New Physics with Dijets at CMS

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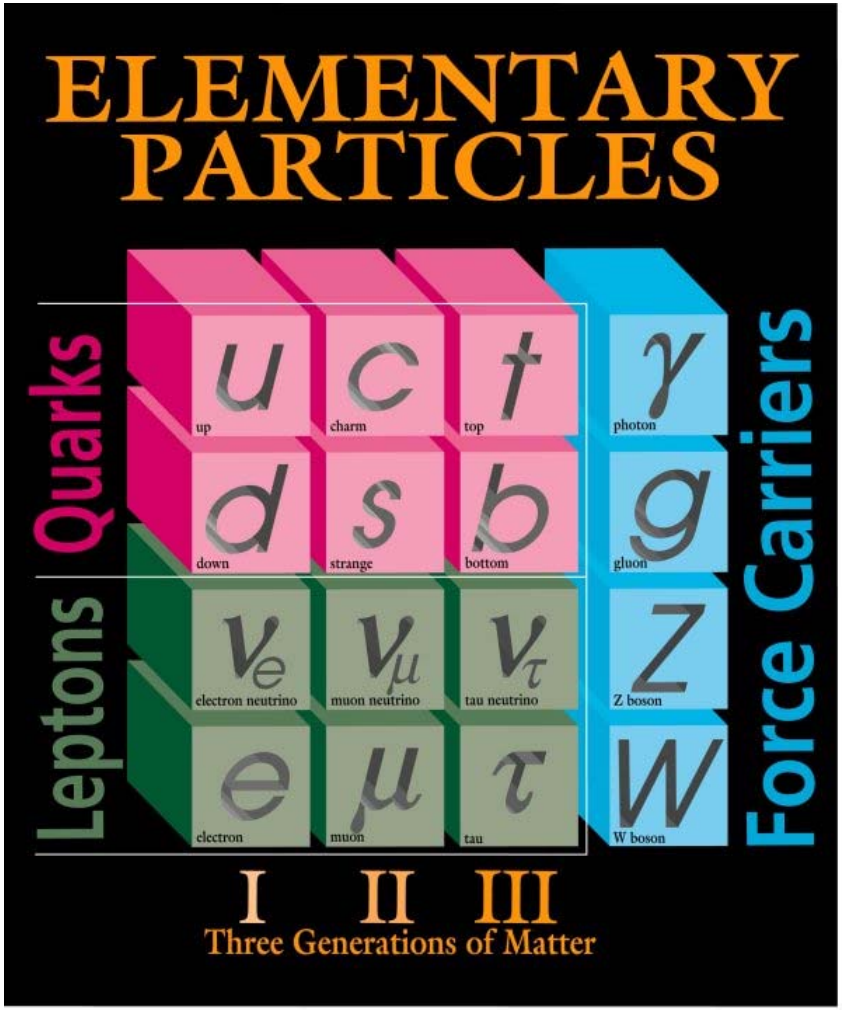
Outline

- Introduction to the Physics
- CMS Jet Trigger and Dijet Mass Distribution
- CMS Sensitivity to Dijet Resonances
- CMS Sensitivity to Quark Contact Interactions
- Conclusions

Standard Model of Particle Physics

- In the standard model nature contains
  - 6 quarks
    - **u** and **d** quark make nucleons in atom
  - 6 leptons
    - electrons complete the atoms
  - 4 force carrying particles
    - γ : electromagnetism
    - W & Z : weak interaction
    - g : color (nuclear) interaction.
  - Higgs particle to give W & Z mass
    - Higgs not discovered yet.
- Tremendously successful.
  - Withstood experimental tests for the last 30 years.
    - "Tyranny of the Standard Model".
- Why should there be anything else ?
  - Other than the Higgs.



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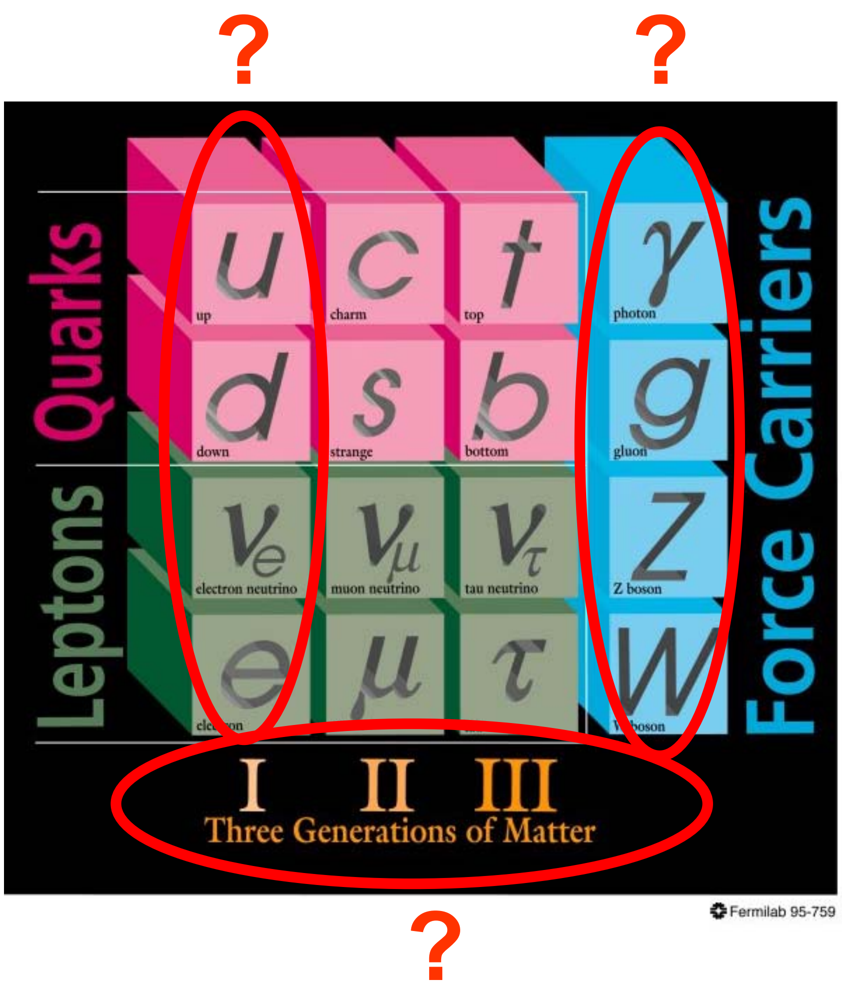
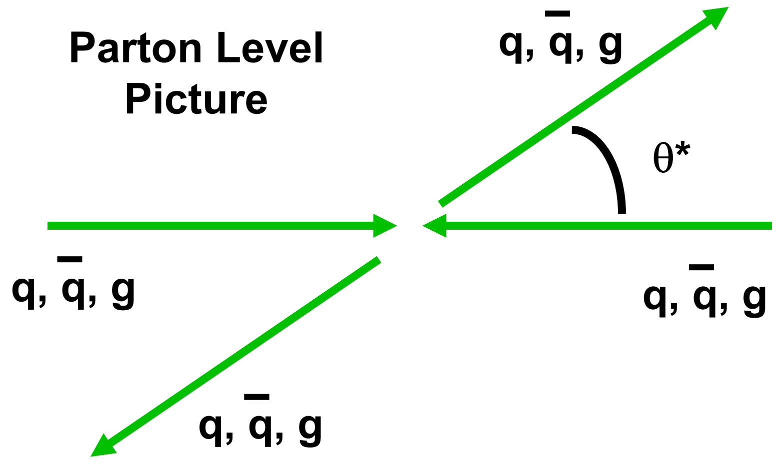
Beyond the Standard Model

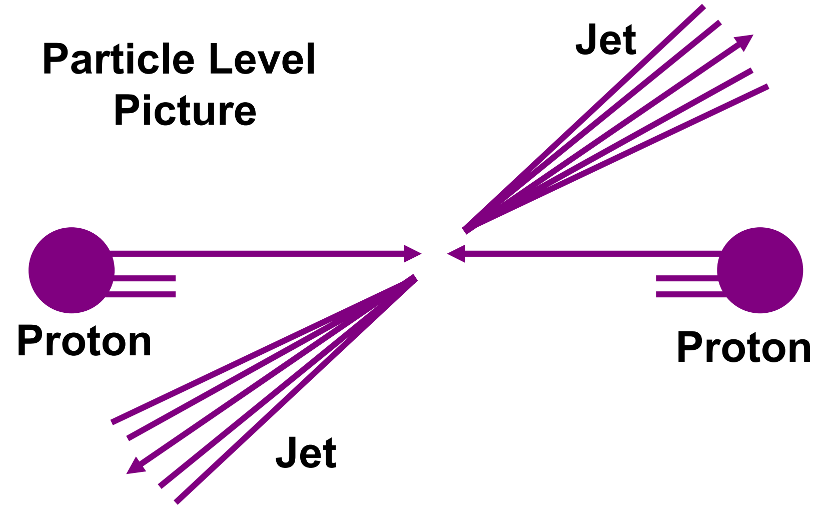
- The Standard Model raises questions.
- Why three nearly identical generations of quarks and leptons?
  - Like the periodic table of the elements, does this suggest an underlying physics?
- What causes the flavor differences within a generation?
  - Or mass difference between generations?
- How do we unify the forces ?
  - γ, Z and W are unified already.
  - Can we include gluons ?
  - Can we include gravity ?
  - Why is gravity so weak ?
- These questions suggest there will be new physics beyond the standard model.
  - We will search for new physics with dijets.



Dijets in the Standard Model

- What's a dijet?
- Parton Level
  - Dijets result from simple 2 → 2 scattering of "partons"
  - quarks, anti-quarks, and gluons.
- Particle Level
  - Partons come from colliding protons (more on this later)
  - The final state partons become jets of observable particles via the following chain of events
    - The partons radiate gluons.
    - Gluons split into quarks and antiquarks
    - All colored objects "hadronize" into color neutral particles.
    - Jet made of π, k, p, n, etc.
- Dijets are events which primarily consist of two jets in the final state.





Models of New Physics with Dijets

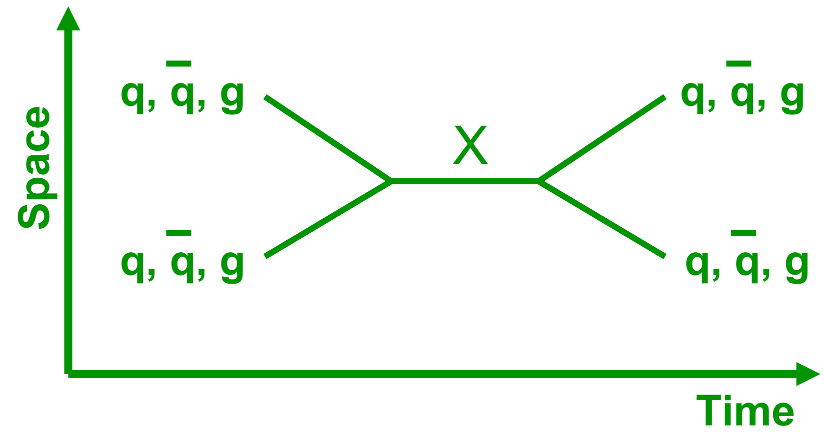
- Two types of observations will be considered.
  - Dijet resonances are new particles beyond the standard model.
  - Quark contact Interactions are new interactions beyond the standard model.

- Dijet resonances are found in models that try to address some of the big questions of particle physics beyond the SM, the Higgs, or Supersymmetry
  - Why Flavor ? → Technicolor or Topcolor → Octet Technirho or Coloron
  - Why Generations ? → Compositeness → Excited Quarks
  - Why So Many Forces ? → Grand Unified Theory → W' & Z'
  - Can we include Gravity ? → Superstrings → E6 Diquarks
  - Why is Gravity Weak ? → Extra Dimensions → RS Gravitions

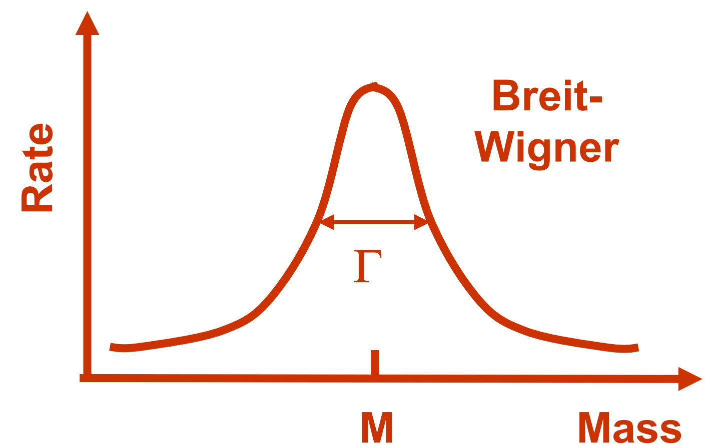
- Quark contact interactions result from most new physics involving quarks.
  - Quark compositeness is the most commonly sought example.

