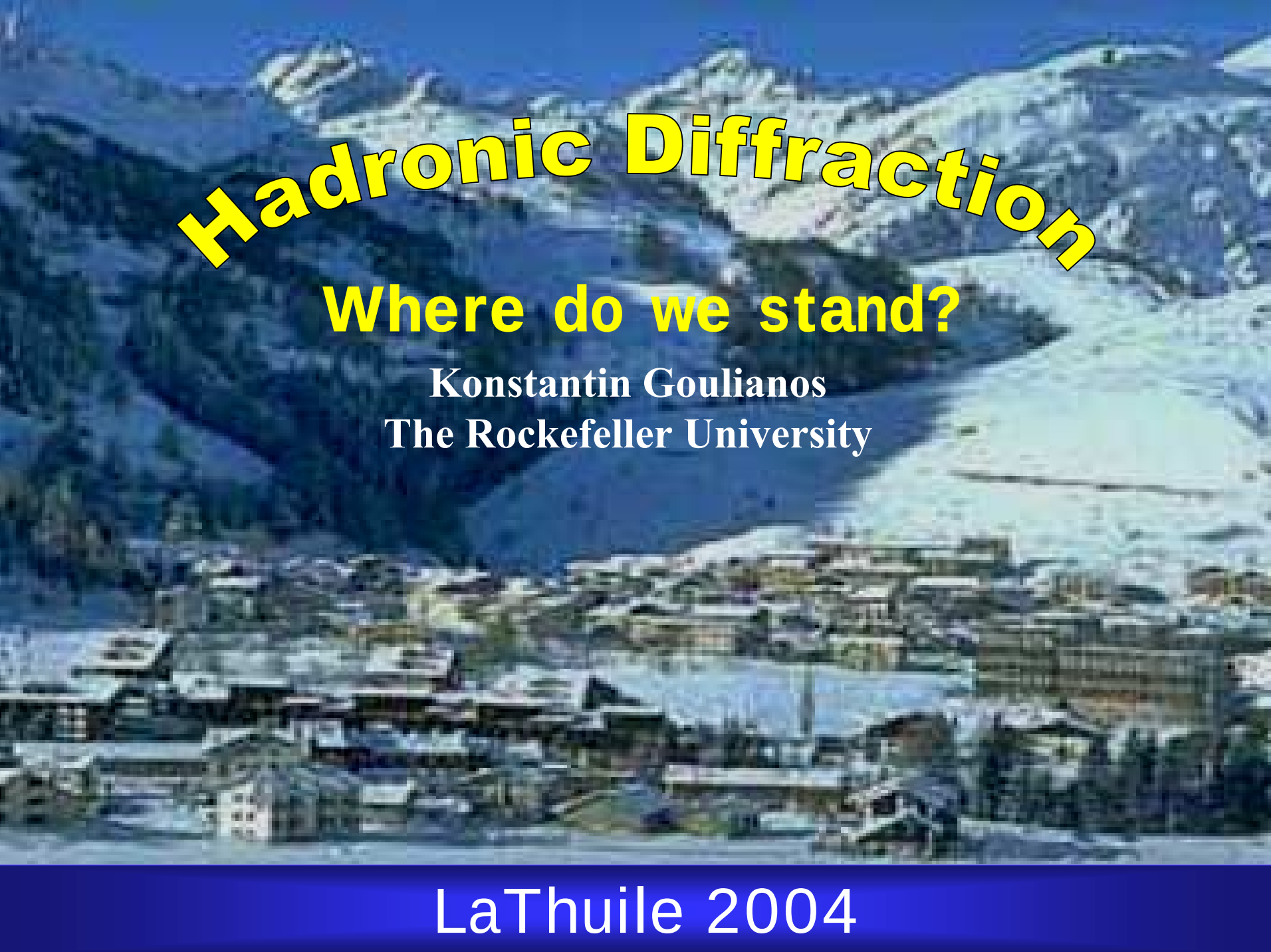


A scenic view of a town at the foot of snow-capped mountains. The town is built on a valley floor, with numerous buildings and houses. The mountains in the background are covered in snow and have some rocky peaks visible. The sky is a clear, deep blue.

Hadronic Diffraction

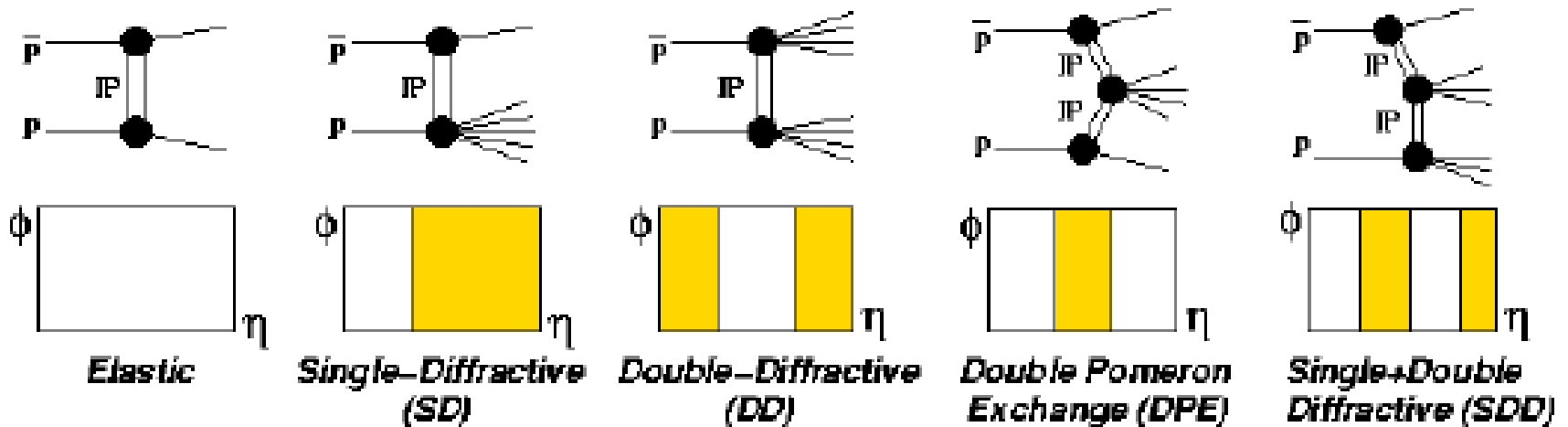
Where do we stand?

