Diffractive Structure Functions and Exclusive Production from CDF to LHC

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HERA AND THE LHC

3rd workshop on the implications of HERA for LHC physics

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DESY Hamburg

Contents

- Introduction
- Elastic and total cross sections
- Soft diffraction
- Hard diffraction
- Exclusive Production

$\bar{p}$-p Interactions

Non-diffractive:

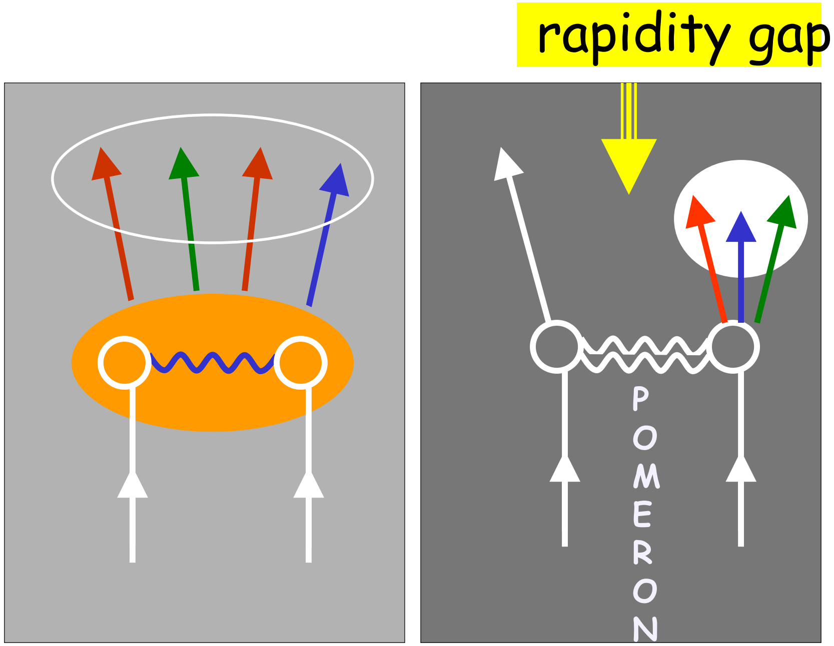
Color-exchange

Diffractive:

Colorless exchange with vacuum quantum numbers

Incident hadrons acquire color and break apart

CONFINEMENT



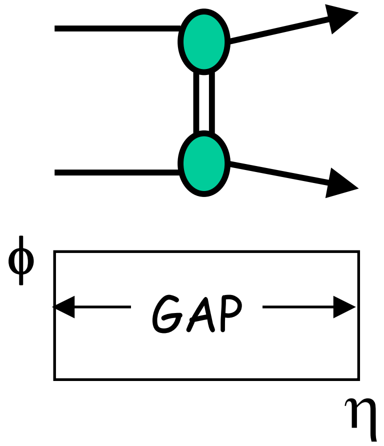
Incident hadrons retain their quantum numbers remaining colorless

pseudo-DECONFINEMENT

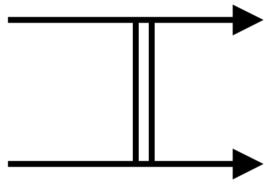
Goal: understand the QCD nature of the diffractive exchange

Diffractive $\bar{p}p$ Processes

Elastic scattering

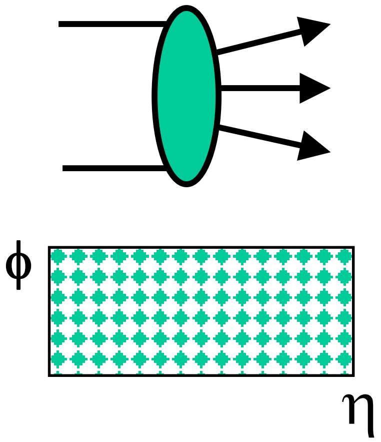


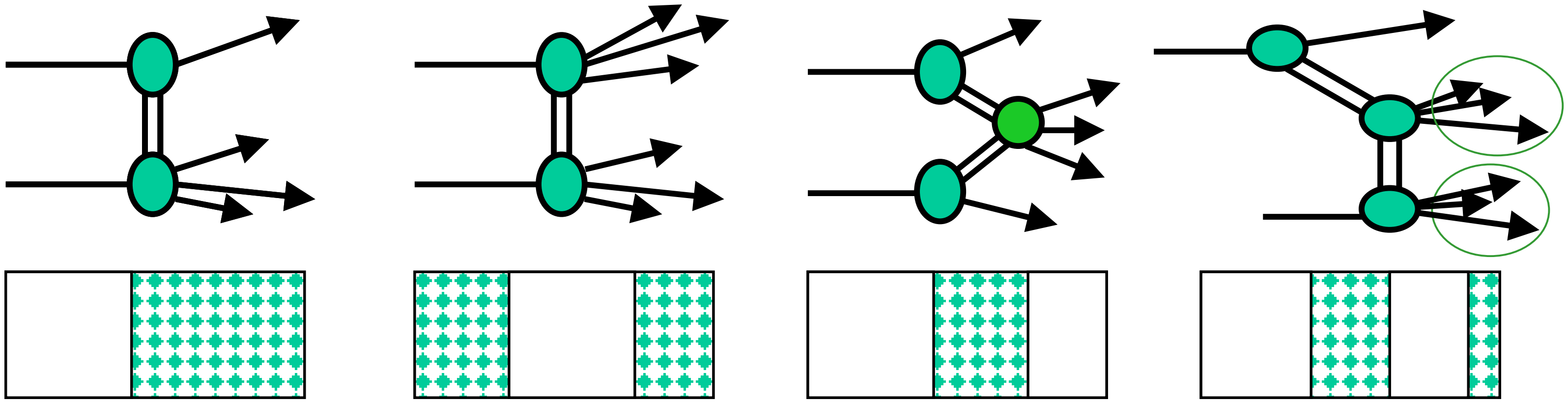
$\sigma_T = \mathrm{Im}\, f_{el}\ (t=0)$



OPTICAL THEOREM

Total cross section





SD

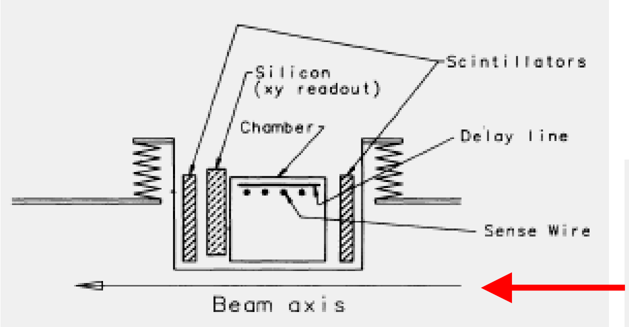
DD

DPE

SDD=SD+DD

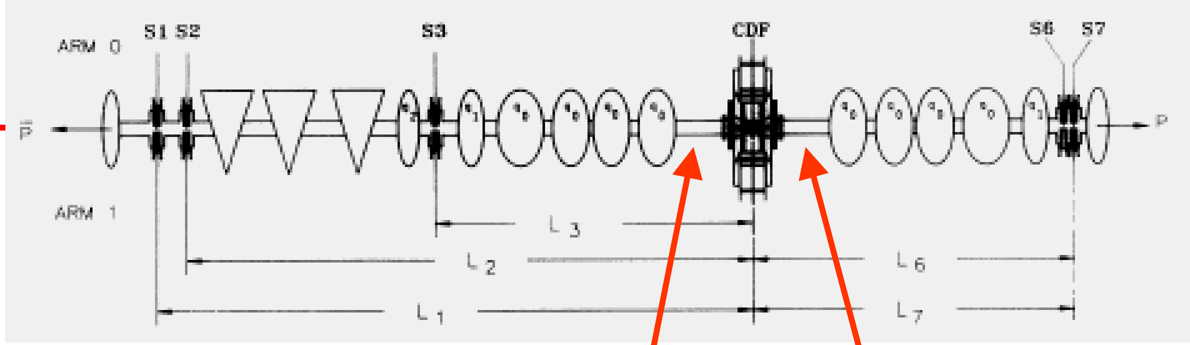
CDF Run 1-0 (1988-89)

Elastic, diffractive, and total cross section @ 546 and 1800 GeV



Roman Pot Spectrometers

CDF-I



Roman Pot Detectors

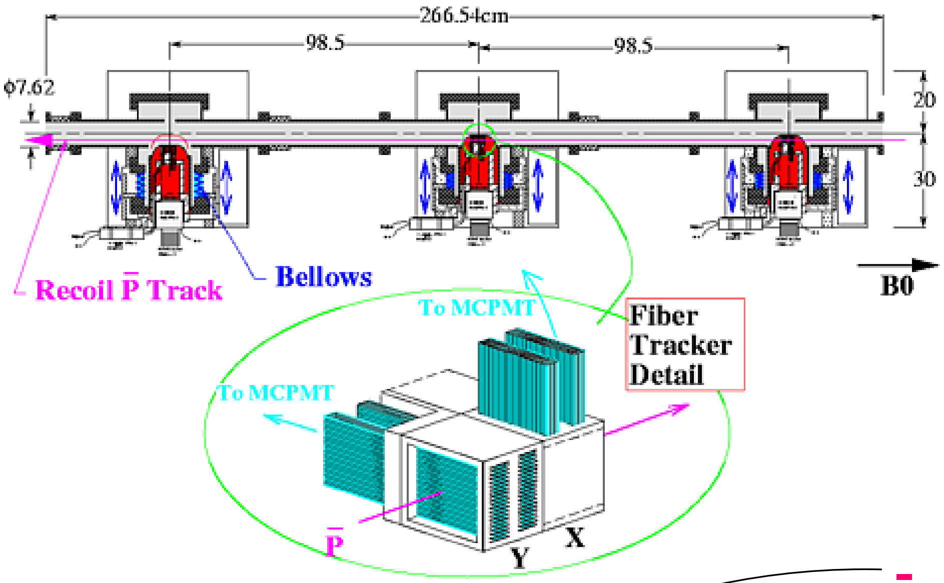
- Scintillation trigger counters
- Wire chamber
- Double-sided silicon strip detector

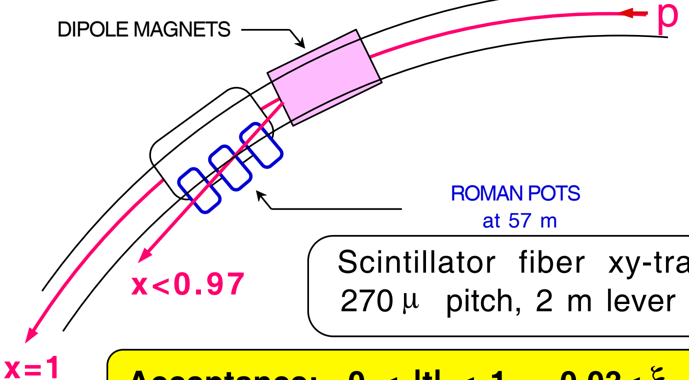
Roman Pots with Trackers up to $|\eta| = 7$

