Hadronic Diffraction and Cosmic Rays

Mike Albrow, Fermilab

→ Basic Introduction to Hadronic Diffraction

→ Examples: ISR → HERA → Tevatron

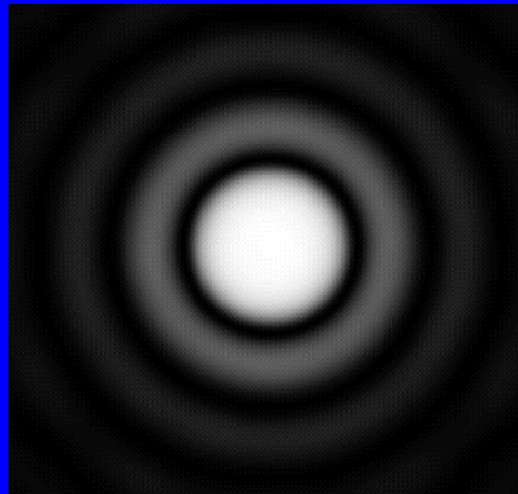
→ Forward Coverage of Experiments

→ Central Exclusive Production ($\pi^+\pi^-$ to W^+W^-)

→ LHC Experiments (CMS, TOTEM, ATLAS ...)

Diffraction: Optical and Particles

Light on a disc

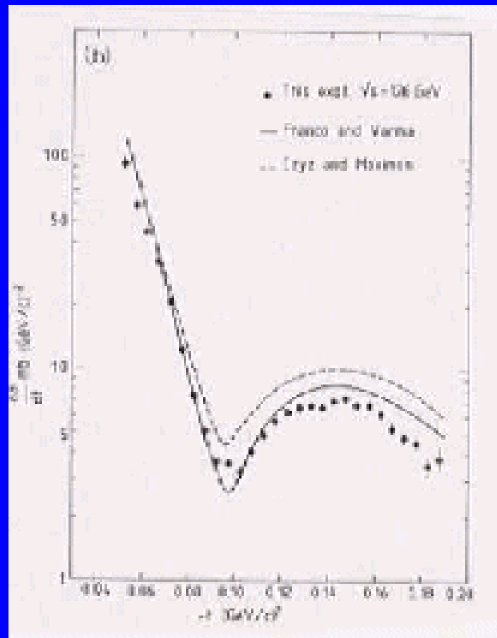


αα elastic scattering

$\mathrm{ISR}: \sqrt{s} = 126\ \mathrm{GeV}$

Diffraction minimum at
t = -0.1 GeV^2 → 5 mrad
target size ~ 1 fm

$$\frac{d\sigma}{dt}$$



$$-t \approx p_T^2 \approx p^2 (\sin\vartheta)^2$$

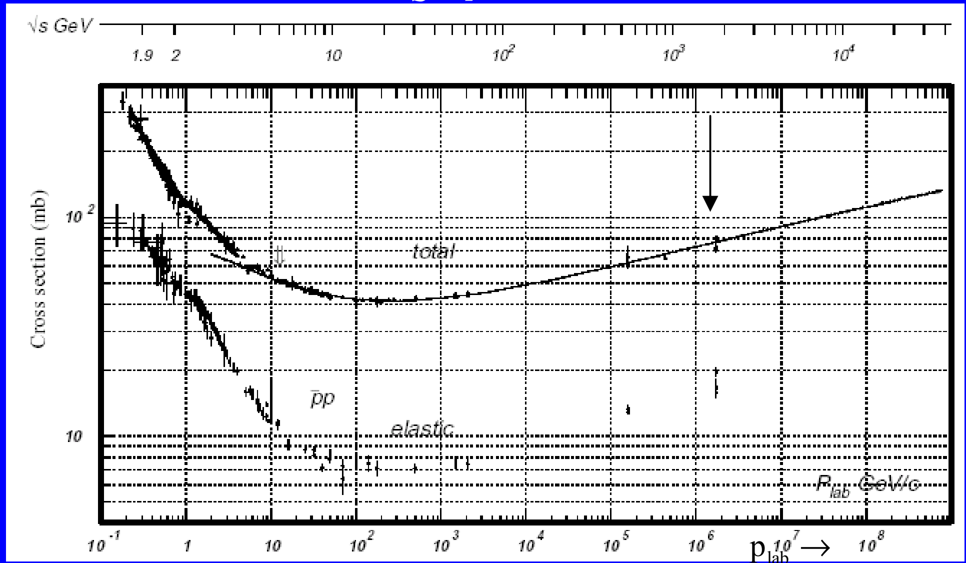
α α

α $\pi^+\pi^-$ α

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

$s \rightarrow$

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



$p_{lab} \rightarrow$

10^{18} eV

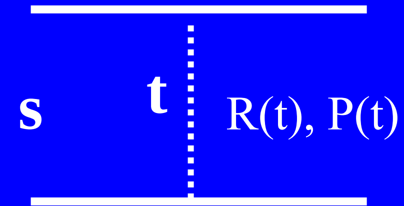
Two terms: $s^{\alpha_i(t=0)-1}$

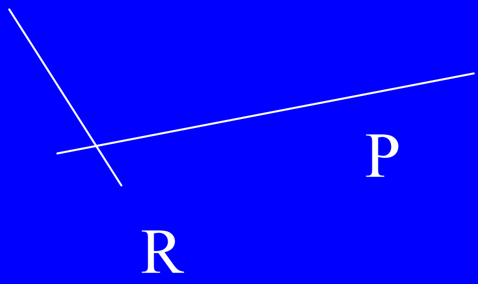
$\alpha_R(t=0) \approx 0.55 \Rightarrow s^{-0.45}$

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

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

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



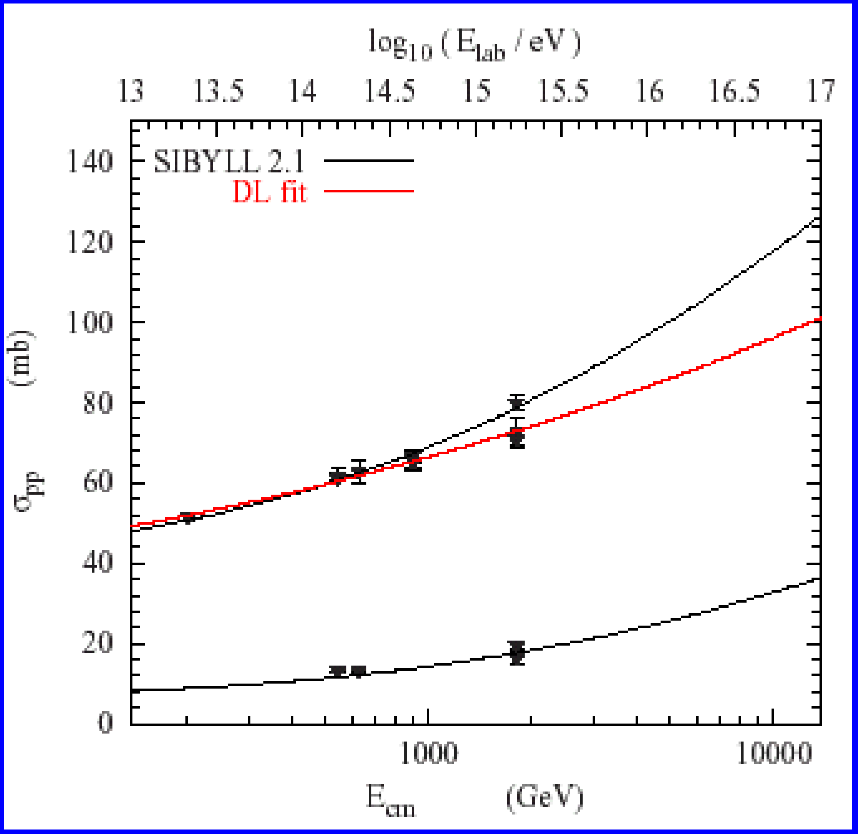


R (Reggeon) = sum of all allowed $q\bar{q}$ meson exchanges ρ, ω, ρ' etc

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

Behaviour of total cross section uncertain at HE

$\sqrt{s} = 14\text{TeV (LHC)} \equiv 10^{17}\text{ eV (pp)}$



Unfortunately TeV(1800) data are inconsistent:

$\text{CDF}: \sigma_T = 80.26 \pm 2.25\text{ mb}$

$\text{E710}: \sigma_T = 72.81 \pm 3.10\text{ mb}$

$\text{E811}: \sigma_T = 71.71 \pm 2.02\text{ mb}$

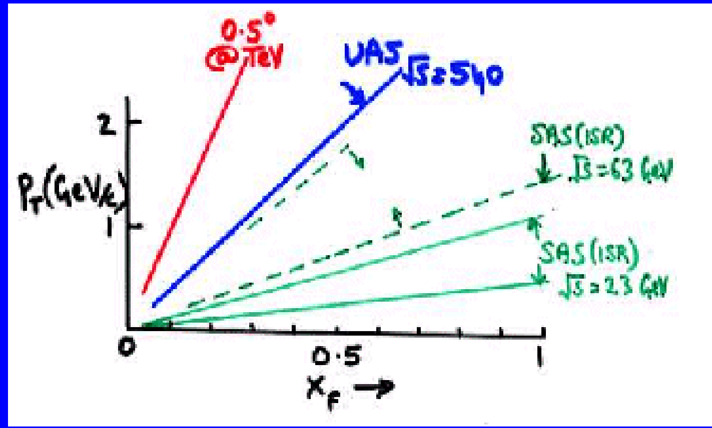
No plans to repeat σ_T

~ 4% measurement of σ_{inel} might be done (?)

with s-scan 500 – 2000 GeV (?)

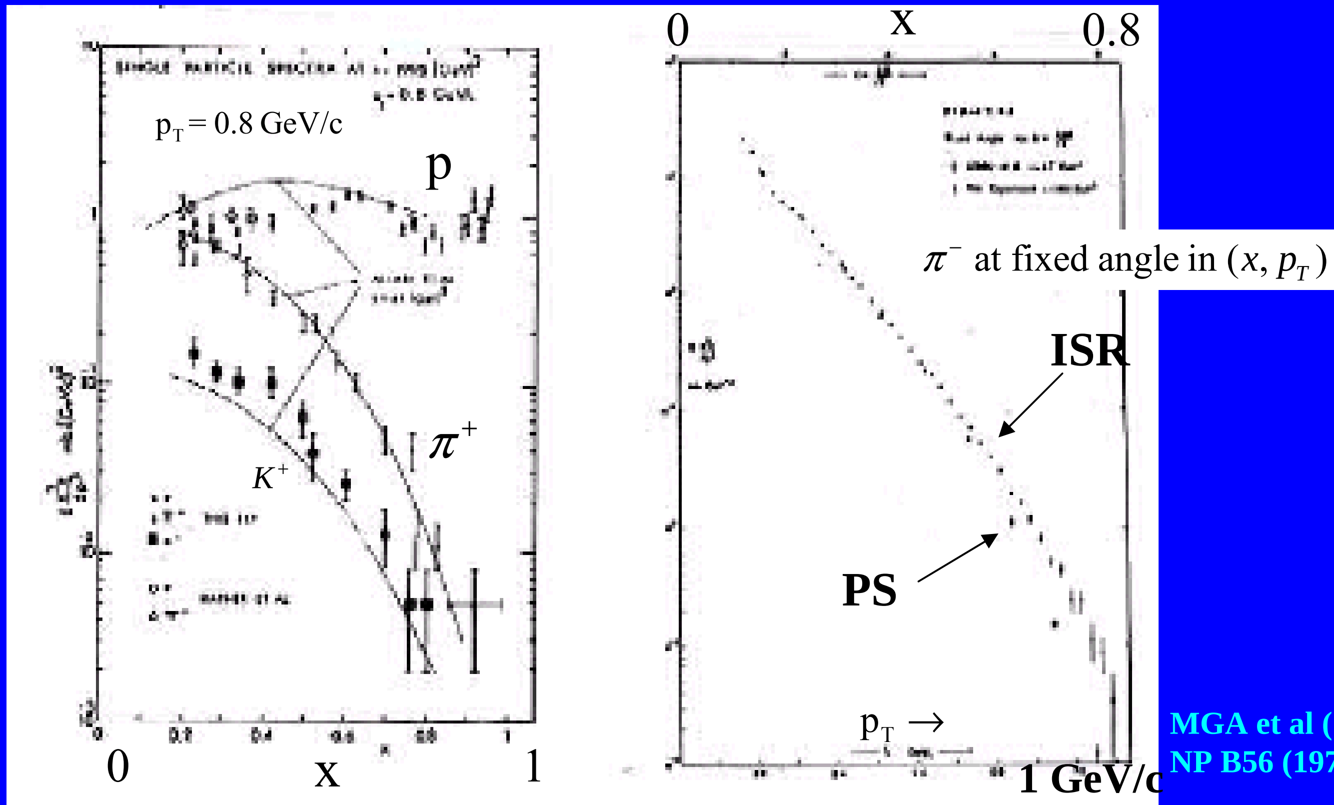
Particle Production: Medium x_F at Low p_T

Coverage ~ non-existent above ISR
except for leading proton (Roman pots)



Small Angle Spectrometer at ISR:

Feynman scaling
1st hint of quasi-elastic proton peak

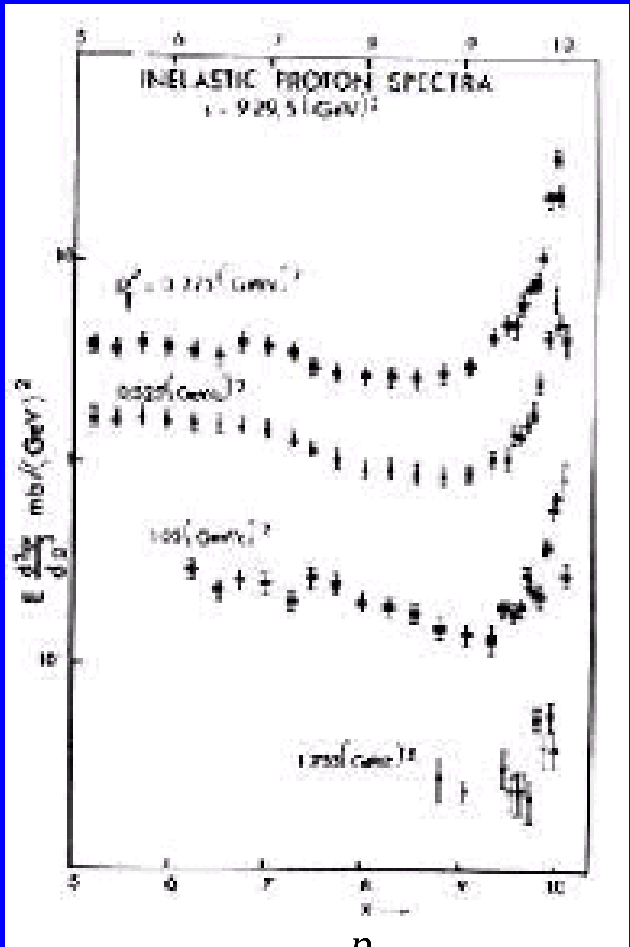


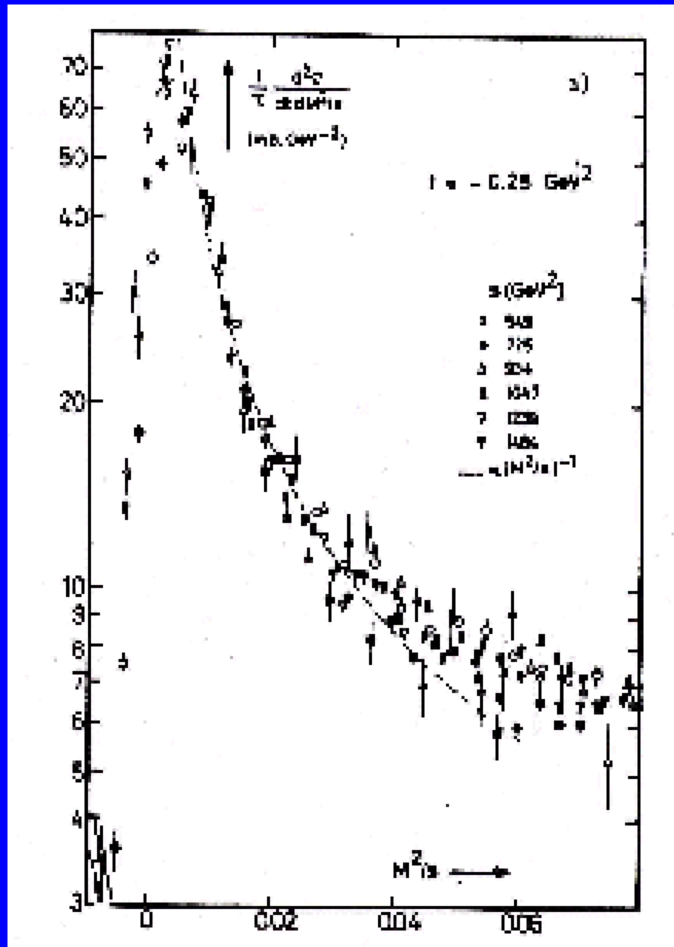
MGA et al (CHLM)
NP B51 (1973) 388

MGA et al (CHLM)
NP B56 (1973) 333

Single Diffractive Excitation

Pre-ISR (PS, AGS) SDE to M ~ 1.5 GeV (resonance region)
ISR at sqrt(s) = 63 GeV, M(max) ~ 14 GeV





$$x_{Feynman} = \frac{p_L}{p_{beam}}$$

High Mass Diffraction at CERN ISR

M.G.Albrow, ... N.A.McCubbin, ... et al., NP B108 (1976) p.1

CERN-Holland-Manchester-Lancaster (CHLM)

High-x peak in p-spectra measured

CHLM: 9 $\sqrt{s}$ values:

$\frac{1}{M^2}$ behaviour

$\frac{M^2}{s}$ scaling

Exchange as in elastic scattering (pomeron)

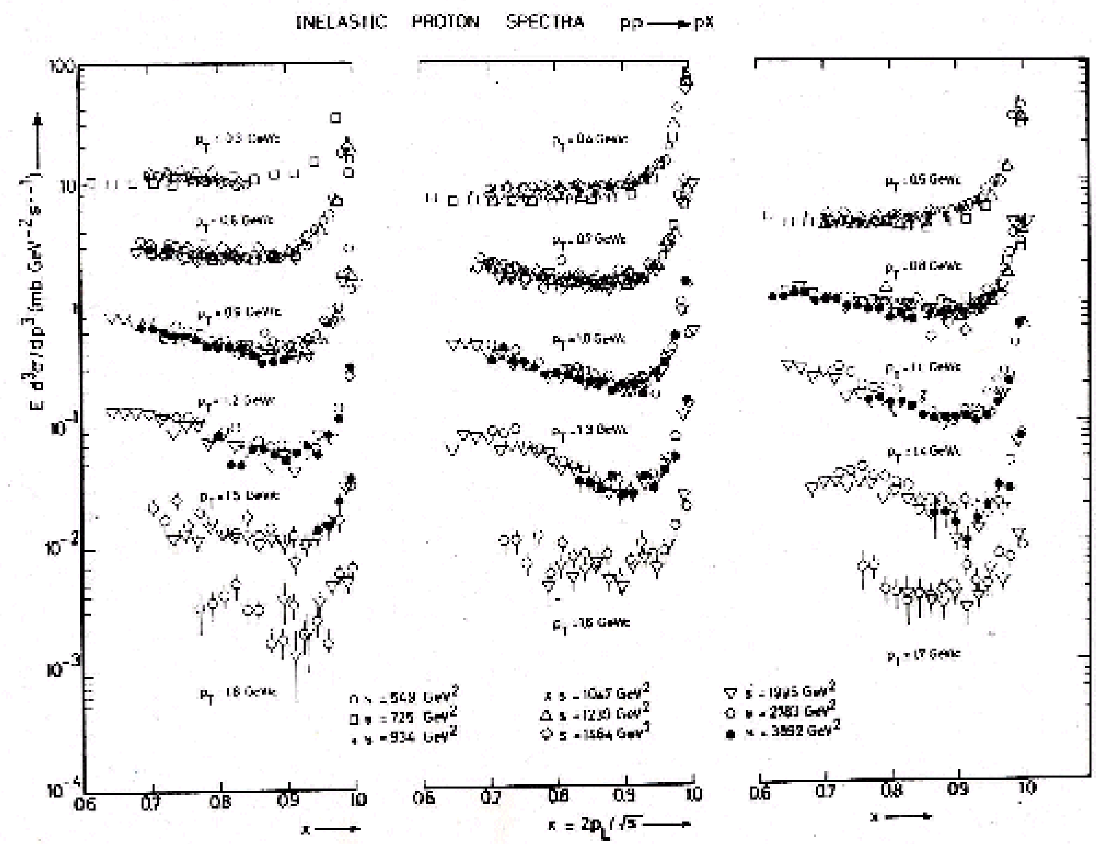
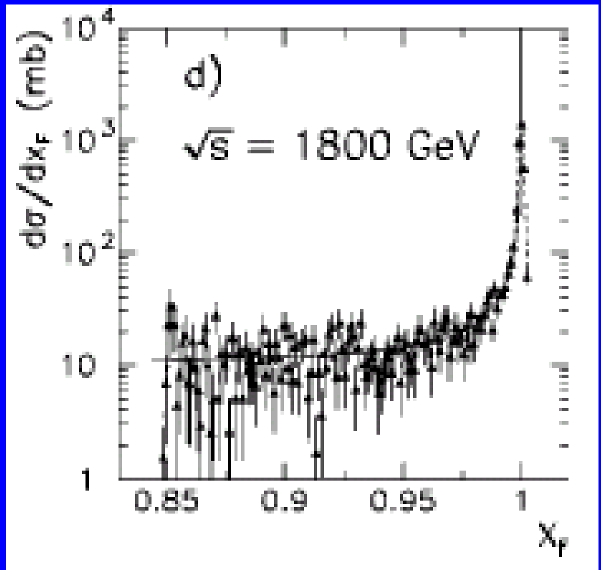


Fig. 6. (a) The invariant inelastic cross section at fixed values of p_T as a function of x and s.

Single Diffractive Excitation of High Masses

High-x proton peak continues to high energies (~ scaling)

CDF data

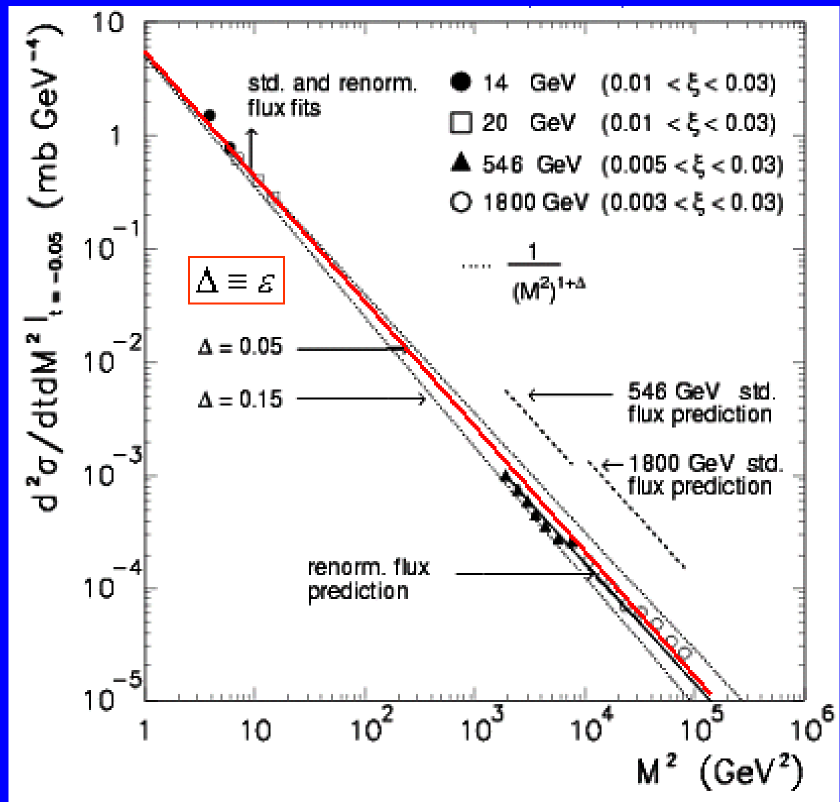


$\leftarrow \frac{M^2}{s}$

Spectrum ~ $\frac{1}{M^2}$

renormalization

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



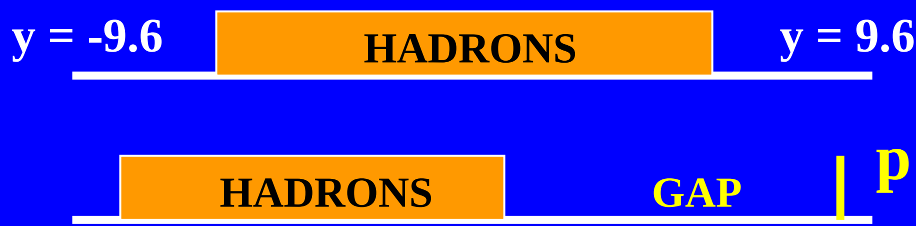
K.Goulianos & J.Montanha
PRD **59** (1999) 114017

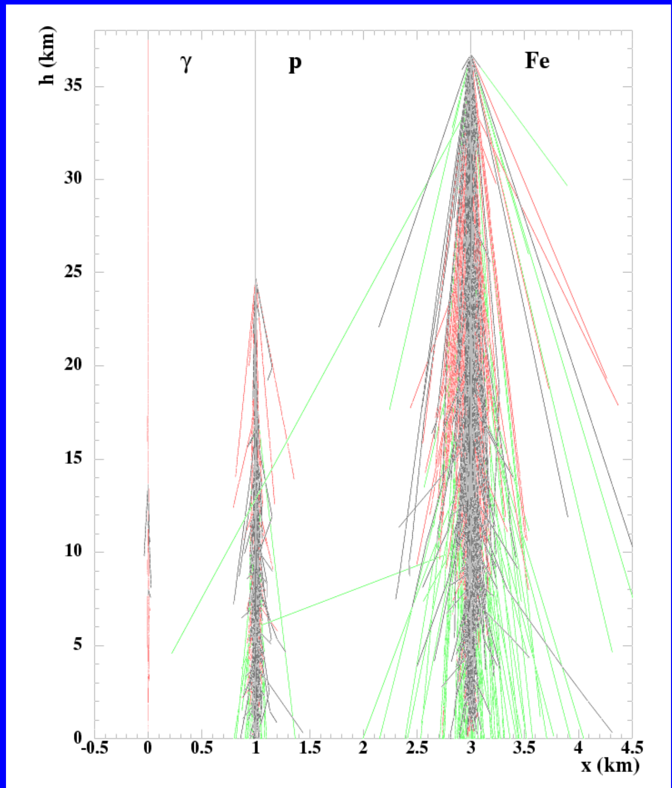
Characteristics of VHE Hadronic Interactions

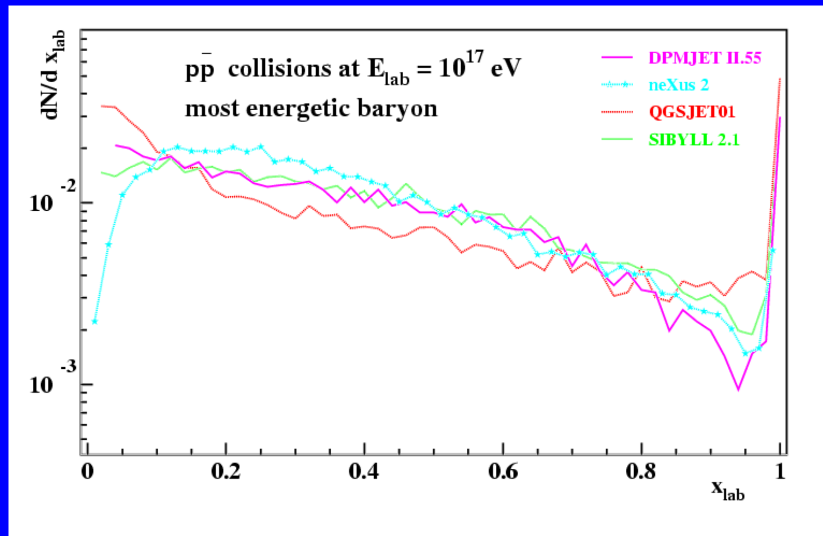
Diffractive: can have leading, low inelasticity hadron. Affects shower development

At LHC ($\equiv 10^{17}$ eV)

$$y_{max} - y_{min} = 2 \ln \frac{\sqrt{s}}{m_p} = 19.2$$







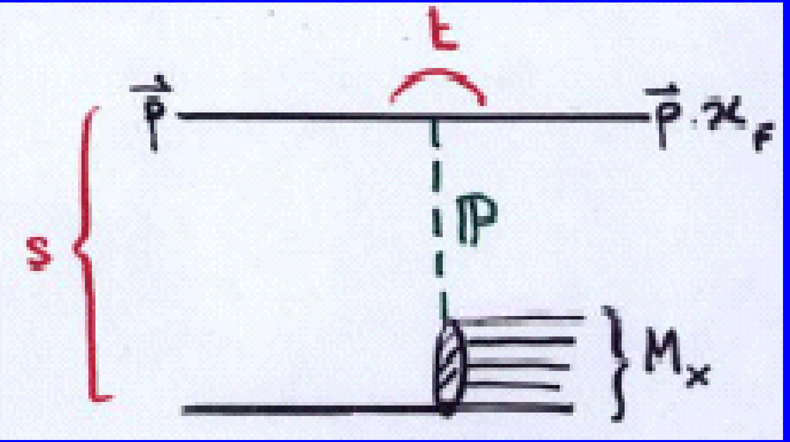
Single Diffractive Excitation

x_F = Feynman $x = p_L / p_{BEAM}$

$\therefore \xi$ = fractional momentum loss

Coherence condition:

$$\delta\phi_{\text{I-O}} = \frac{\delta\lambda}{\lambda} \cdot \frac{2R}{\gamma} < \frac{\lambda}{2\pi} \Rightarrow \xi = 1 - x_F <\sim 0.05$$