Konstantin Goulios
The Rockefeller University

LaThuile 2004

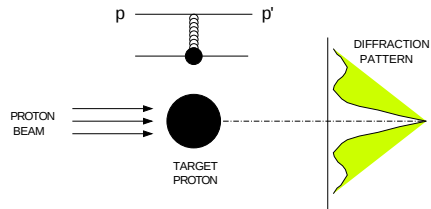
Diffraction signatures

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

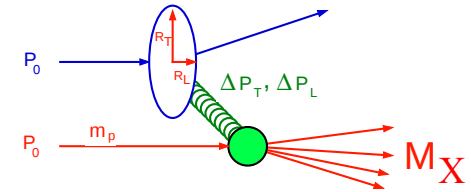


Leading hadrons

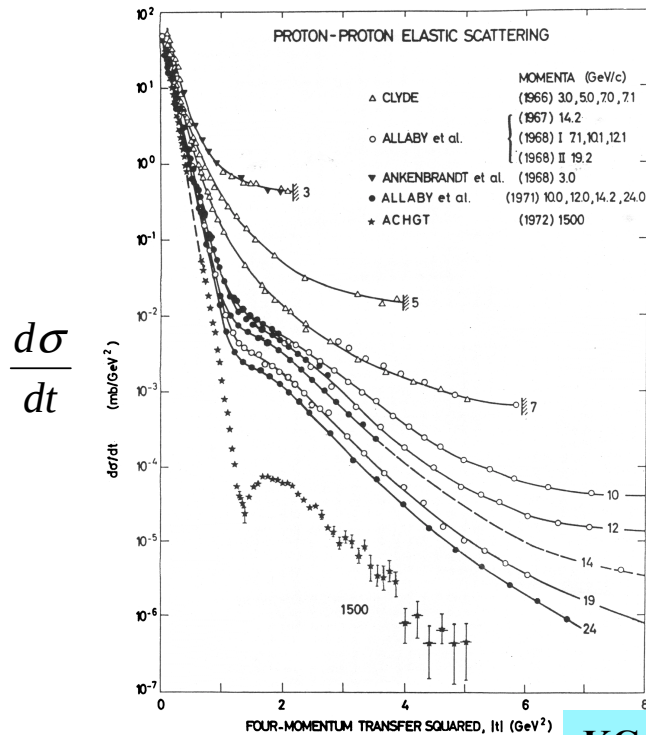
PROTON-PROTON ELASTIC SCATTERING



Diffraction dissociation

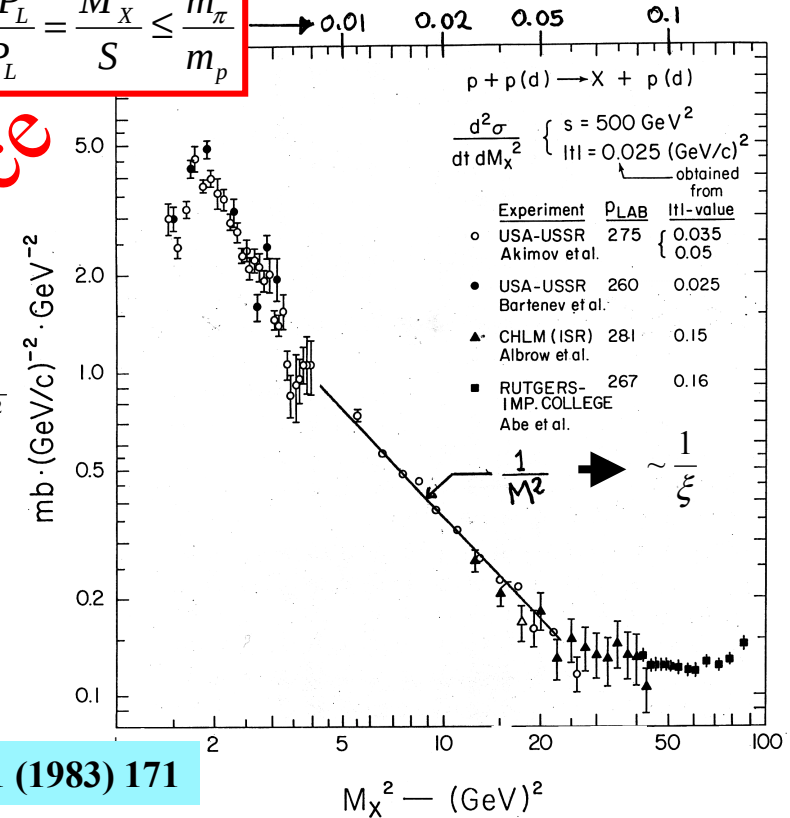


$$\xi = \frac{\Delta P_L}{P_L} = \frac{M_X^2}{S} \leq \frac{m_\pi}{m_p}$$



coherence

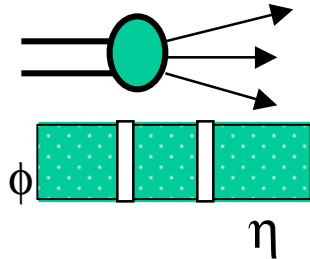
$$\frac{d^2\sigma}{dt dM^2}$$



KG, Phys. Rep. 101 (1983) 171

Rapidity gaps

❖ Minimum bias

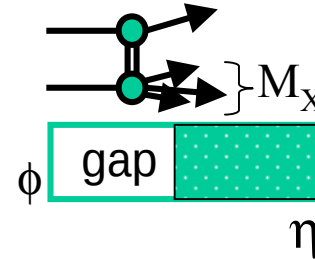


From Poisson statistics:

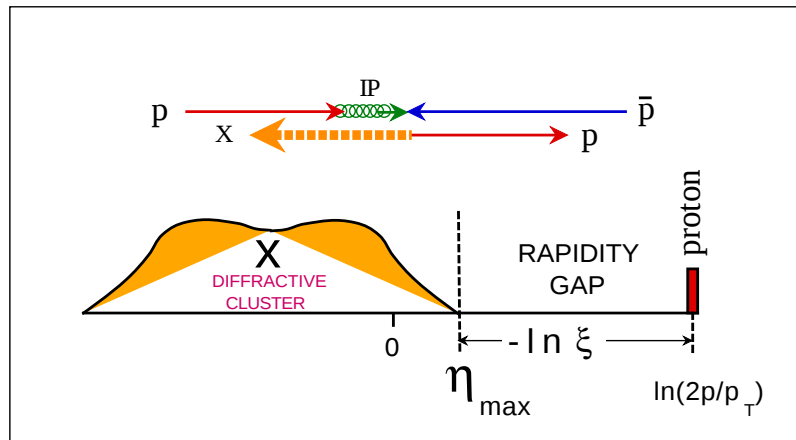
$$P(\Delta y) = e^{-\rho \Delta y} \quad \left(\rho = \frac{dn}{dy} \right)$$

Gaps exponentially suppressed

❖ Diffraction dissociation



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



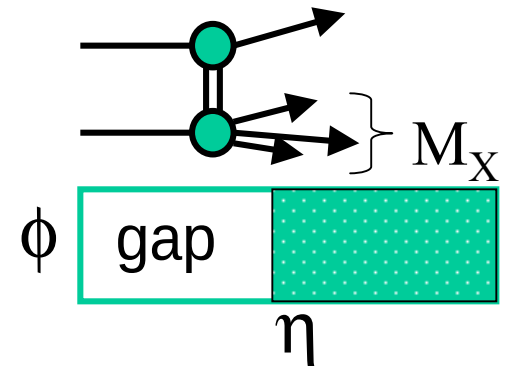
$$\frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \quad \rightarrow \quad \frac{d\sigma}{dy} \propto \text{constant}$$

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

dark energy?

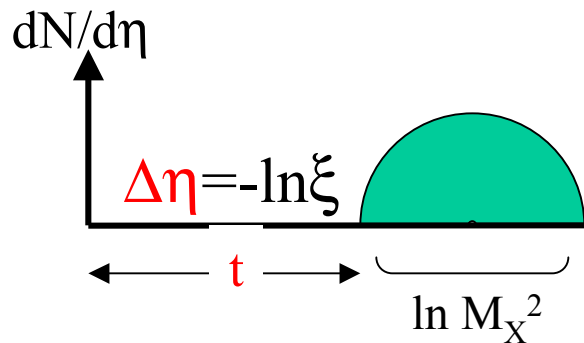
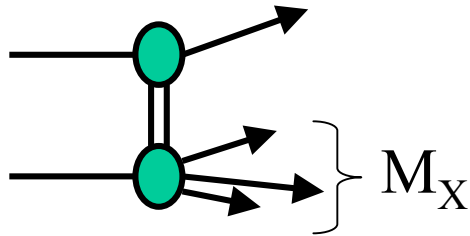
History of Diffraction

40 years of diffraction

✚	1960	Good and Walker
✚	1960's	BNL: first observation
✚	1970's	Fermilab fixed target, ISR, SPS
✚	1883	KG, Phys. Rep. 101, 169 (1983)
✚	1992	UA8: diffractive dijets ⇨ hard diff
✚	1993-2003	Golden decade: HERA, Tevatron, RHIC

Soft and Hard Diffraction

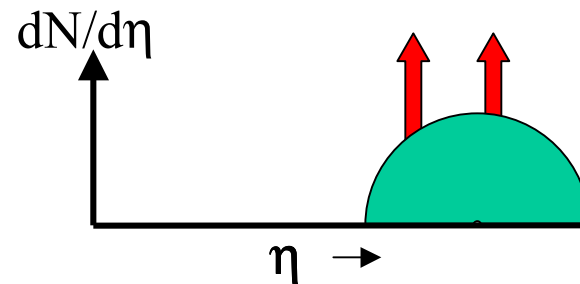
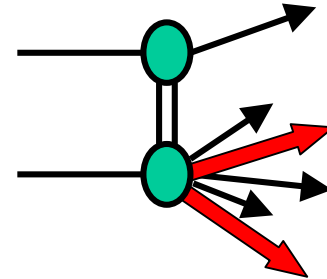
SOFT DIFFRACTION



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

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

HARD DIFFRACTION



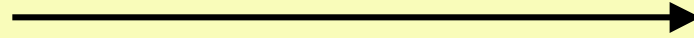
Hard scatter variables: (x, Q^2)

