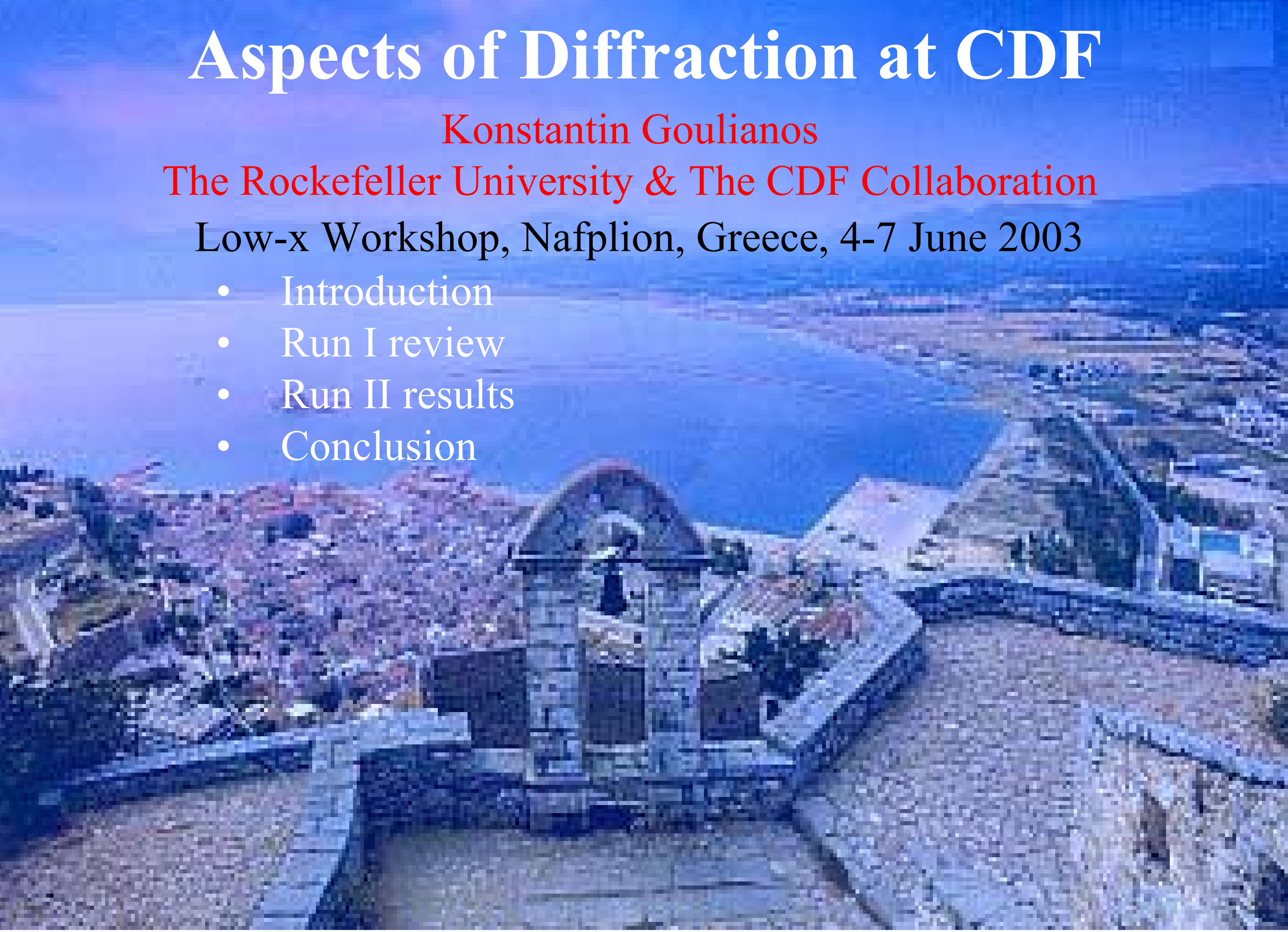


Aspects of Diffraction at CDF

Konstantin Goulianos

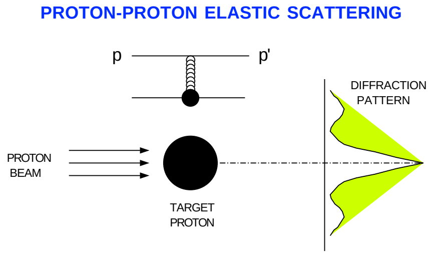
The Rockefeller University & The CDF Collaboration

Low-x Workshop, Nafplion, Greece, 4-7 June 2003

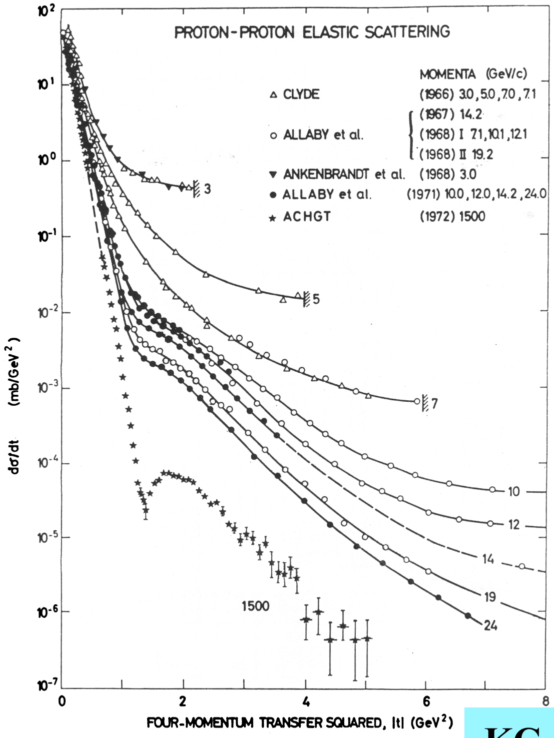
- Introduction
- Run I review
- Run II results
- Conclusion

Introduction

What is hadronic diffraction?



$$\frac{d\sigma}{dt}$$

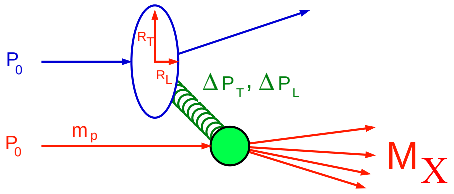


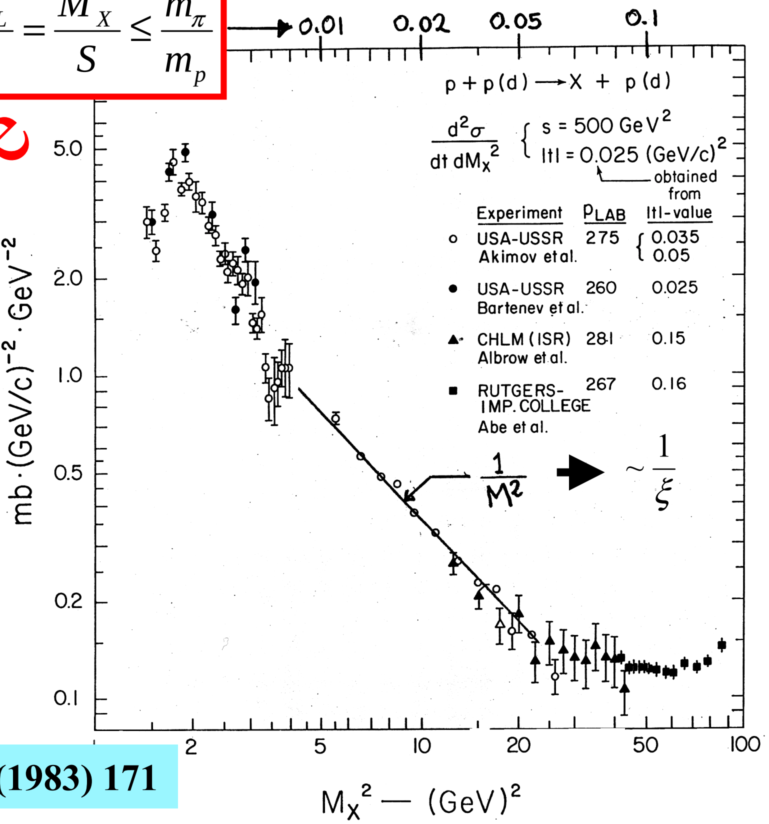
coherence

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

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

Diffraction dissociation





KG, Phys. Rep. 101 (1983) 171

Diffraction and Rapidity Gaps

✓rapidity gaps are regions of rapidity devoid of particles

- ❑ Non-diffractive interactions:
  rapidity gaps are formed by multiplicity fluctuations

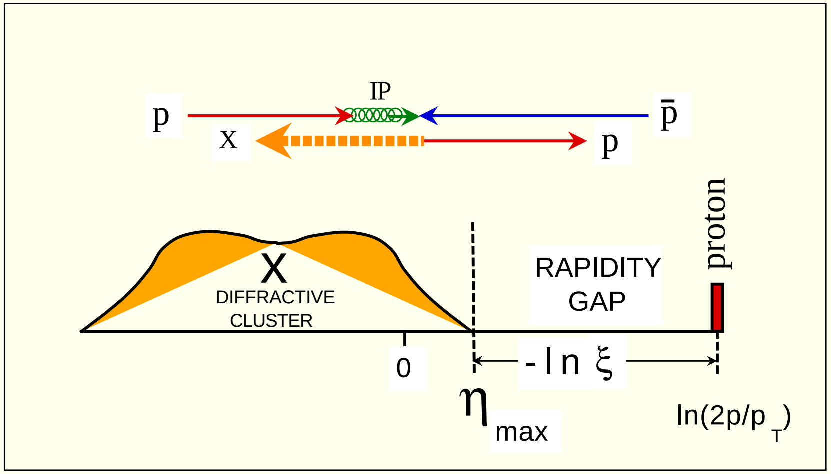
- ❑ Diffractive interactions:
  rapidity gaps, like diamonds, 'live for ever'

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

From Poisson statistics:

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

(r=particle density in rapidity space)



Gaps are exponentially suppressed

$$\boxed{\frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \quad \rightarrow \quad \frac{d\sigma}{d\Delta y} \sim \text{constant}}$$

✓ large rapidity gaps are signatures for diffraction

The Pomeron

- Quark/gluon exchange across a rapidity gap:

POMERON

- No particles radiated in the gap:

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

- Rapidity gap formation:

NON-PERTURBATIVE

- Diffraction probes the large distance aspects of QCD:

?

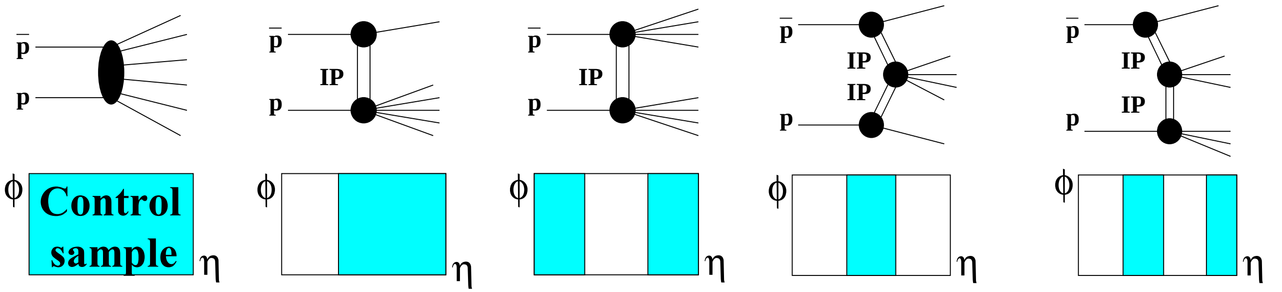
POMERON ⟷ **CONFINEMENT**

❑ **PARTONIC STRUCTURE**
❑ **FACTORIZATION**

Diffraction at CDF in Run I

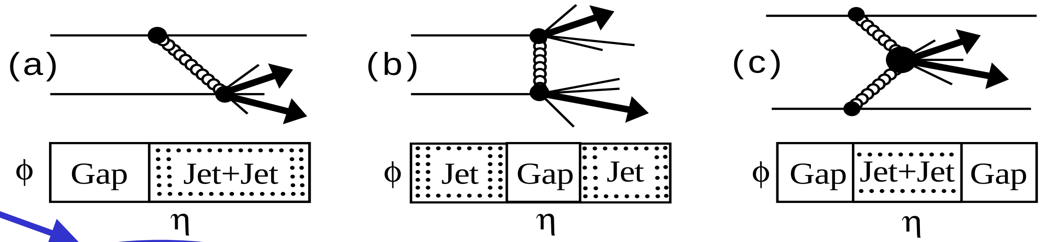
- Elastic scattering PRD 50 (1994) 5518
- Total cross section PRD 50 (1994) 5550
- Diffraction

SOFT diffraction



Non−Diffractive (ND)	*Single−Diffractive (SD)*	*Double Diffractive (DD)*	*Double Pomeron Exchange (DPE)*	*Single + Double Diffractive (SDD)*
	PRD 50 (1994) 5535	PRL 87 (2001)141802	PRL to be sub'd	PRL submitted

