

# Diffraction: from HERA & Tevatron to LHC

DIFFRACTION AT THE LHC

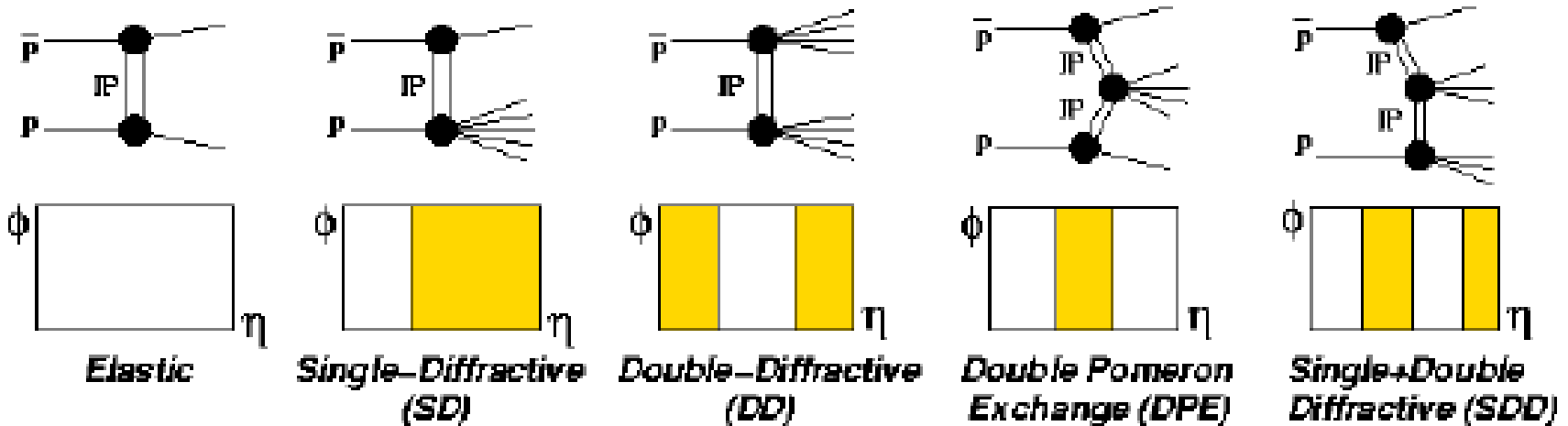
RIO DE JANEIRO, BRAZIL, 31 March - 2 April 2004

K. Goulianos, The Rockefeller University



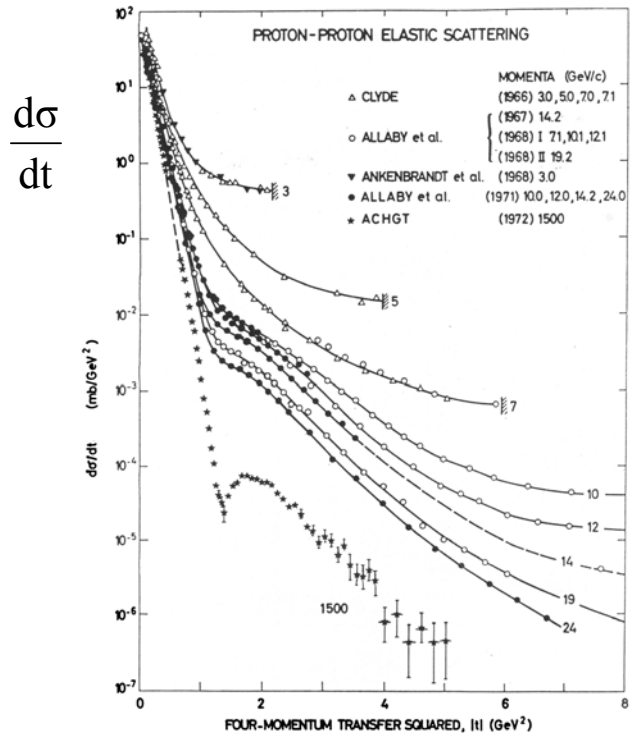
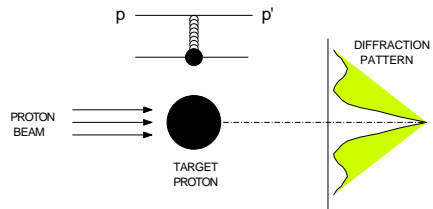
# Diffractive signatures

- Leading hadron(s)
- Rapidity gap(s)

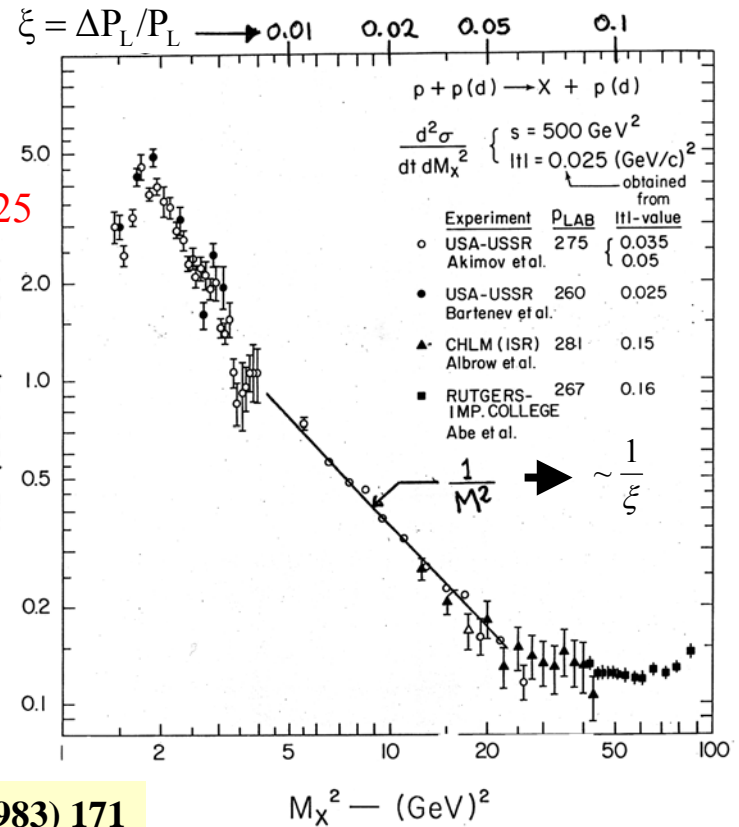
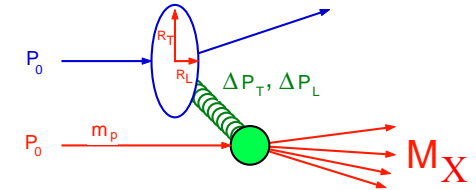


# Leading hadrons

## PROTON-PROTON ELASTIC SCATTERING



## Diffraction dissociation

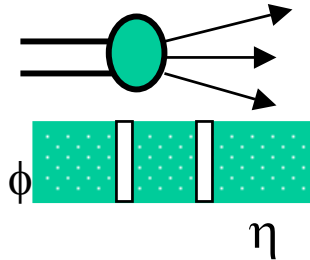


$$\left. \frac{d^2\sigma}{dt dM^2} \right|_{t=0.025}$$

KG, Phys. Rep. 101 (1983) 171

# Rapidity gaps

## ❖ Minimum bias

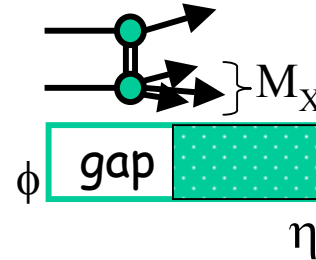


From Poisson statistics:

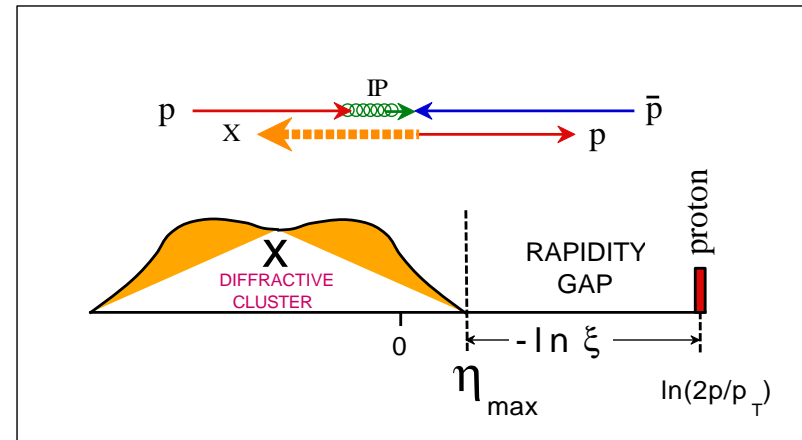
$$P(\Delta y) = e^{-\rho \Delta y} \quad \left( \rho = \frac{dn}{dy} \right)$$

Gaps exponentially suppressed

## ❖ Diffraction dissociation



$$\Delta y \approx -\ln \xi = \ln s - \ln M^2$$

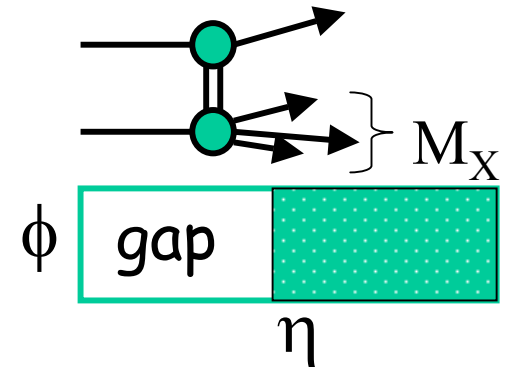


$$\frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \quad \leftrightarrow \quad \frac{d\sigma}{dy} \propto \text{constant}$$

# QCD aspects of diffraction

- Quark/gluon exchange across a rapidity gap:

**POMERON**



- No particles radiated in the gap:

the exchange is **COLOR-SINGLET** with vacuum quantum numbers

- Rapidity gap formation:

**NON-PERTURBATIVE**

- Diffraction probes the large distance aspects of QCD:

