Twenty Years of Diffraction at the Tevatron

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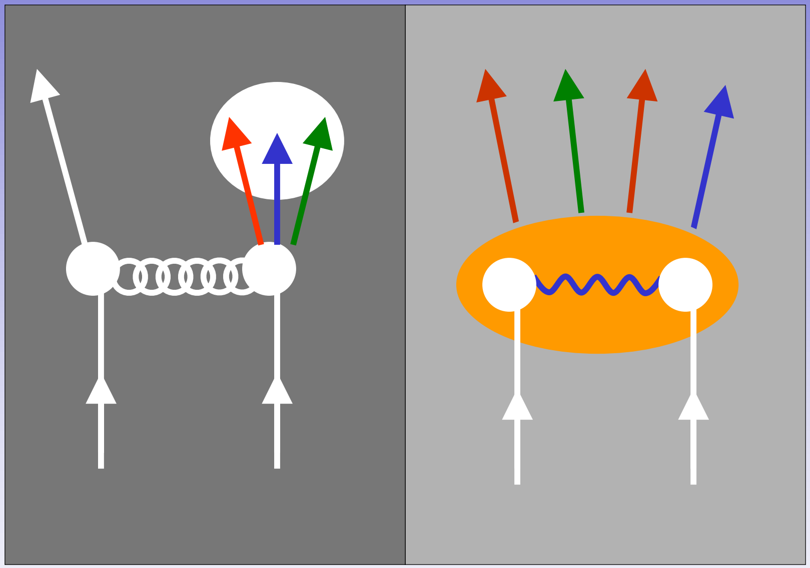
http://physics.rockefeller.edu/dino/my.html

$\bar{p}$-p Interactions

Diffractive:

vacuum exchange

Protons retain their quantum numbers



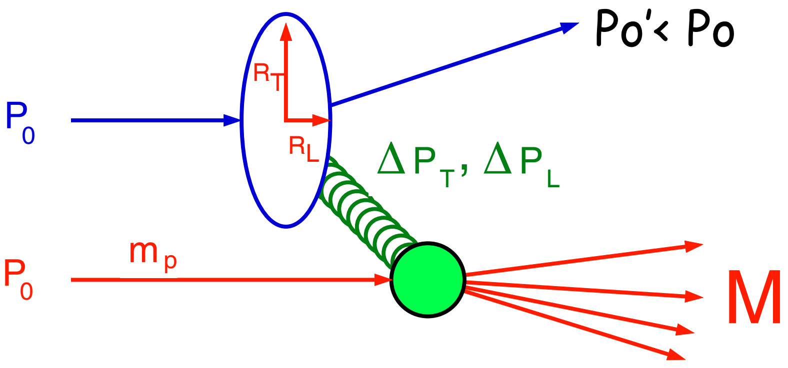
Non-diffractive:

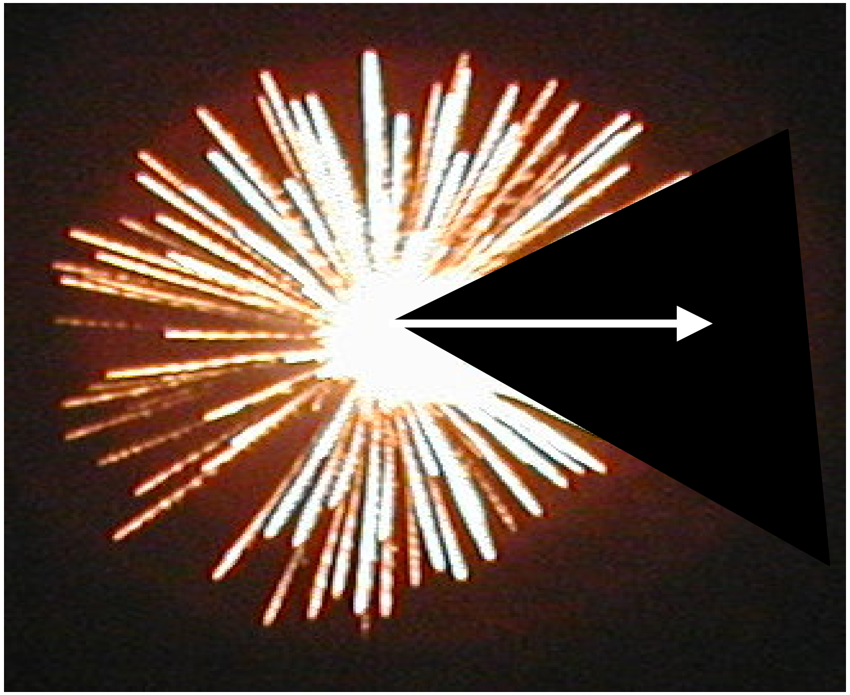
color exchange

Protons acquire color and break apart

Why Study
Particle Diffraction?

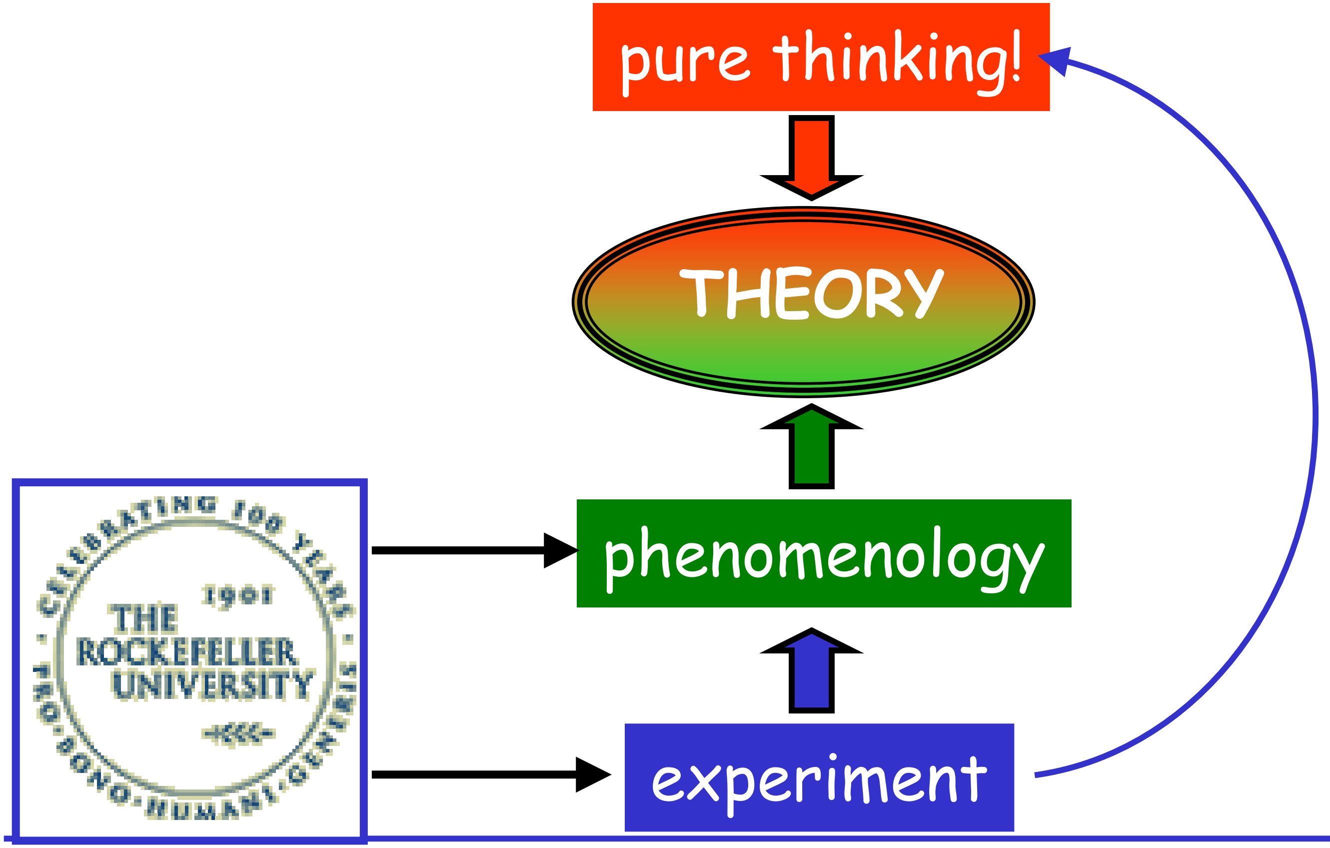
Asymmetric Fireworks?





