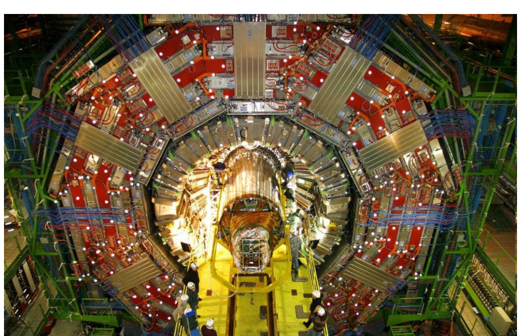
Outline

A short introduction to the models
- Graviton from the ADD model of Extra-Dimensions
- Dijet Resonances from various BSM models
- Contact Interactions from Quark Compositeness





Jets with CMS
- The CMS Detector
- Jet reconstruction and correction in CMS



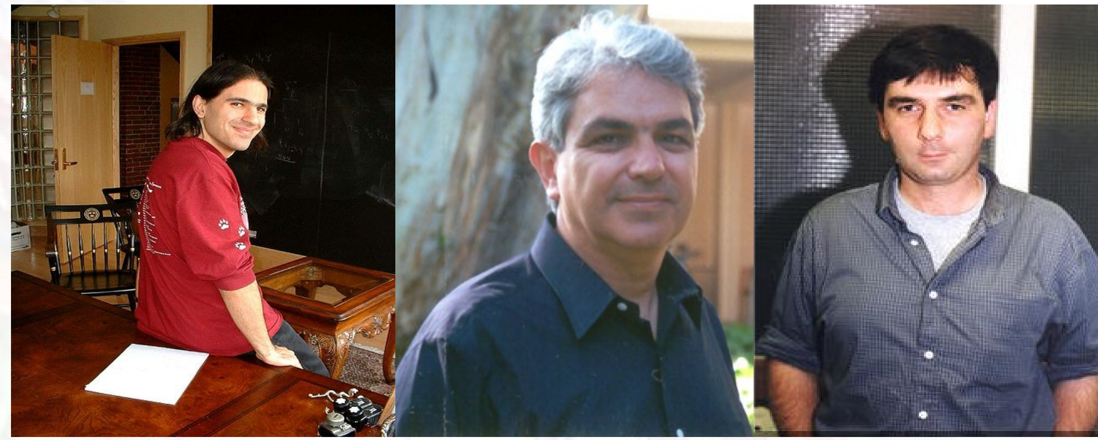
Searches with Dijet events
- Inclusive Jet rate vs. Jet p_T : Contact Interactions
- Dijet Rate vs. Dijet Mass: Resonances
- Dijet Ratio: Resonances and Contact Interactions

Searches with Monjet events
- Counting experiment
- $Z(\nu\nu)$ + Jets data driven background estimate
- Other background data driven estimates

Conclusions
- Discovery potential and exclusion limits

A short introduction to the models

The ADD model of Extra-Dimensions



Solution to a SM problem

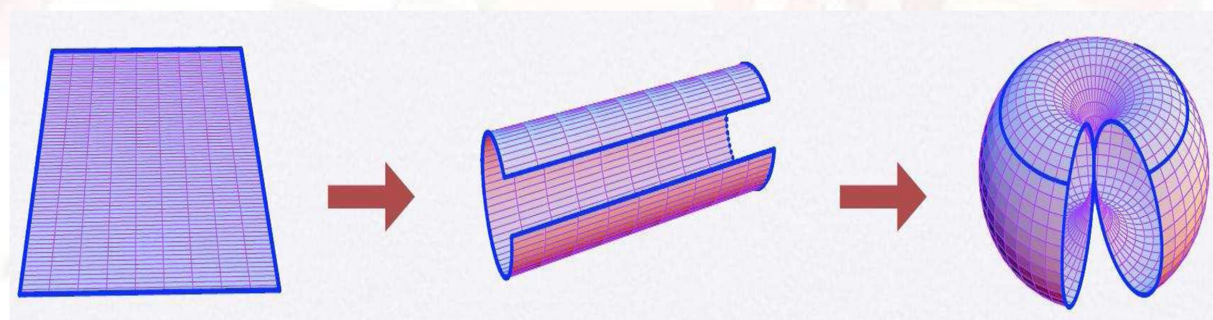
- A hierarchy problem occurs between the Electroweak (~10^2GeV) and the Plack (~10^{19}GeV) scales

- The Arkani-Hamed, Dimopoulos, Dvali model solves the h. p. by introducing δ extra spatial dimensions

- In the simplest case the extra dimensions are compactified over a torus and all have the same radius R

- The Planck scale become an effective scale, related to the fundamental scale via the relation: $M_D^{\delta+2} R^{\delta} \sim M_P^2$

Sketch of compactification on a torus



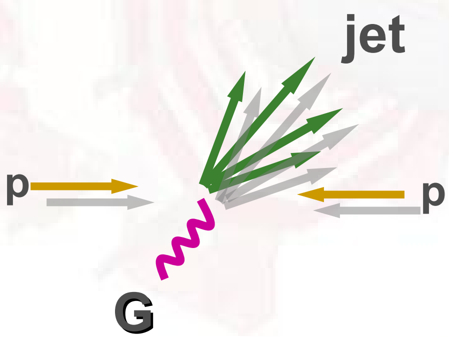
ADD signatures

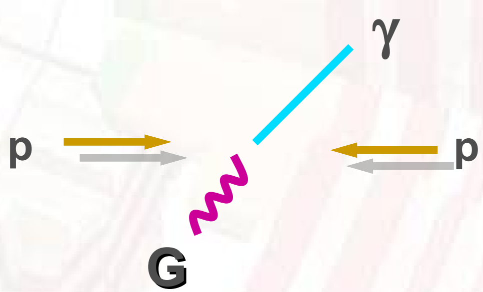
Consequences of the ADD model

- Extra dimensions can be 'macroscopic' for TeV-ish M_D scales and be tested at colliders
- Gravitons interact 'weakly' with ordinary SM particles and escape detection

Two clear ADD signatures (among others)

- The Jet and Photon + MET signatures (direct graviton production)





Cross-sections in pb

	$\delta = 2$	$\delta = 3$	$\delta = 4$	$\delta = 5$	$\delta = 6$
$M_D = 1$ TeV	279.11	171.79	109.98	70.50	44.45
$M_D = 2$ TeV	33.03	17.41	10.64	6.92	4.58
$M_D = 3$ TeV	7.28	3.02	1.57	0.93	0.58

M_D / n	$n = 2$	$n = 4$	$n = 6$
$M_D = 1.0$ TeV	58.0 fb	86.8 fb	90.1 fb
$M_D = 3.0$ TeV	2.43 fb	2.21 fb	1.82 fb
$M_D = 5.0$ TeV	0.35 fb	0.16 fb	0.09 fb

We will focus on the Monojet signature which has a larger cross-section

Dijet resonances

- In a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry $SU(3)_L \times SU(3)_R$, there are axial vector particles called **Axigluons** which decay to quark-antiquark pairs

- The flavor-universal coloron model also embeds the SU(3) of QCD in a larger gauge group, and predicts the presence of a **Color-octet Coloron** which decays to quark-antiquark pairs

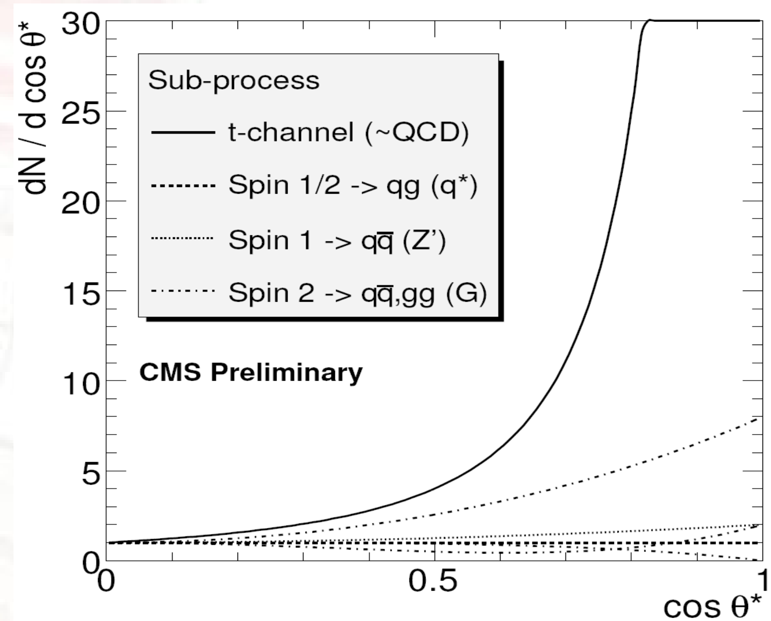
- If quarks are composite particles then excited states are expected, and we search for mass degenerate **Excited quarks q*** that decay to quark-gluon pairs

- Grand unified theory based on the E6 gauge group predicts the presence of **Scalar Diquarks D and D^c** which decay to antiquark and quark pairs

- The Randall-Sundrum model of extra dimensions predicts massive **Gravitons** which decay to quark-antiquark and gluon pairs

- Models which propose new gauge symmetries often predict **New Gauge Bosons W' and Z'** which decay to quark-antiquark pairs

Dijet Angular Distributions



In this plot resonance angular distributions are compared to the t-channel term which dominates the QCD background. Compared to the irreducible QCD background all these angular distributions are relatively isotropic: pretty flat in cos ϑ^*

Resonances properties

Model	J	Color	Cross Section (pb)					
			M=0.7 TeV		M=2.0 TeV		M=5.0 TeV	
			$\|\eta\| < 1$	$\|\eta\| < 1.3$	$\|\eta\| < 1$	$\|\eta\| < 1.3$	$\|\eta\| < 1$	$\|\eta\| < 1.3$
q*	1/2	Triplet	7.95×10^{2}	1.27×10^{3}	9.01	1.36×10^{1}	1.82×10^{-2}	2.30×10^{-2}
A,C	1	Octet	3.22×10^{2}	5.21×10^{2}	5.79	8.82	1.55×10^{-2}	2.04×10^{-2}
D	0	Triplet	8.11×10^{1}	1.26×10^{2}	4.20	5.97	4.65×10^{-2}	5.75×10^{-2}
G	2	Singlet	3.57×10^{1}	5.47×10^{1}	1.83×10^{-1}	2.60×10^{-1}	2.64×10^{-4}	3.19×10^{-4}
W'	1	Singlet	1.46×10^{1}	2.37×10^{1}	3.49×10^{-1}	5.31×10^{-1}	8.72×10^{-4}	1.17×10^{-3}
Z'	1	Singlet	8.86	1.44×10^{1}	1.81×10^{-1}	2.77×10^{-1}	5.50×10^{-4}	7.26×10^{-4}

Spin ½

$(qg \to q^*)$ $dN/d\cos\theta^* \sim 1 + \cos\theta^*$

Spin 1

$(q\bar{q}, gg \to A \text{ or } C;\ q\bar{q} \to Z';\ q_1\bar{q}_2 \to W')$

$dN/d\cos\theta^* \sim 1 + \cos^2\theta^*$

Spin 2

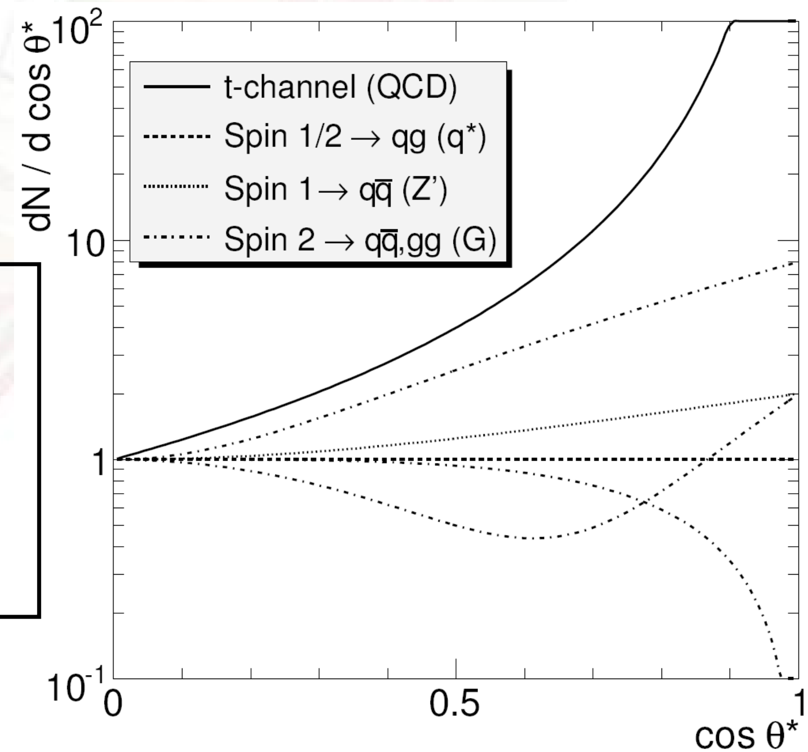
$(q\bar{q} \to G \to q\bar{q})$ $dN/d\cos\theta^* \sim 1 - 3\cos^2\theta^* + 4\cos^4\theta^*$

$(gg \to G \to gg)$ $dN/d\cos\theta^* \sim 1 + 6\cos^2\theta^* + \cos^4\theta^*$

$(\bar{q}q \to G \to gg,\ gg \to G \to \bar{q}q)$

$dN/d\cos\theta^* \sim 1 - \cos^4\theta^*$

(QCD) $dN/d\cos\theta^* \sim 1/(1 - \cos\theta^*)^2$

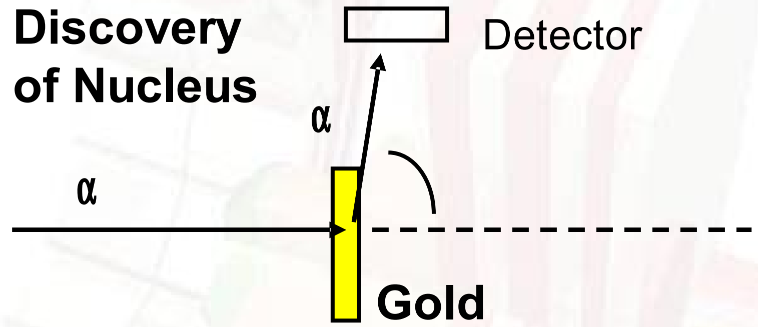


Contact Interactions

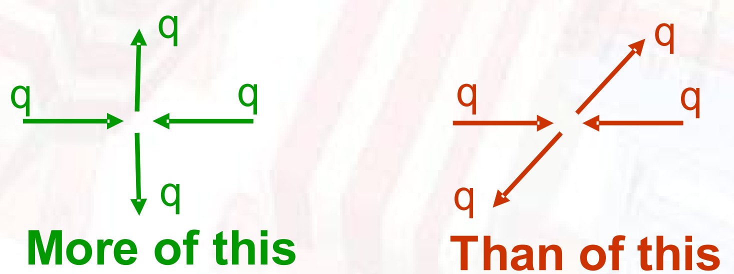
- Three nearly identical generations suggests quark compositeness.
  - Compositeness is also historically motivated.
    - Molecules → Atoms → Nucleus → Protons & Neutrons → Quarks → Preons ?