CDF-I

Run-IC

Run-IA,B

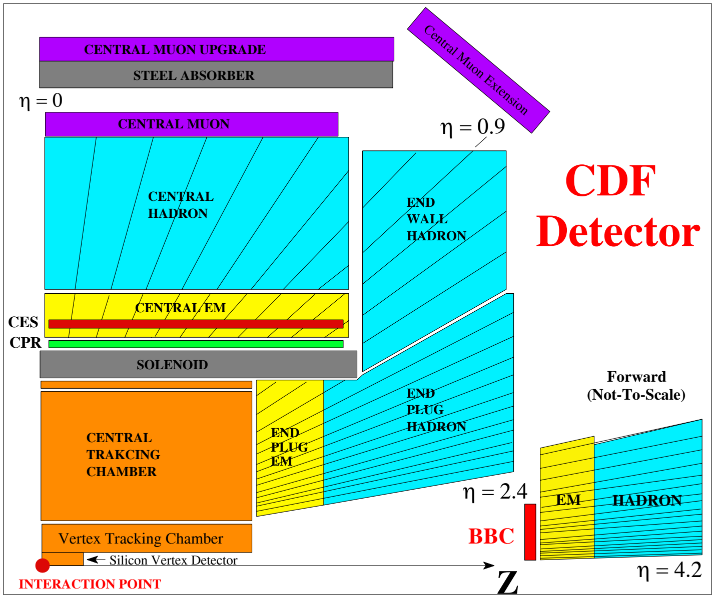




Scintillator fiber xy-tracker
270 µ pitch, 2 m lever arm

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

beam

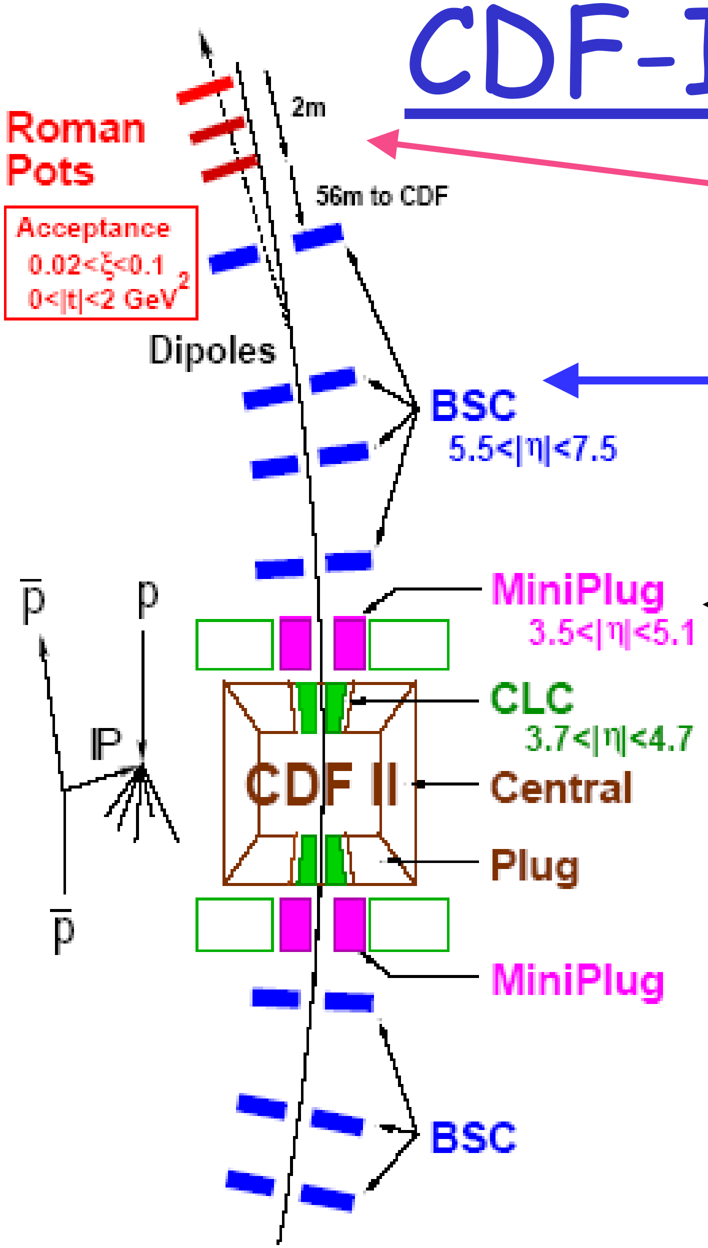


Forward Detectors

BBC 3.2<η<5.9

FCAL 2.4<η<4.2

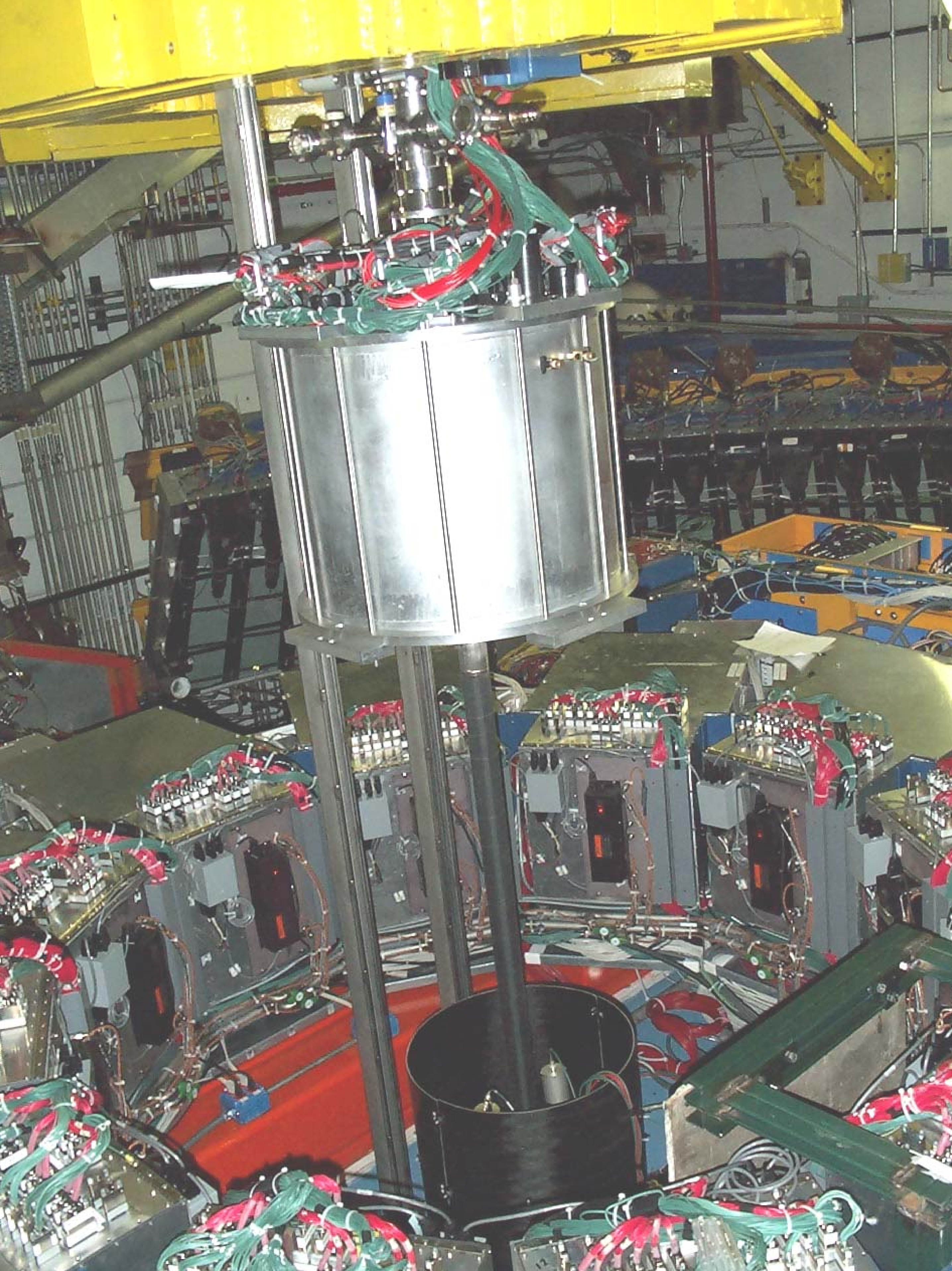
CDF-II



ROMAN POT DETECTORS

BEAM SHOWER COUNTERS:
Used to reject ND events

MINIPLUG CALORIMETER



ELASTIC AND TOTAL CROSS SECTIONS

@ Tevatron: CDF and E710/811
→ use luminosity independent method ←

$$\sigma_T^2 \sim \frac{1}{L}\,\frac{1}{1+\rho^2}\,\frac{dN_{el}}{dt}\bigg|_{t=0} \qquad \& \qquad \sigma_T \sim \frac{1}{L}\left(N_{el}+N_{inel}\right)$$

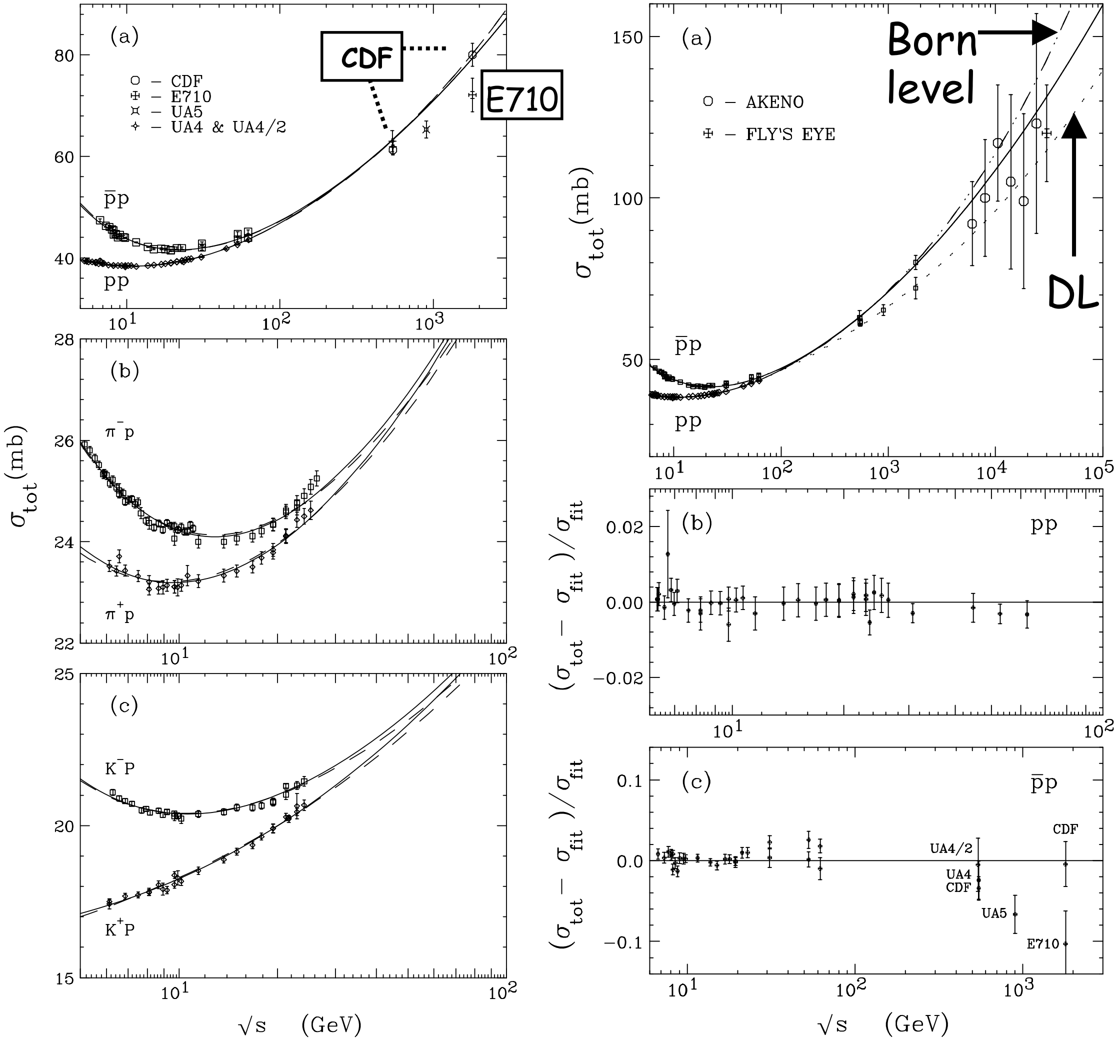
optical theorem

$$\Rightarrow \qquad \sigma_T = \frac{16\pi}{1+\rho^2}\,\boxed{\frac{dN_{el}}{dt}\bigg|_{t=0}}\,\frac{1}{N_{el}+N_{inel}}$$

Alert:

- background N_{inel} yields small σ_T
- undetected N_{inel} yields large σ_T

Total Cross Sections: Regge fit



CMG fit:
Covolan, Montagna, Goulianos
PLB 389 (1995) 176

Simultaneous Regge fit to pp, πp, and Kp x-sections using the eikonal approach to ensure unitarity

