QCD ASPECTS
OF HADRONIC DIFFRACTION

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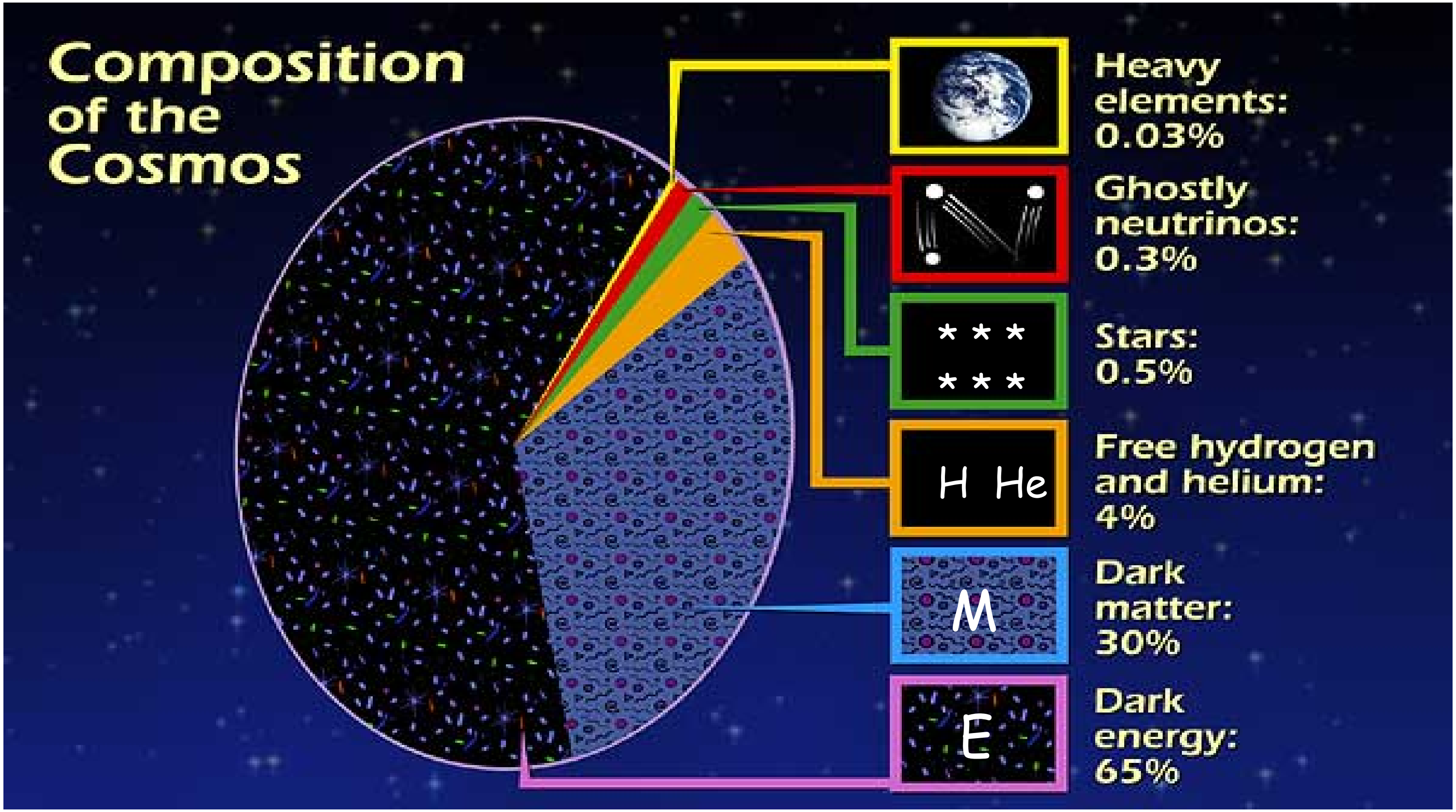
The Rockefeller University

High Energy Physics Seminar

University of Connecticut
7 February 2005

- CDF results
- Comparison with HERA
- QCD aspects
- Tev2LHC

What is Dark Energy?



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:

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

(ρ=particle density in rapidity space)

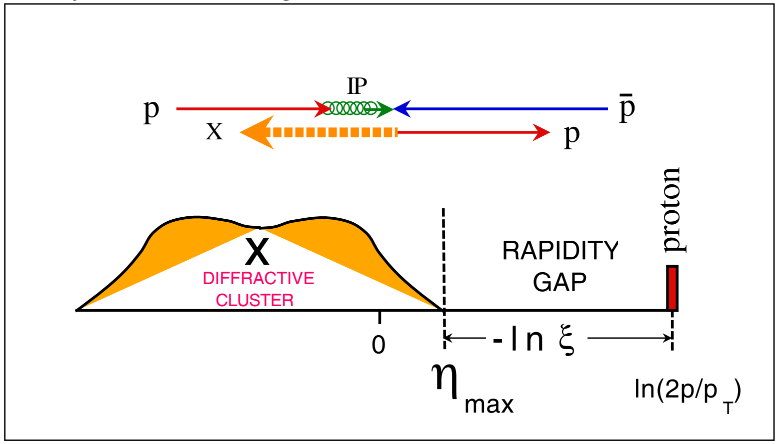
Gaps are exponentially suppressed

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!

Forty Years of Diffraction

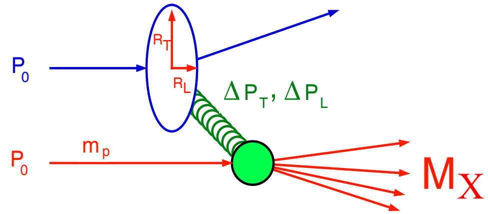
http://physics.rockefeller.edu/dino/my.html

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

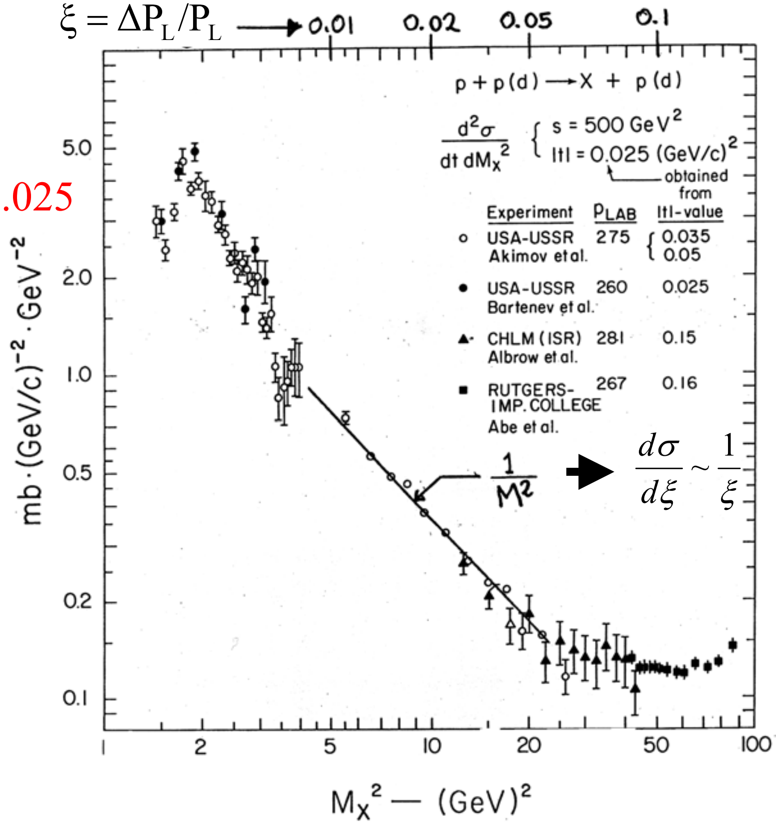
  Review: KG, Phys. Rep. 101 (1983) 169

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

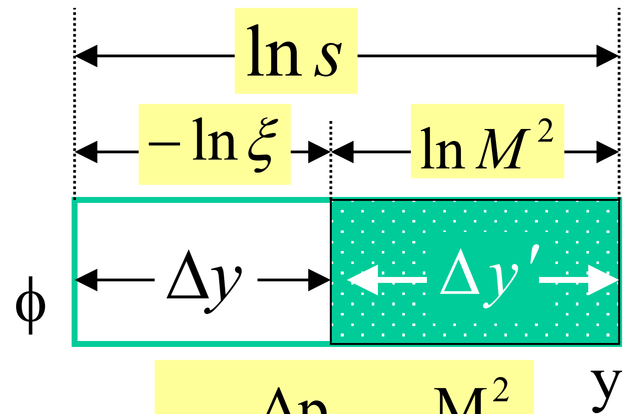
The First 20 Years



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



KG, Phys. Rep. 101 (1983) 171



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

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

POMERON: color singlet w/vacuum quantum numbers

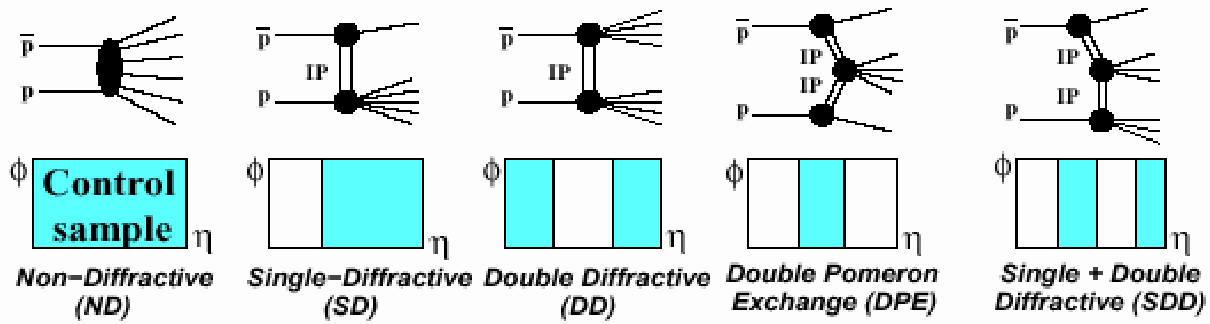
The Last 20 Years

Diffraction@CDF in Run I

16 papers

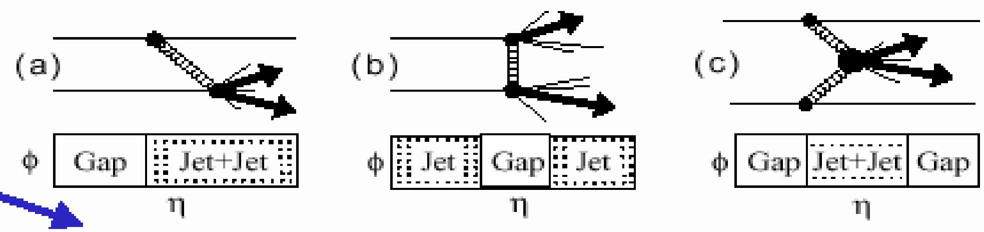
- Elastic scattering PRD 50 (1994) 5518
- Total cross section PRD 50 (1994) 5550
- Diffraction

