Rapidity, Rapidity Gaps and all that

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CDF CM July 04

1) Introduction: strong interactions, confinement

2) Rapidity and its properties

3) Total, elastic, diffraction and diffractive structure functions

4) Central gaps with and without jets

5) Low x gluons and the pomeron

6) Vacuum excitation: "double pomeron exchange"

7) Ideas about the pomeron, speculations

Rapidity, Rapidity Gaps and all that

Bjorken: "...the most important frontier of QCD is
CONFINEMENT

Partons q,g → Color Singlet Subsystems → **hadrons**

Small distances, times → large distances, times

Inescapable, every event, low $Q^2, \alpha_S \sim 1$ & calculations **diverge**

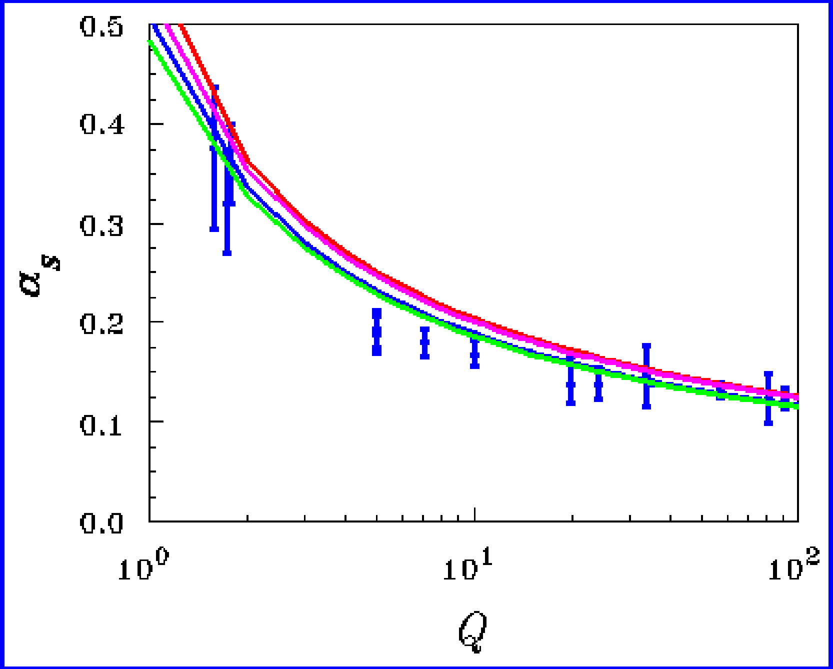
High **impact parameter** (b) collisions → **new phenomena**
to do with confinement. Non-perturbative QCD

Diffraction : rapidity gaps

The REAL Strong Interaction

MACHO ← extended, strong coupling
classical limit?

WIMP → point-like, weak coupling



Many approaches
None complete:

→ Regge Theory: Analyticity + Unitarity + Crossing Symmetry + Complex angular momenta

$\pi^- p \to \pi^0 n \quad \& \quad \pi^- p \to \pi^- p$

→ Lattice Gauge Theory
Discrete spacetime, small volume

→ & many models

Want a complete S.I Theory

$Q^2 = 0 \to \infty$

How does the proton stick together?

β, γ, y, η

- All dimensionless numbers, all measures of speed
- Consider just 1-dimension, z

$$\beta = \frac{1}{c}\frac{dz}{dt} \qquad \beta : 0 \rightarrow 1$$

$$\gamma = \frac{1}{\sqrt{1\text{-}\beta^2}} \qquad \gamma : 1 \rightarrow \infty$$

$$\Rightarrow \quad \beta = \sqrt{1 - \frac{1}{\gamma^2}}$$

$$E=\gamma m \quad ; \quad p=\beta\gamma m \quad ; \quad \beta=\frac{p}{E}$$

Law of addition of speeds:

Non-relativistic approximation

$$\beta_{13} = \beta_{12} + \beta_{23}$$

In relativity

$$\beta_{13} = \frac{\beta_{12} + \beta_{23}}{1+\beta_{12} \bullet \beta_{23}}$$

As β_{12} and $\beta_{23} \Rightarrow 1$, $\beta_{13} \Rightarrow 1$

$$\beta_{13} = \frac{\beta_{12} + \beta_{23}}{1 + \beta_{12} \bullet \beta_{23}}$$

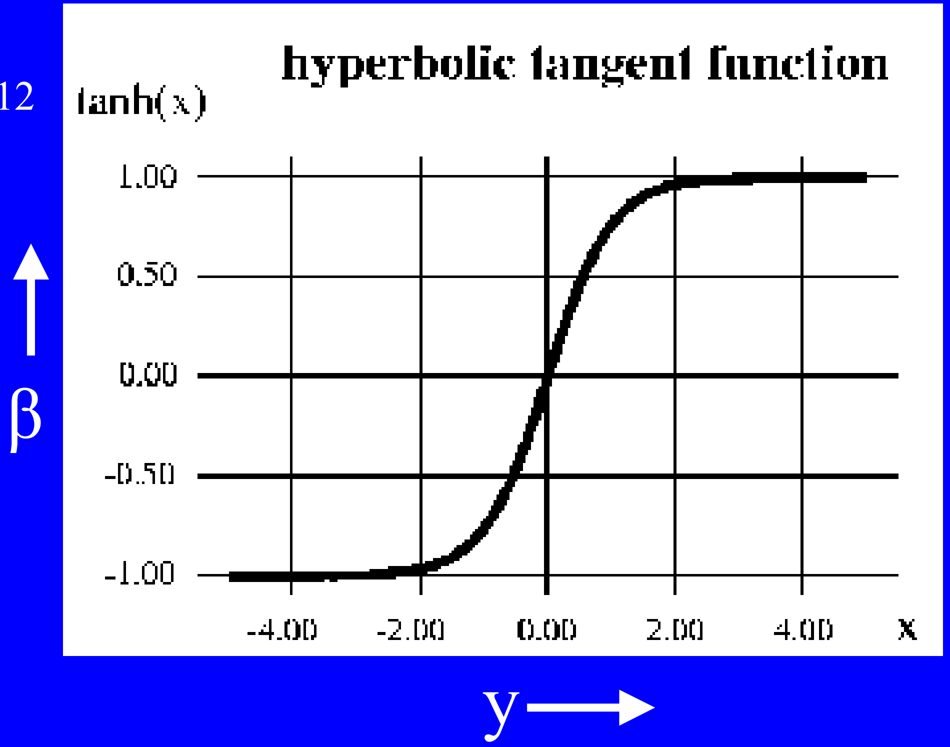
Where have we seen this equation before?

$$\tanh(a+b) = \frac{\tanh a + \tanh b}{1 + \tanh a \bullet \tanh b}$$

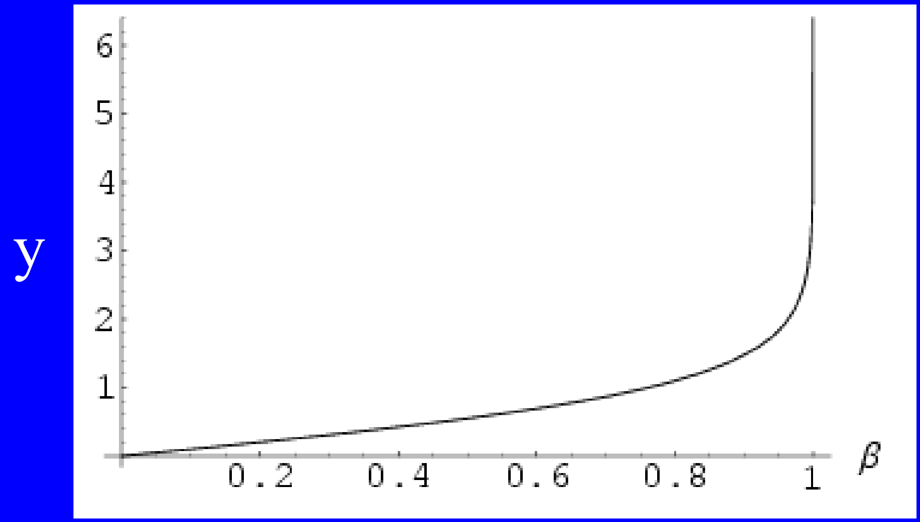
So: identify β_{12} with tanh y_{12}

For small values speed β and rapidity y are identical

$$\text{As } \beta \rightarrow 1.0 \quad y \rightarrow \infty$$



Or the other way round:



With β= tanh y

$$y = \tanh^{-1}\beta = \frac{1}{2}\ln\left(\frac{1+\beta}{1-\beta}\right) = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

DEFINITION

(Longitudinal) Rapidity component along the z-axis.
Rapidity w.r.t. other axes (e.g. jet axis) can also be defined.