**POMERON**  **CONFINEMENT**

- PARTONIC STRUCTURE
- FACTORIZATION PROPERTIES

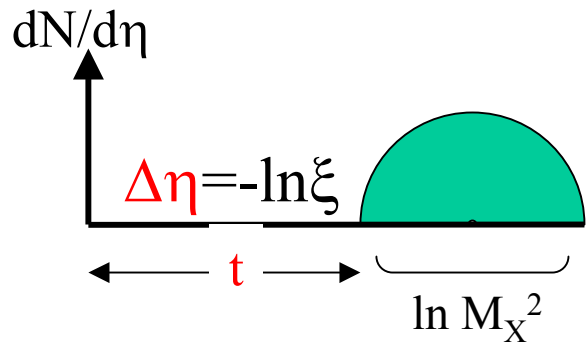
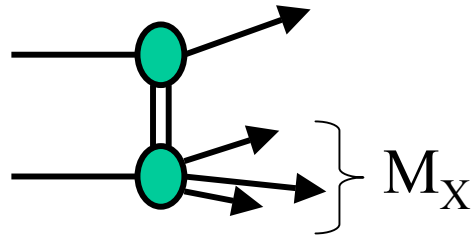
# History of Diffraction

## 40 years of diffraction

- # 1960 Good and Walker
- # 1960's BNL: first observation
- # 1970's Fermilab fixed target, ISR, SPS
- # 1983 KG, Phys. Rep. 101, 169 (1983)
- # 1992 UA8: diffractive dijets  $\Rightarrow$  hard diff
- # 1993-2003 Golden decade: HERA, Tevatron, RHIC

# Soft and Hard Diffraction

## SOFT DIFFRACTION

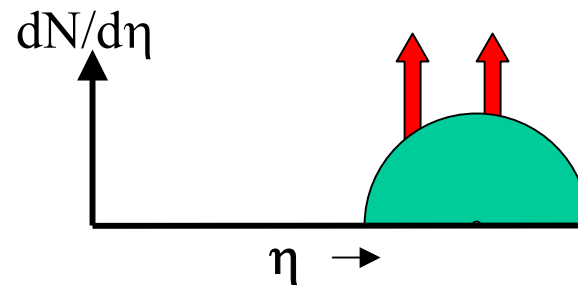
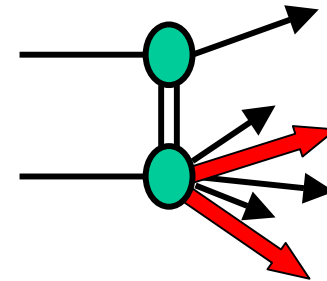


$$\xi = \Delta P_L / P_L$$

$\xi$  = fractional momentum loss  
of scattered (anti)proton

Variables:  $(\xi, t)$  or  $(\Delta\eta, t)$

## HARD DIFFRACTION



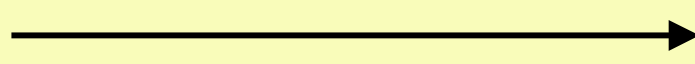
Additional variables:  $(x, Q^2)$

$$x_{Bj} = \sum E_T^{jet} e^{-\eta^{jet}} / \sqrt{s}$$

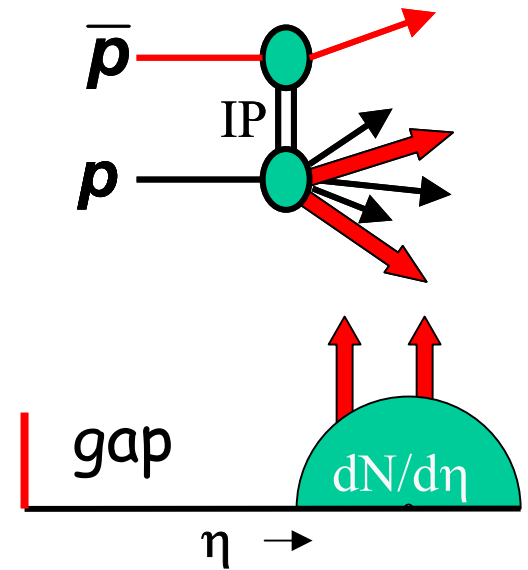
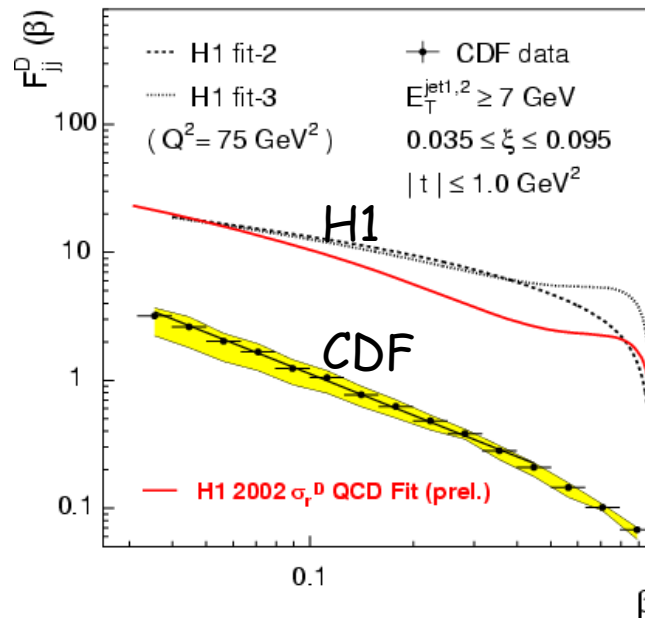
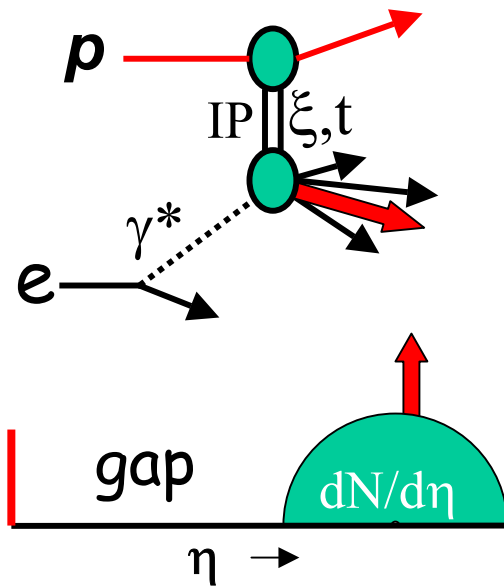
$$x = \beta \xi, \quad Q^2 = (E_T^{jet})^2$$

# Breakdown of QCD factorization

HERA

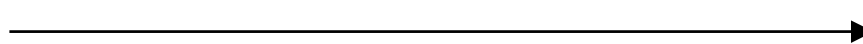


TEVATRON



$$F_2(Q^2, x)$$

$$F_2^D(Q^2, \beta, \xi, t)$$



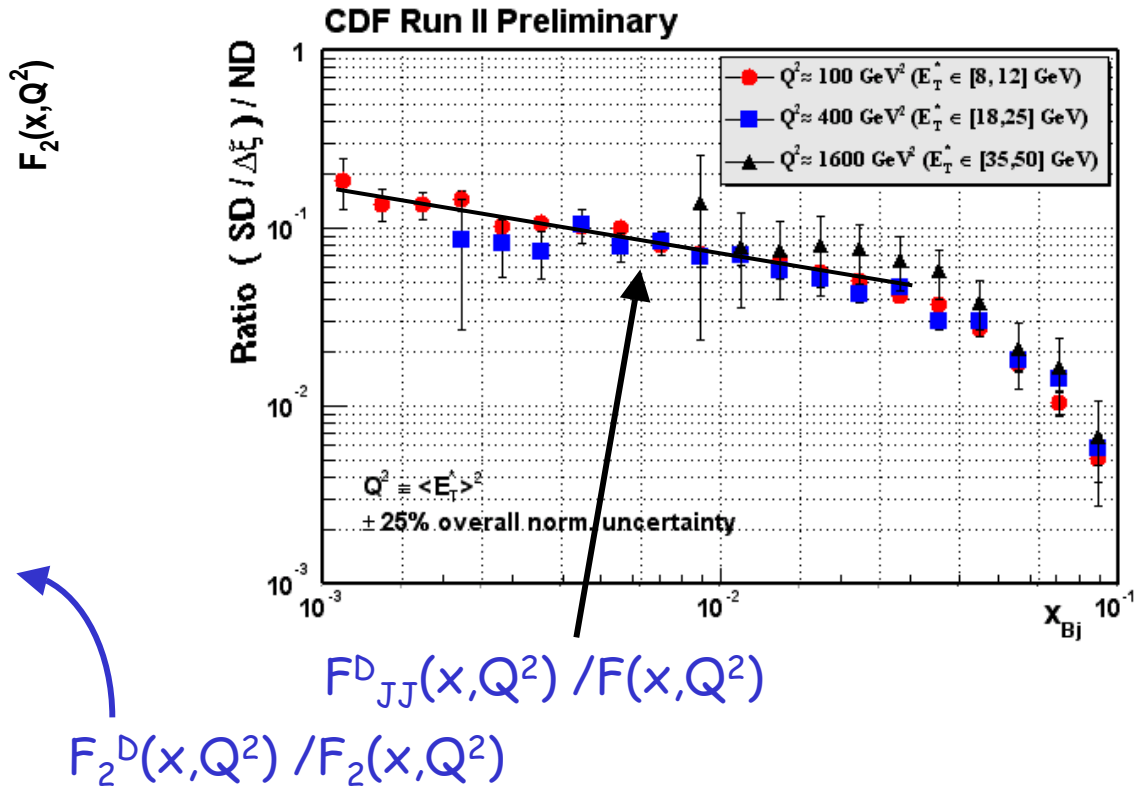
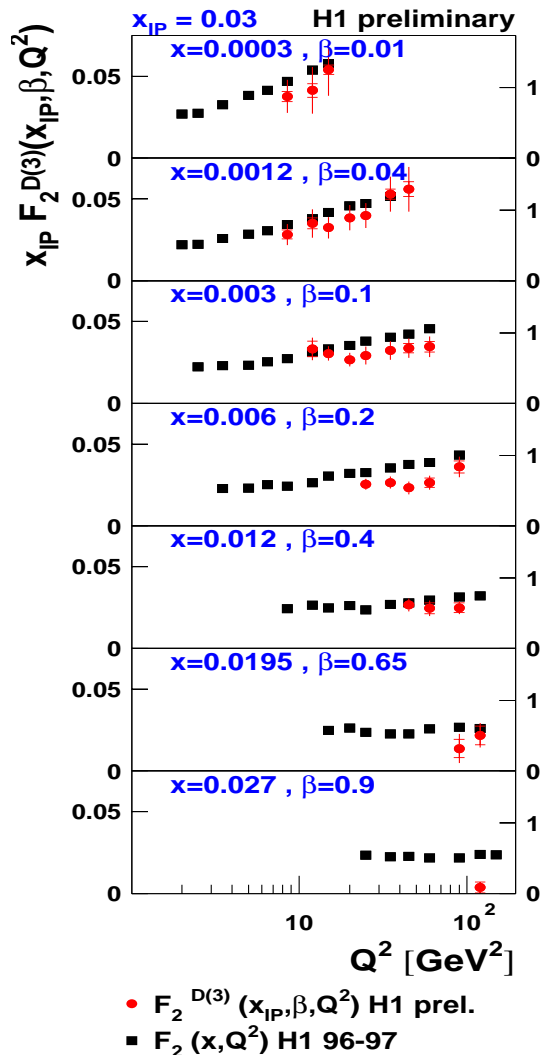
???