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

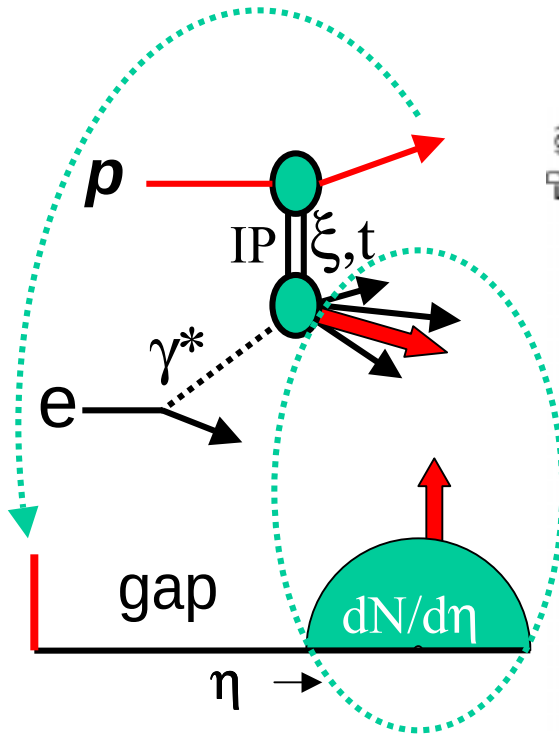
$$x = \beta \xi \leq \xi$$

Breakdown of QCD factorization

HERA

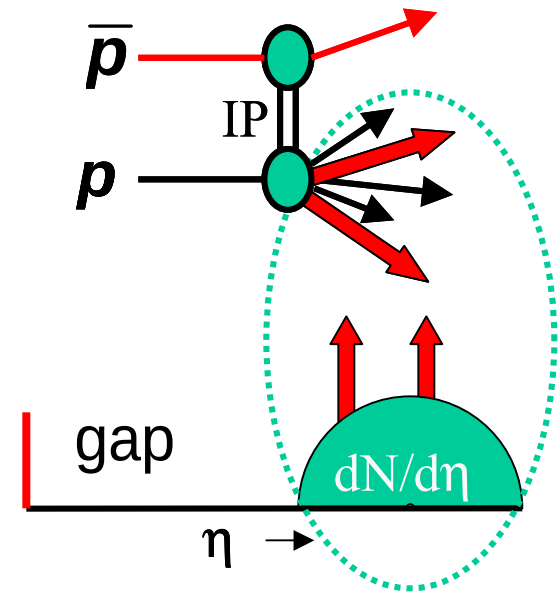
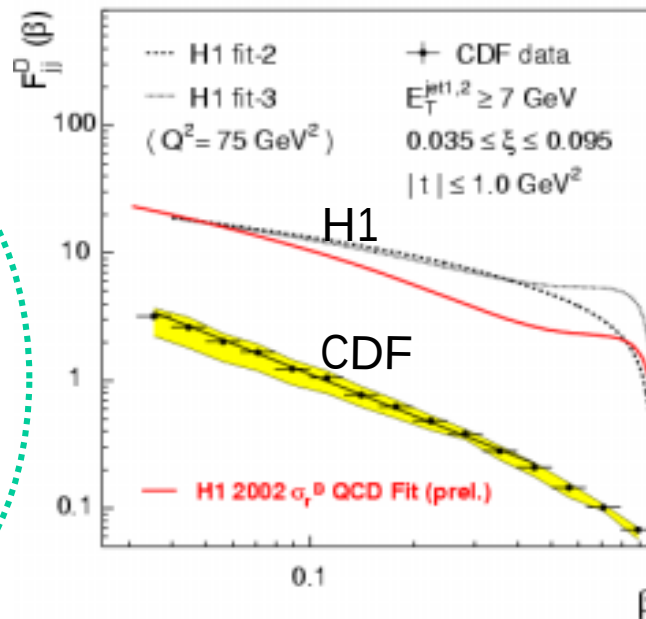


TEVATRON



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

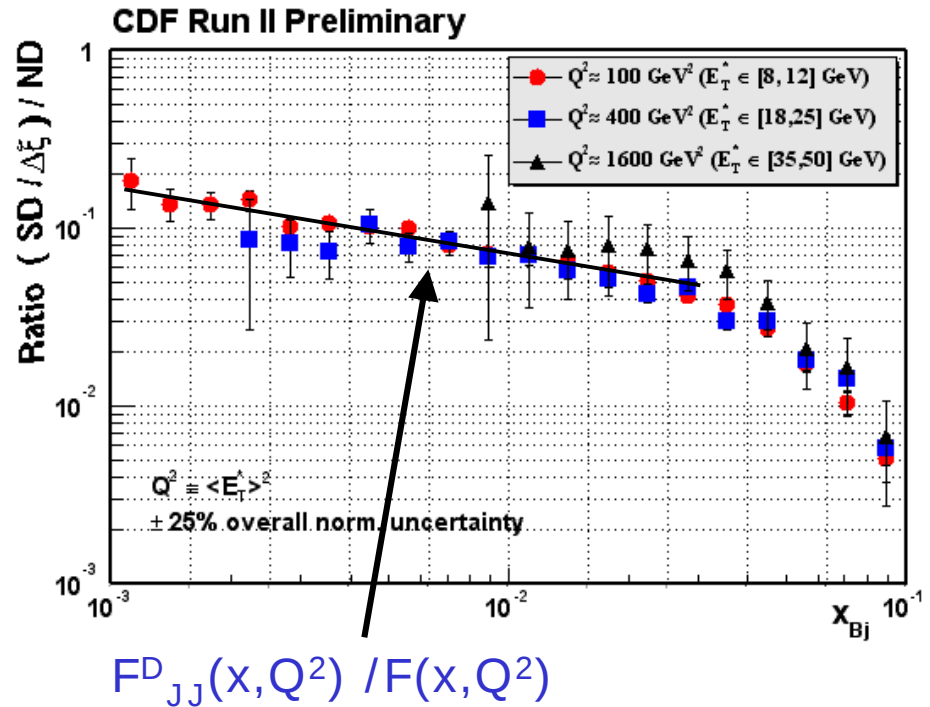
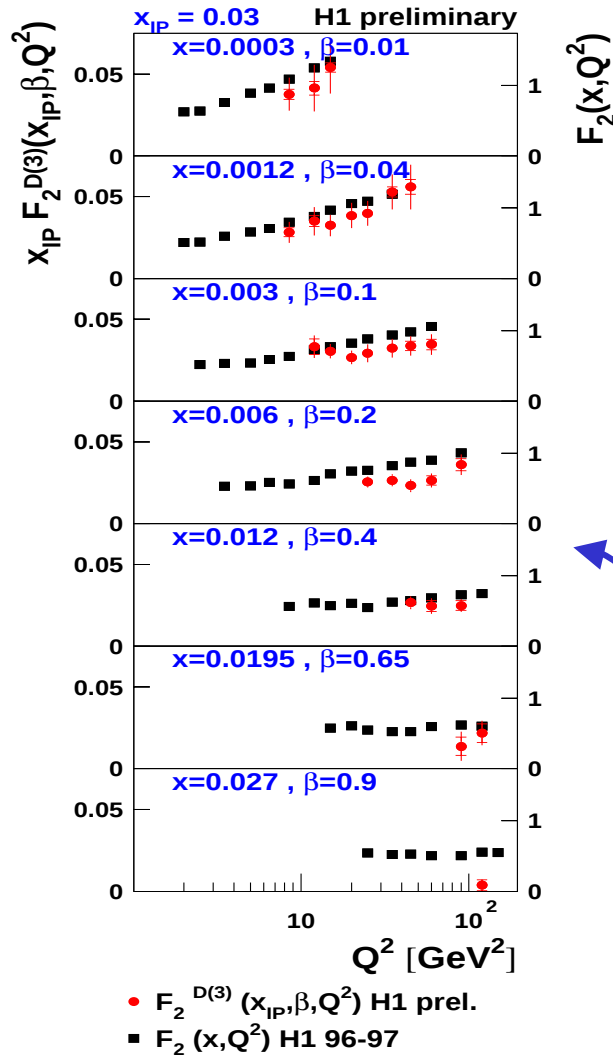
$$F_2^D(Q^2, \beta, \xi, t)$$



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

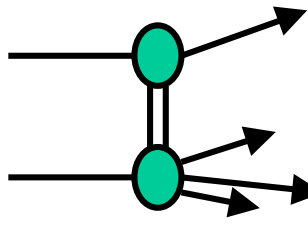
$$F_{JJ}^D(E_T^{Jet}, \beta, \xi, t)$$

Diffractive vs inclusive structure fn's



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

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



Soft Diffraction

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

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

❖ Unitarity problem:

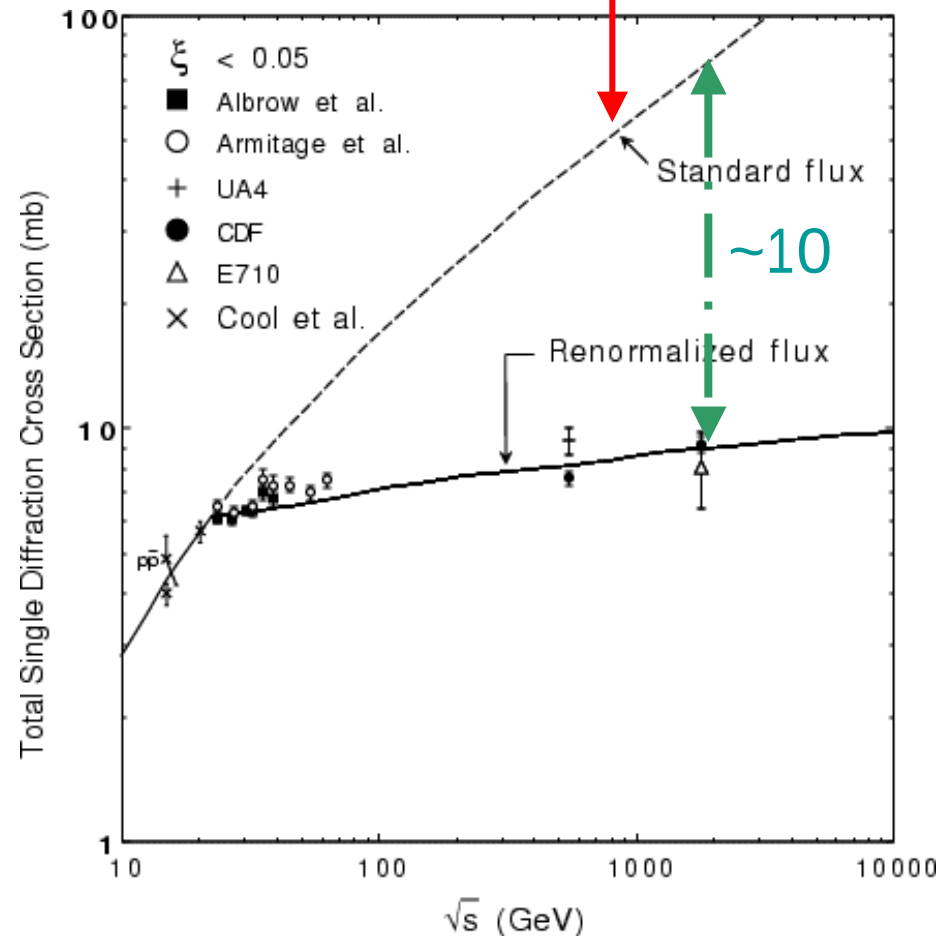
With factorization and std pomeron flux σ_{SD} exceeds σ_T at $\sqrt{s} \approx 2 \text{ TeV}$.

❖ Renormalization:

normalize the pomeron flux to unity

KG, PLB 358 (1995) 379

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



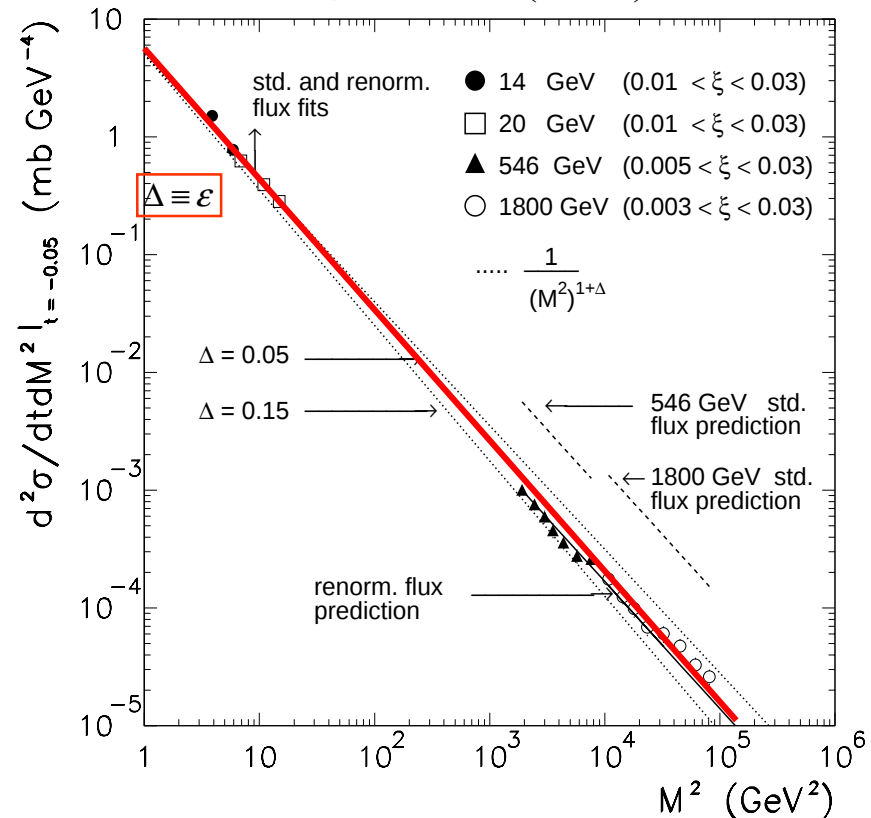
A Scaling Law in Diffraction

Factorization breaks down in favor of a scaling behavior.

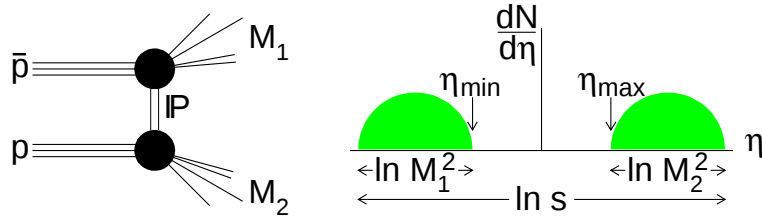
renormalization

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

KG&JM, PRD 59 (1999) 114017

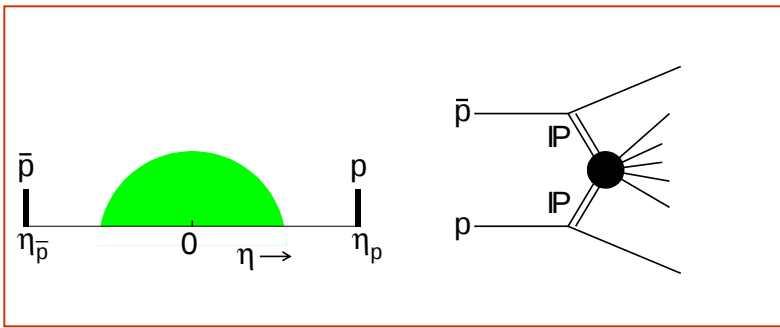


Central and Double Gaps



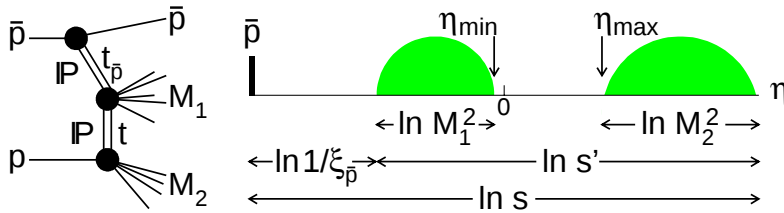
□ Double Diffraction Dissociation

➤ One central gap



□ Double Pomeron Exchange

➤ Two forward gaps



□ SDD: Single+Double Diffraction

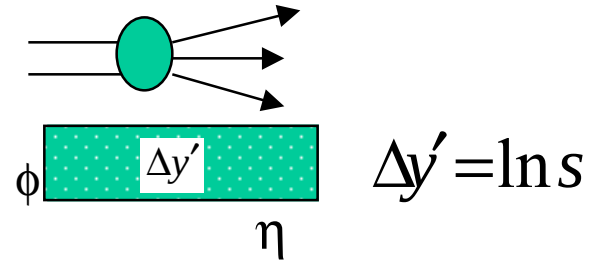
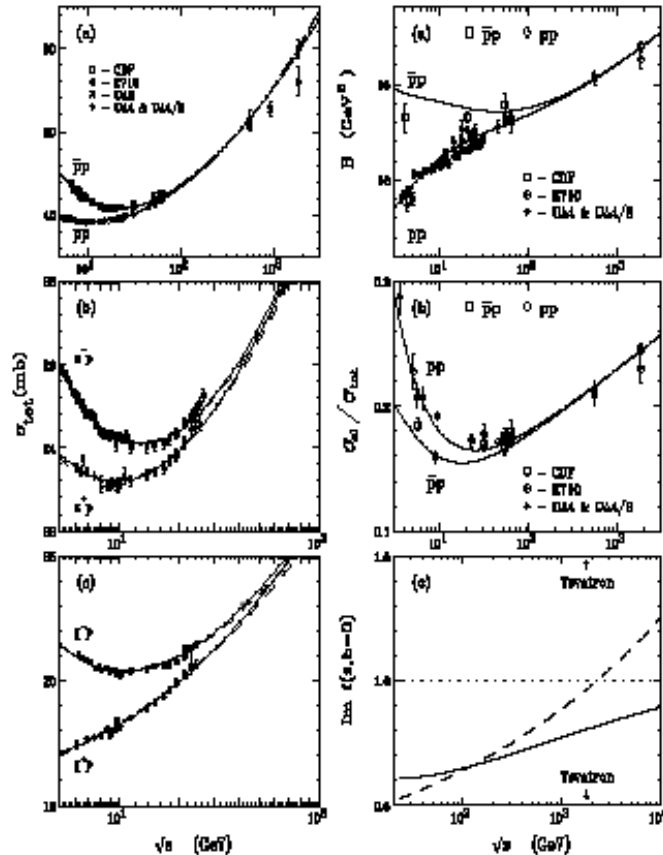
➤ Forward + central gaps