$y' - y = \Delta$ is Lorentz invariant

$$y = \frac{1}{2}\ln\frac{E+p}{E-p}; \quad y' = \frac{1}{2}\ln\frac{E'+p'}{E'-p'}$$

L.T.

$$\begin{aligned} E' &= \gamma E - \gamma\beta p \\ p' &= -\gamma\beta E + \gamma p \end{aligned}$$

$$\frac{E'+p'}{E'-p'} = \frac{1-\beta}{1+\beta} \times \frac{E+p}{E-p}$$

$$\frac{1}{2}\ln\frac{E'+p'}{E'-p'} = \frac{1}{2}\ln\frac{1-\beta}{1+\beta} + \frac{1}{2}\ln\frac{E+p}{E-p}$$

$$\therefore y' = \Delta + y$$

Δ = rapidity difference of frames

Special cases: pT = 0 and m = 0

$$y = \frac{1}{2}\ln\frac{E+p_L}{E-p_L} = \frac{1}{2}\ln\frac{E+p_L}{E-p_L}\times\frac{E+p_L}{E+p_L} = \frac{1}{2}\ln\frac{(E+p_L)^2}{m^2+p_T^2}$$

If $p_T = 0$:

$$y = \frac{1}{2}\ln\frac{(E+p_L)^2}{m^2} = \ln\frac{E+p_L}{m} = \ln(\gamma+\beta\gamma)$$

$$\Rightarrow \ln 2\gamma \text{ (as } \beta \Rightarrow 1)$$

Same speed, same rapidity → $y\,(E_p = 938\text{ GeV}) = y\,(E_\pi = 140\text{ GeV})$

Rapidity & pseudorapidity

Pseudorapidity is rapidity for m = 0, i.e. photons.

If $\quad m = 0 \text{ (or} \sim \text{if } m \ll p_T\text{)}:$

$$y = \frac{1}{2}\ln\frac{(E+p_L)^2}{p_T^2} = \ln\frac{E+p_L}{p_T} = \ln\left[\frac{p}{p_T}+\frac{p_L}{p_T}\right]$$

$$= \ln\left[\frac{1}{\sin\theta}+\frac{1}{\tan\theta}\right] = \ln\left[\frac{1}{\tan\left(\frac{\theta}{2}\right)}\right] = -\ln\tan\frac{\theta}{2} = \eta$$

Did you know that?

Is there a simpler derivation?

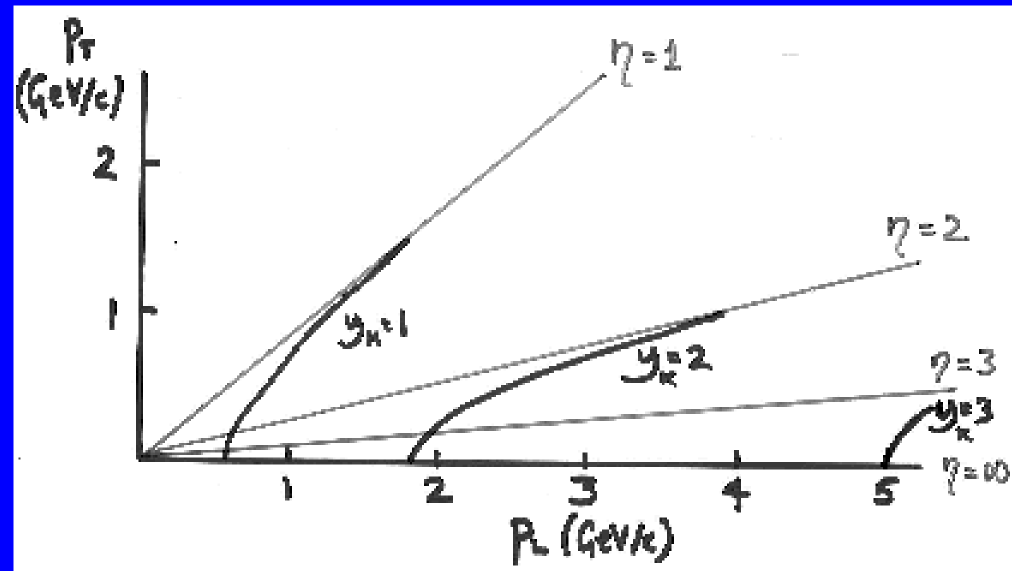
Rapidity → pseudorapidity as pT >> m

Thus for m = 0, photons, $y = \eta$

Otherwise $y < \eta$

At small angles, *very* different

η and y contours on (p_T, p_L) plane



Beam particles have $\eta = \infty$

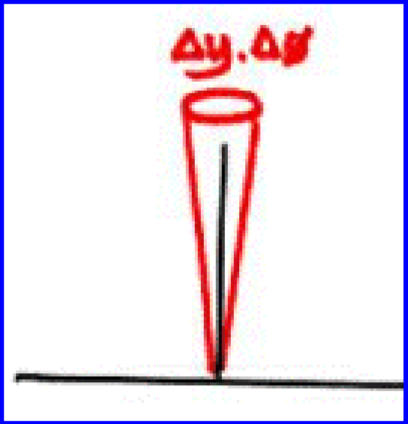
but
$$y_{beam} = \ln \frac{E + p_L}{m_p} \approx \ln \frac{\sqrt{s}}{m_p} = 7.64 \text{ at } \sqrt{s} = 1960 \text{ GeV}$$

$$y_\pi(980\text{GeV}, 0^\circ) = \ln \frac{\sqrt{s}}{m_\pi} = 9.55 \qquad \Delta y = \ln \frac{m_p}{m_\pi}$$

Some other nice things:

At 90^0 $(y = 0)$ $\Delta y = \Delta\theta$(rads)

EfS

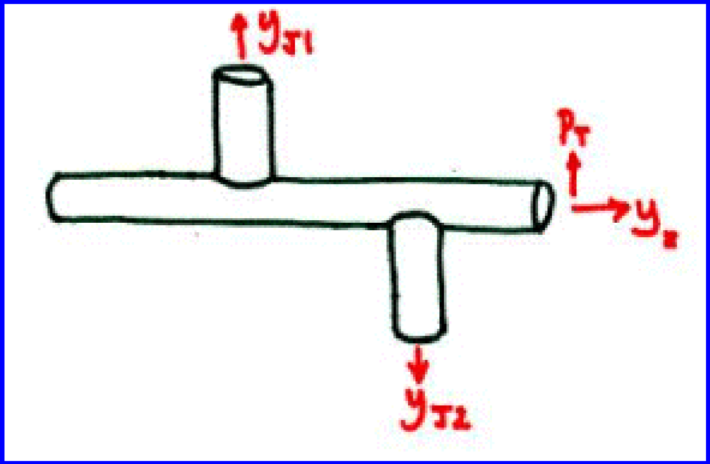


$\Delta\theta = \Delta\phi$ (round jet)

$\therefore R = \sqrt{\Delta\phi^2 + \Delta y^2} =$

measure of distance from jet axis.

& E_T, $\Delta\phi$ and Δy are all invariant under z-boosts



"Limited" pT, expanding y

2-Jet event

Can define y_J = rap along jet axis

y_J, k_T distributions

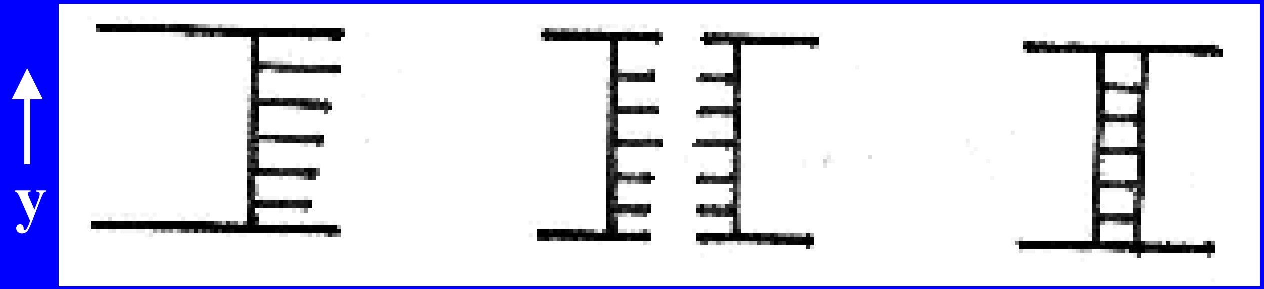
rapidity = 0 rapidity ~ 10^{-10}

Rapidity Gap

Relation between Total Cross Section and Elastic Scattering:

Optical Theorem $\sigma_{tot} = \frac{4\pi}{k} \mathrm{Im}\, f(\theta = 0)$ ***(k ~ p)***

Inelastic cross section inevitably implies elastic cross section



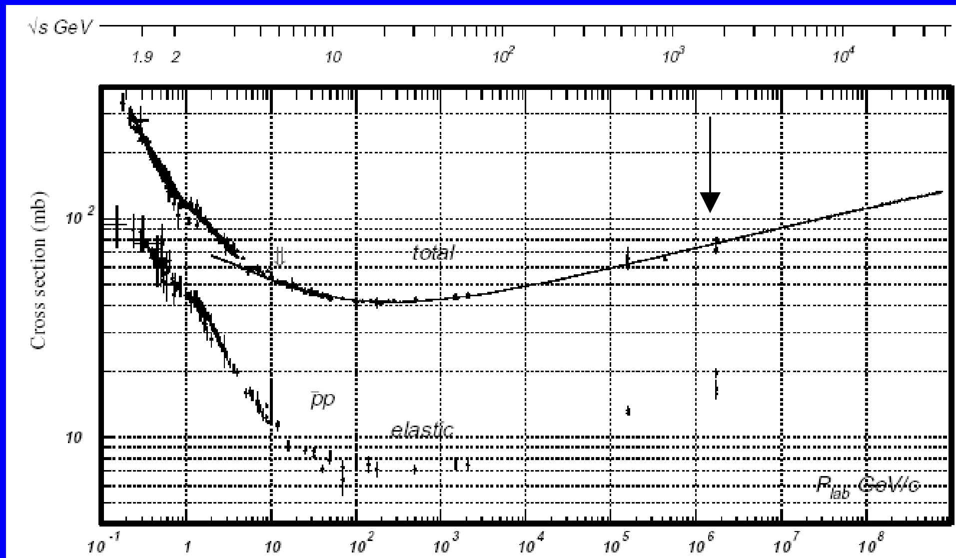
BIG GAP!