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

$(3 = -\ln 0.05)$

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

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

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

"Proton" scatters coherently:

No pion emission, no break-up,

no change of quantum numbers,

isolation in phase space (Δy >~ 3) and real space

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

Approximate Range of Diffractive Masses (Rule of Thumb)

$$\text{Diffraction to } \frac{M^2}{s} \sim 0.05 \text{ (RoT)}$$

$$\text{i.e. } \frac{M}{\sqrt{s}} \sim 0.22 \text{ \& if scaling continues}$$

AGS/CERN-PS $M \rightarrow 1.6$ GeV

ISR $M \rightarrow 14$ GeV

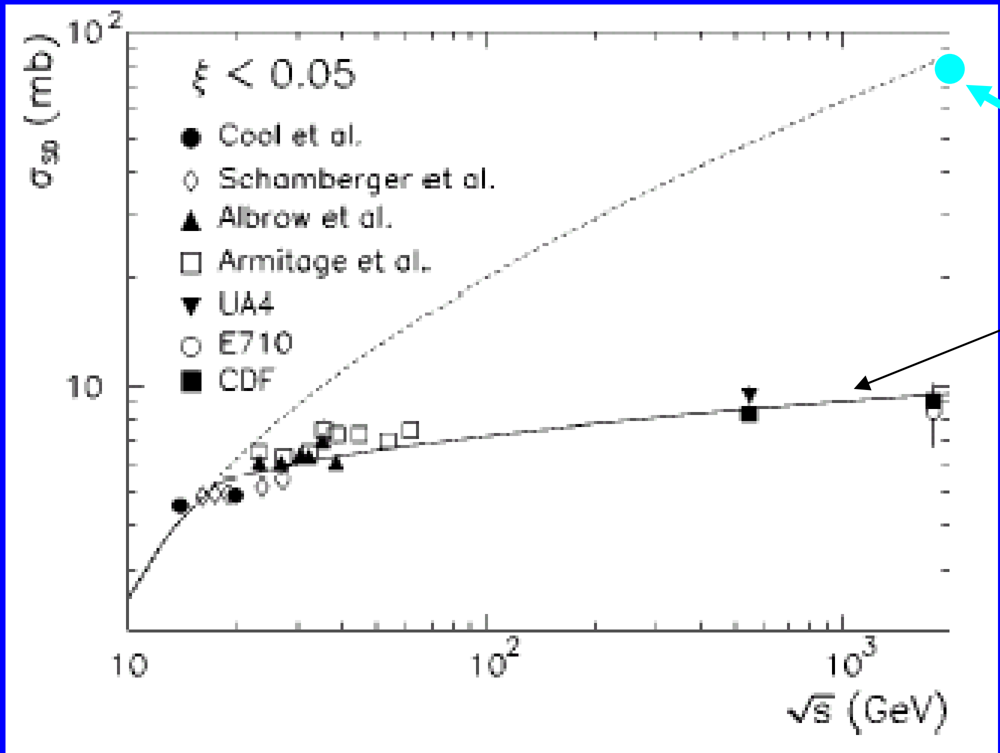
TeV $M \rightarrow 430$ GeV

LHC $M \rightarrow 3$ TeV

UHECR $\rightarrow 100$ TeV

Single Diffractive Cross Section (integrated)

$$\frac{d^2\sigma_{SD}}{dt.dM_X^2} = \frac{s_0}{s^2}\sum_{i,j,k} G_{ijk}(t)\left(\frac{s}{M_X^2}\right)^{\alpha_i(t)+\alpha_j(t)}\left(\frac{M_X^2}{s_0}\right)^{\alpha_k(0)}\cos(\Delta\phi)$$



"Classical" triple Regge

Total cross section

Modified TR (Goulianos)

About 15% of total cross section is single diffractive from ISR to Tevatron

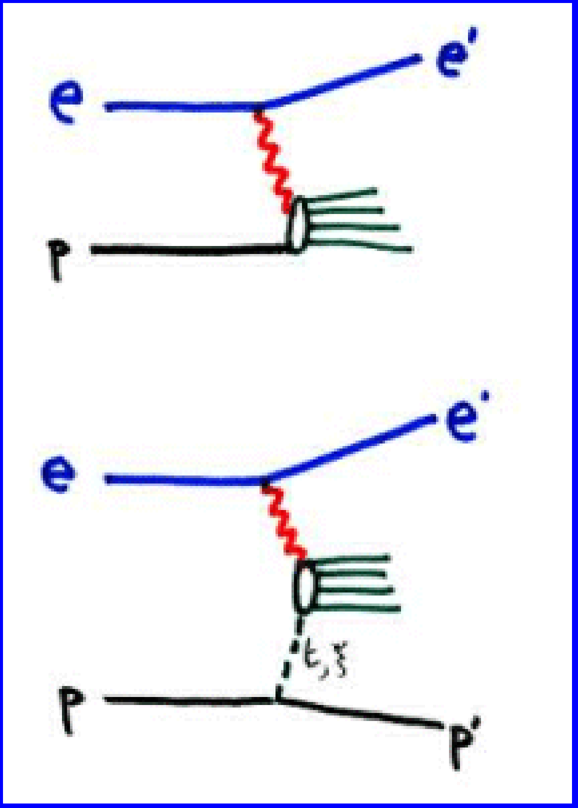
HERA (ep) Deep Inelastic Scattering & Diffractive DIS

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**

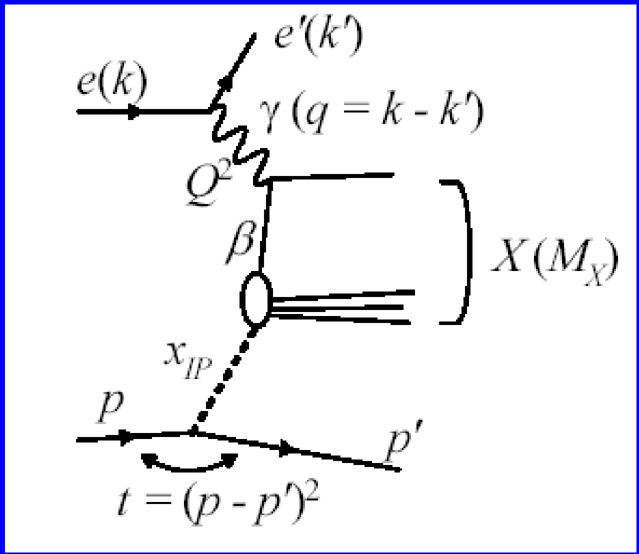


$$\beta = \frac{x_{Bj}}{\xi}$$

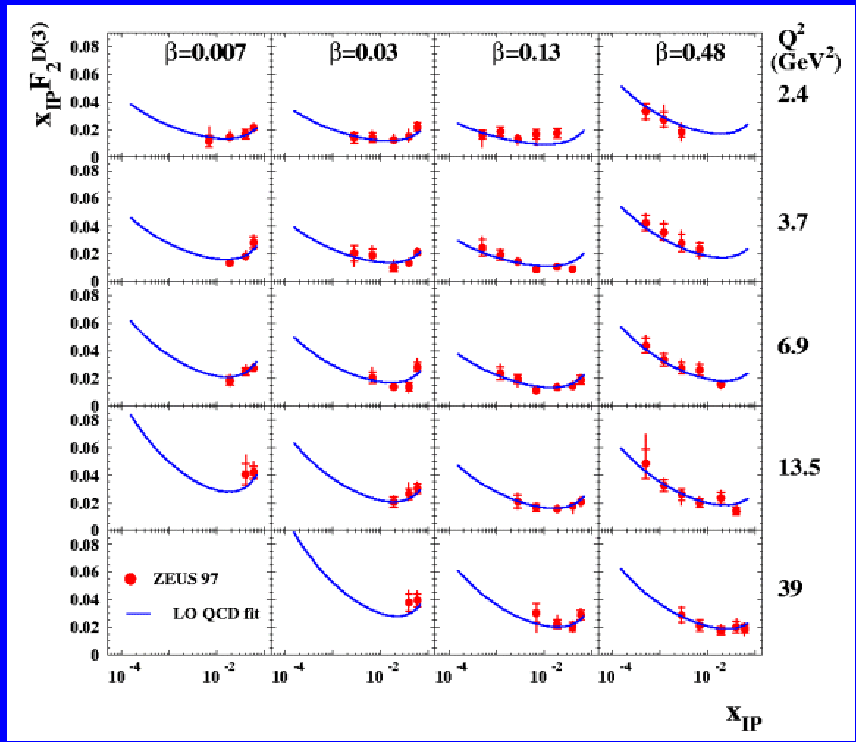
... would be fraction of pomeron momentum carried by struck parton

Diffraction at HERA (cont.)

Diffractive peak of high-x protons leading a large rapidity gap was found at HERA **(predicted by Donnachie and Landshoff)**



ZEUS



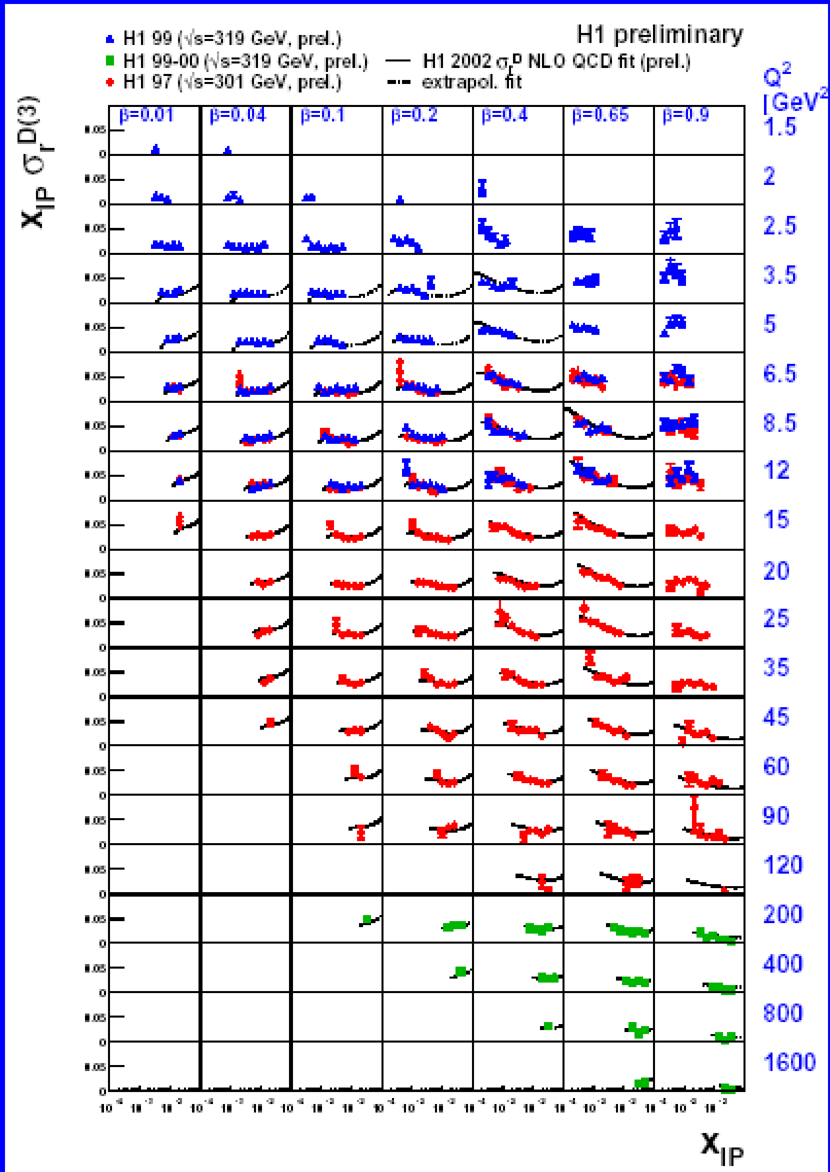
($\leftarrow$ "x_F" goes this way)

"Probing pomeron with photons"

Measure 4-dim cross section

$$\frac{d\sigma}{dM_x.dQ^2.dt.d\xi} \quad (\xi = x_{IP})$$

H1



"All science is either Physics or stamp collecting."

E. Rutherford

How can pomeron (vacuum quantum number exchange) be described/calculated in QCD?
Does it have a parton content?

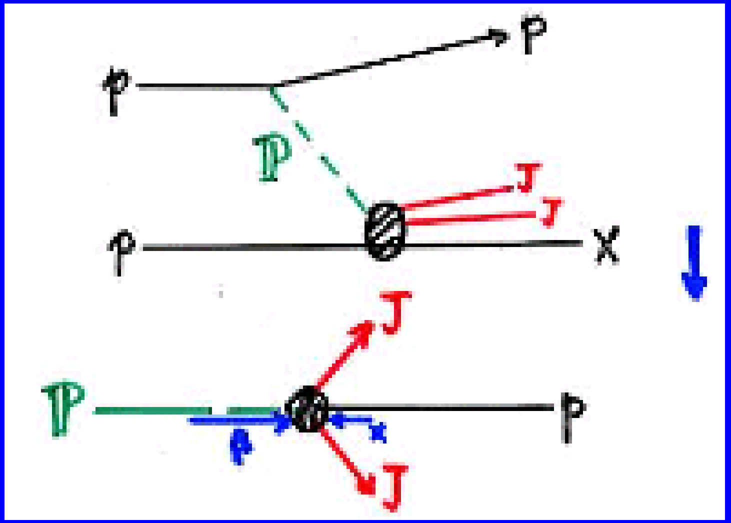
It is non-perturbative, Q^2 small, α_S large, so hard to calculate

Careful : misleading ?

We can probe it experimentally:

With photon in ep, DIS
With hard final states in pp

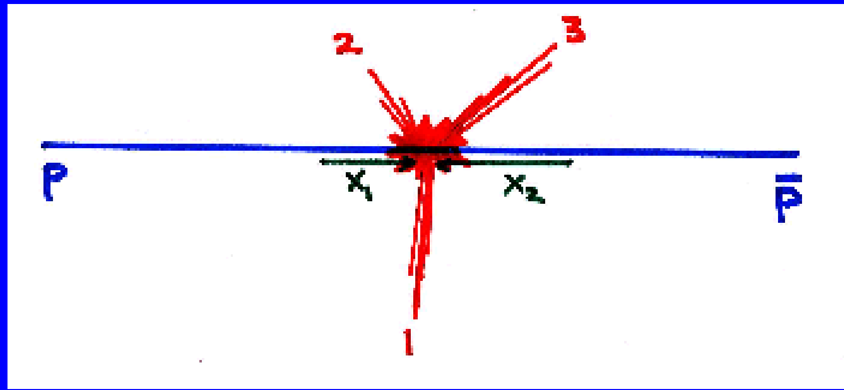
P + p → jets, W/Z, c and b etc.



