Search for New Particles Decaying to Dijets at CMS

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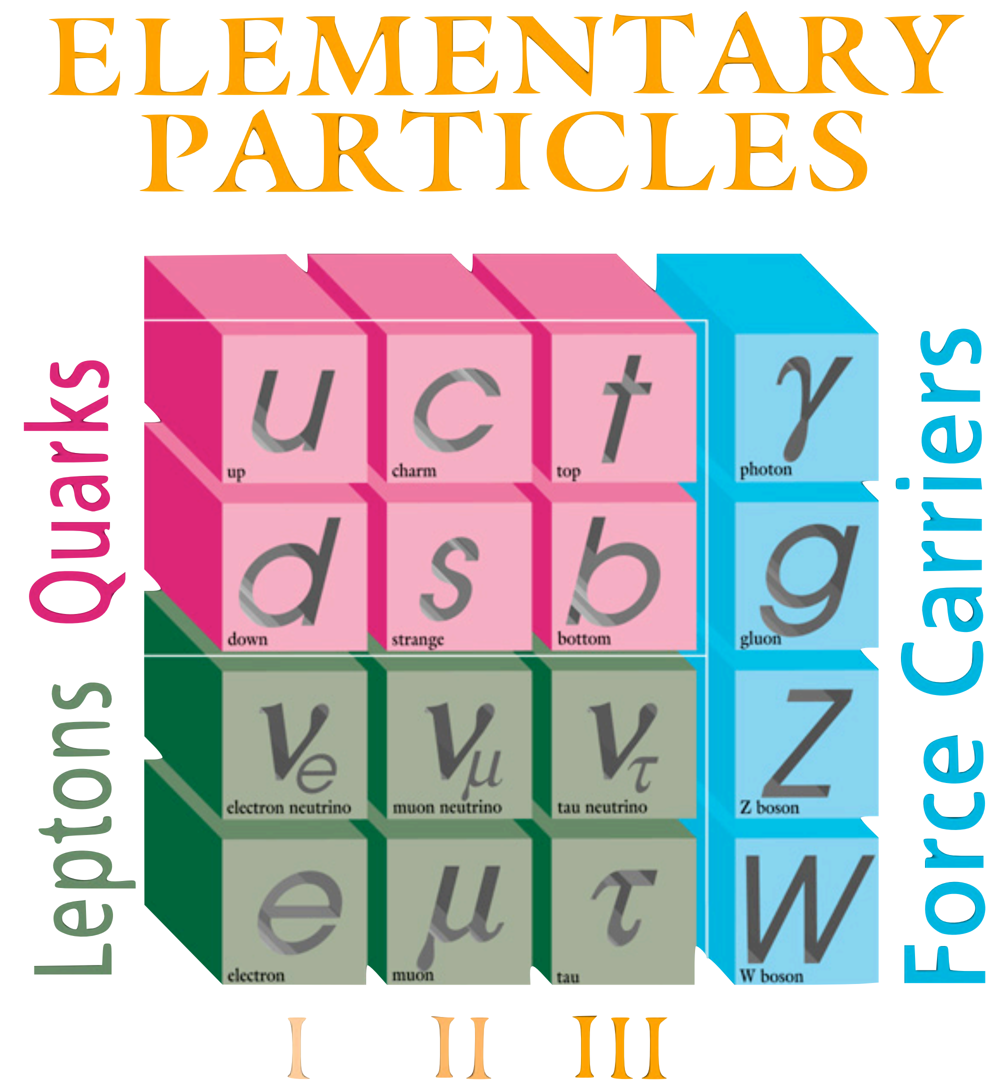
Outline

- Motivation
- Analysis Strategy
- Limits with Statistical Error Only
- Limits with Including Systematics
- Results
- Conclusion

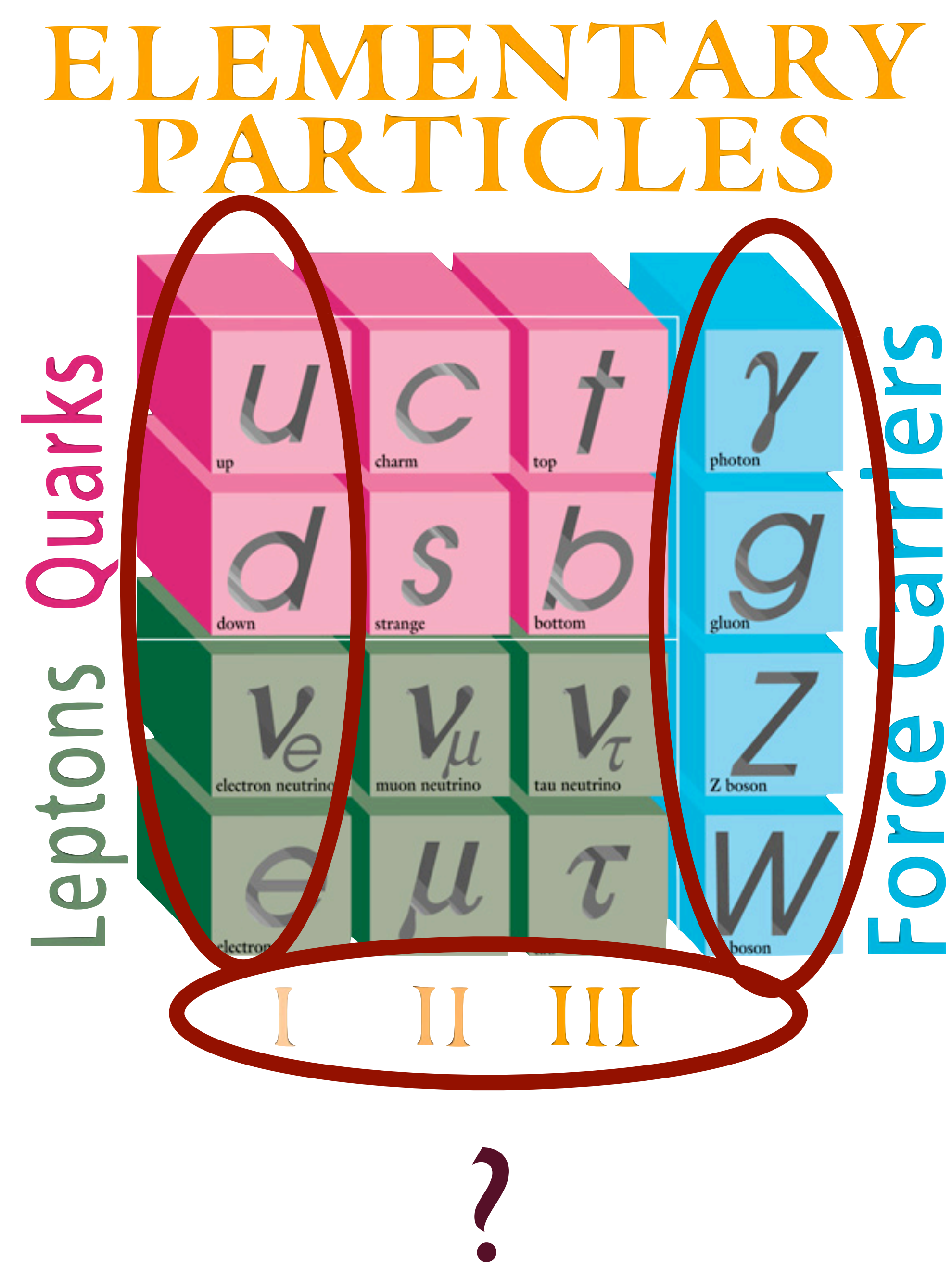
Standard Model

- In terms of Standard Model,
  - ✓ 6 quarks & 6 leptons
    - u and d quarks and electron make matter
  - ✓ 4 force carrying particles
    - Υ: Electromagnetism
    - W & Z: Weak Interaction
    - g: Color (Nuclear) Interaction
  - ✓ Higgs particle to give mass
    - Higgs not discovered



Beyond the SM

- 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?
  - ✓ ϒ, Z and W are unified already.
  - ✓ Can we include gluons?
  - ✓ Can we include gravity?
- These questions suggest there will be new physics beyond the Standard Model.
  - ✓ We will search for new physics with Dijets.



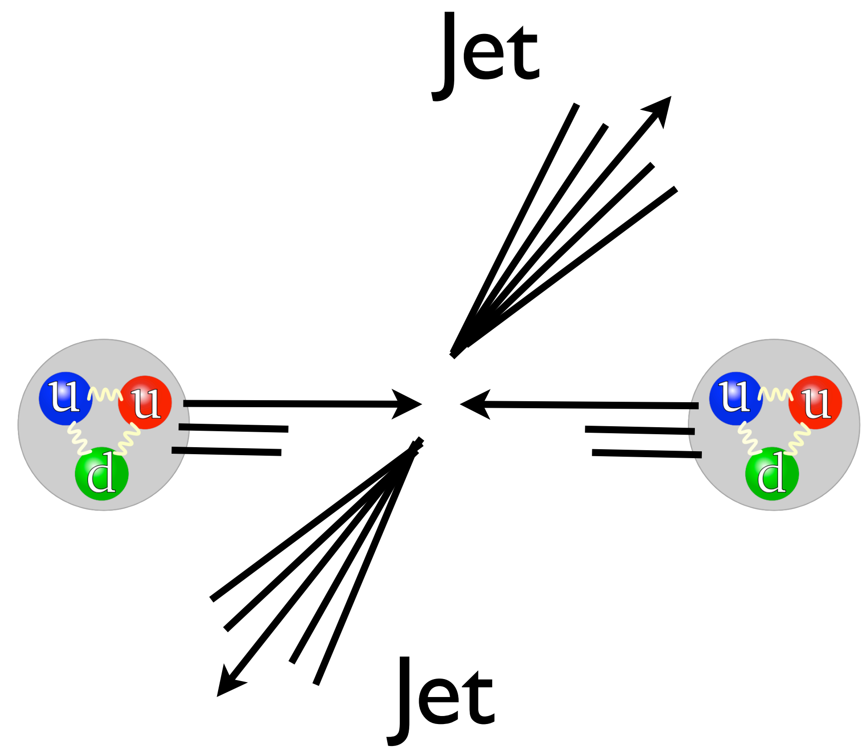
Search for new Physics with Dijets

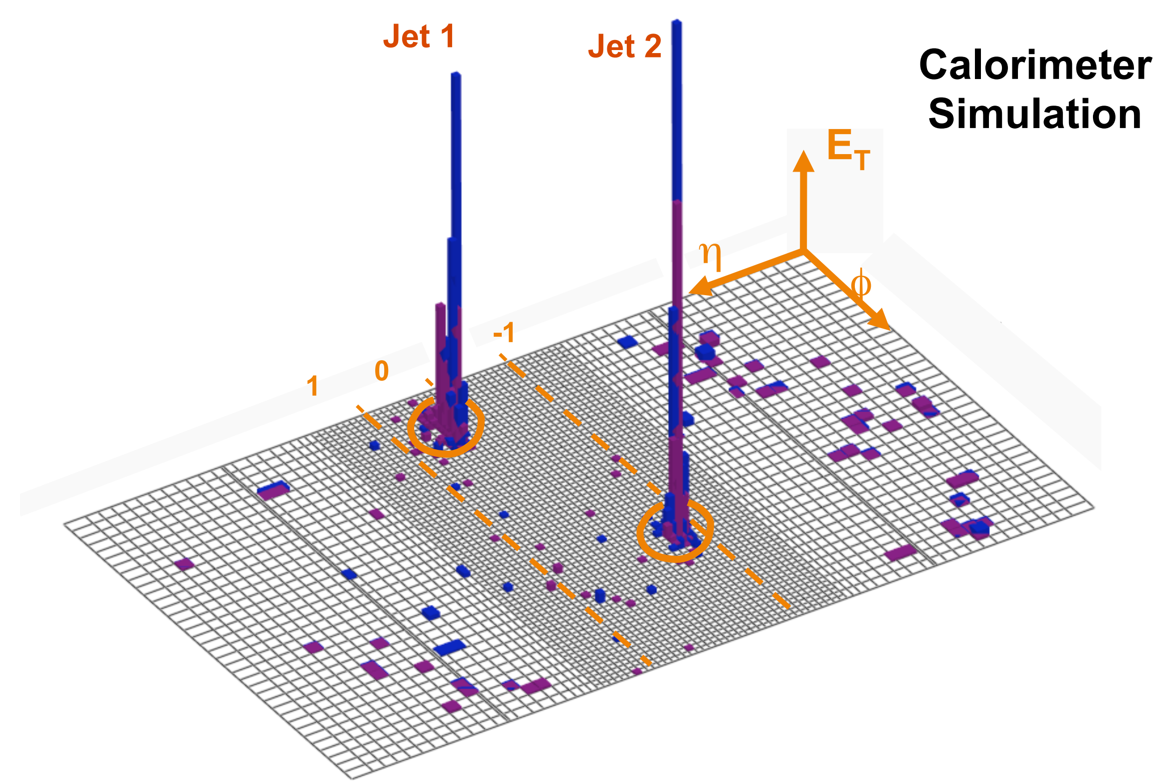
- Mainly focused by LPC (LHC Physics Center) Dijet Topology Group at Fermilab.
- Search for Dijet Resonances in Dijet Mass
  - ✓ Bump hunting in Dijet Mass spectrum
  - ✓ Fitting dijet mass distribution BG Param. + Signal
  - ✓ Calculating of Likelihoods vs resonance cross section
  - ✓ Finding 95% C.L. cross section upper limit
- Dijet Ratio
  - ✓ Calculating dijet mass distribution at central ($|\eta|<0.7$) and forward ($0.7<|\eta|<1.3$) regions.
  - ✓ Finding ratio between central and forward regions.
- Both analysis are High Priority Analysis.

