Diffraction: a different window on QCD and the proton structure
(an overview for non specialists)

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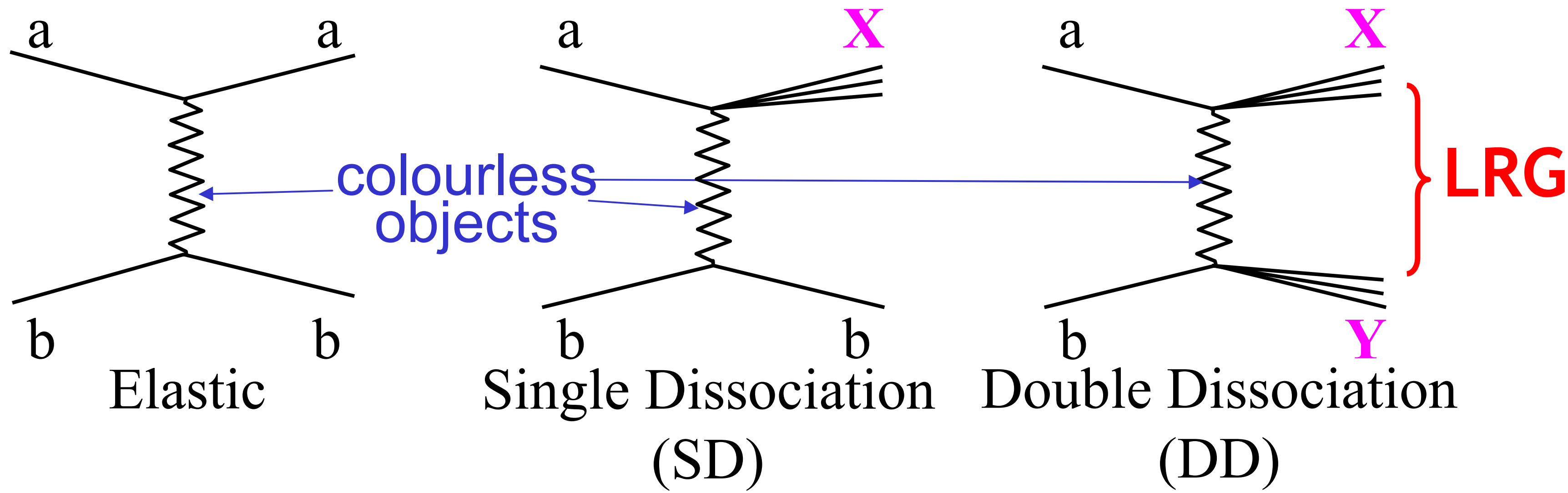
1. Diffraction in terms of quarks, gluons and QCD

2. Diffraction as a tool to probe the proton

3. A look at the future

Diffraction in hadron scattering

Diffraction is a feature of hadron-hadron interactions (30% of σ_{tot})



o) Beam particles emerge intact or dissociated into low-mass states.
Energy ≈ beam energy (within a few %)

o) Final-state particles separated by large polar angle
(or pseudorapidity, ln tan(θ/2)): Large Rapidity Gap (LRG)

o) Interaction mediated by t-channel exchange of object with vacuum
quantum numbers (no colour): the Pomeron

Pomeron ?!

Pomeron goes back to the '60s: Regge trajectory, ie a moving pole in complex angular momentum plane. Would like to understand diffraction in terms of quarks, gluons and QCD (need a hard process)

A worthwhile task:

- **Diffraction is a significant part of σ_{tot}**
- **Elastic part drives σ_{tot} via optical theorem: $d\sigma_{el}/dt|_{t=0} \propto (\sigma_{tot})^2$**
- **Novel tool to study the transition between hard (perturbative) and soft (confinement) regions of QCD & low-x structure of the proton**

In the last 5-10 years, we learned a lot about diffraction by scattering pointlike probes (electrons) on Pomeron – the same technique used for studying the structure of the proton

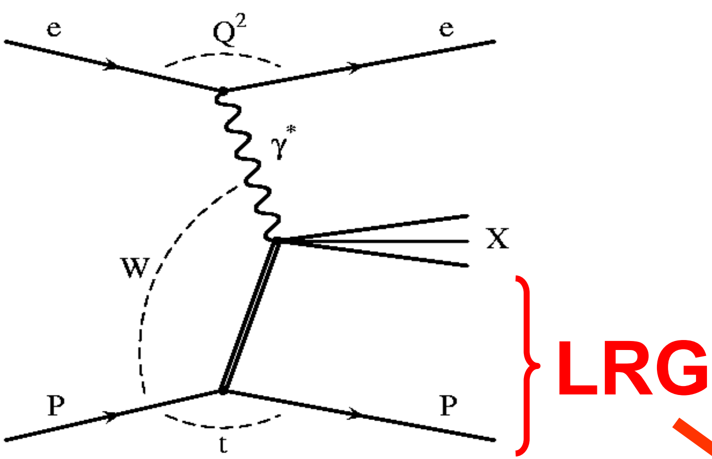
$\rightarrow$ now clear that diffraction has a well deserved place in QCD

NB in following will often refer to Pomeron as if it were real particle (it isn't)

Part I

- The partonic structure of the Pomeron as probed by a pointlike virtual photon
- Diffractive PDFs
- Their applicability in ep and pp, $p\bar{p}$ processes

Diffractive Deep Inelastic Scattering



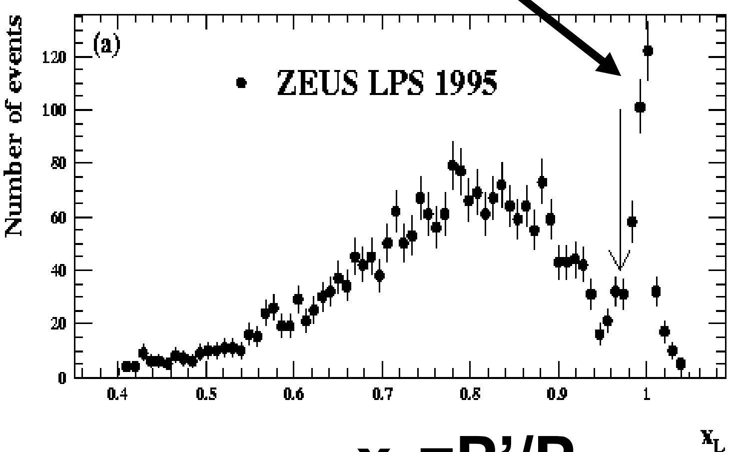
Q^2 = virtuality of photon =
= (4-momentum exchanged at e vertex)^2

t = (4-momentum exchanged at p vertex)^2

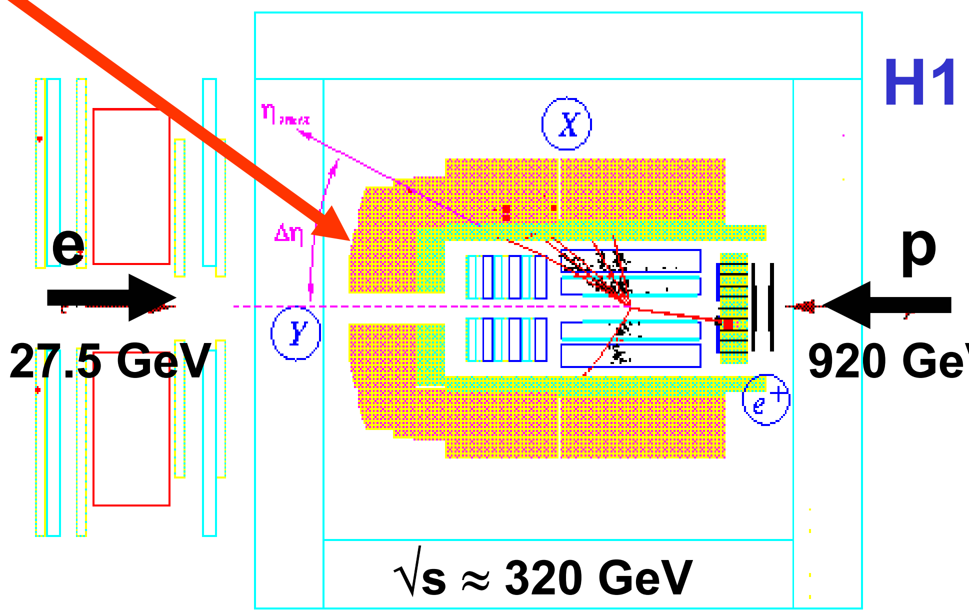
W = invariant mass of photon-proton system

M_X= invariant mass of photon-Pomeron system

Diffractive peak

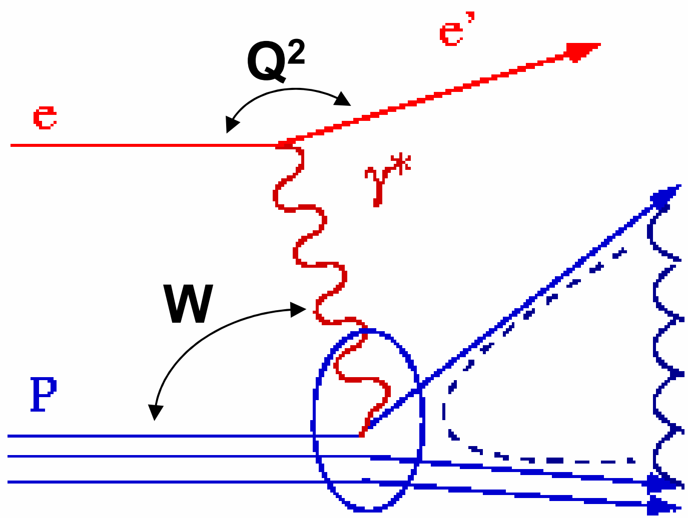


x_L=P'/P_{beam}



Standard Deep Inelastic Scattering

For $Q^2 \ll M_Z^2$:



In a frame in which the proton is very fast (Breit frame):

x = Bjorken's variable=
= fraction of proton's momentum carried by struck quark
$\approx Q^2/W^2$

W = photon-proton centre of mass energy

y = W^2/s

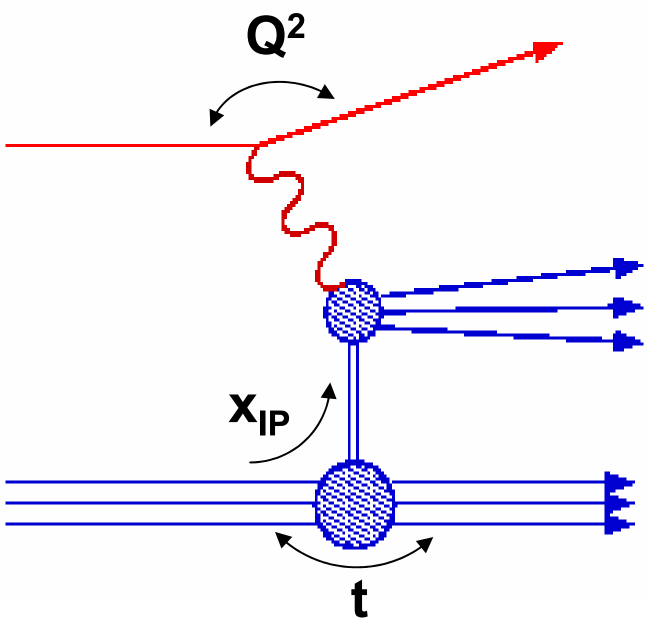
$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left\{1 - y + \frac{y^2}{2[1+R(x,Q^2)]}\right\} F_2(x,Q^2)$$

$F_2 = \sum_i [e_i^2 \, x \, f_i(x,Q^2)]$

$R = \sigma_L/\sigma_T$

DIS probes the partonic structure of the proton

Diffractive Deep Inelastic Scattering



x_{IP} = fraction of proton's momentum taken by Pomeron

= ξ in Fermilab jargon

β = Bjorken's variable for the Pomeron

= fraction of Pomeron's momentum carried by struck quark

= x/x_{IP}

$$\frac{d^4\sigma}{d\beta dQ^2 dx_{IP} dt} = \frac{4\pi\alpha^2}{\beta Q^4}\left\{1 - y + \frac{y^2}{2(1+R^{D(4)})}\right\} F_2^{D(4)}(\beta, Q^2, x_{IP}, t)$$

Naively, if IP were particle: $F_2^{D(4)} \approx f_{IP}(x_{IP},t)\, F_2^{POM}(\beta,Q^2)$

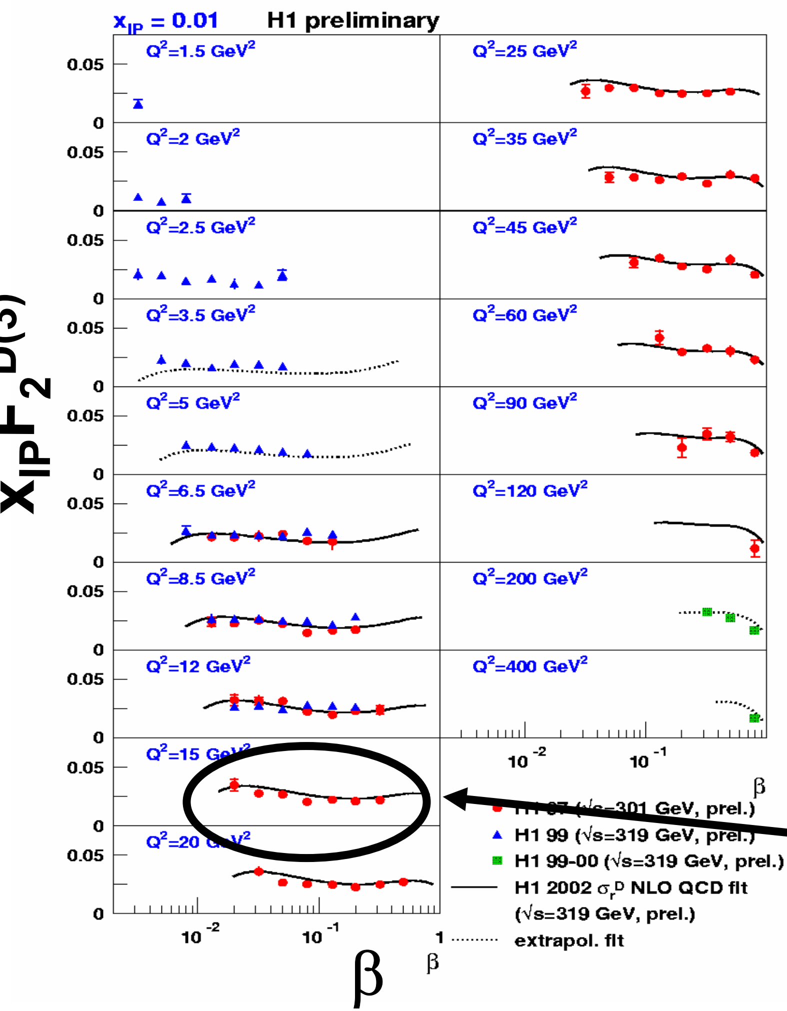
[Ingelman, Schlein]