SOFT diffraction



PRD 50 (1994) 5535 | PRL 87 (2001)141802 | PRL 93(2004)141601 | PRL 91(2003)011802

HARD diffraction

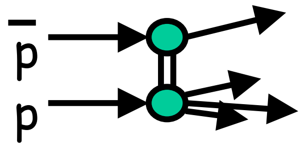


PRL references

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

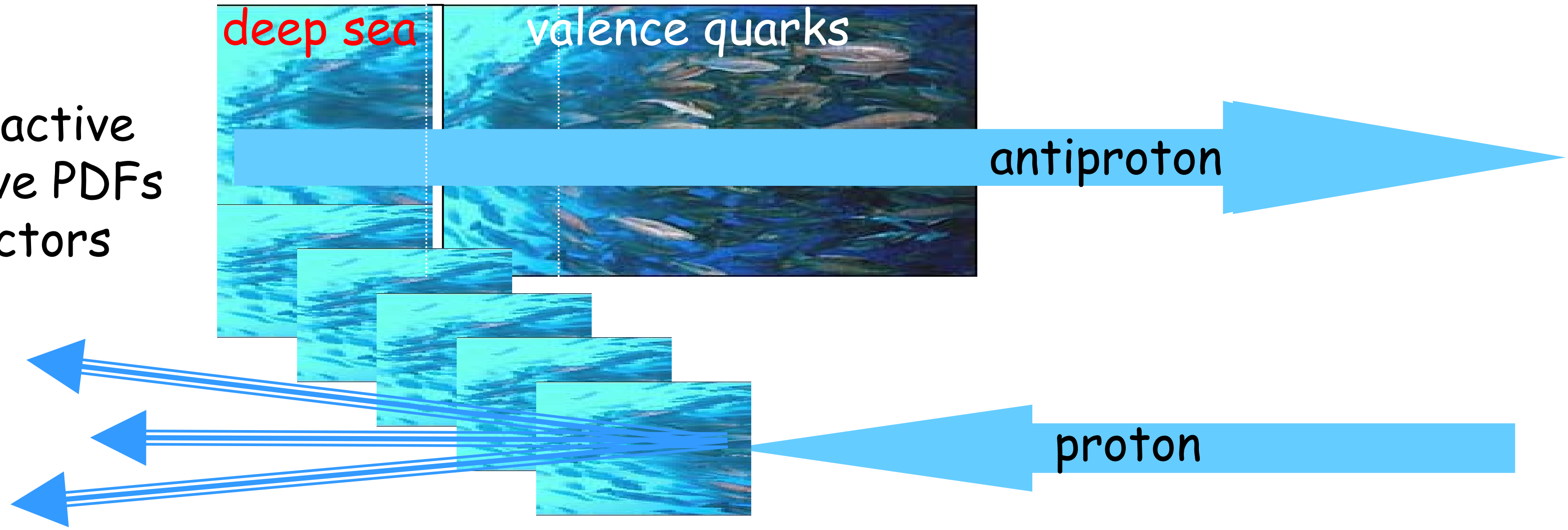
with roman pots

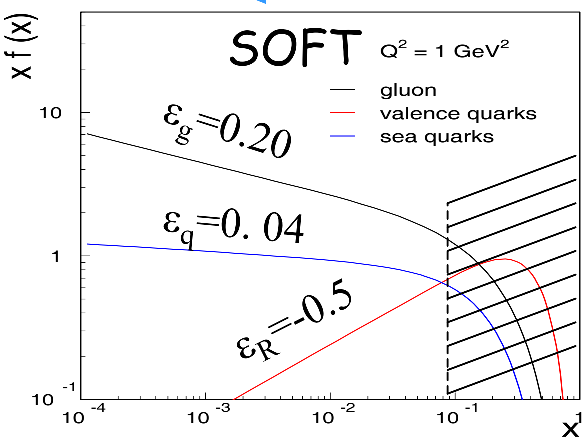
JJ	84 (2000) 5043
JJ	88 (2002) 151802



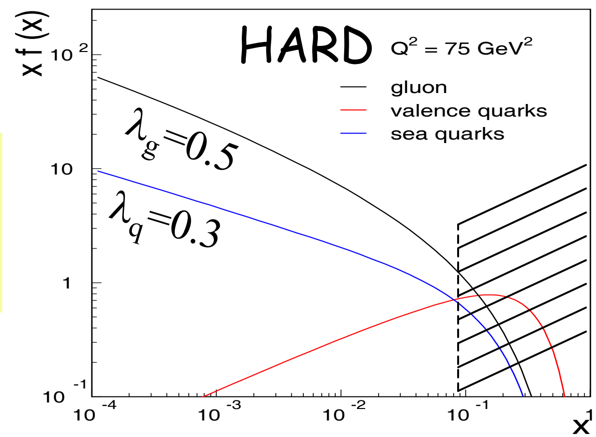
Diffraction in QCD

Derive diffractive from inclusive PDFs and color factors



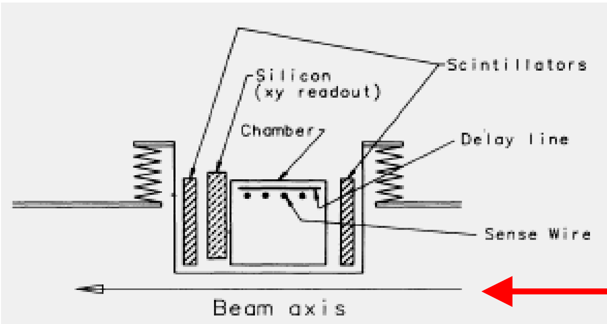


$$x \cdot f(x) = \frac{1}{x^{\varepsilon\,(\mathrm{or}\,\lambda)}}$$

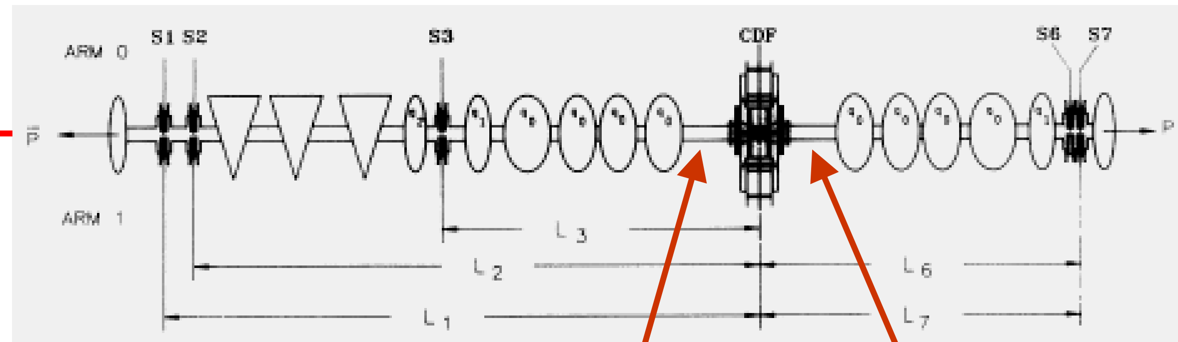


CDF in Run I-0 (1988-89)

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

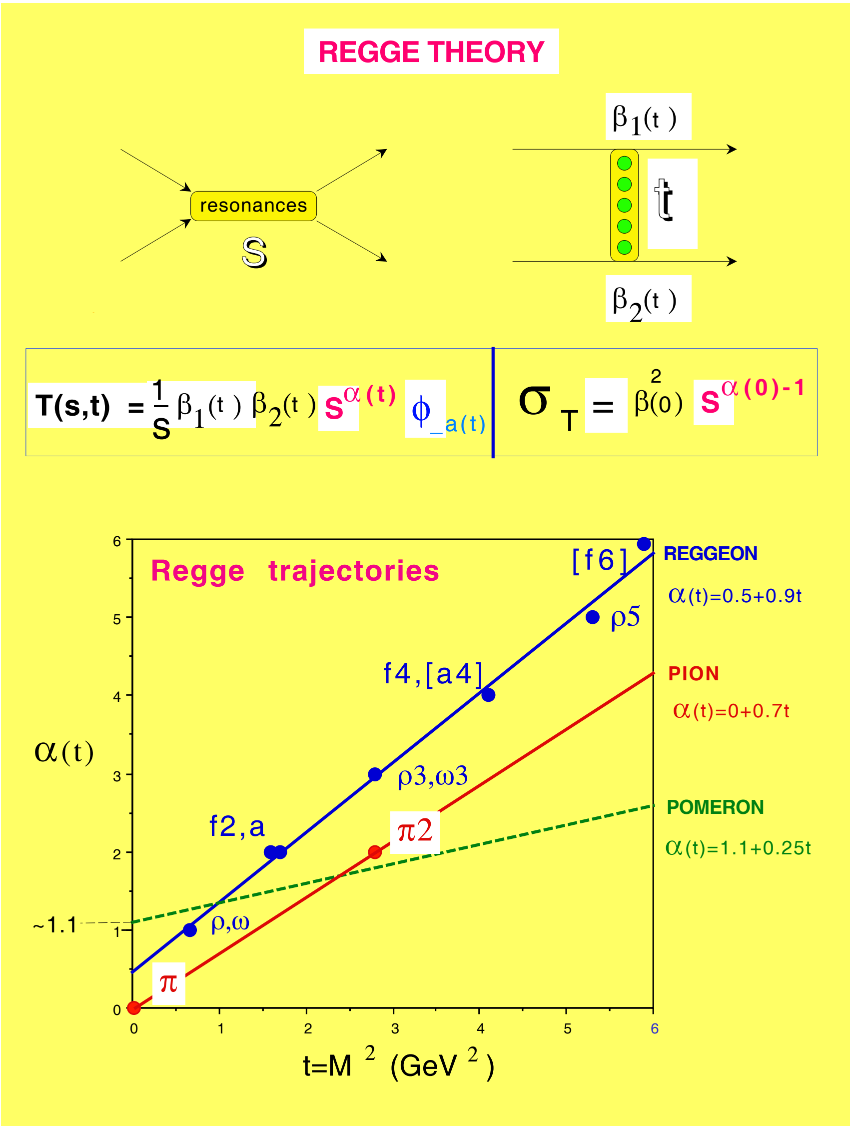
Additional Detectors

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

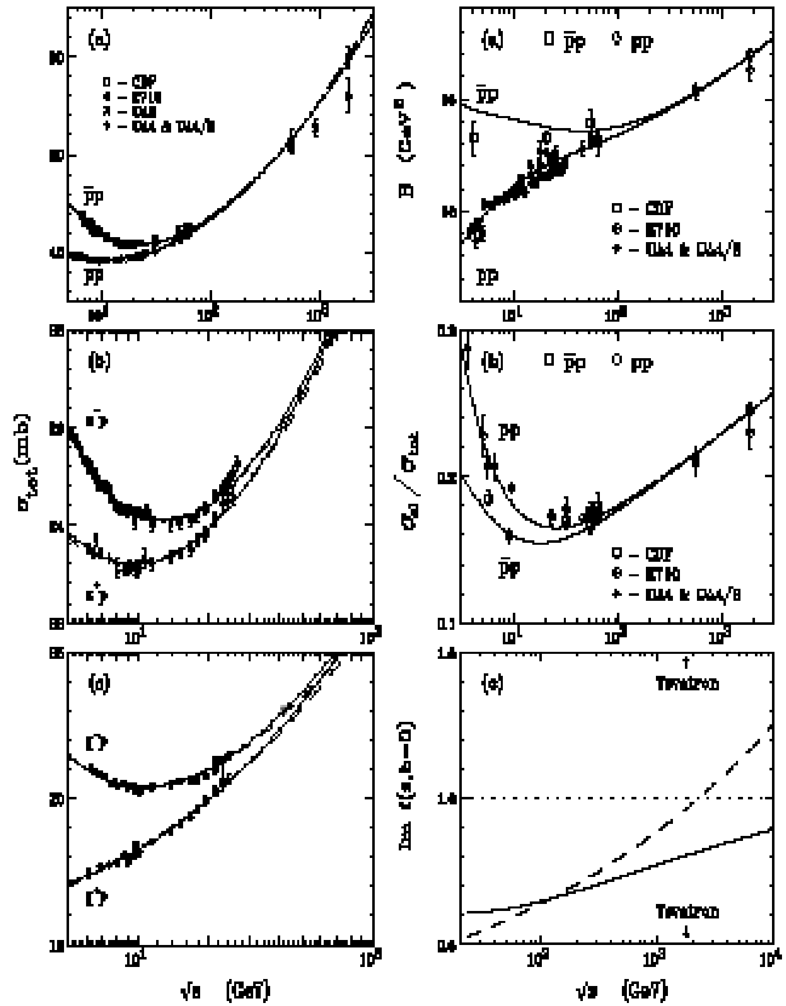
Regge Theory

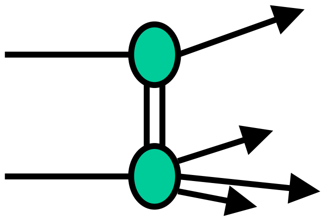


Total and Elastic Cross Sections

Covolan, Montanha and Goulianos, Phys. Lett. B 389 (1996) 176

$\alpha_{I\!P} = 1 + \epsilon(\Rightarrow 0.104) + 0.25t \quad \alpha_{f/a} = 0.68 + 0.82t \quad \alpha_{\omega/\rho} = 0.46 + 0.92t$