Dijet in Standard Model

- What is a Dijet?
  - ✓ Dijet results from simple 2→2 scattering of "partons"
  - ✓ Dijets are events which primarily consist of two jets in the final state.
- Dijet Mass from final state

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

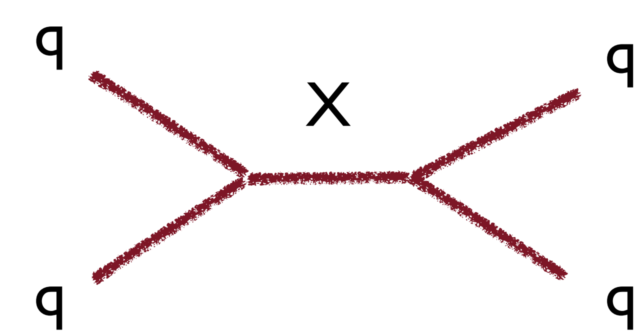




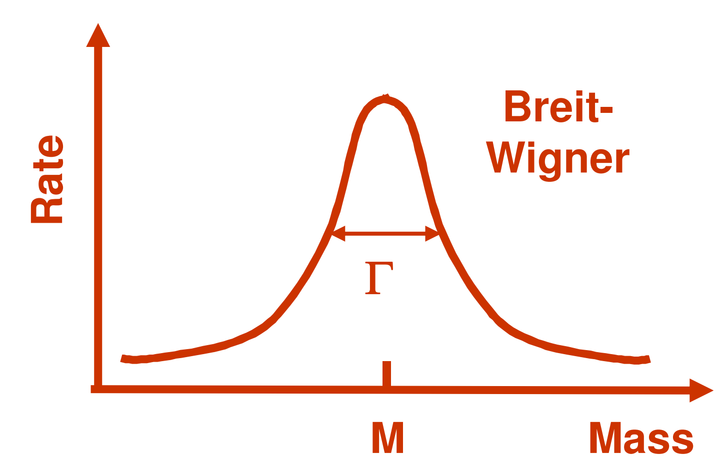
Dijet Resonance Models

- Theoretical Motivation
- Dijet Resonances found in **many models** that address fundamental questions.
- Why Generations ? → Compositeness → Excited Quarks
- Why So Many Forces ? → Grand Unified Theory → W ' & Z '
- Can we include Gravity ? → Superstrings & GUT → E6 Diquarks
- Why is Gravity Weak ? → Extra Dimensions → RS Gravitons
- Why Symmetry Broken ? → Technicolor → Color Octet Technirho
- More Symmetries ? → Extra Color → Colorons & Axigluons

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	$q\bar{q}$



s-channel



Jet Types in CMS

The jet algorithms take as input sets of 4-vectors:

1. GenJets
Stable simulated particles (after hadronization and before interaction with the detector).

2. CaloJets
Calorimeter energy depositions grouped in CaloTowers.

3. JetPlusTrack
Calorimeter jets whose energy has been corrected with jet-track association.

4. PFJets
Individually reconstructed particles by combination of multiple detector inputs (particle flow objects).

5. TrackJets
Tracks

Particles, CaloTowers, PF, Tracks → **Jet Algorithm** → GenJets, CaloJets, PFJets, TrackJets, JetPlusTrack

Jet Reconstruction Algorithm in CMS

1. Iterative Cone R = 0.5
Simple and fast cone algorithm. Used by HLT. Not recommended for analysis !!!!
2. Anti-k_T D = 0.5, 0.7
Belong to the k_T family. For all practical purposes it behaves as a cone algorithm. Infrared & collinear safe. Recommended by JetMET for startup (D = 0.5) !!!
3. k_T D = 0.4, 0.6
Infrared & collinear safe.
4. Seedless Infrared Safe Cone (SISCone) R = 0.5, 0.7
Infrared & collinear safe but CPU intensive in a "busy" environment. Will be eventually dropped in favor of anti-k_T.

Algorithm	Size	GenJets	CaloJets	PFJets
anti-k_T	**0.5**	**ak5GenJets**	**ak5CaloJets**	**ak5PFJets**
anti-k_T	0.7	ak7GenJets	ak7CaloJets	ak7PFJets
k_T	0.4	kt4GenJets	kt4CaloJets	kt4PFJets
k_T	0.6	kt6GenJets	kt6CaloJets	kt6PFJets
SISCone	0.5	sisCone5GenJets	sisCone5CaloJets	sisCone5PFJets
SISCone	0.7	sisCone7GenJets	sisCone7CaloJets	sisCone7PFJets
iterativeCone	0.5	iterativeCone5GenJets	iterativeCone5CaloJets	iterativeCone5PFJets

JetID for CaloJets in CMS

- Electromagnetic energy fraction (EMF). A low cut defends against HCAL noise. A high cut defends again ECAL noise (dangerous a low jets pt)
- n90hits. Minimum number of rechits in the calotowers which carry 90% of the jet energy.
- fHPD. Fraction of the energy contributed by the hottest HPD.

- **Dijet Analyses**
- Standard Loose JetID Cut for both jets
  - ✓ EMF>0.01 & EMF<1.
  - ✓ fHPD<0.98
  - ✓ n90Hits>1

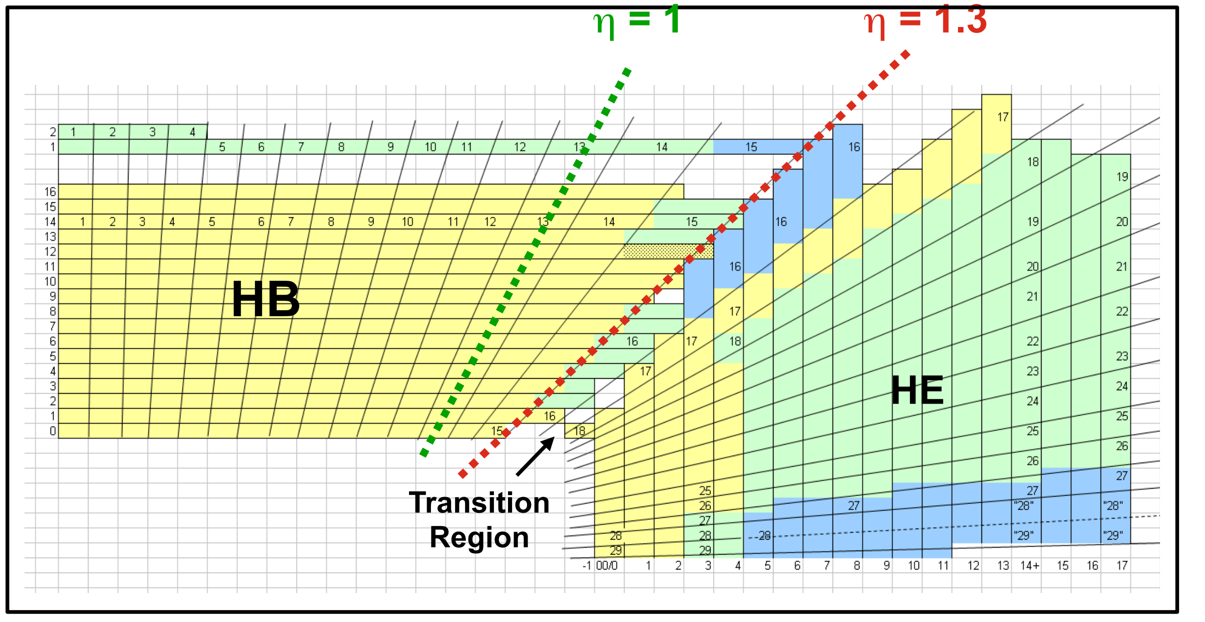
Analyses Strategy

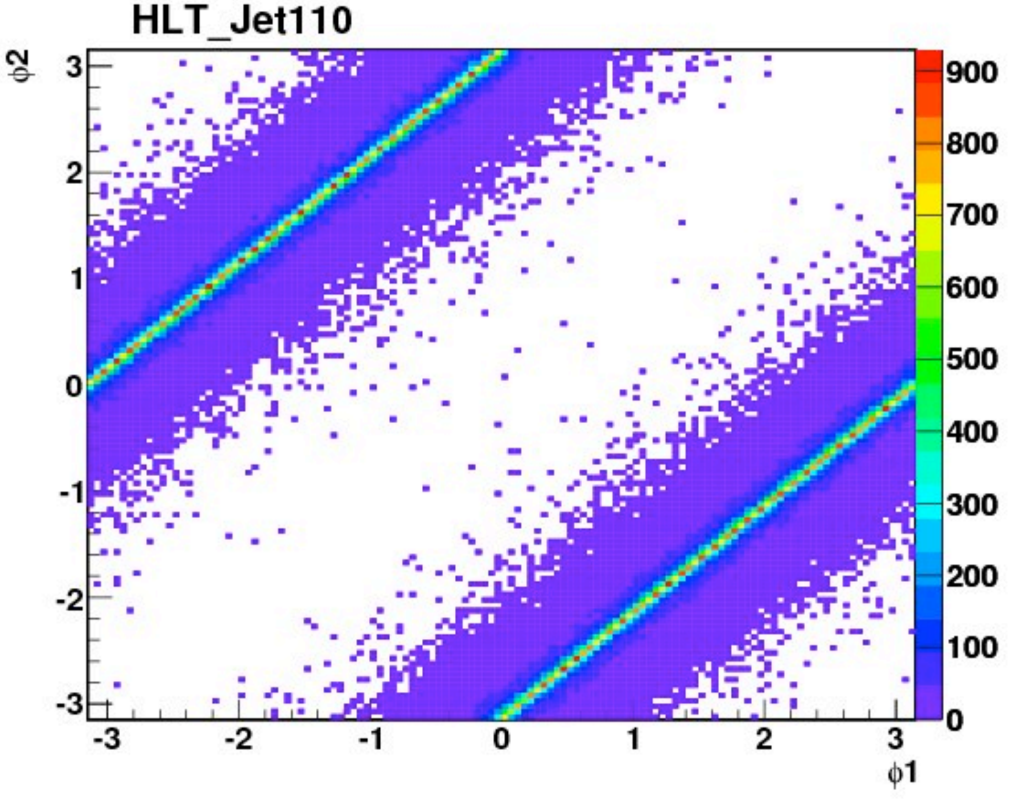
- All result are done assuming 10 TeV LHC energy with 10 pb^{-1}.
- Signal
  - ✓ G→gg, q*→qg and G→qq resonances at 0.7 TeV, 2 TeV and 5 TeV.
- Background
  - ✓ QCD Multijet
- Event Selection
  - ✓ |Jet η|<1.3
  - ✓ Jets from SisCone algorithm with R=0.7
    - We intend to use Anti-kt algorithm for data analyses.
  - ✓ MET/SumET<0.3 to reject unphysical events.
  - ✓ Dijet Mass plots use variable dijet mass bins
    - The bins are equal to dijet mass resolution
  - ✓ Unprescaled jet trigger (HLT_Jet110)

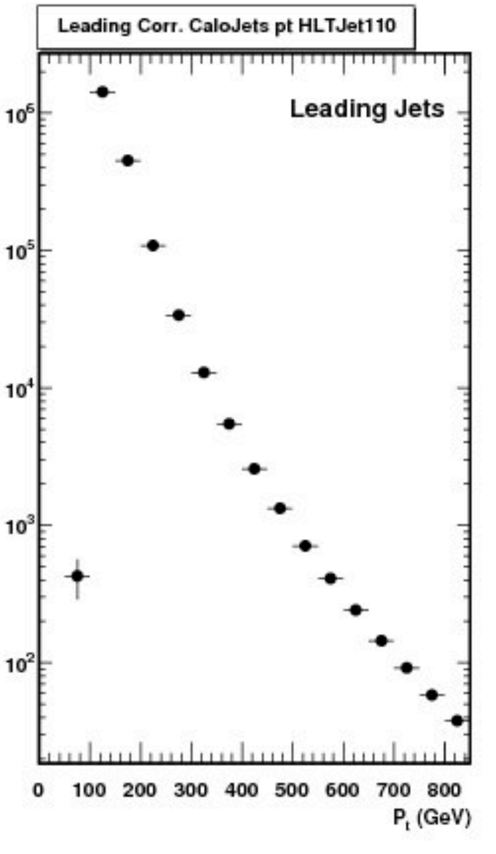
Kinematic Cut

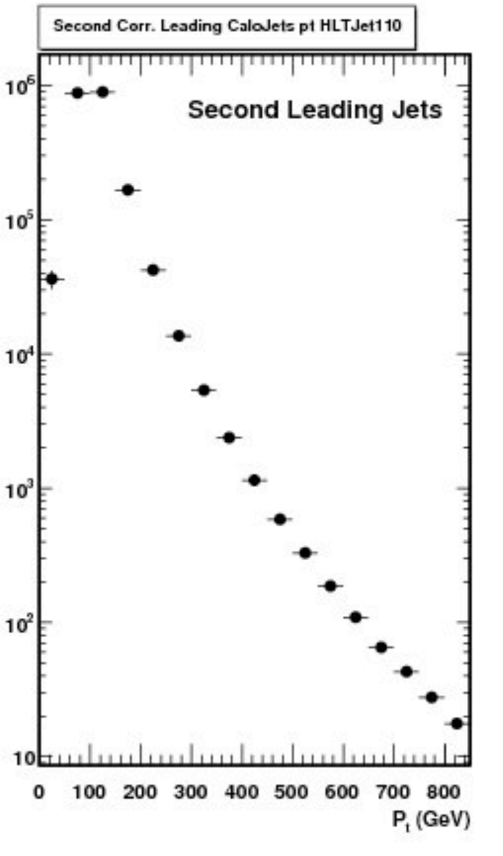
- Two leading jets required to have $|\eta|<1.3$
  - ✓ Uniform acceptance
  - ✓ Higher pt reach
  - ✓ Higher sensitivity to new physics

