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Hard Diffraction

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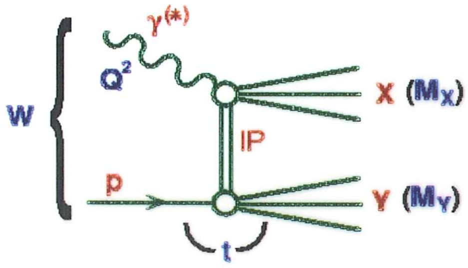
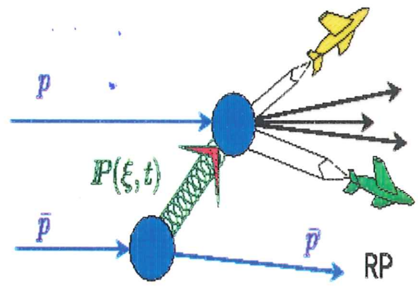




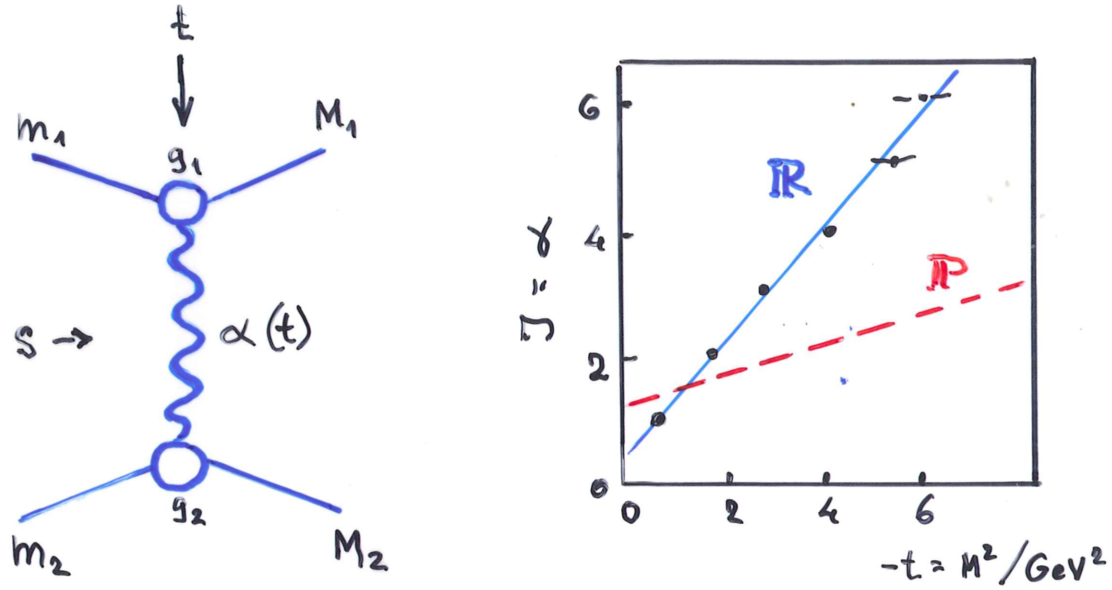
Outline

- **Introduction:**
  Regge → QCD → Effective Field Theory ?
- **Hard diffraction at HERA:**
  probing the partonic structure of diffractive exchange
- **Hard diffraction at the Tevatron:**
  testing the Pomeron universality
- **Recent developments in theory:**
  how many Pomerons?
- **Summary and Outlook**

Introduction – RFT

60's-70's: Regge Approach

- **Simple Regge pole model**



$$\alpha(t) = \alpha(0) + \alpha' t$$

$$A(s,t) = g_1(m_1, M_1, t) g_2(m_2, M_2, t) \frac{s^{\alpha(t)} \pm (-s)^{\alpha(t)}}{sin(\pi\alpha(t))}$$

- **Reggeon Calculus ((V.Gribov)**

  asymptotic behavior of $A_{ab}(s,t)$ at $s \to \infty, \ \frac{t}{s} \ll 1$ is independent on underlying dynamics!

- **AGK cutting rules (Abramovski, Gribov,Kancheli) → multi Pomeron exchange amplitude and multiparticle production**

⇒ RFT – effective 2-dim. field theory (t, s factorized)

Regge theory – side remark

A common prejudice:

Regge approach represents an outdated, old-fashioned phenomenology, which now is fully substituted by QCD.

⇒ This is wrong !

In Gribov's formulation Regge theory is a very general relativistic field theory for any two body scattering at high energies, provided the processes involving large virtual masses are damped (i.e. short range forces have non singular behavior)

Recent example:

A Model for High Energy Scattering in Quantum Gravity
by T.Banks and W. Fischler, hep-th/9906038

- discussing two body scattering at $\sqrt{s}$ bigger than Plank scale
- formation, decaying (and perhaps scattering?) of black holes

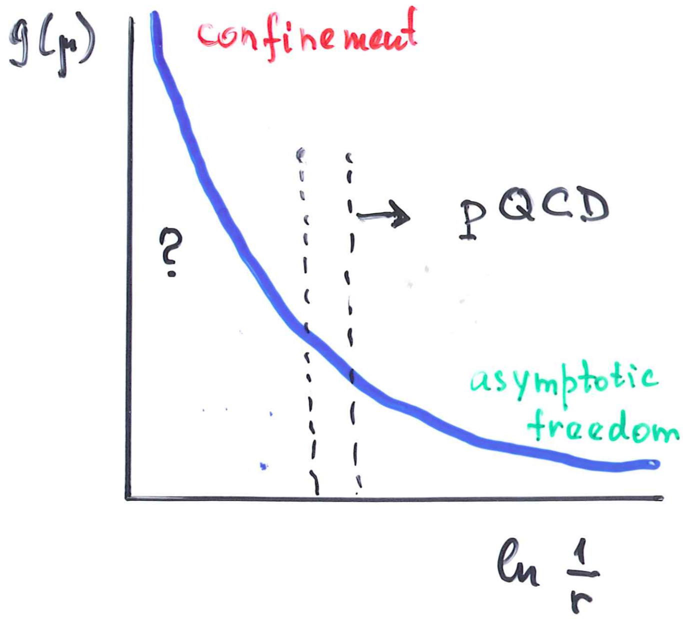
Remember also:

A string theory was originally invented as a model to reproduce a Regge behavior for high energy scattering in hadron physics.

