Diffractive and Total Cross Sections @ Tevatron and LHC

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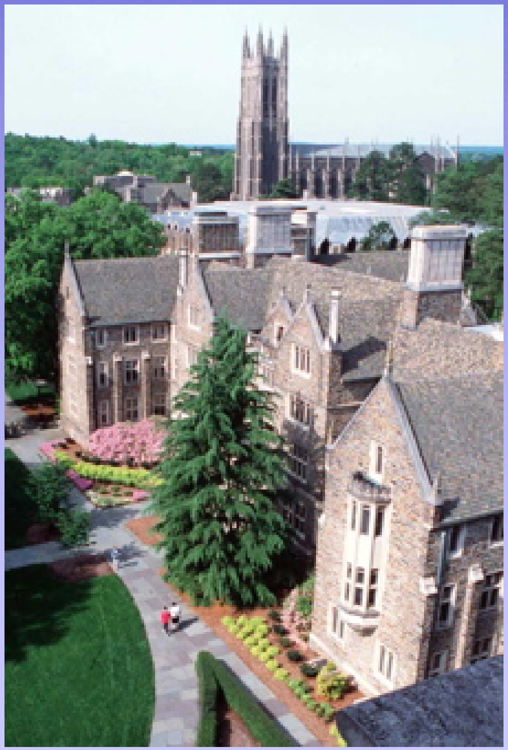
The Rockefeller University

→ CDF results are presented on behalf of the CDF Collaboration ←



Contents

$\bar{p}$-p Interactions

Non-diffractive:

Color-exchange

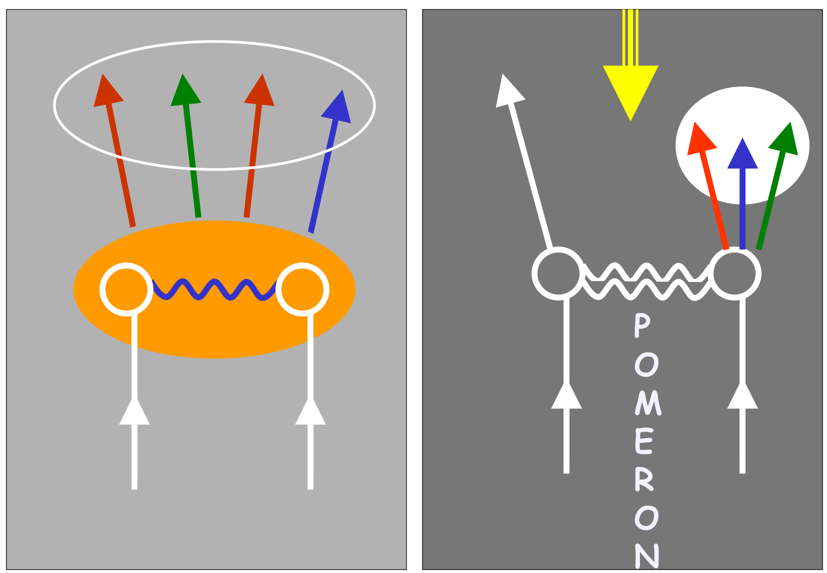
Diffractive:

Colorless exchange with vacuum quantum numbers

rapidity gap

Incident hadrons acquire color and break apart

CONFINEMENT



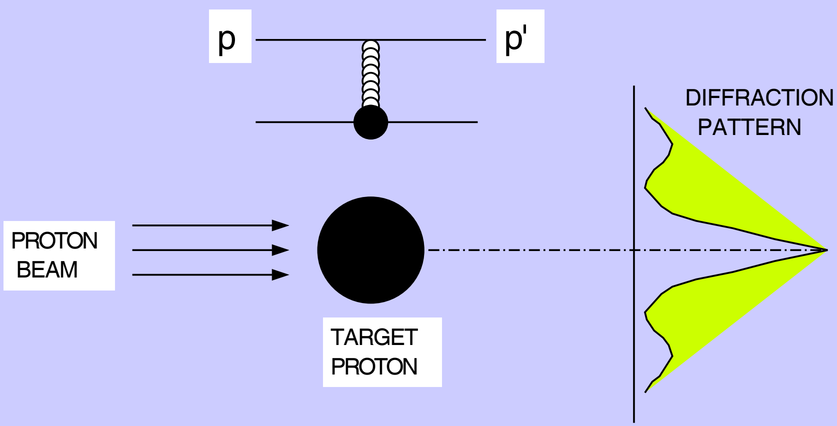
Incident hadrons retain their quantum numbers remaining colorless

pseudo-DECONFINEMENT

Goal: understand the QCD nature of the diffractive exchange

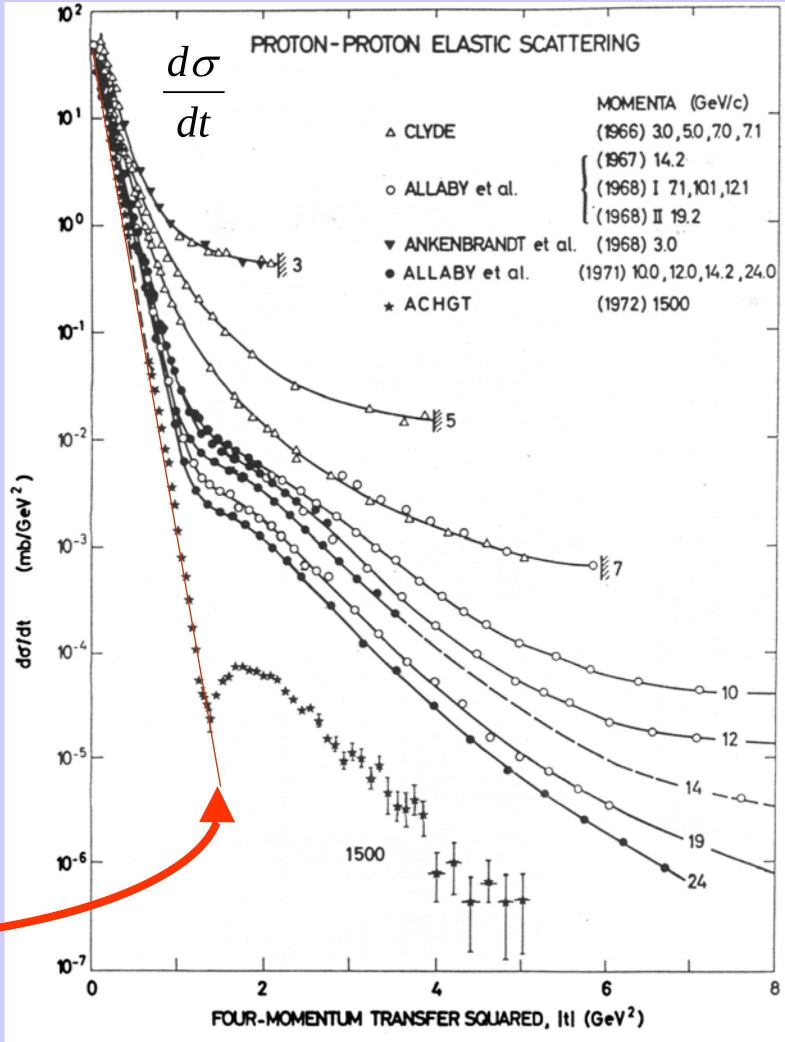
Elastic Scattering

PROTON-PROTON ELASTIC SCATTERING

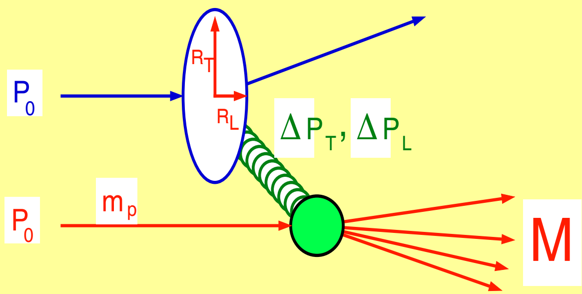


$$\frac{d\sigma}{dt} \sim e^{bt} \sim e^{-\frac{R^2}{4}(p\theta)^2}$$

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



Diffraction Dissociation



Momentum loss fraction

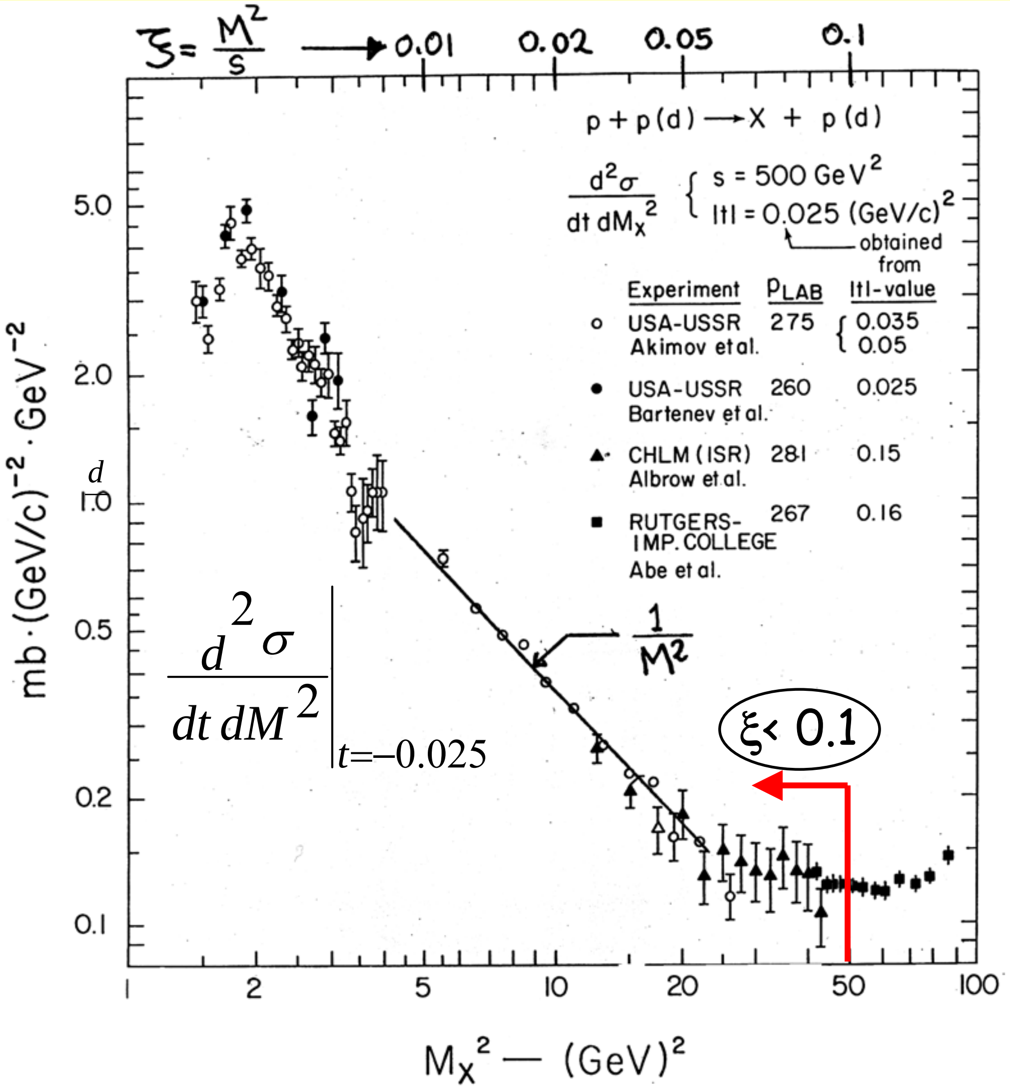
$$\xi = \frac{\Delta P_L}{P_L} = \frac{M_X^2}{S}$$