Renormalization

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

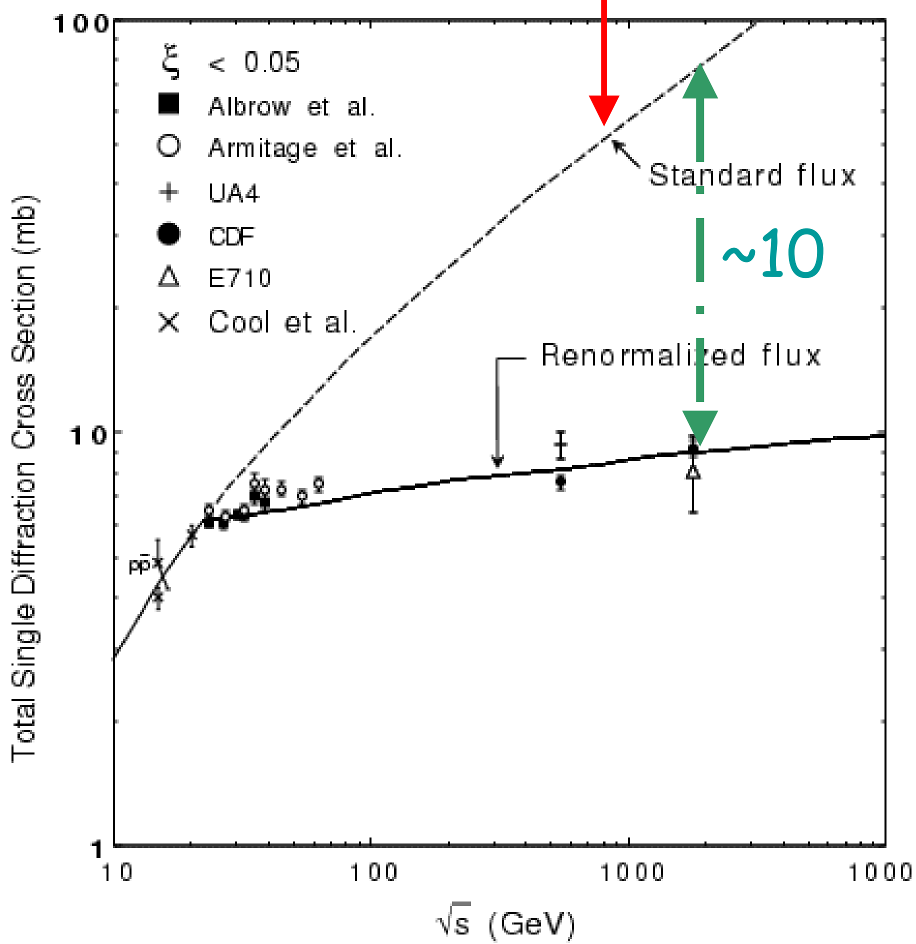
$$\sigma_{SD} \sim s^{2\varepsilon}$$

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

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

KG, PLB 358 (1995) 379

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



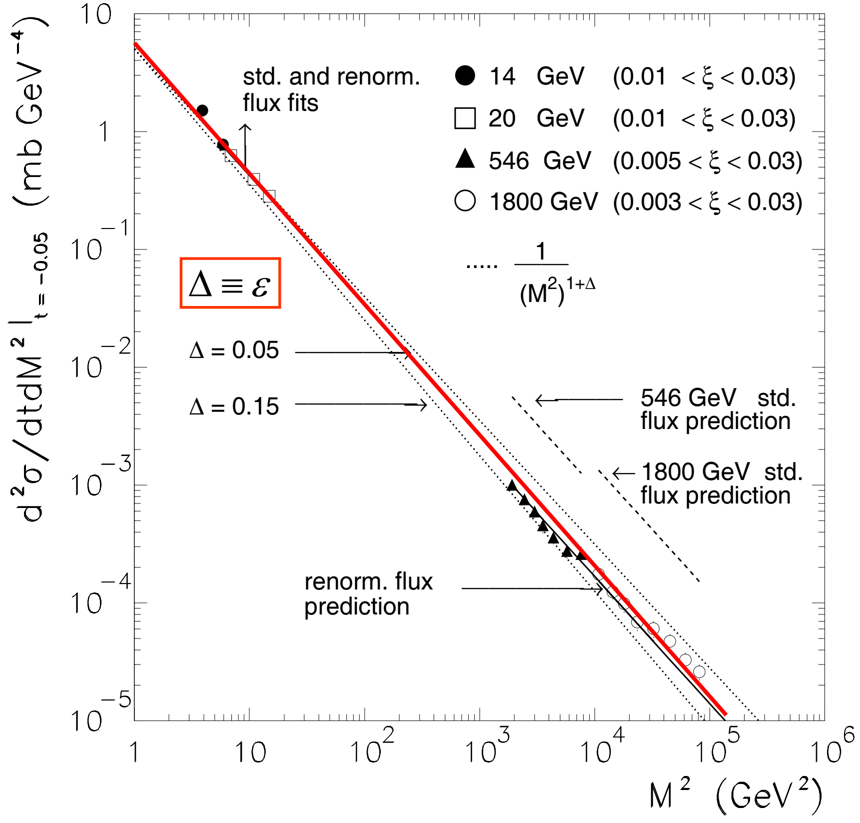
A Scaling Law in Diffraction

Factorization breaks down in favor of M^2-scaling

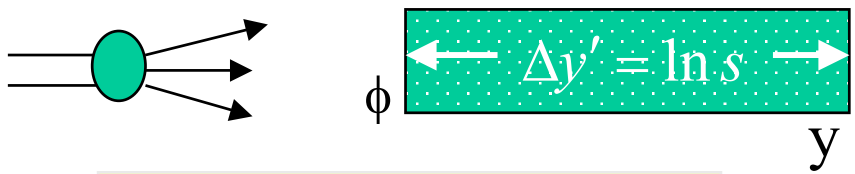
renormalization

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

KG&JM, PRD 59 (1999) 114017

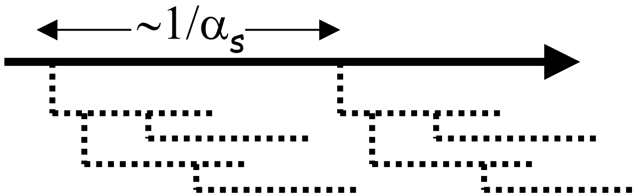


The QCD Connection



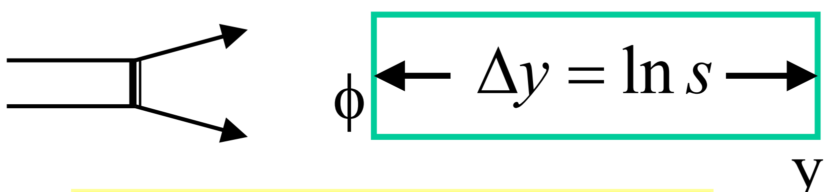
$$\sigma_T(s) = \sigma_o\, s^{\varepsilon} = \sigma_o\, e^{\varepsilon \Delta y'}$$

Total cross section:
power law rise with energy



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)

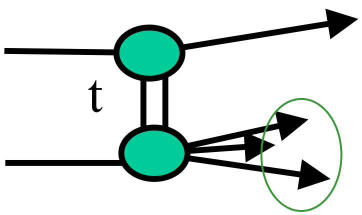


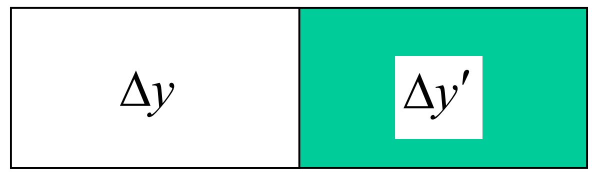
$$\mathrm{Im}\, f_{el}(s,t) \propto e^{(\varepsilon + \alpha' t)\Delta y}$$

Elastic cross section
forward scattering amplitude

QCD Basis of Renormalization

(KG, hep-ph/0205141)





2 independent variables: $t, \Delta y$

color factor

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

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

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

The Factors κ and ε

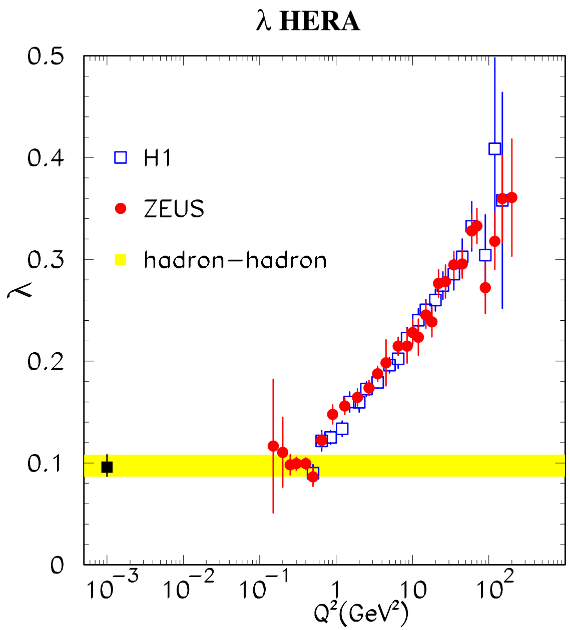
Experimentally:

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

KG&JM, PRD 59 (114017) 1999

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

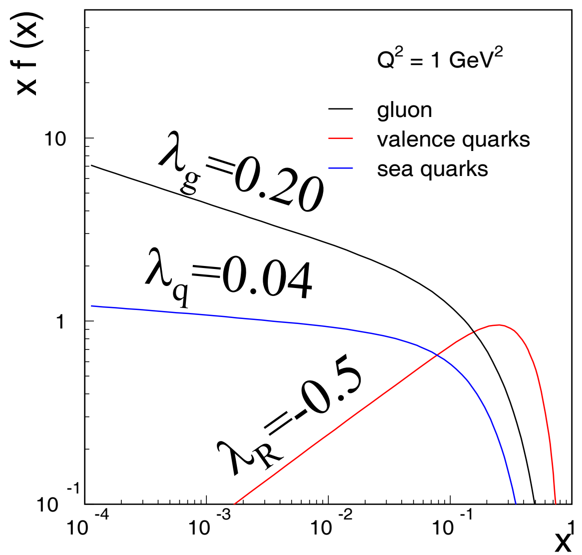


$$x \cdot f(x) = \frac{1}{x^{\lambda}}$$

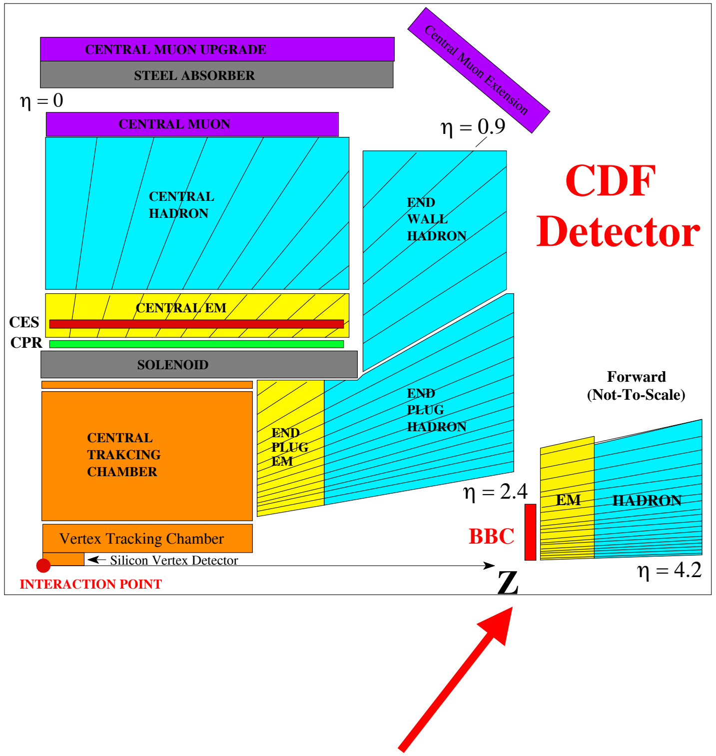
f_g=gluon fraction
f_q=quark fraction

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

CTEQ5L



Run-I A,B: Rapidity Gap Studies

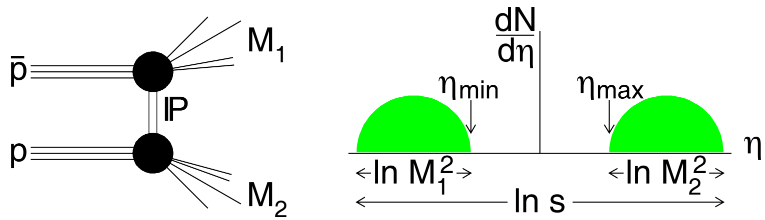


Forward Detectors

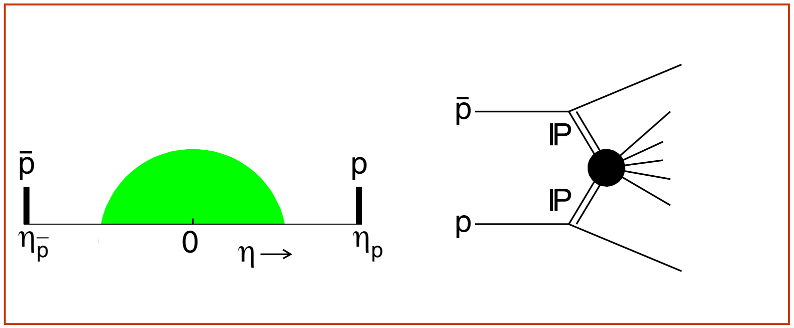
BBC $3.2<\eta<5.9$

FCAL $2.4<\eta<4.2$

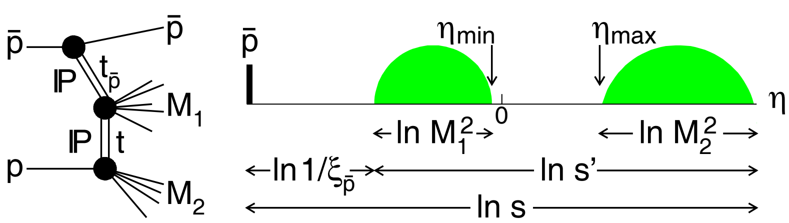
Central and Double Gaps



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



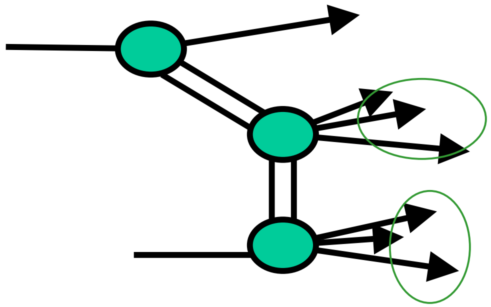
- **Double Pomeron Exchange**
  - **Two forward gaps**

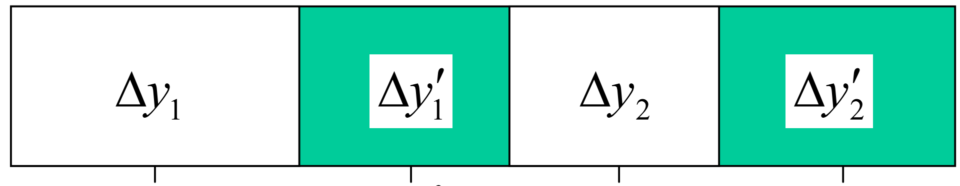


- **SDD: Single+Double Diffraction**
  - **One forward + one central gap**

Multigap Renormalization

(KG, hep-ph/0205141)





5 independent variables: y_1', y_2, t_1, $\Delta y = \Delta y_1 + \Delta y_2$, 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 $\sim e^{2\varepsilon \Delta y}$

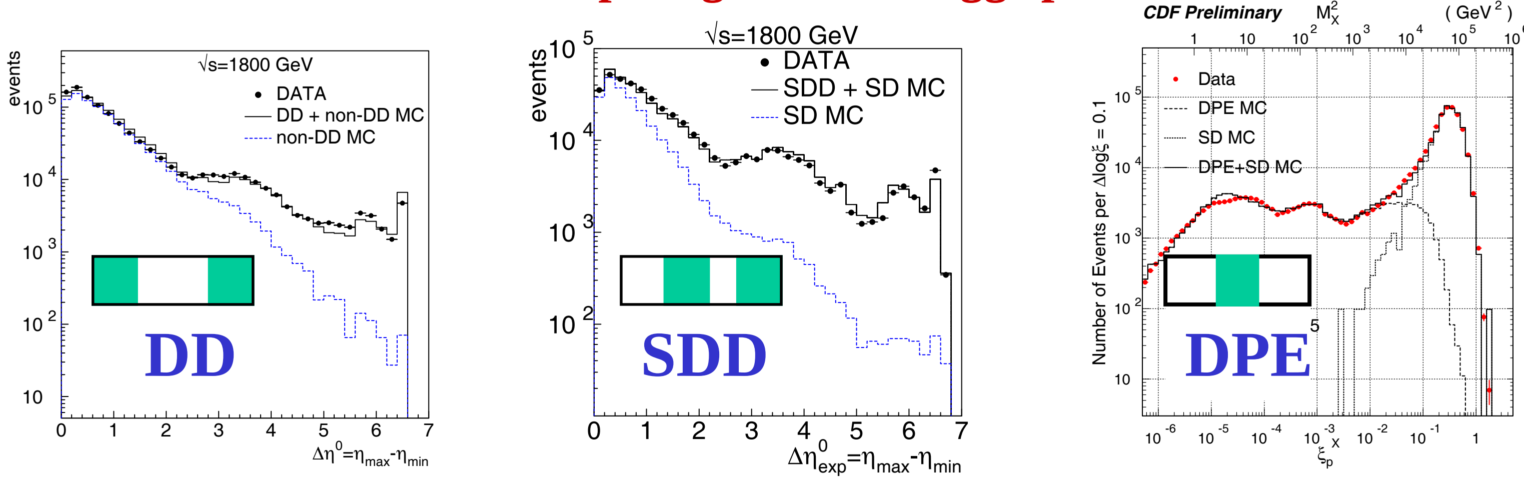
Sub-energy cross section (for regions with particles)

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

Same suppression as for single gap!

