Dijet Production at DØ

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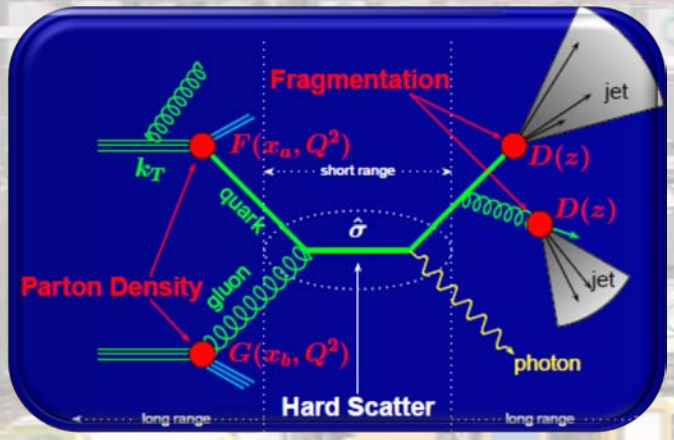
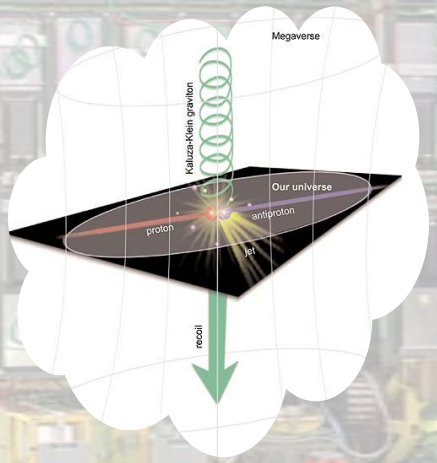
for the DØ Collaboration





SUSY09
Northeastern
June 6, 2009

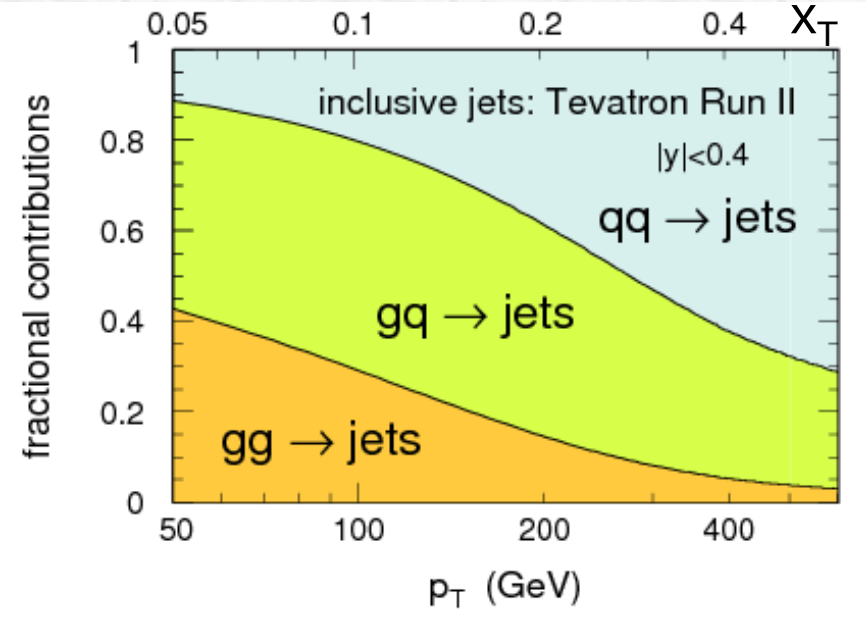
Outline

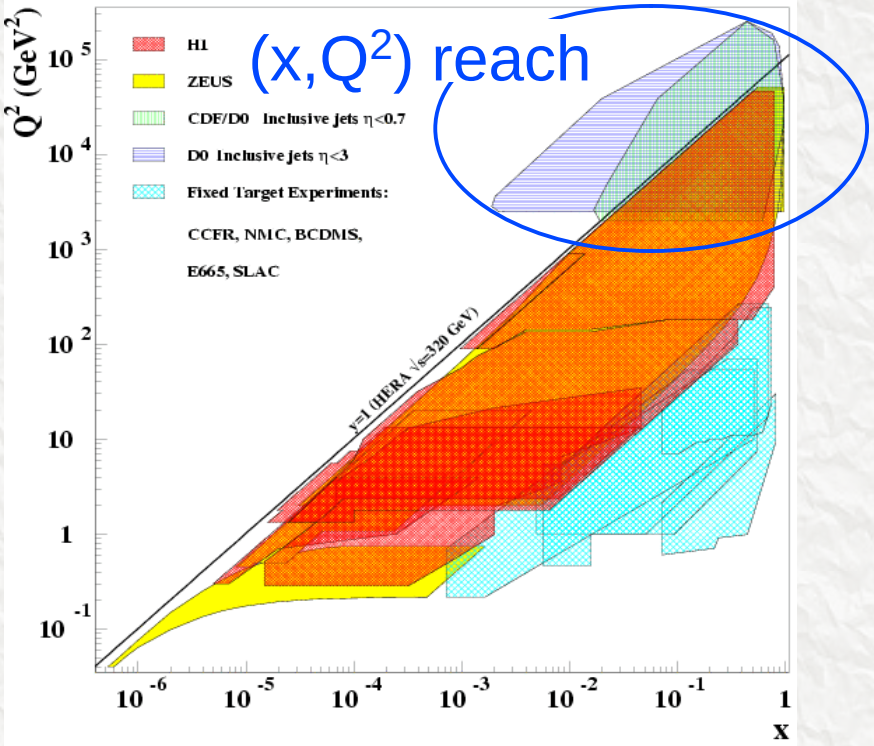
- Introduction
- Tevatron Run II and DØ Detector
- Jets @ DØ
  - Reconstruction, Calibration, and Performance
- Dijet Mass Cross Sections
- Dijet Angular Distributions
- Comparisons to QCD
- Limits on BSM Models
- Summary

High-p_T Jets

- **Confront pQCD calculations**
  - **NLO predictions reliable @ 10% level**
- **Sensitive to dynamics, PDFs, α_s**
  - **Reach to high-x gluons**

Large kinematic reach



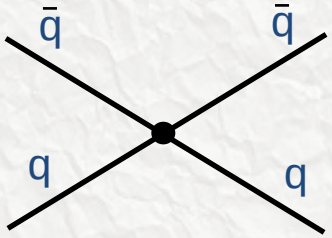


- **Sensitivity to new physics (e.g., quark substructure, new particles decaying into jet final states, extra dimensions, ...)**

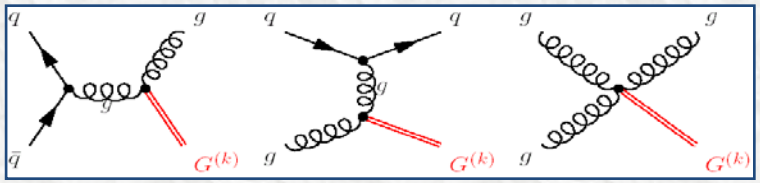
Compositeness and Large Extra Dim.