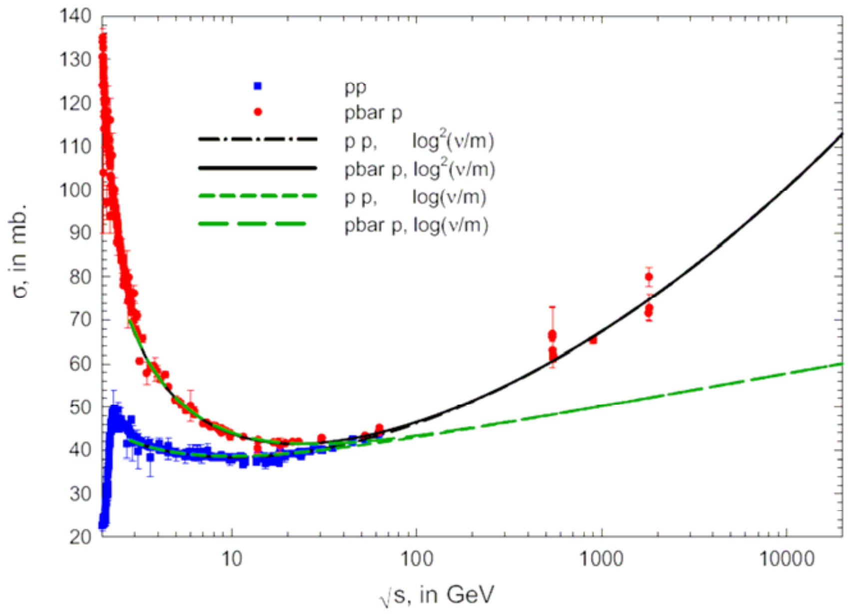
$\sigma \rightarrow s^{\varepsilon}$

$\varepsilon = 1.104 \pm 0.002$

$\rightarrow \sigma_{LHC} = 115$ mb

@14 TeV

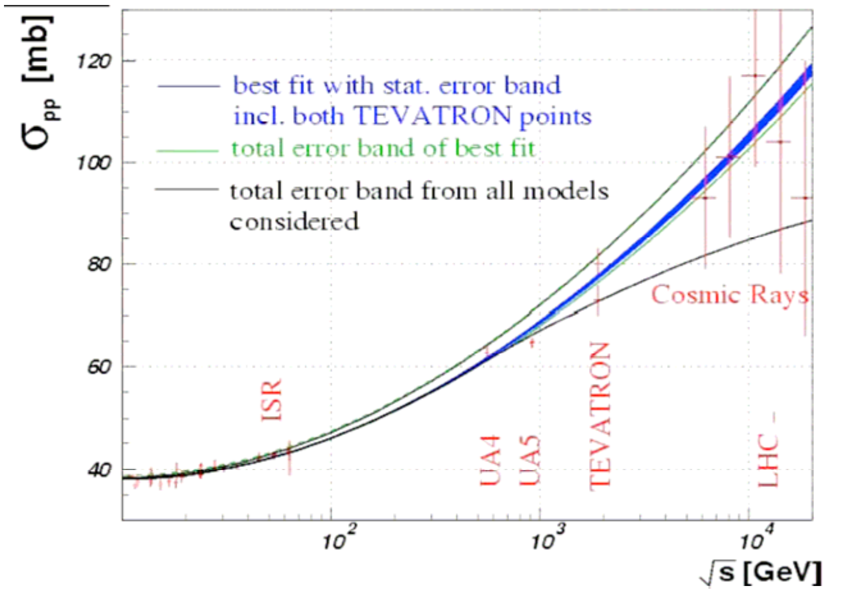
σ_T: other approaches



eg, M. Block, arXiv:hep-ph/0601210 (2006)

➔ fit data using analyticity constraints

M. Block and F. Halzen, Phys. Rev. D **72,** 036006



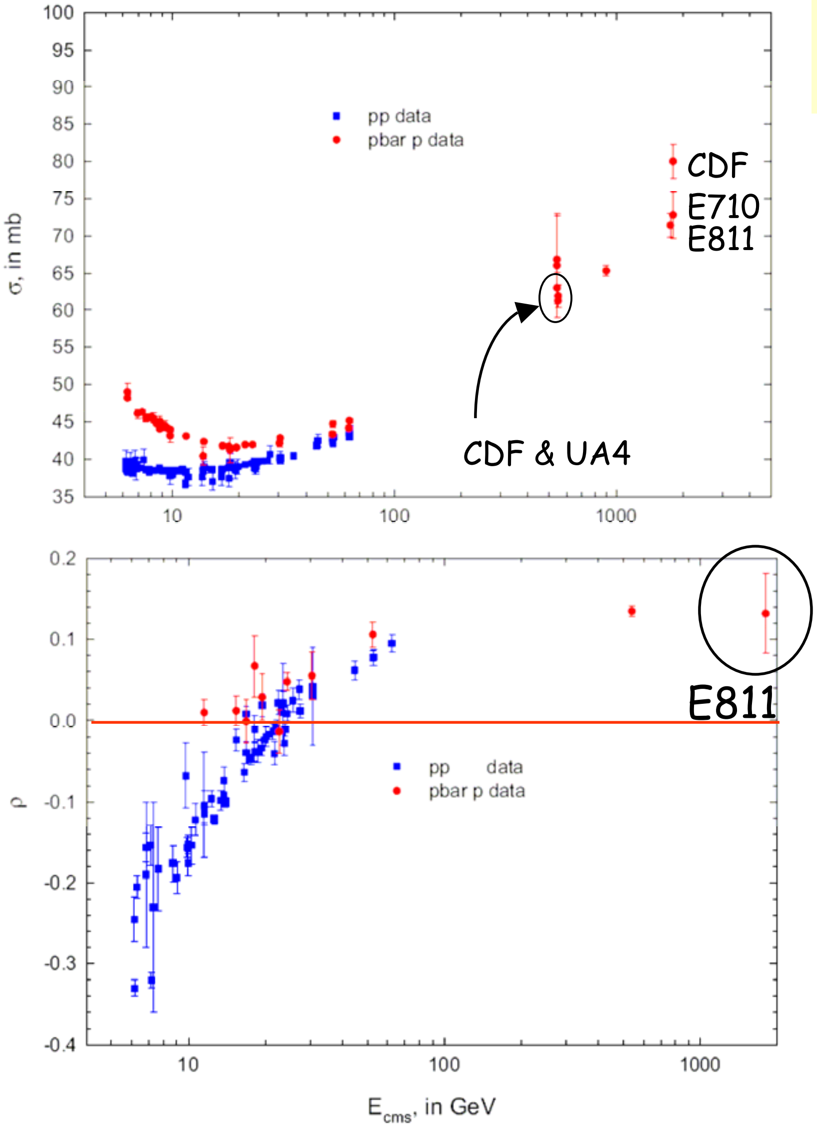
COMPETE Collaboration fits all available hadronic data and predicts:

LHC: $\boxed{\sigma_{tot} = 111.5 \pm 1.2 \; {}^{+4.1}_{-2.1} \text{ mb}}$ [PRL 89 201801 (2002)]

σ_T(LHC) = 107.3 ± 1.2 mb

Recall CMG Regge fit: 115 mb

σ_T and ρ-values from PDG



ρ = ratio of real/imaginary parts
of elastic scattering amplitude at t=0

CDF and E710/811 disagree

σ_T

↕ **optical theorem**

Im $f_{el}(t=0)$

↕ **dispersion relations**

Re $f_{el}(t=0)$

N. Khuri and A. Martin:

measuring ρ at the LHC tests
discreteness of space-time

SOFT DIFFRACTION

Key words:

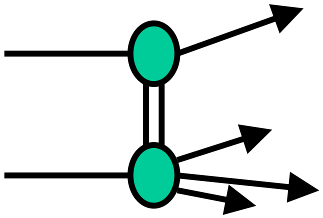
renormalization

scaling

QCD

multi-gap

Renormalization



Factorization ➔

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

Pomeron flux

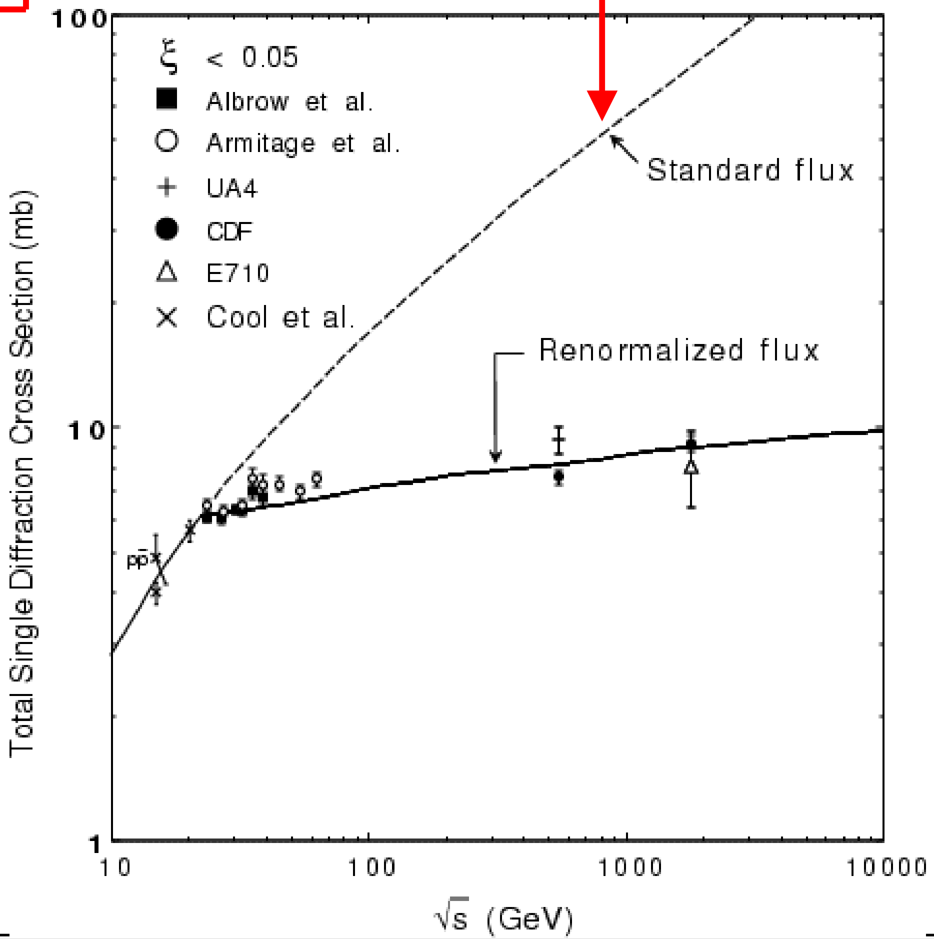
$$\boxed{\sigma_{SD} \sim s^{2\varepsilon}}$$