- Scattering probes compositeness.
- In 1909 Rutherford discovered the nucleus inside the atom via scattering.
  - Scattered α particles off gold foil.
  - Too many scattered at wide angles to the incoming α beam
  - Hit the nucleus inside the atom!
- A century later, we can discover quark compositeness in a similar way !
  - **Rate**: more jets at high p_T than QCD.
  - **Angle**: more dijets in center of the CMS barrel than at the edge. Measured with dijet ratio (more later)
  - Today we model quark compositeness with contact interactions.

Discovery of Nucleus



Quark Compositeness Signal



Contact Interactions

Quark compositeness (scale Λ):

$\Lambda < \sqrt{s} \Rightarrow$ Narrow resonant states of excited fermions on shell

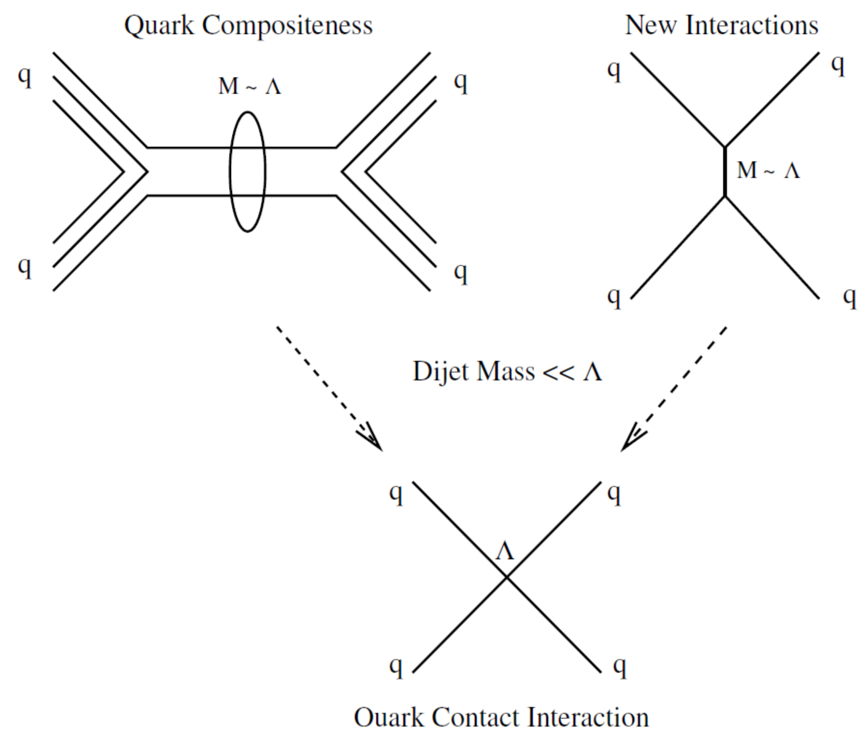
$\Lambda >> \sqrt{s} \Rightarrow$ Effective 4 fermions Contact Interaction:

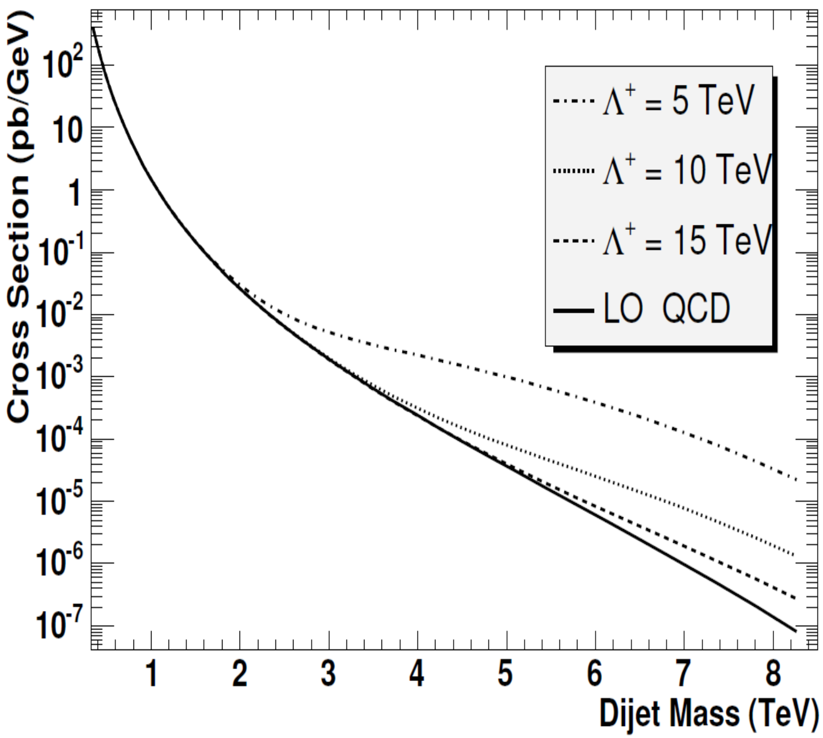
$$L_{qqqq} = A\ (g^2/2\Lambda^2_{LL})\ q_L\gamma^\mu \bar{q}_L q_L \gamma^\mu \bar{q}_L$$

In the following we will use:

A= +1 destructive interference sign; $g^2 = 4\pi$

New physics at a scale Λ above the mass of the final state is effectively modeled as a Contact Interaction

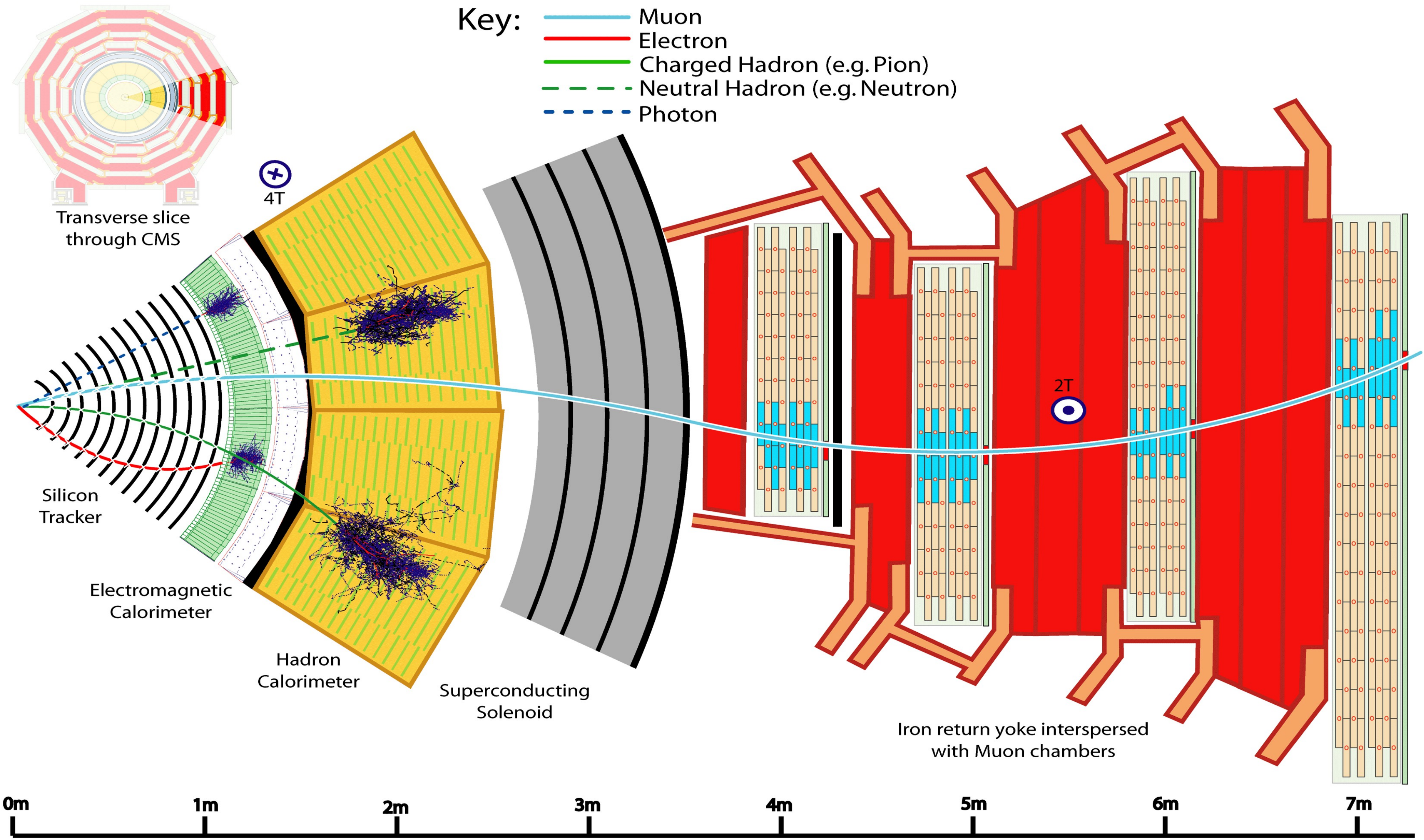




- Contact Interactions produce a rise in rate relative to QCD at high dijet mass or high inclusive jet p_T
- They can also produce observable effects in the dijet angular distributions, which benefit from much smaller measurement systematic uncertainties

Jets with CMS

Particle detection in CMS

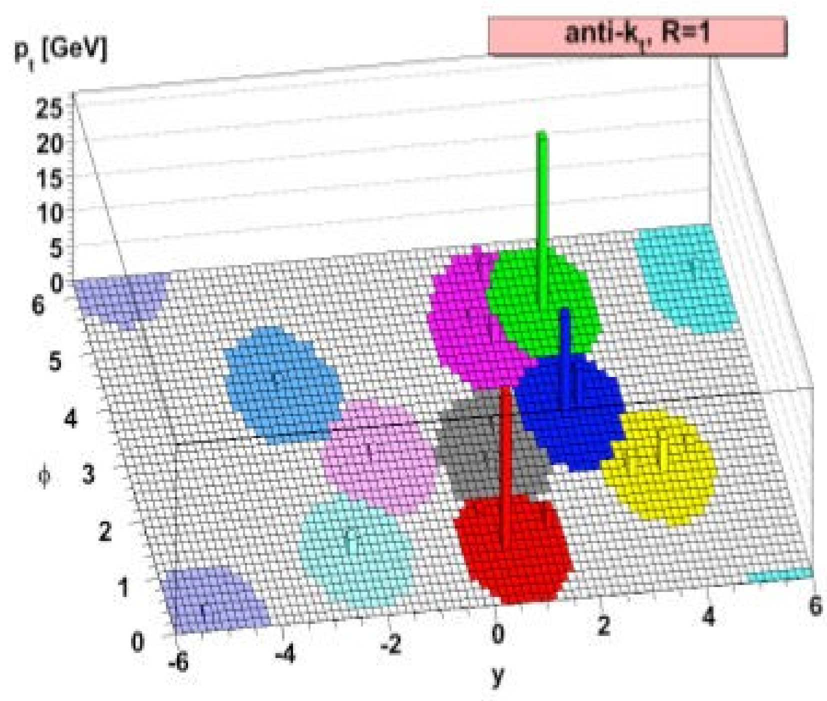


Jet reconstruction in CMS

In CMS various algorithms are in use:
- Iterative Cone (IC), Midpoint Code (MC), SISCone, Kt, AntiKt, etc

The ideal jet algorithm must:
- be IRC-safe
- have good energy and position resolution, good efficiency, etc
- allow to correct for contamination originating from the primary interaction by Pile Up (PU) activity
- CPU efficient
- suitable for any PU conditions through the lifetime of the CMS experiment

AntiKt is the most suitable of the algorithms
- IRC-safe :-)
- but produce circular cone shaped jets :-)
- very stable vs p_T
- optimal response in presence of UE and PU: expected smearing of transverse momenta of 200 GeV leading jets in QCD dijet sample induced by adding high-lumi (25) PU to the event



Preliminary studies in CMS show that AntiKt has the best p_T and η resolution
- AntiKt will be the first algo to be supported in CMS at start-up