HARD diffraction



PRL reference

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		

with roman pots

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

Soft diffraction

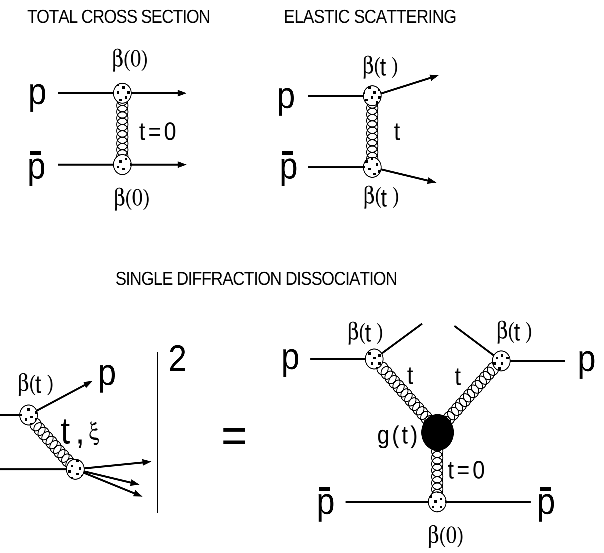
Factorization & Renormalization

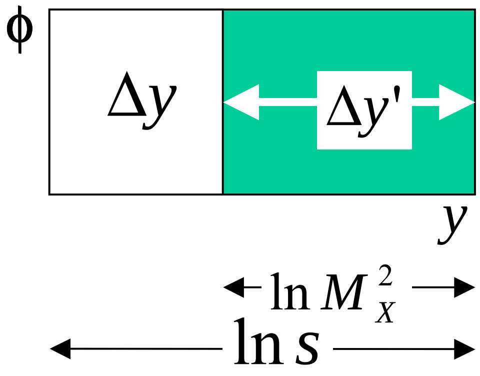
parton model

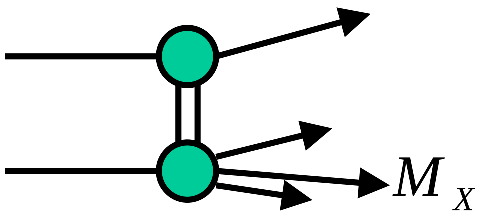
$$\boxed{\sigma_T = \sigma_o s^{\varepsilon}} = \sigma_o e^{\varepsilon \ln s} = \sigma_o s^{\alpha_{IP}(0)-1}$$

$$\boxed{\alpha_{\rm IP}(t) = 1 + \varepsilon + \alpha' t}$$

Pomeron trajectory







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

$$\boxed{\frac{d^2\sigma}{d\Delta y'\, dt} = f_{IP/p}(\Delta y, t) \times \sigma_{IP-p}(\Delta y')}$$

$$C \cdot \left(e^{[\varepsilon + \alpha' t]\Delta y} F_p(t)\right)^2 \qquad \kappa \times \sigma_o e^{\varepsilon \Delta y'}$$

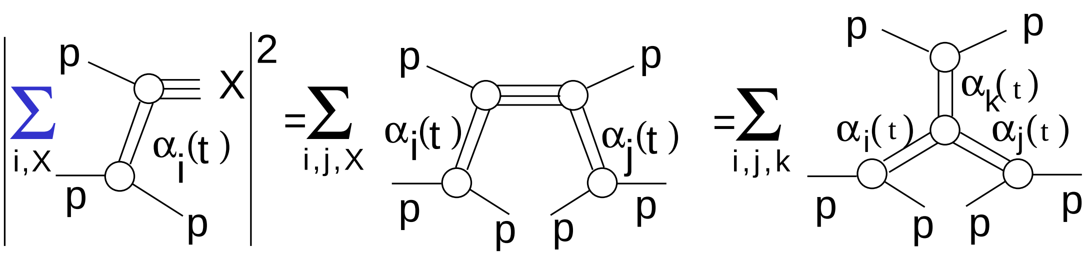
Renormalize to unity
KG, PLB 358(1995)379

← **Gap probability**

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

COLOR FACTOR

Reggeons



Key players:

$IP-IP-IP$	$\sim\frac{s^{\varepsilon}}{\xi^{1+\varepsilon}}$	$\sim\frac{s^{2\varepsilon}}{\left(M^2\right)^{1+\varepsilon}}$	$\sim s^{2\varepsilon}$
$IP-IP-R$	$\sim\frac{1/\sqrt{s}}{\xi^{1+2\varepsilon+0.5}}$	$\sim\frac{s^{2\varepsilon}}{\left(M^2\right)^{1+2\varepsilon+0.5}}$	$\sim s^{2\varepsilon}$
$\pi-\pi-IP$	$\sim s^{\varepsilon}\ \xi^{1+\varepsilon}$	$\sim\frac{1}{s^2}\left(M^2\right)^{1+\varepsilon}$	$\sim s^{\varepsilon}$
$R-R-IP$	$\sim s^{\varepsilon}\ \xi^{\varepsilon}$	$\sim\frac{1}{s}\left(M^2\right)^{\varepsilon}$	$\sim s^{\varepsilon}$

- **Both rise at small ξ**
  but integral does not fit data;
- **M^2-dependence of *IP-IP-R***
  does not fit low-s data;

=> KG: Renormalize *IP-IP-IP*

- **Reggeon contribution:**
  important at large ξ

KG & JM: use renormalized *IP-IP-IP* plus π–π-*IP* with only g $_{IP\text{-}IP\text{-}IP}$ as free parameter

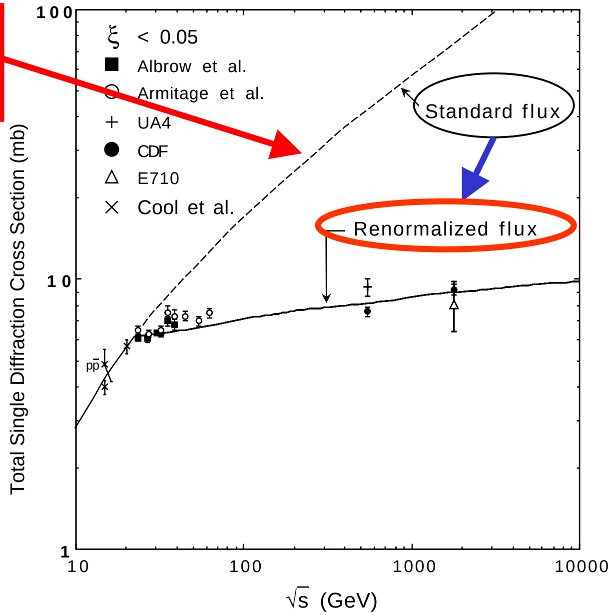
Soft Single Diffraction Data

$$\boxed{p(\bar{p}) + p \rightarrow p(\bar{p}) + X}$$

$$\boxed{\sigma \sim s^{2\varepsilon}}$$

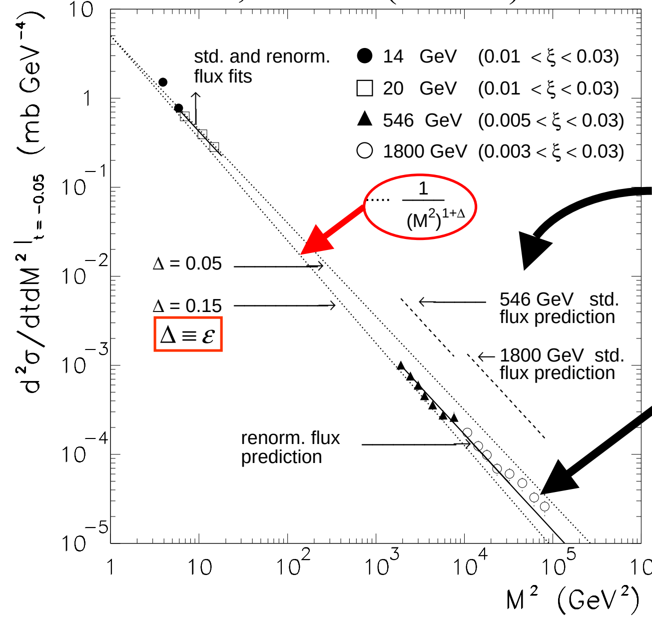
Total cross section

KG, PLB 358 (1995) 379



Differential cross section

KG&JM, PRD 59 (114017) 1999



REGGE

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

RENORM

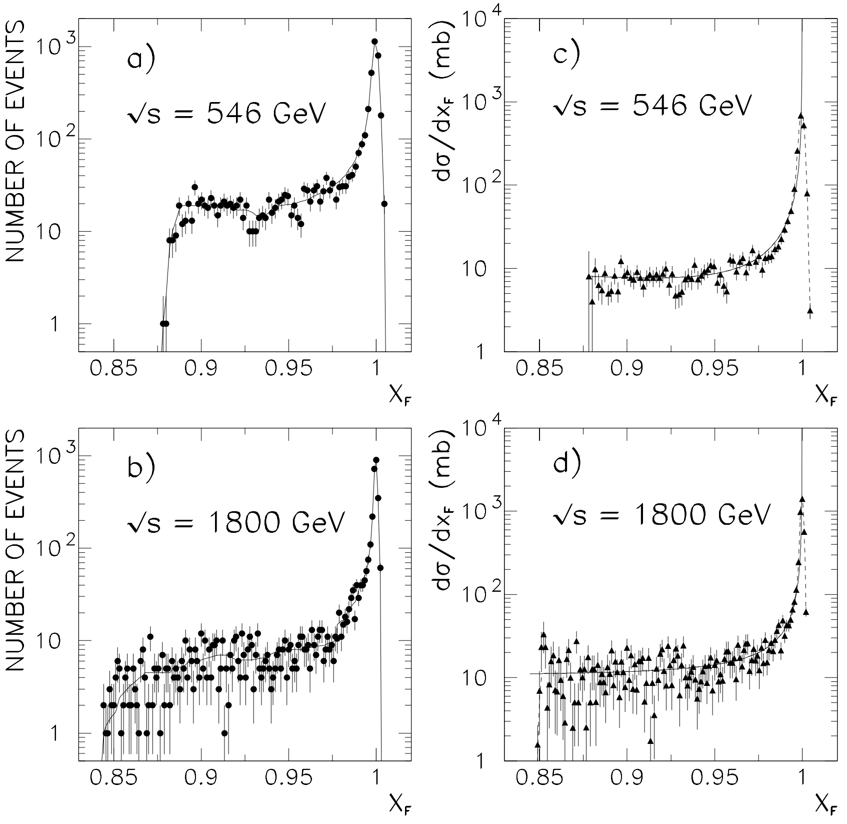
$$\frac{d\sigma}{dM^2} \propto \frac{1}{(M^2)^{1+\varepsilon}}$$

s-independent

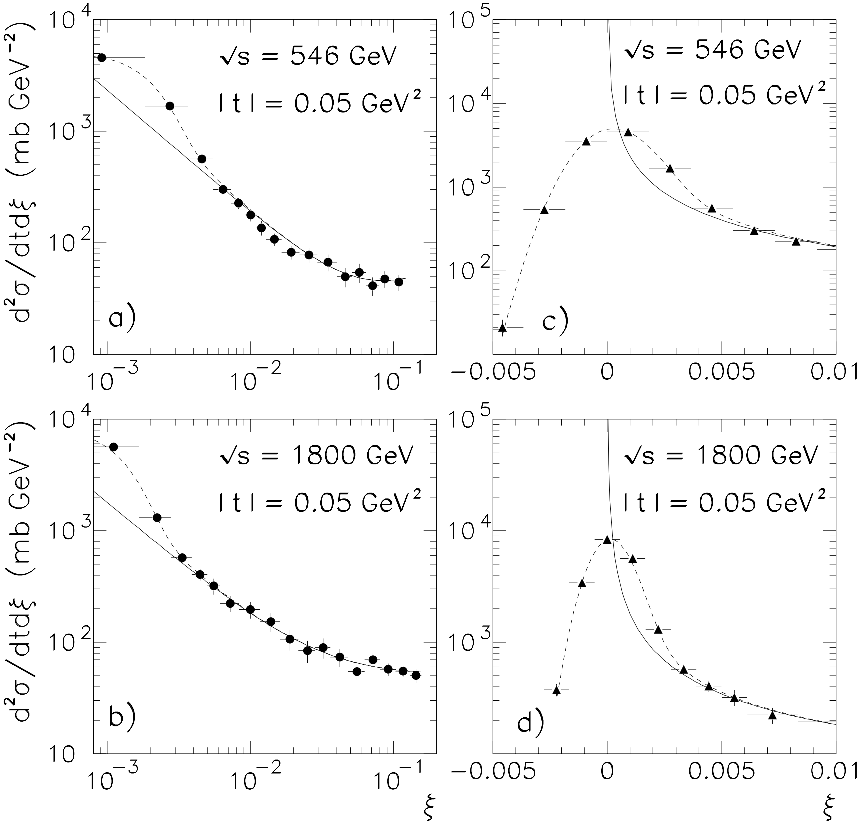
- ☐ Differential shape agrees with Regge
- ☐ Normalization is suppressed by factor $\sim s^{2\varepsilon}$
- ☐ Renormalize Pomeron flux factor to unity

