Diffraction for all:
from Tevatron to LHC and Beyond

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Recent references
Diffraction at the Tevatron: CDF results
http://pos.sissa.it//archive/conferences/035/016/DIFF2006_016.pdf

Renormalized diffractive parton densities
http://pos.sissa.it//archive/conferences/035/044/DIFF2006_044.pdf

Contents

- Introduction
- Elastic and Total Cross Sections
- Diffraction
- Exclusive Production

$\bar{p}$-p Interactions

Non-diffractive:

Color-exchange

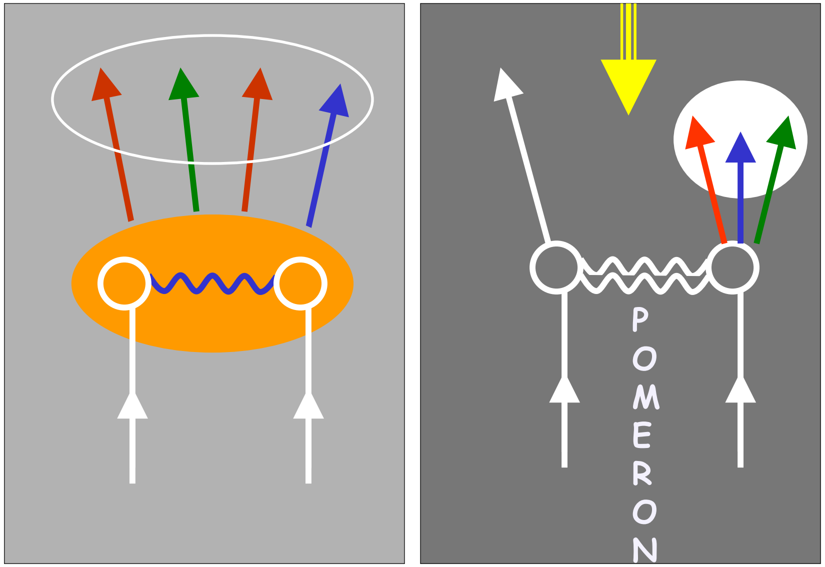
Diffractive:

Colorless exchange with vacuum quantum numbers

rapidity gap

Incident hadrons acquire color and break apart

CONFINEMENT



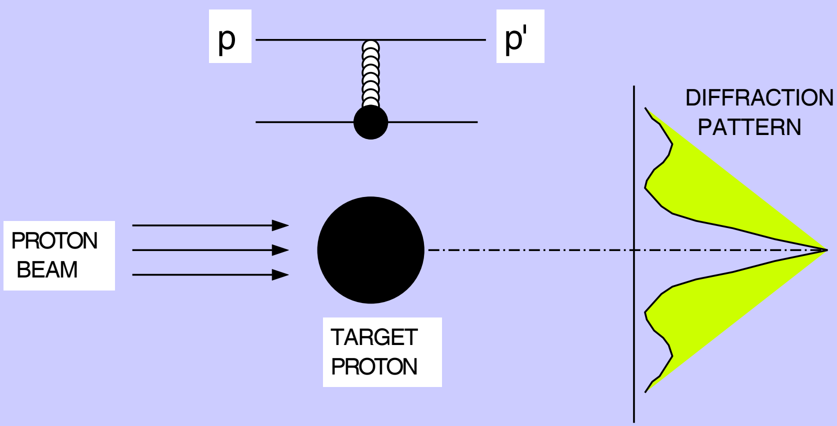
Incident hadrons retain their quantum numbers remaining colorless

pseudo-DECONFINEMENT

Goal: understand the QCD nature of the diffractive exchange

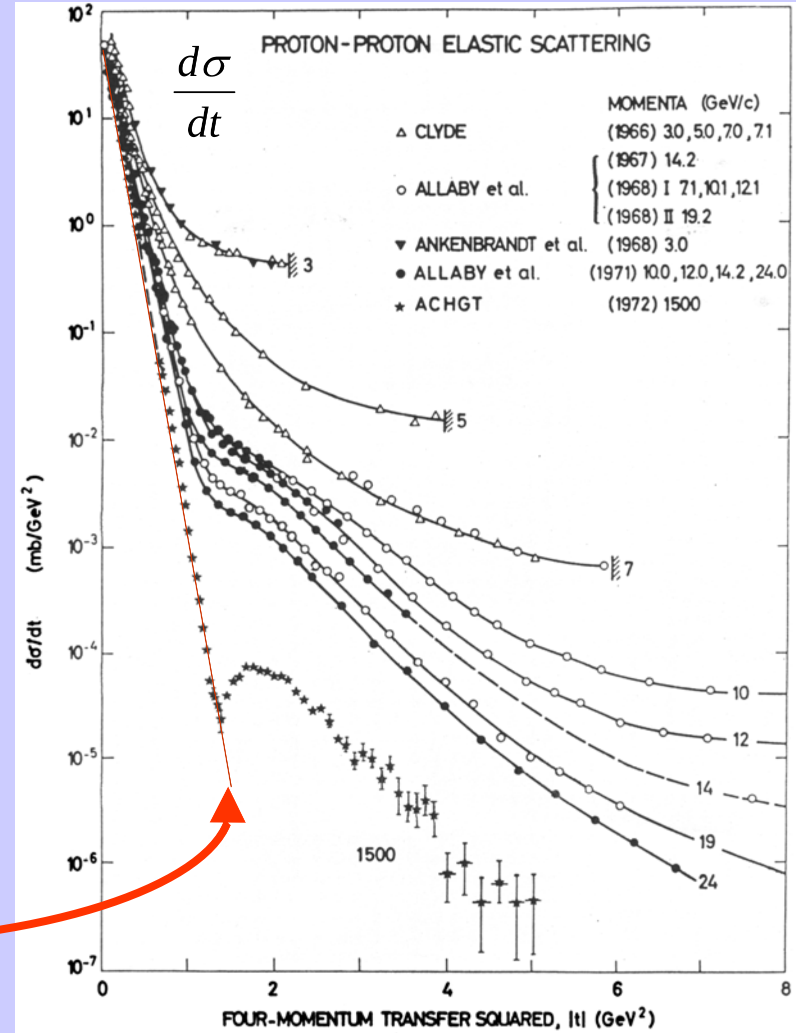
Elastic Scattering

PROTON-PROTON ELASTIC SCATTERING

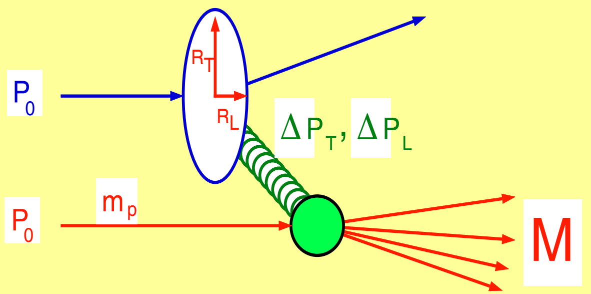


$$\frac{d\sigma}{dt} \sim e^{bt} \sim e^{-\frac{R^2}{4}(p\theta)^2}$$

$$R = \frac{1}{m_\pi} \Rightarrow b \approx 13 \left(\frac{GeV}{c}\right)^{-2}$$



Diffraction Dissociation

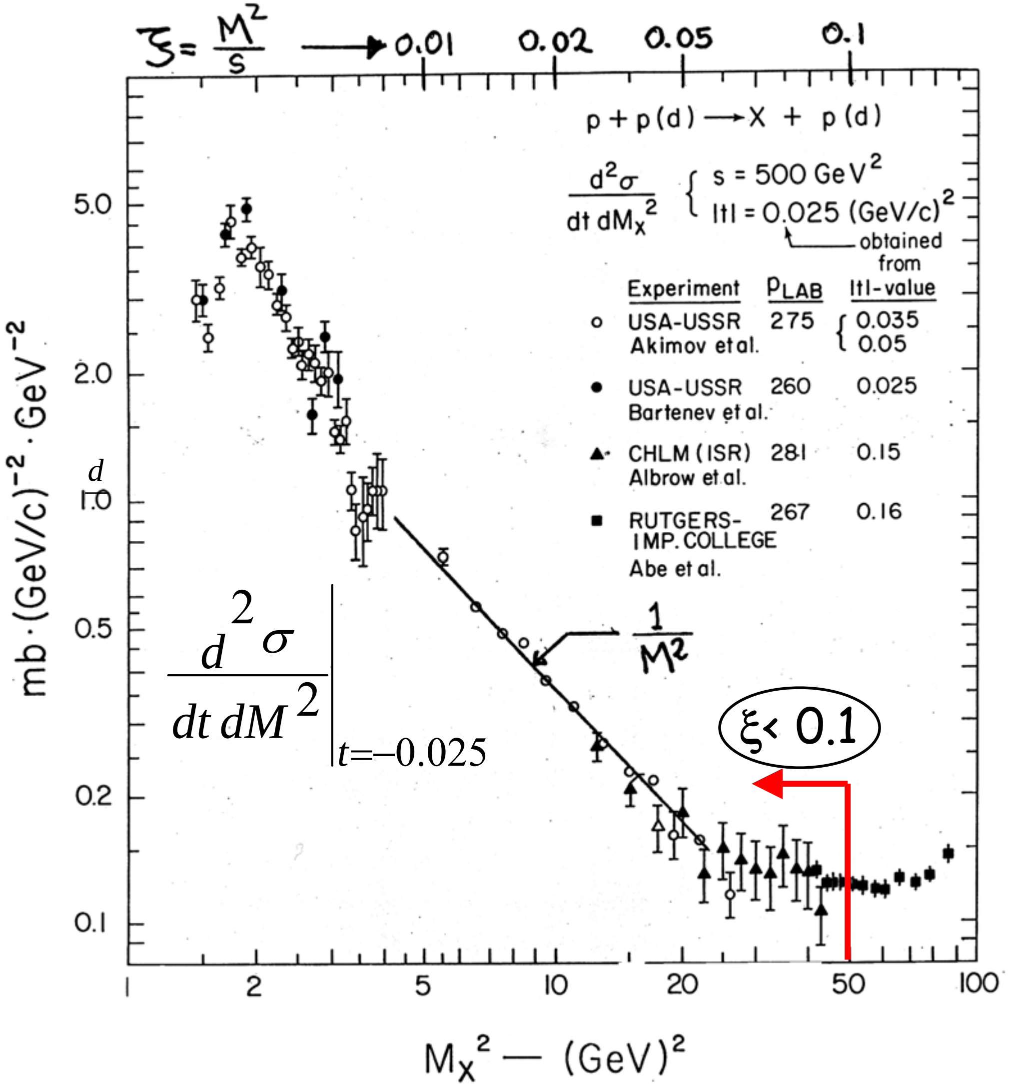


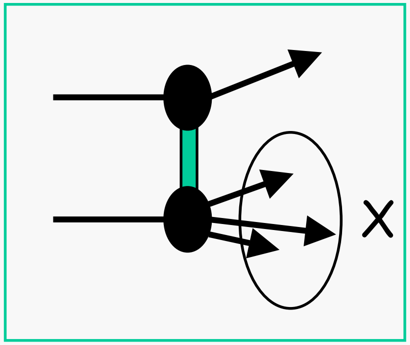
Momentum loss fraction $\xi = \frac{\Delta P_L}{P_L} = \frac{M^2}{s}$

COHERENCE CONDITION $\xi < \frac{m_\pi}{m_p} \approx 0.1$

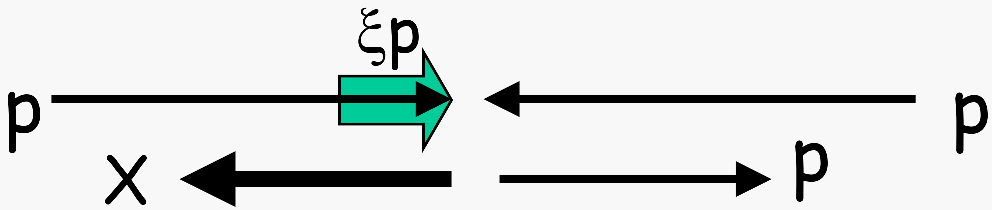
Tevatron	M ➔	0.6 TeV
LHC	➔	4.4 TeV

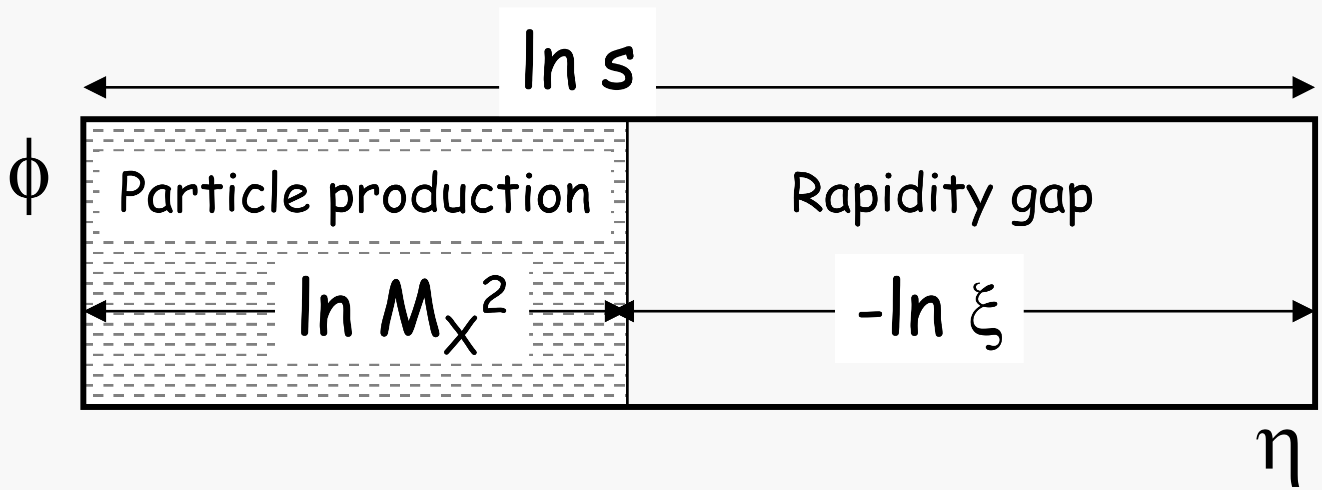
But why $\frac{d\sigma}{dM^2} \sim \frac{1}{M^2}$?