- **Quark Compositeness:**
  - **For $\sqrt{\hat{s}} << \Lambda$ the composite interactions can be represented by contact terms:**

$$L_{qq} = \pm \frac{g^2}{2\Lambda^2} \bar{q}_L \gamma^\mu q_L \bar{q}_L \gamma_\mu q_L$$



    - **Eichten, Lane, Peskin, PRL 50, 811 (1983)**
    - **$\Lambda=\infty$ → point-like quarks**
    - **Λ=finite → substructure of mass scale Λ**

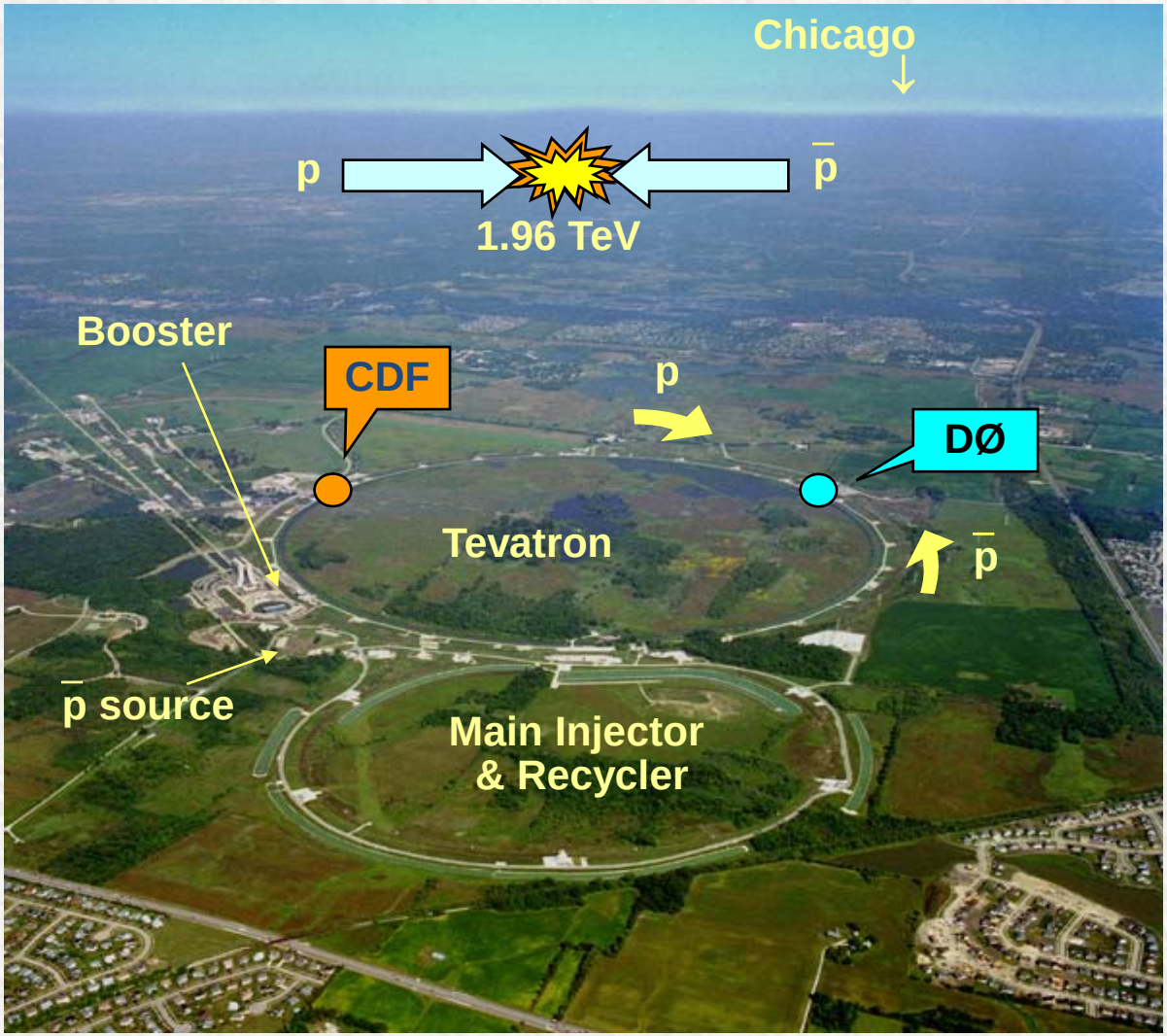


- **Large Extra Dimensions (LED)**
  - **In the ADD Model:**
    - **N.Arkani-Hamed, S.Dimopoulos, G.R.Dvali, PLB 429, 263 (1998), *et al.***
    - **3+n spacelike dimensions**
    - **n dimensions compactified to a n-torus with radius R**
      - **R~1 mm for n=2, R~3 nm for n=3, …**
    - **All SM fields are confined to a 3-dim membrane (*brane)***
    - **Only gravity propagates in all dimensions *(bulk)***
  - **Mass hierarchy problem is solved**
  - **The unification scale can be lowered to M_s~TeV**

TeV^{-1} Extra Dimensions

- **In the TeV^{-1} Extra Dimension Model**
  - **K.Dienes, E.Dudas, T.Gherghetta, Nucl. Phys. B 537, 47 (1999)**
  - **A.Pomarol, M.Quirós, PLB 438, 255 (1998)**
  - **I.Antoniadis, K.Benakli, M.Quirós, PLB 460, 176 (1999), *et al.***
- **Matter resides on a *p*-brane (spacelike dim *p*>3):**
- **Fermions are confined to 3-dim world**
- **SM gauge bosons can also propagate in the extra (*p*-3) dimensions**
  - **SM cross sections are modified due to the exchange of virtual Kaluza-Klein excitations ($M_n = \sqrt{M_{SM}^2 + n^2/R^2}$, *n*=1,2,…) of the SM gauge bosons (e.g., gluons) through the ED**
  - **Compact dimension R=1/M_C (M_C is the compactification scale)**
    - **the 95% CL limit: M_C=6.6 TeV from combined LEP data**

Tevatron Complex



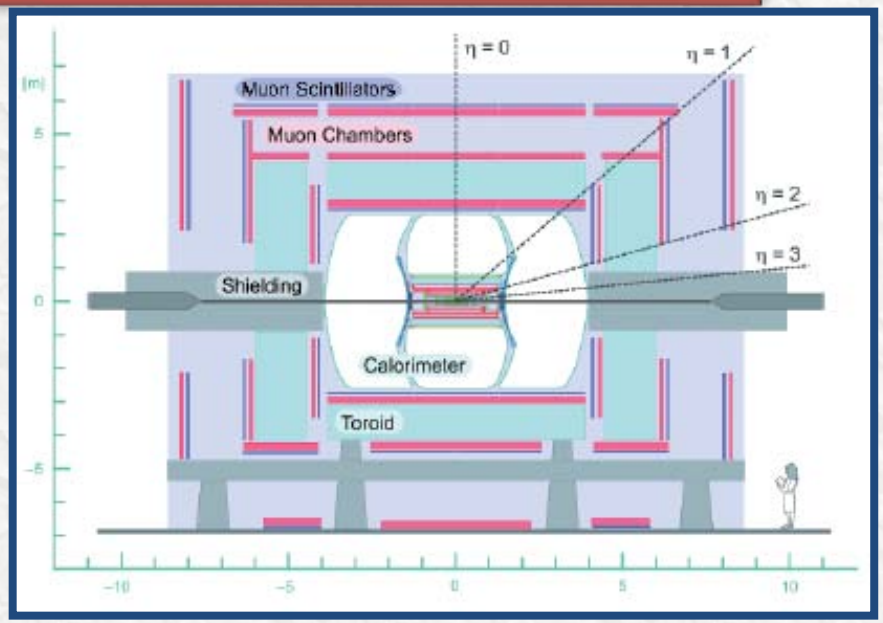
Run I
1992-1996
E_{CM} = 1.8 TeV
~120 pb^{-1}
(0.63 TeV ~600 nb^{-1})