Non-perturbative QCD

- Important for understanding hadron structure and quark confinement
- Need to develop new mathematical methods
- Diffraction offers an arena on which to confront non-pQCD



Forty Years of Diffraction
Twenty Years at the Tevatron

- 1960's BNL: first observation of pp -> pX
- 1970's Fermilab fixed target, ISR, SPS
  → Regge theory & factorization

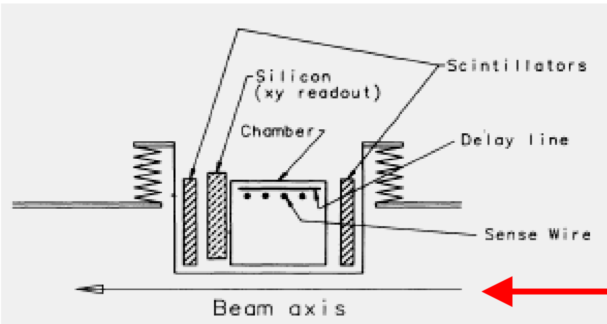
  Review: KG, Phys. Rep. 101 (1983) 169

- 1980's UA8: diffractive dijets ⇨ hard diffraction
- 1990's Tev Run-I: Regge factorization breakdown
  Tev vs HERA: QCD factorization breakdown
- 21st C Multigap diffraction: restoration of factorization
  Ideal for diffractive studies @ LHC

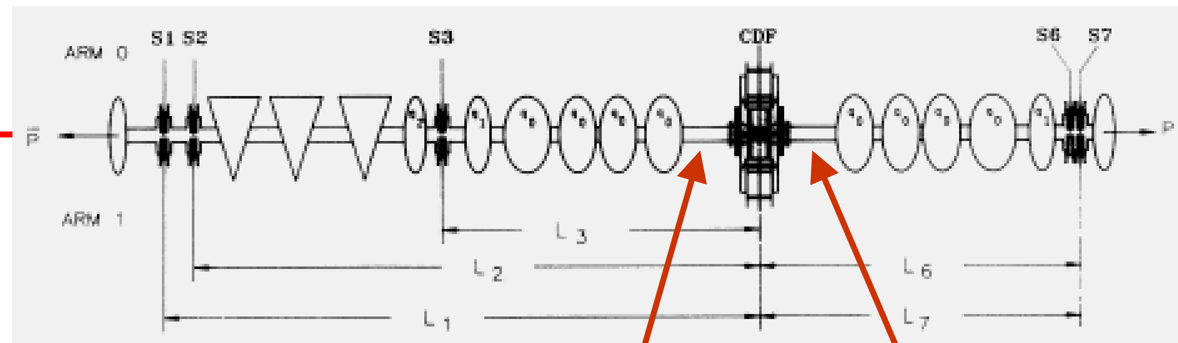
CDF Run 1-0 (1988-89)

Elastic, single diffractive, and total cross sections

@ 546 and 1800 GeV



Roman Pot Spectrometers



Roman Pot Detectors

- Scintillation trigger counters
- Wire chamber
- Double-sided silicon strip detector

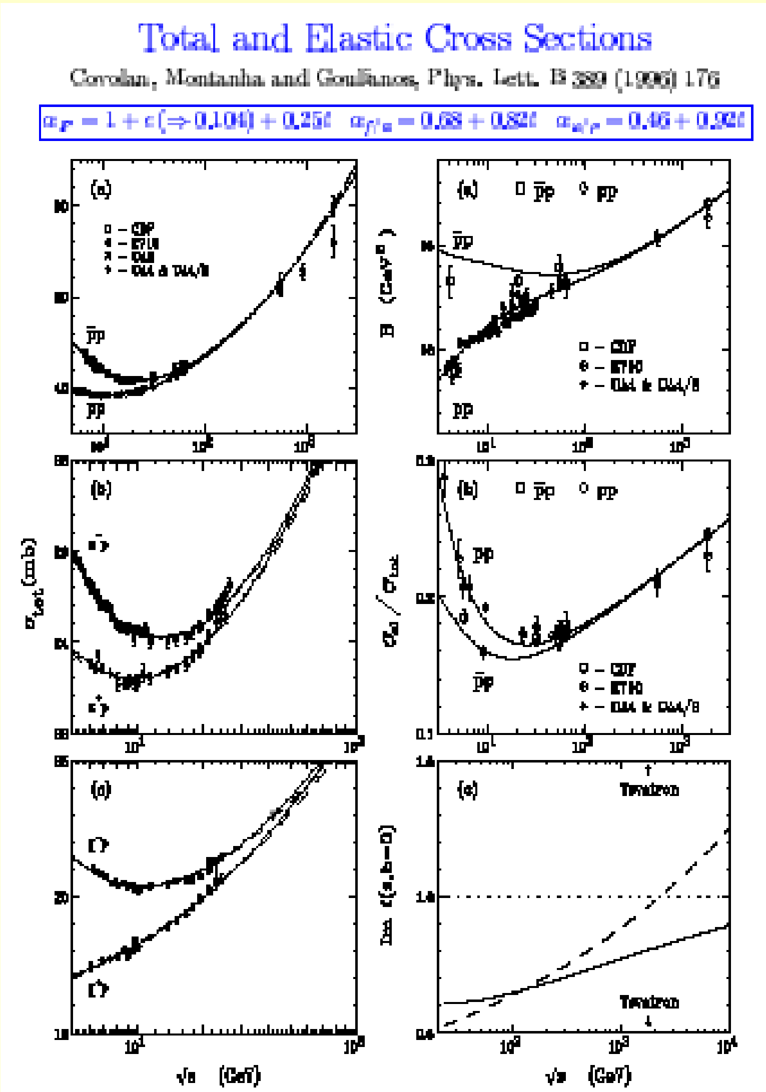
Additional Detectors

Trackers up to $|\eta| = 7$

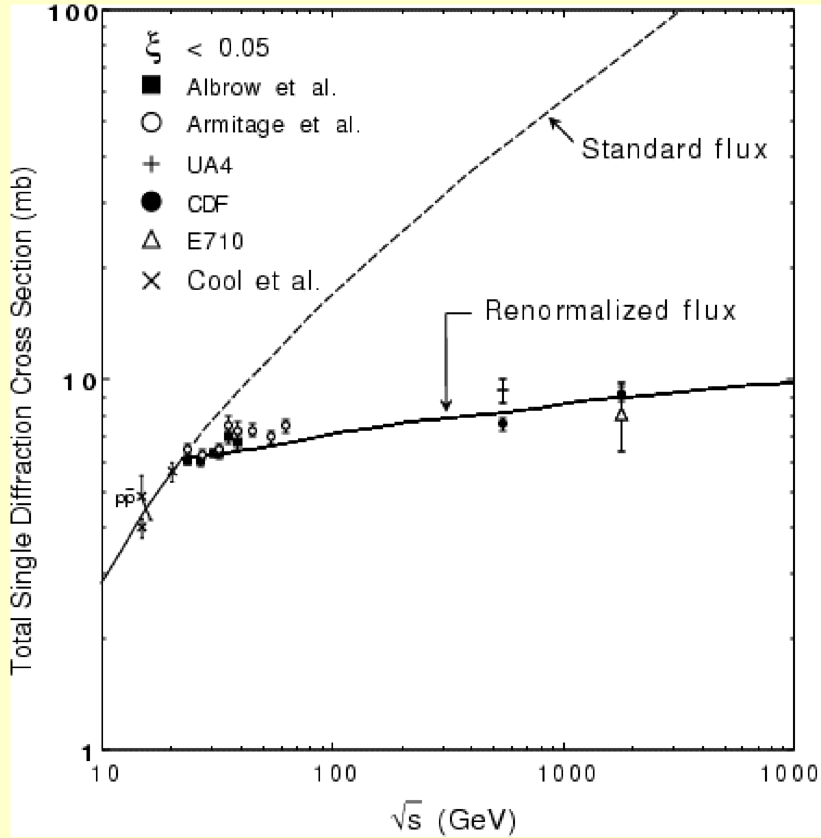
Results

- Total cross section $\sigma^{tot} \sim s^{\varepsilon}$
- Elastic cross section $d\sigma/dt \sim \exp[2\alpha' \ln s]$ → shrinking forward peak
- Single diffraction Breakdown of Regge factorization

