Tevatron and LHC QCD Physics at Different Center-of-Mass Energies

- **Highlights of previous Tevatron running at different $\sqrt{s}$ values**
- **Some possible Run II studies vs. $\sqrt{s}$**
- **LHC at different $\sqrt{s}$, especially 2 TeV**
- **Formulating a $\sqrt{s}$ scanning plan**

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Introduction

- The $\sqrt{s}$ dial is an important one to turn at a hadron collider

- The Tevatron has already operated at 4 different center-of-mass energies

546 GeV	630 GeV	1800 GeV	1960 GeV
Run 0	Run 0, Run I	Run I	Run II
10's of nb^{-1}	200 nb^{-1}	100 pb^{-1}	4-8 fb^{-1}

- Small integrated luminosity at low energies
- Separated in time, not a continuous "scan"
- Detectors have evolved over time

- Any future program of $\sqrt{s}$ scanning can be linked with possible initiative to run the LHC 2 TeV $\rightarrow$ 14 TeV

- LHC at 2 TeV allows interesting pp vs. $\bar{p}p$ comparisons

Run-0 Low-Energy Publications from CDF

Elastic, diffraction, total cross section

1. **"Measurement of small angle antiproton-proton elastic scattering at 546 and 1800 GeV",** PRD 50 (1994) 5518

2. **"Measurement of pbar-p single diffraction dissociation at 546 and 1800 GeV"**, PRD 50 (1994) 5535

3. **"Measurement of the antiproton-proton total cross section at 546 and 1800 GeV",** PRD 50 (1994) 5550

Jet production

4. **"Comparison of jet production in pbar-p collisions at 546 GeV and 1800 GeV",** PRL 70 (1995) 1376

Particle distributions

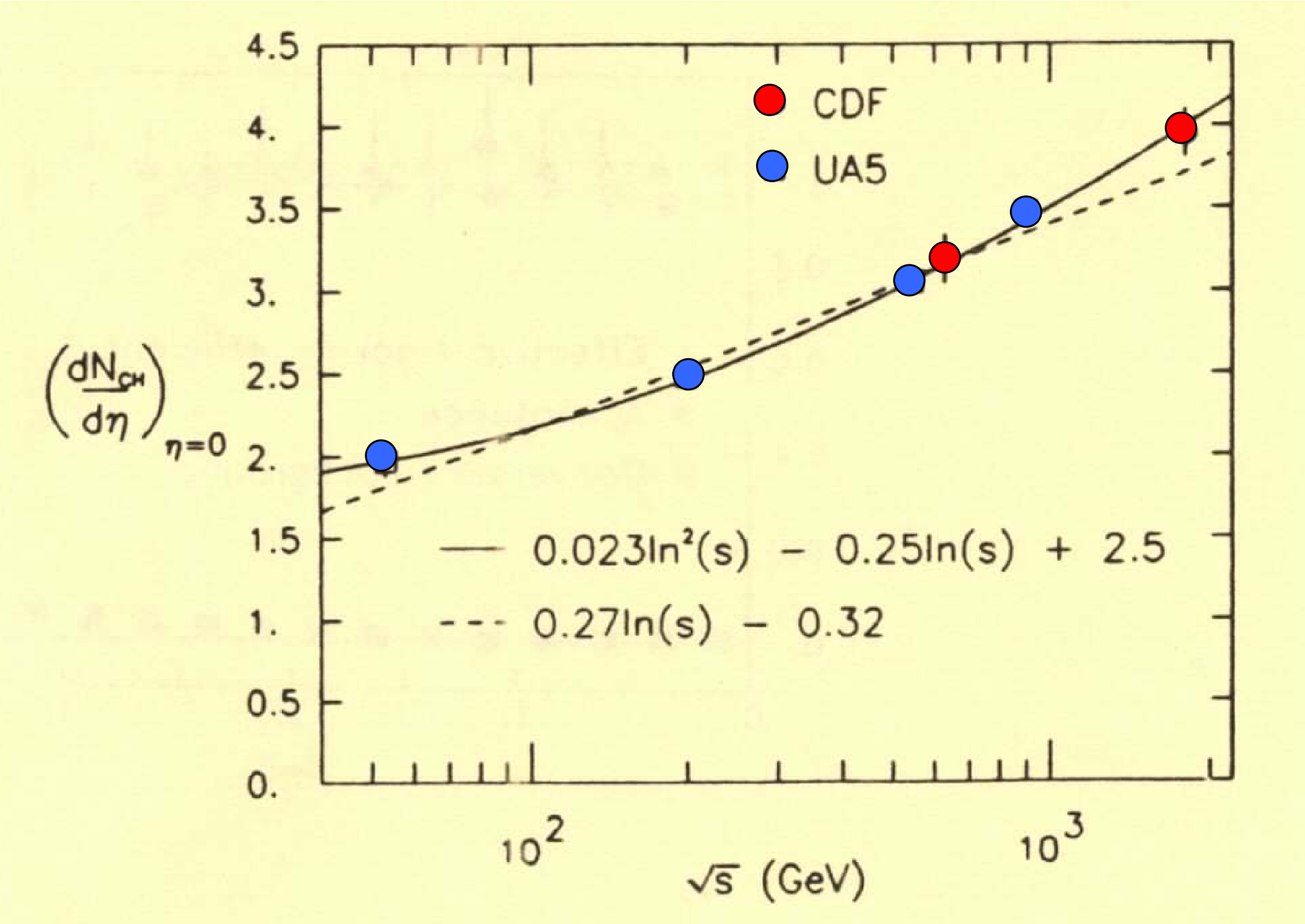
5. **"Pseudorapidity distributions of charged particles produced in p anti-p interactions at 630 and 1800 GeV",** Phys. Rev. D **41**, 2330 (1990)
6. **"Transverse-momentum distributions of charged particles produced in p anti-p interactions at 630 and 1800 GeV",** Phys. Rev. Lett. **61**, 1819 (1988)

Kaons

7. **K(s) production in p anti-p interactions at 630 and 1800 GeV",** Phys. Rev. D **40**, 3791 (1989)

7 Papers

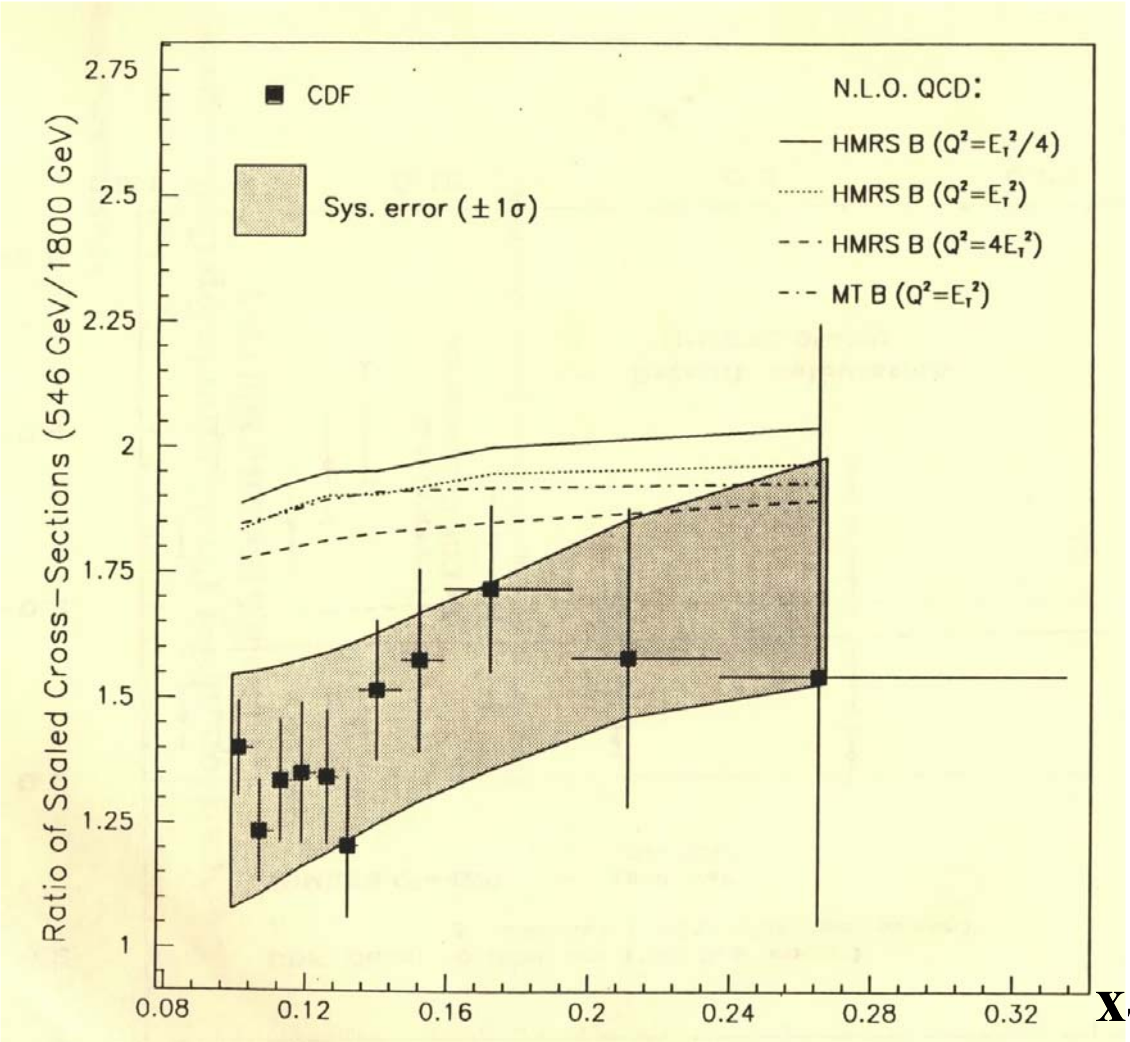
Charged Particle Multiplicity



CDF at 630 and 1800 GeV, Run 0

Combined UA5 and CDF results call for $\ln^2(s)$ term in evolution

CDF Inclusive Jet Cross Sections 546/1800 vs. $x_T = \frac{2E_T^{jet}}{\sqrt{s}}$



x_T

- **Troubling discrepancy: Ratio below theory predictions at low x_T**
- **Prompted more low energy running late in Run I**

- **Center-of-mass energy 546 GeV -- first SPS collider energy**
- **Integrated luminosity 8.6 nb^{-1}**

CDF and DØ proposals for late-Run I 630 GeV run

DØ

DØ Note 2581
8 June 1995

DØ Running at Center of Mass Energies of 630 GeV and 1200 GeV

G. Blazey, A. Brandt, V. Elvira, S. Fahey, P. Grannis, T. Heuring,
R. Hirosky, K. Johns, J. Krane, B. May, R. McCarthy,
H. Montgomery, G. Snow

CDF

CDF/DOC/CDF/CDFR/2196
Version 1
August 20, 1993

Proposal for a Special Run at $\sqrt{s} = 630$ GeV

Steve Behrends
Brandeis University
Brenna Flaugher, John Huth, Rob Plunkett
Fermi National Accelerator Laboratory
Steve Kuhlmann
Argonne National Laboratory
Tom LeCompte
University of Illinois