Dijet Resonances

- New particles that decay to dijets
  - Produced in "s-channel"
  - Parton - Parton Resonances
    - Observed as dijet resonances.
  - Many models have small width Γ
    - Similar dijet resonances (more later)

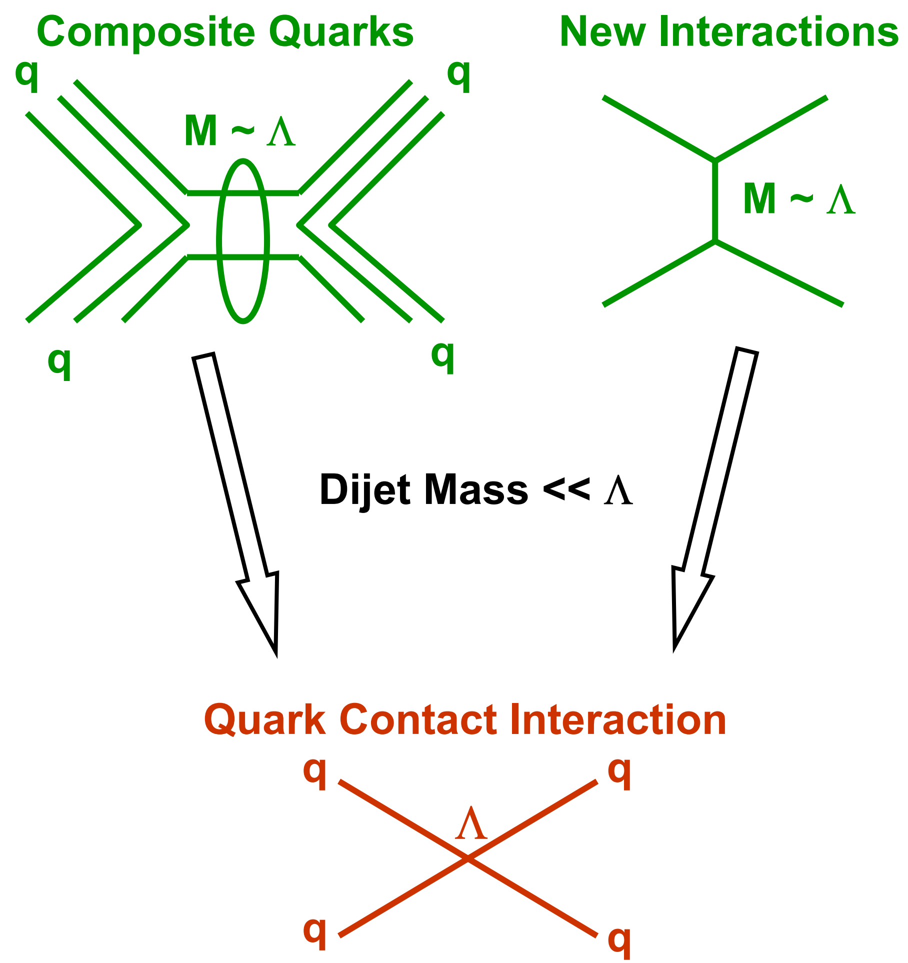


Model Name	X	Color	J^P	Γ / (2M)	Chan
E_6 Diquark	D	Triplet	0^+	0.004	ud
Excited Quark	q*	Triplet	$½^+$	0.02	qg
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
Octet Technirho	ρ_{T8}	Octet	1^-	0.01	$q\bar{q}$,gg
R S Graviton	G	Singlet	2^-	0.01	$q\bar{q}$,gg
Heavy W	W '	Singlet	1^-	0.01	$q_1\bar{q}_2$
Heavy Z	Z '	Singlet	1^-	0.01	$q\bar{q}$



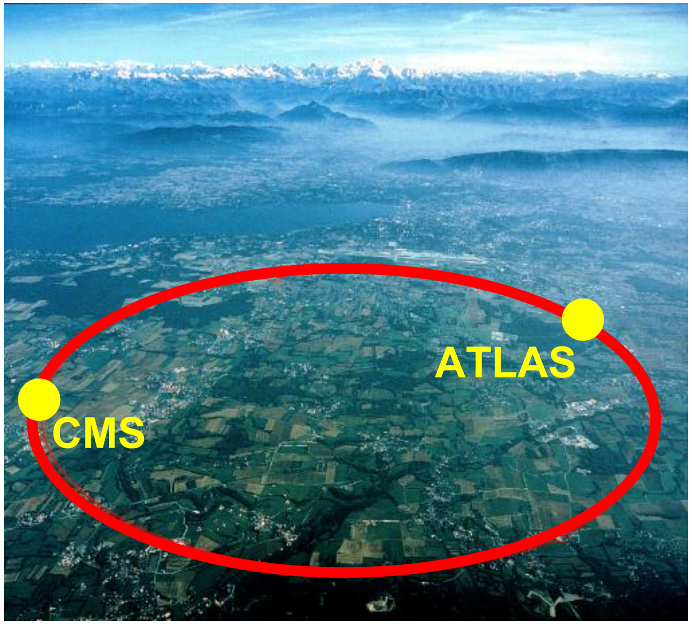
Quark Contact Interactions

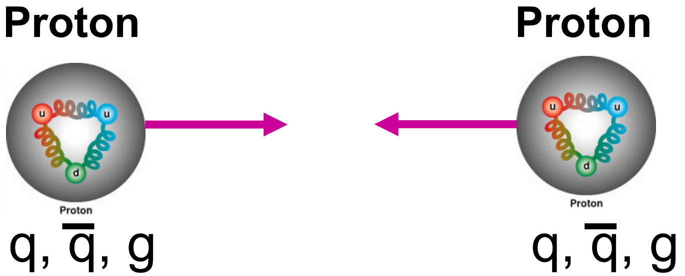
- New physics at large scale Λ
  - Composite Quarks
  - New Interactions
- Modelled by contact interaction
  - Intermediate state collapses to a point for dijet mass << Λ.
- Observable Consequences
  - Has effects at high dijet mass.
  - Higher rate than standard model.
  - Angular distributions can be different from standard model.
  - We will use a simple measure of the angular distribution at high mass (more later).



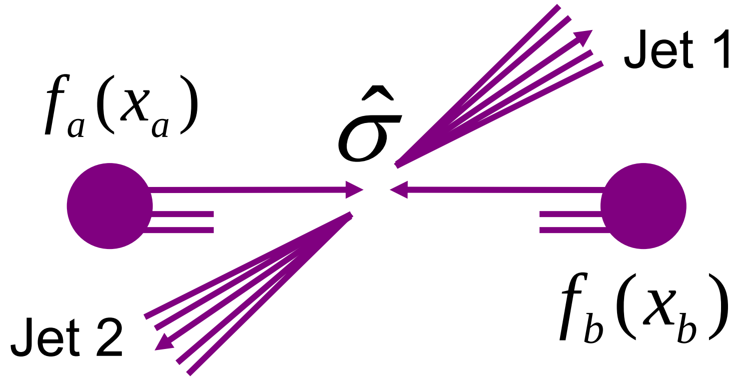
The Large Hadron Collider

- The LHC will collide protons with a total energy of $\sqrt{\mathbf{s}}$ =14 TeV.
  - The collisions take place inside two general purpose detectors: CMS & ATLAS.
- Protons are made of partons.
  - Quarks, anti-quarks and gluons.
  - Three "valence" quarks held together by gluons.
  - The anti-quarks come from gluons which can split into quark-antiquark pairs while colliding.
- The collisions of interest are between two partons
  - One parton from each proton.
- Also extra pp collisions (pile-up).





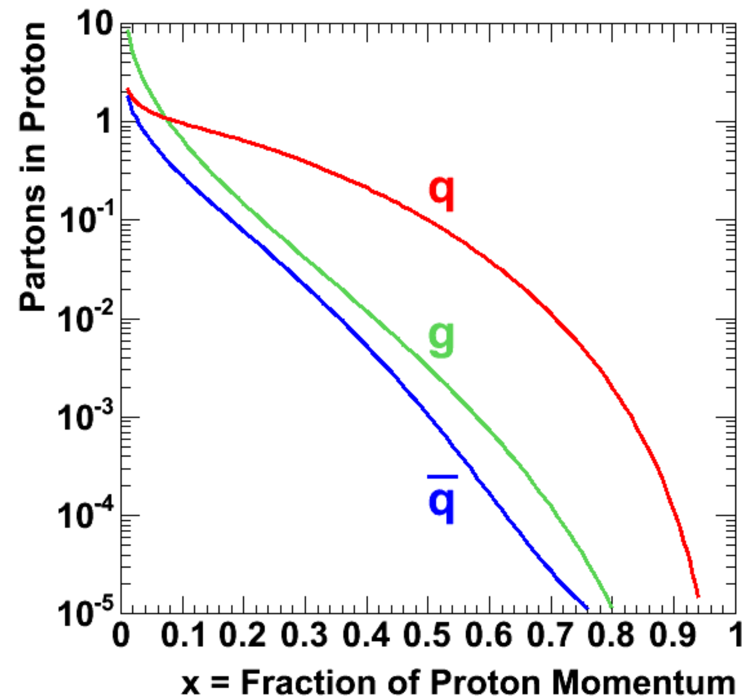
Dijet Cross Sections at the LHC



$$\frac{d\sigma}{dm} \sim \sum_{a,b} f_a(x_a)\, f_b(x_b)\, \frac{d\hat{\sigma}}{dm}(ab \to 12)$$

$$m = \sqrt{\hat{s}} = \sqrt{x_a x_b s} \qquad \sqrt{s} = 14 \ \text{TeV}$$

- Product of 3 probabilities
  - $f_a(x_a)$: parton of type a with fractional momentum x_a.
  - $f_b(x_b)$: parton of type b with fractional momentum x_b
  - $\hat{\sigma}(a\, b \to 12)$: subprocess cross section to make dijets.
- Falls rapidly with total collision energy, equal to final state mass, m.



Standard Model Background: QCD

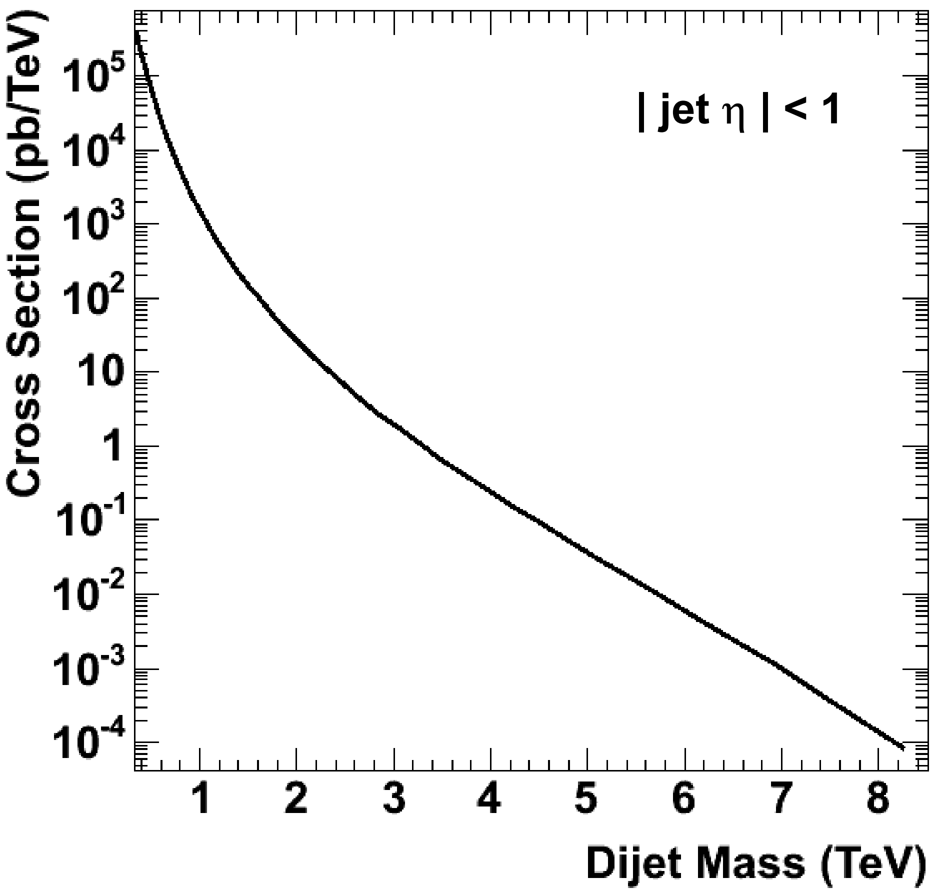
- Dijet Mass from Final State

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

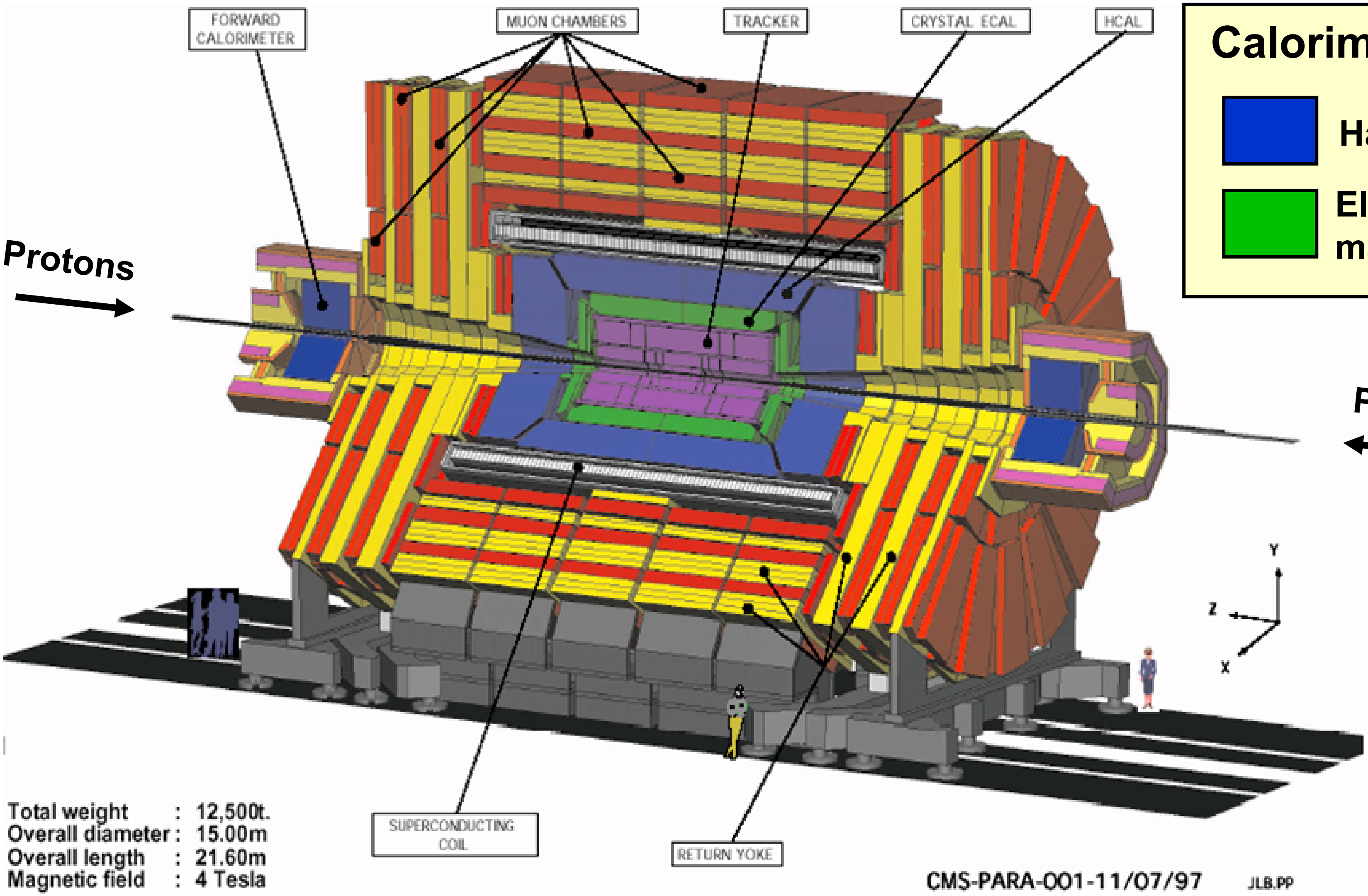
- QCD Prediction for Dijet Mass Distribution
  - Expressed as a cross section
  - Rate = Cross Section times Integrated Luminosity (∫Ldt)

- In Δm= 0.1 TeV for ∫Ldt = 1 fb^{-1}
  - ~1 dijet with m = 6 TeV
  - ~10^5 dijets with m = 1 TeV
  - ~10^8 dijets with m = 0.2 TeV

- Will need a trigger to prevent a flood of low mass dijets!