- **Regge theory**
  σ_{SD} exceeds σ_T at
  $$\sqrt{s} \approx 2\ \text{TeV}.$$

- **Renormalization**
  Pomeron flux integral (re)normalized to unity

KG, PLB 358 (1995) 379

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



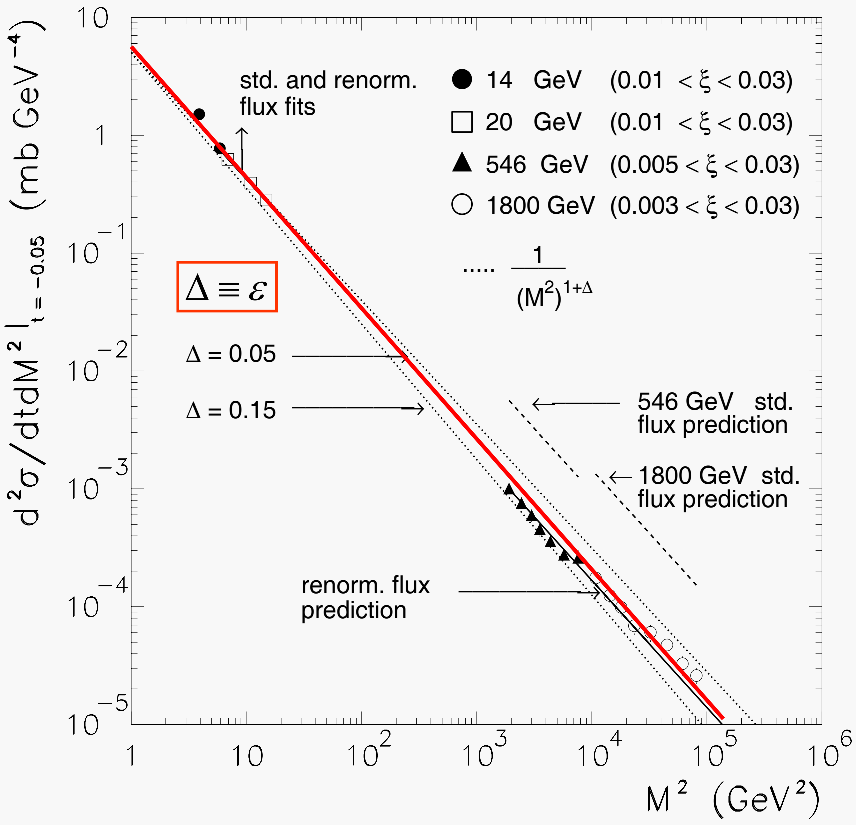
A Scaling Law in Diffraction

renormalization

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

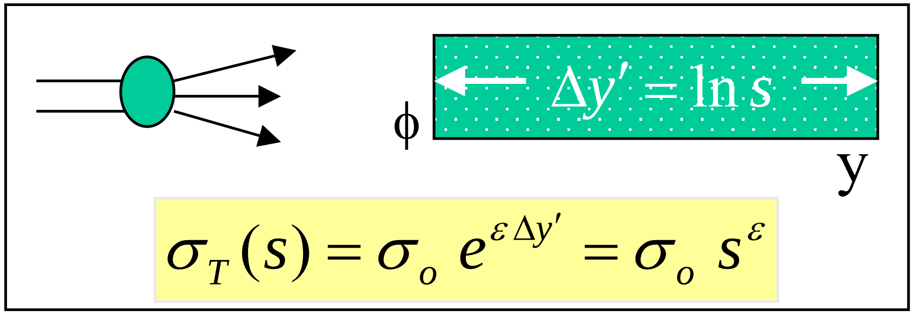
➔ Independent of S over 6 orders of magnitude in M² !

KG&JM, PRD 59 (1999) 114017



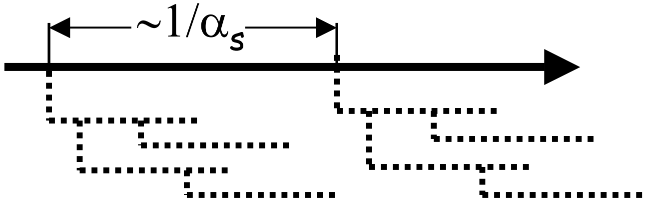
Factorization breaks down so as to ensure M²-scaling!

The QCD Connection



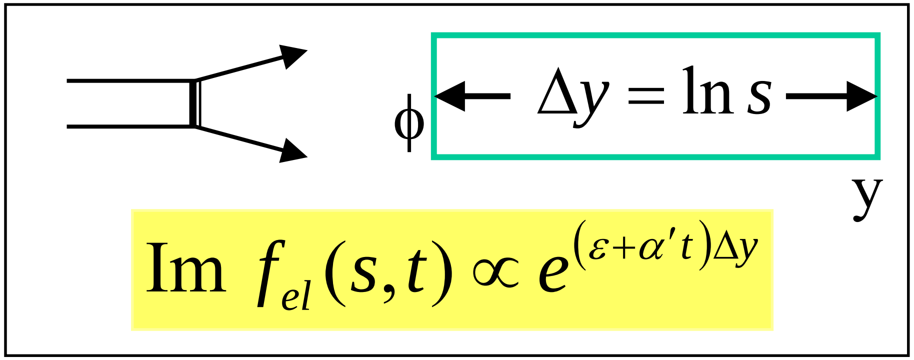
$$\sigma_T(s) = \sigma_o\, e^{\varepsilon \Delta y'} = \sigma_o\, s^{\varepsilon}$$

Total cross section:
power law increase versus s



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

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

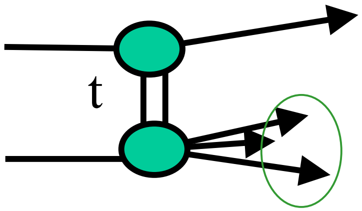


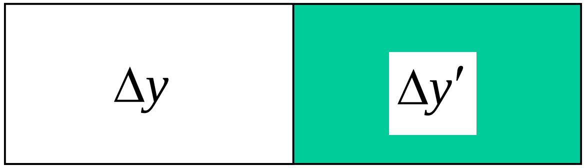
$$\mathrm{Im}\ f_{el}(s,t) \propto e^{(\varepsilon+\alpha' t)\Delta y}$$

Elastic cross section:
forward scattering amplitude

Single Diffraction in QCD

(KG, hep-ph/0205141)





$$\left.\frac{d\sigma}{dM^2}\right|_{\mathrm{REGGE}} \propto \frac{\boxed{s^{2\varepsilon}}}{(M^2)^{1+\varepsilon}}$$

2 independent variables: $t, \Delta y$

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

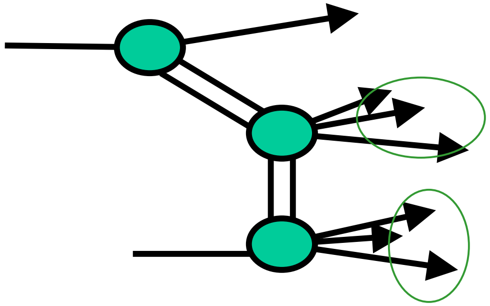
$$\downarrow$$

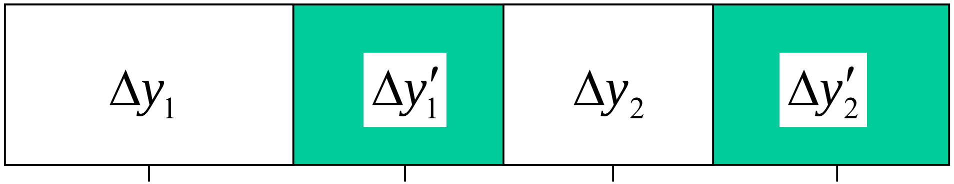
$$\sim e^{2\varepsilon \Delta y} \longrightarrow \boxed{\int_{\Delta y_{\min}}^{\Delta y = \ln s} s^{2\varepsilon\, \Delta y} \approx s^{2\varepsilon}}$$

Renormalization removes the s-dependence → SCALING

Multi-gap Renormalization

(KG, hep-ph/0205141)





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

color factors

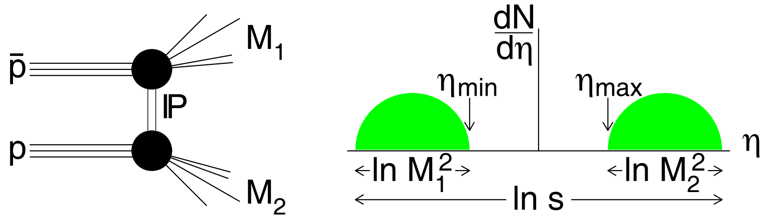
$$\frac{d^5\sigma}{\prod_{i=1-5} dV_i} = \underbrace{C\times F_p^2(t_1)\prod_{i=1-2}\left\{e^{(\varepsilon+\alpha' t_i)\Delta y_i}\right\}^2}_{\text{Gap probability}} \times \kappa^2 \underbrace{\left\{\sigma_o\, e^{\varepsilon(\Delta y_1'+\Delta y_2')}\right\}}_{\text{Sub-energy cross section (for regions with particles)}}$$

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

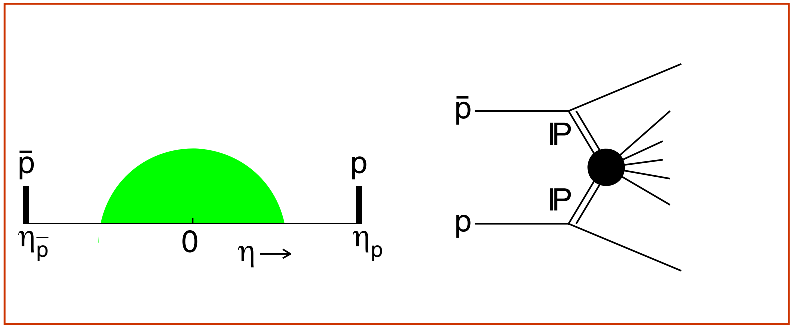
$$\boxed{\int_{\Delta y_{\min}}^{\Delta y=\ln s} s^{2\varepsilon\,\Delta y} \approx s^{2\varepsilon}}$$

Same suppression as for single gap!

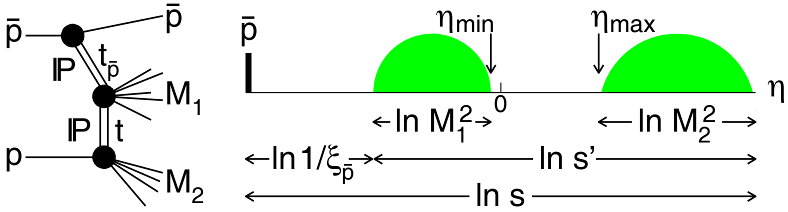
Central and Double Gaps @ CDF



- **Double Diffraction Dissociation**
  - One central gap



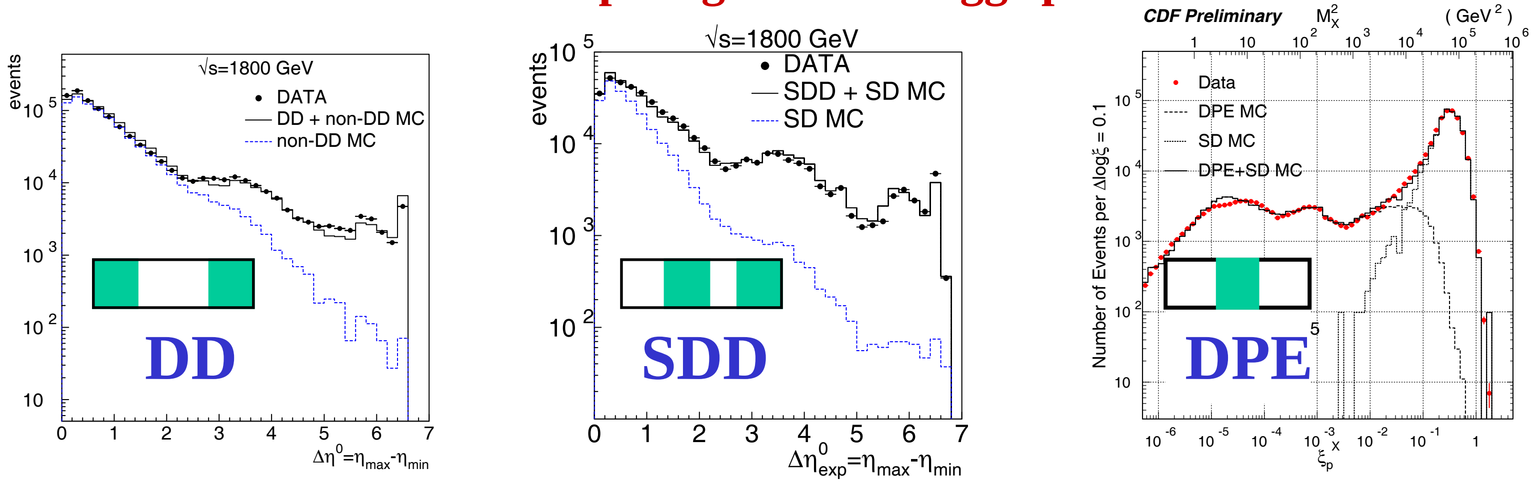
- **Double Pomeron Exchange**
  - Two forward gaps