630 GeV Run Publications from DØ and CDF

… and many Ph.D. theses

Jet physics

1. D0: **"The ratio of jet cross sections at 630 GeV and 1800 GeV",** Phys. Rev. Lett. 86, 2523 (2001)
2. D0: **"High-pT Jets at 630 and 1800 GeV",** Phys. Rev. D 64, 032003 (2001)
3. D0: **"Subjet multiplicity of gluon and quark jets reconstructed with the k_T algorithm in pbar-p collisions",** Phys. Rev. D 65, 052008 (2002)

Direct photon physics

4. D0: **"The ratio of isolated photon cross sections in pbar-p collisions at 630 and 1800 GeV",** Phys. Rev. Lett. 87, 251805 (2001)
5. CDF: **"Comparison of the Isolated Direct Photon Cross Sections in p anti-p Collisions at 1.8 TeV and 0.63 TeV",** Phys. Rev. D65, 112003 (2002)

W and Z

6. D0: **"Extraction of the Width of the W Boson from Measurements of σ(p-pbar -> W+X)*B(W -> e+nu) and σ(p-pbar -> Z+X)*B(Z -> ee) and their Ratio",** Phys. Rev. D {61} 072001 2000

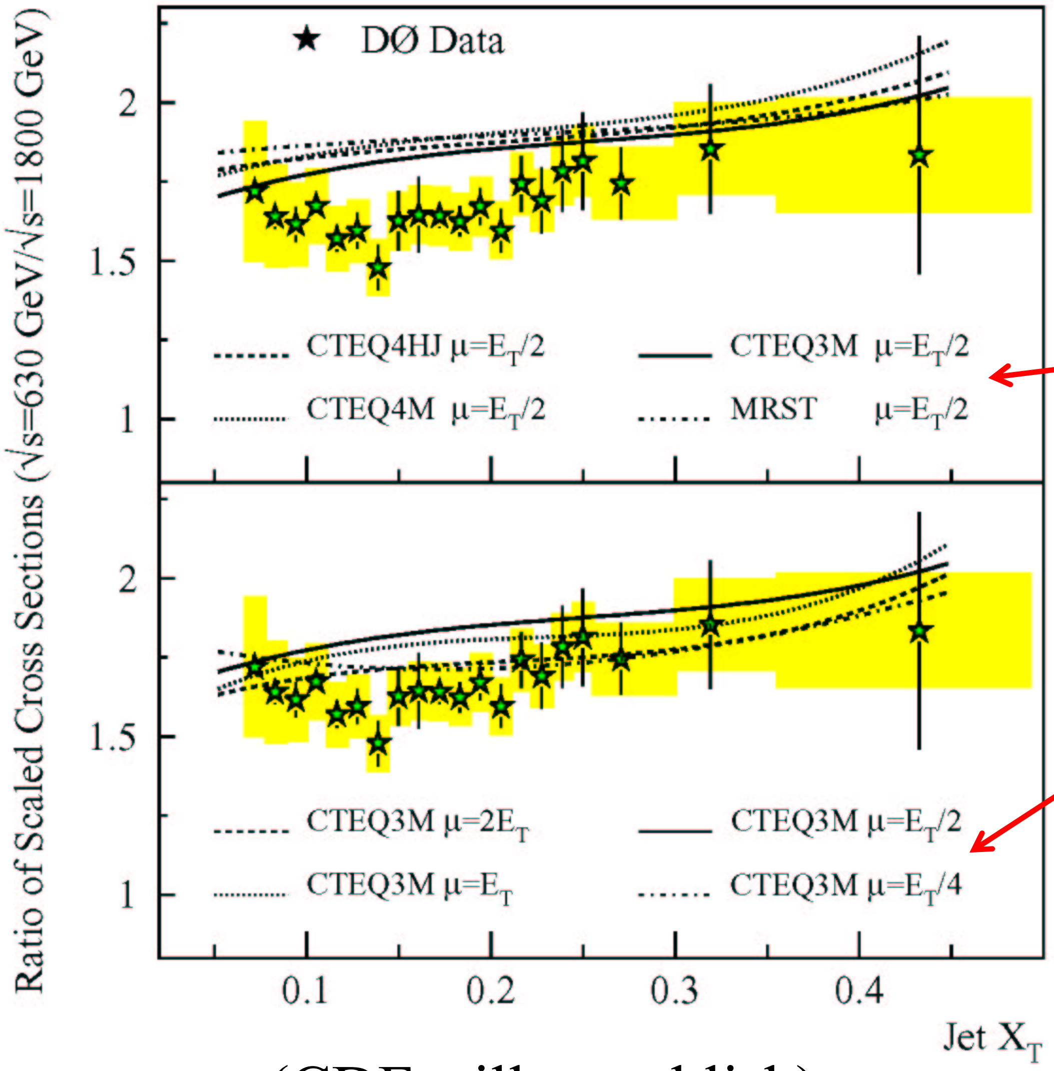
b-quark physics

7. CDF: **"Measurement of the Ratio of b Quark Production Cross Sections in p anti-p Collisions at 630 GeV and 1800 GeV",**Phys. Rev. D66, 032002 (2002)

Rapidity gaps, hard diffraction, BFKL dynamics

8. D0: **"Probing Hard Color-Singlet Exchange at 630 GeV and 1800 GeV",** Phys. Lett. B {440} 189 (1998)
9. D0: **"Hard Single Diffraction in Collisions at 630 and 1800 GeV",** Phys. Lett. B {531}, 52 (2002)
10. D0: **"Probing BFKL Dynamics in Dijet Cross Section at Large Rapidity Intervals at 1800 and 630 GeV",** Phys. Rev. Lett. {84}, 5722 (2000)
11. CDF: **"Diffractive Dijet Production at 630 and 1800 GeV at the Fermilab Tevatron",** Phys. Rev. Lett. 88, 151802 (2002)
12. CDF: **"Soft and Hard Interactions in p anti-p Collisions at 1800 and 630 GeV",** Phys. Rev. D65, 072005 (2002)
13. CDF: **"Events with a Rapidity Gap between Jets in p anti-p Collisions at 630 GeV",** Phys. Rev. Lett. 81, 5278 (1998)

Inclusive Jet Cross Sections 630/1800 vs. x_T



J. Krane Ph.D.

NLO QCD with different pdf's

NLO QCD with different renormalization scales

Data is systematically lower than theory in mid-x_T range, but full χ^2 comparison good for all theory parameters.

(CDF still to publish)

Direct Photons

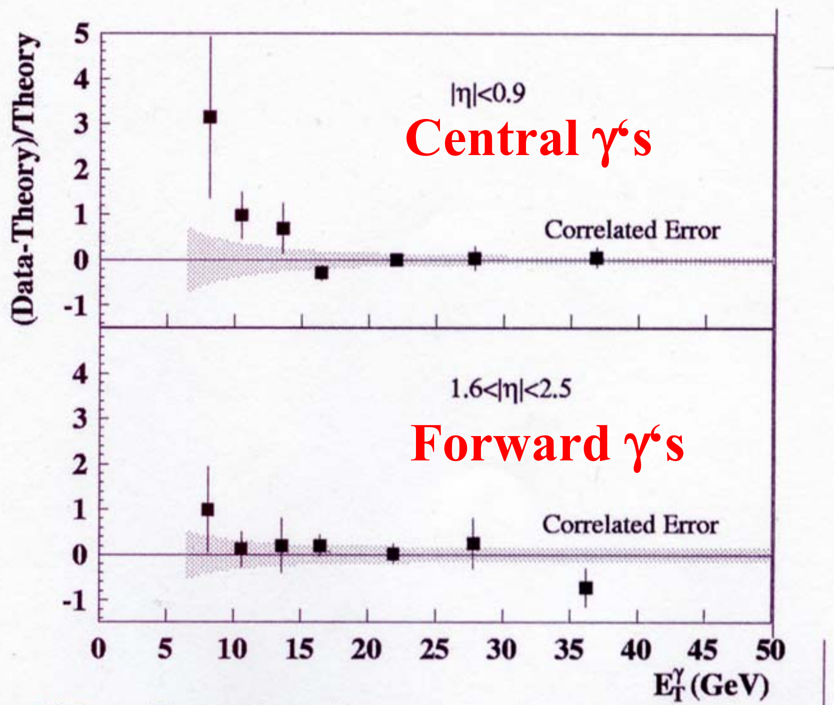


FIG. 4. Comparison of the measured cross section for production of isolated photons at $\sqrt{s} = 630$ GeV with the prediction of NLO QCD using CTEQ5M parton distribution functions.