$$F_{JJ}(E_T^{Jet}, x)$$

$$F_{JJ}^D(E_T^{Jet}, \beta, \xi, t)$$



# Diffractive vs inclusive structure fn's



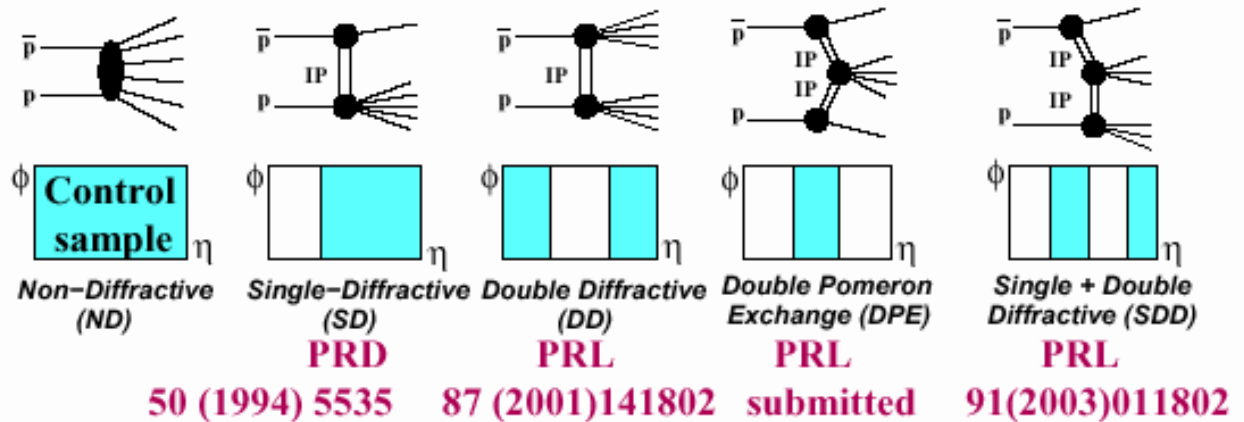
$$R \left( \frac{F^D(Q^2, x, \xi)}{F(Q^2, x)} \right) \Rightarrow \begin{cases} \sim \text{no } Q^2 \text{ dependence} \\ \sim \text{flat at HERA} \\ \sim 1/x^{0.5} \text{ at Tevatron} \end{cases}$$

# Diffraction@CDF in Run I

16 papers

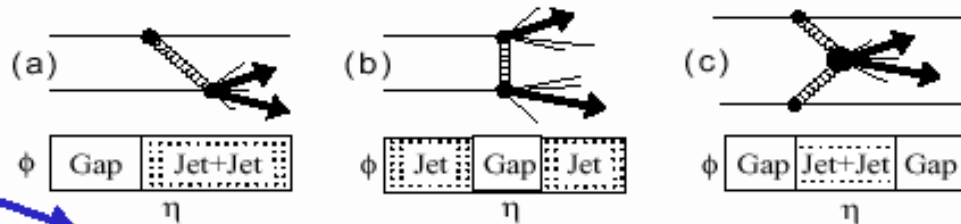
- Elastic scattering PRD 50 (1994) 5518
- Total cross section PRD 50 (1994) 5550
- Diffraction

## SOFT diffraction



## HARD diffraction

PRL references

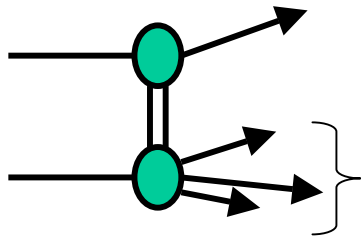


with roman pots

|    |                  |
|----|------------------|
| JJ | 84 (2000) 5043   |
| JJ | 88 (2002) 151802 |

|           |                  |    |                |    |                |
|-----------|------------------|----|----------------|----|----------------|
| W         | 78 (1997) 2698   | JJ | 74 (1995) 855  | JJ | 85 (2000) 4217 |
| JJ        | 79 (1997) 2636   | JJ | 80 (1998) 1156 |    |                |
| b-quark   | 84 (2000) 232    | JJ | 81 (1998) 5278 |    |                |
| J/ $\psi$ | 87 (2001) 241802 |    |                |    |                |

# Soft Diffraction



$M_X$

$$\frac{d^2\sigma_{SD}}{dt d\xi} = f_{IP/p}(t, \xi) \cdot \sigma_{IP-\bar{p}}(M_X^2)$$

$$\sigma_{SD} \sim S^{2\varepsilon}$$

## ❖ Unitarity problem:

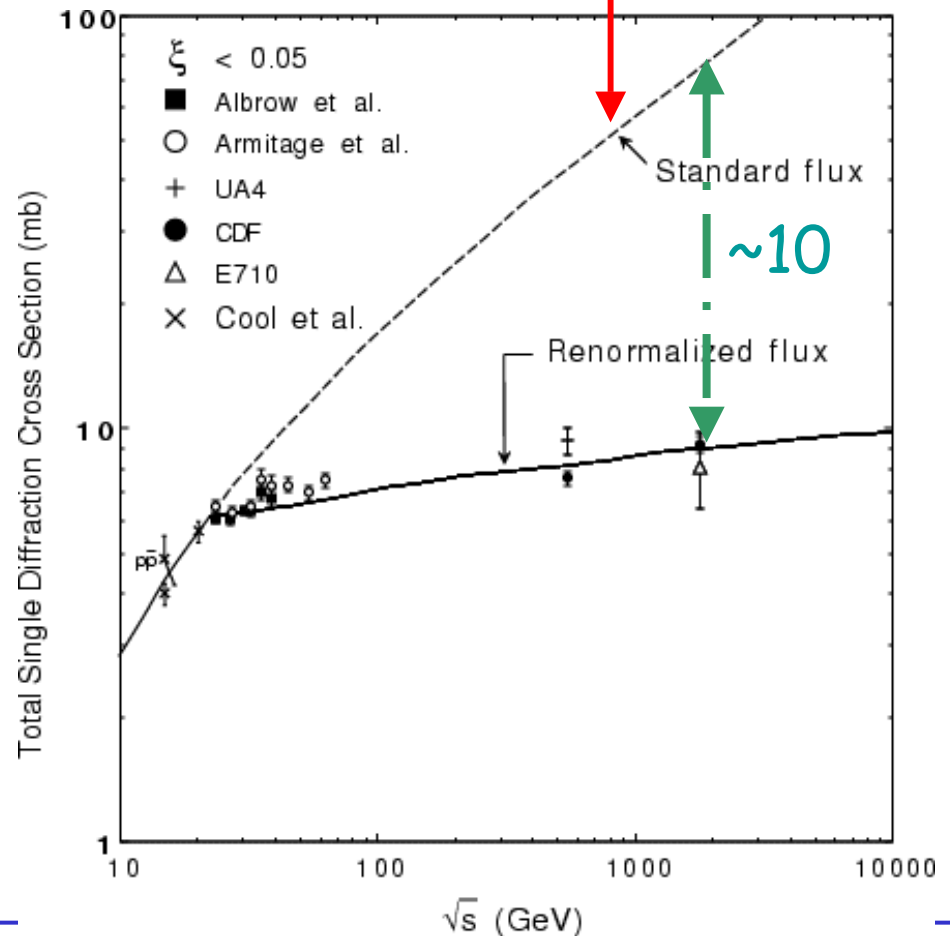
With factorization and std pomeron flux  $\sigma_{SD}$  exceeds  $\sigma_T$  at  $\sqrt{s} \approx 2 \text{ TeV}$ .