Flux of Pomerons

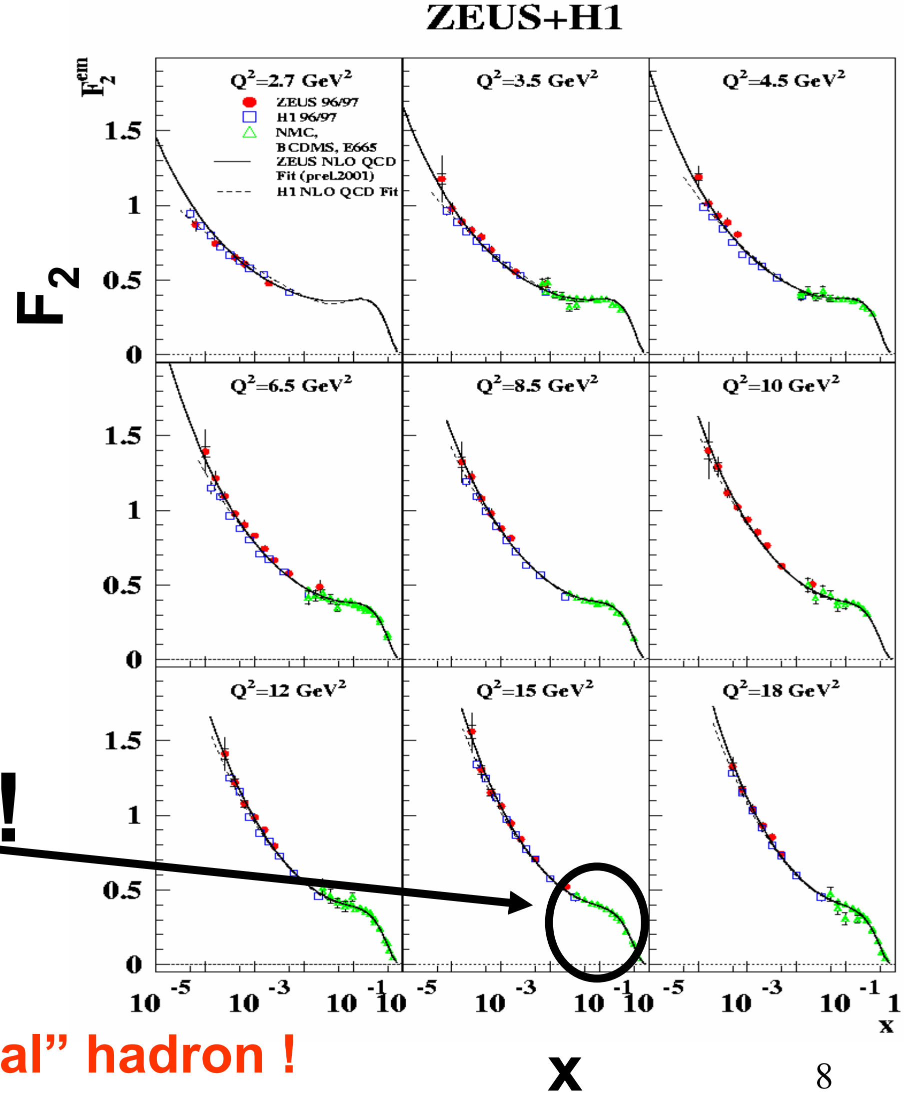
"Pomeron structure function"

Diffractive Structure Function vs β

Pomeron:



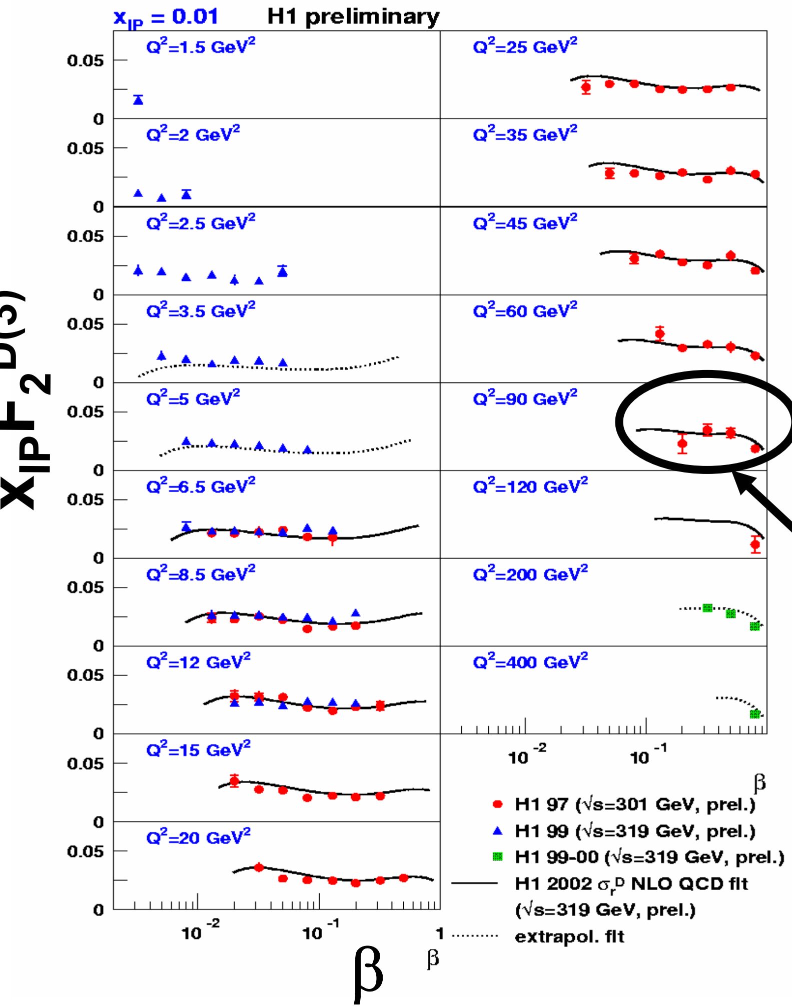
Proton:



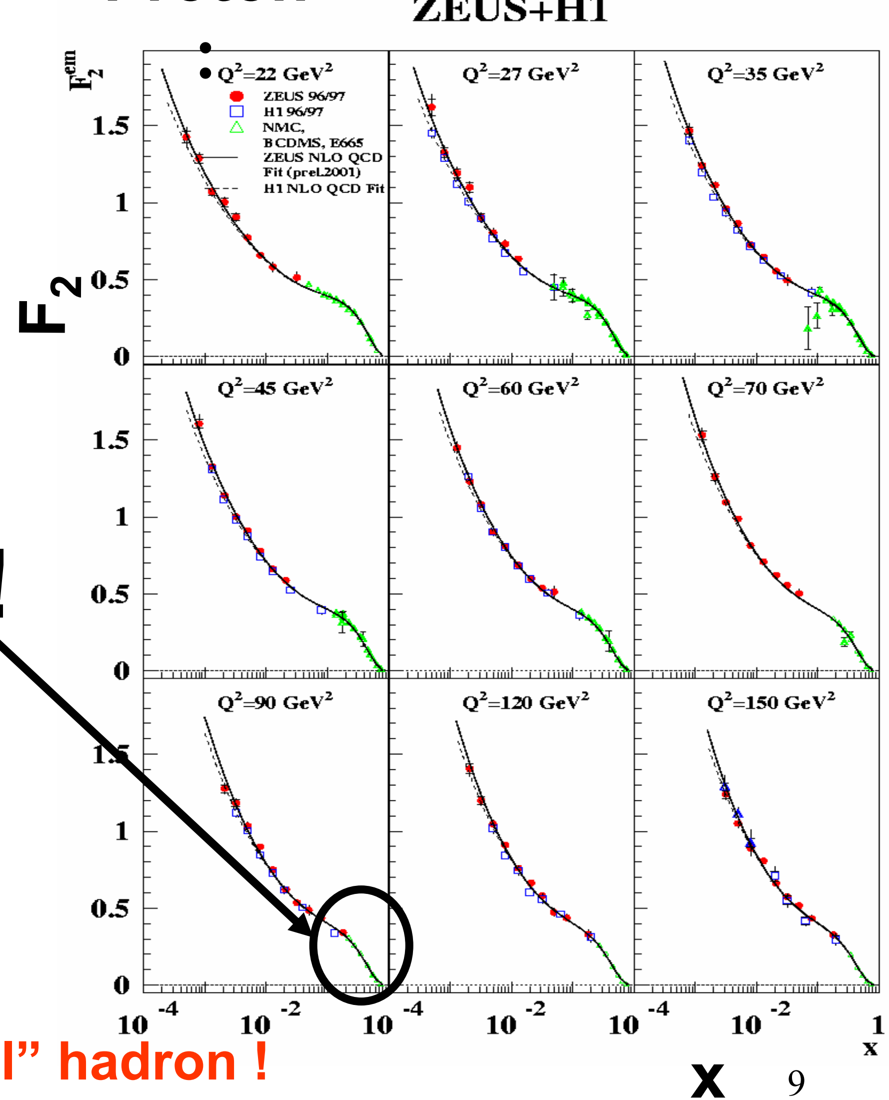
Weak β dependence – not a "normal" hadron !

Diffractive Structure Function vs β

Pomeron:



Proton

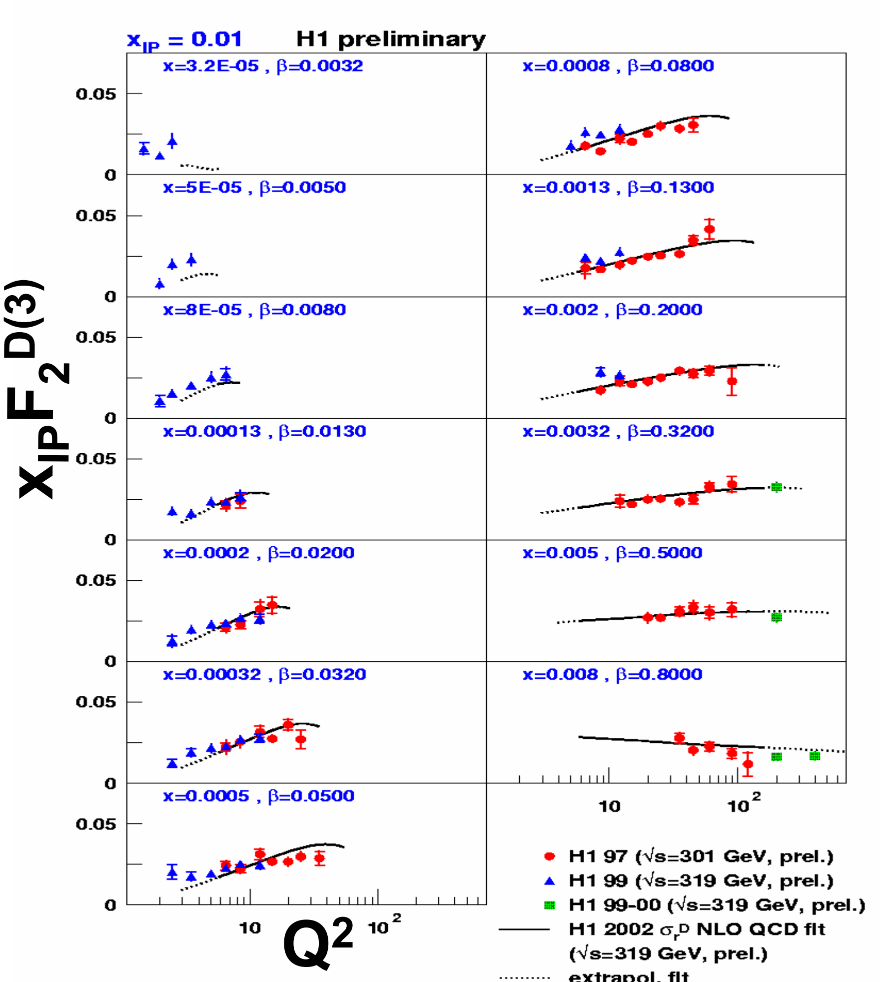


!

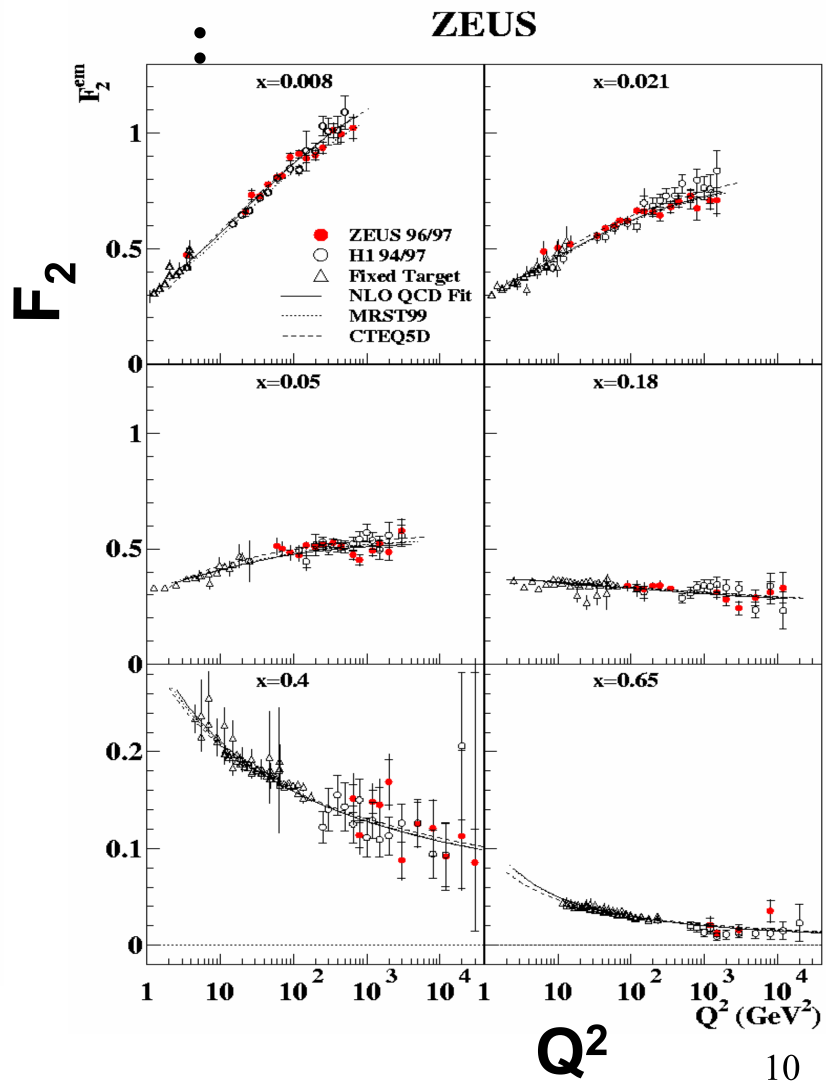
Weak β dependence – not a "normal" hadron !