Hcal towers and η cuts



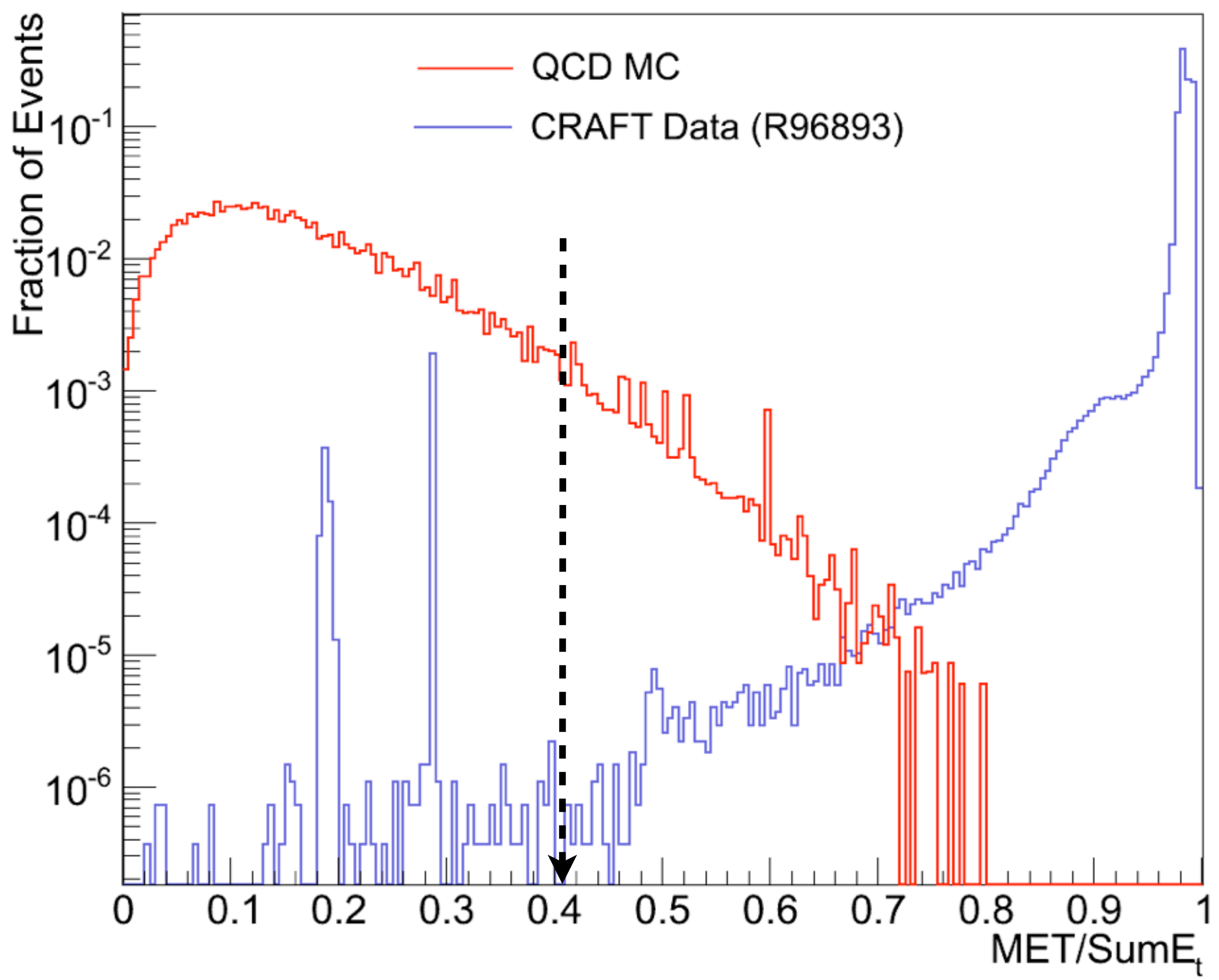






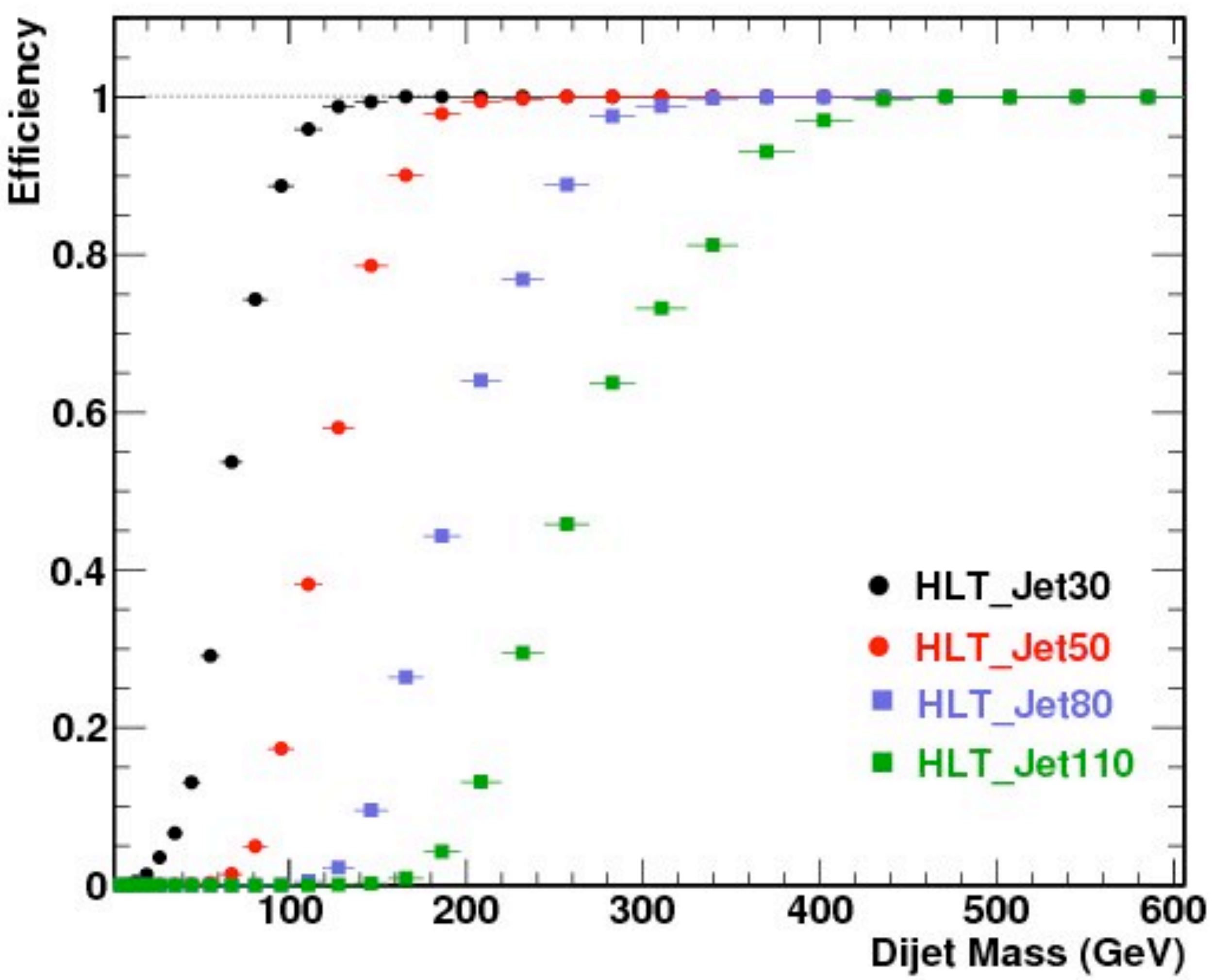
MET/SumEt Cut

- MET/SumEt<0.3 to reject noise, cosmic background, beam halo events.



Trigger Efficiency

- HLT_Jet110 trigger is used.
  - ✓ Full efficient after 420 GeV.



99% Efficiency point

Trigger	Mjj (GeV)
HLT_Jet30	136
HLT_Jet50	204
HLT_Jet80	318
HLT_Jet110	420

Dijet Mass Cross Section

Event counting in bins of dijet mass.

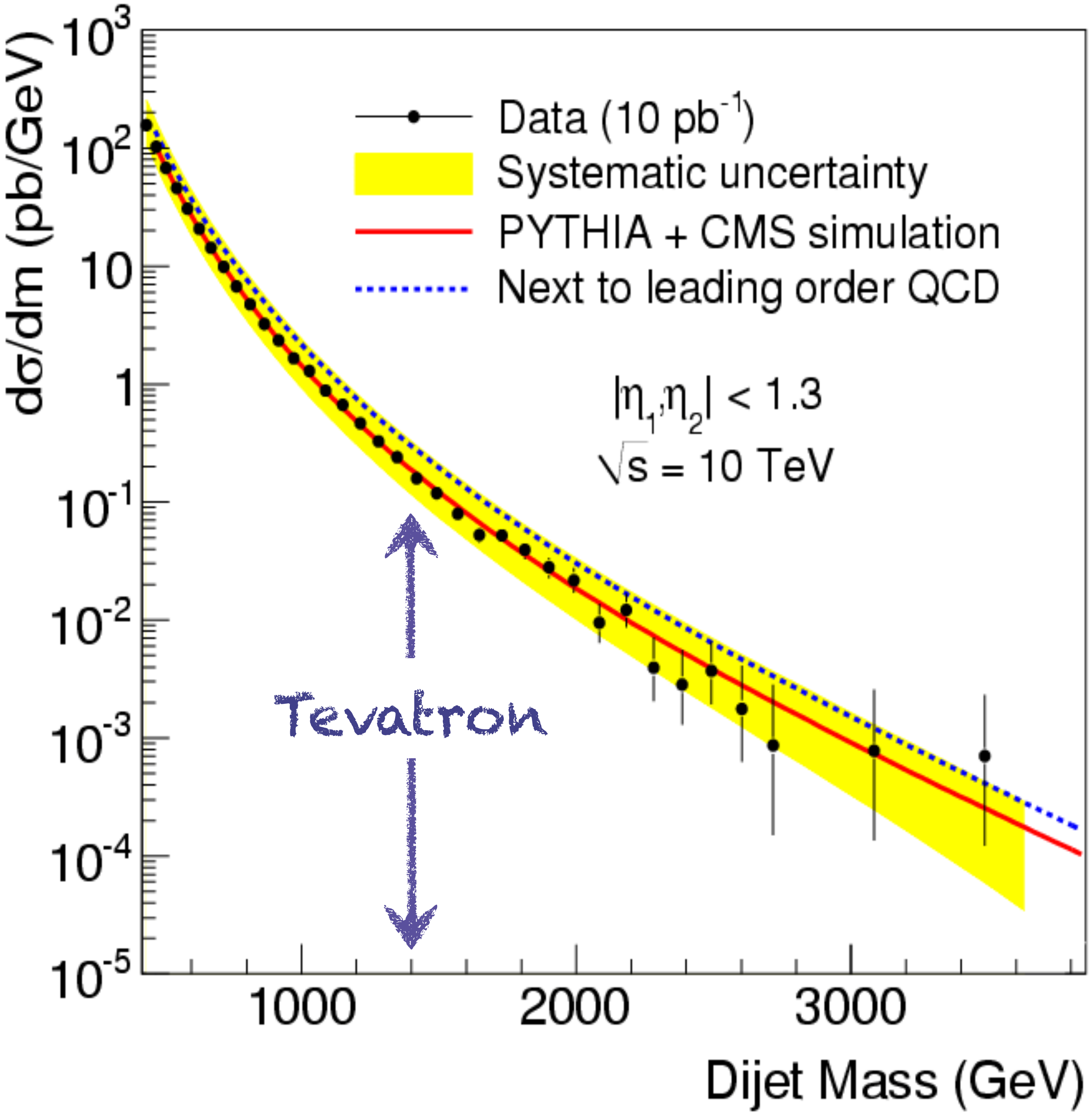
$$\frac{d\sigma}{dM} = \frac{1}{\mathcal{L} \cdot \epsilon} \cdot \frac{N_{dijets}}{\Delta M}$$