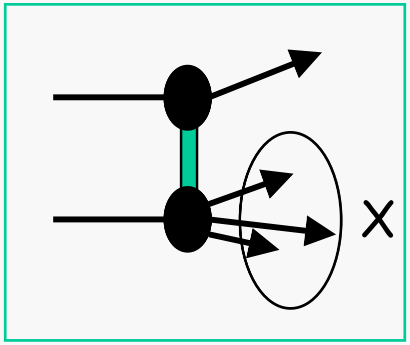
COHERENCE CONDITION

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

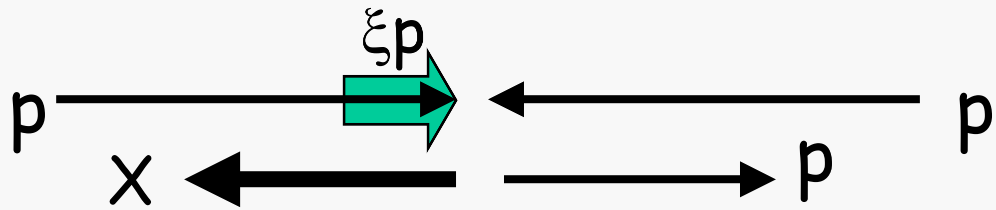
@Tevatron M_X ➔ 600 GeV
@ LHC ➔ 4.4 TeV

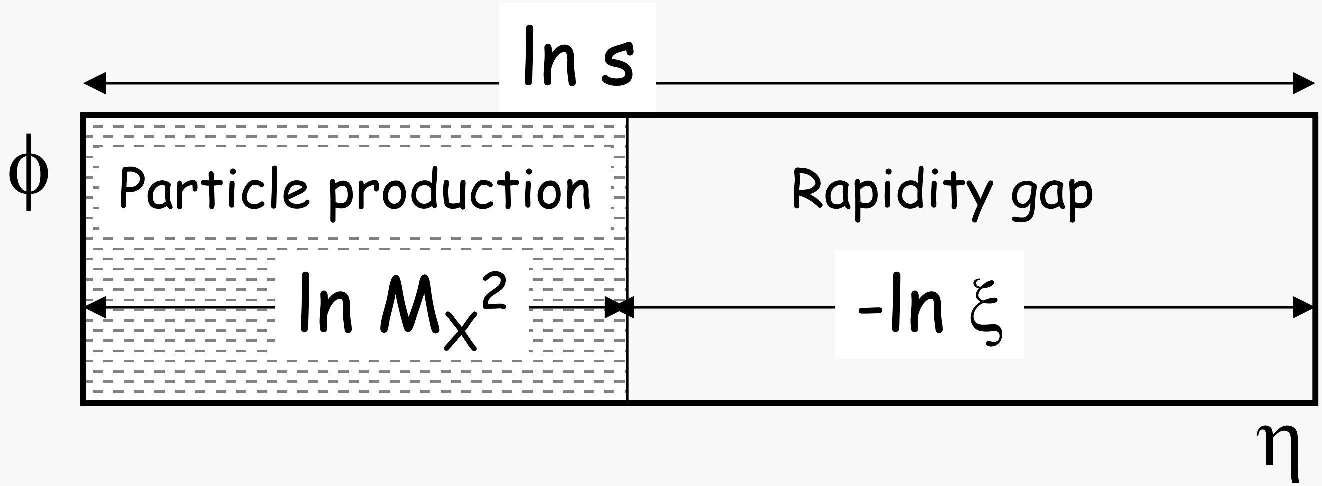
But why $\dfrac{d\sigma}{dM^2} \sim \dfrac{1}{M^2}$?





Rapidity Gaps

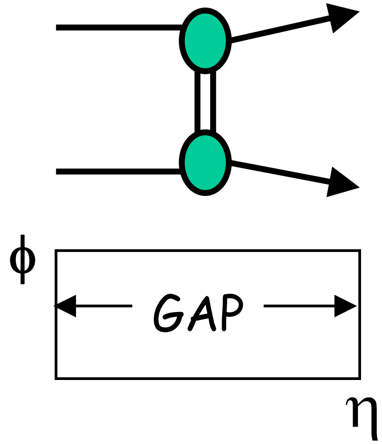




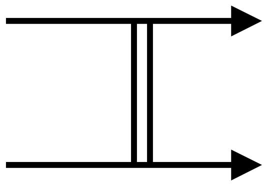
$$\left(\frac{d\sigma}{d\Delta\eta}\right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \Rightarrow \frac{d\sigma}{d\xi} \sim \frac{1}{\xi}$$

Diffractive $\bar{p}p$ Processes

Elastic scattering

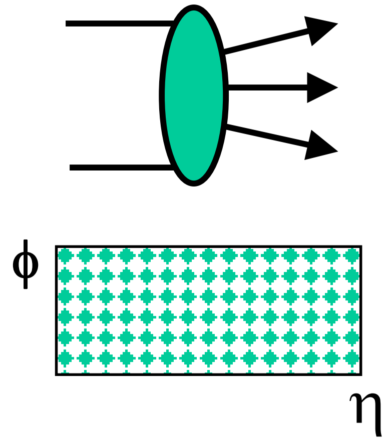


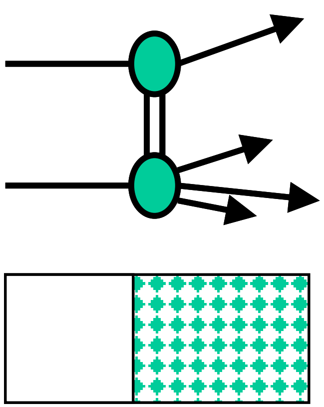
$\sigma_T = \text{Im}\, f_{el}\,(t=0)$



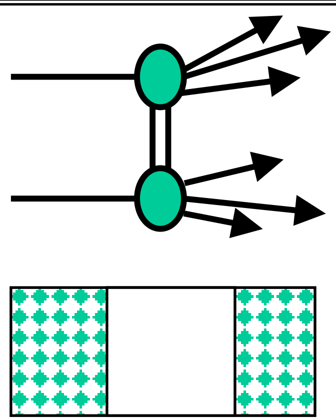
OPTICAL THEOREM

Total cross section

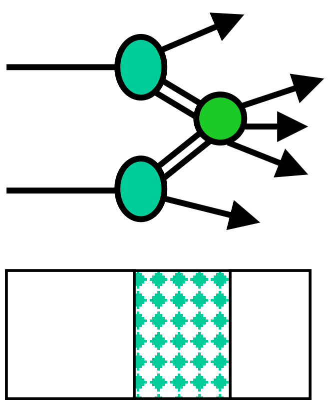




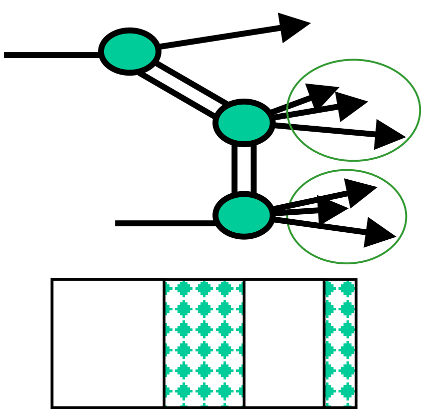
SD



DD



DPE



SDD=SD+DD

Rapidity Gaps in Fireworks

The Physics

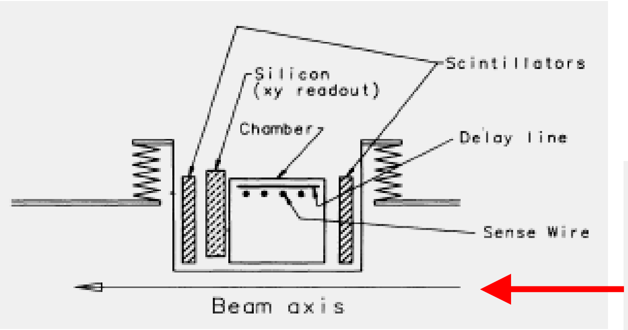
- Elastic and Total Cross Sections:..........pp→pp and pp→X
  - ✓ Fundamental Quantum Mechanics
    - Froissart Unitarity Bound.........$\sigma_T < C \ln^2 s$
    - Optical theorem...........................$\sigma_T \sim Im\, f(t=0)$
    - Dispersion relations.....................$Re\, f(t=0) \sim Im\,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

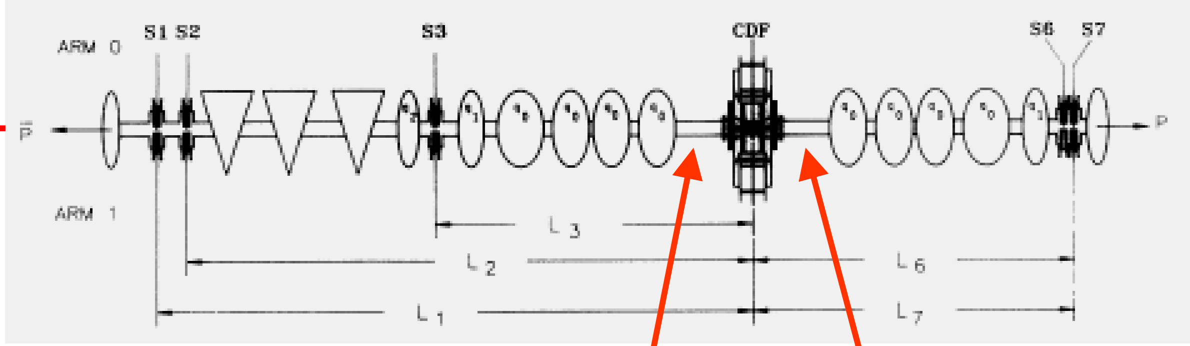
CDF Run 1-0 (1988-89)

