# Diffractive Production of Jets and Vector Bosons at the Tevatron

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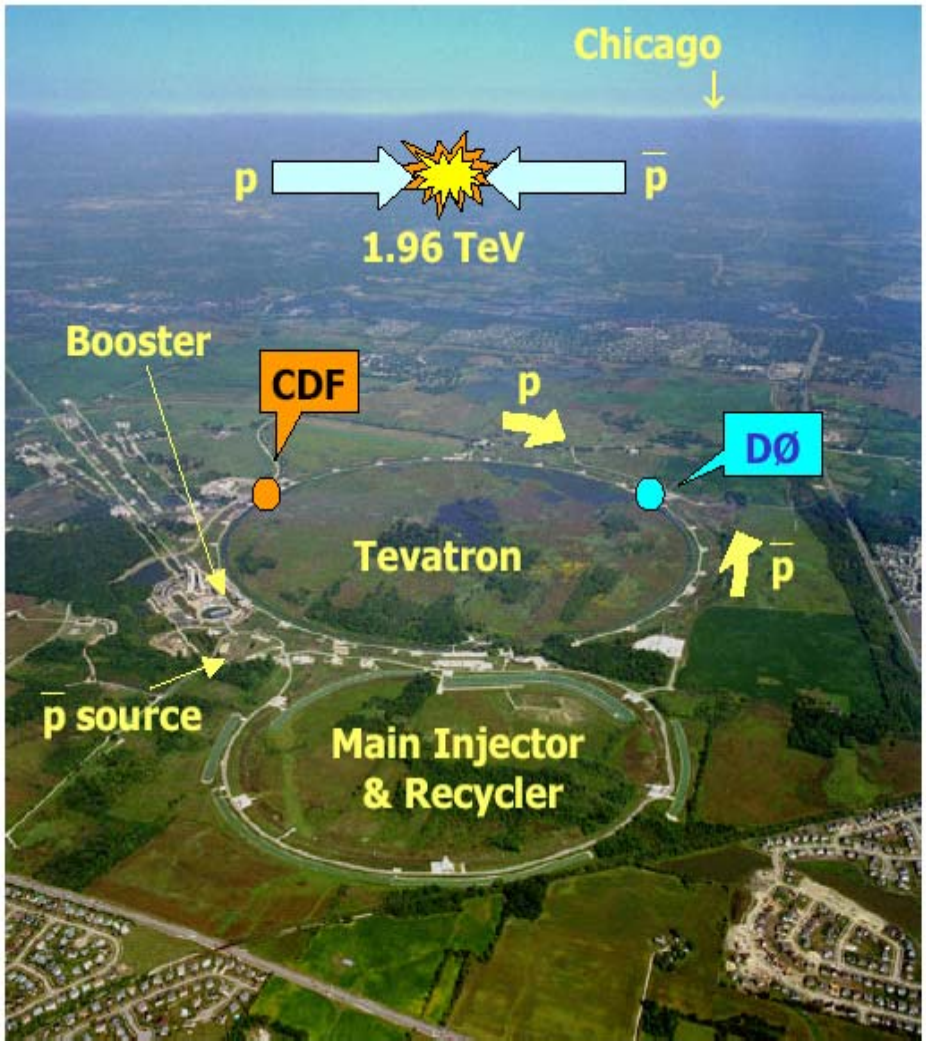
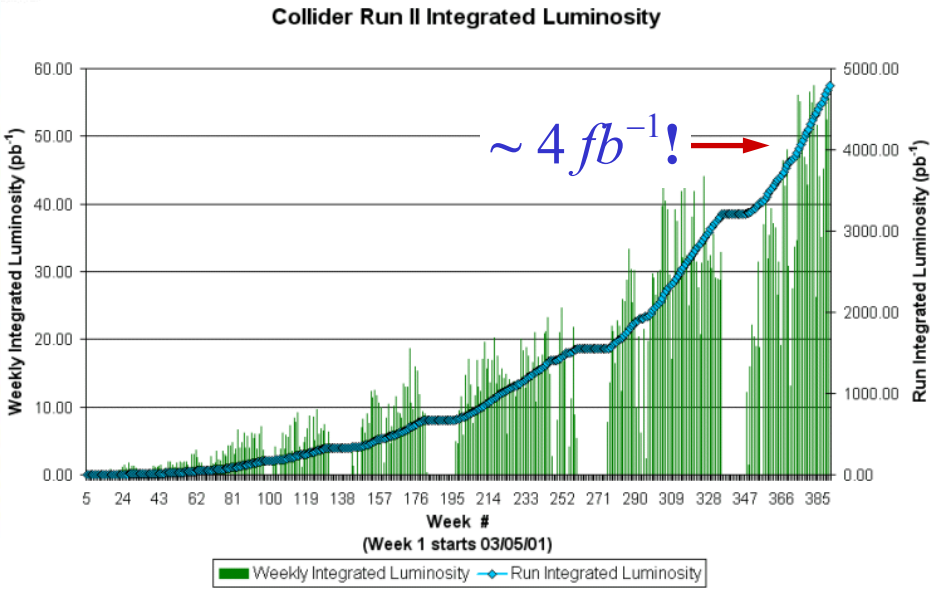
(for the CDF Collaboration)

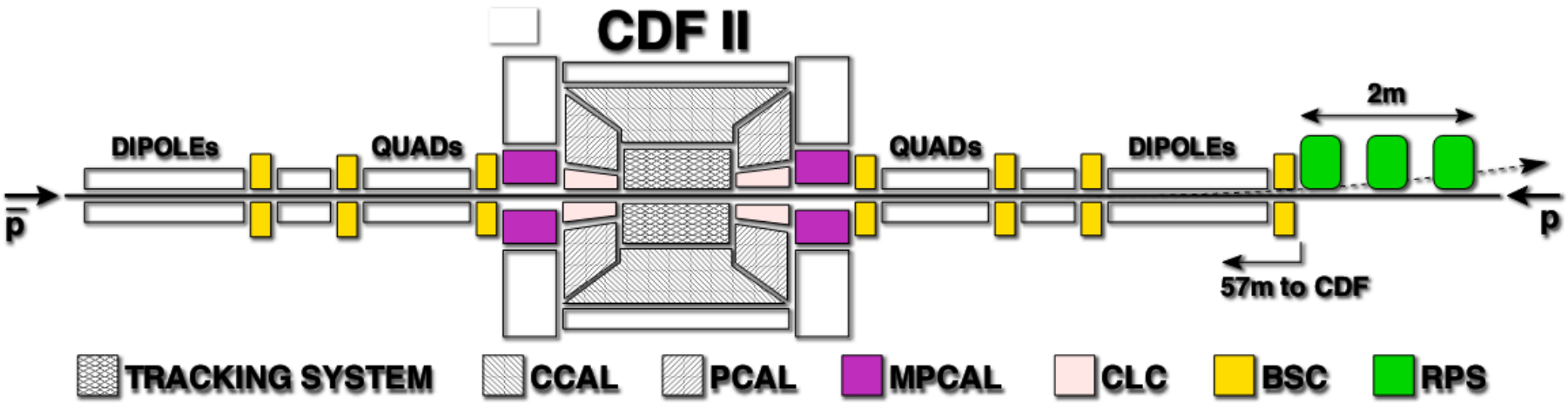
# The Fermilab Tevatron Collider




- Proton-antiproton collider
- Run I (1992-1996)
  - $\sqrt{s}$ = 1.8 TeV, ~100 $pb^{-1}$
- Run II (2001-)
  - $\sqrt{s}$ = 1.96 TeV
  - Delivered luminosity now >4 $fb^{-1}$
  - Projection ~ 6-8 $fb^{-1}$ by 2009



# The CDF II Detectors

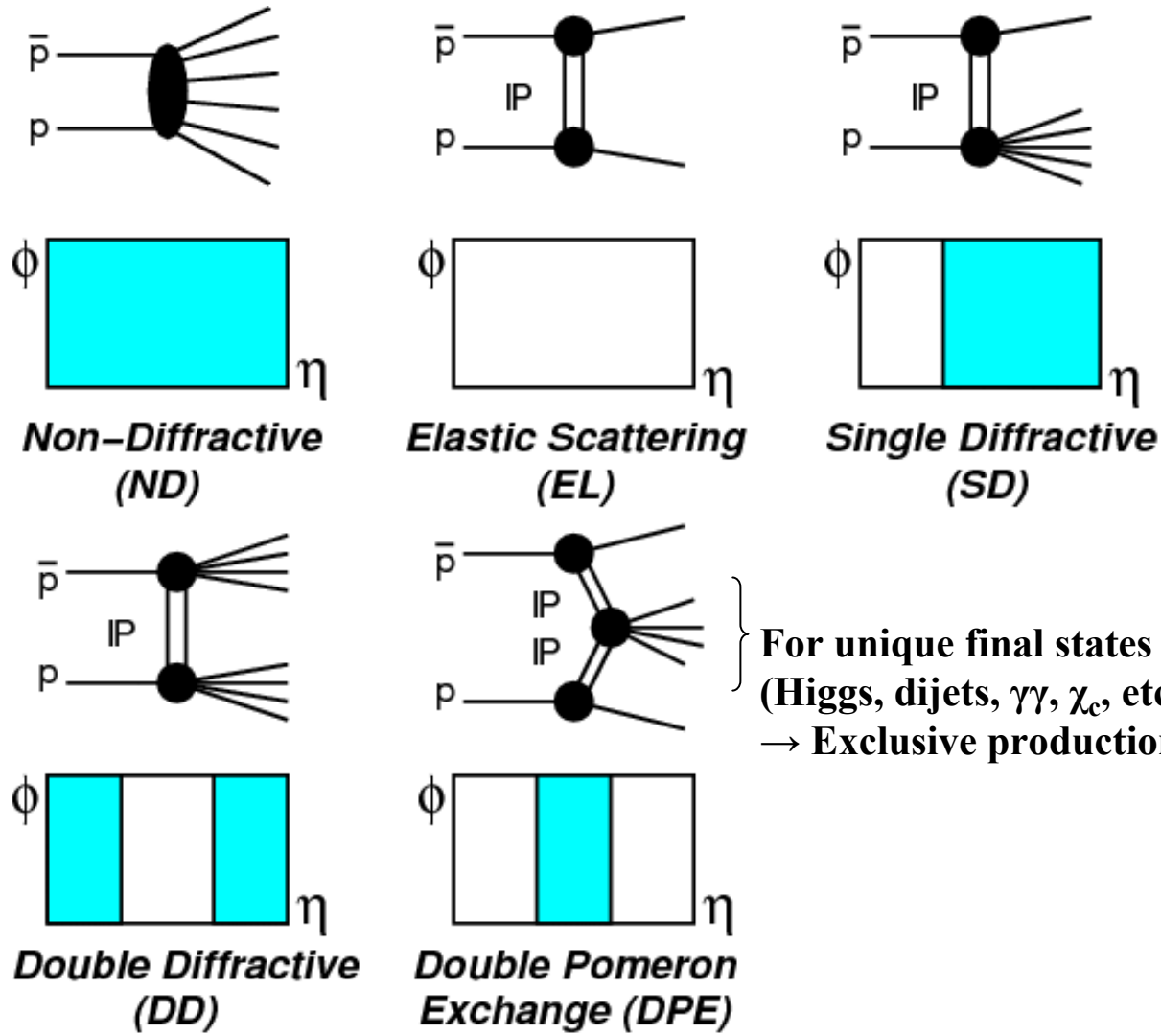



- Tracking Detectors: $|\eta| < 2$
- Calorimeters: $|\eta| < 5.2$
- Beam Shower Counters: $5.4 < |\eta| < 7.4$
- Roman Pot Spectrometer (RPS) : $0.03 < \xi_{\bar{p}} < 0.1$