Jets' Rapidity and E_T → Bjorken x's

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

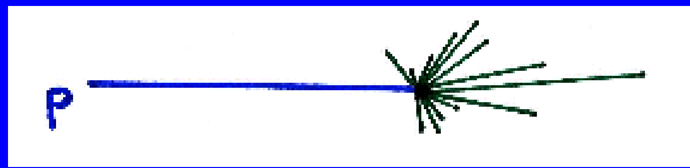
$$x_{1,2} = \frac{1}{\sqrt{s}} \sum_{\text{jets}} E_T e^{\pm y} \approx \frac{1}{\sqrt{s}} \sum_{\text{jets}} E_T e^{\pm \eta}$$



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

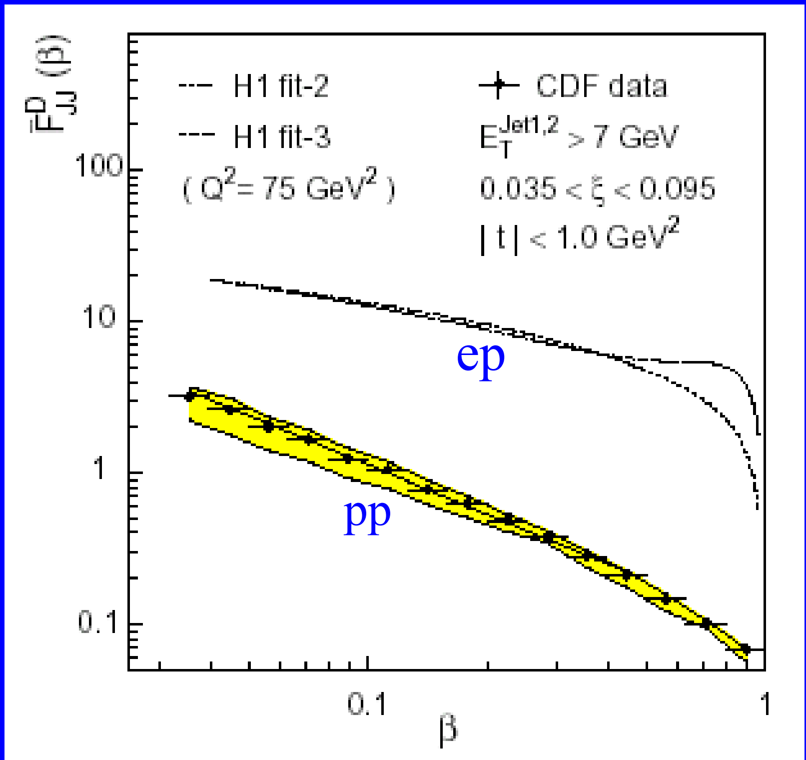
$$\xi = \frac{1}{\sqrt{s}} \sum_{\text{particles}} E_T^i \, e^{\pm y\,(\eta)}$$

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



Diffractive Structure Functions / pdfs

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



CDF: measured with jets

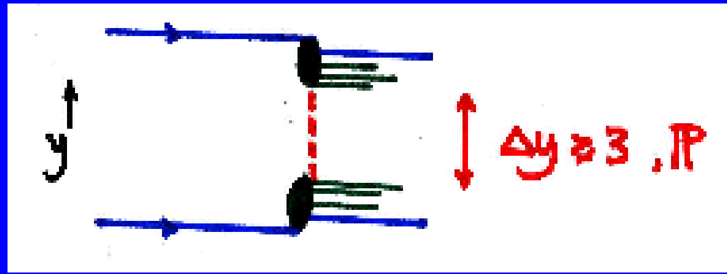
$$F_{JJ}(x) = x\,\{g(x) + \frac{4}{9}\sum[q(x)+\bar{q}(x)]\}$$

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

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

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

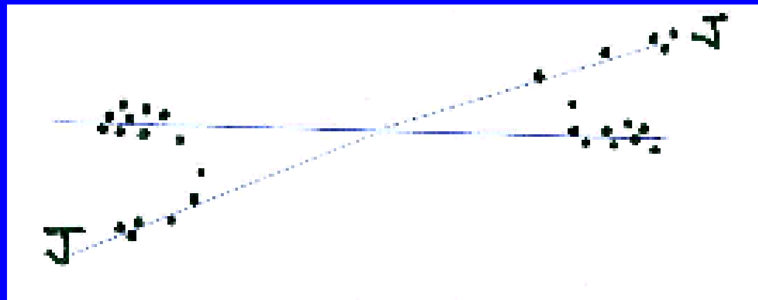
Double Diffractive Dissociation with Jets



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

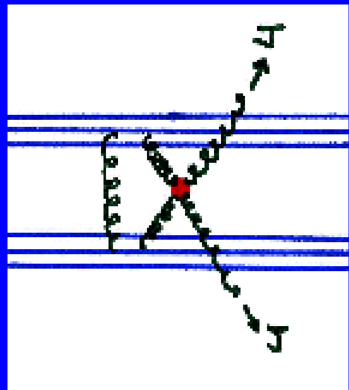
But CDF and D0 **discovered JGJ = Jet-Gap-Jet**
4-momentum transfer-squared, -t > 1000 GeV^2

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



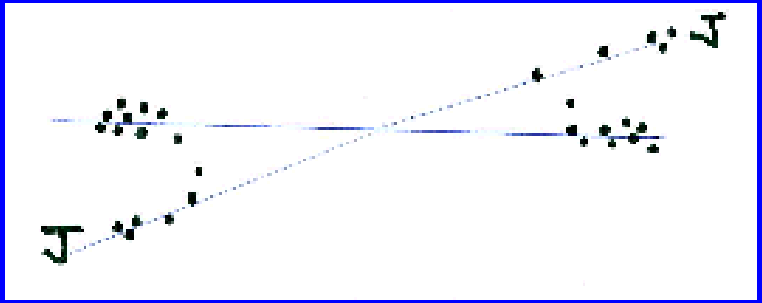
Hard scatter – high Q2 – short time
& rap gap – soft process – long time

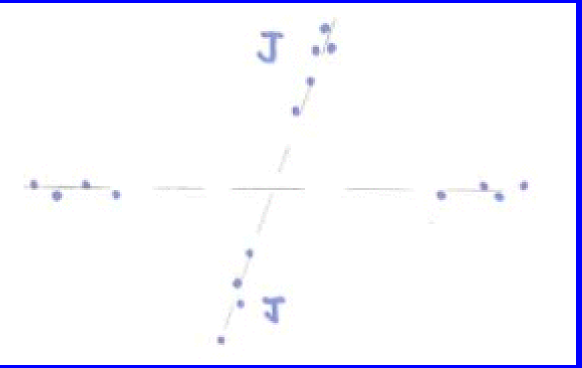
Soft Color Interactions (SCI) make gaps:
Central gap → jets forward
or forward gaps → jets central



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

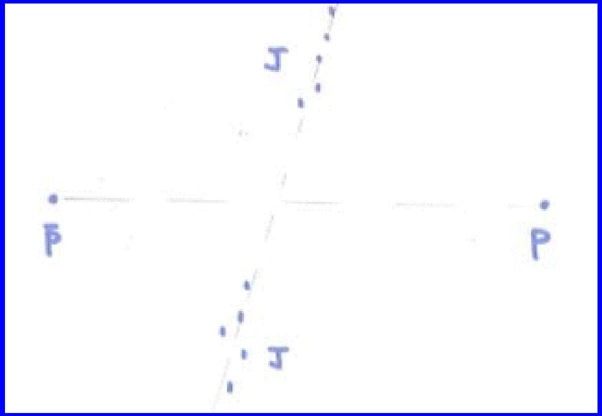
Soft – hard interplay

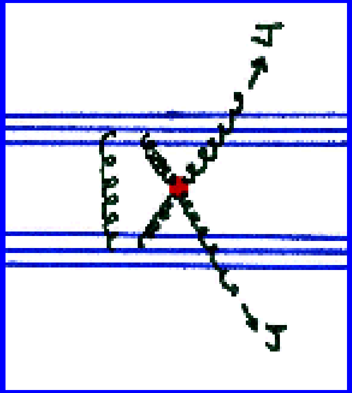




Same diagram with large angle scatter
→ jets central

Forward "clusters"
can even be single protons

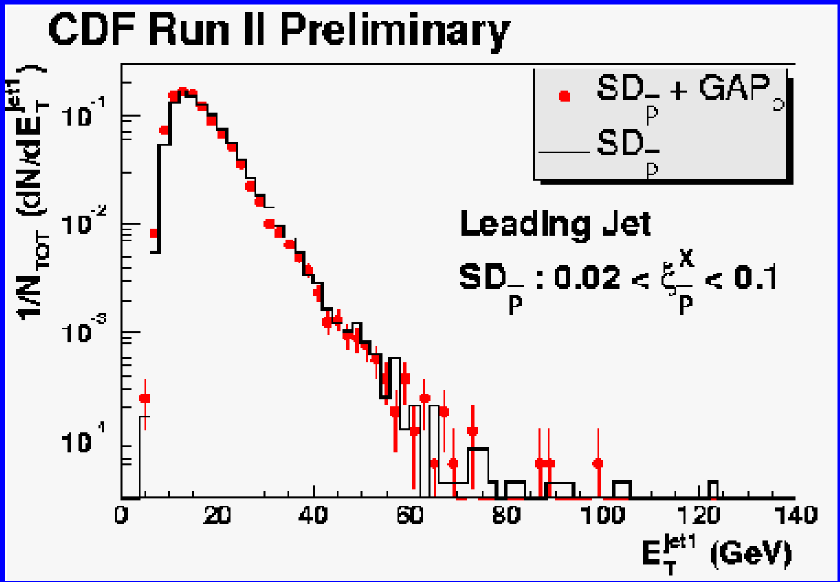


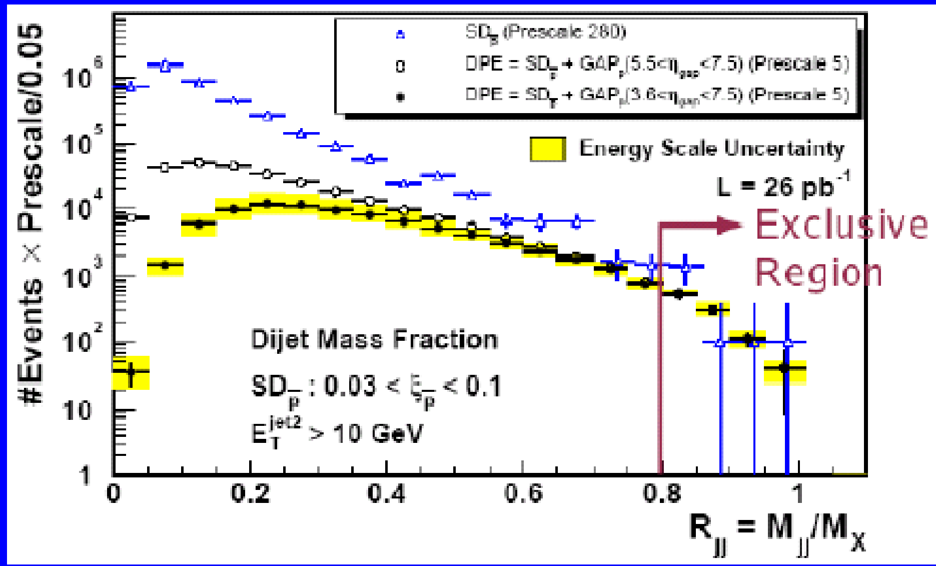


Central di-jet production by DPE

Exclusive Dijets?

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





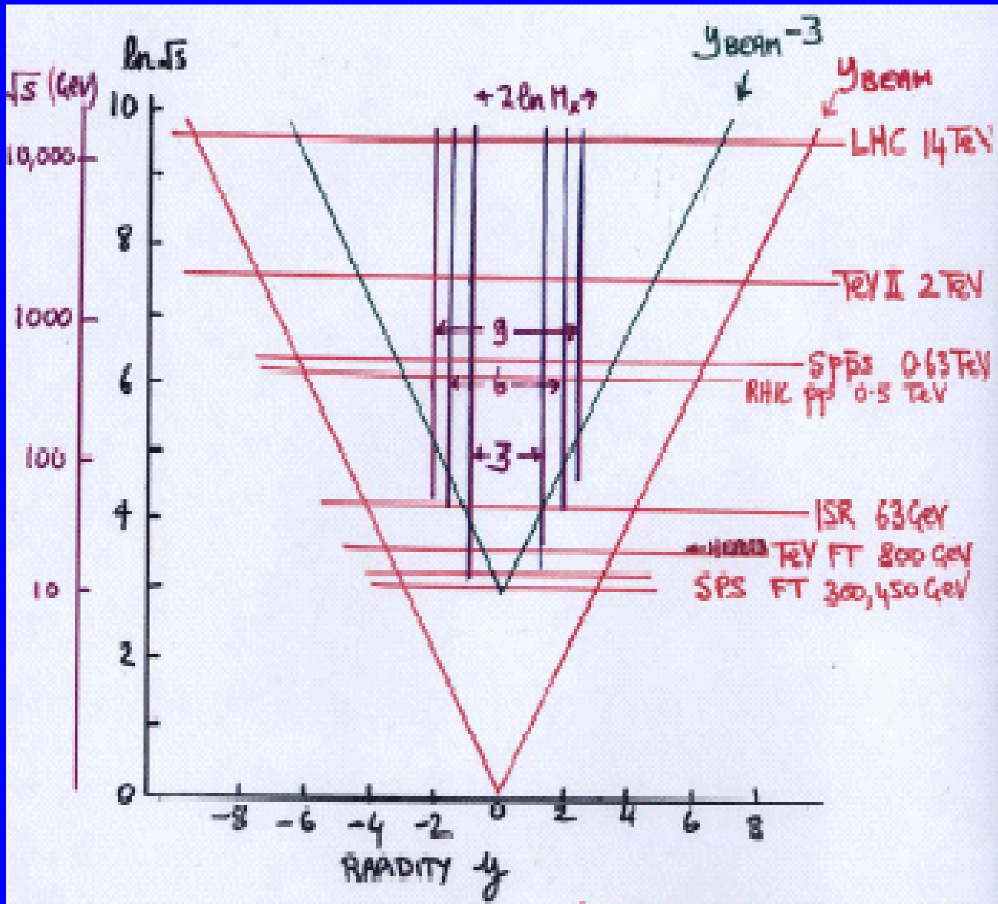
So far: upper limit ~ theoretical expectations
Expect enhancement rather than peak
They should all be gluon jets !

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
UHECR(10^20) ~ 20 TeV



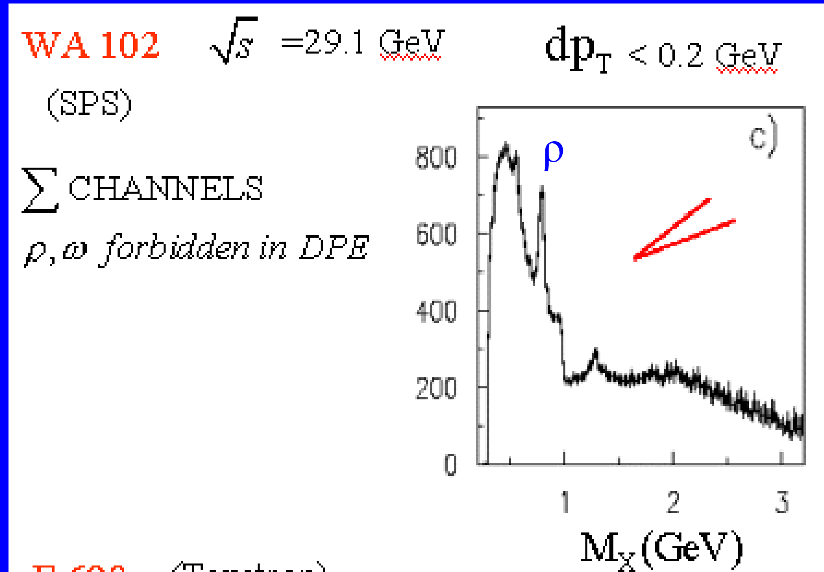
Tevatron/RHIC ideal
for low mass DPE
... and into jet domain.
LHC well into top, W, Z domain
UHECR ...??