Run 1-0 results in perspective

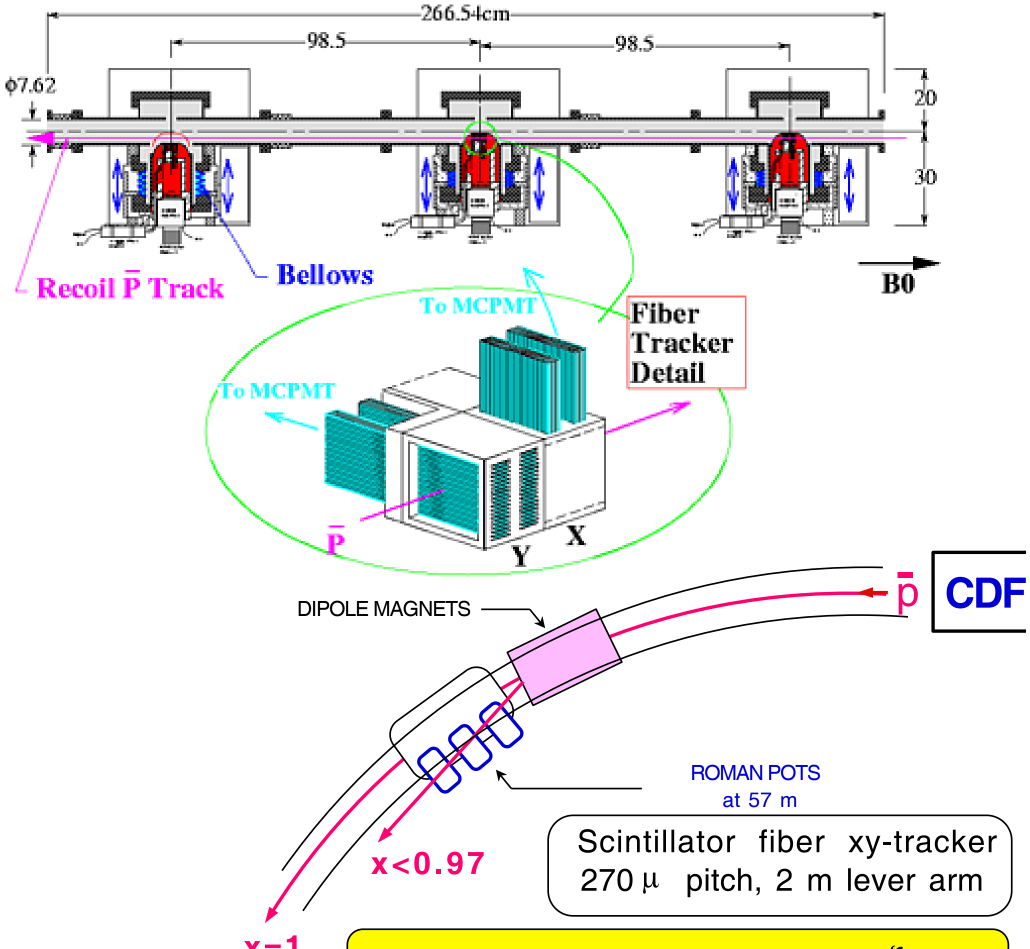


KG, PLB 358 (1995) 379



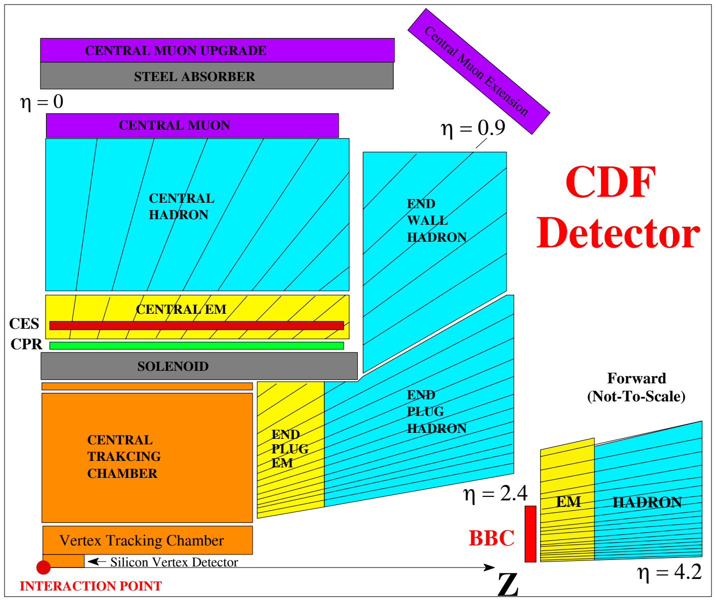
CDF Run 1 (1992-1995)

Run-IC



Acceptance: 0 < |t| < 1, 0.03< ξ < 0.1

Run-IA,B



Forward Detectors

BBC 3.2<η<5.9

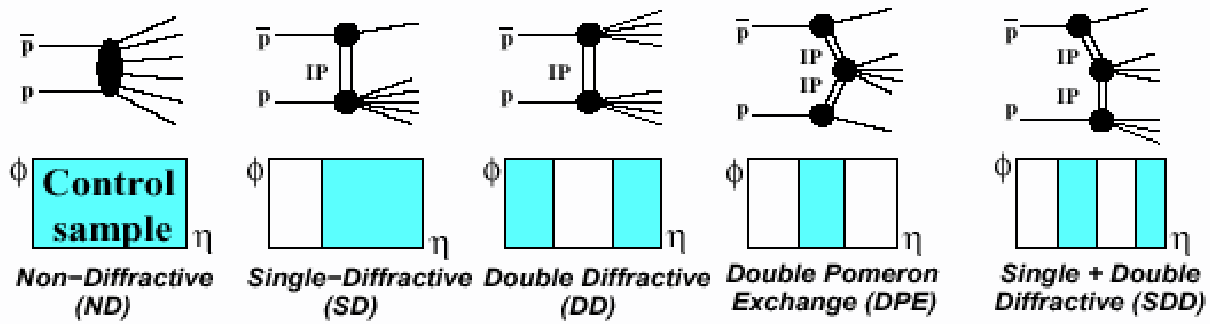
FCAL 2.4<η<4.2

Diffraction@CDF in Run I

16 papers

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

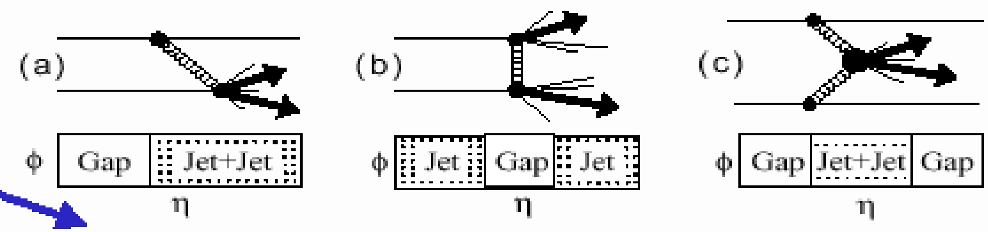
SOFT diffraction



SD	DD	DPE	SDD
PRD 50 (1994) 5535	PRL 87 (2001)141802	PRL 93(2004)141601	PRL 91(2003)011802

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		

Diffractive Fractions @ CDF

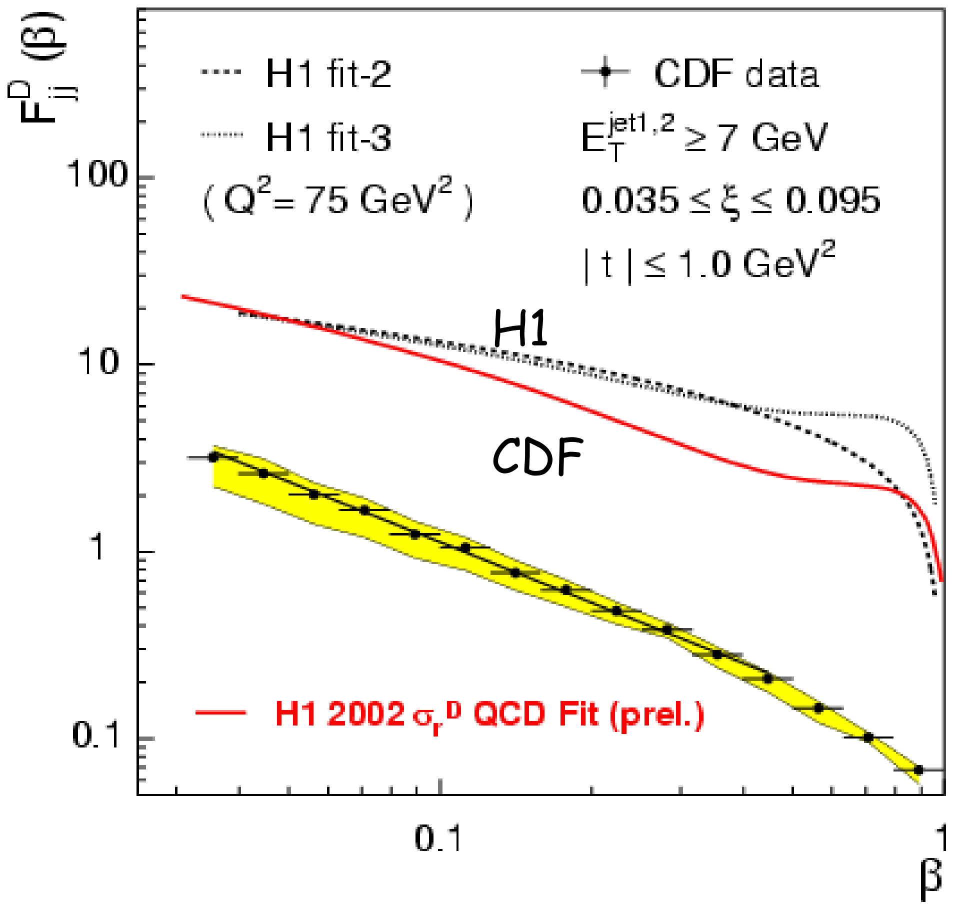
$$\bar{p}p \rightarrow (Hd + X) + \text{gap}$$

Fraction:
SD/ND ratio at 1800 GeV

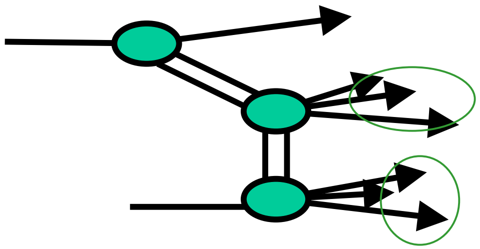
Hd	Fraction(%)
W	1.15 (0.55)
JJ	0.75 (0.10)
b	0.62 (0.25)
J/ψ	1.45 (0.25)