$\boxed{M^2 \text{ SCALING}}$

CDF Single Diffraction Data and Fits

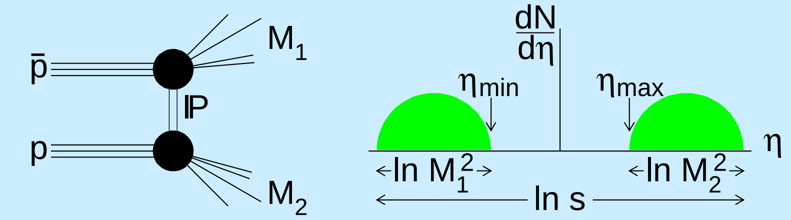


Data versus MC
based on triple-Pomeron plus Reggeon
CDF PRD 50 (1994) 5535

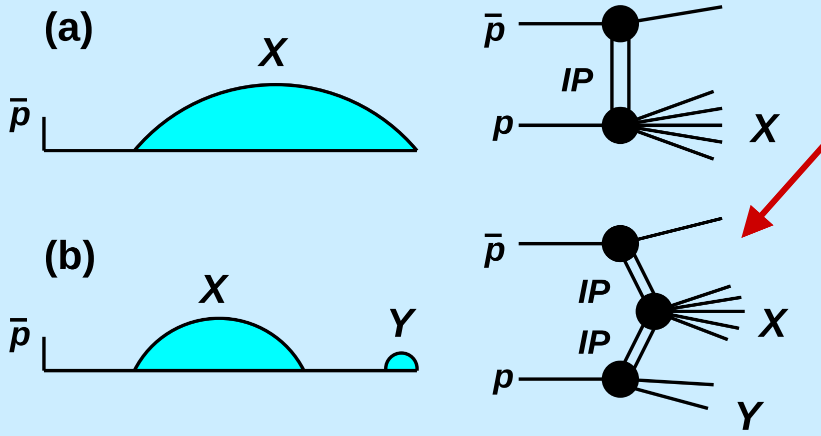


Data at $|t|$=0.05 GeV^2
corrected for acceptance
KG&JM, PRD 59 (114017) 1999

Central and Double Gaps



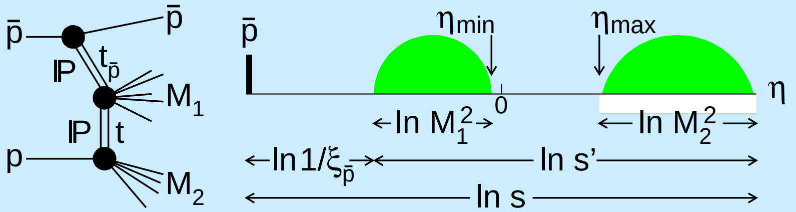
- ☐ **Double diffraction**
  - ➢ **Plot #Events versus Δη**



- ☐ **Double Pomeron Exchange**
  - ➢ **Measure**

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

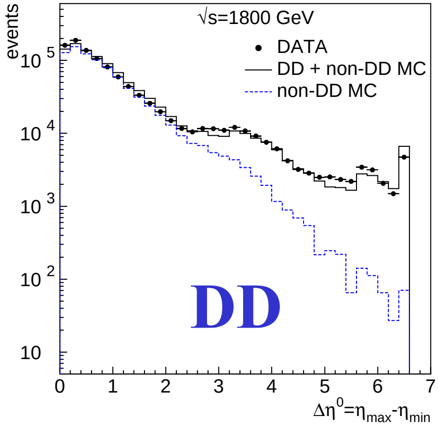
  - ➢ **Plot #Events versus log(ξ)**

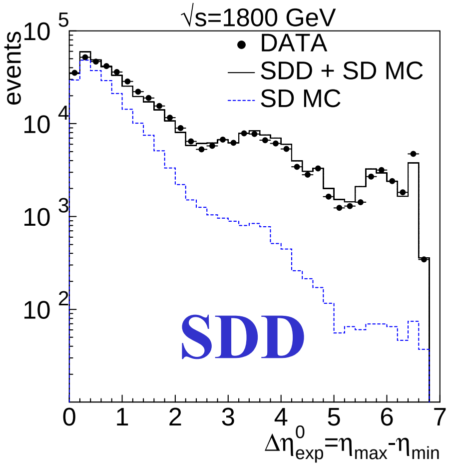


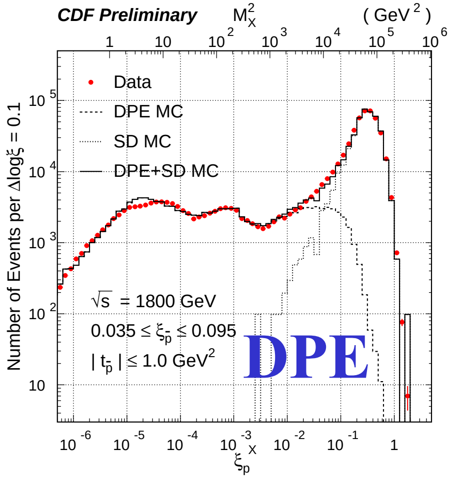
- ☐ **SDD: single+double diffraction**
  - ➢ **Central gaps in SD events**

Central and Double-Gap Results

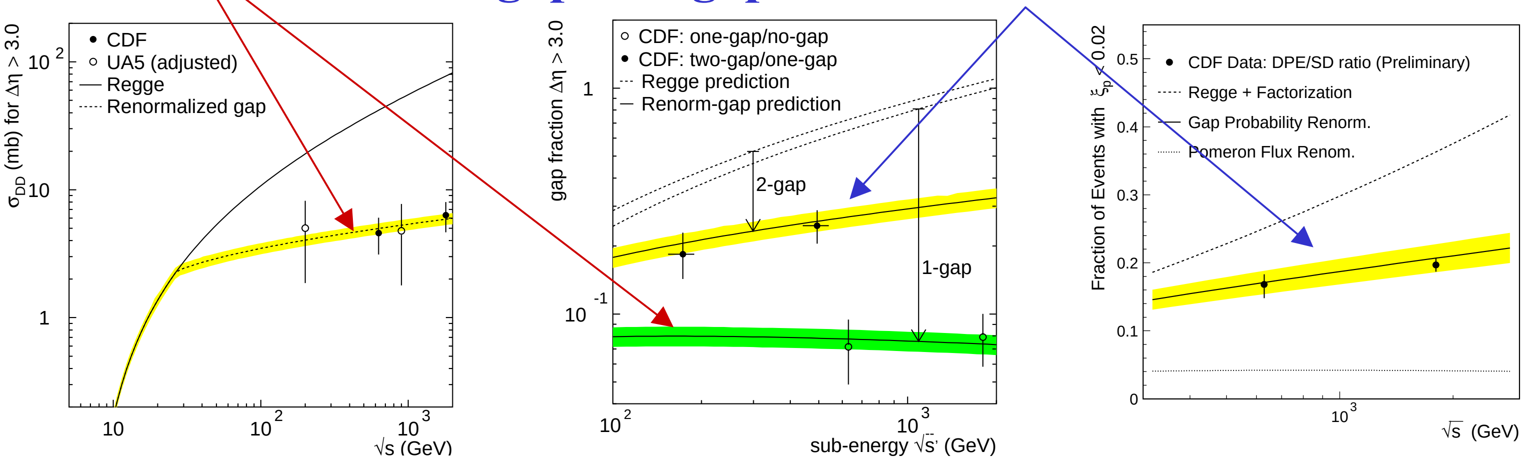
Differential shapes agree with Regge predictions



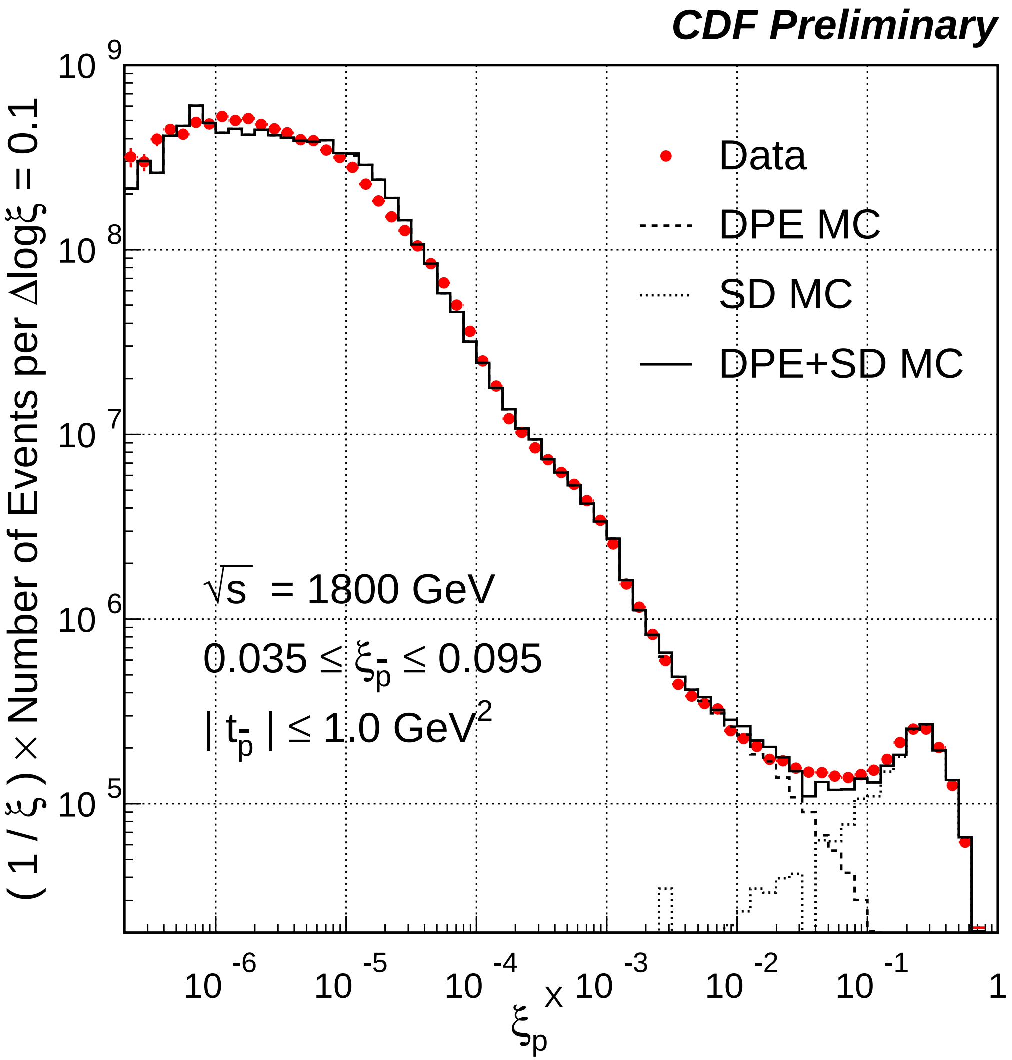




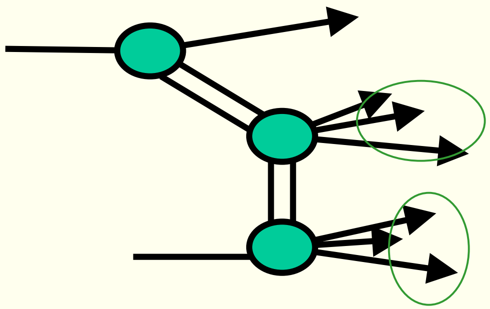
- One-gap cross sections require renormalization
    - Two-gap/one-gap ratios are $\approx \kappa =\approx 0.17$

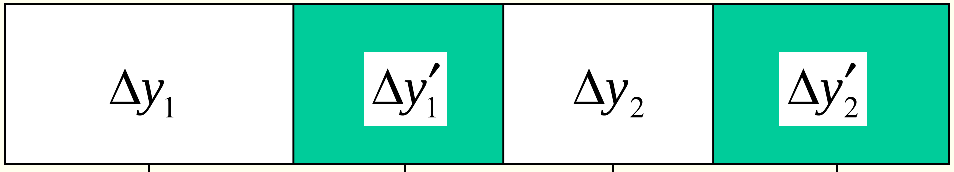


Soft Double Pomeron Exchange



Two-Gap Diffraction (hep-ph/0205141)





$y_1 \quad y_1' \quad y_2 \quad y_2'$

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

color factor

$$\frac{d^7\sigma}{\prod_{i=1-7} dV_i} = C \times \underbrace{\prod_{2\text{ gaps}} \left\{ e^{(\varepsilon+\alpha' t_i)\Delta y_i} F_p(t_1) \right\}^2}_{\textbf{Gap probability}} \times \underbrace{\kappa^2 \left\{ \sigma_o \, e^{\varepsilon(\Delta y_1' + \Delta y_2')} \right\}}_{\substack{\textbf{Sub-energy cross section} \\ \textbf{(for regions with particles)}}}$$

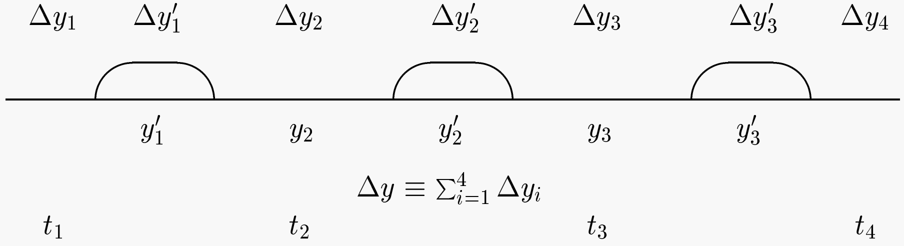
$$\boxed{\text{Integral } \sim s^{2\varepsilon}} \longleftarrow \sim e^{2\varepsilon \Delta y}$$

Renormalization removes the s-dependence → SCALING

Multigap Diffraction (hep-ph/0205141)

Renormalize gap probability to calculate multigap cross sections

$$\boxed{f(\Delta y,t) \propto e^{(\varepsilon+\alpha' t)\Delta y}}$$ ← Amplitude



← 5 region-centers
← 1 sum of all gaps
← 4 t-values

V_i
10 variables

- $$\frac{d^{10}\sigma}{\Pi_{i=1}^{10} dV_i} = P_{gap} \times \sigma(\text{sub}-\text{energy})$$

$$\boxed{\kappa = \frac{g(t)}{\beta(t)} \approx 0.17}$$

one κ factor for each gap

- $$\sigma(\text{sub}-\text{energy}) = \kappa^4 \left[\sigma_0 \, e^{\epsilon \Delta y'}\right] \quad (\Delta y' = \Sigma_{i=1}^{3} \Delta y'_i)$$ ← Use amplitude at t=0 for x-section

- $$P_{gap} = \frac{1}{N} \Pi_{i=1}^{4} \left[e^{(\epsilon+\alpha' t_i)\Delta y_i}\right]^2 \times \underbrace{[F_p(t_1) \, F_p(t_4)]^2}_{\text{form factors}}$$ ← Use amplitude squared for gaps

$$P_{gap} = \frac{1}{N} \times e^{2\epsilon \Delta y} \cdot f(V_i)|_{i=1}^{10}$$ ← P_{gap} depends on sum of gaps

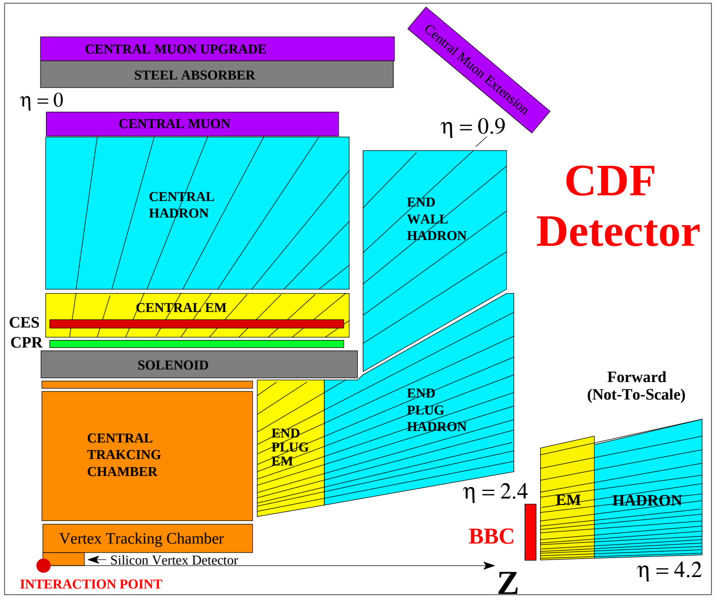
Renormalize: set integral of P_{gap} to unity

- $\boxed{N \propto s^{2\epsilon}}$ $\Longleftarrow$ renormalization depends only on s — independent of the number of gaps!