Elastic & total σ

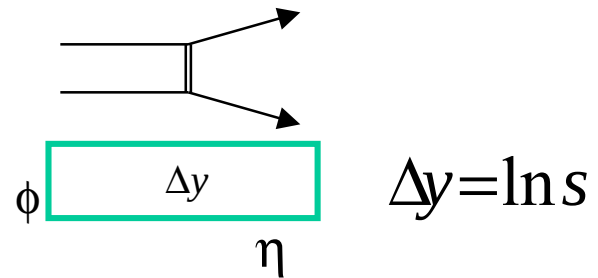
Total and Elastic Cross Sections

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

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



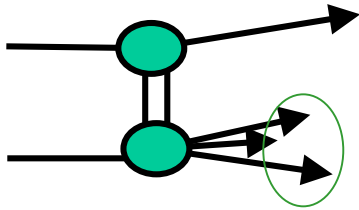
$$\sigma_T(s) = \sigma_o s^\epsilon = \sigma_o e^{\epsilon \Delta y'}$$



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

Generalized renormalization

(KG, hep-ph/0205141)



2 independent variables: $t, \Delta y$

color
factor

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

$$\frac{d^2\sigma}{dt d\Delta y} = C \cdot F_p^2(t_1) \cdot \underbrace{\left\{ e^{(\varepsilon + \alpha' t) \Delta y} \right\}^2}_{\text{Gap probability}} \cdot \underbrace{\kappa \cdot \left\{ \sigma_o e^{\varepsilon \Delta y'} \right\}}_{\text{color factor}}$$

Gap probability



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

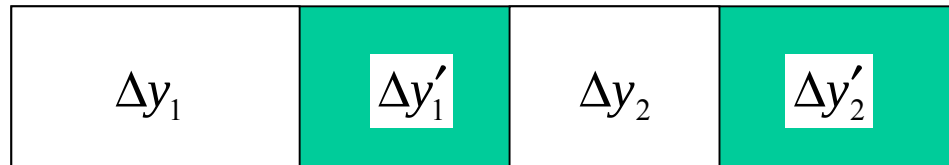
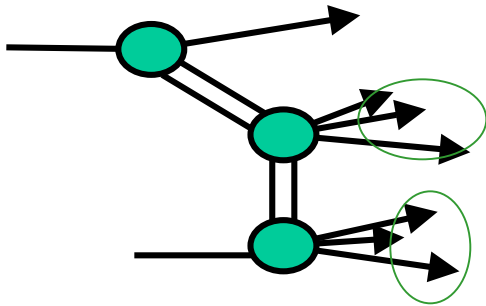


$$\text{Integral} \sim s^{2\varepsilon}$$

Renormalization removes the s-dependence → SCALING

Two-Gap Diffraction

(KG, hep-ph/0205141)



5 independent variables $\left\{ \begin{array}{l} t_1 \\ \Delta y = \Delta y_1 + \Delta y_2 \\ t_2 \end{array} \right.$

$$\prod_{i=1-5} \frac{d^5 \sigma}{dV_i} = \underbrace{C \times F_p^2(t_1) \prod_{i=1-2} \left\{ e^{(\varepsilon + \alpha' t_i) \Delta y_i} \right\}^2}_{\text{Gap probability}} \times \underbrace{\kappa^2 \left\{ \sigma_o e^{\varepsilon(\Delta y'_1 + \Delta y'_2)} \right\}}_{\text{Sub-energy cross section (for regions with particles)}}$$

color factor

$$\text{Integral} \sim s^{2\varepsilon} \leftarrow \sim e^{2\varepsilon \Delta y}$$

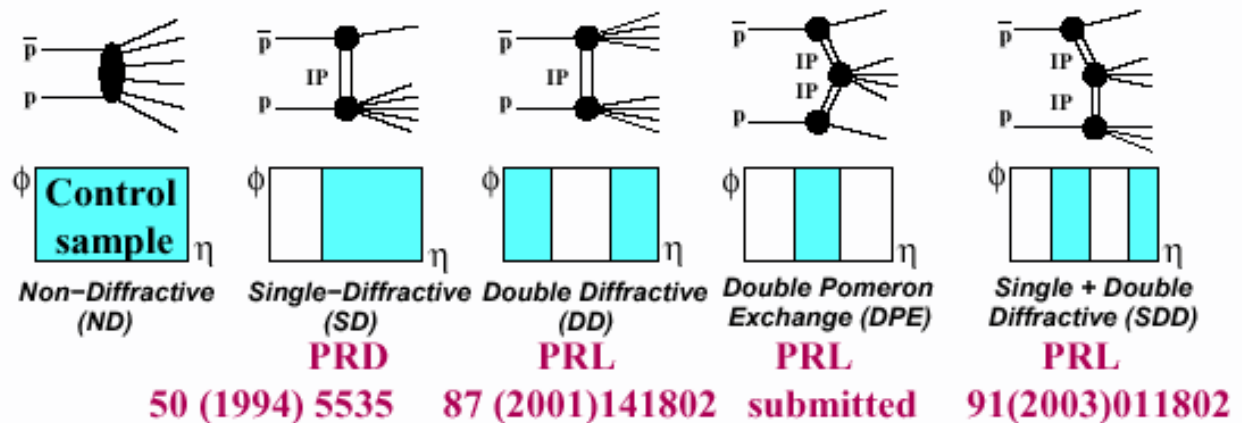
Renormalization removes the s-dependence → SCALING

Diffraction@CDF in Run I

16 papers

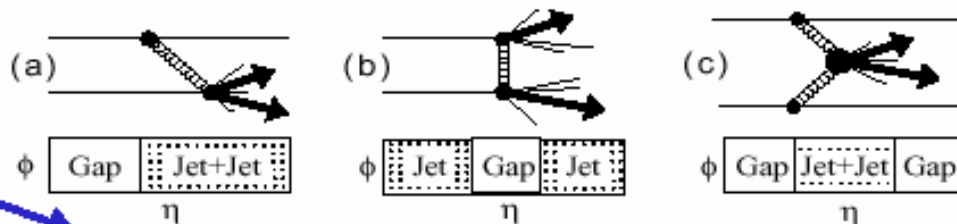
- ❑ Elastic scattering PRD 50 (1994) 5518
- ❑ Total cross section PRD 50 (1994) 5550
- ❑ Diffraction

SOFT diffraction



HARD diffraction

PRL references



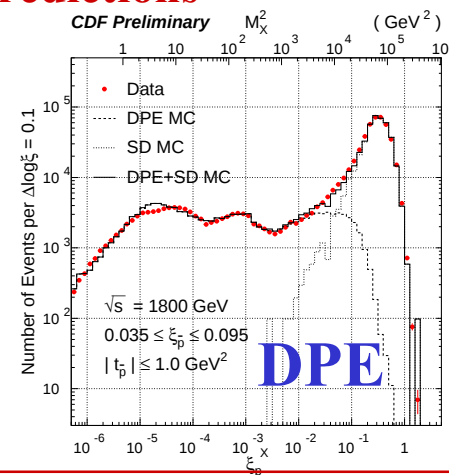
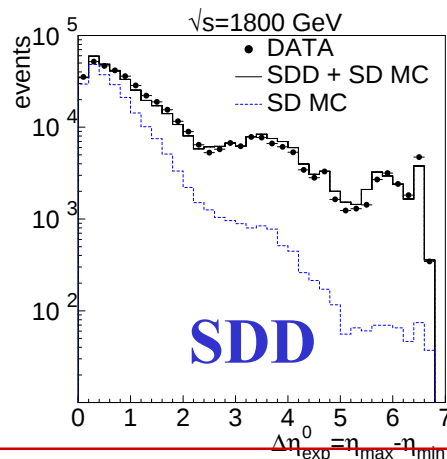
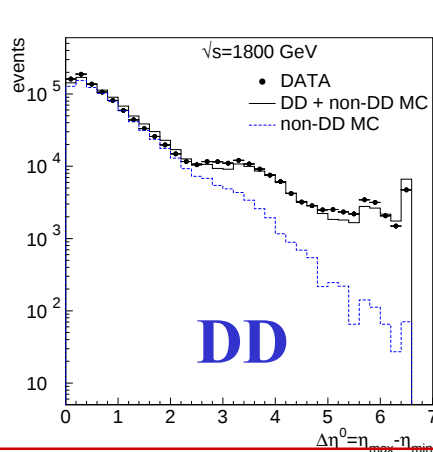
with roman pots