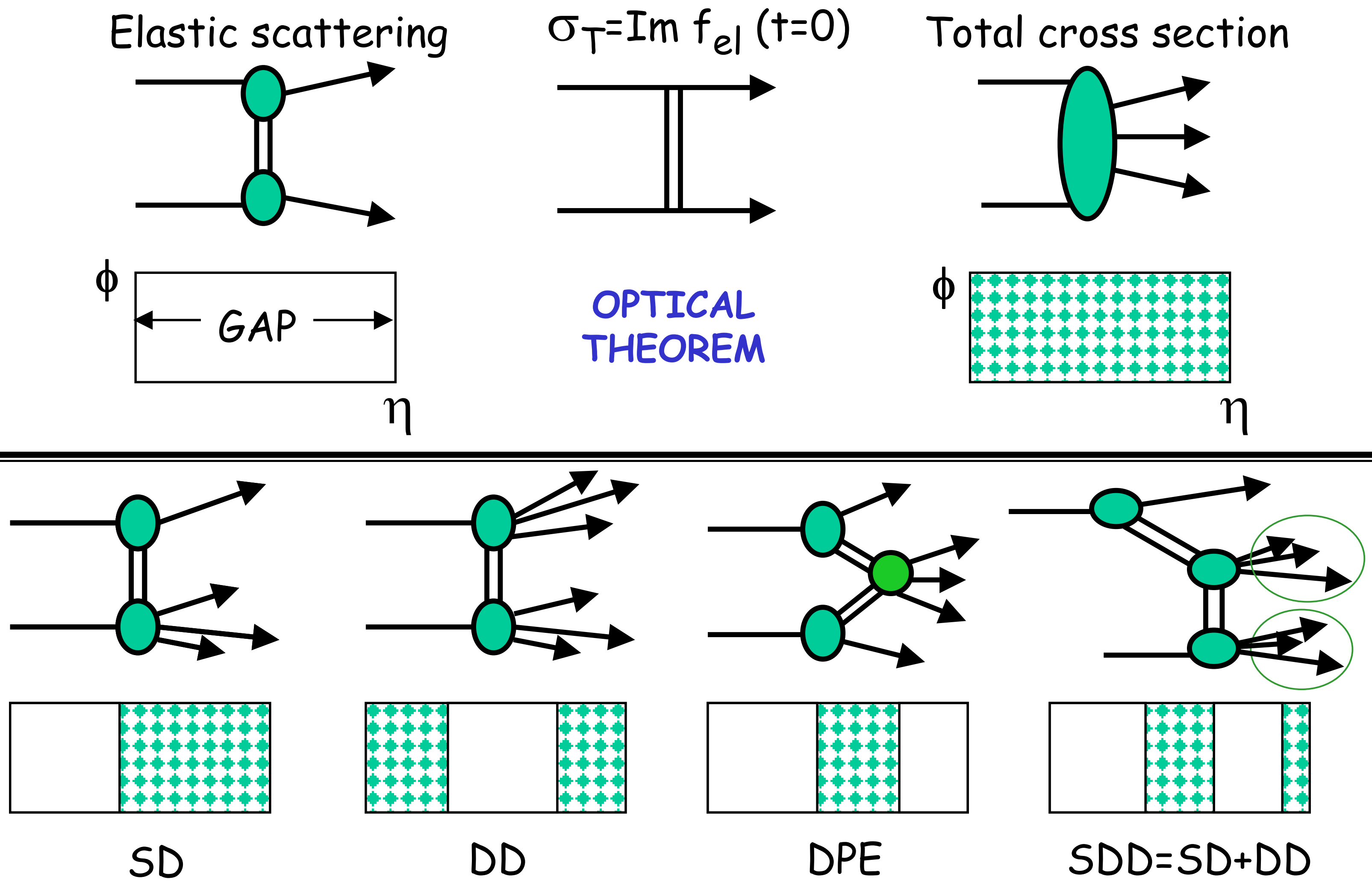
Rapidity Gaps





$$\left(\frac{d\sigma}{d\Delta\eta}\right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \Rightarrow \frac{d\sigma}{d\xi} \sim \frac{1}{\xi}$$

Diffractive $\bar{p}p$ Processes



Rapidity Gaps in Fireworks

The Physics

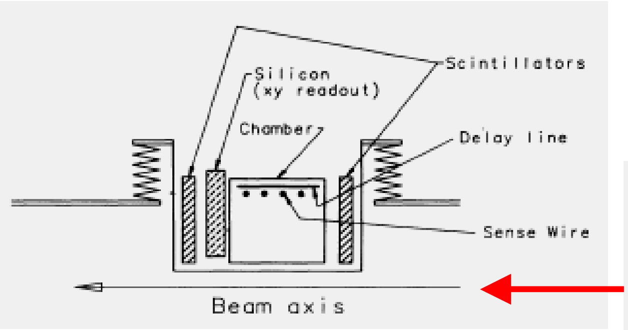
- Elastic and Total Cross Sections:..........pp→pp and pp→X
  - ✓ Fundamental Quantum Mechanics
    - Froissart Unitarity Bound..........$\sigma_T < C \ln^2 s$
    - Optical theorem............................$\sigma_T \sim \mathrm{Im}\, f(t=0)$
    - Dispersion relations.....................Re f(t=0)~Im f(t=0)
    - Is space-time discrete? → Measure σ_T and ρ-value at LHC!
- Diffraction Dissociation:..................pp→pX, XgX, pXp, pXgX, …
  - ✓ Non-perturbative QCD
    - Soft & hard diffraction
    - Factorization
    - Multi-gap diffraction
    - Diffraction in QCD:............what is the Pomeron?
    - Dark energy?
- Exclusive Production:..........................pp→pp+H (jet+jet, $\gamma+\gamma$, …, H^0)
  - ✓ Discovery channel
    - Diffractive Higgs production at the LHC (?)

Tevatron Experiments

Info / Exp	Roman Pots	El	σ_T	Soft diffraction	Hard diffraction
E710/811 **Scint. Counters**	p, pbar	x	x	sd	
CDF-0	p, pbar	x	x	sd	
CDF-I	pbar			sd,dd,dpe,sdd	JJ,b,J/ψ,W,JGJ
CDF-II	pbar			sd	JJ,W,Z,JGJ Exclusive JJ,$\gamma\gamma$,…
D0-I					JJ,W,Z,JGJ, …
D0-II	p, pbar	x	x	sd,dpe,…	JJ,W,Z,JGJ,… Exclusive ???

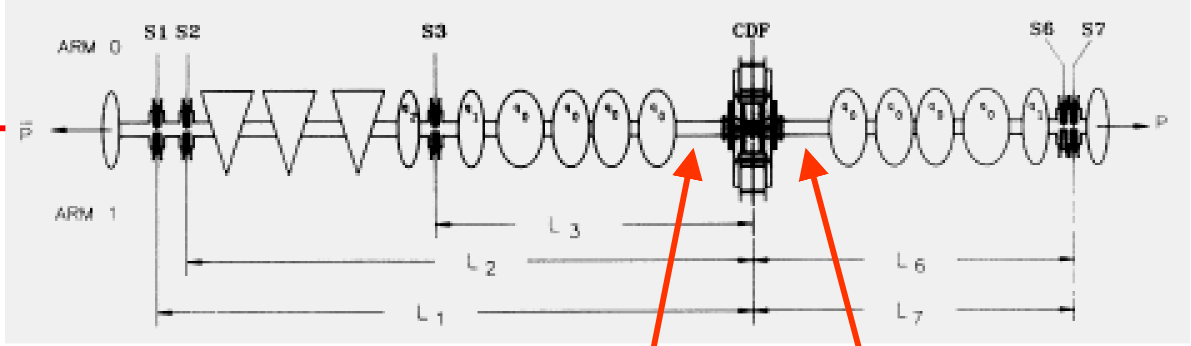
CDF Run 1-0 (1988-89)