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



Roman Pot Spectrometers

CDF-I



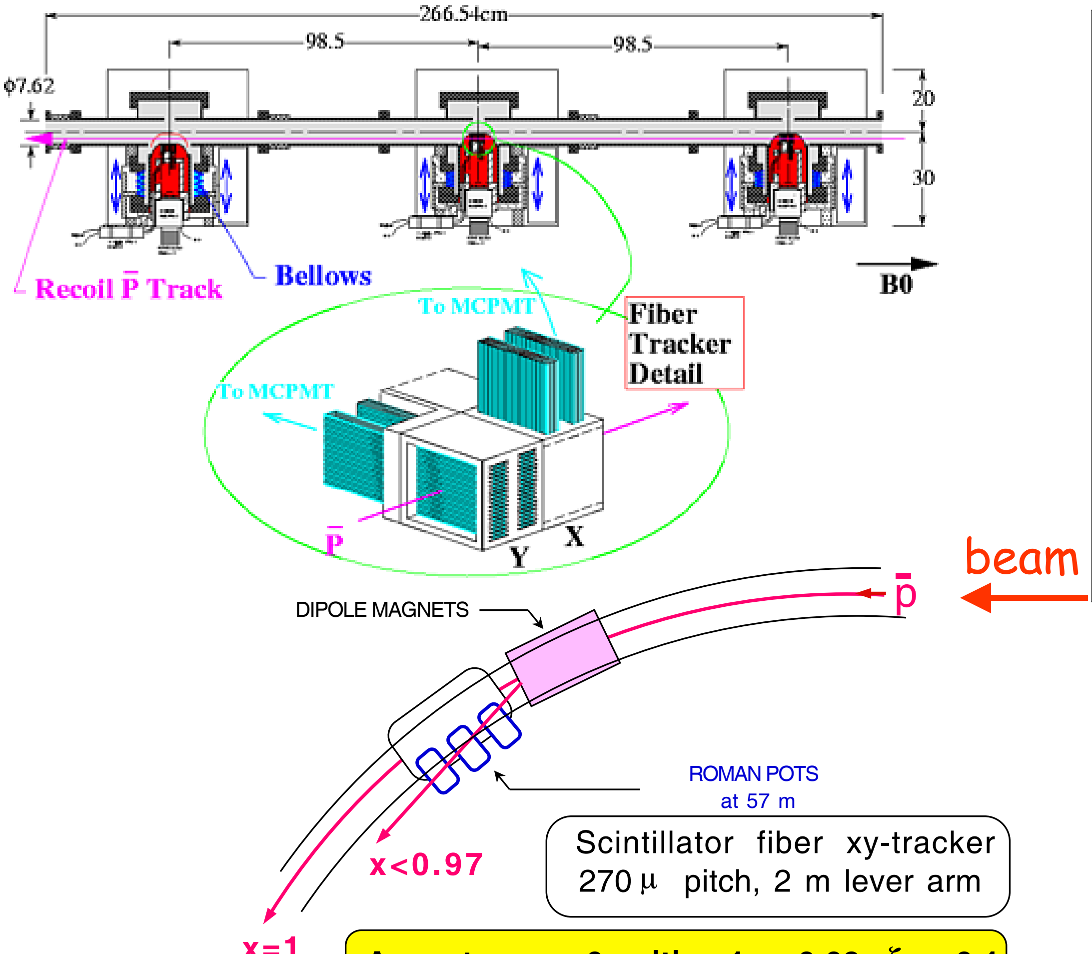
Roman Pot Detectors

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

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

CDF-I

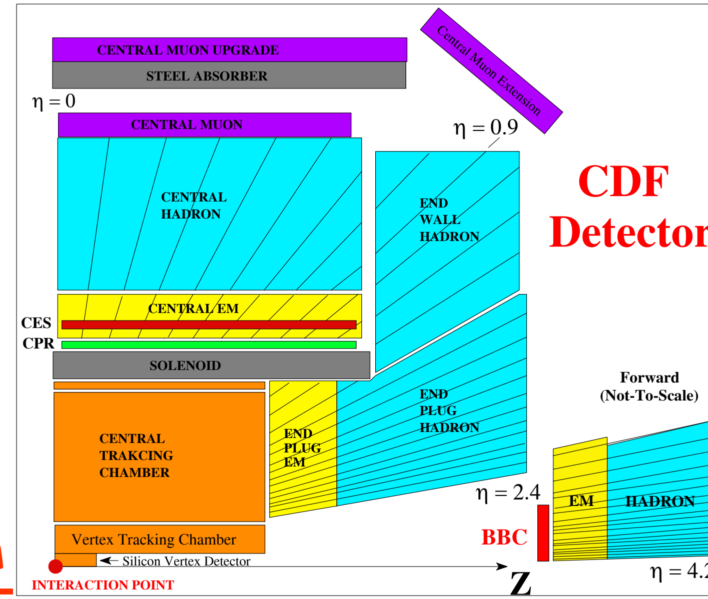
Run-IC



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

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

Run-IA,B

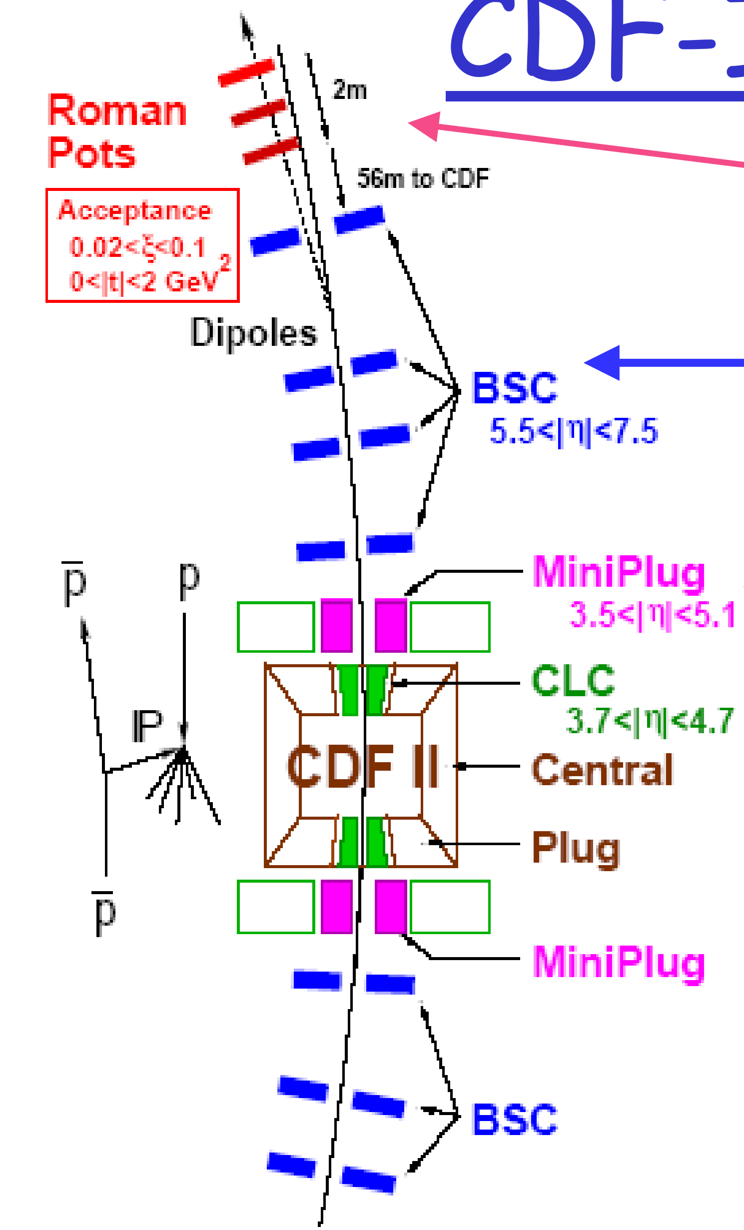


Forward Detectors

BBC 3.2<η<5.9

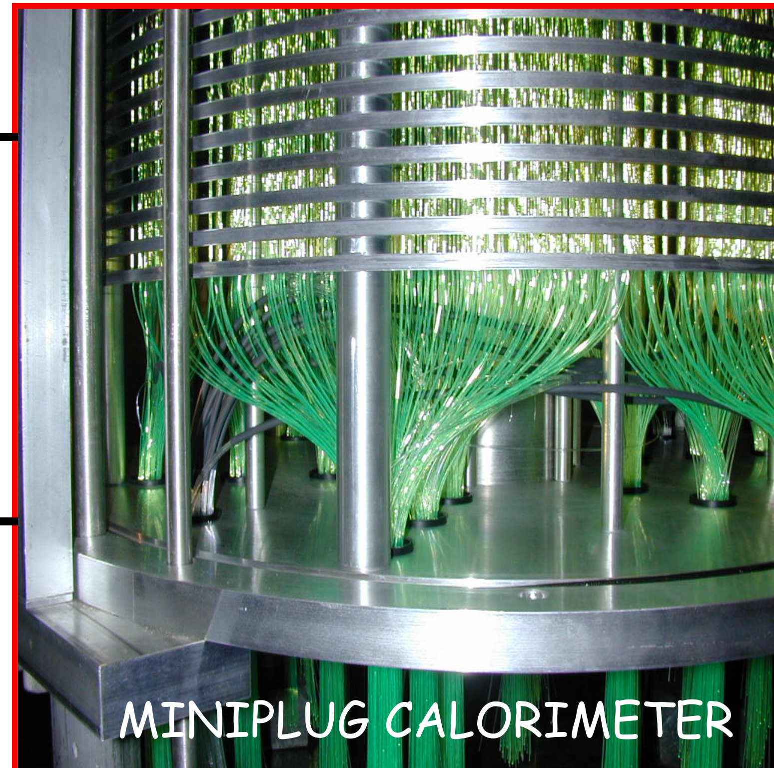
FCAL 2.4<η<4.2

CDF-II

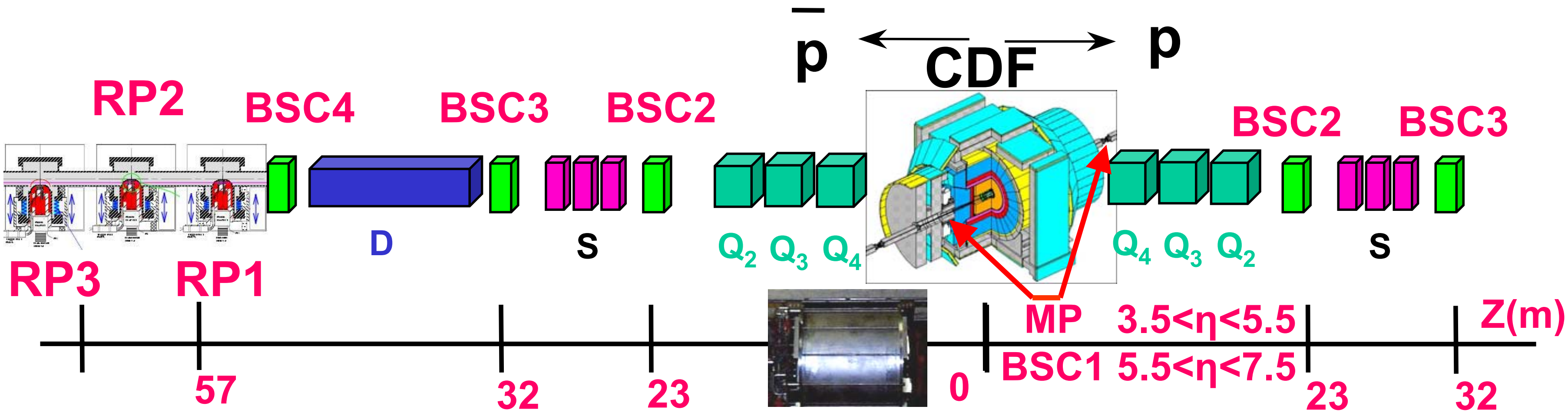


ROMAN POT DETECTORS

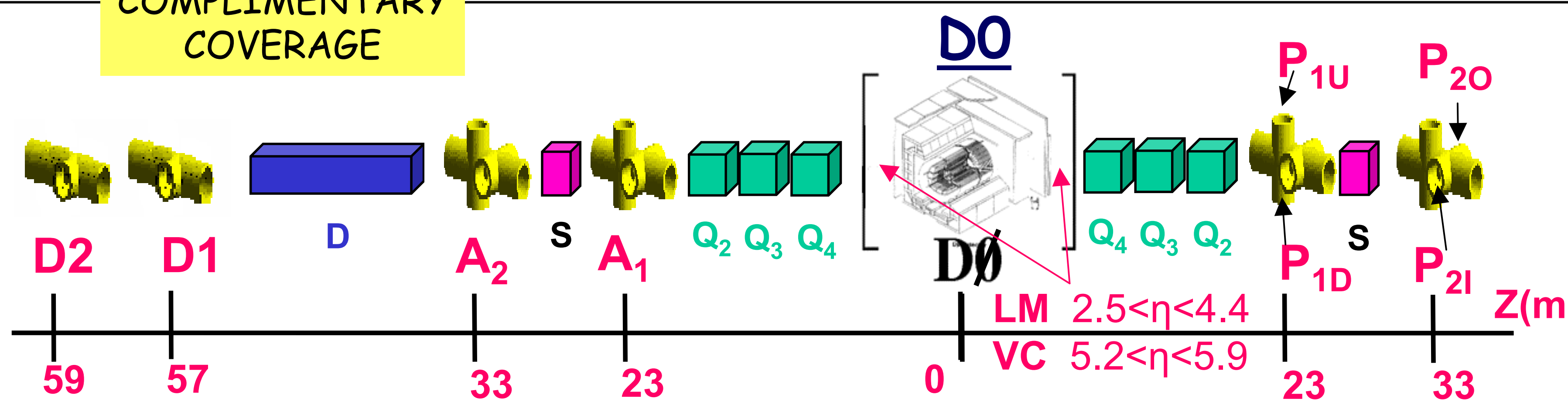
BEAM SHOWER COUNTERS:
Used to reject ND events



CDF & DO - Run II



CDF & D0:
COMPLIMENTARY
COVERAGE



From Barreto's talk in small-x

ELASTIC AND TOTAL CROSS SECTIONS

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

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

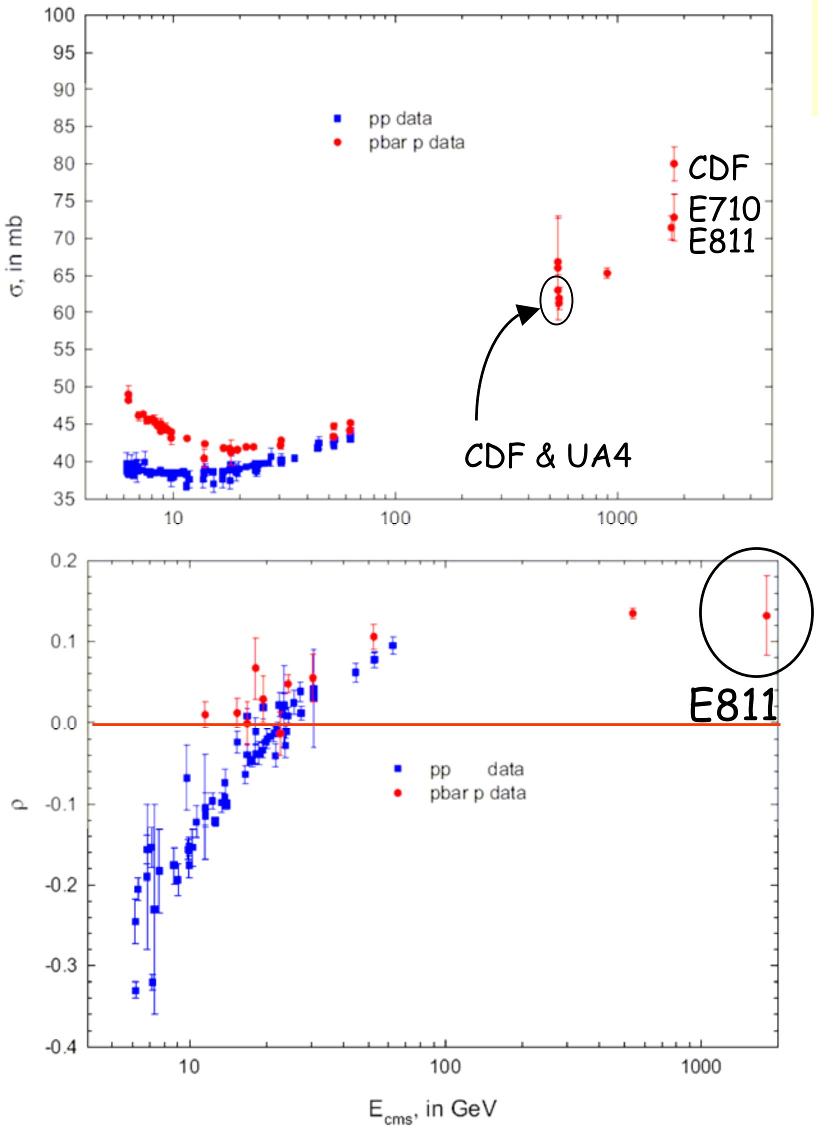
optical theorem

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

Alert:

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

σ_T and ρ-values from PDG



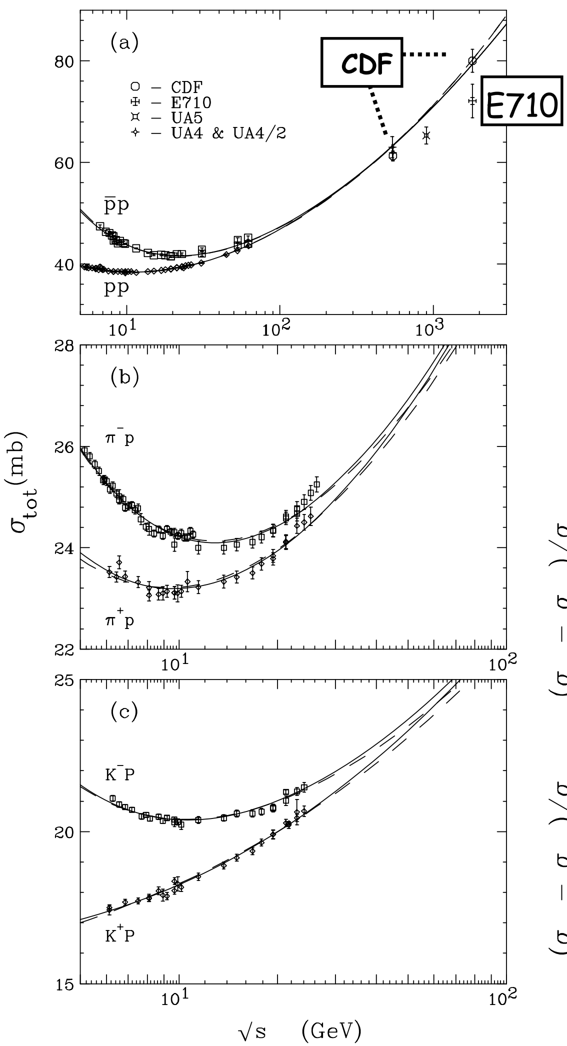
ρ = ratio of real/imaginary parts of elastic scattering amplitude at t=0

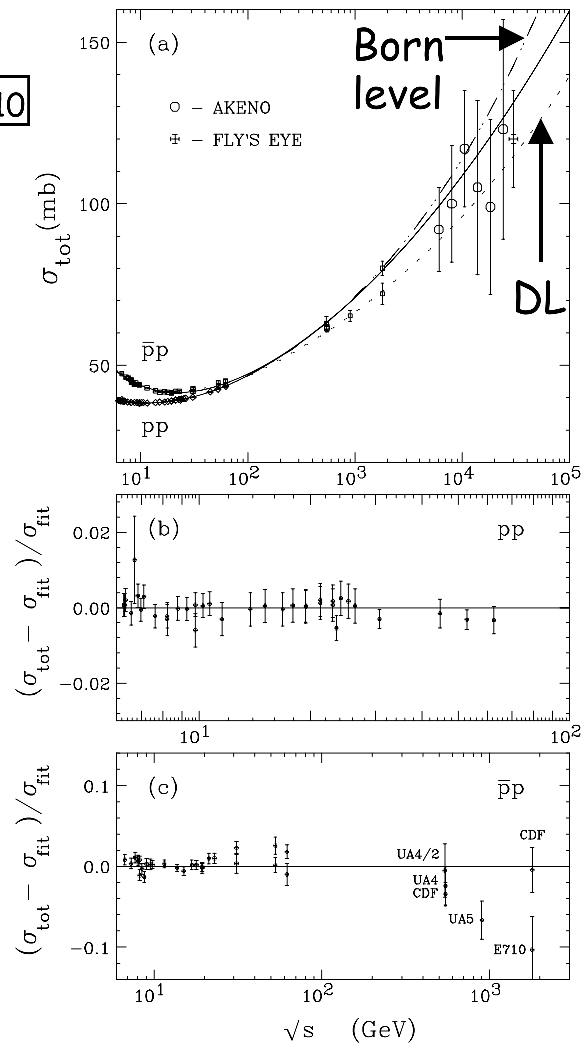
CDF and E710/811 disagree

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 eikonal approach to ensure unitarity

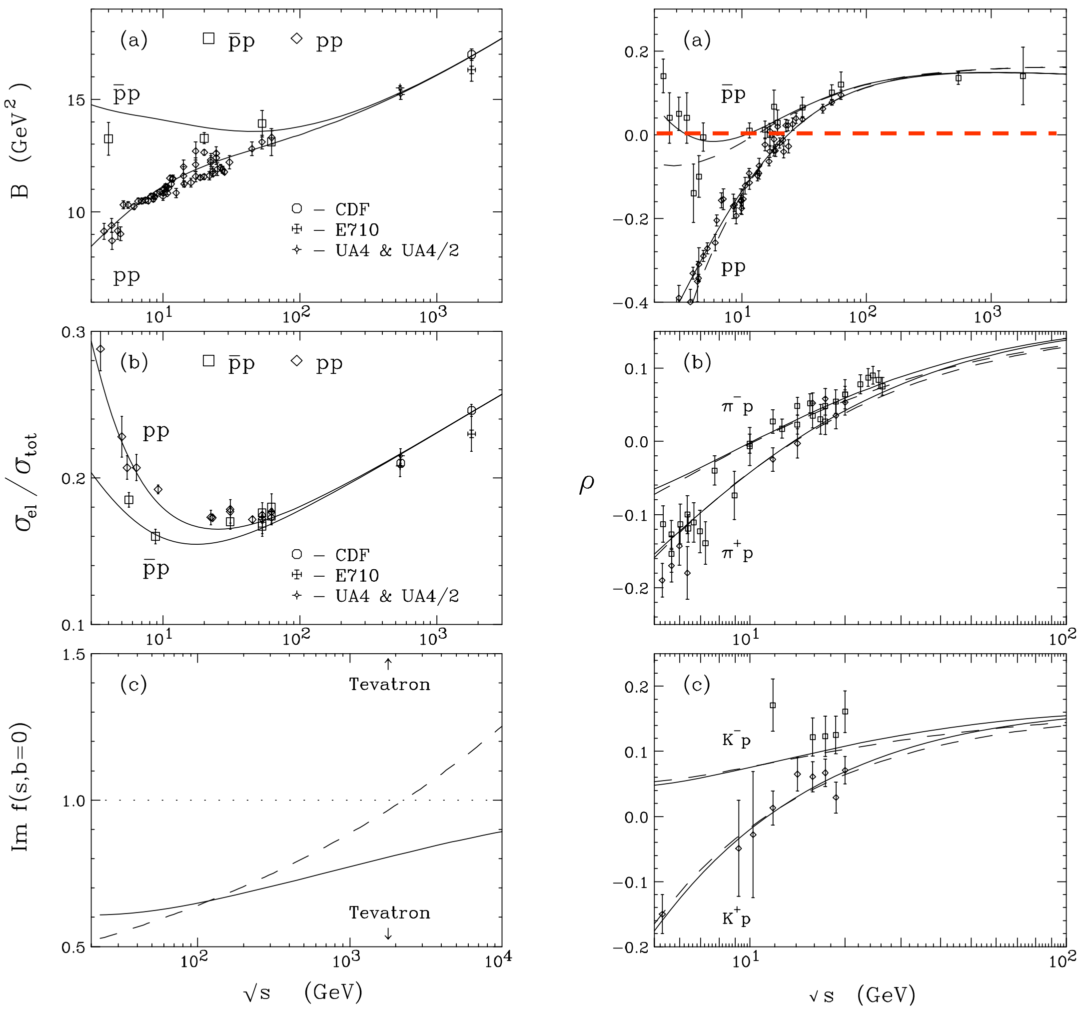
$\sigma \rightarrow s^{\varepsilon}$

$\varepsilon = 1.104 +/- 0.002$

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

@14 TeV

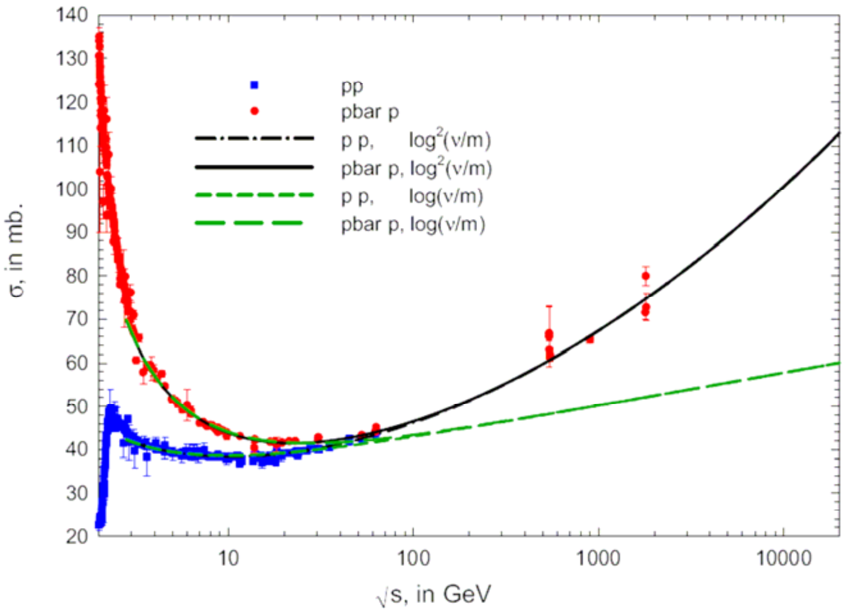
Elastic/Total and ρ-values: Regge fit

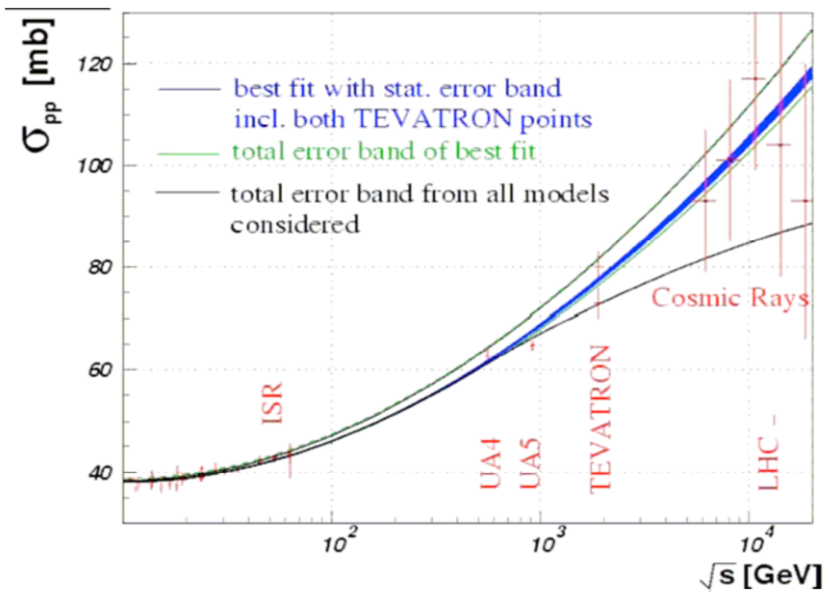


Covolan, Montagna, and G
PLB 389 (1995) 176

- Agreement with data on:
  - b-slopes
  - σ_{el}/σ_T
  - ρ-values
- Unitarity assured