  $0 < |t_{\bar{p}}| < 1\ \mathrm{GeV}^2$

# Introduction

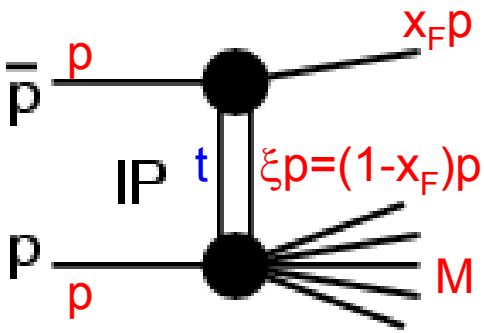
Diffraction in high energy hadron physics refers to a reaction in which no quantum numbers are exchanged between colliding particles.

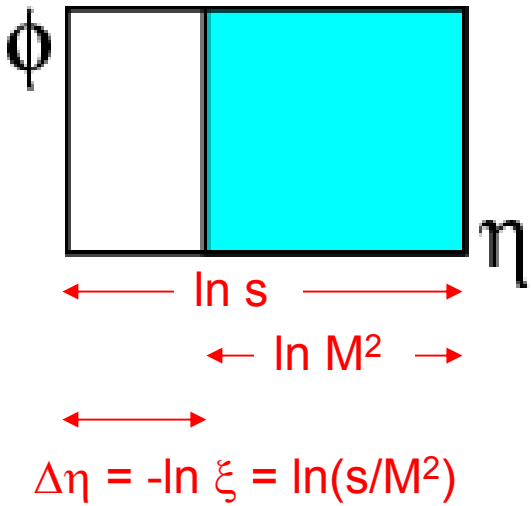



For unique final states (Higgs, dijets, $\gamma\gamma$, $\chi_c$, etc) → Exclusive production

Shaded Area : Region of Particle Production

# Kinematics of a Diffractive Interaction

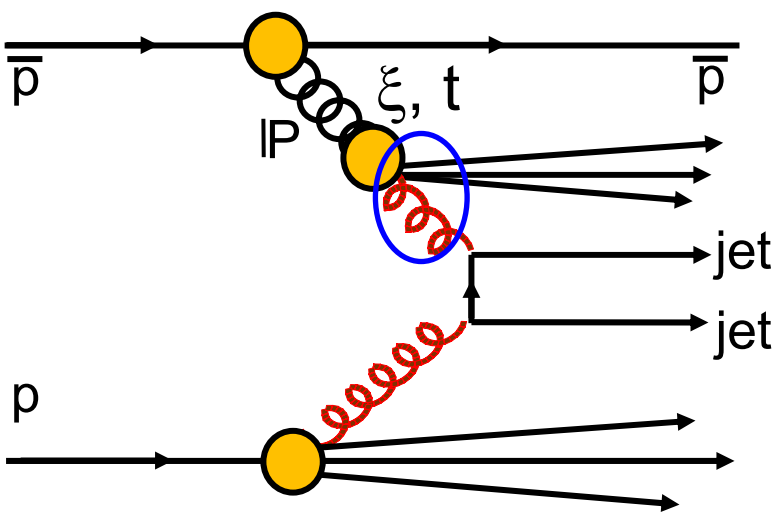



- $\xi$ = fractional momentum loss of (anti)proton
- t = four-momentum transfer squared
- CDF Roman pot acceptance: ~80% for $0.03<\xi_{\bar{p}}<0.10$, $0<|t_{\bar{p}}|<1$ GeV$^2$
  - Outside this $\xi_{\bar{p}}$ region, we tag diffractive events by finding a rapidity gap

# Diffractive Dijet Production

- Use high $p_T$ jets as a probe to determine the partonic structure of the diffractive exchange




- Diffractive dijet cross section:

$$\sigma(\bar{p}p \to \bar{p}X) \approx F_{jj} \otimes F_{jj}^{D} \otimes \hat{\sigma}(\to jj)$$

$$F_{jj}^{D} = F_{jj}^{D}\left(\xi, t, x_{Bj}, Q^2\right)$$

  - Experimentally determine the diffractive structure function $F_{jj}^{D}$:

$$R(x_{Bj}) = \frac{\sigma_{jj}(SD)}{\sigma_{jj}(ND)} \approx \frac{F_{jj}^{D}(x_{Bj}, Q^2)}{F_{jj}(x_{Bj}, Q^2)}$$

measure ratio

$F_{jj}$: known proton structure function

Phys. Rev. Lett. 84, 5043-5048 (2000).

# Diffractive Structure Function – Run I

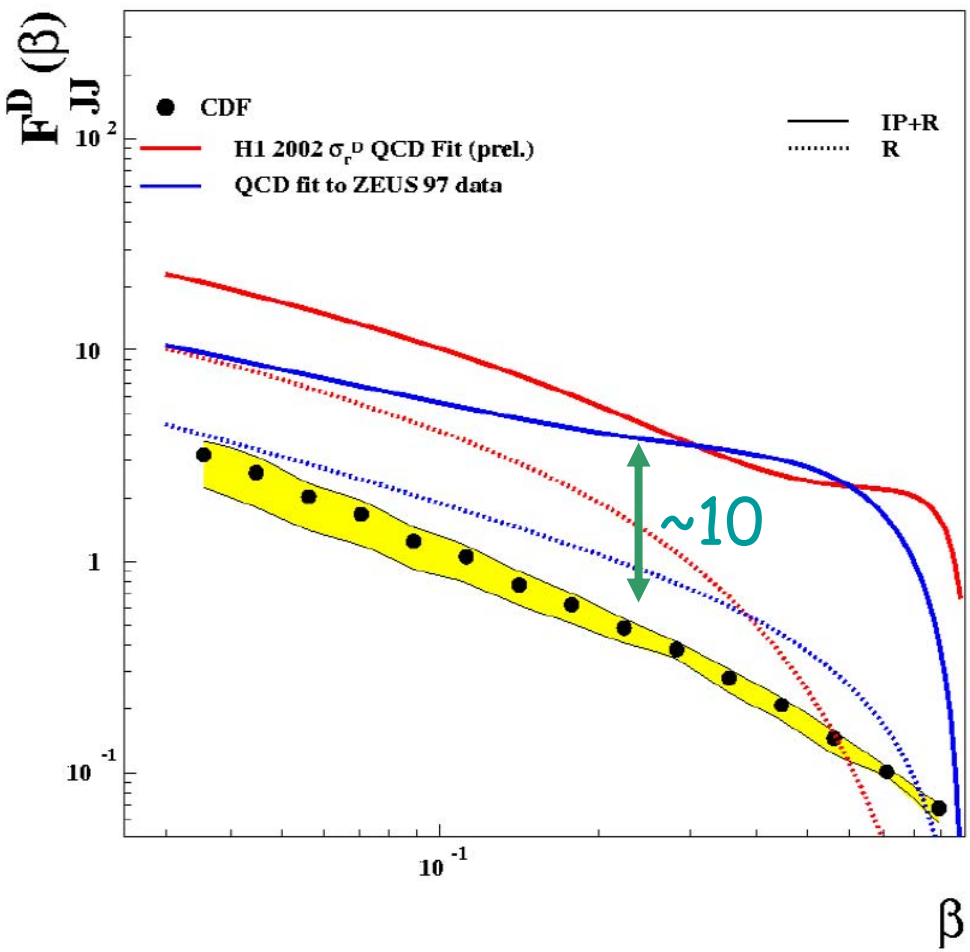
## from single diffractive (SD) dijet production

- The diffractive structure function measured using SD dijet events at the Tevatron is smaller than that at HERA by approximately an order of magnitude.

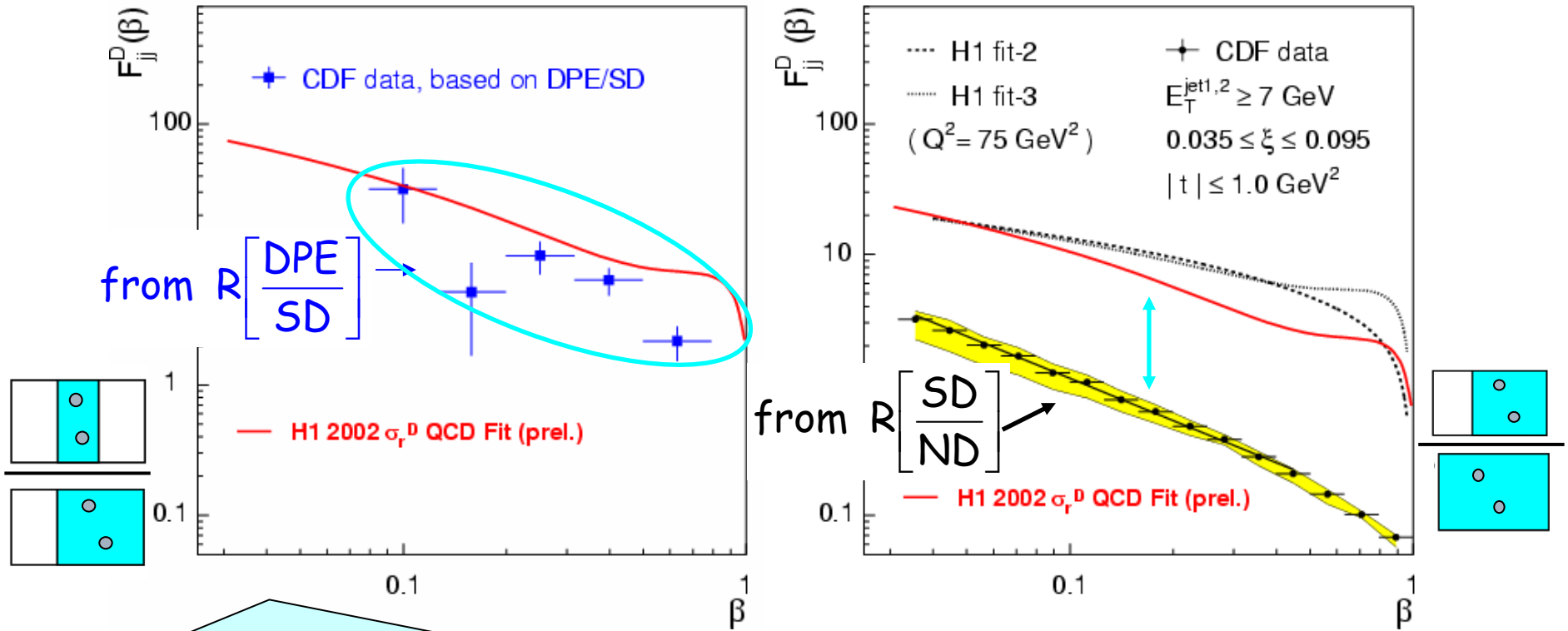
⇩

Factorization Breakdown

- The discrepancy is generally attributed to additional color exchanges which spoil the "diffractive" rapidity gap.