Low Mass Central Exclusive Production

$pp \rightarrow p \quad X \quad p$
X all measured

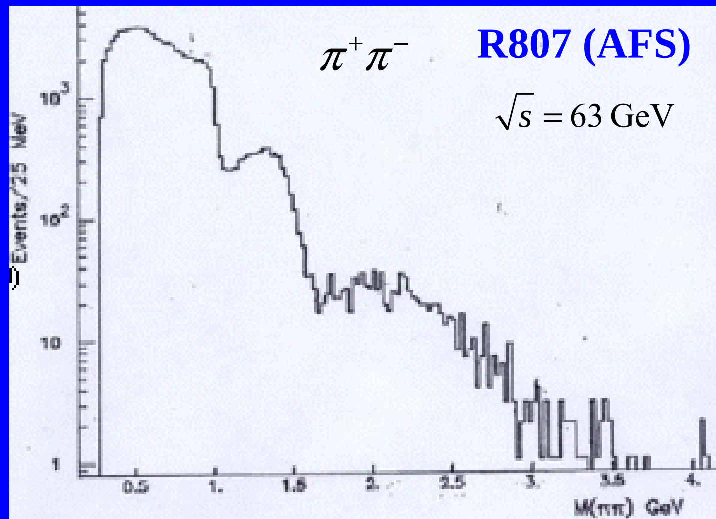
ρ

Resonances, but too low s
for DPE dominance.



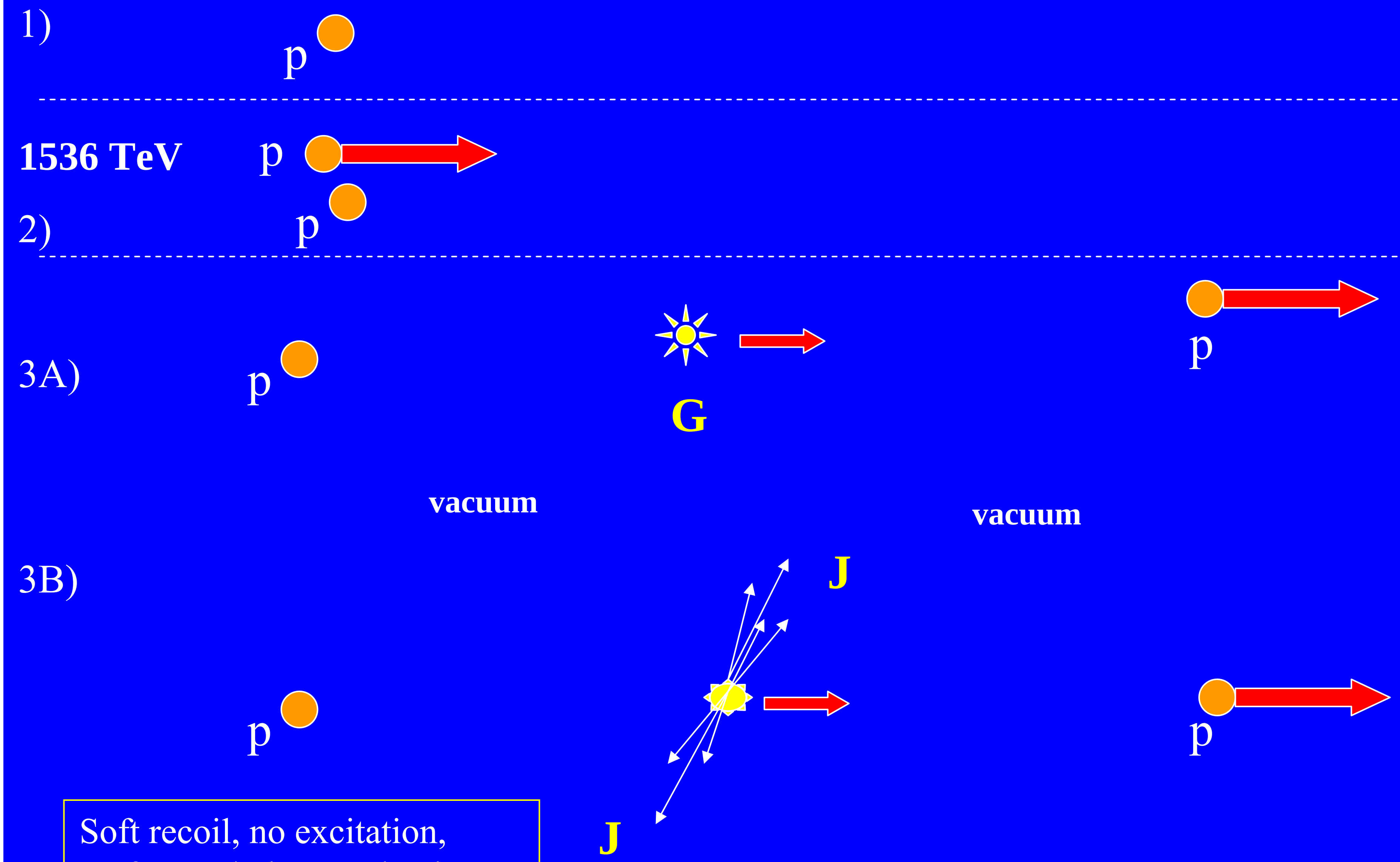
ISR

No ρ



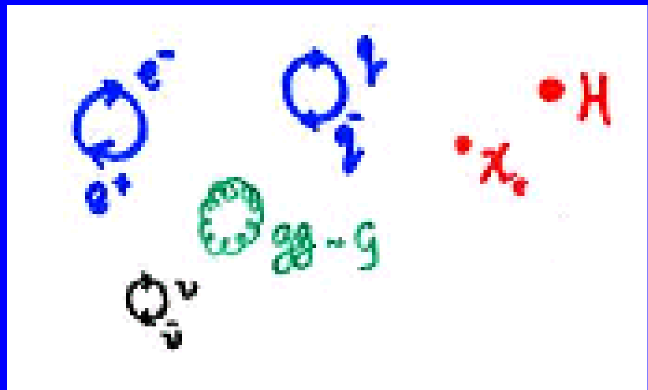
Structures not well understood
above f(980).
Not studied at higher sqrt(s)

Vacuum Excitation **(Tevatron but Lab frame)**



Soft recoil, no excitation,
no forward pion production, ...

$$\text{Vacuum} = \sum_{\text{all}} \text{Physics}$$



Any state with vacuum quantum numbers can be made real by injecting energy: particle collision.

"Vacuum Excitation"

Can even have pp → p   H   p

Central Exclusive Production

gg fusion: main channel for H production.

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

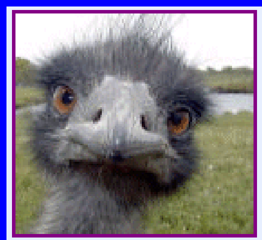
$$p\,p \rightarrow p \quad + \quad H \quad + \quad p$$

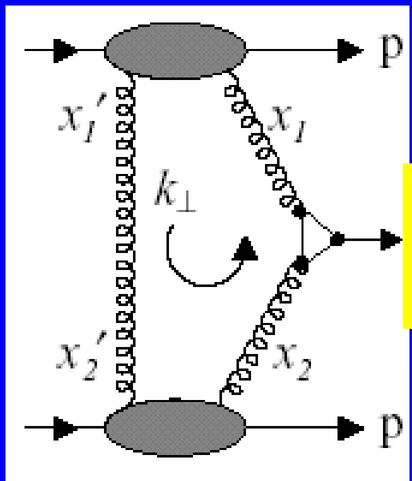
Theoretical uncertainties in cross section, involving skewed gluon distributions, gluon k_T, gluon radiation, Sudakov ff etc.
→Probably $\sigma(SMH) \sim 0.2$ fb at Tevatron, not detectable, but may be possible at LHC (higher L and $\sigma \sim 3$ fb?)

Nothing else on emu vertex!

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

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





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.

Pomeron in Perturbative QCD

The pomeron in QCD is a challenge!

In all soft processes α_S large, no convergence

Techniques such as Regge theory ... relation to QCD ???

BFKL pomeron (Balitsky, Fadin, Kuraev & Lipatov)

LO diagram for qq → qq by one gluon exchange: not gauge invariant.

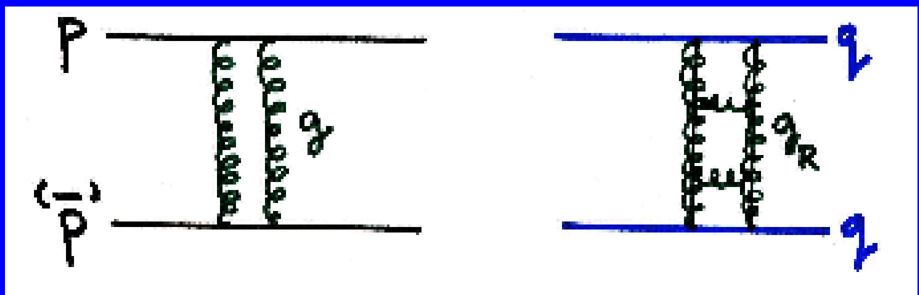
Need to sum all diagrams with gluon quantum numbers

→ "reggeized gluon" $A \propto s^{\alpha(t)}$

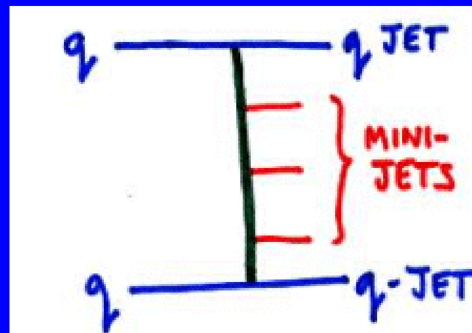
BFKL pomeron = 2 reggeized gluons in ladder

Experimental (& theoretical) situation unclear.

Mini-jets between jets

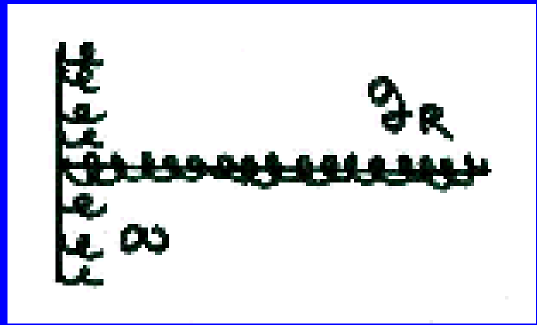


Change in qq scattering



The White Pomeron and Color Sextet Quarks

Alan White (ANL) **hep-ph/0412062**



Asymptotic Freedom is saturated in ARW's Critical Pomeron theory:
→ 16 color triplet quark q flavors. We know only 6.
(Higher) Color Sextet Quarks Q count 5 x q: so two Q's {U,D} will saturate.

color triplets			color sextets
u	c	t	U
d	s	b	D

+ $L\ \nu_6$? ← **WIMP**

Local plateau in α_s

Color Sextet Quarks and Hadrons

Q's have 0 current mass, EW scale constituent mass.
Stronger color charge than q.
Electric charges like $\overline{q}$ → Can form "SuperHadrons":

$$P_6 = \{UUD\} ; N_6 = \{UDD\}$$

STABLE

Dark Matter?

SIMP at EWK scale, WIMP at low Q^2
In UHE Cosmic rays (AUGER)?

$$\text{Hadrons}: Q\bar{Q} \Rightarrow \{\Pi^-\Pi^0\Pi^+\} \quad \eta_6$$

$\{\Pi^+\Pi^0\Pi^-\}$ are composite zero-helicity components of $\{W^- Z^0 W^+\}$

(Get "eaten" by massless $\{W^- Z^0 W^+\}$)

η_6 plays role of Higgs, EW symmetry breaking

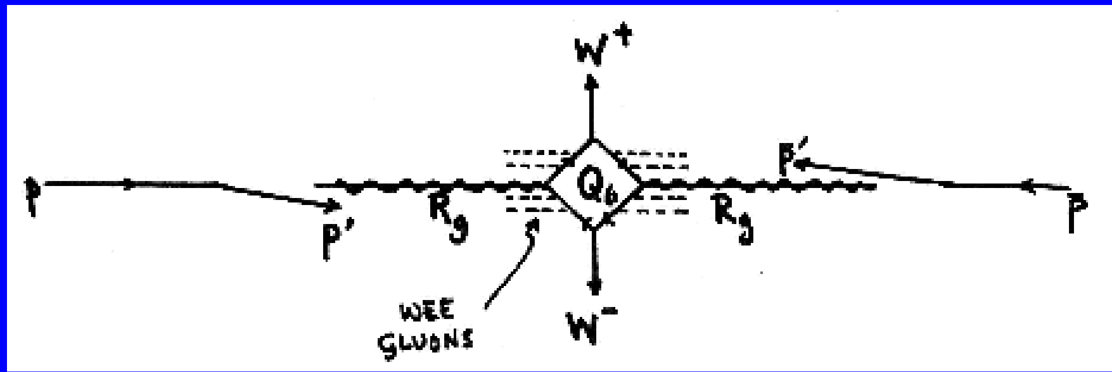
There is no fundamental Higgs Boson in this theory!

(η_6 has very different properties)

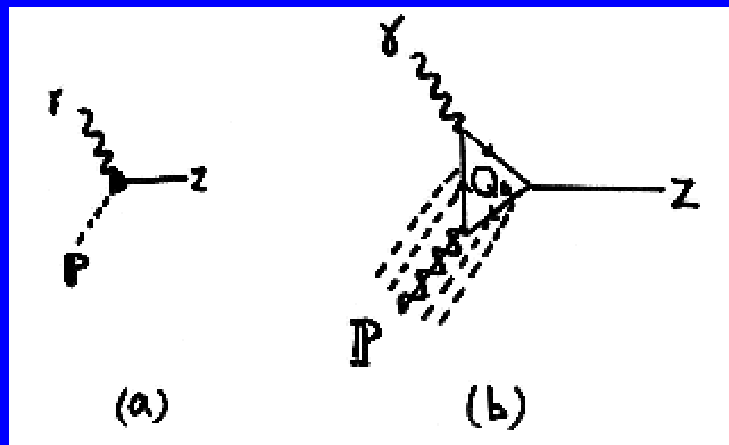
Once above ElectroWeak scale, should have prolific production of W's and Z's .... at UHE Cosmic Ray energies they are almost like pions! Auger project should see this (how?). CR energies will be underestimated, perhaps by big factor! Perhaps we glimpse that?