Hard diffraction in Run I

CDF Forward Detectors

Rapidity gaps

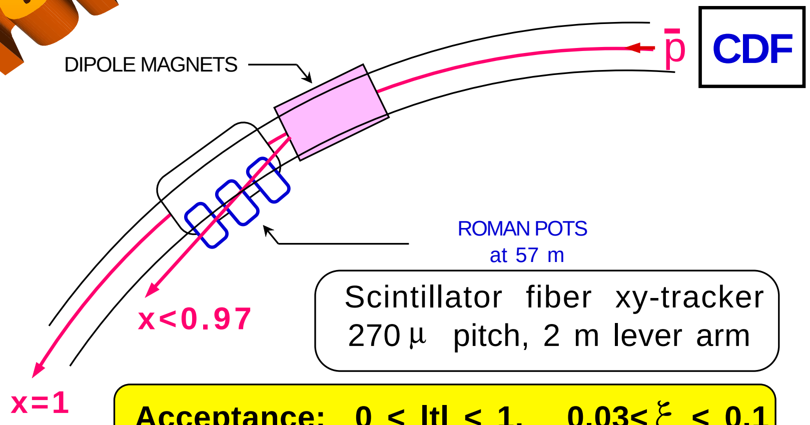


CDF Detector

BBC $3.2<\eta<5.9$

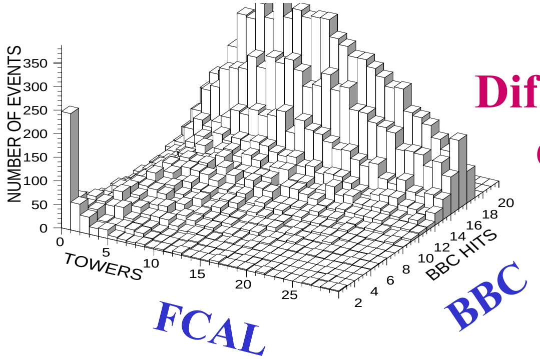
FCAL $2.4<\eta<4.2$

Antiproton tag



Scintillator fiber xy-tracker
270 μ pitch, 2 m lever arm

Acceptance: $0 < |t| < 1$, $0.03 < \xi < 0.1$



Diffractive dijets

Hard Diffraction Using Rapidity Gaps

❑ SINGLE DIFFRACTION

$$\bar{p}p \rightarrow X + \text{gap}$$

SD/ND gap fraction (%) at 1800 GeV

X	CDF	D0
W	1.15 (0.55)	
JJ	0.75 (0.10)	0.65 (0.04)
b	0.62 (0.25)	
J/ψ	1.45 (0.25)	

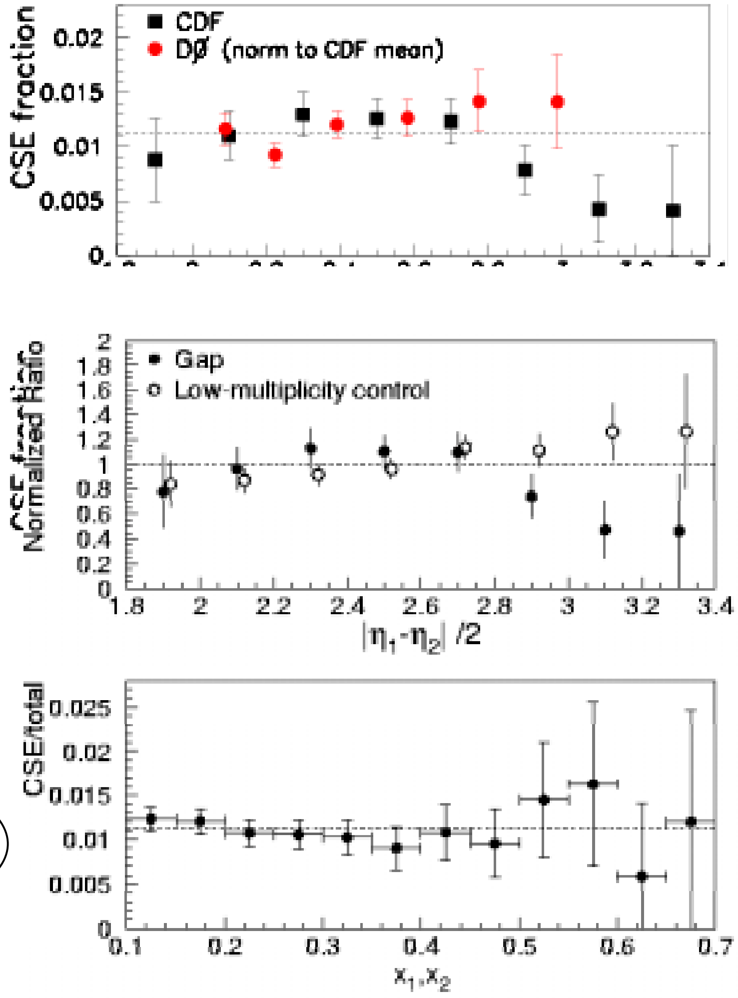
- **All SD/ND fractions ~1%**
- **Gluon fraction** $f_g = 0.54 \pm 0.15$
- **Suppression by ~5 relative to HERA**

Just like in ND except for the suppression due to gap formation

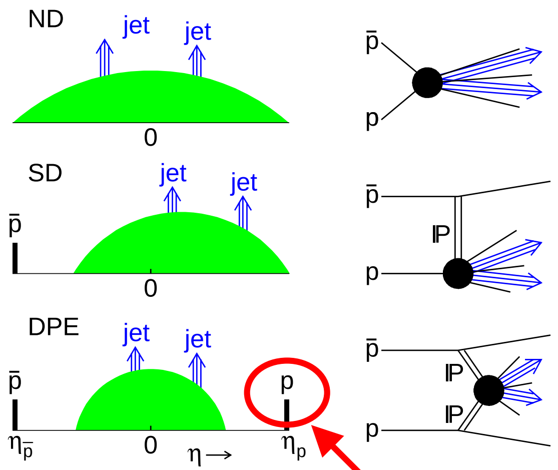
❑ DOUBLE DIFFRACTION

$$\bar{p}p \rightarrow Jet - \text{gap} - Jet$$

DD/ND gap fraction at 1800 GeV



Diffractive Dijets with Leading Antiproton



(not detected)

$x_{Bj}^{\bar{p}}$ **Bjorken-x of antiproton**

$$\boxed{x_{Bj}^{\bar{p}} = \frac{1}{\sqrt{s}} \sum_{\#\,jets} E_T^i \, e^{-\eta^i}}$$

$F^{ND}(x,Q^2)$ **Nucleon structure function**

$F^{SD}(\xi,t,x,Q^2)$ **Diffractive structure function**

ISSUES: **1) QCD factorization** > $\boxed{F^{SD}(\xi,t,x,Q^2)}$ **is F^{SD} universal?**

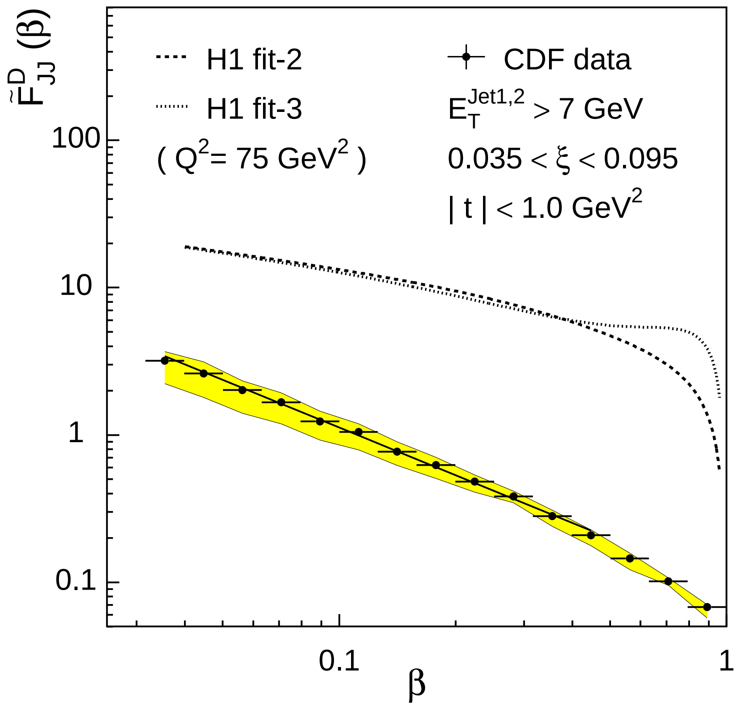
2) Regge factorization > $\boxed{F^{SD}(\xi,t,\beta,Q^2) = f_{IP-\text{flux}}(\xi,t) \times f_{IP}(\beta,Q^2)}$ **?**

$\beta \equiv x/\xi$ **momentum fraction of parton in *IP***

METHOD of measuring F^{SD} : measure ratio R(ξ,t) of SD/ND rates for given ξ,t
set R(ξ,t)=F^{SD}/FND
evaluate F^{SD} = R * FND

Dijets in Single Diffraction

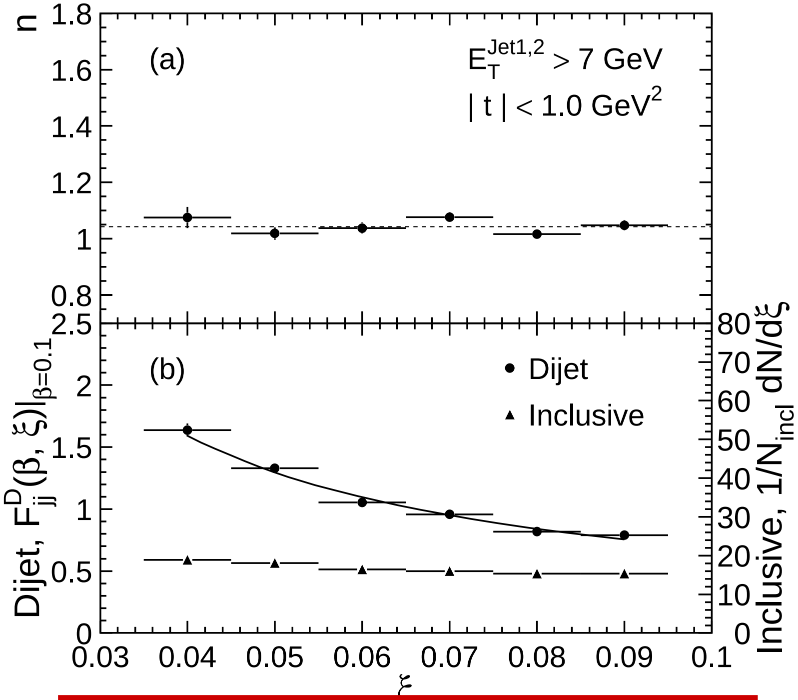
Test QCD factorization



$$\boxed{F^D_{JJ}(\beta)}$$

Suppressed at the Tevatron relative to predictions based on HERA parton densities

Test Regge factorization



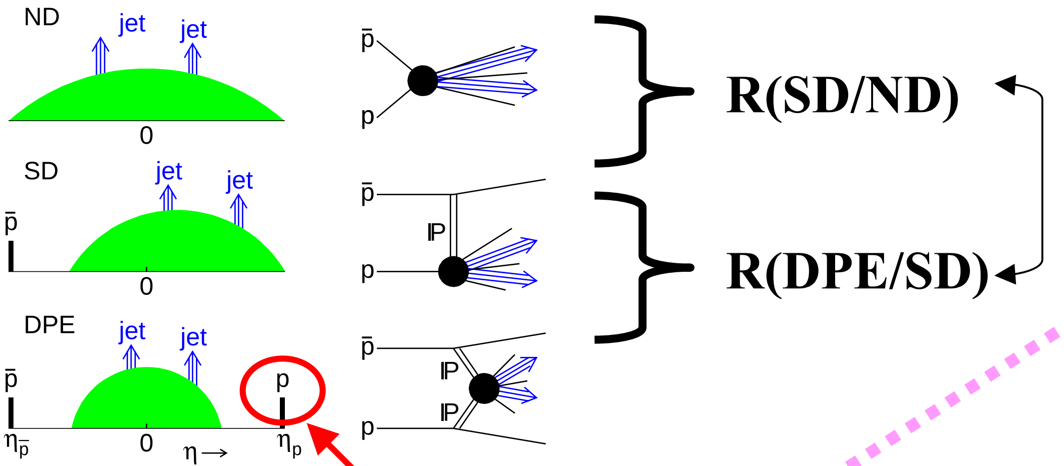
$$\boxed{F^D_{JJ}(\xi,\beta) = C\ \beta^{-n}\ \xi^{-m}}$$

Regge factorization holds

$$\boxed{m \approx 1 \Rightarrow \text{Pomeron exchange}}$$!!!