# Diffractive Structure Function – Run I




The diffractive structure function measured using DPE dijets is approximately equal to expectations from HERA!

Factorization restored

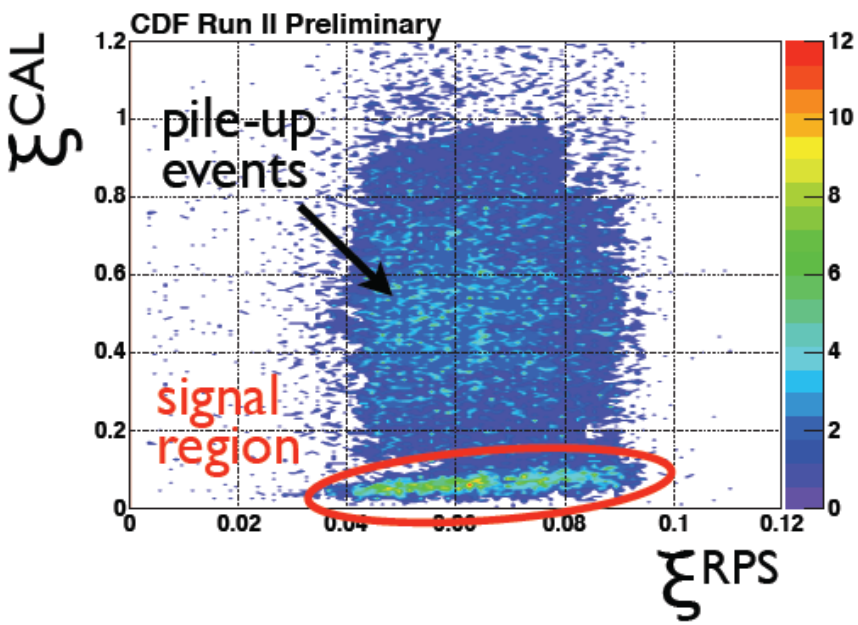
As expected from the renormalization model, gap survival model, etc

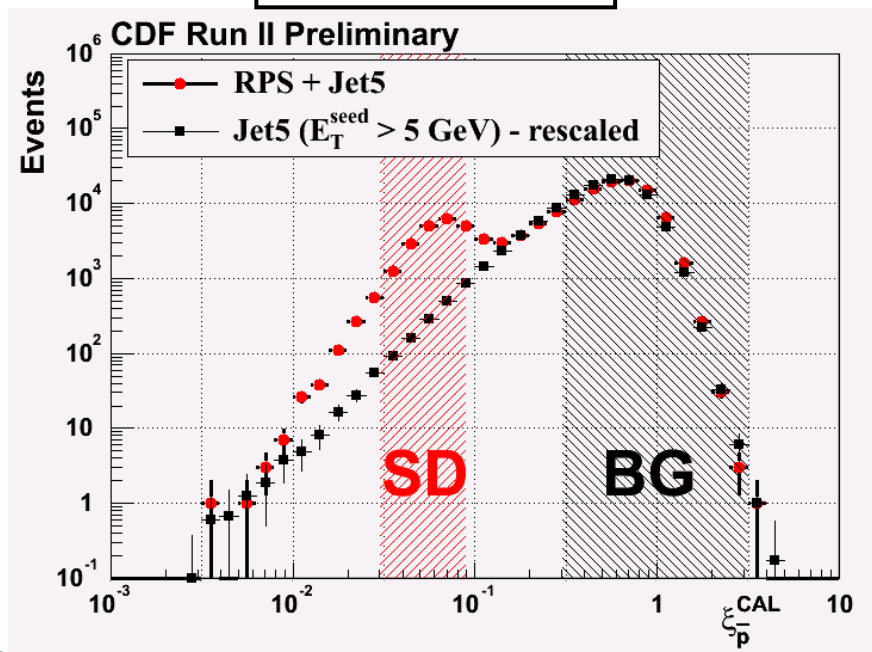
# Challenge in Run II

Among problems we had to overcome, the most challenging one is multiple proton-antiproton interactions (pile-up) that spoil diffractive signatures

- Determine ξ using Roman Pot tracking
- Can also determine ξ from $E_T$ in calorimeters

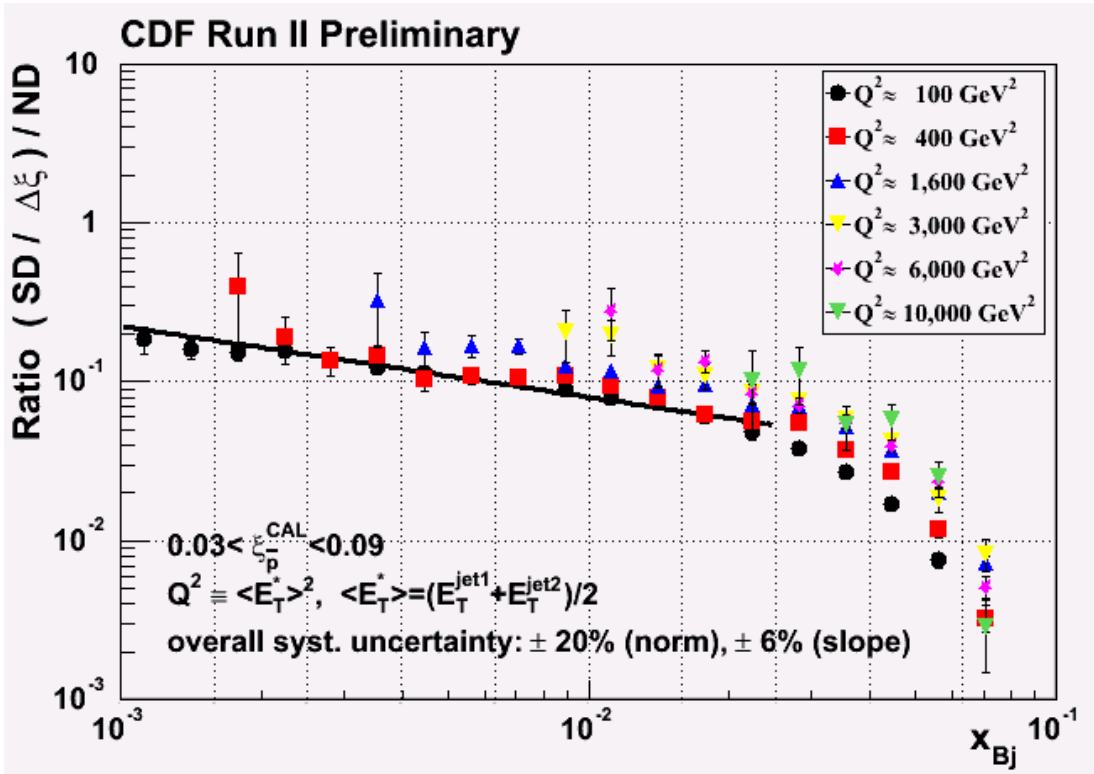
$$\xi^{cal} = \sum_{towers} \frac{E_T}{\sqrt{s}} e^{-\eta}$$




- Use to reject overlap events (require $\xi^{cal}$<0.1)
  - e.g. non-diffractive dijet + soft diffractive interaction