Double Pomeron → W+W- via Q6 Loop

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

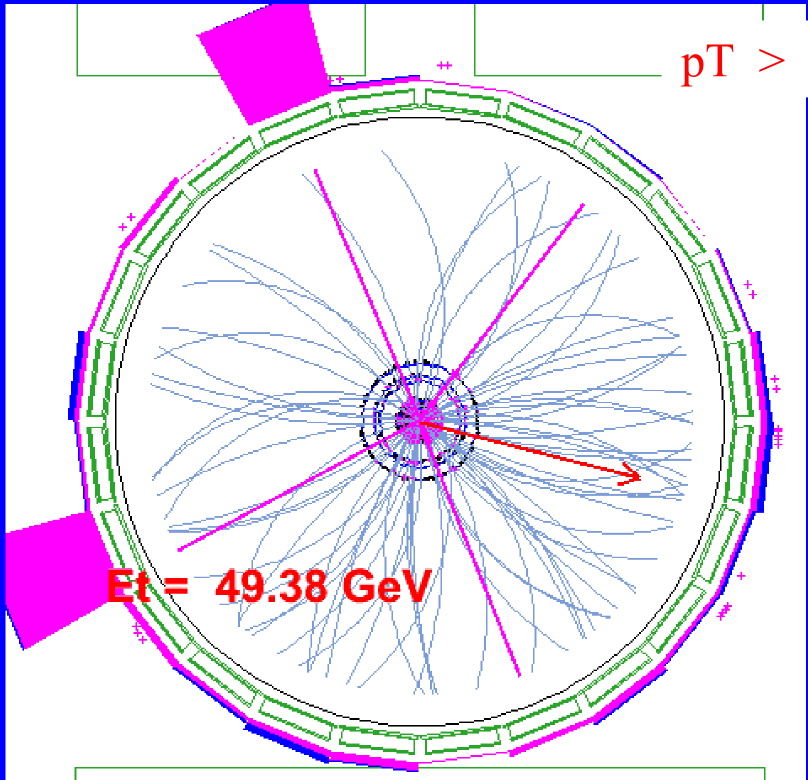


Photon-Pomeron-Z vertex via Q6 loop

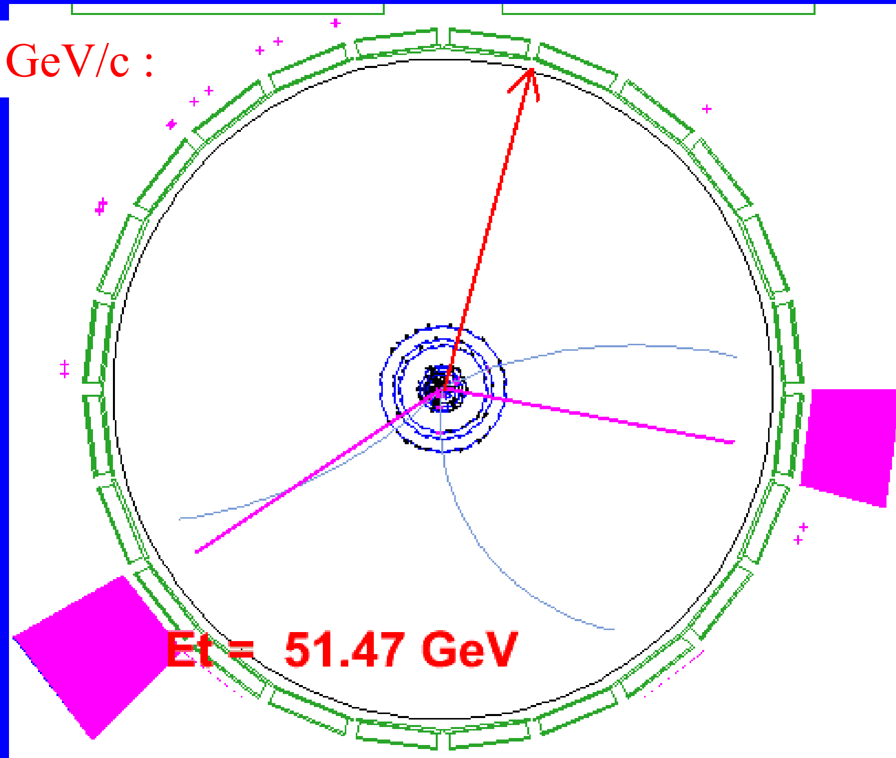


→ep
(eg LC+p (Tev,HERA,LHC)) could be *very* interesting!

Two interesting Run II CDF events (2 / ~ 20)



pT > 0.4 GeV/c :



1) 147806 ev 1167222
Probable ZZ, 4e > 20 GeV.
Not in PRL(s) 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 17 events in PRL(s)
y < 1 : **2**
→ forward MP & CLC v.low activity

Fluctuation? High-b? MC + more data

Is there any evidence for the Color Sextet Quark theory?

...or something unusual happening around this energy?

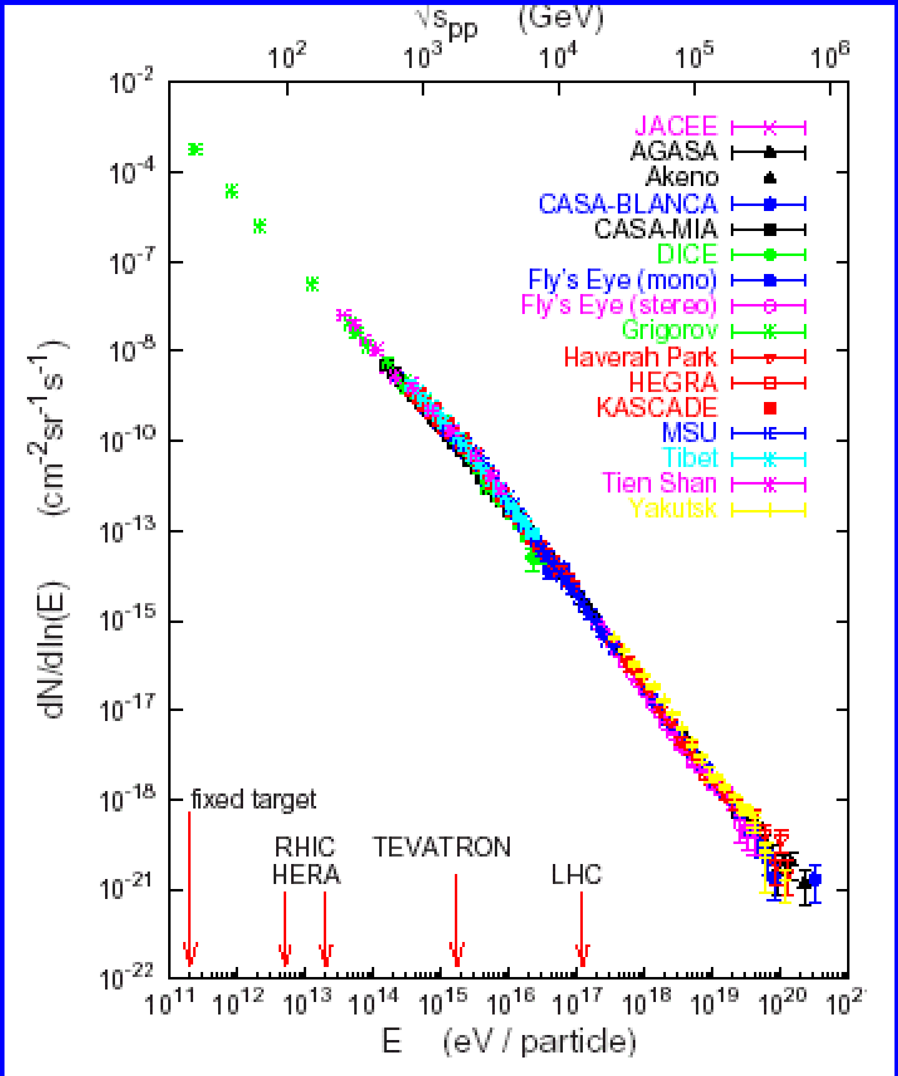
1) Knee in cosmic ray spectrum?

2) Large excess of high ET dijets (cores) in cosmic ray events and (?) CDF High ET jet excess → anomalous appearance of α_S

3) Dark Matter: evidence for some heavy neutral stable particles

.... but probably will have to wait for LHC for proper test.

Cosmic Ray Spectrum

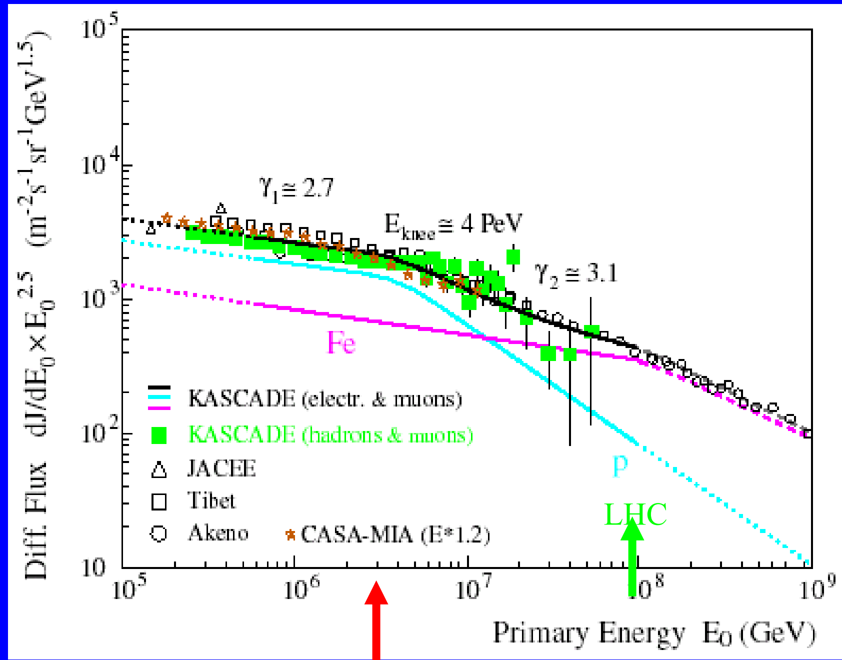


Slope change ("knee") between Tevatron & LHC

Cosmic Ray Spectrum

From M.Boratav and A.Watson
hep-ph/0009469

Region of the "knee"



$$E_0 \sim 3.10^6 \text{ GeV} \Rightarrow \sqrt{s} = 2.5 \text{ TeV}$$

In ARW theory W's and Z's start to be strongly pair produced and more of the interaction energy goes into neutrinos.
Also transverse profile broader than in SM.
Hence incoming energy underestimated (by Standard Models)
Hence spectrum seems to steepen. For Fe happens 56 x higher than for p

Z.Cao, L.K.Ding, Q.Q.Zhu and Y.D.He PRD56 (1997) 7361

Cosmic ray showers in large emulsion chambers on mountains.

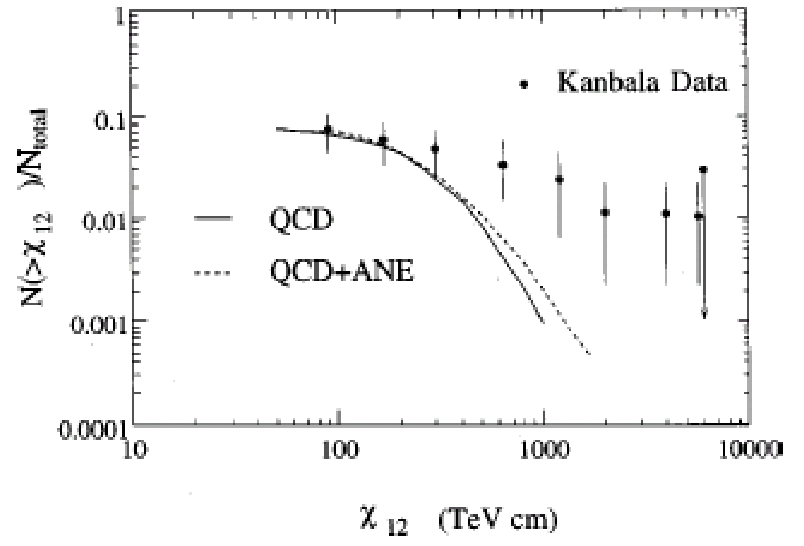
Above $\sqrt{s} \sim 5$ TeV

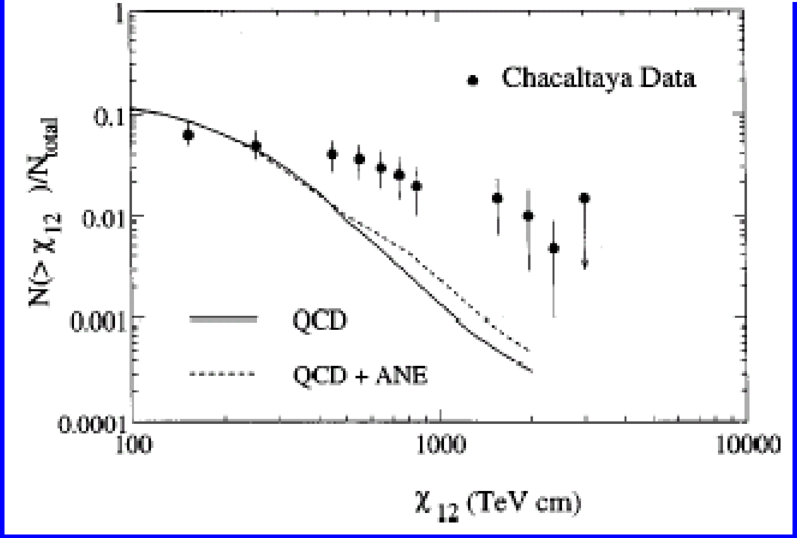
QCD MC simulation tuned to FT and Collider data (including SppS and CDF)

Select two high ET jets ("cores")

Large excess over QCD seen at large $E_T \times R_{12}$

Local plateau in α_s **? W/Z jets?**



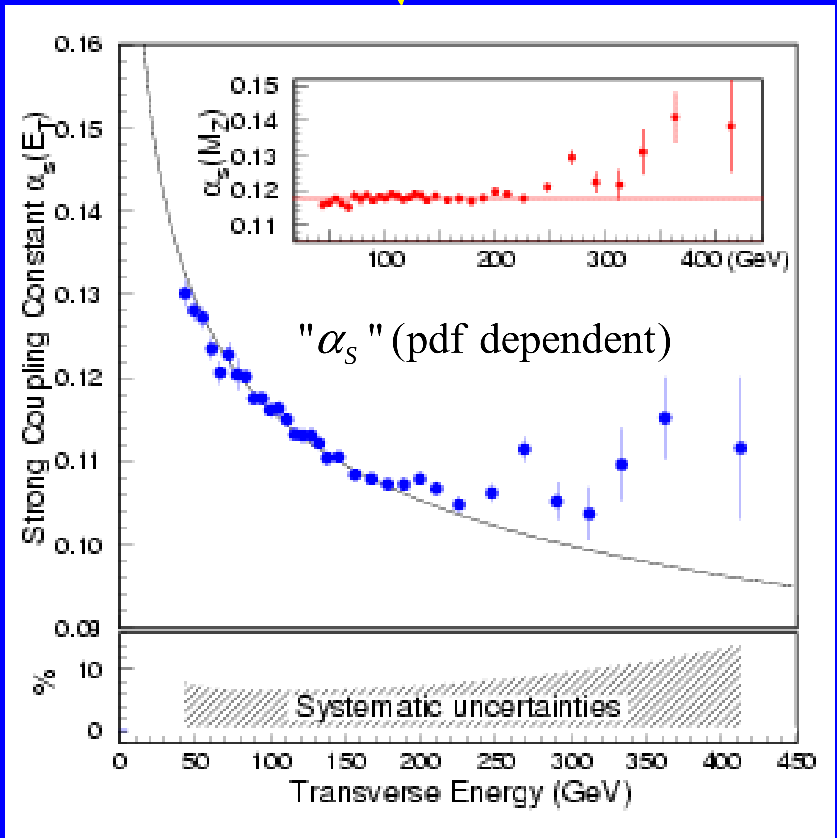


CDF High E_T Jet Excess (?)

