# DIFFRACTION FROM THE TEVATRON TO LHC

**Konstantin Goulianos**
**The Rockefeller University**

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# Forty Years of Diffraction

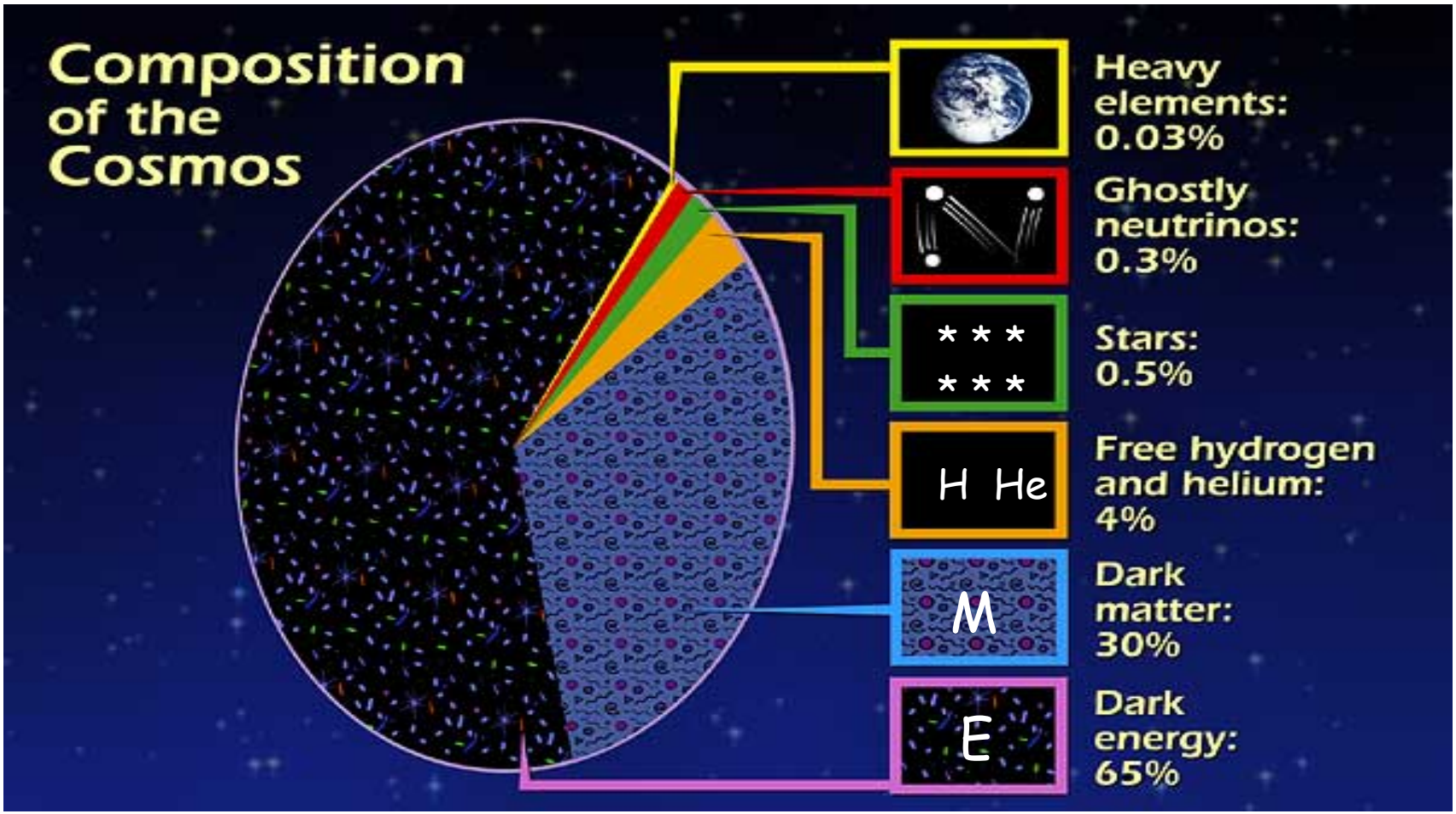
http://physics.rockefeller.edu/dino/my.html

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

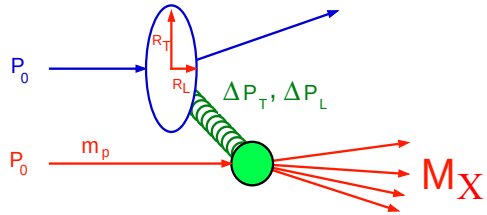
Review: KG, Phys. Rep. 101 (1983) 169

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

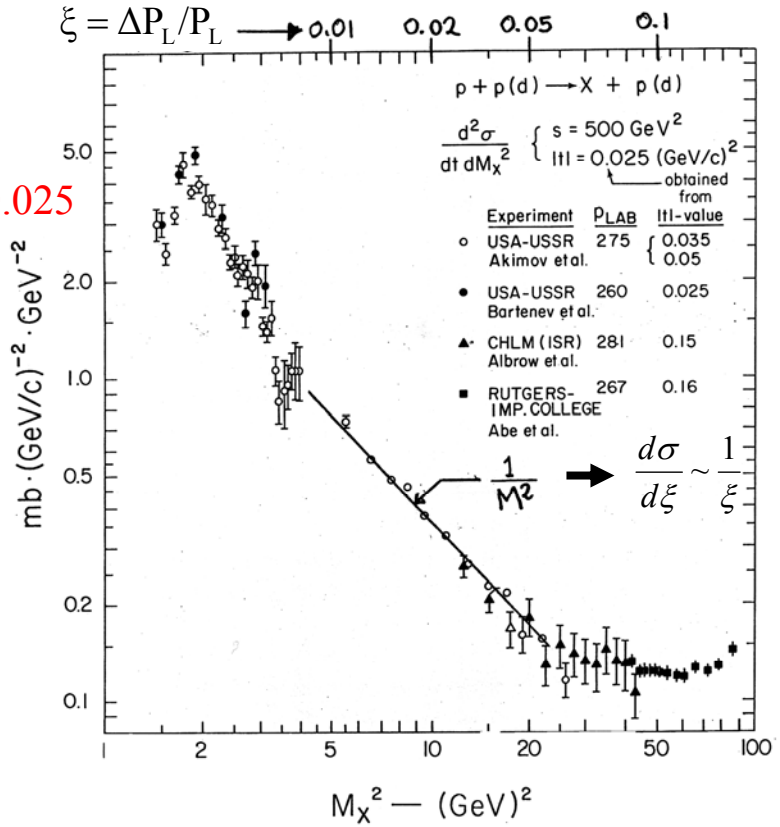
# What is Dark Energy??

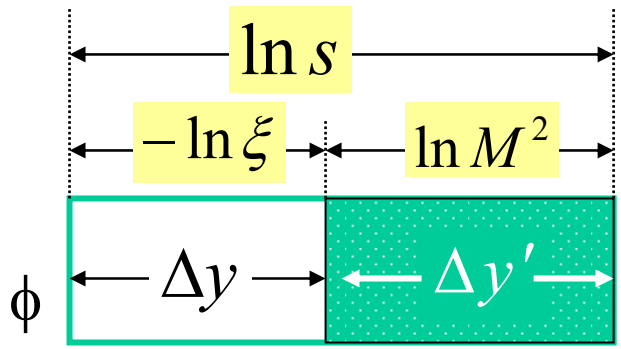


# Diffraction Dissociation




$$\left.\frac{d^2\sigma}{dt\,dM^2}\right|_{t=0.025}$$




$$\xi = \frac{\Delta p_L}{p_L} = \frac{M^2}{s}$$

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

**KG, Phys. Rep. 101 (1983) 171**

POMERON: color singlet w/vacuum quantum numbers

# Rapidity Gaps

Bj, PRD 47 (1993) 101: regions of (pseudo)rapidity devoid of particles

## Non-diffractive interactions

Rapidity gaps are formed by multiplicity fluctuations.

From Poisson statistics:

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

(ρ=particle density in rapidity space)

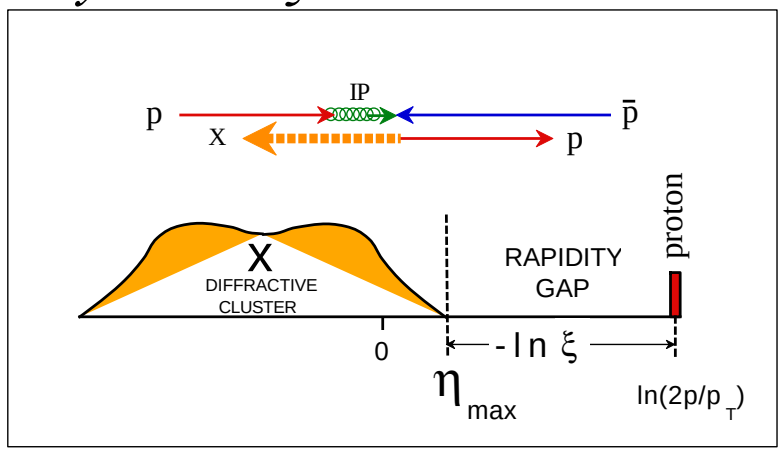
Gaps are exponentially suppressed

## Diffractive interactions

Rapidity gaps at t=0 grow with Δy.

$$\xi \equiv \Delta p / p$$

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




$$\left( \frac{d\sigma}{d\Delta y} \right)_{t=0} \sim e^{2\varepsilon \Delta y} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{\left(M^2\right)^{1+\varepsilon}}$$

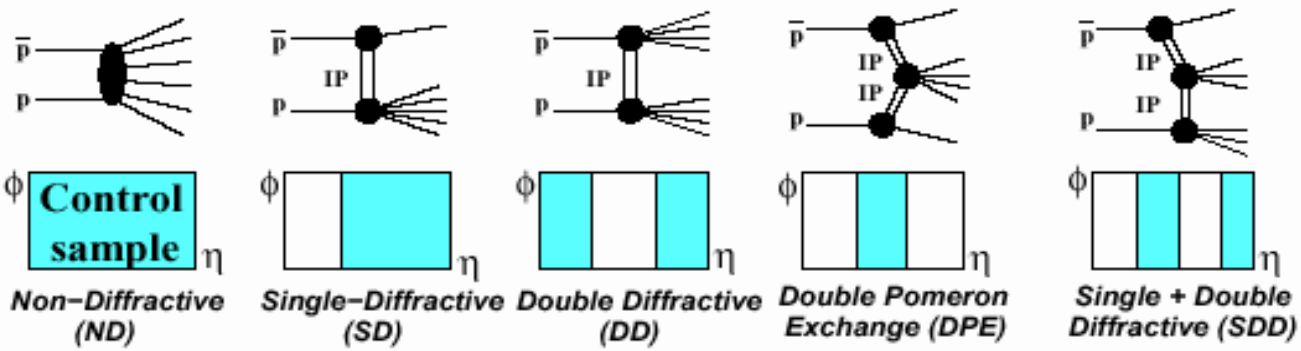
2ε: negative particle density!

# Diffraction@CDF in Run I

16 papers

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

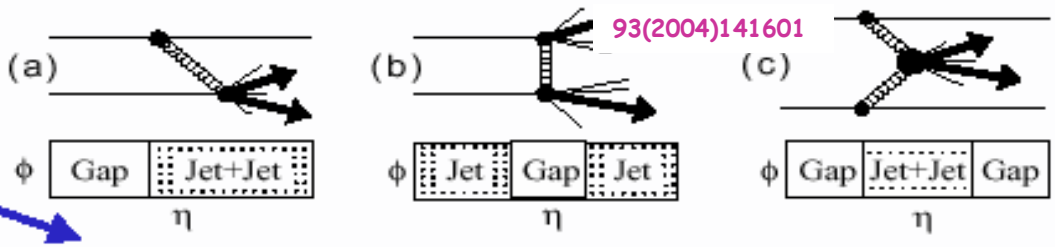
**SOFT diffraction**




PRD 50 (1994) 5535 | PRL 87 (2001)141802 | PRL submitted | PRL 91(2003)011802

**HARD diffraction**

93(2004)141601

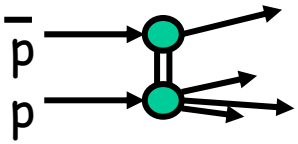



**PRL references**

**with roman pots**

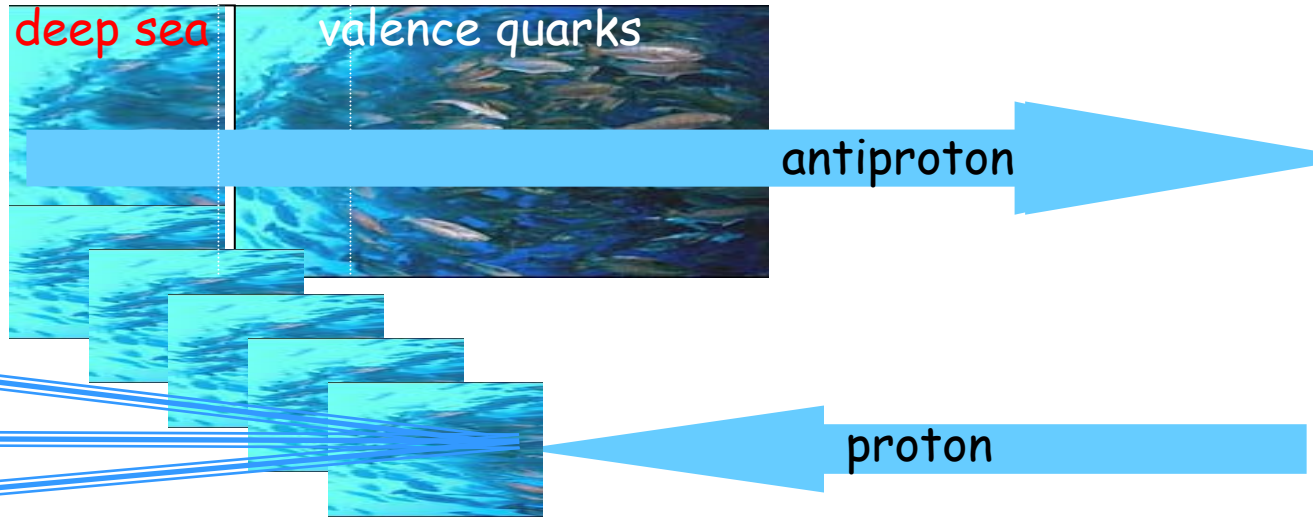
| | | |
|---|---|---|
| JJ 84 (2000) 5043 | | |
| JJ 88 (2002) 151802 | | |

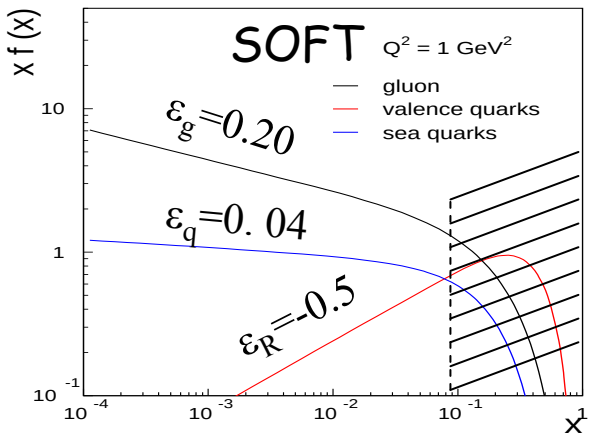
| | | |
|---|---|---|
| W 78 (1997) 2698 | JJ 74 (1995) 855 | JJ 85 (2000) 4217 |
| JJ 79 (1997) 2636 | JJ 80 (1998) 1156 | |
| b-quark 84 (2000) 232 | JJ 81 (1998) 5278 | |
| J/ψ 87 (2001) 241802 | | |