# Diffractive to Non-Diffractive Ratio – Run II



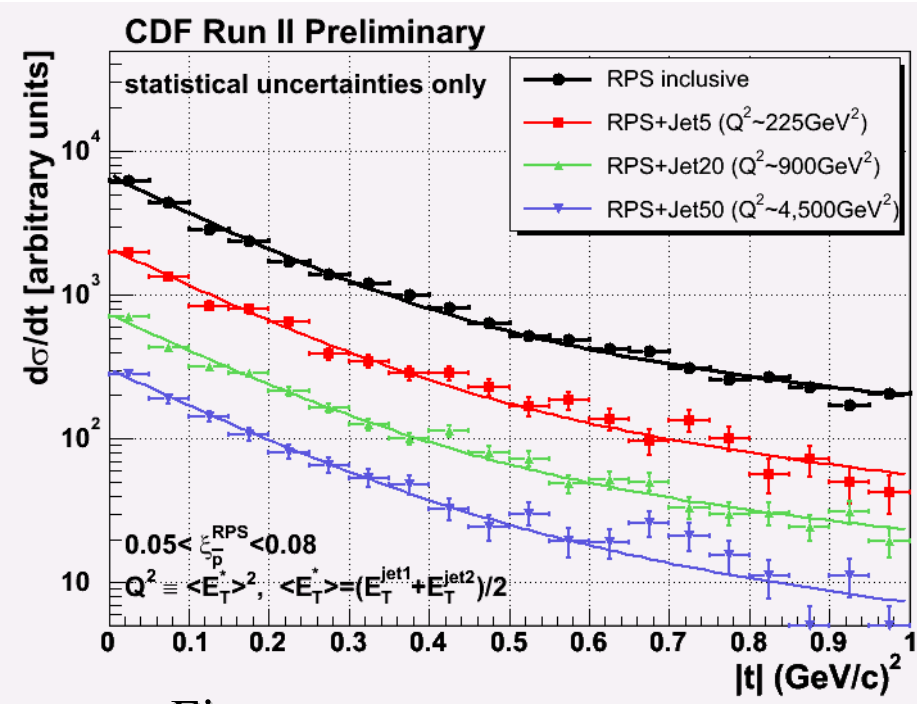

$$R_{\frac{SD}{ND}}(x_{Bj}) = R_0 x_{Bj}^{-r}, \quad r \approx 0.45$$

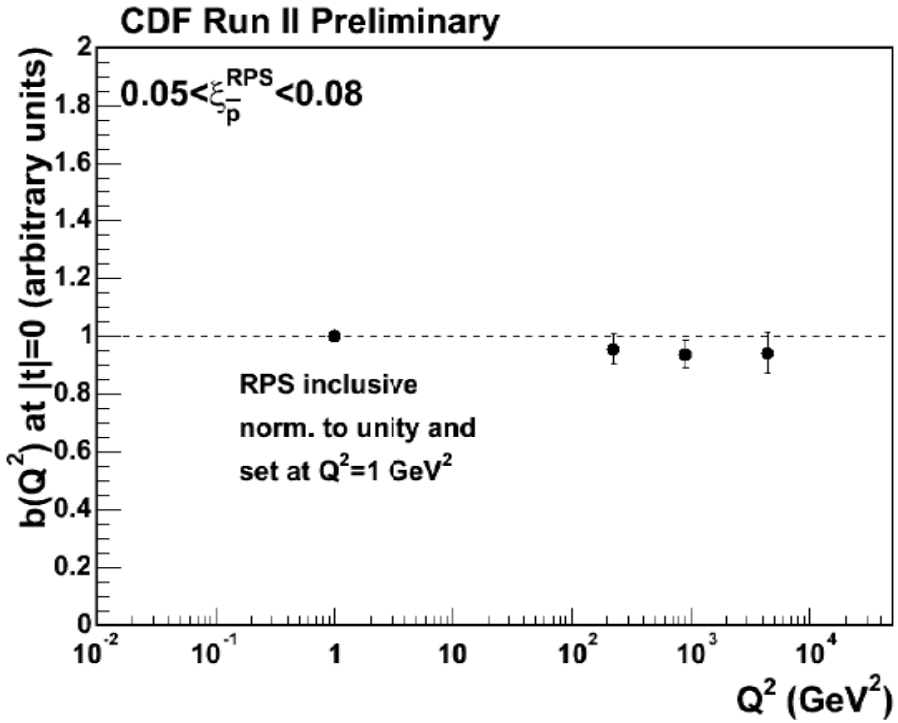
- Confirms Run I result

- No appreciable $Q^2$ dependence in SD/ND ratio for $100 < Q^2 < 10000$ GeV$^2$

→ Pomeron evolves similarly to proton

# Diffractive *t* Distribution – Run II




Fit to:

$$d\sigma / dt \propto 0.9 \cdot e^{b1 \cdot t} + 0.1 \cdot e^{b2 \cdot t}$$

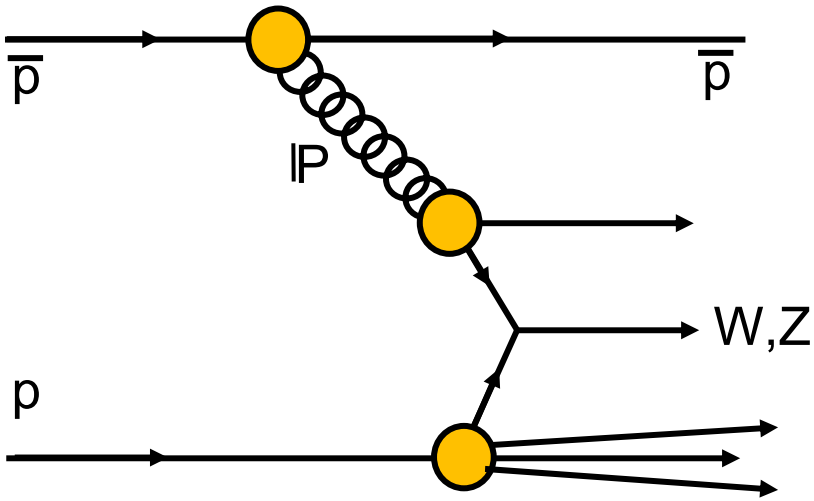
- No diffractive dips
- No $Q^2$ dependence in slope from inclusive to $Q^2 \sim 10^4$ GeV$^2$

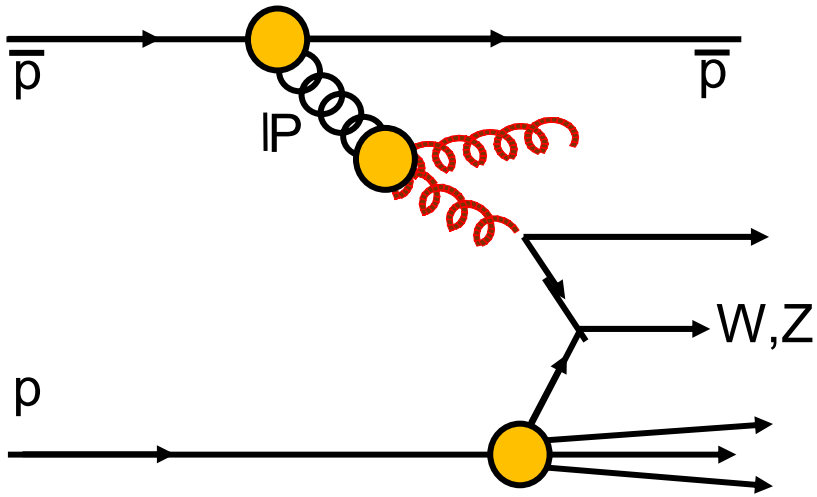
Ongoing work:

- Absolute |t|-slope values
- High |t| range

# Diffractive W/Z Production

- The study of diffractive W/Z production helps to determine the quark content of the pomeron
  - To leading order, the W/Z is produced by a quark in the pomeron
  - Production by gluons is suppressed by a factor of $\alpha_S$, and can be distinguished from quark production by an additional jet



# Diffractive W/Z Production - Run I

- Run I diffractive W studies done with rapidity gaps instead of Roman-pots
- CDF: Phys Rev Lett **78**, 2698 (1997)
  - Fraction of W events due to SD for $\xi<0.1$ (corrected for gap acceptance)

    $[1.15 \pm 0.51(\text{stat}) \pm 0.20(\text{syst})]\%$
  - Together with jet/b-quark data, the quark/gluon content of the Pomeron was determined to be

    $f_g = 0.54^{+0.16}_{-0.14}$
- DØ: Phys Lett B **574**, 169 (2003)
  - Fraction of events with rap gap (uncorrected for gap acceptance)

    W: $[0.89^{+0.19}_{-0.17}]\%$

    Z: $[1.44^{+0.61}_{-0.52}]\%$
  - Corrected for gap acceptance

    W: 5.1%

    (if correction factor from POMPYT model of 0.21±0.04 is used)

# Diffractive W Production – Run II

- Identify diffractive events using Roman pots
  - Accurate $\xi$ measurement!
  - No gap acceptance correction needed
- As in diffractive dijet production, we can calculate $\xi$ from the energy in the calorimeter

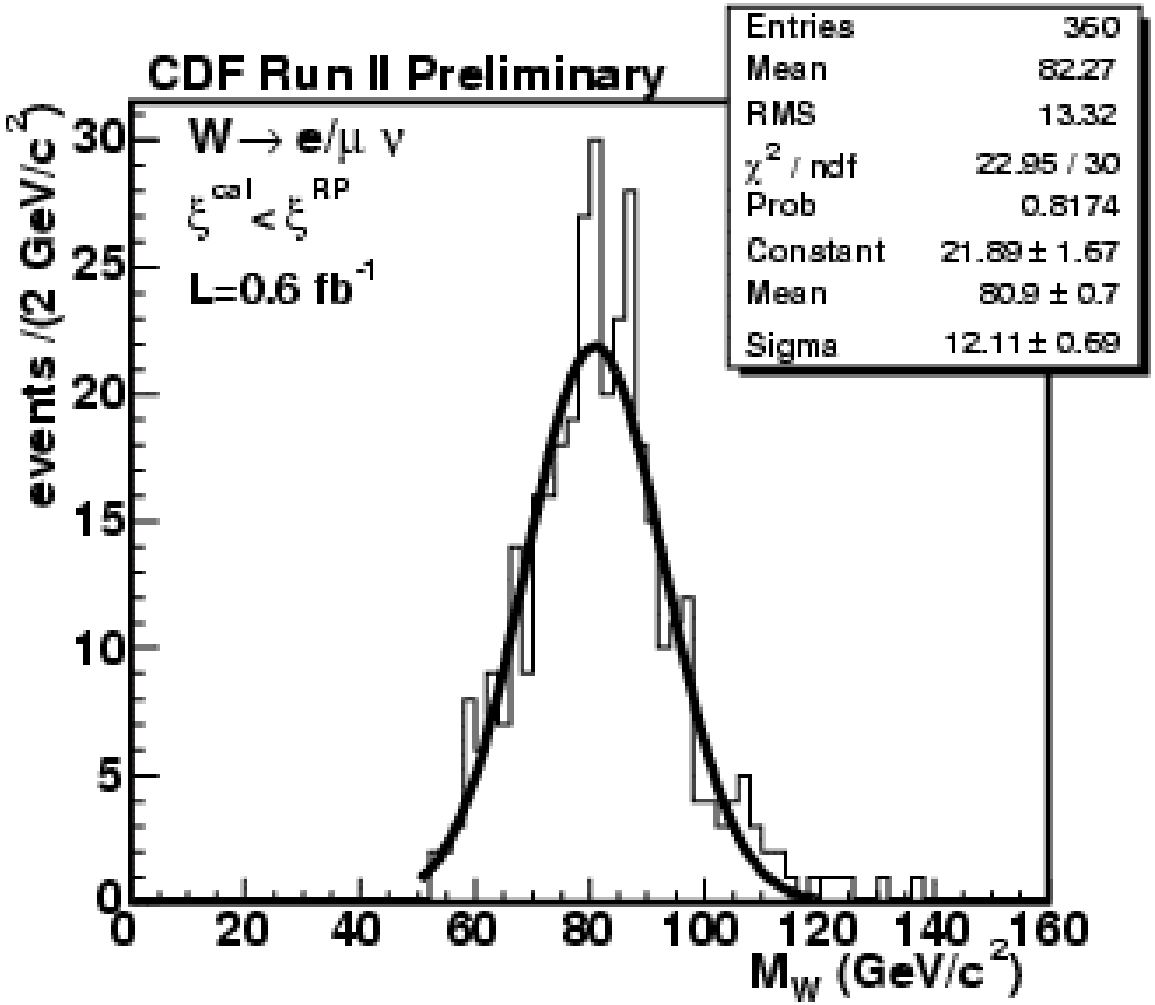
$$\xi^{cal} = \sum_{towers} \frac{E_T}{\sqrt{s}} e^{-\eta}$$

- In W production, the difference between $\xi^{cal}$ and $\xi^{RP}$ is related to missing $E_T$ and $\eta_\nu$, which allows us to determine
  - Neutrino kinematics
  - W kinematics
  - $x_{bj}$.