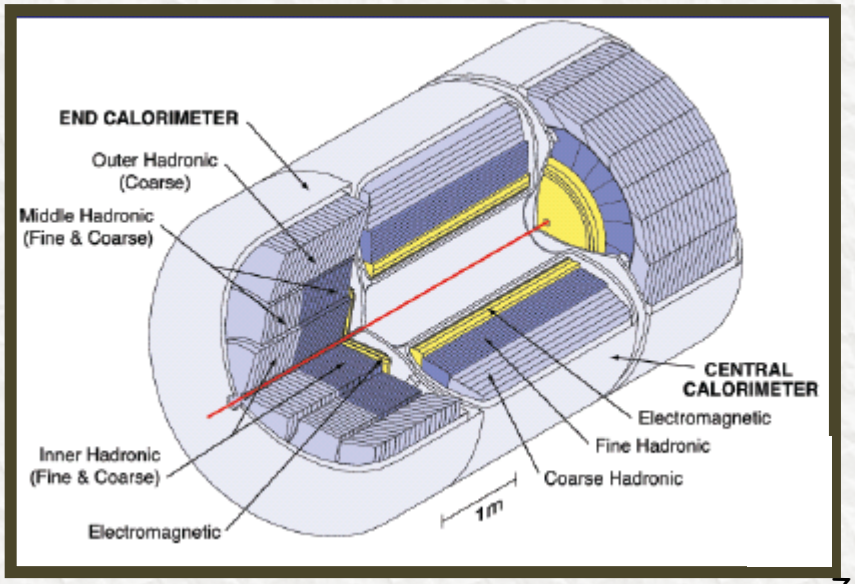
Run IIA
2002-2005
E_{CM} = 1.96 TeV
~ 1.5 fb^{-1}

Run IIB
2006-
E_{CM} = 1.96 TeV
~ 5.5 fb^{-1}

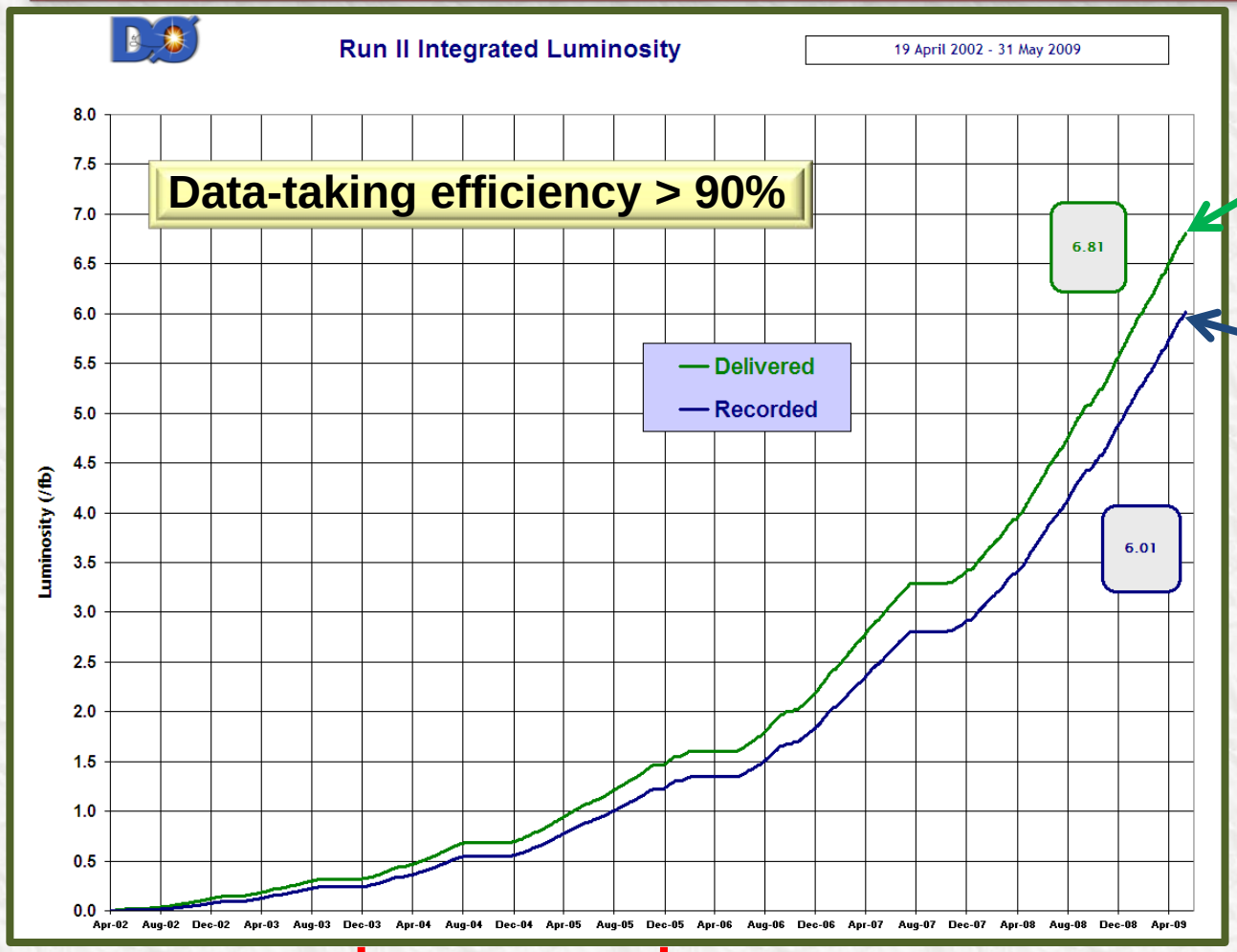
DØ Detector

- Multipurpose Detector
  - Silicon Microstrip and Scintillating Fiber Tracker
  - 2-T Superconducting Solenoid
  - EM and Hadronic Calorimeters
    - Uranium – Liquid Argon
    - Coverage: $|\eta|<4.2$ ($\theta \sim 2^0$)
    - Finely segmented
    - Compensating $e/\pi \sim 1$
  - Muon Detectors





Luminosity



Data-taking efficiency > 90%

Delivered 6.8 fb^{-1}

Recorded 6 fb^{-1}

Analyses presented here use $\int L \sim 0.7$ fb^{-1}

Dijet Data Selection

- **Online Selection:**
  - **Single inclusive jet triggers with p_T thresholds:**
    - **15, 25, 45, 65, 95, and 125 GeV**
  - **Dijet mass triggers with M_{jj} thresholds: 250 and 430 GeV**
- **Offline Selection:**
  - **Jets reconstructed with the Run II Midpoint Cone Jet Algorithm with R_{cone} = 0.7**
  - **Jet energies are corrected back to the particle (hadron) level**
  - **Events required to have:**
    - **Z position of the primary vertex ± 50 cm of detector center**
    - **Missing p_T/leading jet p_T > 0.7 – cosmics cleanup**
    - **at least two jets with p_T > 40 GeV**