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/ ψ	87 (2001) 241802				

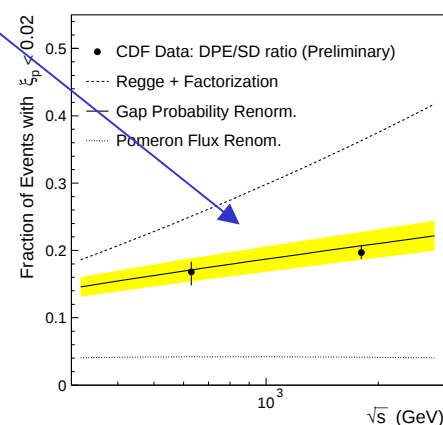
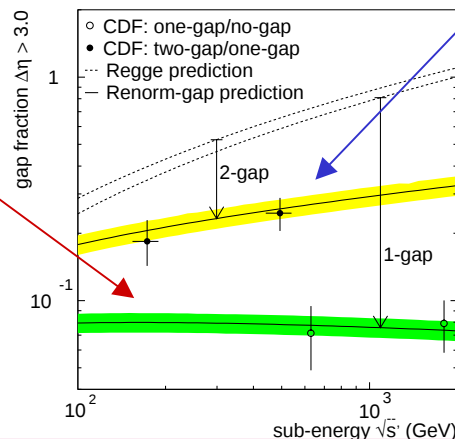
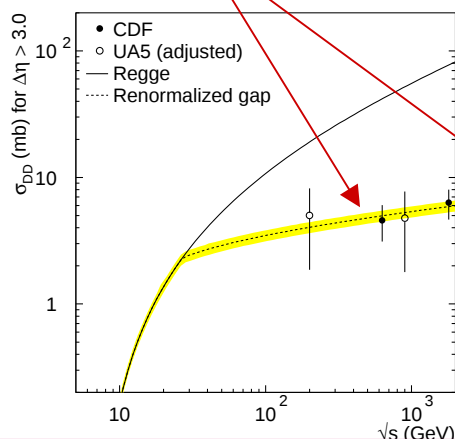
Central & Double-Gap Results

Differential shapes agree with Regge predictions



➤ One-gap cross sections require renormalization

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



Hard Diffraction & QCD

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

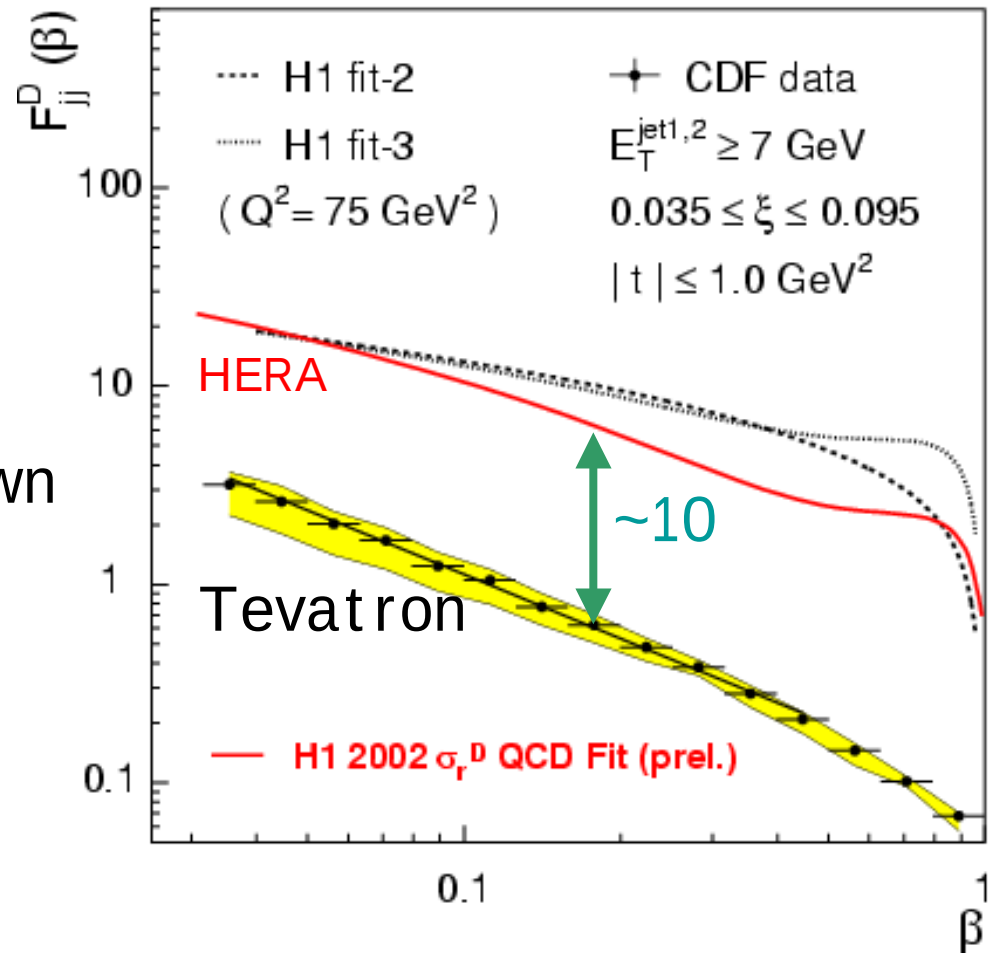
- The diffractive structure function measured using SD dijets at the Tevatron is suppressed by about an order of magnitude relative to predictions based on diffractive DIS at HERA



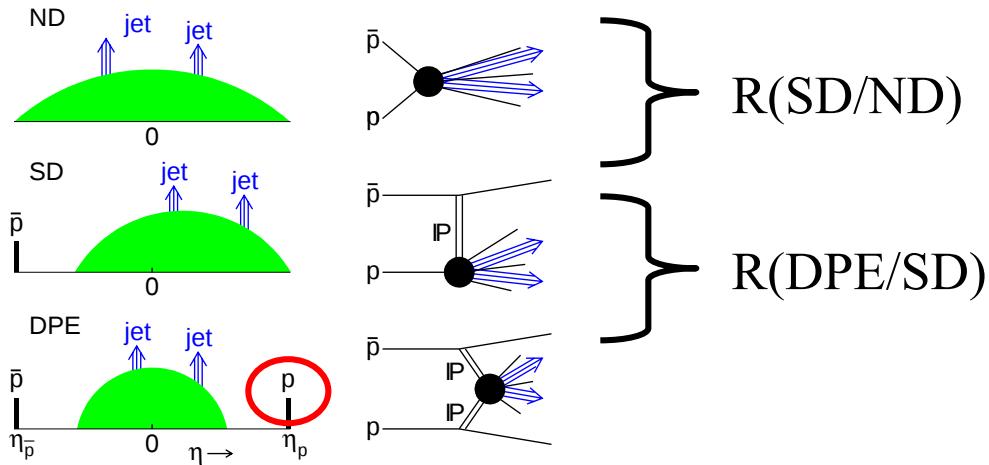
Factorization Breakdown

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

Diffractive structure function

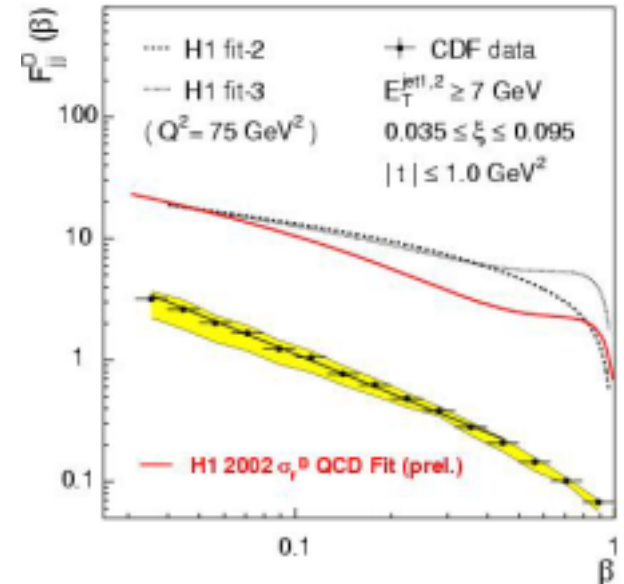
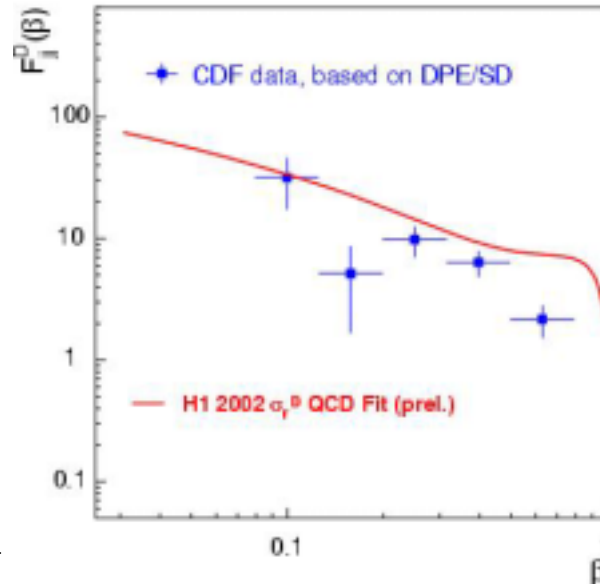
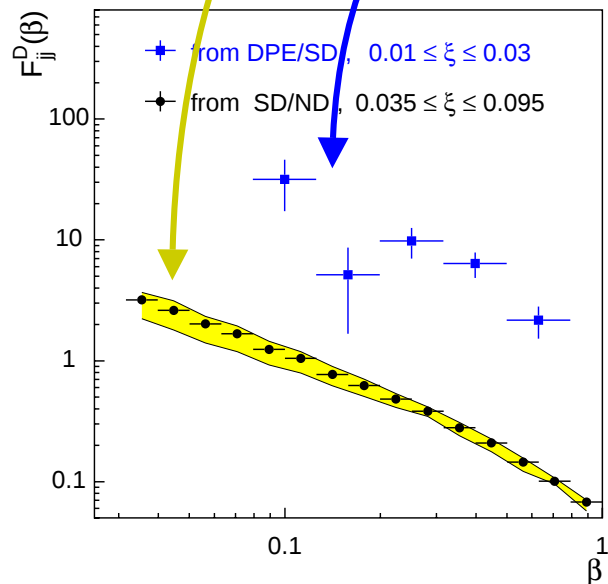