630 GeV (data-theory)/theory

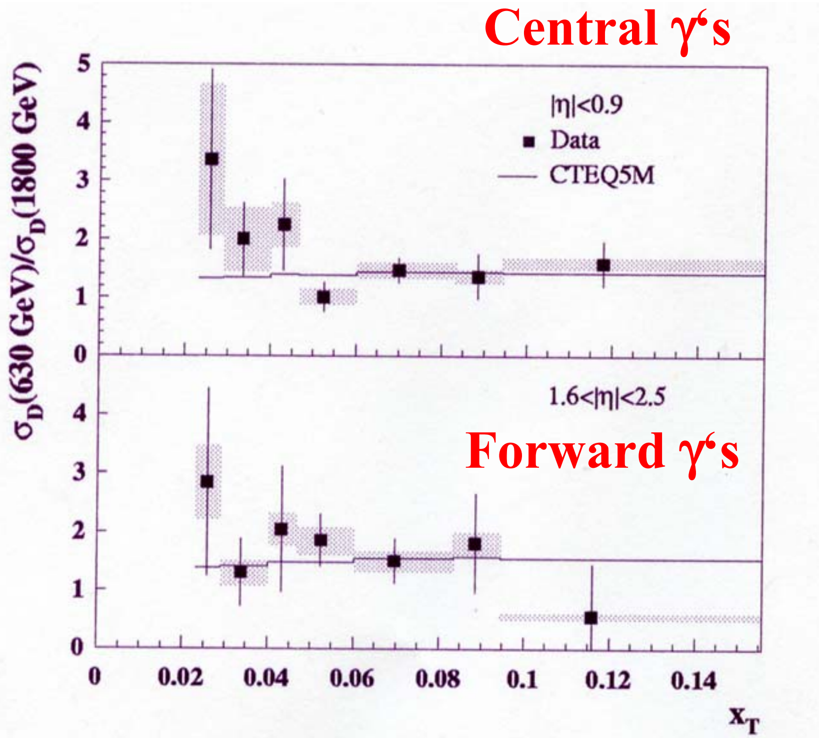


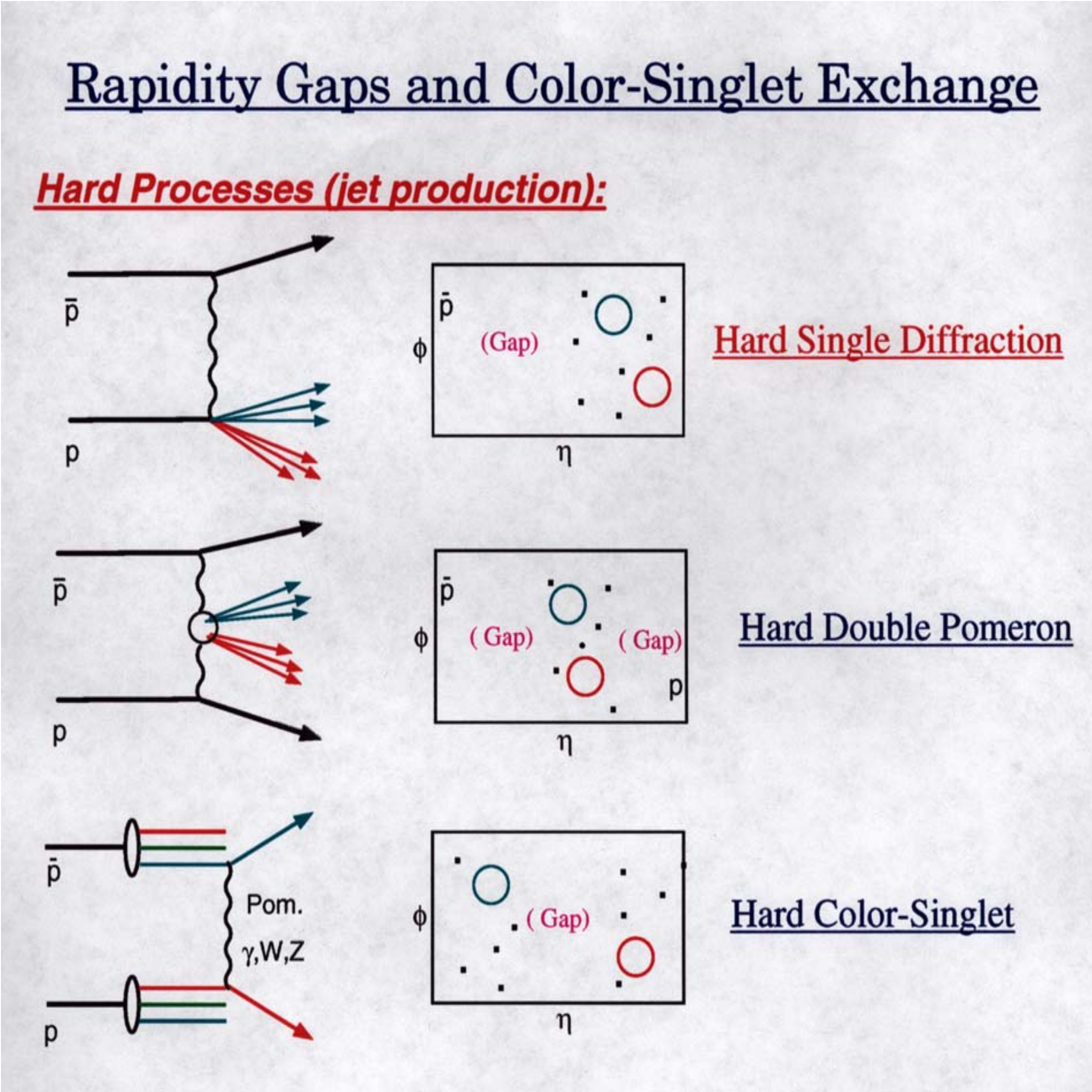
FIG. 5. The ratio of the dimensionless cross sections, $\sigma_D(\sqrt{s} = 630 \text{ GeV})/\sigma_D(\sqrt{s} = 1800 \text{ GeV})$. The error bars indicate the uncorrelated uncertainty and the shaded bands indicate the correlated uncertainty.

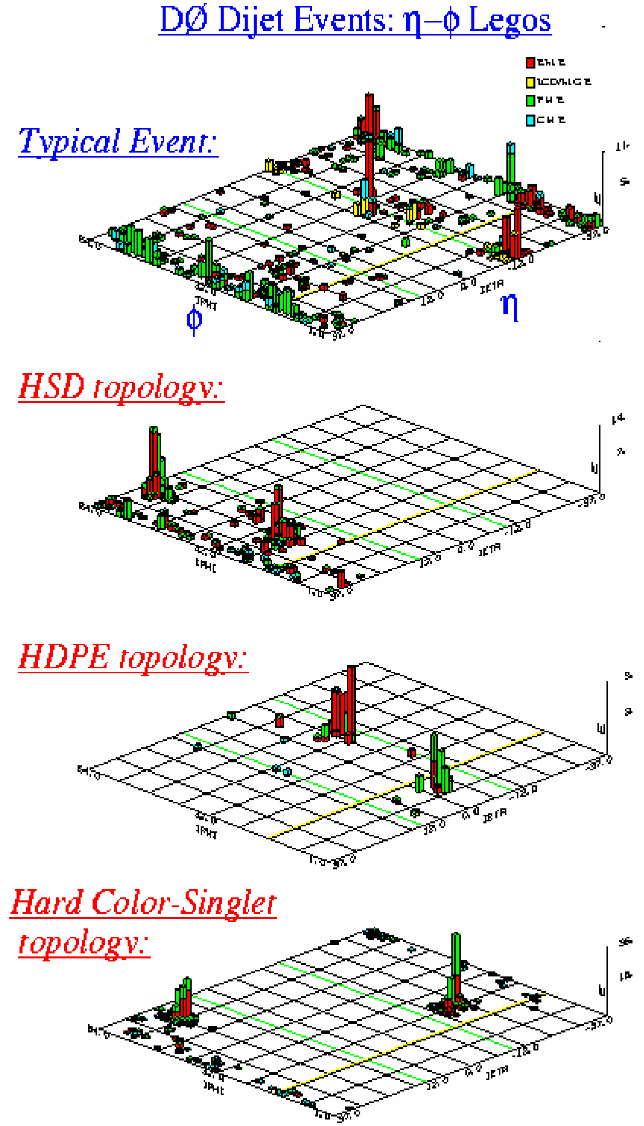
630/1800 GeV (data-theory)/theory

Well-known discrepancy at low E_T^γ present at all $\sqrt{s}$ values

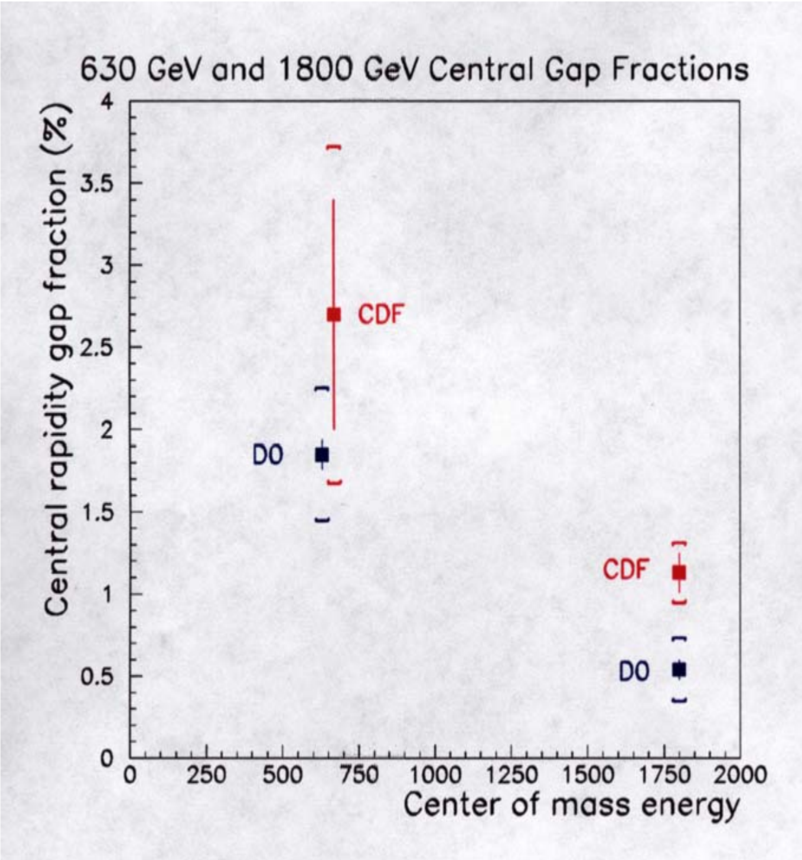
Tevatron Hard Diffraction Studies

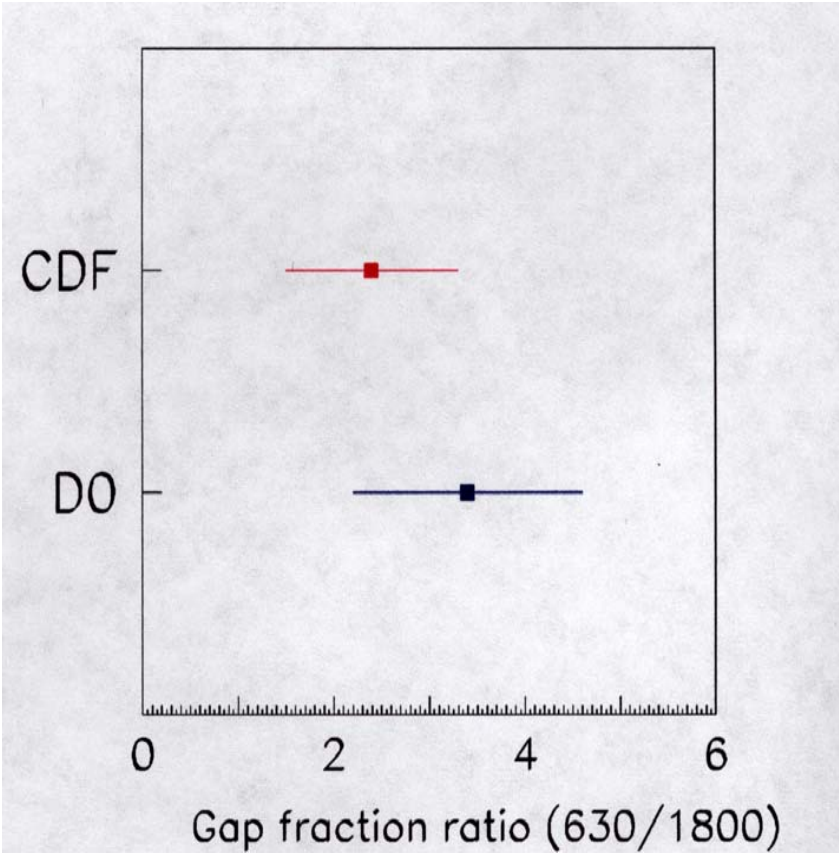
Understand the Pomeron via ……





Jet-central gap-jet fraction vs. $\sqrt{s}$





D0:

f_s^{630} = 1.85 ±0.09±0.37

f_s^{1800} = 0.54 ±0.06±0.16
(stat) (sys)