## ❖ Renormalization:

normalize the pomeron flux to unity

KG, PLB 358 (1995) 379

$$\int_{\xi_{\min}}^{0.1} \int_{t=-\infty}^0 f_{IP/p}(t, \xi) d\xi dt = 1$$



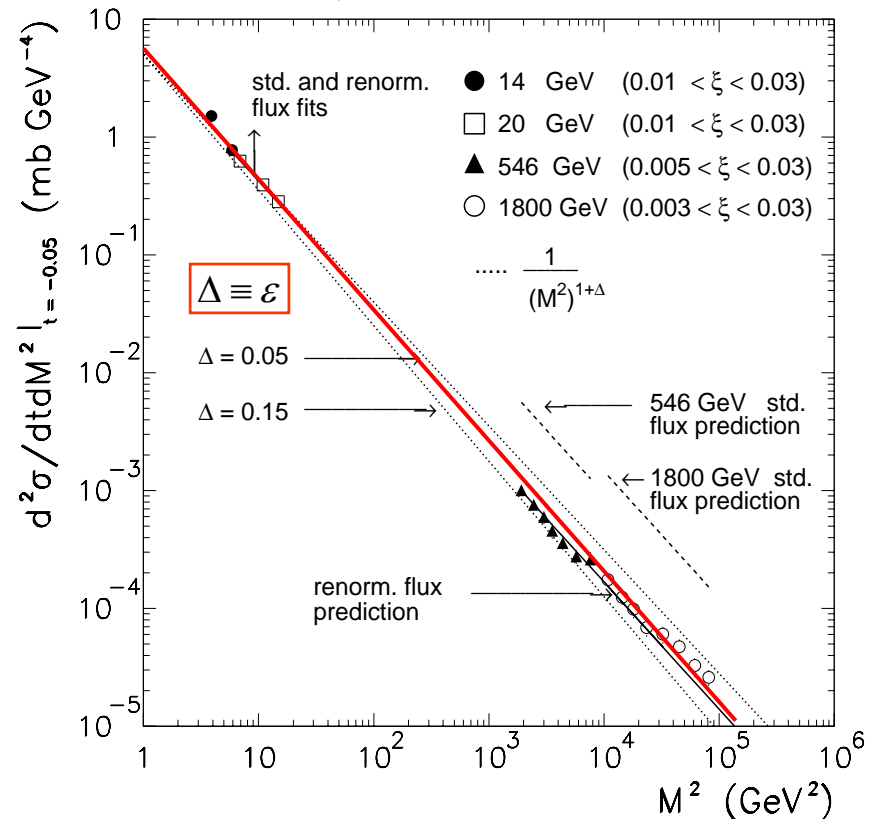
# A Scaling Law in Diffraction

Factorization breaks down in favor of  $M^2$ -scaling

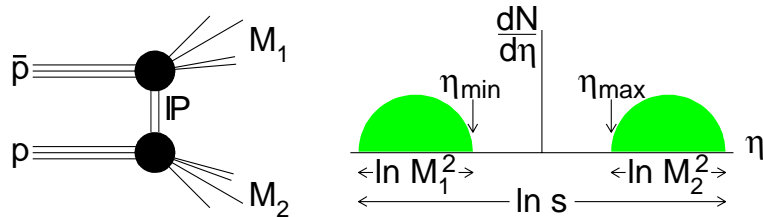
renormalization

$$\frac{d\sigma}{dM^2} \propto \frac{s^{2\varepsilon} \rightarrow 1}{(M^2)^{1+\varepsilon}}$$

KG&JM, PRD 59 (1999) 114017

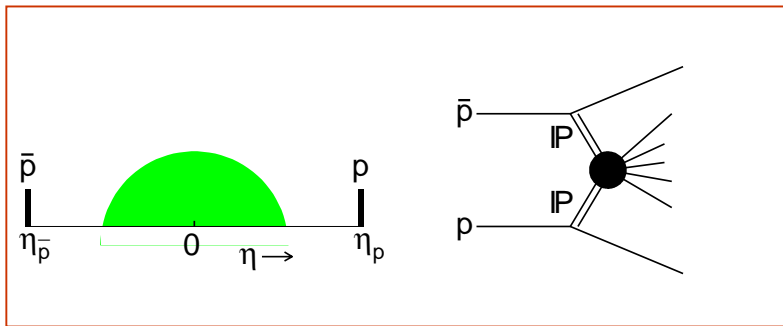


# Central and Double Gaps



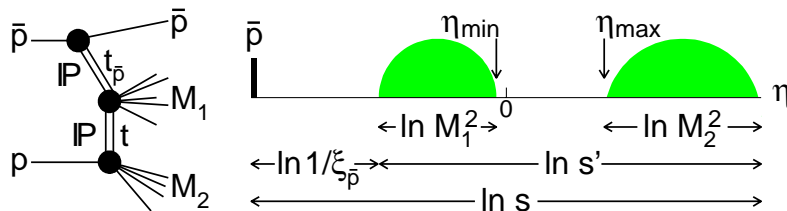
## □ Double Diffraction Dissociation

➤ One central gap



## □ Double Pomeron Exchange

➤ Two forward gaps



## □ SDD: Single+Double Diffraction

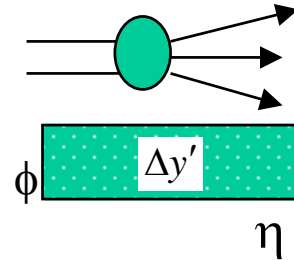
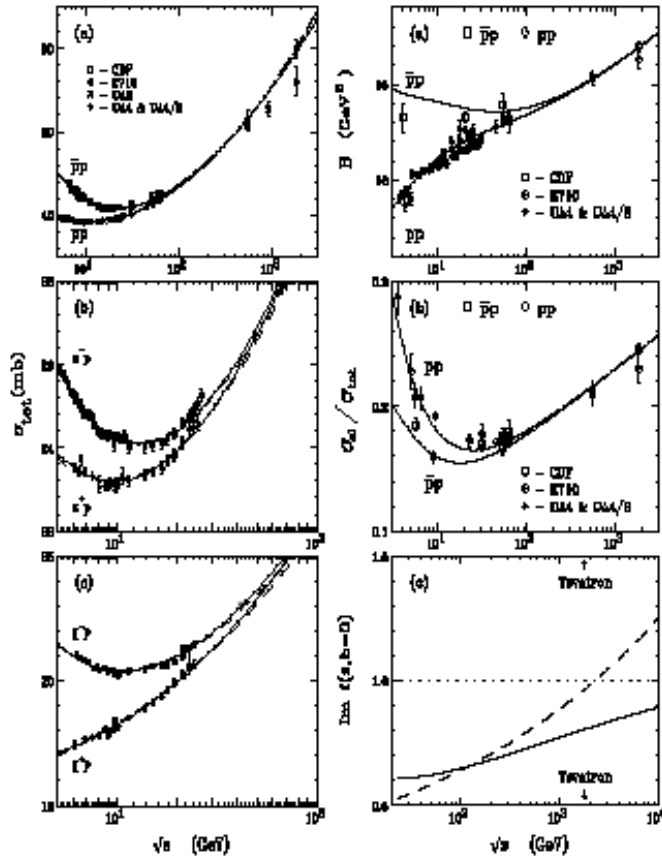
➤ Forward + central gaps

# Elastic & total $\sigma$

## Total and Elastic Cross Sections

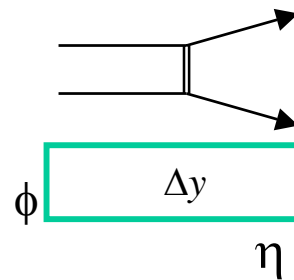
Corrochin, Montanha and Goulianos, Phys. Lett. B 389 (1996) 176

$$\alpha_P = 1 + \epsilon (\Rightarrow 0.104) + 0.25t \quad \alpha_{P'n} = 0.68 + 0.82t \quad \alpha_{\omega'P} = 0.46 + 0.92t$$



$$\Delta y' = \ln s$$

$$\sigma_T(s) = \sigma_o s^\epsilon = \sigma_o e^{\epsilon \Delta y'}$$

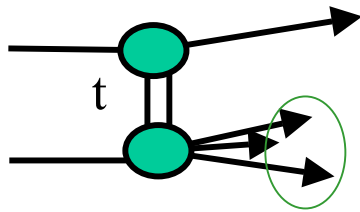


$$\Delta y = \ln s$$

$$\sigma_{el}(s, t) \propto \left( e^{(\epsilon + \alpha' t) \Delta y} \right)^2$$

# Generalized renormalization

(KG, hep-ph/0205141)



2 independent variables:  $t, \Delta y$

color factor

$$\kappa = \frac{g_{IP-IP-IP}(t)}{\beta_{IP-p-p}(0)} \approx 0.17$$

$$\frac{d^2\sigma}{dt d\Delta y} = C \cdot F_p^2(t_1) \cdot \left\{ e^{(\varepsilon + \alpha' t)\Delta y} \right\}^2 \cdot \kappa \cdot \left\{ \sigma_0 e^{\varepsilon \Delta y'} \right\}$$

Gap probability

$$\sim e^{2\varepsilon \Delta y}$$

$$\int_{\Delta y_{\min}}^{\Delta y = \ln s} s^{2\varepsilon \Delta y} \approx s^{2\varepsilon}$$

Renormalization removes the s-dependence → SCALING

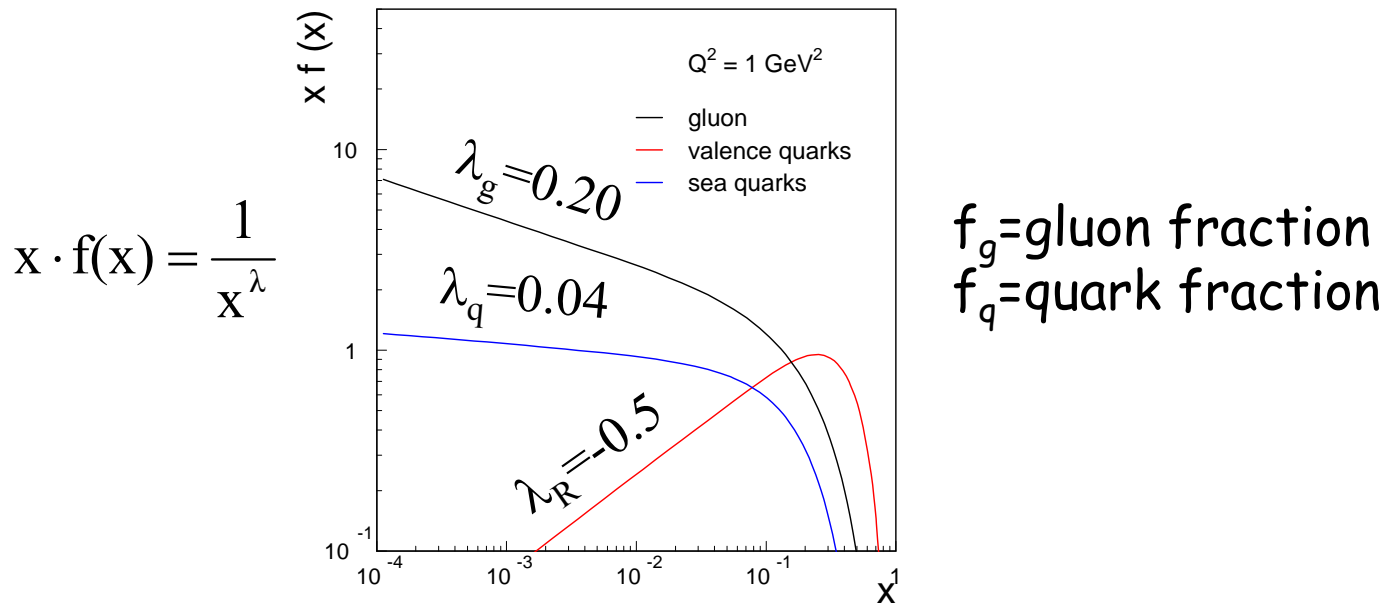
# The factors $K$ and $\varepsilon$

Experimentally:

$$K = \frac{g_{IP-IP-IP}}{\beta_{IP-p}} = 0.17 \pm 0.02 \quad \leftarrow \text{KG\&JM, PRD 59 (114017) 1999}$$