Diffractive Structure Function vs Q^2

Pomeron:



Proton:

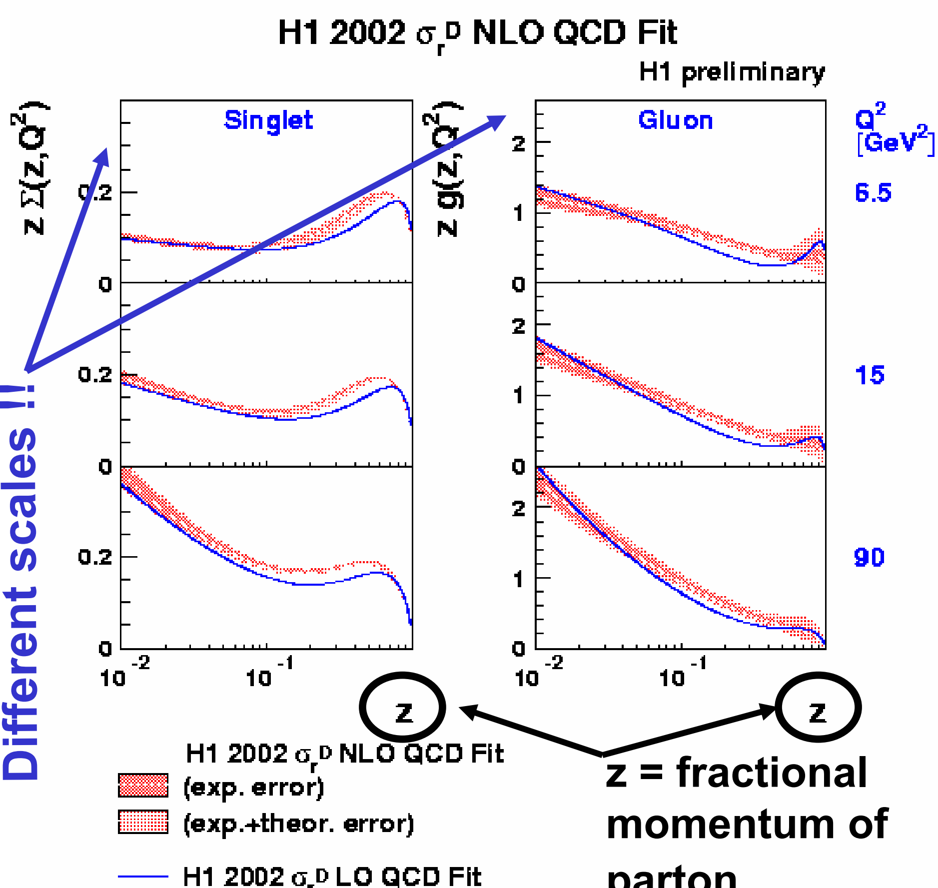


Positive scaling violations:
lots of gluons !

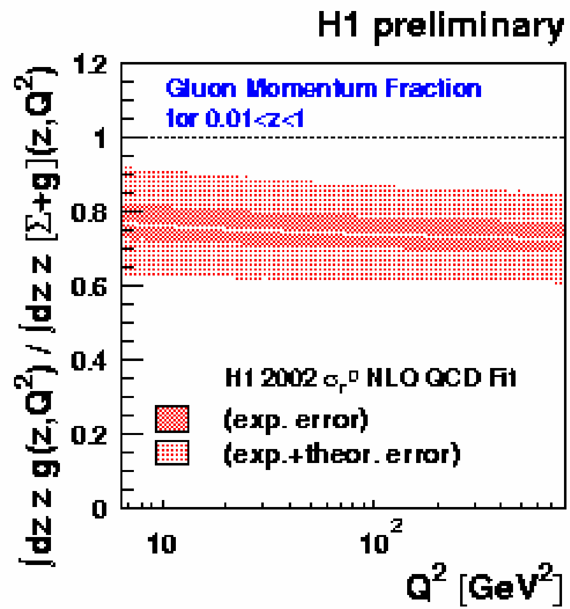
Diffractive PDFs

NLO DGLAP fit:

- **Parametrise Flavour Singlet (quarks+antiquarks) and Gluons at Q^2= 3 GeV^2**
- **Evolve with NLO DGLAP and fit**



z = fractional momentum of parton



Gluon dominated: integrated fraction of exchanged momentum carried by gluons (75 $\pm$ 15)%

(Diffractive) hard scattering factorisation

Diffractive PDFs are universal (in DIS): diffractive DIS, like inclusive DIS, is factorisable into a hard part and a soft part
[Collins (1998); Trentadue, Veneziano (1994); Berera, Soper (1996)…]:

$$F_2^D \sim f_{i/p}^D \otimes \widehat{\sigma}_i$$

universal partonic cross section

diffractive parton distribution functions: evolve according to DGLAP

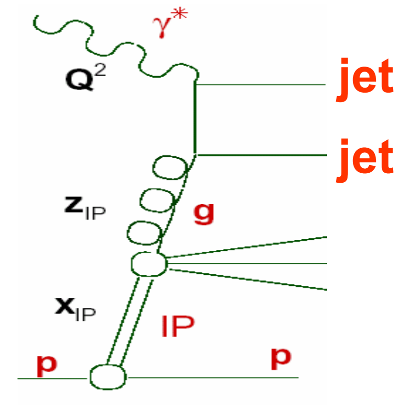
$f_{i/p}^D(z,Q^2,x_{IP},t)$: probability to find, with probe of resolution Q^2, in a proton, parton *i* with momentum fraction *z*, under the condition that proton remains intact, emerging with small energy loss and momentum transfer given by x_{IP}, *t*

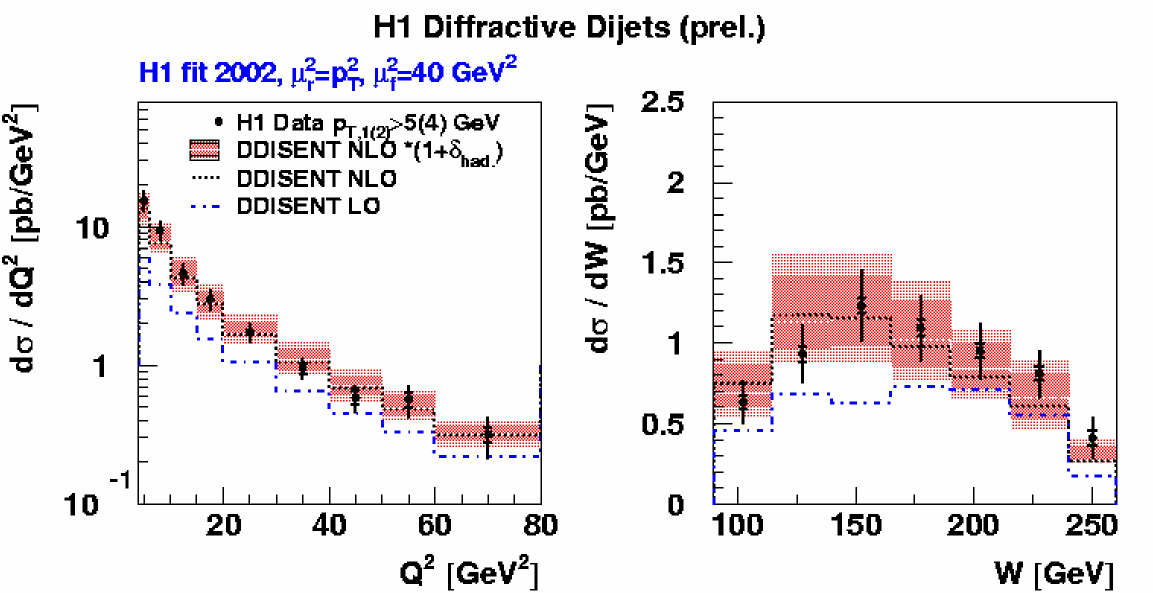
A new type of PDFs, with same dignity as standard PDFs. Applies when vacuum quantum numbers are exchanged

Rather than IP exchange: probe diffractive PDFs of proton

Test factorisation in ep events

Use diffractive PDFs extracted from DGLAP fits of F_2^D to predict the rate of diffractive dijet production





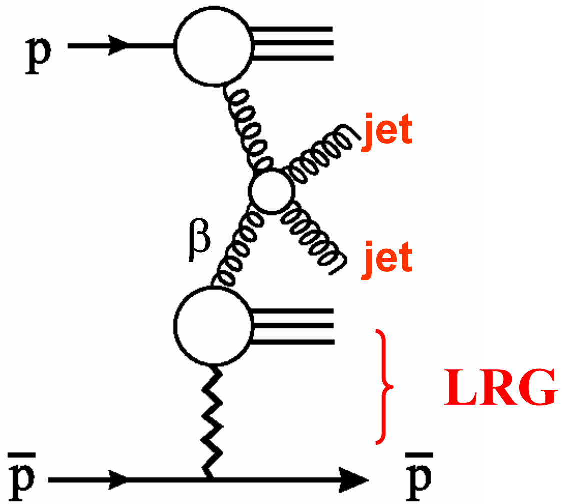
$4<Q^2<80$ GeV^2
CDF cone algorithm
$P_t^{jet\ 1(2)} > 5(4)$ GeV
$x_{IP}<0.05$

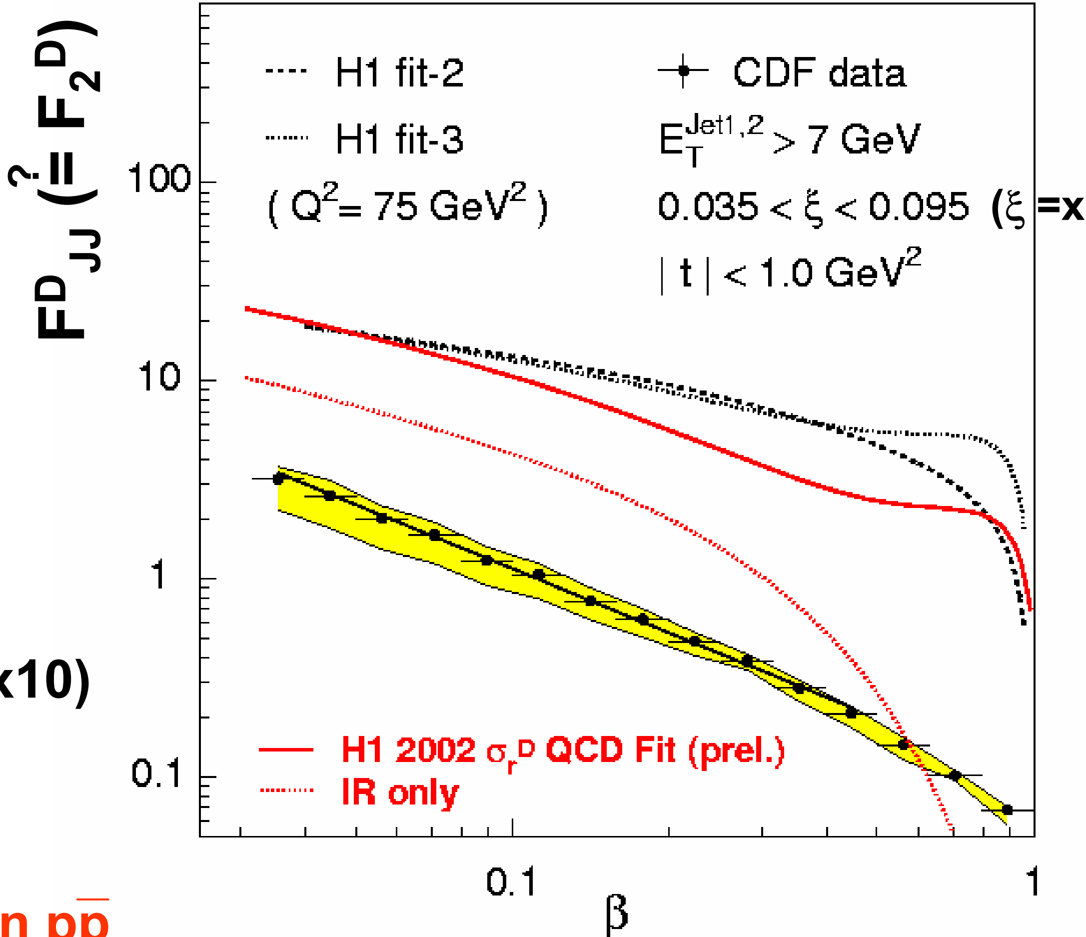
- **Normalisation and shape of data described ok**
- **Same conclusion for charm production**

Hard scattering factorisation works in diffractive DIS

Test factorisation in $p\bar{p}$ events

Factorisation of diffractive PDFs not expected to hold for pp, $p\bar{p}$ scattering – indeed it does not:



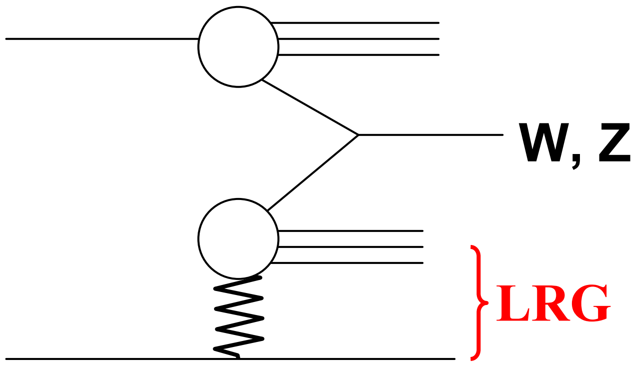


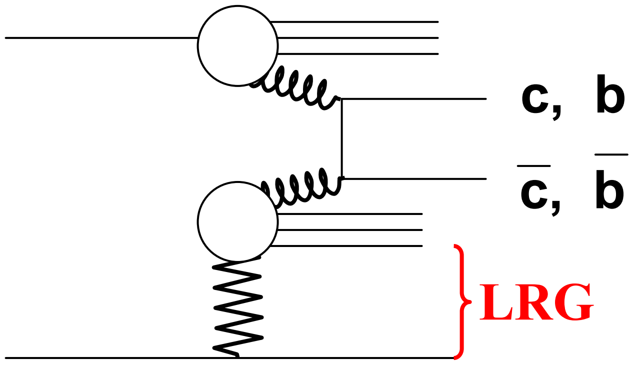
Normalisation discrepancy (x10)
(depends on √s [CDF, D0])

Hard scattering factorisation violated in $p\bar{p}$

Test factorisation in $p\bar{p}$ events (II)

In addition to diffractive production of di-jets, measured diffractive production of W, Z-bosons (CDF, D0); J/ψ, b-mesons (CDF)



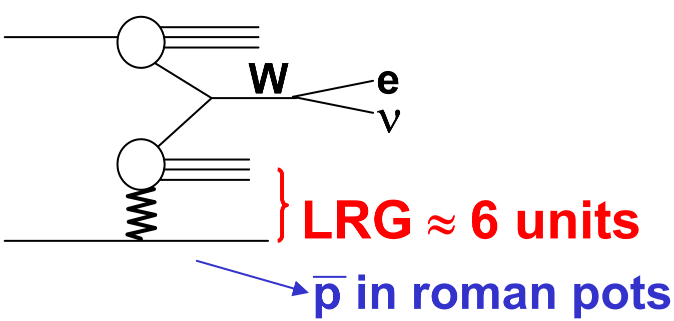


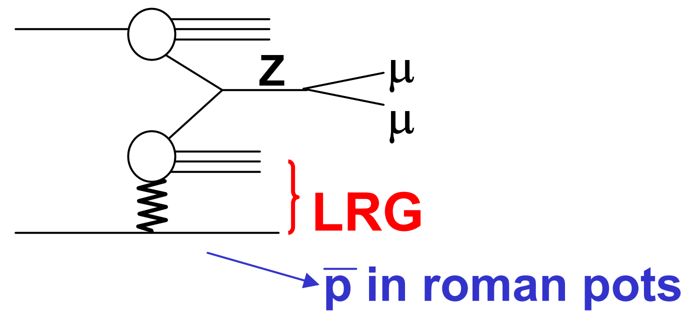
(mostly) sensitive to quarks

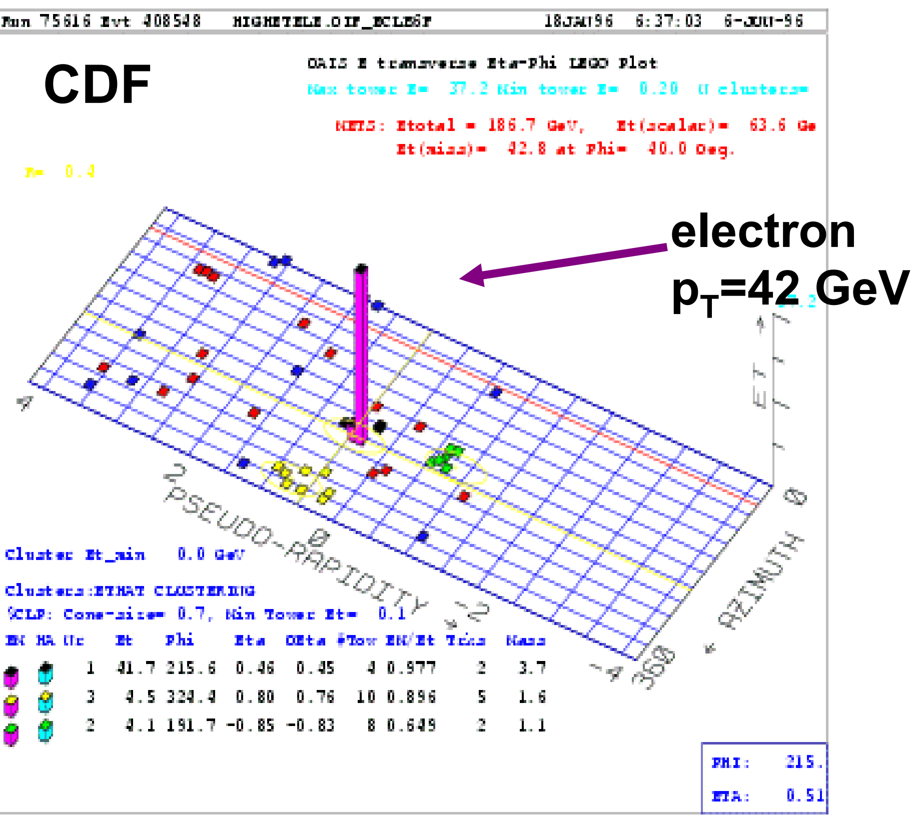
sensitive to gluons

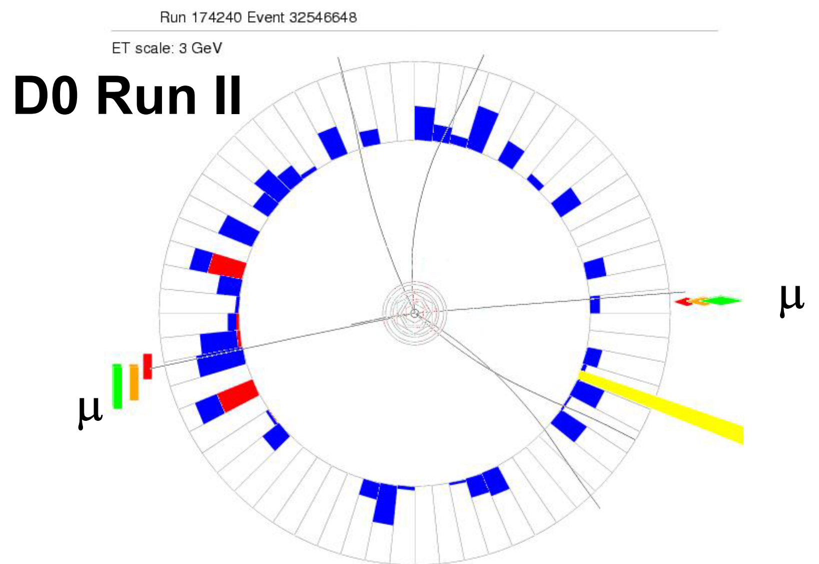
Rates are ~1% of the non-diffractive vs ~10% expectation based on HERA PDFs

⇒ Hard scattering factorisation violated

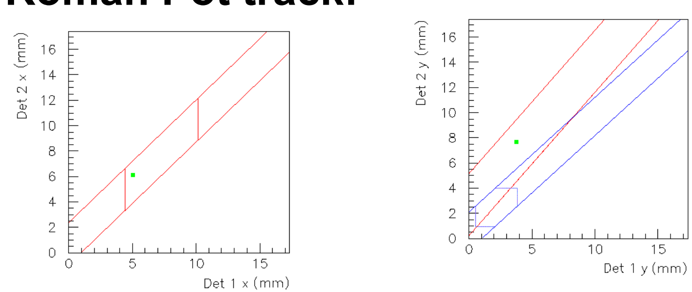








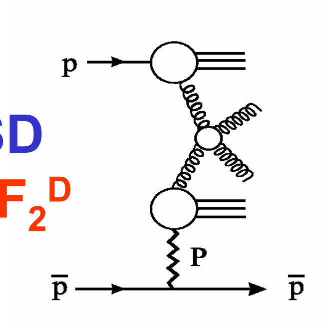
Roman Pot track:



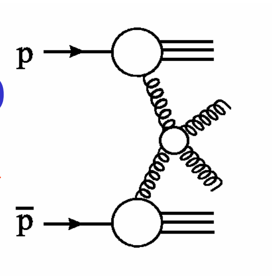
Test factorisation in $p\bar{p}$ events (III)

Even within the $p\bar{p}$ data alone hard diffractive factorisation does not hold:

SD
$\propto F_2^D$

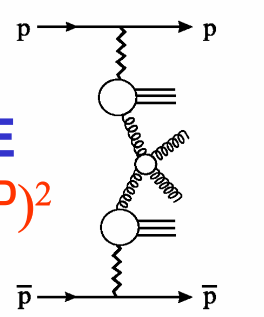


ND
$\propto 1$

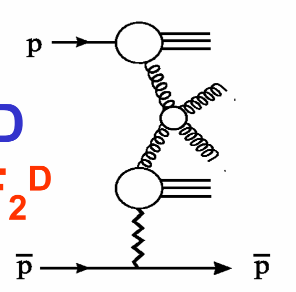


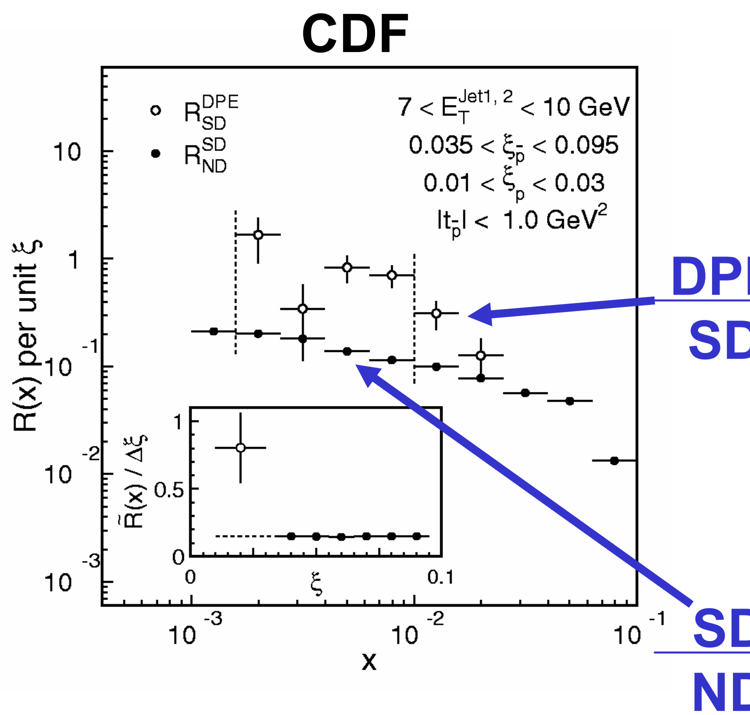
? =

DPE
$\propto (F_2^D)^2$



SD
$\propto F_2^D$



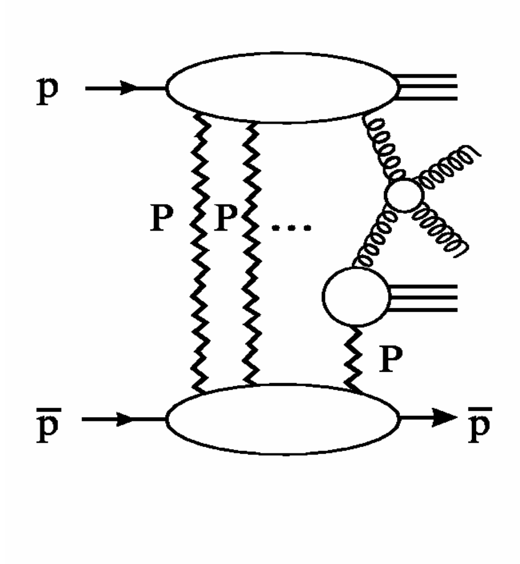


$$\frac{SD}{ND}\Big/\frac{DPE}{SD} = 0.19 \pm 0.07 \ (\neq 1\ !)$$

Probability for 2 LRGs > (probability for 1 LRG)^2, ie get different F_2^D from 1 LRG and 2 LRG events → **Hard scattering factorisation violated**

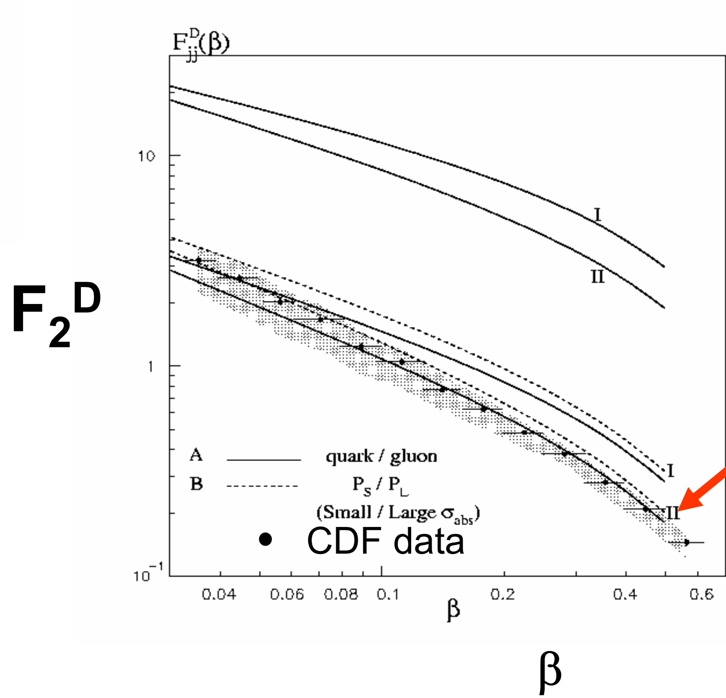
Why is factorisation violated ?

Violation of factorisation understood in terms of (soft) rescattering corrections of the spectator partons (Kaidalov, Khoze, Martin, Ryskin):



- Two-component eikonal model a` la Good & Walker, Pumplin, Gribov – pre-QCD !