CDF:

f_s^{630} = 2.7±0.7±0.7

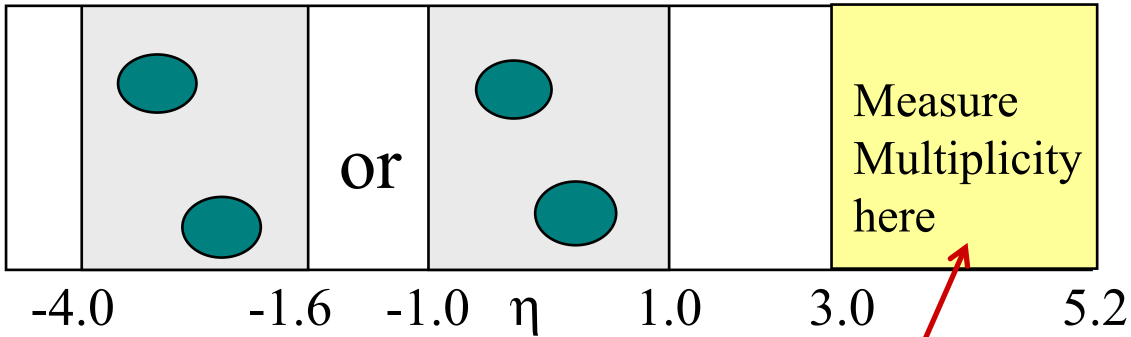
f_s^{1800} = 1.13±0.12±0.11
(stat) (sys)

Ratio (630/1800)

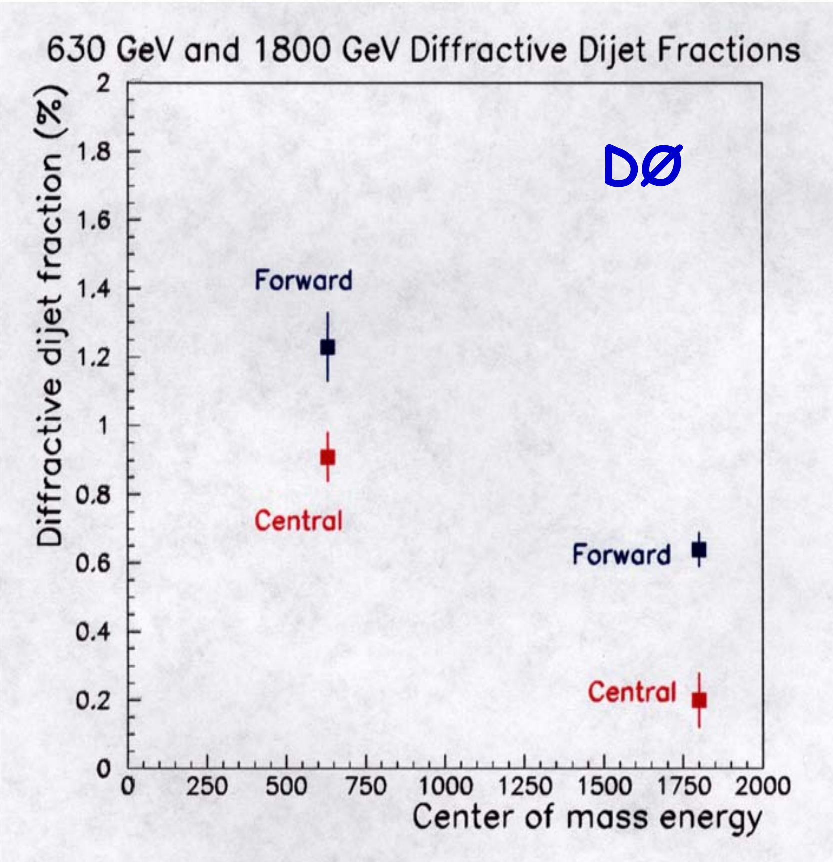
CDF: 2.4 ± 0.9
PRL 81, 5279 (1998)
D0: 3.4 ± 1.2
PLB 440, 189 (1998)

Hard Single Diffraction vs. $\sqrt{s}$

Dijets either forward or central

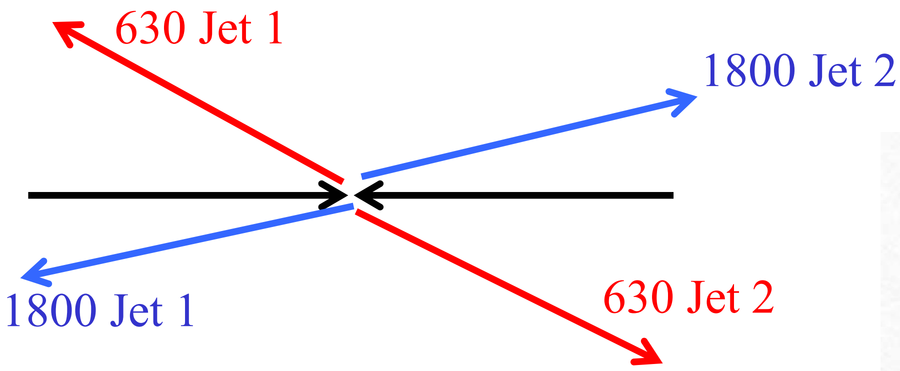


… using forward cal and forward scintillators



- Forward > Central Jets Gap Fraction
- 630 GeV > 1800 GeV Gap Fraction
- Again, different $\sqrt{s}$ values revealing
- Double-gap events (i.e. double Pom) also observed at both energies

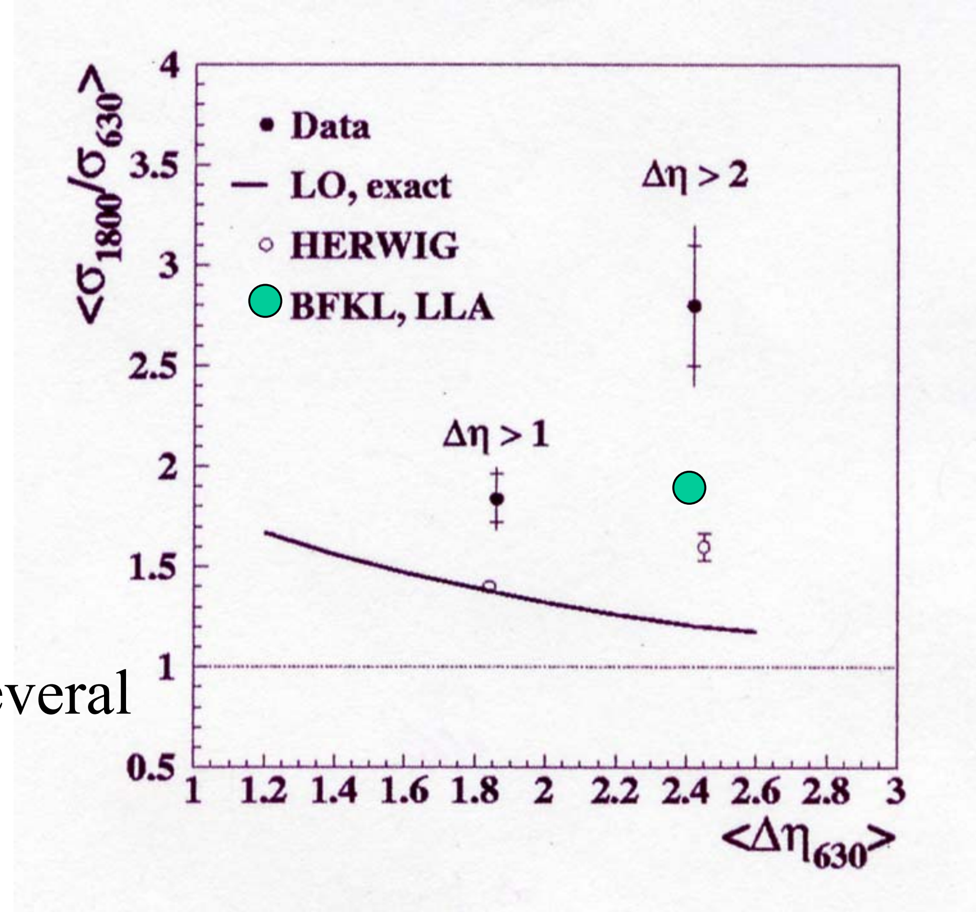
Dijets with large Δη: Muller-Navelet Dijets



$$R = \frac{\sigma(x_1, x_2, 1800\,GeV, \Delta\eta^{1800})}{\sigma(x_1, x_2, 630\,GeV, \Delta\eta^{630})}$$

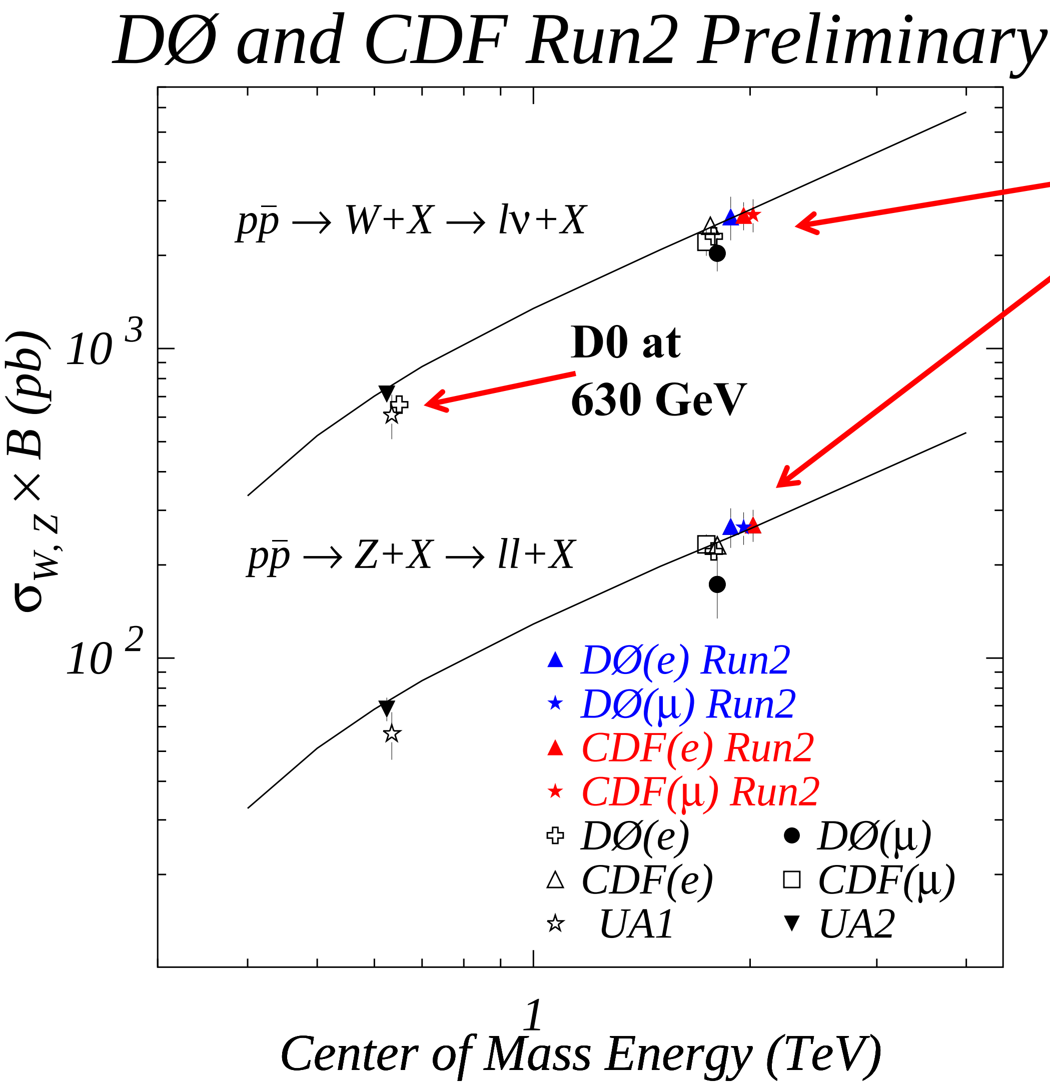
With x_1, x_2, Q^2 fixed, pdf's cancel and underlying dynamics revealed.