Color factor: 
$$K = f_g \times \frac{1}{N_c^2 - 1} + f_q \times \frac{1}{N_c} \xrightarrow{Q^2 \rightarrow 0} \approx 0.75 \times \frac{1}{8} + 0.25 \times \frac{1}{3} = 0.18$$

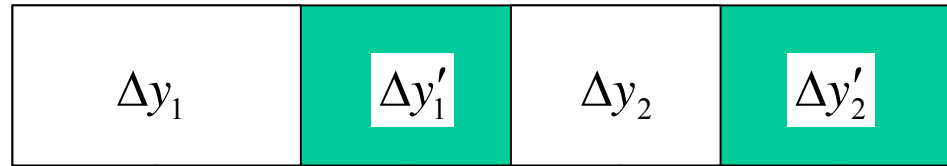
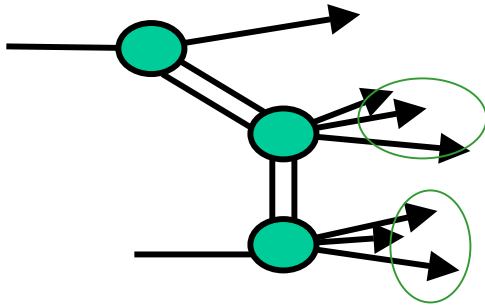
Intercept: 
$$\varepsilon = \lambda_g \cdot w_g + \lambda_q \cdot w_q = 0.12$$





# Two-Gap Diffraction

(KG, hep-ph/0205141)



5 independent variables

$$\left\{ \begin{array}{c} t_1 \\ \Delta y = \Delta y_1 + \Delta y_2 \\ t_2 \end{array} \right.$$

color factor

$$\frac{d^5 \sigma}{\prod_{i=1-5} dV_i} = C \times F_p^2(t_1) \prod_{i=1-2} \left\{ e^{(\varepsilon + \alpha' t_i) \Delta y_i} \right\}^2 \times \kappa^2 \left\{ \sigma_o e^{\varepsilon (\Delta y'_1 + \Delta y'_2)} \right\}$$

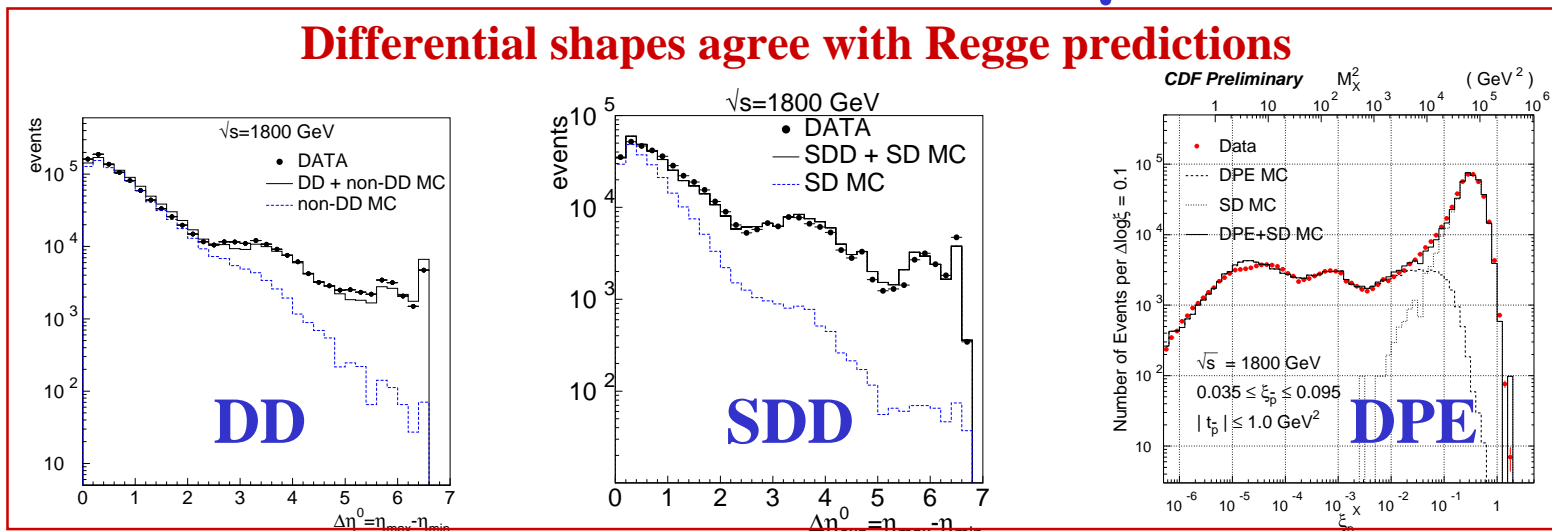
Gap probability  
 $\sim e^{2\varepsilon \Delta y}$

Sub-energy cross section  
 (for regions with particles)

$$\int_{\Delta y_{\min}}^{\Delta y = \ln s} s^{2\varepsilon \Delta y} \approx s^{2\varepsilon} \quad \text{Same suppression as for single gap!}$$