- Main uncertainty is that on F_2^D



Predictions based on rescattering assuming HERA diffractive PDFs

Why is factorisation violated ? (cont'd)

- **Understanding of breaking encouraging – more work needed**

- **If this works, can use at Tevatron the diffractive PDFs from HERA, and vice versa**

NB several other important approaches:

o) Bjorken (1993)
o) Gotsman, Levin, Maor (1993)
o) Goulianos (1995) → **IP flux renormalisation (*pre*-diction !)**
o) Buchmueller, Gehrmann, Hebecker (1997)
o) Cox, Forshaw, Loennblad (1999)
o) Enberg, Ingelman, Timneanu (2000) → **Soft Colour Interactions**
o) Erhan, Schlein (2000) → **$\sqrt{s}$-dependent IP trajectory**
o) Bialas, Peschanski (2002)
o) [list is incomplete]

Summary I

- **We have measured the partonic content of the exchange responsible for elastic and diffractive interactions – mainly gluons [ie we think we know what a Pomeron is]**

- **This has led to a new kind of PDFs which apply to the class of QCD events where vacuum quantum numbers are exchanged: diffractive PDFs**

- **Rather than consider diffraction as due to the exchange of IP $\rightarrow$ exchange of partons belonging to the proton**

- **Hard scattering factorisation of diffractive PDFs works in DIS. We are on the way to understanding the *large* breaking of factorisation observed in ep vs $p\bar{p}$**

Open questions

- How safe is a QCD analysis of F_2^D ? Whole β range ok?
- Relevance of assuming $F_2^{D(4)} \approx f_{IP}(x_{IP},t)\, F_2^{POM}(\beta,Q^2)$?
- Map the size of factorisation breaking as a function of as many variables as possible
  – input from Fermilab essential, Run II results eagerly awaited !
  (some already on the way, cf Q^2 dependence of F_2^D by CDF at this workshop)
- Can we see factorisation breaking at HERA ?
  ie can we make the photon behave as a normal hadron (eg at Q^2=0) ? cf H1's measurement of dijet photoproduction
- Understand rescattering corrections in terms of QCD

Part II

Diffraction as a tool to probe the proton:

- **Consider ep diffractive scattering:**
  move to proton rest frame at HERA, find out that
  $\sigma^{\mathrm{diffr}} \propto$ **[gluon density in proton]^2**

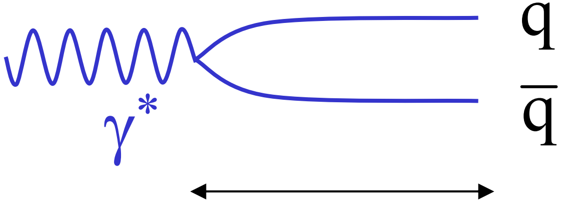
  Example: exclusive vector meson production

  Calculable in QCD !

- **Correlations in the proton: GPDs**

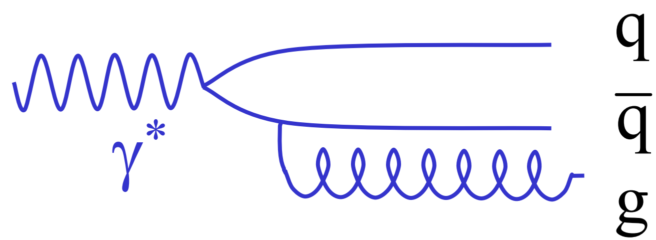
Diffractive DIS in the proton rest frame

Virtual photon fluctuates to $q\bar{q}$, $q\bar{q}g$ states (colour dipoles)



$$\propto \frac{1}{\sqrt{Q^2 + M_{q\bar{q}}^2}}$$

$$\propto E_\gamma \sim W^2 \sim 1/x$$

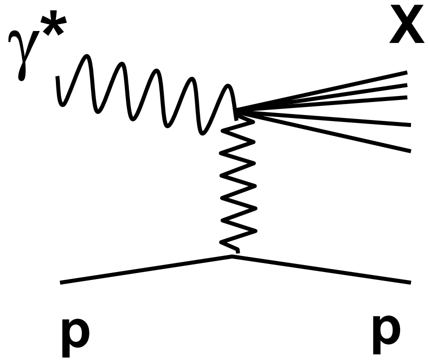


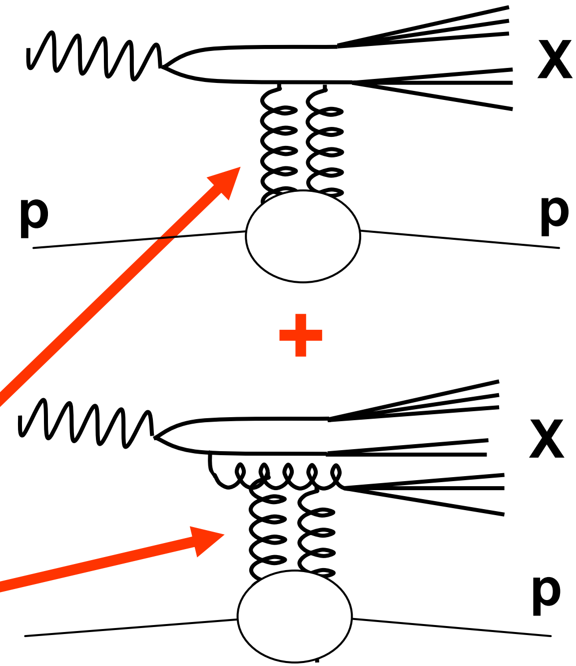
- **cf Vector Meson Dominance ($q\bar{q}$, $q\bar{q}g$ have $J^{PC}=1^{--}$)**
- **This is why can do diffraction in ep collisions !**
- **Lifetime of dipoles very long because of large γ boost ($E_\gamma \approx$ 50TeV!)**
- **Transverse size proportional to $1/\sqrt{(Q^2+ M_{q\bar{q}}^2)}$**

(for *longitudinally* polarised photons)

Transverse size of incoming hadron beam can be reduced at will. Can be so small that strong interaction with proton becomes perturbative (colour transparency) !

Diffractive DIS in the proton rest frame





2-gluon exchange:
LO realisation of vacuum
quantum numbers in QCD

Cross section proportional to probability of finding 2 gluons in the proton

$$\sigma \propto [x\, g]^2$$

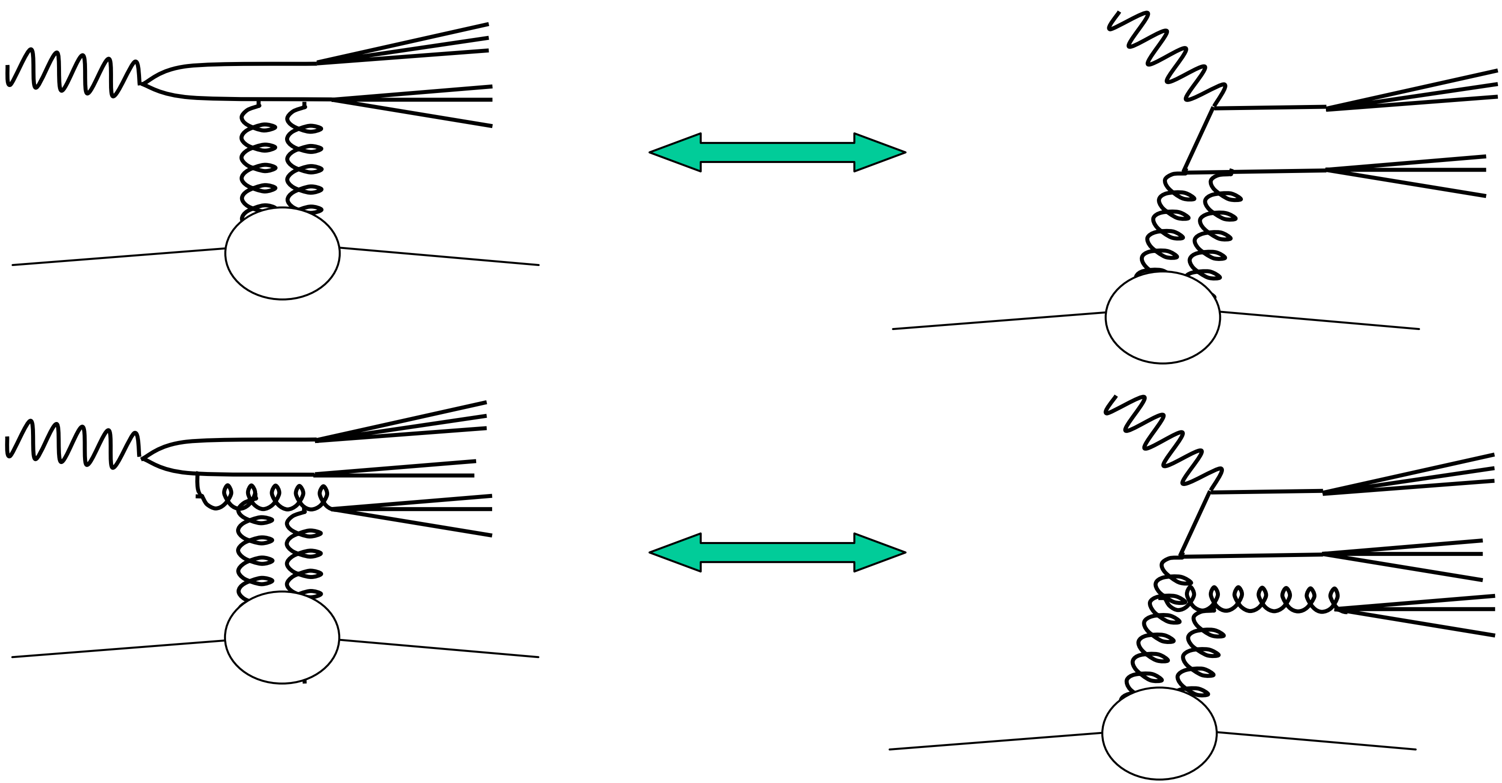
!

Gluon density in the proton

Digression: proton rest frame vs Breit

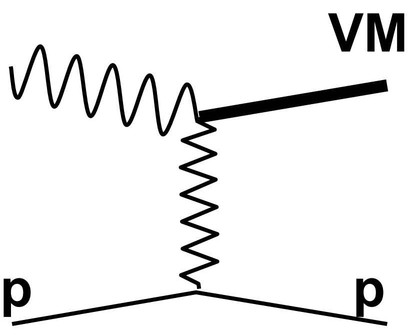
Proton rest frame:
photon fluctuates into colour dipole which scatters on p via 2-gluon exchange

Breit frame (proton very fast):
pointlike photon probes parton content of exchange

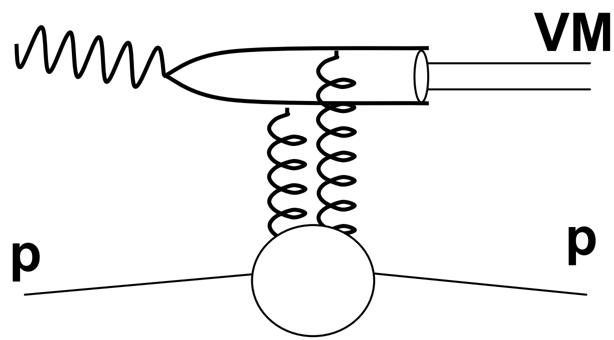


The two pictures are equivalent (at LO)

Example: Vector Meson production



($J^{PC}=1^{--}$): ρ, ϕ, J/ψ, Υ,...



$$\sigma \propto [x\, g(x, Q^2 + M_V^2)]^2$$

$$x = (Q^2 + M_V^2)/W^2$$

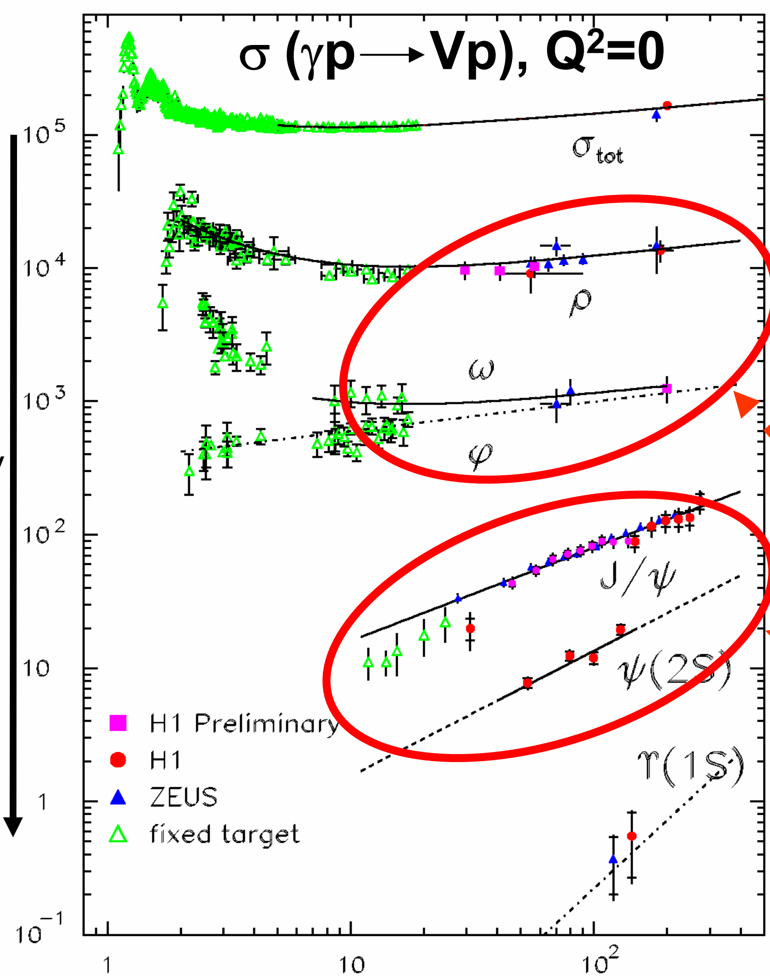
Growth of cross section with decreasing x, hence with increasing W, at large $Q^2 + M_V^2$, reflecting large gluon density at low x

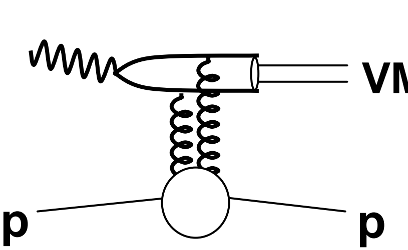
Ryskin (1993), Nikolaev et al (1994), Brodsky et al (1994),...