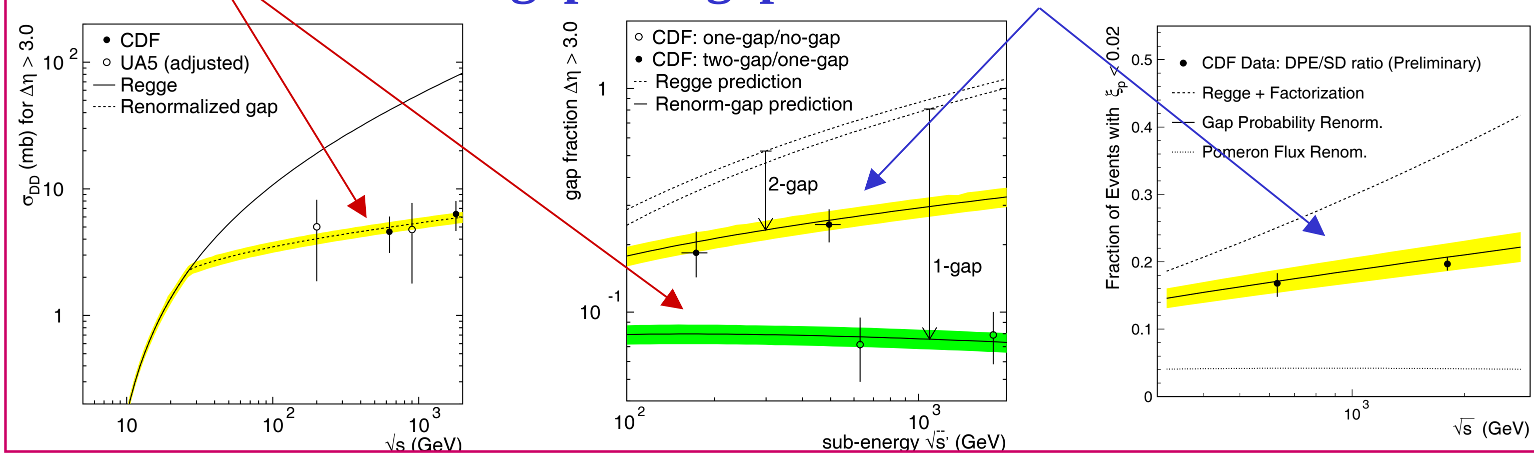
Central & Double-Gap Results

Differential shapes agree with Regge predictions

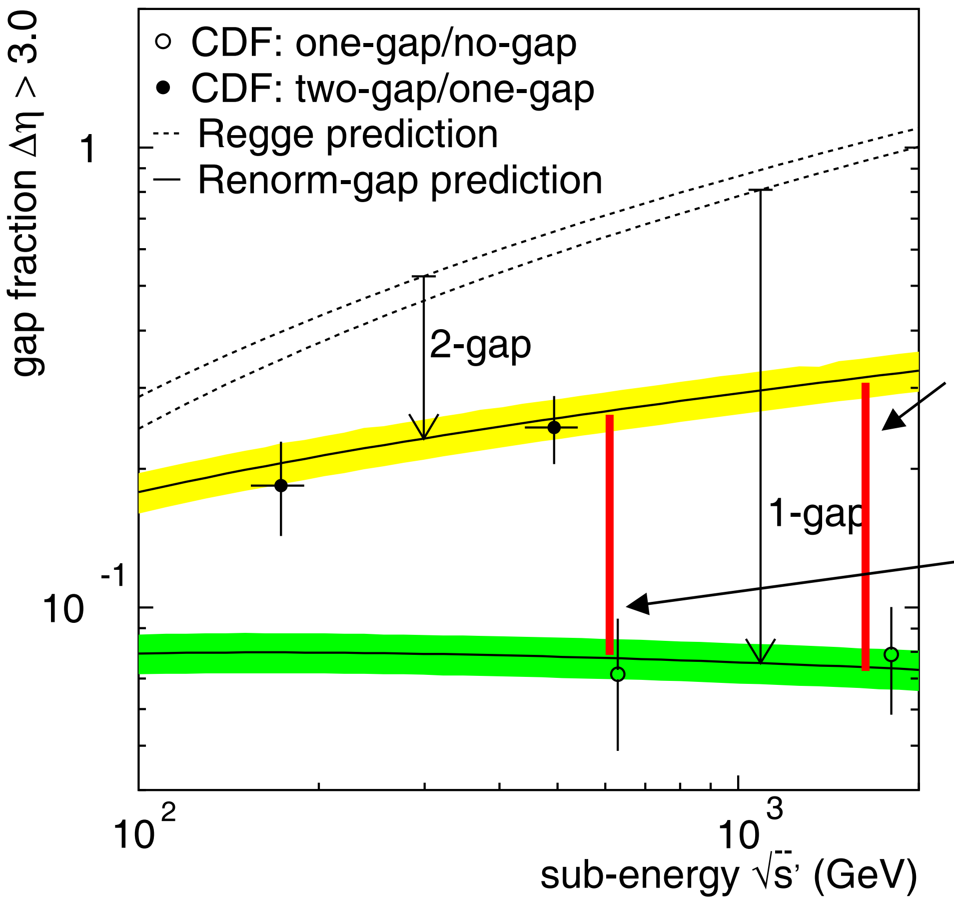


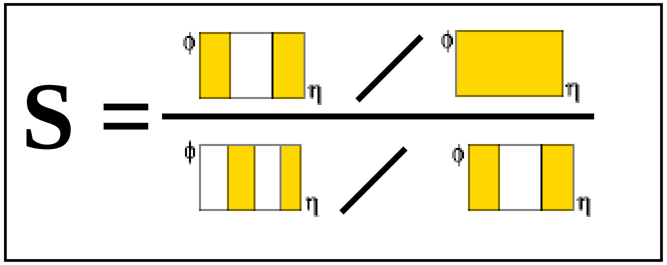
➢ **One-gap cross sections are suppressed**

➢ **Two-gap/one-gap ratios are** $\approx \kappa = 0.17$



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:

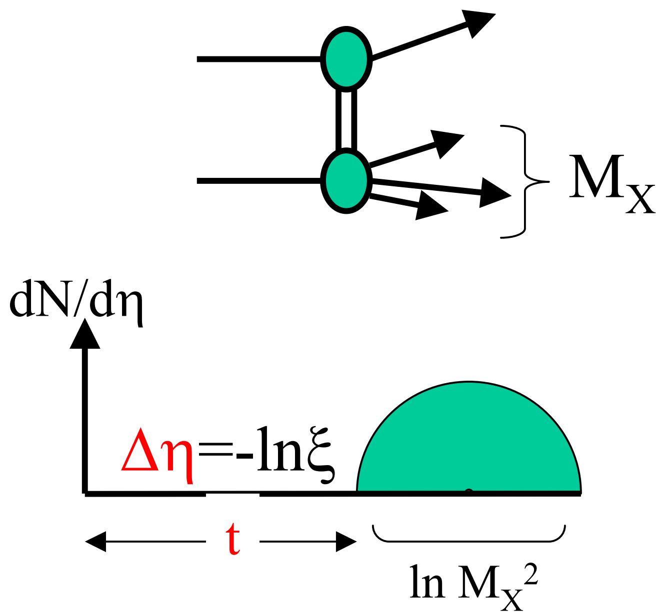
- M^2 - scaling
- Non-suppressed double-gap to single-gap ratios

Phenomenology:

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

Hard Diffraction @ CDF

- SOFT DIFFRACTION

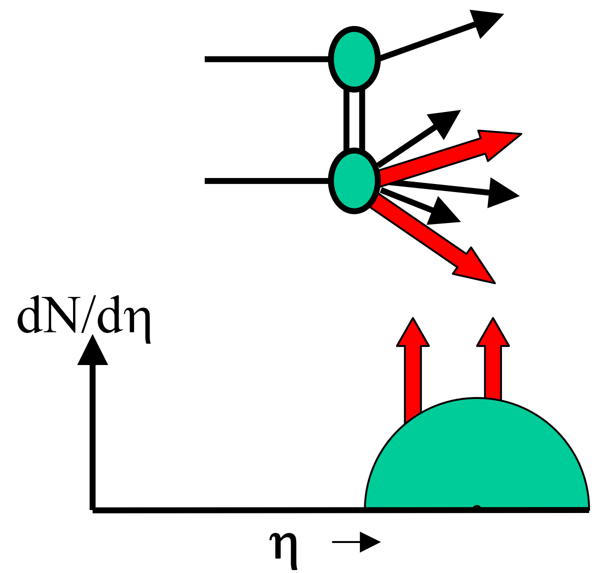


$\xi = \Delta P_L / P_L$

ξ=fractional momentum loss of scattered (anti)proton

Variables: (ξ, t) or (Δη, t)

- HARD DIFFRACTION



Additional variables: ($\boldsymbol{x}$, Q^2)

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

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

Diffractive Fractions @ CDF

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

SD/ND fraction at 1800 GeV

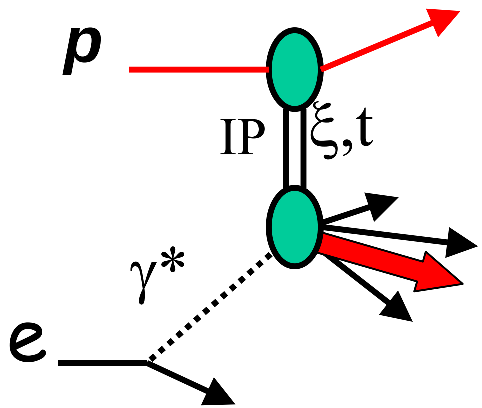
X	Fraction(%)
W	1.15 (0.55)
JJ	0.75 (0.10)
b	0.62 (0.25)
J/ψ	1.45 (0.25)