The CMS Detector

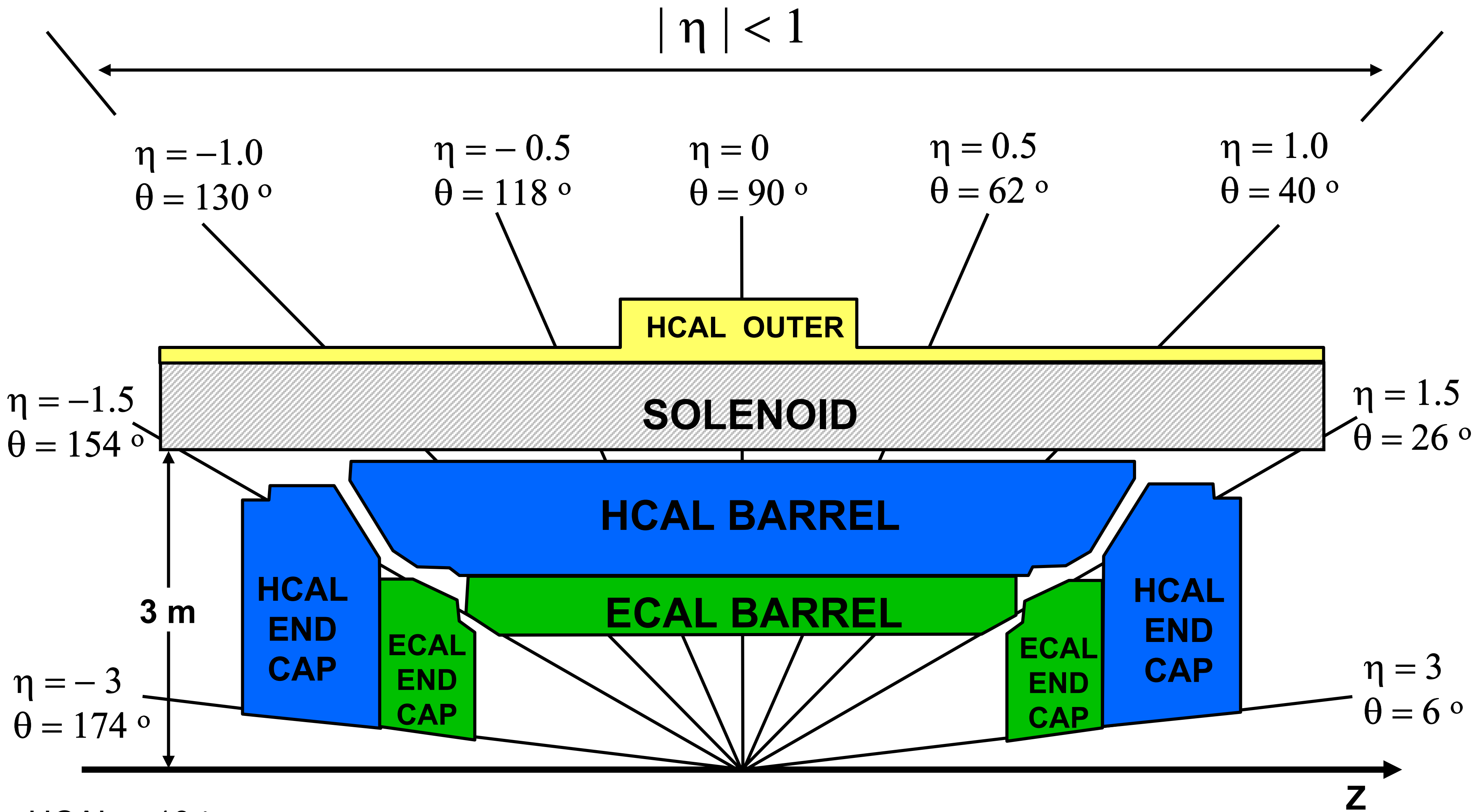


Calorimeters

- Hadronic
- Electro-magnetic

CMS Barrel & Endcap Calorimeters

(r-z view, top half)



HCAL > 10 λ_I

ECAL > 26 λ_0

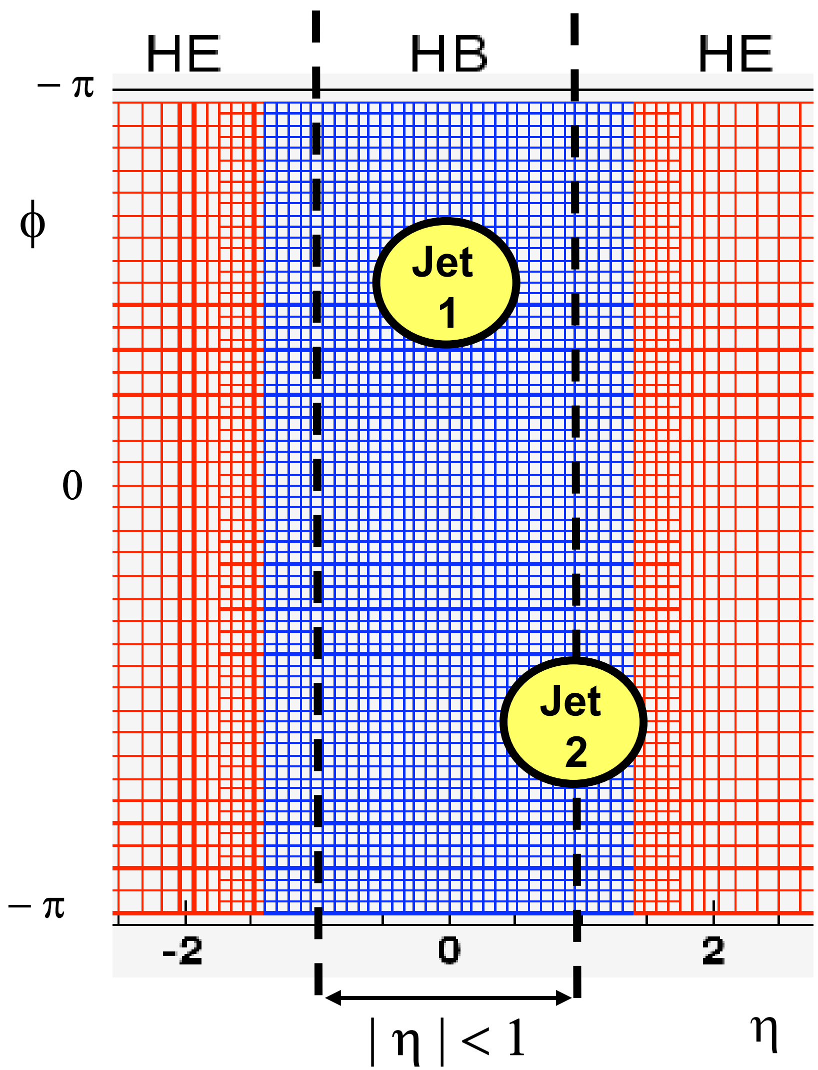
Calorimeter & Jets

- Jets are reconstructed using a cone algorithm
  - Energy inside a circle of radius R centered on jet axis is summed:

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

- This analysis requires jet $|\eta| < 1$.
  - Well contained in barrel.

- Jet energy is corrected for
  - Calorimeter non-linear response
  - Pile-up of extra soft proton-proton collisions on top of our event
    - Event is a hard parton-parton collision creating energetic jets.
  - Correction varies from 33% at 75 GeV to 7% at 2.8 TeV.
    - Mainly calorimeter response.



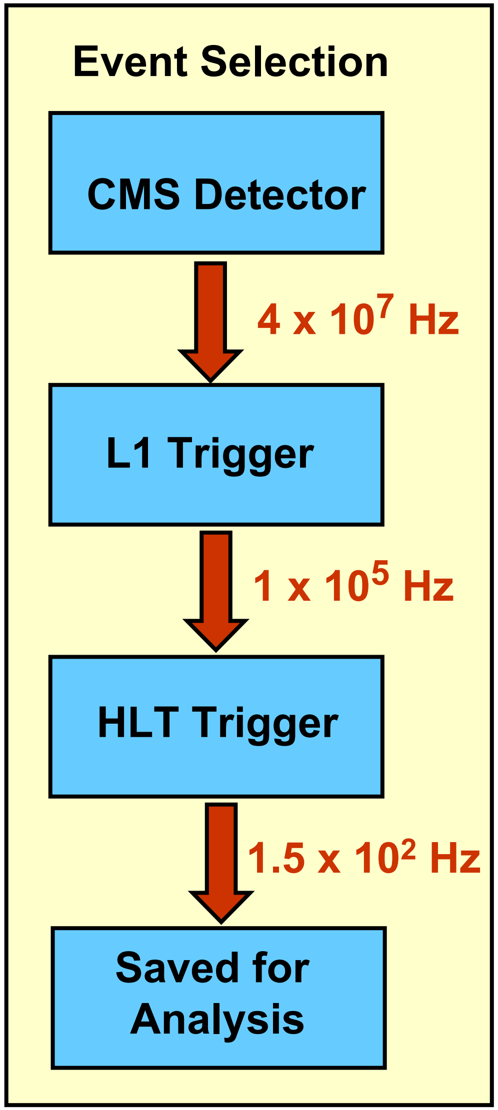
CMS Jet Trigger

&

Dijet Mass Distribution

Trigger

- Collision rate at LHC is expected to be 40 MHz
  - 40 million events every second !
  - CMS cannot read out and save that many.
- Trigger chooses which events to save
  - Only the most interesting events can be saved
- Two levels of trigger are used
  - Level 1 (L1) is fast custom built hardware
    - Reduces rate to 100 KHz: chooses only 1 event out of 400
  - High Level Trigger (HLT) is a PC farm
    - Reduces rate to 150 Hz: chooses only 1 event out of 700.
- Trigger selects events with high energy objects
  - Jet trigger at L1 uses energy in a square $\Delta\eta$ x $\Delta\phi$ = 1 x 1
  - Jet trigger at HLT uses same jet algorithm as analysis.



Design of Jet Trigger Table for CMS

- The jet trigger table is a list of jet triggers CMS could use.
  - We consider triggers that look at all jets in the Barrel and Endcap
  - Requires a jet to have $E_T = E \sin\theta >$ threshold to reduce the rate.
  - Jet triggers can also be "prescaled" to further reduce the rate by a factor of N.
    - The prescale just counts events and selects 1 event out of N, rejecting all others.

- Guided by Tevatron experience, we've designed a jet trigger table for CMS.
  - Chose reasonable thresholds, prescales, and rates at L1 & HLT.
  - Evolution of the trigger table with time (luminosity)

- Driven by need to reconstruct dijet mass distribution
  - To low mass to constrain QCD and overlap with Tevatron.
  - For realistic search for dijet resonances and contact interactions.

- Running periods and sample sizes considered
  - Luminosity = **10^{32} cm^{-2} s^{-1}**. Month integrated luminosity **~ 100 pb^{-1}**. 2008 ?
  - Luminosity = **10^{33} cm^{-2} s^{-1}**. Month integrated luminosity **~ 1 fb^{-1}**. 2009 ?
  - Luminosity = **10^{34} cm^{-2} s^{-1}**. Month integrated luminosity **~ 10 fb^{-1}**. 2010 ?

Jet Trigger Table and Dijet Mass Analysis

- HLT budget is what constrains the jet trigger rate to roughly 10 Hz.
- Table shows L1 & HLT jet E_T threshold and analysis dijet mass range.

$L = 10^{32}$
$100\ pb^{-1}$

Path	L1 E_T (GeV)	L1 Pre-scale	L1 Rate (KHz)	HLT E_T (GeV)	HLT Rate (Hz)	ANA Dijet Mass (GeV)
Low	**25**	2000	0.146	**60**	2.8	**NONE**
Med	**60**	40	0.097	**120**	2.4	**330 - 670**
High	**140**	1	0.044	**250**	2.8	**670 - 1130**

$L = 10^{33}$
$1\ fb^{-1}$

Add New Threshold (Ultra). Increase Prescales by 10.

Ultra	**270**	1	0.019	**400**	2.6	**1130-1800**

$L = 10^{34}$
$10\ fb^{-1}$

Add New Threshold (Super). Increase Prescales by 10.

Super	**450**	1	0.014	**600**	2.8	**> 1800**

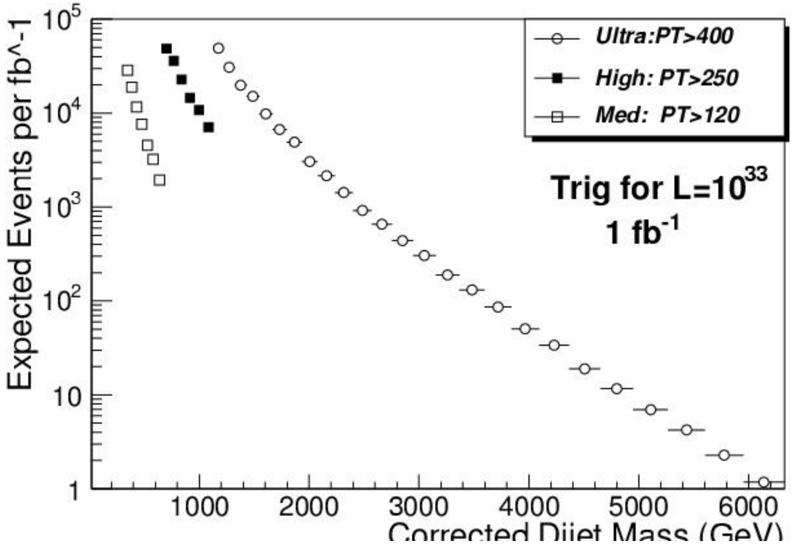
Analysis done for 3 values of integrated lum:
$100\ pb^{-1}$
$1\ fb^{-1}$
$10\ fb^{-1}$

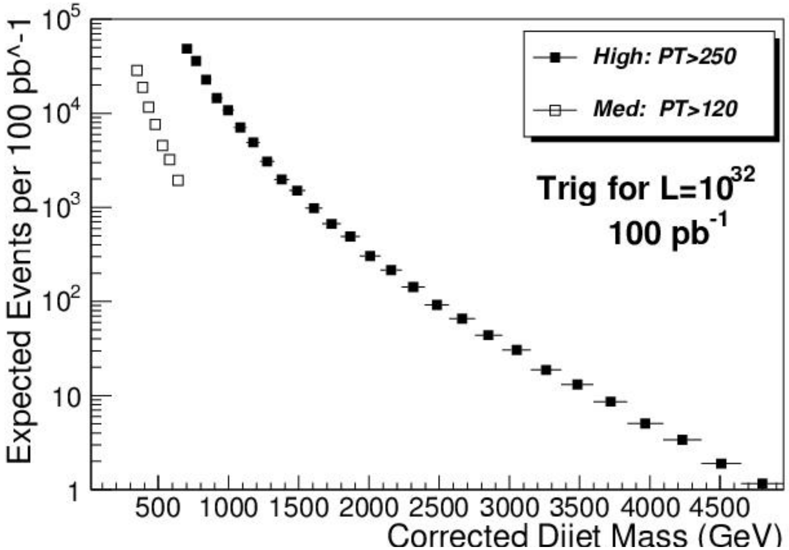
Each has new unprescaled threshold

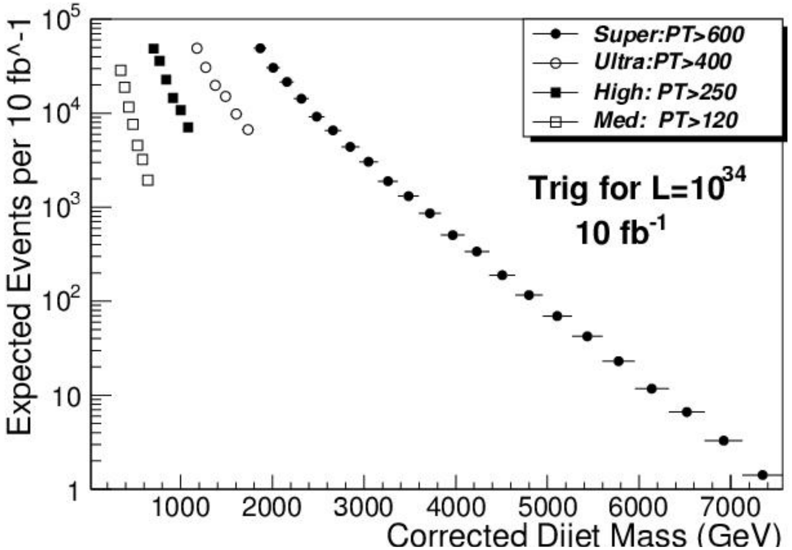
Mass ranges listed are fully efficient for each trigger