VM: sensitivity to gluons in proton

$$\sigma \propto [x\, g(x, M_V^2)]^2$$

$$x = M_V^2 / W^2$$



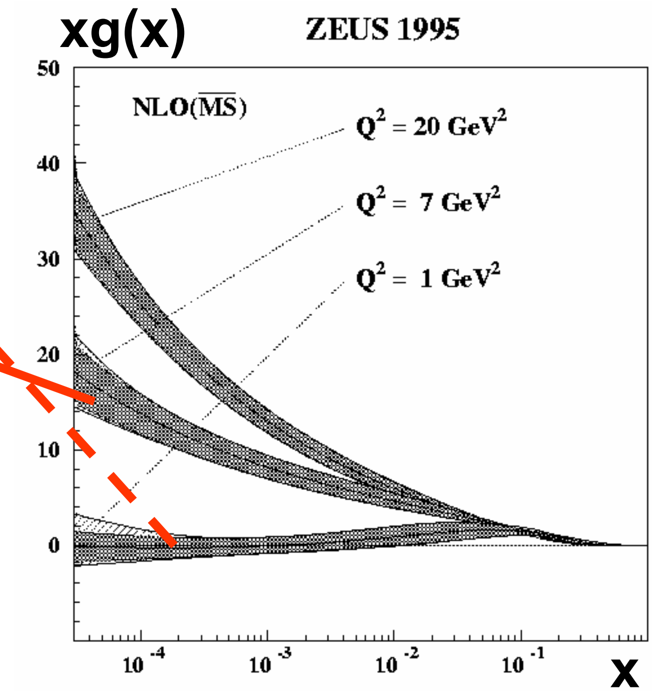


$\propto$ **W$^{0.2}$**

$\propto$ **W$^{0.8}$**

$\propto$ **W$^{1.7}$**

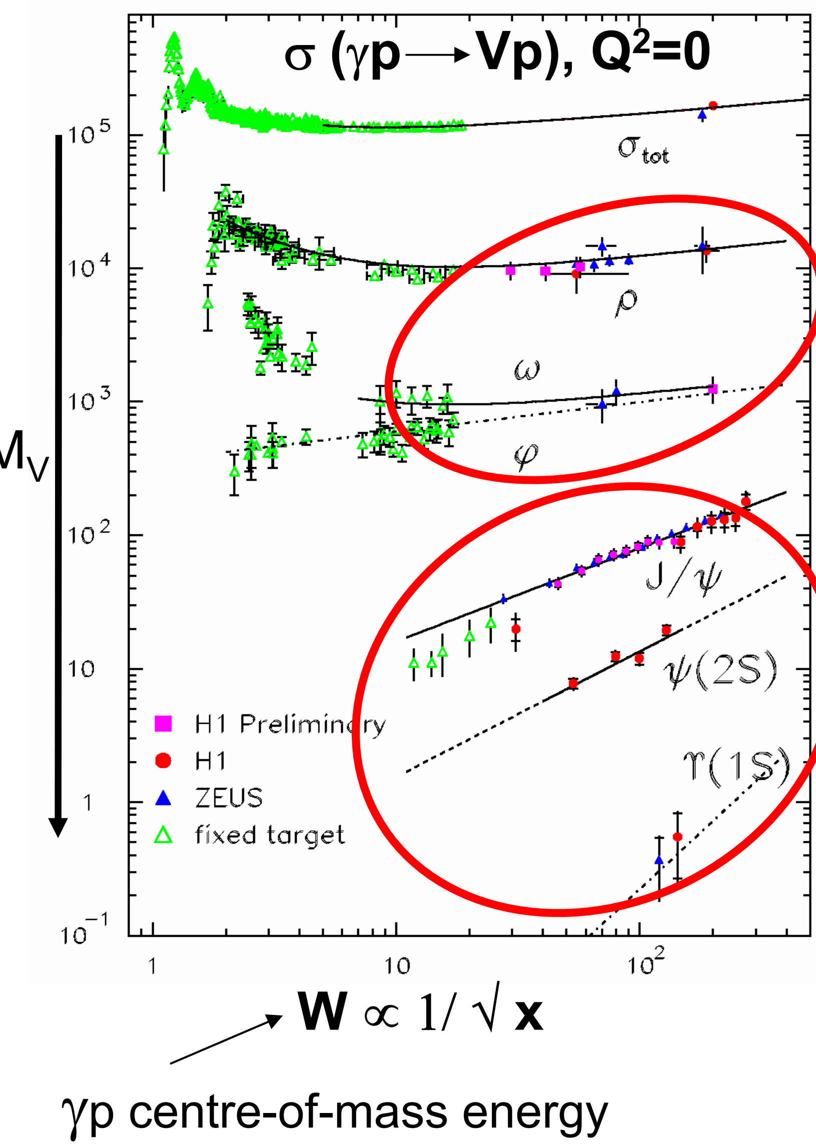
M_V



W $\propto 1/\sqrt{}$ x

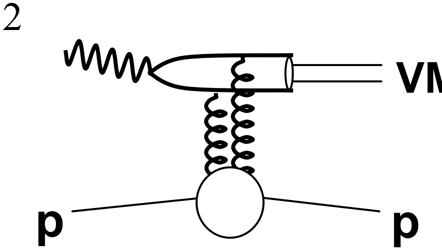
γp centre-of-mass energy

VM: sensitivity to gluons in proton



$$\sigma \propto [x\, g(x, M_V^2)]^2$$

$$x = M_V^2 / W^2$$

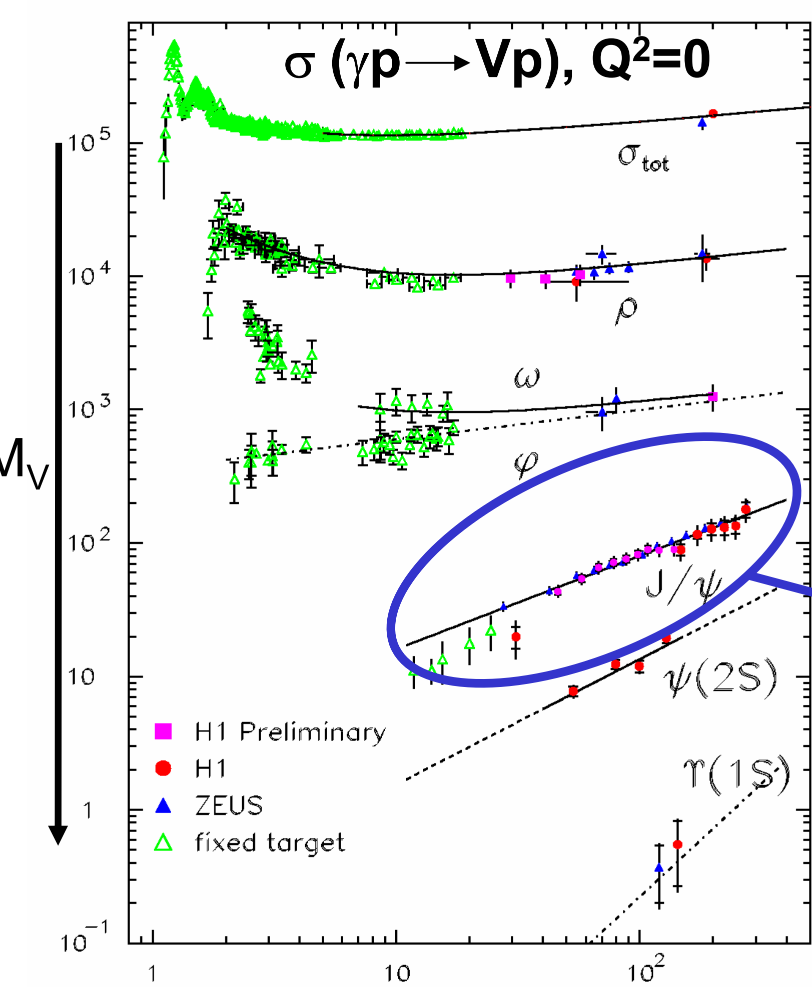


•At small M_V ($M_V^2 \approx 1$ GeV²):
Incoming dipole behaves like a normal-size hadron: the two exchanged gluons are soft – cf $\sigma_{tot}(\gamma p)$

Flat σ vs W reflects flat gluon distribution for $Q^2 \to 0$

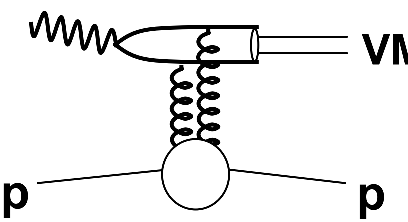
•At large M_V :
Fast growth of σ with W reflects growth of gluon distribution with decreasing x

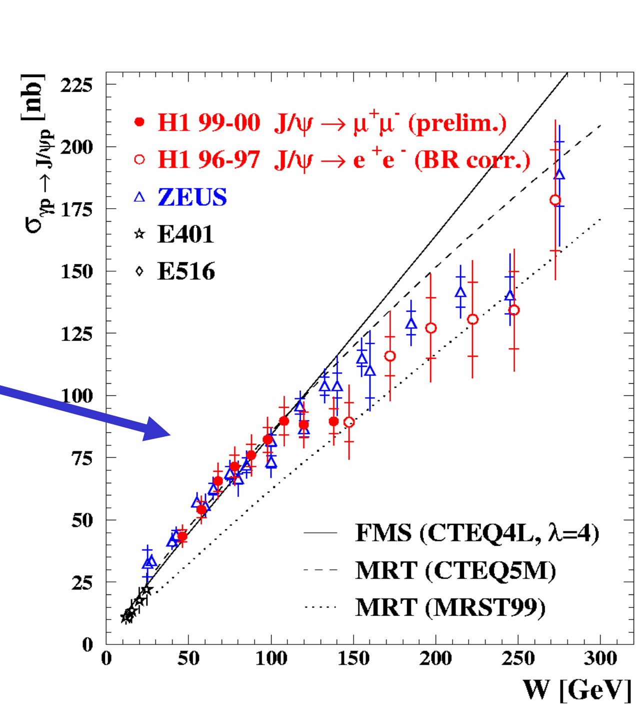
VM: sensitivity to gluons in proton



$$\sigma \propto [x\, g(x, M_V^2)]^2$$

$$x = M_V^2 / W^2$$





$\mathbf{W} \propto 1/\sqrt{\mathbf{x}}$

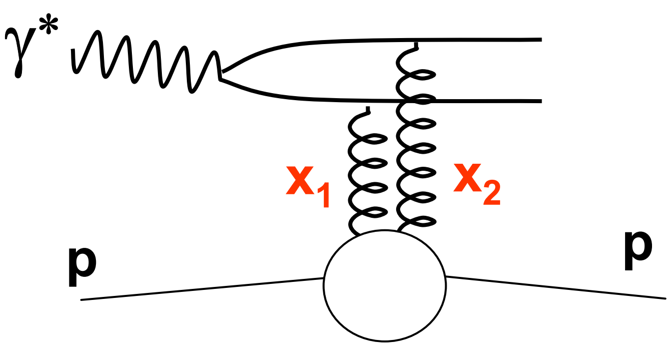
γp centre-of-mass energy

At large M_V, data well reproduced by pQCD

Summary II

- **Hard diffraction sensitive to proton structure and calculable in QCD**

- **(not discussed) Hard diffraction sensitive to correlations in the proton:**



In general, $x_1 \neq x_2$:

$$\sigma \propto [x\, g(x)]^2$$

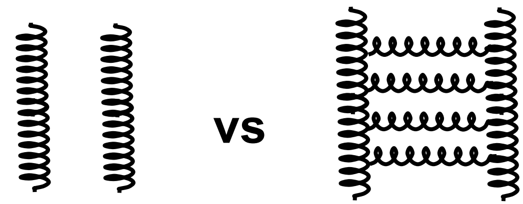
$$\downarrow$$

$$\boxed{\sigma \propto [H(x_1, x_2)]^2}$$

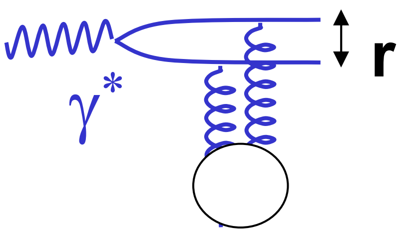
Generalised parton distribution functions (GPD)

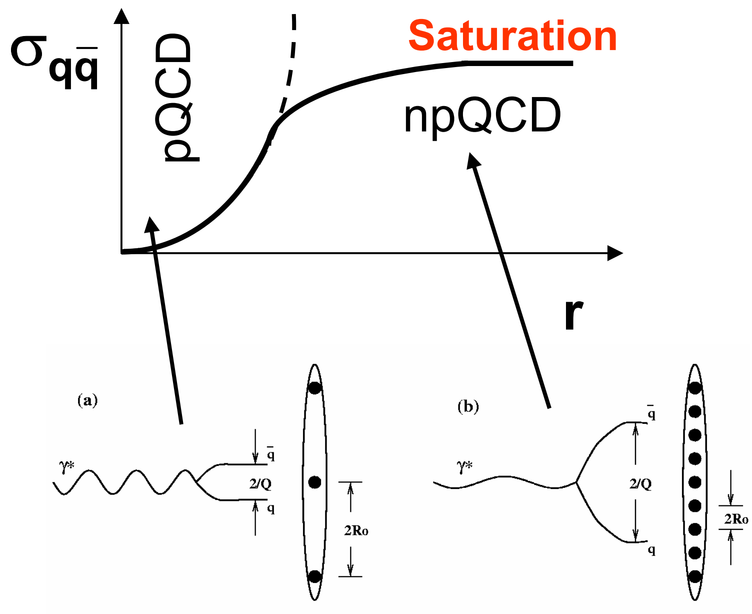
Open questions II

- Detailed understanding of higher orders:



- Transition to $(Q^2+M_{q\bar{q}}^2)=0$ and non-perturbative QCD:





connection to high-density QCD, saturation of parton densities, colour glass condensate, RHIC

- ...