differential cross section

integrated luminosity

jetID & event cleanup efficiency

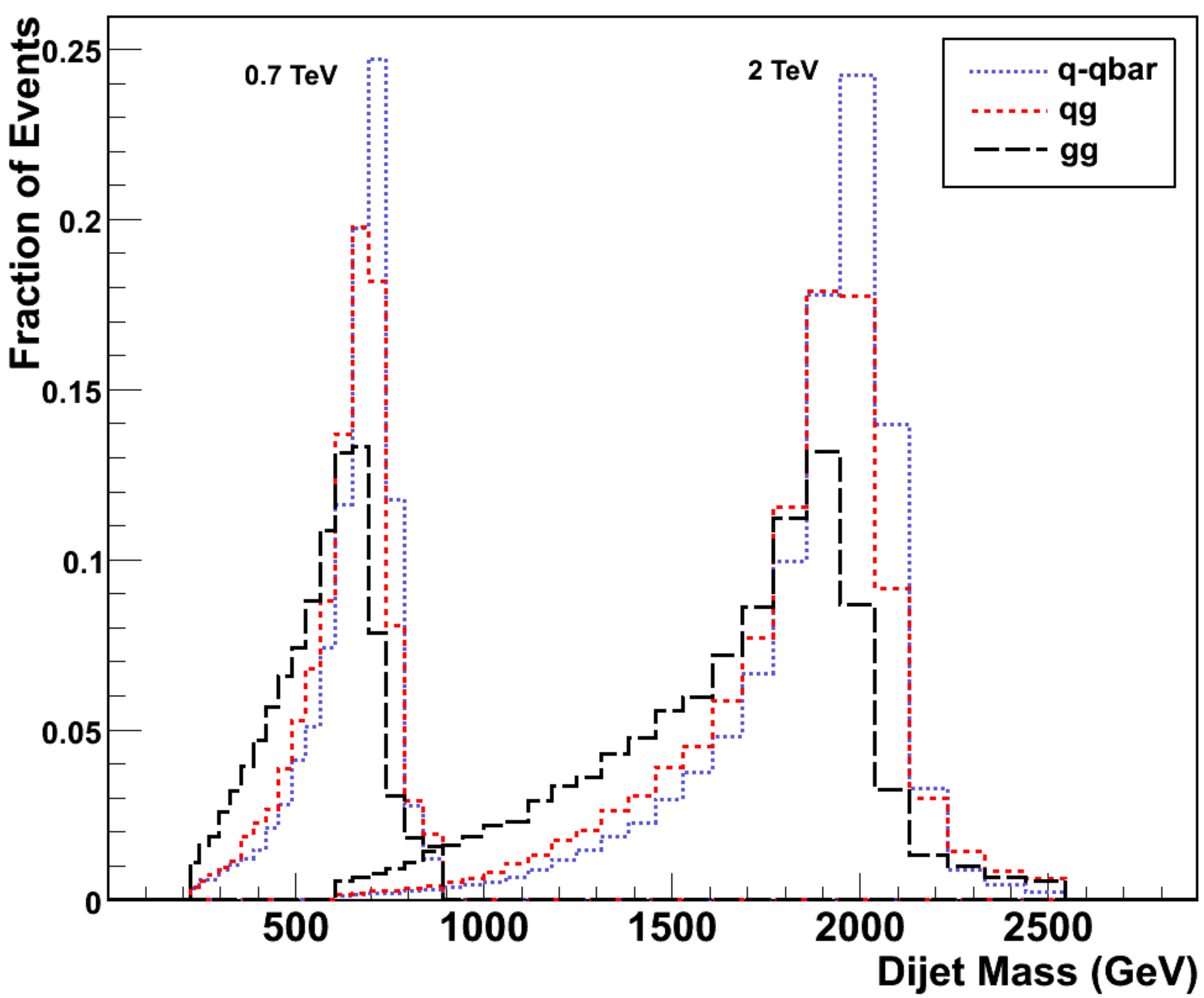
Pseudo-data from QCD

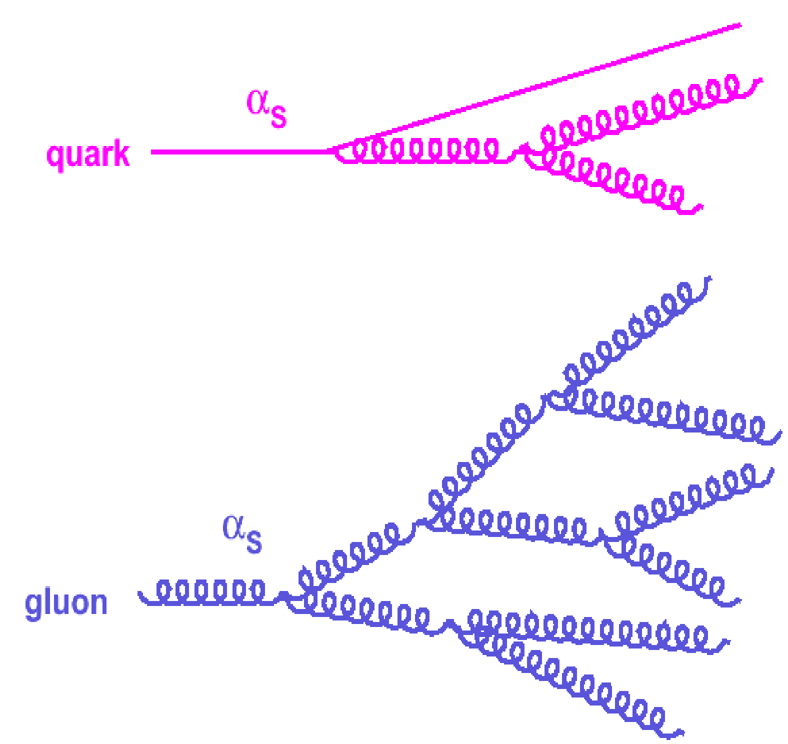


- We generated a pseudo-data.
  - ✓ A toy generator was written to produce random statistical fluctuation in smooth QCD curve.
  - ✓ Compared to PHYTIA simulation and NLO QCD.

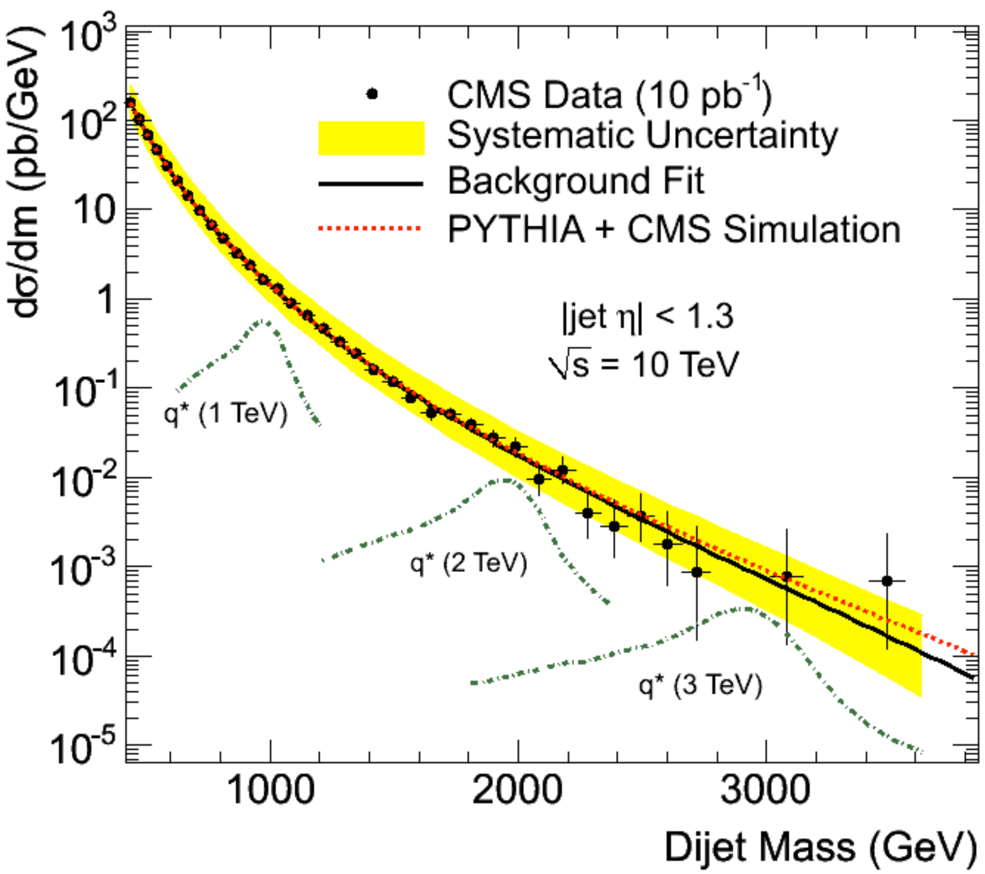
Resonance Shapes

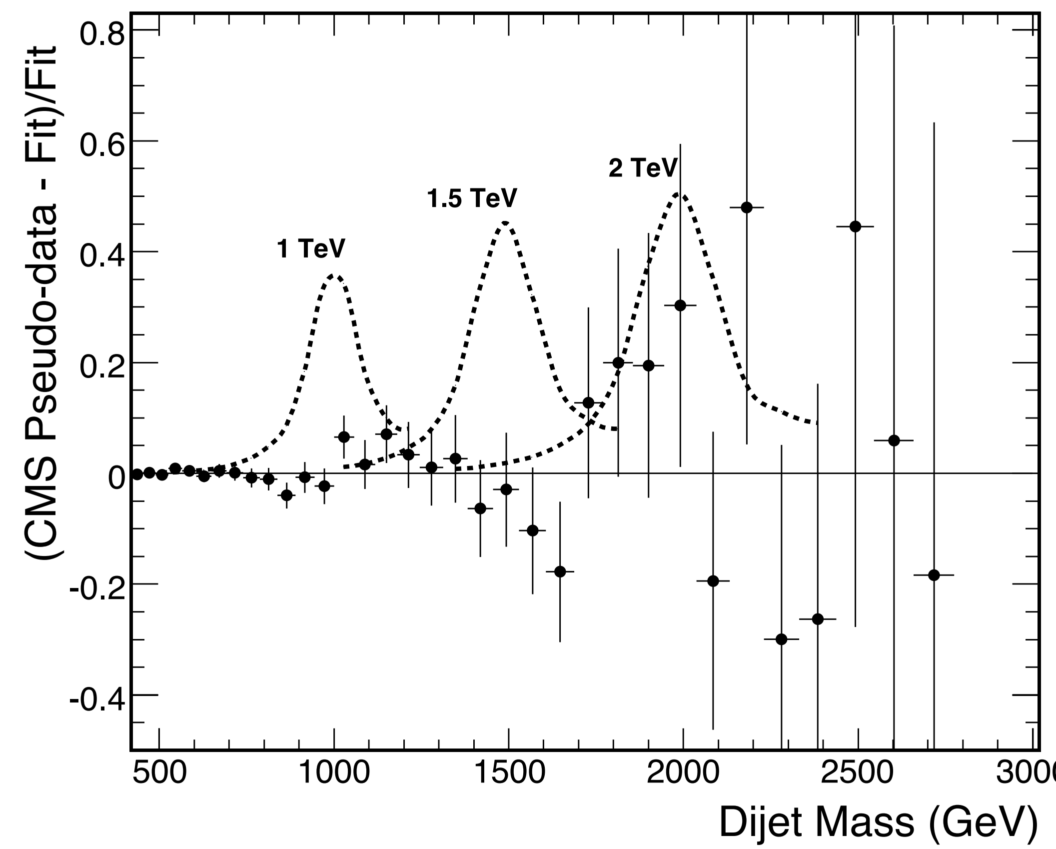
- Dijet resonance shapes from qq, qg and gg have small differences.
  - ✓ Due to differences in ISR, FSR and CMS jet response.
  - ✓ The width of dijet resonance increase with number of gluons because gluons emit more radiation than quarks.

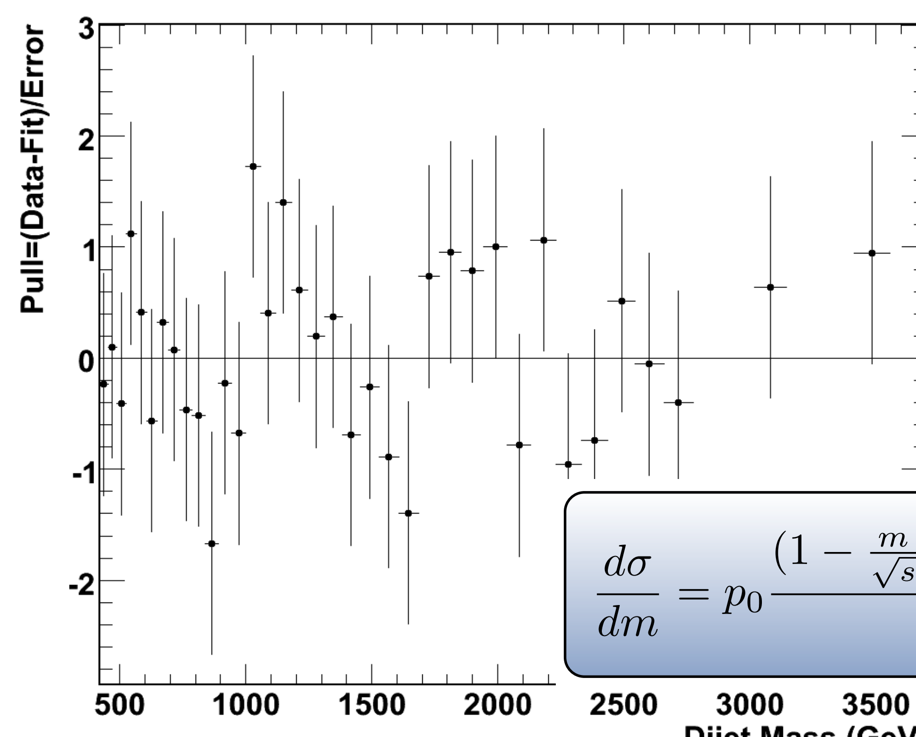




Pseudo-Data compared to Signal







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

- The pseudo-data is compared to excited quark signal
  - ✓ There is no evidence for dijet resonances
- We would proceed to set limits

Setting Limits

- To calculate limit on new particle cross section we use a binned likelihood.