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



Roman Pot Spectrometers

CDF-I



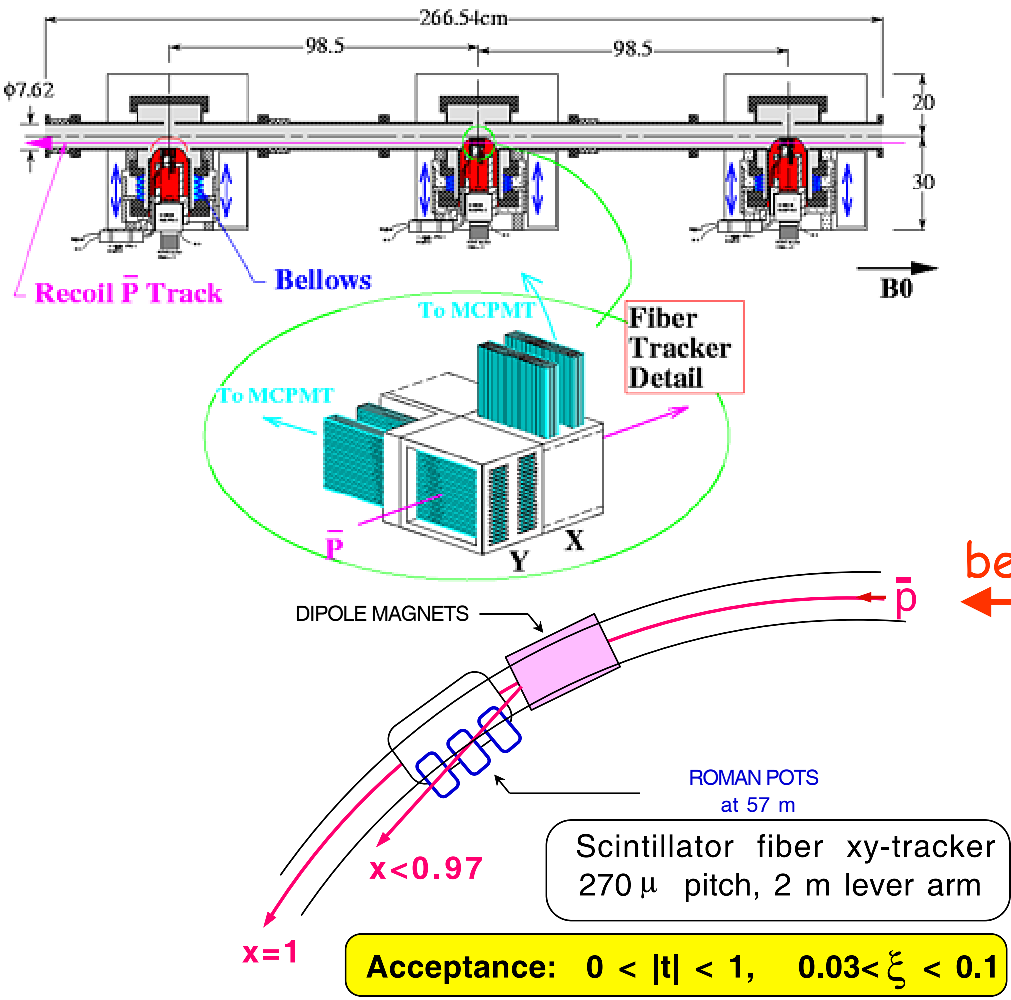
Roman Pot Detectors

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

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

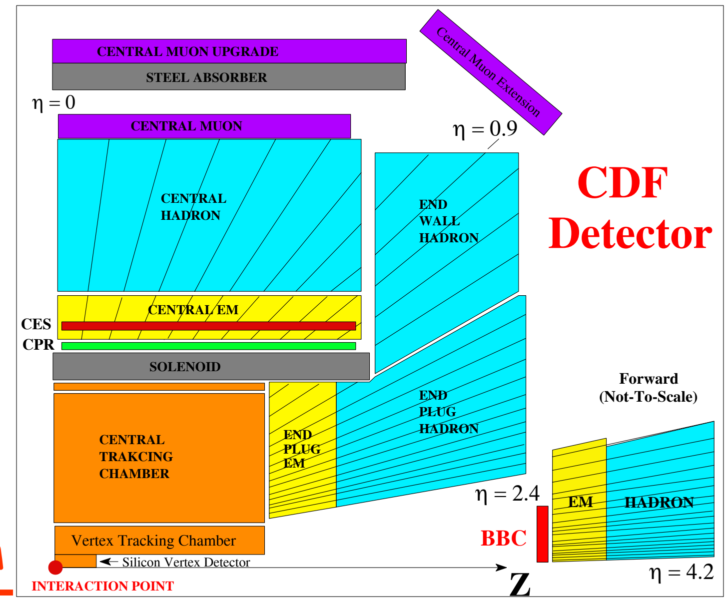
CDF-I

Run-IC



beam

Run-IA,B

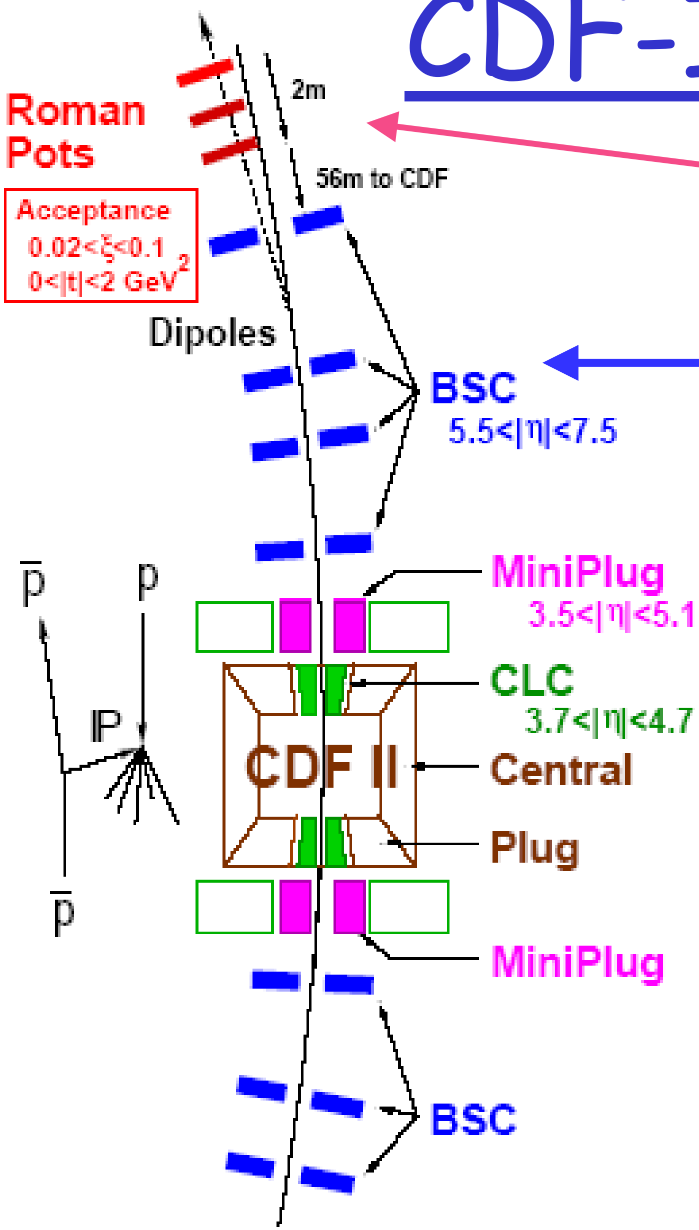


Forward Detectors

BBC 3.2<η<5.9

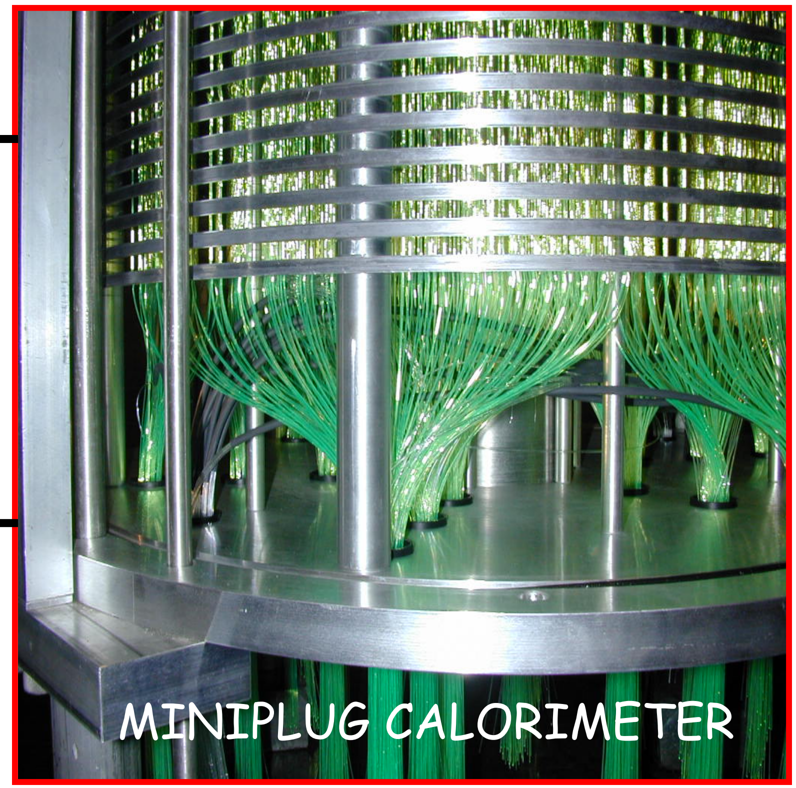
FCAL 2.4<η<4.2

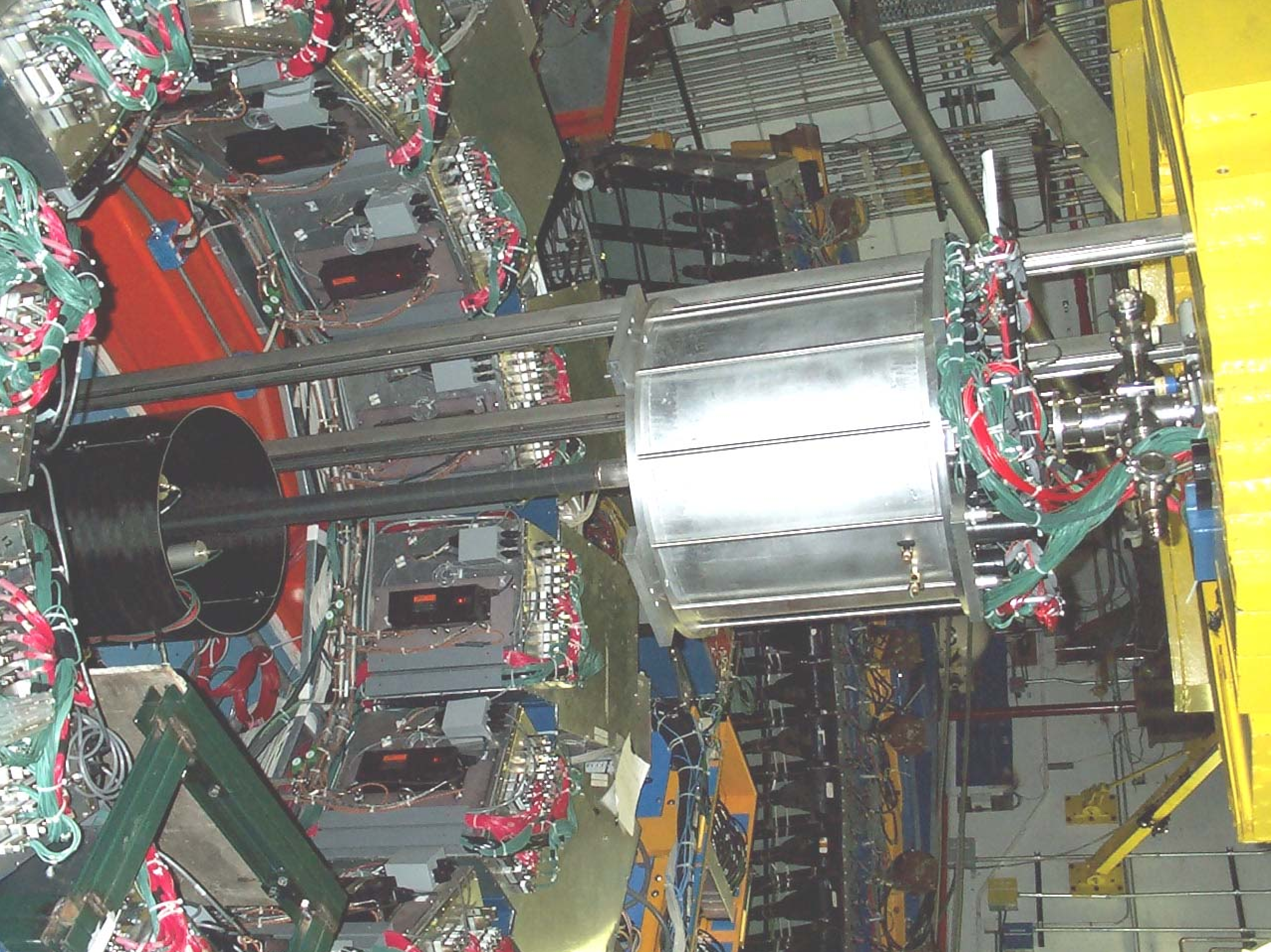
CDF-II



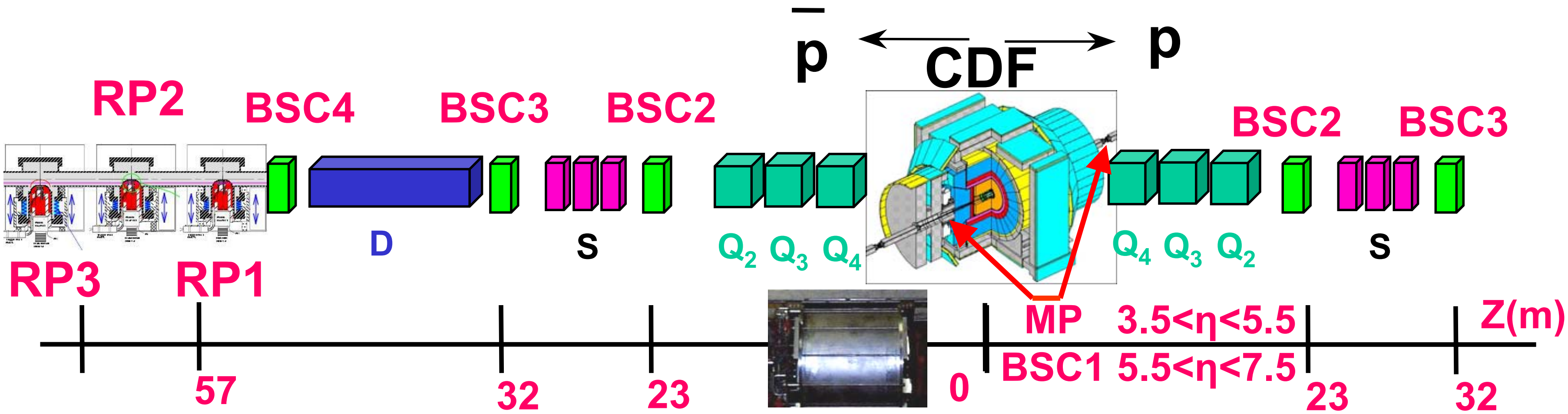
ROMAN POT DETECTORS

BEAM SHOWER COUNTERS:
Used to reject ND events

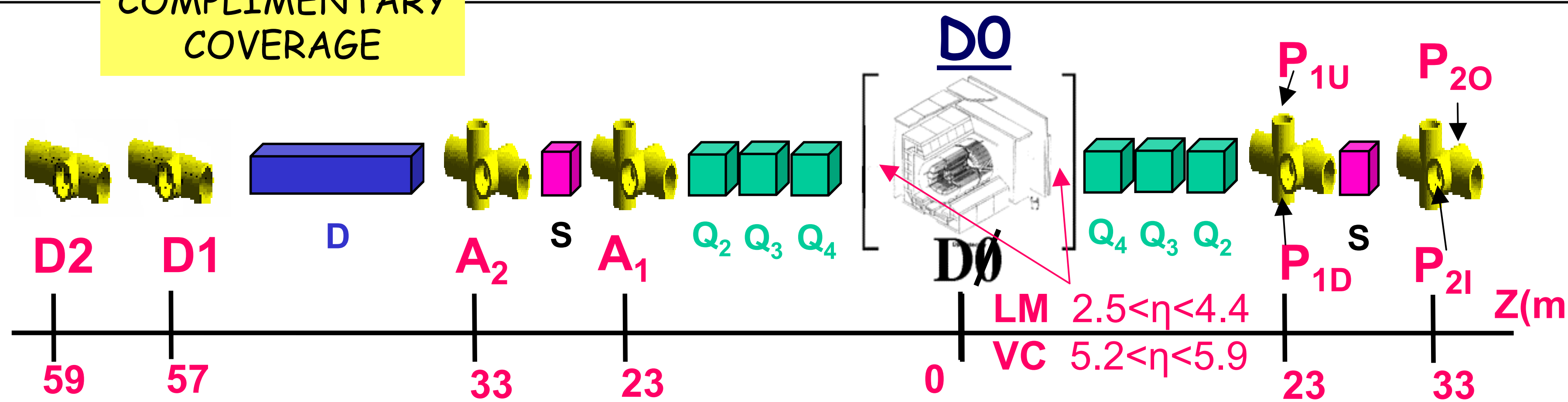




CDF & DO - Run II



CDF & DO:
COMPLIMENTARY
COVERAGE



From Barreto's talk in small-x

ELASTIC AND TOTAL CROSS SECTIONS

@ Tevatron: CDF and E710/811

➔ use luminosity independent method ➔

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

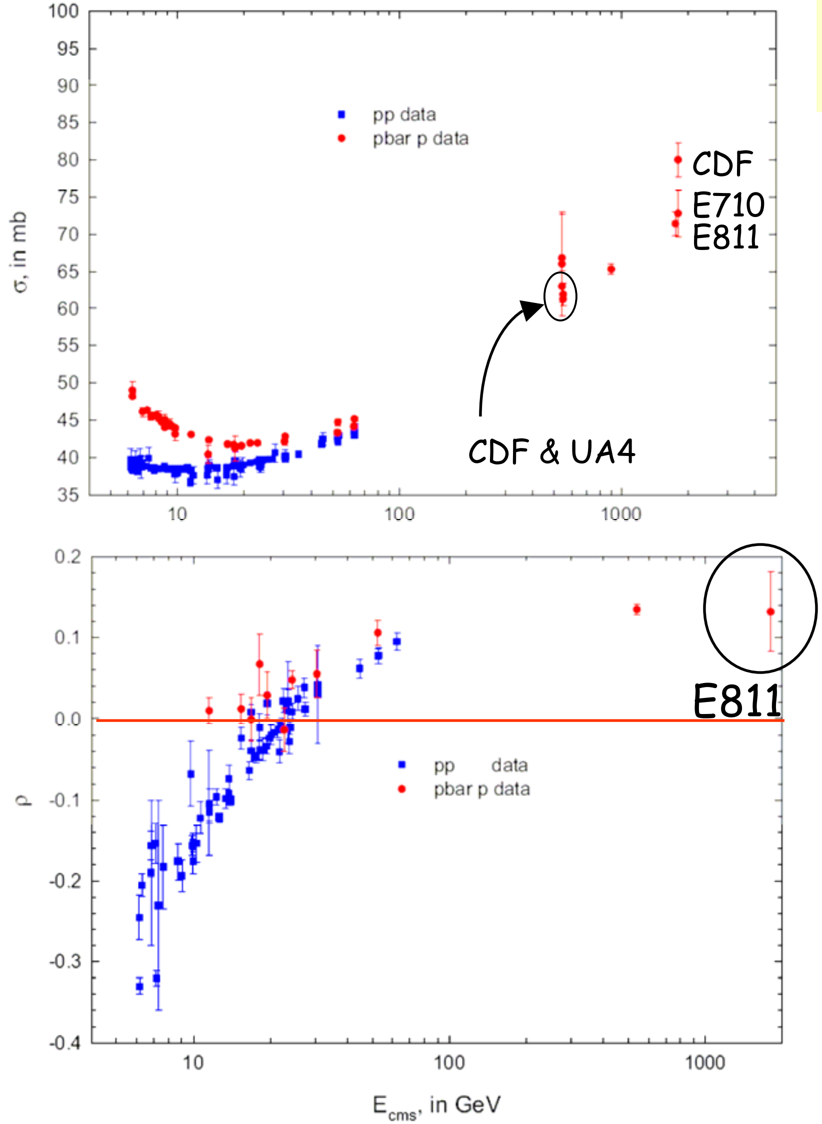
optical theorem

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

Alert:

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

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)