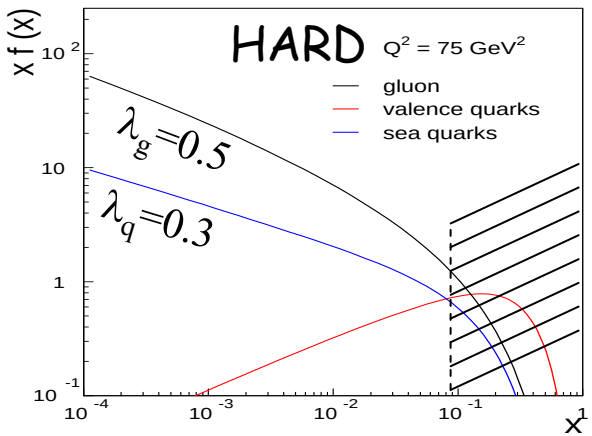

# Diffraction in QCD

Derive diffractive from inclusive PDFs and color factors



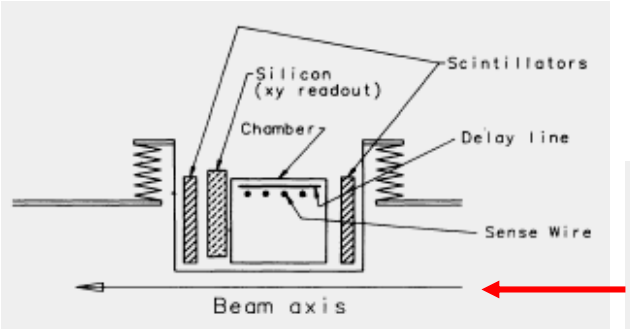




$$x \cdot f(x) = \frac{1}{x^{\varepsilon\,(\text{or}\,\lambda)}}$$

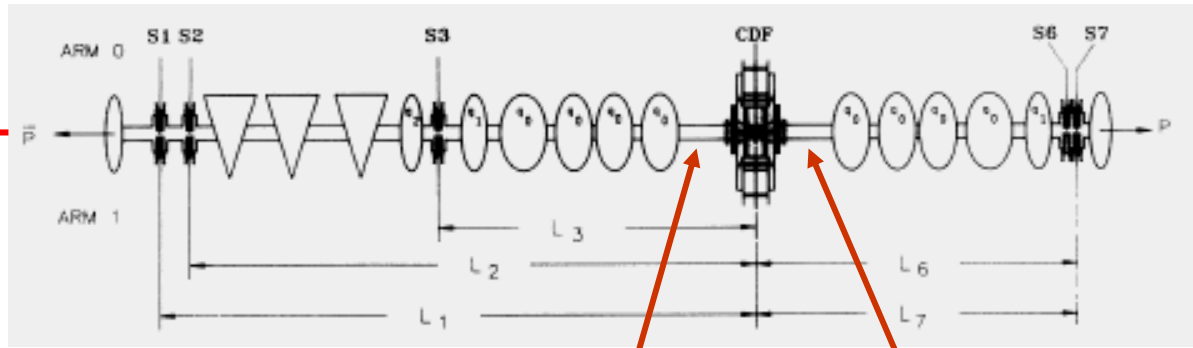


# CDF in Run I-0 (1988-89)

## Elastic, single diffractive, and total cross sections @ 546 and 1800 GeV




### Roman Pot Spectrometers




### Roman Pot Detectors

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

### Additional Detectors

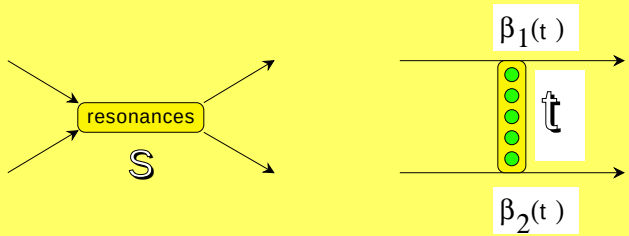
Trackers up to $|\eta| = 7$

### Results

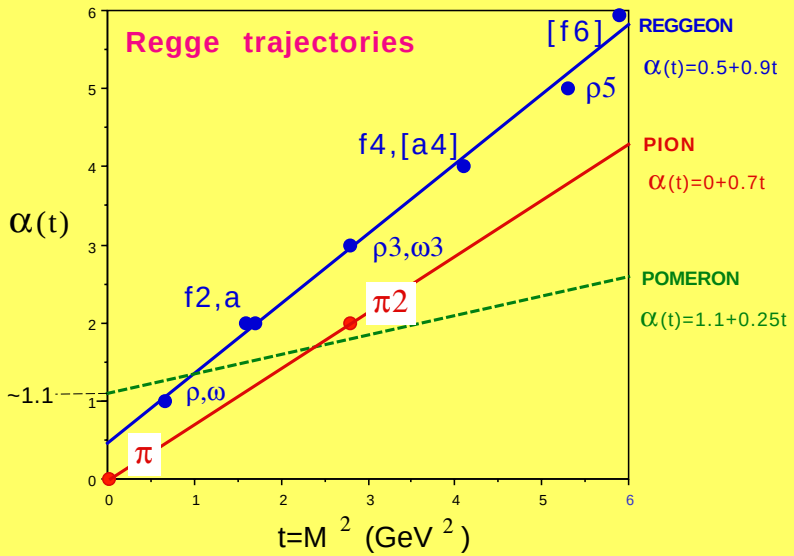
- Total cross section $\sigma^{tot} \sim s^{\varepsilon}$
- Elastic cross section $d\sigma/dt \sim \exp[2\alpha' \ln s]$ → shrinking forward peak
- Single diffraction Breakdown of Regge factorization

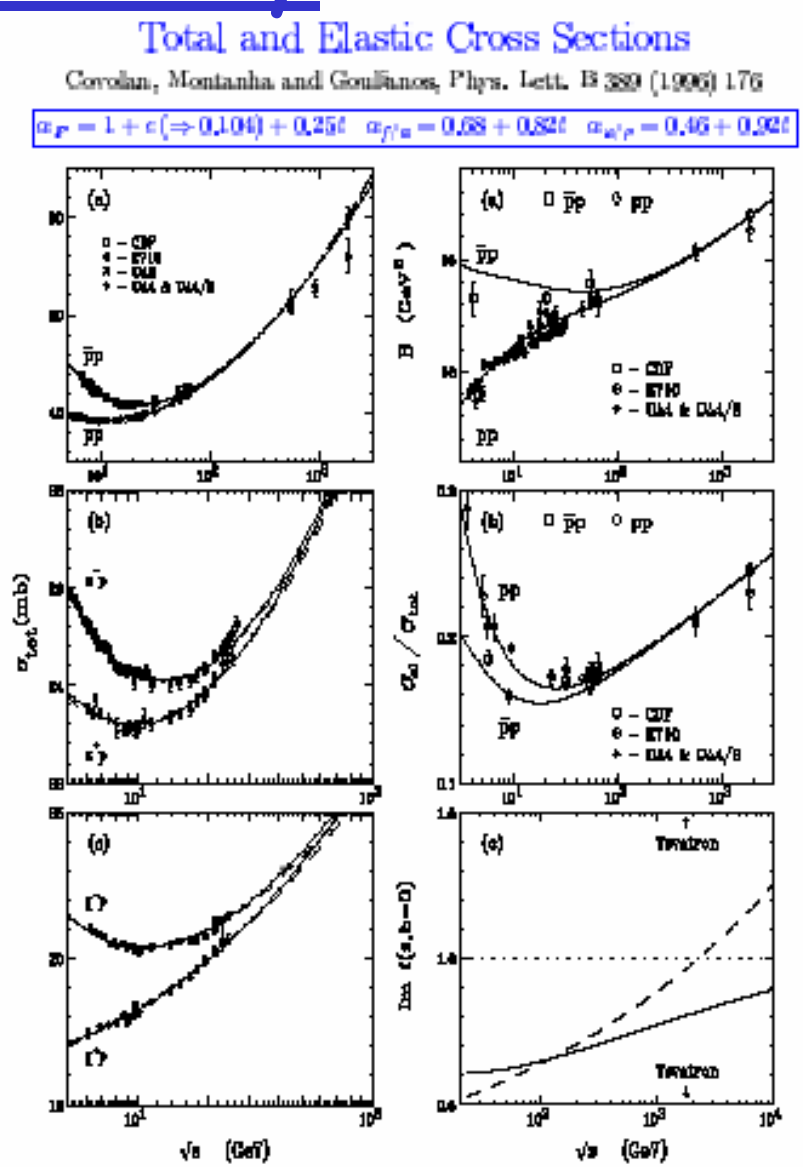
# Regge Theory

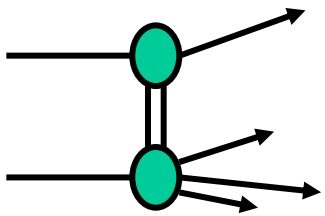
**REGGE THEORY**




$$T(s,t) = \frac{1}{s}\beta_1(t)\,\beta_2(t)\,s^{\alpha(t)}\,\phi_{a(t)} \qquad \sigma_T = \beta^2(0)\,s^{\alpha(0)-1}$$





# Renormalization

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

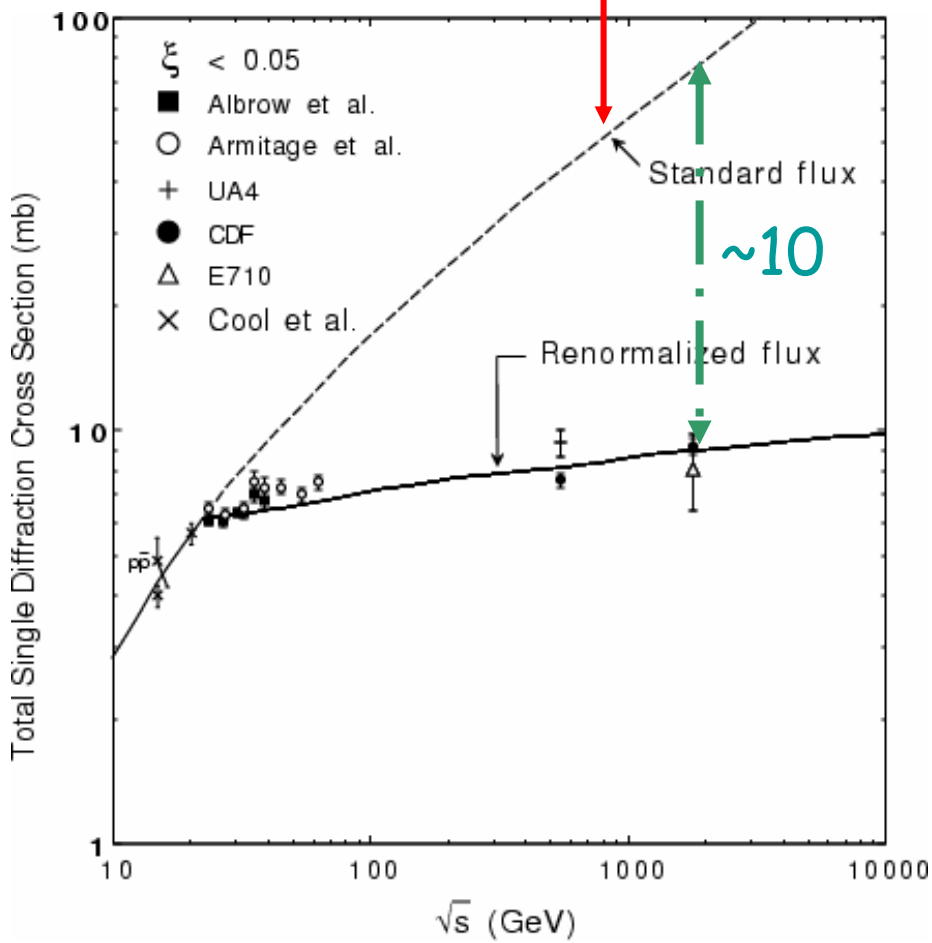
$$\sigma_{SD} \sim s^{2\varepsilon}$$

- **Unitarity problem:**
  With factorization and std pomeron flux $\sigma_{SD}$ exceeds $\sigma_T$ at $\sqrt{s} \approx 2$ TeV.

- **Renormalization:**
  normalize the pomeron flux to unity

KG, PLB 358 (1995) 379

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



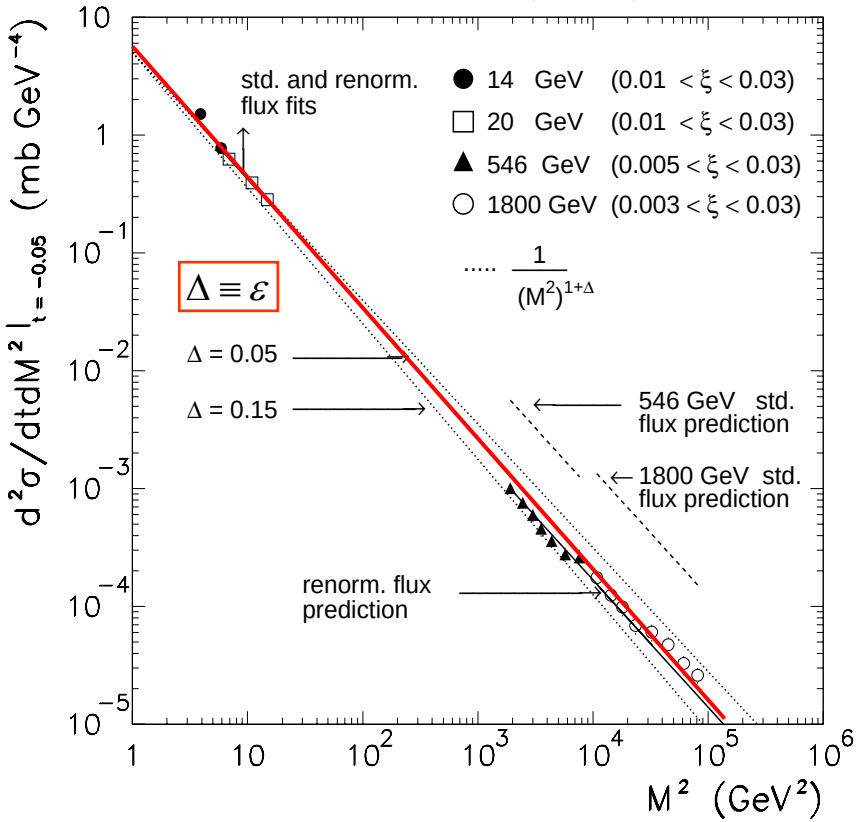
# A Scaling Law in Diffraction

Factorization breaks down in favor of $M^2$-scaling

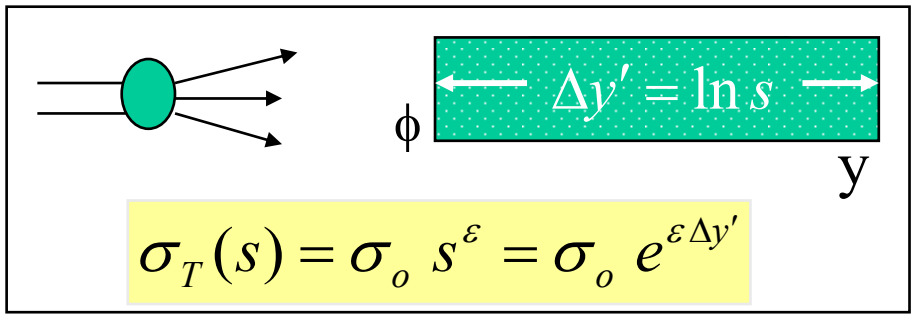
renormalization

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

KG&JM, PRD 59 (1999) 114017



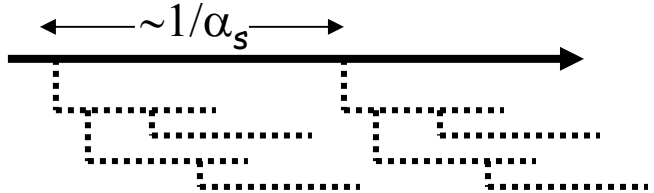
# The QCD Connection

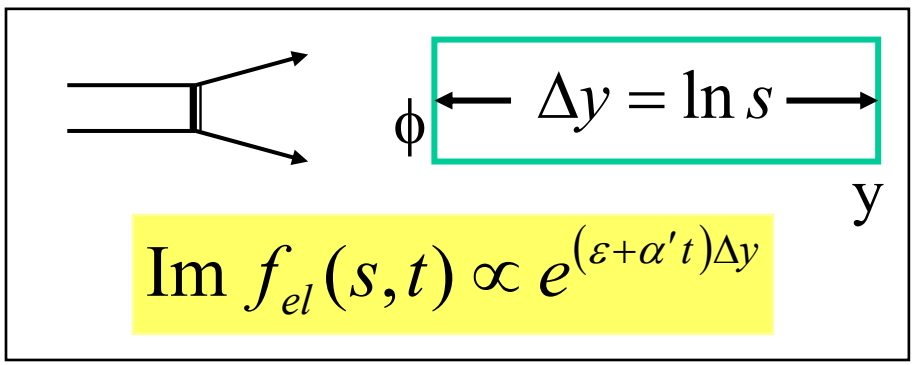



The exponential rise of $\sigma_T(\Delta y')$ is due to the increase of wee partons with $\Delta y'$