Rates for Measuring Cross Section (QCD + CMS Simulation)

- Analyze each trigger where it is efficient.
  - Stop analyzing data from trigger where next trigger is efficient
- Prescaled triggers give low mass spectrum at a conveniently lower rate.
- Expect the highest mass dijet to be
  - ~ 5 TeV for 100 pb^{-1}
  - ~ 6 TeV for 1 fb^{-1}
  - ~ 7 TeV for 10 fb^{-1}

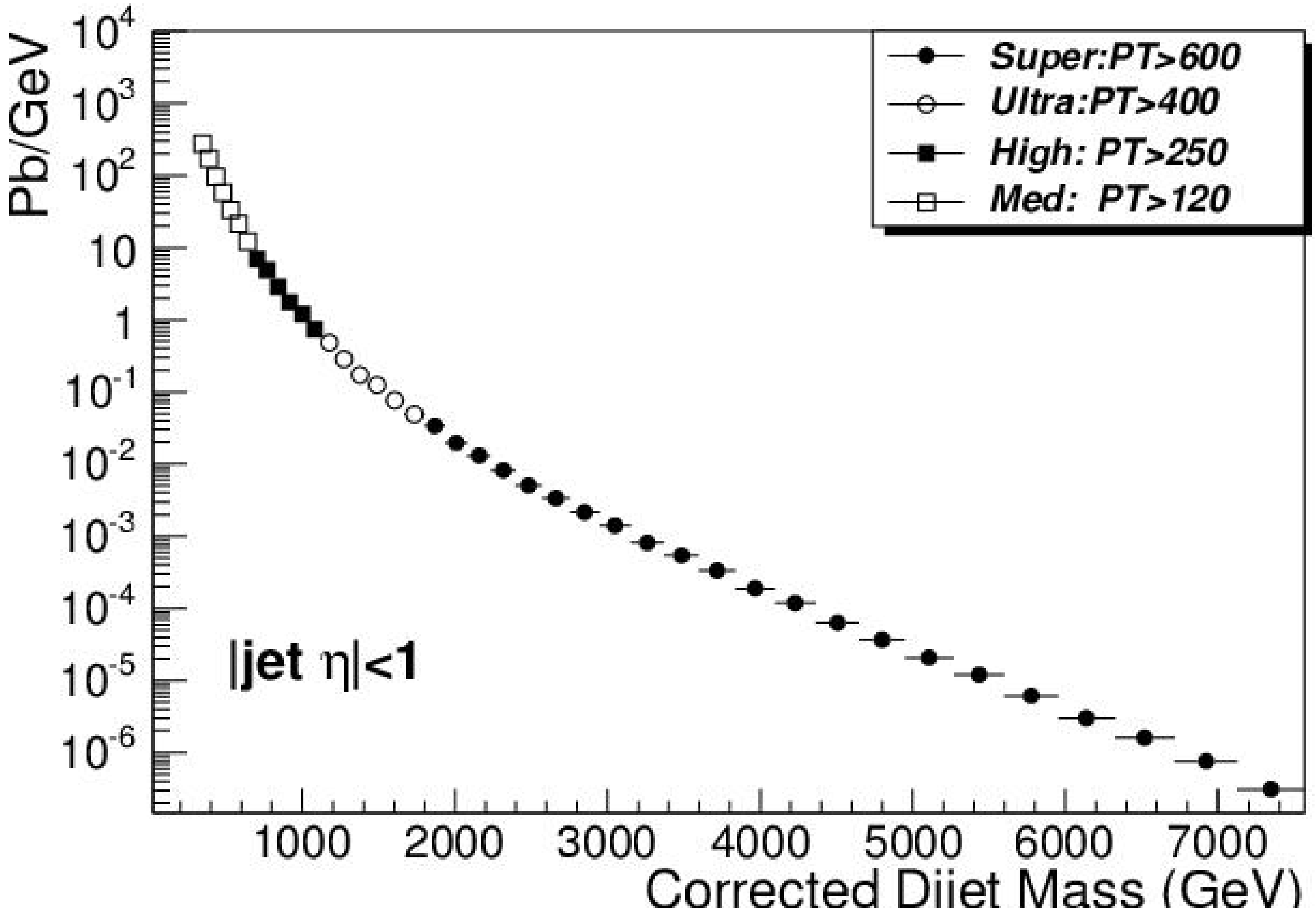






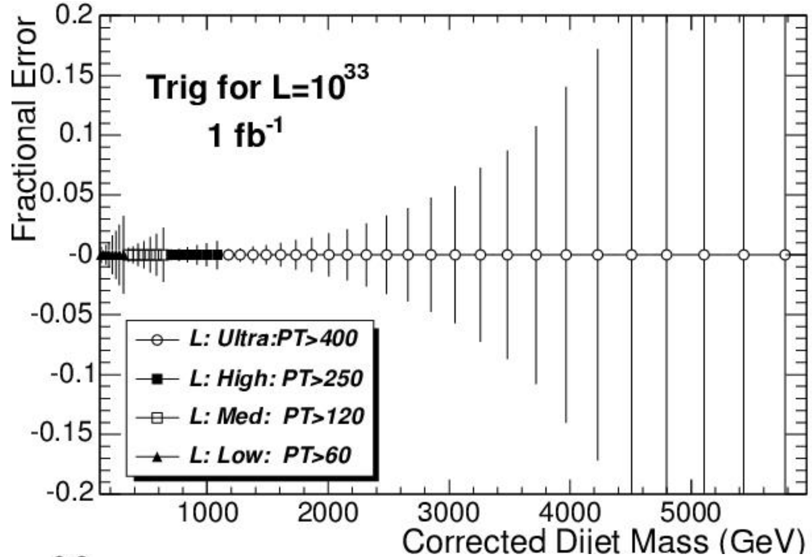
Dijet Mass Cross Section
(QCD + CMS Simulation)

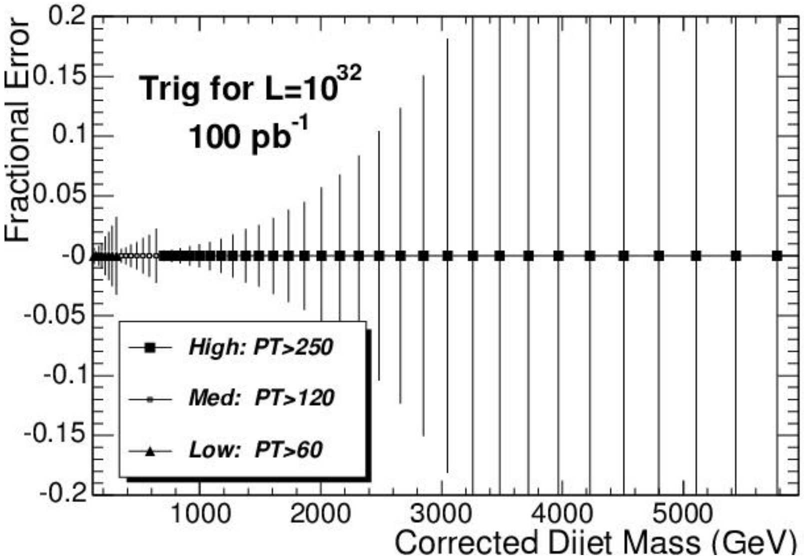
- Put triggers together for dijet mass spectrum.
- Prescaled triggers give us the ability to measure mass down to 300 GeV.
- Plot dijet mass in bins equal to our mass resolution.

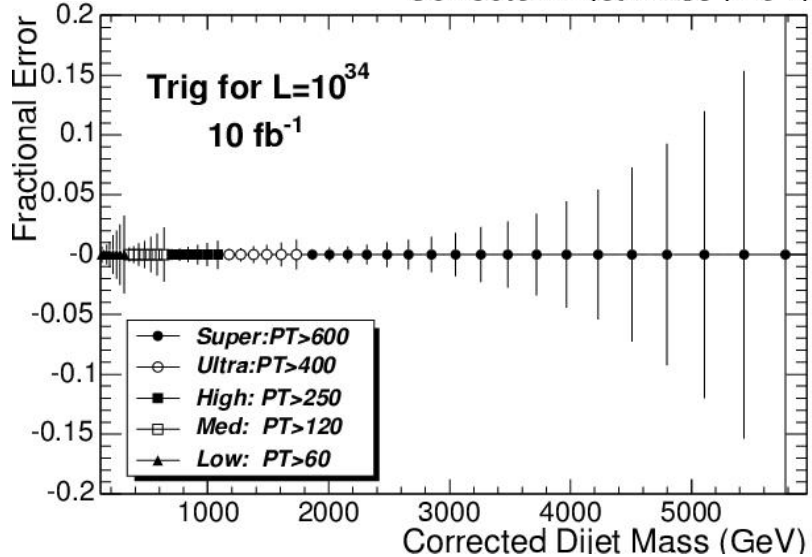


Statistical Uncertainties

- Simplest measure of our sensitivity to new physics as a fraction of QCD.
- Prescaled Triggers
  - 1-3% statistical error to nail QCD
- Unprescaled Triggers
  - ~1% statistical error at threshold
  - 1st one begins at mass=670 GeV
    - Overlaps with Tevatron measurements.

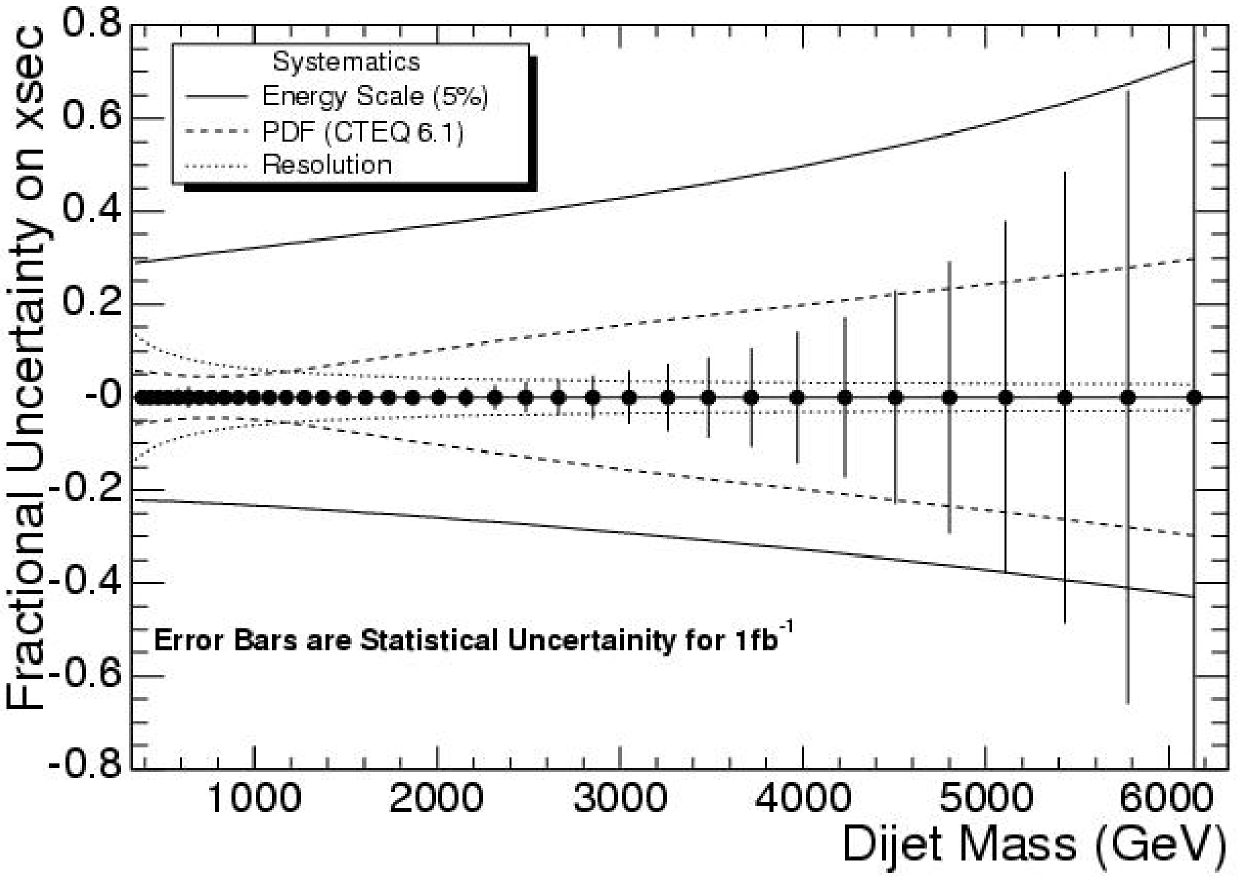






Systematic Uncertainties

- Jet Energy
  - CMS estimates **+/- 5 %** is achievable.
  - Changes dijet mass cross section between 30% and 70%
- Parton Distributions
  - CTEQ 6.1 uncertainty
- Resolution
  - Bounded by difference between particle level jets and calorimeter level jets.



- Systematic uncertainties on the cross section vs. dijet mass are large.
  - But they are correlated vs. mass. The distribution changes smoothly.

CMS Sensitivity to

Dijet Resonances

Motivation

- **Theoretical Motivation**
  - The many models of dijet resonances are ample theoretical motivation.
  - But experimentalists should not be biased by theoretical motivations . . .
- **Experimental Motivation**
  - The LHC collides partons (quarks, antiquarks and gluons).
    - LHC is a parton-parton resonance factory in a previously unexplored region
    - The motivation to search for dijet resonances is intuitively obvious.
      - **We <u>must</u> do it.**
  - We should search for generic dijet resonances, not specific models.
    - Nature may surprise us with unexpected new particles. It wouldn't be the first time …
  - One search can encompass ALL narrow dijet resonances.
    - Resonances more narrow than the jet resolution all produce similar line shapes.