Other Approaches





COMPETE Collaboration fits all available hadronic data and predi

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

LHC: $\sigma_{tot} = 111.5 \pm 1.2 \begin{array}{c} +4.1 \\ -2.1 \end{array}$ mb

[PRL 89 201801 (2002

➔ fit data using analyticity constraints

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

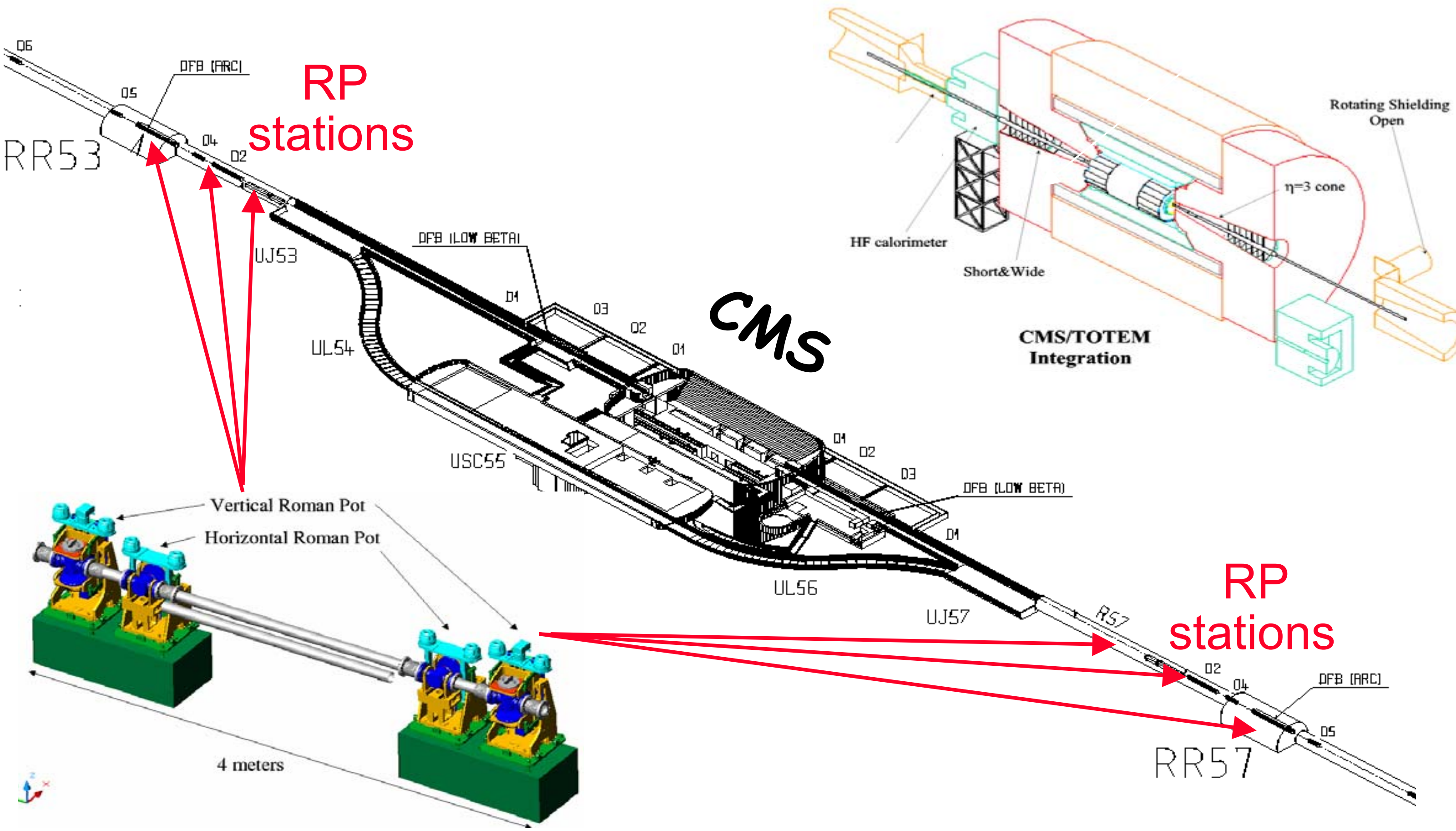
σ_T (LHC) = 107.3 ± 1.2 mb

Recall CMG Regge fit: 115 mb

TOTEM experiment @ LHC

Total Cross Section, Elastic Scattering, and Diffraction Dissociation

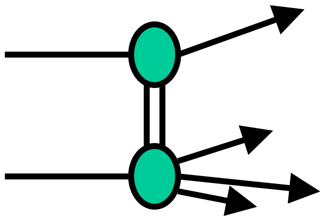
Aim at 1% accuracy on σ_T



DIFFRACTION

- Soft & hard diffraction
- Factorization / renormalization
- Multi-gap diffraction
- Diffraction in QCD
- Dark energy ???

A unitarity issue



Factorization →

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

Pomeron flux

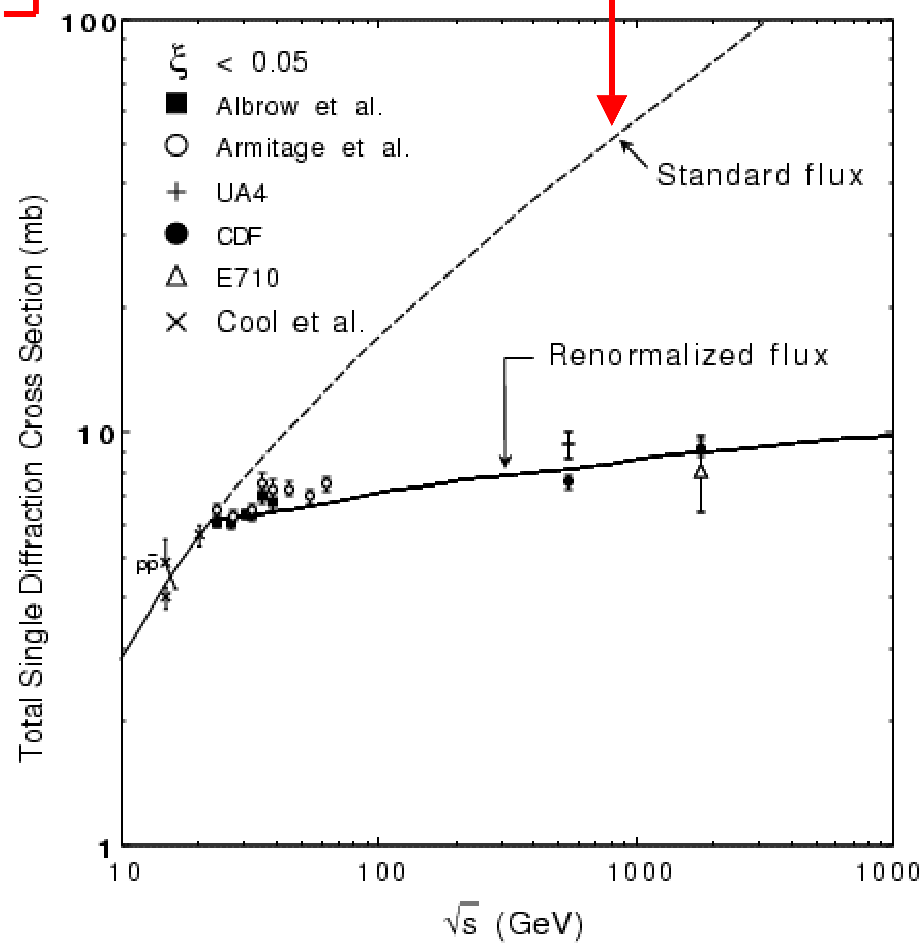
$$\sigma_{SD} \sim s^{2\varepsilon}$$

- **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

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



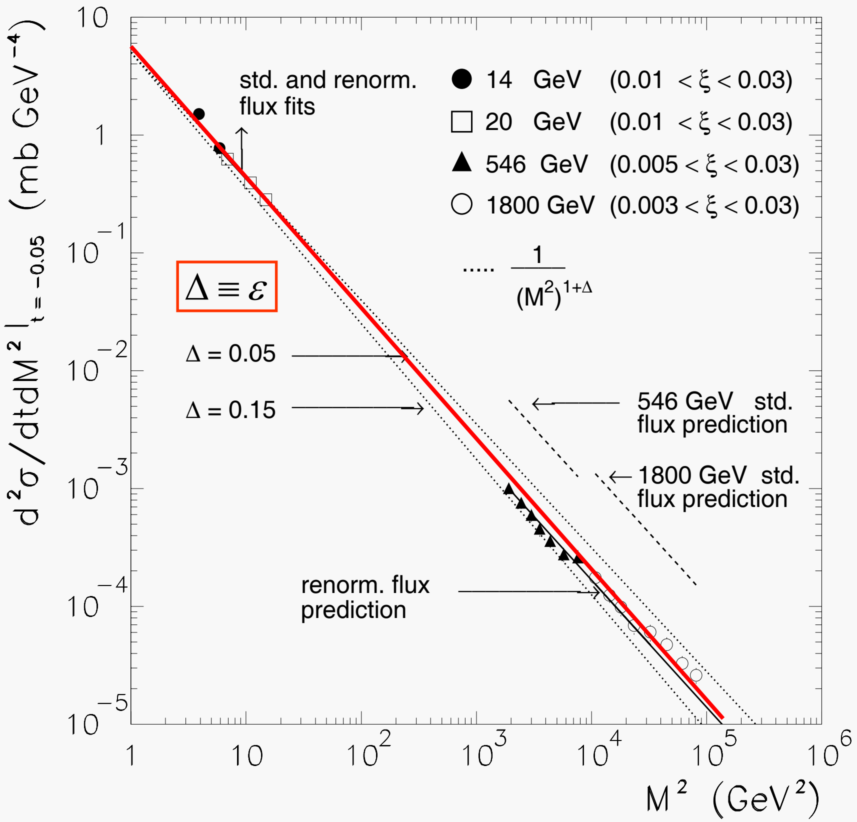
A Scaling Law in Diffraction

renormalization

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

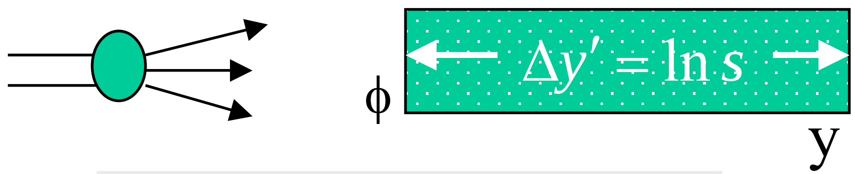
➔ Independent of S over 6 orders of magnitude in M^2 !

KG&JM, PRD 59 (1999) 114017



Factorization breaks down so as to ensure M^2-scaling!

The QCD Connection

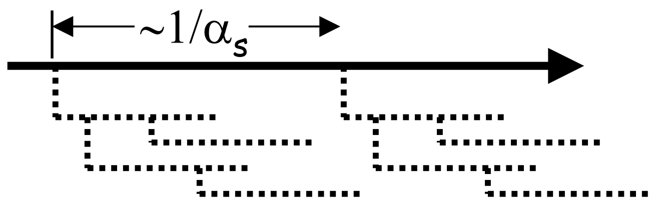


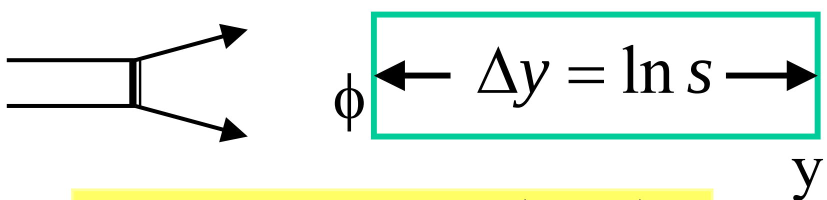
$$\sigma_T(s) = \sigma_o\, e^{\varepsilon\,\Delta y'} = \sigma_o\, s^{\varepsilon}$$

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

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

Total cross section:
power law increase versus s



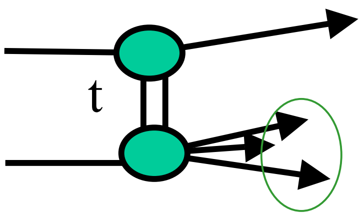


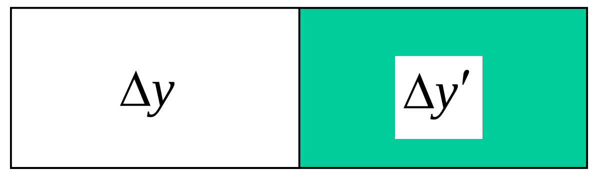
$$\text{Im}\; f_{el}(s,t) \propto e^{(\varepsilon+\alpha' t)\Delta y}$$

Elastic cross section:
forward scattering amplitude

Single Diffraction in QCD

(KG, hep-ph/0205141)