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

Total cross section:
power law rise with energy

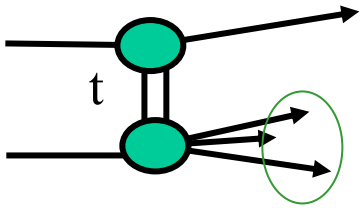


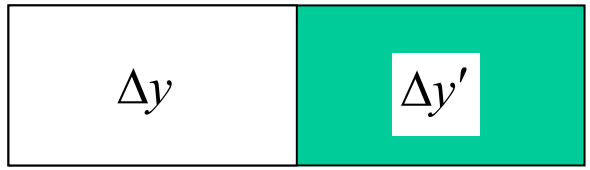




Elastic cross section
forward scattering amplitude

# QCD Basis of Renormalization

(KG, hep-ph/0205141)




2 independent variables: $t, \Delta y$

color factor

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

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

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

Renormalization removes the s-dependence ⟶ SCALING

# The Factors κ and ε

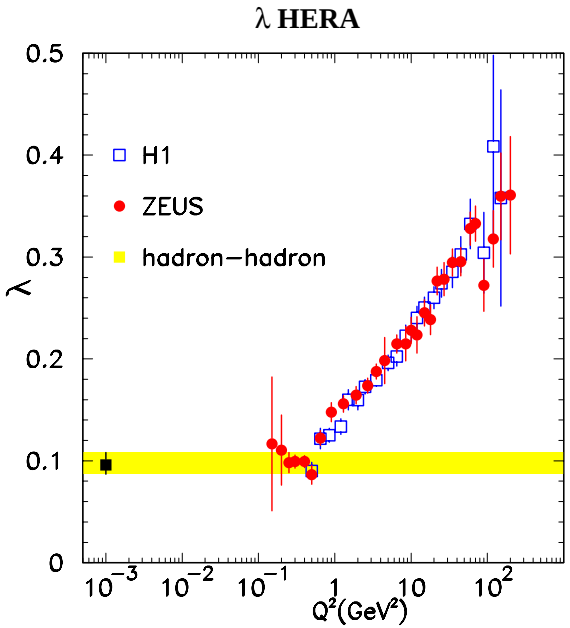
Experimentally:

KG&JM, PRD 59 (114017) 1999

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

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

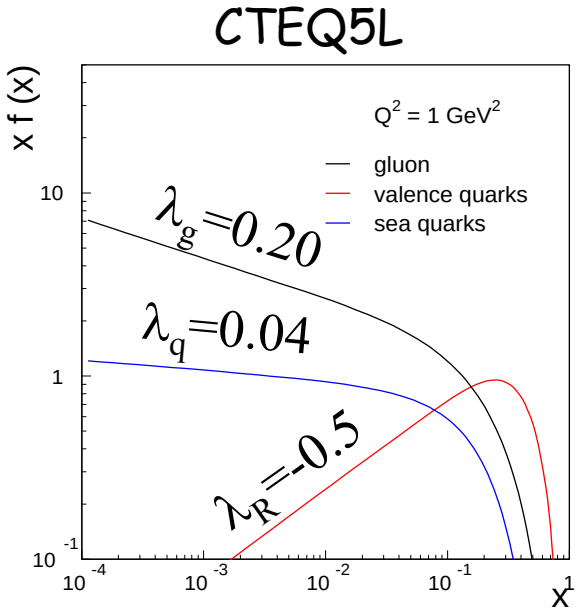
Pomeron intercept: $\varepsilon = \lambda_g \cdot w_g + \lambda_q \cdot w_q = 0.12$



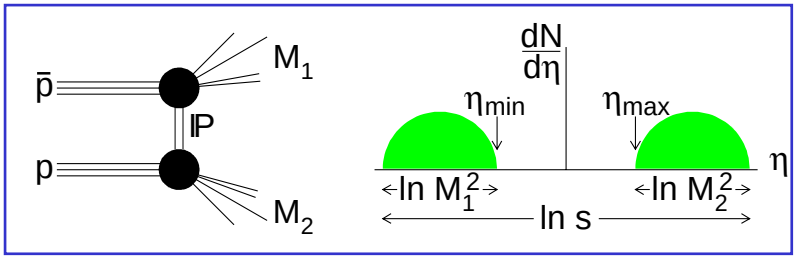

$$x \cdot f(x) = \frac{1}{x^{\lambda}}$$

$f_g$=gluon fraction
$f_q$=quark fraction

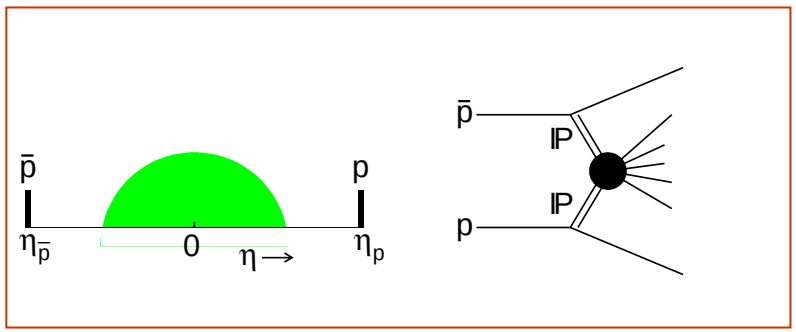
$$\int_{x=1/s}^{1} f(x)\,dx \sim s^{\lambda}$$



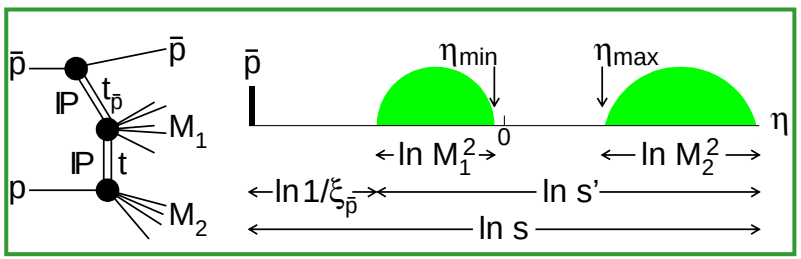
# Central and Double Gaps




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



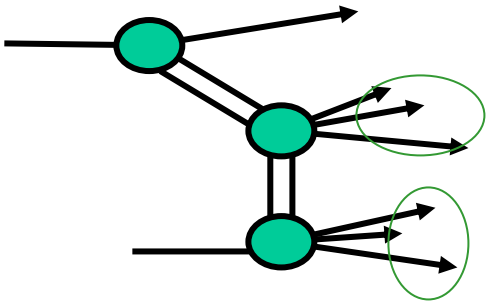

- **Double Pomeron Exchange**
  - **Two forward gaps**

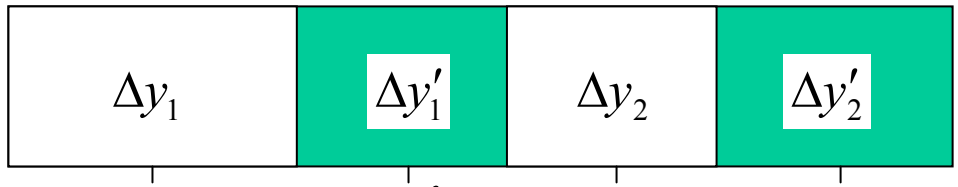



- **SDD: Single+Double Diffraction**
  - **One forward + one central gap**

# Multigap Renormalization

(KG, hep-ph/0205141)






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

color factors

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

Gap probability

Sub-energy cross section (for regions with particles)

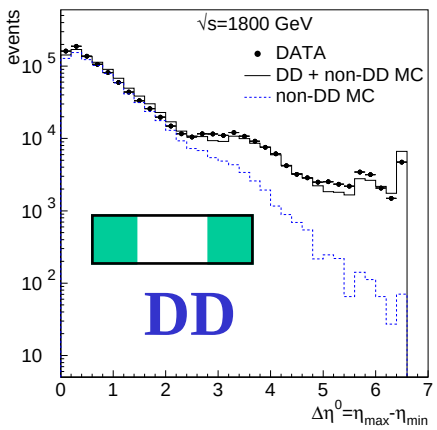
$$\sim e^{2\varepsilon \Delta y}$$

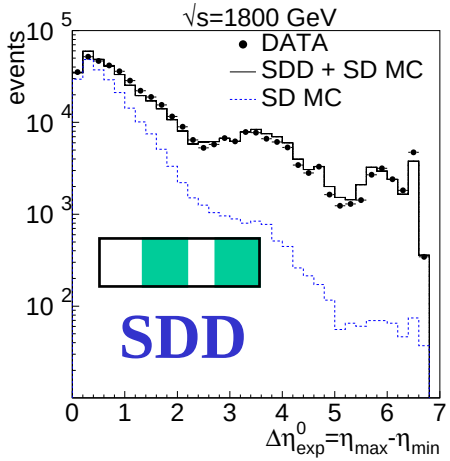
$$\int_{\Delta y_{\min}}^{\Delta y = \ln s} s^{2\varepsilon\,\Delta y} \approx s^{2\varepsilon}$$

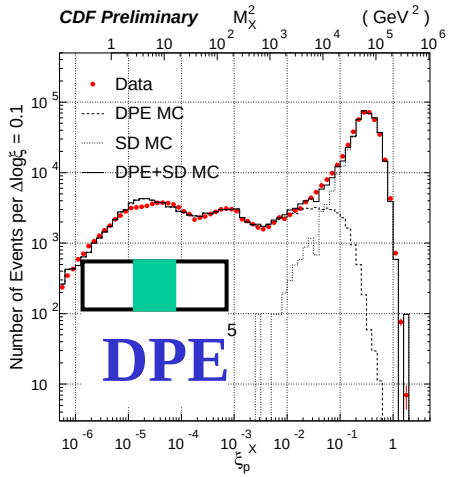
Same suppression as for single gap!

# Central & Double-Gap Results

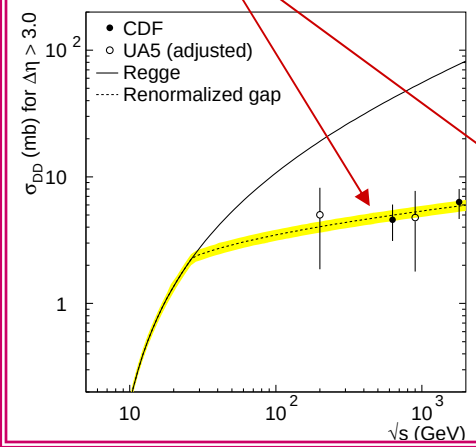
## Differential shapes agree with Regge predictions

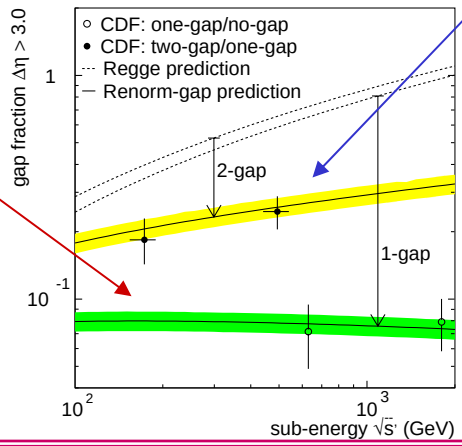


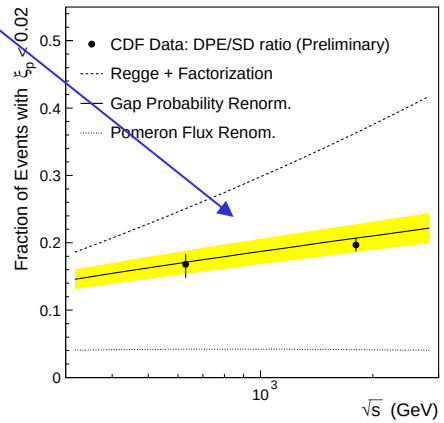




- **One-gap cross sections are suppressed**
- **Two-gap/one-gap ratios are** $\approx \kappa = 0.17$



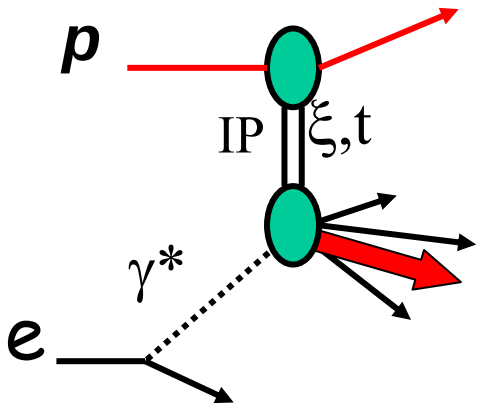



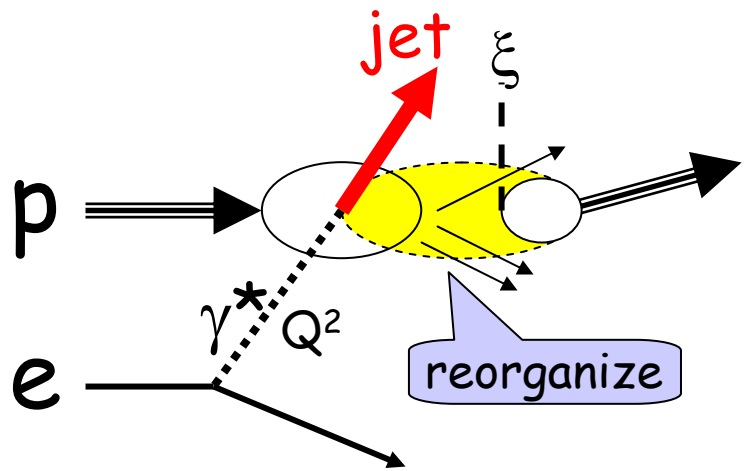
# Diffractive DIS @ HERA

J. Collins: Factorization should hold

Pomeron exchange



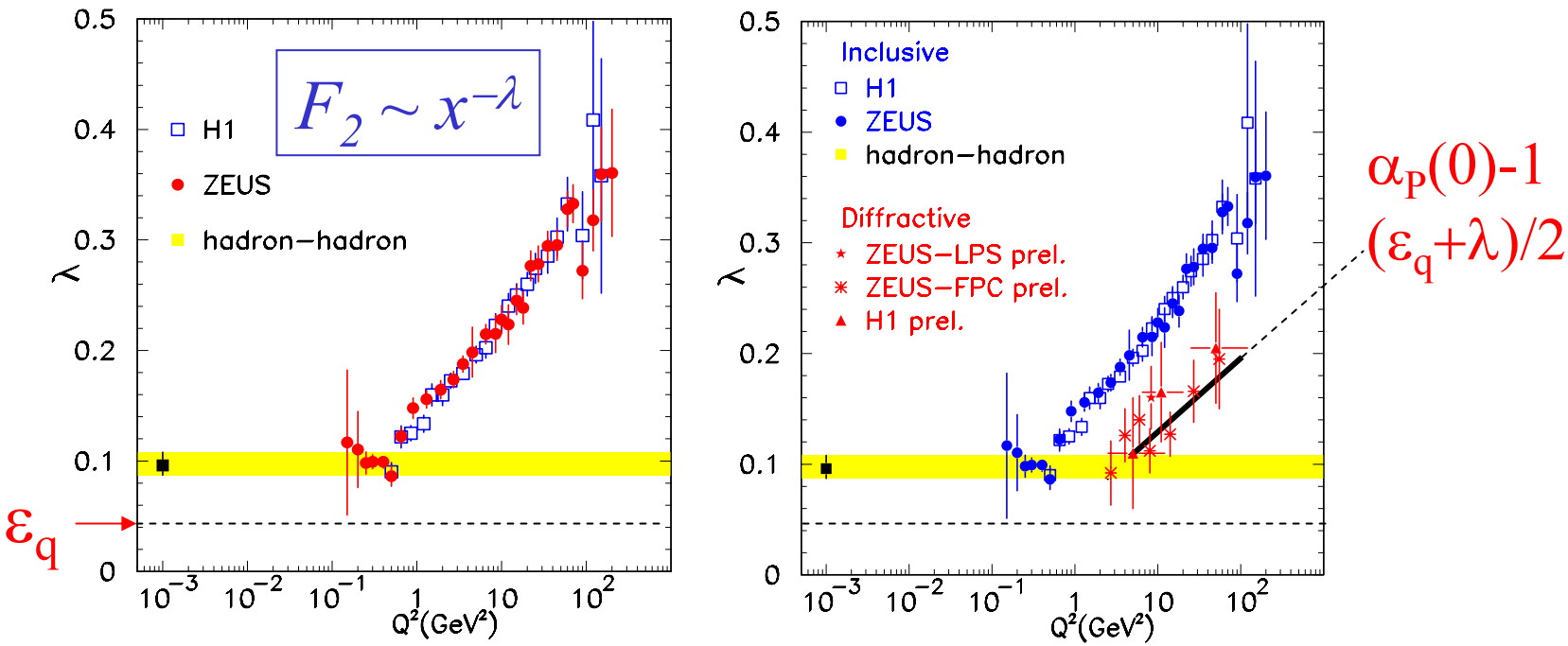

Color reorganization




$$F_2^{D(3)}(\xi, x, Q^2) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot F_2(x, Q^2)$$