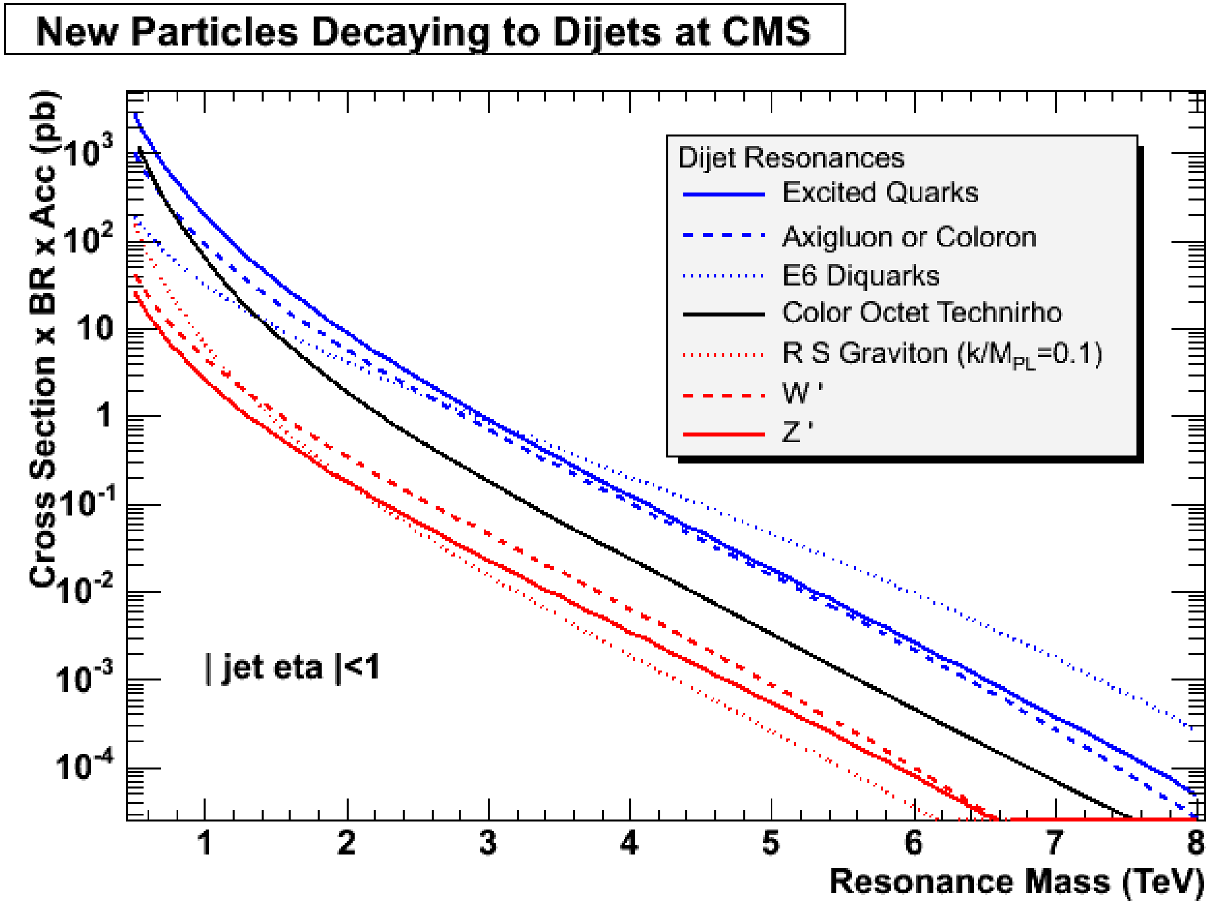
Resonance Cross Sections & Constraints

- Resonances produced via color force, or from valence quarks in each proton, have the highest cross sections.

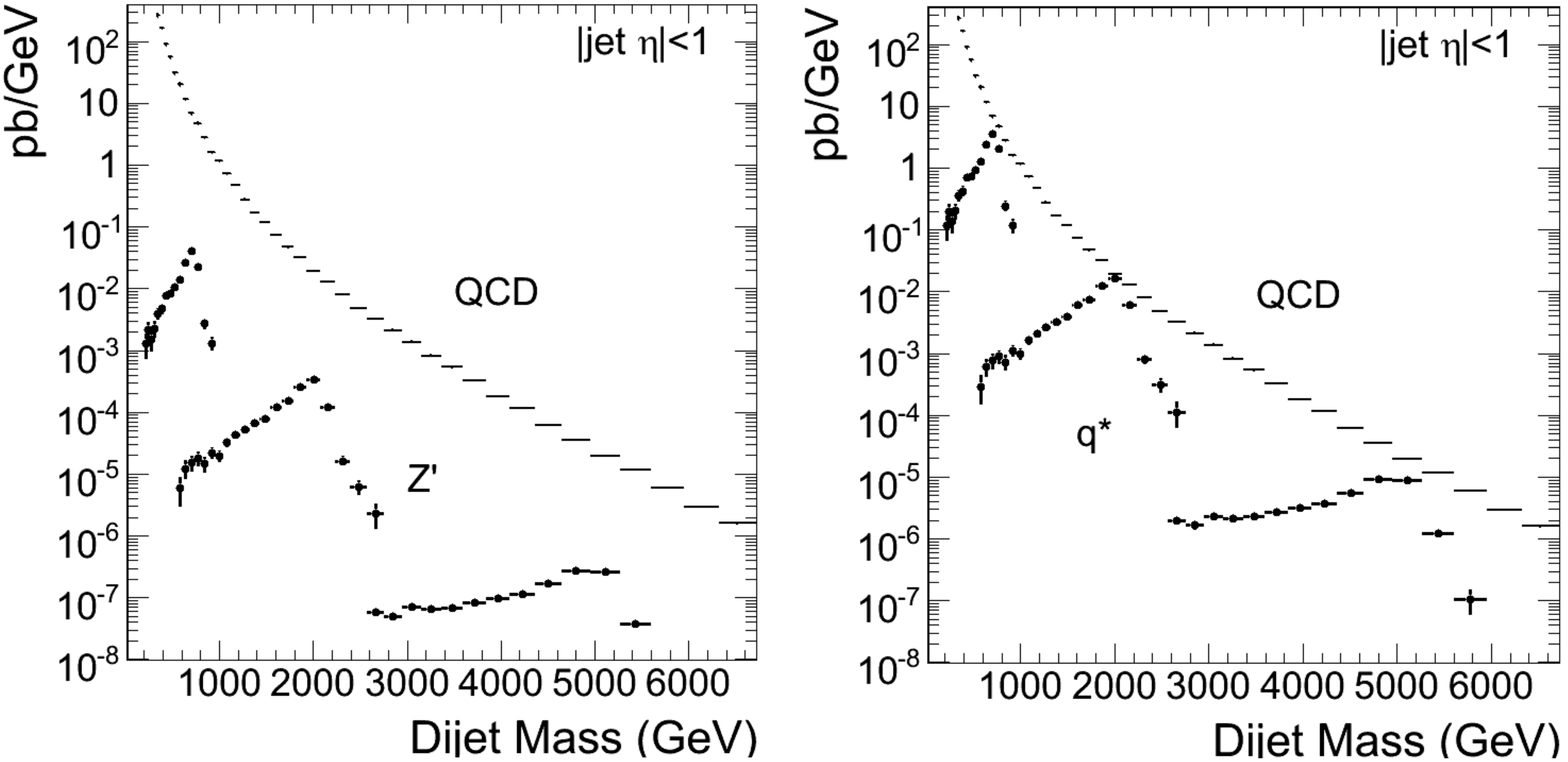
- Published Limits in Dijet Channel in TeV :
  - ➔ q* > 0.775 (D0)
  - ➔ A or C > 0.98 (CDF)
  - ➔ E_6 Diq > 0.42 (CDF)
  - ➔ ρ_{T8} > 0.48 (CDF)
  - ➔ W ’ > 0.8 (D0)
  - ➔ Z ’ > 0.6 (D0)

CDF: hep-ex/9702004

D0: hep-ex/0308033



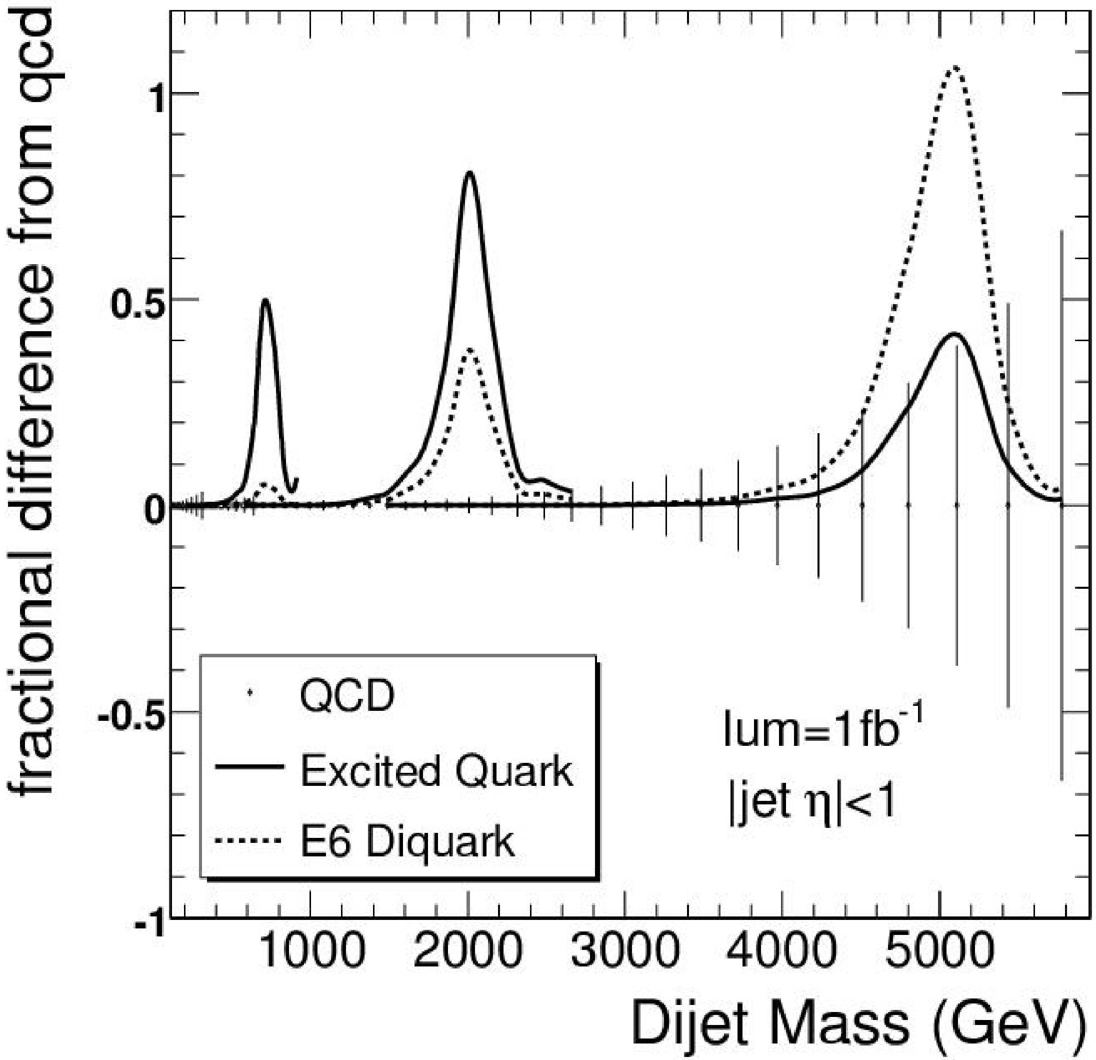
Signal and Background



- QCD cross section falls smoothly as a function of dijet mass.
- Resonances produce mass bumps we can see if xsec is big enough.

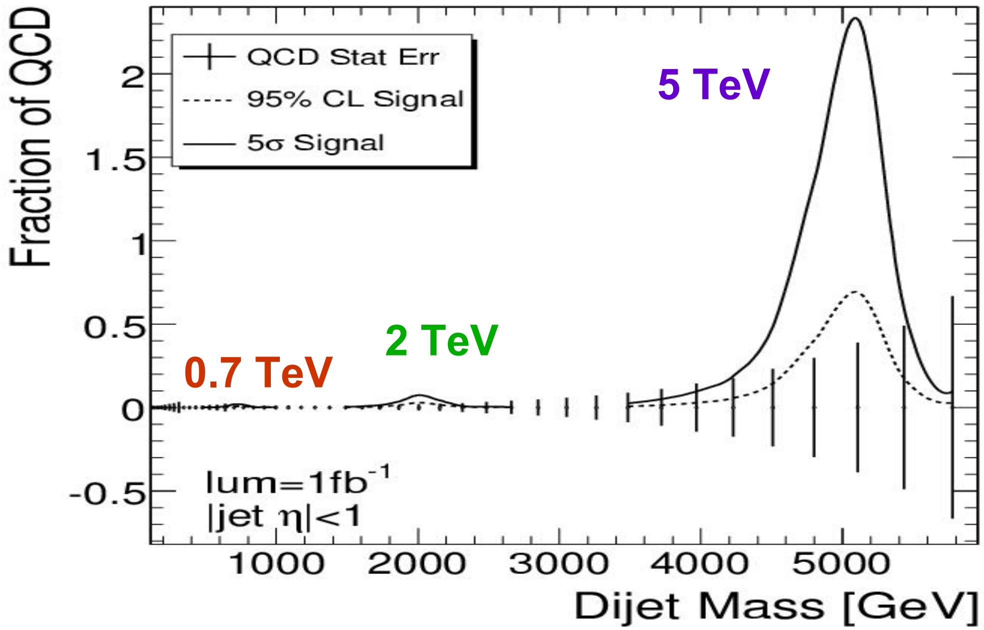
Signal / QCD

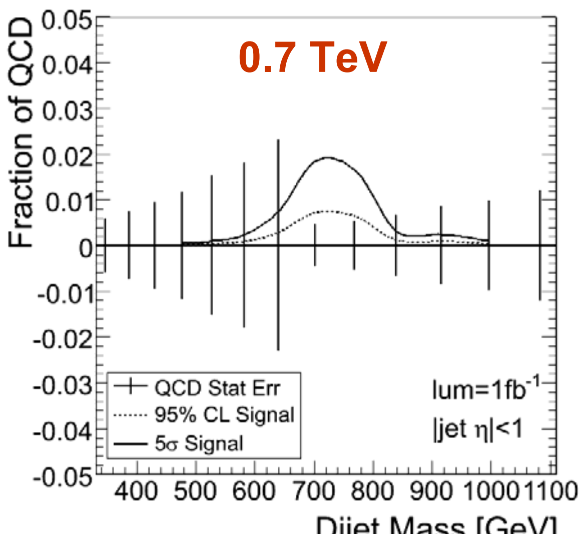
- Many resonances give obvious signals above the QCD error bars
  - Resonances produced via color force
    - q* (shown)
    - Axigluon
    - Coloron
    - Color Octet ρ_T
  - Resonances produced from valence quarks of each proton
    - E6 Diquark (shown)
- Others may be at the edge of our sensitivity.