Part III

The future:

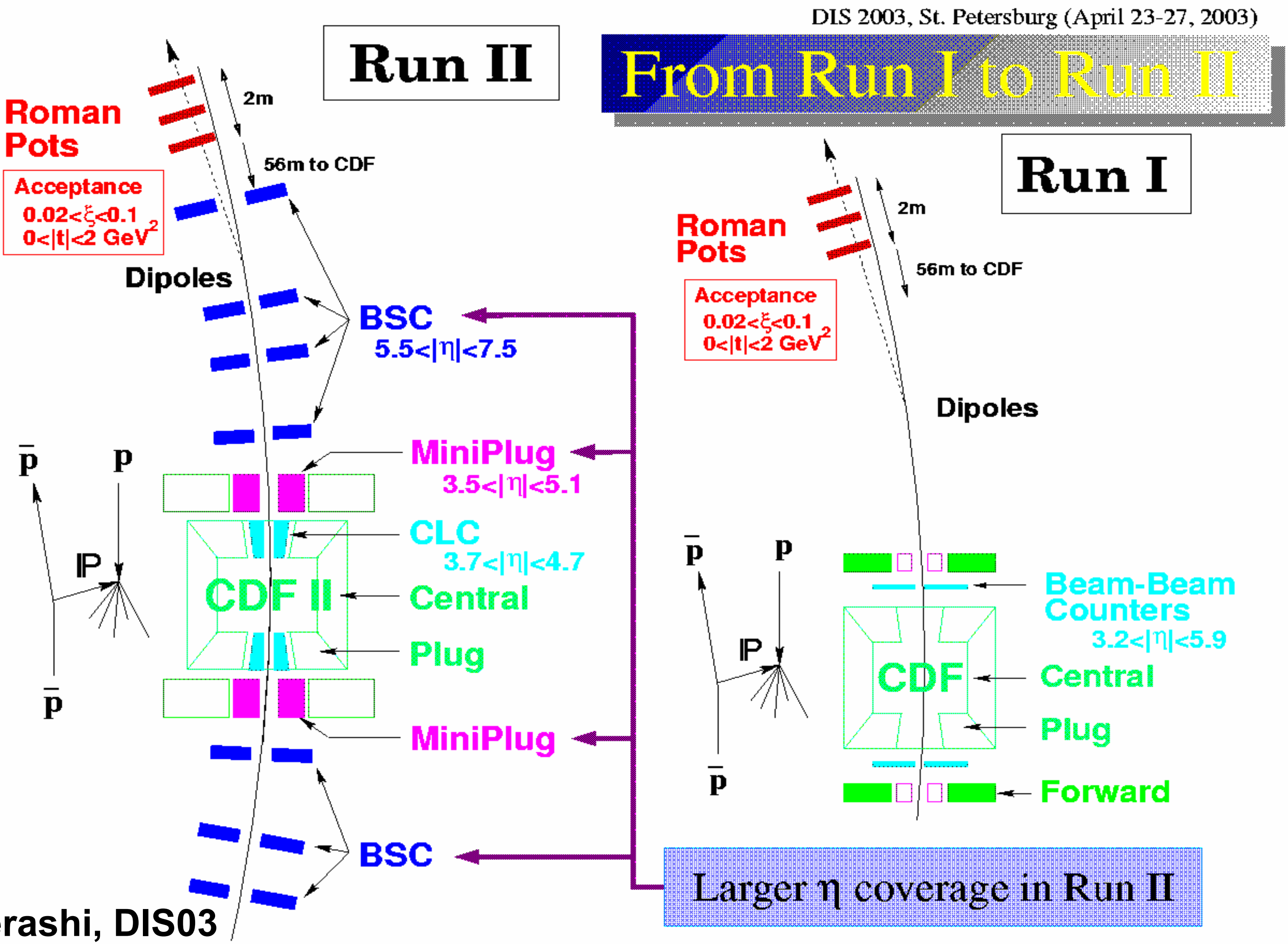
- **Diffractive physics programs at Fermilab, DESY, CERN**
- **Diffractive Higgs production – the way to discover a light Higgs ?!**

A look at the future

Aggressive diffractive programs at Fermilab, DESY and CERN:

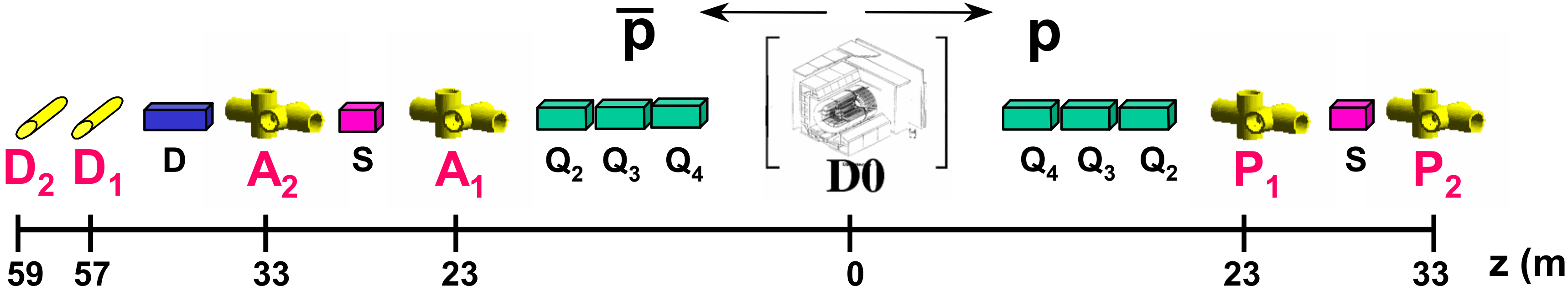
- **CDF: new Beam Shower Counters, miniplug calorimeters**
- **D0: new Roman Pot spectrometer**
- **H1: new Very Forward Proton Spectrometer**
- **DESY: HERA III after 2006 ?**
- **CMS/TOTEM Forward Physics Project: study diffraction and forward physics at full LHC luminosity.**
  Roman Pots and microstations
- **ATLAS: studying the feasibility of forward detectors**

New ‘diffractive’ detectors at CDF



K. Terashi, DIS03

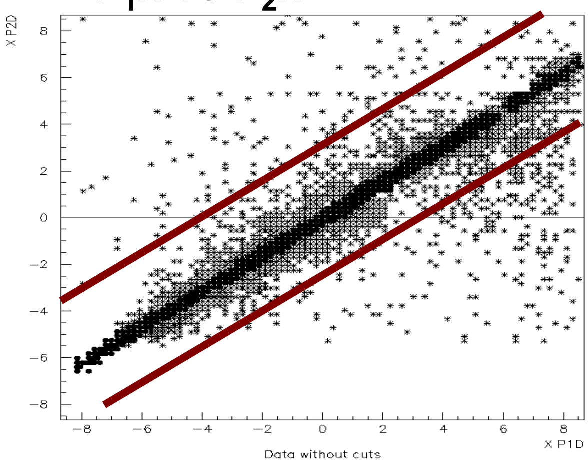
D0 Forward Proton Detectors



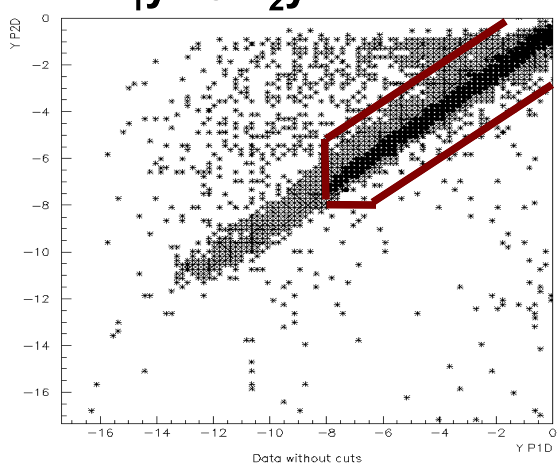
Currently partially integrated into D0 readout, full 18 pot system will be integrated when data taking restarts in November

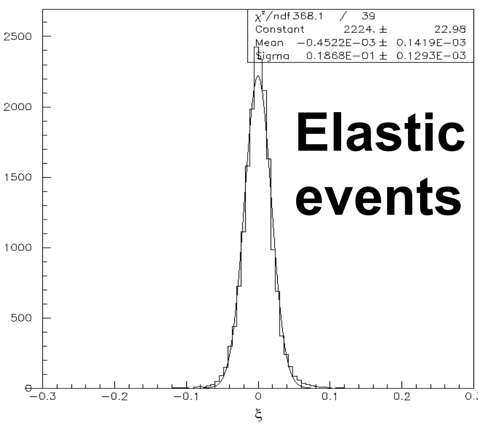
Run 2 data:

P_1x vs P_2x



P_1y vs P_2y





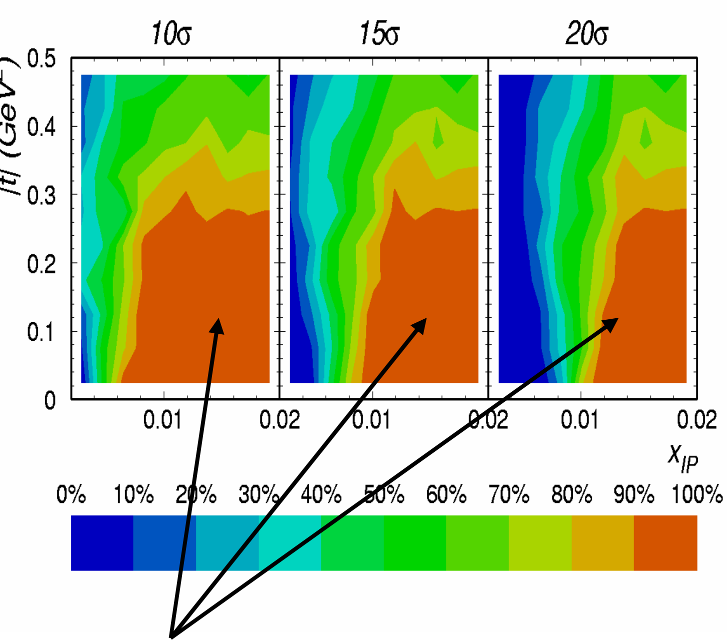
$\xi = x_{IP}$

● MC
* Data

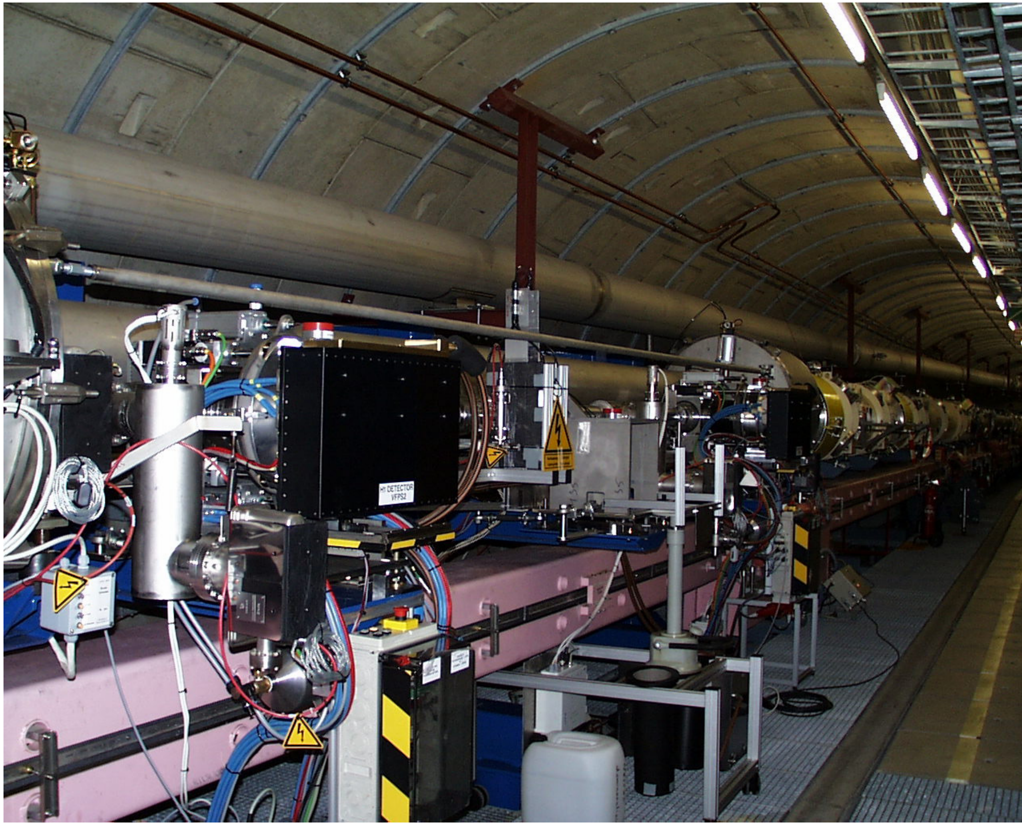
H1 Very Forward Proton Detector

- 2 stations at 220 m from interaction point (cold section !)
- Acceptance down to t=0 for x_{IP}=10^{-2},
- 100% for t<0.2 and 0.01<x_{IP}<0.02

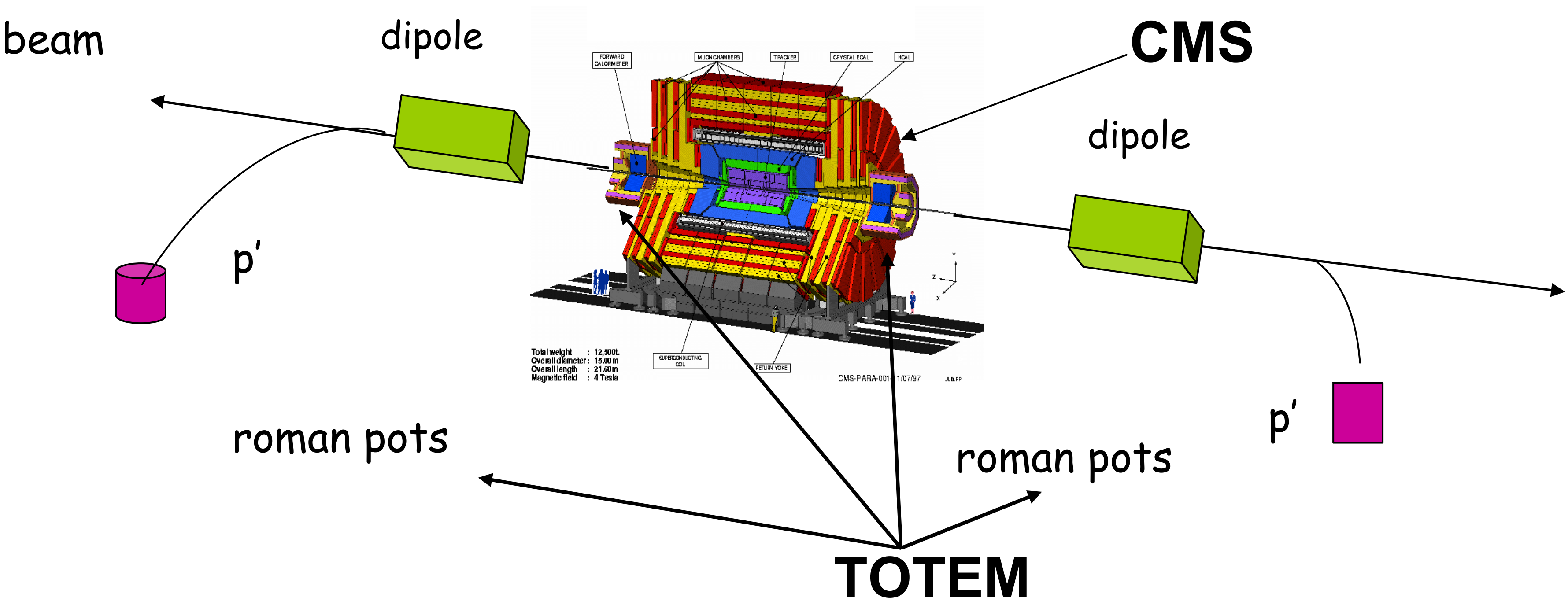
Acceptance t vs x_{IP}



>90% !