Dijets in Double Pomeron Exchange

Test of factorization

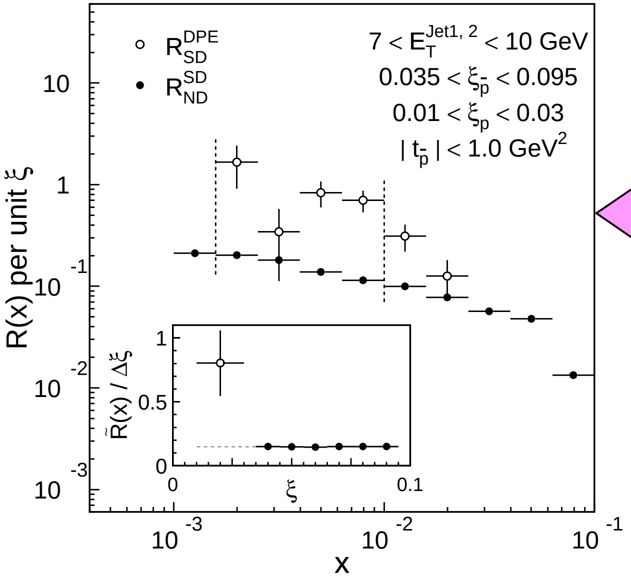


R(SD/ND)

R(DPE/SD)

equal?

(not detected)

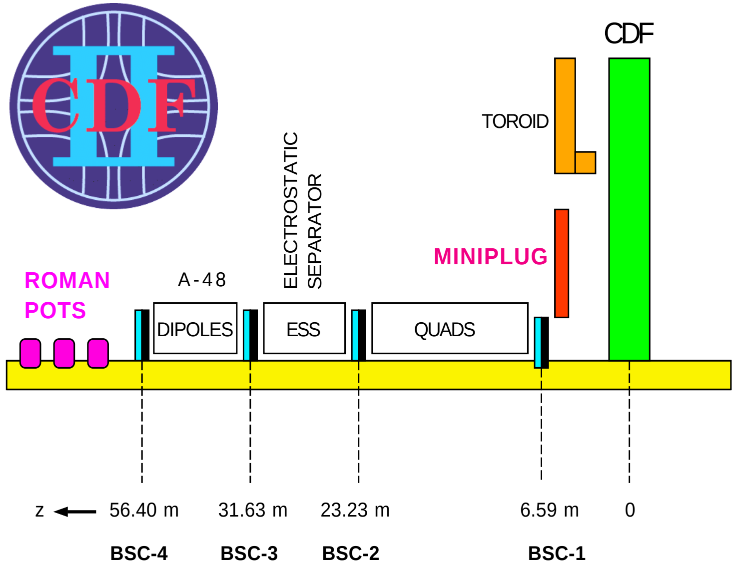


$$R^{DPE}_{SD} \approx 5 \times R^{SD}_{ND}$$

Factorization breaks down

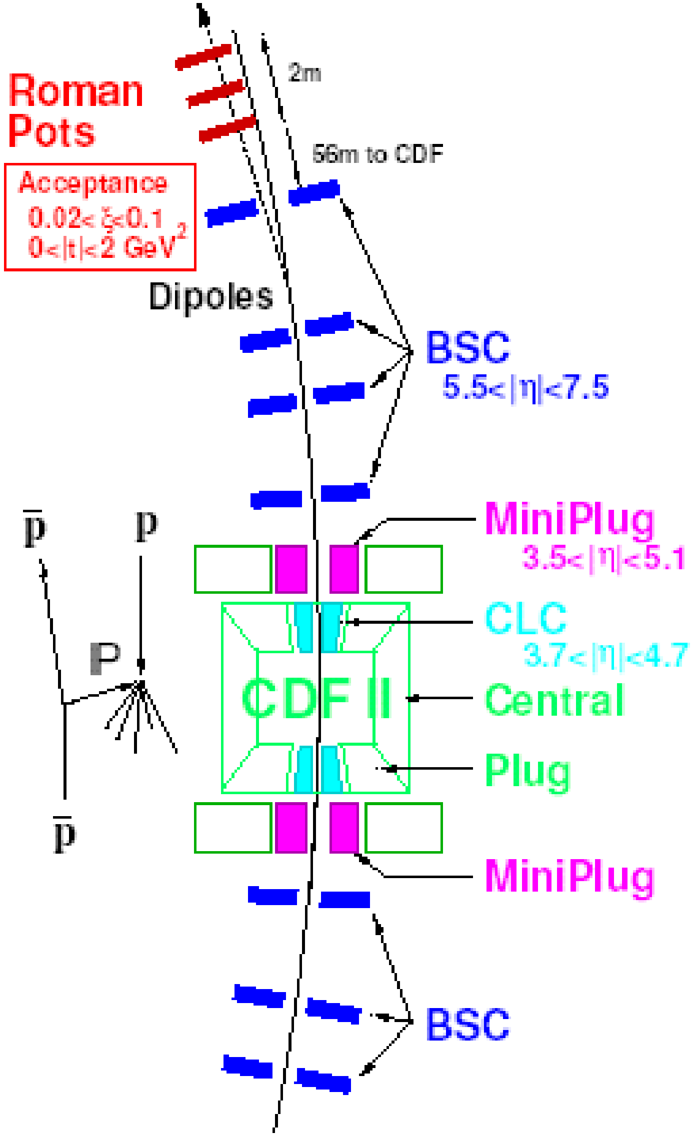
The second gap is un-suppressed!!!

CDF Forward Detectors



- ✓ **MiniPlug calorimeters (3.5<η<5.5)**
- ✓ **Beam Shower Counters (5.5<η<7.5)**
- ✓ **Antiproton Roman Pot Spectrometer**

Run II Forward Detector Layout



Roman Pots

Acceptance
$0.02 < \xi < 0.1$
$0 < |t| < 2$ GeV^2

2m

56m to CDF

Dipoles

BSC
$5.5 < |\eta| < 7.5$

$\bar{p}$ p

P

$\bar{p}$

MiniPlug
$3.5 < |\eta| < 5.1$

CDF II

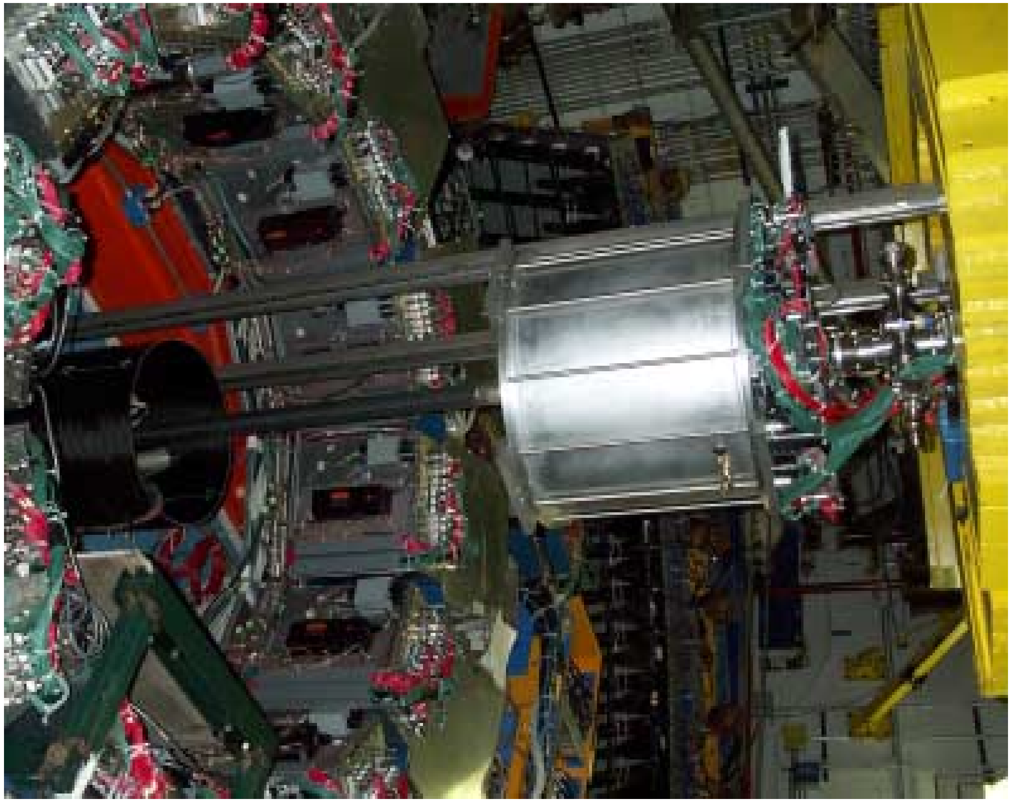
CLC
$3.7 < |\eta| < 4.7$

Central

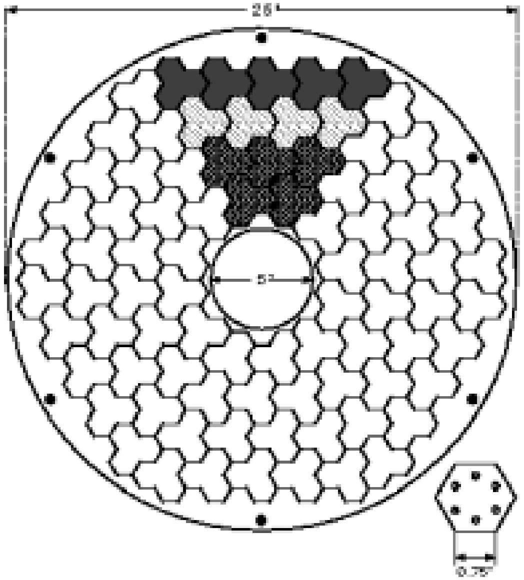
Plug

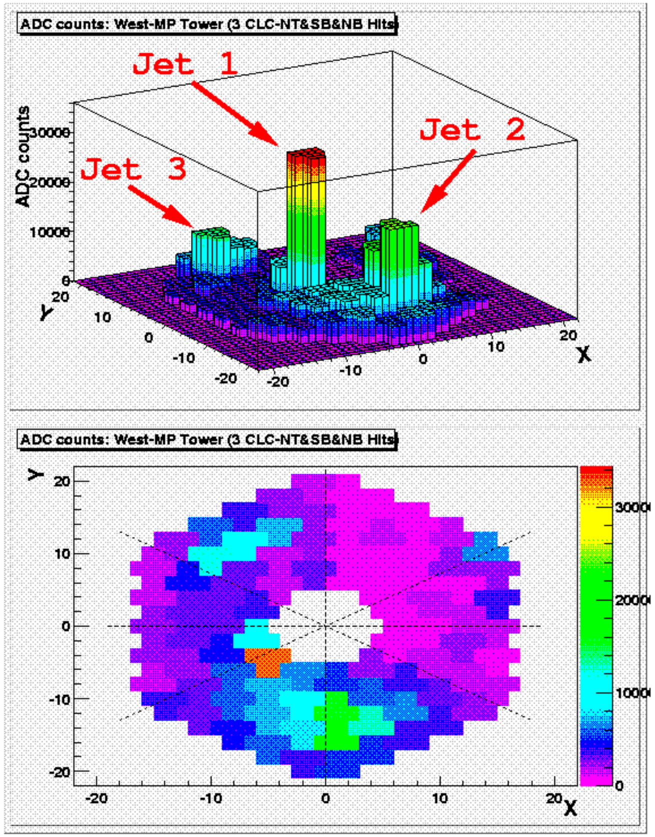
MiniPlug

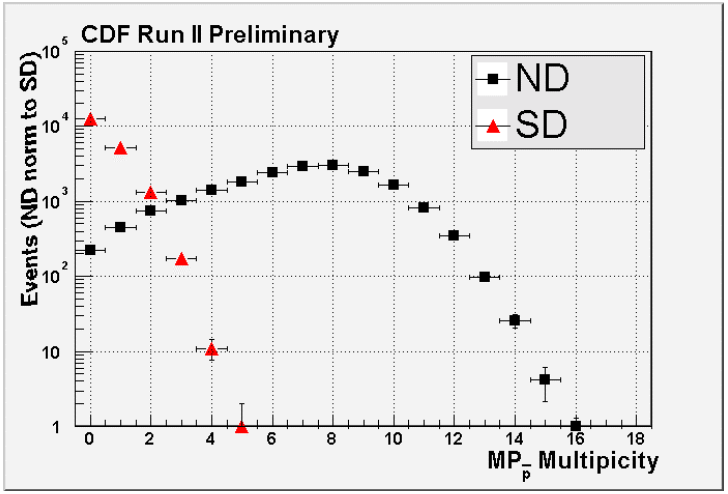
BSC



MiniPlug Run II Data







Multiplicity distribution in SD and ND events

ADC counts in MiniPlug towers in a pbar-p event at 1960 GeV.