Introduction – QCD

70's-80's: QCD Era

- **Successes:**
  mainly in perturbative sector



- **Problems:**
  in the regime of confinement

- **Simplest $I\!\!P \Rightarrow 2g$ exchange**

- **Fundamental questions:**

  ▷ **what to do in non-perturbative sector?**

  ▷ **how to reproduce RFT properties?**

  ▷ **how the transition from soft to hard physics proceeds?**

90's (today): Towards Effective Field Theory

From reggeons through gluons to reggeized gluons

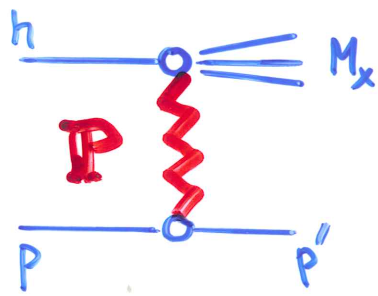
Attempts to reformulate QCD at high energies as an effective field theory for reggeized gluons

(L.Lipatov et al)

(BFKL equations / dynamics)

Introduction – Experiments

- **Fixed target hh data**



  ▷ $\sqrt{s} < 20$ **GeV;** $M_x^2/s \ll 1 \rightarrow$ **low** M_x

  ▷ **high statistics, many experimantal data on** $\sigma_{tot}, \sigma_{el}, d\sigma/dt, d\sigma/dM_x^2$**, inclusive spectra ...**

⇒ **diffraction is soft, periferal process**

$\alpha_{\mathbb{P}}(t) = 1.08 + 0.25t$

- **Hadron Colliders**

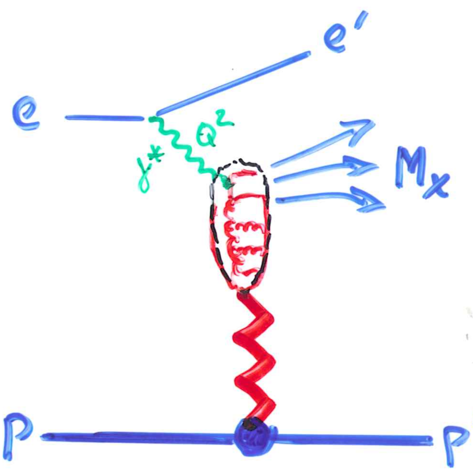
  ▷ $30 < \sqrt{s} < 1800$ **GeV** $\rightarrow$ **high mass diffraction!**

  ▷ **largest available energies** $\rightarrow$ **asymptotic regime**

  ▷ **hard scattering (jets) in diffraction**

⇒ **interesting but complicated picture;**
an interplay of soft and hard physics

- **HERA**



  ▷ $\gamma^*(Q^2)$ **provides additional resolving power** ($10^{-8} < Q^2 < 10^5$ **GeV**^{2})

  ▷ $x/Q^2 \geq 10^{-5}$ **GeV**$^{-2}$ $\rightarrow$ **low** x **regime** $\rightarrow$ **high parton densities**

  ▷ **asymmetric beam configuration** $\rightarrow$ **excellent acceptance for** γ^* **diffractive dissociation system**

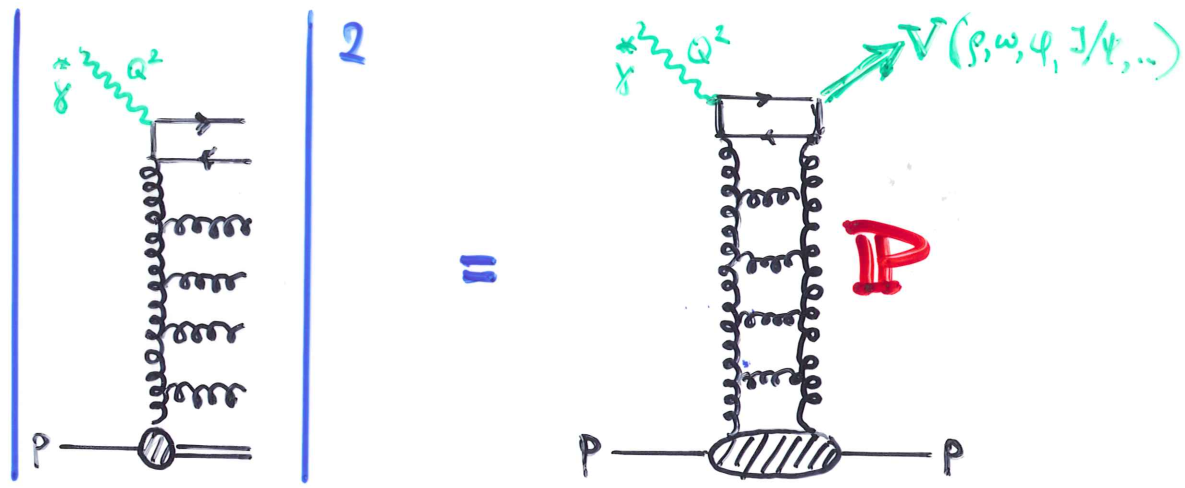
⇒ **unique facility**
to probe partonic content of diffractive exchange ($\mathbb{P}$)
to study the transition from soft to hard regime