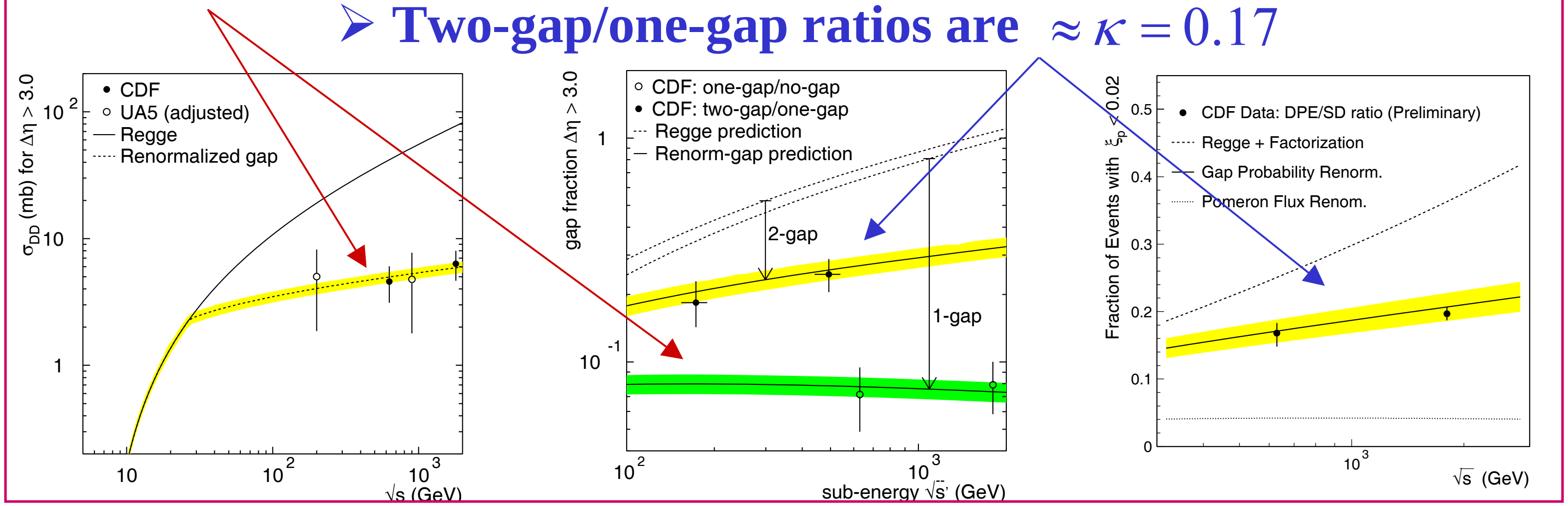
- **SDD: Single+Double Diffraction**
  - One forward + one central gap

Central & Double-Gap CDF Results

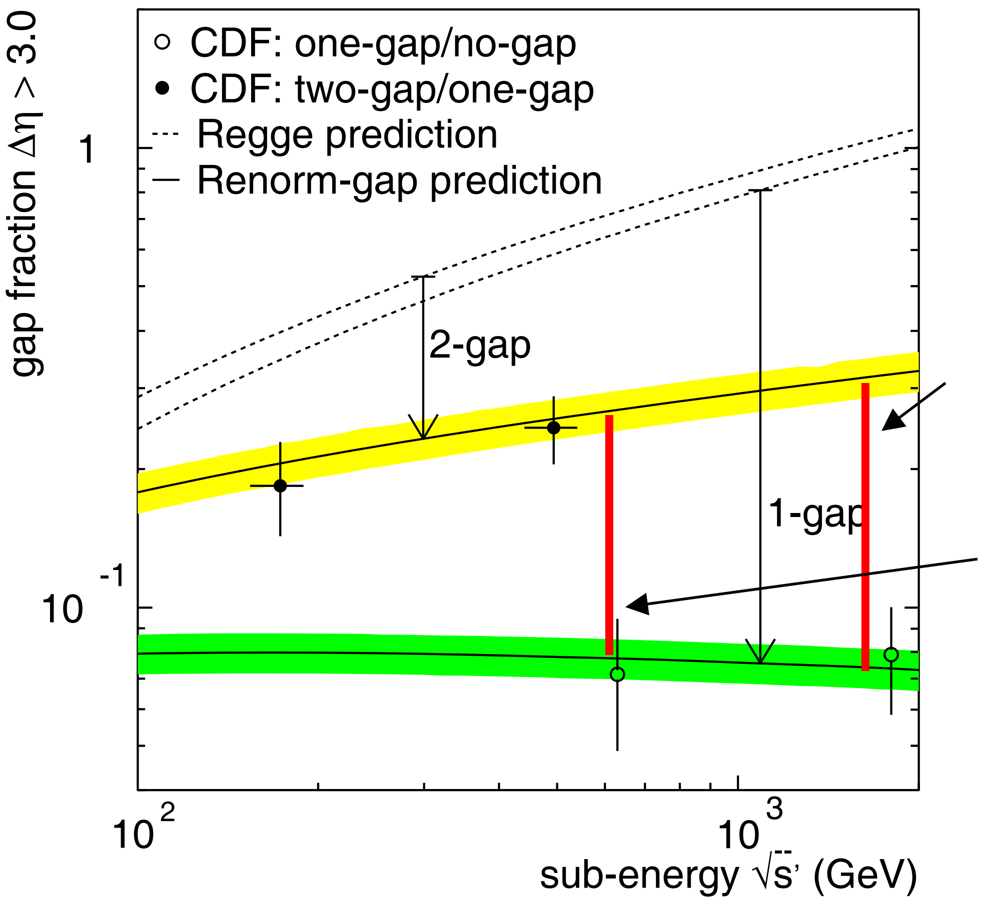
Differential shapes agree with Regge predictions

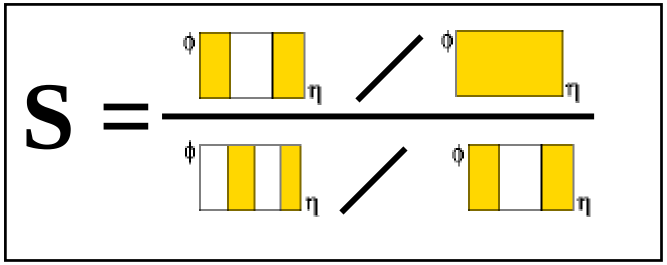


- ➢ One-gap cross sections are suppressed
  - ➢ Two-gap/one-gap ratios are $\approx \kappa = 0.17$



Gap Survival Probability





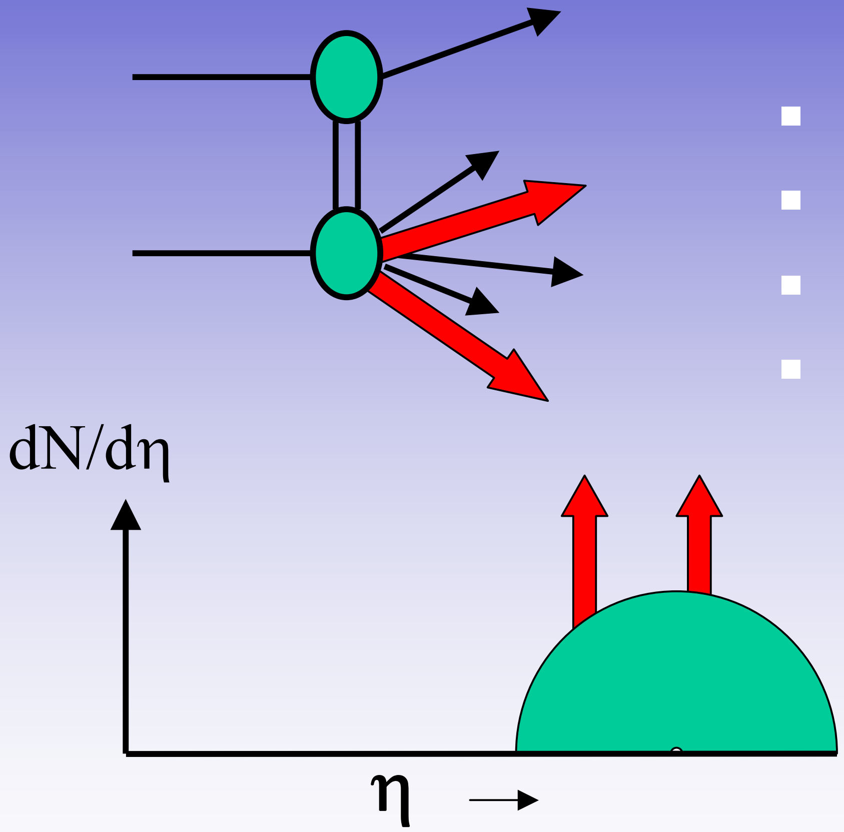
$$S^{1-gap/0-gap}_{2-gap/1-gap}(1800\ \text{GeV}) \approx 0.23$$

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

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

HARD DIFFRACTION

- Diffractive fractions
- Diffractive structure function
  ➔ factorization breakdown
- Restoring factorization
- Q^2 dependence
- t dependence
- Hard diffraction in QCD



JJ, W, b, J/ψ

Diffractive Fractions @ CDF

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

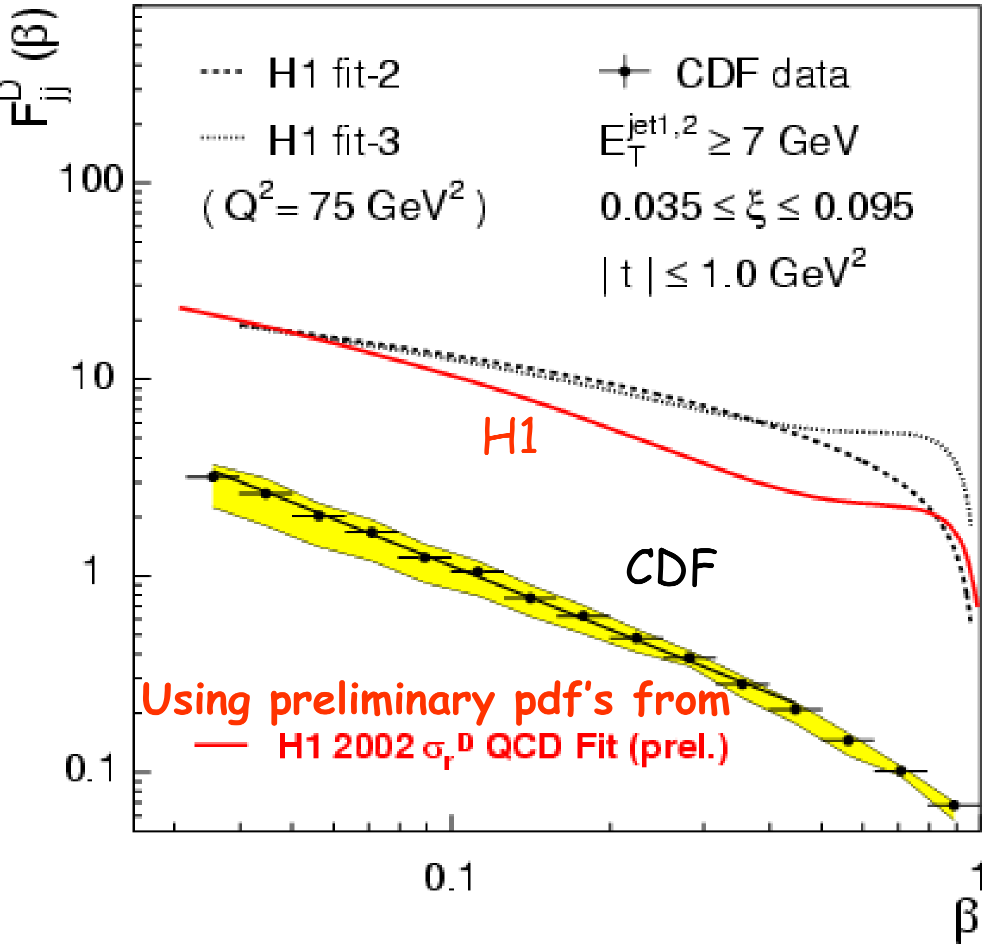
Fraction:
SD/ND ratio
at 1800 GeV

☼	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 !

Diffractive Structure Function:

Breakdown of QCD Factorization

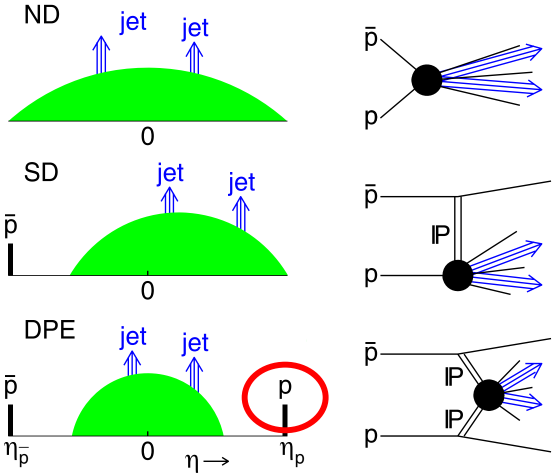


β = momentum fraction of parton in Pomeron

The diffractive structure function at the Tevatron is suppressed by a factor of ~10 relative to expectation from pdf's measured by H1 at HERA

Similar suppression factor
as in soft diffraction
relative to Regge expectations!