$$L = \prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!} \qquad \mu_i = \alpha N_i(S) + N_i(B).$$

n_i: Measured # of events in data

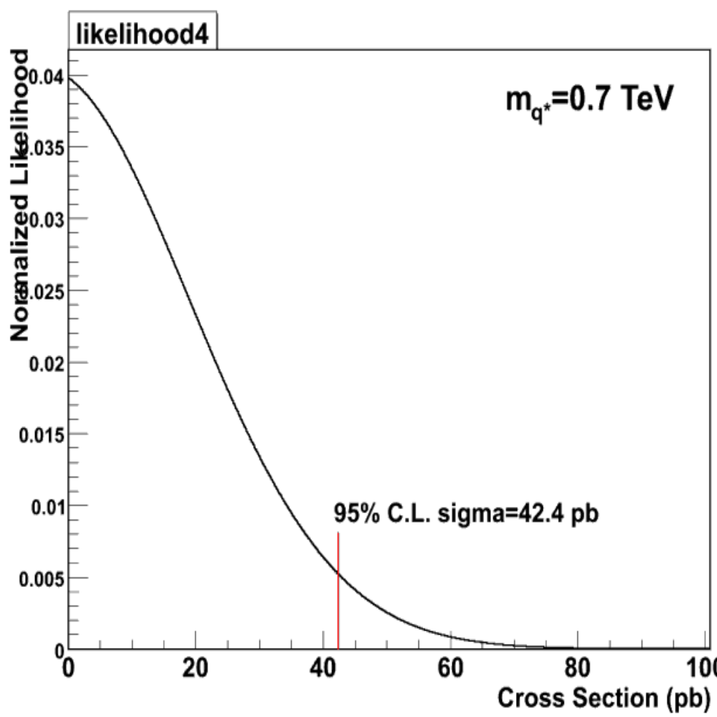
$N_i(S)$: # of event from signal

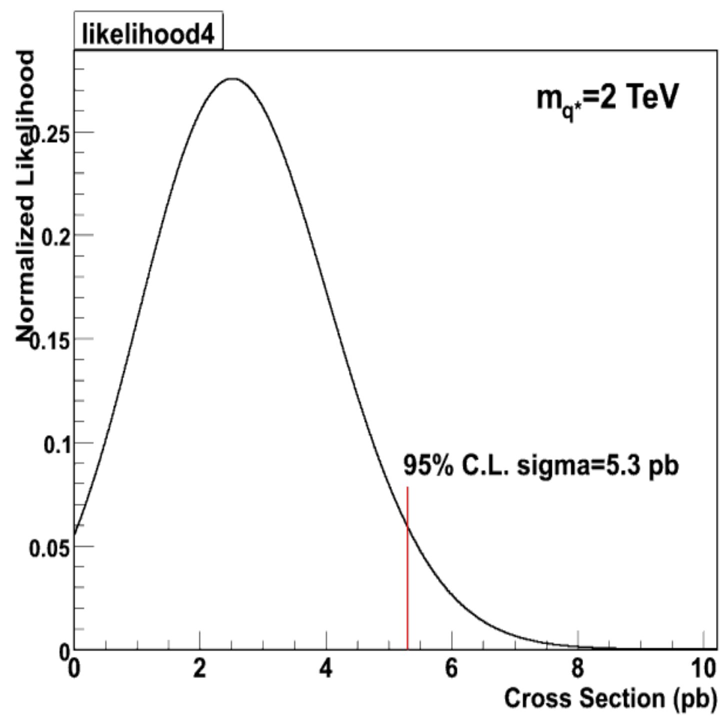
$N_i(B)$: Expected # of event from background

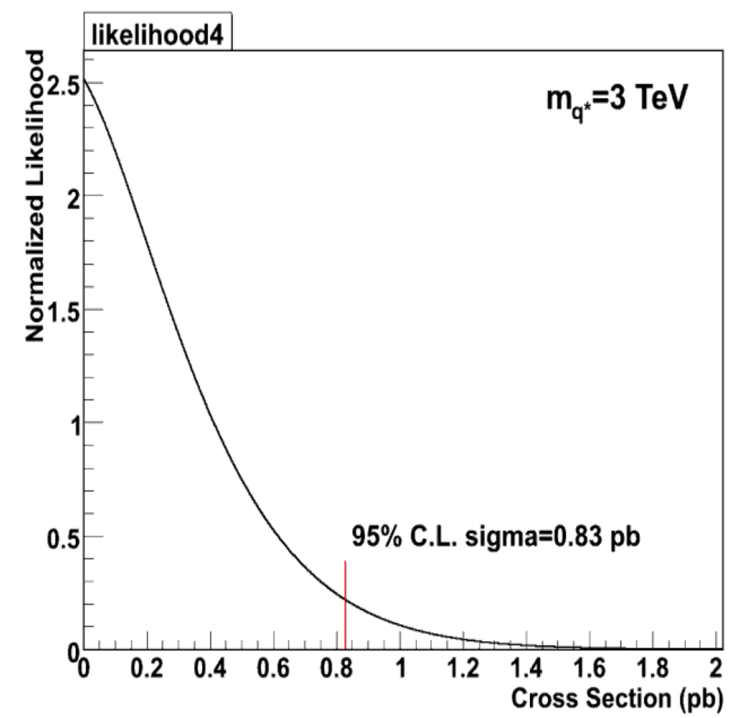
- The signal comes from our dijet resonance shapes for qq, qg and gg.
- The background comes from fit (BG+Signal).
- We calculate likelihood as a function of signal cross section for resonances with mass from 0.7 TeV to 3.5 TeV in 0.1 TeV steps.

Likelihood with Statistical Error

- Likelihood distributions as function of signal cross section for different resonance mass are shown.
- 95% C.L. upper limit on cross section calculated.



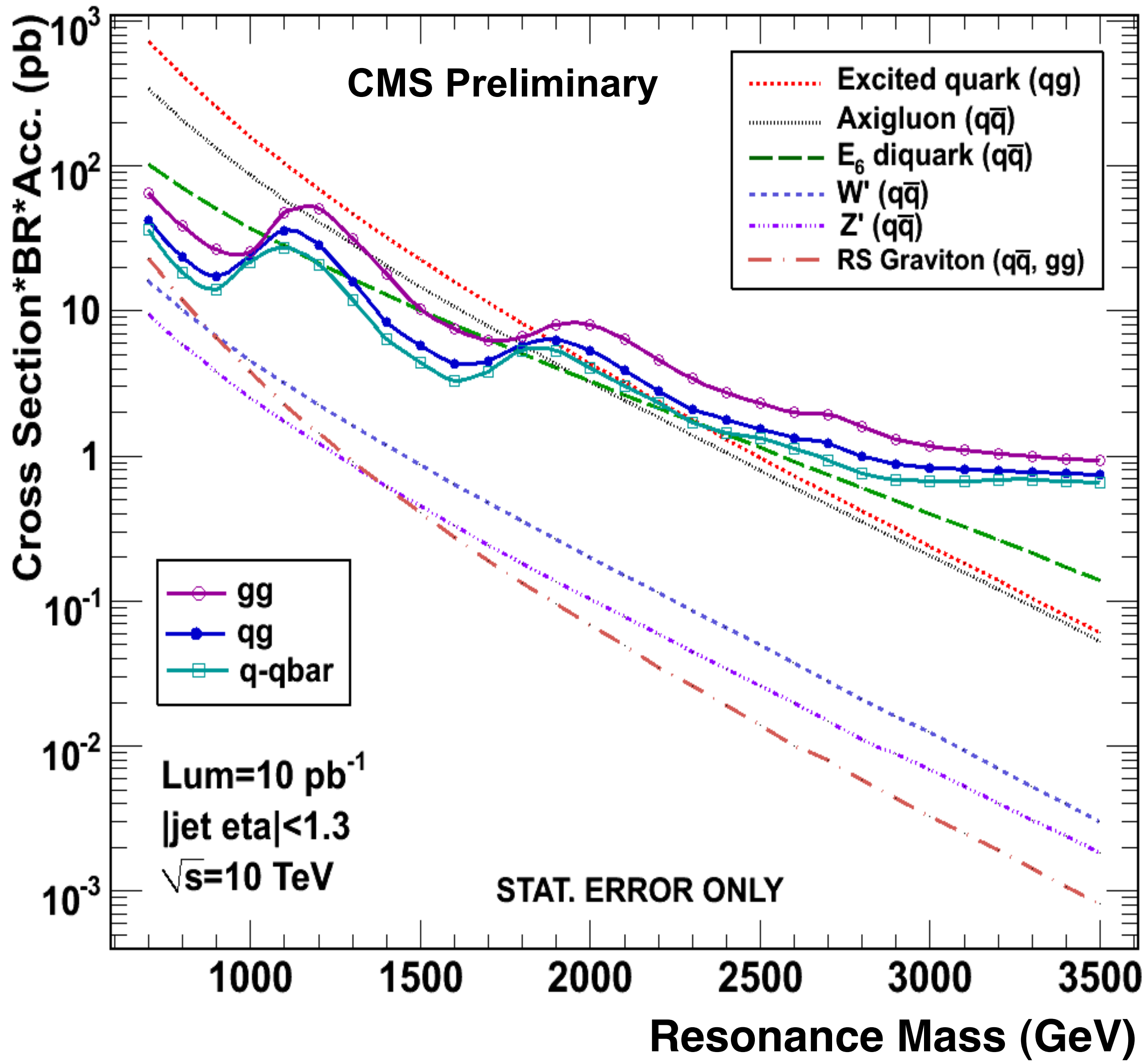




$$\frac{\int_0^{\sigma_{95}} L(\sigma)d\sigma}{\int_0^{\infty} L(\sigma)d\sigma} = 0.95$$

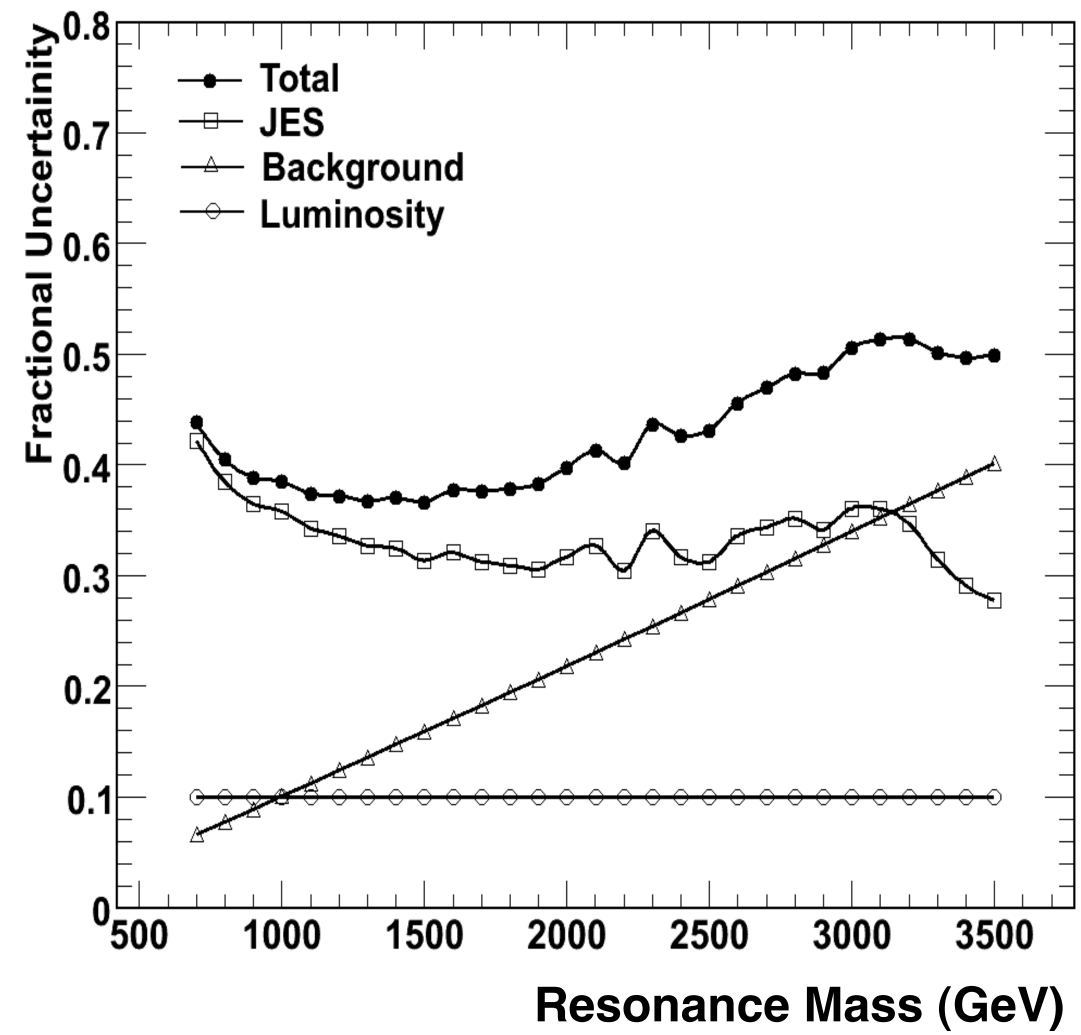
Dijet Resonance Limits with Statistical Uncertainties Only

- 95% C.L. upper limit compared to cross section for various models.
  - ✓ Shown separately for qq, qg and gg resonances.
  - ✓ The sensitivity for qq parton pair resonances is higher than the others parton pair resonances