$\alpha_{\mathbb{P}} = ?$

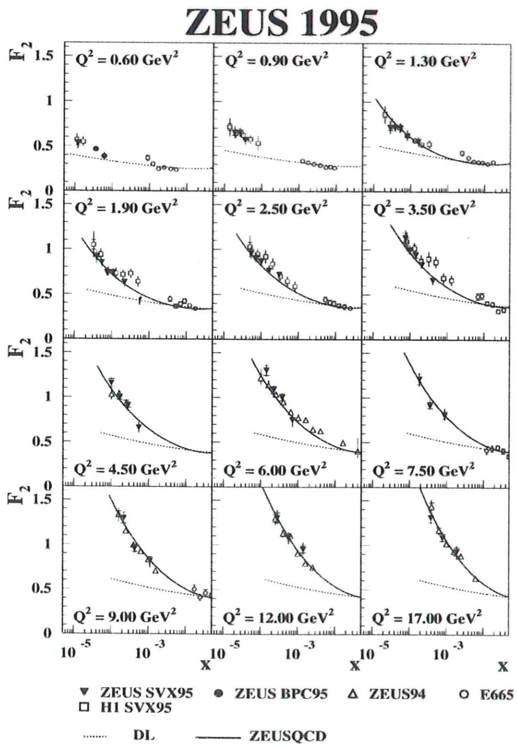
low Q^2 ↙ ↘ high Q^2

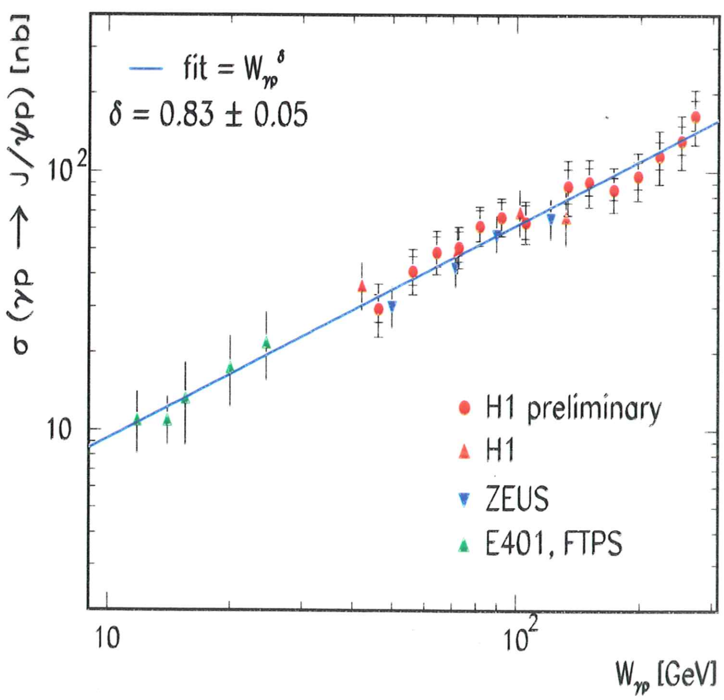
Low x physics and the Pomeron

Relating $F_2^p(x, Q^2) \sim \sigma_{tot}^{\gamma^* p}$ with elastic scattering via the optical theorem:

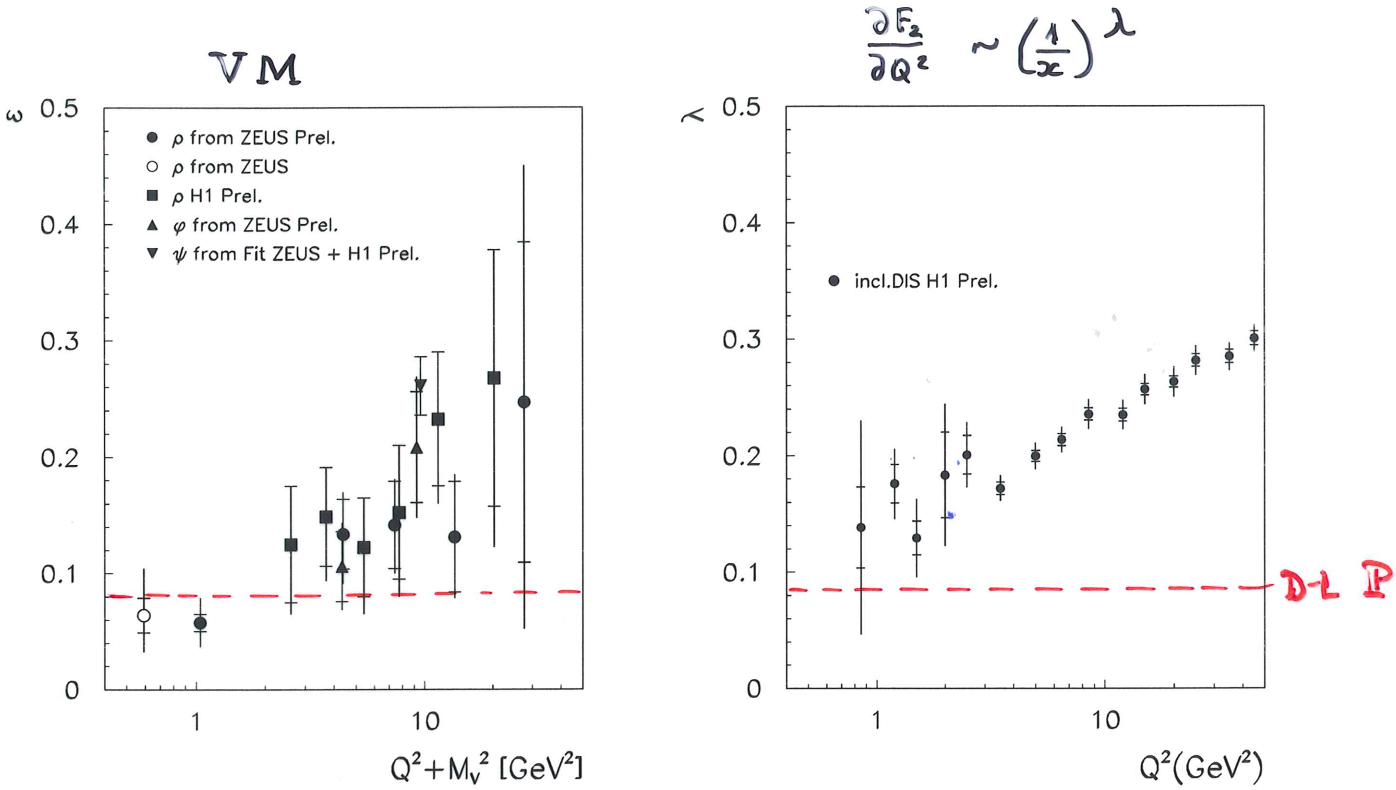


$\sigma_{tot}^{\gamma^* p} \sim s^{\epsilon}$ $\qquad\qquad$ $\sigma_{el}(\gamma^* p \rightarrow V p) \sim s^{2\epsilon}$





Scale Dependence of the Energy Behavior



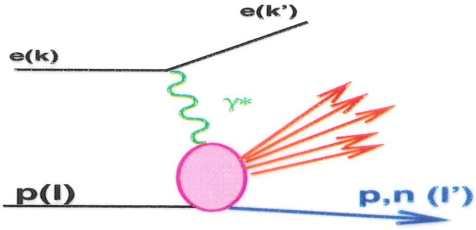
- **Data:** ▷ Striking similarity !
  ▷ Picture differs from 'soft' ℙ :
  $\alpha_{\mathbb{P}}(t) = 1.08 + 0.25t$

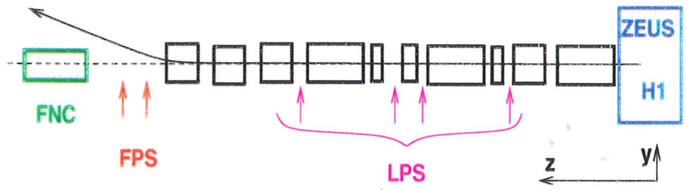
- **Speculations:**
  ▷ Sign of 'hard' ℙ ? (BFKL: $\varepsilon_{LO} \simeq 0.5$, $\varepsilon_{NLO} < \varepsilon_{LO}$)
  ▷ unitarity corrections ? ($\alpha_{\mathbb{P}}(Q^2)$ – CKMT)

The partonic structure of diffractive exchange

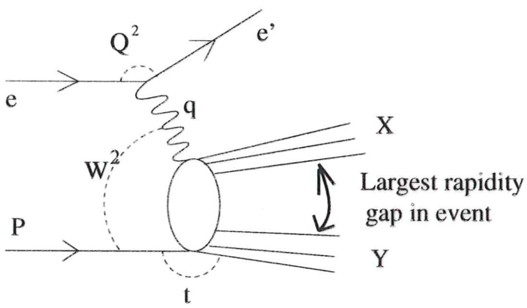
Experimental methods:

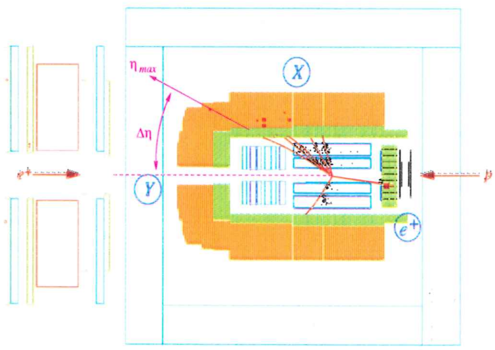
- Tagging highly energetic protons in the FPS detectors (H1, ZEUS)



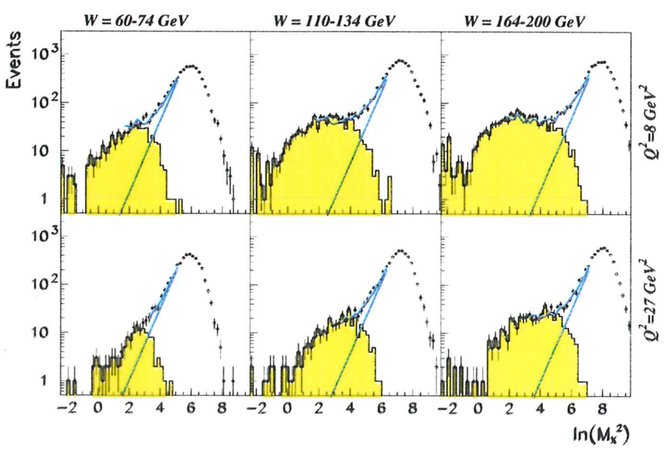


- Selecting Large Rapidity Gap (LRG) events (H1)