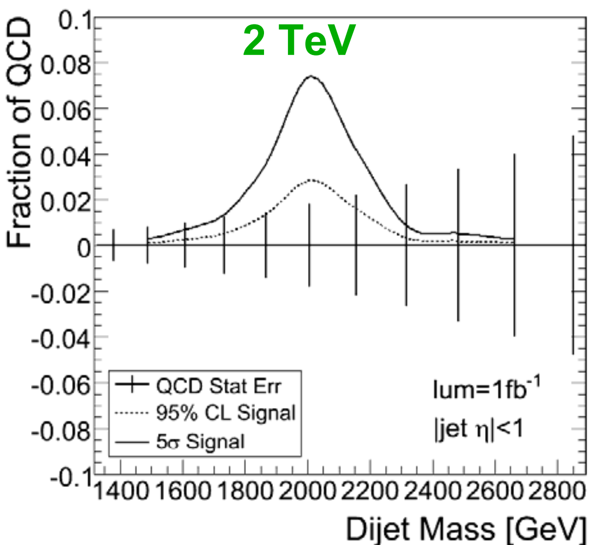


Statistical Sensitivity to Dijet Resonances

- Sensitivity estimates
  - Statistical likelihoods done for both discovery and exclusion
- 5σ Discovery
  - We see a resonance with 5σ significance
    - 1 chance in 2 million of effect being due to QCD.
- 95% CL Exclusion
  - We don't see anything but QCD
  - Exclude resonances at 95% confidence level.
- Plots show resonances at 5σ and 95% CL
  - Compared to statistical error bars from QCD.

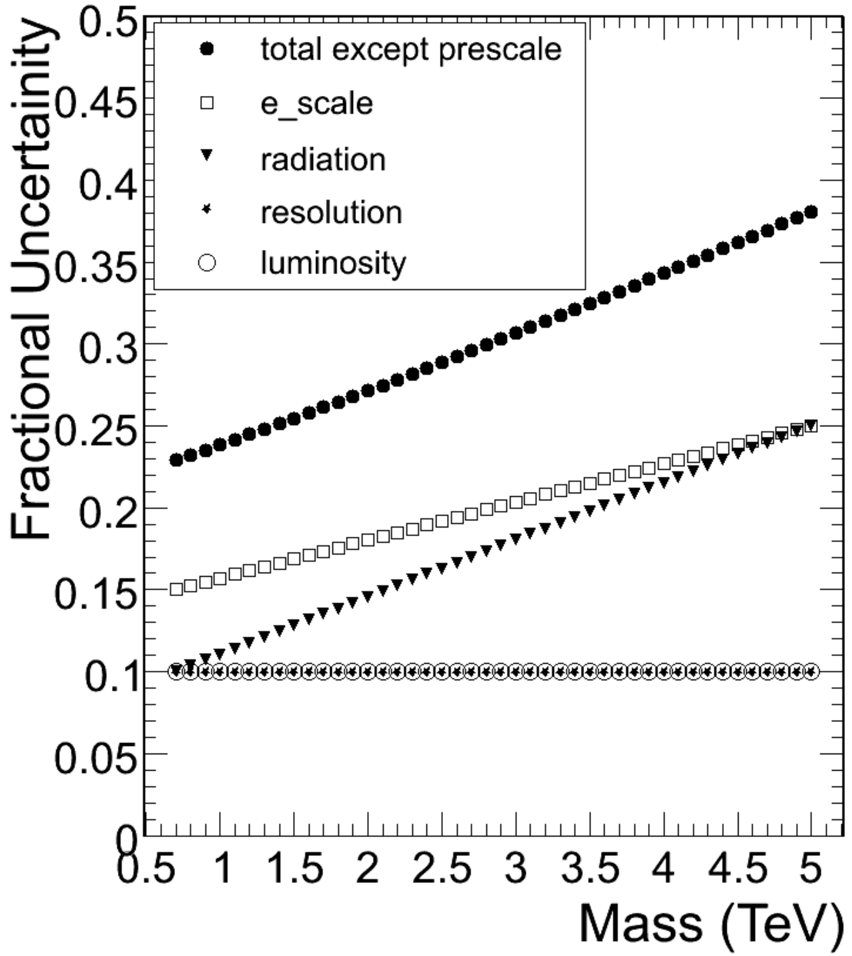






Systematic Uncertainties

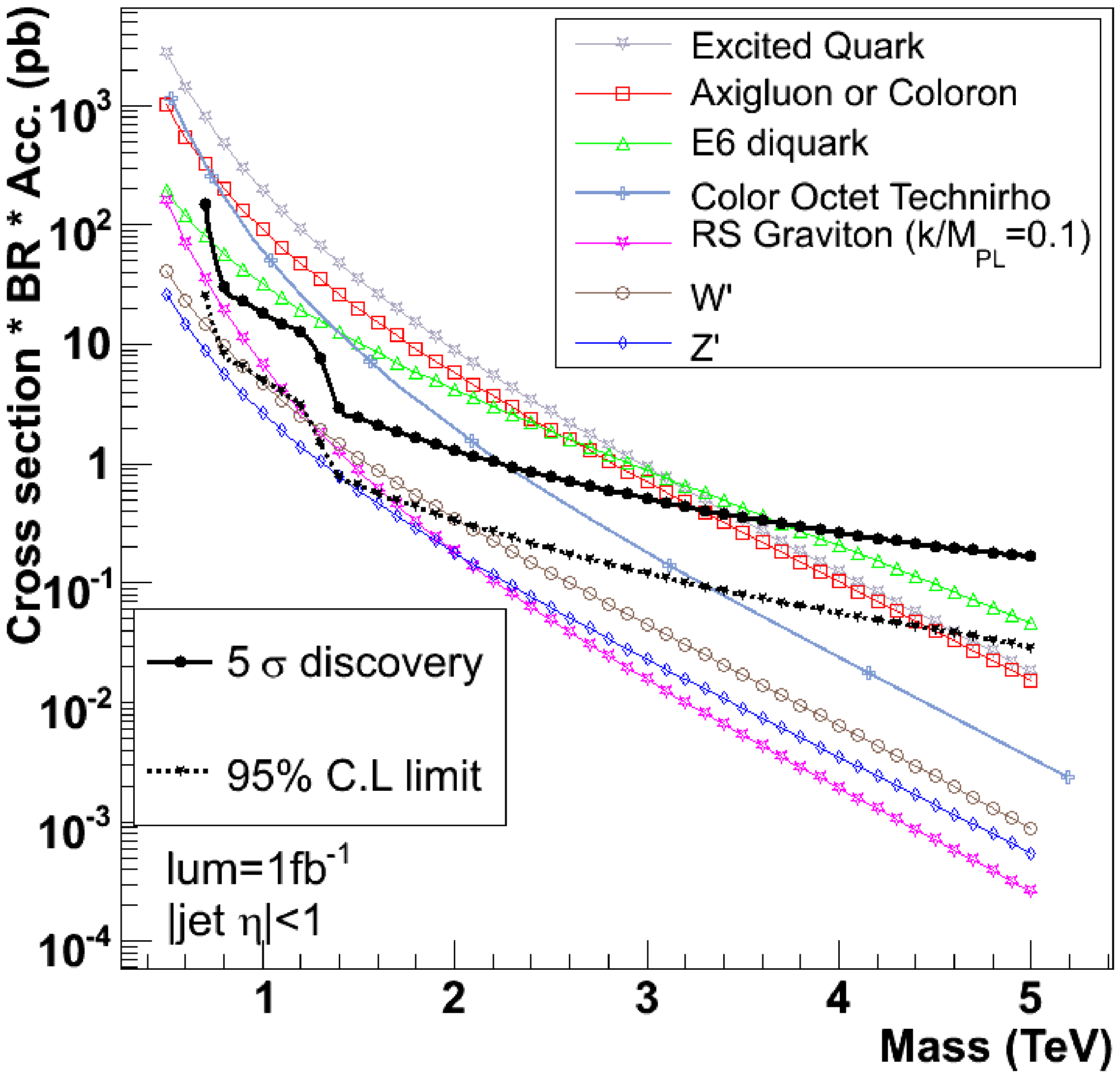
- Uncertainty on QCD Background
  - Dominated by jet energy uncertainty (±5%).
    - **Background will be measured.**
- Trigger prescale edge effect
  - Jet energy uncertainty has large effect at mass values just above where trigger prescale changes.
- Resolution Effect on Resonance Shape
  - Bounded by difference between particle level jets and calorimeter level jets.
- Radiation effect on Resonance Shape
  - Long tail to low mass which comes mainly from final state radiation.
- Luminosity



- We include all these systematic uncertainties in our likelihood distributions

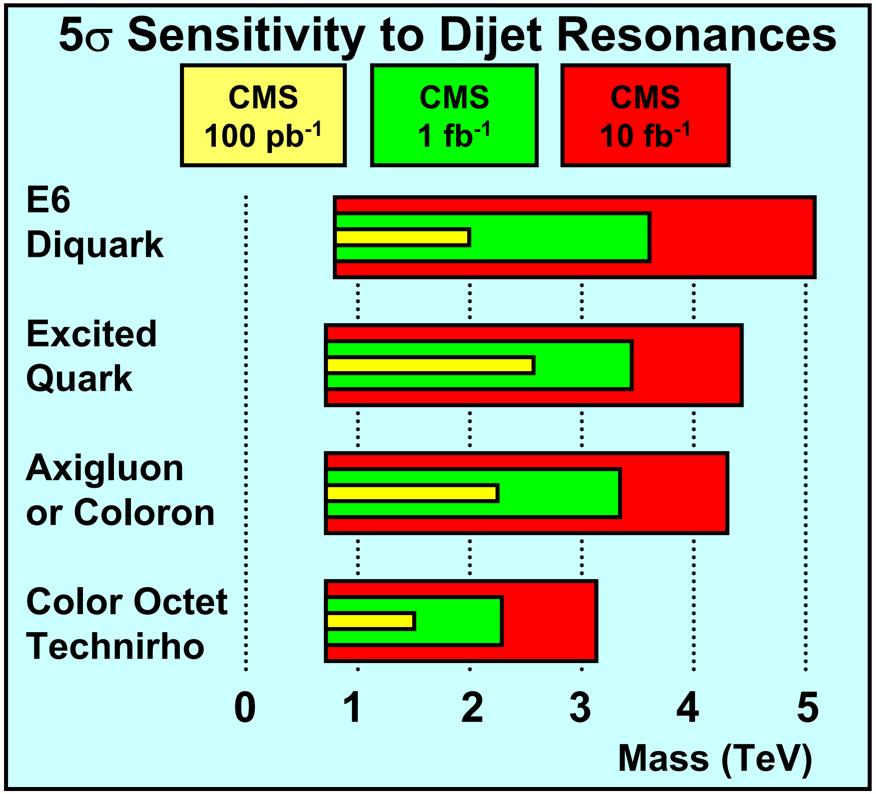
Sensitivity to Resonance Cross Section

- Cross Section for Discovery or Exclusion
  - Shown here for 1 fb^{-1}
  - Also for 100 pb^{-1}, 10 fb^{-1}
- Compared to cross section for 8 models
- CMS expects to have sufficient sensitivity to
  - Discover with 5σ significance any model above solid black curve
  - Exclude with 95% CL any model above the dashed black curve.
- Can discover resonances produced via color force, or from valence quarks.



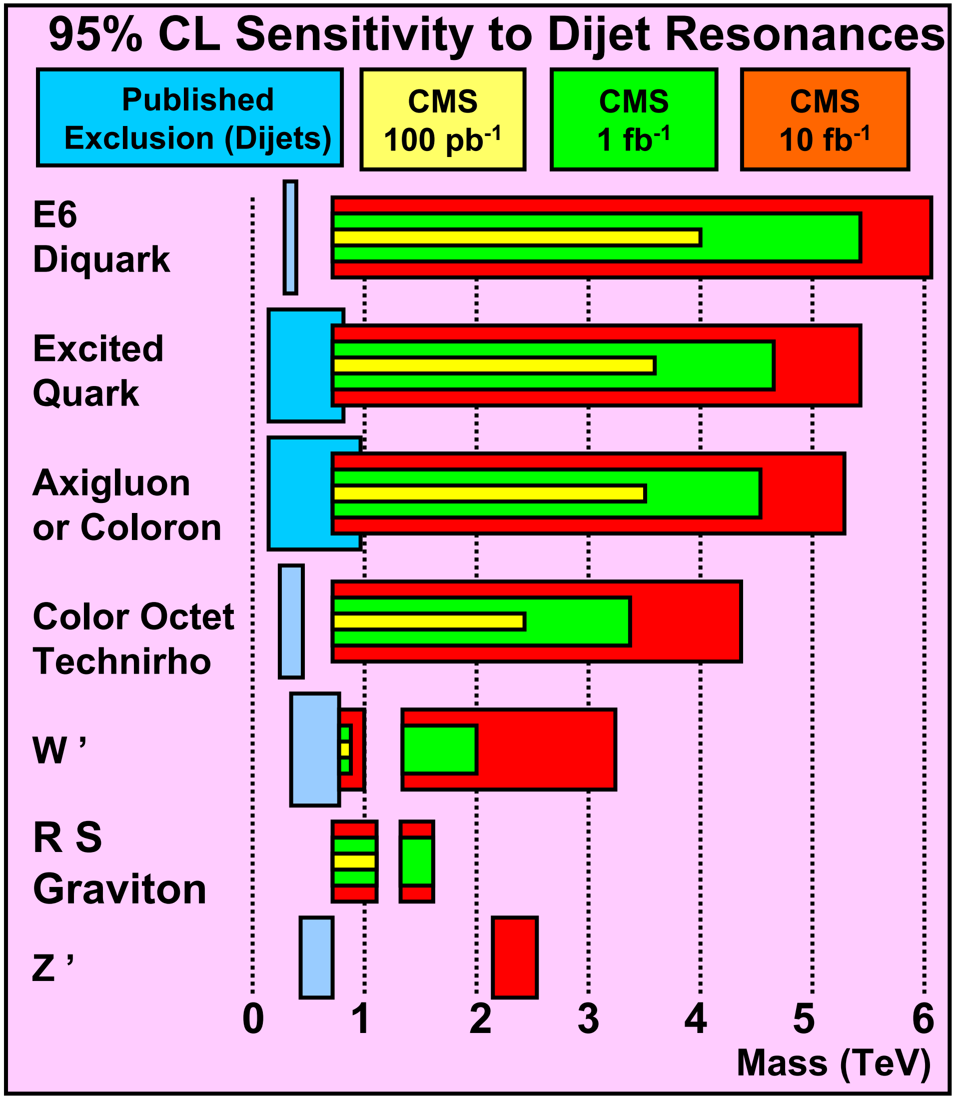
Discovery Sensitivity for Models

- Resonances produced by the valence quarks of each proton
  - → Large cross section from higher probability of quarks in the initial state at high x.
  - → E6 diquarks (ud → D → ud) can be discovered up to 3.7 TeV for 1 fb^{-1}
- Resonances produced by color force
  - → Large cross sections from strong force
  - → With just 1 fb^{-1} CMS can discover
    - → Excited Quarks up to 3.4 TeV
    - → Axigluons or Colorons up to 3.3 TeV
    - → Color Octet Technirhos up to 2.2 TeV.
- Discoveries possible with only 100 pb^{-1}
  - → Large discovery potential with 10 fb^{-1}



Sensitivity to Dijet Resonance Models

- Resonances produced via color interaction or valence quarks.
  - Wide exclusion possibility connecting up with many exclusions at Tevatron
    - CMS can extend to lower mass to fill gaps.
- Resonances produced weakly are harder.
  - But CMS has some sensitivity to each model with sufficient luminosity.
  - Z' is particularly hard.
    - weak coupling and requires an anti-quark in the proton at high x.