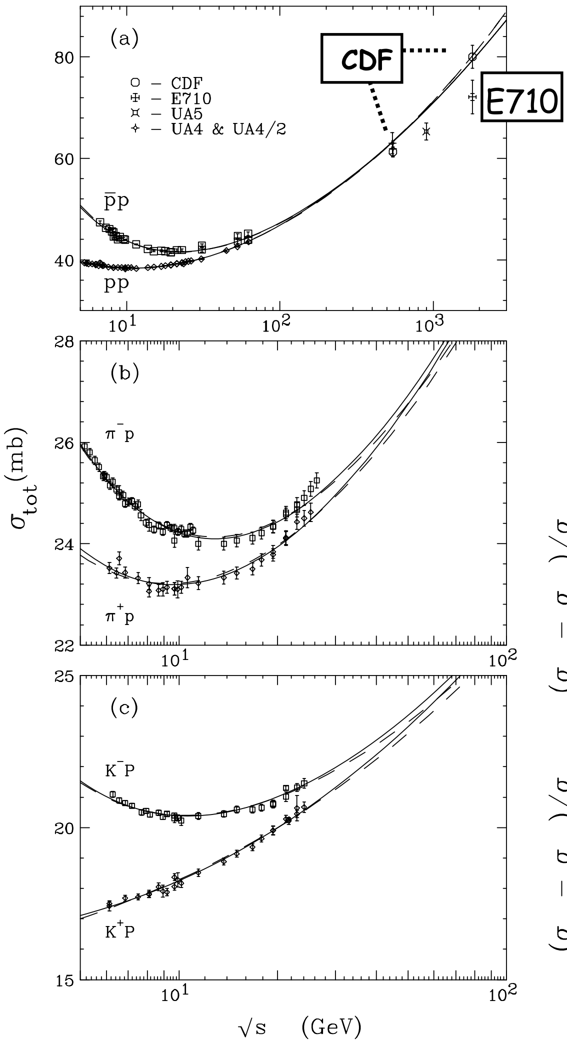
↕ **dispersion relations**

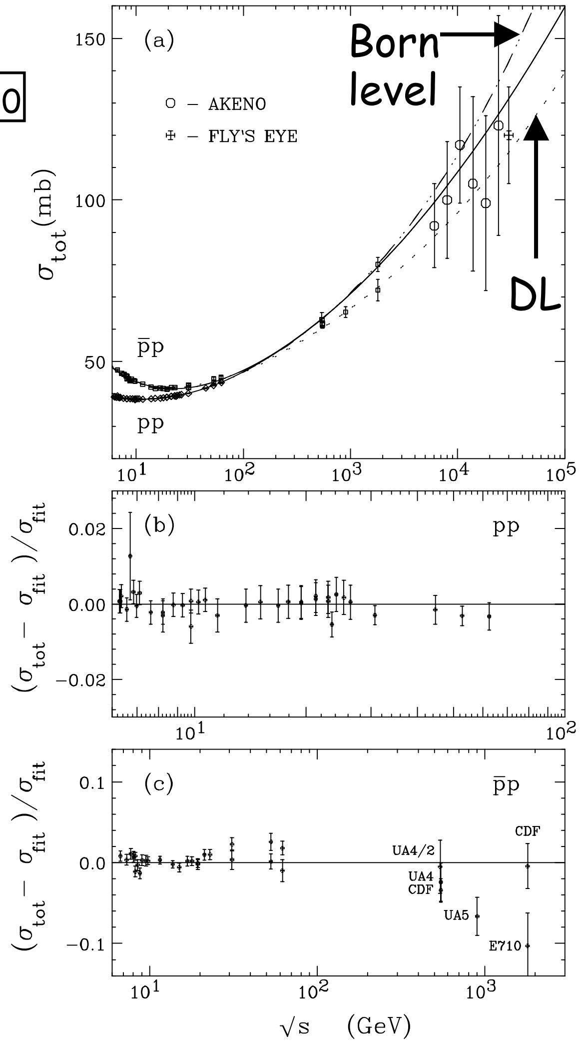
Re f_{el}(t=0)

N. Khuri and A. Martin:

measuring ρ at the LHC tests discreteness of space-time

Total Cross Sections: Regge fit





CMG: Covolan, Montagna, and G
PLB 389 (1995) 176

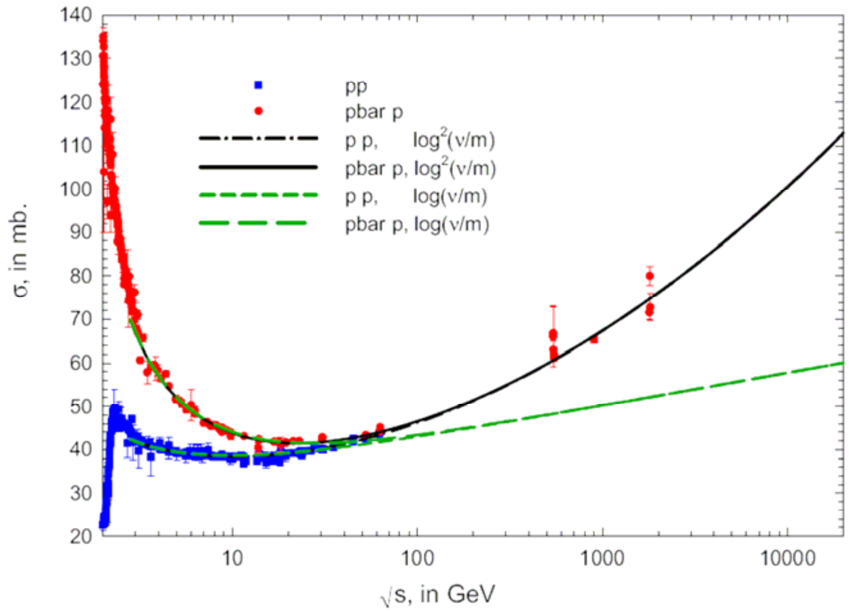
Simultaneous Regge fit to pp, πp, and Kp x-sections using the <u>eikonal approach</u> to ensure unitarity

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

ε = 1.104 +/- 0.002

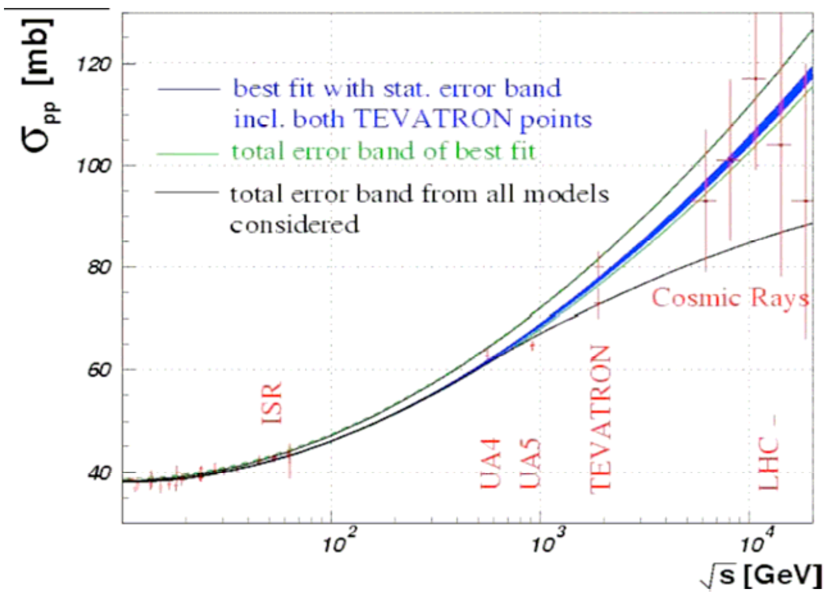
→ σ_{LHC} = 115 mb
@14 TeV

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: $\sigma_{tot} = 111.5 \pm 1.2 \begin{array}{l} +4.1 \\ -2.1 \end{array}$ mb [PRL 89 201801 (2002)]

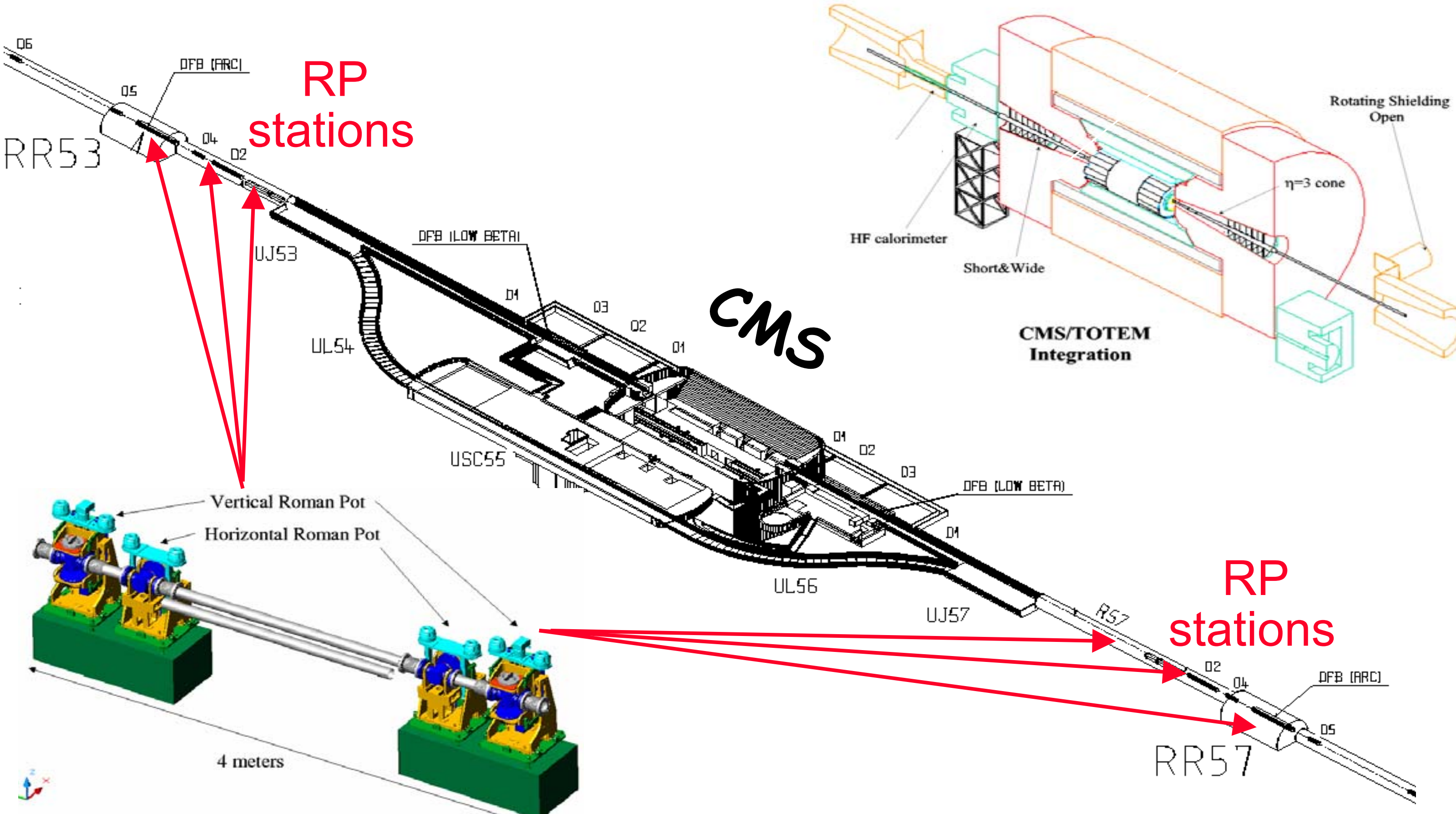
σ_T (LHC) = 107.3 ± 1.2 mb

Recall CMG Regge fit: 115 mb

TOTEM experiment @ LHC

Total Cross Section, Elastic Scattering, and Diffraction Dissociation

Aim at 1% accuracy on σ_T



CMS/TOTEM LOI: Prospects for Diffractive and Forward Physics at the LHC

SOFT DIFFRACTION

Key words:

renormalization

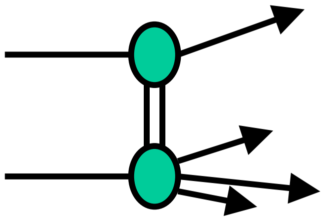
scaling

QCD

multi-gap

- Dark energy ???