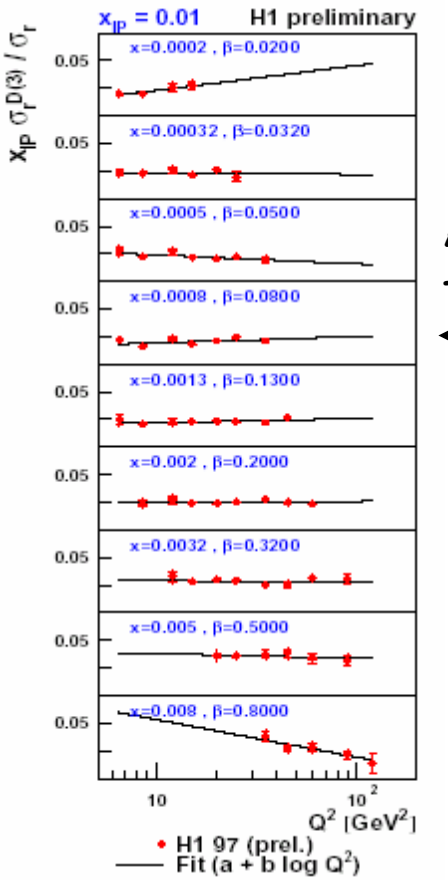
# Inclusive vs Diffractive DIS

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



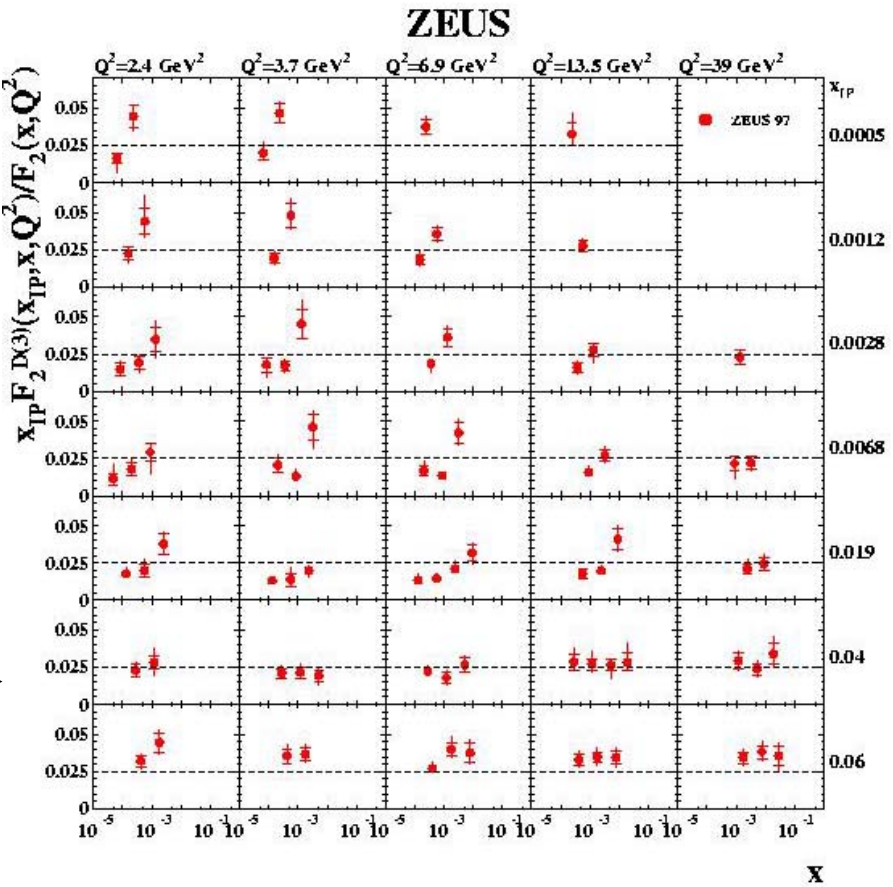

$$F_2^{D(3)}(\xi,\beta,Q^2) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot \frac{C(Q^2)}{(\beta\xi)^{\lambda(Q^2)}} \propto \frac{1}{\xi^{1+\varepsilon+\lambda}} \cdot \frac{C}{\beta^{\lambda}}$$

# $\sigma^{diff}/\sigma^{incl}$ DIS at HERA



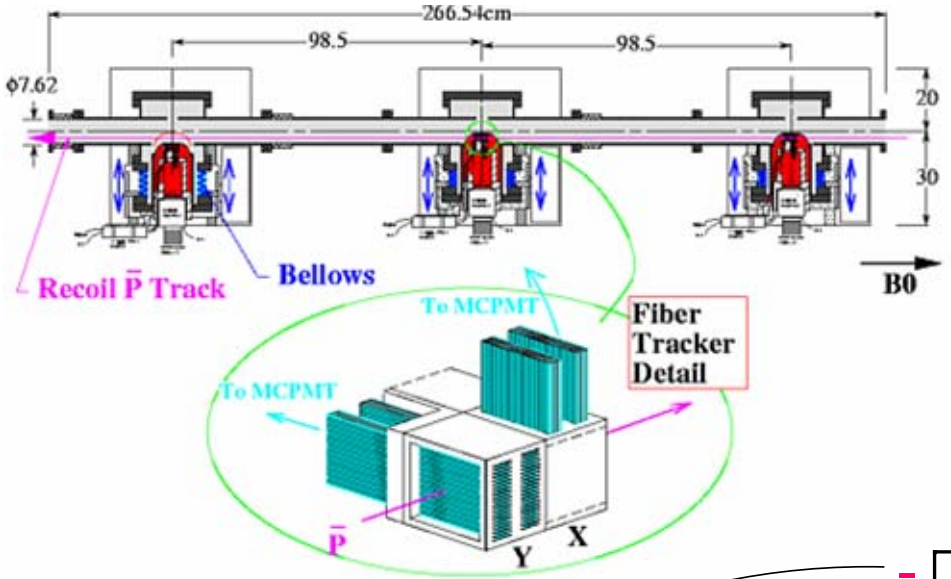

At fixed x:
flat $Q^2$-dependence

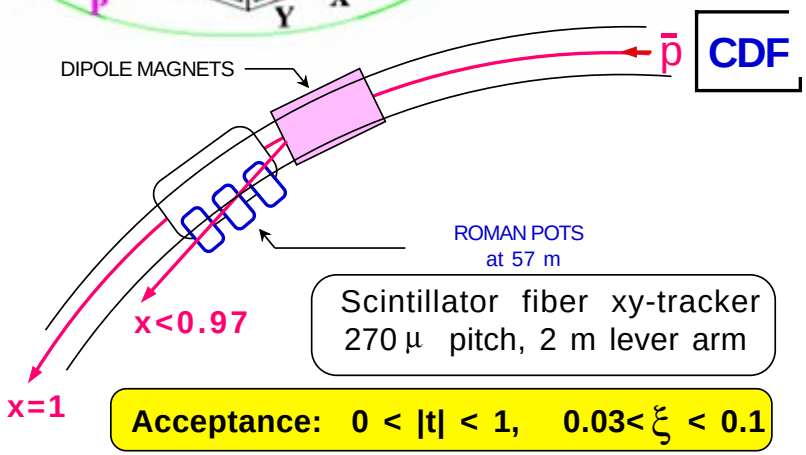
At fixed $Q^2$:
flat x-dependence



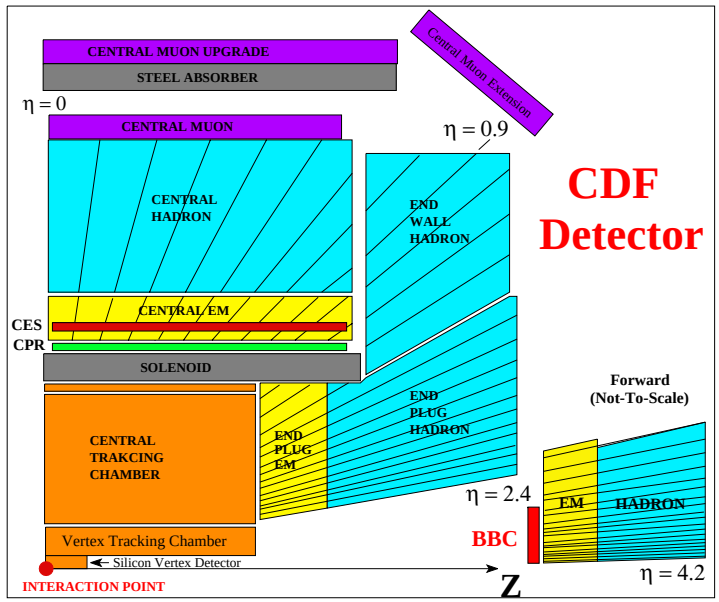
# CDF-IC

## Run-IC




## Run-IA,B




## Forward Detectors

**BBC 3.2<η<5.9**

**FCAL 2.4<η<4.2**

# Diffractive Fractions @ CDF

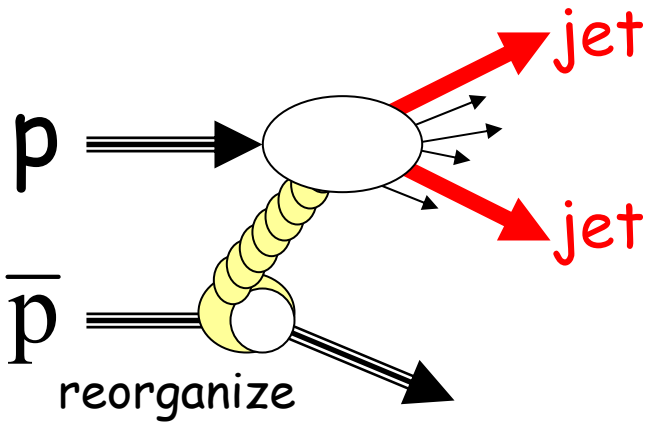
$$\bar{p}p \rightarrow X + \text{gap}$$

**SD/ND fraction at 1800 GeV**

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

All fractions ~ 1%
➔ Factorization ~ OK @ Tevatron
at fixed c.m.s. energy.

# Diffractive Dijets @ Tevatron




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

# Diffractive Structure F'n @CDF

$$\bar{p} + p \rightarrow \bar{p} + Jet + Jet + X$$

- Measure ratio of SD/ND dijet rates as a f'n of $x_{\bar{p}}$

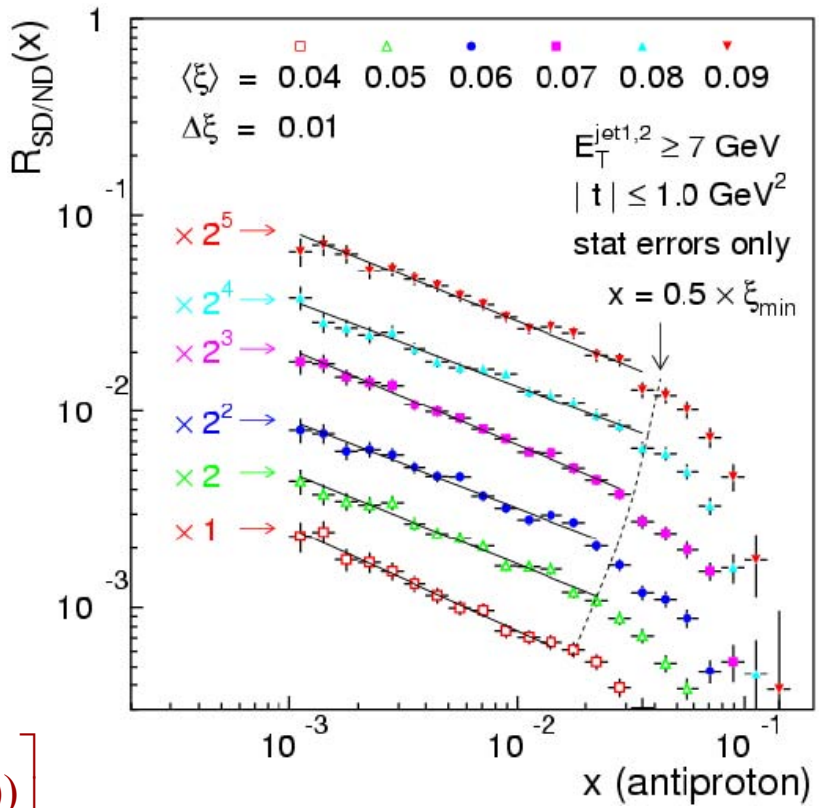
$$x_{\bar{p}} \equiv p_{g,q}/p_{\bar{p}} = \frac{\sum_{i=1}^{2(3)} E_T^i \cdot e^{-\eta^i}}{\sqrt{s}}$$

$$R_{\frac{SD}{ND}}(x_{\bar{p}}) \approx R_0 \cdot x_{\bar{p}}^{-0.45}$$

- In LO-QCD ratio of rates equals ratio of structure fn's

$$F_{jj}(x_{\bar{p}}) = x_{\bar{p}}\left[ g(x_{\bar{p}}) + \frac{C_F}{C_A}\sum (q_i(x_{\bar{p}}) + \bar{q}_i(x_{\bar{p}})) \right]$$

SD/ND Rates vs $x_{\bar{p}}$



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

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

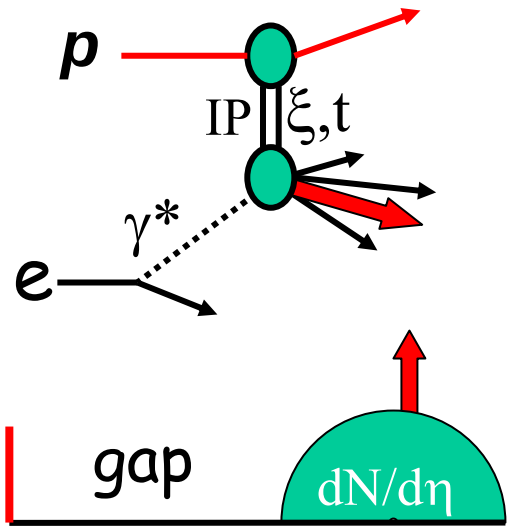
$$N^{-1}_{\text{renorm}} = \int_{\xi_{\min}}^{1} \frac{d\xi}{\xi^{1+2\varepsilon}} \xrightarrow{\xi_{\min} = \frac{x_{\min}}{\beta} \sim \frac{1}{\beta s}} (\beta s)^{2\varepsilon}$$