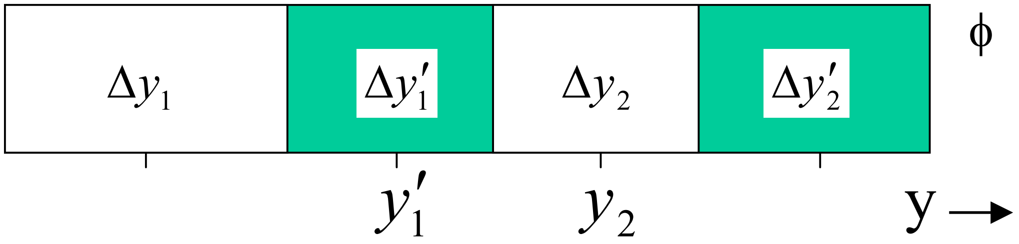
All ratios ~ 1%
➔ ~ uniform suppression
~ FACTORIZATION

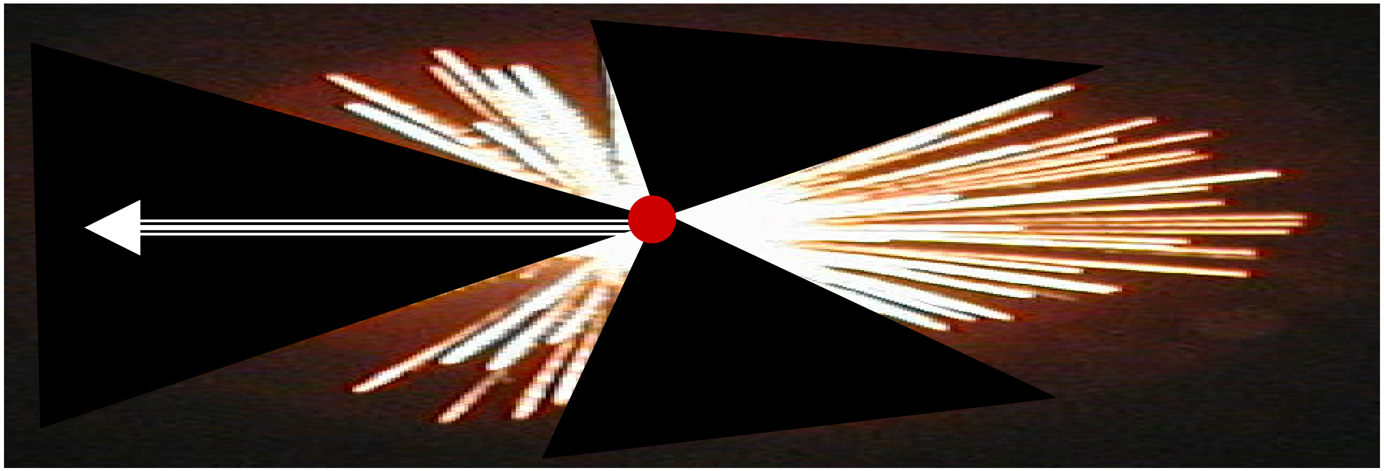
Tevatron vs HERA: Breakdown of QCD Factorization



Multigap Diffraction
(KG, hep-ph/0205141)

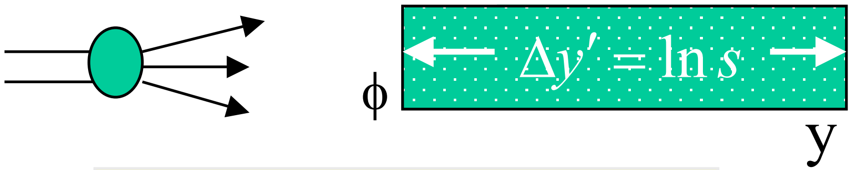






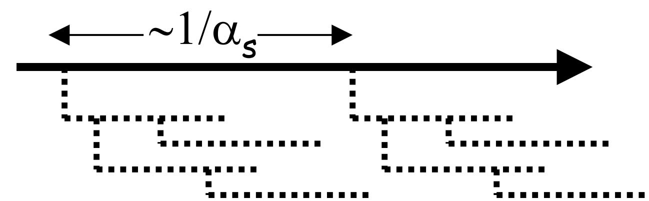
Elastic and Total Cross Sections

QCD expectations



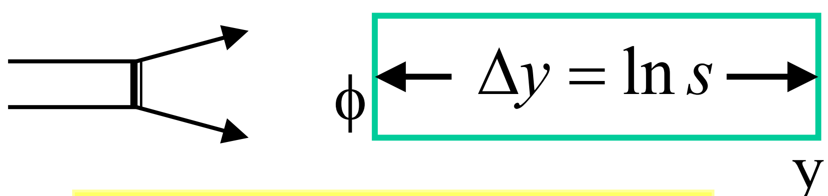
$$\sigma_T(s) = \sigma_o\, s^{\varepsilon} = \sigma_o\, e^{\varepsilon \Delta y'}$$

Total cross section:
power law rise with energy



The exponential rise of $\sigma_T(\Delta y')$ is due to the increase of wee partons with $\Delta y'$

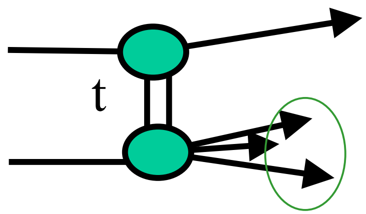
(see E. Levin, An Introduction to Pomerons,Preprint DESY 98-120)

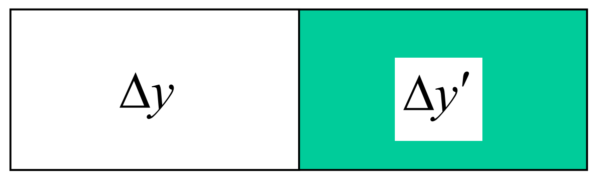


$$\mathrm{Im}\, f_{el}(s,t) \propto e^{(\varepsilon + \alpha' t)\Delta y}$$

Elastic cross section:
forward scattering amplitude

Single Diffraction





2 independent variables: $t, \Delta y$

color factor

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

$$\frac{d^2\sigma}{dt\, d\Delta y} = \underbrace{C \cdot F_p^2(t) \cdot \left\{ e^{(\varepsilon+\alpha' t)\Delta y} \right\}^2}_{\text{gap probability}} \cdot \kappa \cdot \underbrace{\left\{ \sigma_o\, e^{\varepsilon\, \Delta y'} \right\}}_{\text{sub-energy x-section}}$$

Gap probability MUST be normalized to unity!

Single diffraction (re)normalized

$$\frac{d^2\sigma}{dt\,d\Delta y} = N_{gap} \cdot \underbrace{C \cdot F_p^2(t) \cdot \left\{e^{(\varepsilon+\alpha' t)\Delta y}\right\}^2}_{P_{gap}(\Delta y,t)} \cdot \kappa \cdot \left\{\sigma_o\, e^{\varepsilon\,\Delta y'}\right\}$$

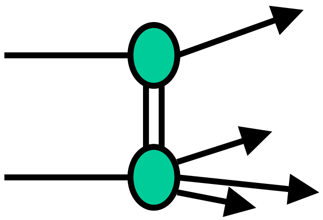
$$N_{gap}^{-1}(s) = \int_{\Delta y,t} P_{gap}(\Delta y,t)\, d\Delta y\, dt \xrightarrow{s\to\infty} C' \cdot \frac{s^{2\varepsilon}}{\ln s}$$

$$\frac{d^2\sigma}{dt\,d\Delta y} = C'' \left[e^{-\varepsilon(\ln s-\Delta y)} \cdot \ln s\right] e^{(b_0+2\alpha'\Delta y)t}$$

Grows slower than ln*s*

→ No unitarity problem after eikonalization of the elastic amplitude

Total Single Diffractive x-Section



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

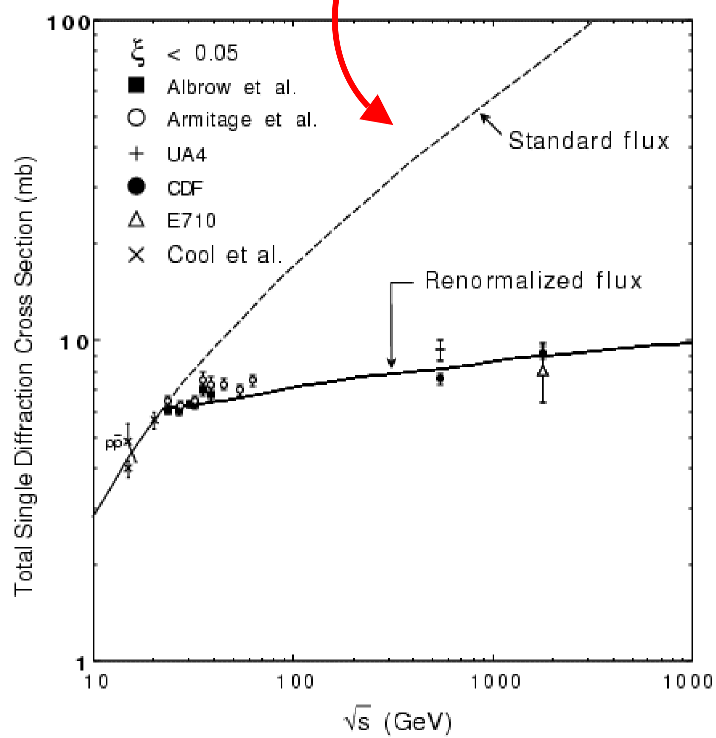
$\sigma_{SD} \sim s^{2\varepsilon}$

- **Unitarity problem:**
  Using factorization
  and std pomeron flux
  σ_{SD} exceeds σ_T at $\sqrt{s} \approx 2$ TeV.