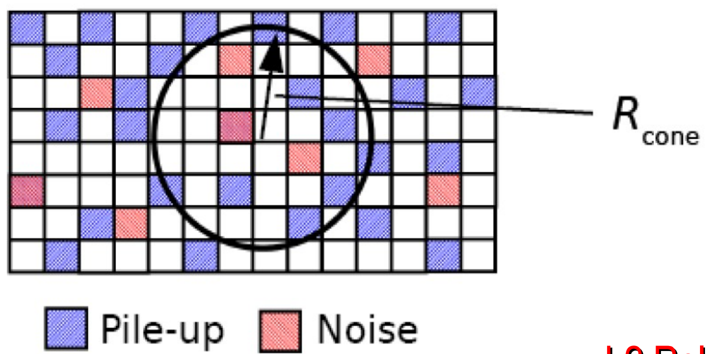
Jet corrections in CMS

Jet energy measured in the detector has to be corrected to the energy of final state particle or parton

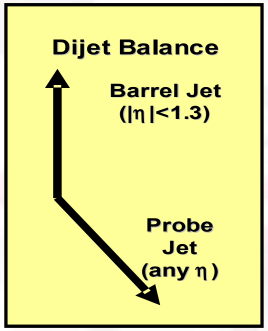
Method to correct jets adopted in CMS is factorized and multilevel independent

- L1 Offset: removal of pile-up and residual electronic noise
- L2 Relative (η): variations in response with η relative in control region
- L3 Absolute (p_T): correction to particle level versus jet p_T in control region
- L4 EM fraction: correct for scale variation as a function of EMF
- L5 Flavor: correction to particle level for different types of jet (b, τ, etc)
- L6 Underlying Event: luminosity independent spectator energy in the event
- L7 Parton: correction to parton level

The first 3 levels of corrections are required, while the others are optional



L1 Offset:
- Cone size dependent effect
- Use of Zero Bias events in order to measure offset energy
- Corrected vs η



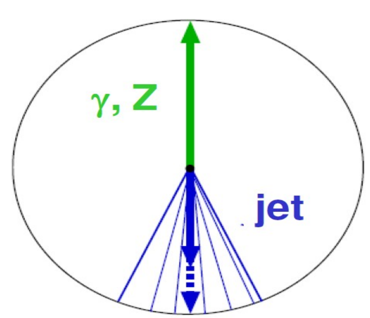
L2 Relative:
- Flatten relative response vs η
- Extract relative response respect to the barrel

$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$

$$c(\eta, \langle p_T^{probe} \rangle) = \frac{1}{r(\eta, \langle p_T^{probe} \rangle)}$$



L3 Absolute:
- Flatten absolute response vs p_T
- Balance in transverse plane
- γ + jet: used for large p_T corrections
- Z + jet: used for smaller systematics at low p_T

Searches with Dijet events

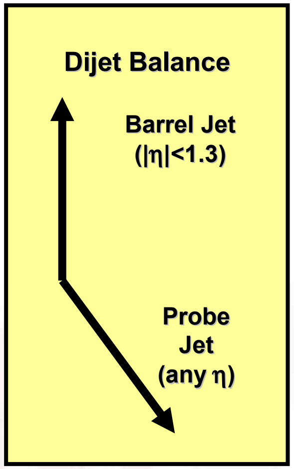
Dijet reconstruction and selection

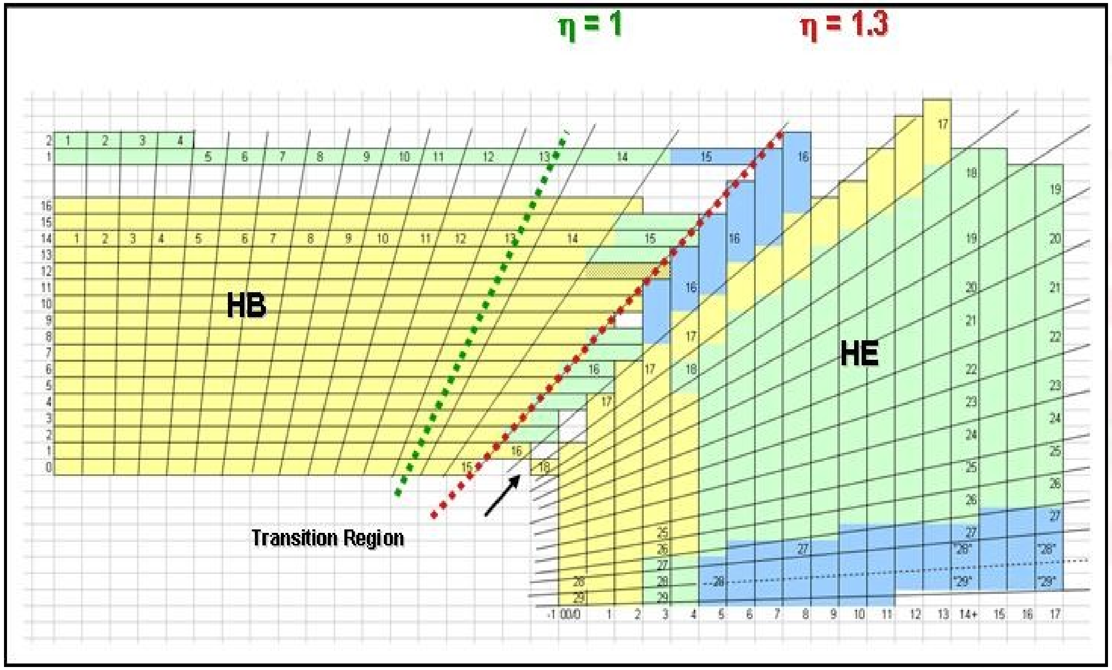
Standard jet reconstruction
- Cone algorithm R=0.5
  - Midpoint & iterative cone indistinguishable at high p_T
- Standard jet kinematics
  - Jet $E = \Sigma E_i$, Jet $\vec{p} = \Sigma \vec{p}_i$
  - $\theta = \tan^{-1}(p_y/p_x)$
  - $E_T = E \sin\theta$, $p_T = \sqrt{p_x^2 + p_y^2}$

Standard MC jet corrections
- Scales Jet (E, p_x, p_y, p_z) by
  - ~1.5 at E_T = 70 GeV
  - ~1.1 at E_T = 3 TeV
  - for jets in barrel region

Dijet is two leading jets

$$m = \sqrt{(E_1+E_2)^2 - (\vec{p}_1+\vec{p}_2)^2}$$





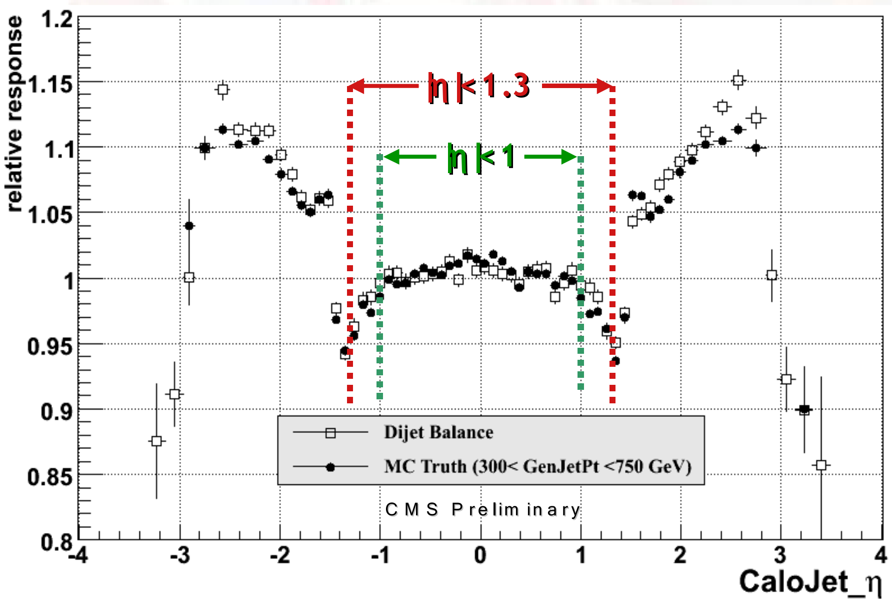
Barrel jets have uniform response & sensitive to new physics
- Jet response changes smoothly and slowly up to | jet η | = 1.3
  - CaloTowers with |η| < 1.3 are in barrel with uniform construction
  - CaloTowers with 1.3< |η| < 1.5 are in barrel / endcap transition region
- Some of our analyses use | jet η | < 1.3, others still use | jet η | < 1
  - All are migrating to | jet η | < 1.3 which is optimal for dijet resonances

Measure relative response vs. jet η in data with dijet balance
- Data will tell us what is the region of response we can trust

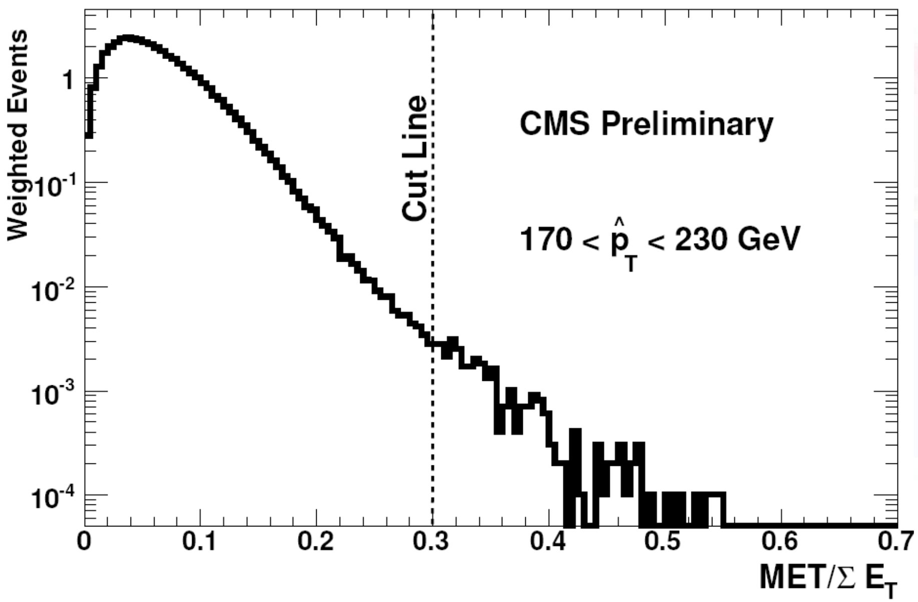
Analysis strategies

- Use jets in the Barrel which are sensitive to New Physics
- Cut on MET/ΣE_T to reject catastrophic noise/beam halo/cosmics rays
- Inclusive Jet Rate vs Jet p_T: Contact Interactions (Large rate compared to QCD)
- Dijet Rate vs Dijet Mass: Resonances
  - Simple bump hunting in Dijet Spectra
- Dijet Ratio = N ($|\eta|$<0.7) / N (0.7<$|\eta|$<1.3): both searches
  - Simple measure of angular distribution vs dijet mass