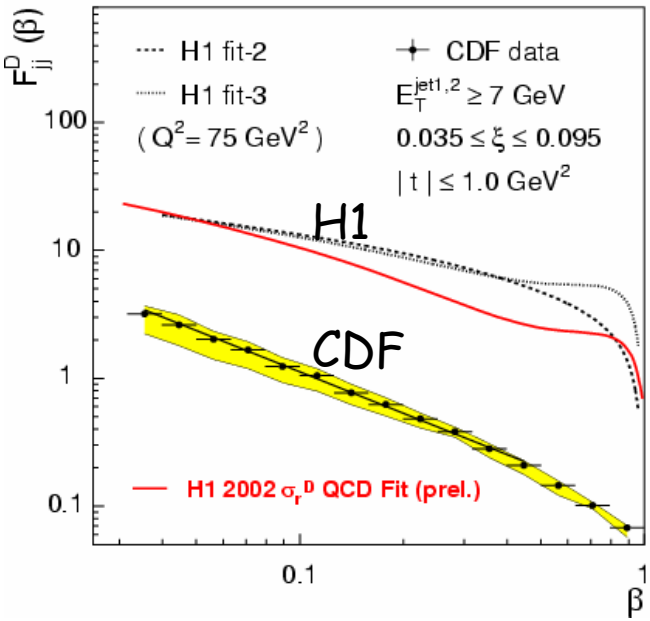
$$\text{RENORM} \quad \Rightarrow \quad R^{SD}_{ND}(x) \sim \frac{1}{s^{2\varepsilon}} \frac{1}{\xi^{1-\lambda(Q^2)}} \cdot x^{-(2\varepsilon)}$$

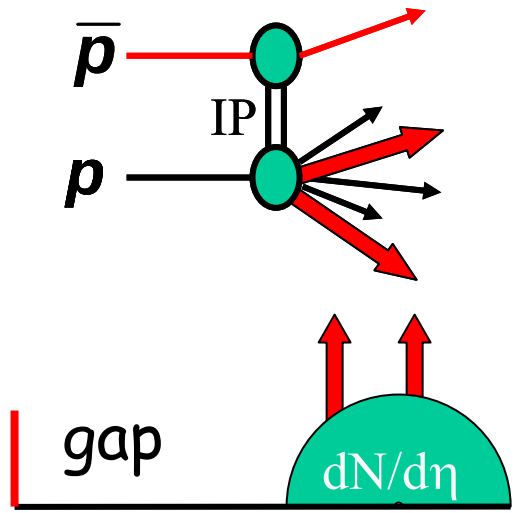
$$\varepsilon_g = 0.2 \rightarrow x^{-0.4}$$

# Tevatron vs HERA: Factorization Breakdown

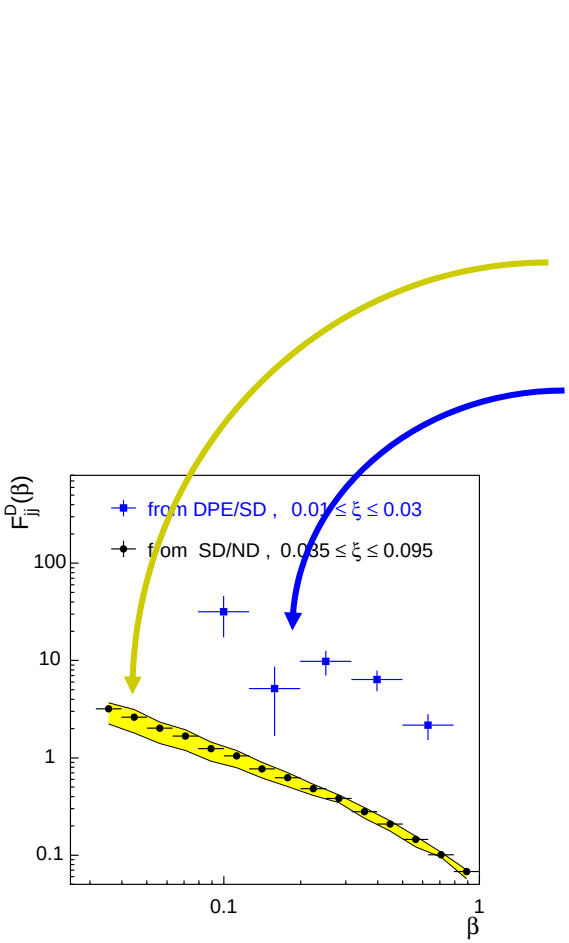
Predicted in KG, PLB 358 (1995) 379

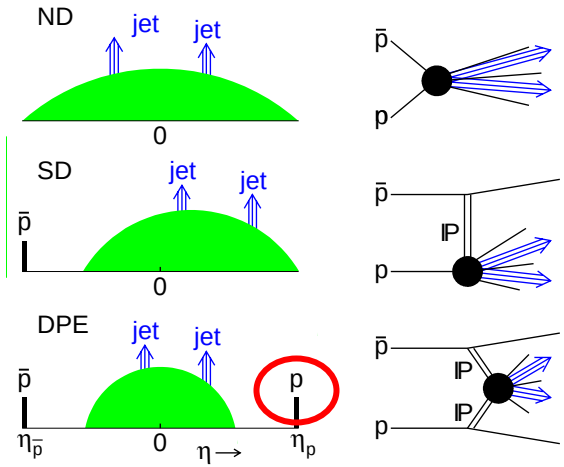


# Restoring Factorization

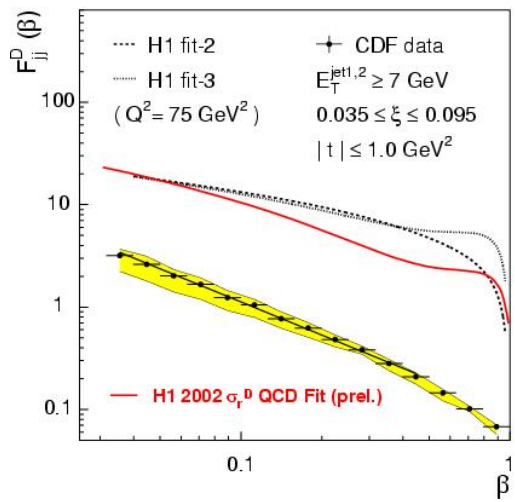


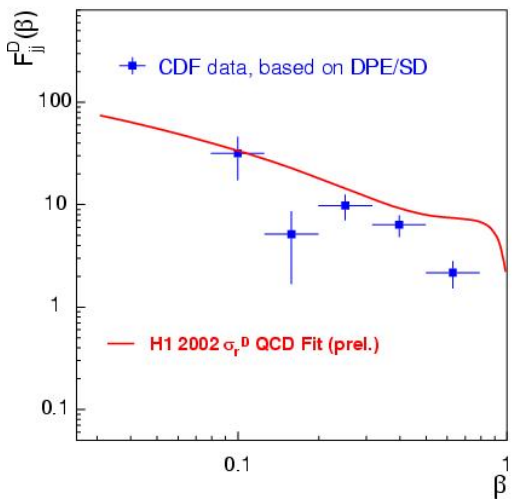




R(SD/ND)

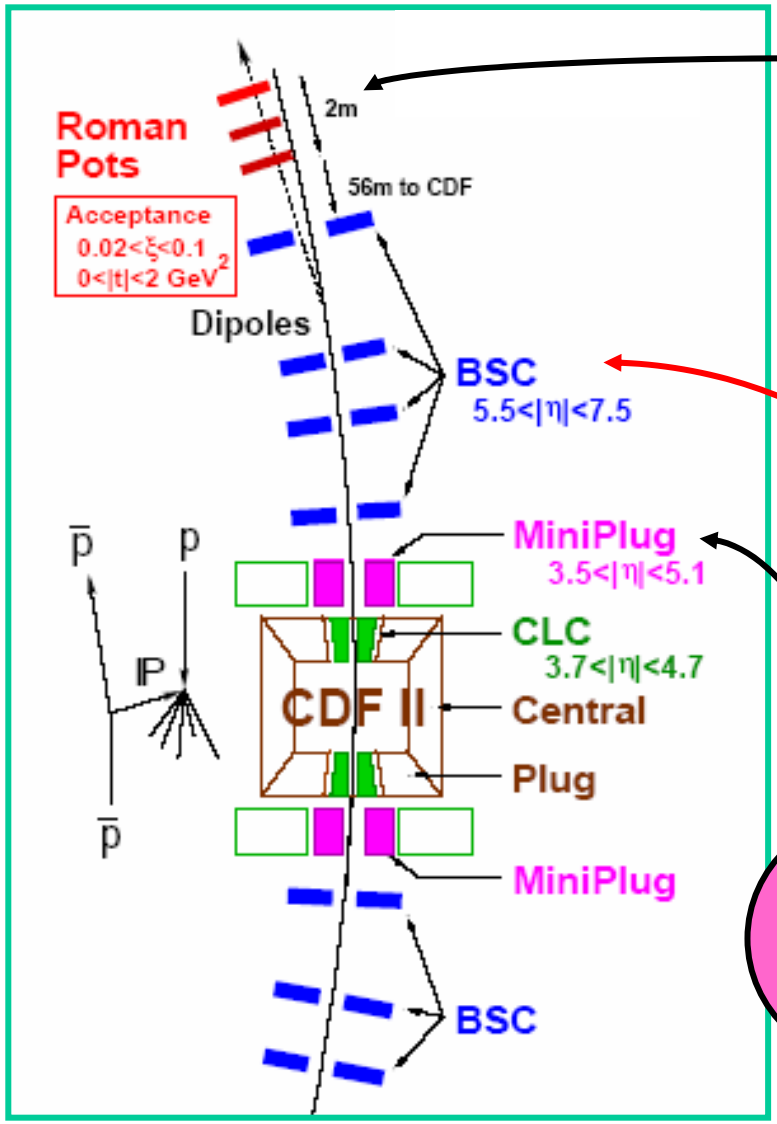
R(DPE/SD)

DSF from two/one gap: factorization restored!