Double-Gap Hard Diffraction @TEV vs HERA

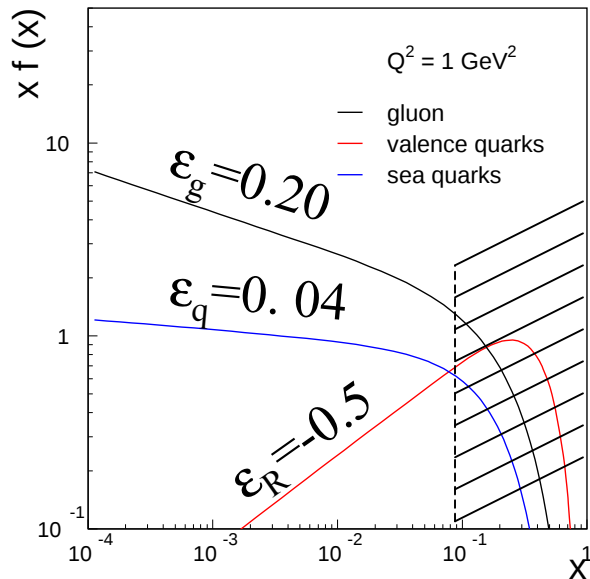


DSF from double-gaps

DSF from single-gaps



Diffractive structure functions from inclusive pdf's (KG)



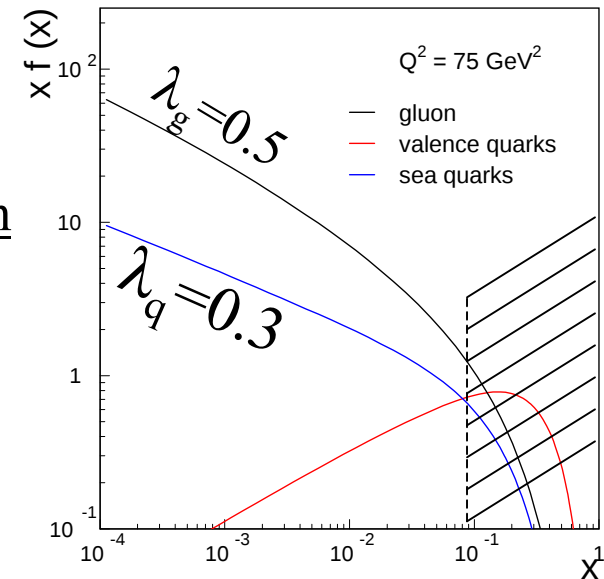
$$x \cdot f(x) = \frac{1}{x^\epsilon}$$

Power-law region

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

$$x_{\max} = 0.1$$

$$\beta < 0.05\xi$$



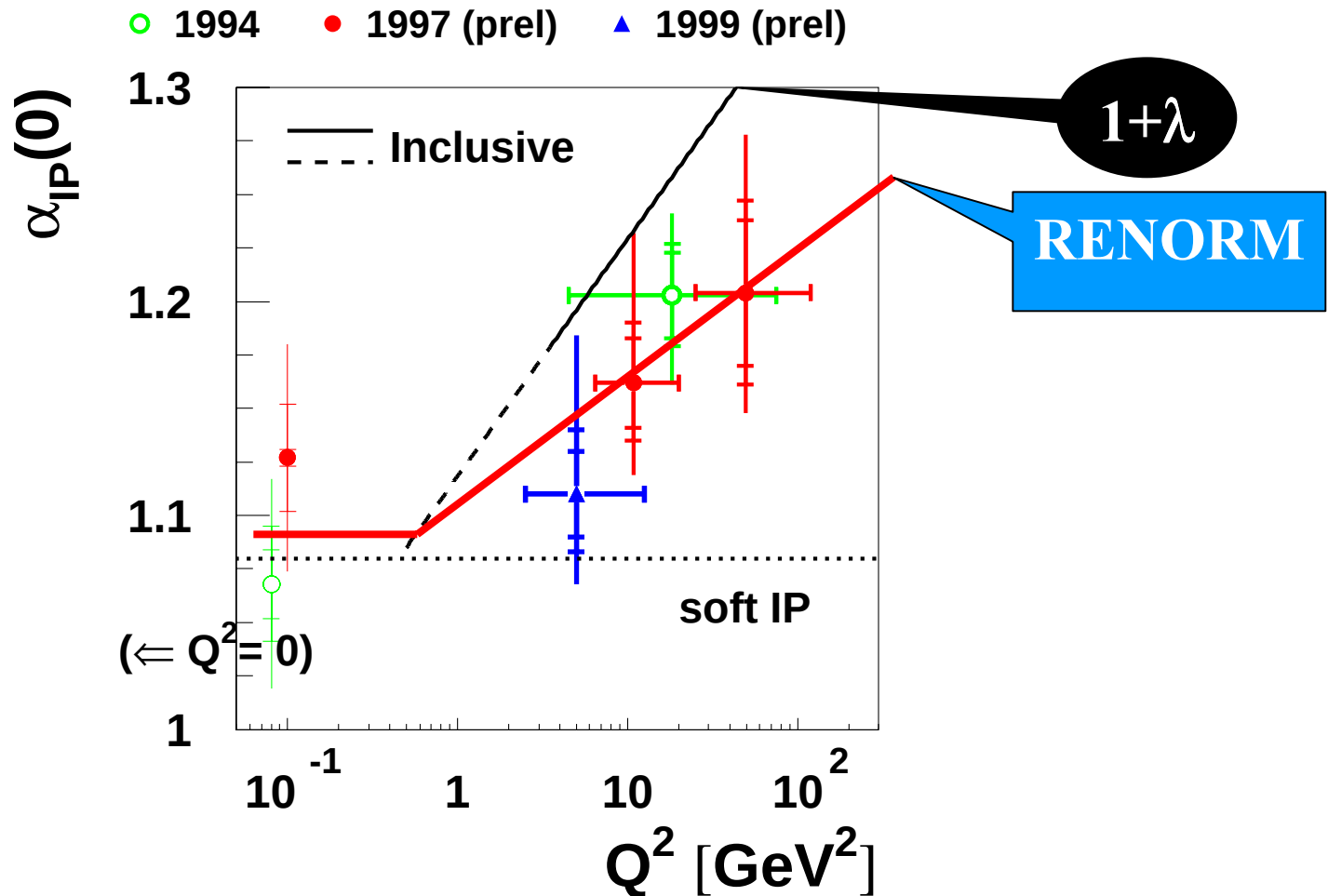
$$F^D(q^2, x, \xi) \propto \frac{1}{\xi^{1+\epsilon}} \cdot F(q^2, x) \propto \frac{1}{\xi^{1+\epsilon}} \cdot \frac{C(q^2)}{(\beta\xi)^{\lambda(q^2)}} \Rightarrow \frac{A_{\text{NORM}}}{\xi^{1+\epsilon+\lambda}} \cdot \kappa \cdot \frac{C}{\beta^\lambda}$$

$$\text{HERA(no RENORM): } R_{\text{DIS}}^{DDIS} \xrightarrow{\text{fixed } \xi} \text{constant, } 2\epsilon_{\text{DIS}}^D = \epsilon + \lambda(q^2)$$

$$\text{TEVATRON (RENORM): } R_{\text{JJ}}\left(\frac{SD}{ND}\right) \propto x^{-(1+\lambda)}$$