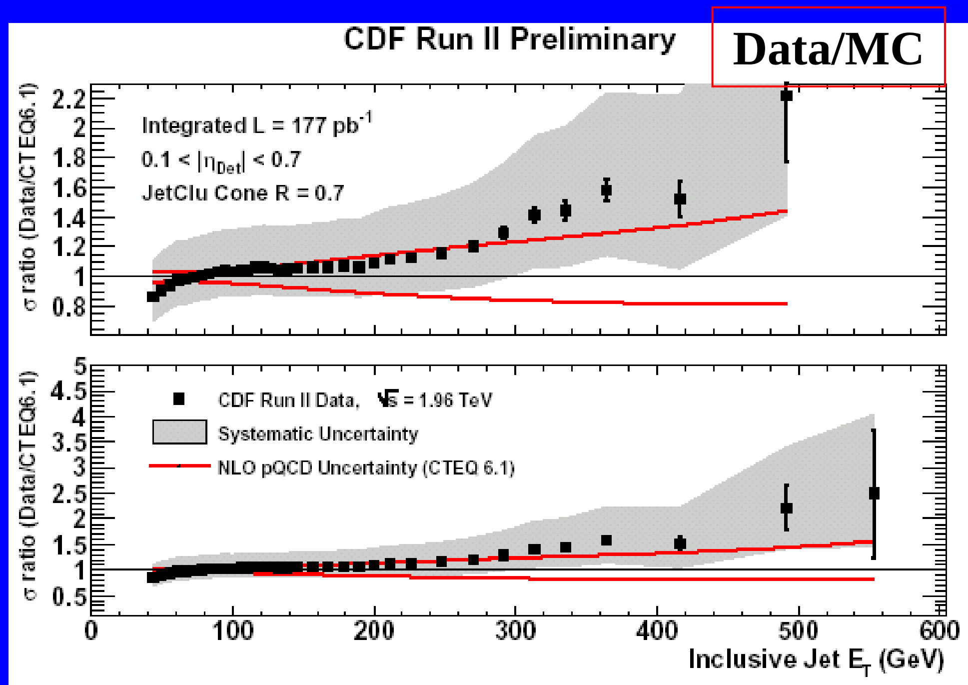
α_S **running will slow down or plateau;**
when Qs interactions become perturbative it will start falling again → 0.

Measurement of the Strong Coupling from Inclusive Jet Production ...

Run I : $\sqrt{s} = 1800$ GeV

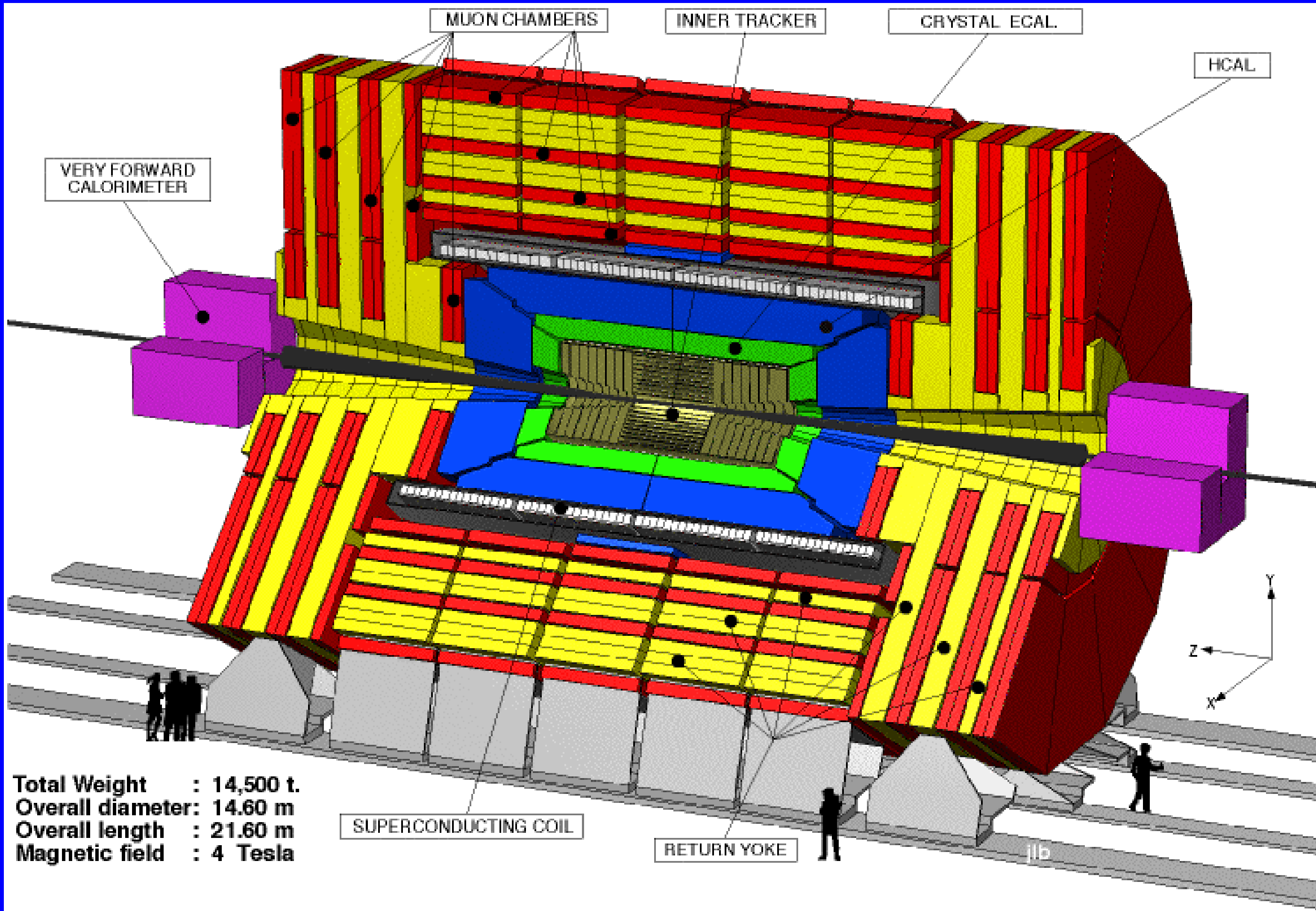


Run II : $\sqrt{s} = 1960$ GeV



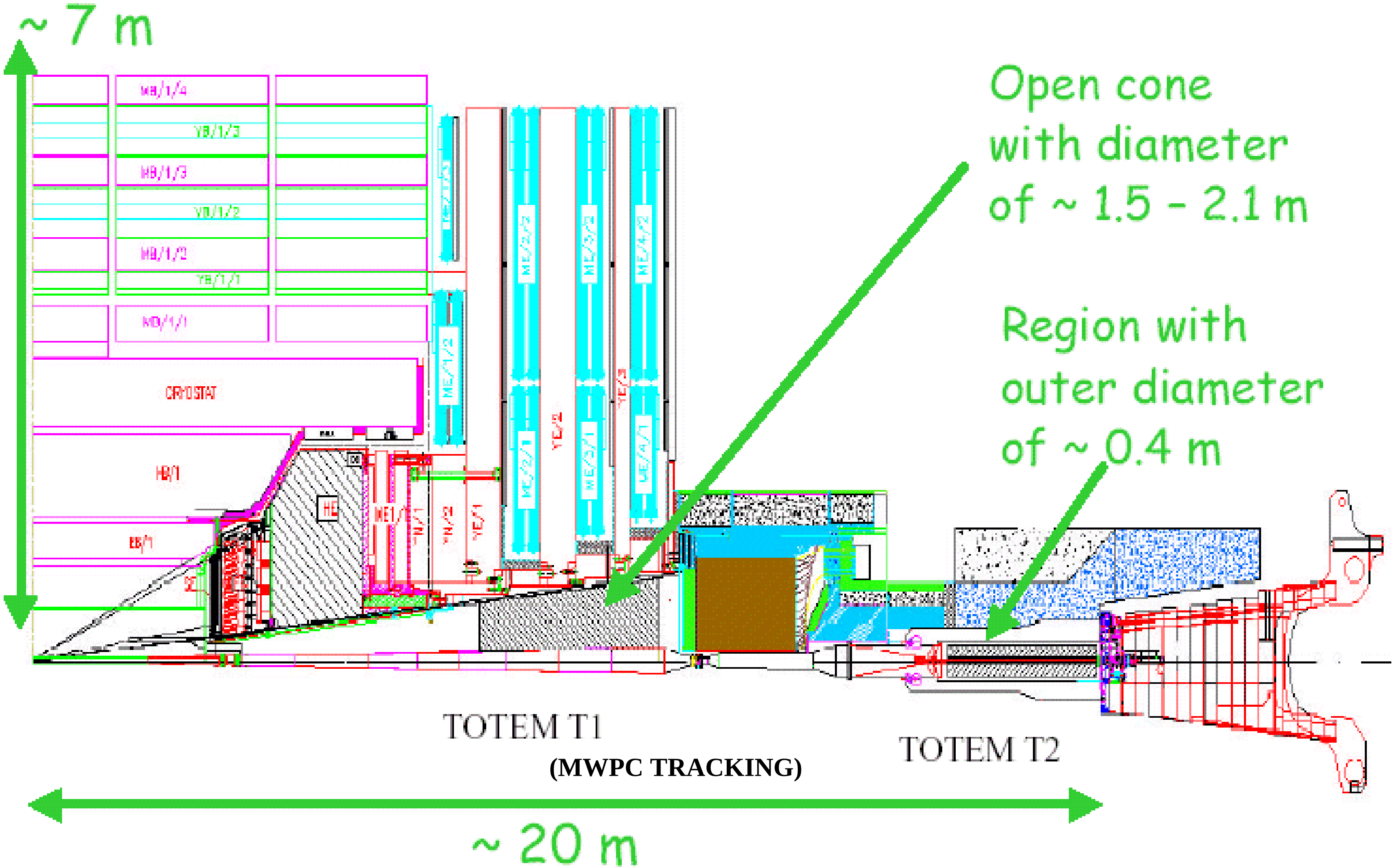
One can stretch gluon pdf ...

CMS at LHC

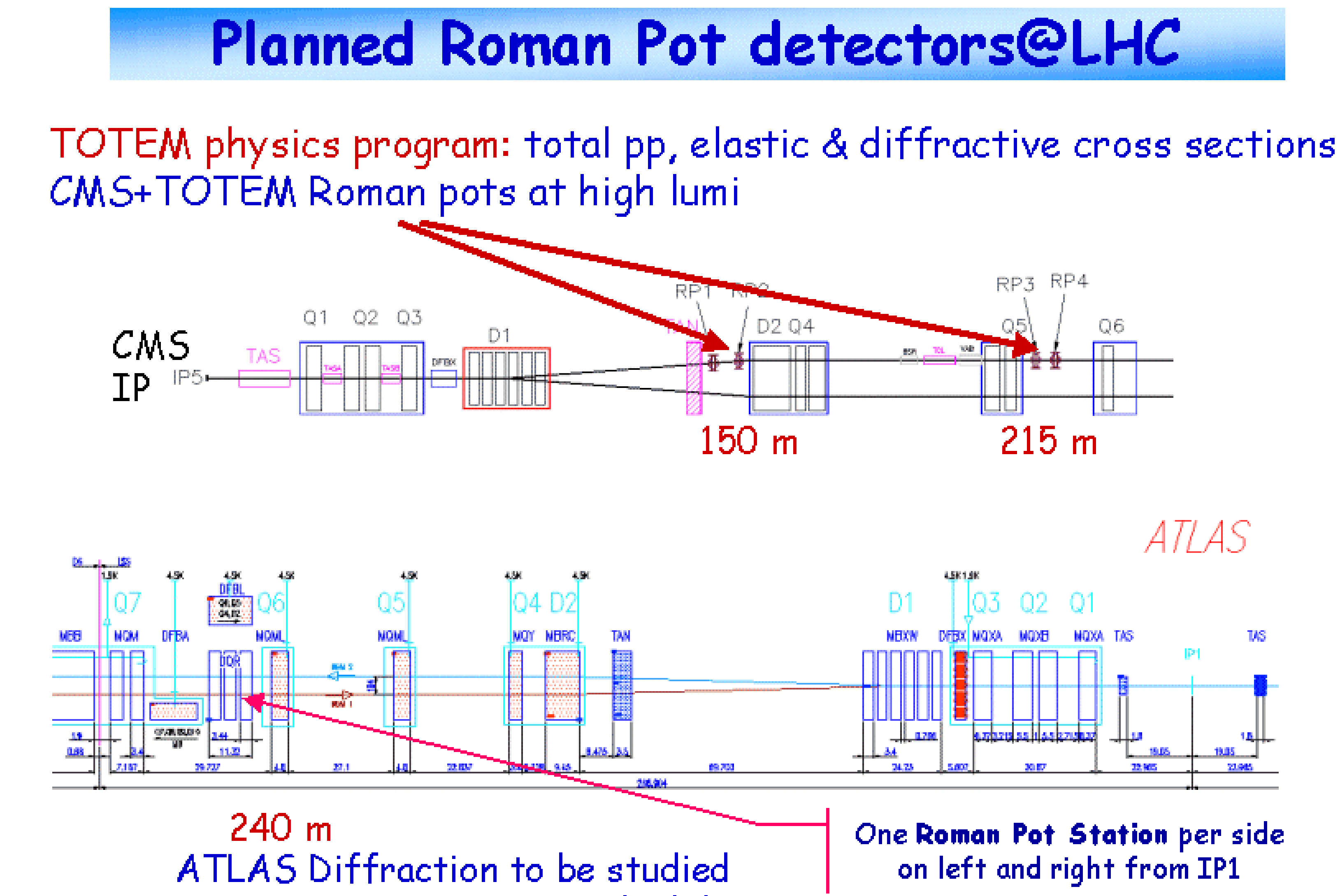


MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
Y
Z
X
jlb
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