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

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

❖ Regge theory

σ_{SD} exceeds σ_T at

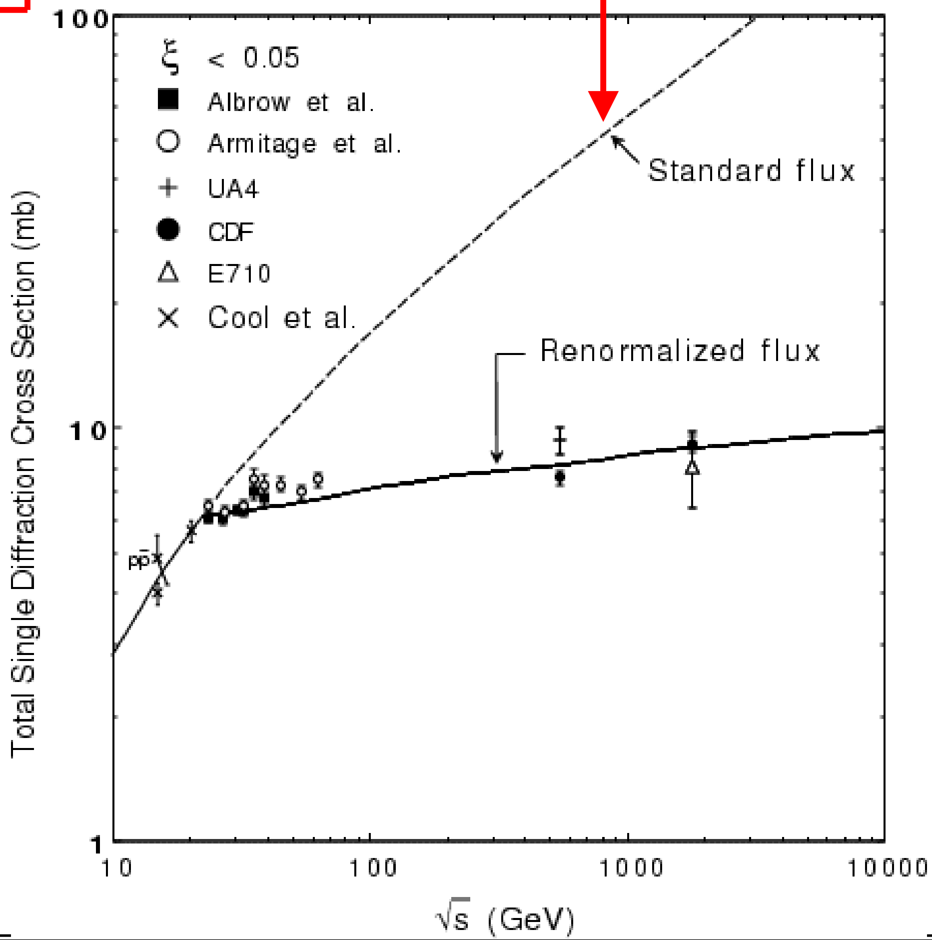
$$\sqrt{s} \approx 2\ \text{TeV}.$$

❖ Renormalization

Pomeron flux integral (re)normalized to unity

KG, PLB 358 (1995) 379

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



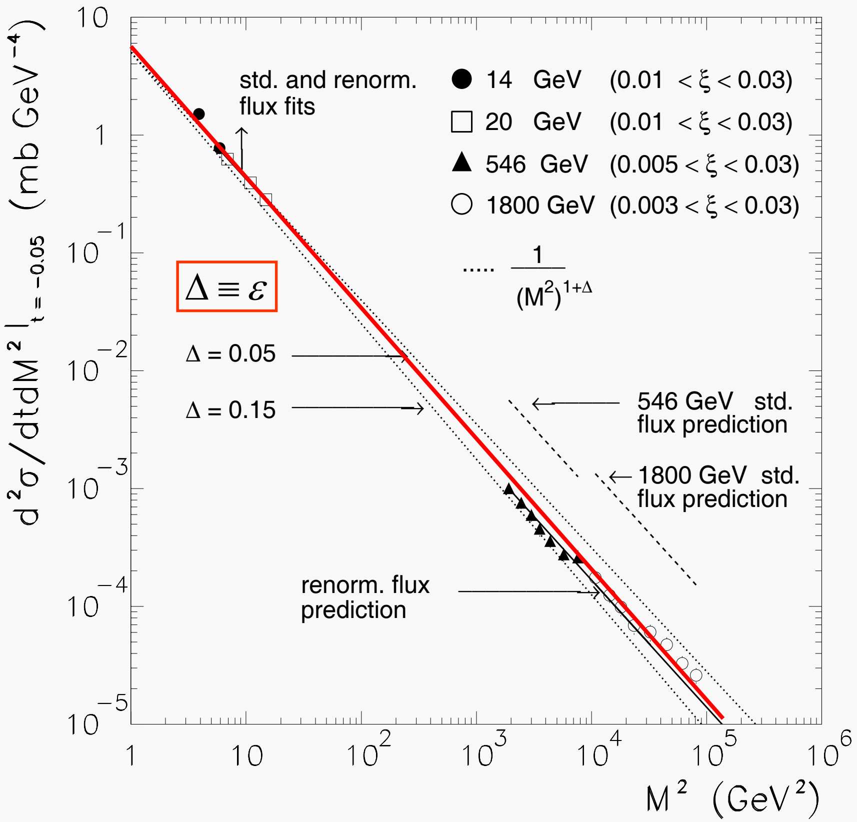
A Scaling Law in Diffraction

renormalization

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

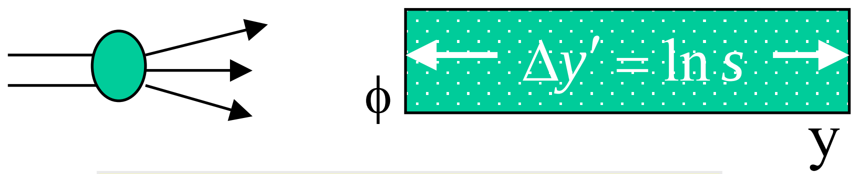
➔ Independent of S over 6 orders of magnitude in M² !

KG&JM, PRD 59 (1999) 114017



Factorization breaks down so as to ensure M²-scaling!

The QCD Connection

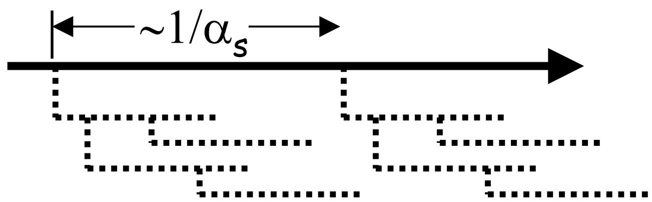


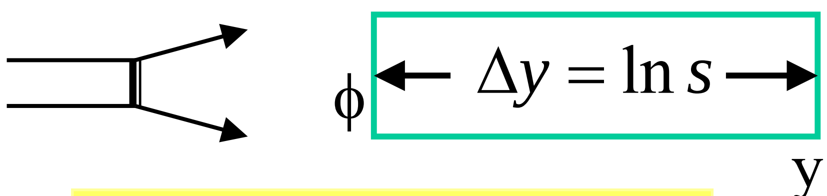
$$\sigma_T(s) = \sigma_o\, e^{\varepsilon \Delta y'} = \sigma_o\, s^{\varepsilon}$$

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

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

Total cross section: power law increase versus s



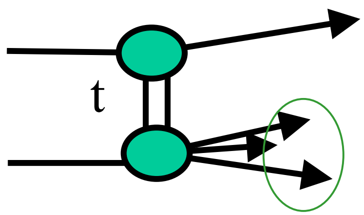


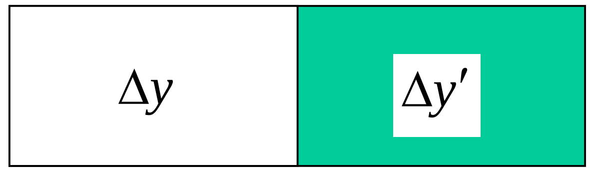
$$\operatorname{Im} f_{el}(s,t) \propto e^{(\varepsilon+\alpha' t)\Delta y}$$

Elastic cross section: forward scattering amplitude

Single Diffraction in QCD

(KG, hep-ph/0205141)





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

2 independent variables: $t, \Delta y$

color factor

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

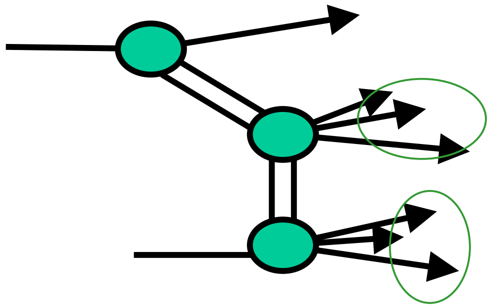
Gap probability

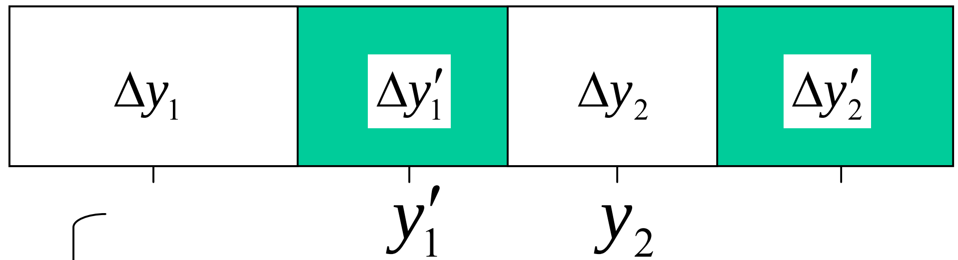
$$\sim e^{2\varepsilon \Delta y} \longrightarrow \int_{\Delta y_{\min}}^{\Delta y = \ln s} s^{2\varepsilon\, \Delta y} \approx s^{2\varepsilon}$$

Renormalization removes the s-dependence → SCALING

Multi-gap Renormalization

(KG, hep-ph/0205141)





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

color factors

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

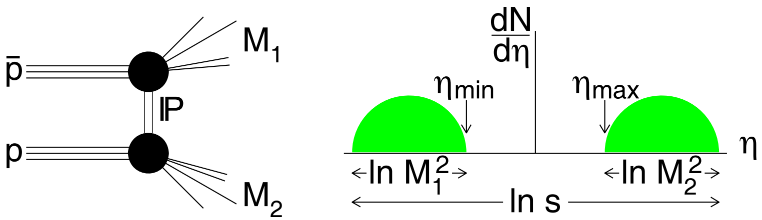
Gap probability $\sim e^{2\varepsilon \Delta y}$

Sub-energy cross section (for regions with particles)

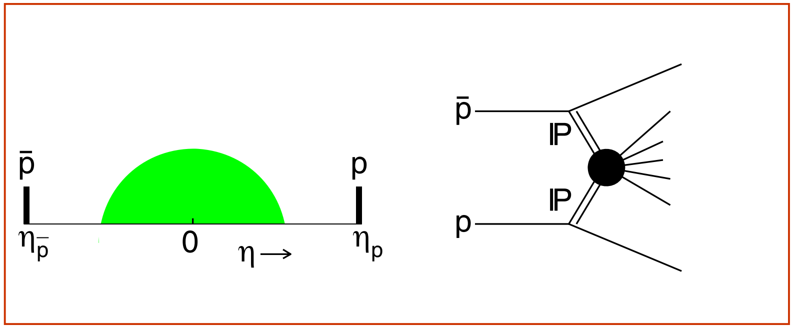
$$\int_{\Delta y_{\min}}^{\Delta y = \ln s} s^{2\varepsilon \Delta y} \approx s^{2\varepsilon}$$

Same suppression as for single gap!

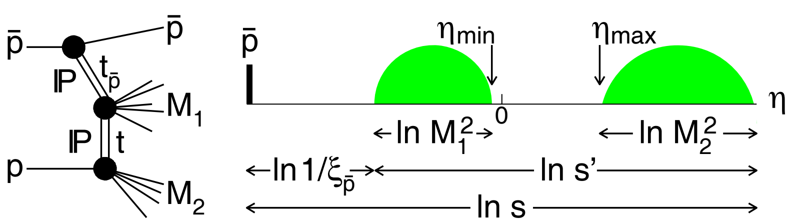
Central and Double Gaps @ CDF



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



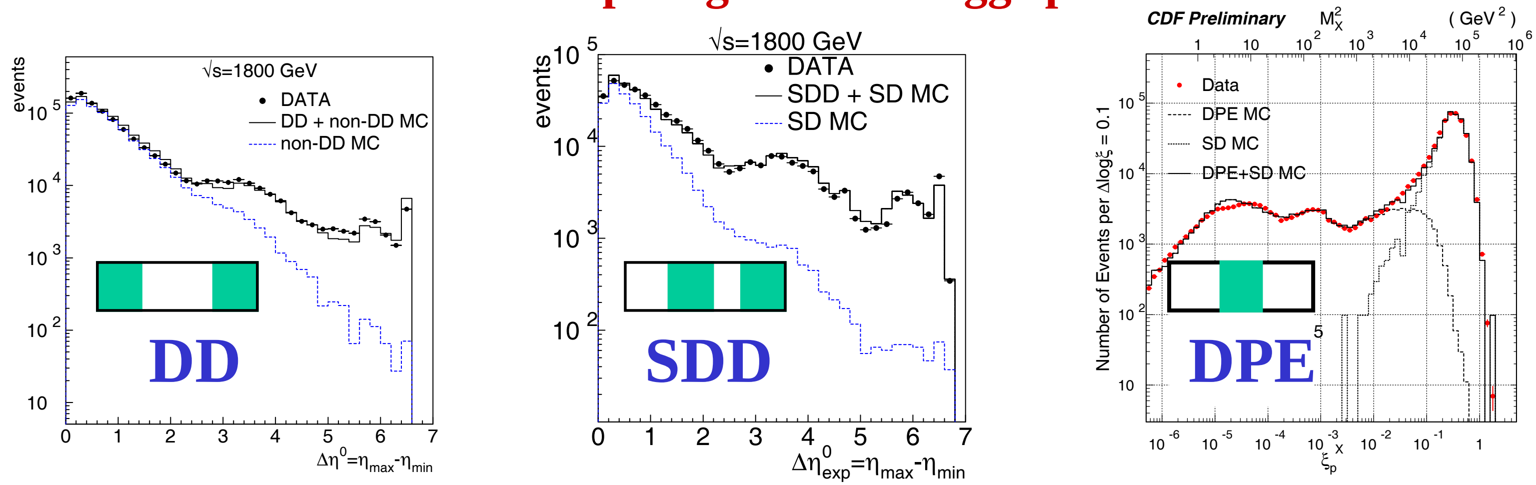
- **Double Pomeron Exchange**
  - **Two forward gaps**



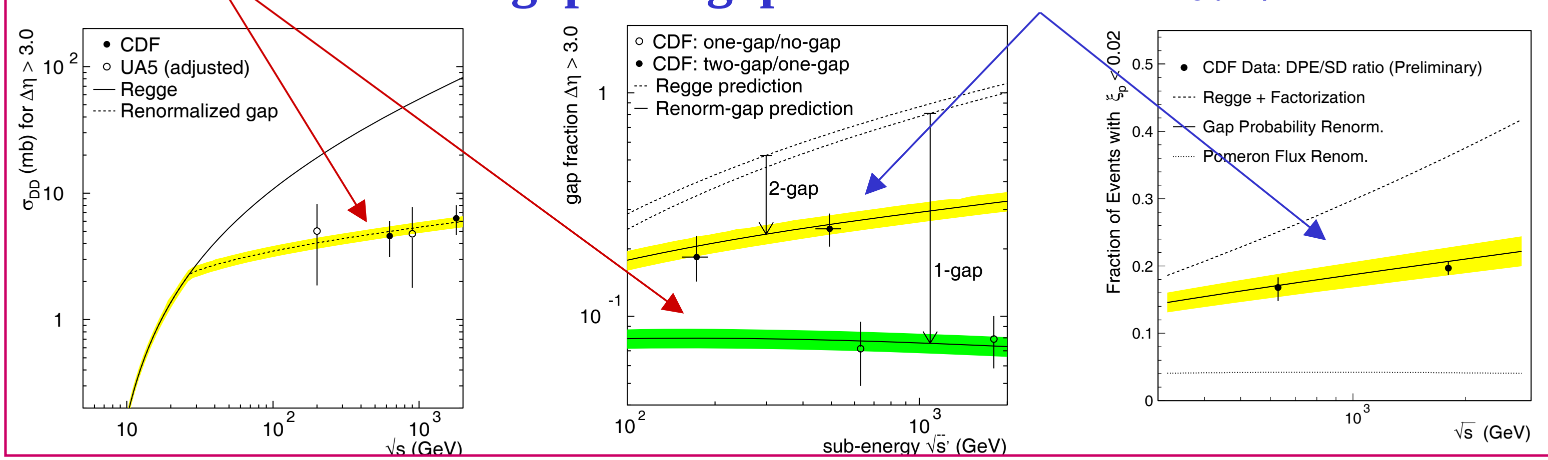
- **SDD: Single+Double Diffraction**
  - **One forward + one central gap**