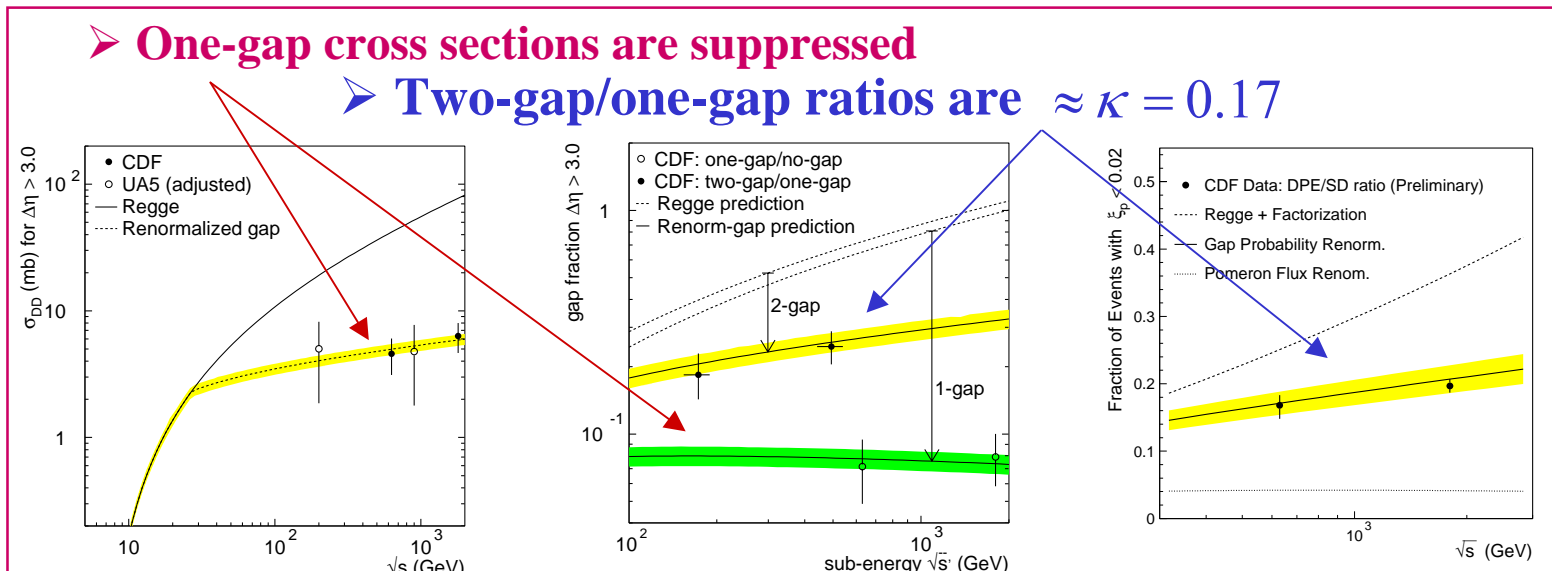
# Central & Double-Gap Results

## Differential shapes agree with Regge predictions



➤ One-gap cross sections are suppressed

➤ Two-gap/one-gap ratios are  $\approx \kappa = 0.17$



# Soft Double Pomeron Exchange

➤ Roman Pot triggered events

➤  $0.035 < \xi\text{-pbar} < 0.095$

$|t\text{-pbar}| < 1 \text{ GeV}^2$

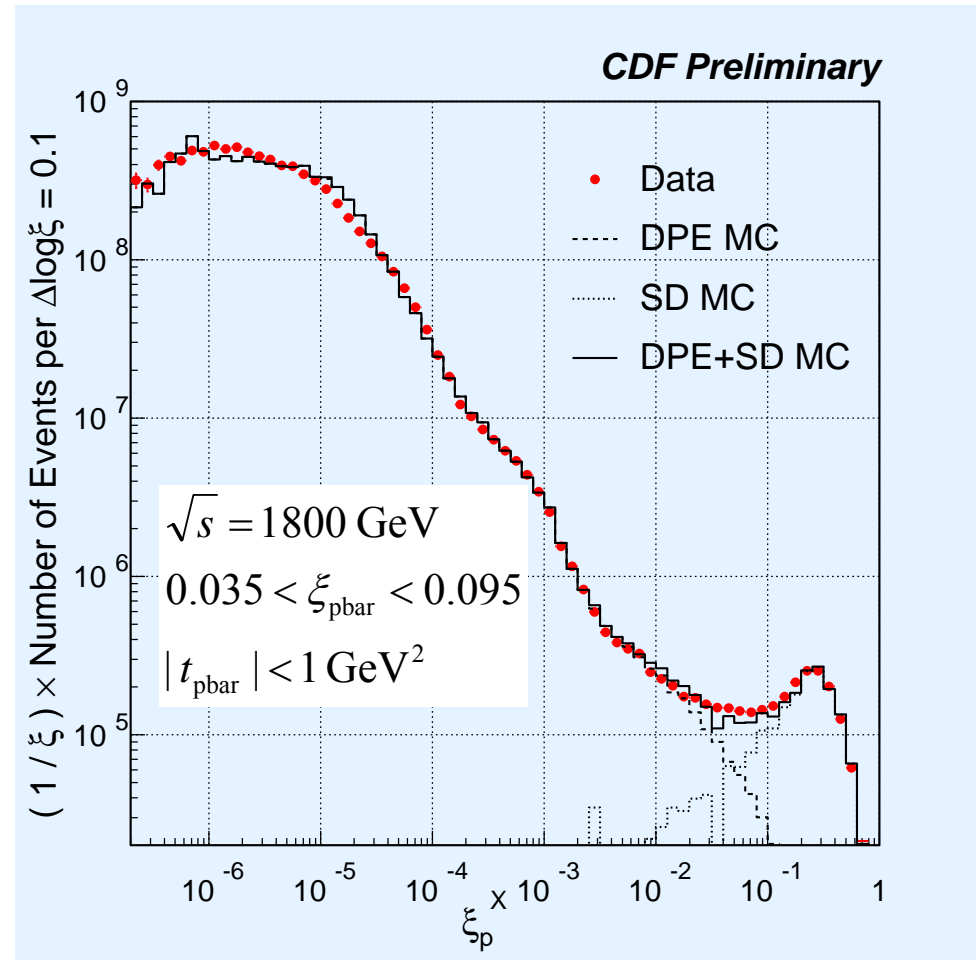
➤  $\xi$ -proton measured using

$$\xi_p = \frac{1}{\sqrt{s}} \sum_{\text{all particles}} E_T^i \cdot e^{\eta_i}$$

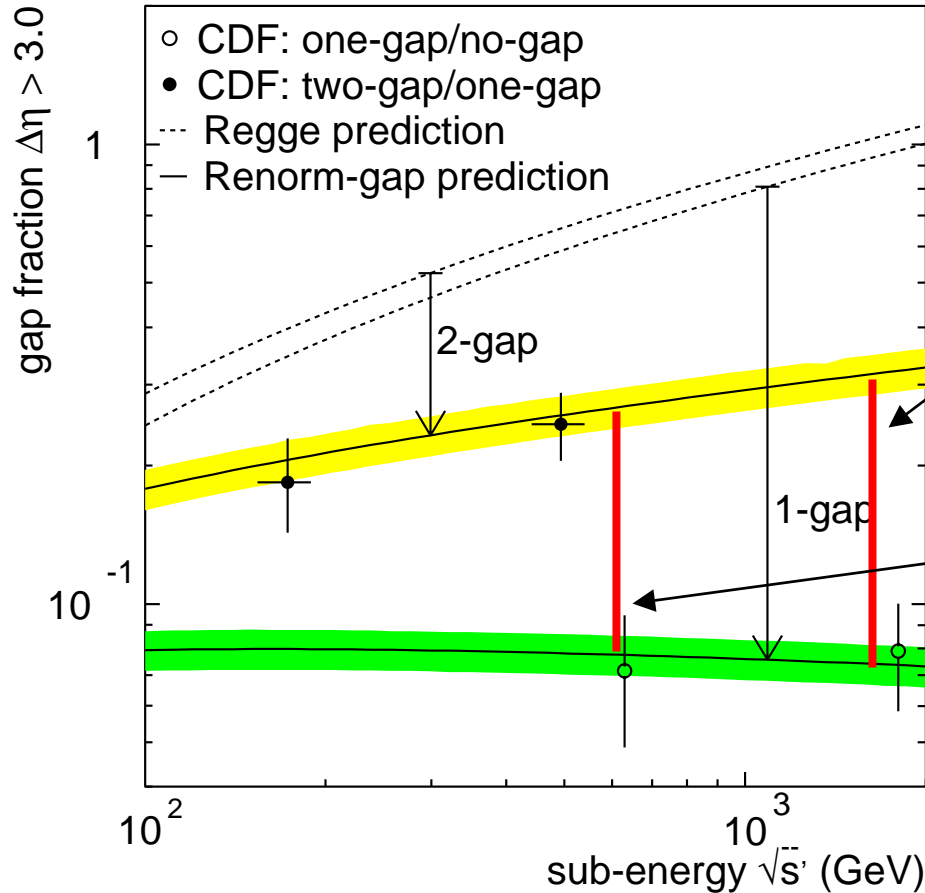
➤ Data compared to MC based on Pomeron exchange with

➔ Pomeron intercept  $\epsilon=0.1$

➤ Good agreement over 4 orders of magnitude!



# Soft gap survival probability



$$S = \frac{\phi \left[ \begin{array}{c} \text{gap} \\ \eta \end{array} \right] / \phi \left[ \begin{array}{c} \text{no-gap} \\ \eta \end{array} \right]}{\phi \left[ \begin{array}{c} \text{gap} \\ \eta \end{array} \right] / \phi \left[ \begin{array}{c} \text{gap} \\ \eta \end{array} \right]}$$

$$S_{2\text{-gap}/1\text{-gap}}^{1\text{-gap}/0\text{-gap}} (1800 \text{ GeV}) \approx 0.23$$

$$S_{2\text{-gap}/1\text{-gap}}^{1\text{-gap}/0\text{-gap}} (630 \text{ GeV}) \approx 0.29$$

# Hard Diffraction & QCD

$$\bar{p} + p \rightarrow \bar{p} + Jet + Jet + X$$

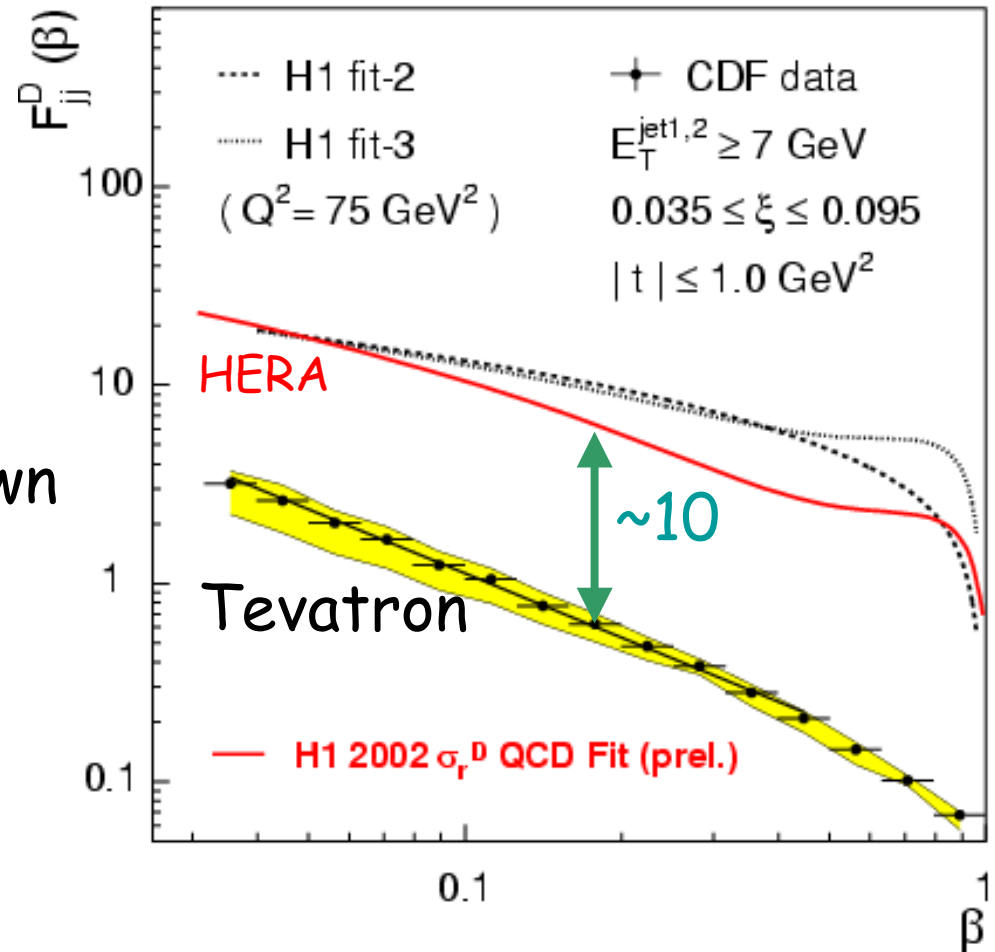
- The diffractive structure function measured using SD dijets at the Tevatron is suppressed by about an order of magnitude relative to predictions based on diffractive DIS at HERA



## Factorization Breakdown

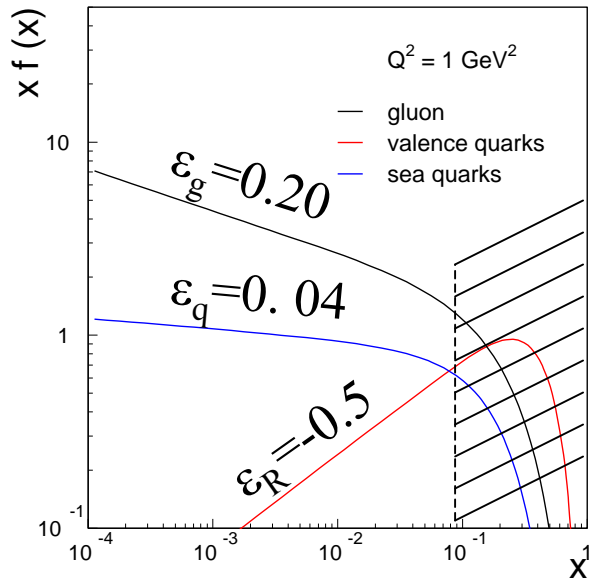
- The discrepancy is generally attributed to additional color exchanges which spoil the diffractive rapidity gap.