Total cross sections ***all*** (including $\gamma\gamma$) eventually rise with energy.
Increasing **opacity** and increasing **size** (cf elastic slope b)

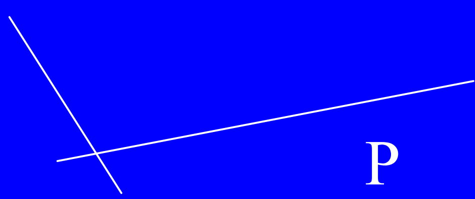
This has ***something*** (what?) to do with confinement.

Total and elastic cross sections: **fall then rise (universal)**

$\sigma(p\bar{p})$



ln s



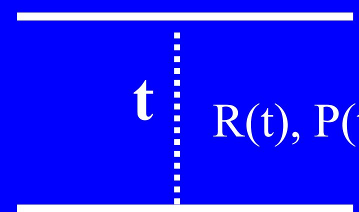
Two terms: $s^{\alpha_i(t=0)-1}$

$\alpha_R(t=0) \approx 0.55 \Rightarrow s^{-0.45}$

$\alpha_P(t=0) \approx 1.08 \Rightarrow s^{+0.08}$

Total Elastic : $\sim s^{2\alpha(t=0)-2}$

$\alpha(t) \equiv$ effective spin of exchange

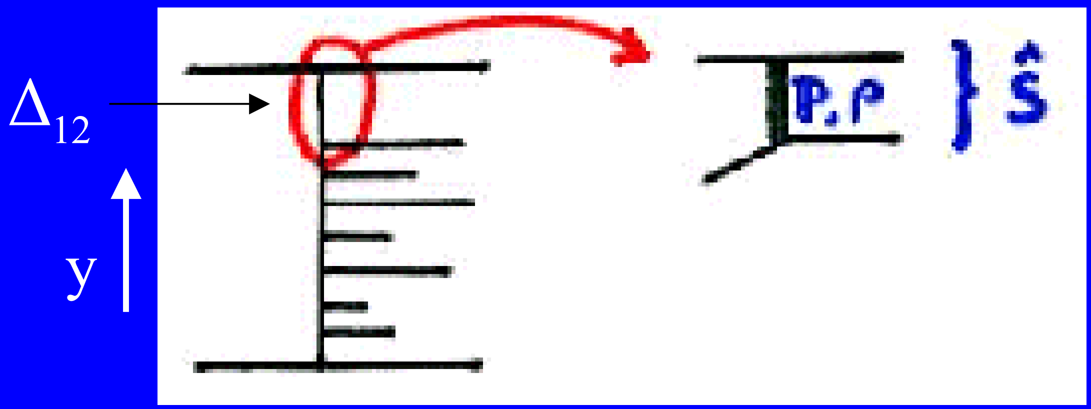


R (Reggeon) = sum of all allowed $q\bar{q}$ meson exchanges ρ, ω, ρ′ etc

P (Pomeron) = (?) sum of all allowed non-meson (gg etc?) exchanges. Glueballs

Generalized Particle Production (Inelastic Collisions)

Multiperipheral Diagram:



$$\Delta_{12} = \ln \frac{s_{12}}{m^2}$$

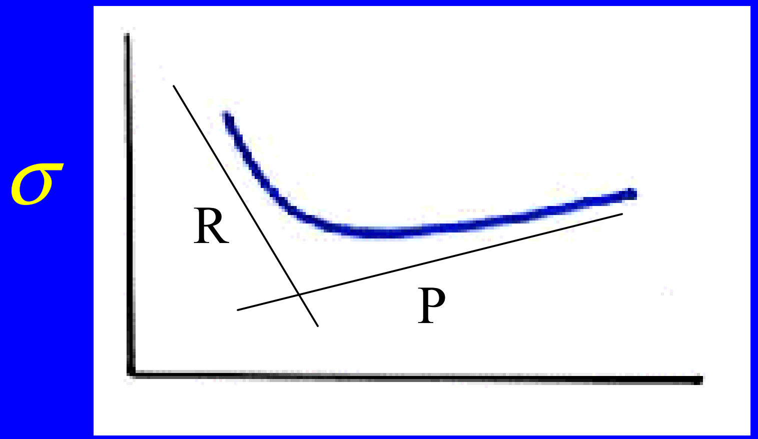
$$m_{12}^2 \equiv s_{12} = m^2 e^{\Delta_{12}}$$

$$\text{Regge: } \sigma \sim s^{\alpha(0)-1}$$

$$\alpha_R(t=0) \sim 0.5 \;\Rightarrow \sigma \sim e^{-0.5\Delta}$$

$$\alpha_P(t=0) \sim 1.1 \;\Rightarrow \sigma \sim e^{0.1\Delta}$$

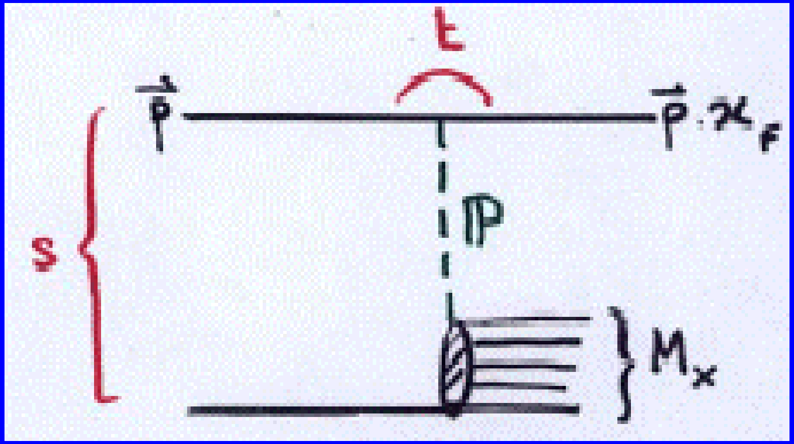
Large (>~ 3) rapidity gaps are dominated by pomeron exchange. >~ 4 is better!



$$\Delta_{ij} = 2\ln\frac{\sqrt{s}}{m}$$

Single Diffractive Excitation

$\Delta E_{\text{p-frame}} <\sim m_\pi \Rightarrow \xi = 1 - x_F <\sim 0.05$



$$\ln M_X^2 \leq \ln s - 3$$

$$M_X^2 \leq e^{(\ln s - 3)} = \frac{e^{\ln s}}{e^3} = \frac{s}{20}$$

$$\frac{M_X^2}{s} = 1 - x_F = \xi \leq 0.05$$

$\Delta y \equiv -\ln \xi$

$(3 = -\ln 0.05)$

"Proton" scatters coherently:

No pion emission, no break-up,

no change of quantum numbers,

isolation in phase space (large Δy)

Only (-ve) 4-momentum (squared) t exchanged.

What has vacuum quantum numbers and carries four-momentum transfer (squared) t ?

It's called the pomeron P (after Pomeranchuk)

What is that in QCD? Does it have a parton content?

It is non-perturbative, Q^2 small, α_S large, **so hard to calculate**

We can probe it experimentally:

P + p → jets, W/Z, c and b etc.

HERA (ep) Deep Inelastic Scattering & Diffractive DIS

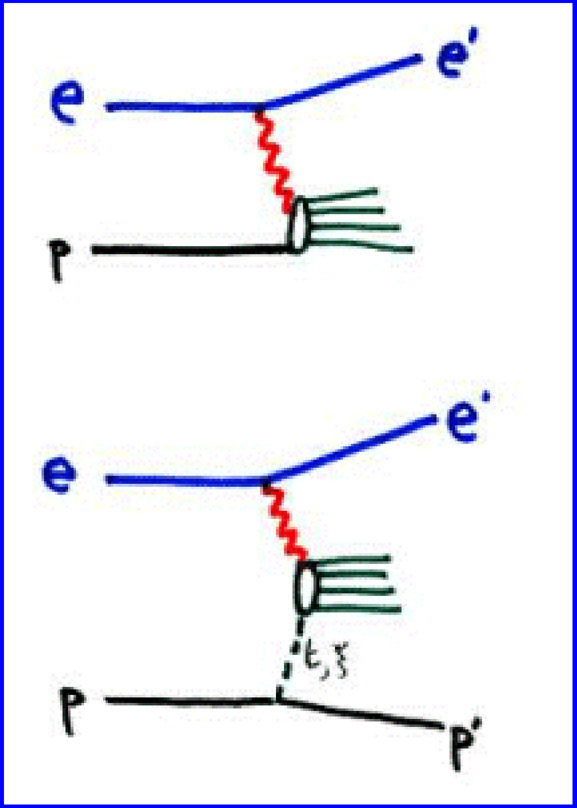
The normal structure function conditional on leading proton (or gap)

$$F_2(x,Q^2) \equiv x\sum_q e_q^2 q(x) \Rightarrow F_2^{diff}(x,Q^2,\xi,t)$$

Defined independently of notion of the exchange ("pomeron")
Measured in detail by H1 and ZEUS