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

2 independent variables: $t, \Delta y$

color factor

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

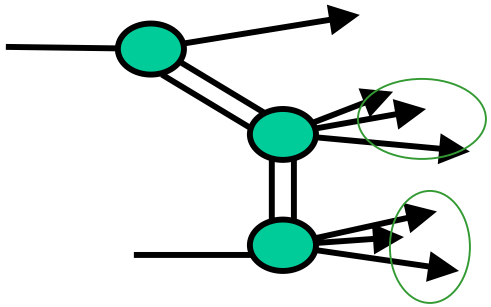
Gap probability

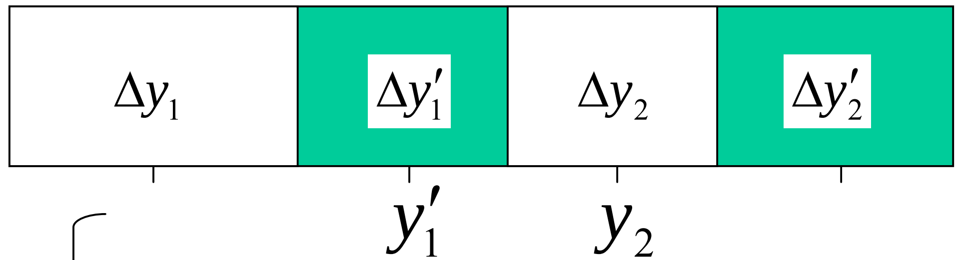
$$\sim e^{2\varepsilon \Delta y} \longrightarrow \int_{\Delta y_{min}}^{\Delta y = \ln s} s^{2\varepsilon\, \Delta y} \approx s^{2\varepsilon}$$

Renormalization removes the s-dependence → SCALING

Multi-gap Renormalization

(KG, hep-ph/0205141)





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

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

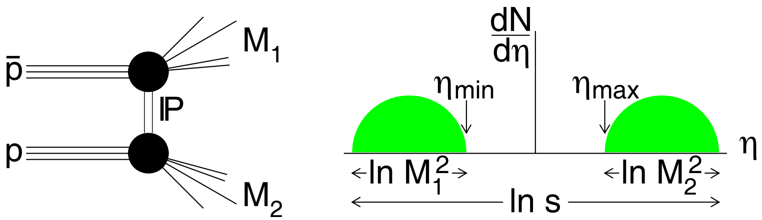
$\sim e^{2\varepsilon \Delta y}$

Sub-energy cross section (for regions with particles)

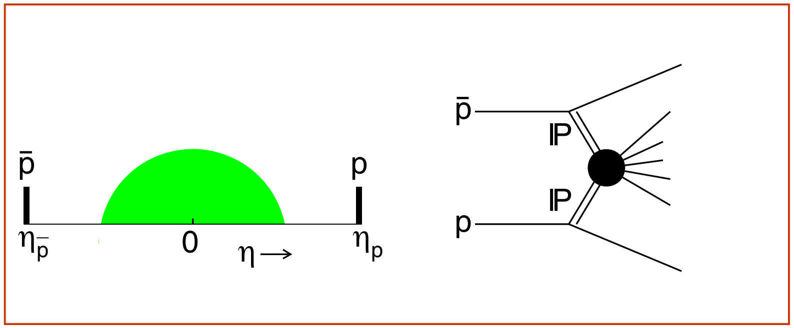
$$\int_{\Delta y_{\min}}^{\Delta y = \ln s} s^{2\varepsilon \Delta y} \approx s^{2\varepsilon}$$

Same suppression as for single gap!

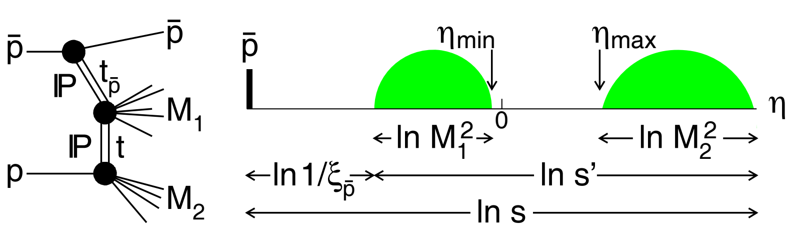
Central and Double Gaps @ CDF



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



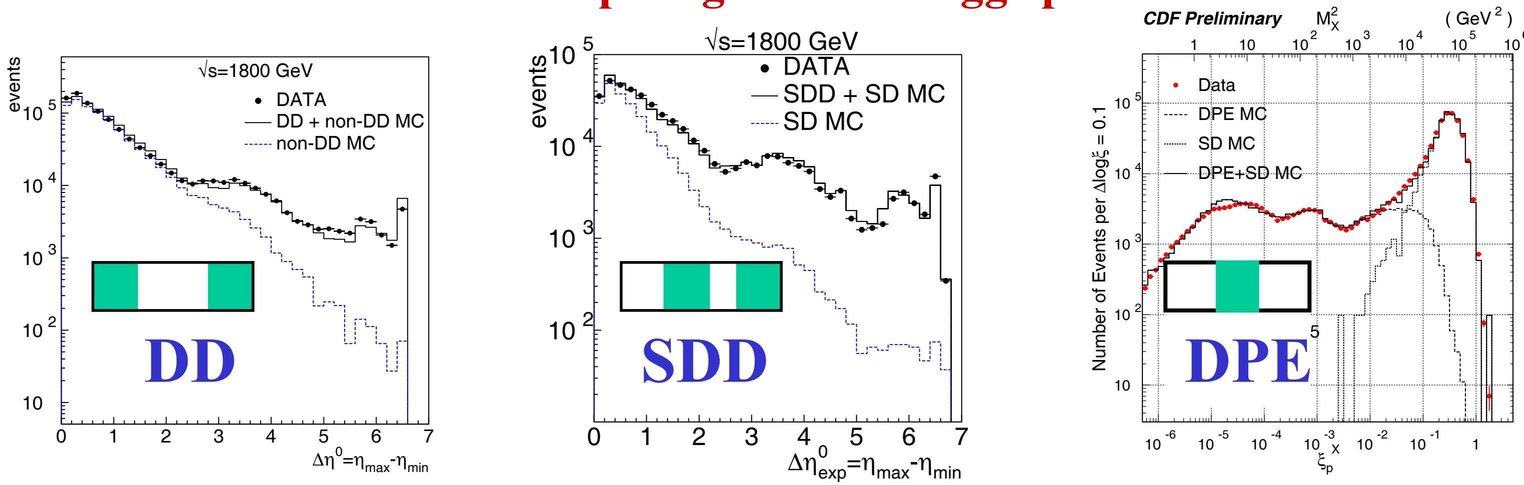
- **Double Pomeron Exchange**
  - **Two forward gaps**



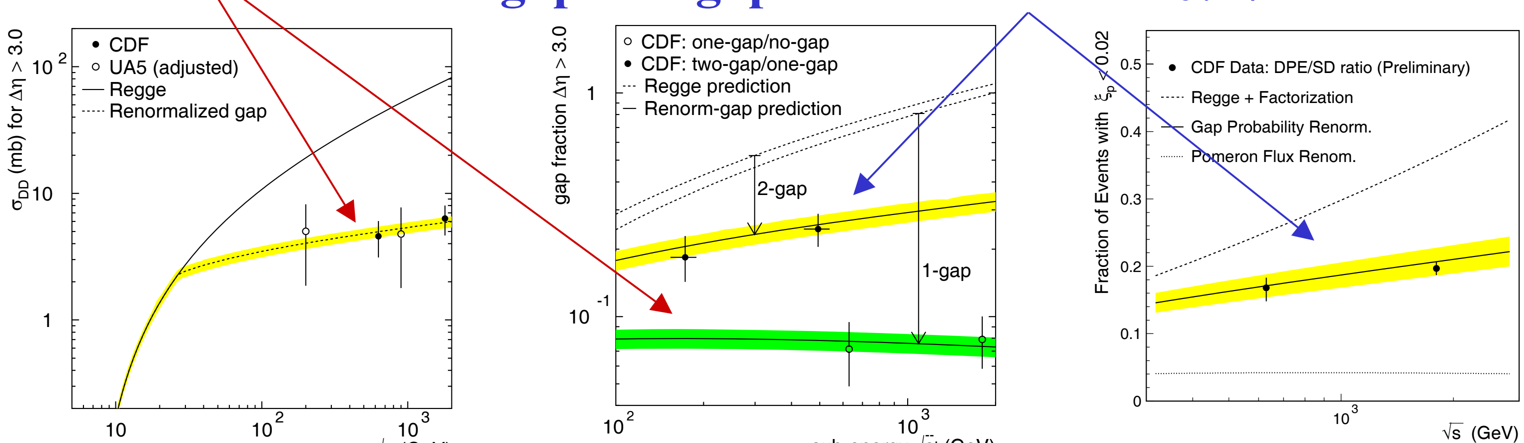
- **SDD: Single+Double Diffraction**
  - **One forward + one central gap**

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:

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

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

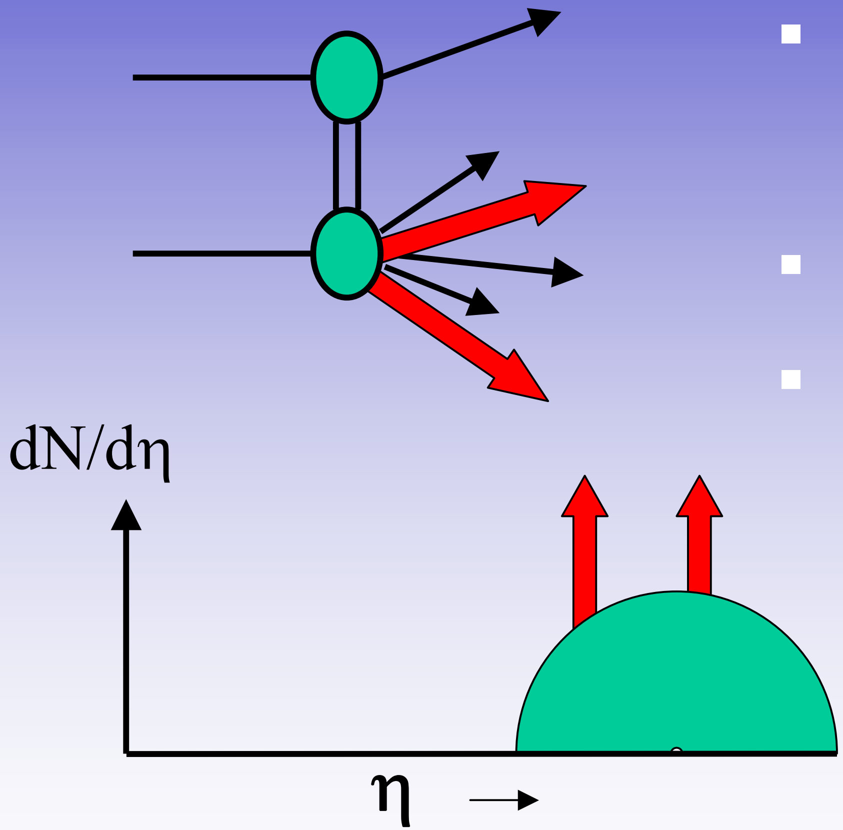
2ε: negative particle density!

⬇

Gravitational repulsion?