- Extract α_{BFKL} intercept?
- $\alpha_{BFKL} = 1.65 \pm 0.07$ average of several x_1, x_2 bins and one Q^2 bin.
- BFKL prediction using this value lower than data point



- This measurement would benefit from several $\sqrt{s}$ values and higher statistics at each energy.

$\sqrt{s}$ evolution of W and Z Production Cross Sections



D0 and CDF at 1800 and 1960 GeV

$$\frac{\sigma_{W\to e\nu}(1960\text{ GeV})}{\sigma_{W\to e\nu}(1800\text{ GeV})} = 1.15 \pm 0.19$$

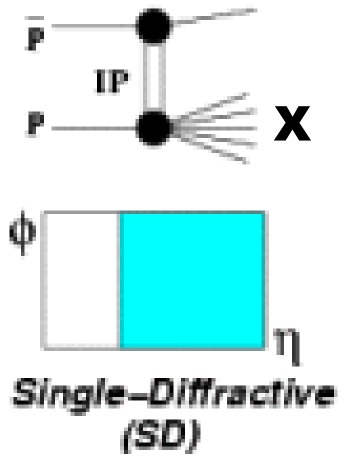
$$\frac{\sigma_{Z\to ee}(1960\text{ GeV})}{\sigma_{Z\to ee}(1800\text{ GeV})} = 1.20 \pm 0.19$$

$$\frac{\sigma_{Z\to \mu\mu}(1960\text{ GeV})}{\sigma_{Z\to \mu\mu}(1800\text{ GeV})} = 1.48 \pm 0.32$$

Theory Predicts increase of 9%

Map $\sqrt{s}$ region between 630 and 1800? Good input for pdf fits.

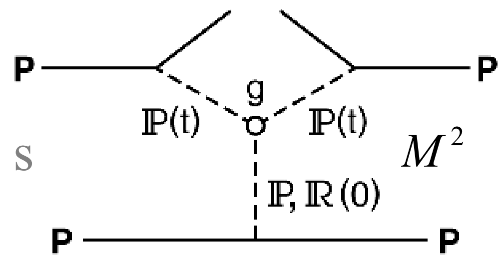
Single Diffractive Excitation



$$\sigma_{inv} = \frac{m_0^2}{16\pi^2}\frac{1}{s}\sum_{iij} G_{iij}(t)\left(\frac{s}{M^2}\right)^{2\alpha_i(t)}\left(\frac{M^2}{m_0^2}\right)^{\alpha_j(0)} + \ldots$$

s-dependence at various fixed t, $M^2 \Rightarrow \alpha_i(t)$

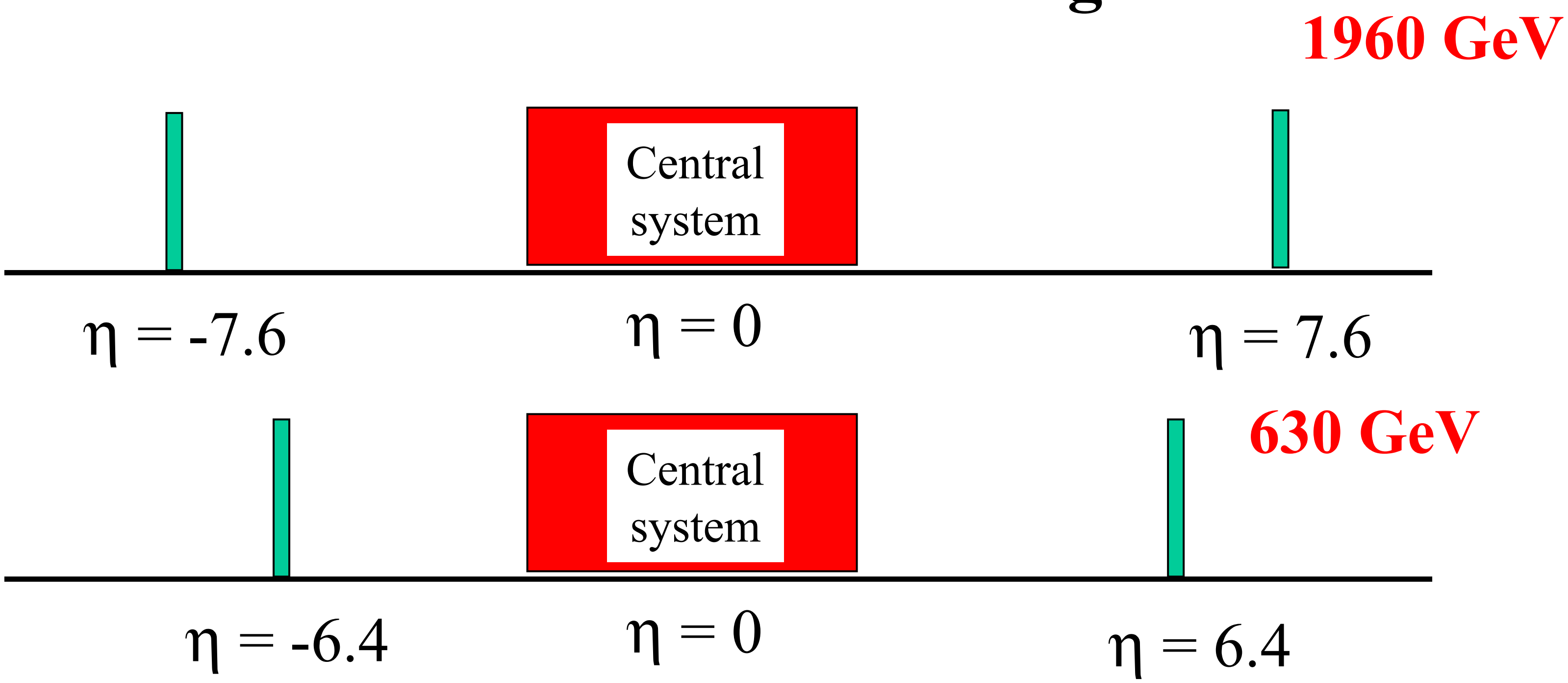
System X can be soft (all low pT)
or hard (jets, W, Z).
HERA-Tevatron difference – universal screening?
Pomeron trajectory probably different for
hard and soft systems. Similar seen at HERA in



$\gamma^* p \rightarrow \rho \quad p$ (soft) and $\gamma^* p \rightarrow \psi/\Upsilon \quad p$ (hard)

Systematic study of trajectories, needs s-dependence
→ run at sqrt{s} = 630, 900, 1300, 1960 GeV
(~ log spacing, modest runs at lower sqrt{s})

Double Pomeron Exchange



- Interesting to study central system (both soft and hard) as function of rapidity separation from outgoing beam particles.

- This would call for lowest c.m. energy possible, 300 GeV, for greater reach.

Luminosity Considerations

Suggest 4 center-of-mass energies equally spaced in log(s).
Hence 630, 920, 1340, 1960 GeV. (Lower? Minimum is 300 GeV.)

$$\text{Luminosity} = \frac{N_p N_{\bar{p}} b f \beta \gamma}{2\pi\beta^*(\varepsilon_p + \varepsilon_{\bar{p}})}$$

N_p and $N_{\bar{p}}$ = number of protons, antiprotons/bunch

b = number of bunches, f = revolution frequency

β and γ are the velocity and Lorentz factor of beams

β^* is the beta function at the interaction point

ε_p and $\varepsilon_{\bar{p}}$ are the normalized transverse emittances

Luminosity roughly scales with γ, consistent with earlier 630 GeV experience where L_{630} was 1/3 L_{1800} when 630 GeV conditions were stable.

Luminosity Considerations

$\sqrt{s}$	γ of beam	Peak Luminosity	Integrated L per week
1960 GeV	1045	6.0×10^{31} cm^{-2} s^{-1}	12.0 pb^{-1}
1340 GeV	714	4.1×10^{31} cm^{-2} s^{-1}	8.2 pb^{-1}
920 GeV	490	2.8×10^{31} cm^{-2} s^{-1}	5.6 pb^{-1}
630 GeV	336	1.9×10^{31} cm^{-2} s^{-1}	3.8 pb^{-1}

Based on present 1960 GeV luminosity; will increase.

2-3 months yields 10's of pb^{-1} at each energy.

Why run LHC at $\sqrt{s} = 2.0$ TeV?

- Natural to exploit physics of pp interactions at several $\sqrt{s}$ values

- Since σ(pp) ≈ σ($p\bar{p}$) for several processes at $\sqrt{s}$ = 2.0 TeV, experiments can check ability to measure a cross section

$$\sigma(pp) = \frac{\text{Number of events}}{\int Ldt \cdot (\text{acceptance}) \cdot \varepsilon_1 \cdots \varepsilon_n}$$

LHC

→ compare to $\sigma(\bar{p}p)$

CDF/DØ

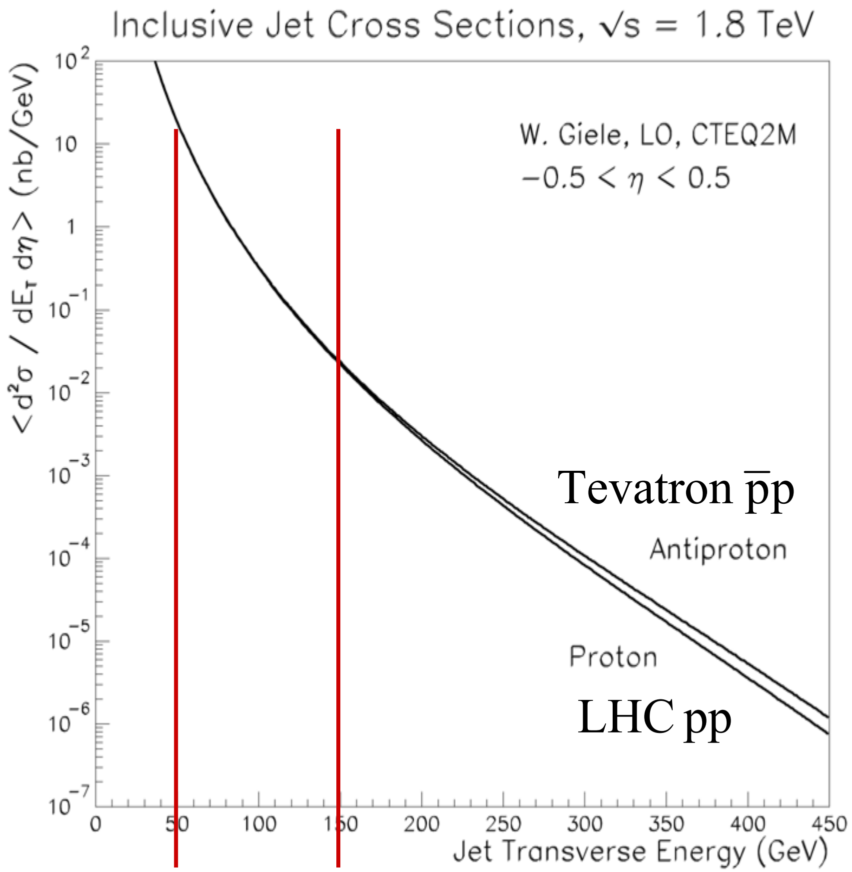
- For processes where σ(pp) ≠ σ($p\bar{p}$), interesting to compare CDF/DØ cross sections with LHC cross sections