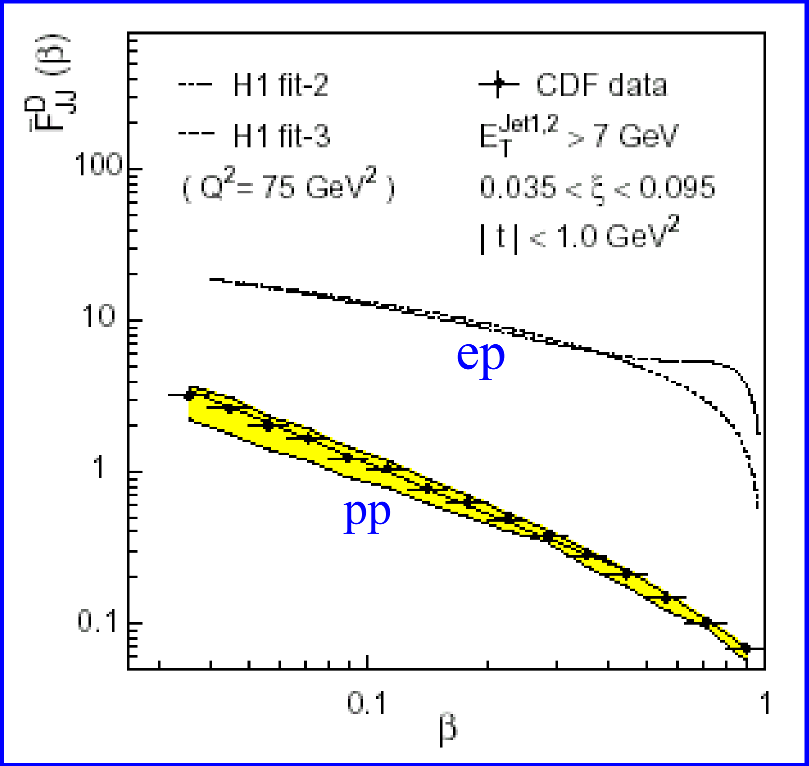
Interpretable as measuring the structure of the pomeron

$$\beta = \frac{x_{Bj}}{\xi}$$



Diffractive Structure Functions / pdfs

The normal structure function conditional on leading proton (or gap)



CDF: measured with jets

$$F_{JJ}(x) = x\{g(x) + \frac{4}{9}\sum[q(x)+\bar{q}(x)]\}$$

$$x = \frac{1}{\sqrt{s}} \sum_{jets} E_T\ e^{-y}$$

EfS

Rapidity gaps suppressed in pp compared with ep. Gaps don't survive additional interactions.

$$\beta = \frac{x_{Bj}}{\xi}$$ = momentum fraction in "P"

Central rapidity gaps

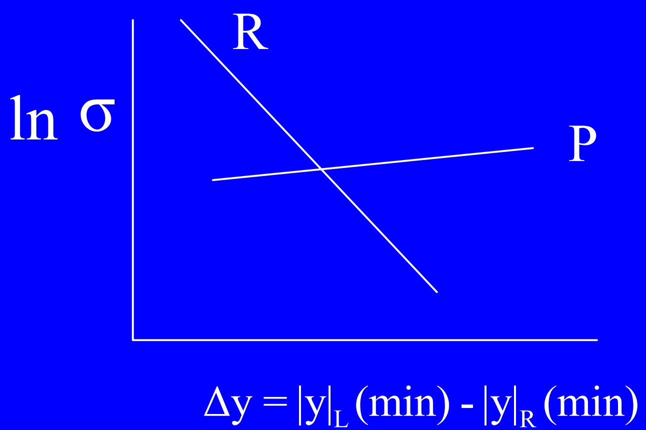
pp collision at **very** short times – see only colored partons

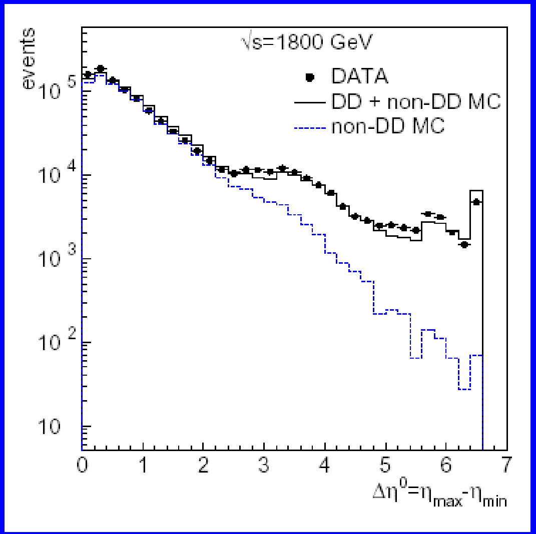
CONFINEMENT

At long times – only color singlet hadrons

At intermediate times can have color singlet clusters:

RAPIDITY GAP → SPATIAL GAP



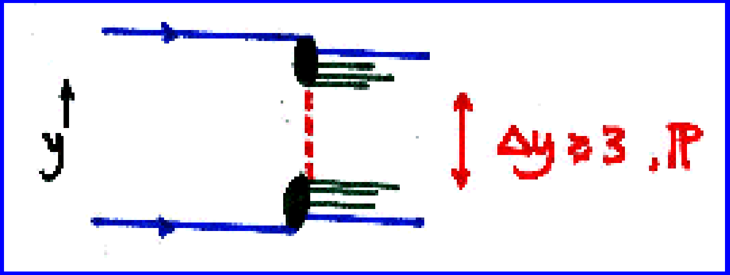


CDF PRL 87:141802,2001

Another Gap

Double Diffractive Dissociation with Jets

Pomeron exchanged across gap (if large)
Normally considered soft physics

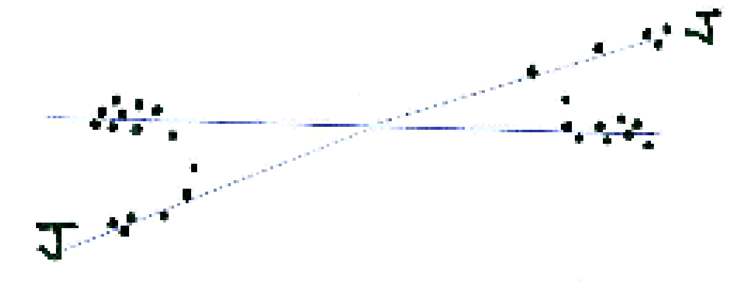


But CDF (+D0?) **discovered JGJ = Jet-Gap-Jet**
4-momentum transfer-squared, t > 1000 GeV^2

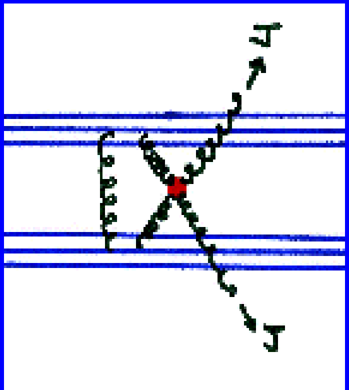
PRL 74 (1995) 855

Color Singlet Exchange: γ, W, Z, $\{g_H g_S\}$?

Hard scatter – high Q2 – short time
& rap gap – soft process – long time

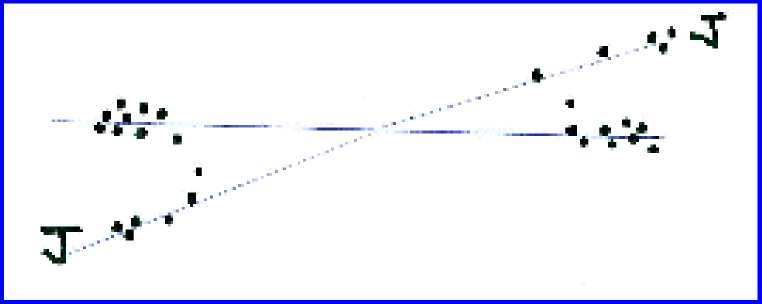


Soft Color Interactions (SCI) make gaps:
Central gap → jets forward
or forward gaps → jets central

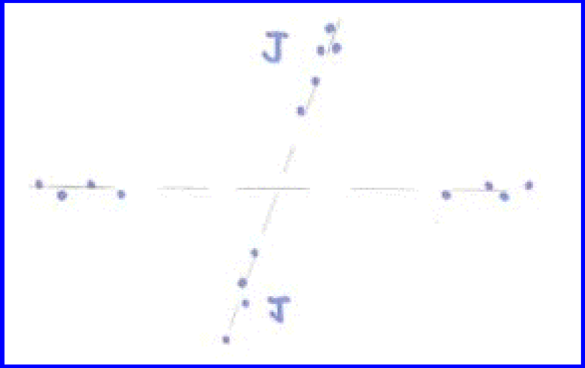


With or w/o
p break-up
g radiation ...

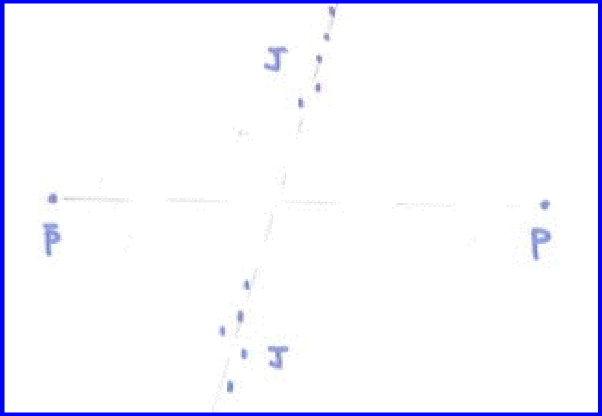
Soft – hard interplay

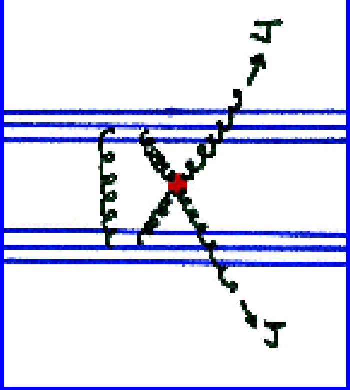


Same diagram with large angle scatter
→ jets central



Forward "clusters"
can even be single protons





Central di-jet production by DPE

Price paid per Gap

Rules of thumb:
1/10th of hard interactions at HERA (ep) are diffractive
1/100th of hard interactions at Tevatron are diffractive.