- **Renormalization:**
  Normalize the Pomeron
  flux to unity

KG, PLB 358 (1995) 379

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



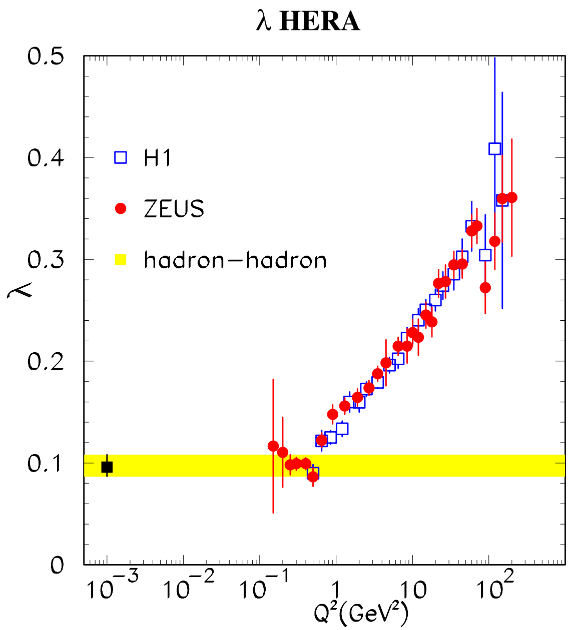
The Factors κ and ε

Experimentally: $$\kappa = \frac{g_{IP-IP-IP}}{\beta_{IP-p}} = 0.17 \pm 0.02, \qquad \varepsilon = 0.104$$

KG&JM, PRD 59 (114017) 1999

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

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

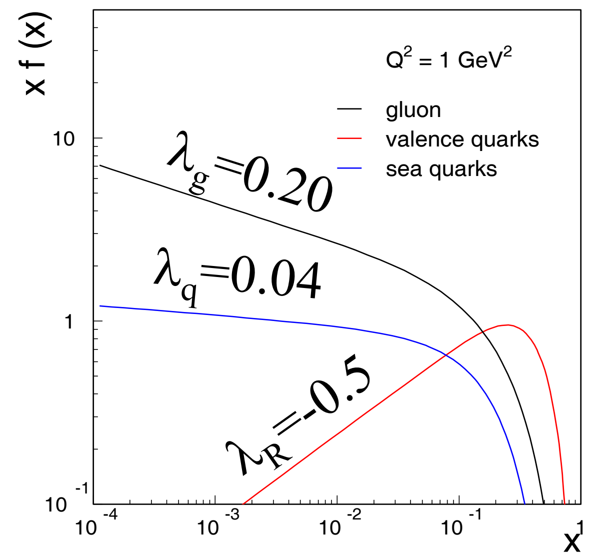


$$x \cdot f(x) = \frac{1}{x^{\lambda}}$$

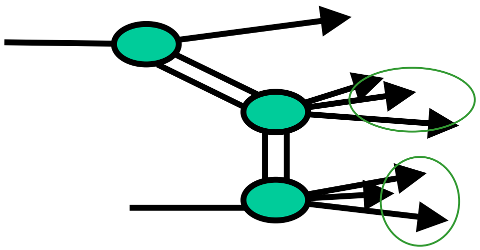
f_g=gluon fraction
f_q=quark fraction

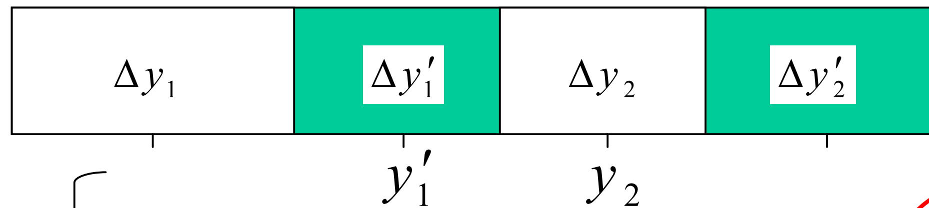
$$\int_{x=1/s}^{1} f(x)\,dx \sim s^{\lambda}$$

CTEQ5L



Multigap Cross Sections





5 independent variables: t_1, $\Delta y = \Delta y_1 + \Delta y_2$, t_2, y_1', y_2

color factors

$$\frac{d^5\sigma}{\prod_{i=1-5} dV_i} = C \times F_p^2(t_1) \prod_{i=1-2} \left\{ e^{(\varepsilon+\alpha' t_i)\Delta y_i} \right\}^2 \times \kappa^2 \left\{ \sigma_o \, e^{\varepsilon(\Delta y_1' + \Delta y_2')} \right\}$$

Gap probability

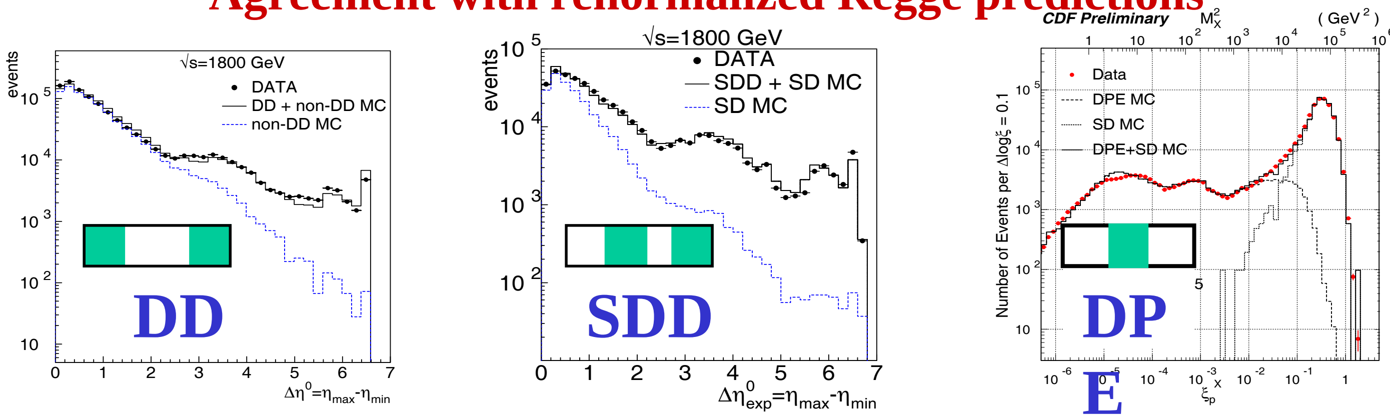
$$\int_{\Delta y, t} \sim s^{2\varepsilon} / \ln s$$

Sub-energy cross section (for regions with particles)

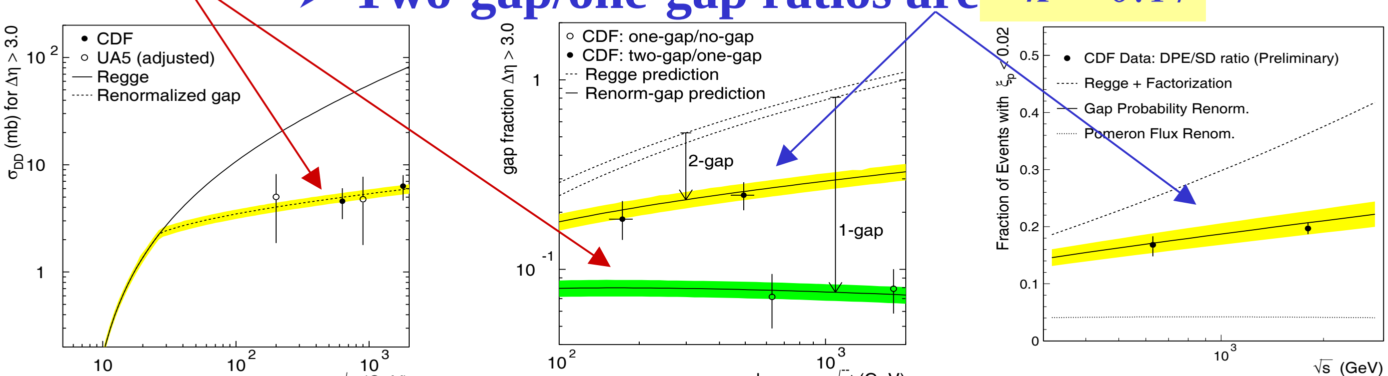
Same suppression as for single gap!