- Examine $\sqrt{s}$ dependence of processes in pp

σ(pp) 2 TeV → σ(pp) 14 TeV

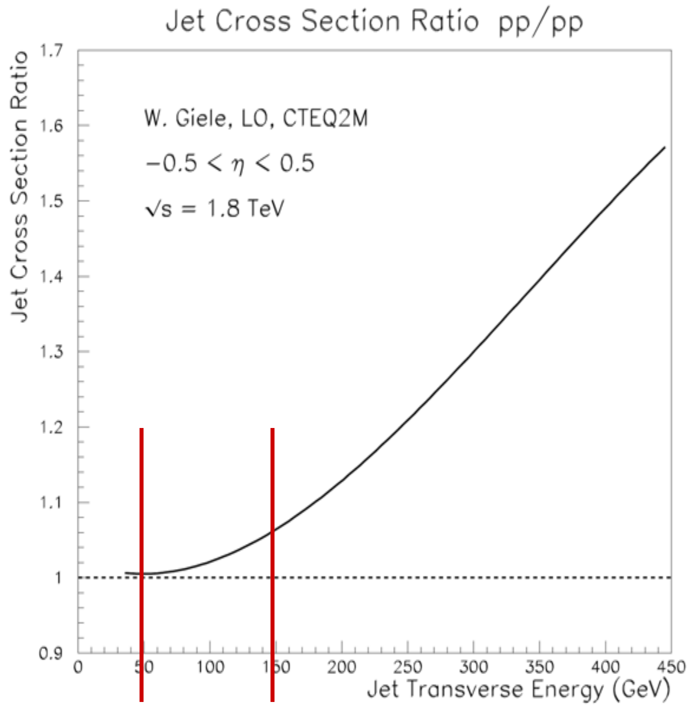
- Leads to several new Ph.D. thesis topics

Inclusive jets vs. E_T^{jet} for $\bar{p}p$, pp at 1.8 TeV



Agreement better than 10% for E_T^{jet} < 150 GeV

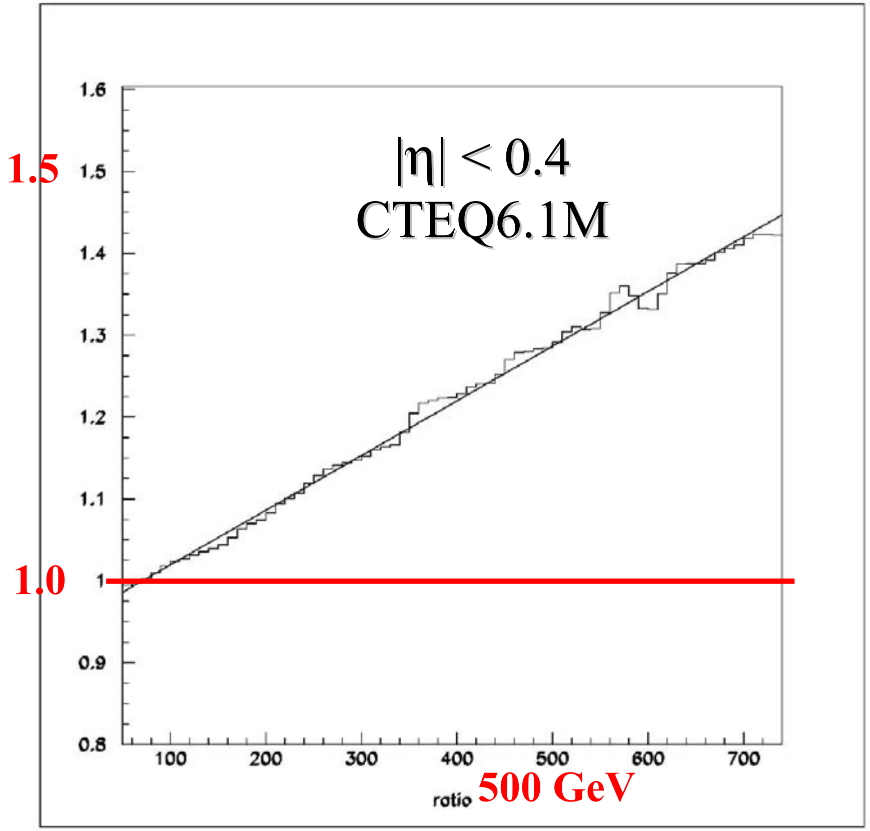
Ratio $\frac{\bar{p}p}{pp}$ vs. E_T^{jet}

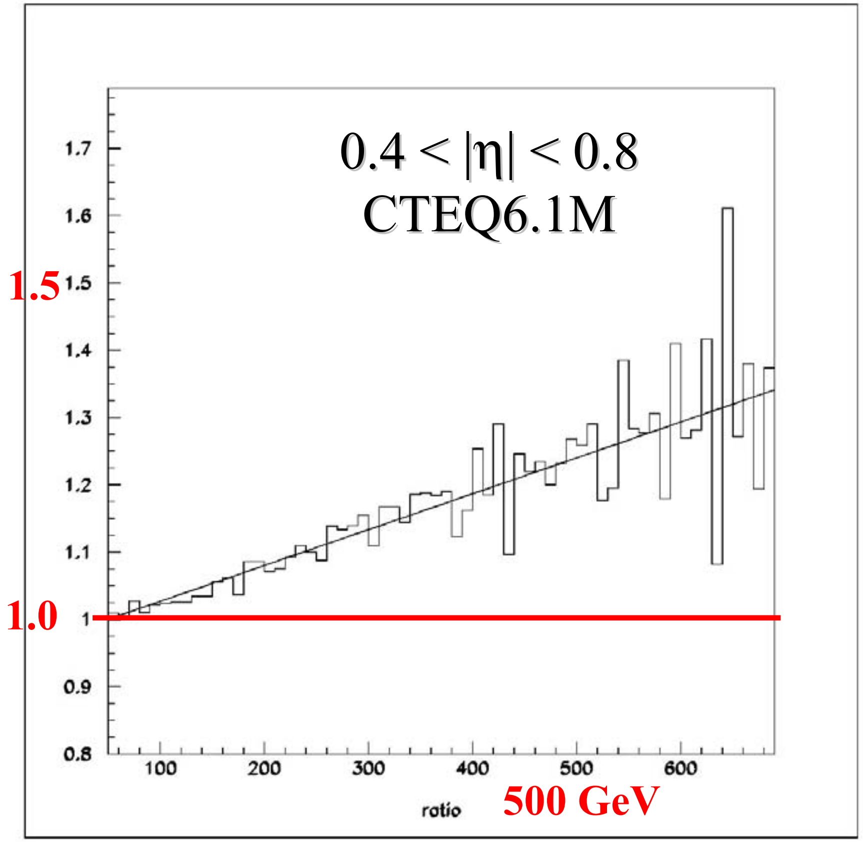


- Confirm ingredients in LHC X-section measurement for low E_T
- Good pdf test for high E_T