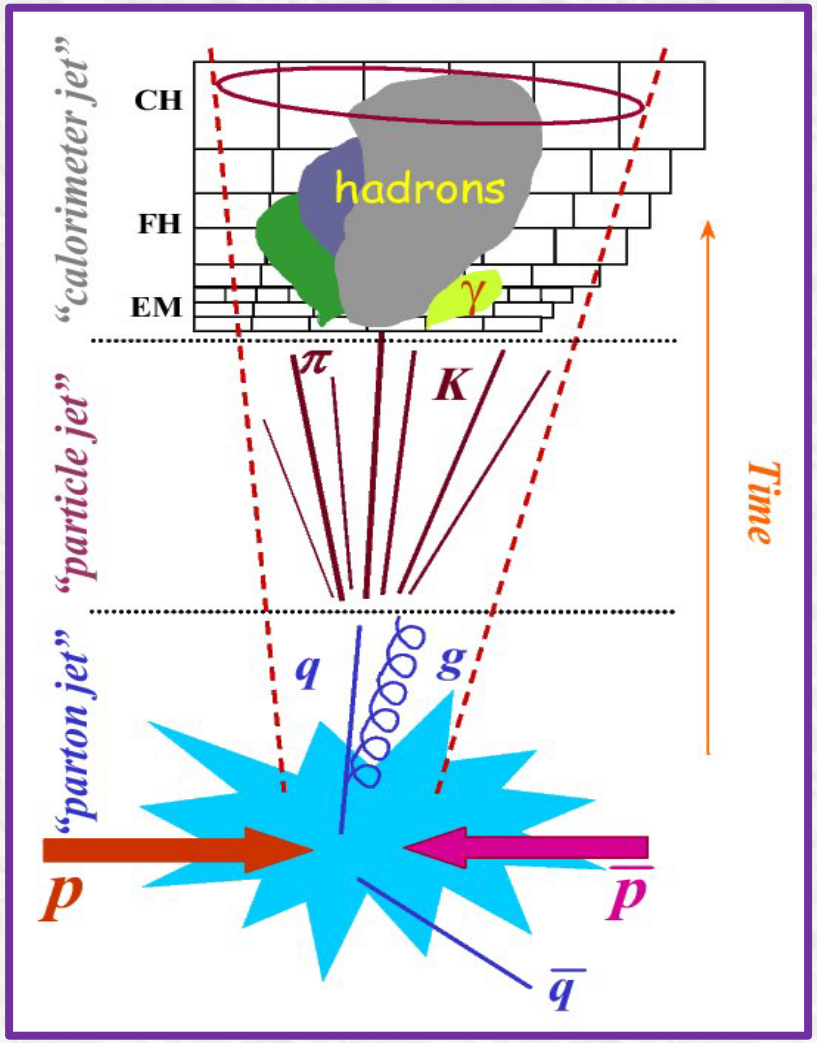
Jet Energy Calibration

- **Jet energies are calibrated to *particle level***

$$p_T^{part} = \frac{p_T^{calo} - Offset}{R_{response} \times \text{Out_of_Cone_Showering}}$$

  - **Offset: noise, pile-up, multiple $p\bar{p}$ interactions**
  - **$R_{response}$: fraction of particle jet energy deposited in the calorimeter**
    - **measured in situ using p_T balance in γ/Z+jet events**
  - **Out of Cone Showering: account for energy emitted inside (outside) the jet cone but showered outside (inside) the calorimeter jet cone**

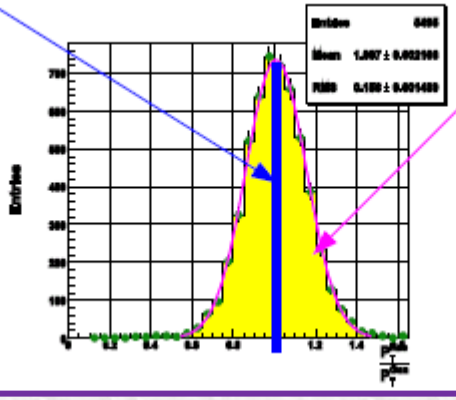
Jet Energy Uncertainty ~ 1%



Jet Energy Resolution

Perfect detector:

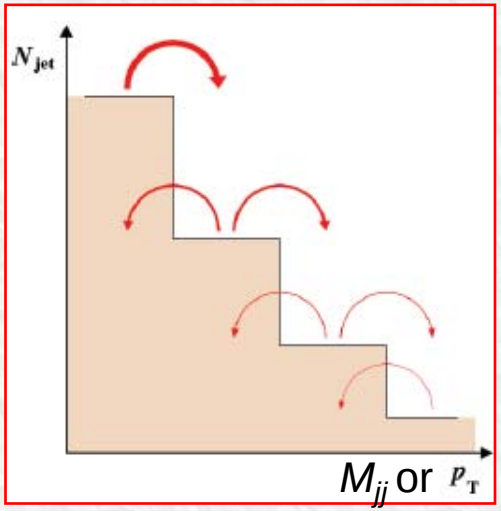
$$x = \frac{p_T^{observed}}{p_T^{particle}} = 1$$



Real detector:

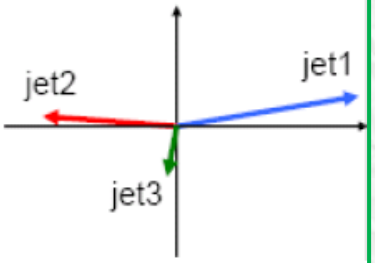
$$f = A\, e^{\frac{-(x-1)^2}{2\sigma^2}}$$

$$Resolution = \sigma(f)$$



- In true dijet events jets should balance exactly in p_T.
  In reality we usually see a small third jet contribution and a non-zero asymmetry in p_T given by:

$$A = \frac{(p_T^{jet1} - p_T^{jet2})}{(p_T^{jet1} + p_T^{jet2})}$$

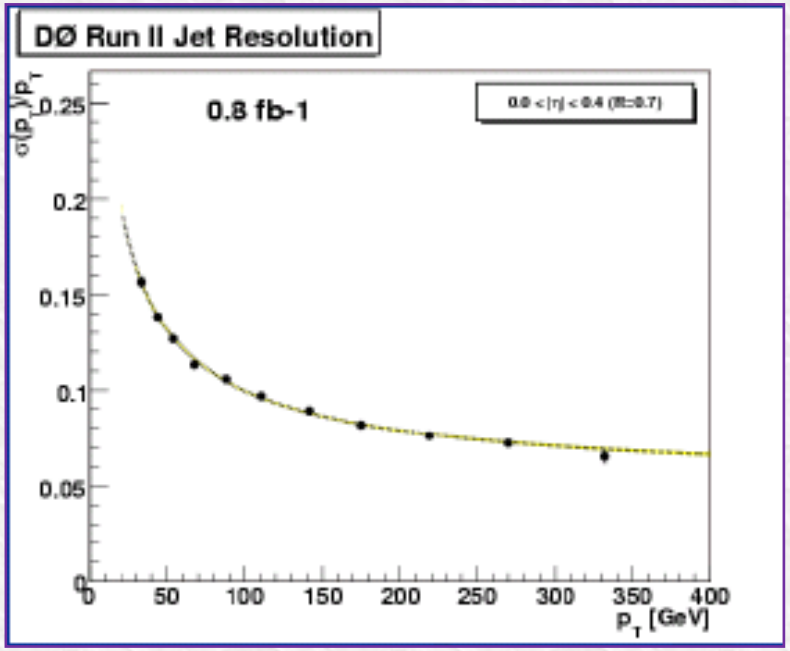


where jet1 and jet2 are

the 2 leading jets in the event

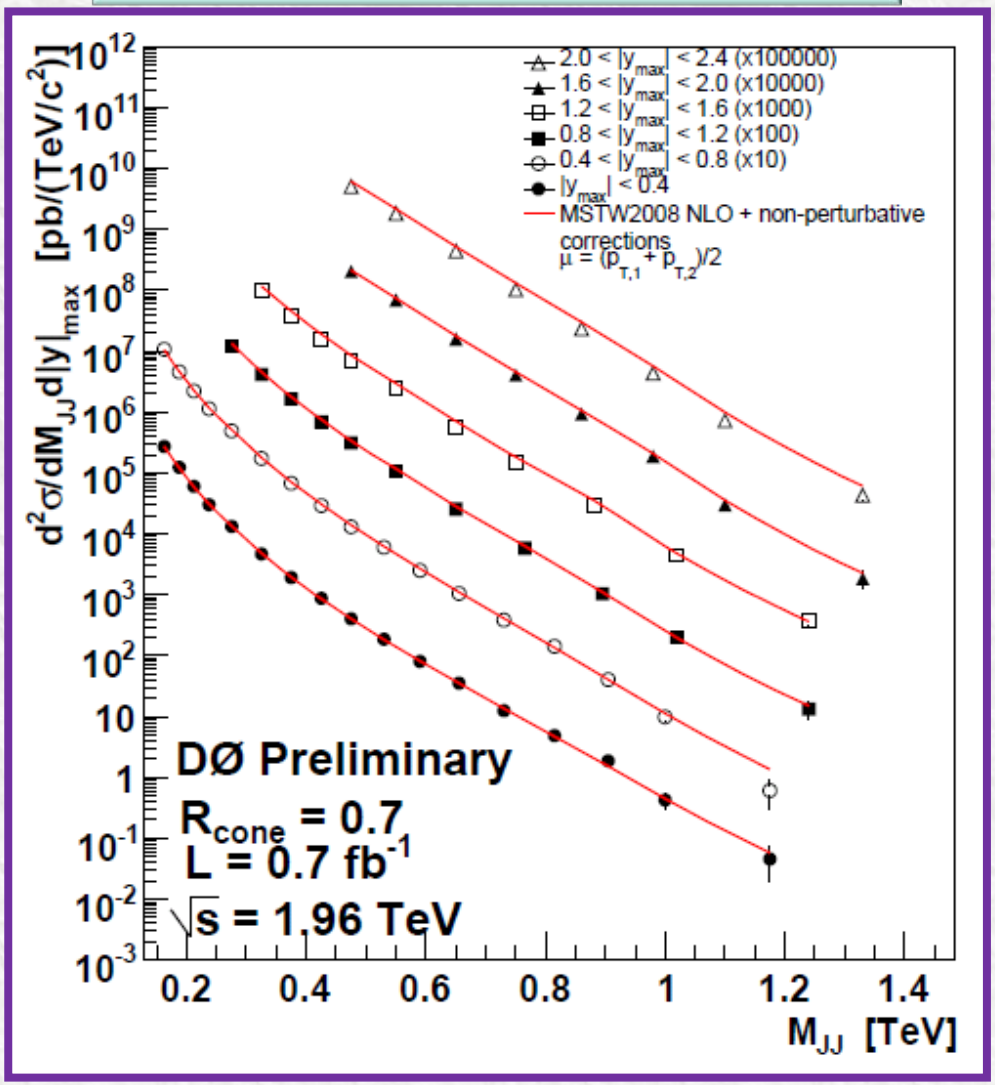
- The calorimeter resolution is related to the width of the asymmetry distribution by: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_A$