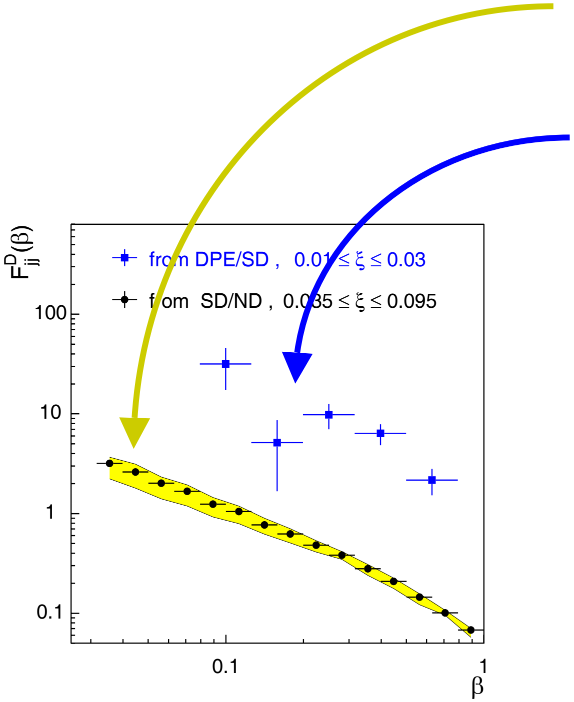
Restoring QCD Factorization

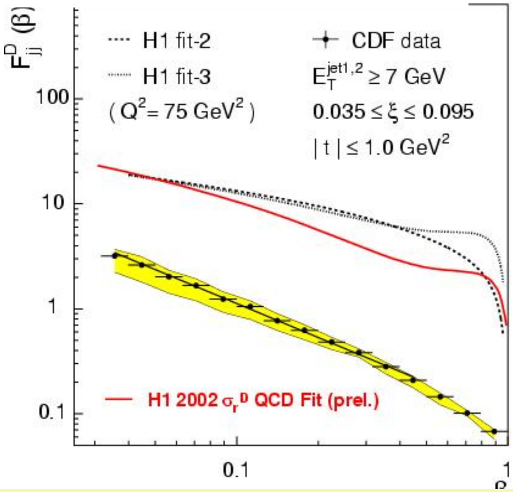


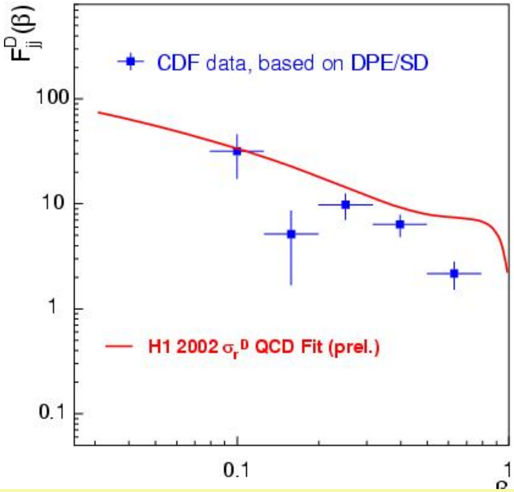
R(SD/ND)

R(DPE/SD)

DSF from two/one gap: factorization restored!



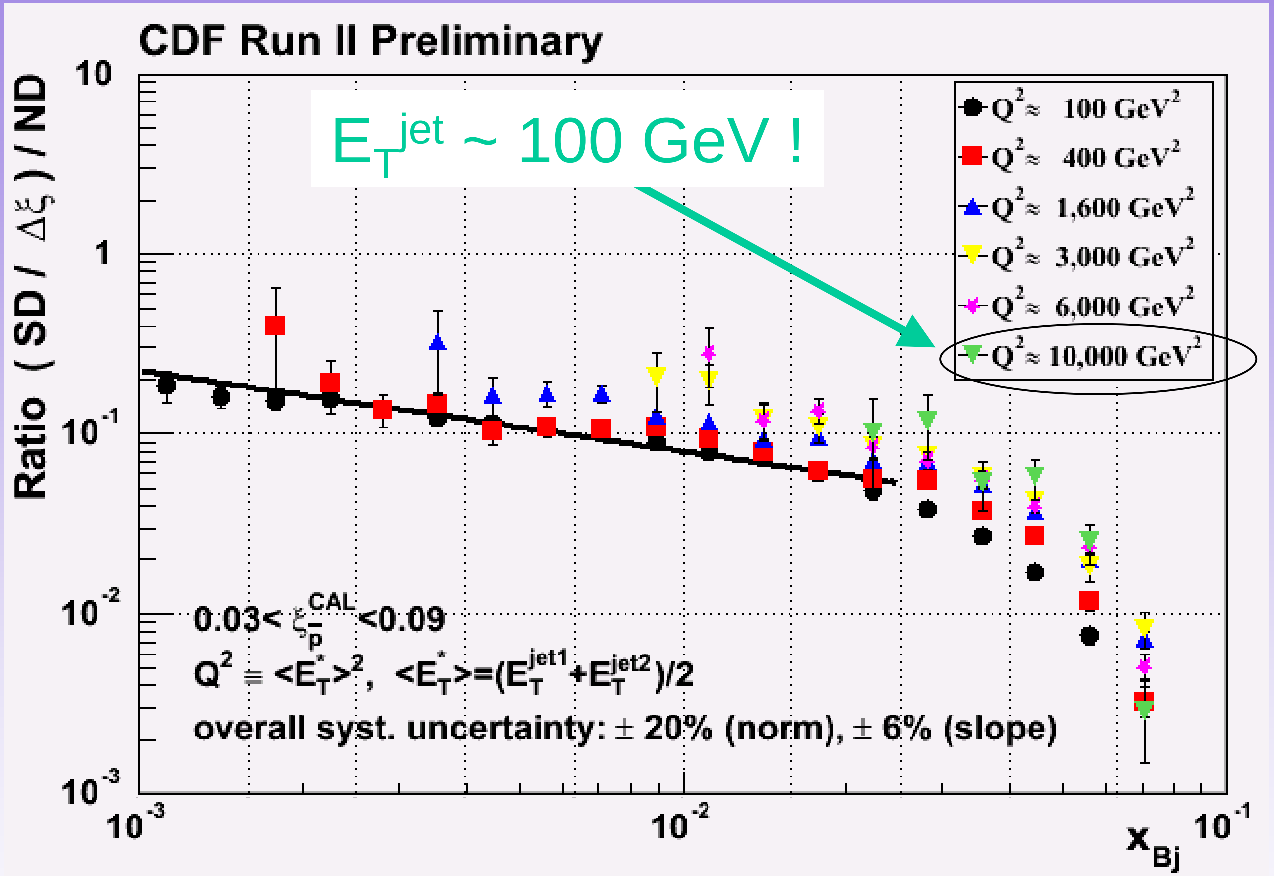




The diffractive structure function measured on the proton side in events with a leading antiproton is NOT suppressed relative to predictions based on DDIS

Diffractive Structure Function:

Q^2 dependence



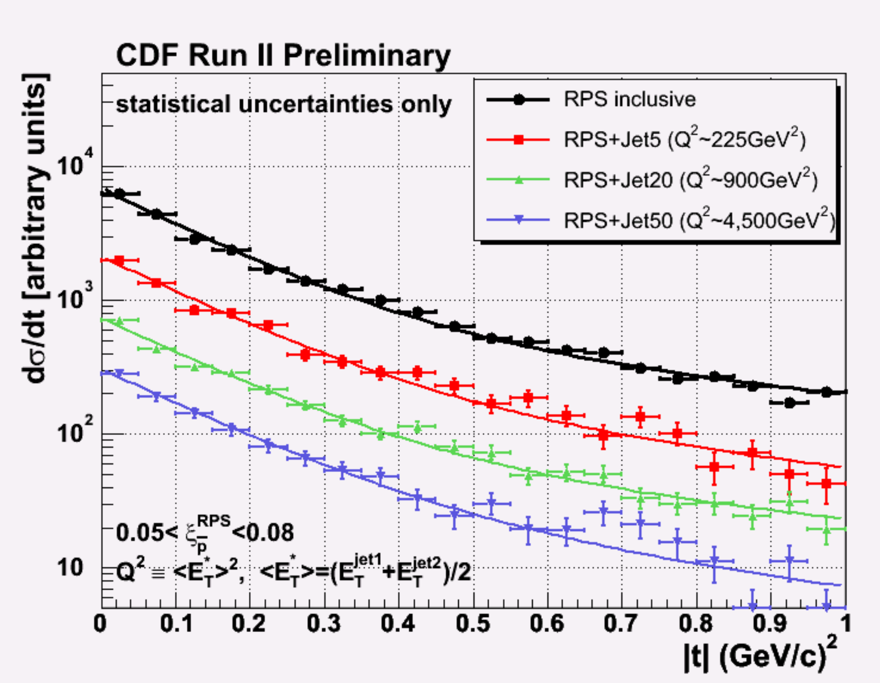
$E_T^{jet} \sim 100$ GeV !

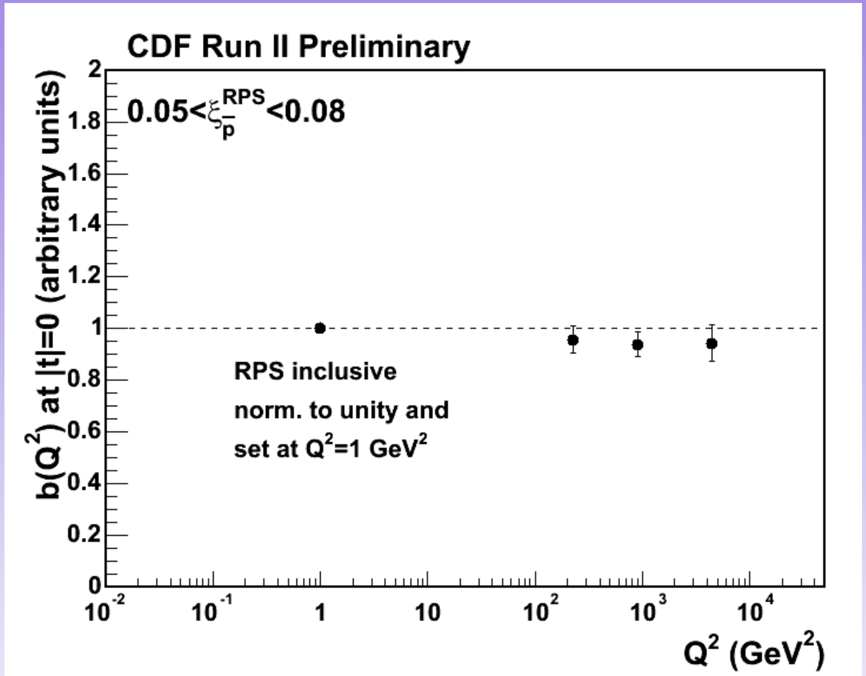
Small Q^2 dependence in region $100 < Q^2 < 10{,}000$ GeV^2

⇨ Pomeron evolves as the proton!