Inclusive jets vs. E_T^{jet} for $\bar{p}p$, pp at 1.96 TeV

NLOJET++ program of Zoltan Nagy
http://www.cpt.dur.ac.uk/~nagyz/nlo++



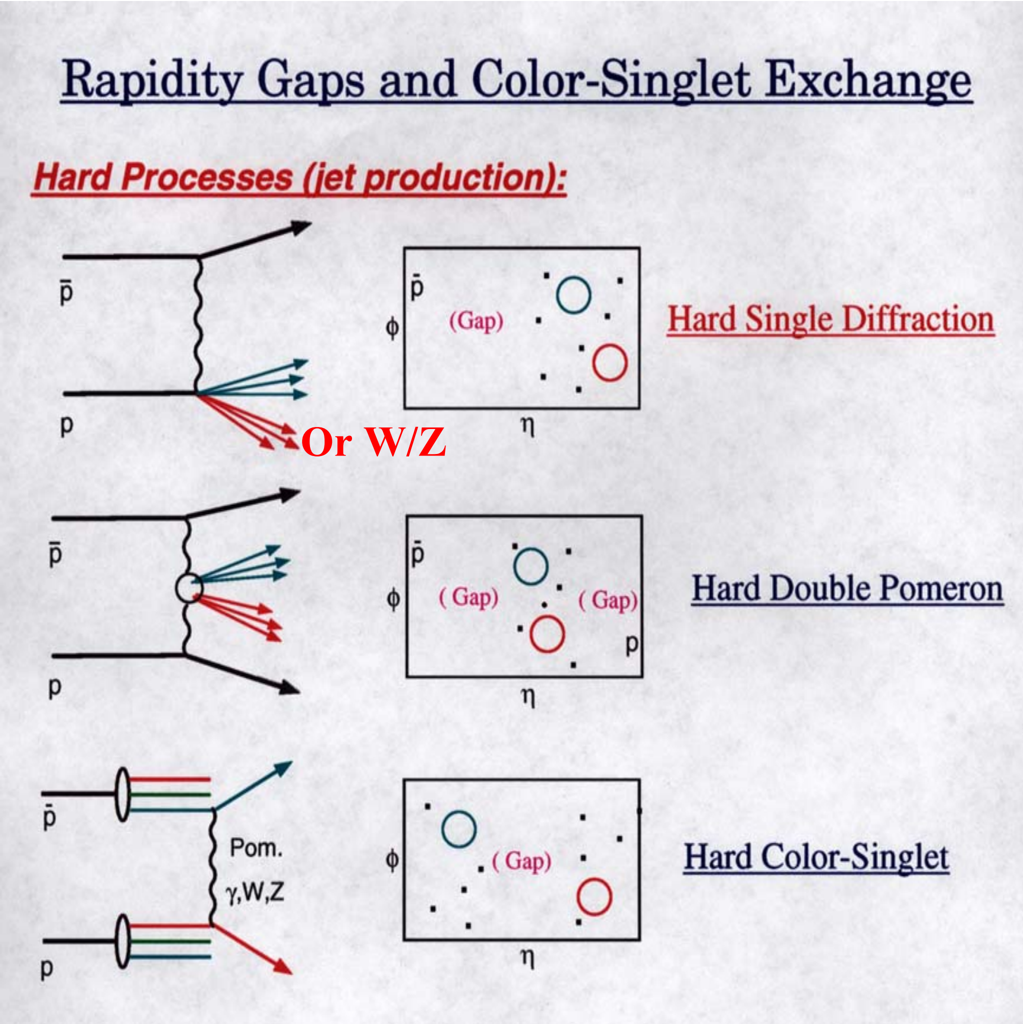


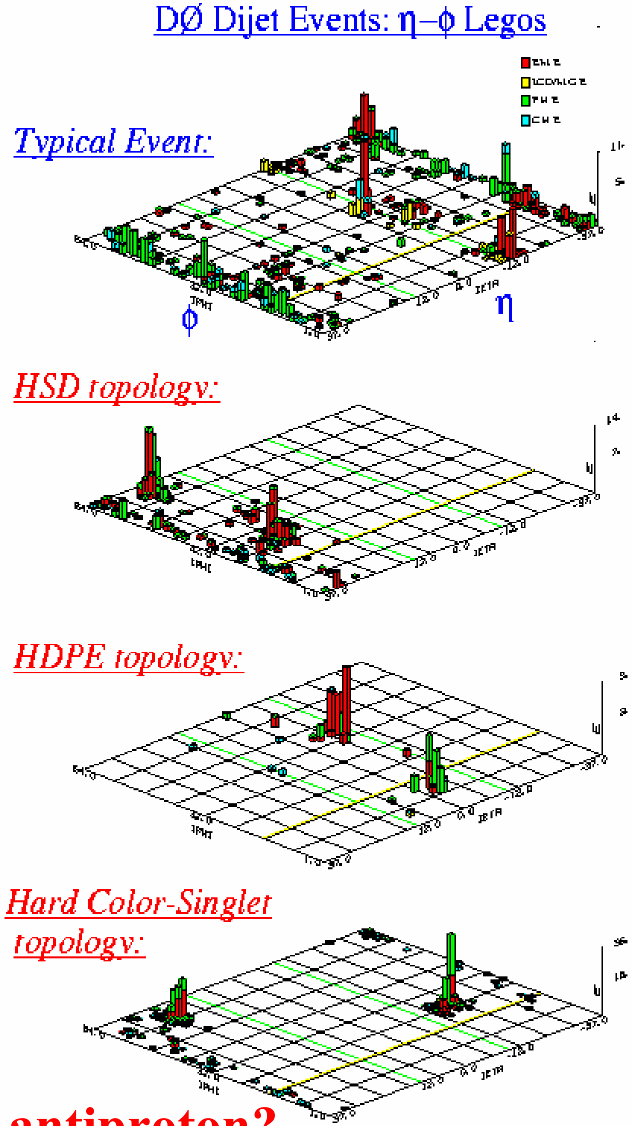
$$\text{Ratio } \frac{\bar{p}p}{pp} \text{ vs. } E_T^{jet}$$

(Fluctuations from Monte Carlo statistics)

Hard Diffraction Studies

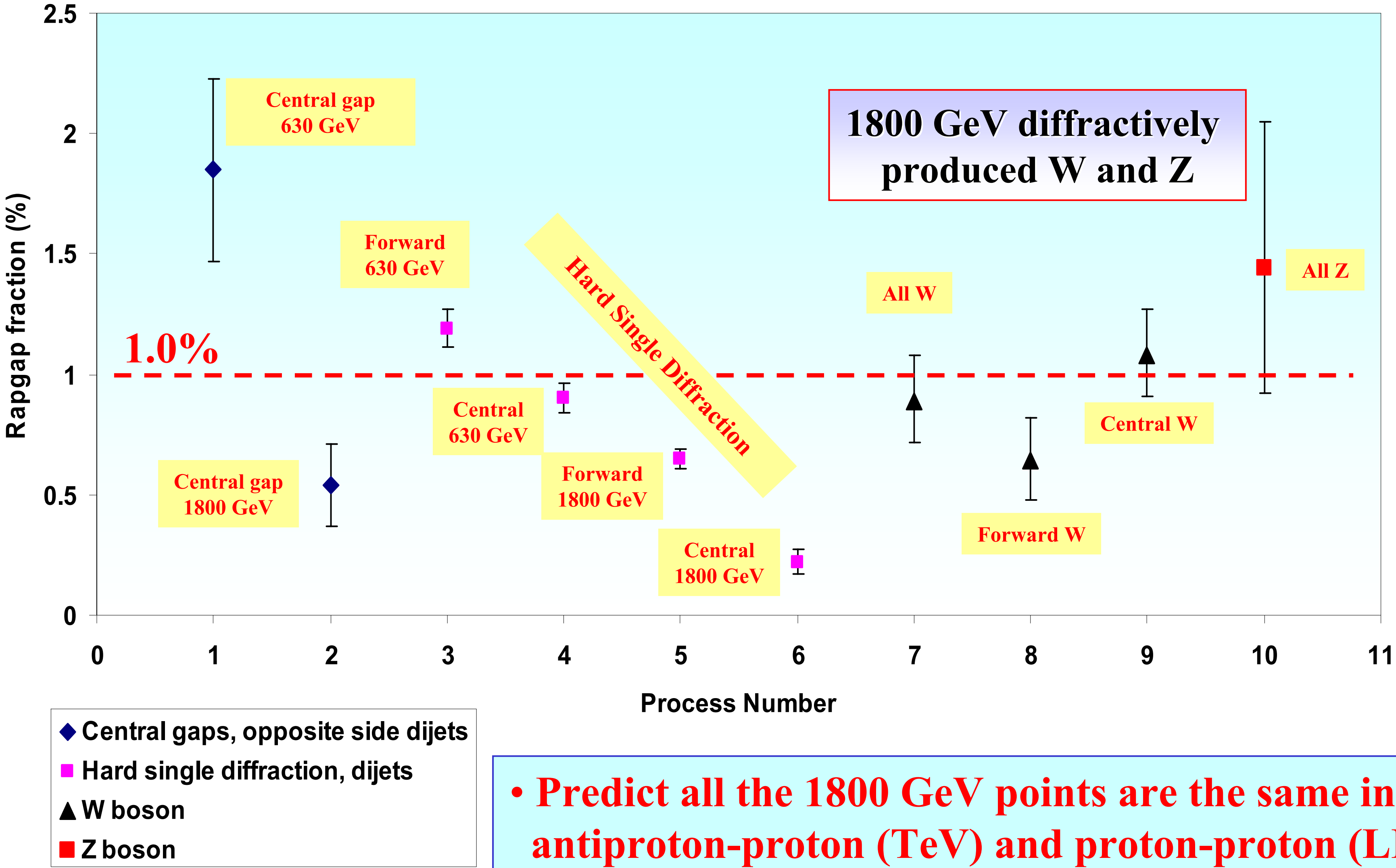
Understand the Pomeron via ……





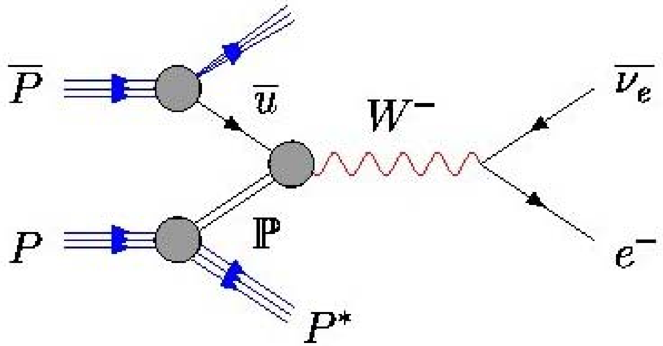
Does the Pomeron care if it comes from a proton or antiproton?

Rap gap fractions for different processes



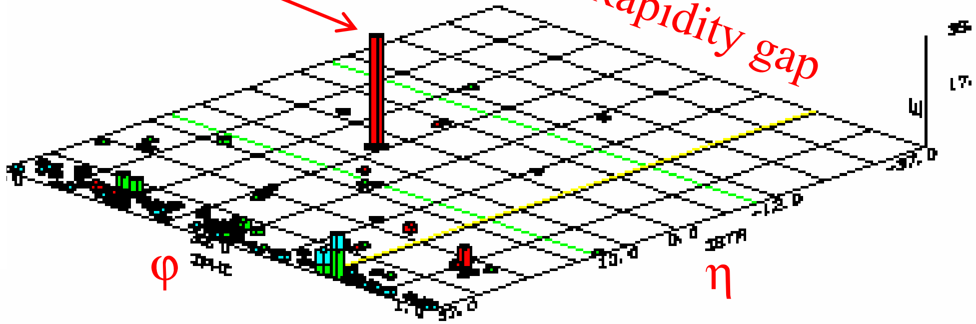
- Predict all the 1800 GeV points are the same in antiproton-proton (TeV) and proton-proton (LHC)
- Watch evolution to higher $\sqrt{s}$