Central & Double-Gap CDF Results

Differential shapes agree with Regge predictions



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



Dark Energy

Non-diffractive interactions

Rapidity gaps are formed by multiplicity fluctuations:

$$P(\Delta y) = e^{-\rho \Delta y}, \quad \rho = \frac{dN_{particles}}{dy}$$

P(Δy) is exponentially suppressed

Diffractive interactions

Rapidity gaps at t=0 grow with Δy:

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

$$P(\Delta y)\Big|_{t=0} \sim e^{2\varepsilon \Delta y}$$

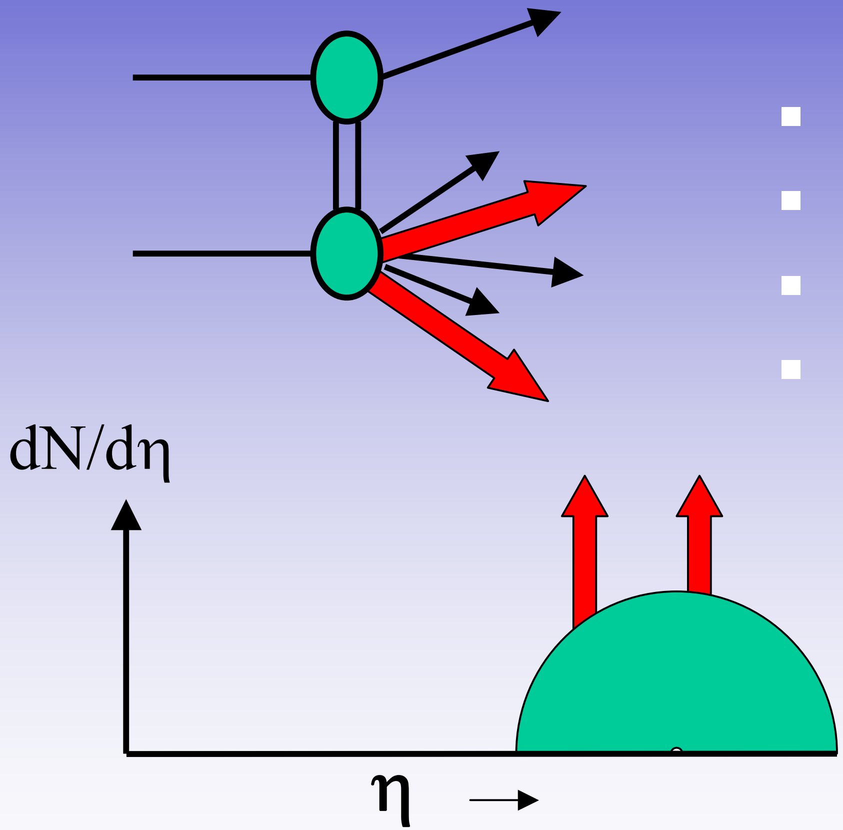
2ε: negative particle density!

⬇

Gravitational repulsion?

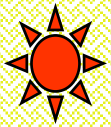
HARD DIFFRACTION

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

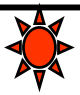


JJ, W, b, J/ψ

Diffractive Fractions @ CDF

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

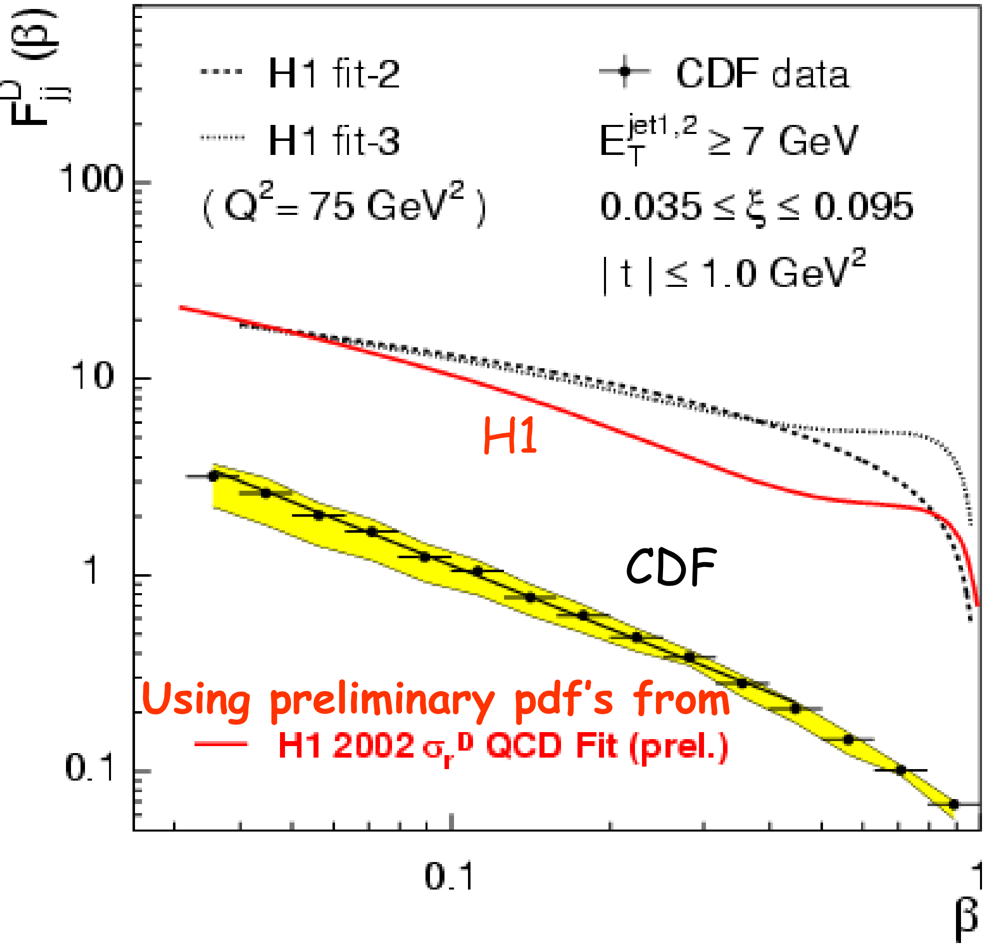
Fraction:
SD/ND ratio at 1800 GeV

	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

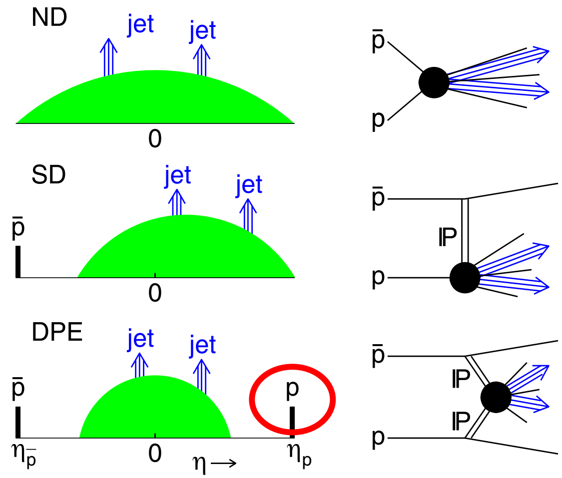


β = momentum fraction of parton in Pomeron

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!

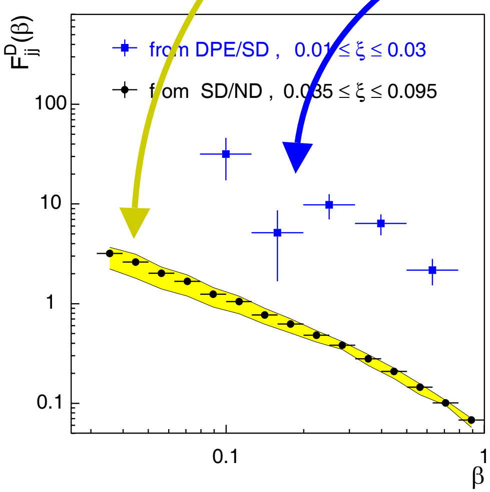
Restoring QCD Factorization

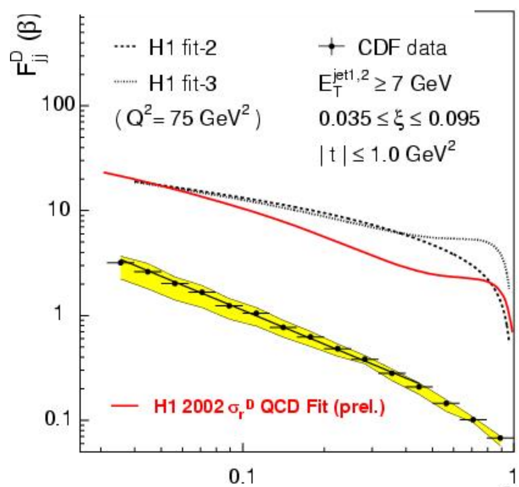


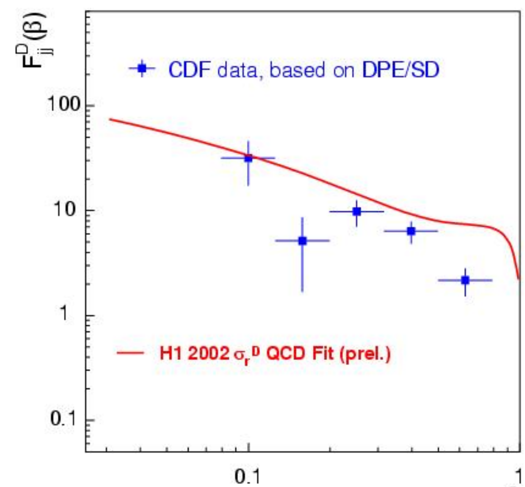
R(SD/ND)

R(DPE/SD)

DSF from two/one gap: factorization restored!

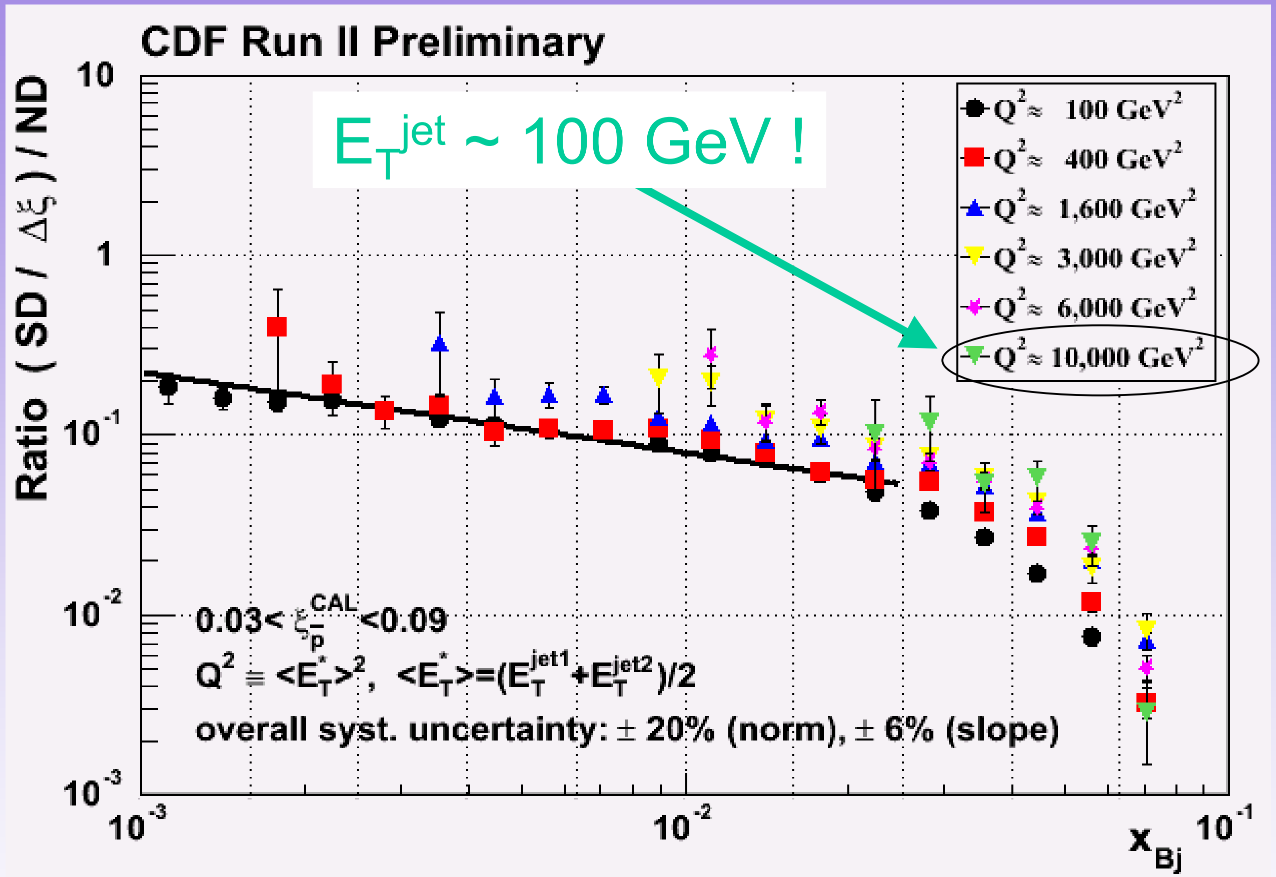






The diffractive structure function measured on the proton side in events with a leading antiproton is NOT suppressed relative to predictions based on DDIS

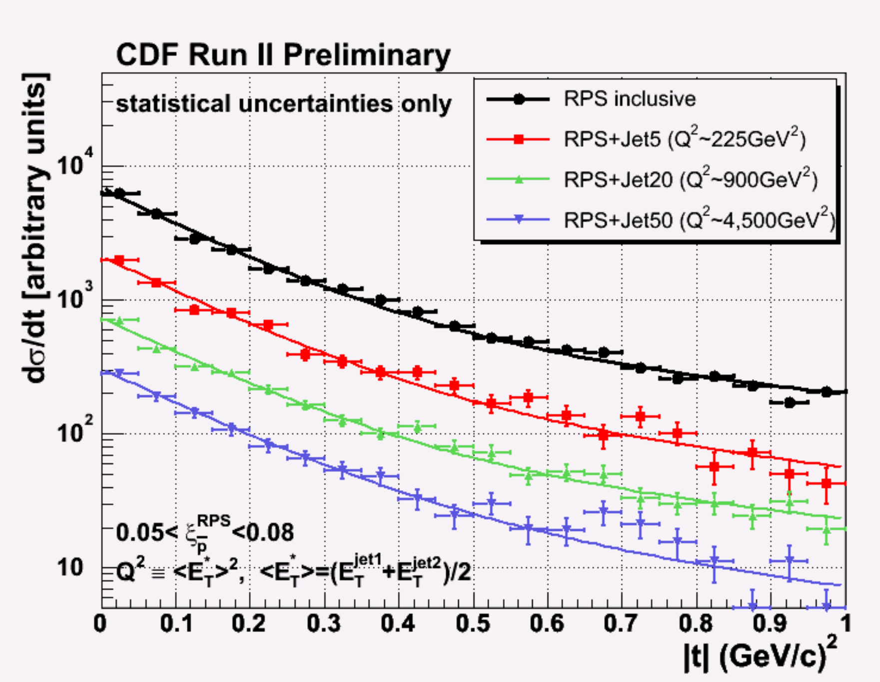
Diffractive Structure Function: Q^2 dependence