$W \rightarrow (1.15 \pm 0.51 \pm 0.20)\%$

$JJ \rightarrow (0.75 \pm 0.05 \pm 0.09)\%$

$b\bar{b} \rightarrow (0.62 \pm 0.19 \pm 0.16)\%$

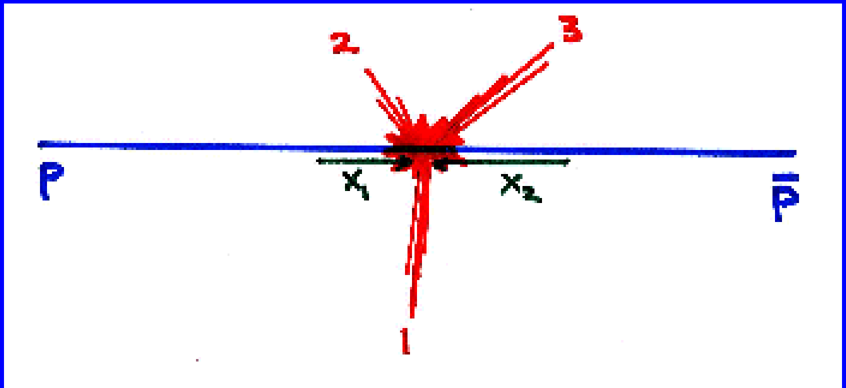
From differences, f(g) ~ 0.54 +/- 0.15 ... at high-ish Q^2

~ 1/10th of {JJG} have a second gap (not 1/100th)
→ If 1st gap survives, 2nd gap is likely to survive too.

Jets' Rapidity and E_T → Bjorken x's

partons $x_1 + x_2 \Rightarrow$ jets 1,2,...n

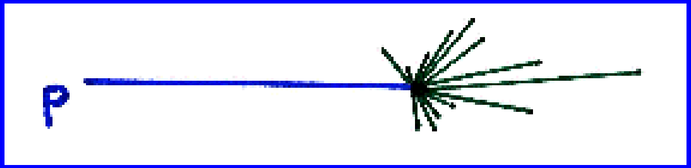
$$x_{1,2} = \frac{1}{\sqrt{s}} \sum_{\text{jets}} E_T e^{\pm y} \approx \frac{1}{\sqrt{s}} \sum_{\text{jets}} E_T e^{\pm \eta}$$



Proton's $\xi = 1 - x_F$ can be found even if don't see p but see everything else from:

$$\xi = \frac{1}{\sqrt{s}} \sum_{\text{particles}} E_T^i \, e^{\pm y\,(\eta)}$$

EfS



[+ for $\overline{p}$, - for p (at +ve y)]

Low-x

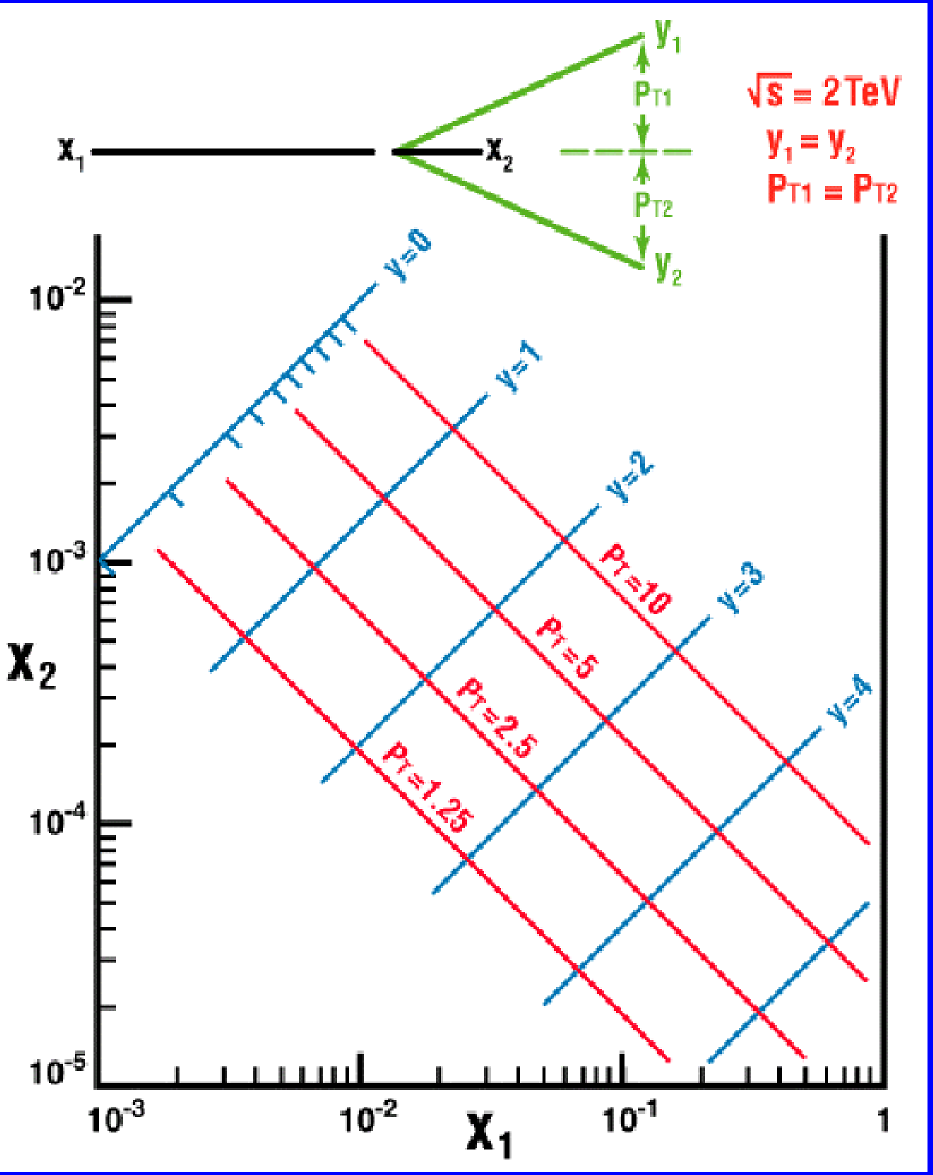
2 partons : $E_{T1}=E_{T2}$, $y_1=y_2$

$$x_1 = \frac{2}{\sqrt{s}} E_T\, e^{-y}; \quad x_2 = \frac{2}{\sqrt{s}} E_T\, e^{+y}$$

$$x_1 x_2 = 4\frac{E_T^2}{s} \text{ independent of } y$$

e.g. $\sqrt{s} = 2000$ GeV; $E_T = 10$ GeV

$$\Rightarrow x_1 x_2 = 10^{-4}$$



Mapping:

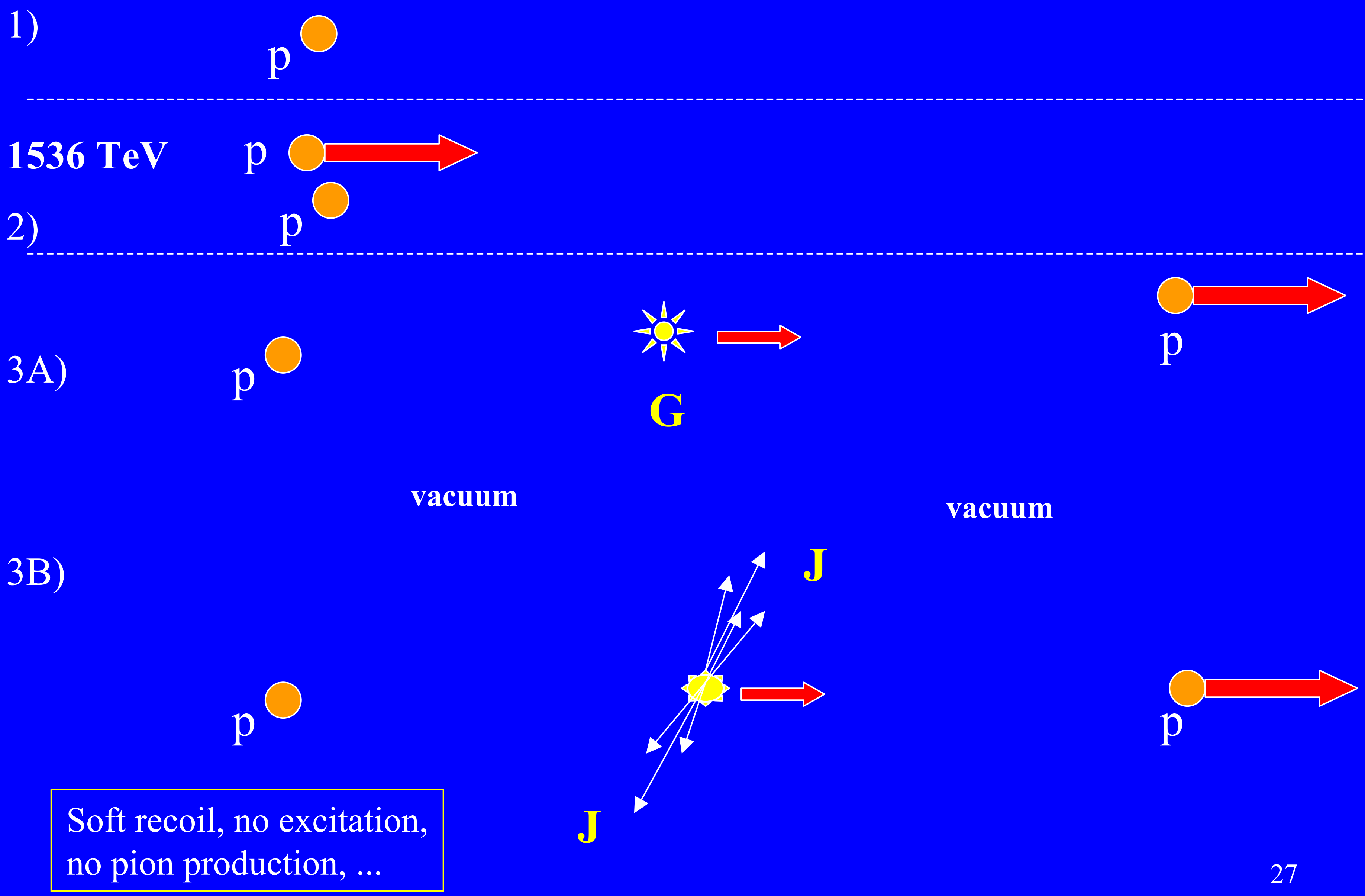
partons' x_1, x_2 to

jets' y, p_T for $y_1 = y_2$

Forward $D\bar{D}$ → low x gluons.

Pomeron related to low-x g(x)

Vacuum Excitation (Lab frame)



Central DPE : Kinematic Limits "Rule of Thumb"

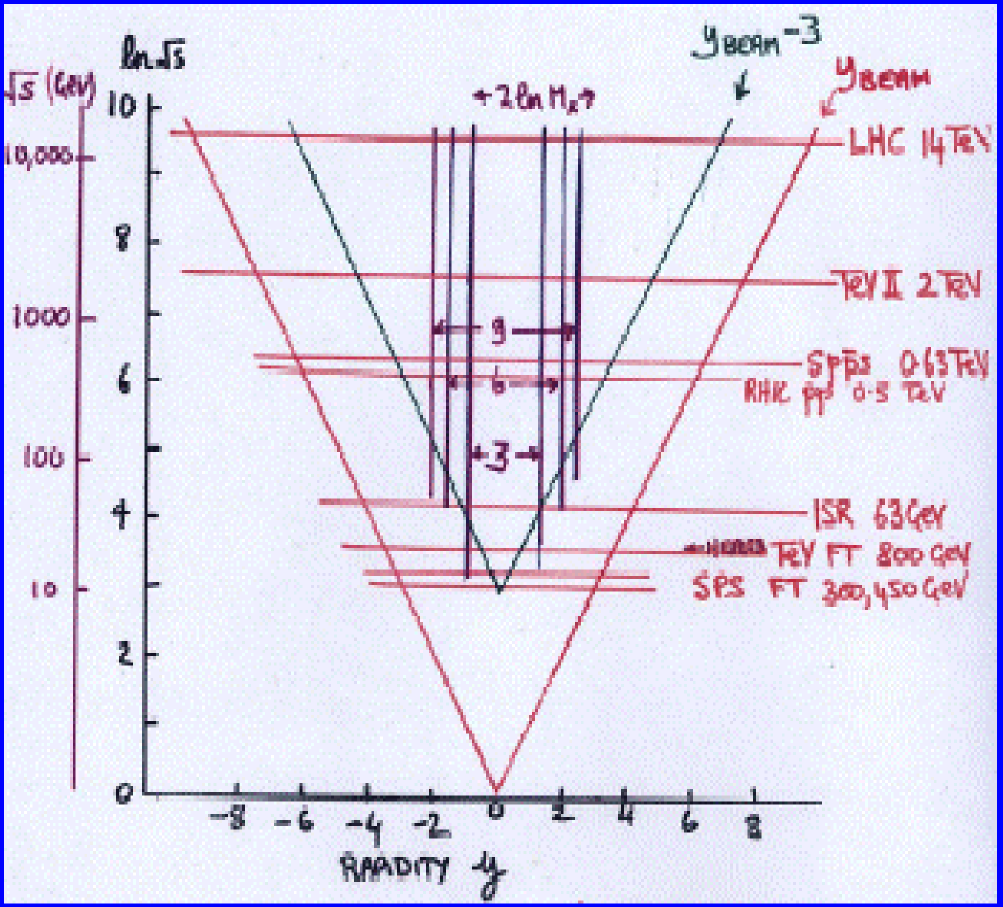
$$y_{BEAM} = \ln\frac{\sqrt{s}}{M_p}\;;\;\; y_{CEN} \text{ spans } 2\ln M_X \;;\; 3 \text{ units GAP}$$

Simply (equivalent) : $M_X(\max) \sim \frac{\sqrt{s}}{20}$

FT Expts right on edge
ISR good to ~ 3 GeV
TeV good to ~ 100 GeV
LHC good to ~ 700 GeV

Tevatron is the perfect place
for low mass DPE
... and into jet domain.

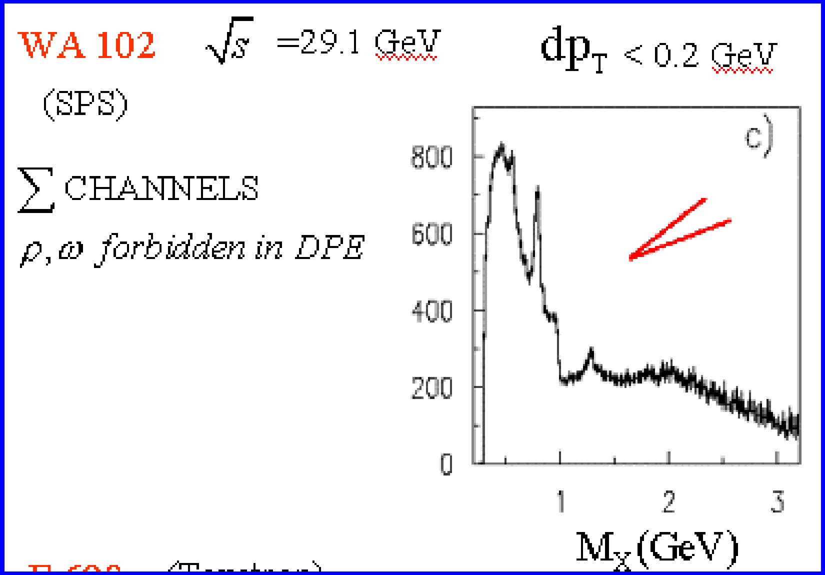
LHC well into top, W, Z domain



Low Mass Central Exclusive Production

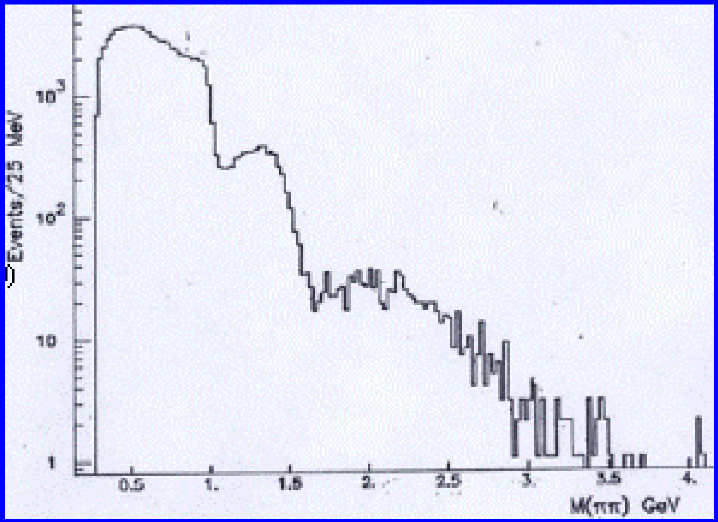
Resonances but too low s for DPE dominance.

ρ



ISR sqrt(s) = 63 GeV

No ρ



Structures not well understood.
Not studied at higher sqrt(s)

Central Exclusive Production

gg fusion: main channel for H production.

Another g-exchange can cancel color, even leave p intact.

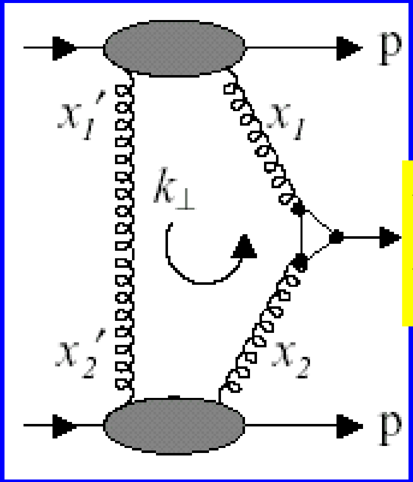
$$p\,p \rightarrow p \;+\; H \;+\; p$$

Theoretical uncertainties in cross section, involving skewed gluon distributions, gluon k_T, gluon radiation, Sudakov ff etc.
→Probably $\sigma(SMH) \sim 1$ fb at Tevatron, not detectable, but may be possible at LHC (higher L and $\sigma \sim 40$ fb?)