- Analysing mass distribution of the hadronic final state (ZEUS)

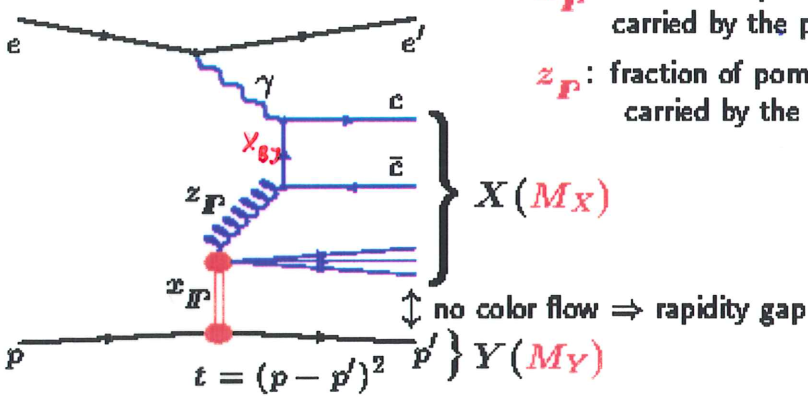


Models of diffractive DIS

Three approaches to describe diffractive processes in DIS:

- **Regge motivated models with factorizable Pomeron**
- **Perturbative QCD calculations (2-gluon exchange, BFKL ladder)**
- **Non-pomeron mechanisms, generating large rapidity gap events**

- **Resolved Pomeron** (e.g. Ingelmann, Schlein)



$x_{I\!P}$: fraction of proton momentum carried by the pomeron $(\equiv \xi)$

$z_{I\!P}$: fraction of pomeron momentum carried by the gluon $(\equiv \beta)$

$\left(\beta = \frac{x}{x_{I\!P}}\right)$

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

with (assuming factorization)

$$F_2^{D(4)}(Q^2, x_{I\!P}, \beta, t) = \Phi(x_{I\!P}, t) F_2^D(\beta, Q^2)$$

'Regge' flux:

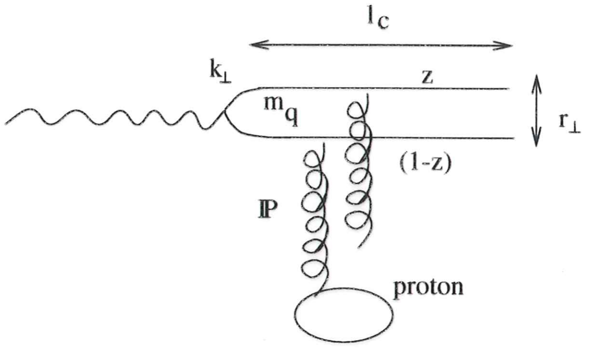
$$\Phi_{I\!P/p}(x_{I\!P}, t) = \left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}(t)-1} \cdot e^{+bt}$$

$\Rightarrow \int t \Rightarrow$

$$\Phi(x_{I\!P}) = x_{I\!P}^{-n} \qquad (n = 2\bar{\alpha}_{I\!P} - 1)$$

Models of diffractive DIS (cont'd)

- **pQCD exchange** **(BFKL, e.g. Ryskin et al, or 2-gluon model, e.g. Bartels,Lotter,Wüsthoff)**

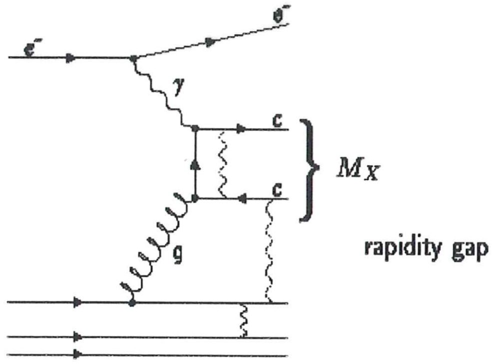


Those usually exploit Gribov's idea to describe the process in the *proton rest frame*, **which is very convenient at low x.**

$$\gamma \to q\bar{q},\ q\bar{q}g,\ \ldots$$

$$\sigma \sim |x_{\mathbb{P}} G_p(x_{\mathbb{P}}, \mu^2)|^2 \quad \text{at scale} \quad \mu^2 = (k_\perp^2 + m_q^2)/(1-\beta)$$

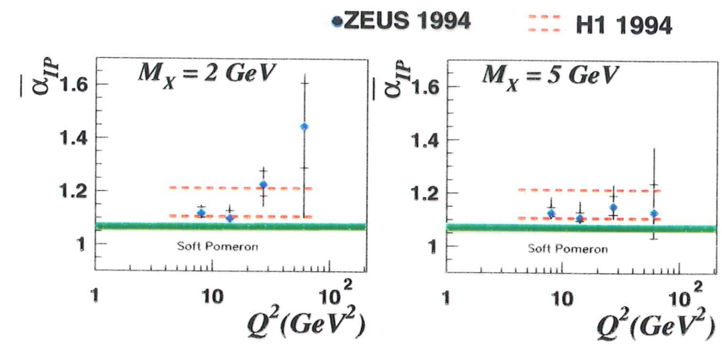
- **Soft Colour Interactions** **(e.g. Ingelmann, Rastman) – Mimic non-perturbative effects**



LRG are produced by the normal BGF with additional emittion of soft gluons, neutralizing the colour flow.