- “jet” indicates an energy cluster and may be just a hadron.
- Approximately 1000 counts = 1 GeV

Run II Data Samples

Triggers

J5	At least one cal tower with ET > 5 GeV
RP inclusive	Three-fold coincidence in RP trigger counters
RP+J5	Single Diffractive dijet candidates
RP+J5+BSC-GAP_p	Double Pomeron Exchange dijet candidates

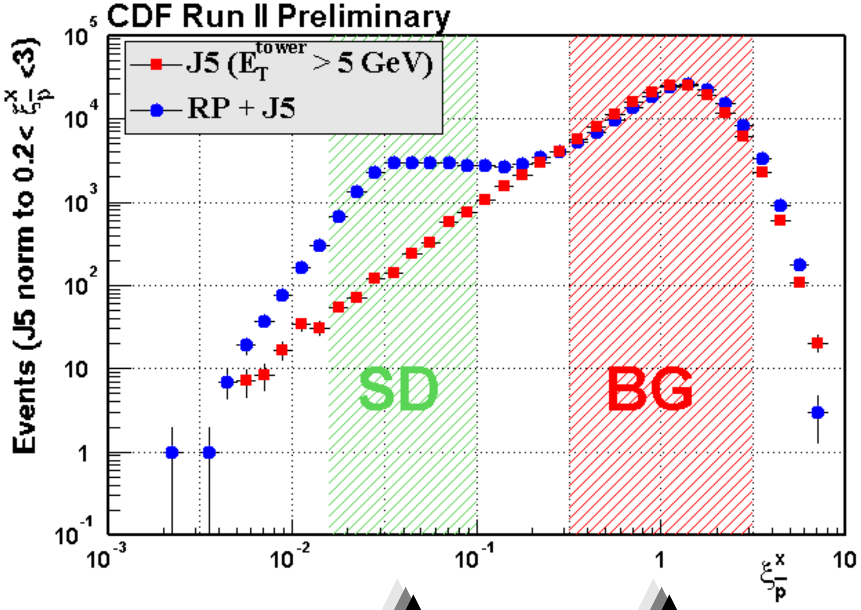
- ❑ Results presented are from ~26 pb^{-1} of data
- ❑ The Roman Pot tracking system was not operational for these data samples
- ❑ The ξ of the (anti)proton was determined from calorimeter information:

$$\boxed{\xi^X = \frac{1}{\sqrt{s}} \sum_{\text{cal towers}} E_T^i \, e^{(-)+\eta^i}}$$

(-)+ is for (anti)proton

Diffractive Dijet Sample

$\xi_{\bar{p}}^{X}$ *– distribution*



SD events

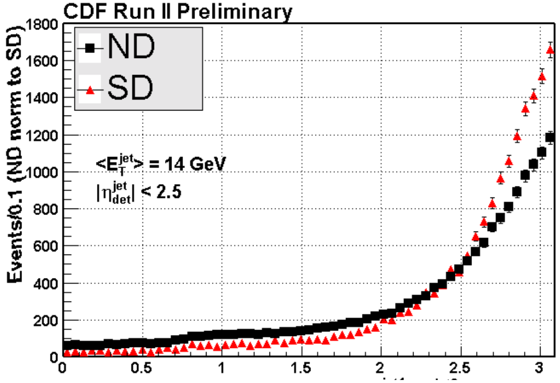
0.03<ξ<0.1

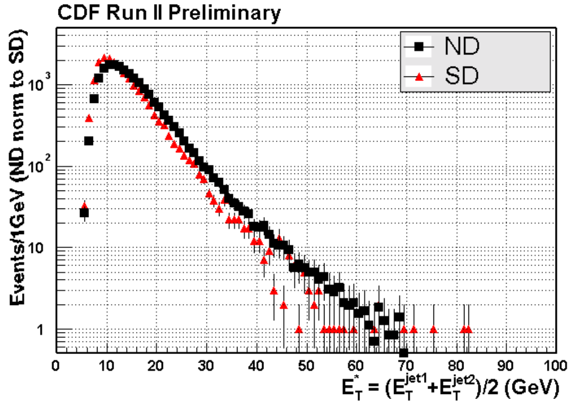
ND+SD & SD+MB overlap events

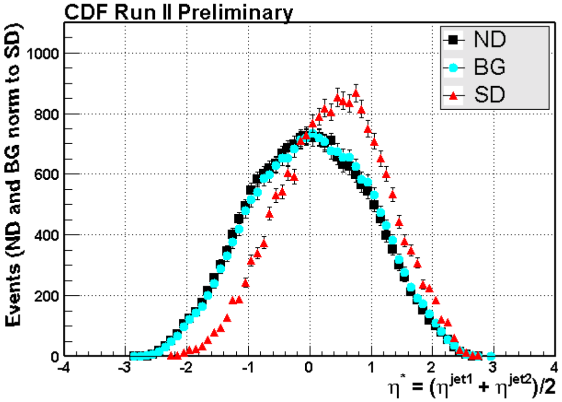
ξ ~ 1

Flat region

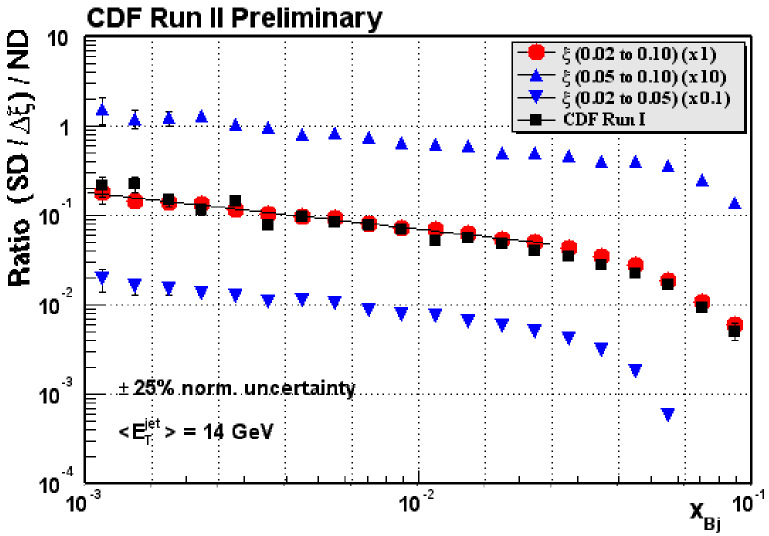
$$\frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \Rightarrow \frac{d\sigma}{d\log\xi} = \text{constant}$$





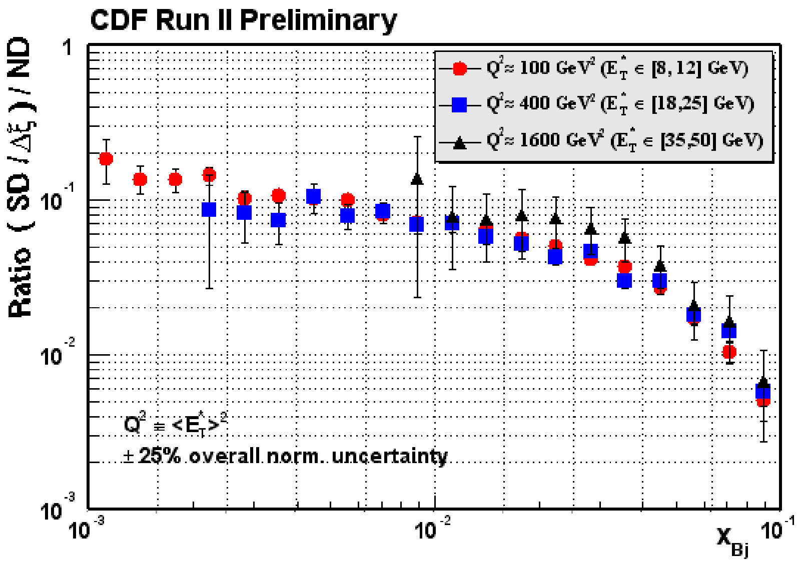


Diffractive Dijet Structure Function



Ratio of SD to ND dijet event rates
as a function of x_{Bj}
compared with Run I data

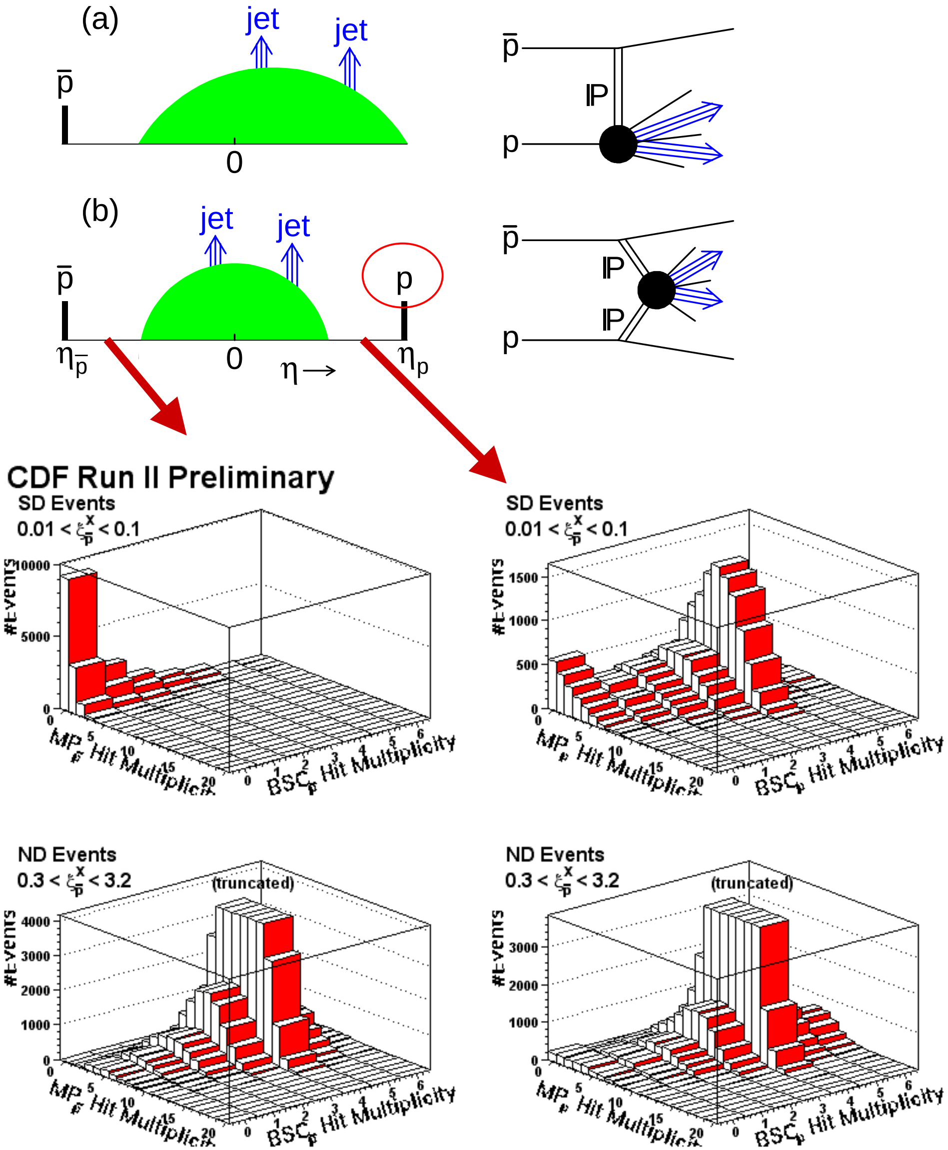
No ξ dependence observed within 0.03 < ξ <0.1
(confirms Run I result)



Ratio of SD to ND dijet eventrates
as a function of x_{Bj}
for different values of $Q^2=ET^2$

No appreciable Q2 dependence observed
within 100 < Q2 < 1600 GeV

Dijets in DPE

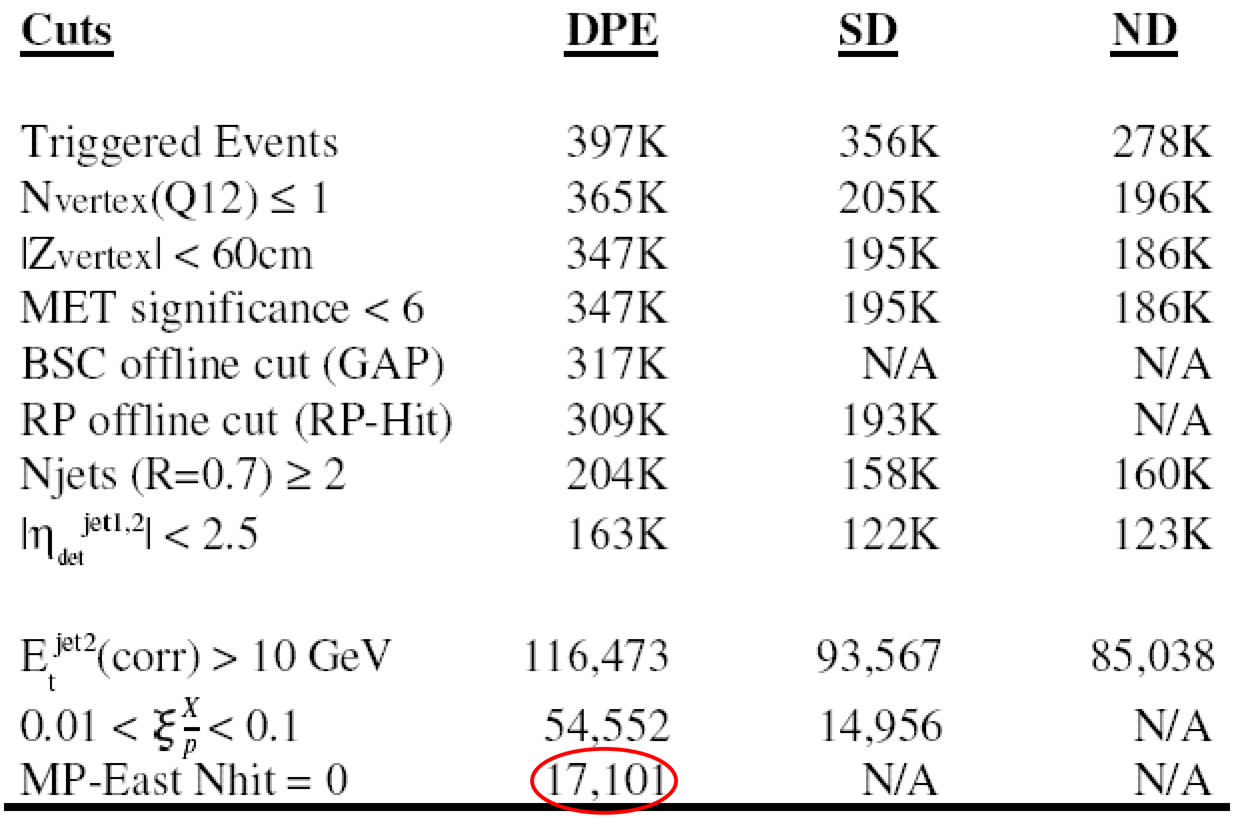


In SD data with RP+J5 trigger select events with rapidity gap in both the BSC_p and MP_p