HARD DIFFRACTION

- Diffractive fractions
- Diffractive structure function
  - ➔ factorization breakdown
- Restoring factorization
- Hard diffraction in QCD



JJ, W, b, J/ψ

Diffractive Fractions @ CDF

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

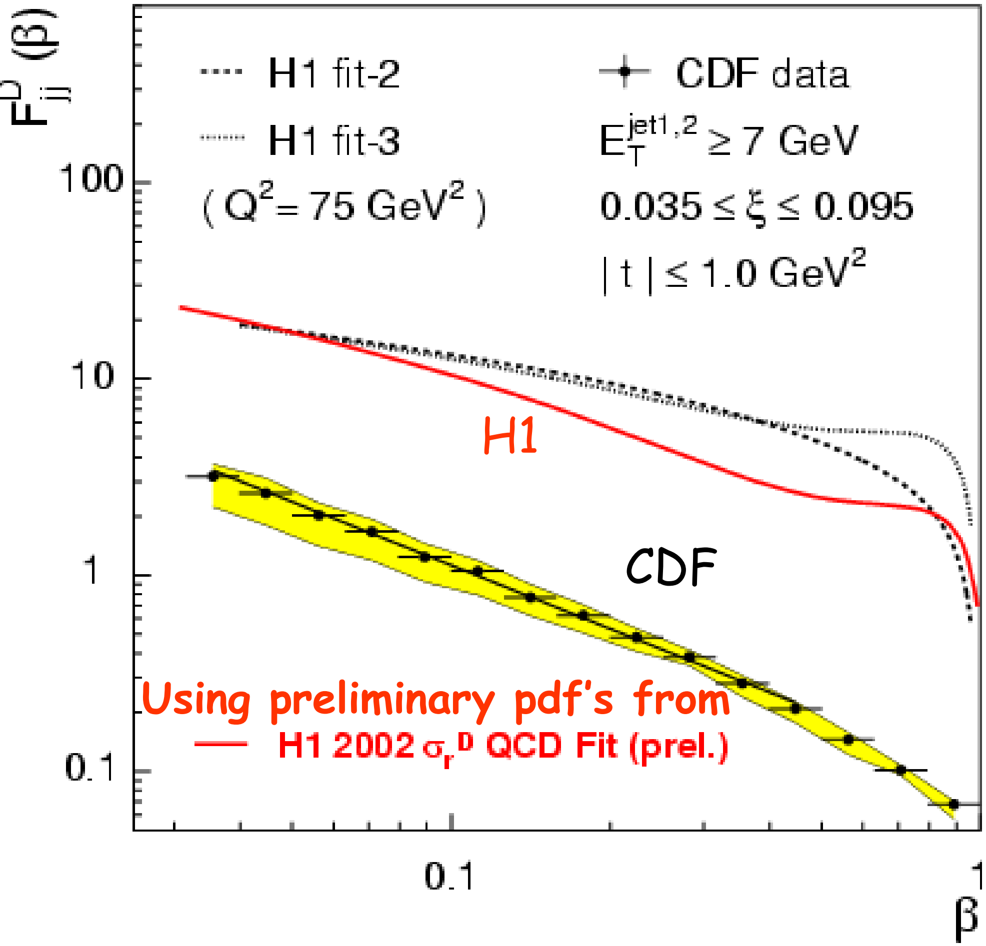
Fraction:
SD/ND ratio at 1800 GeV

$\star$	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

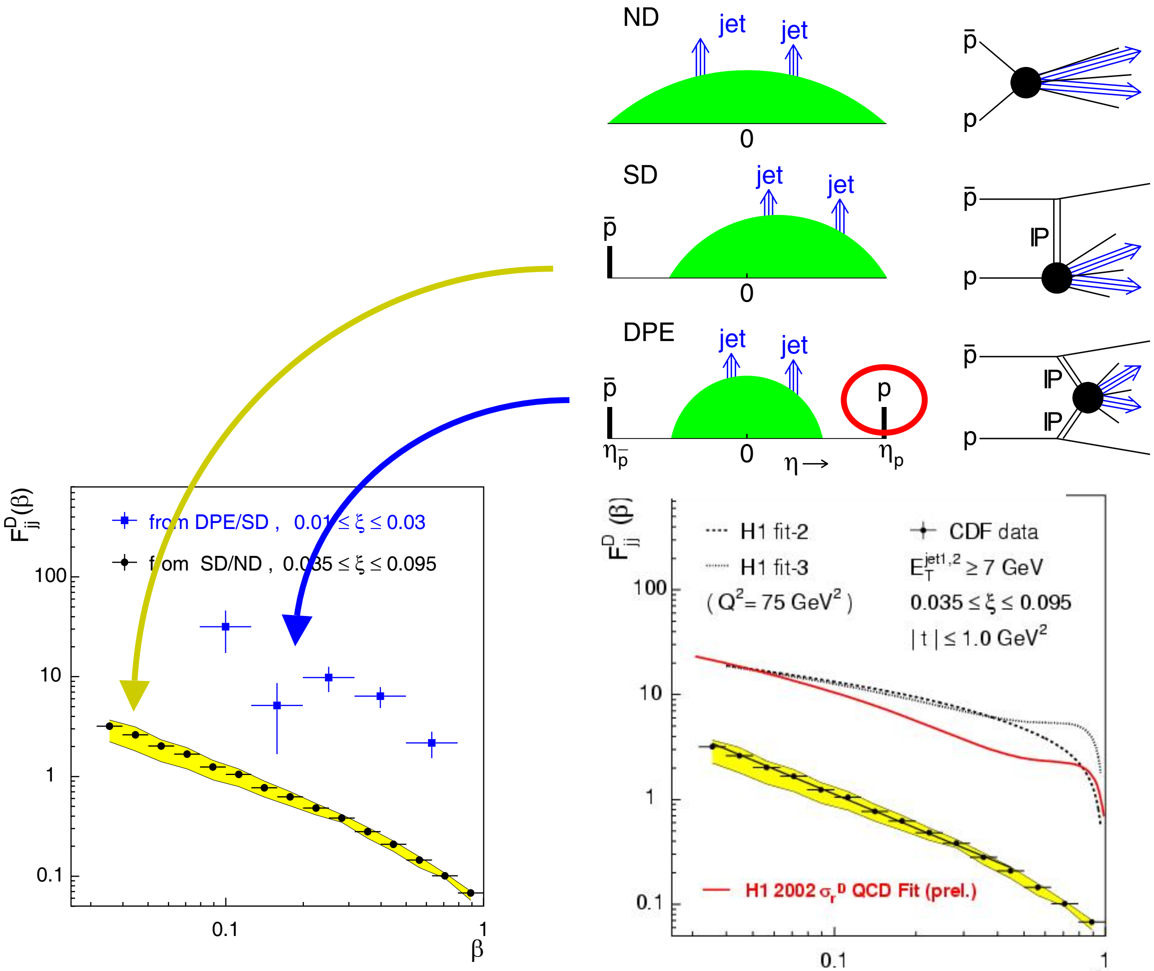


β = momentum fraction of parton in Pomeron

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!

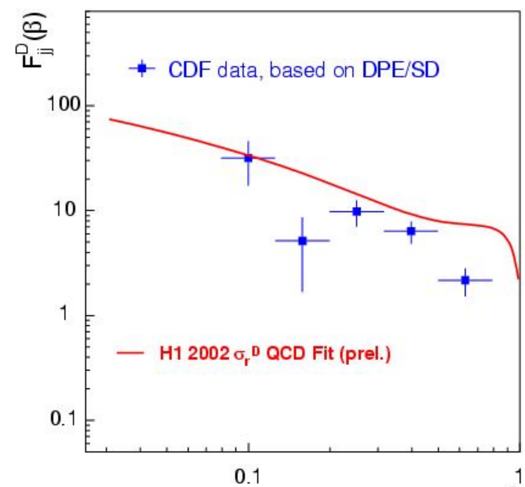
Restoring QCD Factorization



R(SD/ND)

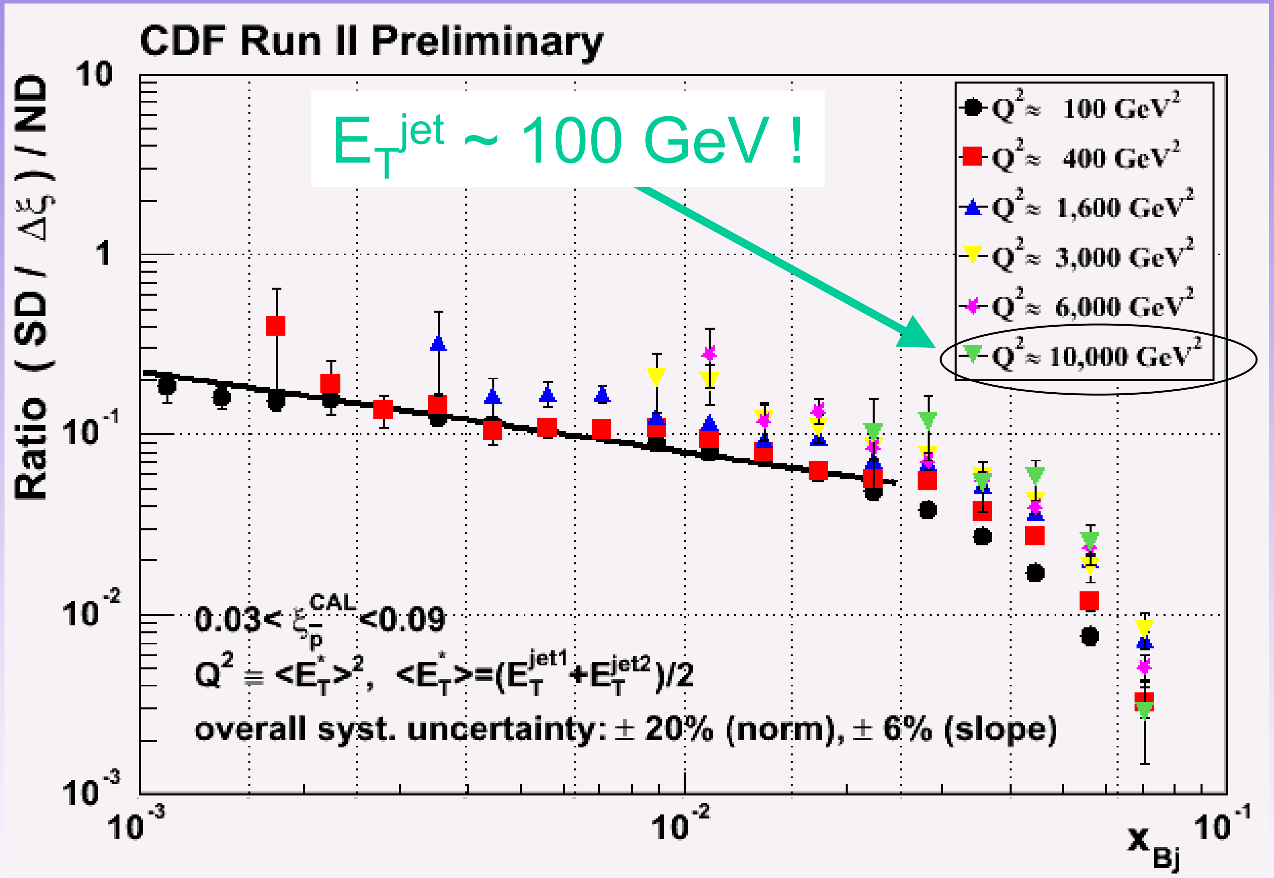
R(DPE/SD)

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

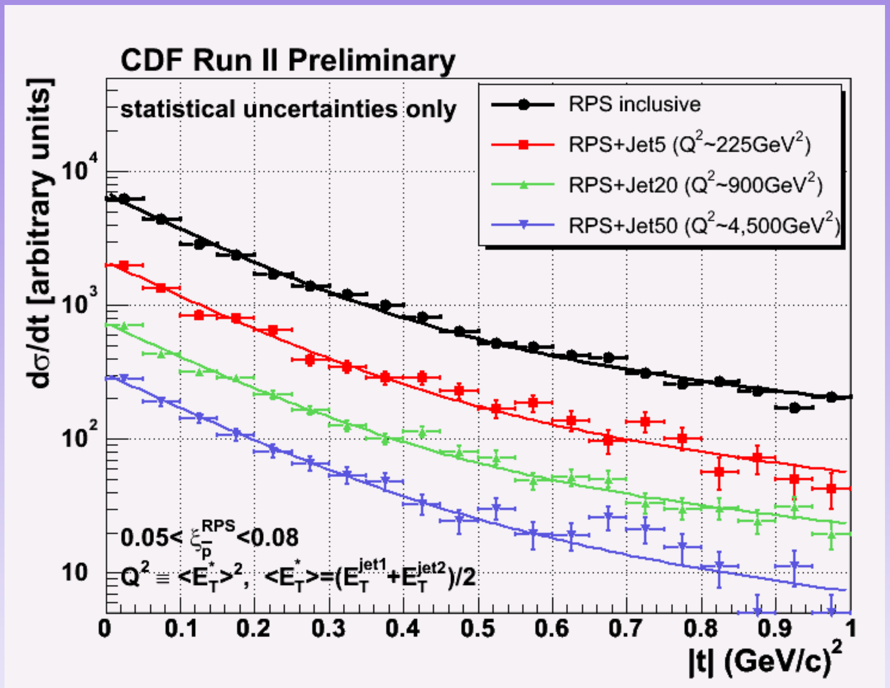
Diffractive Structure Function:
Q^2 dependence

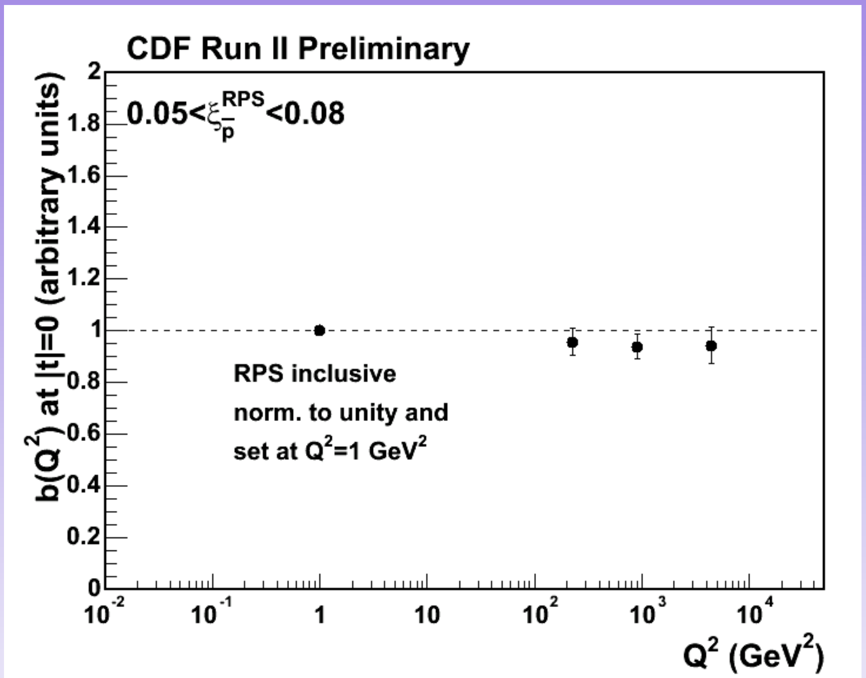


Small Q^2 dependence in region 100 < Q^2 < 10,000 GeV^2

⇨ Pomeron evolves as the proton!