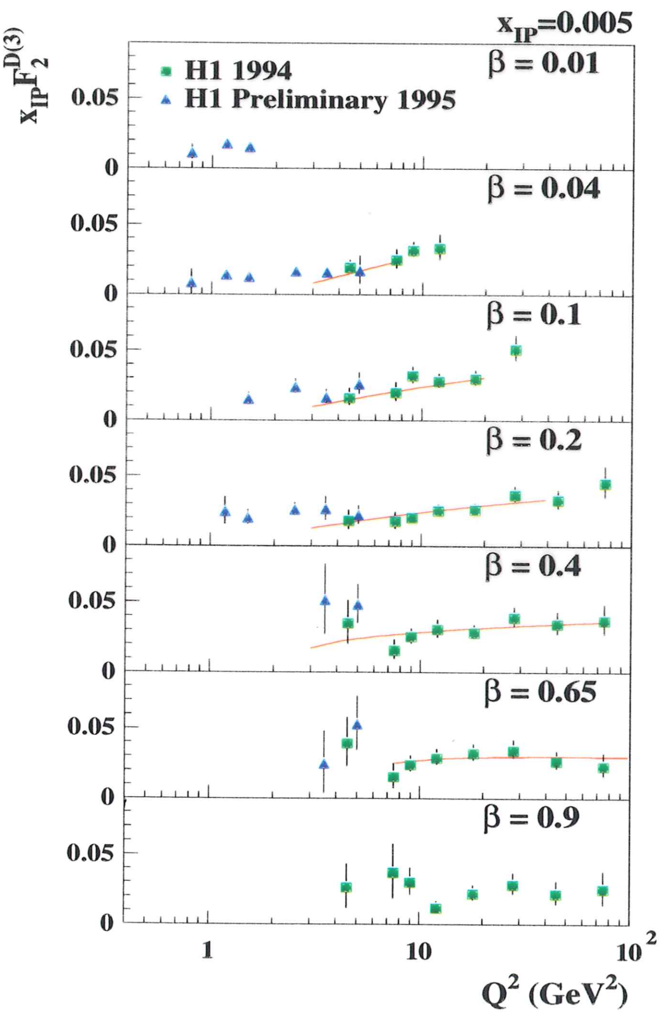
⇒ leading gluon behaviour

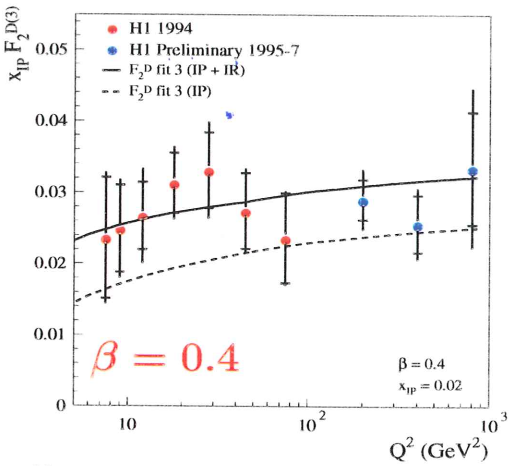
Scaling violation of F_2^D

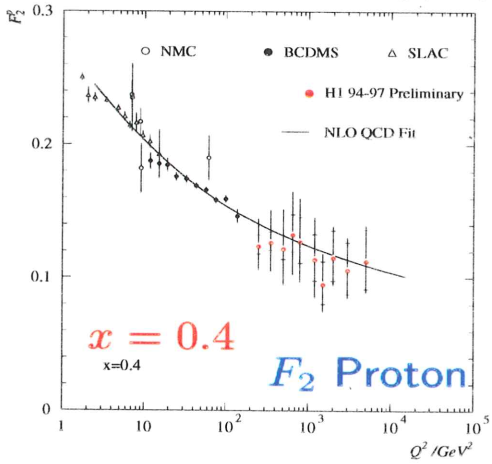


$\alpha_P(0) \simeq 1.2$

→ Larger than for soft hh-physics



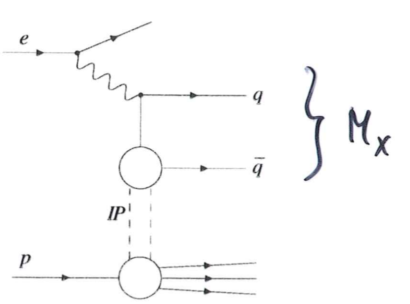