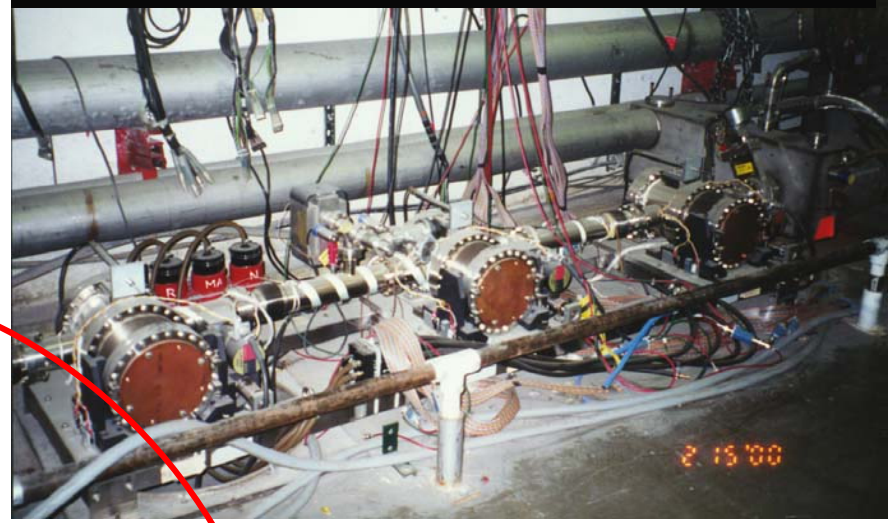


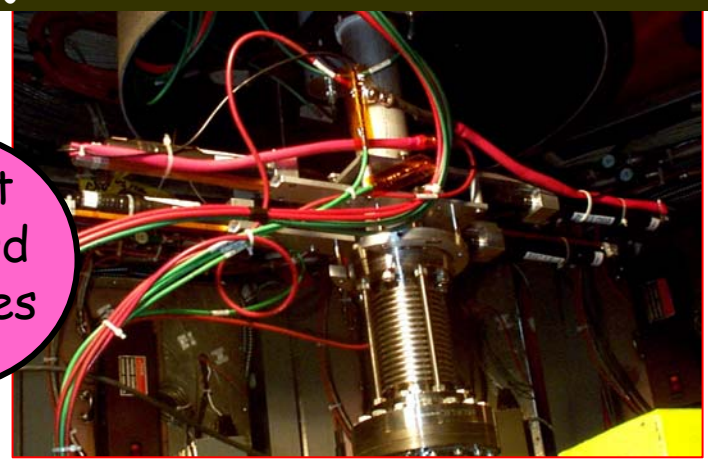
# CDF-II




Tag leading p-bar @ $0.02 < \xi < 0.1$

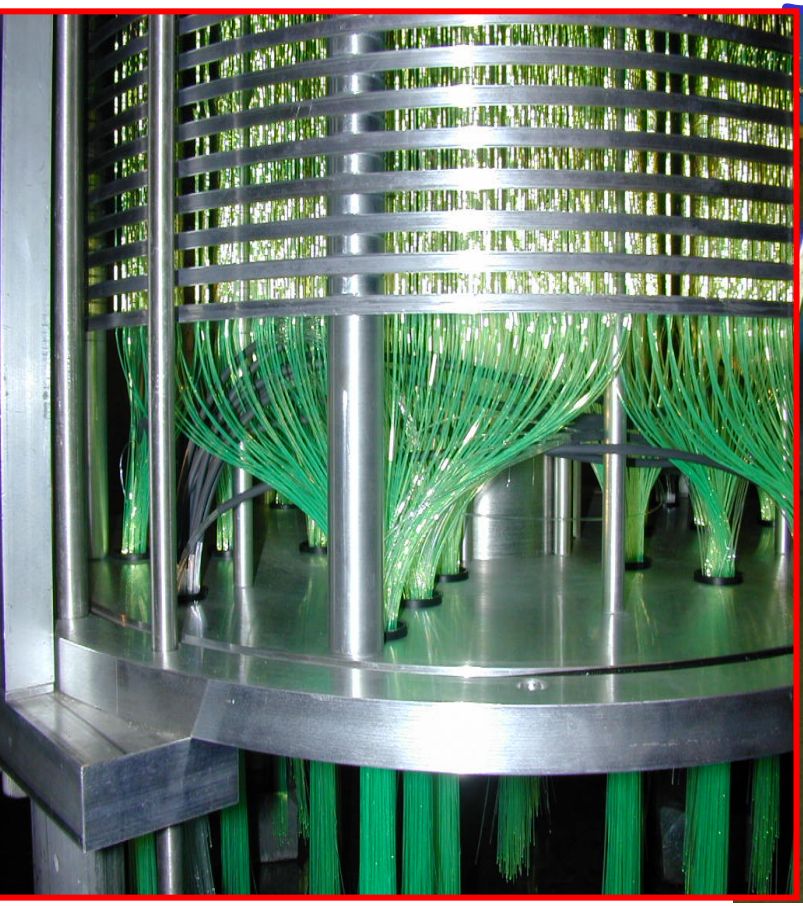


Reject (retain) 95% of ND (SD)events



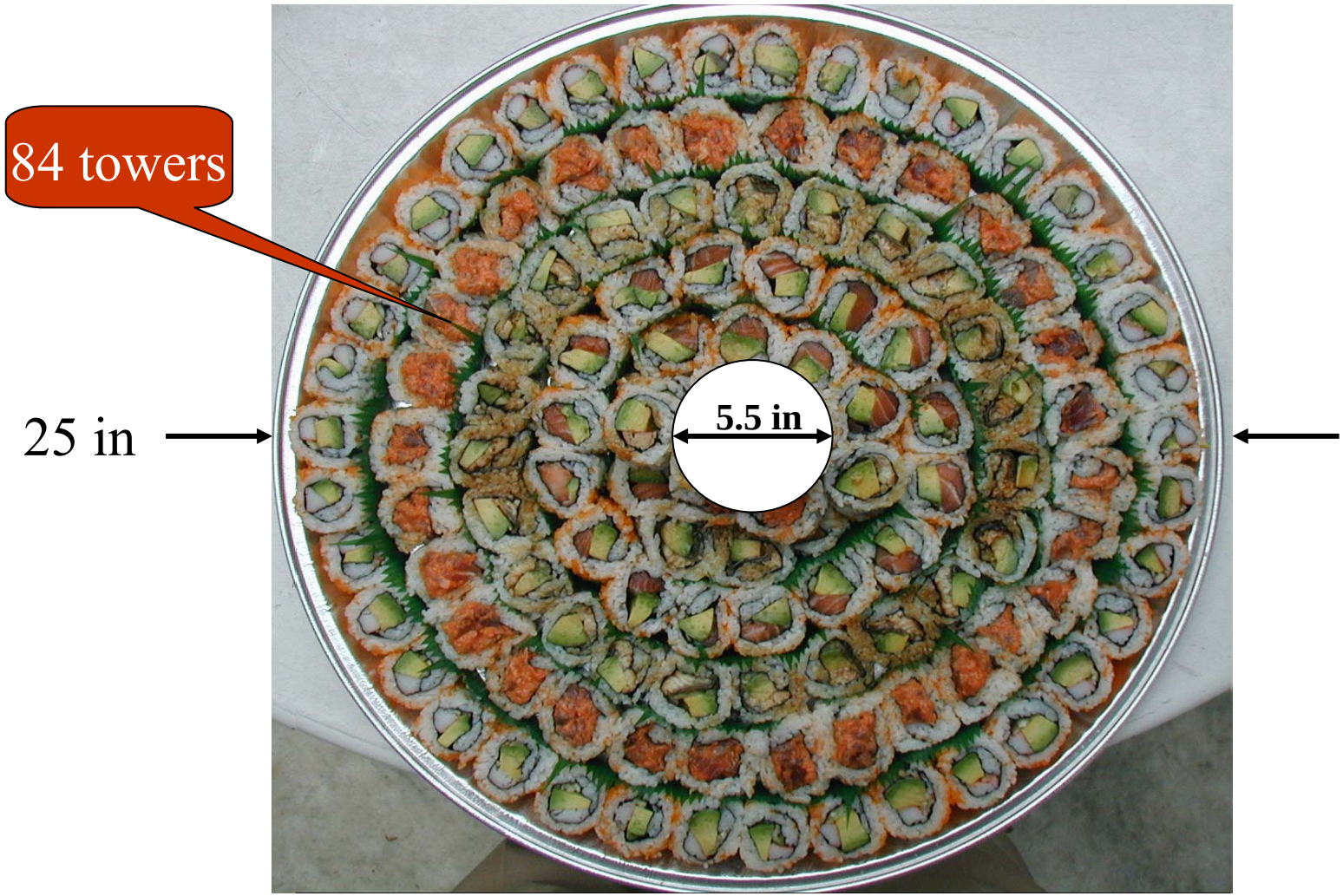
detect forward particles

# MiniPlug Calorimeter



About 1500 wavelength shifting fibers of 1 mm dia. are 'strung' through holes drilled in 36x$\frac{1}{4}$" lead plates sandwiched between reflective Al sheets and guided into bunches to be viewed individually by multi-channel photomultipliers.

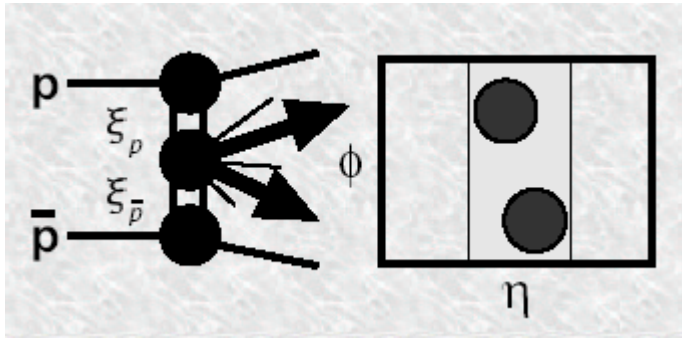
# Artist's View of MiniPlug



# Exclusive Dijets in DPE

Interest in diffractive Higgs production

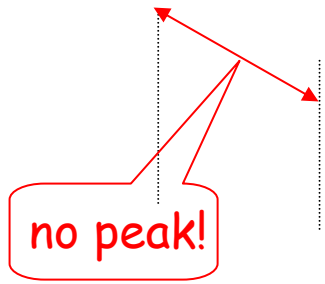
Calibrate on exclusive dijets




Dijet mass fraction

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

| $E_T^{jet}$ | $\sigma_{DPE}^{excl\ jj}(R_{jj} > 0.8)$ |
|---|---|
| 10 GeV | $970 \pm 65 \pm 272$ pb |
| 25 GeV | $34 \pm 5 \pm 10$ pb |

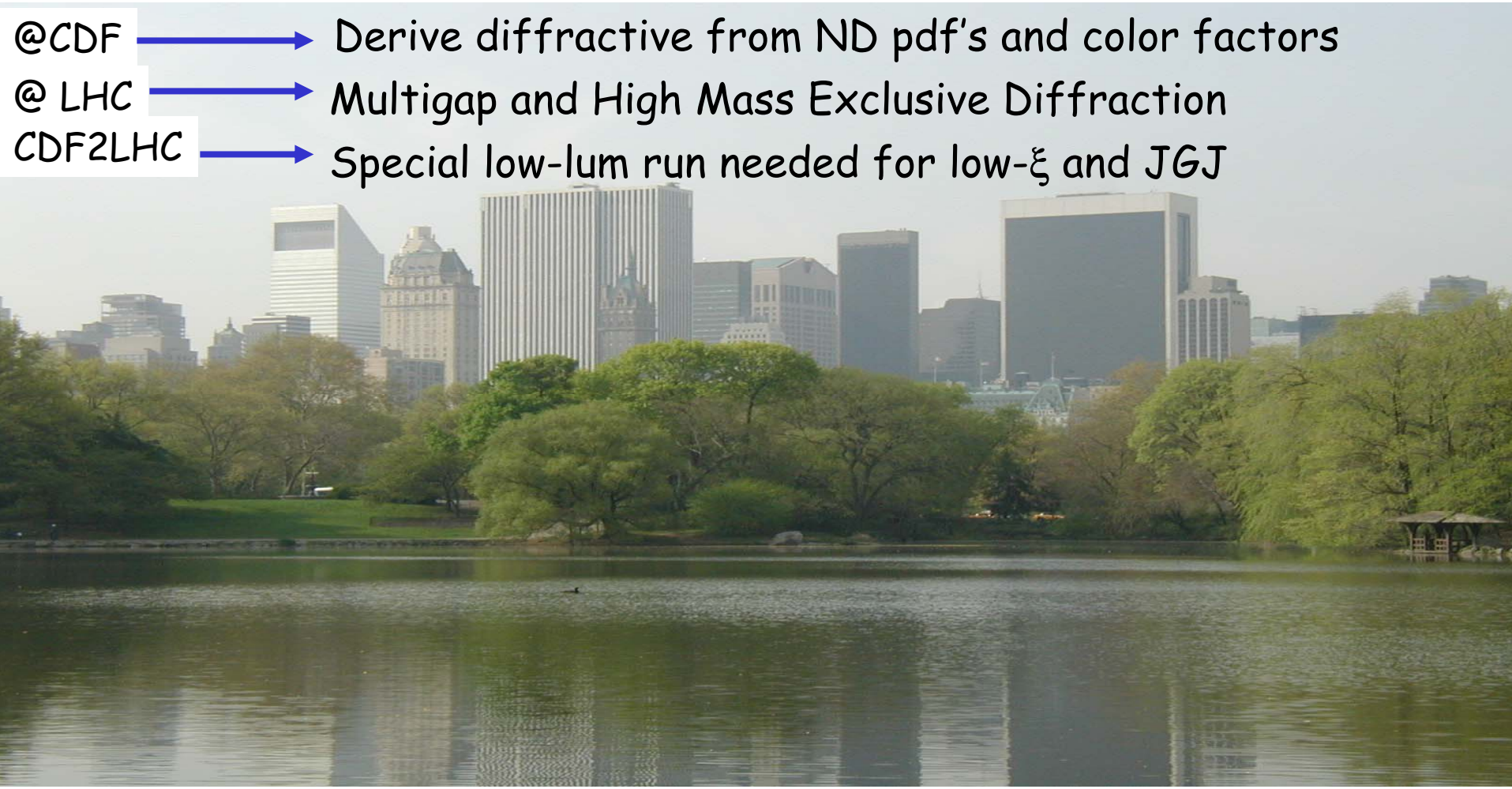



Upper limit for excl DPE-jj consistent with theory: KMR → 60 pb @ $25 < E_T^J < 35$ GeV

# Diffraction @ LHC

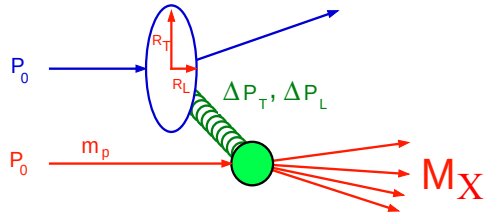
- Multigap diffraction
- Exclusive production of high mass states

# Summary

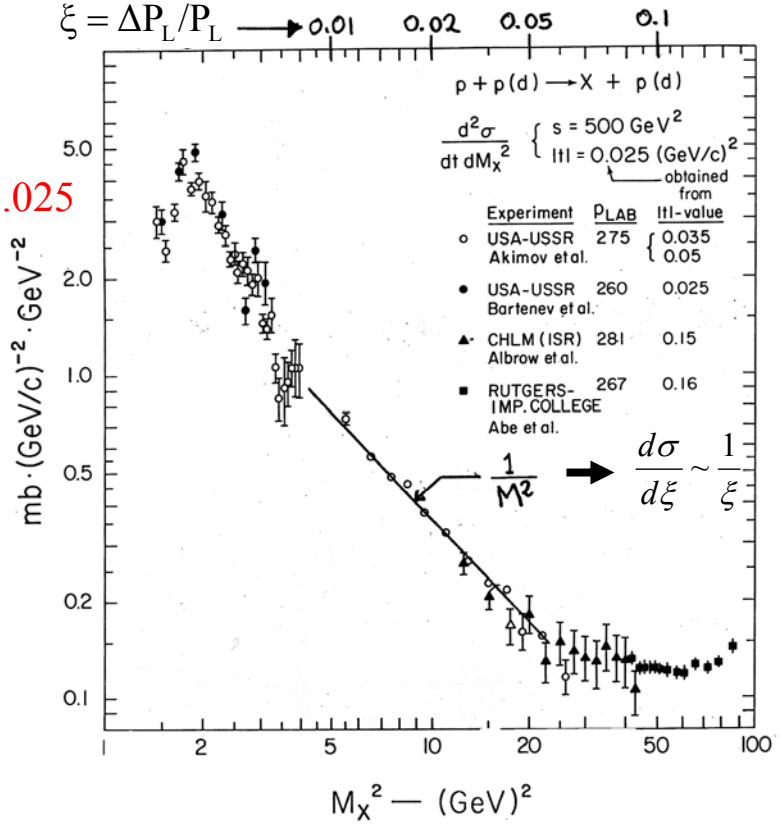

@CDF → Derive diffractive from ND pdf's and color factors
@ LHC → Multigap and High Mass Exclusive Diffraction
CDF2LHC → Special low-lum run needed for low-ξ and JGJ