Diffractive Structure Function: t- dependence





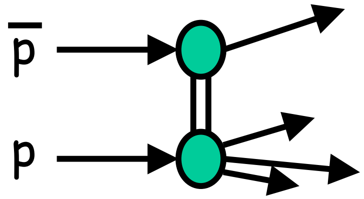
Fit dσ/dt to a double exponential:

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

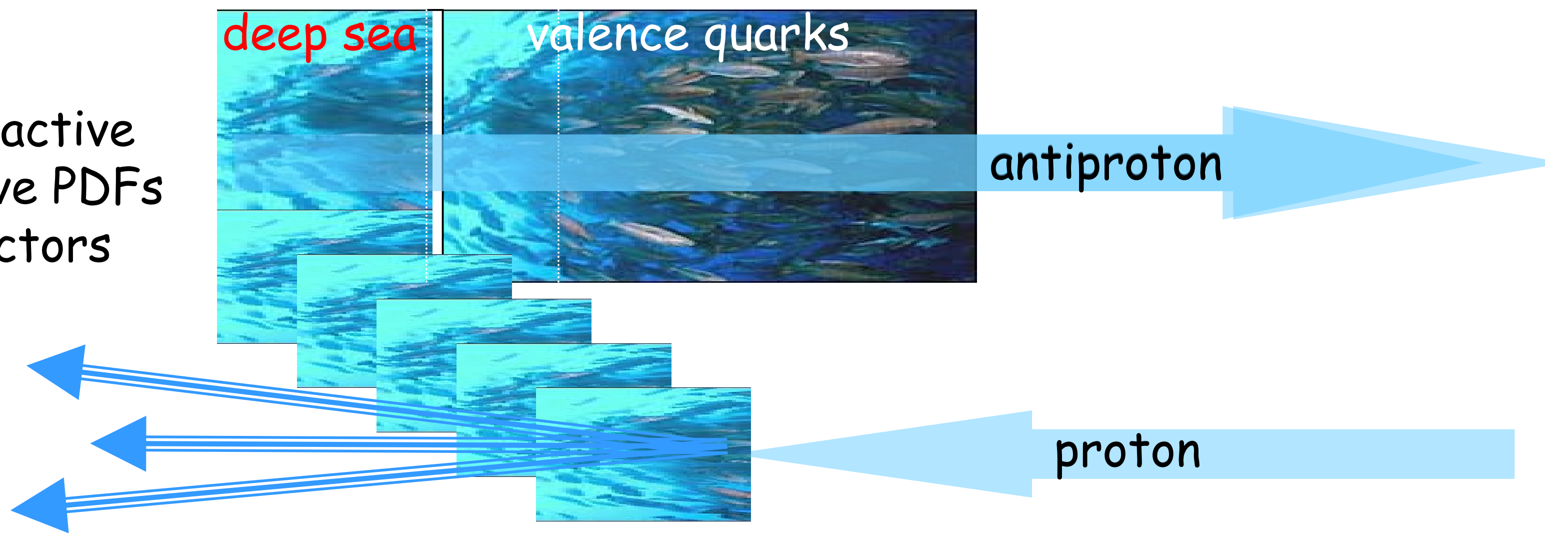
- No diffraction dips
- No Q2 dependence in slope from inclusive to $Q^2 \sim 10^4$ GeV^2

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

Hard Diffraction in QCD

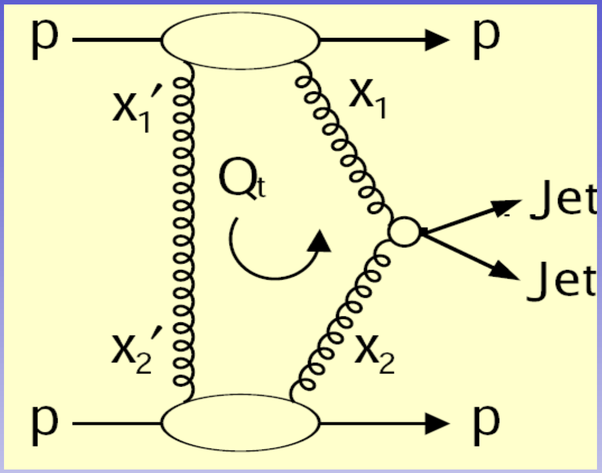


Derive diffractive from inclusive PDFs and color factors



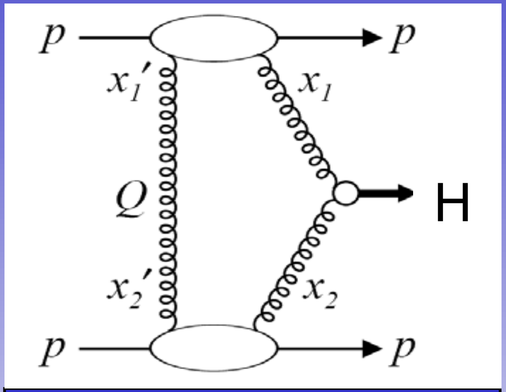
EXCLUSIVE PRODUCTION

Measure exclusive jj & γγ ➔ ➔ ➔ 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

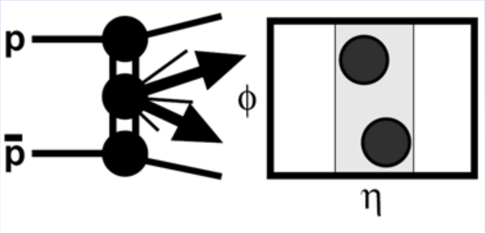


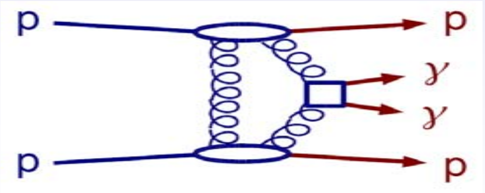
KMR: σ_H(LHC) ~ 3 fb
S/B ~ 1 if ΔM ~ 1 GeV

Search for exclusive dijets:
Measure dijet mass fraction

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

Look for signal as M_{jj} ➔ 1





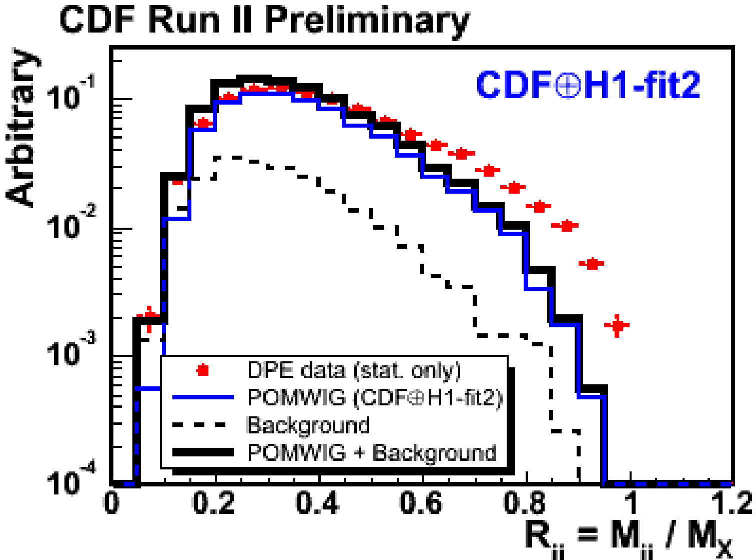
Search for exclusive γγ

Search for events with two high E_T gammas and no other activity in the calorimeters or BSCs

Exclusive Dijet and γγ Search

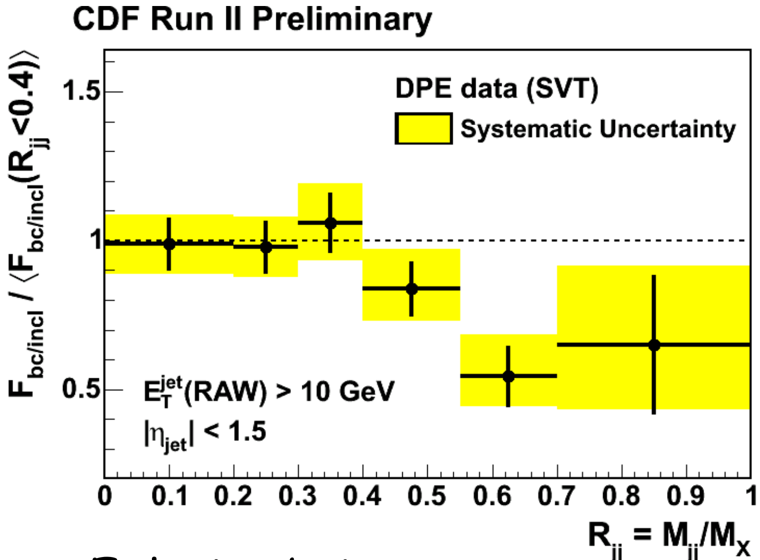
DIJETS

Dijet fraction – all jets



Excess over MC predictions at large dijet mass fraction

b-tagged dijet fraction



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

Systematic uncertainties under study: tune in this summer for results

Exclusive γγ

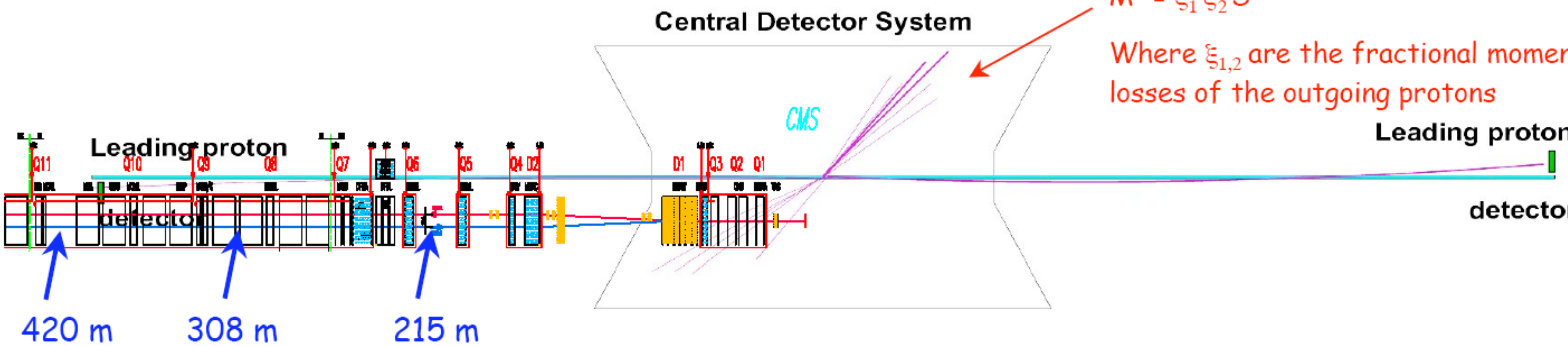
Based on 3 events observed: $\sigma_{MEAS} = 0.14^{+0.14}_{-0.04}(\text{stat}) \pm 0.03(\text{syst})\ \text{pb}$

Good agreement with KMR: $\sigma_{KMR} = 0.04 \pm 0.04(\times 2-3)\ \text{pb}$

Looking forward @ LHC

$M^2 = \xi_1 \xi_2 S$

Where $\xi_{1,2}$ are the fractional momentum losses of the outgoing protons



TOTEM/CMS
ATLAS

<u>FP420 project</u>

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