where σ_A is a sigma of the asymmetry distribution

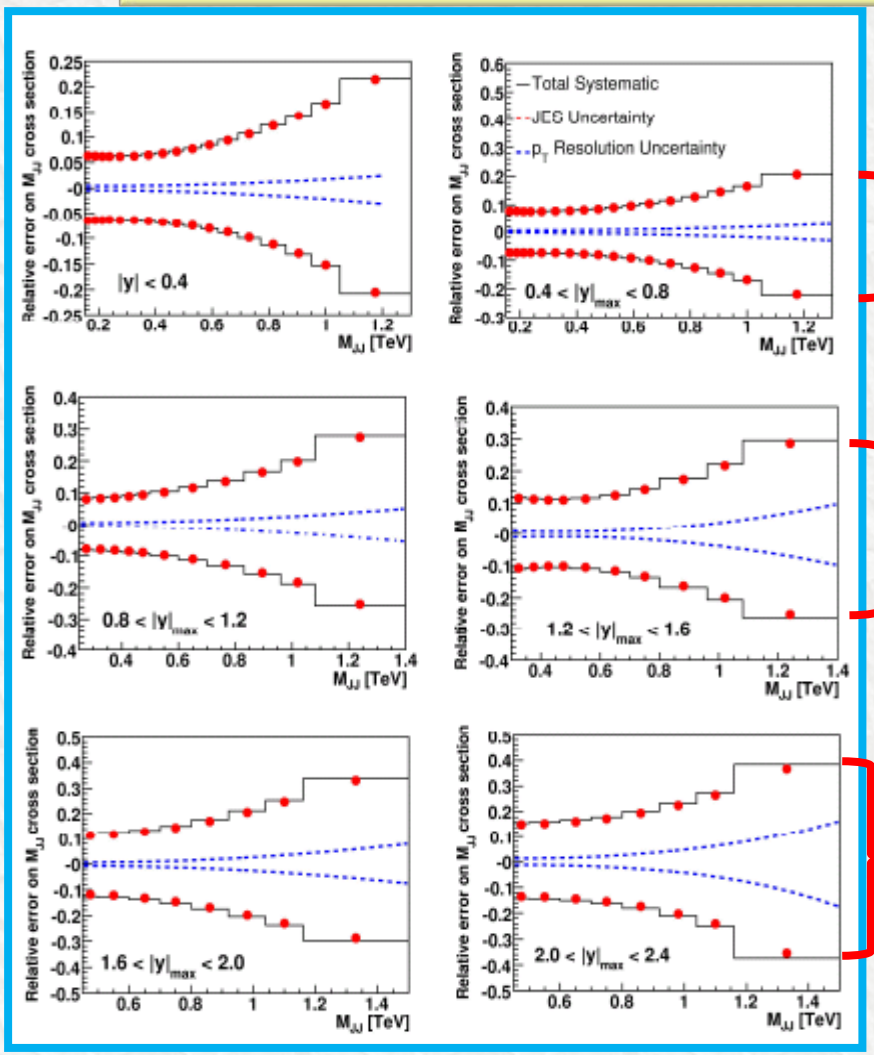


Dijet Mass Cross Sections

Unfolded Cross Sections



Systematic Uncertainties *(dominated by Jet Energy Scale)*



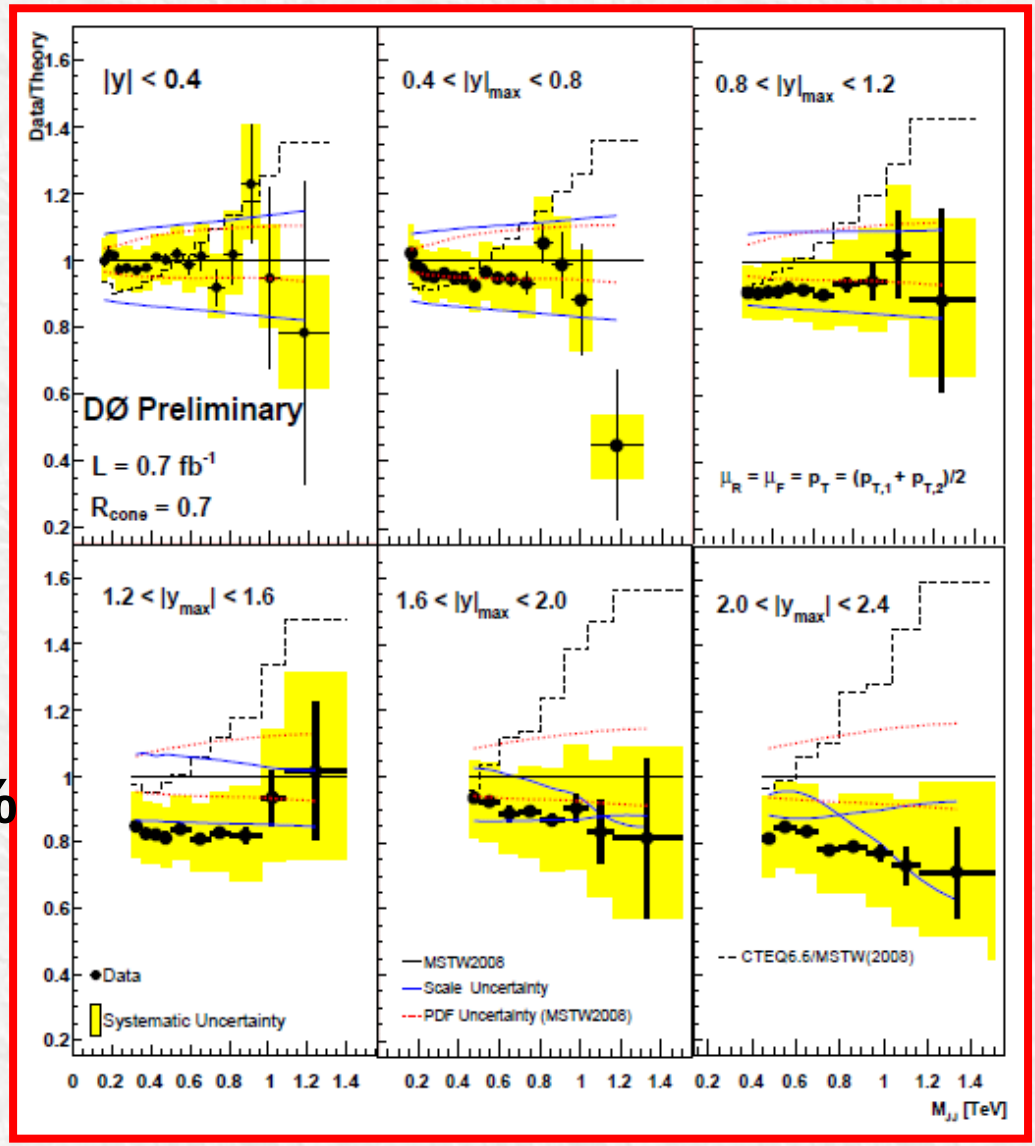
± 20%

± 30%

± 40%

Dijet Mass: Data vs. Theory

- **Theory**
  - **NLO pQCD (NLOJET++)**
  - **$\mu_R = \mu_F = \langle p_T \rangle = (p_{T1}+p_{T2})/2$**
  - **PDF: MSTW2008**
  - **Hadronization+Underlying Event corrections applied to the theory (5-20%)**
- **Theory uncertainties**
  - **PDFs: (MSTW2008) 5-15%**
  - **Scale ($\langle p_T \rangle/2$–$2\langle p_T \rangle$): 10-15%**
- **Luminosity: ± 6%**
- **Good agreement with theory**

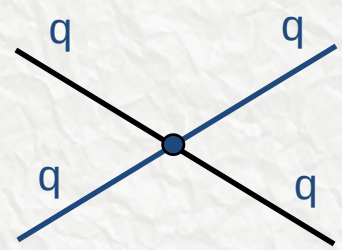


Dijet Angular Distributions

$d\sigma \sim$ [QCD + Interference + Compositeness]

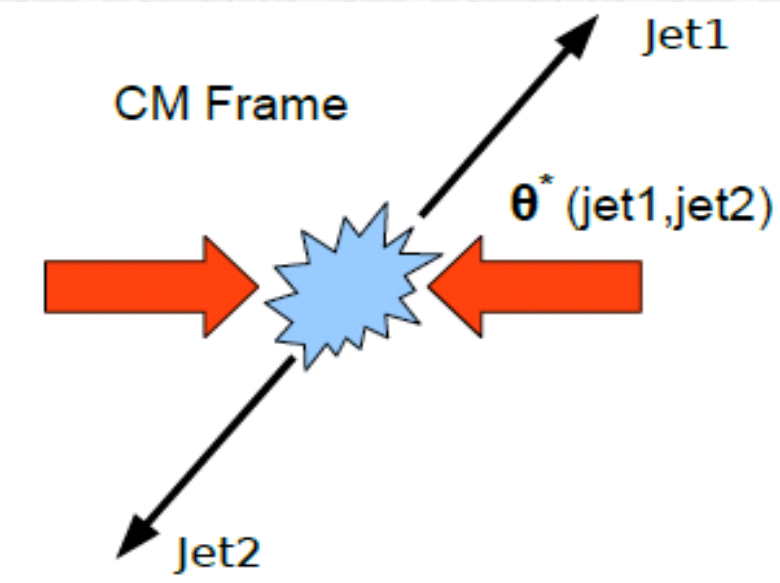
$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}}\cdot\frac{\hat{u}^2}{\Lambda^2} \qquad \left(\frac{\hat{u}}{\Lambda^2}\right)^2$$

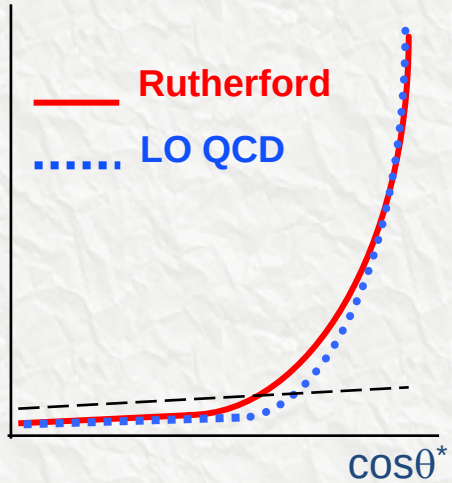
$d\sigma \sim 1/(1-\cos\theta^*)^2$ angular distribution



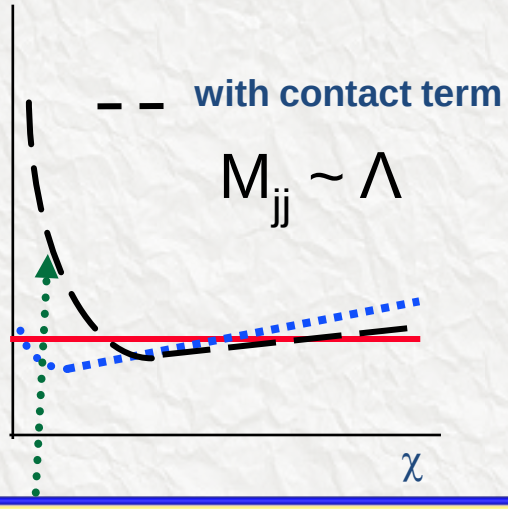
$\sqrt{\hat{s}} << \Lambda$

$d\sigma \sim (1+\cos\theta^*)^2$ angular distribution





$\Longrightarrow$



dN/dχ sensitive to contact interactions

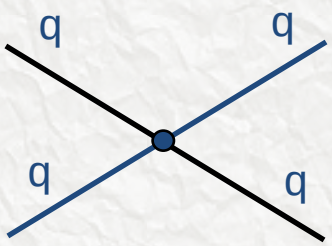
Dijet Angular Distributions

$d\sigma \sim$ [QCD + Interference + Compositeness]

$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}}\cdot\frac{\hat{u}^2}{\Lambda^2} \qquad \left(\frac{\hat{u}}{\Lambda^2}\right)^2$$