Diffractive Structure Function:

t- dependence





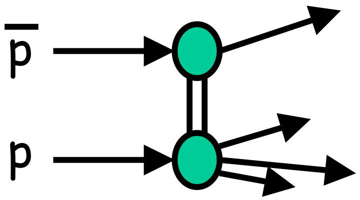
Fit dσ/dt to a double exponential:

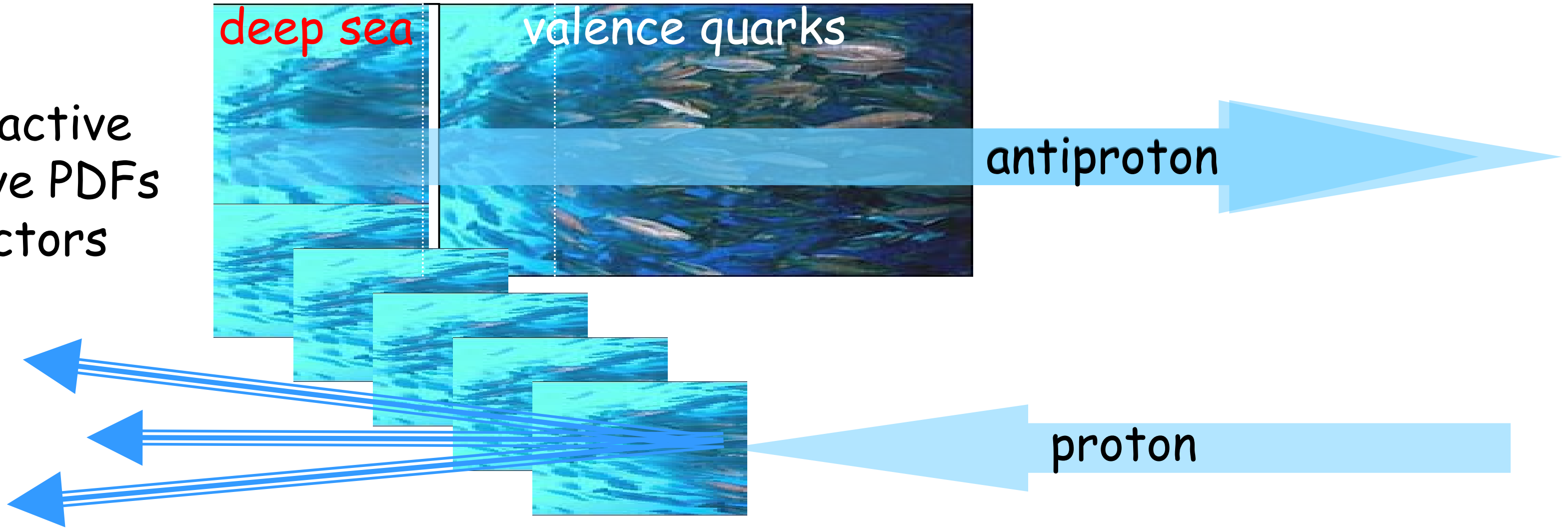
$$F = 0.9 \cdot e^{b_1 \cdot t} + 0.1 \cdot e^{b_2 \cdot t}$$

- ➢ No diffraction dips
- ➢ No Q2 dependence in slope from inclusive to $Q^2 \sim 10^4$ GeV^2

- ➢ Same slope over entire region of $0 < Q^2 < 4{,}500$ GeV^2 across soft and hard diffraction!

Hard Diffraction in QCD

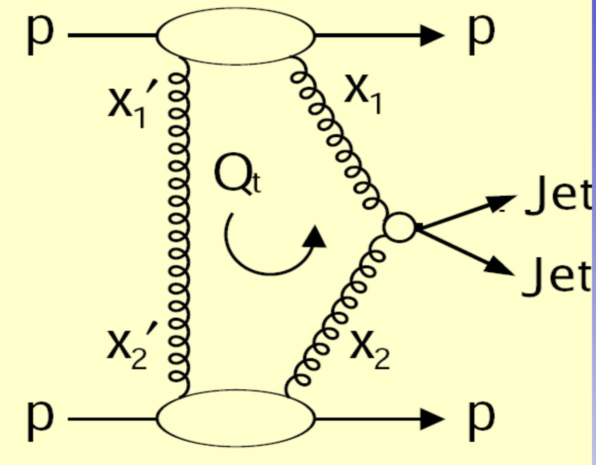




Derive diffractive
from inclusive PDFs
and color factors

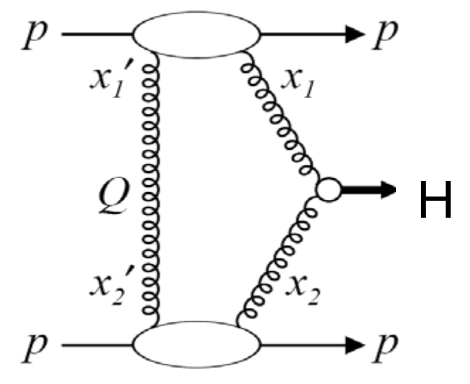
EXCLUSIVE PRODUCTION

Measure exclusive jj & $\gamma\gamma$ → → → Calibrate predictions for H production rates @ LHC



Bialas, Landshoff,
Phys.Lett. B 256,540 (1991)
Khoze, Martin, Ryskin,
Eur. Phys. J. C23, 311 (2002);
C25,391 (2002);C26,229 (2002)
C. Royon, hep-ph/0308283
B. Cox, A. Pilkington,
PRD 72, 094024 (2005)
OTHER……………………………

Clean discovery channel



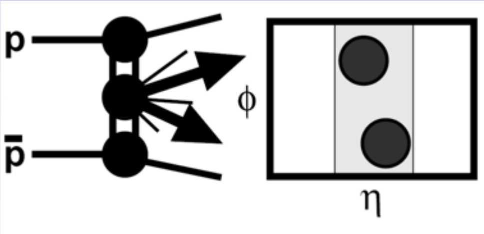
KMR: σ_H(LHC) ~ 3 fb
S/B ~ 1 if ΔM ~ 1 GeV

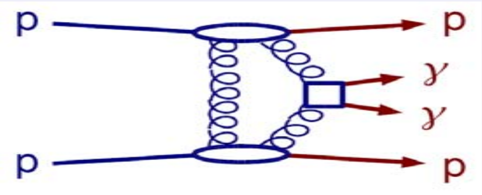
Search for exclusive dijets:

Measure dijet mass fraction

$$R_{jj} = \frac{M_{jj}}{M_X(\text{all calorimeters})}$$

Look for signal as $M_{jj} \rightarrow 1$





Search for exclusive $\gamma\gamma$

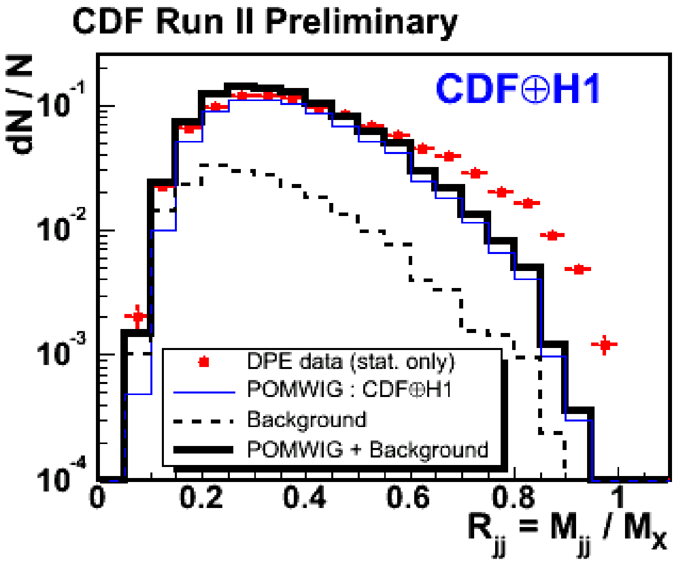
- ✓ 3 candidate events found
- ✓ 1 (+2/-1) predicted from ExHuME MC*
- ✓ background under study

* See talk by V. Khoze

Exclusive Dijet Signal

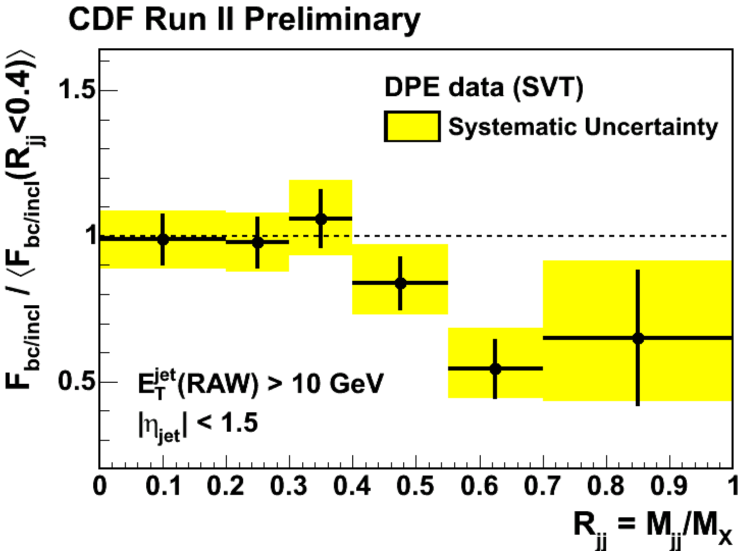
DIJETS

Dijet fraction – all jets



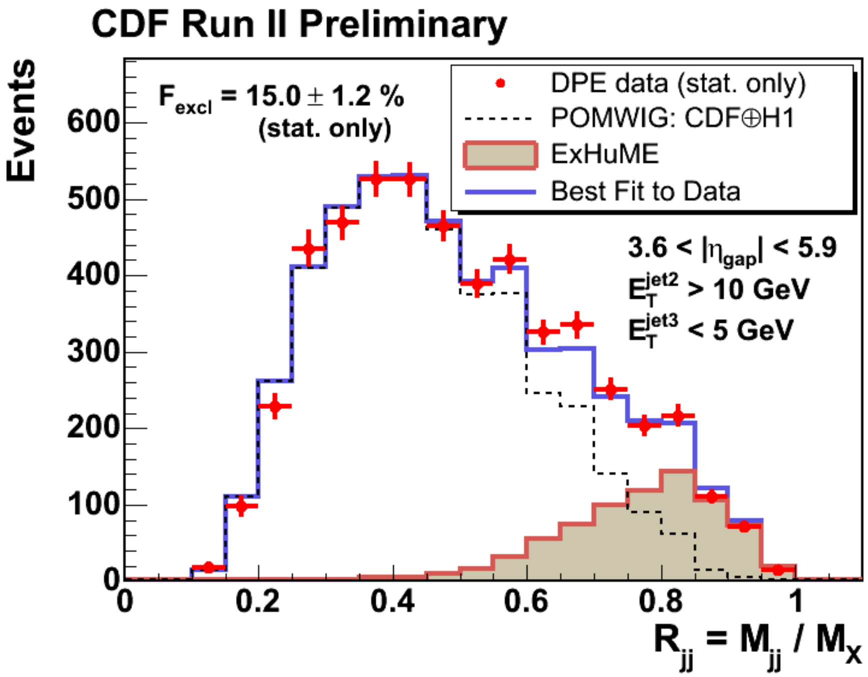
Excess over MC predictions at large dijet mass fraction

b-tagged dijet fraction



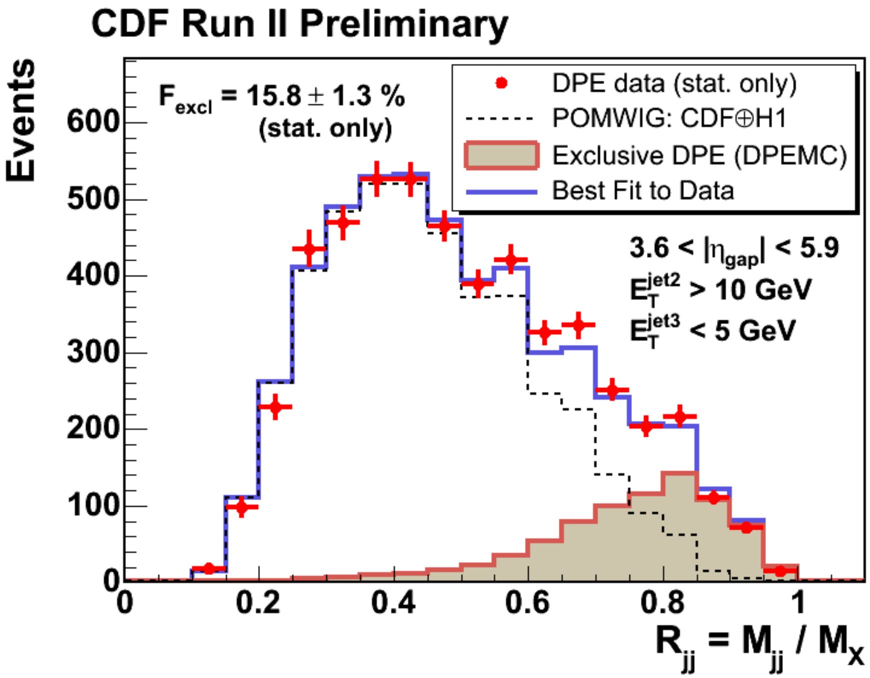
Exclusive b-jets are suppressed by J_Z= 0 selection rule