# BACKUP

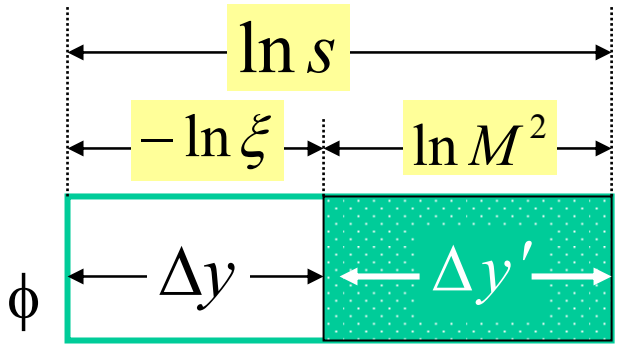
# The First 20 Years




$\xi = \Delta P_L / P_L$




$$\left.\frac{d^2\sigma}{dt\,dM^2}\right|_{t=0.025}$$



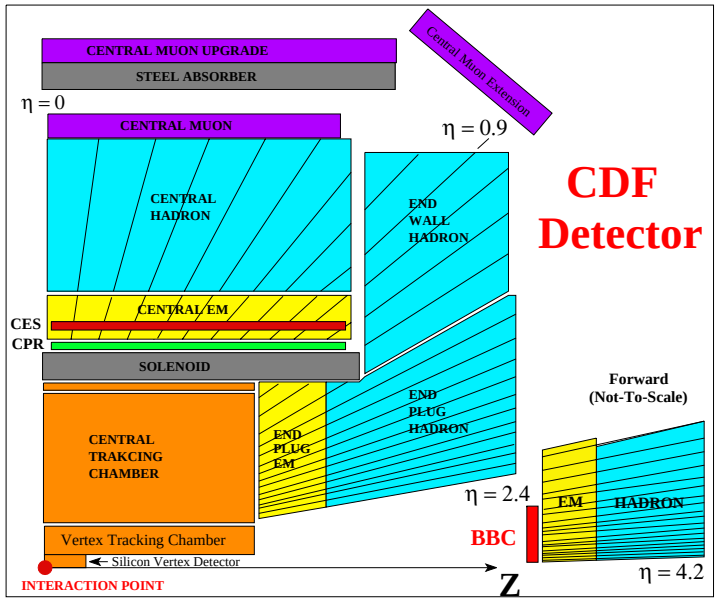

$$\xi = \frac{\Delta p_L}{p_L} = \frac{M^2}{s}$$

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

**KG, Phys. Rep. 101 (1983) 171**

POMERON: color singlet w/vacuum quantum numbers

# Run-I A,B: Rapidity Gap Studies



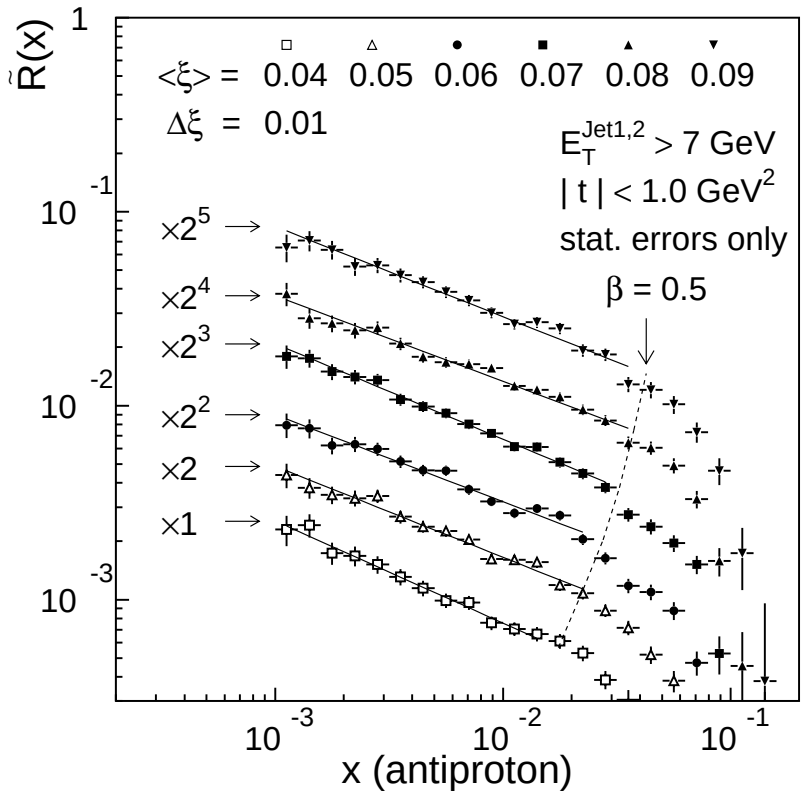

**Forward Detectors**

**BBC $3.2<\eta<5.9$**

**FCAL $2.4<\eta<4.2$**

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

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



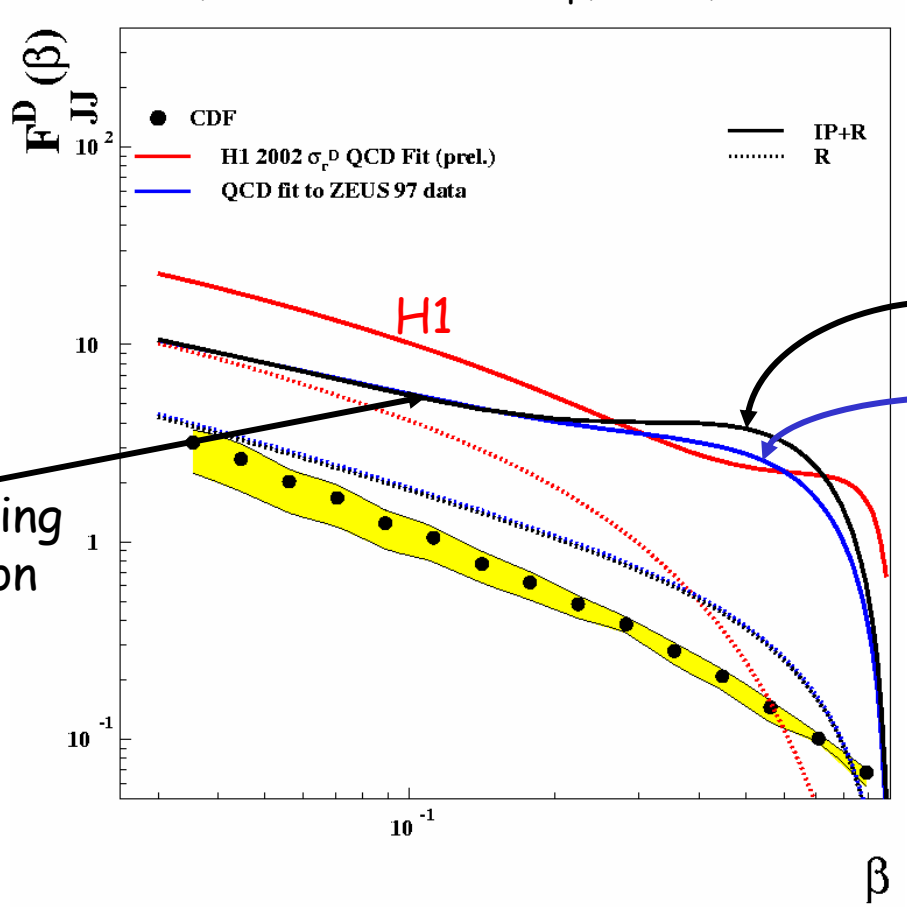

0.035 < ξ < 0.095

Flat ξ dependence

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

# New: $F^{D}_{JJ}(\beta)$ from ZEUS-LPS Data

M. Arneodo, HERA/LHC workshop, CERN, 11-13 Oct 2004

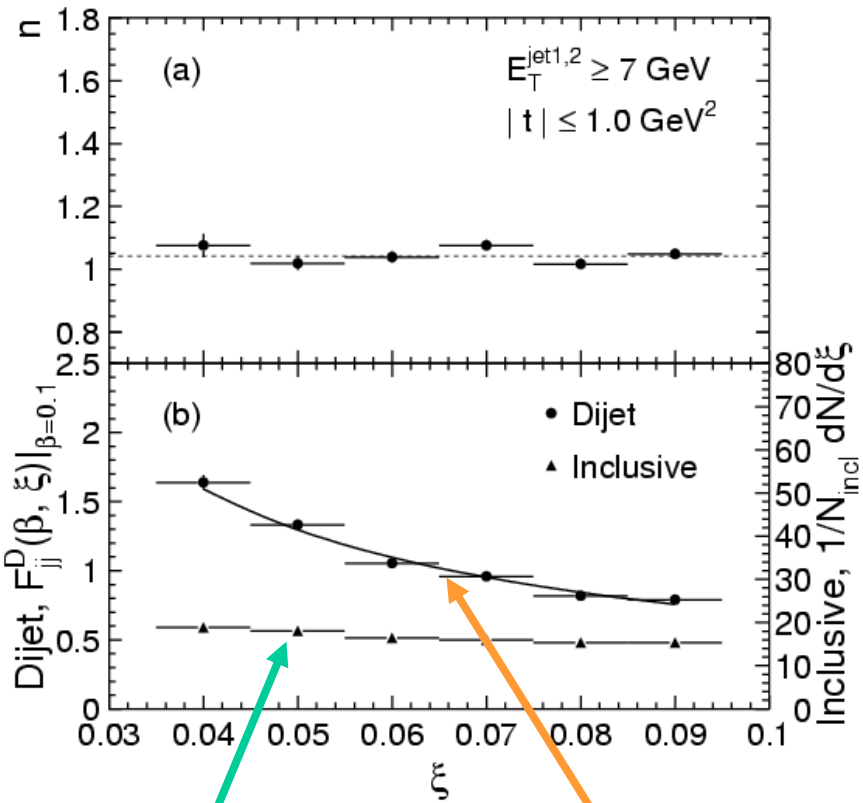


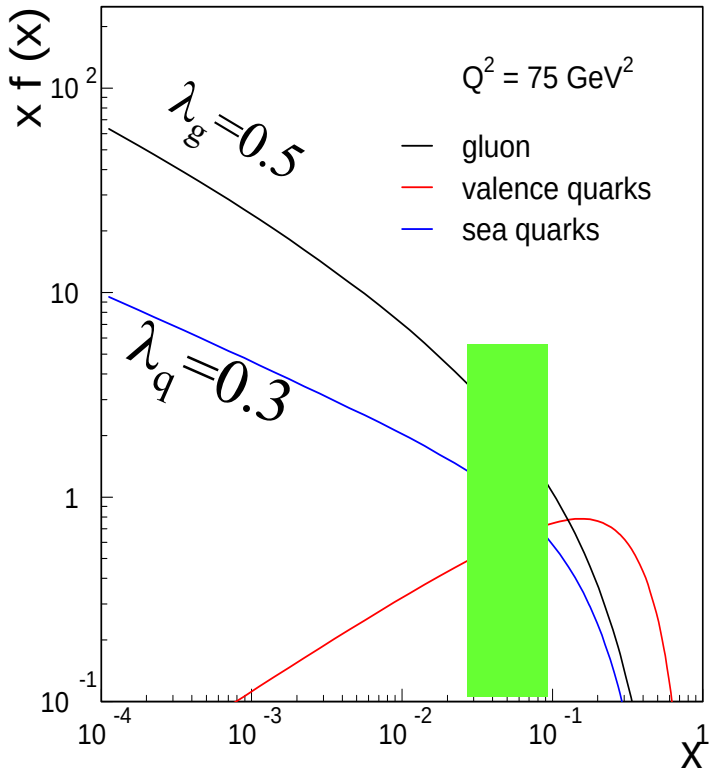

ZEUS Fit including charm data

Fit without charm data

Flat after subtracting Reggeon contribution

# ξ-dependence: Inclusive vs Dijets



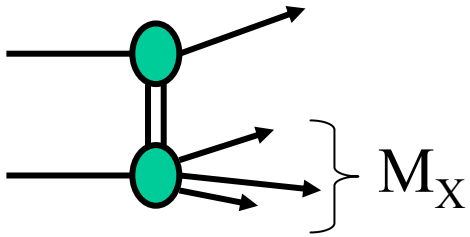

$$\frac{d\sigma_{incl}}{d\xi} \propto \text{constant}$$

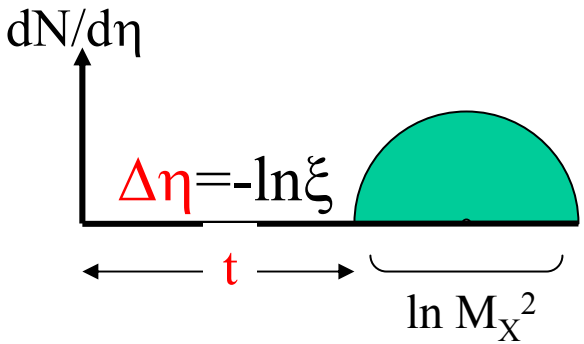
$$F_{jj}^D(\beta,\xi) \propto \frac{1}{\beta^n} \cdot \frac{1}{\xi^m} \qquad (n = 1.0 \pm 0.1, \quad m = 0.9 \pm 0.1)$$

Pomeron dominated

# Hard Diffraction @ CDF

- SOFT DIFFRACTION



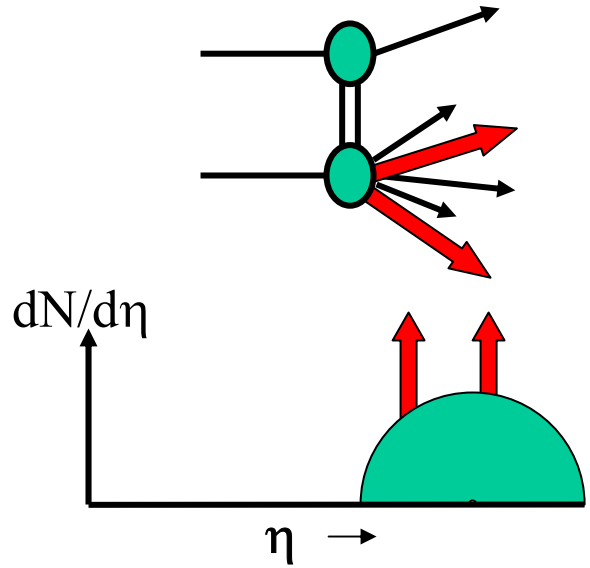




$\xi = \Delta P_L / P_L$

$\xi$=fractional momentum loss of scattered (anti)proton

Variables: ($\xi$, t) or ($\Delta\eta$, t)

- HARD DIFFRACTION

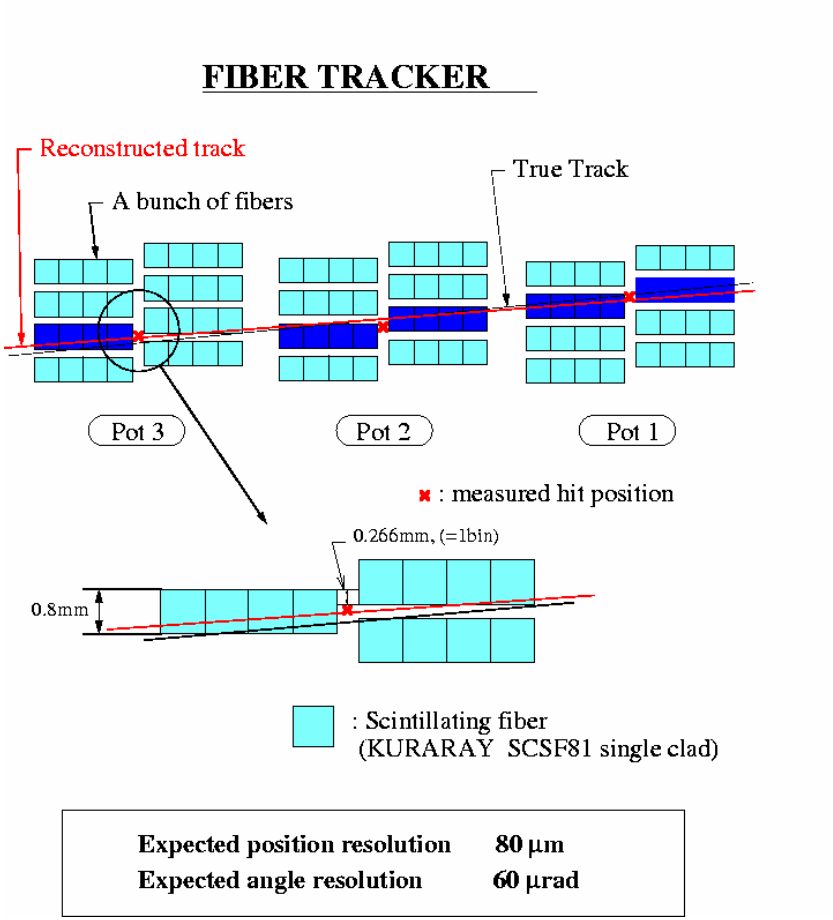



Additional variables: ($x$, $Q^2$)

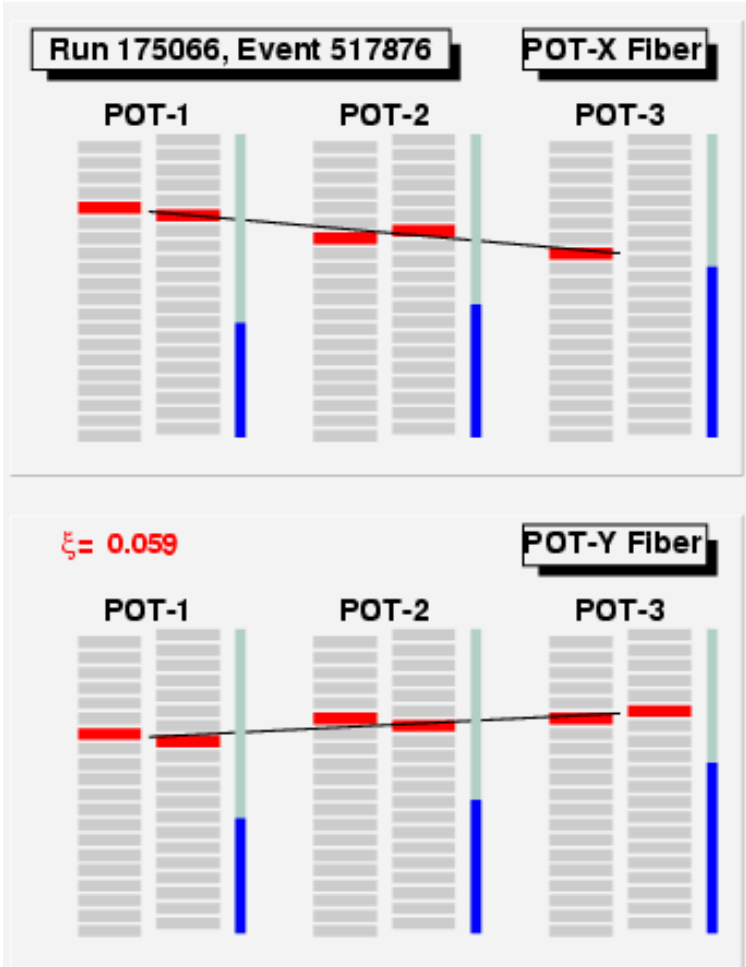
$$x_{Bj} = \sum E_T^{jet} e^{-\eta^{jet}} / \sqrt{s}$$

$$x = \beta\,\xi, \quad Q^2 = (E_T^{jet})^2$$

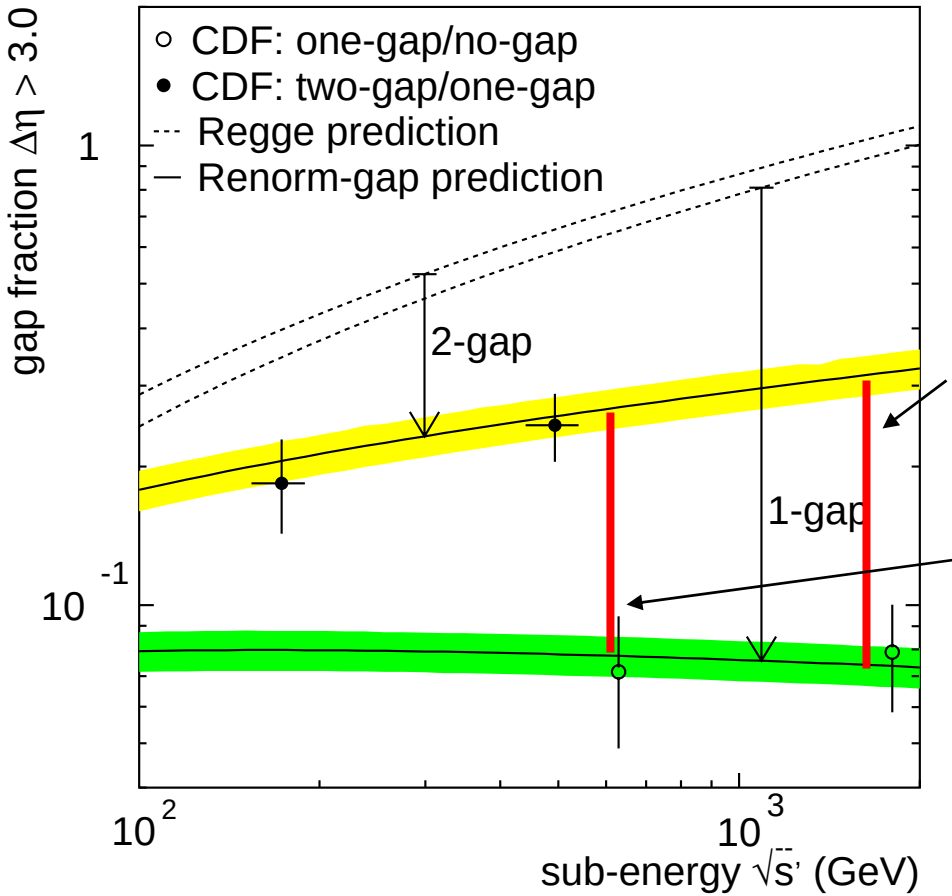
# Roman Pot tracking

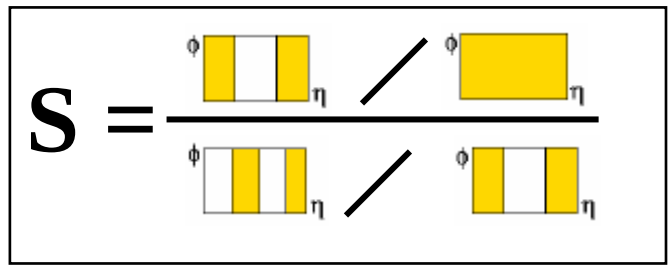



| | |
|---|---|
| **Expected position resolution** | **80 μm** |
| **Expected angle resolution** | **60 μrad** |