Central and Two-Gap CDF Results

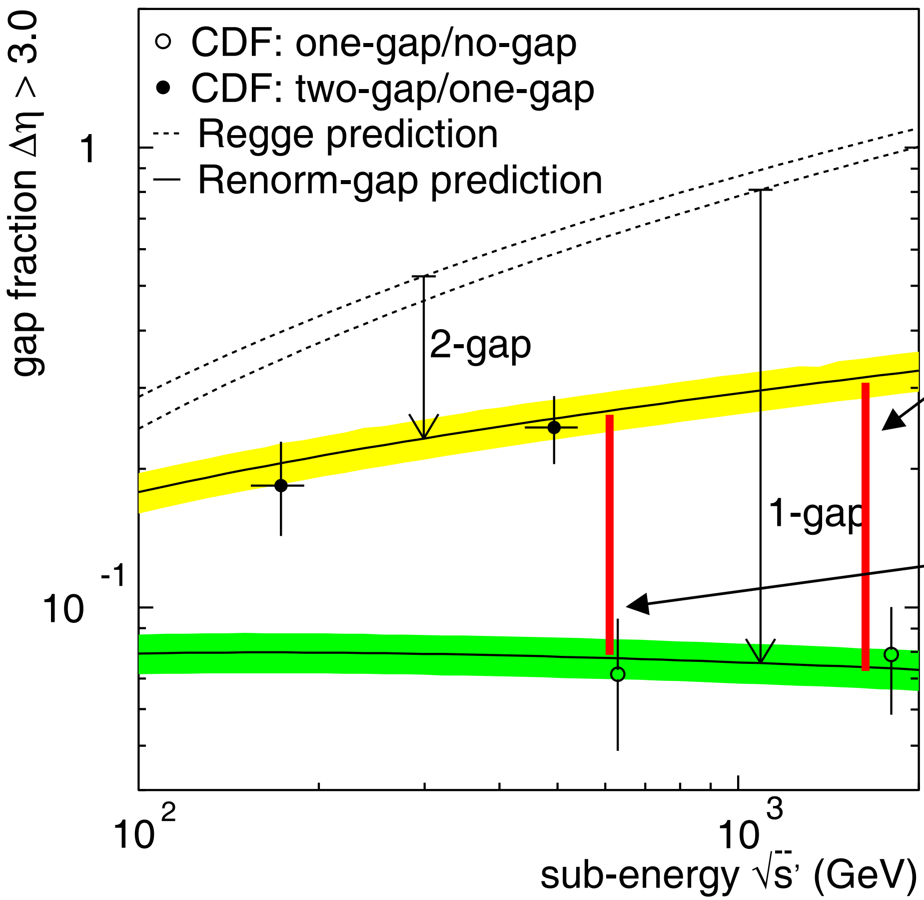
Agreement with renormalized Regge predictions

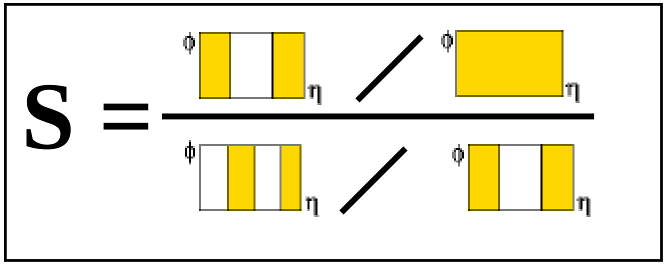


- **One-gap cross sections are suppressed**
- **Two-gap/one-gap ratios are $\approx \kappa = 0.17$**



Gap Survival Probability





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

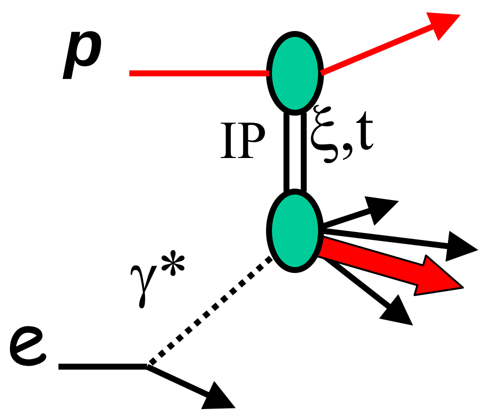
$$S^{1-gap/0-gap}_{2-gap/1-gap}(630\ \text{GeV}) \approx 0.29$$

Results similar to predictions by:
Gotsman-Levin-Maor
Kaidalov-Khoze-Martin-Ryskin
Soft color interactions

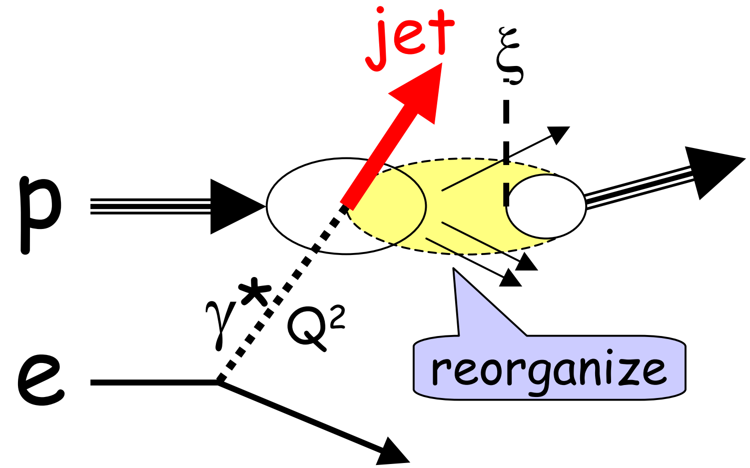
Diffractive DIS @ HERA

Factorization holds: J. Collins

Pomeron exchange



Color reorganization

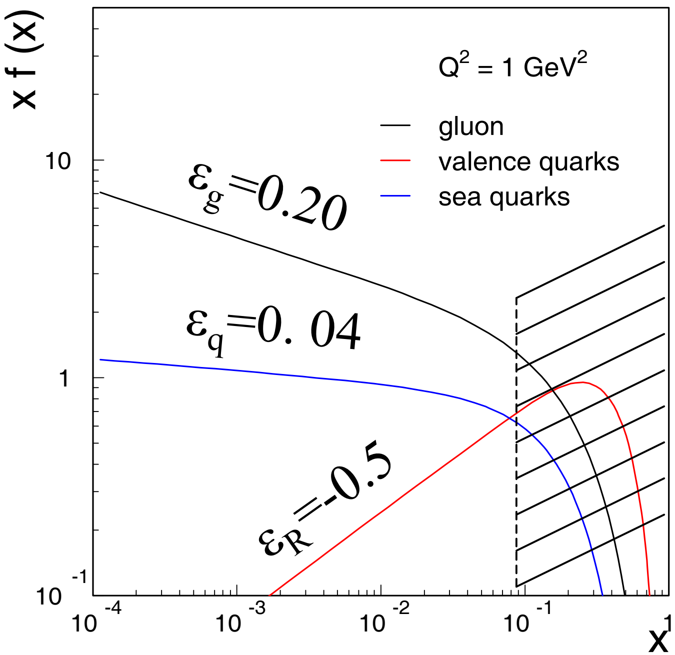


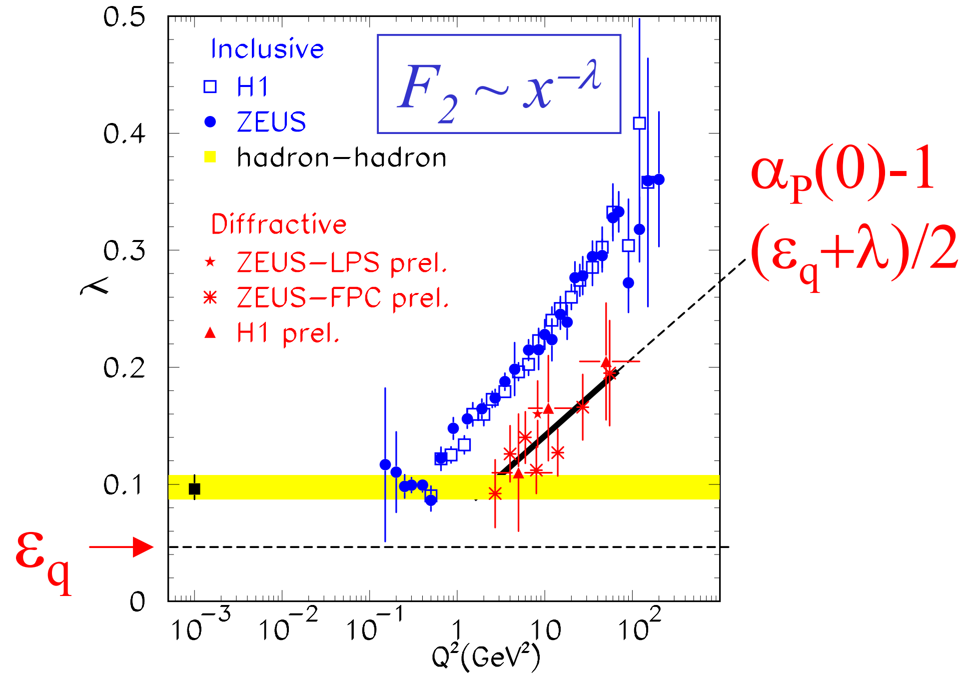
$$F_2^{D(3)}(\xi, x, Q^2) \propto f_q(\xi, Q^2 = m_{hadron}^2) \cdot F_2(x, Q^2)$$

Brodsky et al. rescattering?