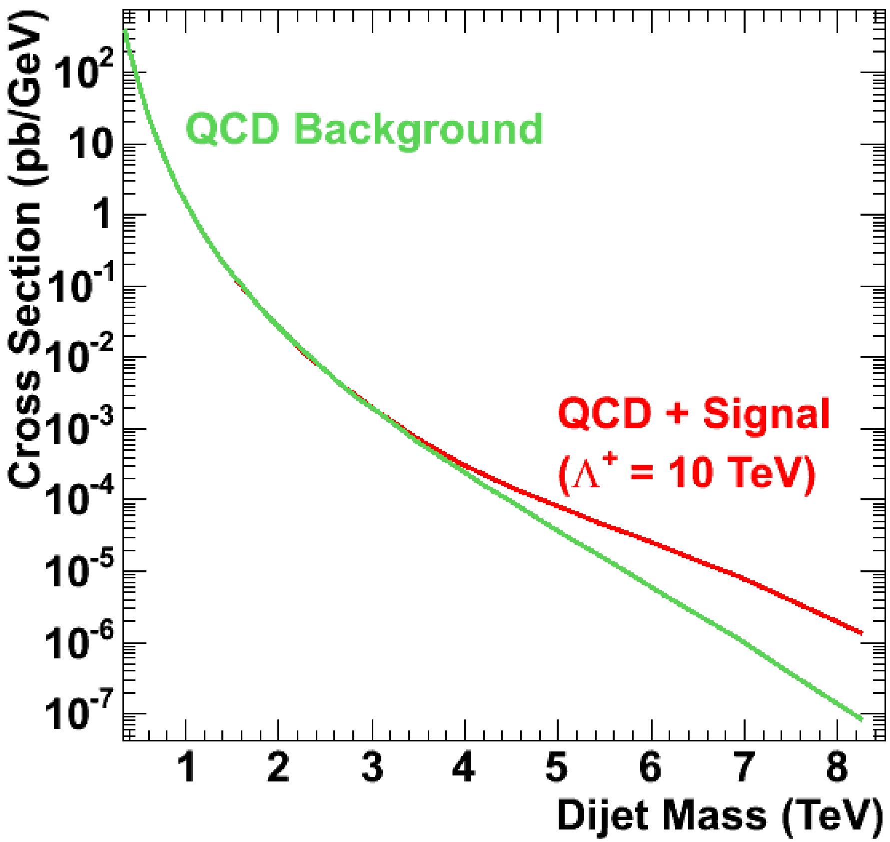


CMS Sensitivity to

Quark Contact Interactions

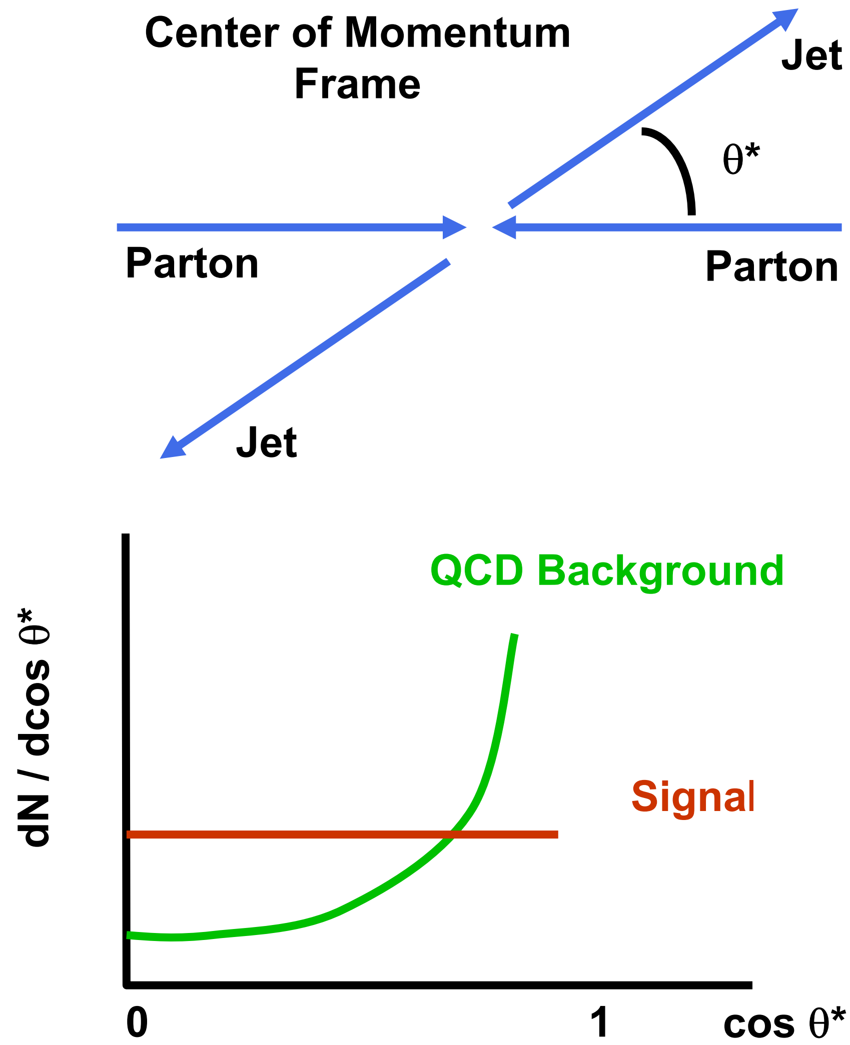
Contact Interactions in Mass Distribution

- Contact interaction produces rise in rate relative to QCD at high mass.
- Observation in mass distribution alone requires precise understanding of QCD cross section.
- Hard to do
  - Jet energy uncertainties are multiplied by factor of ~6-16 to get cross section uncertainties
  - Parton distribution uncertainties are significant at high mass = high x and Q^2.



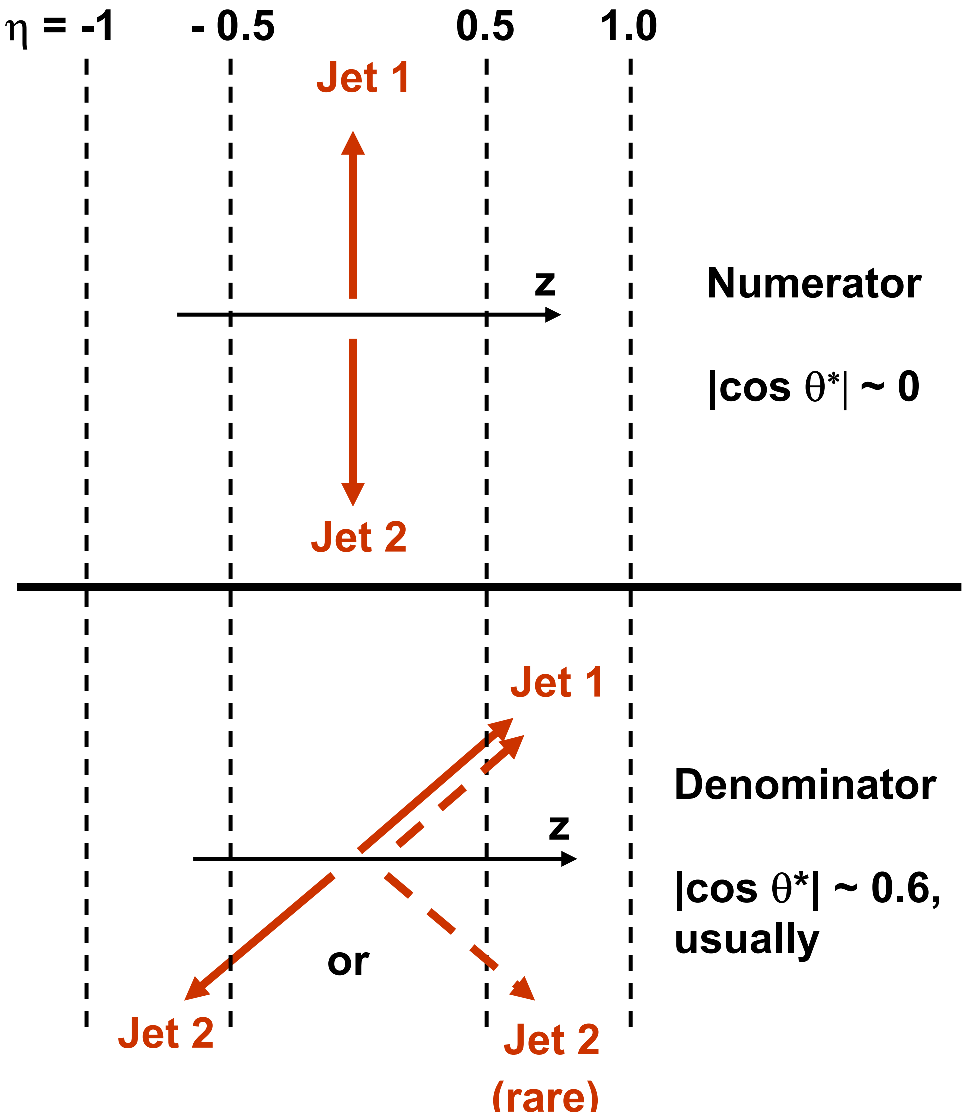
Contact Interactions in Angular Distribution

- Contact interaction is often more isotropic than QCD.
  - For example, the standard contact interaction among left-handed quarks introduced by Eichten, Lane and Peskin.
- Angular distribution has much smaller systematic uncertainties than cross section vs. dijet mass.
- But we want a simple single measure (one number) for the angular distribution as a function of dijet mass.
  - See the effect emerge at high mass.



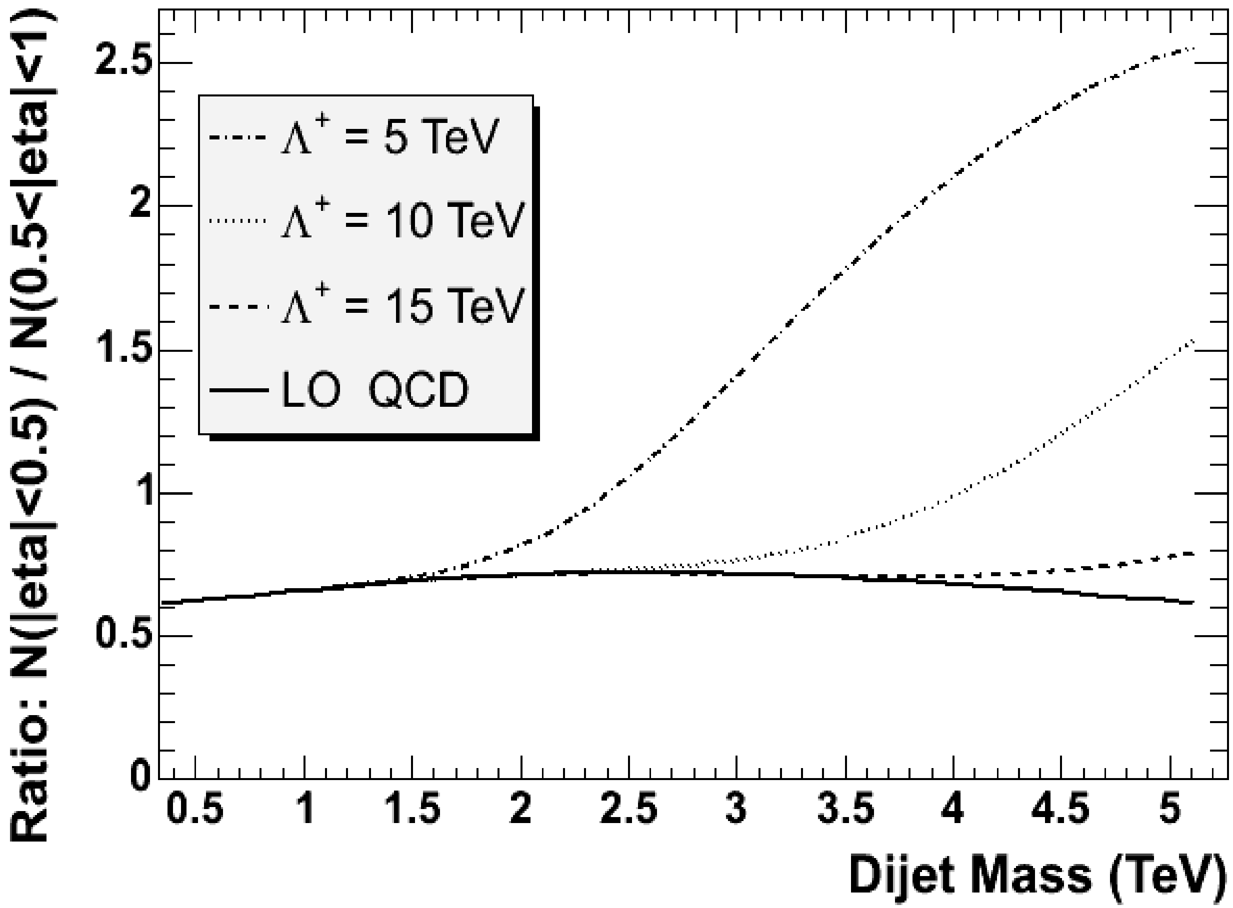
Sensitive Variable for Contact Interactions

- Dijet Ratio is the variable we use
  - Simple measure of the most sensitive part of the angular distribution.
  - We measure it as a function of mass.
  - It was first introduced by D0 (hep-ex/980714).
- Dijet Ratio = $N(|\eta|<0.5) / N(0.5<|\eta|<1)$
  - Number of events in which each leading jet has $|\eta|<0.5$, divided by the number in which each leading jet has $0.5<|\eta|<1.0$
  - We will show systematics on the dijet ratio are small.