# Gap Survival Probability




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

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

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

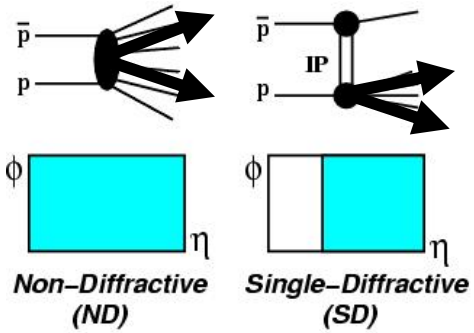
# Soft Diffraction Summary

## Experiment:

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

## Phenomenology:

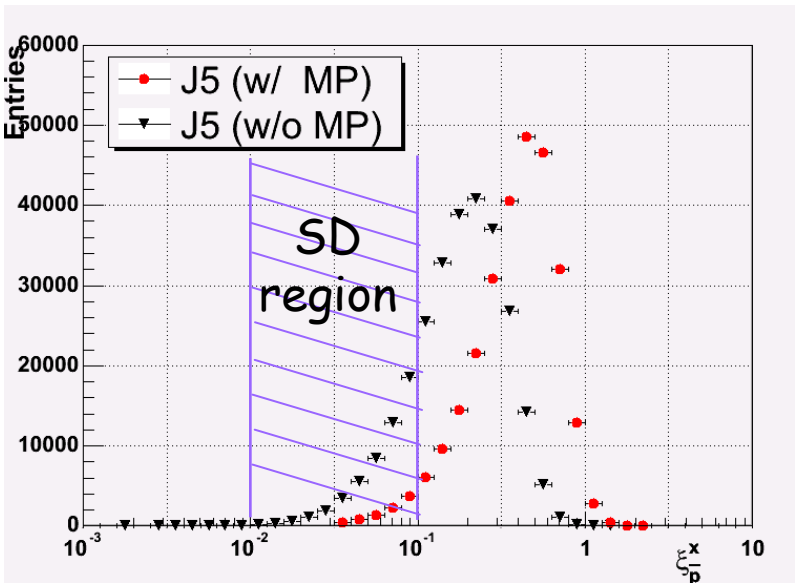
- Generalized renormalization
- Obtain Pomeron intercept and tripe-Pomeron coupling from inclusive PDF's and color factors

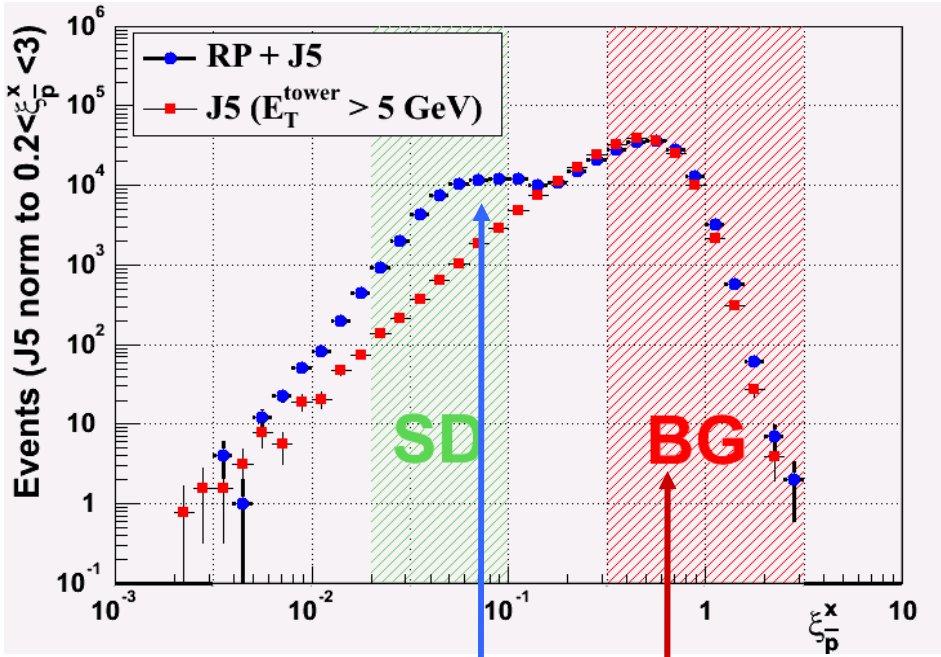



# Diffractive dijets

$\xi$ : momentum loss fraction of pbar

$$\xi = \frac{\Sigma_{(\text{all towers})} E_T \, e^{-\eta}}{\sqrt{s}}$$



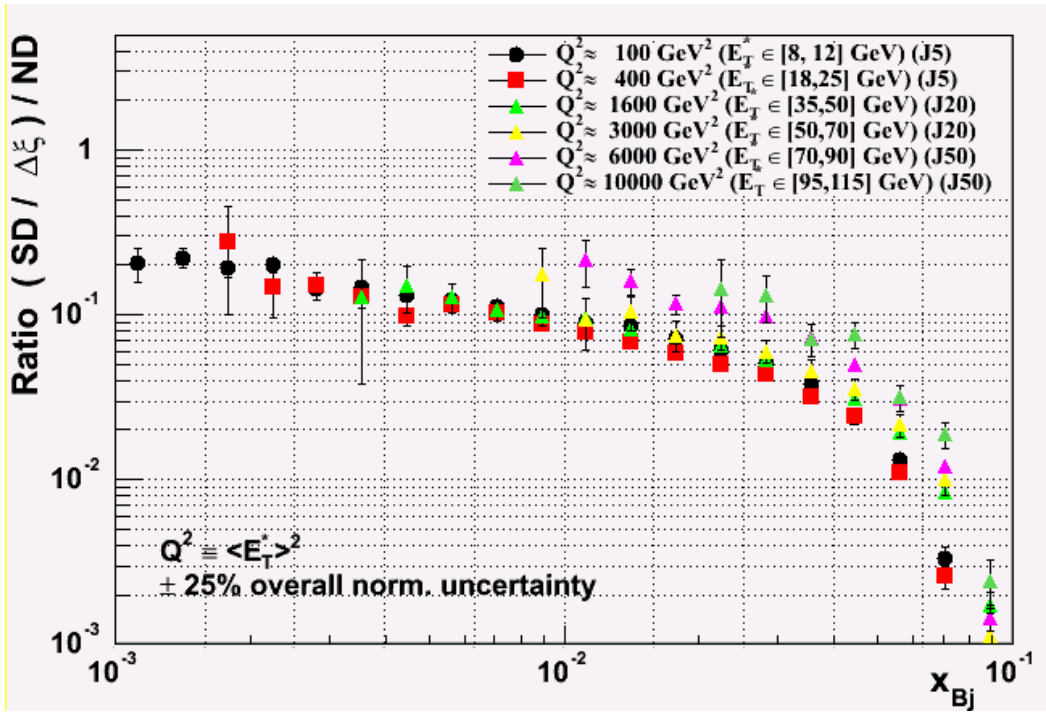

Approx. flat at $\xi$<0.1

$$\frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \rightarrow \frac{d\sigma}{d(\log\xi)} = \text{const}$$

overlap events

MP energy scale: ±25% →Δlog$\xi$ = ±0.1
RP acceptance (0.03<$\xi$< 0.1) ~ 80% (Run I)

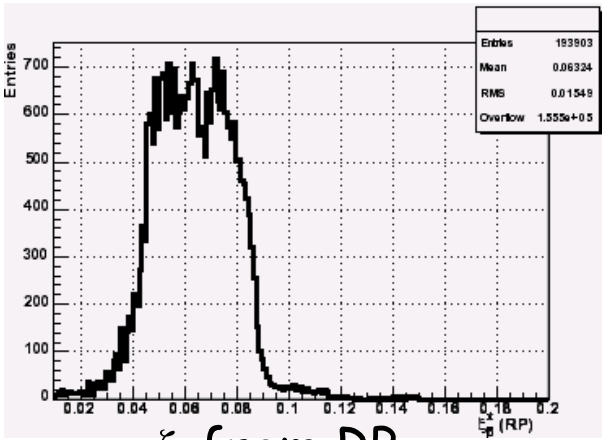
# $Q^2$-dependence of SD/ND ratio



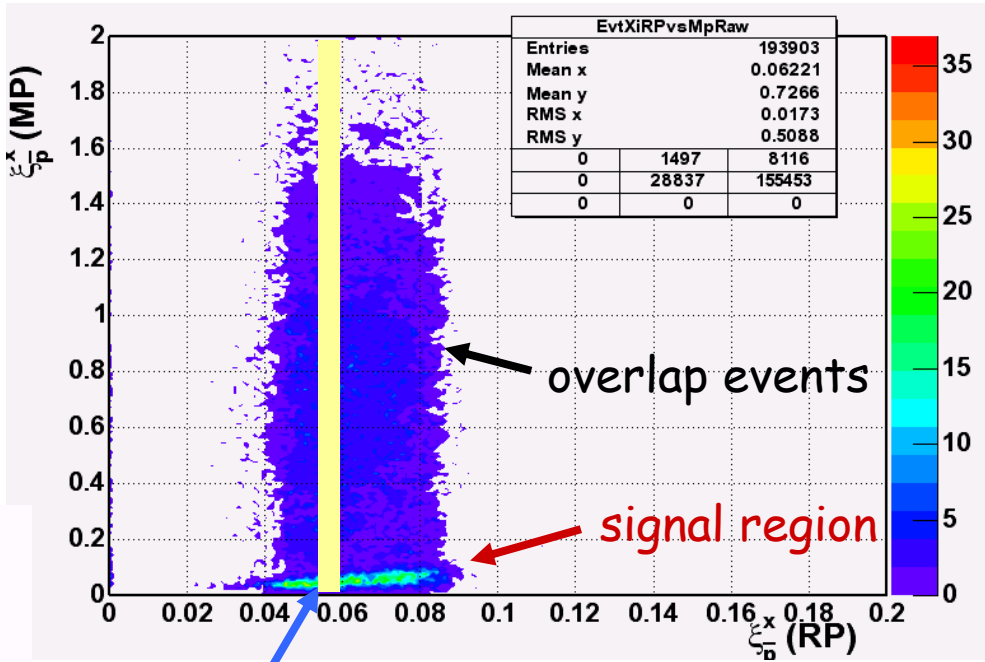

- No appreciable $Q^2$ dependence within $100 < Q^2 < 10{,}000$ GeV$^2$

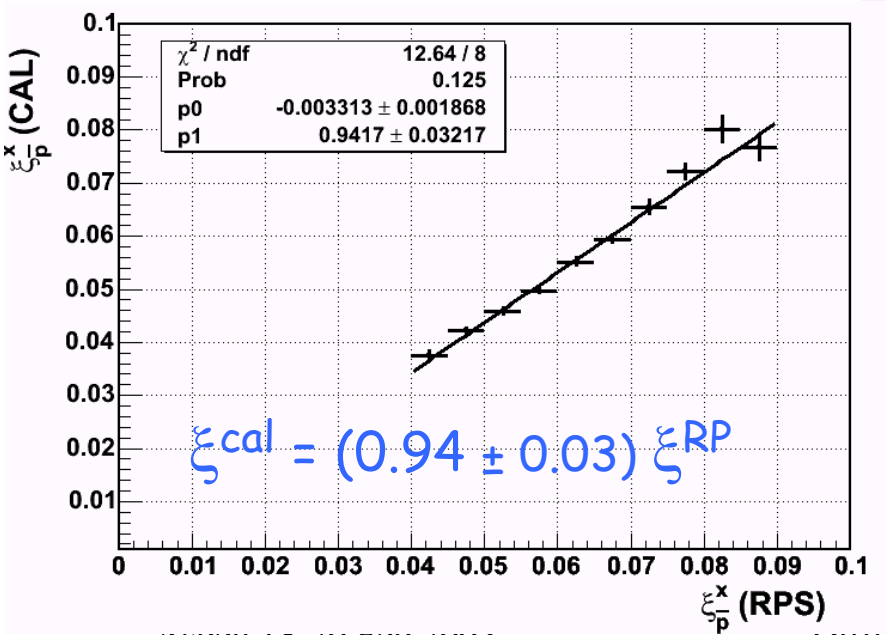
⇨ Pomeron evolves similarly to proton

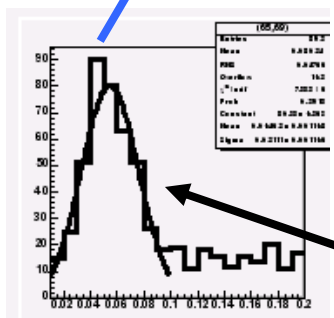
# ξ: RP vs calorimeter




ξ from RP



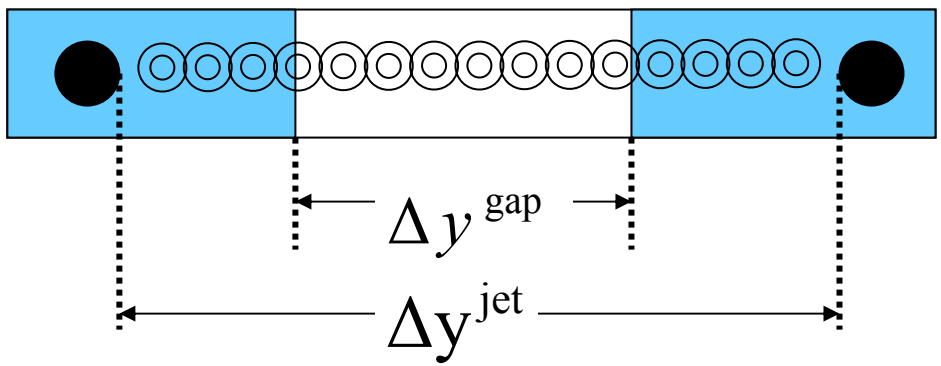



$\xi^{cal}$ distribution for slice of $\xi^{RP}$

σ/mean ~ 30%

# CDF2LHC

| TOPIC | STATUS |
|---|---|
| ➢ $(Q^2, t)$ dependence of DSF | close to ready |
| ➢ Exclusive $\chi_c$ production | close to ready |
| ➢ Low mass states in DPE | need good trigger |
| ➢ Exclusive b-bbar production in DPE | need b-trigger |
| ➢ $\xi$ -dependence of DSF | need low lum run |
| ➢ Jet-gap-Jet $^W$/jets in miniplugs | need low lum run |




$$\Delta y^{gap} = \Delta y^{jet} \Rightarrow \text{BFKL}$$
$$\Delta y^{gap} \neq \Delta y^{jet} \Rightarrow \text{composite}$$