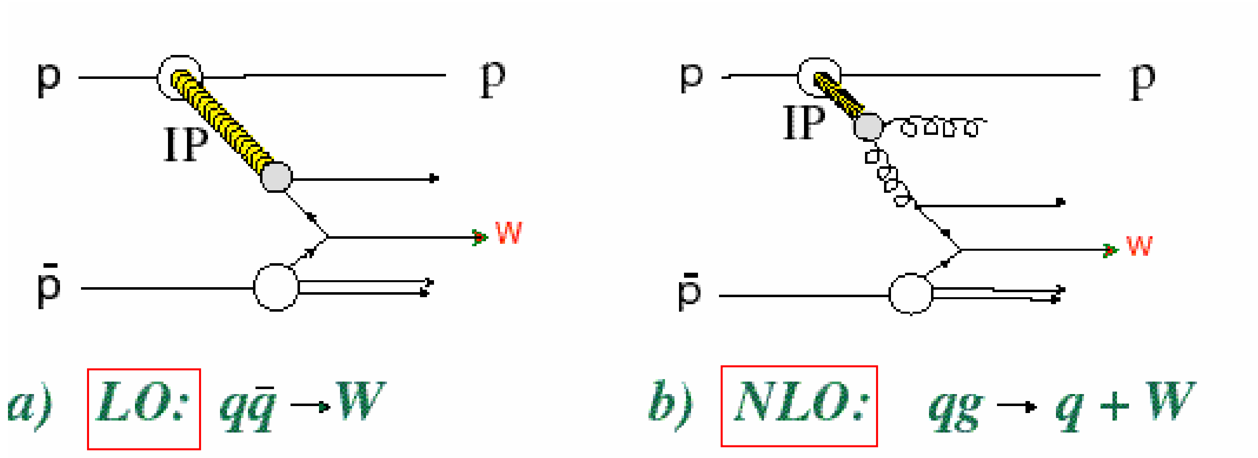
Diffractively Produced W and Z



Process probes quark content of Pomeron

Electron from W decay, with missing E_T



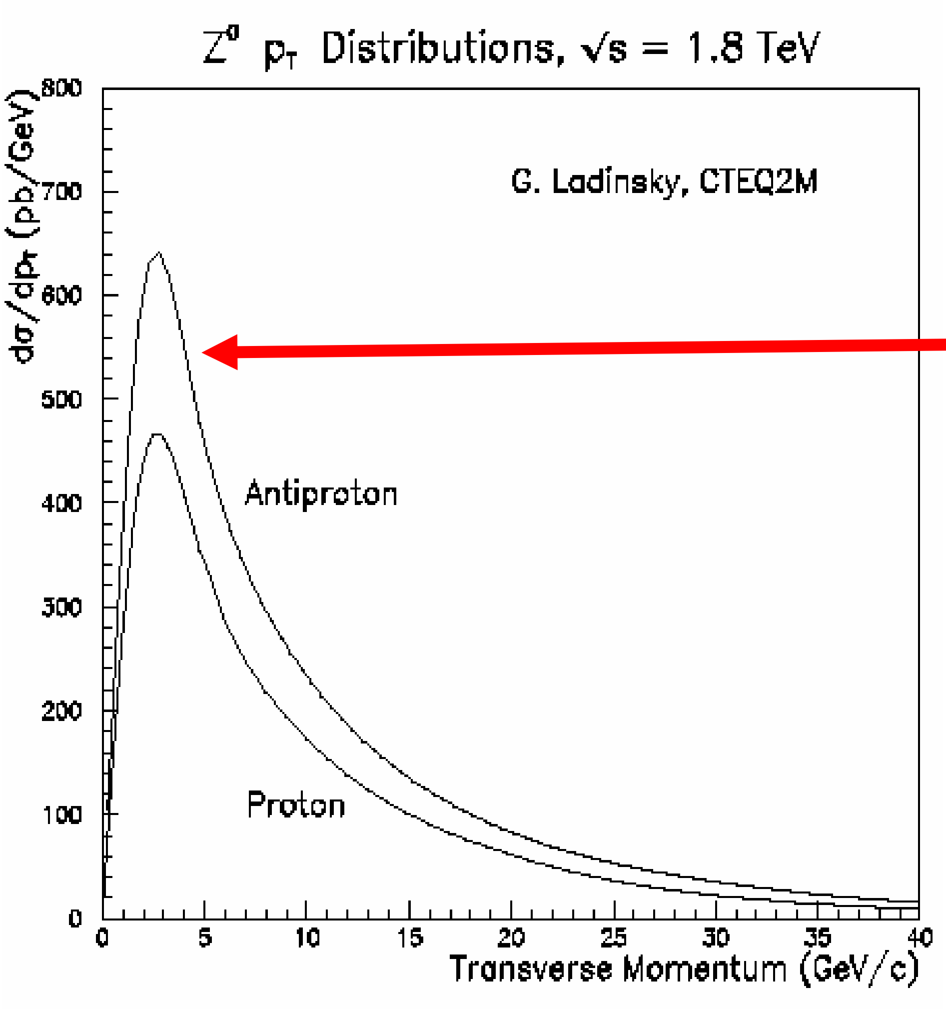


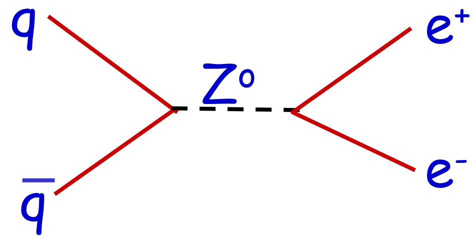
May expect jets accompanying W or Z

$W \to e\nu$
$Z \to e^+e^-$
considered
and
require single interaction to preserve possible rapidity gaps (reduces available stats considerably)

DØ : Phys. Lett. B574 169 (2003)

Inclusive Z (or W) production for $\bar{p}p$ and pp at 2.0 TeV

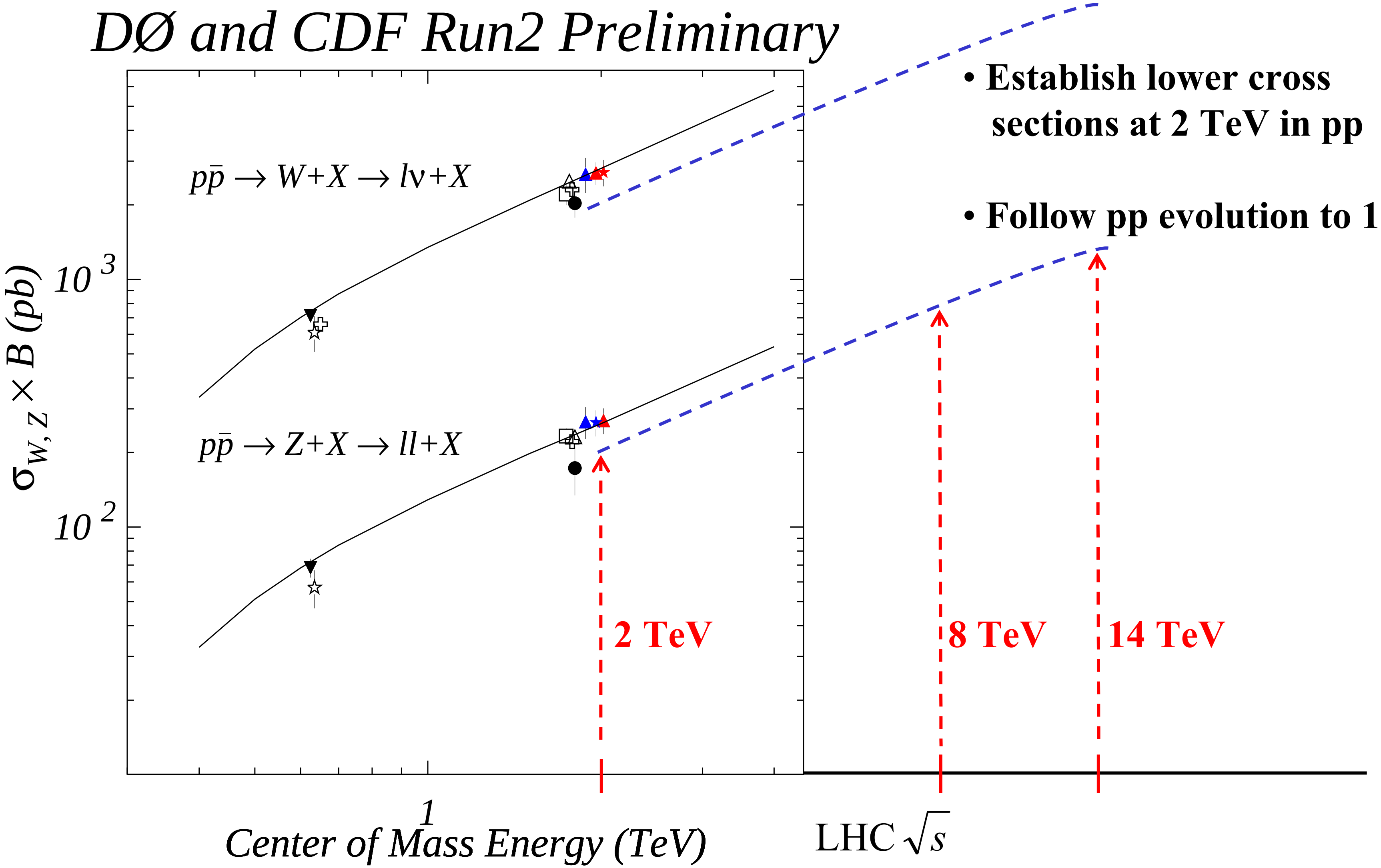




- **36% excess in pbar-p due to valence antiquarks in pbar**
- **Sensitive to parton distribution functions**

$\sqrt{s}$ evolution of W and Z Production Cross Sections

DØ and CDF Run2 Preliminary

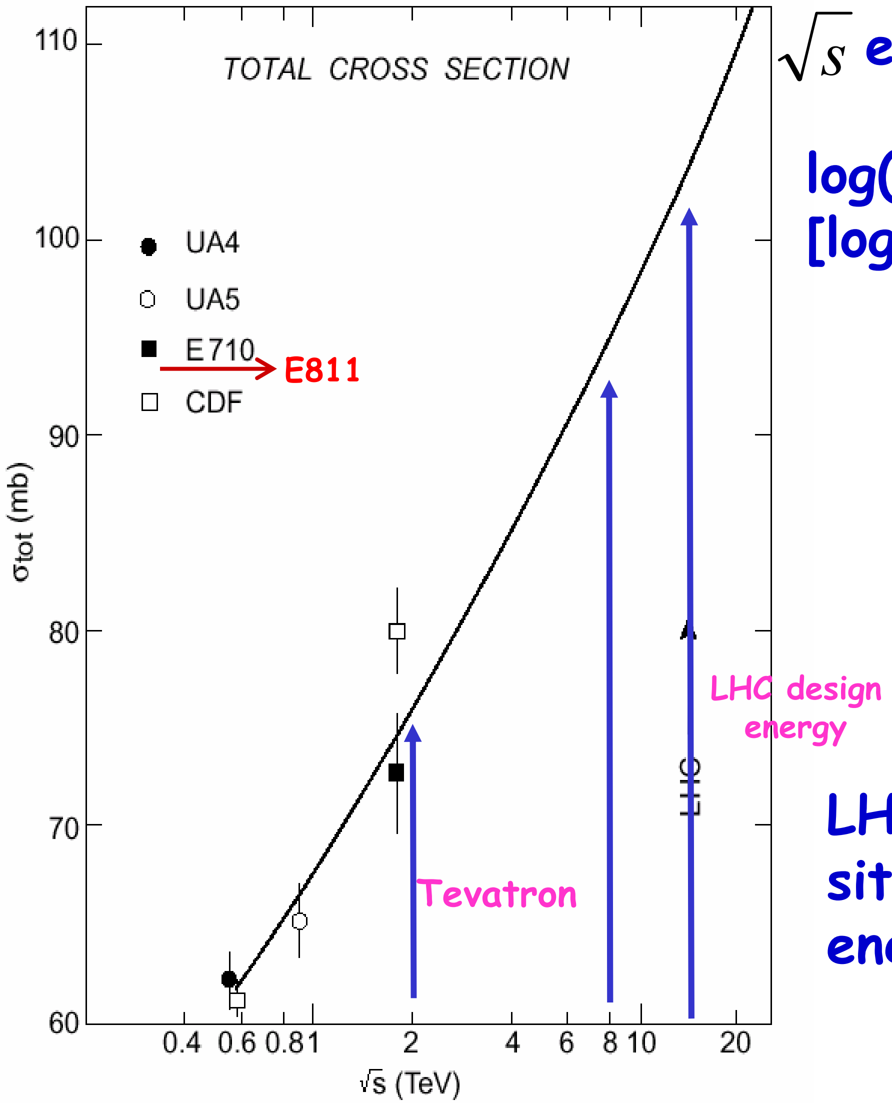


- **Establish lower cross sections at 2 TeV in pp**
- **Follow pp evolution to 14 TeV**

LHC Possibilities: e.g. 2 TeV ($L=2\times10^{32}$) 8 TeV ($L=3.3\times10^{33}$) 14 TeV ($L=10^{34}$)

And of course there are the total $\bar{p}p$, pp cross sections

Note: $\sigma_{tot}(\bar{p}p) = \sigma_{tot}(pp)$ at these energies



$\sqrt{s}$ evolution goes as:

log(s)?
$[\log(s)]^2$?

LHC can ring in on σ_{tot} situation at Tevatron energy

Formulating a $\sqrt{s}$ Scanning Plan

Greg's view:

For late Run II running and/or running at the LHC, we should form a "Root(s) task force" of 5-6 people:

1-2 from CDF

1-2 from DZERO

1-2 theory/phenomenology

Charge:

- **Evaluate critically the published and unpublished results from Tevatron runs at different $\sqrt{s}$ values. What was learned? What were the limitations (number and choice of $\sqrt{s}$ values, available statistics, …). Produce review article and/or TeV4LHC write-up: "Proton-antiproton collision processes at different center-of-mass energies" – useful in general, ammunition for $\sqrt{s}$ scan proposals for Tevatron and LHC.**
- **Develop physics case for old and new processes with energy and integrated luminosity requirements.**