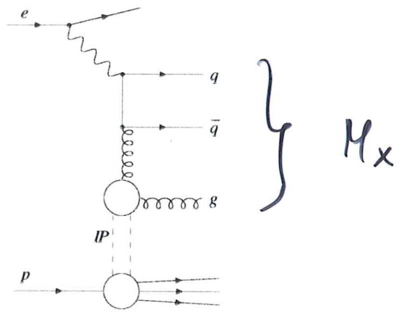


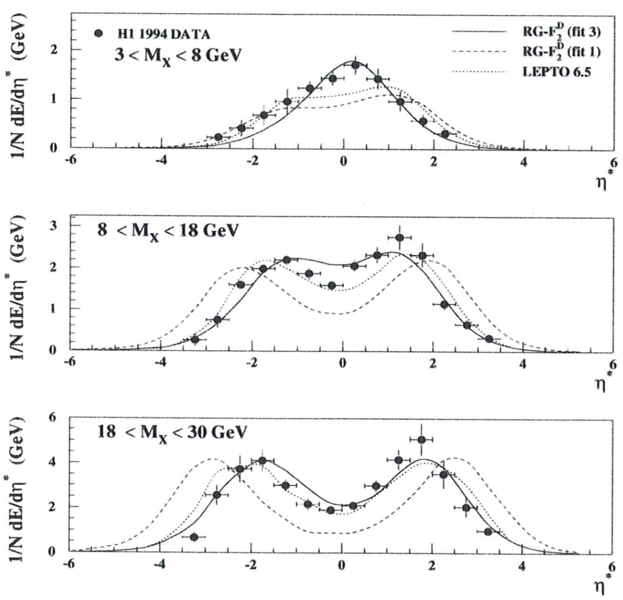
⇒ Gluon dominated mechanism

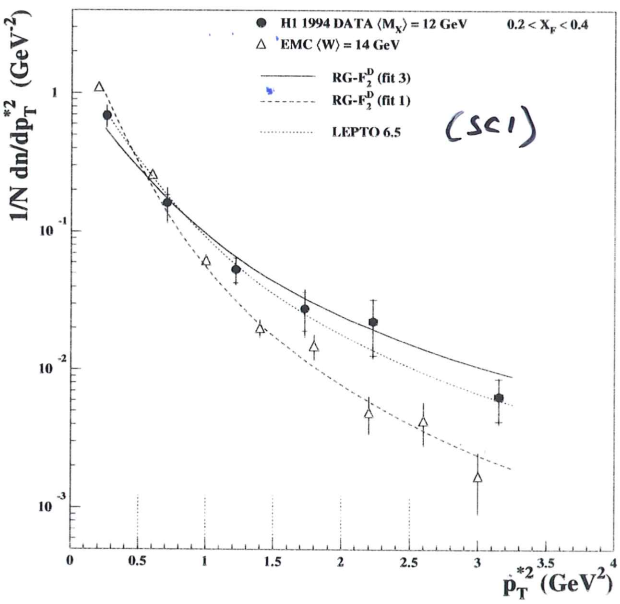
⇒ NLO QCD fit ⇒ pdf extracted ⇒ put in MC ⇒ check HFS.

Diffractive Final State Properties





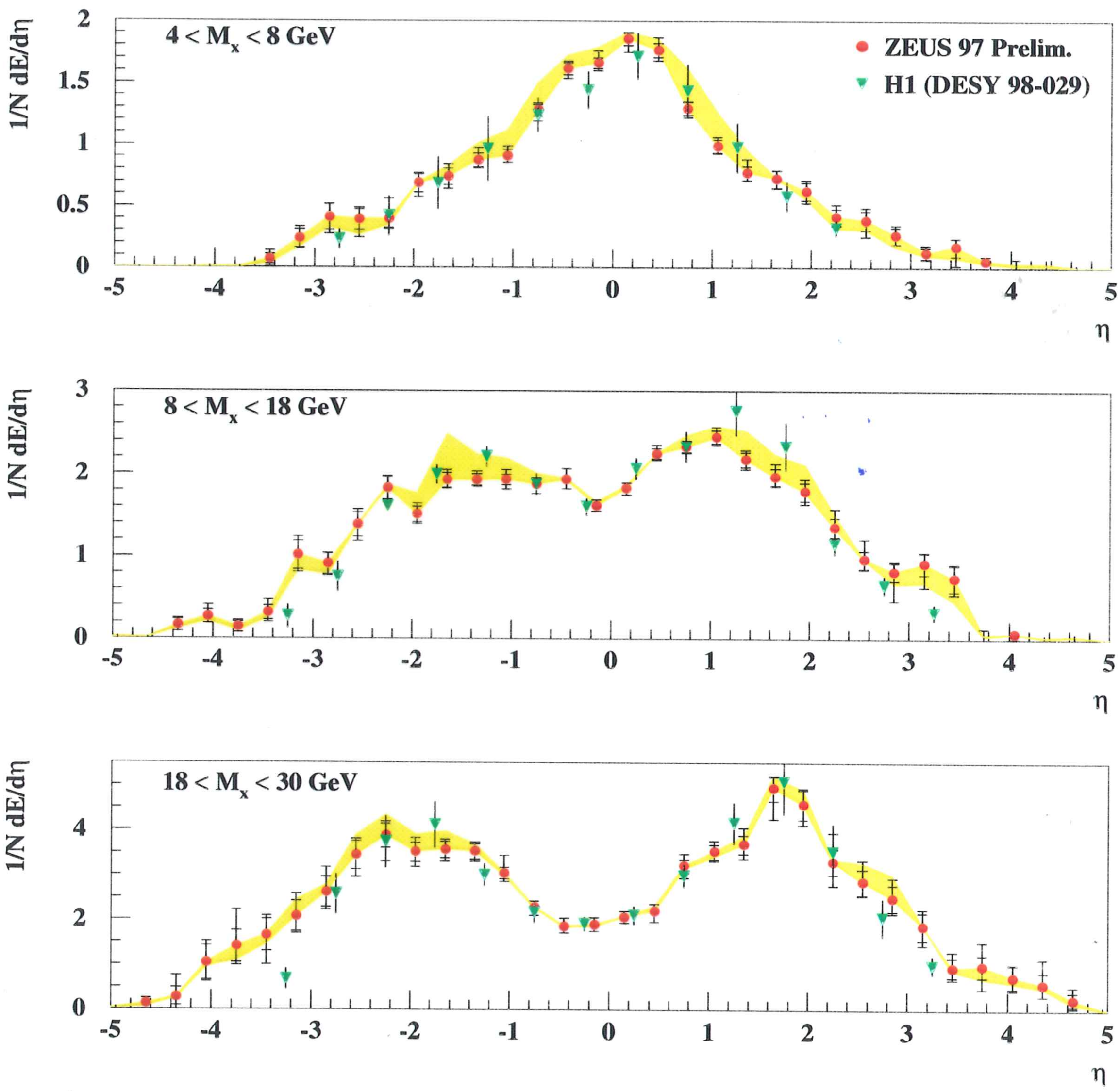




(in γ^* IP system)