CMS/TOTEM Forward Physics Project



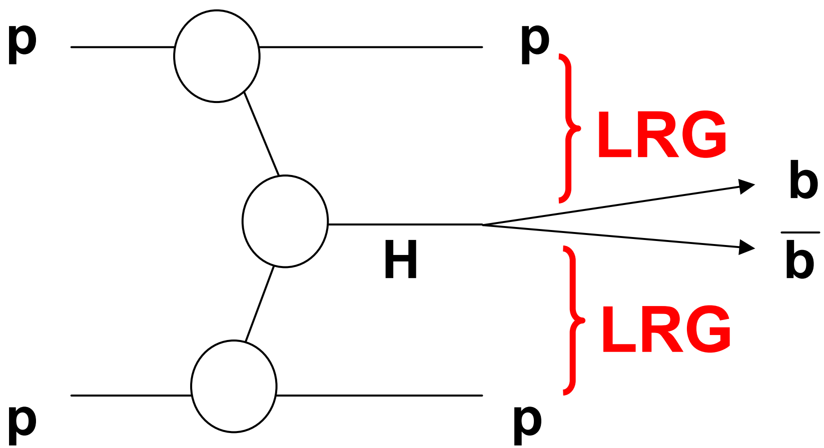
- **Totem:** Measure total & elastic cross sections, soft diffraction. Inelastic detectors (CSC), Roman Pots at 150, 215 m, same I.P. as CMS

- **CMS/Totem Forward Physics Project:** hard diffraction, forward physics at full LHC lumi. Roman Pots/μ–stations at 310/420 m (?), very forward EM/HAD calorimeter, Si-tracker, Zero-degree calorimeter at 140 m $\rightarrow$ EOI by summer '04

Diffractive Higgs at Tevatron/LHC

- **For light Higgs (≈ 120 GeV), $gg \to H$, $H \to b\bar{b}$ mode has highest branching ratio, but signal swamped by $gg \to b\bar{b}$**

- **Signal-to-background ratio improves dramatically for 2 rapidity gaps and/or outgoing protons tagged: S/B~3; for 30 fb^{-1}, observe 11 events** [Khoze, Martin, Ryskin]

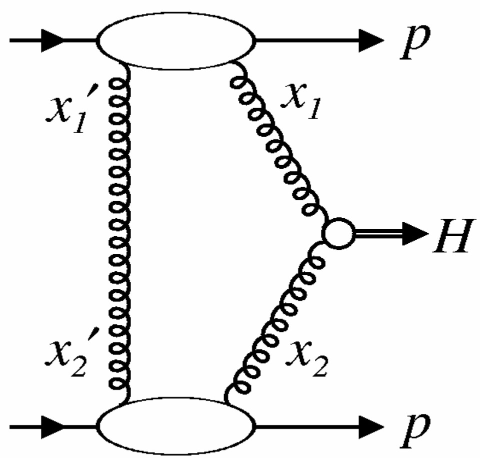


Reconstruct M_H from $b\bar{b}$ and/or from scattered protons with missing mass method
250 MeV resolution at Tevatron
1-2 GeV resolution at LHC

$H \to \tau\tau$, WW also OK

- **Major, but not insurmountable, experimental difficulties – eg (at LHC) event pile-up at high lumi (≈23 interactions/bunch crossing) 'spoils' rapidity gaps; Roman Pot signals too late for L1 trigger**

Diffractive Higgs at Tevatron/LHC



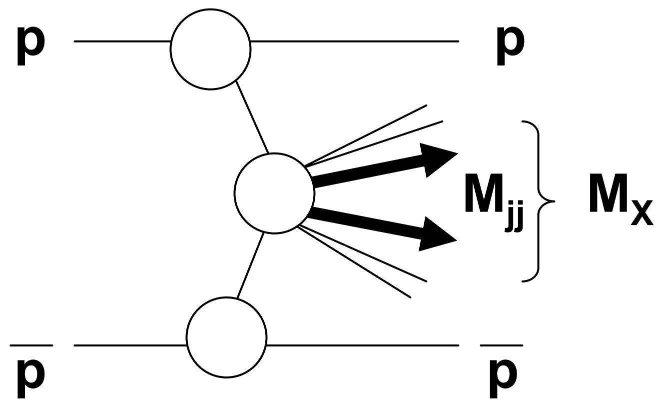
- **Proton diffractive PDFs essential for prediction**
- **Understanding of factorisation breaking ep vs pp, $p\bar{p}$ essential, including √s dependence**

- **Wide range of theoretical predictions – consensus ?**
  Bialas and Landshoff, Cudell and Hernandez; Levin; Kharzeev, Levin; Khoze, Martin and Ryskin; Cox, Forshaw and Heinemann, Boonekamp et al, Enberg et al, Godizov et al, …
  [some ruled out by Tevatron data]

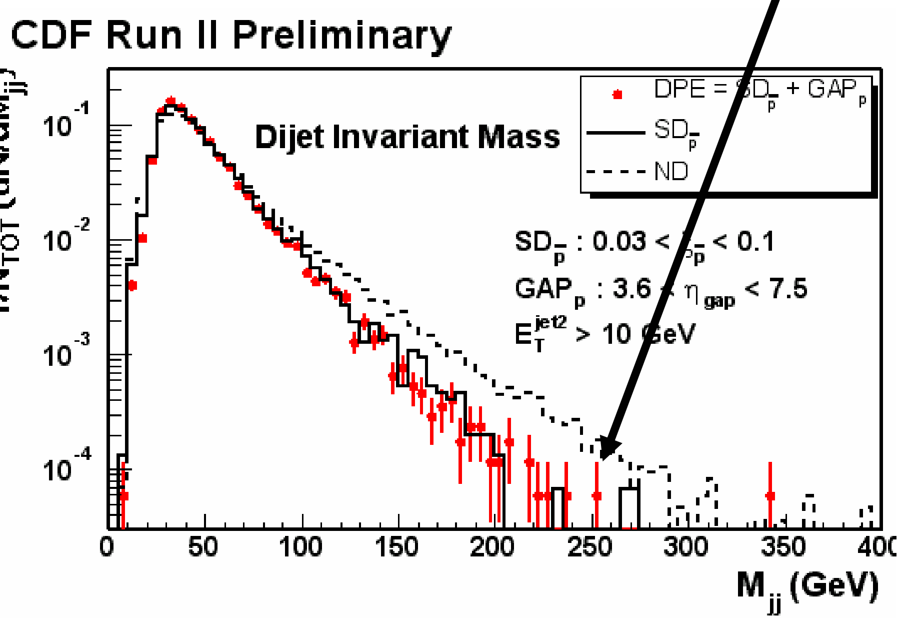
- **A very promising field – lots more theoretical and experimental work necessary**

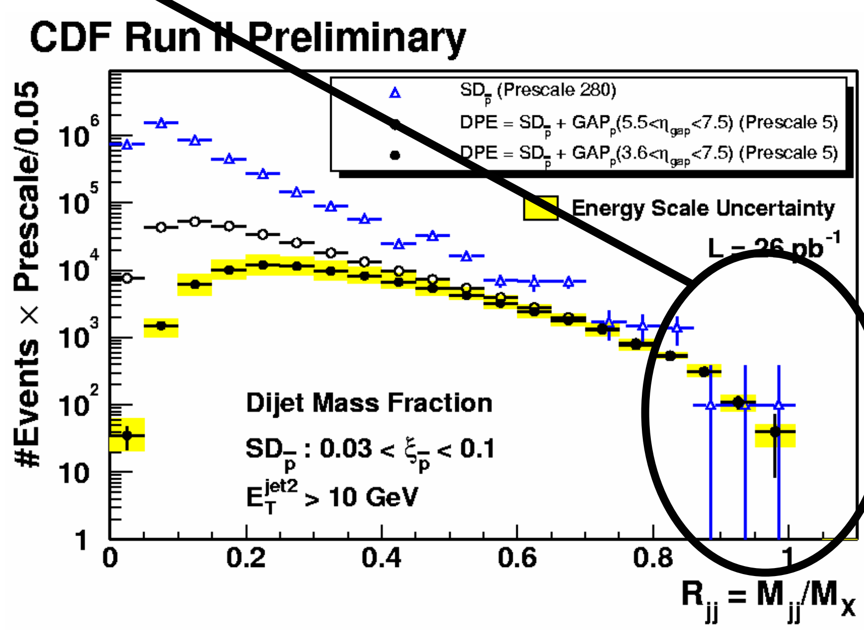
Diffractive dijets at Tevatron

On the way to diffractive Higgs:



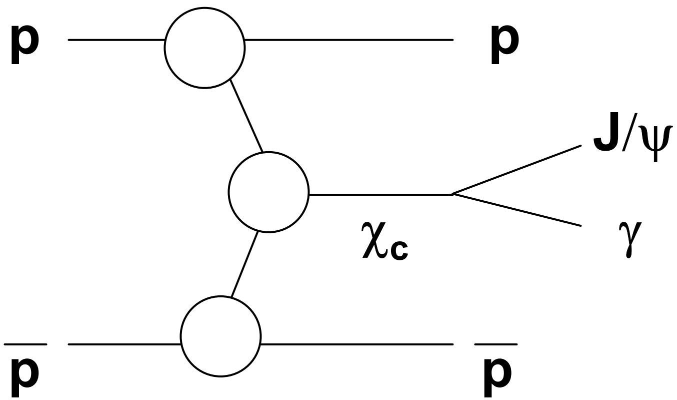
- **Helps constraining theory**
- **Exclusive dijet production would appear as a peak at $R_{jj}=M_{jj}/M_X=1$**
- **Very large values M_{jj} (up to 250 GeV !)**
- **No peak observed in the data (yet...)**

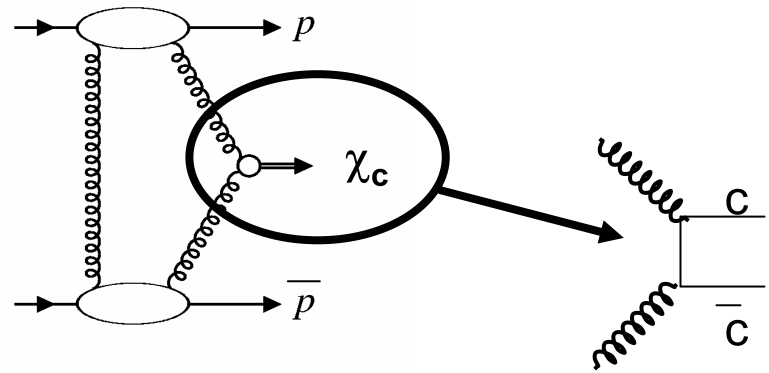




Diffractive χ_c at Tevatron

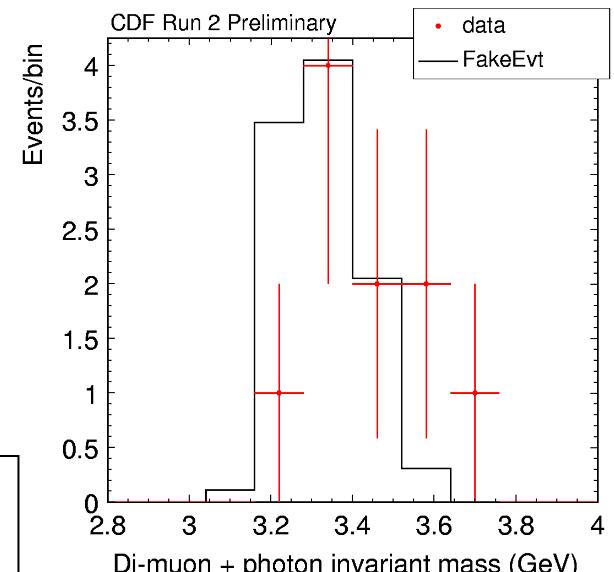
On the way to diffractive Higgs production:





- **H proceeds via the same diagram but t-loop instead of c-loop**

- **Important for calibrating models on diffractive Higgs**



10 candidate events (but unknown background)
$\sigma <$ 49 $\pm$ 18 (stat) $\pm$ 39 (syst) pb
for exclusive χ_c production for $|y|<0.6$

$M_{J/\psi-\gamma}$

Grand summary

- Diffraction is due to the exchange of partons from the proton carrying the vacuum quantum numbers (gluon pairs) $\rightarrow$ probe diffractive PDFs of the proton
- Hard scattering factorisation works in diffractive events (but rescattering corrections to go from ep to pp, $p\bar{p}$)
- Diffraction with a hard scale calculable in QCD
- Sensitivity to gluon density, correlations in proton (GPDs)
- Saturation: a window on the transition to npQCD
- Diffraction as a means to search for new physics
- Plenty more experimental and theoretical work necessary
Input from $p\bar{p}$, pp, AA, ep, eA <u>essential</u>