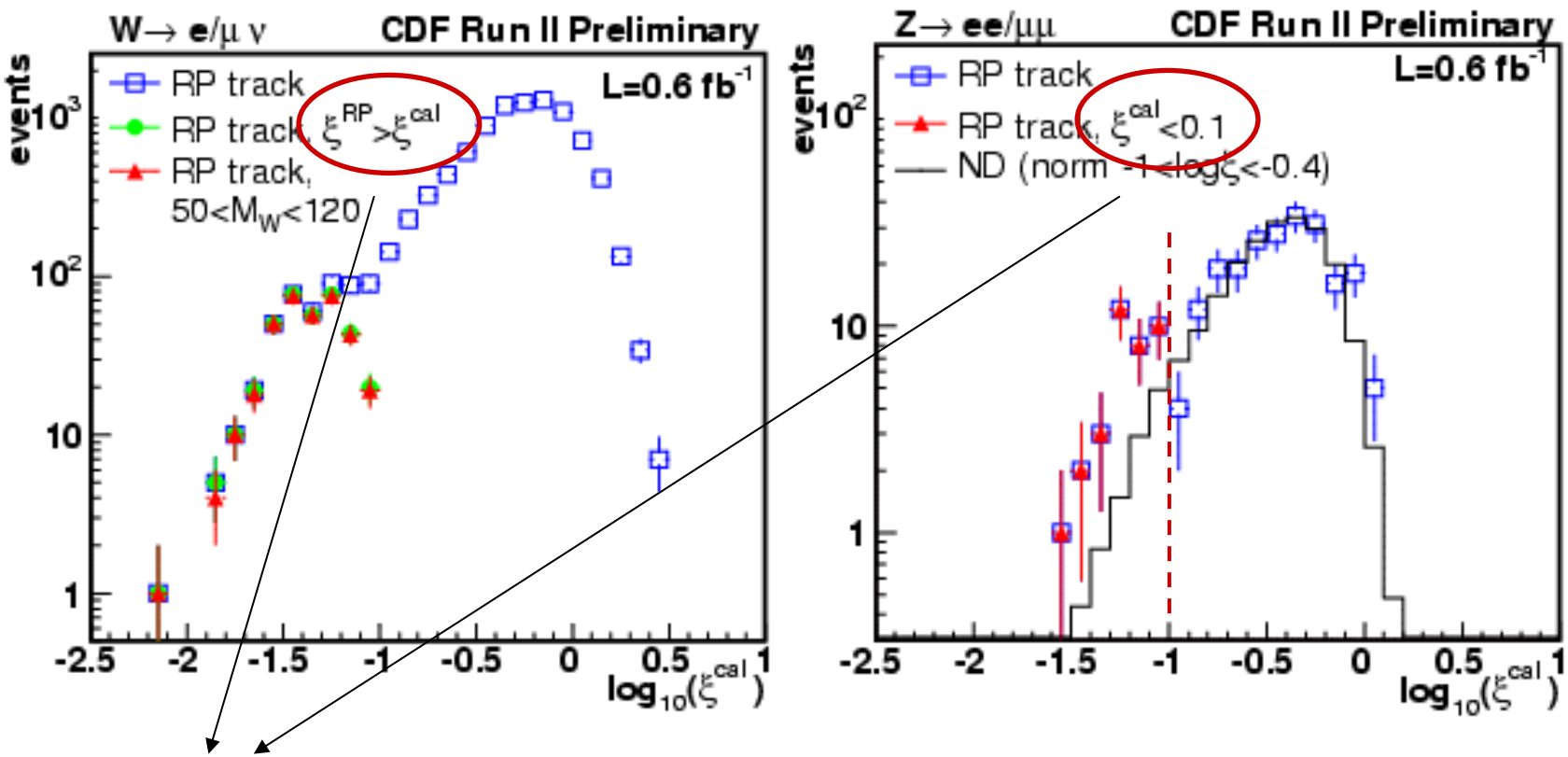
$$\xi^{RP} - \xi^{cal} = \frac{\not{E}_T}{\sqrt{s}} e^{-\eta_\nu}$$

- Hope to use to determine structure function from diffractive W production

# Reconstructed Diffractive W Mass



# Diffractive W/Z Production Measurement




Remove events with non-diffractive W/Z production and soft single diffractive interaction

# Diffractive W/Z Production Measurement

**Measured fraction of W/Z's which are diffractive**

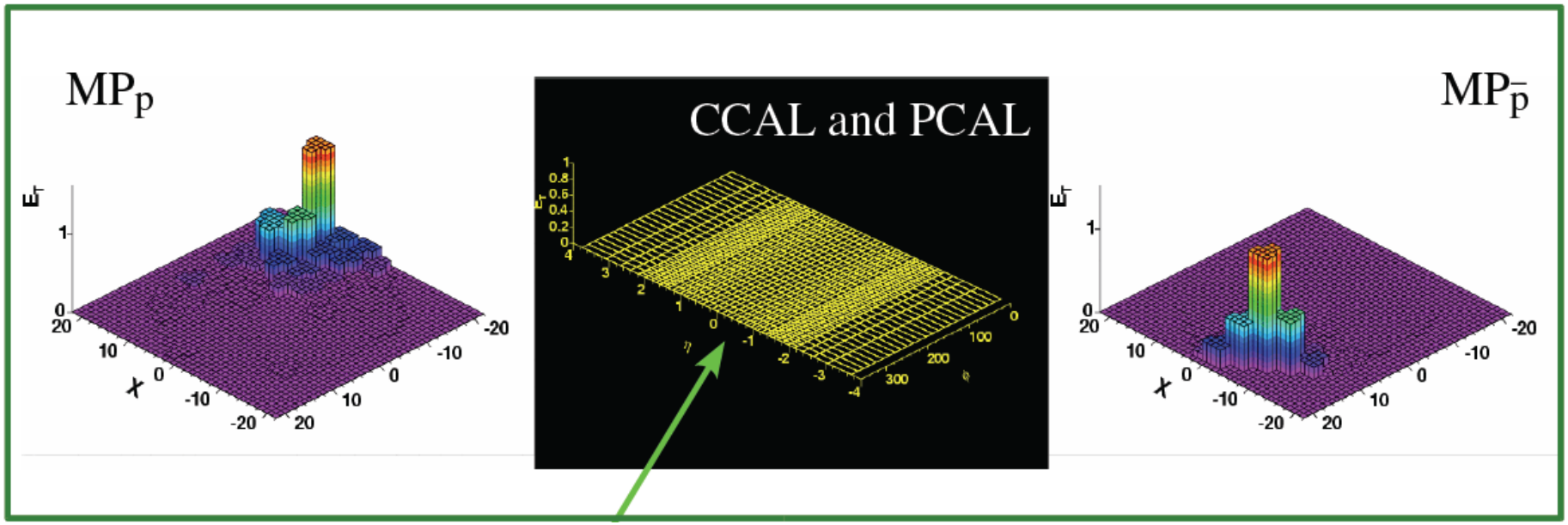
$R_W$ ($0.03<\xi<0.10$, $|t|<1$)= [0.97 ± 0.05(stat) ± 0.11(syst)]%

$R_Z$ ($0.03<\xi<0.10$, $|t|<1$)= [0.85 ± 0.20(stat) ± 0.11(syst)]%

**Comparisons with the Run I results**

- CDF: Phys Rev Lett **78**, 2698 (1997)
  - W: [1.15 ± 0.51(stat) ± 0.20(syst) ]% ($\xi<0.1$, corrected for gap acceptance)
    [0.93 ± 0.44] (for $0.03<\xi<0.1$)
- DØ: Phys Lett B **574**, 169 (2003)
  - W: $[0.89^{+0.19}_{-0.17}]$%
    Z: $[1.44^{+0.61}_{-0.52}]$%
    (uncorrected for gap acceptance)
  - W: 5.1%
    (corrected with gap acceptance from POMPYT model =0.21±0.04)

# Central Rapidity Gaps between Forward Jets

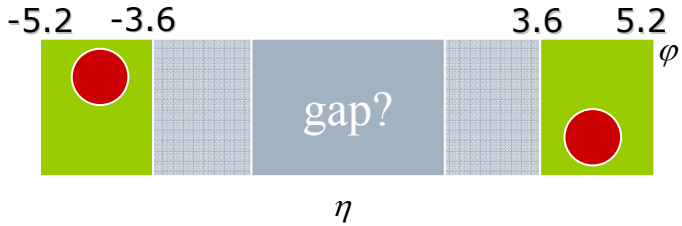


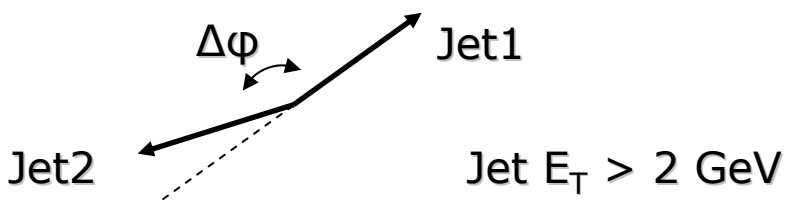

Rapidity gap in the central and plug calorimeters

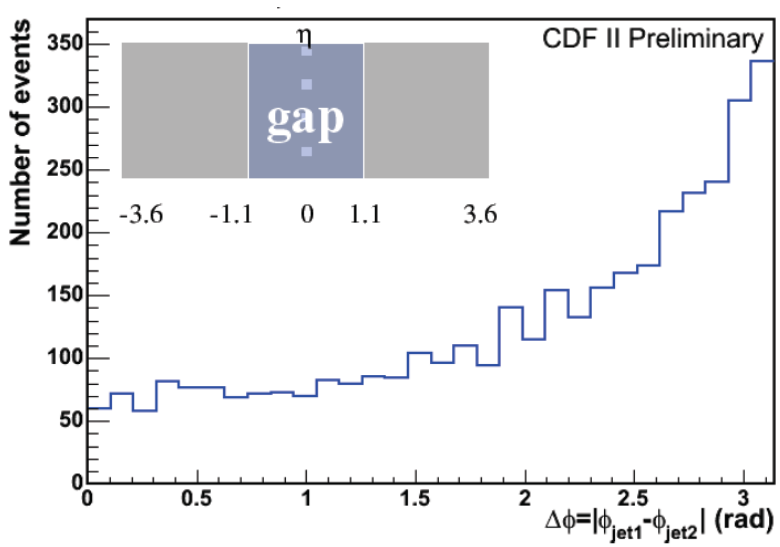
**Goals:**

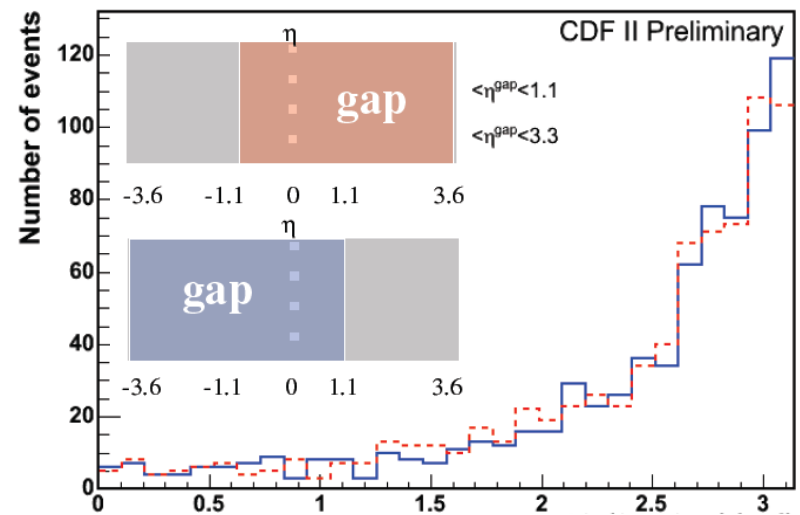
- Characterize rapidity gap formation in forward jet events
  - Fraction of rapidity gap events
  - Dependence on rapidity gap width
- Study Mueller-Navelet jets