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

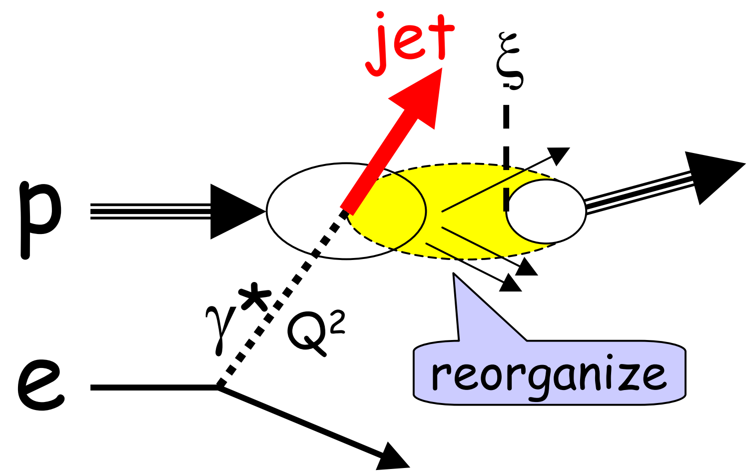
Diffractive DIS @ HERA

J. Collins: Factorization should hold

Pomeron exchange



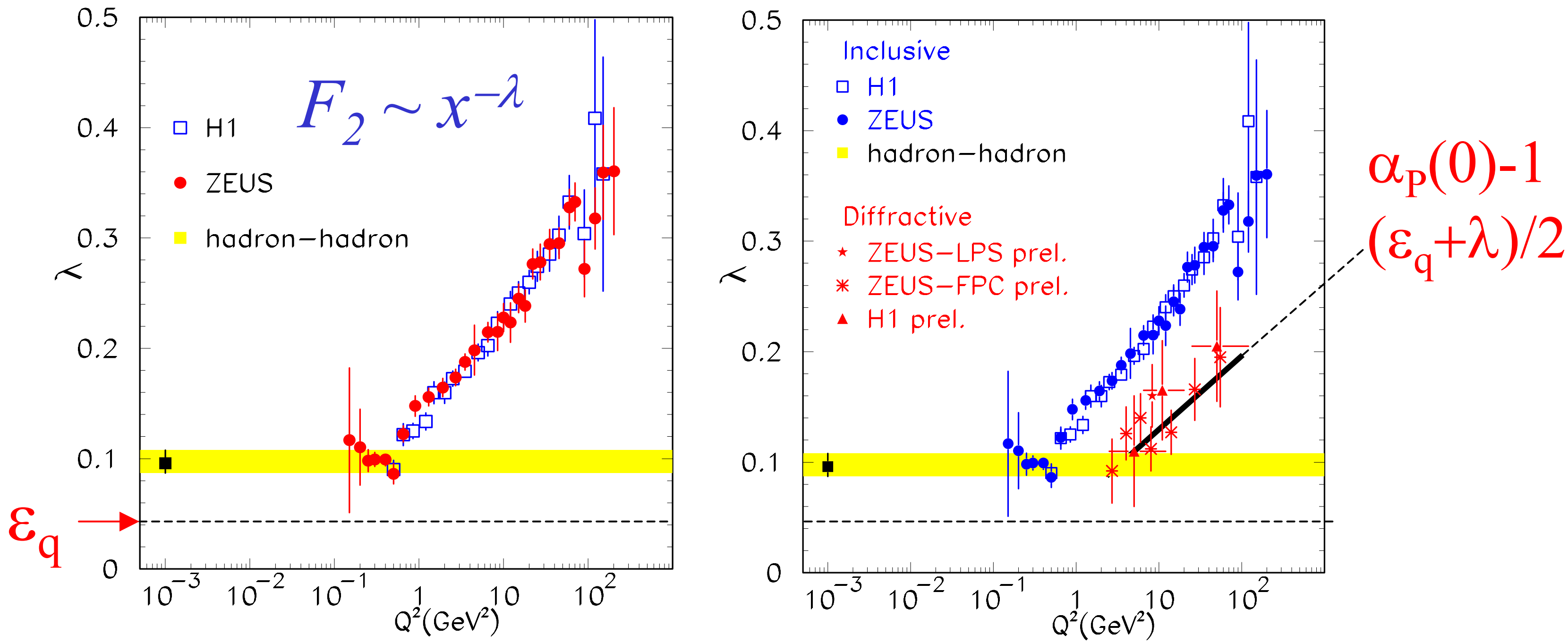
Color reorganization



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

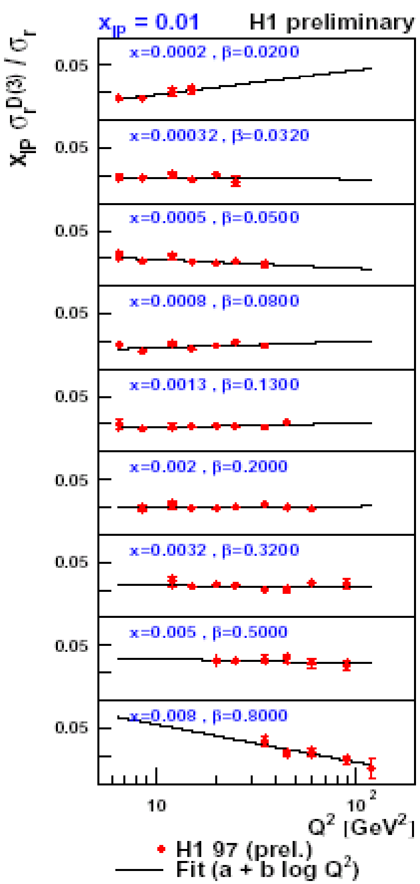
Inclusive vs Diffractive DIS

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



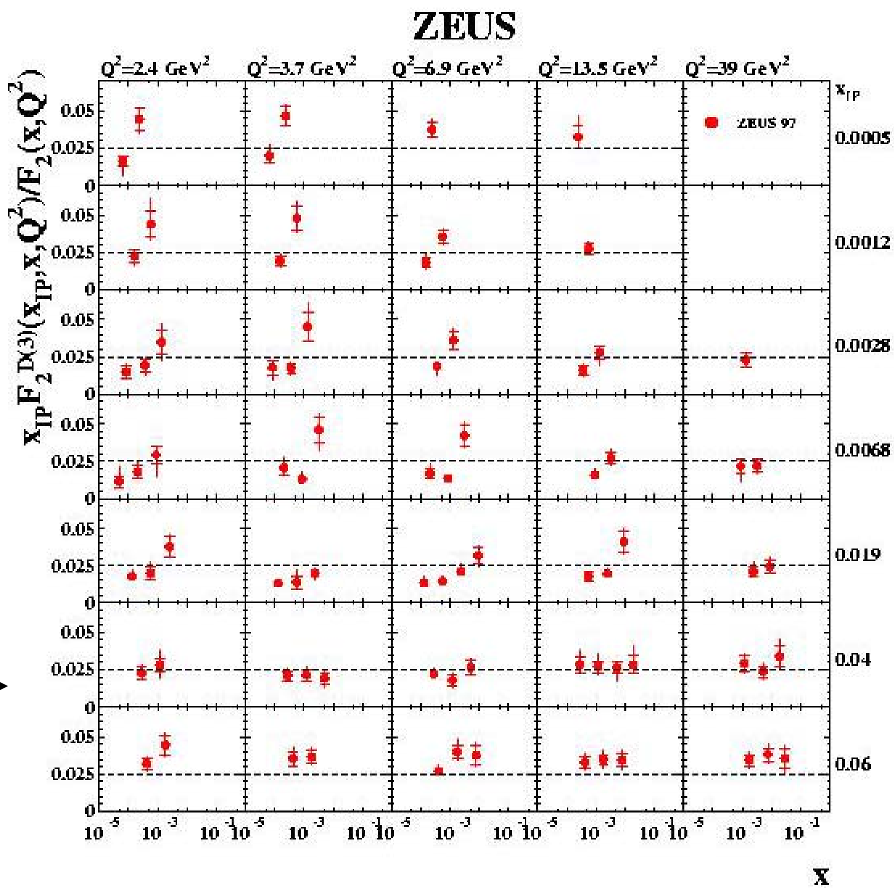
$$F_2^{D(3)}(\xi,\beta,Q^2) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot \frac{C(Q^2)}{(\beta\xi)^{\lambda(Q^2)}} \propto \frac{1}{\xi^{1+\varepsilon+\lambda}} \cdot \frac{C}{\beta^{\lambda}}$$