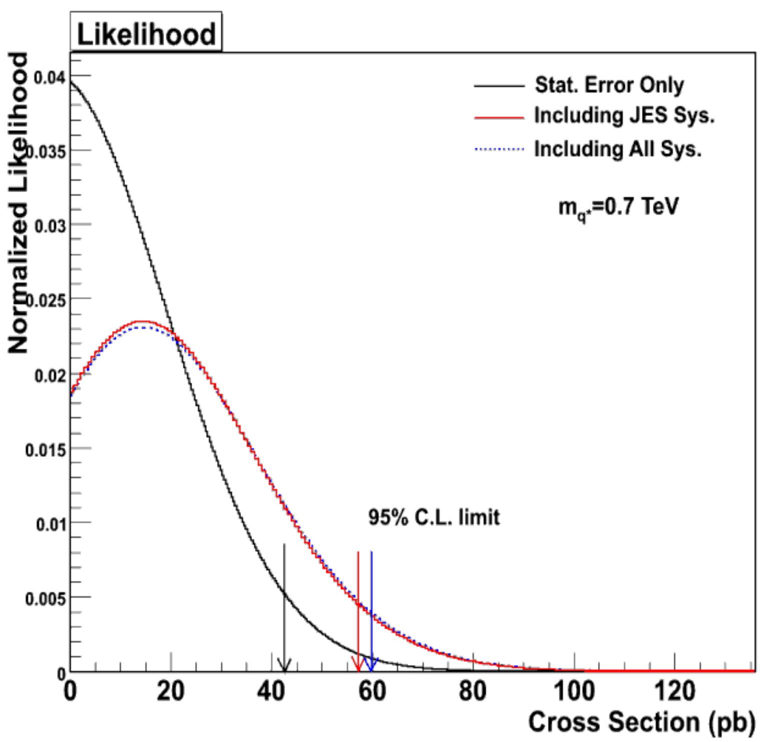
Systematic Uncertainties

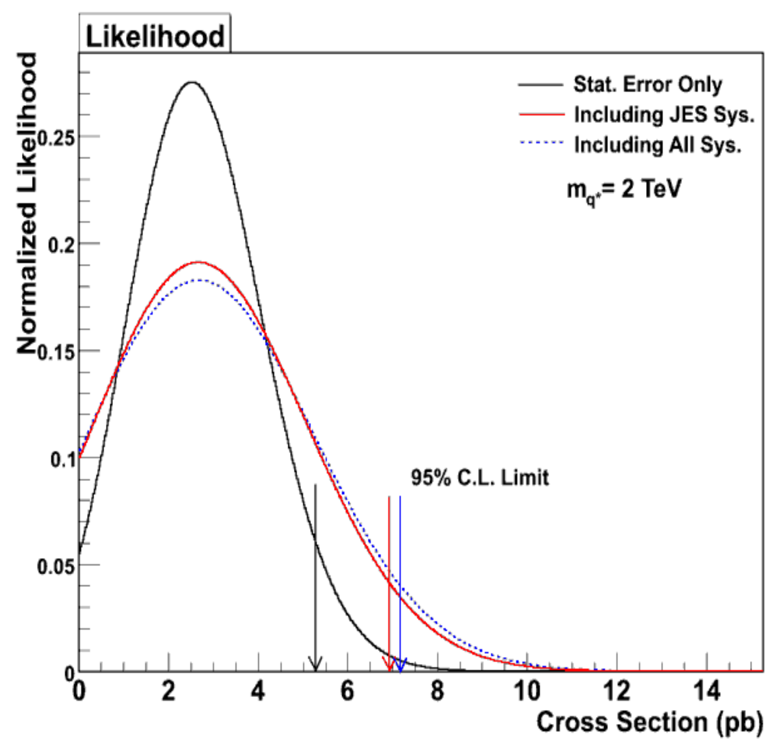
- We found the uncertainty in the dijet resonance cross section from following sources
  - ✓ Jet Energy Scale (JES)
    - Uncertainty assumed to be 10% at start-up
  - ✓ Choice of background parametrization
    - We consider 3 functional form used by CDF
  - ✓ Luminosity
    - Uncertainty assumed to be 10% at start-up
- We add in quadrature the individual systematic uncertainties
  - ✓ Total systematic uncertainty varies from 45% at m=0.7 TeV to 50% at m=3.5 TeV

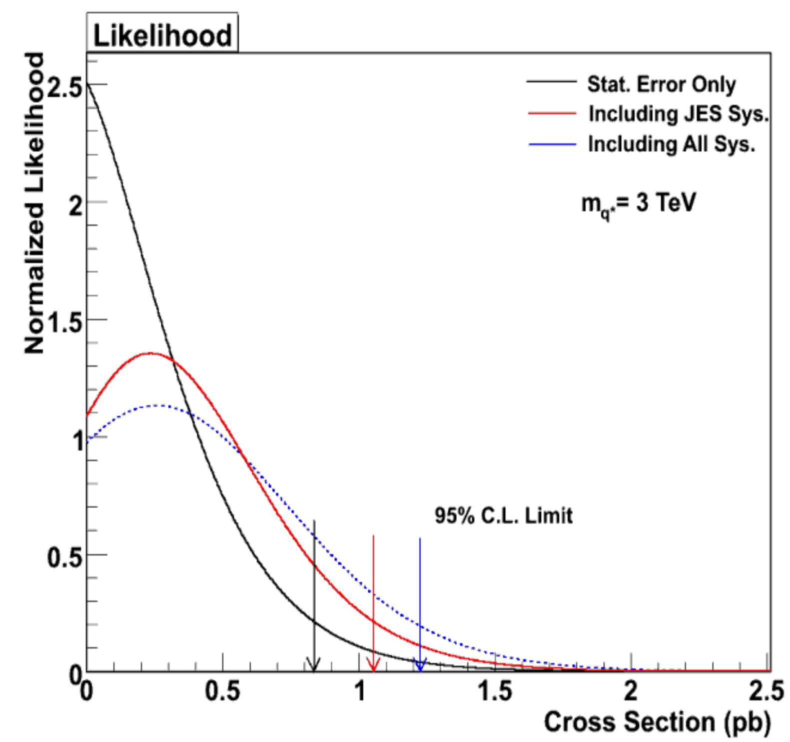


Likelihoods with Systematics (for qg)

- We convolute Poisson likehoods with Gaussian systematics uncertainties.
  - ✓ Total likelihood including systematics is broader and gives higher upper limits.