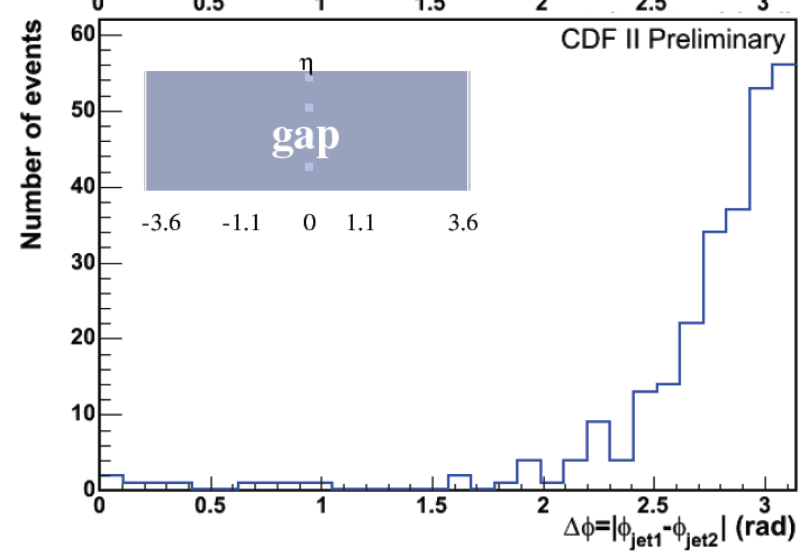
# Two-jet Azimuthal Angle (De)correlation



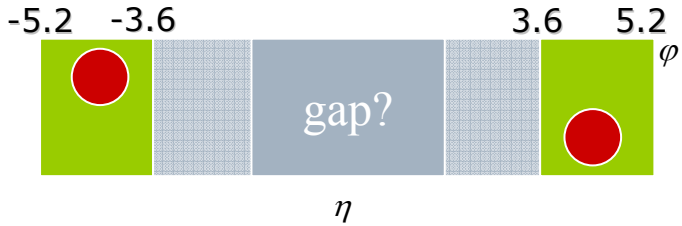



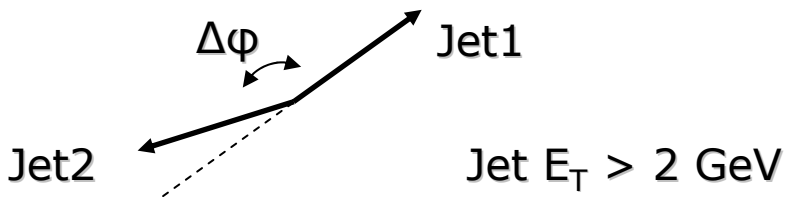



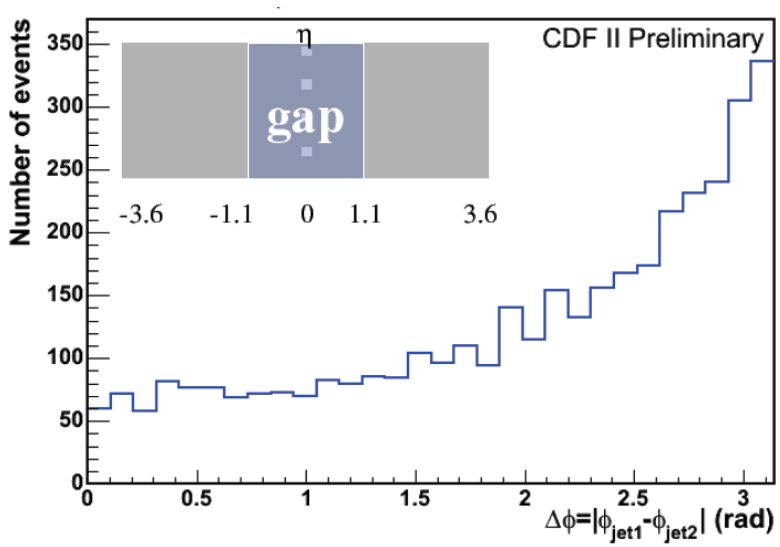



# Two-jet Azimuthal Angle (De)correlation

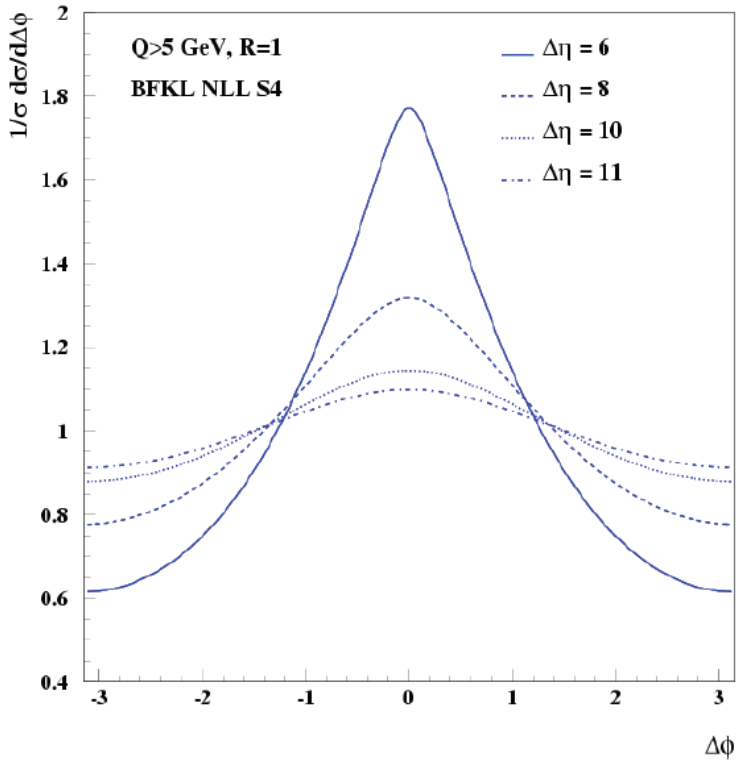



azimuthal decorrelation for CDF kinematics

*from C. Marquet, C. Royon*
*arXiv:0704.3409*

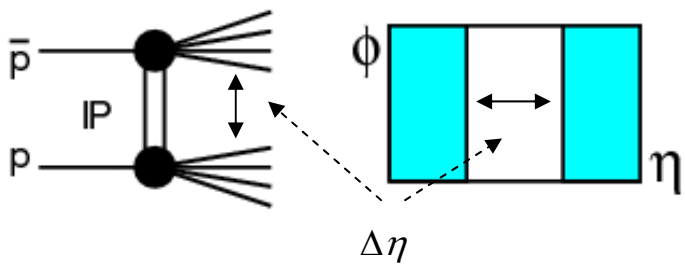



work in progress...

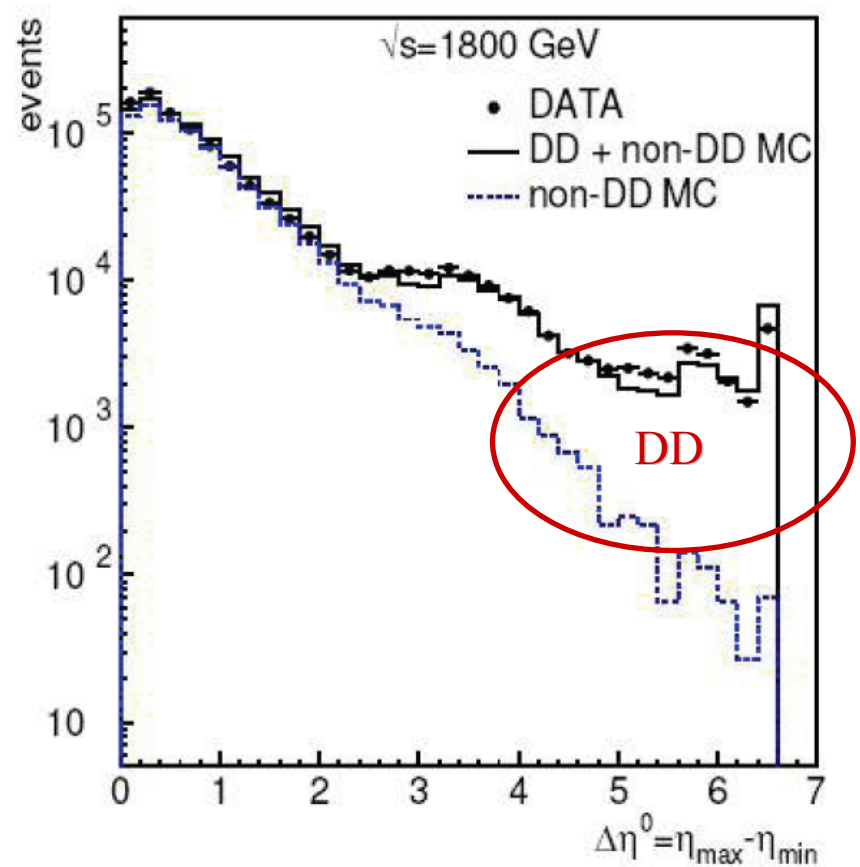
# Rapidity Gap Event Fraction vs Gap Width

**Soft double-diffractive (DD) events**

(no hard scattering required)




PRL 87, 141803 (2001)