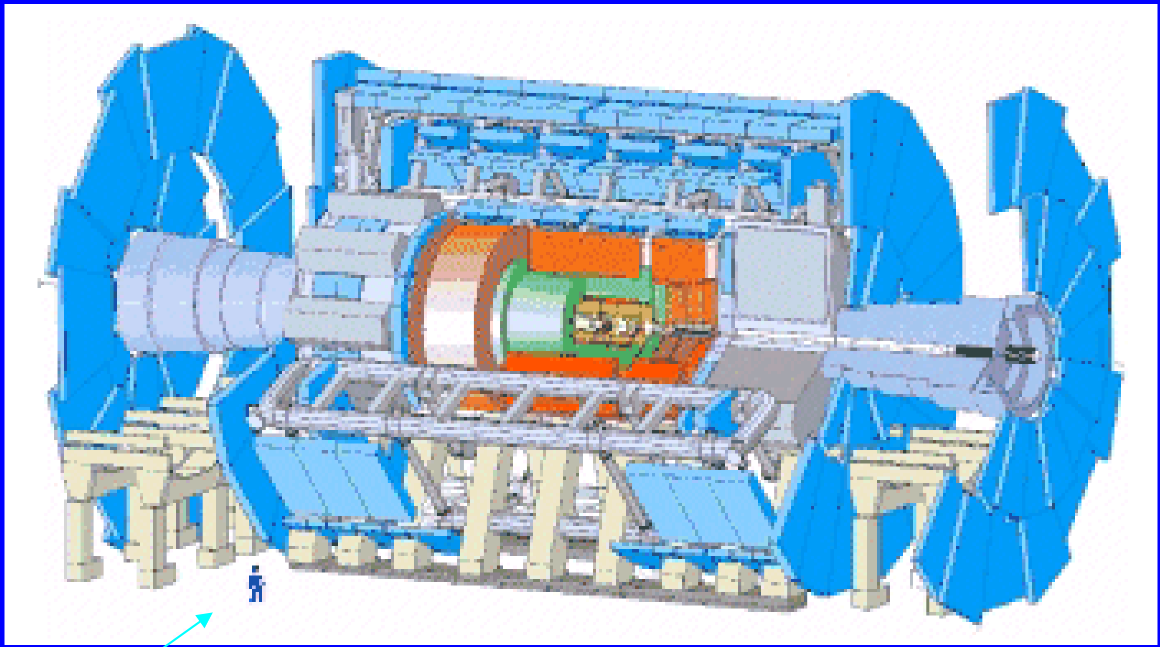
Forward region of CMS



Detecting Protons with $x_F > 0.9$

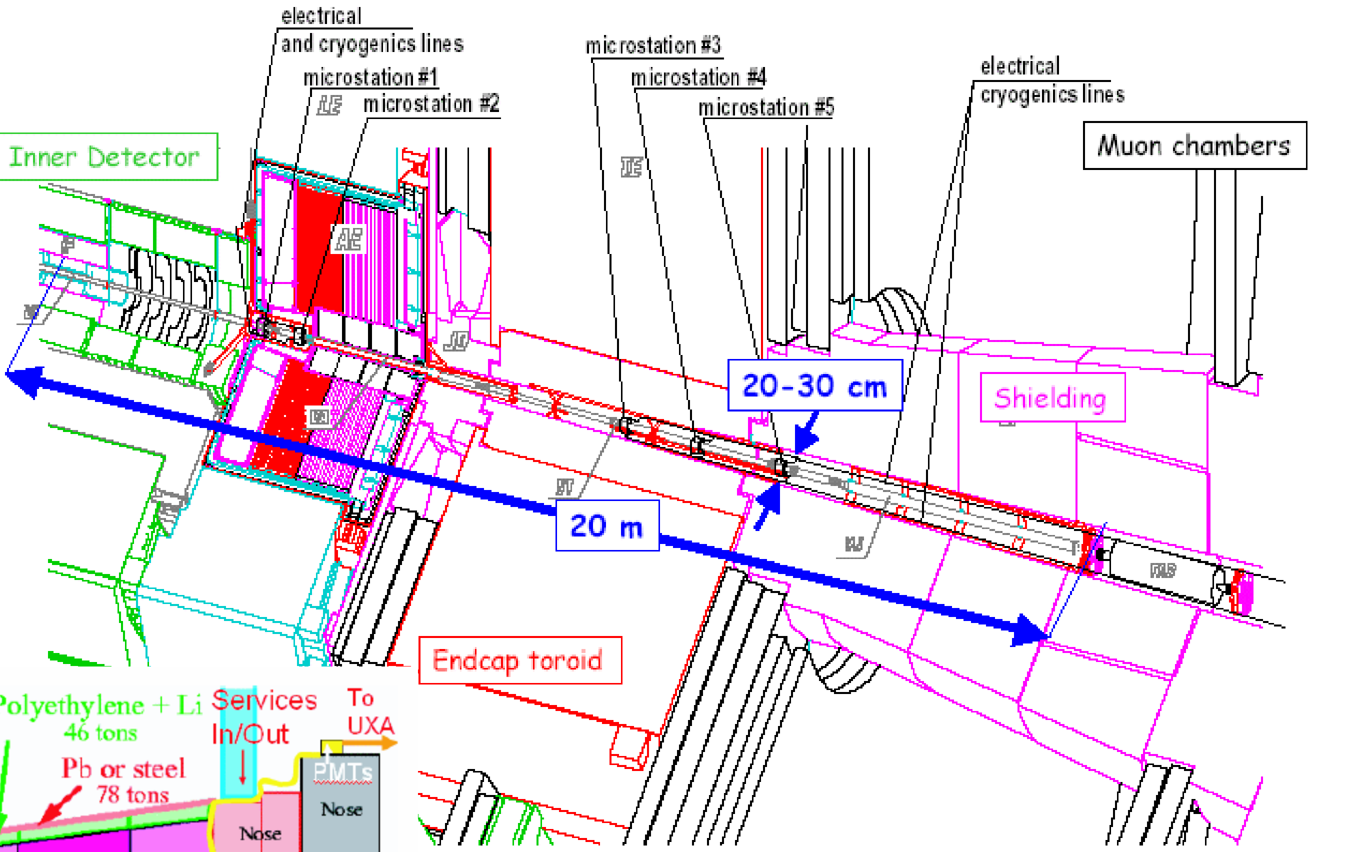


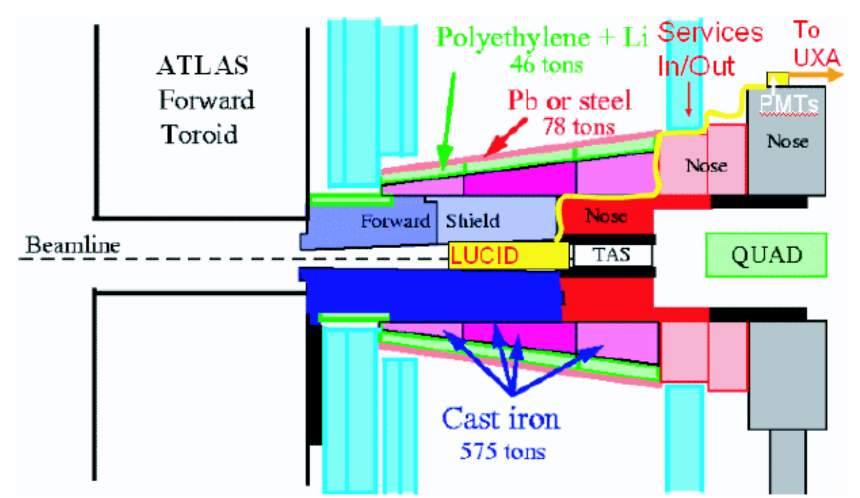
ATLAS



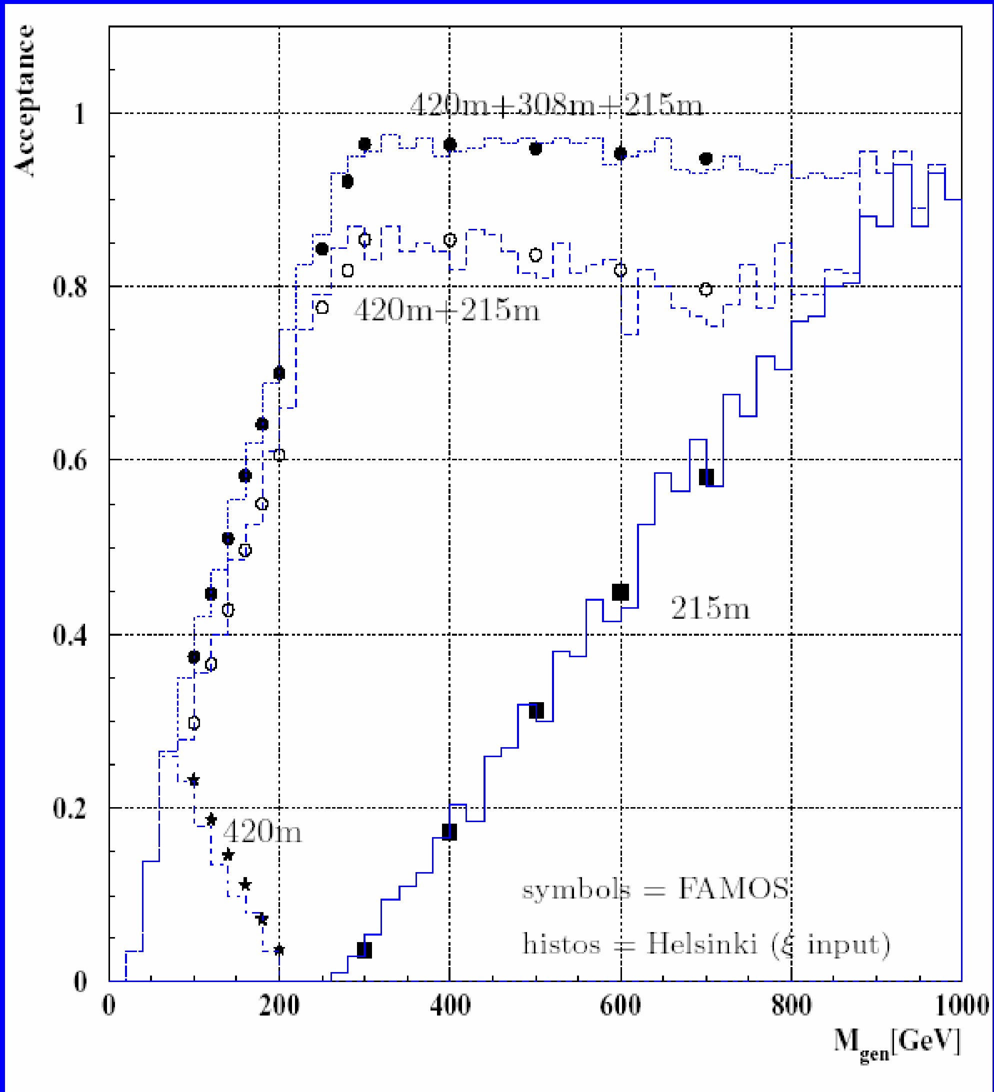
Very Small Person!

Forward region of ATLAS





Acceptances vs Mx for p + p → p + Mx + p



420m detectors

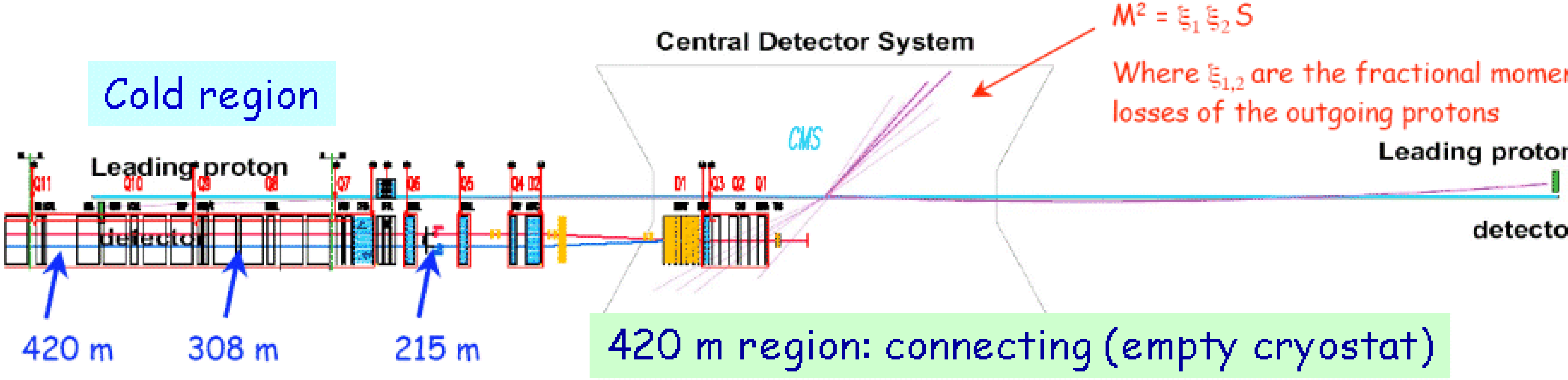
essential for Mx < 400 GeV

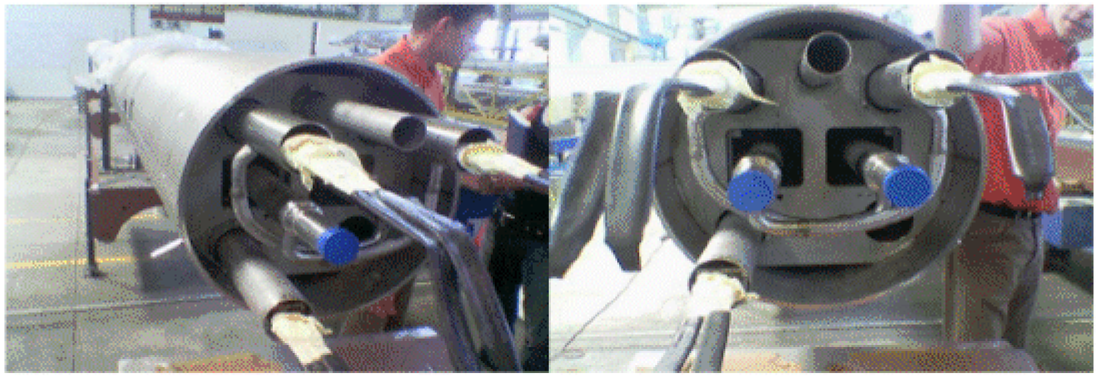
region of H, WW, ZZ

Both ATLAS & CMS want..

R&D proposal → PPARC etc

New Forward Detector Proposal (in prep.)





Proposal to study a modification of the cryostat and to operate compact detectors in the region of 400m (for ATLAS & CMS)
⇒R&D collaboration building: UK groups, Belgian & Finish institutes, CERN…

Summary

Inelastic Diffraction: significant component of VHE interactions

Understanding is more phenomenological than theoretical

Very high masses at Tevatron, LHC and CR (including DPE)

CR need LHC data wherever possible (forward & very forward)

Pomeron ***may*** be a window to **Beyond Standard Model**
e.g. **pp → p WW p** at LHC (**H** or **White Pomeron** or ...)

May be strong effects in Cosmic Ray physics ??

Thank you