Diffractive structure function





# Diffractive structure function from inclusive pdf's (KG)



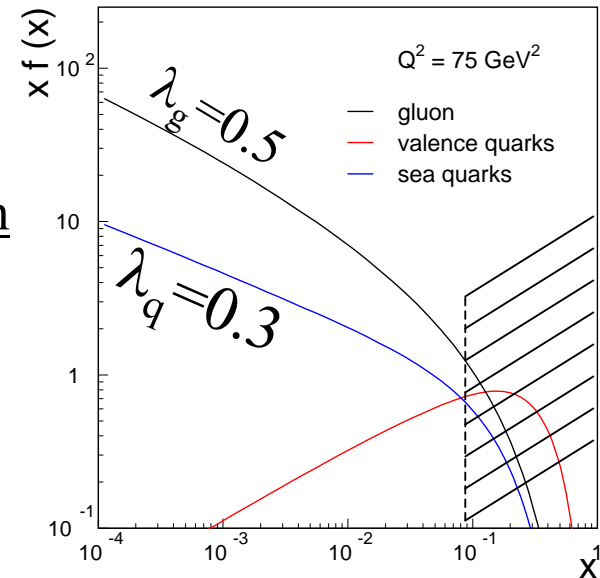
$$x \cdot f(x) = \frac{1}{x^\varepsilon}$$

Power-law region

$$\xi_{\max} = 0.1$$

$$x_{\max} = 0.1$$

$$\beta < 0.05\xi$$



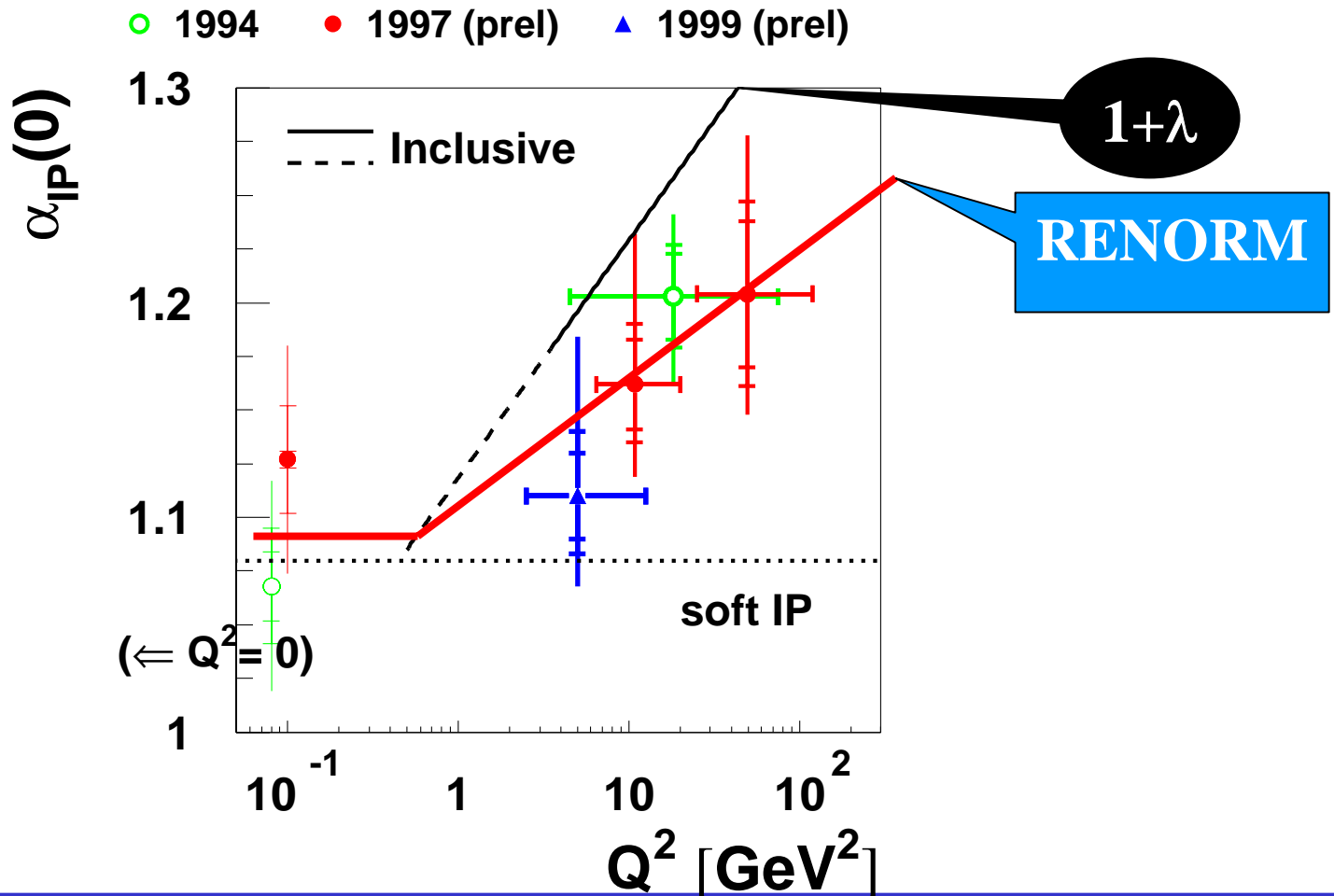
$$F^D(\varrho^2, x, \xi) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot F(\varrho^2, x) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot \frac{C(\varrho^2)}{(\beta\xi)^{\lambda(\varrho^2)}} \Rightarrow \frac{A_{\text{NORM}}}{\xi^{1+\varepsilon+\lambda}} \cdot \kappa \cdot \frac{C}{\beta^\lambda}$$

**HERA(no RENORM):**  $R_{DIS}^{DDIS} \xrightarrow{\text{fixed } \xi} \text{constant}, \quad 2\varepsilon_{DIS}^D = \varepsilon + \lambda(\varrho^2)$

**TEVATRON (RENORM):**  $R_{JJ} \left( \frac{SD}{ND} \right) \propto x^{-(\varepsilon + \lambda)}$

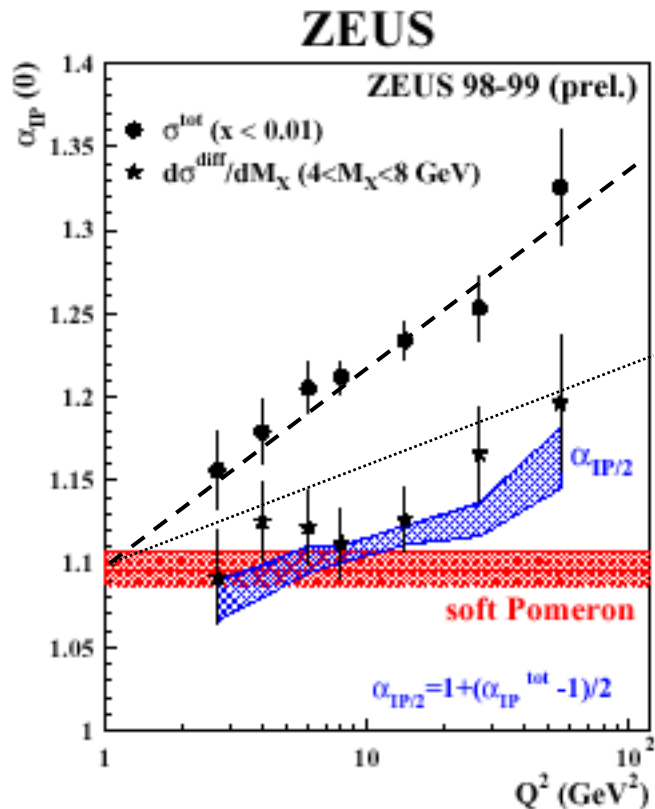
# Pomeron Intercept from H1

H1 Diffractive Effective  $\alpha_{IP}(0)$   $\alpha_{IP}(t) = 1 + \varepsilon + \alpha' t$





# Pomeron intercept from ZEUS



Submitted to the  
International Europhysics Conference on High Energy Physics  
July 17 - 23, 2003, Aachen, Germany