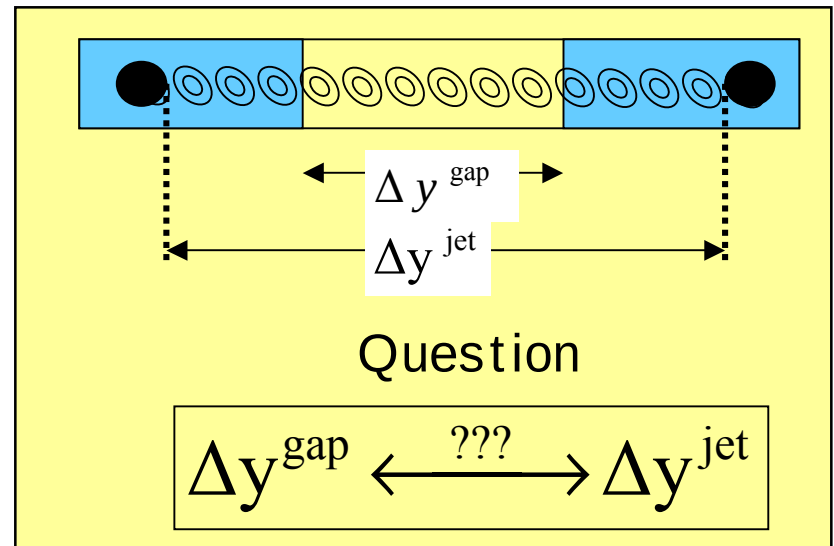
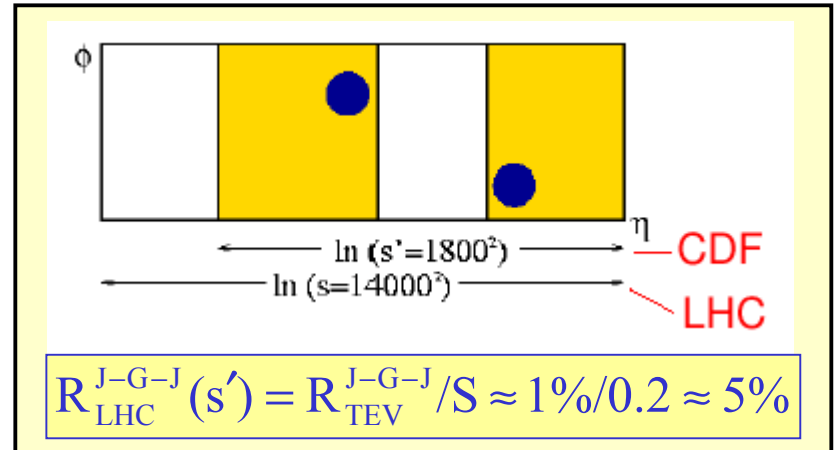
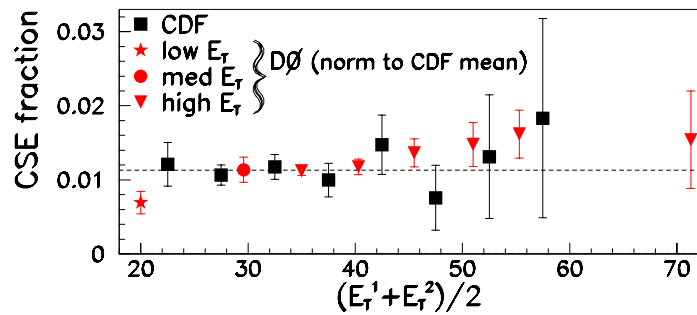
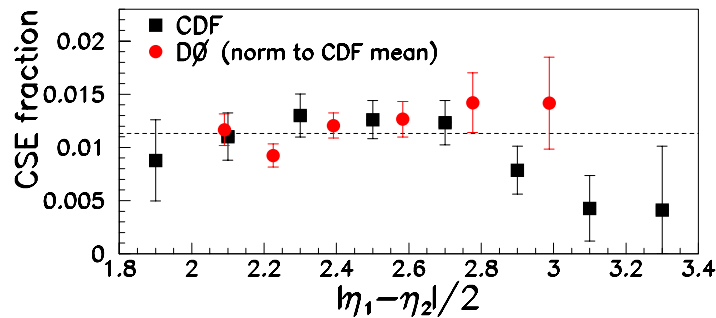
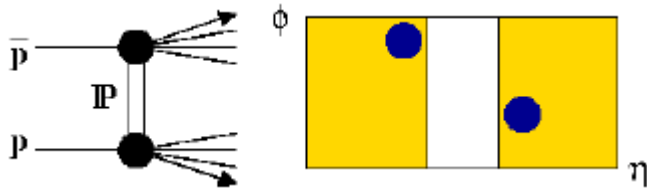
Pomeron Intercept in DDIS

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



Gap between jets

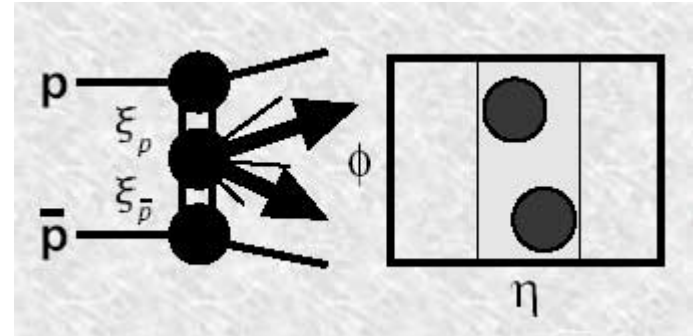
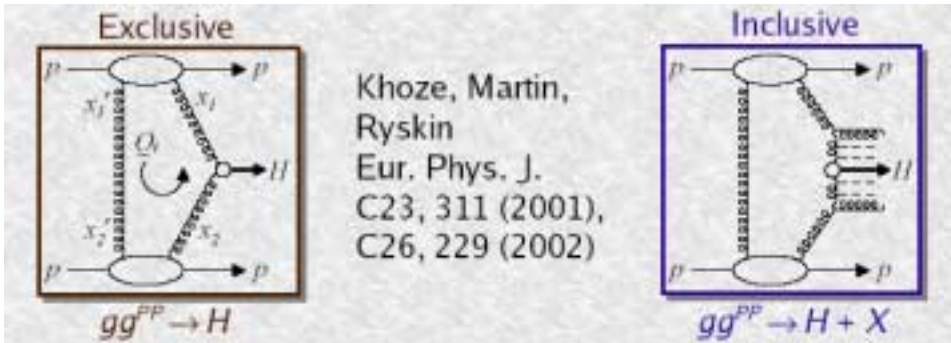
$\bar{p} + p \rightarrow \text{Jet} + \text{Gap} + \text{Jet}$



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^{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

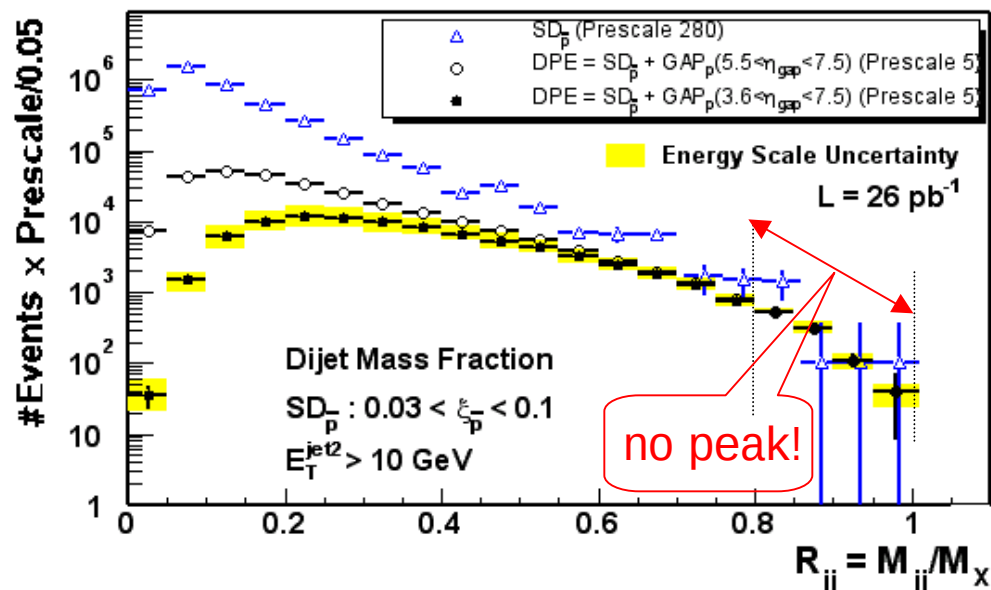
La Thuile 2004

Hadronic Diffraction: where do we stand?

K. Goulios

23

CDF Run II Preliminary



Summary

- Scaling behavior of soft diffractive M^2 - distributions
- Flavor-independent hard diffractive production
- Universality of rapidity gap formation across soft and hard diffraction
- Non-suppressed double-gap to single-gap ratios
- Limit on exclusive dijet production in double-Pomeron exchange

La Thuile

Diffraction

Soft & Hard