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

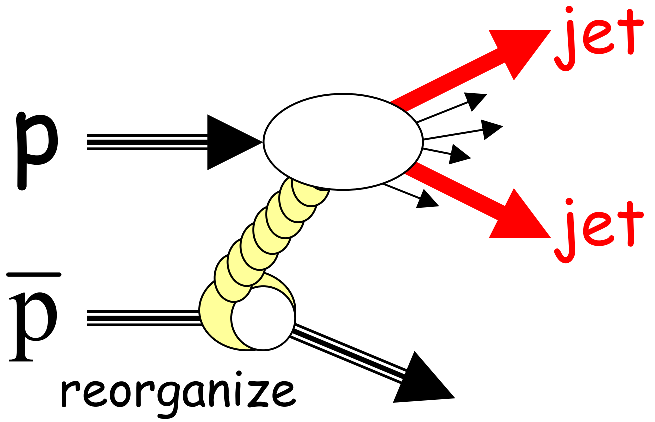


At fixed x:
flat Q^2-dependence

At fixed Q^2:
flat x-dependence



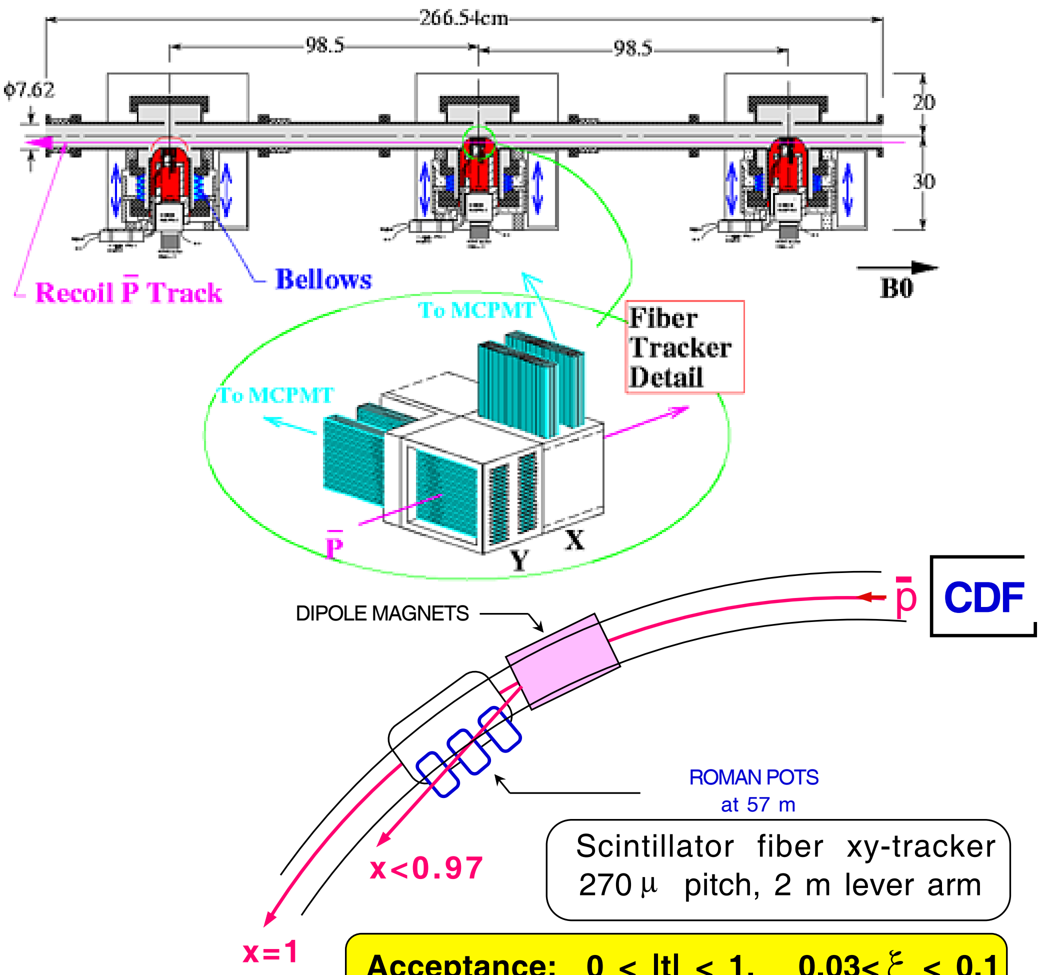
Diffractive Dijets @ Tevatron



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

CDF-IC

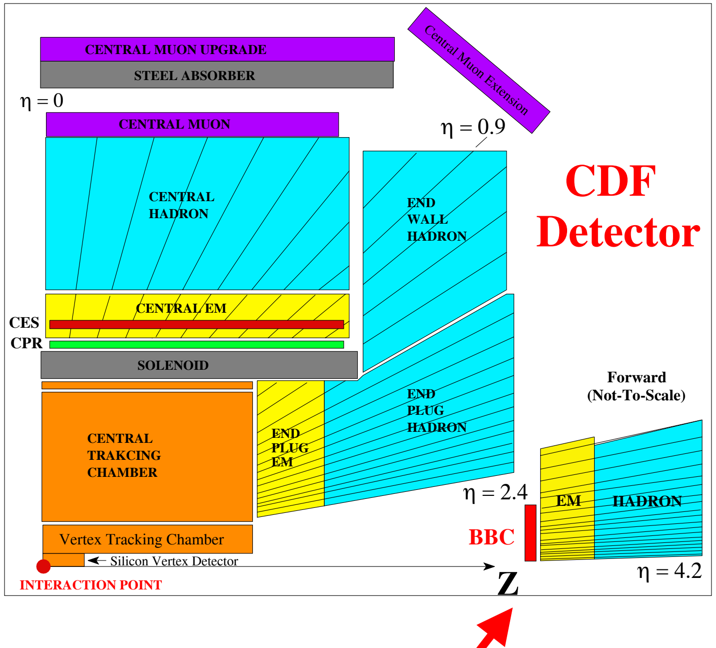
Run-IC



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

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

Run-IA,B

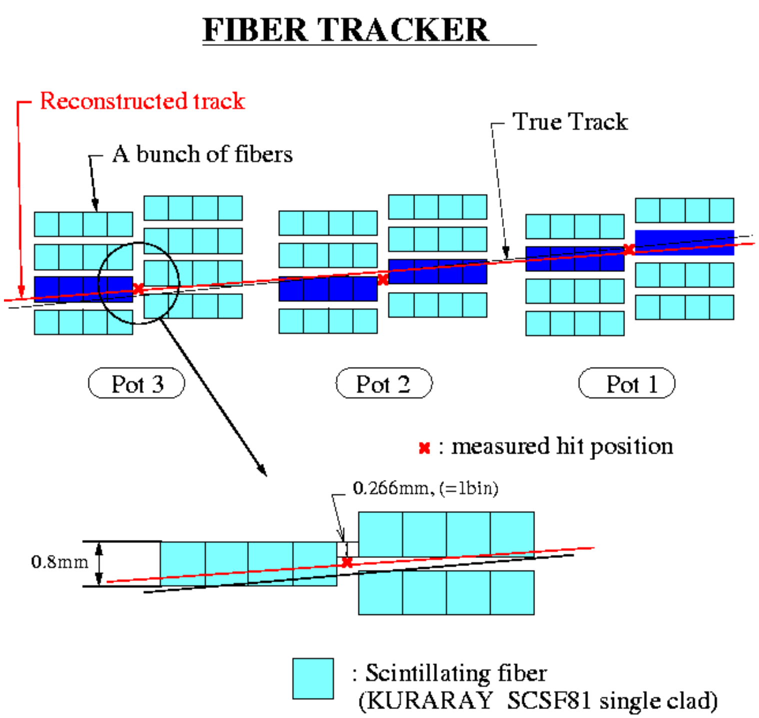


Forward Detectors

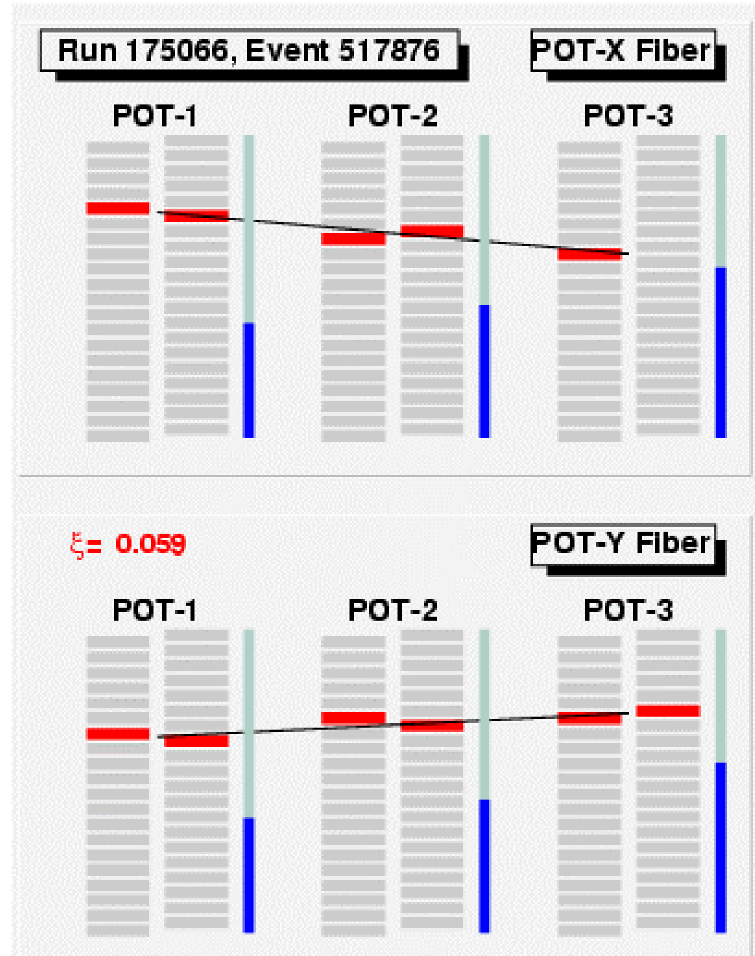
BBC 3.2<η<5.9

FCAL 2.4<η<4.2

Roman Pot tracking



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



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 $x_{\bar{p}}$

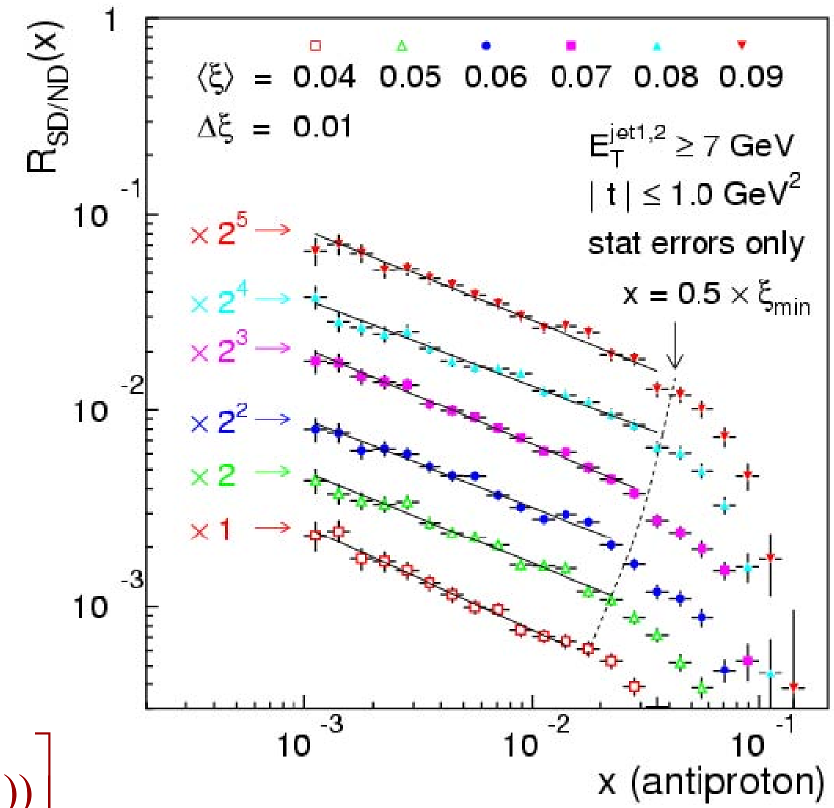
$$x_{\bar{p}} \equiv p_{g,q}/p_{\bar{p}} = \frac{\sum_{i=1}^{2(3)} E_T^i \cdot e^{-\eta^i}}{\sqrt{s}}$$

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

- 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

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

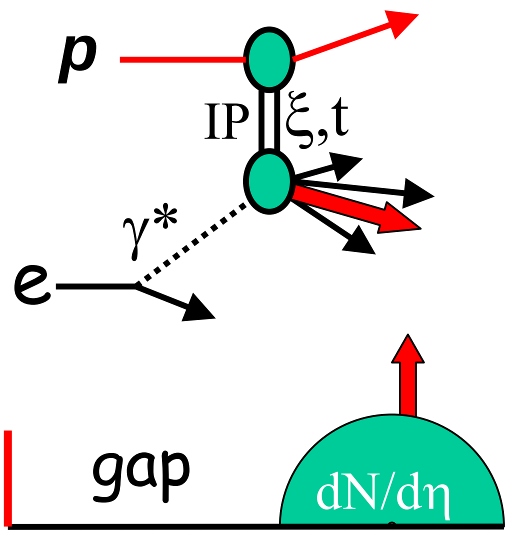
$$N_{\text{renorm}}^{-1} = \int_{\xi_{\min}}^{1} \frac{d\xi}{\xi^{1+2\varepsilon}} \xrightarrow{\xi_{\min} = \frac{x_{\min}}{\beta} \sim \frac{1}{\beta s}} (\beta s)^{2\varepsilon}$$

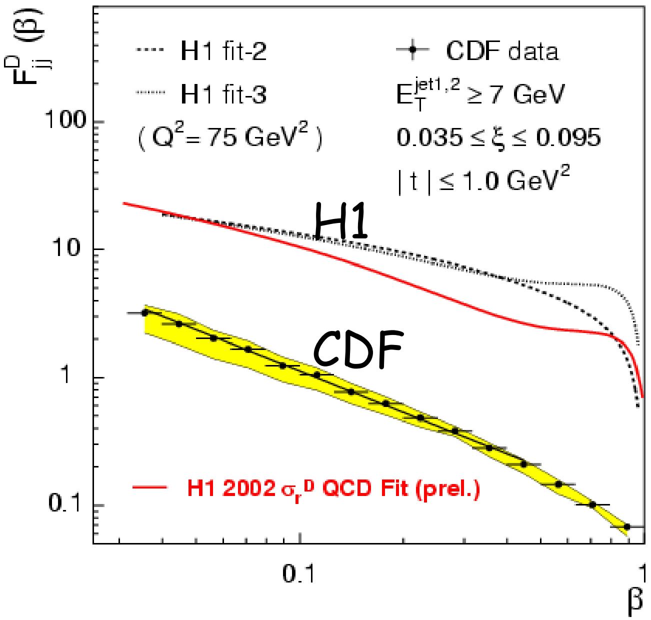
RENORM $\Rightarrow$ $R^{SD}_{ND}(x) \sim \frac{1}{s^{2\varepsilon}} \frac{1}{\xi^{1-\lambda(Q^2)}} \cdot x^{-(2\varepsilon)}$

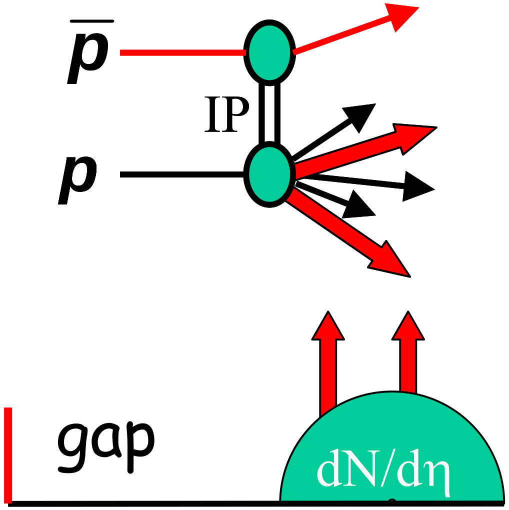
$$\varepsilon_g = 0.2 \rightarrow x^{-0.4}$$