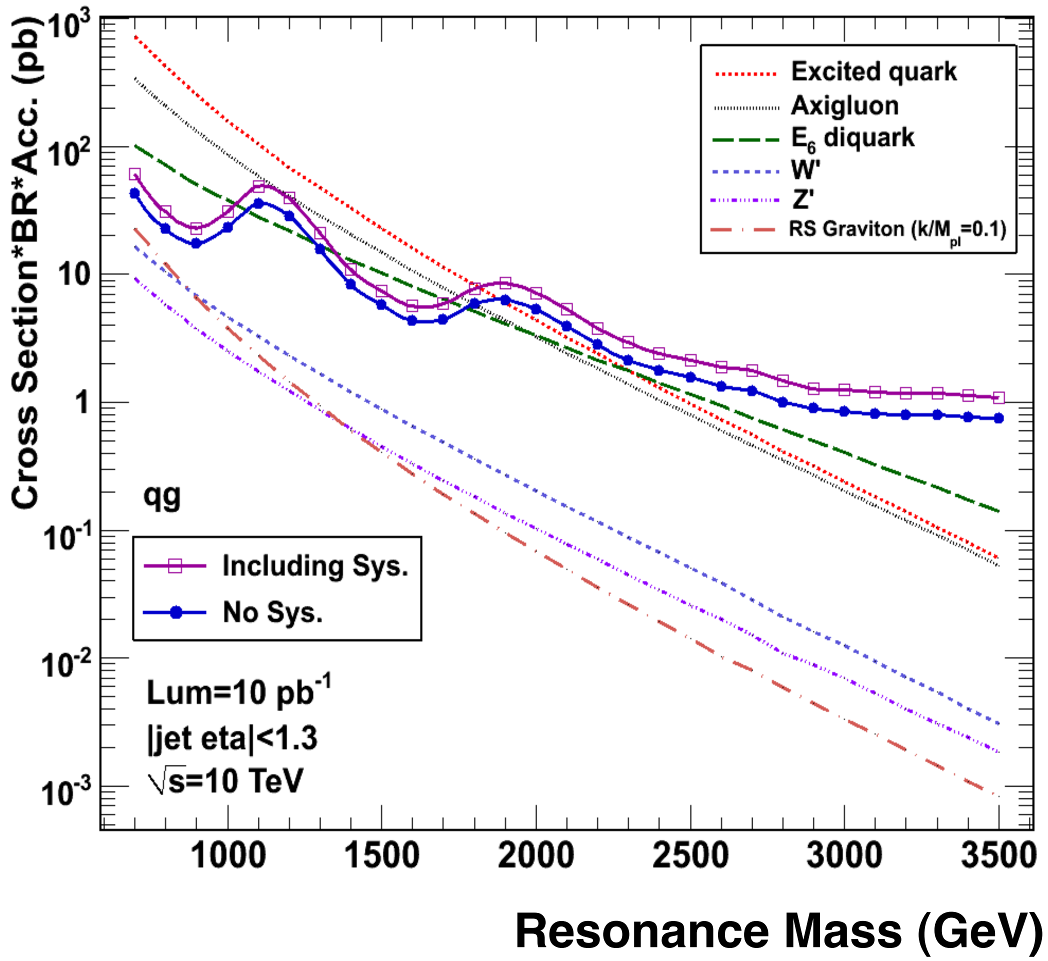


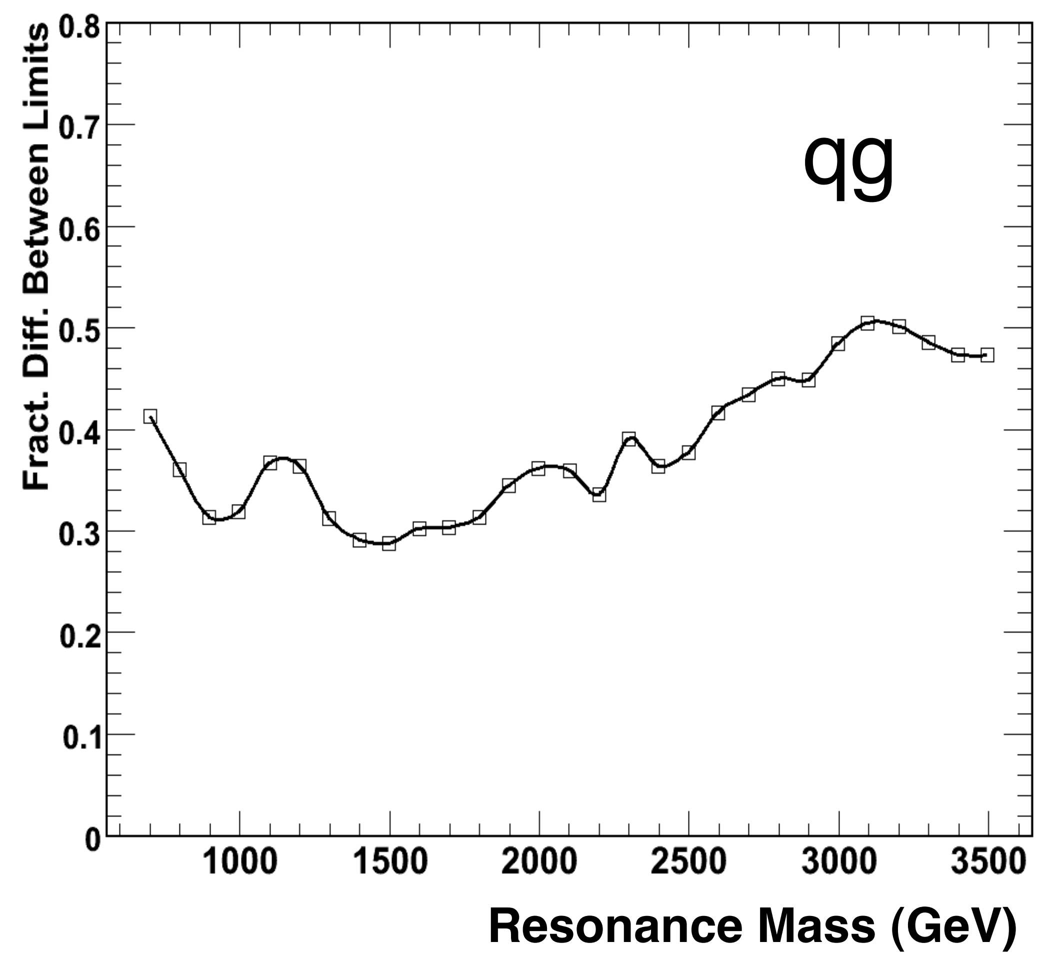




Effect of Systematics on Limit

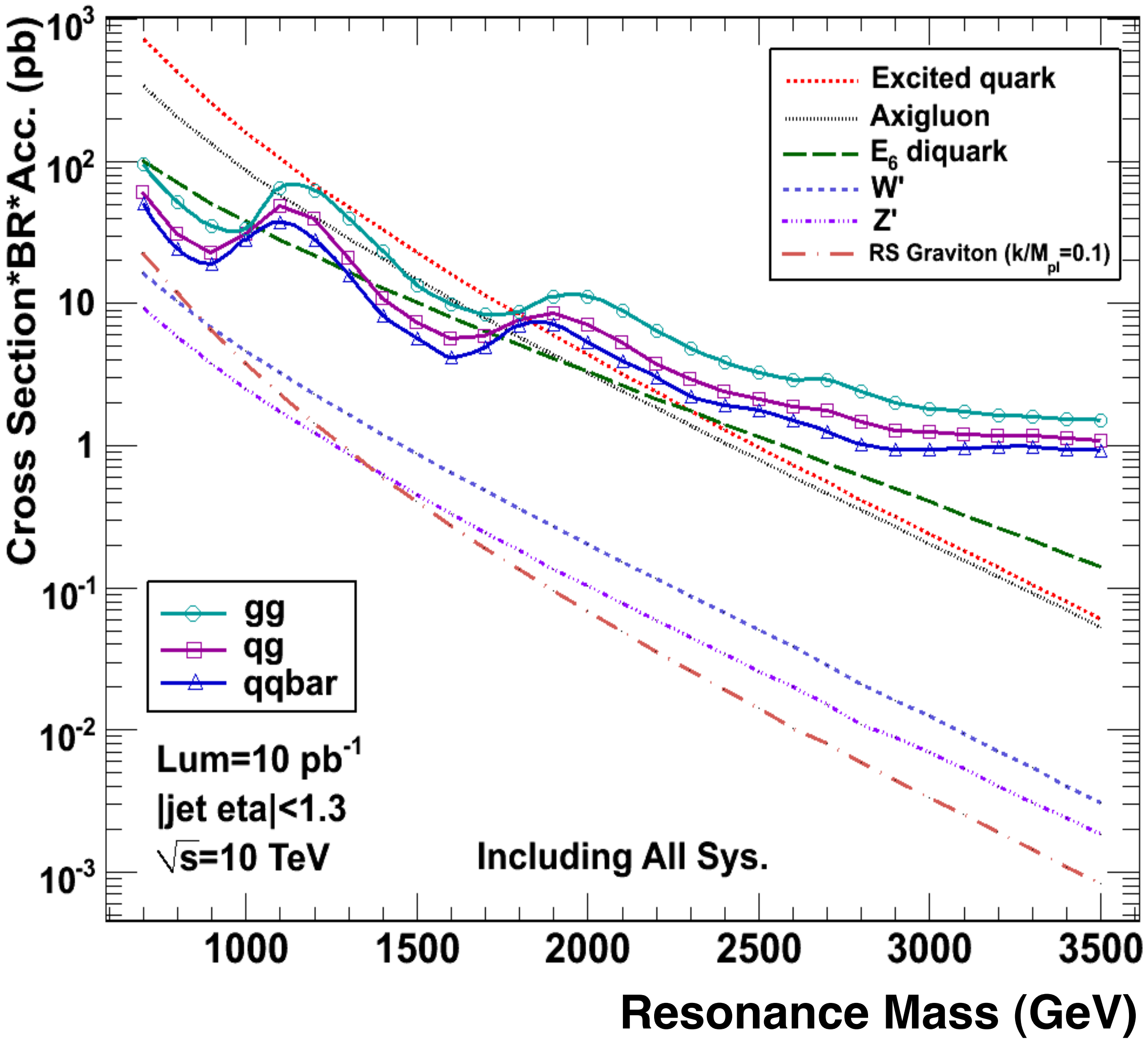
- Cross section limits increase by about 30%-50% with systematic uncertainties
  - ✓ q* mass limits decrease by about 100 GeV with systematic uncertainties.
  - ✓ Similar changes for qq and gg resonances.





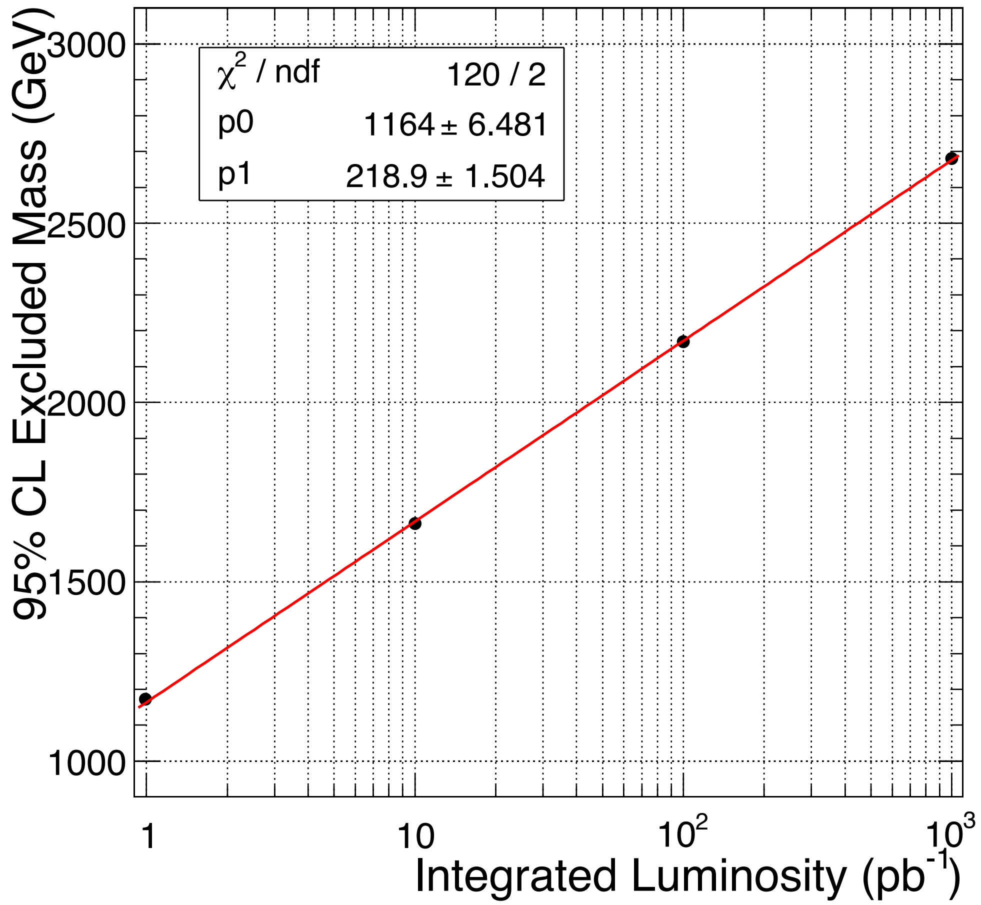
Results

- Final limits for qq, qg, gg resonaces compared to models.
  - ✓ To set limit for excited quark, qg resonance is used.
  - ✓ For axigluon, coloron and E_6 diquark, qq resonance is used.



95% C.L. Excluded Mass (TeV)		
	CMS (10 TeV & 10 pb^{-1})	CDF (1.96 TeV & 1 fb^{-1})
Excited quark	M<1.8	M<0.87
Axigluon, Coloron	M<1.8	M<1.25
E_6 diquark	M<1.1 , 1.3<M<1.7	M<0.63

Expected Limits at 7 TeV (Stat. Error Only)

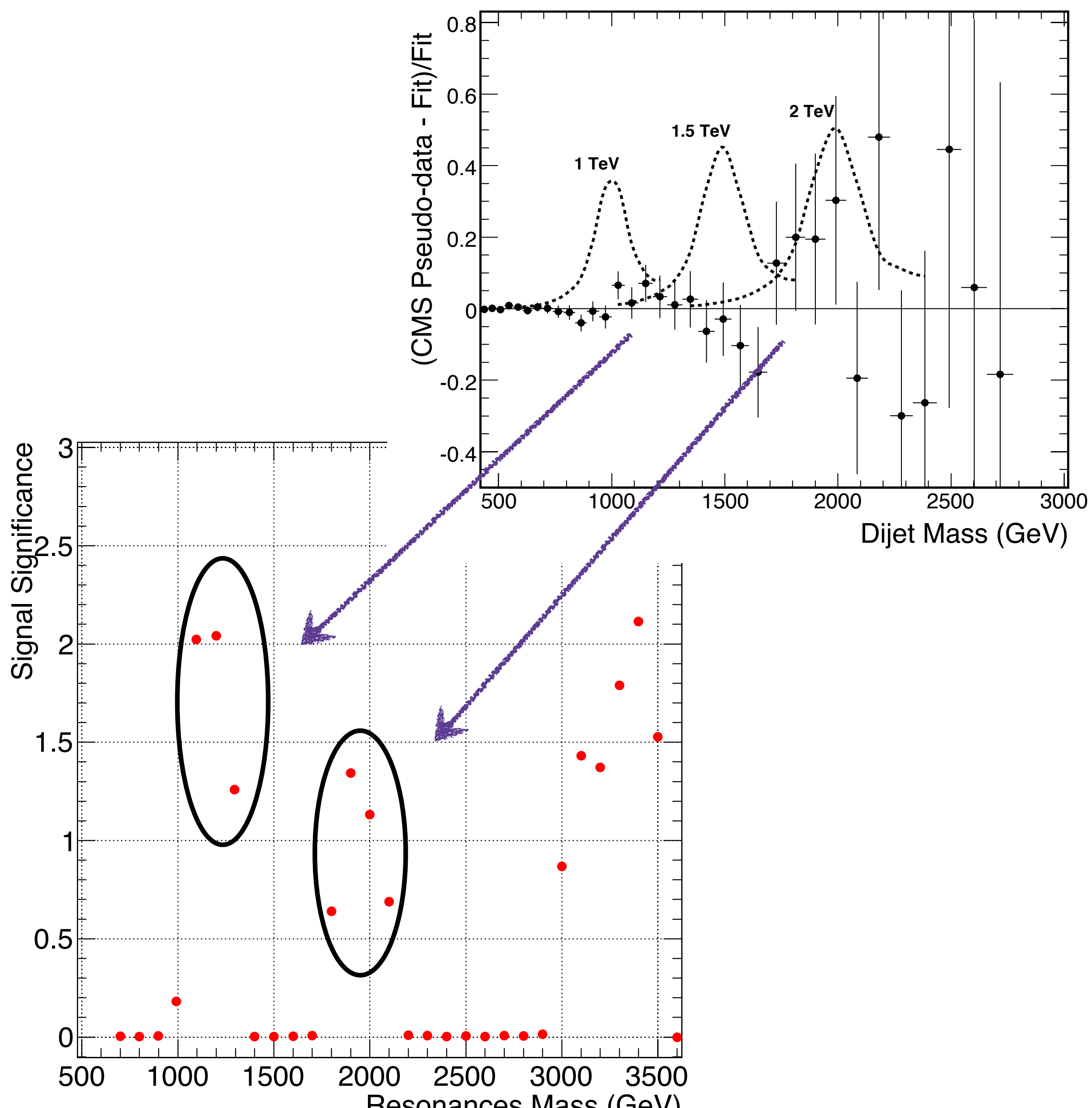


- The results are very preliminary. Study is going on.
- Sensitivity to dijet resonance with 1 pb^{-1}, 10 pb^{-1}, 100 pb^{-1} and 1 fb^{-1} at 7 TeV.
  - ✓ Statistical Error Only.
  - ✓ At 10 TeV, the systematic decreased mass limit by 0.2 TeV.
  - ✓ CMS sensitivity should be comparable to Tevatron with 1 pb^{-1}

95% C.L. Excluded Mass (TeV)					
Model	CMS (Expected at 7TeV) (Statistical Error Only)				CDF (Excluded at 1.96 TeV)
	1 pb^{-1}	10 pb^{-1}	100 pb^{-1}	1 fb^{-1}	1 fb^{-1}
Excited quark	M<1.17	M<1.66	M<2.17	M<2.68	M<0.87
Axigluon/Col.	M<1.08	M<1.64	M<2.20	M<2.70	M<1.25
E6 Diquark	N/A	M<1.78	M<2.60	M<3.35	M<0.63

Signal Significance

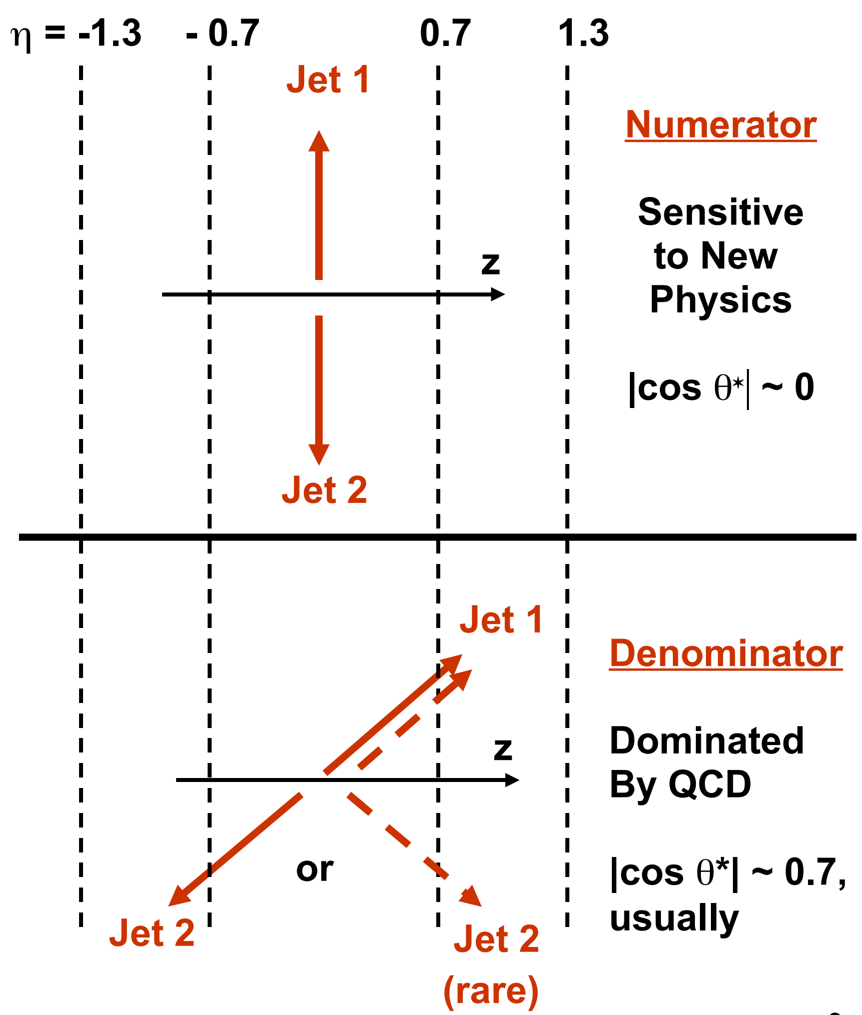
- We used likelihood ratio for signal significance estimation.
  - ✓ Maximum fluctuation with 2σ in the pseudo-data.