($3.5 < \eta < 7.5$)

Data Selection

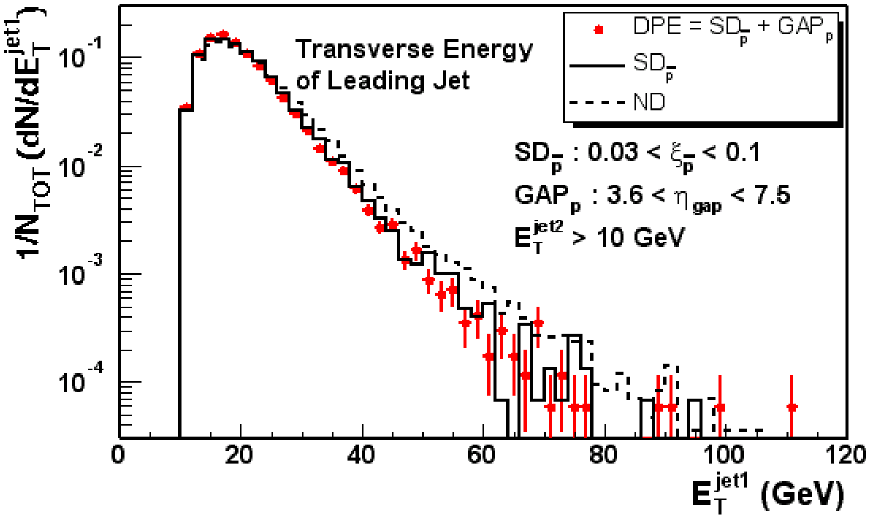
DPE: RP+J5+BSC_GAP_p	**DPE dijet candidates**	**Prescale=5**
SD: RP+J5	**Single Diffractive dijet candidates**	**Prescale=280**
ND: J5	**Tower with ET > 5 GeV**	



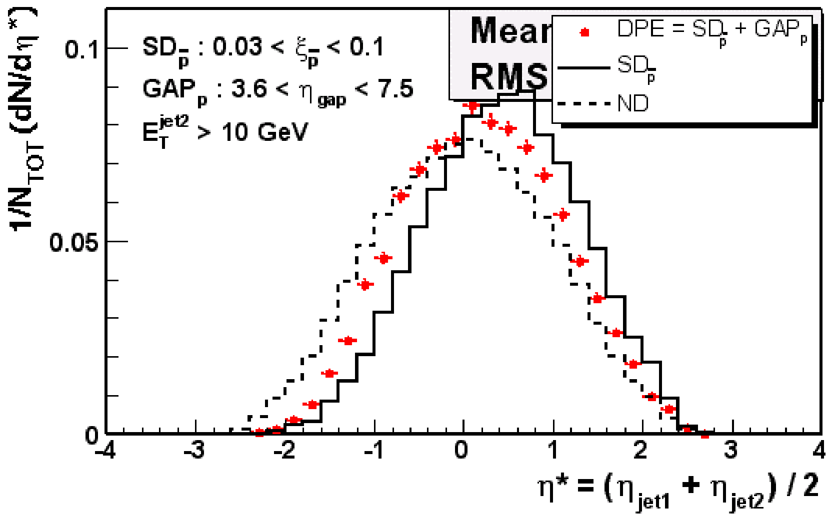
Cuts	DPE	SD	ND
Triggered Events	397K	356K	278K
$N_{vertex}(Q12) \leq 1$	365K	205K	196K
$\|Z_{vertex}\| < 60$cm	347K	195K	186K
MET significance < 6	347K	195K	186K
BSC offline cut (GAP)	317K	N/A	N/A
RP offline cut (RP-Hit)	309K	193K	N/A
Njets (R=0.7) ≥ 2	204K	158K	160K
$\|\eta_{det}^{jet1,2}\| < 2.5$	163K	122K	123K
E_t^{jet2}(corr) > 10 GeV	116,473	93,567	85,038
$0.01 < \xi_{\bar{p}}^{X} < 0.1$	54,552	14,956	N/A
MP-East Nhit = 0	17,101	N/A	N/A

DPE Dijet Kinematics

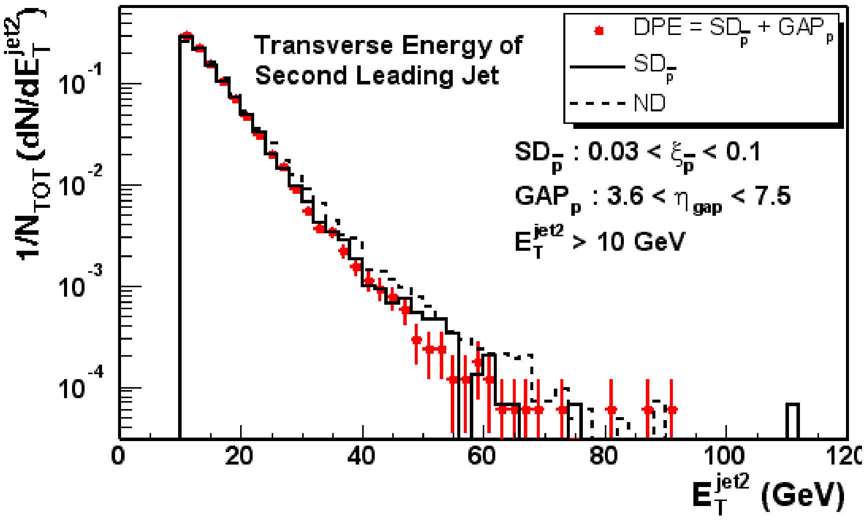
CDF Run II Preliminary



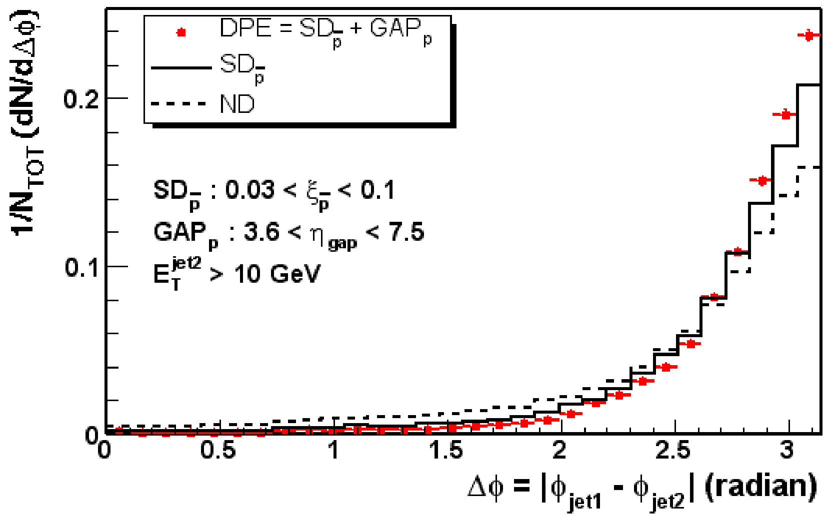
CDF Run II Preliminary



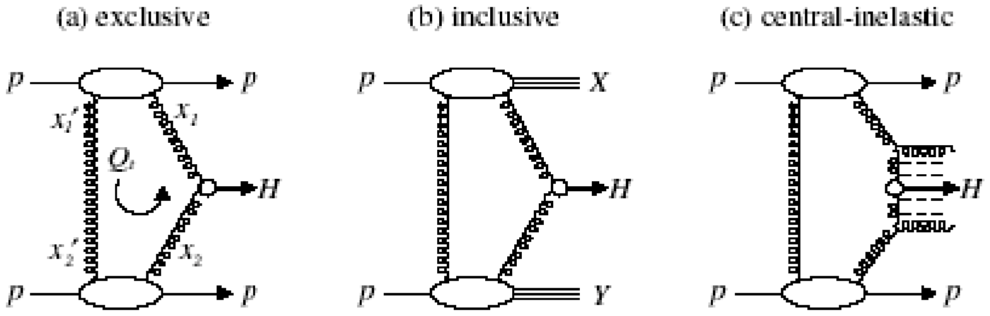
CDF Run II Preliminary



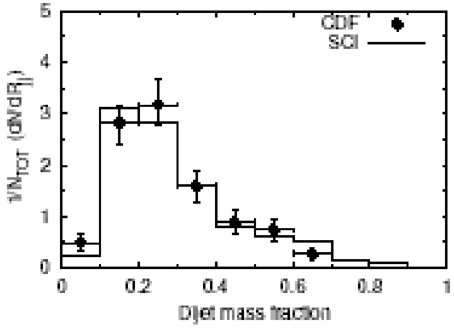
CDF Run II Preliminary



Inclusive/Exclusive DPE Dijet Predictions



Khoze, Martin, Ryskin
Eur. Phys. J. C23, 211 (2001), C26, 229 (2002)

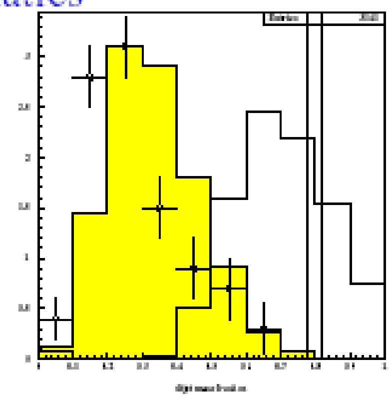


Enberg, Ingelman, Timneanu
Acta. Phys. Polon. B33, 3479 (2002)

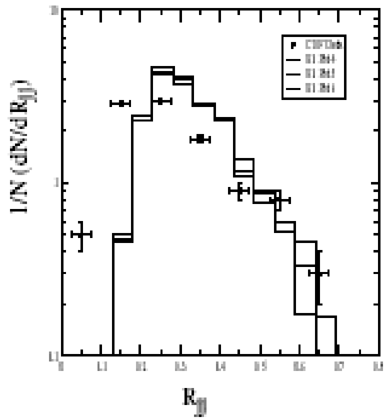
Exclusive dijets in Run I CDF kinematics
~ 1nb (factor 2 uncertainty)

Recent Calculation: ~ 60pb
(25<E_T^{jet}<35 GeV, |η_1-η_2|<2)

Used to normalize calculations to predict e.g, diffractive Higgs production

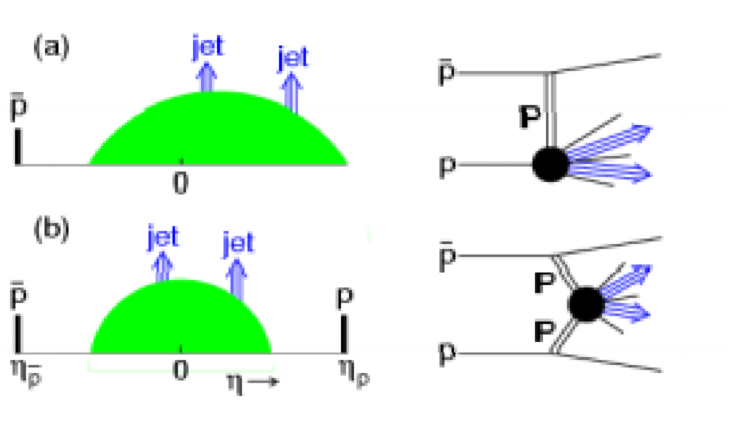


Boonekamp, Peschanski, Royon
Phys. Rev. Lett. 87, 251806 (2001)

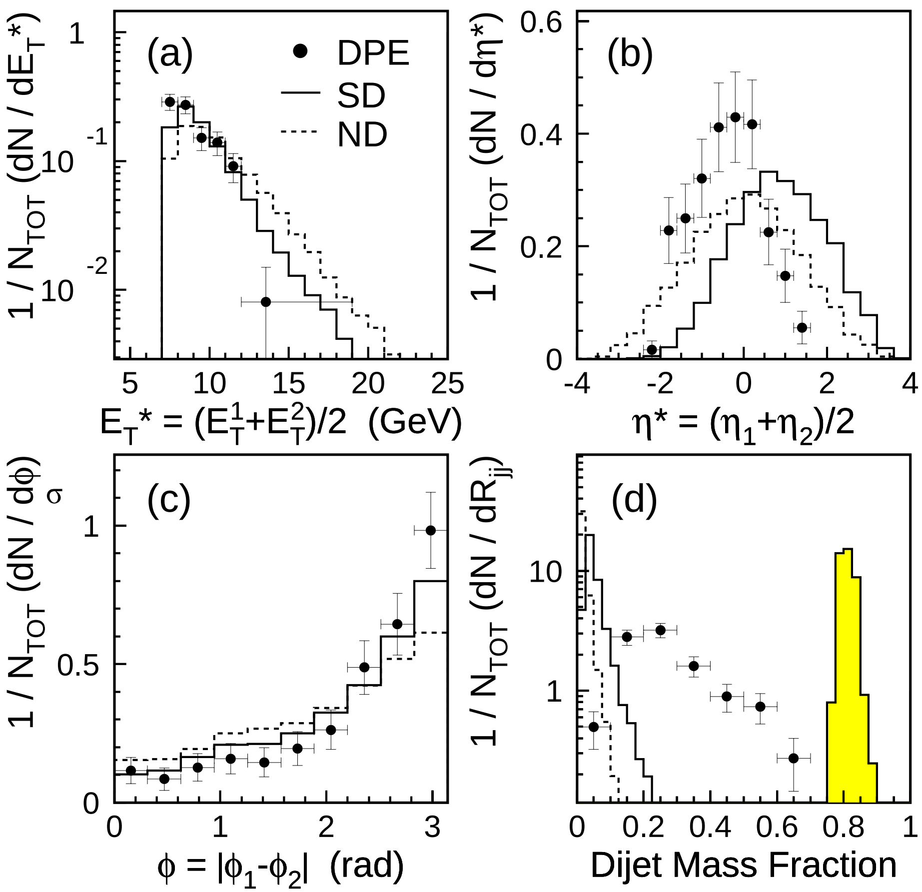


Appleby, Forshaw
Phys. Lett. B541, 108 (2002)