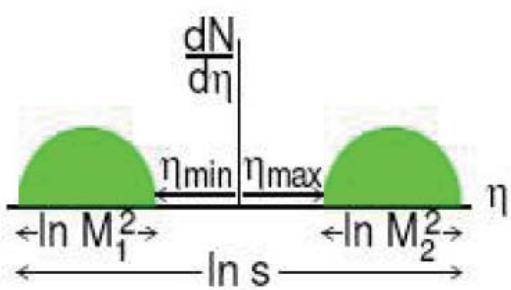

**Analysis Strategy:**

Look for rapidity gaps defined as

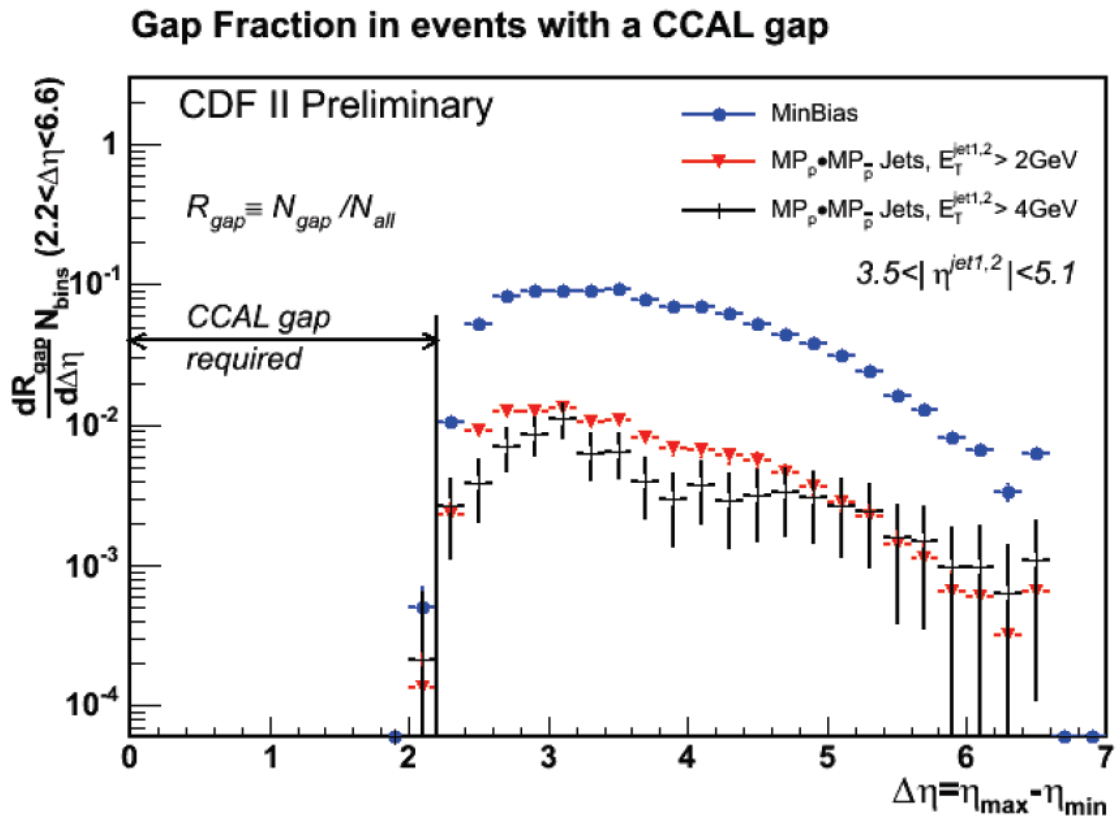
$\Delta\eta \equiv \eta_{max} - \eta_{min}$

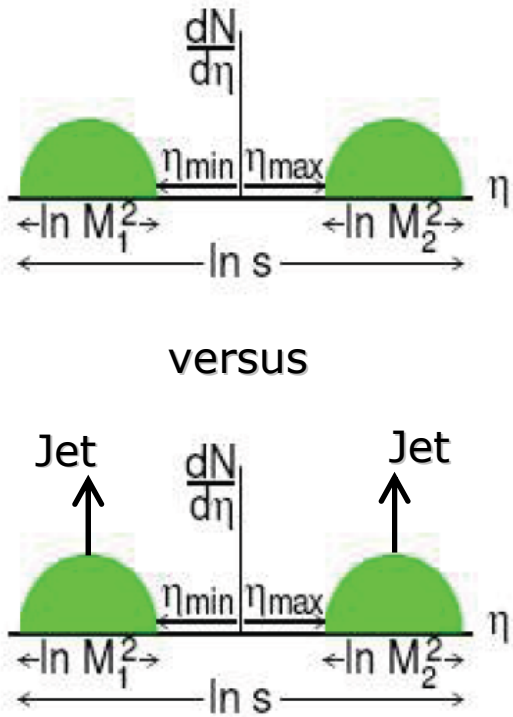
$\eta_{max}(\eta_{min})$-particles closest to

$\eta$=0 in the positive(negative) $\eta$ regions



# Rapidity Gap Event Fraction vs Gap Width

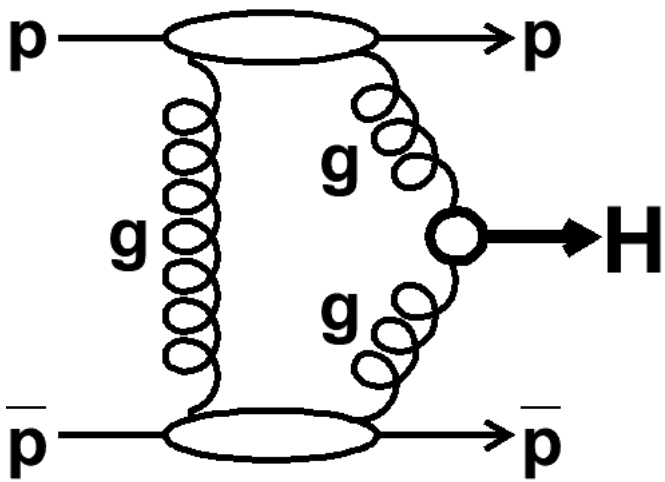



- The event fraction with gaps ~10% in soft events and ~1% in jet events
- The distributions are similar in shape within the uncertainties

# Exclusive Production

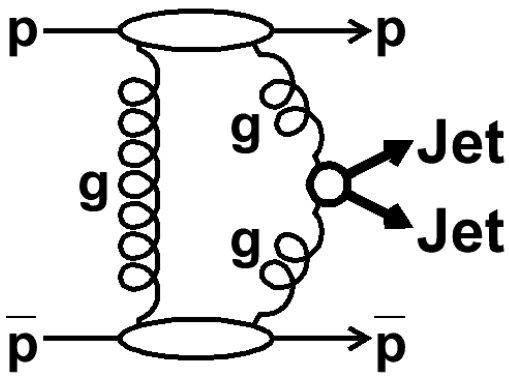
- Test and calibrate predictions for exclusive Higgs production at the LHC
  - Event consists of nothing but leading protons and Higgs



# Exclusive Dijet Production

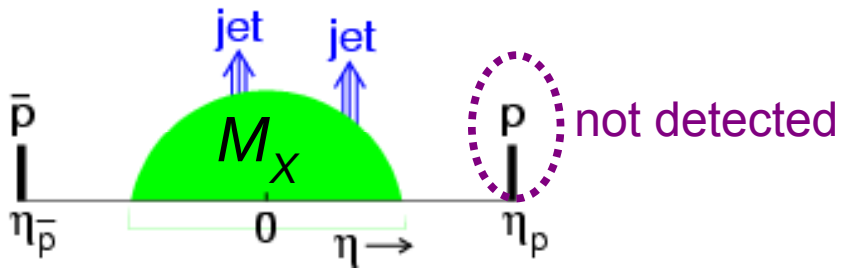
(For studies on other exclusive states, please see Mike Albrow's talk)

- Wide range of theoretical predictions
- Run I CDF limit of $\sigma_{excl}$<3.7 nb (95% CL)




- Run II search:
- Select inclusive Double Pomeron Exchange dijet events:

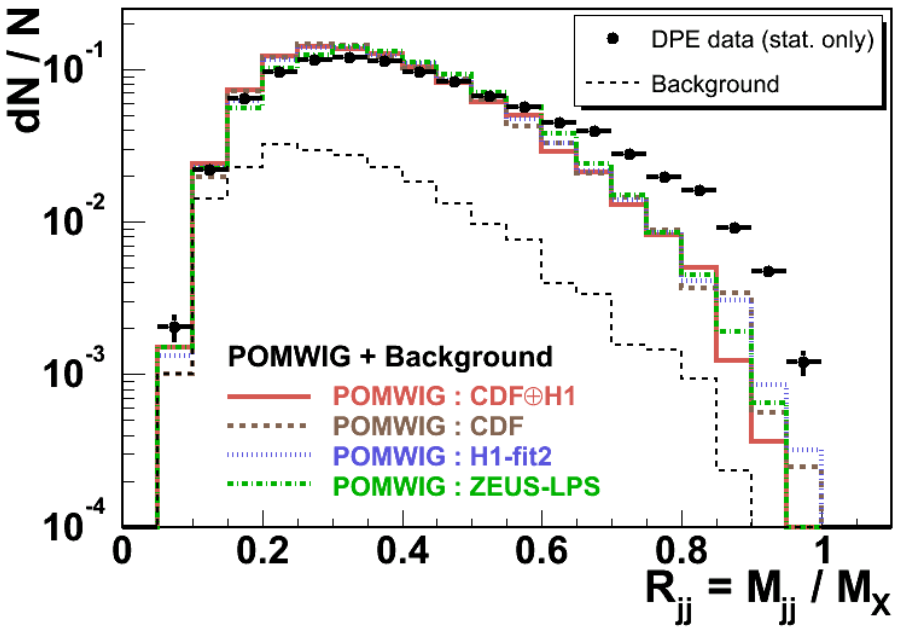
$$p + p \rightarrow IP\ IP \rightarrow p + X\ (\geq 2\ \text{jets}) + \text{gap}$$