Inclusive vs Diffractive DIS

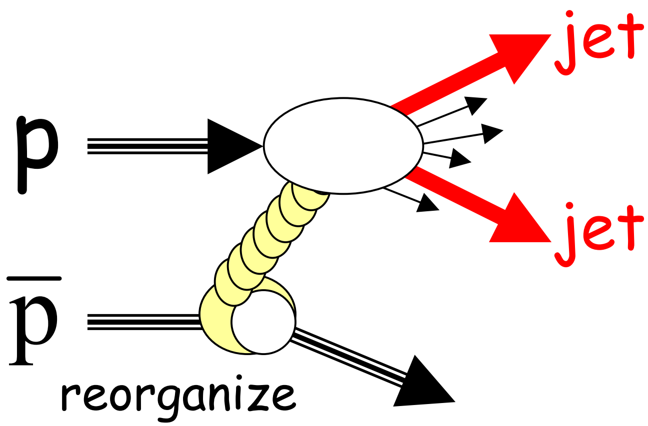
KG, "Diffraction: a New Approach," J.Phys.G26:716-720,2000 e-Print Archive: **hep-ph/0001092**





$$F_2^{D(3)}(\xi,\beta,Q^2) \xrightarrow{\xi\leq 0.05} \sum_{q,R} \frac{1}{\xi^{1+\varepsilon_{q,R}}} \cdot \frac{C_{Q^2}}{(\beta\xi)^{\lambda_{Q^2}}} \propto \sum_{q,R} \frac{1}{\xi^{1+\varepsilon_{q,R}+\lambda_{Q^2}}} \cdot \frac{C_{Q^2}}{\beta^{\lambda_{Q^2}}}$$

Diffractive Dijets @ Tevatron



$$F^D(\xi, x, Q^2) \propto \frac{1}{\xi^{1+2\varepsilon_{soft}}} \cdot F(x/\xi, Q^2)$$

$F^{D}_{JJ}(\xi,\beta,Q^2)$ @ Tevatron

$$F^D(\xi,\beta,Q^2) = \mathrm{N}_{\mathrm{renorm}} \frac{1}{\xi^{1+2\varepsilon}} \cdot \frac{C(Q^2)}{(x/\xi)^{\lambda(Q^2)}} = \frac{2\varepsilon}{(\beta\, s)^{2\varepsilon}} \cdot \frac{1}{\xi^{1+2\varepsilon}} \cdot \frac{C(Q^2)}{\beta^{\lambda(Q^2)}}$$

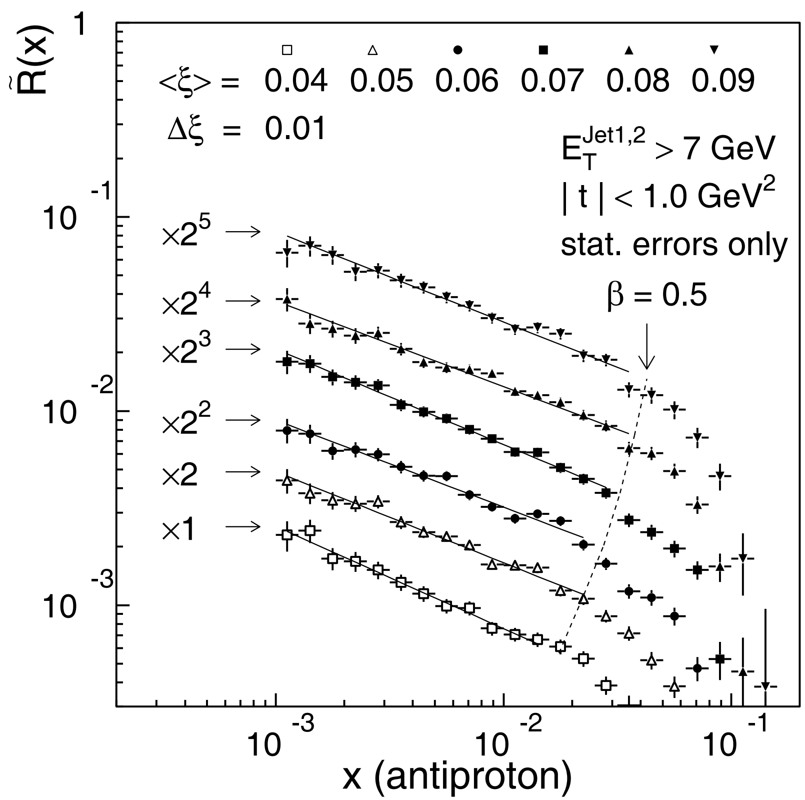
$$\mathrm{N}^{-1}_{\mathrm{renorm}} = \int_{\xi_{\min}}^{1} \frac{d\xi}{\xi^{1+2\varepsilon}} \xrightarrow{\xi_{\min} = \frac{x_{\min}}{\beta} \approx \frac{1}{\beta\, s}} \frac{(\beta\, s)^{2\varepsilon}}{2\varepsilon}$$

$$\text{RENORM} \quad \Rightarrow \quad \mathrm{R}^{SD}_{ND}(x) = \frac{2\varepsilon}{s^{2\varepsilon}} \frac{1}{\xi^{1-\lambda(Q^2)}} \cdot x^{-(2\varepsilon)}$$