R_{JJ}(excl): Data vs MC



ExHuME (KMR): gg→gg process

➔ uses LO pQCD



Exclusive DPE (DPEMC)

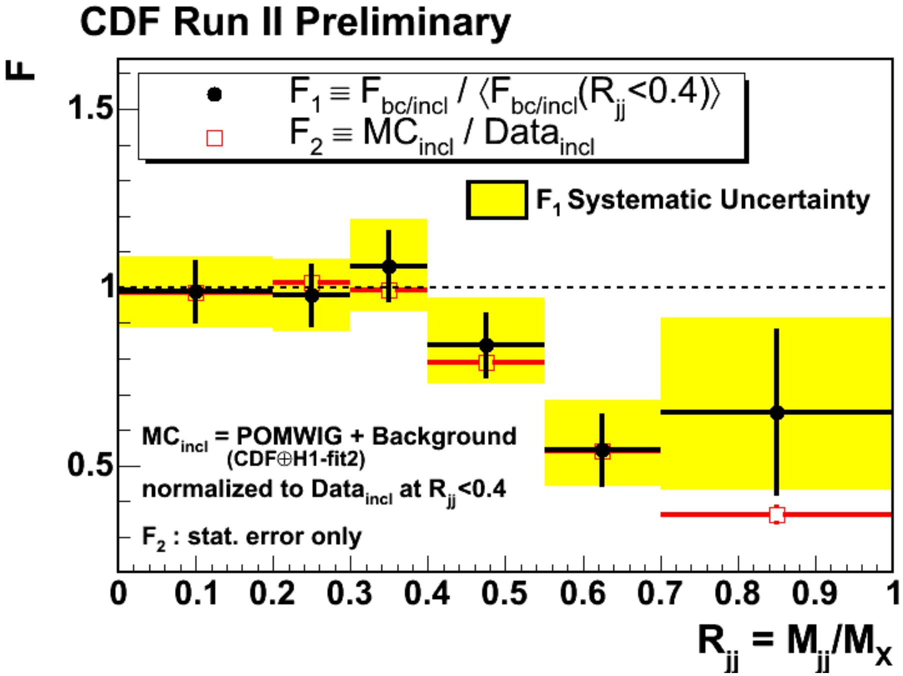
➔ non-pQCD based on Regge theory

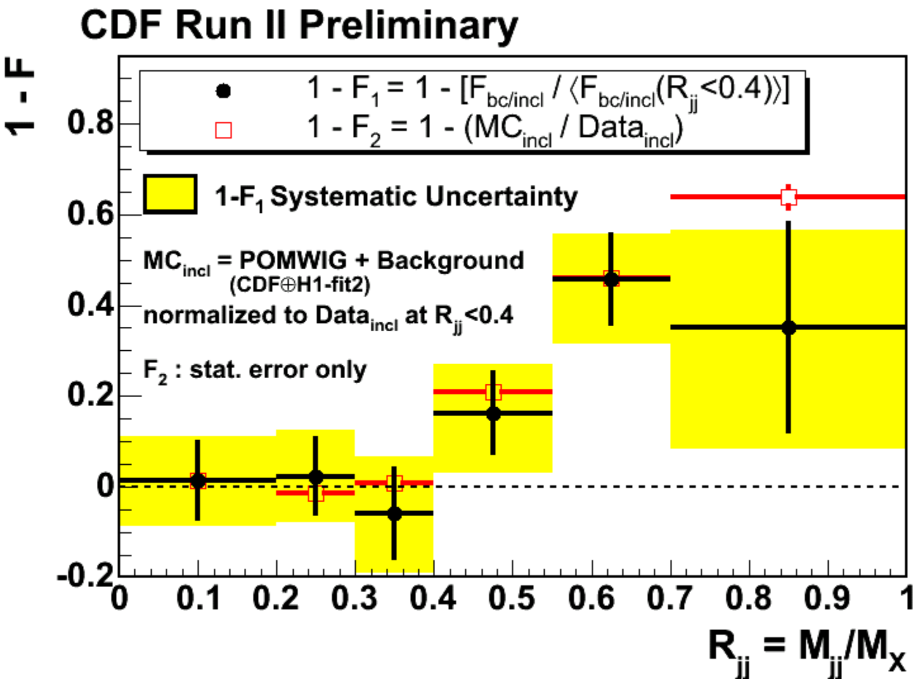
Shape of excess of events at high R_{jj} is well described by both models

jj_{excl}: Exclusive Dijet Signal

COMPARISON

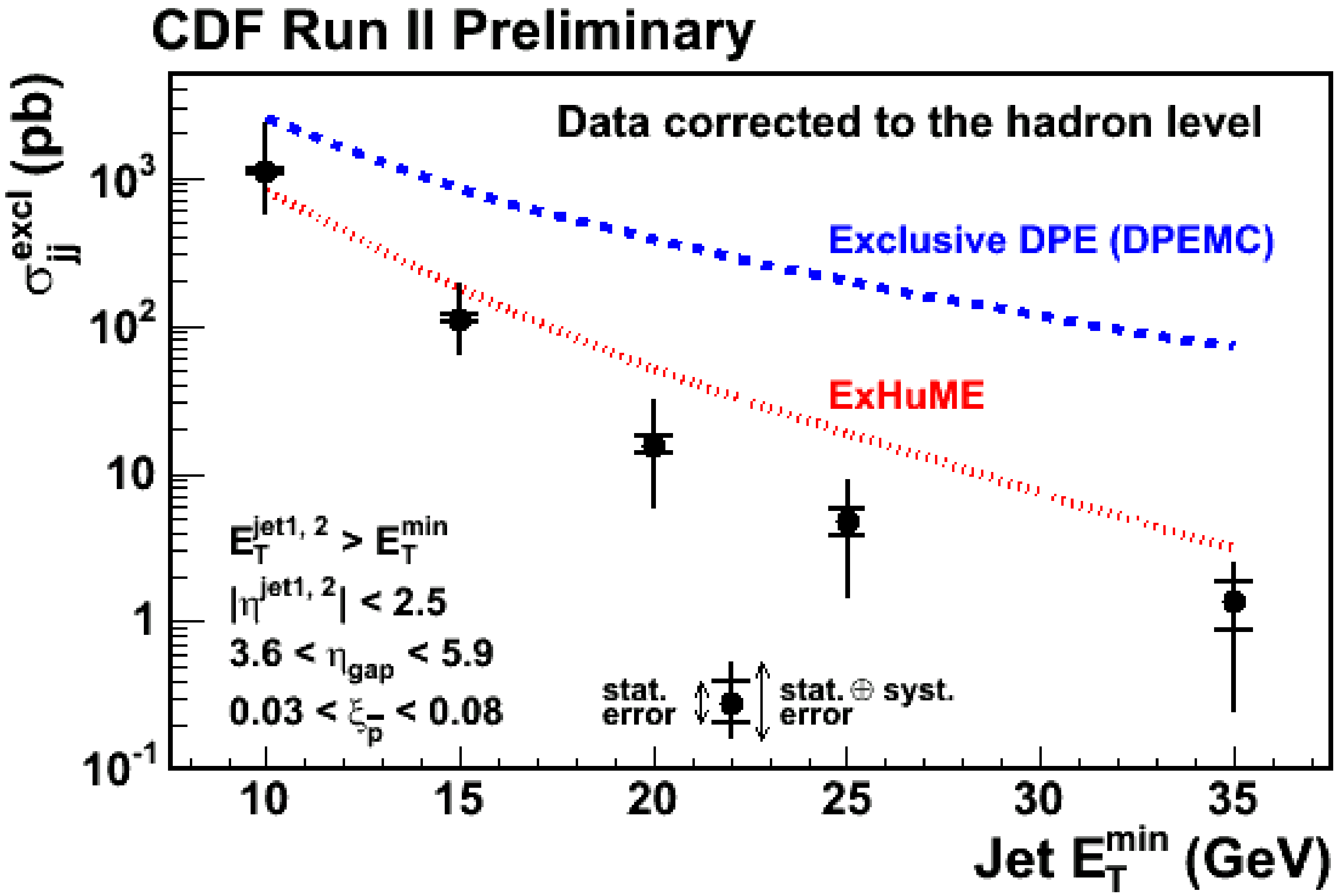
Inclusive data vs MC @ b/c-jet data vs inclusive





JJ_{excl} : x-section vs E_T(min)

Comparison with hadron level predictions

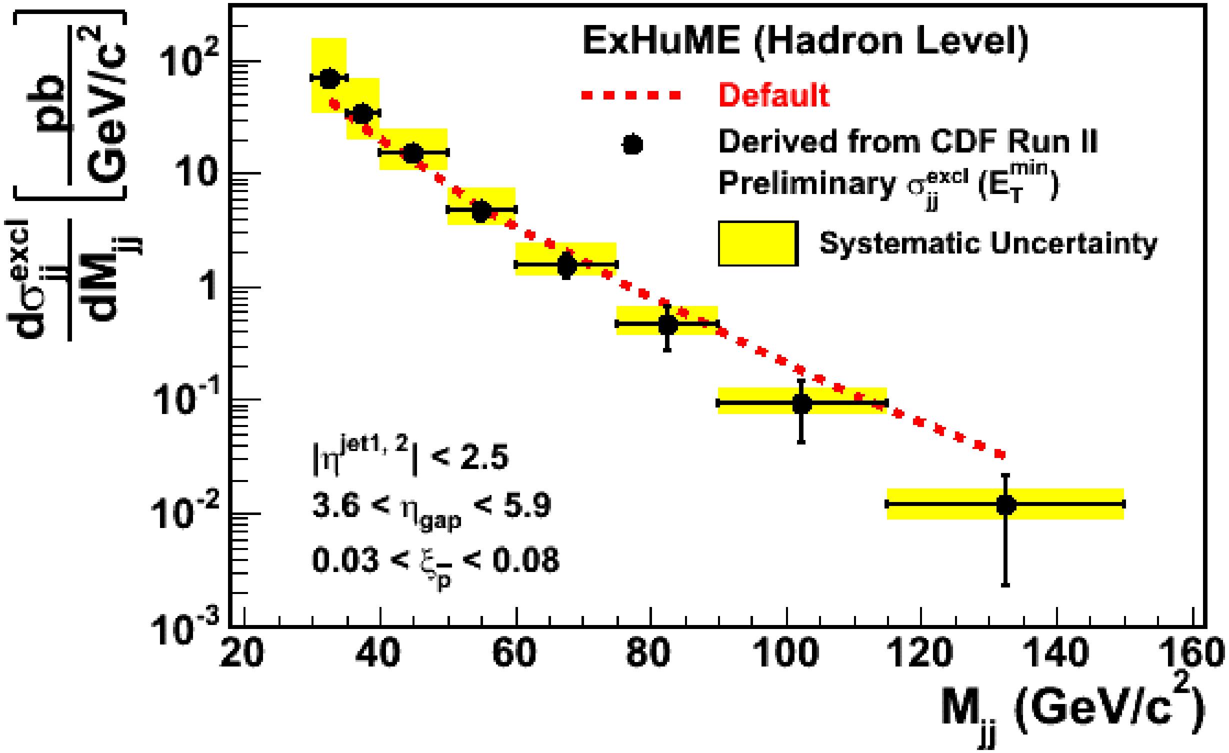


JJ_{excl} : cross section predictions

ExHuME Hadron-Level Differential Exclusive Dijet Cross Section vs Dijet Mass

(dotted/red): Default ExHuME prediction

(points): Derived from CDF Run II Preliminary excl. dijet cross sections



Statistical and systematic errors are propagated from measured cross section uncertainties using ExHuME M_{jj} distribution shapes.

Summary

TEVATRON – what we have learnt

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

➔ Pomeron: composite object made up from underlying pdf's subject to color constraints

LHC - what to do

- ➢ Elastic and total cross sections & ρ-value
- ➢ High mass (➔4 TeV) and multi-gap diffraction
- ➢ Exclusive production (FP420 project)
  - ➔ Reduced bgnd for std Higgs to study properties
  - ➔ Discovery channel for certain Higgs scenarios