Limit on Exclusive DPE Dijets (Run I)



Observed ~100 DPE dijet events



- © **$0.035 < \xi < 0.095$**
- © **Jet $E_T > 7$ GeV**
- © **Rapidity gap in $2.4 < \eta < 5.9$**

Dijet mass fraction

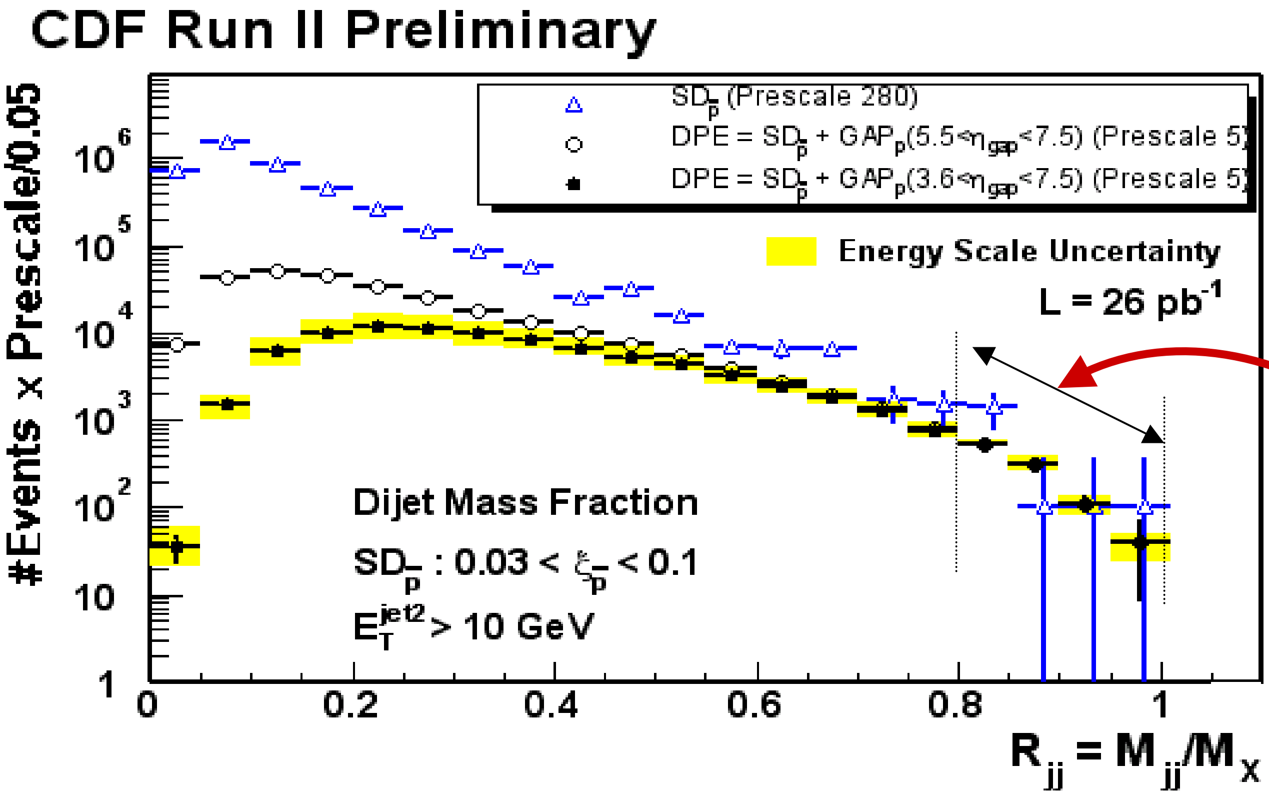
$$R_{jj} = \frac{M_{jj}}{M_X}$$

M_{JJ} based on energy within cone of 0.7
=> look for exclusive dijets in window
$0.7 < R_{JJ} < 0.9$

$$\sigma(\text{inclusive}) = 44.6 \pm 4.4(\text{stat}) \pm 21.6(\text{syst})\ \text{nb}$$

$$\sigma(\text{exclusive}) < 3.7\ \text{nb}\ (95\%\ \text{CL})$$

Run II: Exclusive DPE Dijets ?

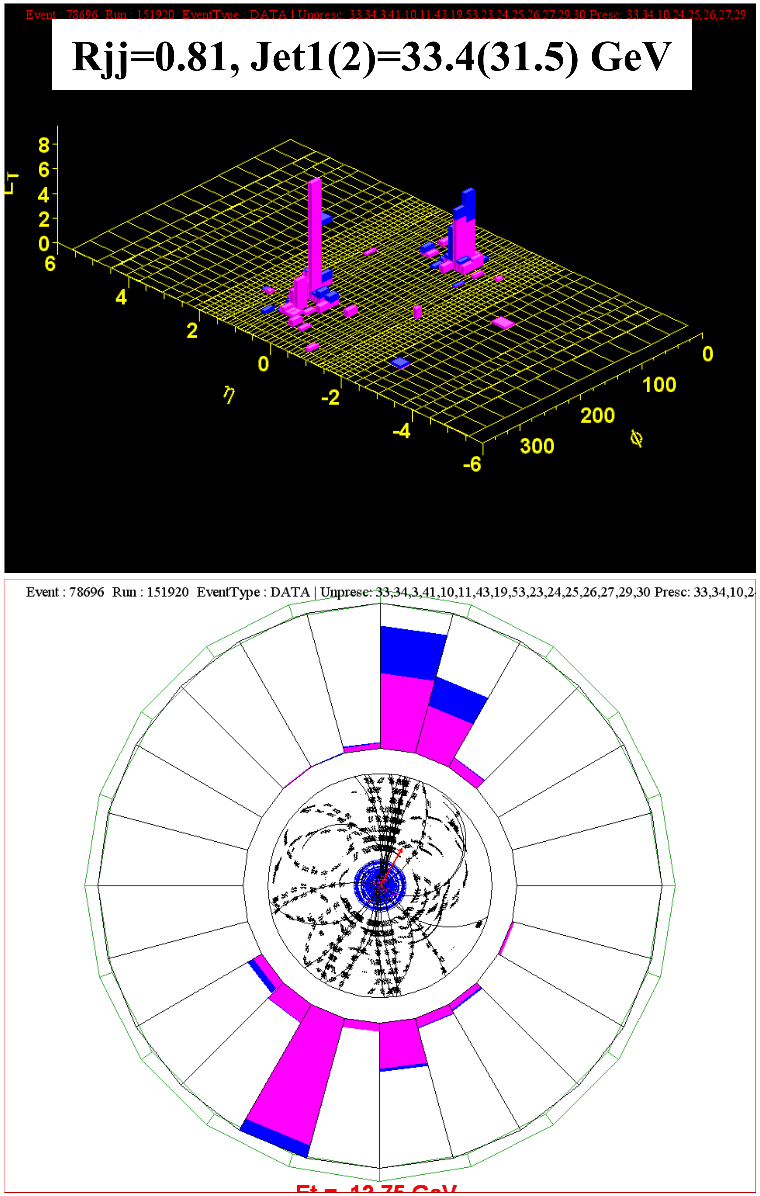


No exclusive dijet bump observed

$|\eta_{jet1,2}|<2.5,\ 0.03<\xi_{\bar{p}}<0.1,\ 3.6<\eta_{gap}<7.5,\ R = 0.7$

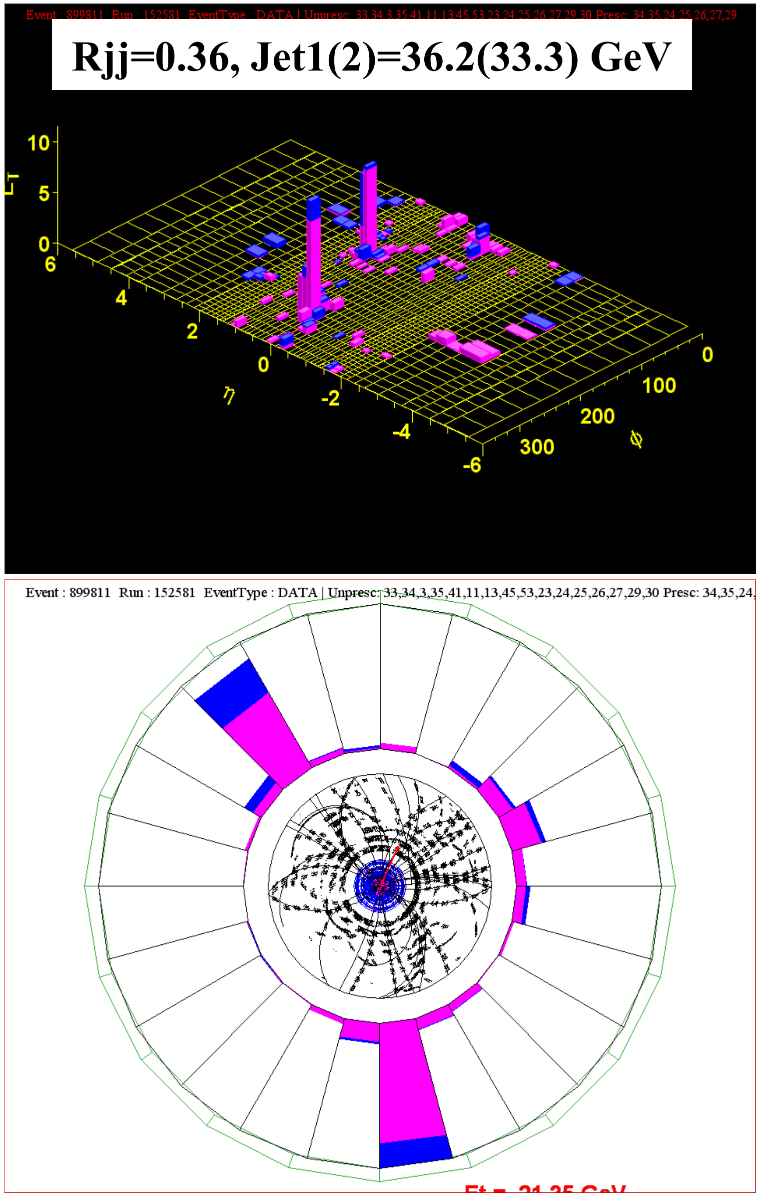
Minimum E_T^{jet1}	Cross Section : $\sigma_{DPE}^{excl.\ jj}(R_{jj} > 0.8)$
10 GeV	**970 ± 65(stat) ± 272(syst) pb**
25 GeV	**34 ± 5(stat) ± 10(syst) pb**

Double Pomeron Exchange Dijet Events



Rjj=0.81, Jet1(2)=33.4(31.5) GeV

Event : 78696 Run : 151920 EventType : DATA | Unpresc: 33,34,3,41,10,11,43,19,53,23,24,25,26,27,29,30 Presc: 33,34,10,2

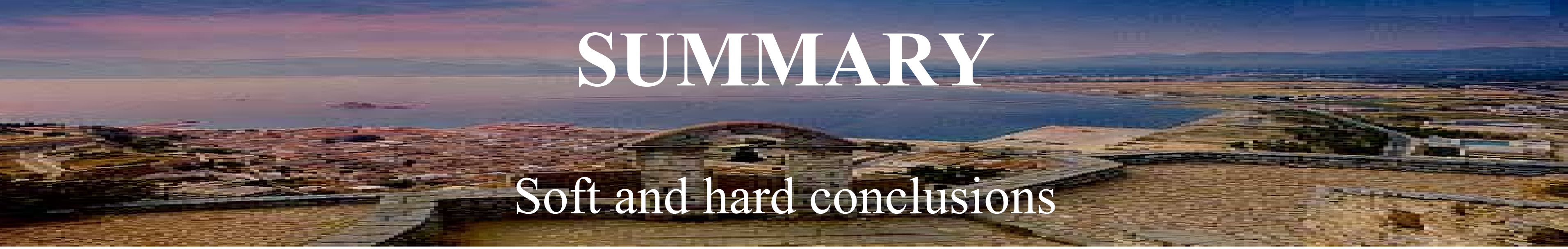


Rjj=0.36, Jet1(2)=36.2(33.3) GeV

Event : 899811 Run : 152581 EventType : DATA | Unpresc: 33,34,3,35,41,11,13,45,53,23,24,25,26,27,29,30 Presc: 34,35,24,

SUMMARY

Soft and hard conclusions



♌ **Soft Diffraction**

♏ **Hard Diffraction**

Use the reduced energy cross section

☞ Pay a color factor κ for each gap

Get gap size from renormalized P_{gap}

Diffraction is an interaction between low-x partons subject to color constraints