$d\sigma \sim 1/(1-\cos\theta^*)^2$ angular distribution

$d\sigma \sim (1+\cos\theta^*)^2$ angular distribution



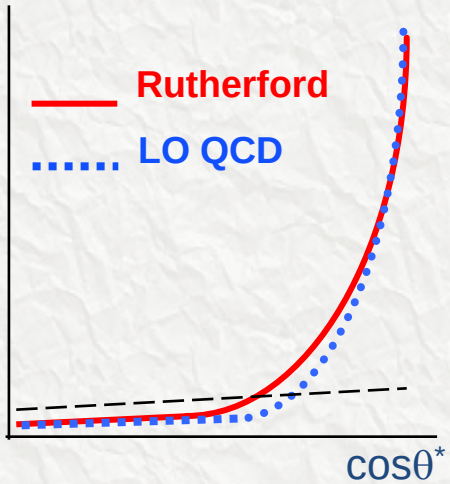
$$\sqrt{\hat{s}} << \Lambda$$

From $\cos\theta^*$ variable to χ

$$\chi = e^{2|y^*|}$$

$$y^* = \frac{1}{2}(y_1 - y_2)$$

$$y_{boost} = \frac{1}{2}(y_1 + y_2)$$



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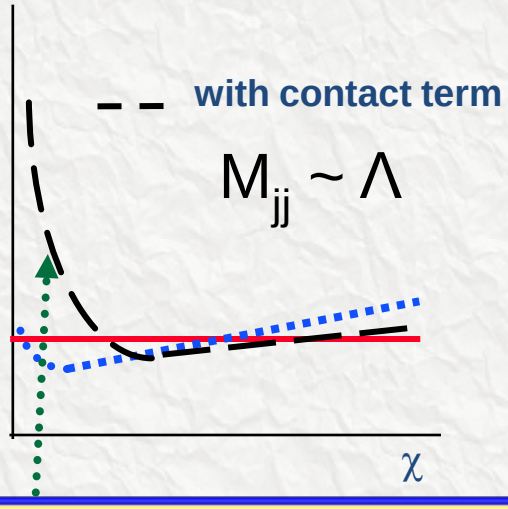
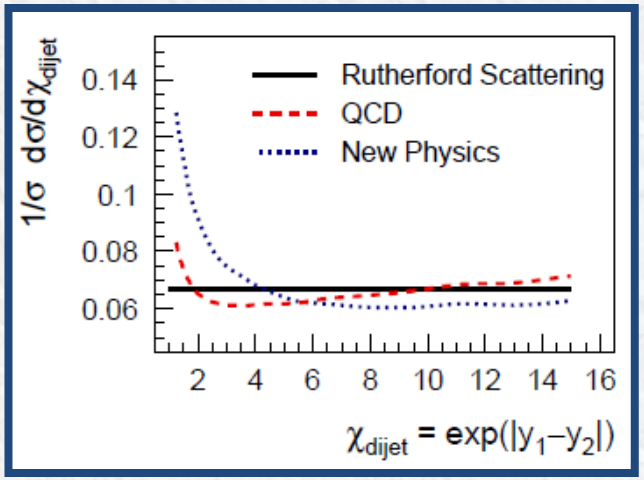


dN/dχ sensitive to contact interactions

Search for BSM Signatures

- **BSM signatures will populate the low-χ region at high M_{jj}:**
  - **Compositeness (scale Λ)**
  - **ADD Large Extra Dimensions (scale M_s)**
  - **TeV^{-1} Extra Dimensions (scale M_C)**



- **Theory implementation:**
  - **Multiply NLO/LO QCD scale factor to New Physics LO:**

$$\sigma_{NP}^{NLO} = \sigma_{QCD}^{NLO} \cdot \frac{\sigma_{NP}^{LO}}{\sigma_{QCD}^{LO}} = \sigma_{NP}^{LO} \cdot \frac{\sigma_{QCD}^{NLO}}{\sigma_{QCD}^{LO}}$$

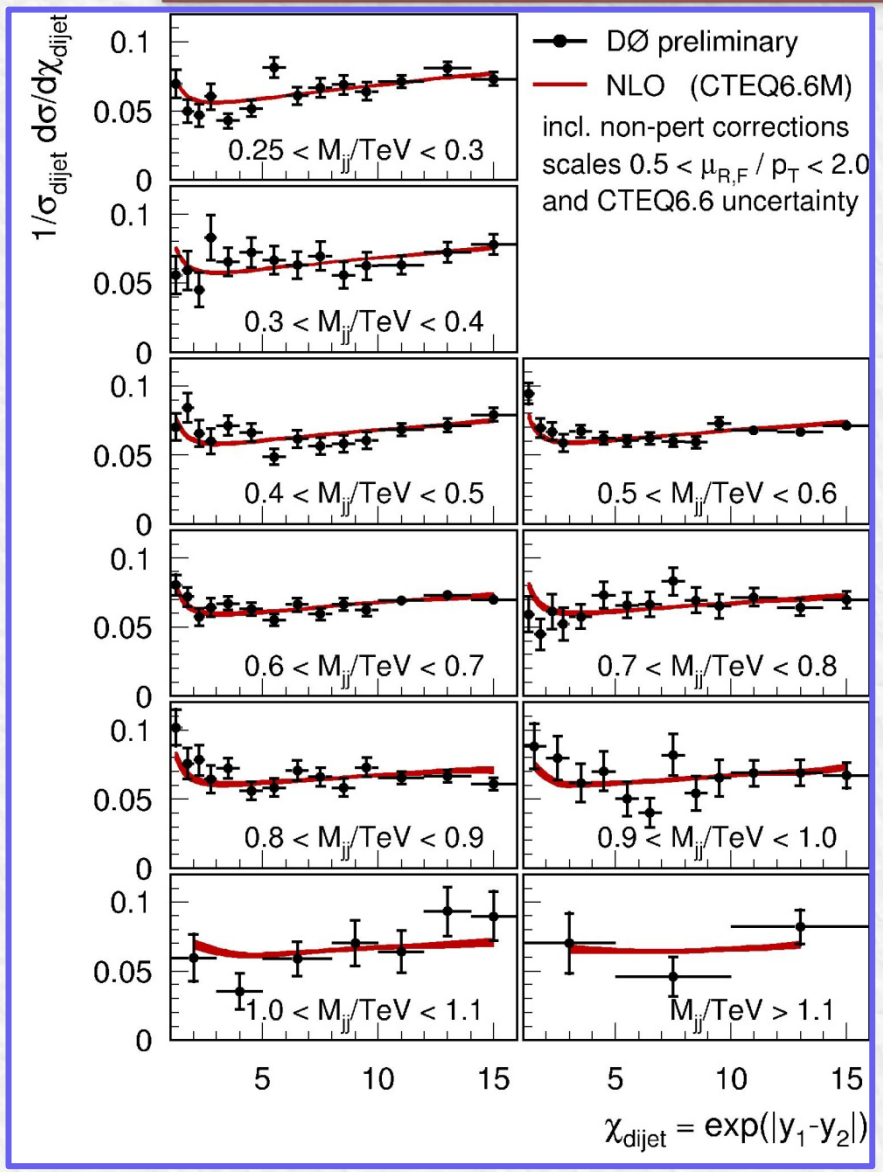
$$\sigma_{NP} = ME_{SM} + \xi \cdot ME_{\text{int}} + \xi^2 \cdot ME_{NP}$$