$$\varepsilon_g = 0.2 \rightarrow x^{-0.4}$$

SD/ND Dijet Ratio vs x_{Bj}@ CDF

$$R(x) = \frac{F_{jj}^{SD}(x)}{F_{jj}^{ND}(x)}$$

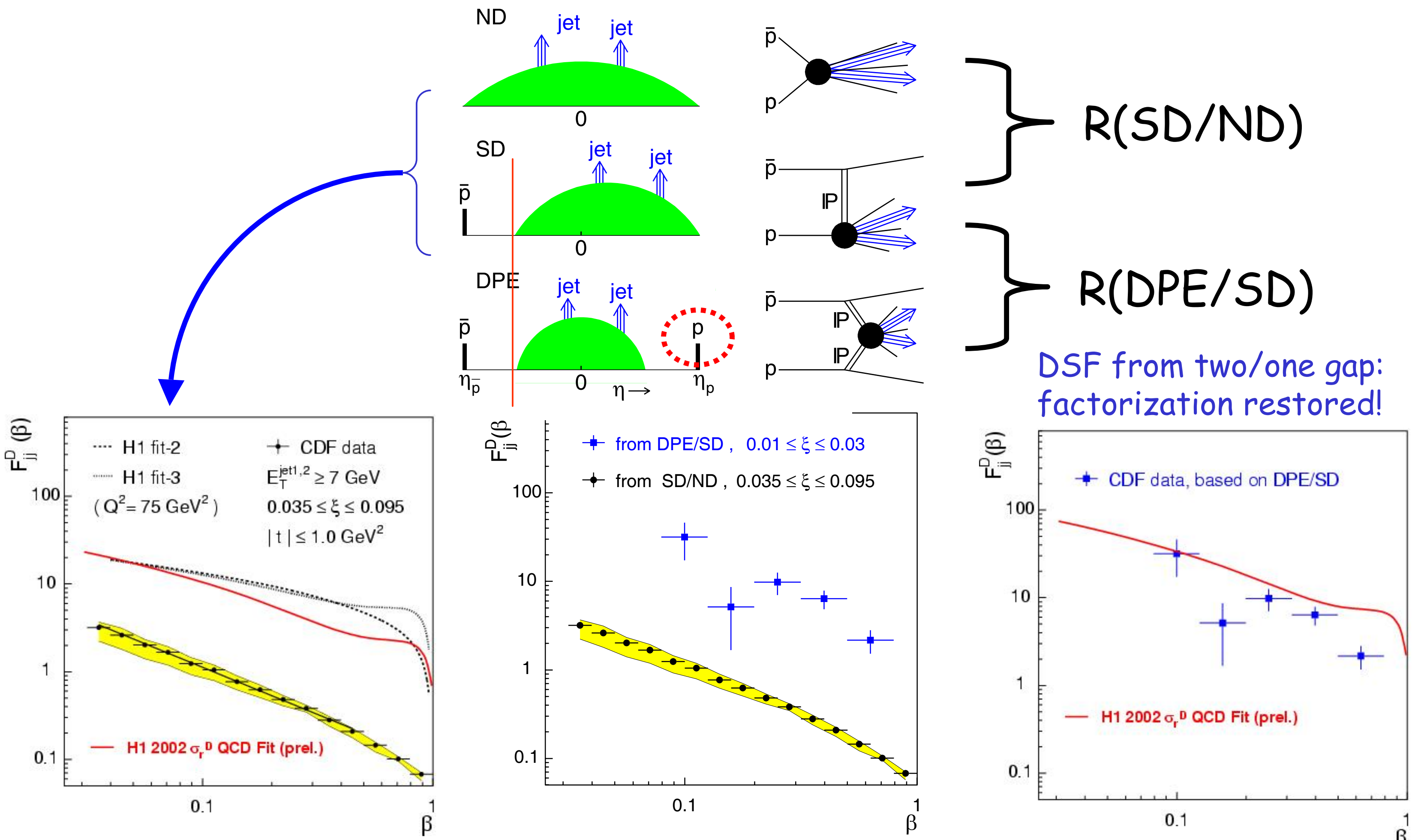


0.035 < ξ < 0.095

Flat ξ dependence

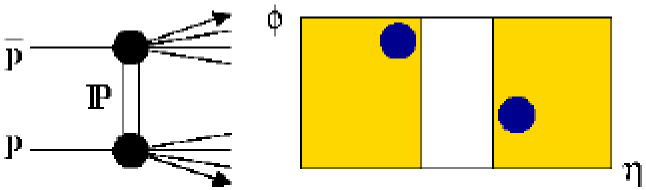
$$R(x) = x^{-0.45}$$

Restoring Factorization @ Tevatron

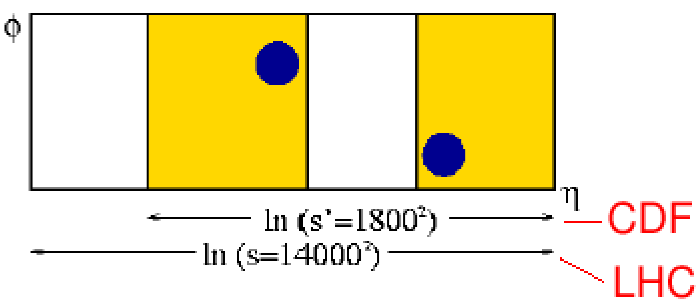


Gap Between Jets

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



$$R_{TEV}^{J-G-J}(s') \approx 1\%/$$

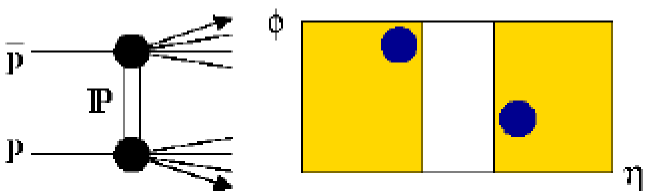


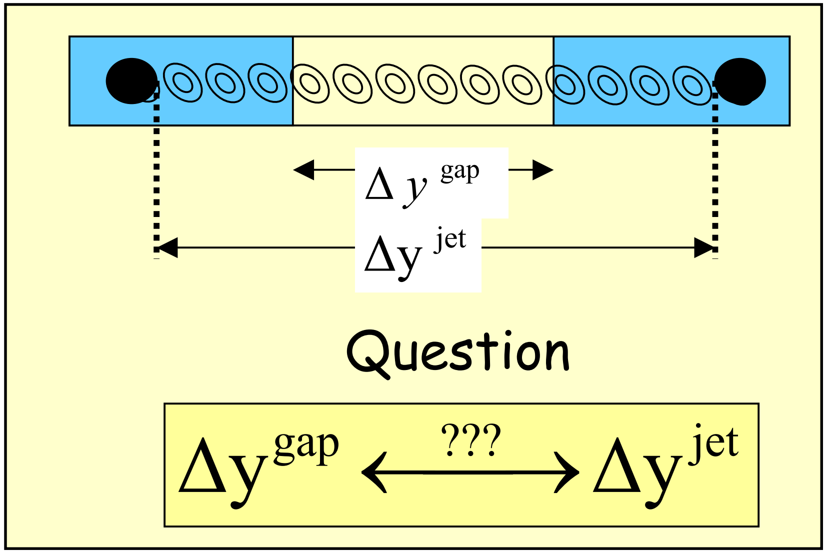
$$R_{LHC}^{J-G-J}(s') = \frac{R_{TEV}^{J-G-J}}{S} \approx \frac{1\%}{0.2} \approx 5\%$$

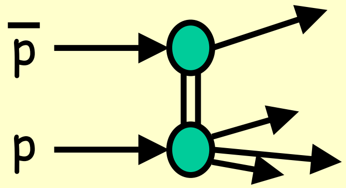
Gap Between Jets

Is the diffractive exchange BFKL-like
or simply a color rearrangement?

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

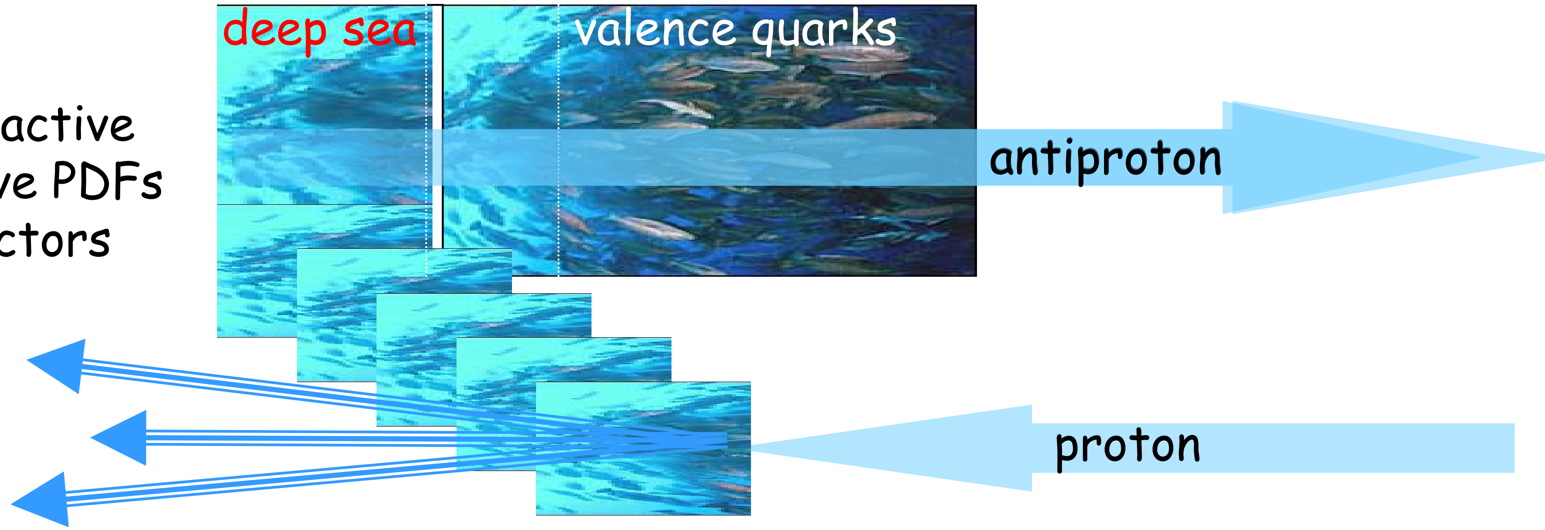


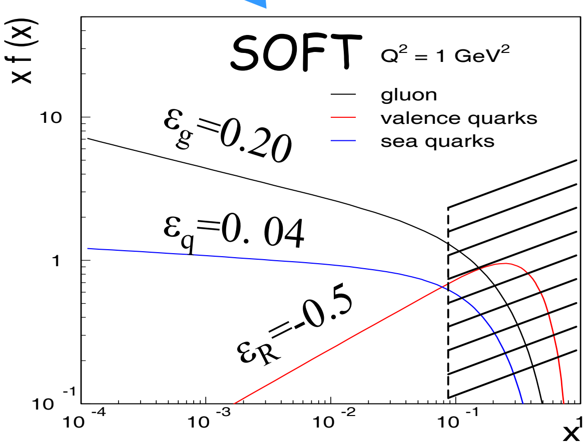




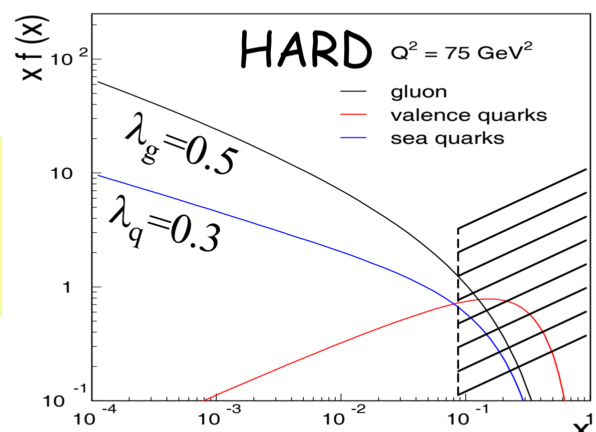
Low-x and Diffraction

Derive diffractive from inclusive PDFs and color factors





$$x \cdot f(x) = \frac{1}{x^{\varepsilon\,(\mathrm{or}\,\lambda)}}$$



Run 2 CDF Diffractive Program

- **Single Diffraction**
  - ξ and Q^2 dependence of F_{jj}^D
  - Process dependence of F^D (W, J/ψ)
- **Double Diffraction**
  - Jet-Gap-Jet: $\Delta\eta^{gap}$ for fixed large $\Delta\eta^{jet}$
- **Double Pomeron Exchange**
  - F_{jj}^D on p-side vs ξ-pbar

Also:

Exclusive central production

- Dijets, χ_c

Other

- Tev4LHC issues

Summary

- Diffraction is a low-x QCD phenomenon subject to color constraints.
- Multigap processes offer the opportunity to study diffraction without complications arising from rapidity gap survival issues.
- Regularities observed in Run 1 at the Tevatron and in results obtained at HERA paint a picture of the Pomeron as a composite object constructed from the underlying inclusive pdf's of the (anti)proton. This picture could be further clarified and advanced to a theory by studies at the LHC.