Tevatron vs HERA: Factorization Breakdown

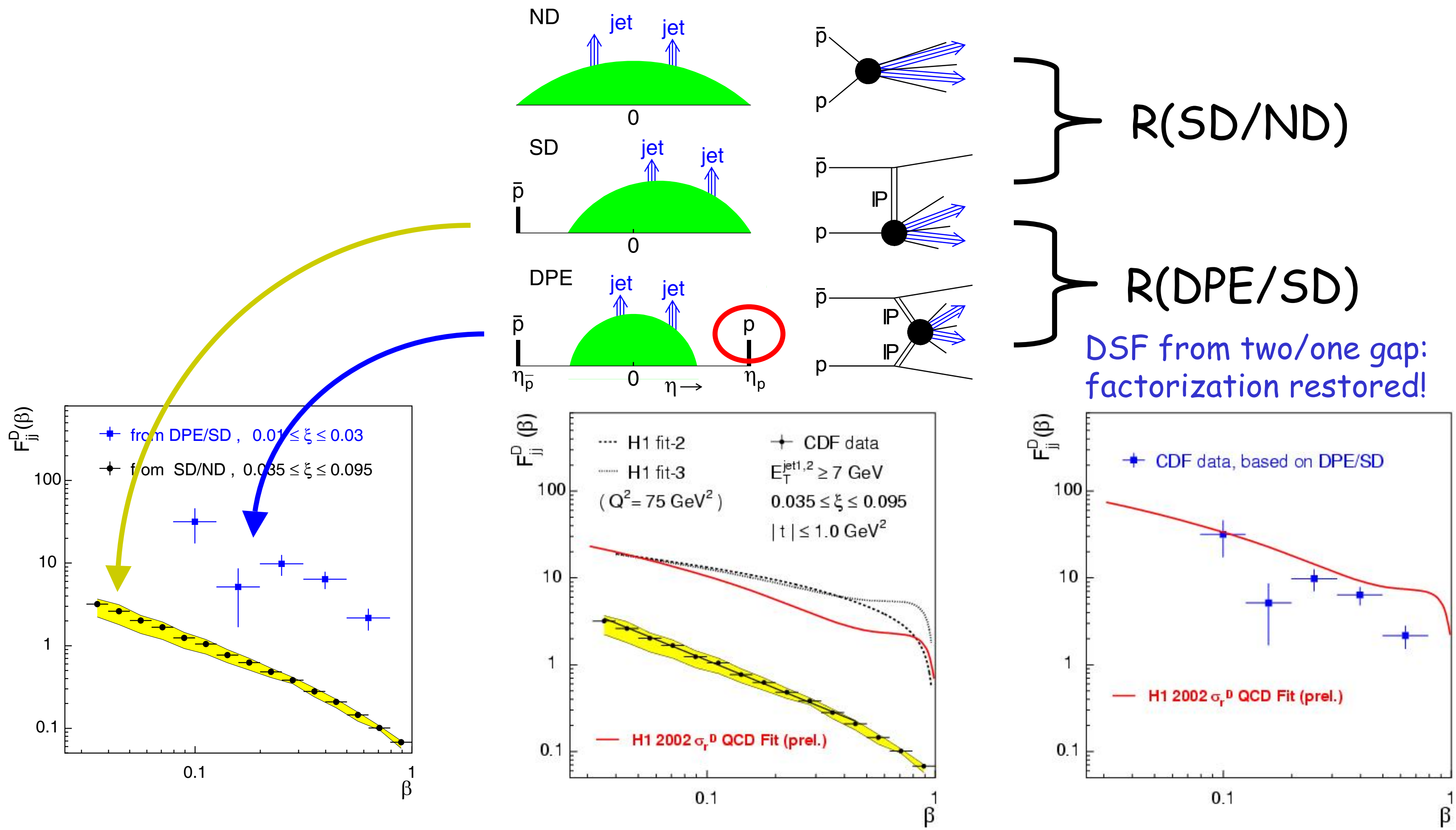
Predicted in KG, PLB 358 (1995) 379



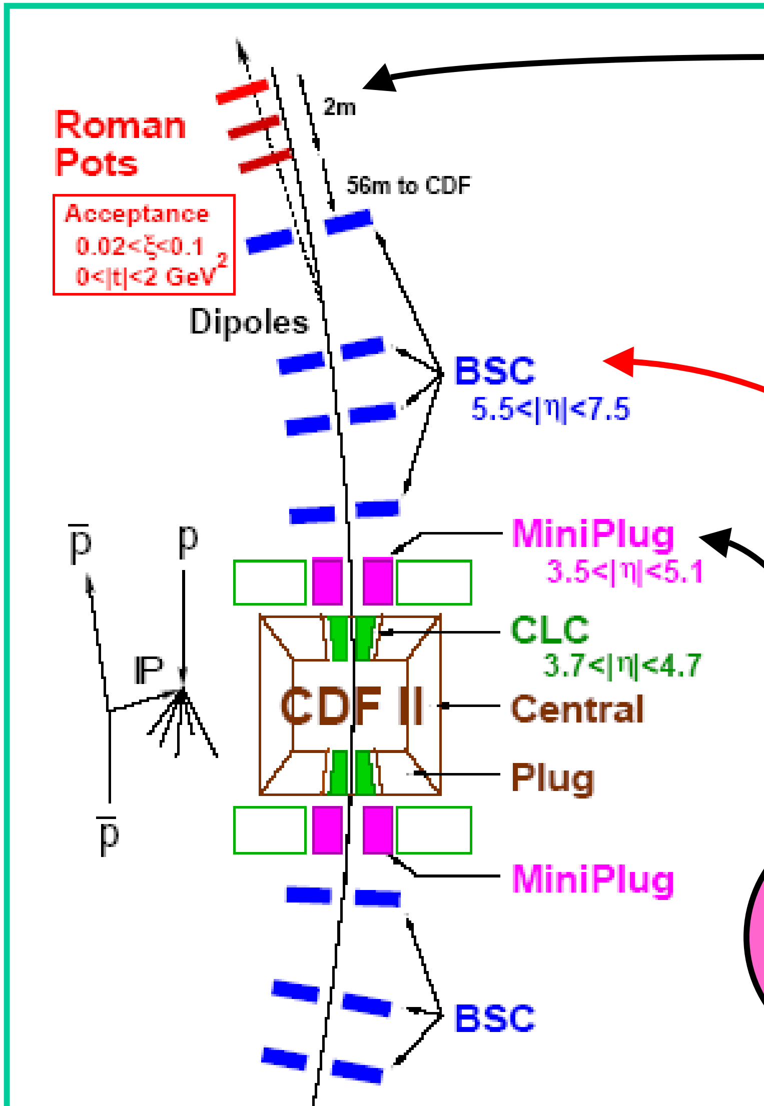




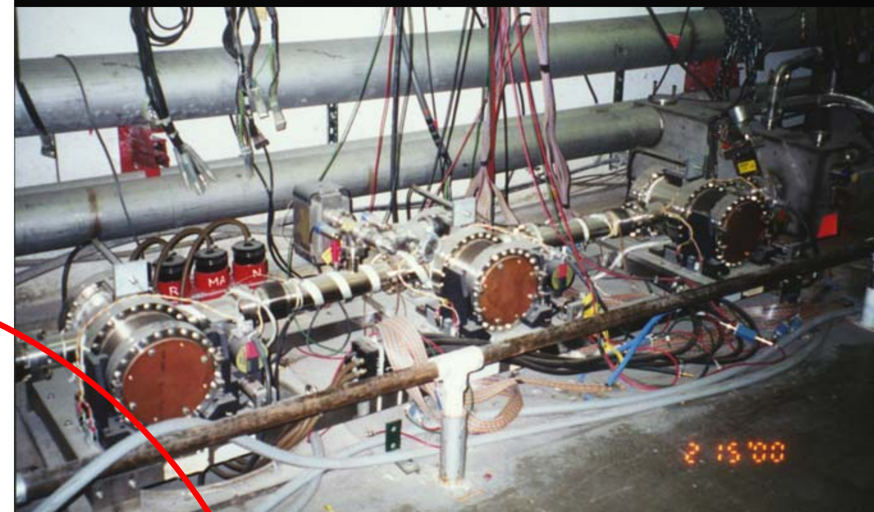
Restoring Factorization



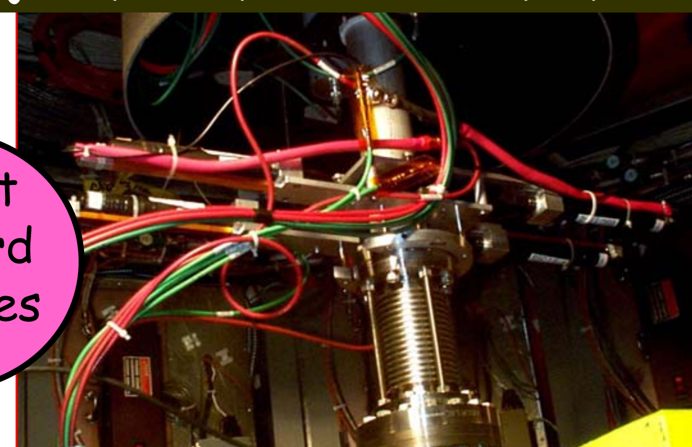
CDF-II



Tag leading p-bar @ 0.02 < ξ< 0.1

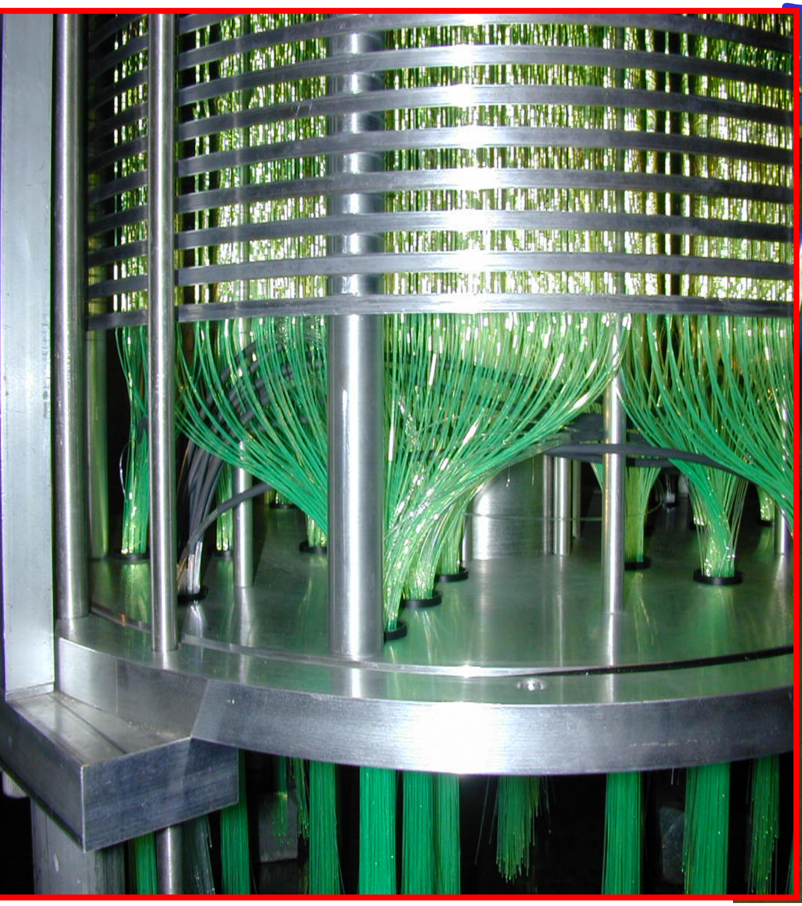


Reject (retain) 95% of ND (SD)events



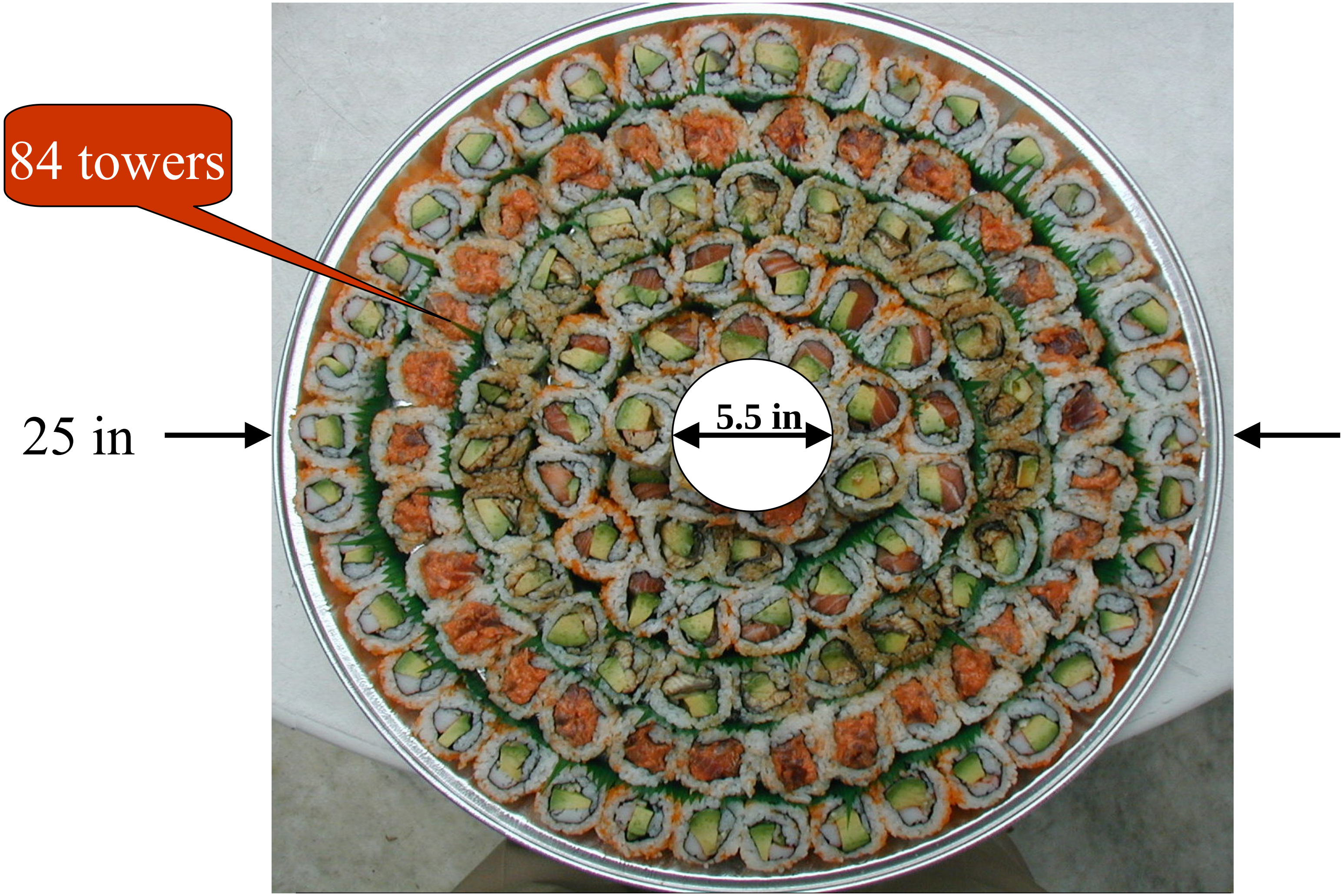
detect forward particles

MiniPlug Calorimeter

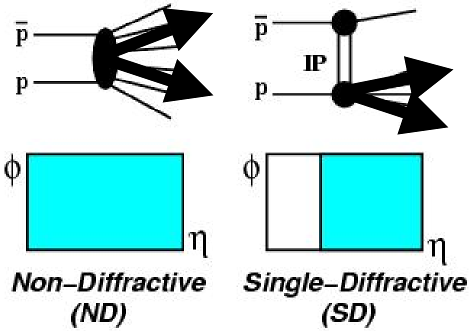


About 1500 wavelength shifting fibers of 1 mm dia. are ‘strung’ through holes drilled in 36x$\frac{1}{4}$" lead plates sandwiched between reflective Al sheets and guided into bunches to be viewed individually by multi-channel photomultipliers.

Artist's View of MiniPlug

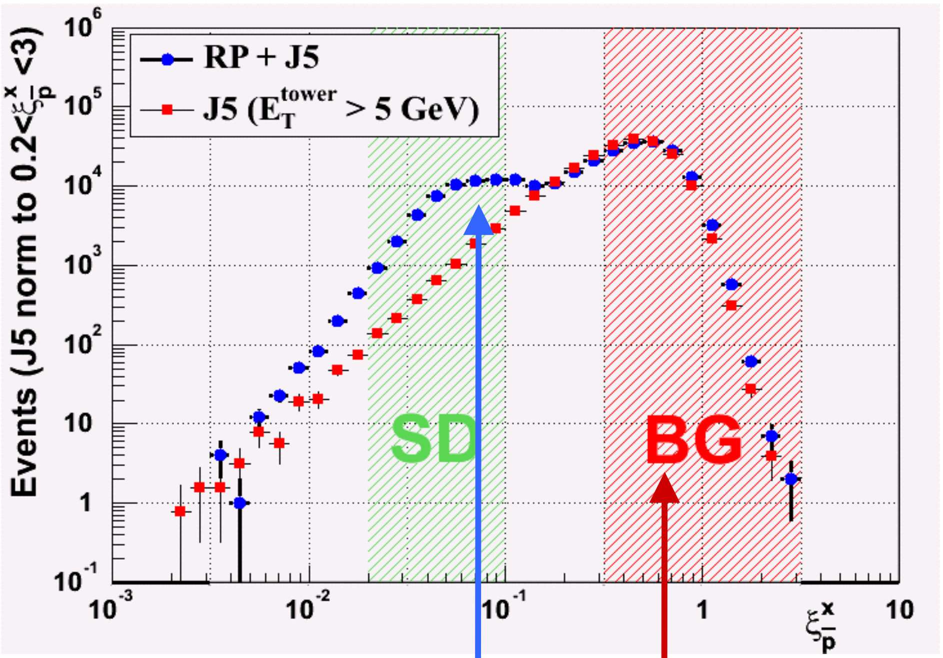


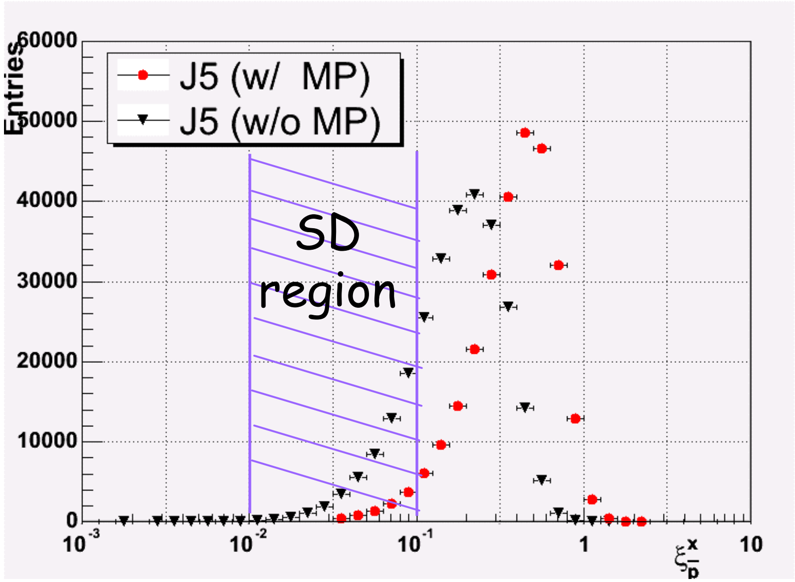
Diffractive dijets



ξ : momentum loss fraction of pbar

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





Approx. flat at ξ<0.1

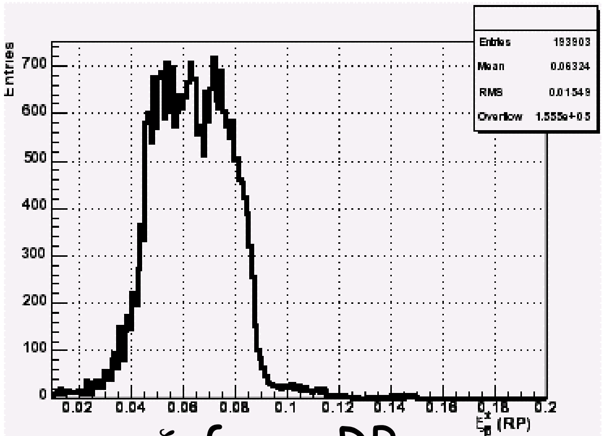
$$\frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \rightarrow \frac{d\sigma}{d(\log\xi)} = \text{const}$$

overlap events

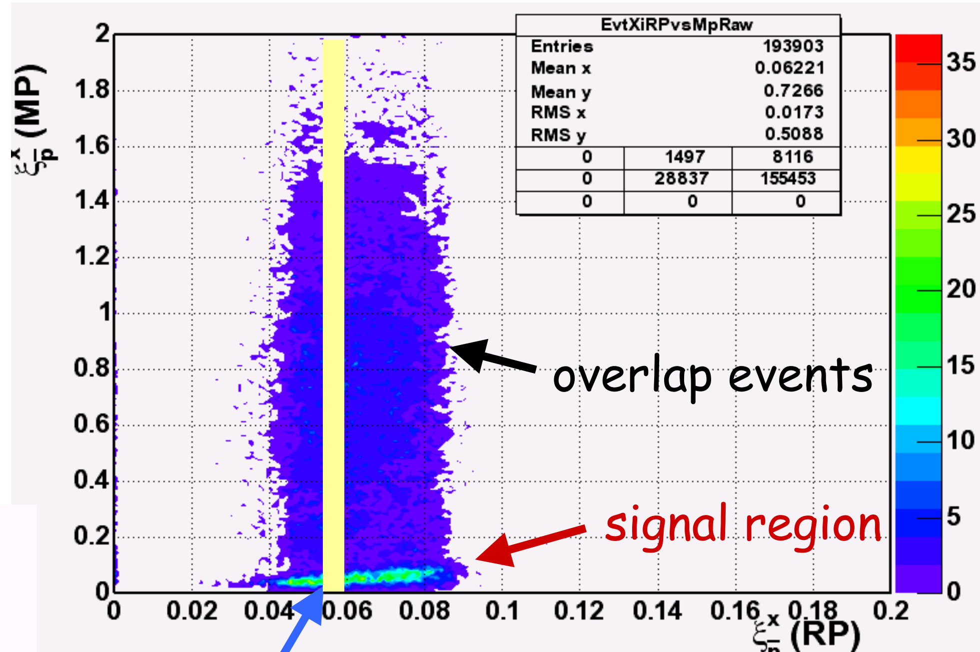
MP energy scale: ±25% →$\Delta\log\xi$ = ±0.1