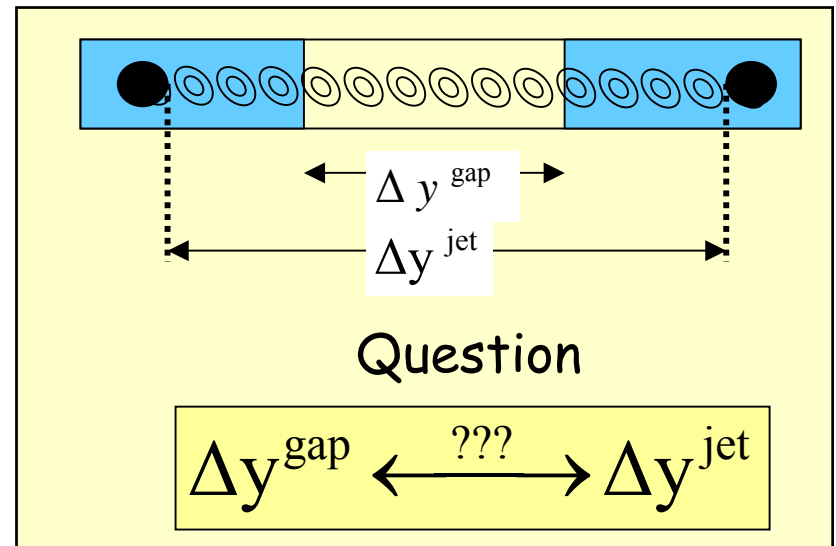
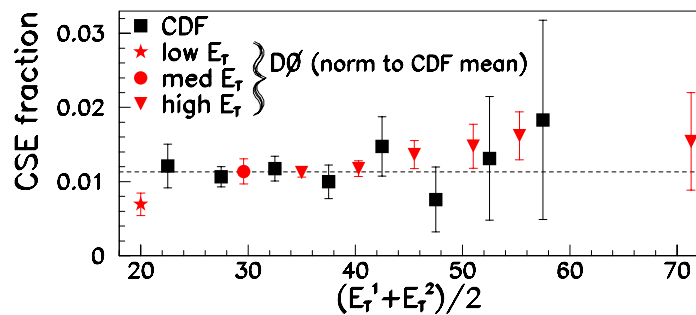
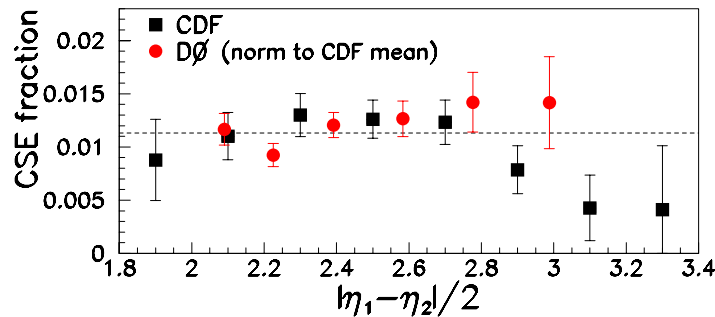
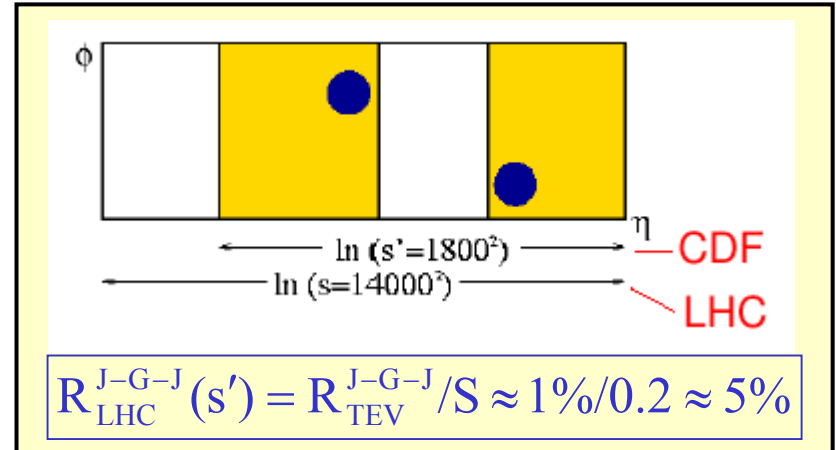
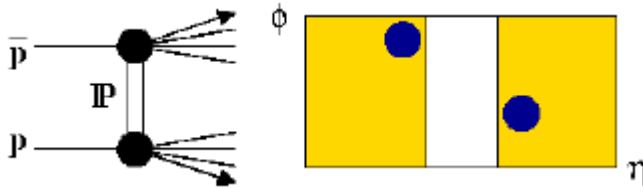
Abstract: 538

Session: HP

Deep inelastic diffractive scattering  
measured with the ZEUS Forward Plug  
Calorimeter

# Gap between jets

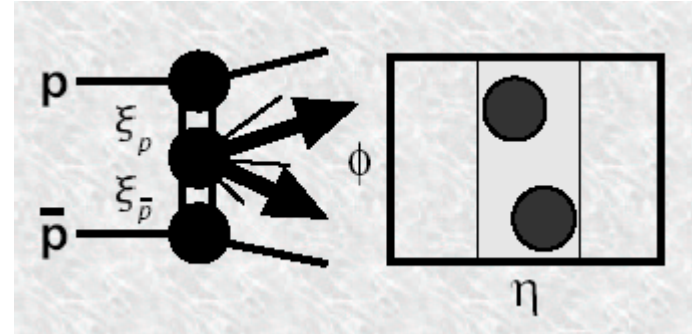
$\bar{p} + p \rightarrow \text{Jet} + \text{Gap} + \text{Jet}$



# Exclusive Dijets in DPE

Interest in diffractive Higgs production

Calibrate on exclusive dijets



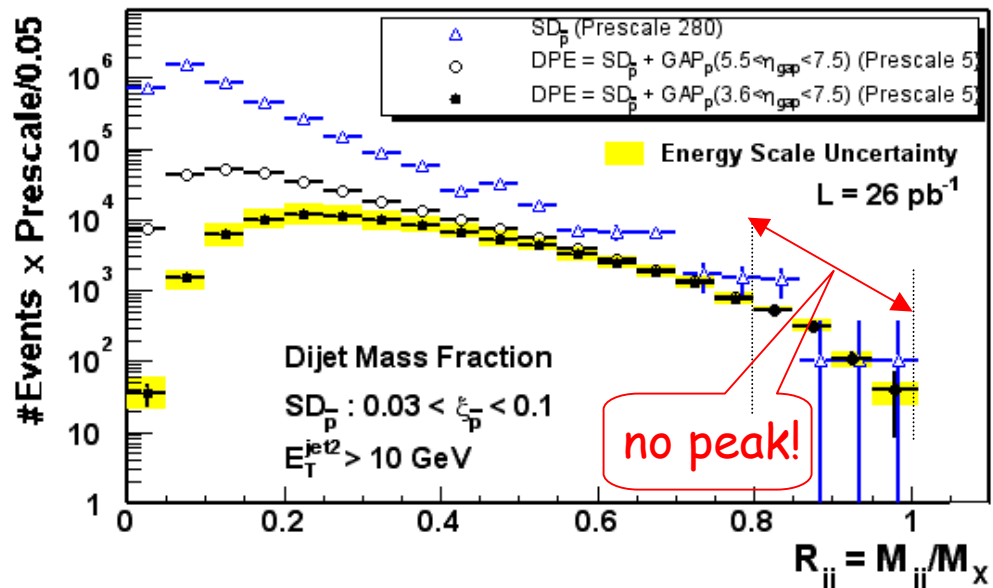
Dijet mass fraction

$$R_{jj} = \frac{M_{jj}^{\text{cone}}}{M_X}$$

| $E_T^{\text{jet}}$ | $\sigma_{\text{DPE}}^{\text{excl jj}} (R_{jj} > 0.8)$ |
|--------------------|---|
| 10 GeV             | $970 \pm 65 \pm 272 \text{ pb}$                       |
| 25 GeV             | $34 \pm 5 \pm 10 \text{ pb}$                          |

Upper limit for excl DPE-jj  
 consistent with theory

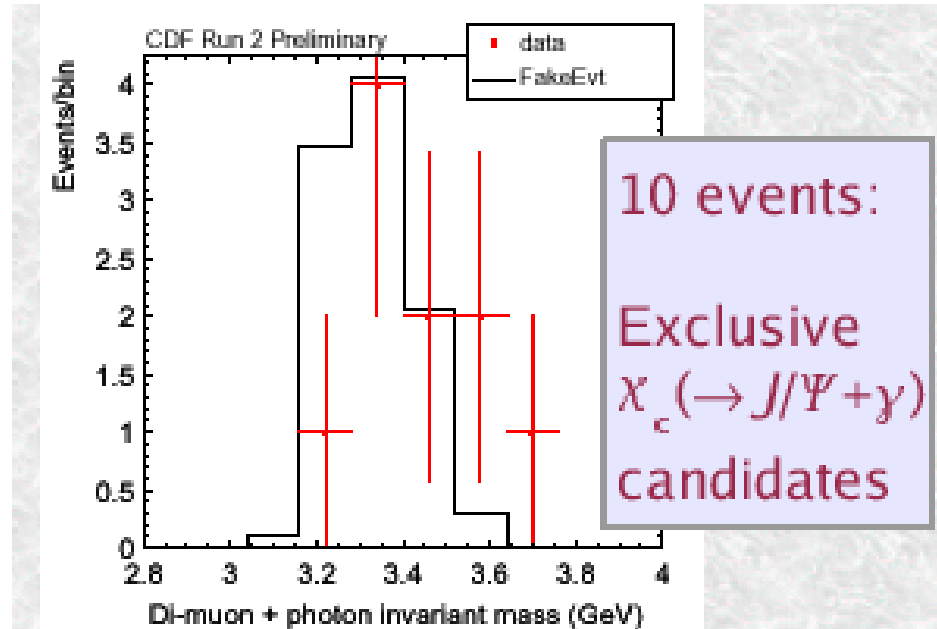
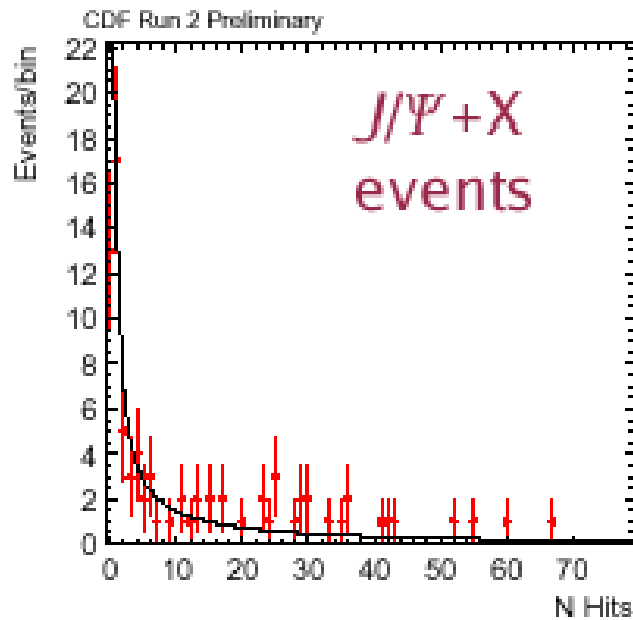
## CDF Run II Preliminary



# Exclusive $\chi_c$ Production in DPE

$$\bar{p} + p \rightarrow \bar{p} + \chi_c (\rightarrow J/\psi + \gamma) + p$$

- Events are triggered on by a **di-muon trigger**
- Muons have  $P_T > 1.5$  GeV,  $|\eta| < 0.6$
- **Reject cosmic rays** with time of flight info.
- Select events in **J/ $\psi$  mass window**.



Cross section upper limit comparable to KMR prediction

# Summary

## SOFT DIFFRACTION

- $M^2$  - scaling
- Non-suppressed double-gap to single-gap ratios

## HARD DIFFRACTION

- Flavor-independence SD/ND ratio
- Get diffractive from non-diffractive pdf's

Universality of gap prob. across soft and hard diffraction

# HERA & Tevatron → LHC

Diffraction



Soft & Hard