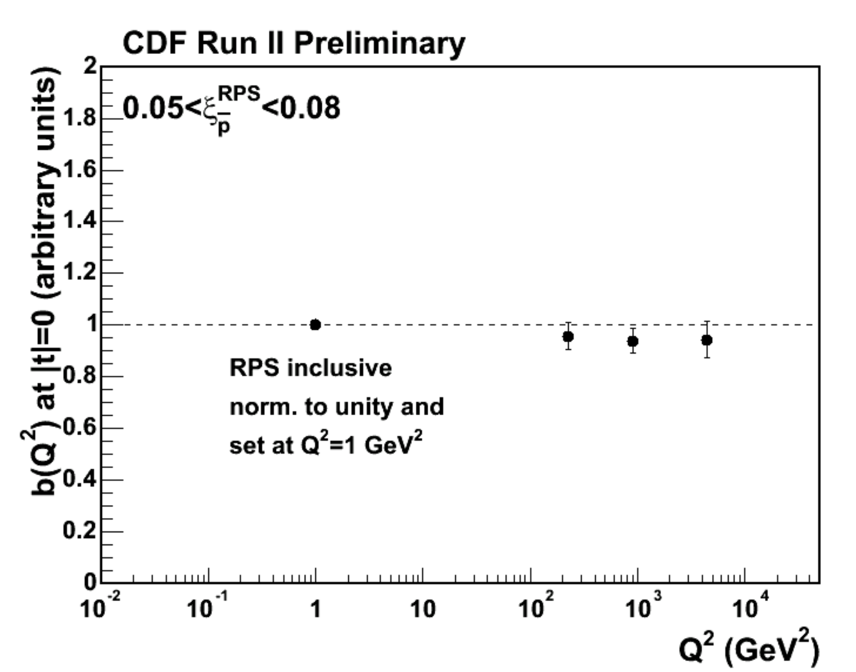


Small Q^2 dependence in region 100 < Q^2 < 10,000 GeV^2

⇨ **Pomeron evolves as the proton!**

Diffractive Structure Function:
t- dependence





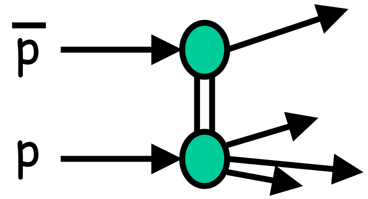
Fit dσ/dt to a double exponential:

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

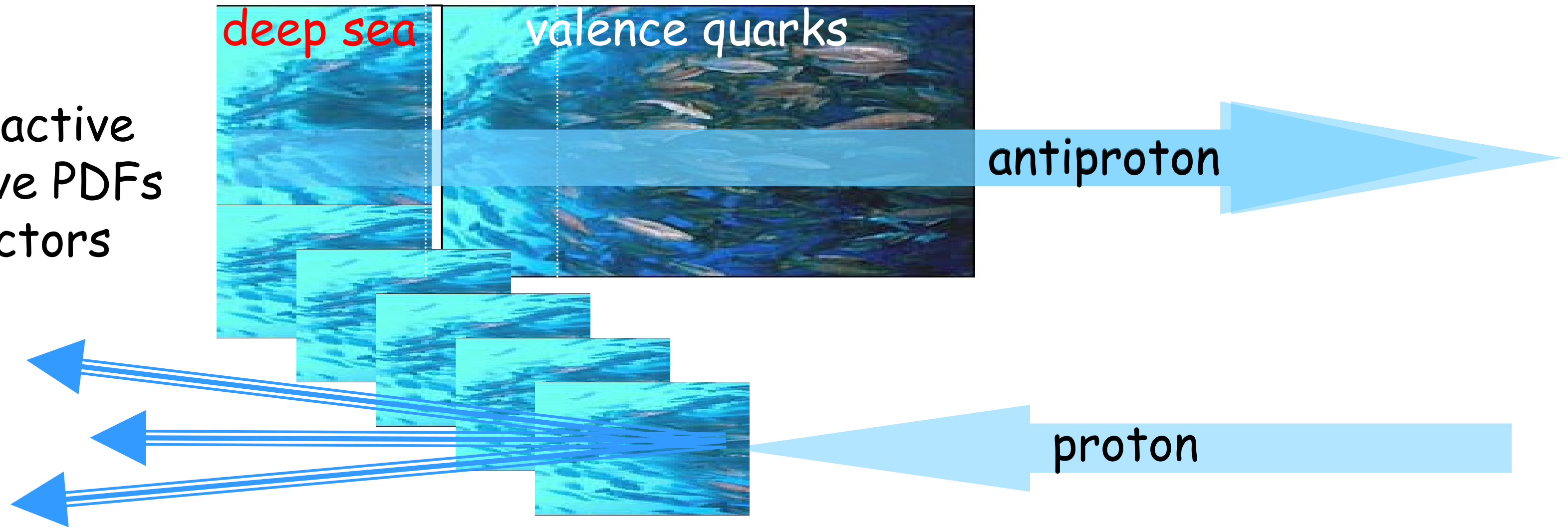
- No diffraction dips
- No Q2 dependence in slope from inclusive to $Q^2 \sim 10^4$ GeV^2

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

Hard Diffraction in QCD

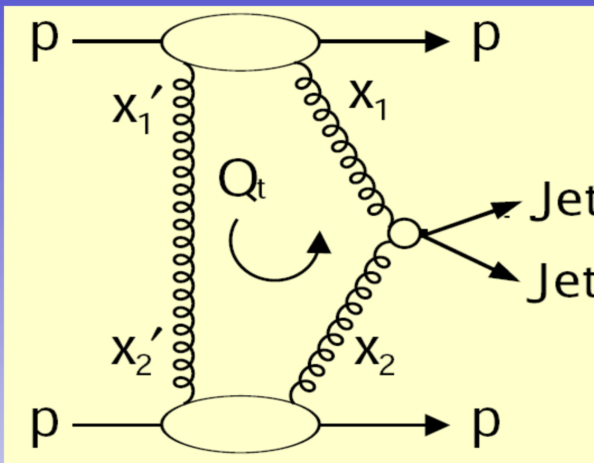


Derive diffractive from inclusive PDFs and color factors



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,
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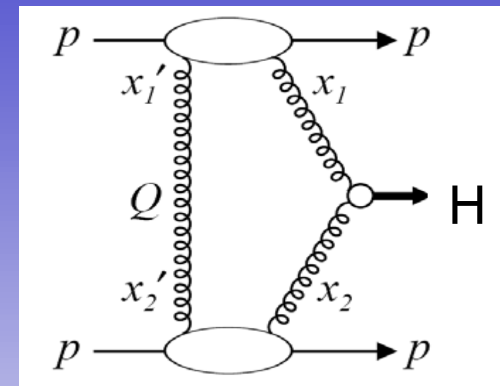
C25,391 (2002);C26,229 (2002)
C. Royon, hep-ph/0308283
B. Cox, A. Pilkington,
PRD 72, 094024 (2005)
OTHER……………………….

Clean discovery channel



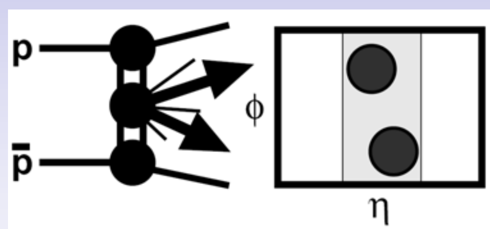
KMR: σ_H(LHC) ~ 3 fb
S/B ~ 1 if ΔM ~ 1 GeV

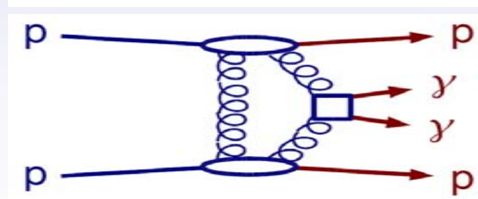
Search for exclusive dijets:

Measure dijet mass fraction

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

Look for signal as M_{jj} → 1





Search for exclusive $\gamma\gamma$

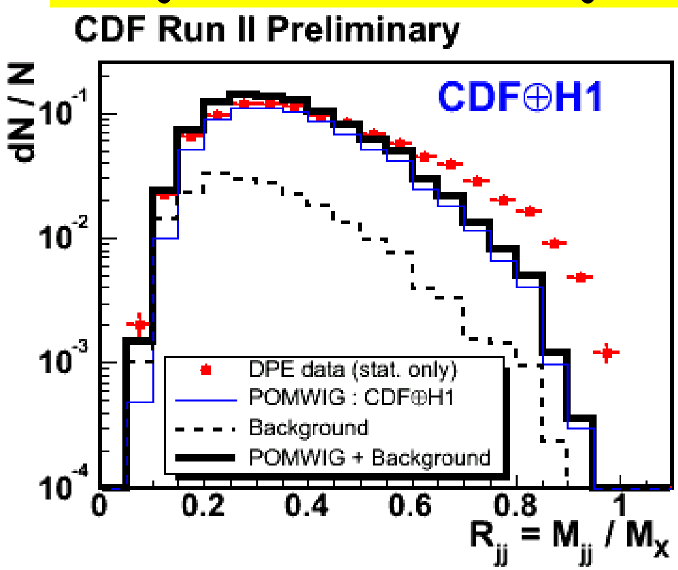
✓ 3 candidate events found
✓ 1 (+2/-1) predicted from ExHuME MC*
✓ background under study

* See talk by V. Khoze

Exclusive Dijet Signal

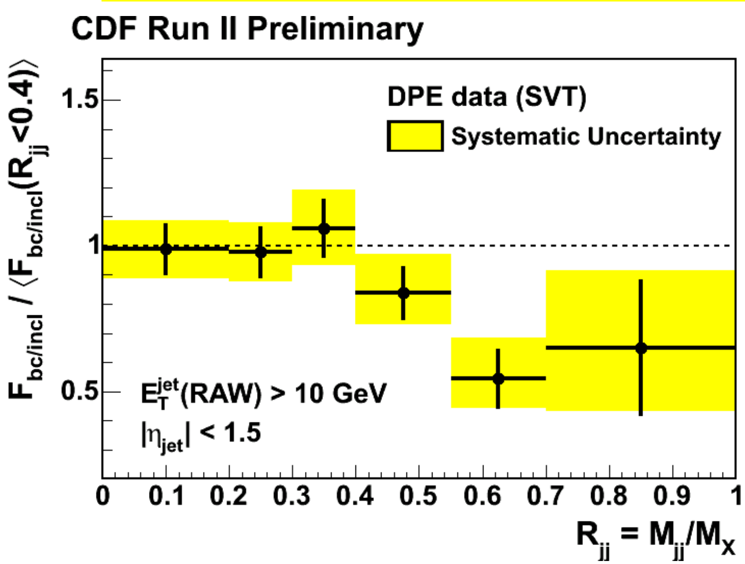
D I J E T S

Dijet fraction – all jets



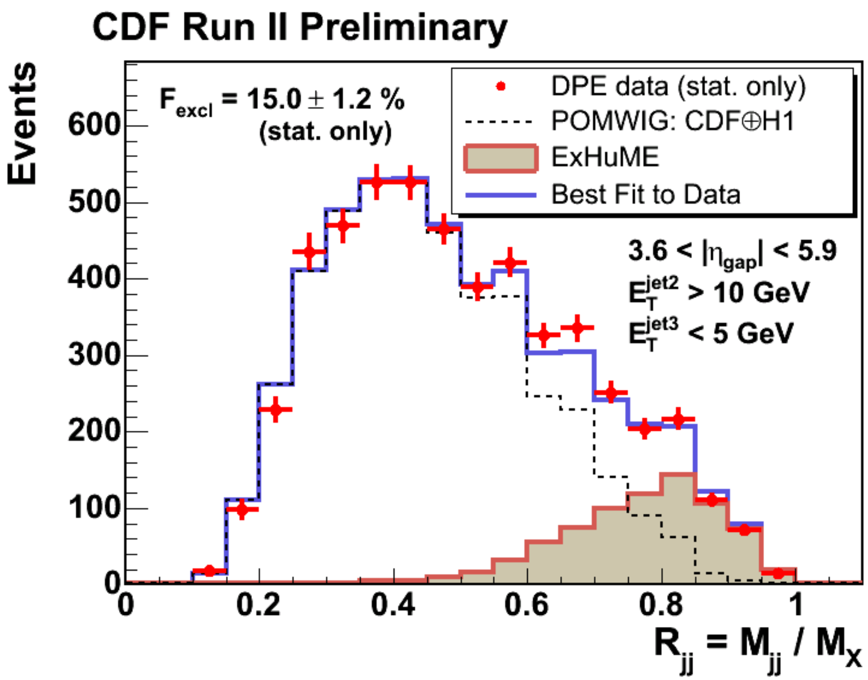
Excess over MC predictions at large dijet mass fraction