Jet Response vs η relative to Barrel



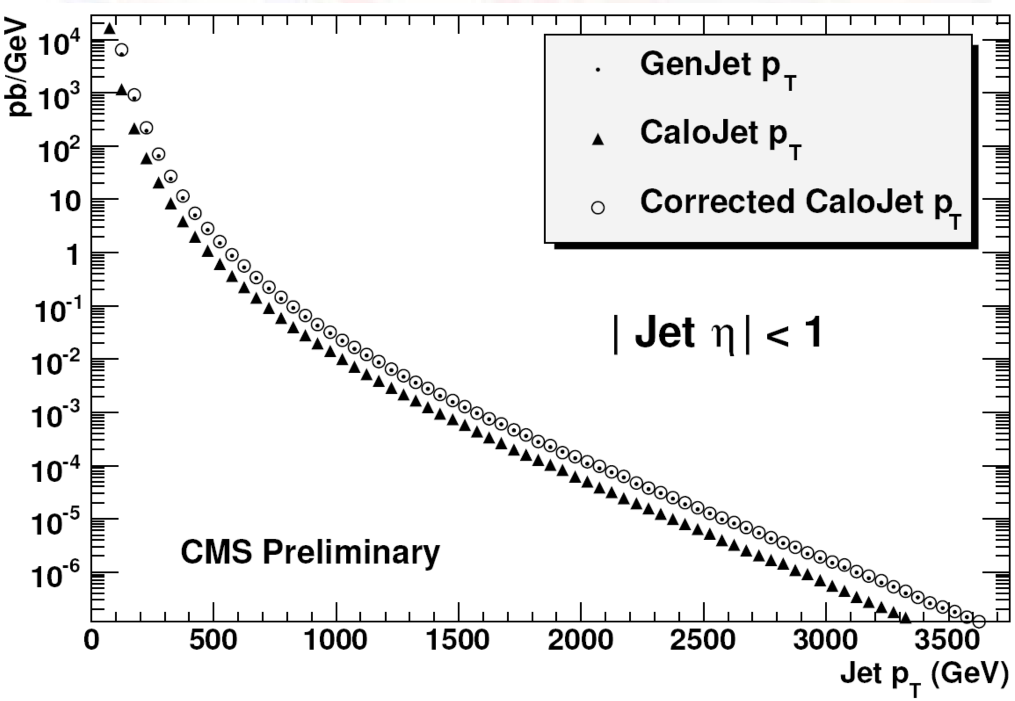
MET / ΣE_T for QCD Dijet and cut



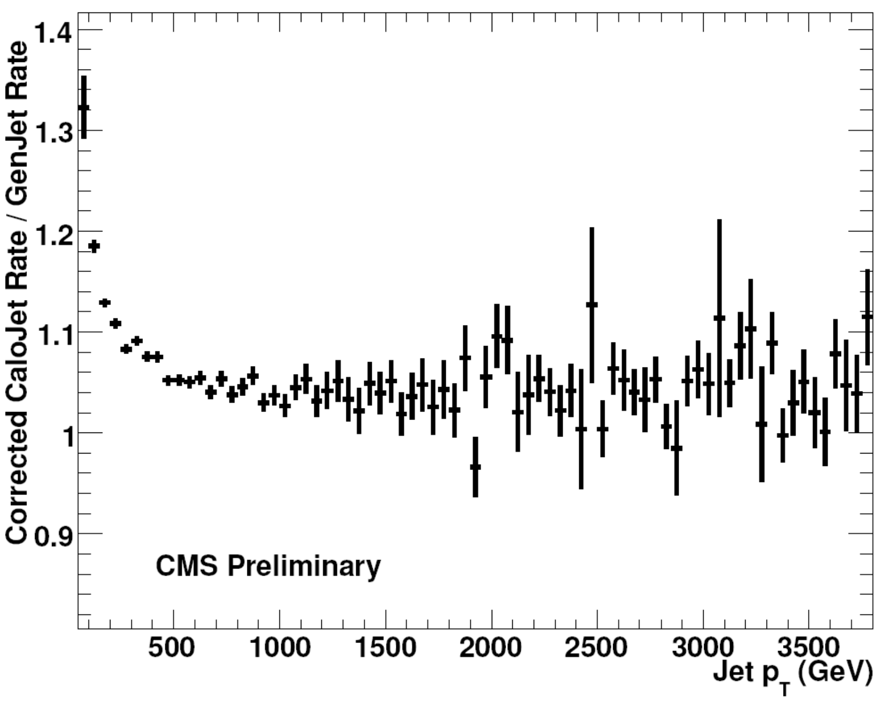
Inclusive Jet p_T

- Inclusive jet p_T is a QCD measurement that is sensitive to new physics
  - Counts all jets inside a p_T bin and interval, and divides by bin width and luminosity
- Corrected CaloJets agree reasonably well with GenJets
  - CaloJets jets before corrections shifted to lower E_T than GenJets
  - Ratio between corrected CaloJets and GenJets is “resolution smearing”: small at high p_T
- Simple correction for resolution smearing in real data is to divide rate by this ratio

Inclusive Jet Cross Section



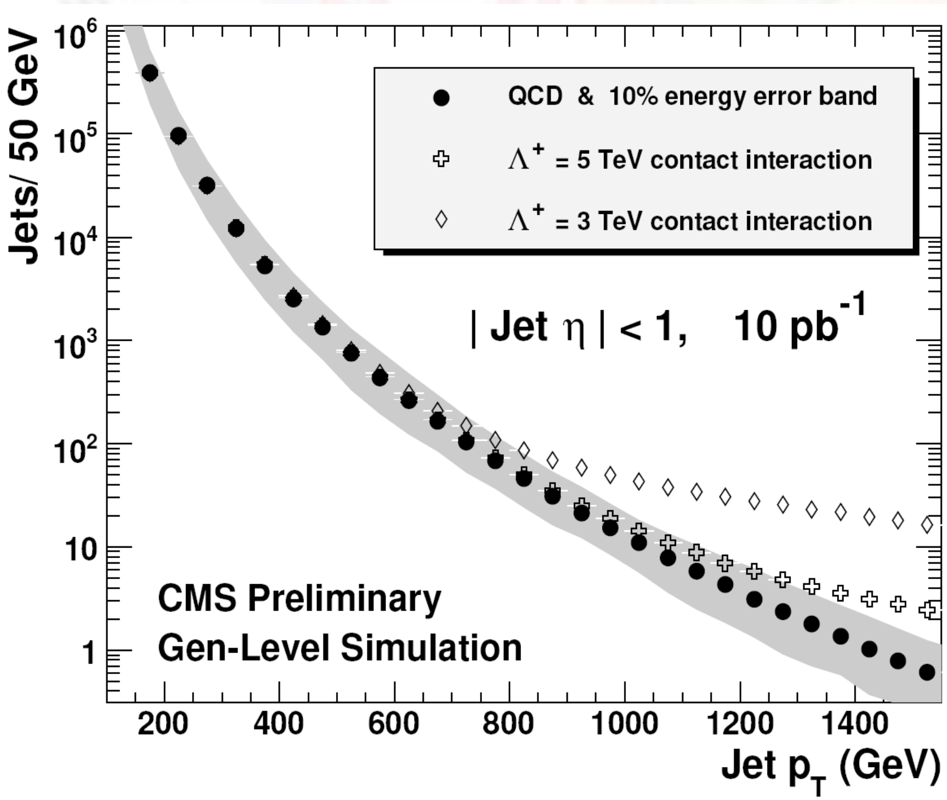
Resolution Smearing



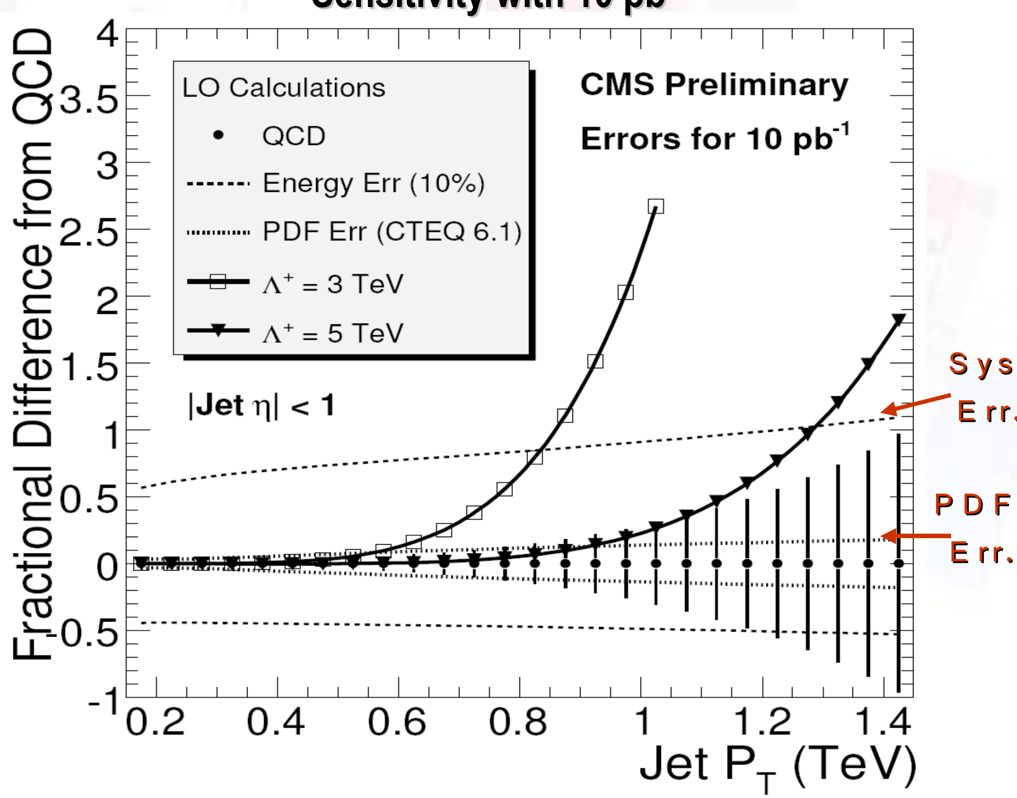
Inclusive Jet p_T and Contact Interactions

- Contact Interactions create large rate at high p_T and immediate discovery possible
  - Error dominated by Jet Energy Scale (~10%) in early running (10 pb^{-1})
    - $\Delta E \sim$ 10% not as big an effect as Λ^+= 3 TeV for p_T>1 TeV
  - PDF "errors" and statistical errors (10 pb^{-1}) smaller than E scale error
- With 10 pb^{-1} we can see new physics beyond Tevatron exclusion of Λ^+ up to 2.7 TeV

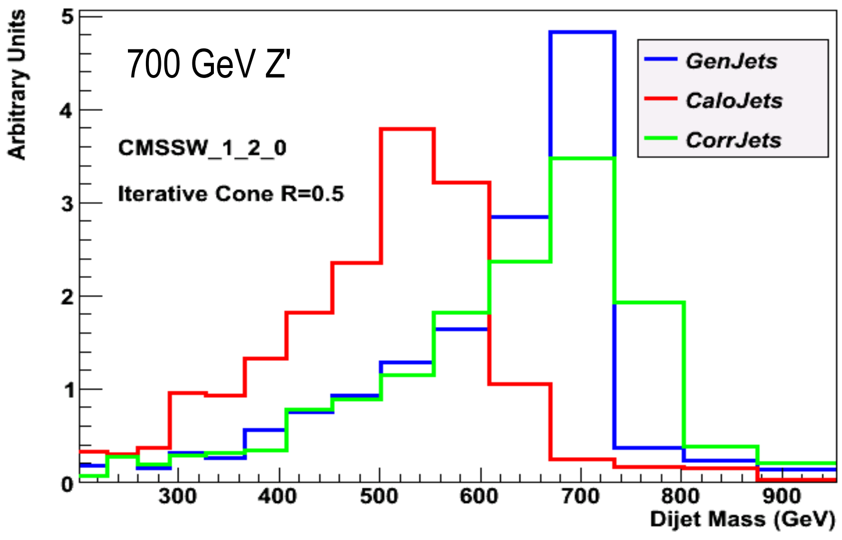
Rate of QCD and Contact Interactions



Sensitivity with 10 pb^{-1}

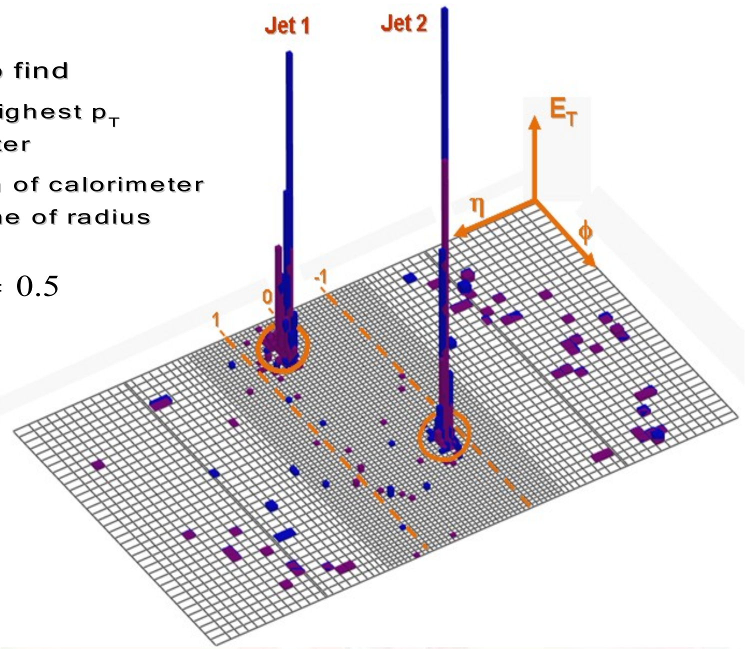


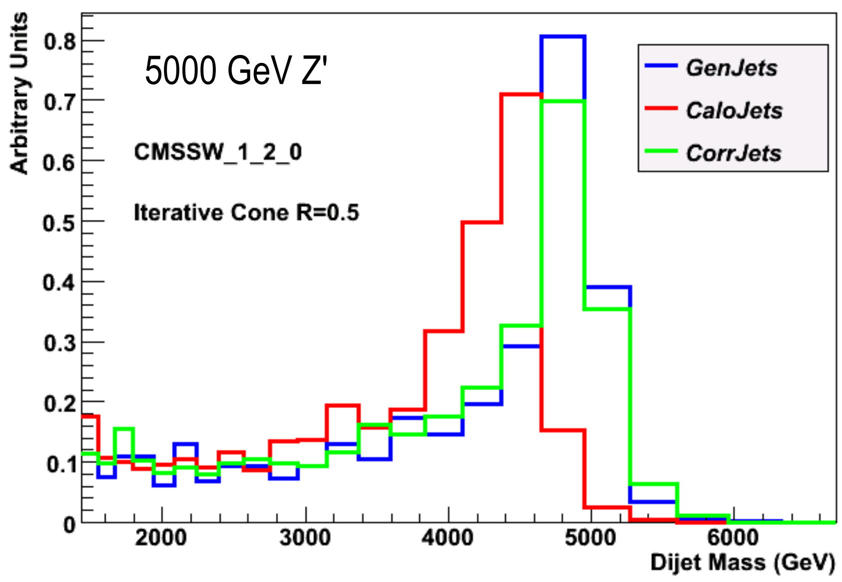
Dijet Resonance Mass Peaks



- Dijets are easy to find
  - Two jets with highest p_T in the calorimeter
  - A jet is the sum of calorimeter energy in a cone of radius

$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$$





GenJets peak at right mass values
- Long tail to low mass due to radiation
- Low mass tail is pronounced for 5 TeV due to pdf effects on tail