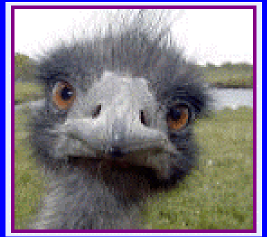
Nothing else on emu vertex!

$$\mathrm{H}(160) \rightarrow \mathrm{W}^+\mathrm{W}^- \rightarrow \mathrm{p}\;\; e^+\mu^-\not{E}_T\;\; \mathrm{p}$$

$$\mathrm{MM}^2 = (p_1 + p_2 - p_3 - p_4)^2 = \mathrm{M}_\mathrm{H}^2$$



u-loop : $\gamma\gamma$ c-loop : χ_c^0
b-loop : χ_b^0 t-loop: H



Theory can be tested, low x gluonic features of proton measured with exclusive $\gamma\gamma$, χ_c^0 and χ_b^0 production.

Exclusive χ_c search: $p\bar{p} \to p \quad \chi_c \quad \bar{p}$

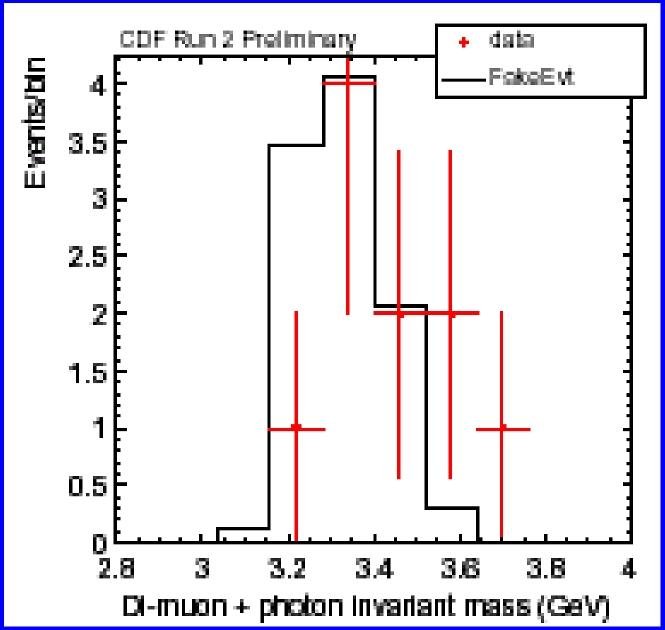
CDFNOTE 6646 (Angela Wyatt)

Predictions for Tevatron ~ 600 nb (~ 20 Hz!)

$$\text{In reality: BR}(\chi_c^o \to J/\psi\,\gamma \to \mu^+\mu^-\gamma)$$

$$\times \text{ no other interaction} \times \text{acceptance(trig)}$$

$$\Rightarrow \text{few pb (1000's in 1 fb}^{-1})$$



$$\sigma(p\,p \to p \quad \chi_b \quad p) \sim 120 \text{ pb (KMR)}$$

$$\times(\text{BR} \to \Upsilon\gamma)\times(\text{BR} \to \mu\mu\gamma) \Rightarrow$$

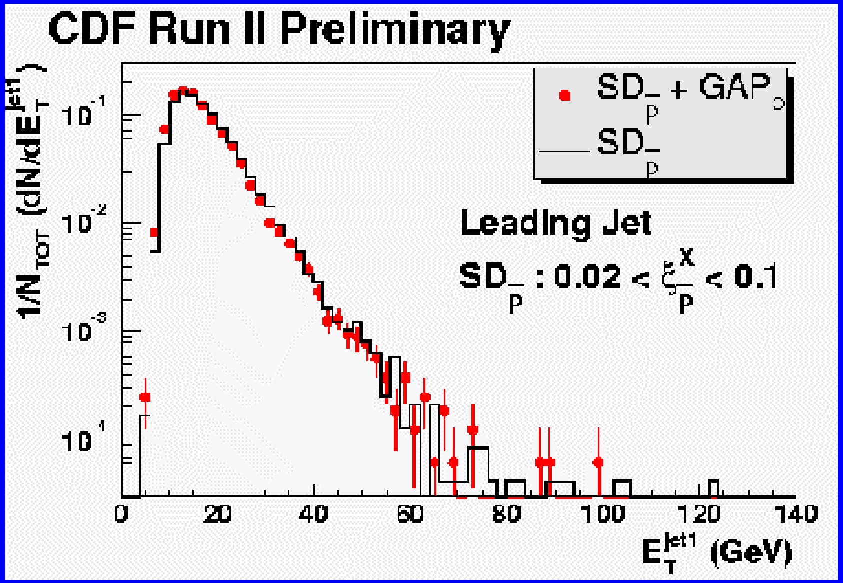
$$> \sim 100 \times \text{Acceptance} / \text{fb}^{-1}$$

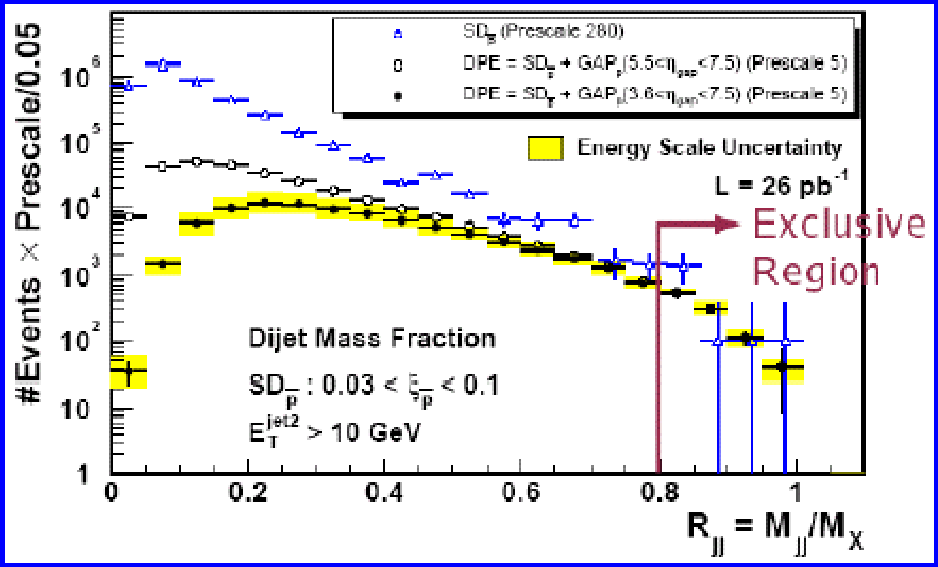
{Measuring forward p → central quantum numbers
2+ forbidden at t=0 for $q\bar{q}$ state}

$$I^G J^P = 0^+ 0^+$$

Exclusive Dijets?

Meaning p p → p JJ p and practically nothing else
See antiproton in roman pots, see rap gap on other side.
CDF Run I discovery {JJX} (130/~10 bg) ... Run II trigger:





So far: upper limit ~ theoretical expectations
Expect enhancement rather than peak
They should all be gluon jets !

Different "Pomerons"

A complete understanding of strong interactions (QCD) should unify these!

Snowmass (1996) accord:

1) The highest Regge trajectory, with the quantum numbers of the vacuum, responsible for the growth of hadronic total cross-sections with energy. {primary, theoretical}
2) The dominant strongly interacting entity exchanged over large rapidity gaps. {practical, experimental}

It is a prime task of our research to investigate the relationship between (or equivalence of) these definitions.

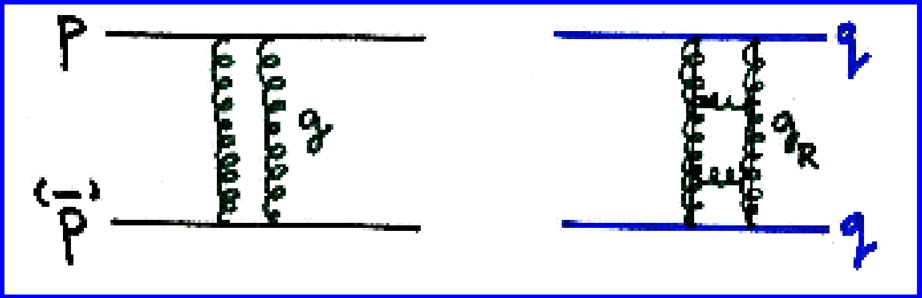
"Classical Soft" and BFKL Pomerons

0^{th} order, soft interactions (low t, Q^2) : {gg} in color singlet.
.... virtual "glueballs", summed over spins. Also {ggg}

As Q2 increases (as seen with partons) $q\bar{q}$ evolve in.

Reggeon = { $q\bar{q}$ } in color singlet, virtual mesons, summed up.