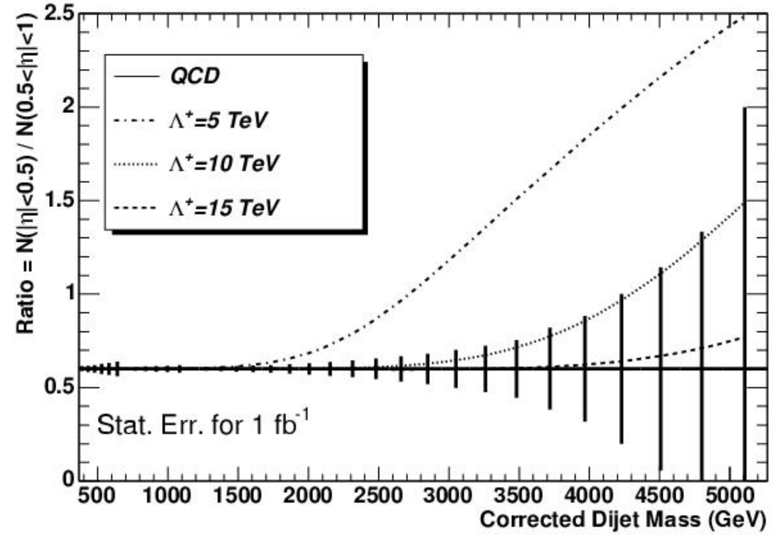
Dijet Ratio

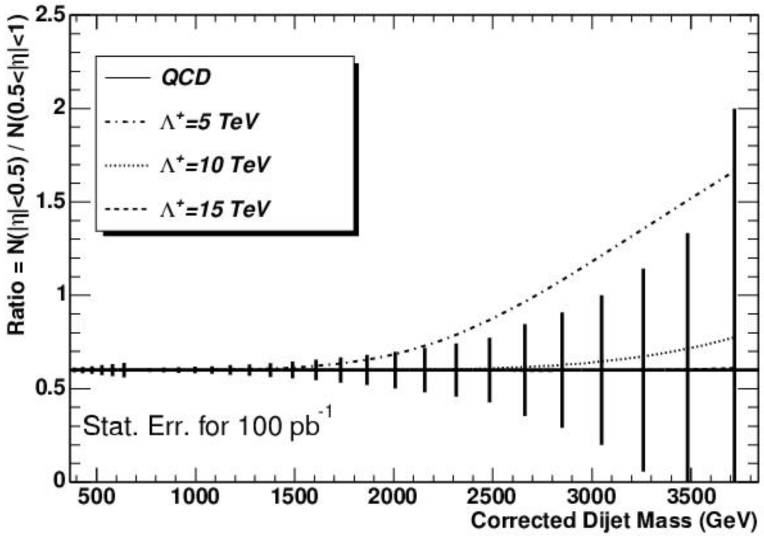
- **Lowest order (LO) calculation.**
  - **Both signal and background.**
- **Same code as used by CDF in 1996 paper**
  - **hep-ex/9609011**
  - **but with modern parton distributions (CTEQ 6L).**
- Signal emerges clearly at high mass
  - QCD is pretty flat

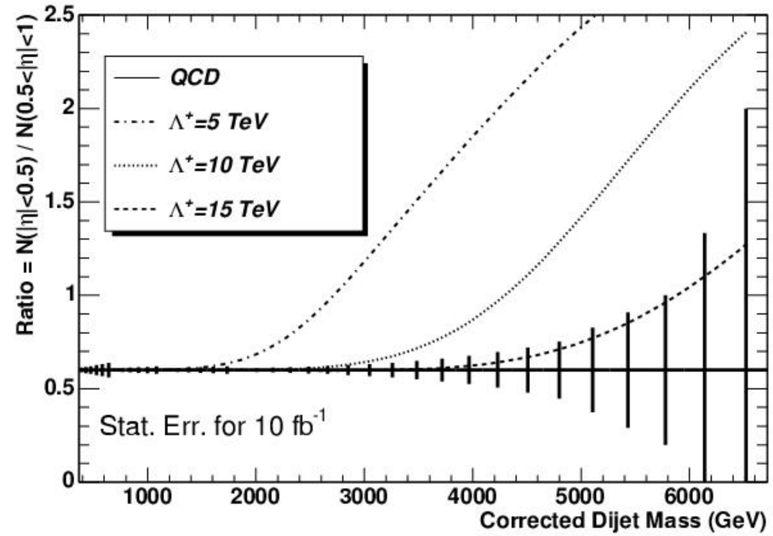


Dijet Ratio and Statistical Uncertainty
(Smoothed CMS Simulation)

- Background Simulation is flat at 0.6
  - Shown here with expected statistical errors for 100 pb^{-1}, 1 fb^{-1}, and 10 fb^{-1}.
- Signals near edge of error bars
  - Λ~5 TeV for 100 pb^{-1}
  - Λ~10 TeV for 1 fb^{-1}
  - Λ~15 TeV for 10 fb^{-1}
- Calculate χ^2 for significance estimates.

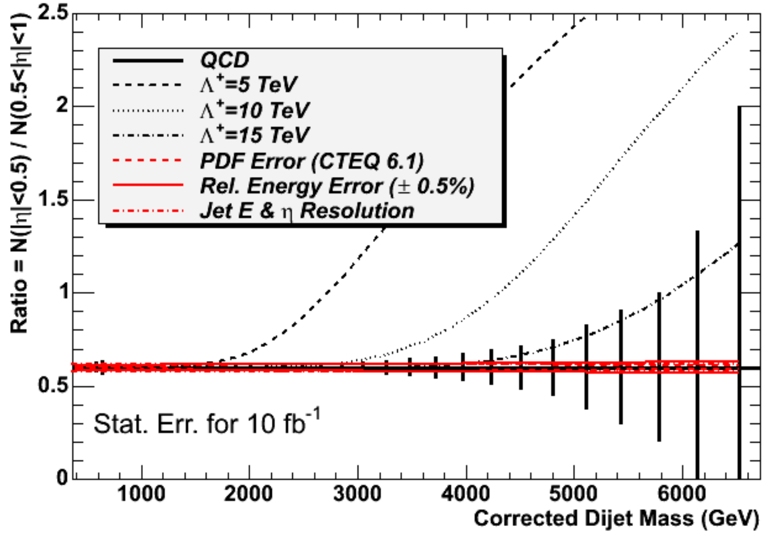


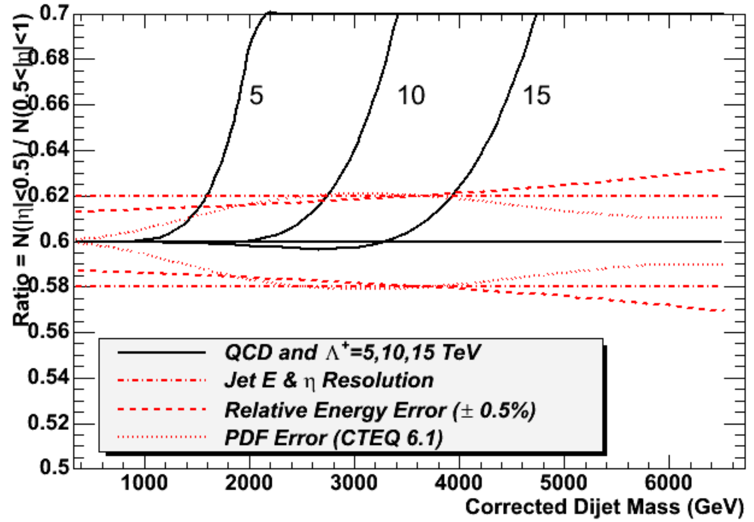




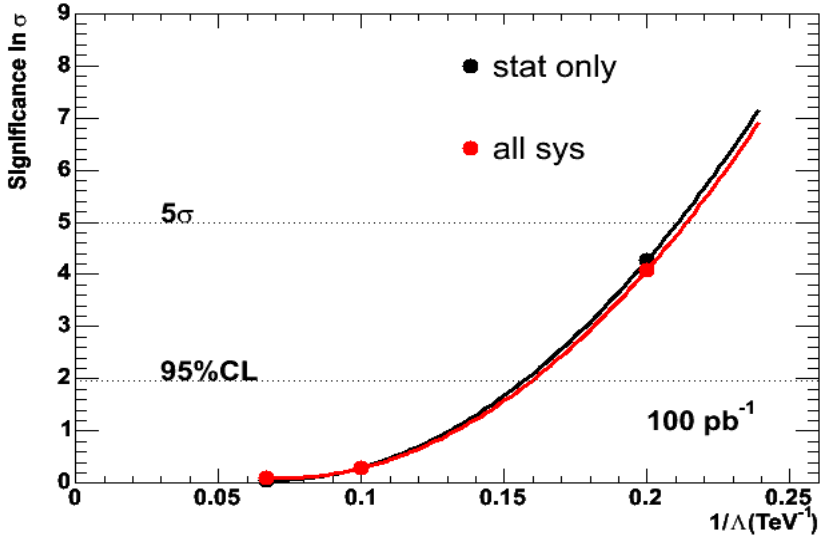
Dijet Ratio and Systematic Uncertainty

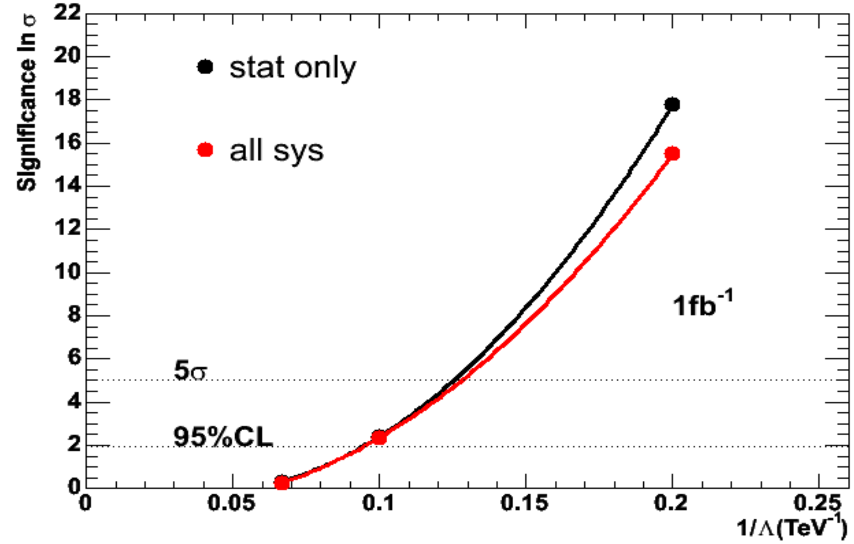
- Systematics are small
  - The largely cancel in the ratio.
  - Upper plot shows systematics & statistics.
  - Lower plot shows zoomed vertical scale.
- Absolute Jet Energy Scale
  - No effect on dijet ratio: flat vs. dijet mass.
  - Causes 5% uncertainty in Λ. (included)
- Relative Energy Scale
  - Energy scale in $|\eta|<0.5$ vs. $0.5 < |\eta| < 1$.
  - Estimate **+/- 0.5 %** is achievable in Barrel.
  - Changes ratio between **+/-.013** and **+/-.032.**
- Resolution
  - No change to ratio when changing resolution
  - Systematic bounded by MC statistics: **0.02.**
- Parton Distributions
  - We've used CTEQ6.1 uncertainties.
  - Systematic on ratio less than 0.02.

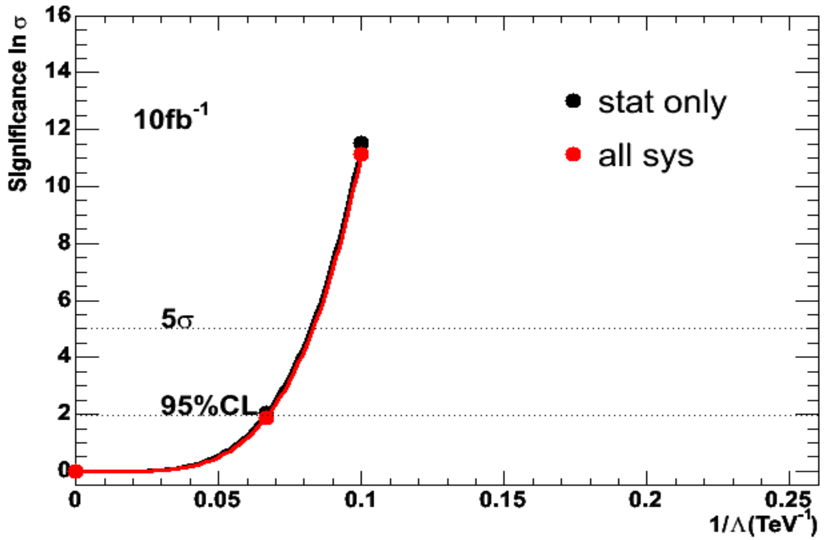




Significance of Contact Interaction Signal





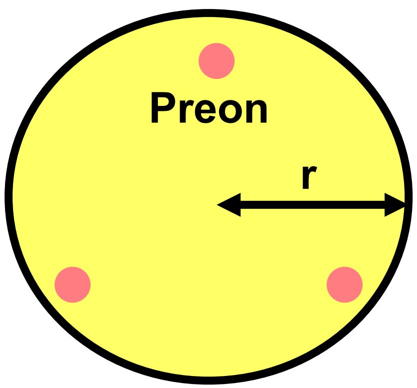


- Significance found from χ^2
  - ➔ 5σ Discoveries
  - ➔ 95% CL Exclusions
- Effect of dijet ratio systematics on the significance is small.

Sensitivity to Contact Interactions

Left-Handed Quark Contact Interaction	Λ^+ for 100 pb^{-1} (TeV)	Λ^+ for 1 fb^{-1} (TeV)	Λ^+ for 10 fb^{-1} (TeV)
95% CL Exclusion	**6.2**	**10.4**	**14.8**
5σ Discovery	**4.7**	**7.8**	**12.0**

- Published Limit from D0: $\Lambda^+ > 2.7$ TeV at 95% CL (hep-ex/980714).
- Λ can be translated roughly into the radius of a composite quark.
  - $\hbar = \Delta x \, \Delta p \sim (2r)(\Lambda / c)$
  - $r = 10^{-17}$ cm-TeV / Λ
  - For $\Lambda \sim 10$ TeV, $r \sim 10^{-18}$ cm
  - Proton radius divided by 100,000 !



Composite Quark

Conclusions

- We've described a jet trigger for CMS designed from Tevatron experience.
  - It will be used to search for new physics with dijets.
- CMS is sensitive to dijet resonances and quark contact interactions
  - We've presented sensivity estimates for 100 pb^{-1}, 1 fb^{-1} and 10 fb^{-1}
  - Capability for discovery (5σ) or exclusion (95% CL) including systematics.
- CMS can discover a strongly produced dijet resonance up to many TeV.
  - Axigluon, Coloron, Excited Quark, Color Octet Technirho or E_6 Diquark
  - Produced via the color force, or from the valence quarks of each proton.
- CMS can discover a quark contact interaction $\Lambda^+ = 12$ TeV with 10 fb^{-1}.
  - Corresponds to a quark radius of order 10^{-18} cm if quarks are composite.
- We are prepared to discover new physics at the TeV scale using dijets.