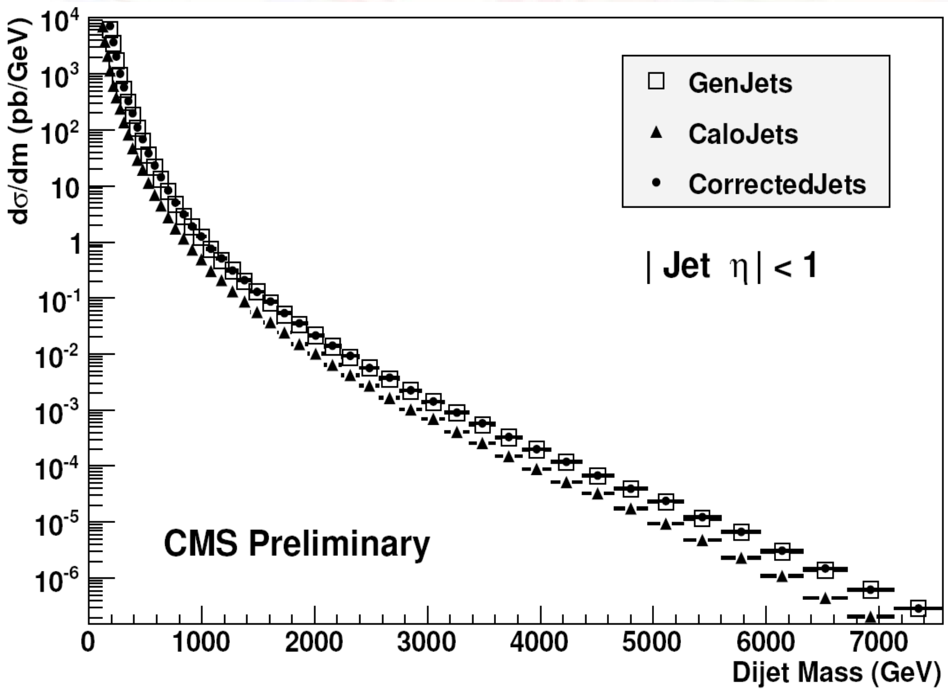
CaloJets peak at lower mass than GenJets
- Due to calorimeter response

Corrected Jets are similar to GenJets

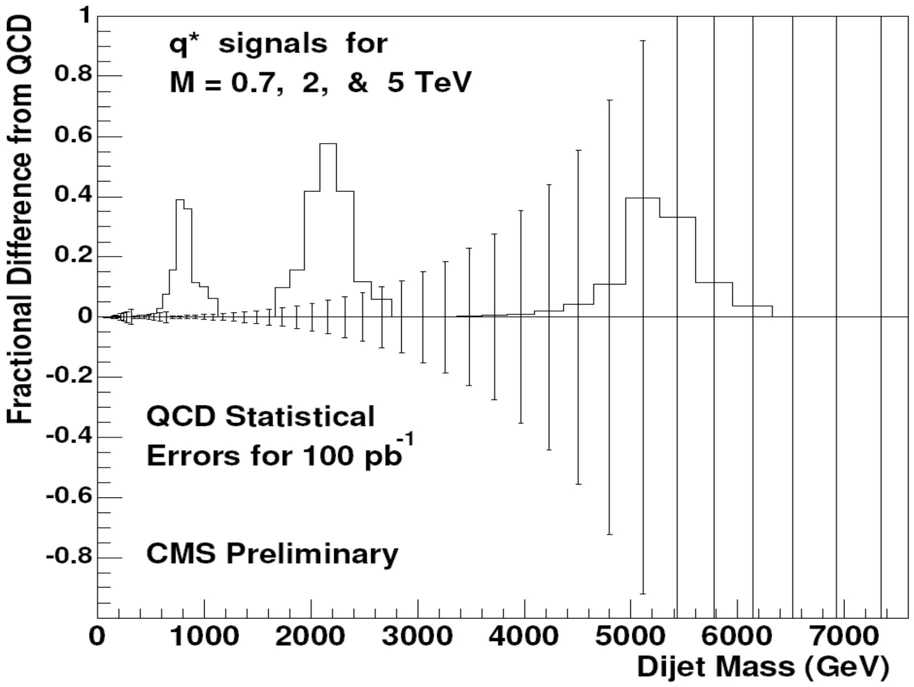
Dijet Resonances in Rate vs Dijet Mass

- Measure rate vs Corrected Dijet Mass and look for resonances
  - Use a smooth parameterized fit or QCD prediction to model background
- Strongly produced resonances can be seen
  - Convincing signal for a 2 TeV excited quark in 100 pb^{-1}
    - Tevatron excluded up to 0.87 TeV

QCD Backgound



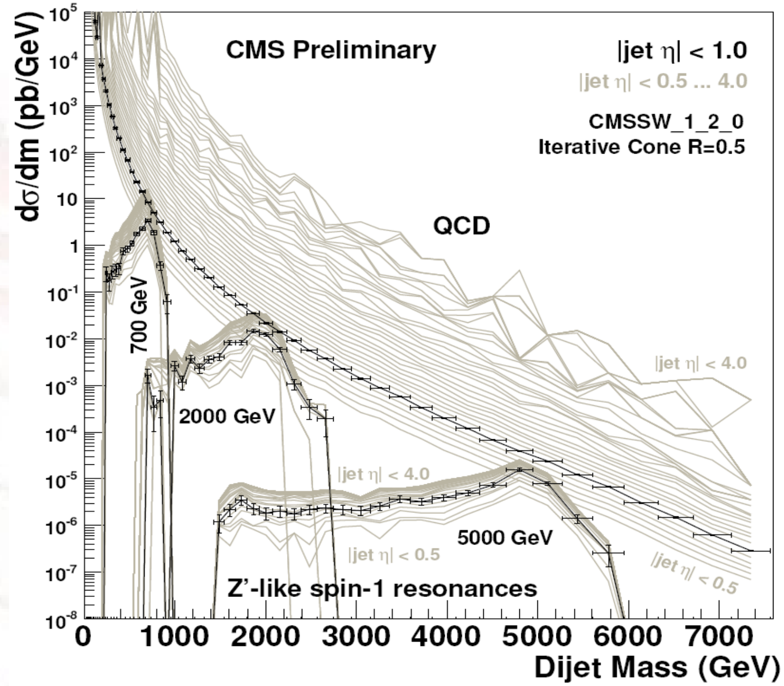
Resonances with 100 pb^{-1}



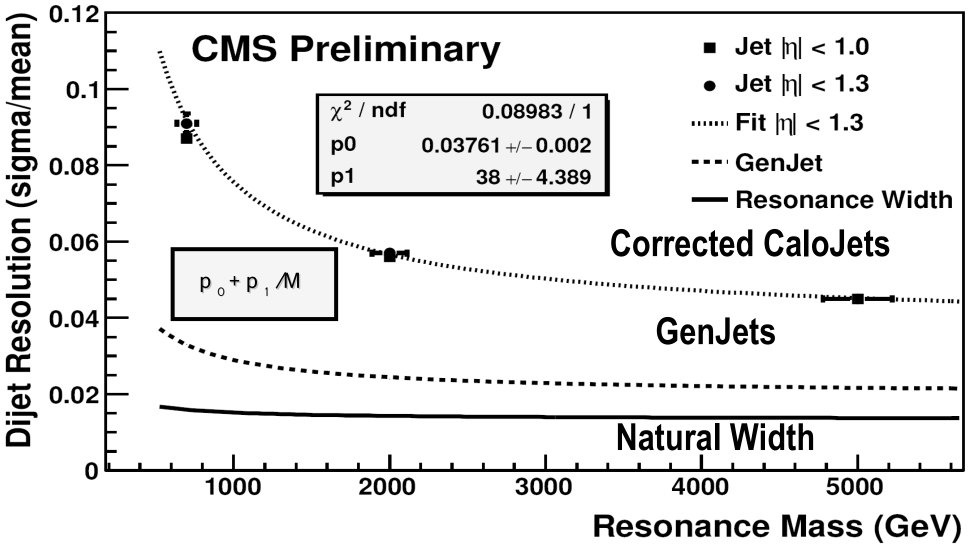
Resonances: η cut & mass resolution

- QCD cross section rises dramatically with $|\eta|$ cut due to t-channel pole
  - Z' signal only gradually increases with $|\eta|$ cut $\Rightarrow$ optimal value at low $|\eta|$
- Optimal cut is at $|\eta| < 1.3$ for a 2 TeV dijet resonance
  - Optimization uses Pythia Z' angular distribution for the resonance

η cut and cross section



Resolution

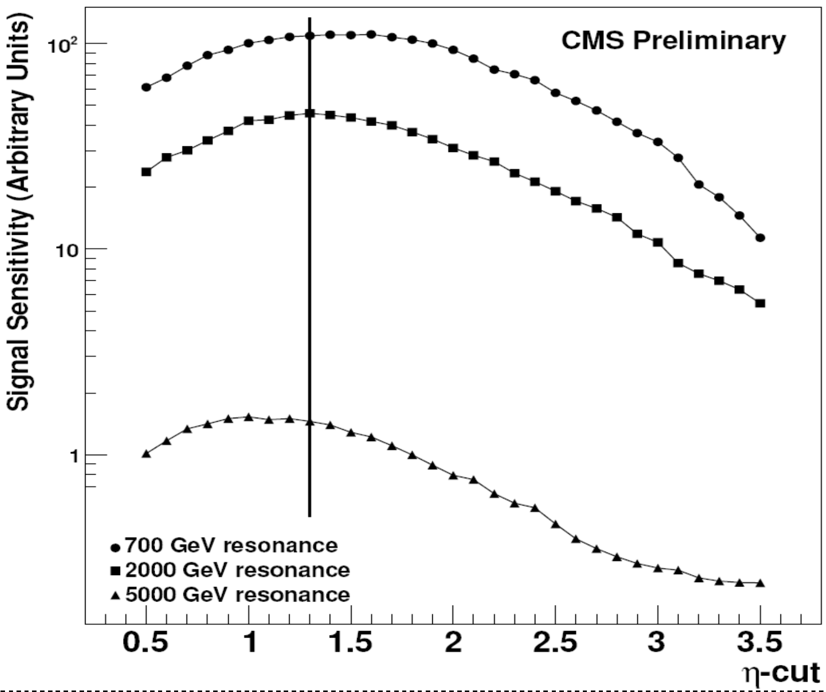


- Gaussian core of resolution for $|\eta|<1$ and $|\eta|<1.3$ is similar
- Resolution for Corrected Jets
  - 9% at 0.7 TeV
  - 4.5% at 5 TeV

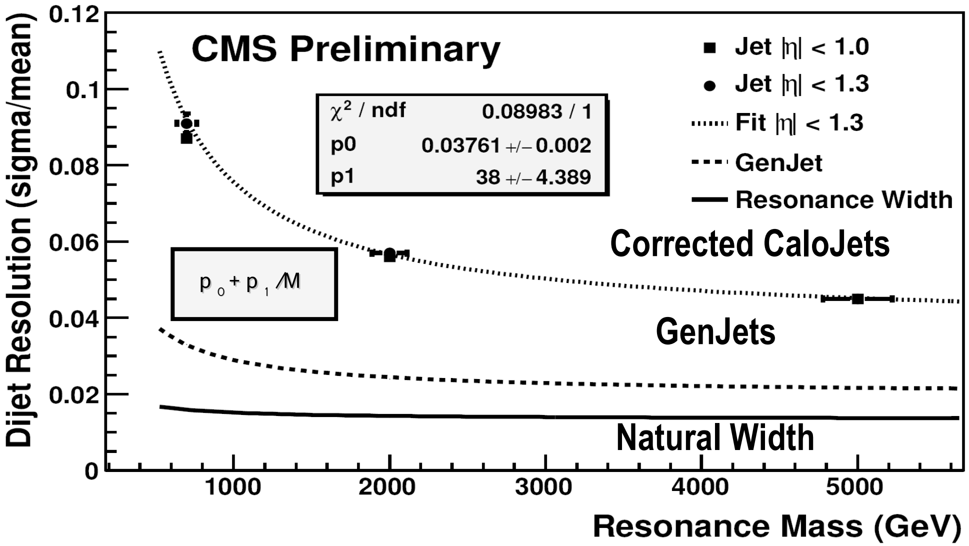
Resonances: η cut & mass resolution

- QCD cross section rises dramatically with |η| cut due to t-channel pole
  - Z' signal only gradually increases with |η| cut ⇒ optimal value at low |η|
- Optimal cut is at |η| < 1.3 for a 2 TeV dijet resonance
  - Optimization uses Pythia Z' angular distribution for the resonance