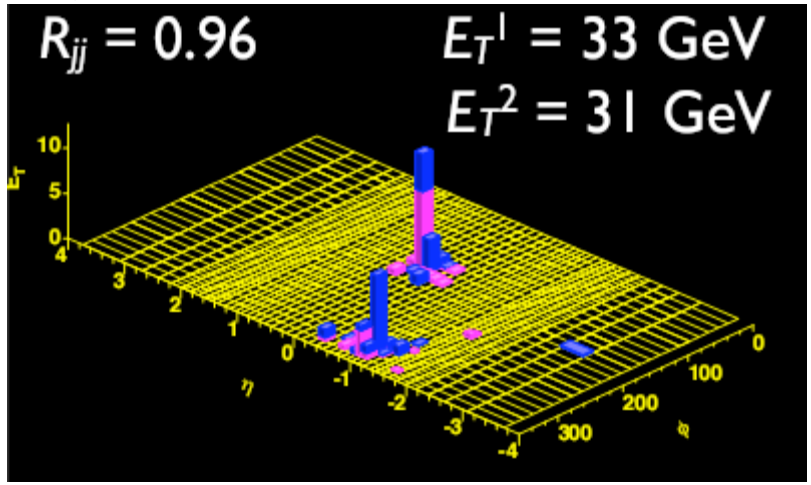


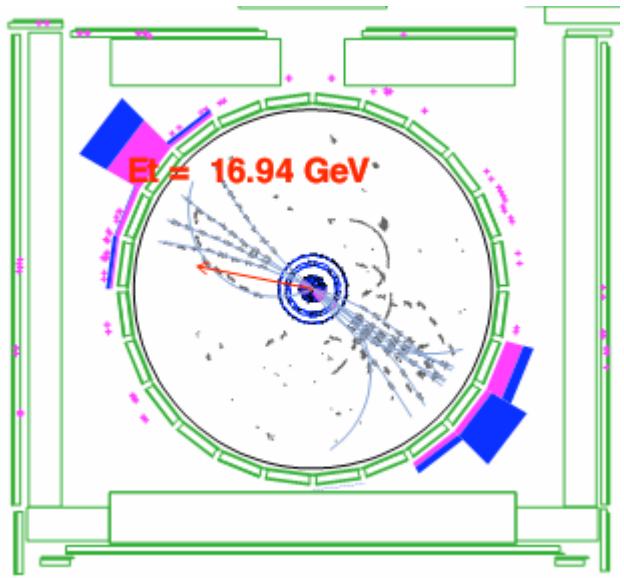

- Look for exclusive signal using dijet mass fraction
  - $R_{jj}$ = ratio of dijet mass $M_{jj}$ to system mass $M_X$

# Observation of Exclusive Dijet Production

PRD 77, 052004 (2008)

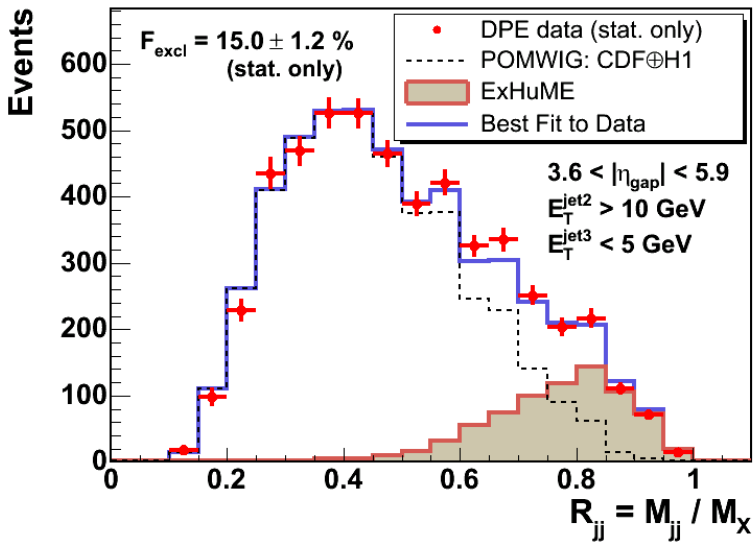


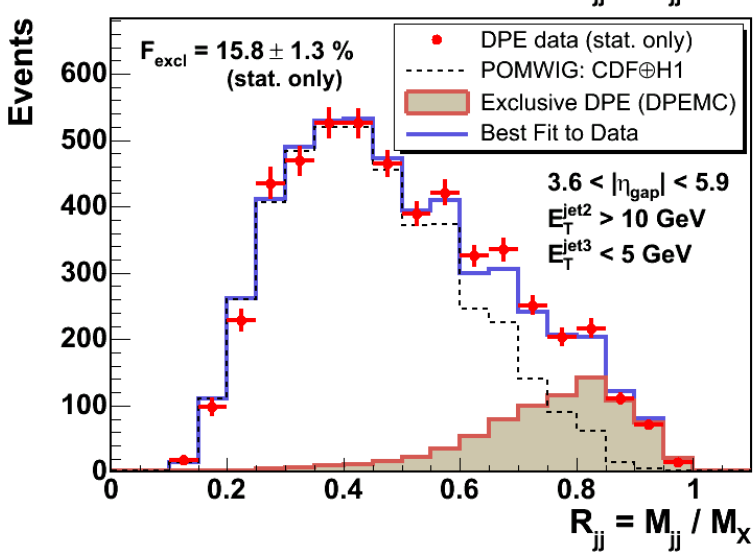



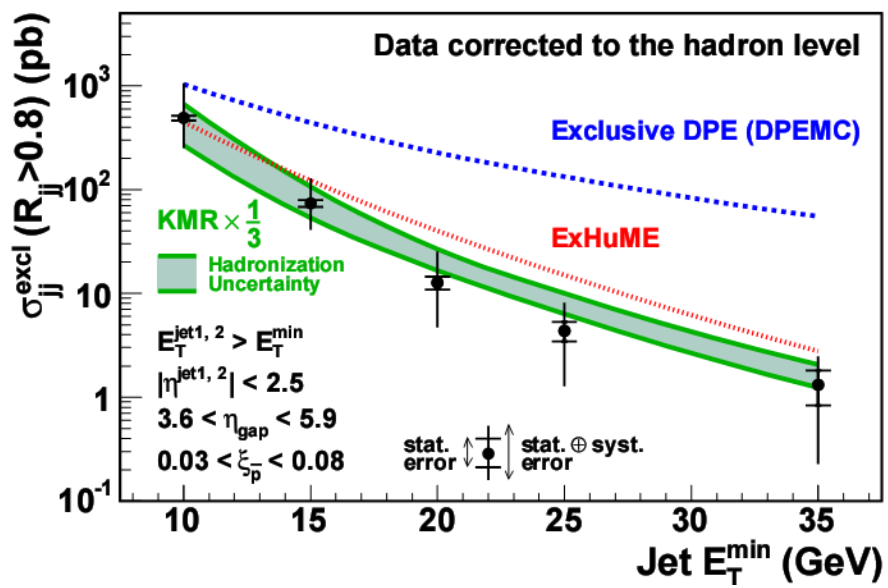

- Observe excess over inclusive DPE dijet MC's at high dijet mass fraction

# Exclusive Dijet Cross Section

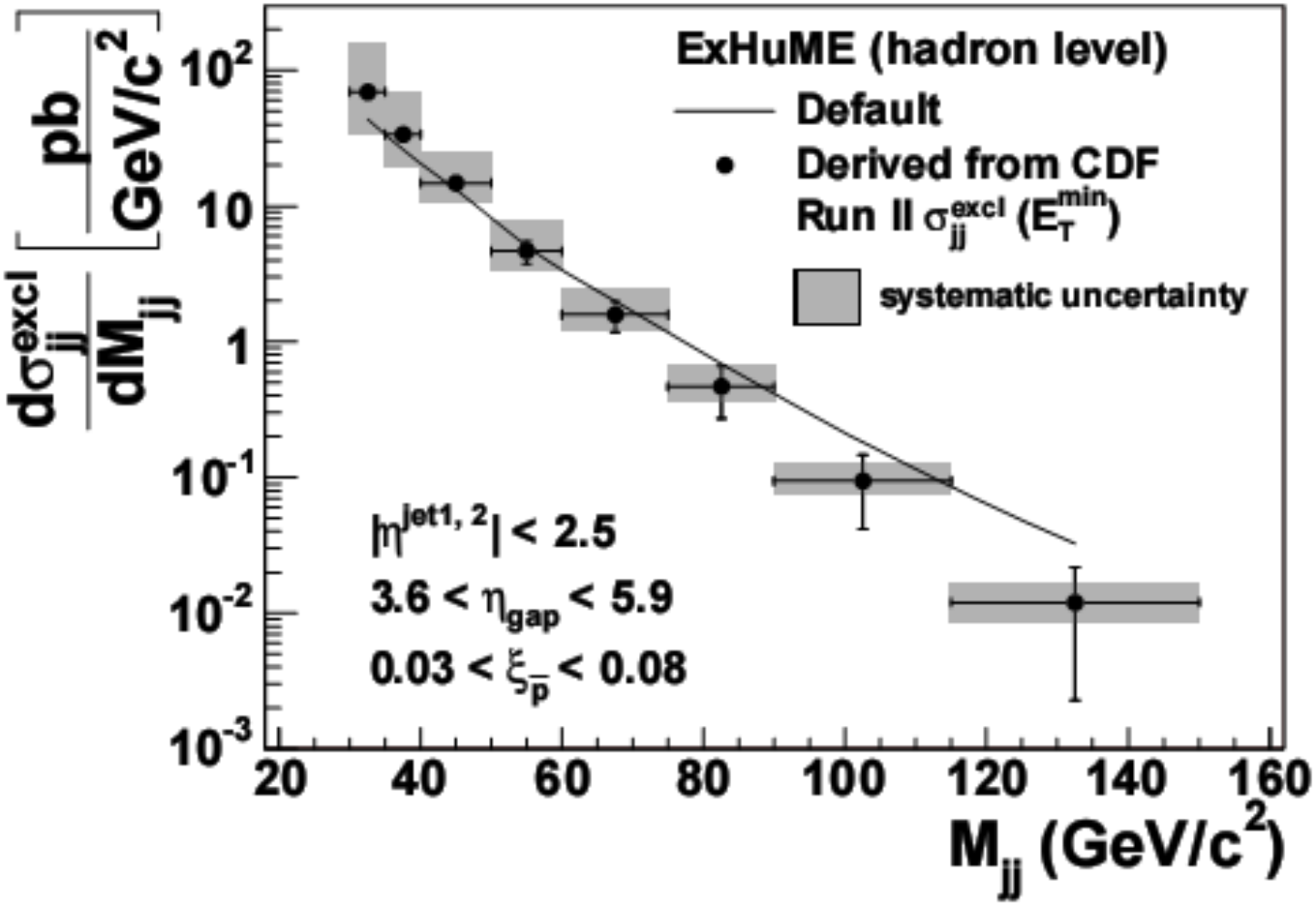



- Shape of excess described by exclusive dijet MC based on two models (ExHuME, DPEMC), but cross section disfavors DPEMC
- Calculation by Khoze, Martin, and Ryskin consistent within its factor of 3 uncertainty. Eur. Phys J C**14**, 525 (2000).



# Exclusive Cross Section vs Dijet Mass



# Conclusions

- The long-standing diffractive program at CDF continues to improve our understanding of the diffractive process
  - Extension of Run I diffractive dijet measurement to a larger $Q^2$ range
  - First measurement of *t* distribution in diffractive dijet production at Tevatron energies
  - Measurement of diffractive W/Z production using Roman pots confirms CDF Run I rapidity gap result
  - Study on events with a rapidity-gap between forward jets in progress
- Measurements of exclusive production at CDF have been essential for calibrating predictions for exclusive Higgs production at the LHC
  - Observation of exclusive dijet production!

Studies on other exclusive states will be presented in next talk