$$\xi = \lambda / \Lambda^2 \text{ (QC)}$$

$$\xi = 1 / M_s^4 \text{ (ADD LED)}$$

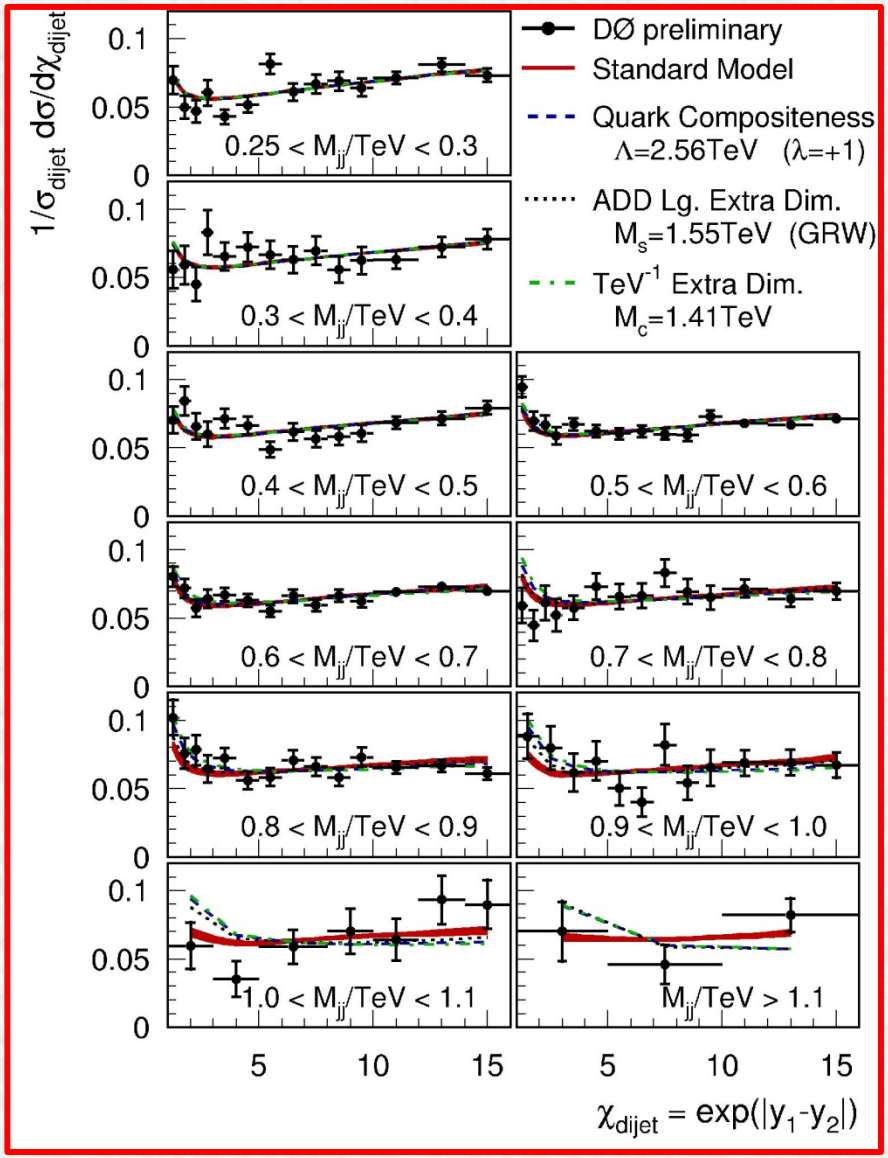
$$\xi = 1 / M_C^2 \text{ (TeV}^{-1}\text{ ED)}$$

Dijet Angular Dist. – Data vs. QCD



- **Theory**
  - **NLO pQCD (NLOJET++)**
  - **$\mu_R = \mu_F = \langle p_T \rangle = (p_{T1}+p_{T2})/2$**
  - **PDF: CTEQ6.6M**
  - **Hadronization+Underlying Event corrections applied to the theory**
- **Theory uncertainties:**
  - **From PDFs and Scale are included in the theory line (i.e., very small)**
- **Good agreement with theory**

Dijet Angular Dist. – BSM Searches



- **Compositeness Matrix Elements:**
  - **P.Chiappetta & M.Perrottet, PLB 253, 489 (1991)**
  - **K.D.Lane, arXiv:hep-ph/9605257**
- **ADD Large Extra Dimensions ME:**
  - **D.Atwood, S. Bar-Shalom & A.Soni, PRD 62, 056008 (2000)**
- **TeV^{-1} Extra Dimensions ME:**
  - **K.Cheung, G.Landsberg, PRD 65, 076003 (2002)**

95% Exclusion Limits

- **Bayesian limit setting procedure**
- **Compositeness (Λ):**
  - $\lambda=+1$: **(prior flat in ξ) 2.58 TeV (prior flat in ξ^2) 2.39 TeV**
  - $\lambda=-1$: **(prior flat in ξ) 2.54 TeV (prior flat in ξ^2) 2.35 TeV**

- **ADD Large Extra Dimensions (GRW, M_s):**
  - **(prior flat in ξ) 1.56 TeV (prior flat in ξ^2) 1.48 TeV**

- **TeV^{-1} Extra Dimensions (M_C):**
  - **(prior flat in ξ) 1.42 TeV (prior flat in ξ^2) 1.33 TeV**

Summary

- Presented the most stringent measurements on dijet mass cross sections and dijet angular distributions at a hadron collider
  - Reach dijet mass > 1 TeV (up to 1.4 TeV)
- Uncertainties have been significantly reduced from previous measurements
- Results are well described by NLO pQCD
- Best limits on quark compositeness, and extra dimension models from a single process at a hadron collider

Backups

95% Exclusion Limits

DØ preliminary 95% CL limits on New Physics models from the dijet angular distribution (in TeV)									
	χ^2 minimum		Bayesian				frequentist		previous
			prior flat in η		prior flat in η^2		$\chi^2 - \chi^2_{\min} = 3.84$		limit
model (parameter)	position	depth	expected	found	expected	found	expected	found	
Quark Composit. (Λ)									
$\lambda = +1$	5.10	0.02	$2.75^{+0.43}_{-0.35}$	2.58	$2.58^{+0.28}_{-0.29}$	2.39	$2.65^{+0.42}_{-0.35}$	2.46	2.73 [10]
$\lambda = -1$	5.22	0.02	$2.78^{+0.38}_{-0.41}$	2.54	$2.55^{+0.31}_{-0.33}$	2.35	$2.65^{+0.45}_{-0.39}$	2.42	2.49 [10]
TeV^{-1} ED (M_C)	2.17	0.66	$1.64^{+0.23}_{-0.25}$	1.42	$1.51^{+0.16}_{-0.19}$	1.33	$1.57^{+0.33}_{-0.24}$	1.35	1.12 [27]
ADD LED (M_S)									
GRW	∞		$1.49^{+0.12}_{-0.14}$	1.56	$1.44^{+0.10}_{-0.10}$	1.48	$1.47^{+0.16}_{-0.14}$	1.54	1.62 [26]
Hewett $\lambda = +1$	∞		$1.33^{+0.11}_{-0.12}$	1.39	$1.28^{+0.09}_{-0.09}$	1.32	$1.31^{+0.14}_{-0.12}$	1.37	1.22 [25]
Hewett $\lambda = -1$	∞		$1.28^{+0.11}_{-0.09}$	1.35	$1.23^{+0.09}_{-0.08}$	1.29	$1.25^{+0.13}_{-0.09}$	1.33	1.10 [25]
HLZ n=3	∞		$1.77^{+0.14}_{-0.16}$	1.85	$1.71^{+0.11}_{-0.12}$	1.76	$1.74^{+0.19}_{-0.16}$	1.83	1.94 [26]
HLZ n=4	∞		$1.49^{+0.12}_{-0.14}$	1.56	$1.44^{+0.10}_{-0.10}$	1.48	$1.47^{+0.16}_{-0.14}$	1.54	1.62 [26]
HLZ n=5	∞		$1.35^{+0.11}_{-0.12}$	1.41	$1.30^{+0.09}_{-0.09}$	1.34	$1.32^{+0.14}_{-0.12}$	1.39	1.46 [26]
HLZ n=6	∞		$1.25^{+0.11}_{-0.10}$	1.31	$1.21^{+0.08}_{-0.09}$	1.25	$1.22^{+0.14}_{-0.11}$	1.29	1.36 [26]
HLZ n=7	∞		$1.19^{+0.09}_{-0.11}$	1.24	$1.14^{+0.08}_{-0.08}$	1.18	$1.17^{+0.13}_{-0.11}$	1.22	1.29 [26]