η cut and sensitivity



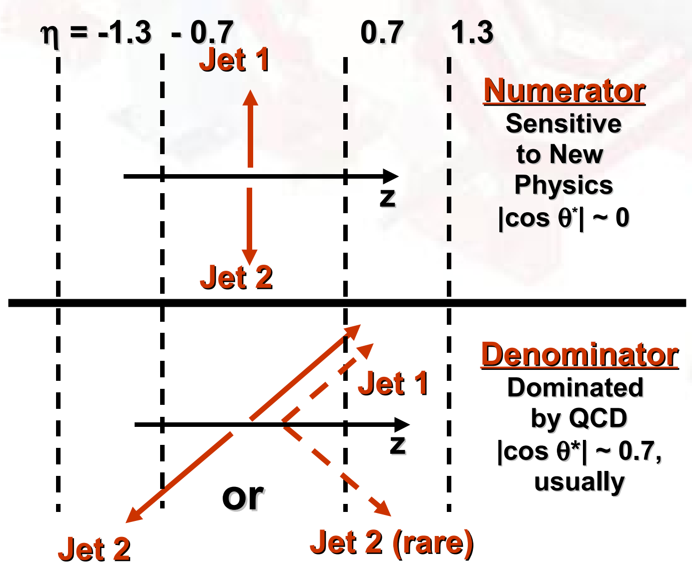
Resolution



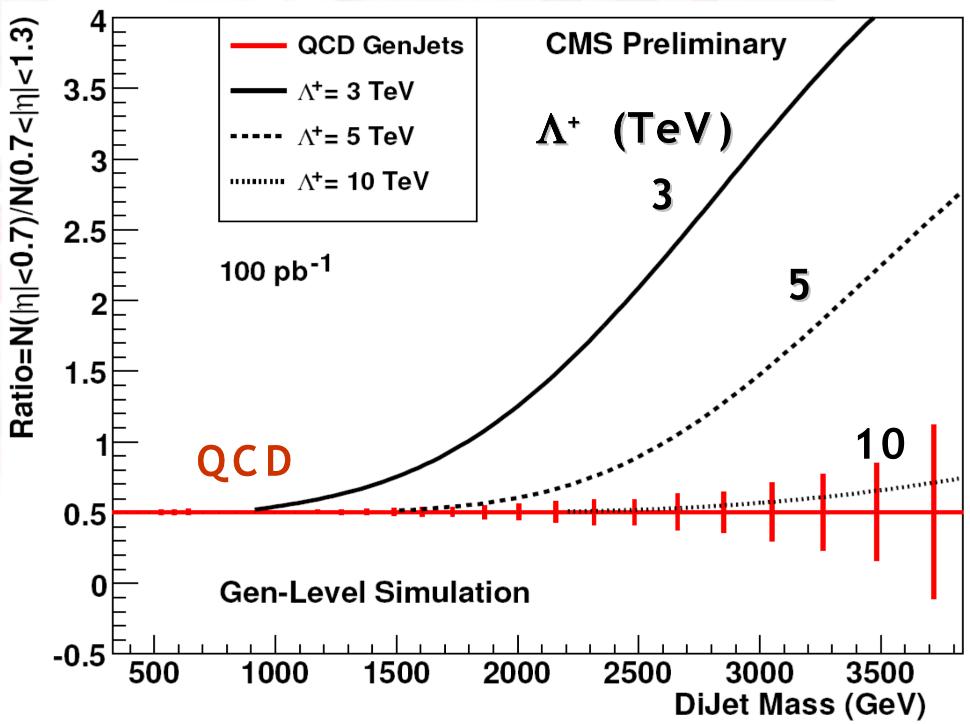
- Gaussian core of resolution for |η|<1 and |η|<1.3 is similar
- Resolution for Corrected Jets
  - 9% at 0.7 TeV
  - 4.5% at 5 TeV

Dijet Ratio from QCD & Contact Interactions

- Dijet Ratio = N(|η|<0.7) / N(0.7<|η|<1.3):
  - Number of events in which each leading jet has |η|<0.7 divided by the number of events in which each leading jet has 0.7<|η|<1.3
  - Dijet Ratio is a simple measure of the dijet angular distribution vs Dijet Mass
  - Numerator is sensitive to New Physics, denominator is dominated by QCD
  - QCD background has flat dijet ratio = 0.5 up to Dijet Mass = 6 TeV
  - Contact interactions increase the Dijet Ratio at high mass
  - CMS can discover Λ^+= 4, 7 & 10 TeV with 10, 100 & 1000 pb^{-1}

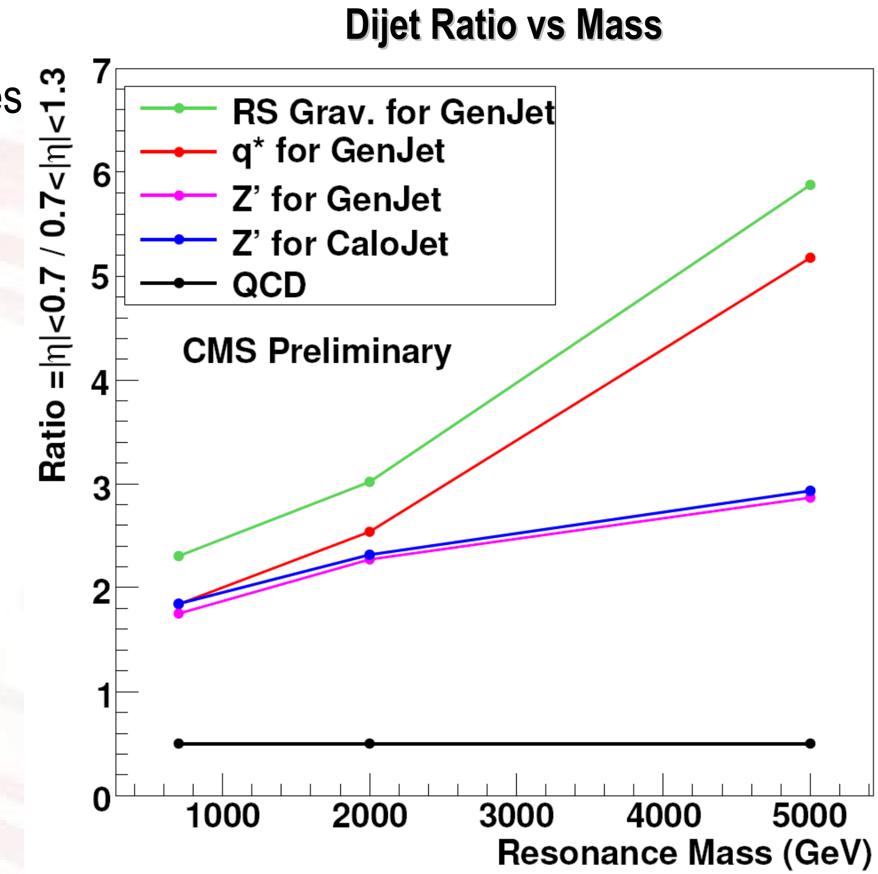


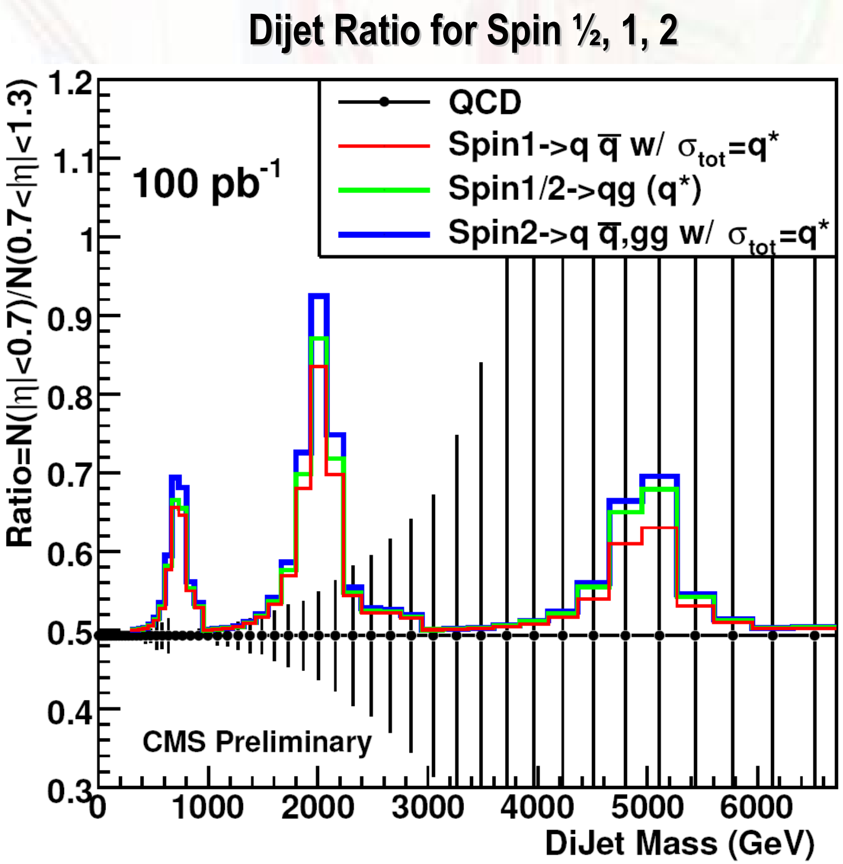
Dijet Ratio



Dijet Resonances with Dijet Ratio

- Spin ½ (q^*), spin 1 (Z'), and spin 2 (RS Graviton) resonances are more isotropic than QCD in dN / dcosθ^*
- Resonances Dijet Ratio larger than for QCD because numerator mainly low cos θ^* and denominator mainly high cos θ^*





- Dijet Ratio from signal + QCD compared to statistical errors for QCD
  - Resonances normalized with q* cross section for |η|<1.3 to see effect of spin
- Convincing signal for 2 TeV strong resonance in 100 pb^{-1} regardless of spin
- Technique for discovery, confirmation and eventually spin measurement

Conclusions

Inclusive jet p_T analysis gives a convincing signal for a Contact Interaction scale Λ^+ = 3 TeV in 10 pb^{-1}

Rate vs. Dijet mass gives a convincing signal for a 2 TeV q* with 100 pb^{-1}

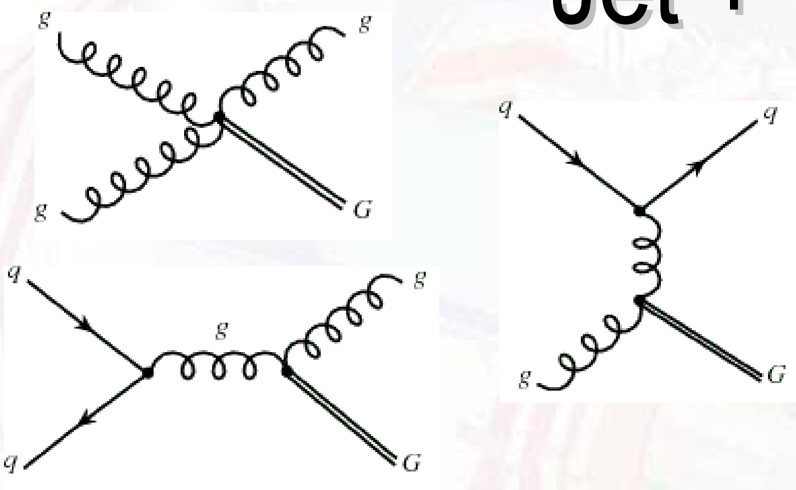
Dijet Ratio can discover
$\Lambda^+ \sim$ 4, 7 and 10 TeV for 10 pb^{-1}, 100 pb^{-1} and 1 fb^{-1}

Dijet Ratio can discover or confirm a dijet resonance, and eventually measure its spin

CMS Collaboration, CMS SBM-07-001

Searches with Monojet events

Jet + MET channel

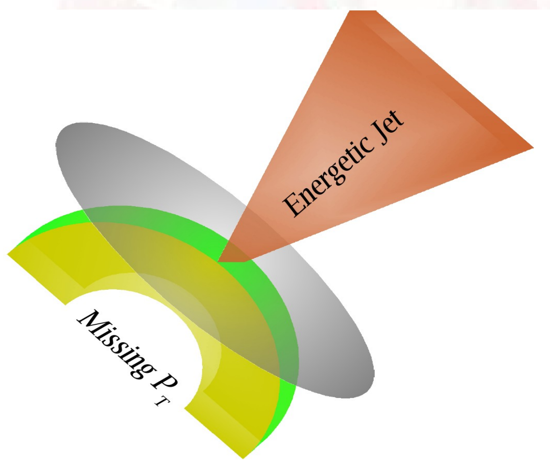


$$\sigma \approx \frac{1}{M_D^2}\left(\frac{\sqrt{\hat{s}}}{M_D}\right)^{\delta}$$

	$\delta = 2$	$\delta = 4$
$M_D = 2$ TeV	49.246 ± 0.056	18.914 ± 0.022
$M_D = 4$ TeV	4.253 ± 0.005	0.998 ± 0.001
$M_D = 6$ TeV	0.862 ± 0.001	0.109 ± 0.001

Values in pb

The direct graviton production associated to a parton produce a distinctive signature



- Leading jet with high pt, at low η and back to back with the MET vector
- Secondary jet almost collinear with primary
- Bulk of the events with at most 2 high pt jets
- No leptons

Signal samples, with M_D ranging from 2 to 7 TeV and δ = 2 to 4 were produced with Sherpa (CTEQ5L and parton p_T > 250 GeV) and simulated with CMS Fast Simulation

Current limits

CDF[1]

Jet + MET analysis with 1.1 fb^{-1}

γ + MET analysis with 2.0 fb^{-1}

DØ[2]

γ + MET with 1.05 fb^{-1}

	LEP	DØ		CDF		
δ	$\gamma + E_T^{miss}$	jet+E_T^{miss}	$\gamma + E_T^{miss}$	jet+E_T^{miss}	$\gamma + E_T^{miss}$	combined
2	1.600	0.99	0.921	1.310	1.080	1.400
3	1.200	0.80	0.877	1.080	1.000	1.150
4	0.940	0.73	0.848	0.980	0.970	1.040
5	0.770	0.66	0.821	0.910	0.930	0.980
6	0.660	0.65	0.810	0.880	0.900	0.940

95% C.L. exclusion limits

[1] CDF Collaboration, 0807.3132v1[hep-ex], Phys. Rev. Lett. **101**, 181602 (2008)

[2] DØ Collaboration, Phys. Rev. Lett. **101**, 011601, (2008)

Background to Jet + MET

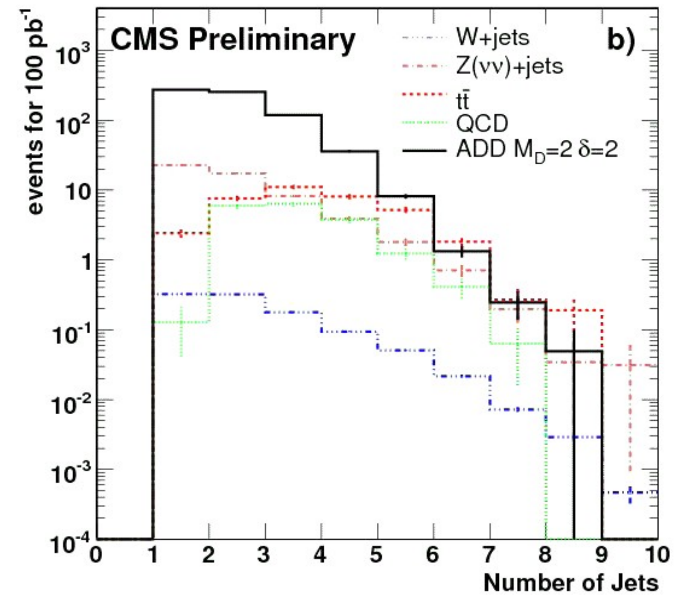
Backgrounds to ADD Jet + MET signal are:

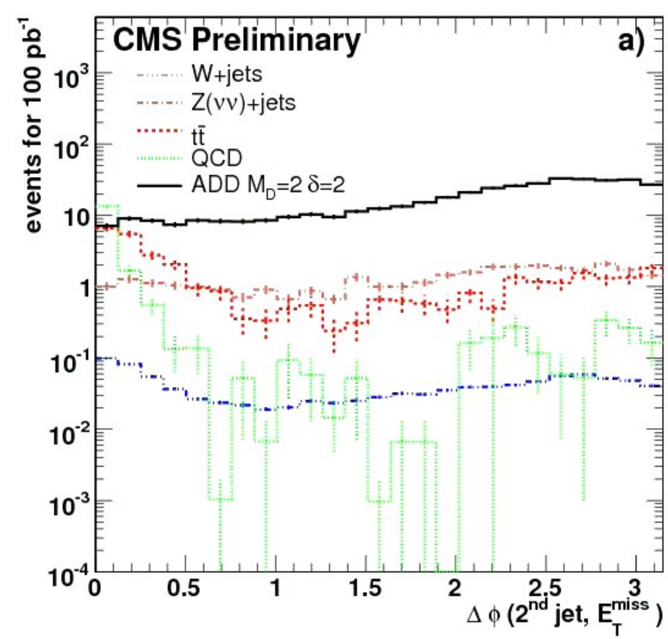
Z($\nu\nu$) + Jets, W($l\nu$) + Jets, QCD and top production

(produced with CMS Full Simulation)

Selection for background rejection

- Only jets with p_T > 40 GeV and $|\eta|$ < 3.0 were considered
- MET > 400 GeV
- Lepton cleaning: JEMF < 0.9 and no isolated tracks with p_T > 15 GeV
- Leading jet with p_T > 350 GeV and $|\eta|$ < 1.7
- Jet multiplicity < 3
- $\Delta\phi$(leading jet, MET) > 2.8
- $\Delta\phi$(secondary jet, MET) > 0.5





Selection efficiencies

	$t\bar{t}$	$Z(\nu\nu)$+jets	QCD	$W(e\nu)$+jets	$W(\mu\nu)$+jets	$W(\tau\nu)$+jets
Trigger	3860	1280	$4.92 \cdot 10^5$	1199	1617	1488
$E_T^{miss} > 400$ GeV	36.6	54.8	17.9	19.5	63.7	36.3
$JEMF < 0.9$	32.0	52.4	17.2	8.8	60.6	32.0
$TIV < 0.1$	12.2	46.3	14.2	4.3	5.9	13.0
$p_T(\text{jet }1) > 350$ GeV, $\lvert\eta(\text{jet }1)\rvert < 1.7$	9.8	36.6	11.8	3.3	4.5	9.9
Number of jets < 3	2.2	28.9	4.6	2.3	2.8	6.9
$\Delta\phi(\text{jet }1, E_T^{miss}) > 2.8$, $\Delta\phi(\text{jet }2, E_T^{miss}) > 0.5$	0.5	25.7	< 0.6	2.0	2.0	5.5

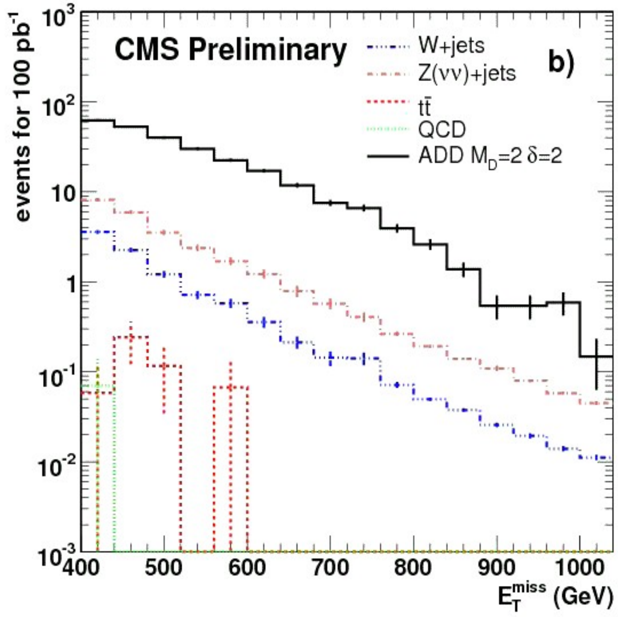
Tables figures are for 100 pb^{-1}

JEMF and TIV are used to reject W(lν)+Jets

Jet multiplicity is used to reduce QCD and top production

Δφ's are used to further reduce QCD

	$\delta = 2$		$\delta = 4$	
	$M_D = 2$ TeV	$M_D = 6$ TeV	$M_D = 2$ TeV	$M_D = 6$ TeV
Trigger	3060	54.4	1190	7.98
$E_T^{miss} > 400$ GeV	691	12.1	244.7	3.05
$JEMF < 0.9$	658.6	11.6	231.8	2.9
$TIV < 0.1$	539.2	9.5	185.2	2.2
$p_T(\text{jet }1) > 350$ GeV, $\lvert\eta(\text{jet }1)\rvert < 1.7$	343.1	6.5	117.1	1.6
Number of jets < 3	286.8	5.4	98.3	1.2
$\Delta\phi(\text{jet }1, E_T^{miss}) > 2.8$, $\Delta\phi(\text{jet }2, E_T^{miss}) > 0.5$	261.5	4.9	90.1	1.1

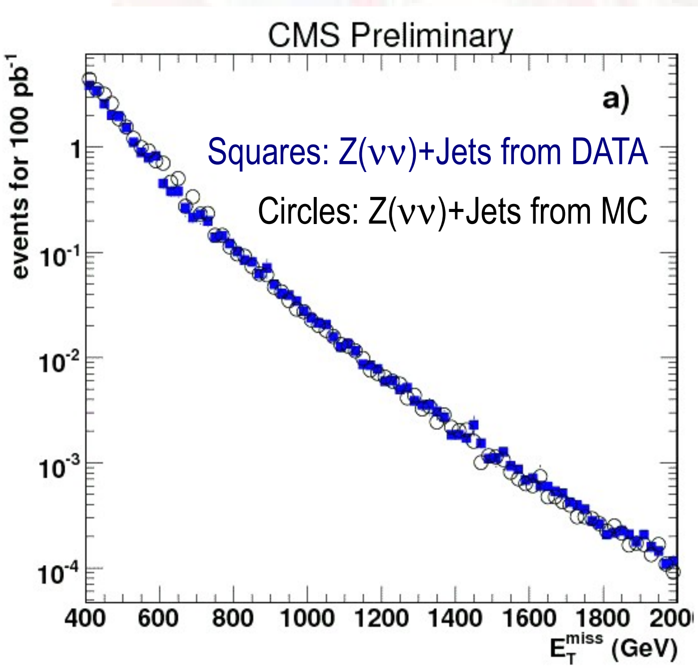


Irreducible background data driven estimate

Z(νν) + Jets can be estimated from a ~ pure W(μν) + Jets sample

- Z(νν) + Jets and W(μν) + Jets ratio is constant at high boson p_T and PDF variations are within 1%
- A control W(μν) + Jets sample is obtained asking:
  - A single muon trigger
  - An isolated muon with p_T > 20 GeV
  - Selections as in the signal region

Selection	$W(\mu\nu)$+jets	$W(\tau\nu)$+jets	$t\bar{t}$
Single isolated μ	453009	16374	7924
$E_T^{miss} > 400$ GeV	40.8	6.8	9.6
$JEMF < 0.9, TIV < 0.1$	34.5	5.8	7.3
$p_T(\text{jet}1) > 350$ GeV, $\lvert\eta(\text{jet}1)\rvert < 1.7$	26.6	4.5	5.1
Number of jets < 3	21.9	3.6	2.5
$\Delta\phi(\text{jet}1, E_T^{miss}) > 2.8$, $\Delta\phi(\text{jet}2, E_T^{miss}) > 0.5$	20.0	3.3	2.0



- The control sample can be rescaled by:
  - The ratio factor
  - The trigger and isolation efficiencies
- The W(τν) + Jets contamination is estimated using Br(τ→μνν)
- The top pair contamination can be treated as a systematic contribution

$$N(Z(\nu\nu)+\text{jets})^{Sig} = 21.9 \pm 4.9\ (\text{stat.})^{+2.1}_{-1.4}\ (\text{syst.})$$

Discovery and exclusion

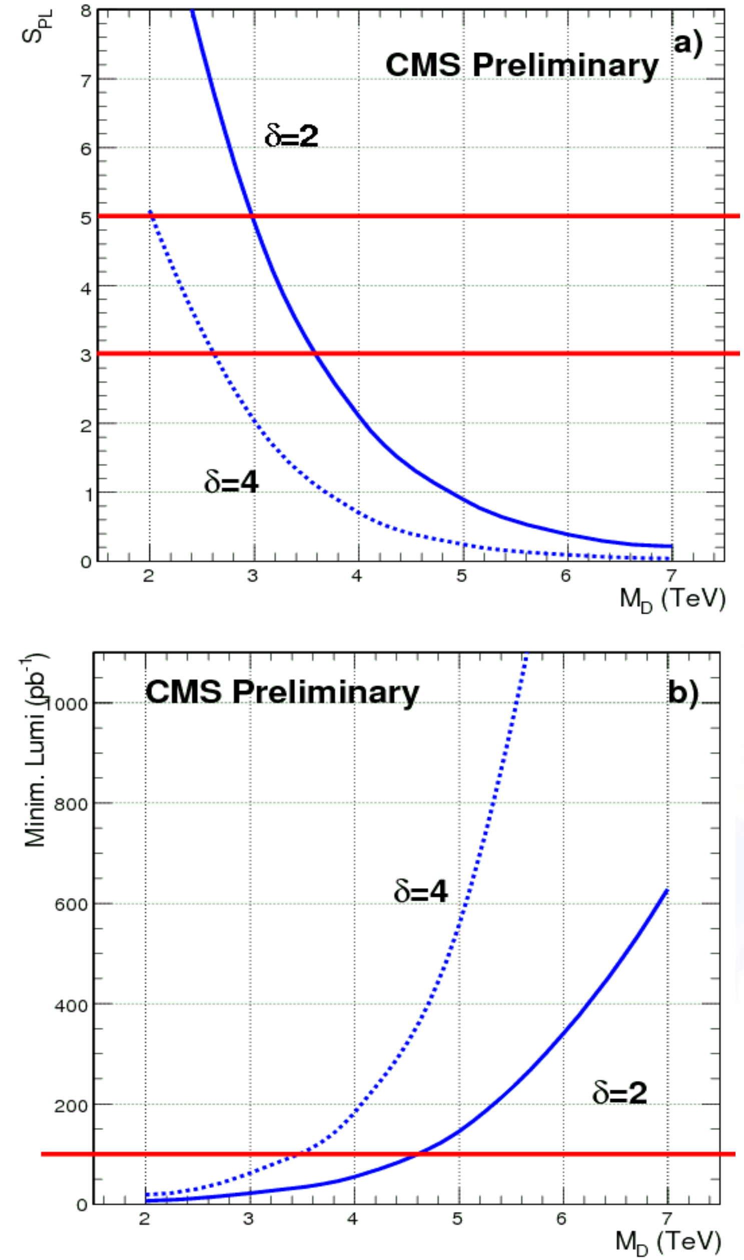
Sources of systematic uncertainties

Source	Effect on number of signal events (%)
Hard process scale	$^{+11}_{-13}$
Background modeling	5.0
PDF	$^{+8.7}_{-6.7}$
Jet energy scale (10%)	$^{-0.8}_{-4.0}$
E_T^{miss}	$^{+17.5}_{-15.9}$
Total theoretical uncertainty on signal	$^{+14.9}_{-15.5}$
Total instrumental uncertainty on signal	$^{+16.7}_{-19.9}$
Luminosity with 100 pb^{-1}	10.0

Sources of background in the signal region:

- $Z(\nu\nu)$ + Jets is estimated from the control region
- QCD contribution is negligible
- $W(\tau\nu)$ + Jets from control region, rescaling by efficiencies and trigger factors
- $W(e/\mu\nu)$ + Jets is estimated from the $W(\tau\nu)$ + Jets by applying MC ratio factors
- Top production is considered as systematic contribution

$$N_B = 30.7 \pm 6.8\ (\text{stat.})^{+2.7}_{-1.5}\ (\text{syst.})\,\text{events}$$