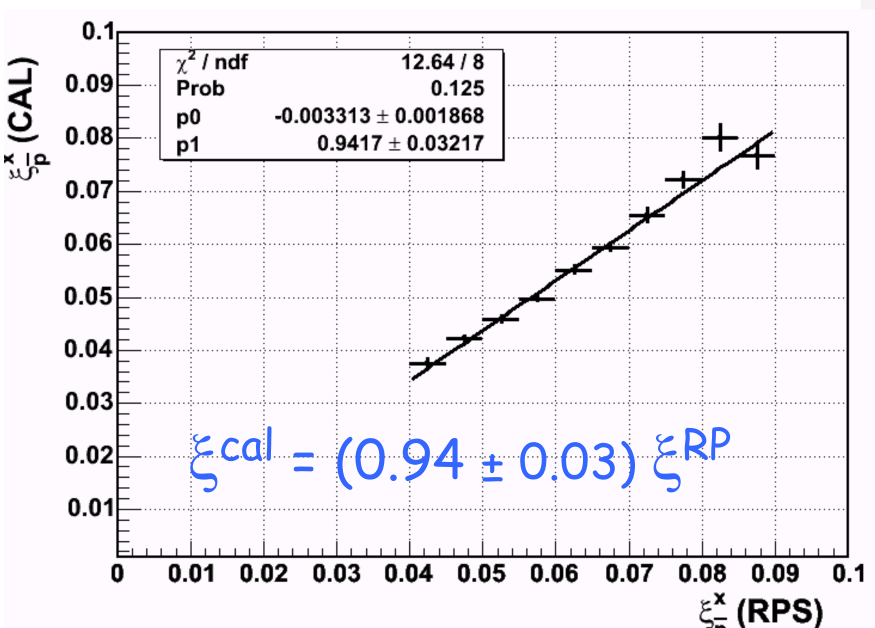
RP acceptance (0.03<ξ< 0.1) ~ 80% (Run I)

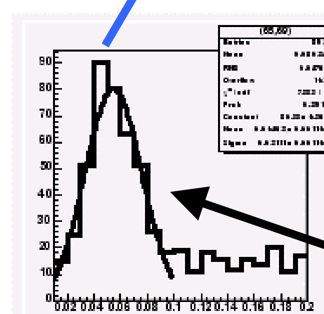
ξ: RP vs calorimeter



ξ from RP



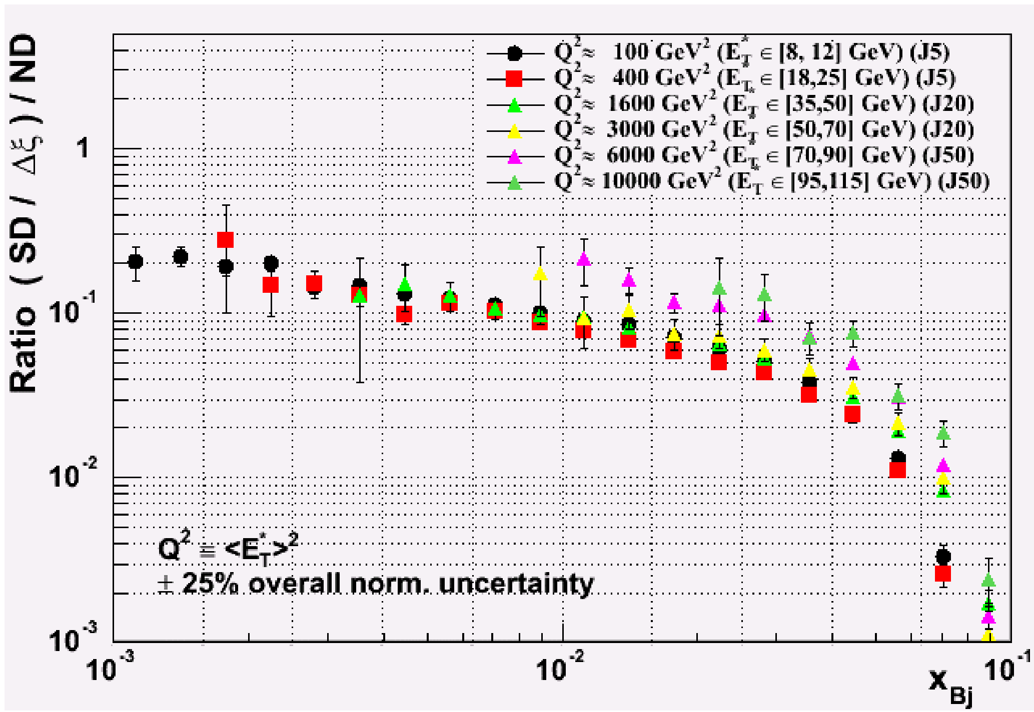




ξ^{cal} distribution for slice of ξ^{RP}

σ/mean ~ 30%

Q^2-dependence of SD/ND ratio



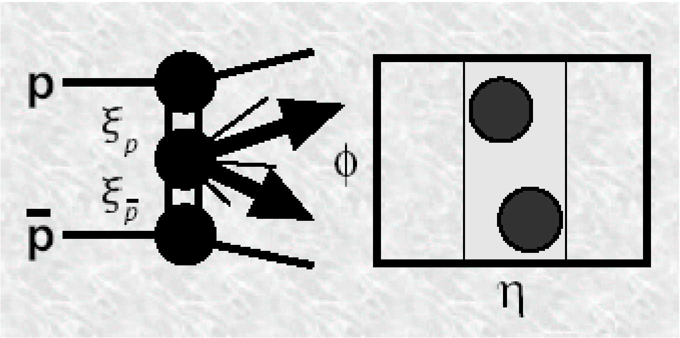
- No appreciable Q^2 dependence within $100 < Q^2 < 10{,}000$ GeV^2

⇨ Pomeron evolves similarly to proton

Exclusive Dijets in DPE

Interest in diffractive Higgs production

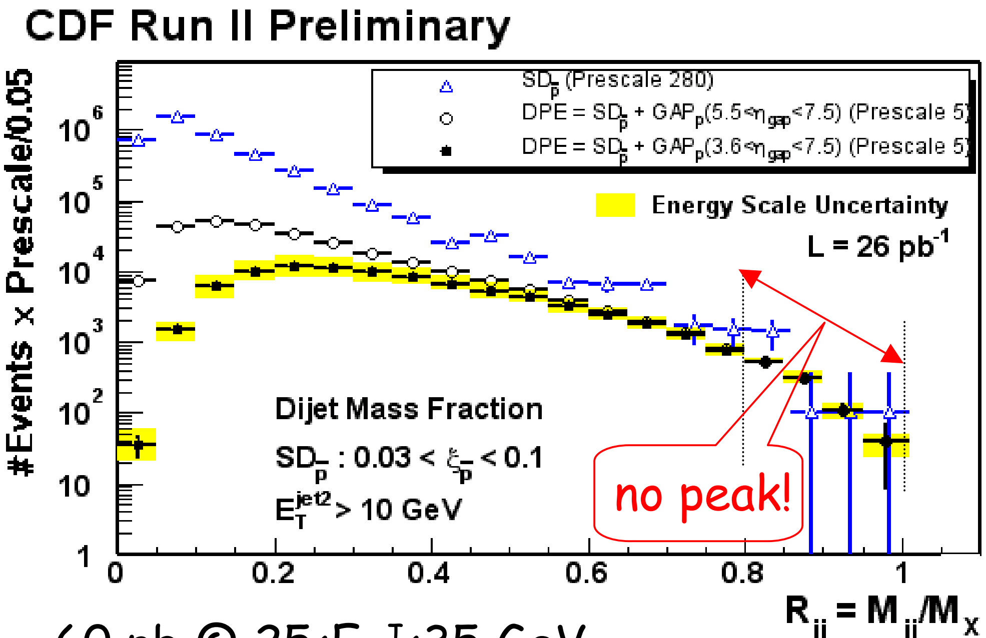
Calibrate on exclusive dijets



Dijet mass fraction

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

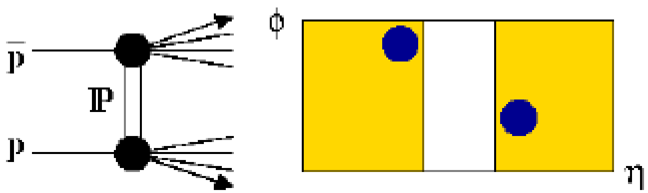
E_T^{jet}	$\sigma_{DPE}^{excl\ jj}(R_{jj} > 0.8)$
10 GeV	$970 \pm 65 \pm 272$ pb
25 GeV	$34 \pm 5 \pm 10$ pb

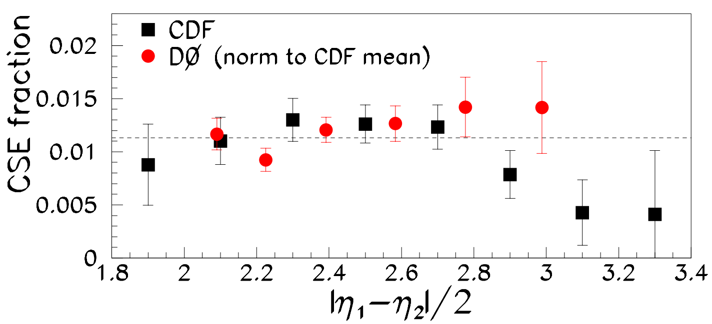


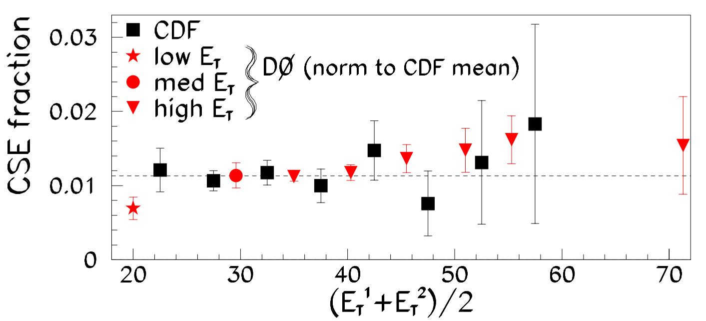
Upper limit for excl DPE-jj consistent with theory: KMR → 60 pb @ $25 < E_T^J < 35$ GeV

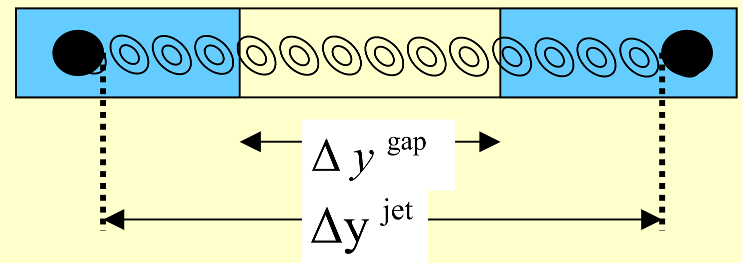
Gap Between Jets

$$\bar{p} + p \rightarrow \text{Jet} + \text{Gap} + \text{Jet}$$



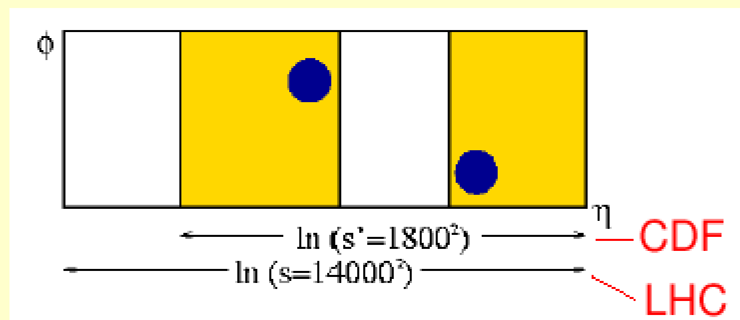






Question

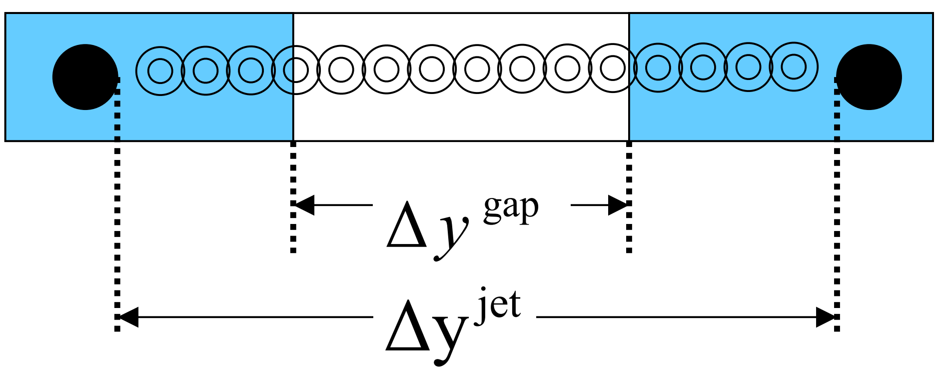
$$\Delta y^{gap} \xleftrightarrow{???} \Delta y^{jet}$$



$$R^{J-G-J}_{LHC}(s') = R^{J-G-J}_{TEV}/S \approx 1\%/0.2 \approx 5\%$$

CDF2LHC

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



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

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

Summary

SOFT DIFFRACTION

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

HARD DIFFRACTION

- Flavor-independent SD/ND ratio
- Little or no Q^2-dependence in SD/ND ratio

✓Universality of gap prob. across soft and hard diffraction
✓ Pomeron evolves similarly to proton

Diffraction appears to be a low-x partonic exchange subject to color constraints