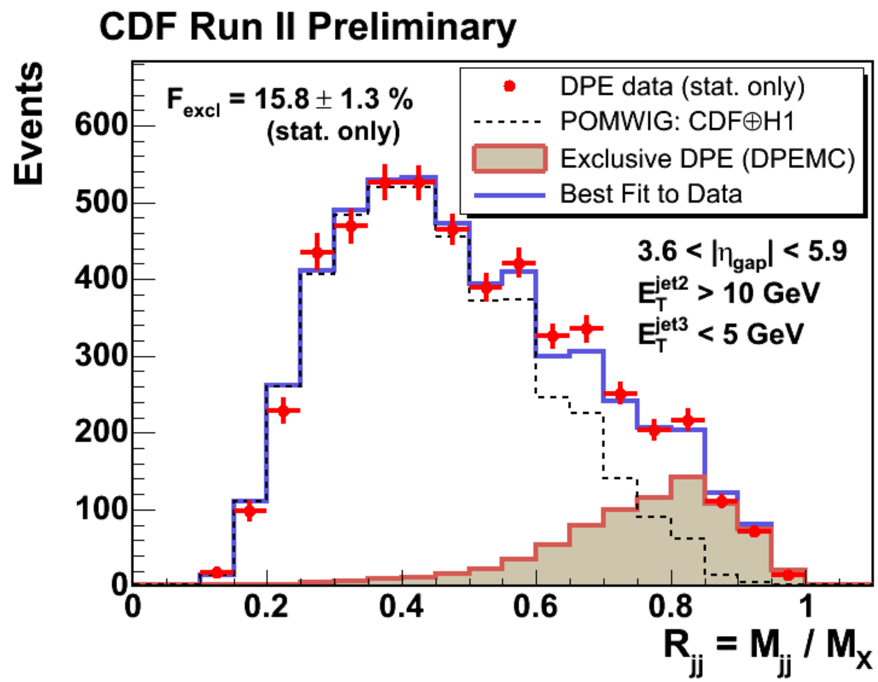
b-tagged dijet fraction



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

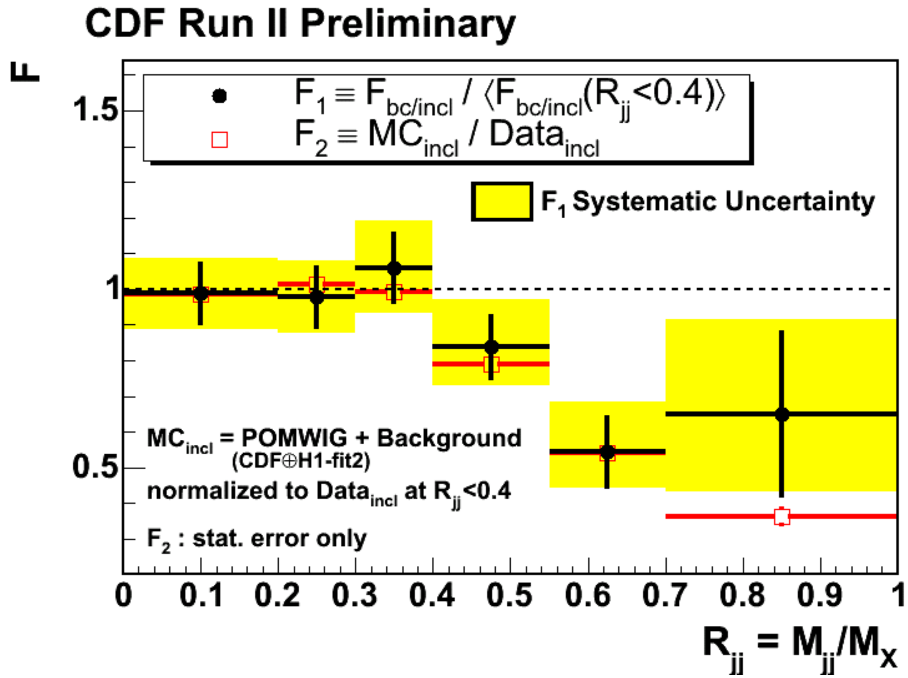
Exclusive DPE (DPEMC)
➔ non-pQCD based on Regge theory

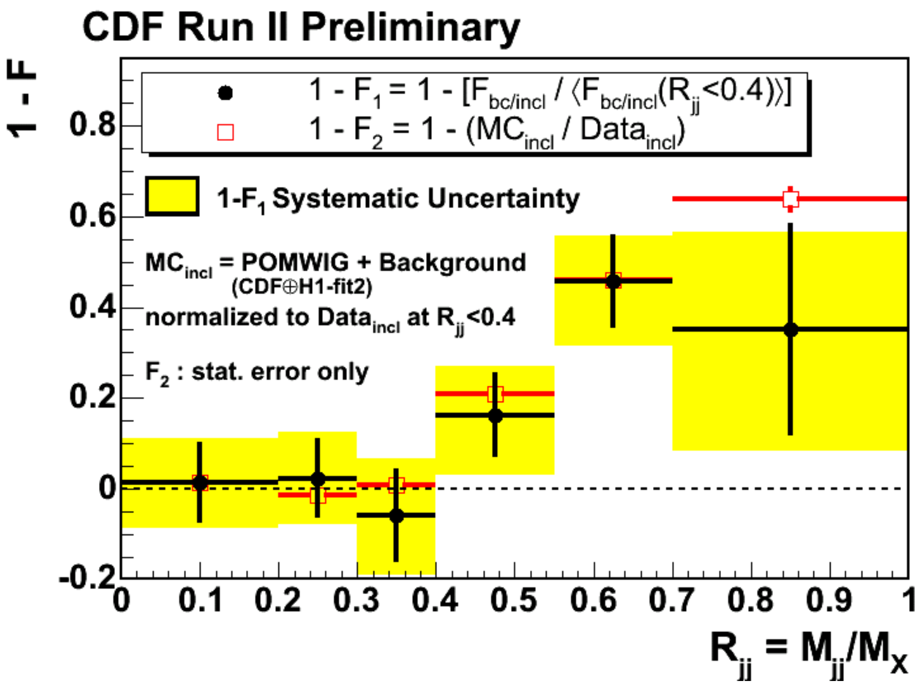
Shape of excess of events at high R_{jj}
is well described by both models

jj_{excl}: Exclusive Dijet Signal

COMPARISON

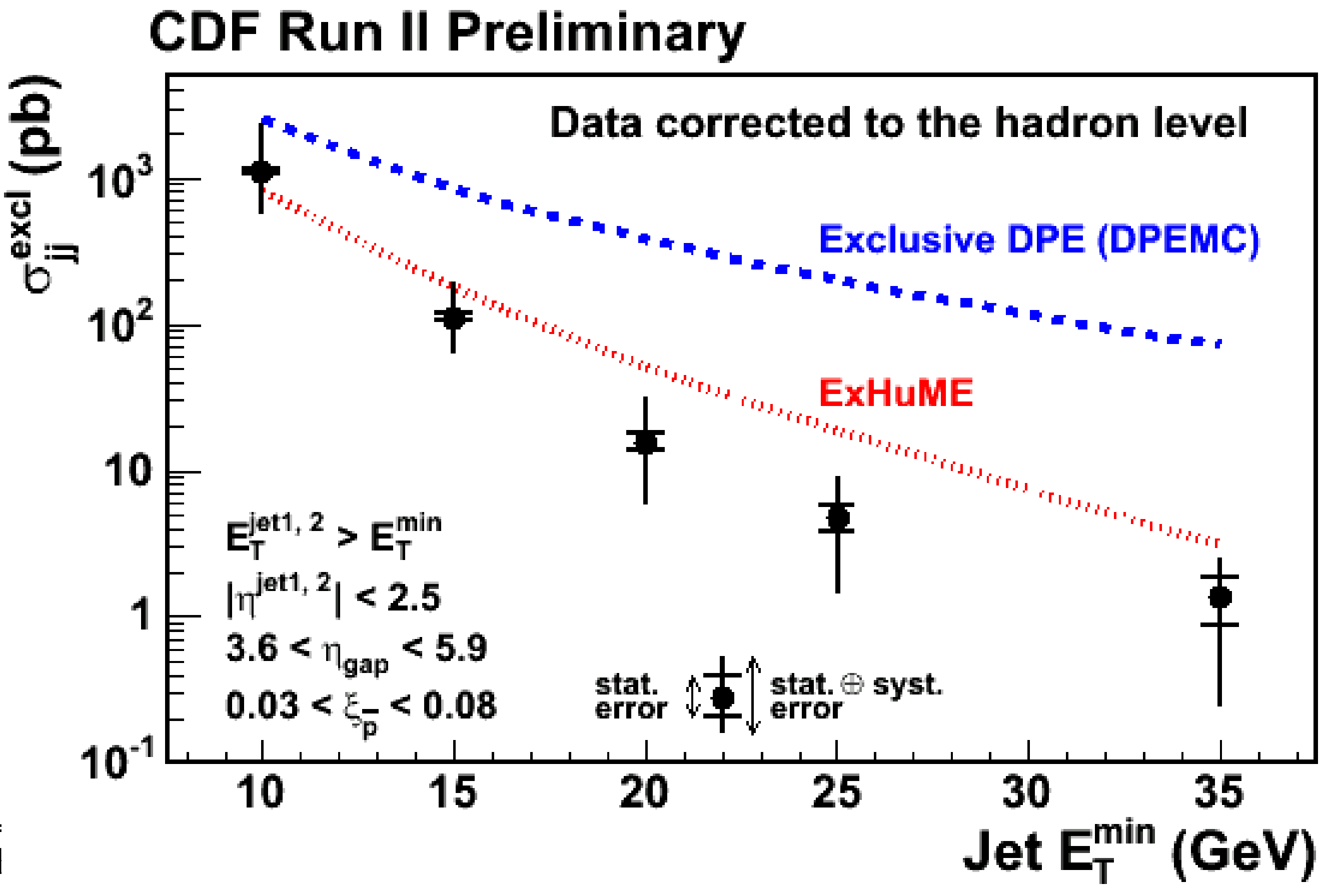
Inclusive data vs MC @ b/c-jet data vs inclusive





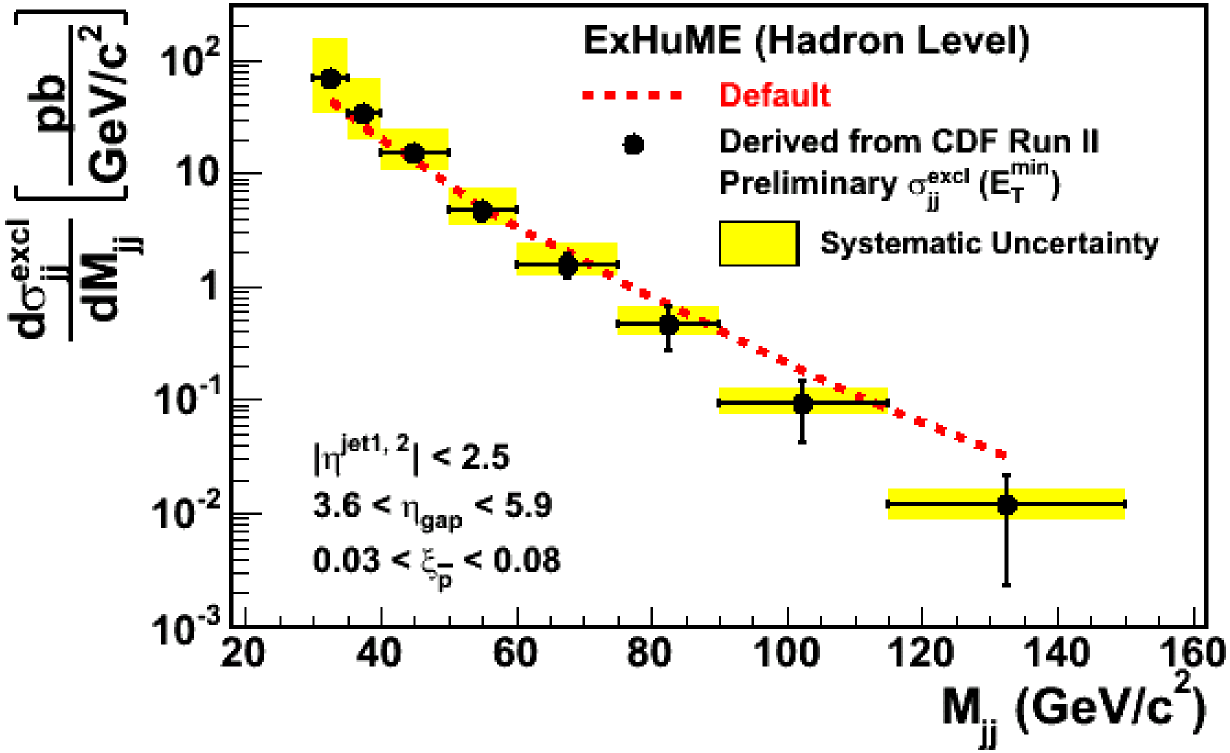
JJ_{excl} : x-section vs E_T(min)

Comparison with hadron level predictions
ExHuME (red)
Exclusive DPE in DPEMC (blue)



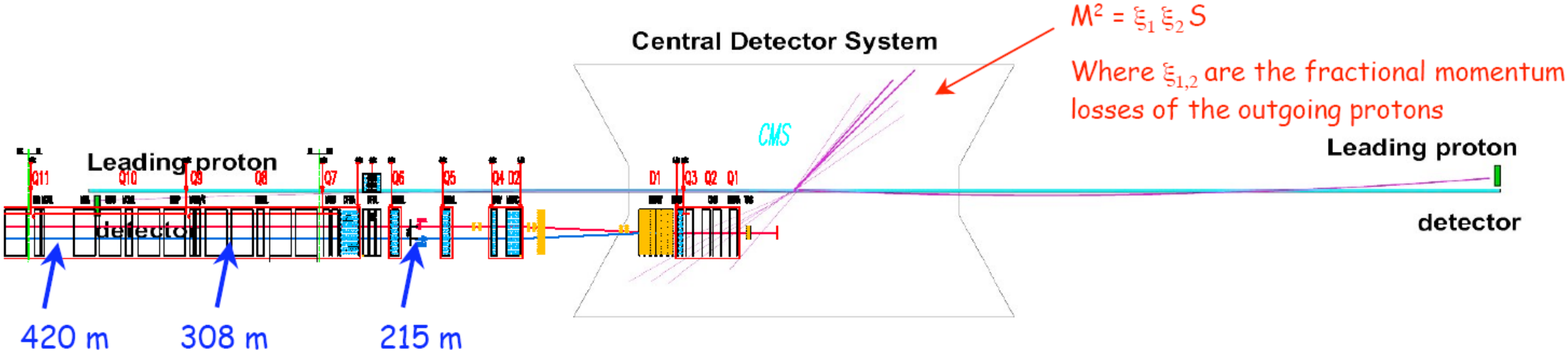
JJ_{excl} : cross section predictions

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.

Looking forward @ LHC



TOTEM/CMS
ATLAS

<u>FP420 project</u>: http://www.fp420.com/
Measure protons at 420 m from the IP during normal high luminosity running to be used in conjunction with CMS and ATLAS
Feasibility study and R&D for Roman Pot detector development

- Physics aim :pp $\rightarrow$ p+ X + p (Higgs, New physics, QCD studies)
- Status: Project funded by the UK

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