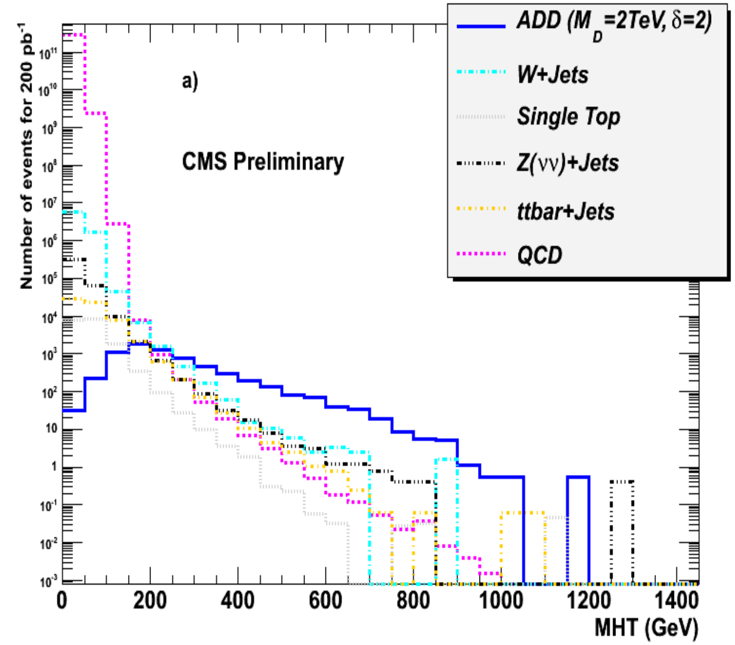


CMS Collaboration, CMS PAS EXO-08-011

Selections at 10 TeV

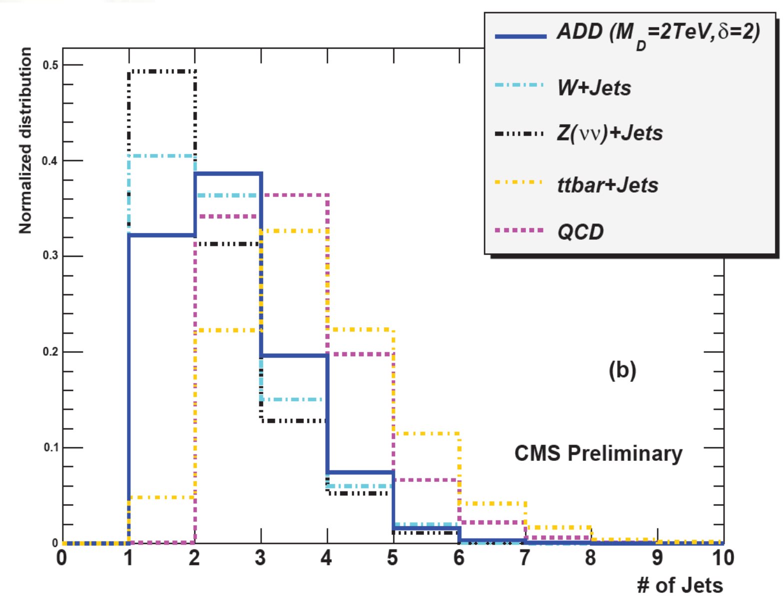
MHT, the vectorial sum of the jet transverse momenta, the lepton cleaning, the angular variables and the jet multiplicity are very effective on signal to background discrimination

$$MHT = \left| \sum_{p_T(\mathrm{jet}) > p_T^0} \vec{p}_T(j) \right|$$

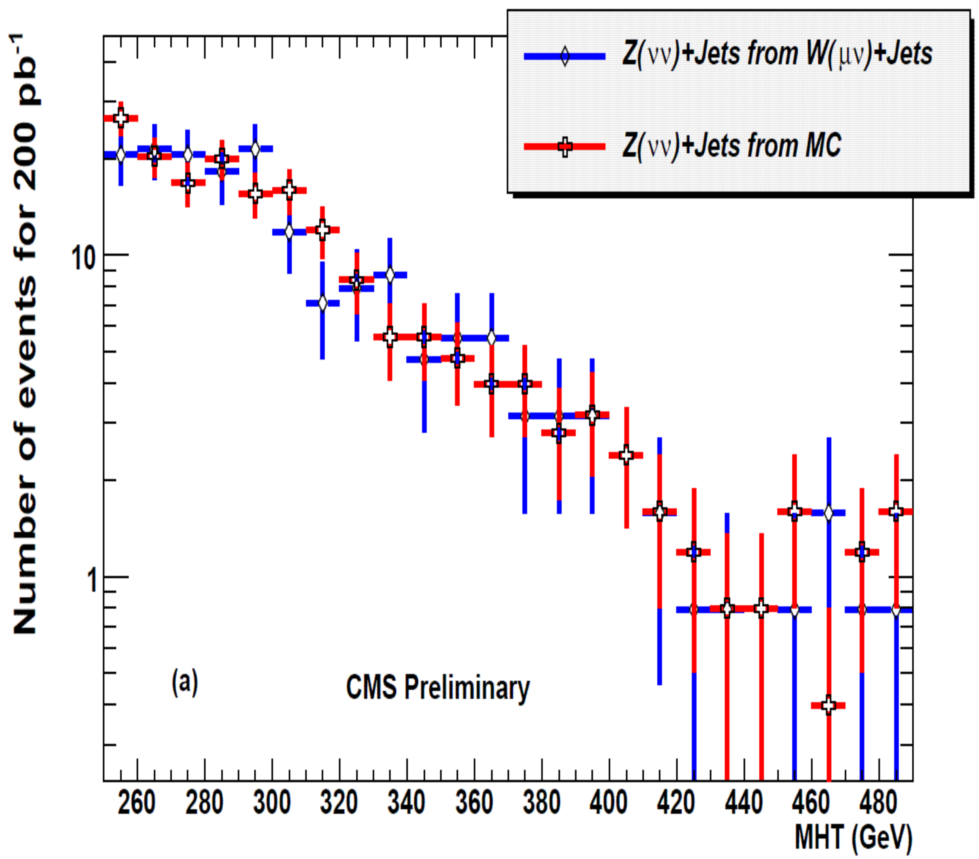


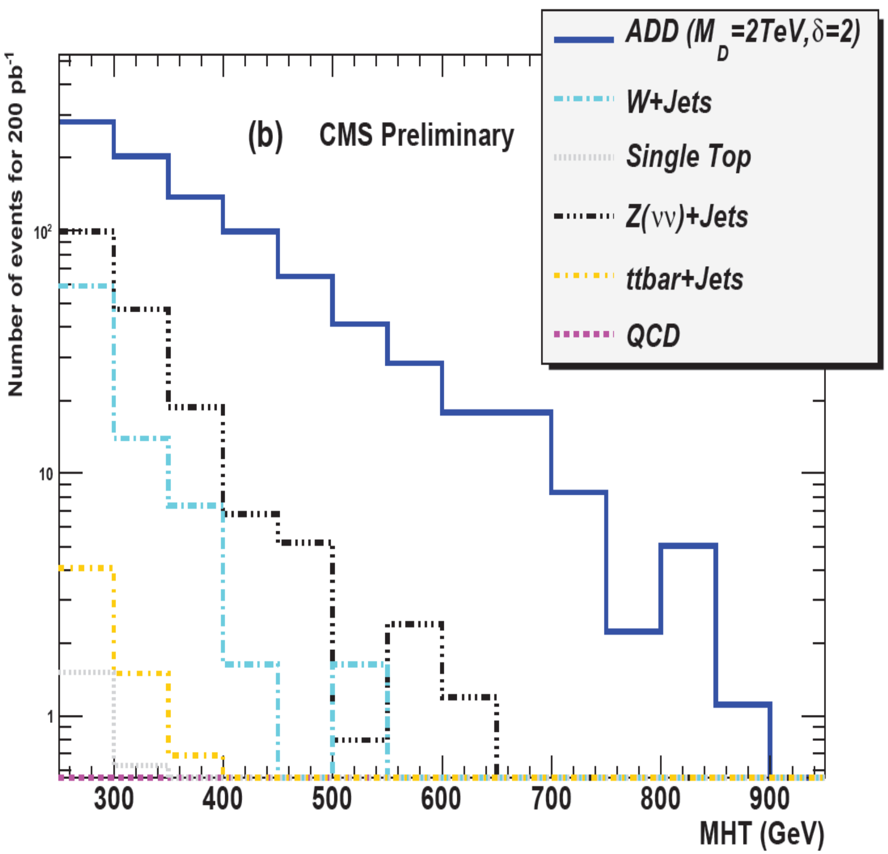
Selection for background rejection

- Only jets with p_T > 50 GeV and $|\eta|$ < 3.0 were considered
- MHT > 250 GeV
- Lepton cleaning: 0.1 < JEMF < 0.9 and
  no isolated tracks with p_T > 20 GeV
- Leading jet with p_T > 200 GeV and $|\eta|$ < 1.7
- Jet multiplicity < 3
- $\Delta\phi$(leading jet, MHT) > 2.8
- $\Delta\phi$(secondary jet, MHT) > 0.5



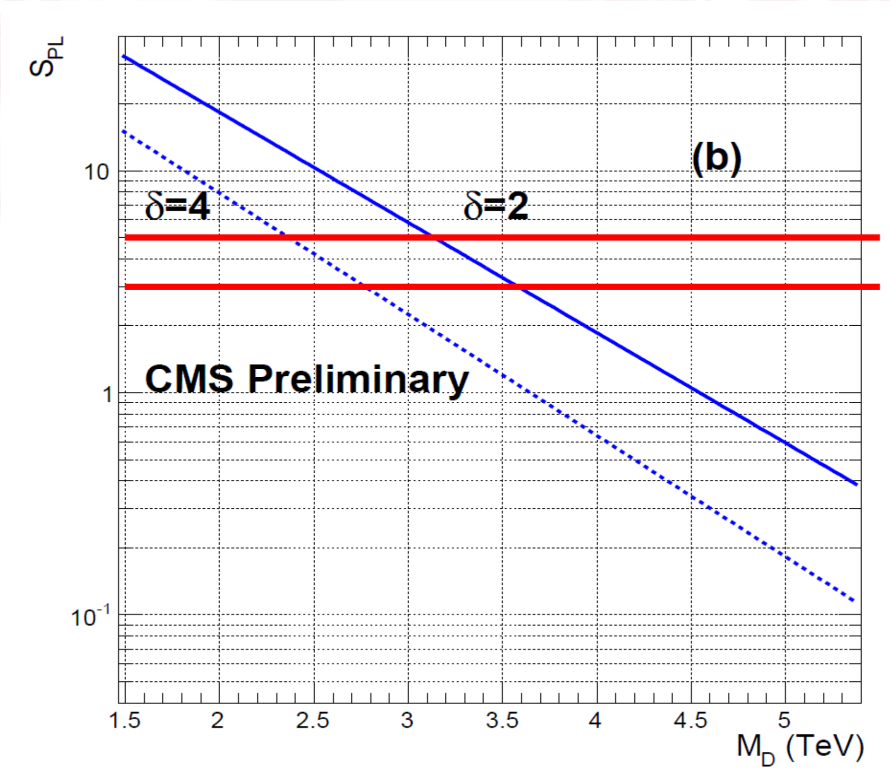
Data-driven Z invisible MHT spectra at 10 TeV

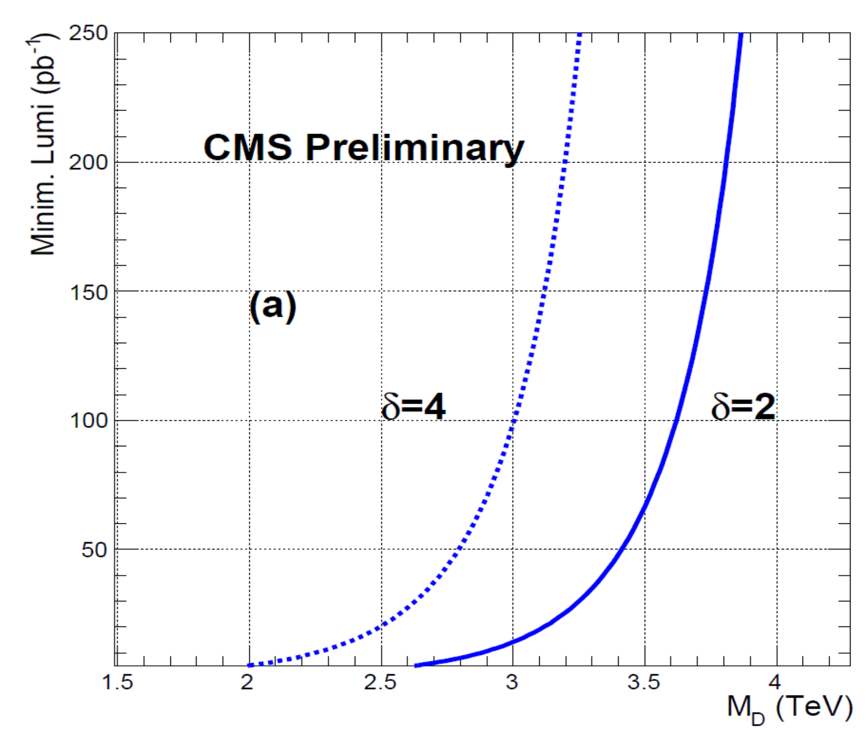




Also in this case:
Z(νν) + Jets can be determined from data, using a control region selecting W(μν) + Jets, after rescaling by cross-section ratio and muon reconstruction efficiency

Discovery and exclusion limits at 10 TeV





M_D lower than 3.1(2.3) TeV for δ = 2(4) can be excluded at 95% C.L.
and M_D = 3(2) TeV for δ = 2(4) can be discovered with 11 pb^{-1}(5 pb^{-1})

CMS Collaboration, CMS EXO-09-013

Conclusions

CMS potential in the ADD Jet + MET channel

- Discovery reach up to M_D = 3.25 / 2.75 / 2.25 TeV for δ = 2 / 3 / 4 after *O*(10 pb^{-1})
  (at 10 TeV same sensitivity achievable with 68 / 85 / 90 pb^{-1})

- Discovery reach up to 3.58 (2.62) TeV for δ = 2 (4) after *O*(100 pb^{-1})
- Exclusion limit up to 4.61 (3.46) TeV for δ = 2 (4) after *O*(100 pb^{-1})

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