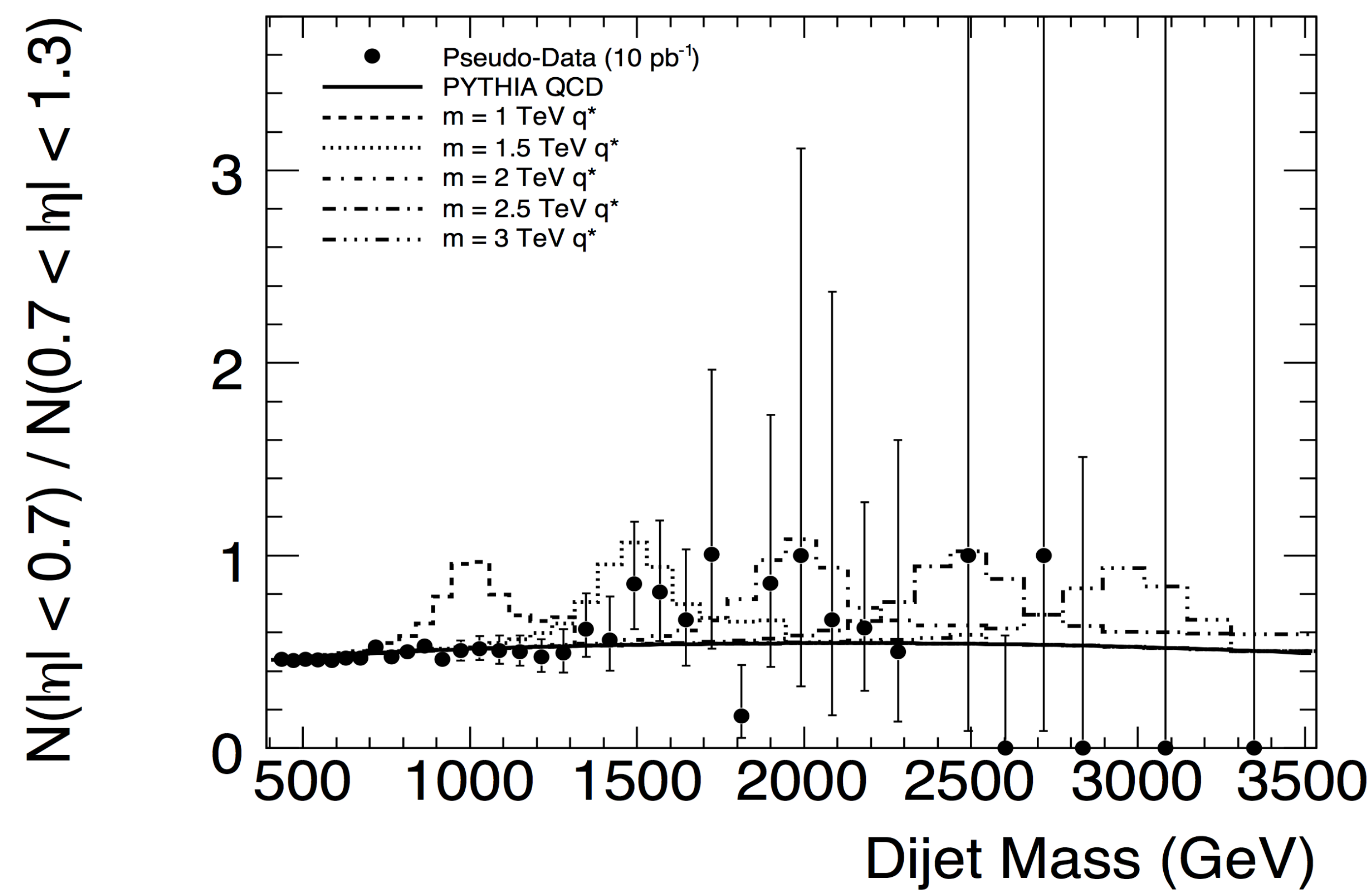


$$S_L = \sqrt{2 \ln \frac{L_{s+b}}{L_b}}$$

- If there is a evidence for dijet resonance, Dijet Ratio analysis will be very critical.

Dijet Ratio



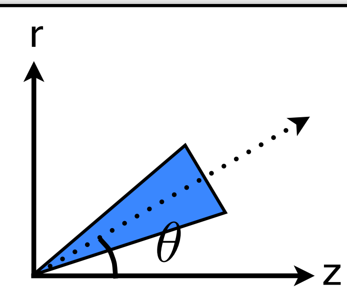


- QCD dominated by t−channel scattering which produces more forward jets than central jets.

QCD:

$$\frac{d\Gamma}{d\cos\theta} \sim \frac{1}{(1-\cos\theta)^2}$$

$\theta \equiv$ jet polar angle in CM frame



Plots from
Dan Miner & Jim Hirschauer

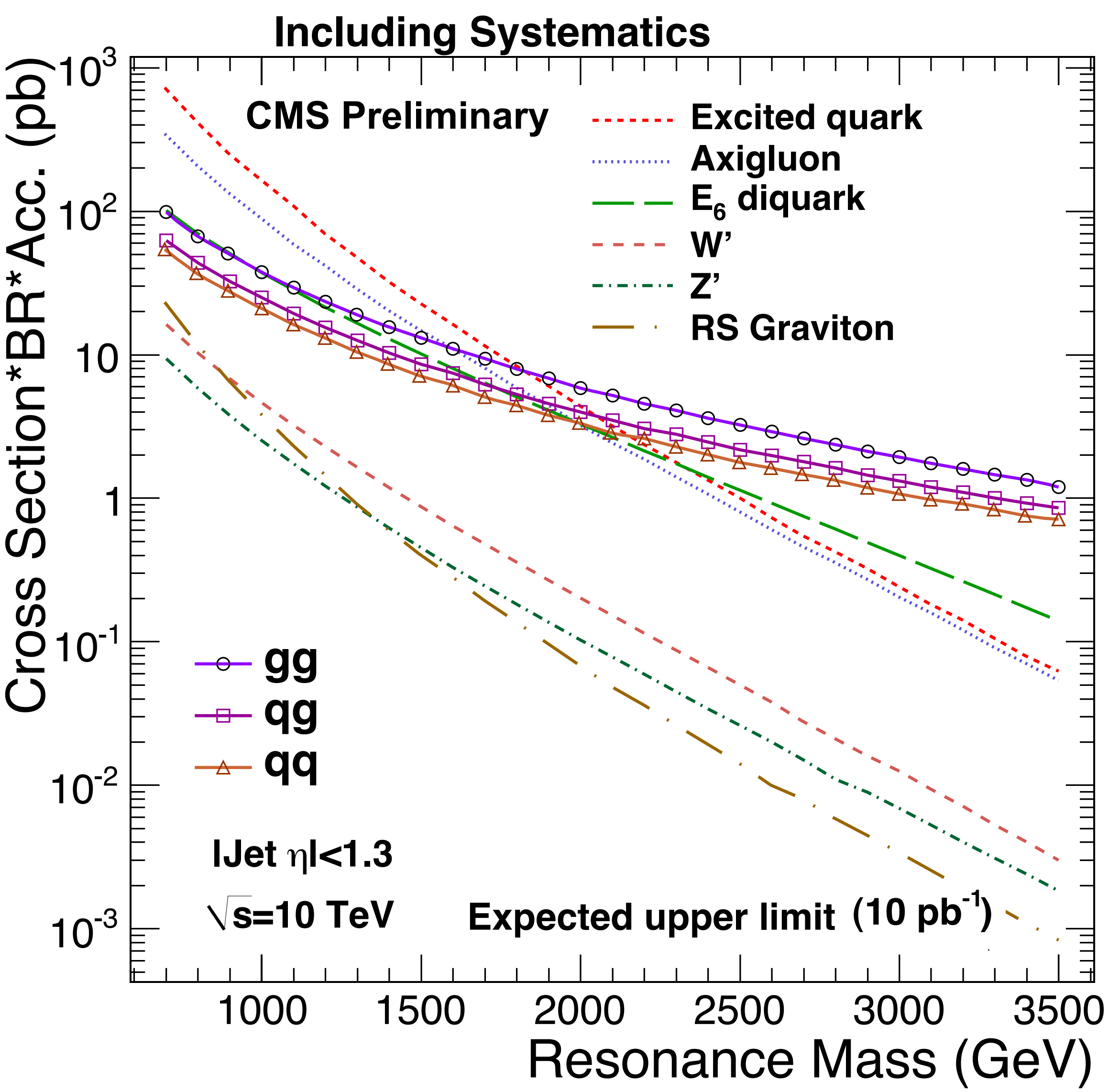
Conclusion

- We are ready to search for new physics at the TeV scale using dijets.
- We plan to search separately for qq, qg and gg resonances.
- CMS should be sensitive to Excited quarks, Axigluon/Coloron and E_6 Diquark up to 2 TeV at 95% C.L. with 10 pb^{-1} for 10 TeV collisions
- LHC will operate at 7 TeV soon. We will be able to search for new physics with data.
  - ✓ High priority analysis for ICHEP time scale (with 1-5 pb^{-1}).
  - ✓ We expect to have comparable (maybe better) results to Tevatron in early data.
- New discoveries are possible even in early CMS data.

Back-Up Slides

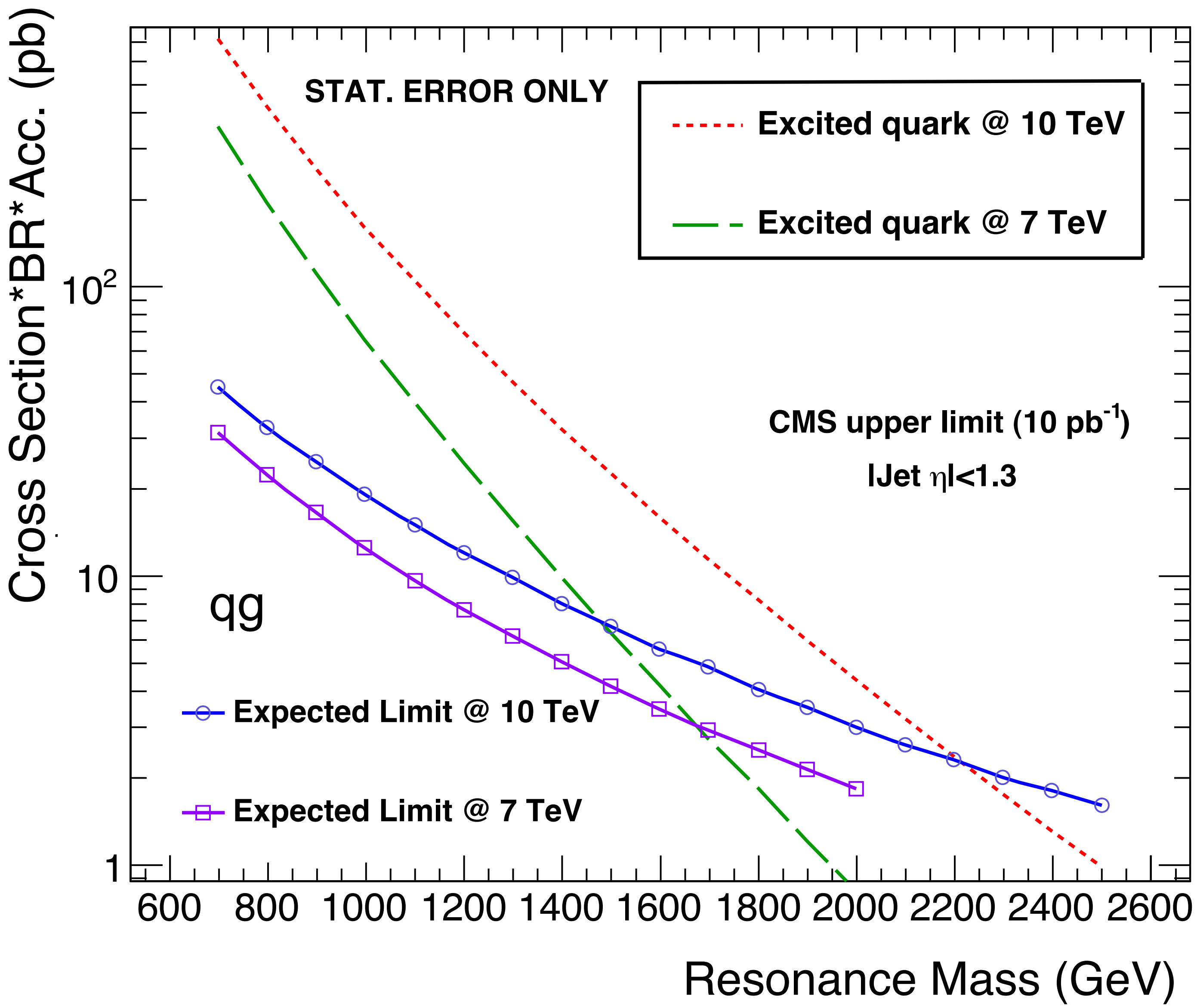
Expected Limit at 10 TeV

- Final limits for qq, qg, gg resonaces compared to models.
  - ✓ To set limit for excited quark, qg resonance is used.
  - ✓ For axigluon, coloron and E_6 diquark, qq resonance is used.



95% C.L. Excluded Mass (TeV)		
	CMS (Expected) (10 TeV & 10 pb^{-1})	CDF (Excluded) (1.96 TeV & 1 fb^{-1})
Excited quark	M<2	M<0.87
Axigluon, Coloron	M<2	M<1.25
E_6 diquark	M<2	M<0.63

Effect of Energy on Limit



- Expected limit for Excited quark;
  - ✓ 2.2 TeV @ 10 TeV
  - ✓ 1.7 TeV @ 7 TeV