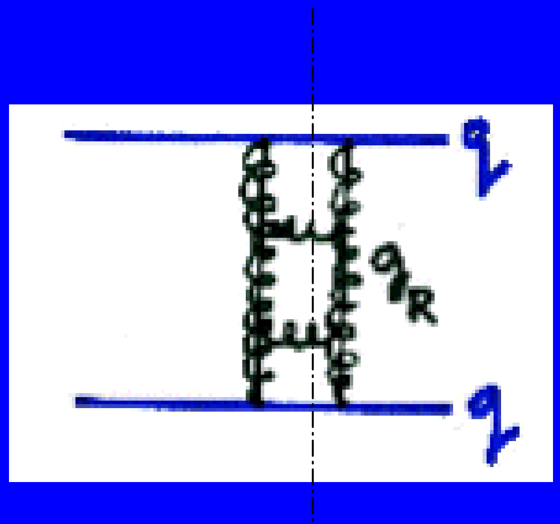
Ambitious attempt to calculate pomeron in QCD: **BFKL** pomeron
{Balitsky, Fadin, Kuraev & Lipatov}
"reggeized gluon ladder"



One g exchange between q (LO diagram)
not gauge invariant, therefore **"sick".**
Many can be summed → gauge invariant
→**reggeized gluon** g_R (still color octet)
Neutralize with two g_R/ladder
→ **BFKL pomeron.**

BFKL Pomeron

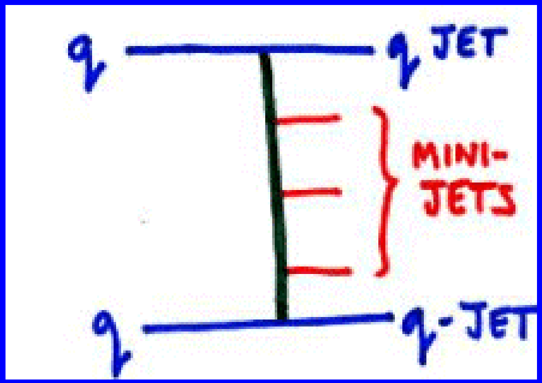
Changes qq & gg scattering
especially at large s, small t



cut

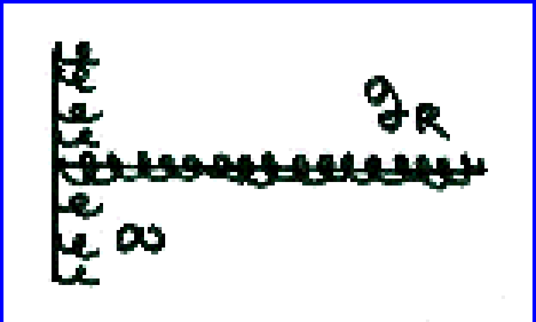
"Cut it" : remember el & tot?

n minijets in between forward jets



The White Pomeron

Alan White (ANL)



One reggeized gluon + sea of wee gluons
Asymptotic freedom → 16 color triplet q's
Only 6 known
AHA! 1 color sextet Q counts 5 x
{ud}+{cs}+{tb} + {UD} works!

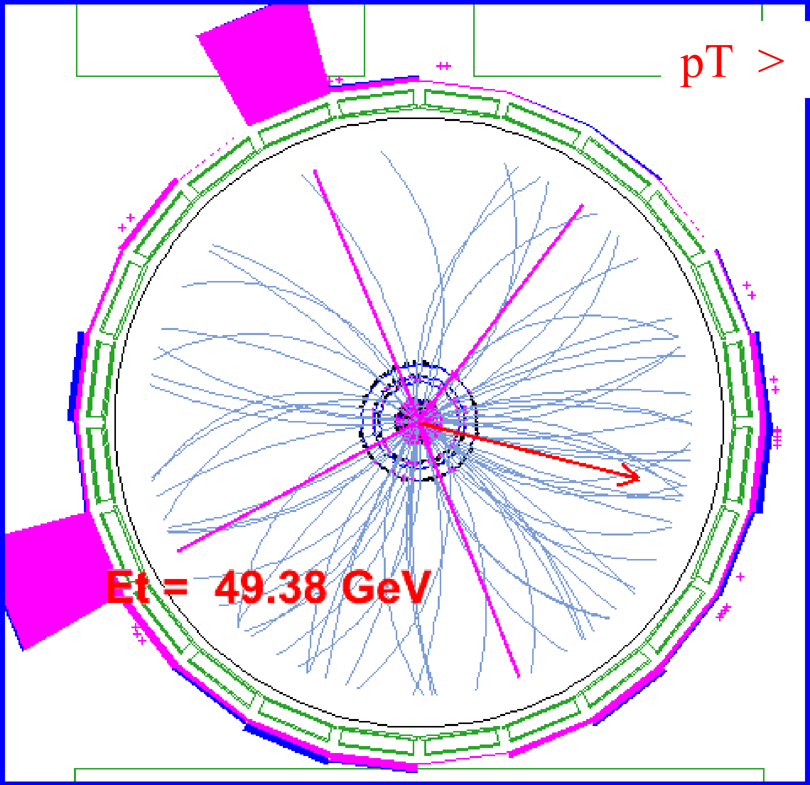
$\Pi = U\bar{D}$ etc,η_6 ....EWSB, role of Higgs

Can be dark matter (N = DDU ~ TeV)

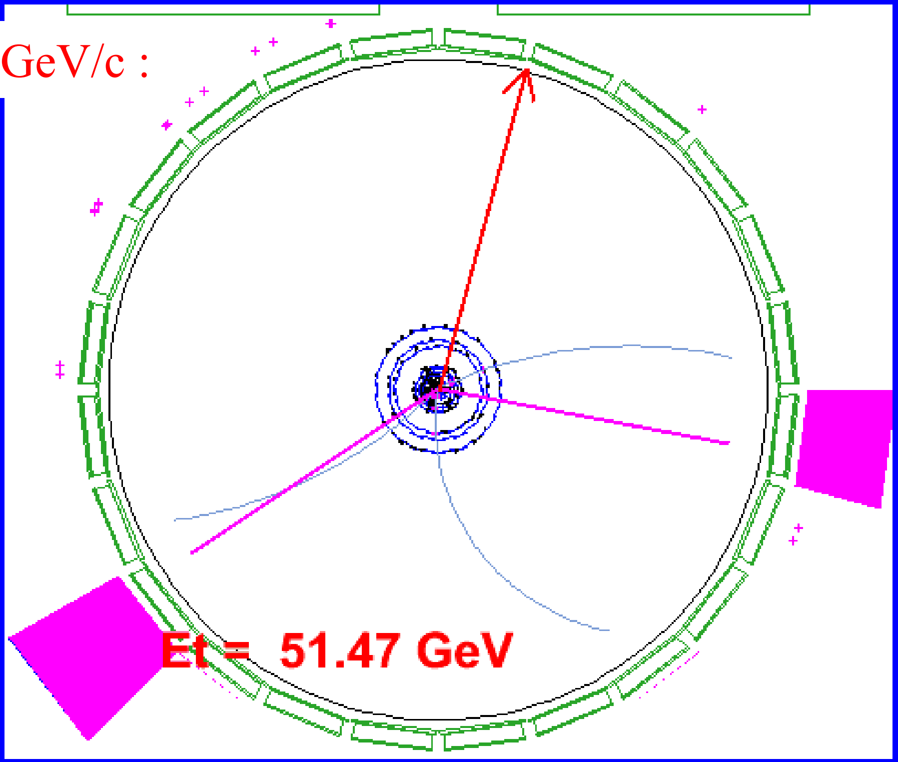
Pomeron couples strongly to WW through U,D loops

→Anomalous (quasi-diffractive) production of WW, ZZ (not WZ) production at LHC **(M(DPE) <~ 700 GeV)**
Probably not at Tevatron **(M(DPE) <~ 100 GeV)**, but look anyway.

Two interesting Run II events



pT > 0.4 GeV/c :



1) 147806 ev 1167222
Probable ZZ, 4e > 20 GeV.
Not in CDF-6920 because one e just fails ISO cut. Too tight for high n?
~ 70 tracks y < 1 : **34**

2) 167053 ev 12891960 ee MET (WW/ZZ)
One of 4 events in CDF-6920.
y < 1 : **2**
→ MP & CLC v.low activity

Fluctuation? High-b? MC + more data

Invitation to Join the Fun!

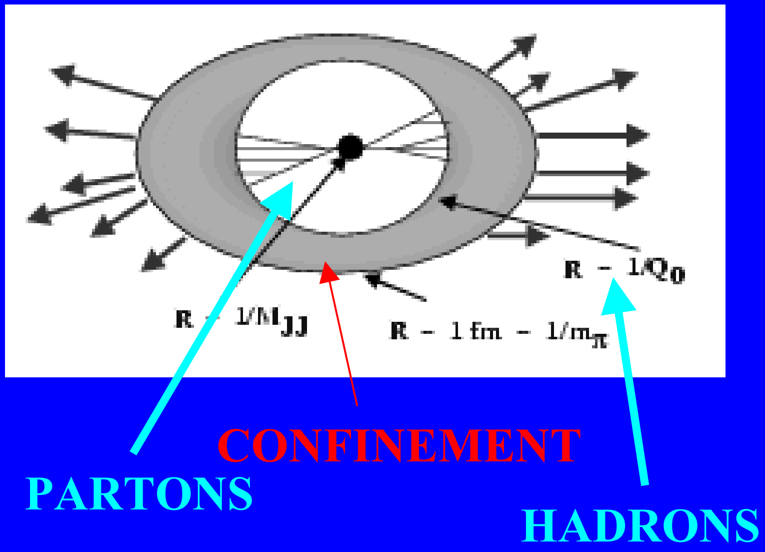
Rapidity gap physics is largely data-driven
Different processes test different aspects:

Jets, W, Z, γ, $\gamma\gamma$, $\chi_{c,b}$, J/ψ, Υ, b-hadrons, b-jets, etc

Typically 1-gap fraction ~ 1%, 2-gap fraction ~ 0.1%
So if you have a sample of > thousands of "anything"
interrogation of forward detectors (BSC, MP, CLC, (PLUG, RP))
can measure diffractive component.

Suggest consult with forward detector experts on gap definition
and what's being done:
e.g. Rockefeller group, Florida group, Angela Wyatt, Andrew Hamilton, MGA etc.

Final Remarks



Rapidity is a useful kinematic variable especially in interface between hard (partonic) and soft (hadronic) physics, diffraction

Total x-sn (mb) ~ 50 ND + 10 D + 20 EL

We do not understand Strong Interactions until we understand the 40% "controlled" by color singlet exchanges ... the pomeron.

Subject is "data-driven" and we are doing much (could do more!)