⇒ Consistent with gluon dominated IP

Energy flow in the $\gamma^* I\!P$ cms frame

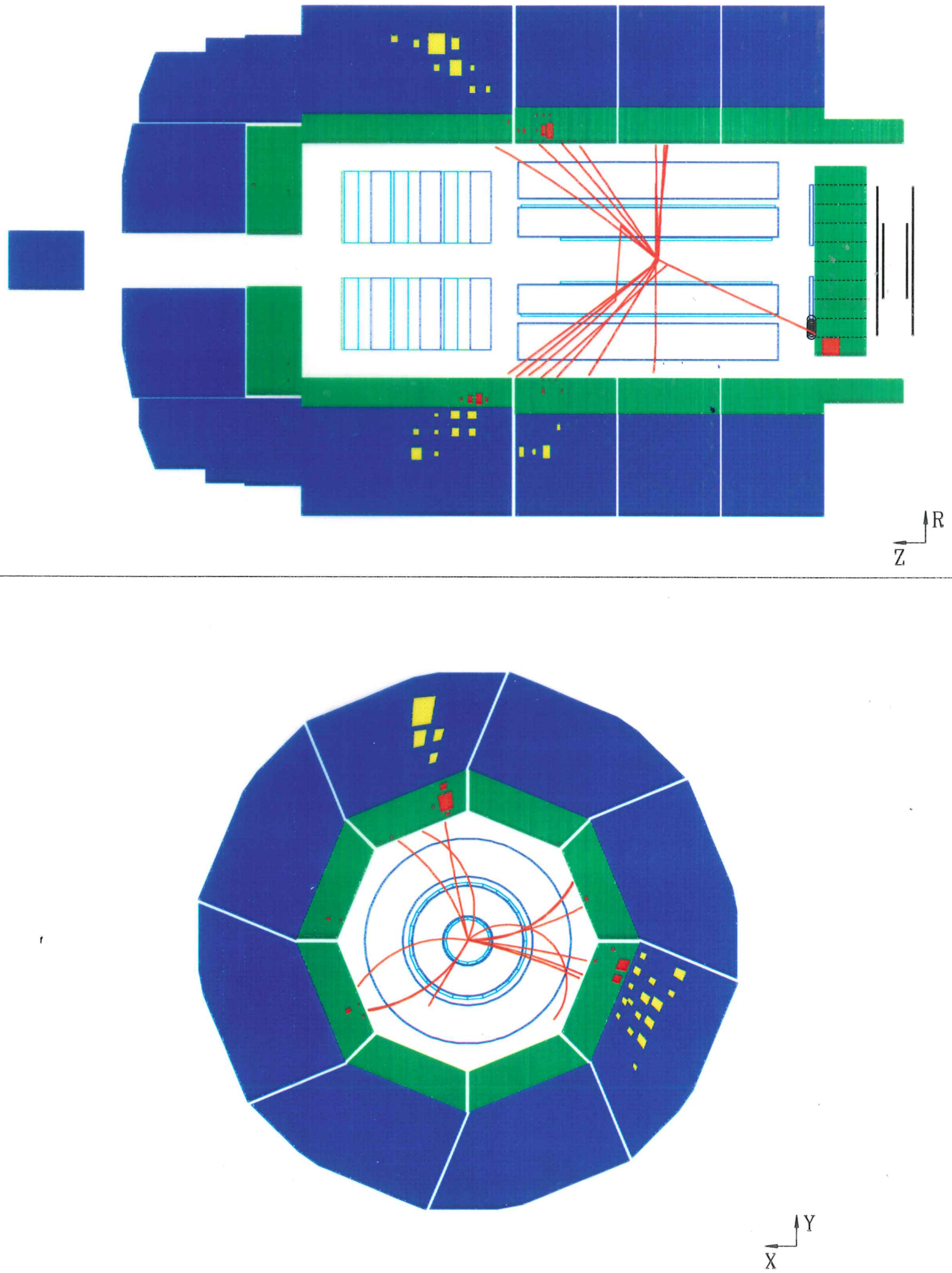


⇒ ZEUS measurement in general agreement with H1 results.

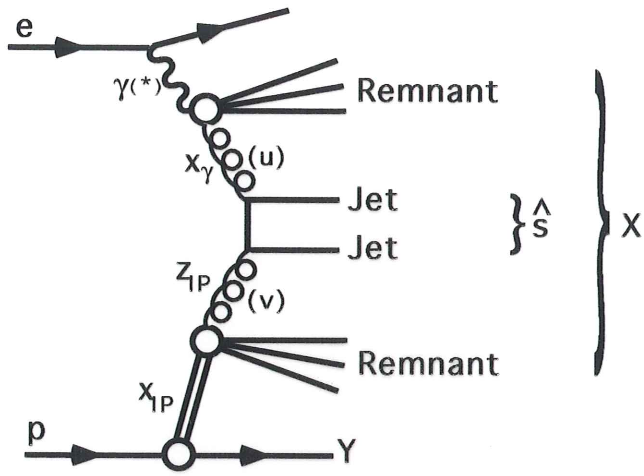
(Different datasets from H1 for $<T>$,$<S>$ and Energy flows. H1 also has different event selection(LRG) and kinematic range: $x_{I\!P} < 0.025$, M_X starts at 3 GeV.)

Run 89259 Event 150578 Class: 2 3 4 9 11 20 22 28 Date 25/07/1995

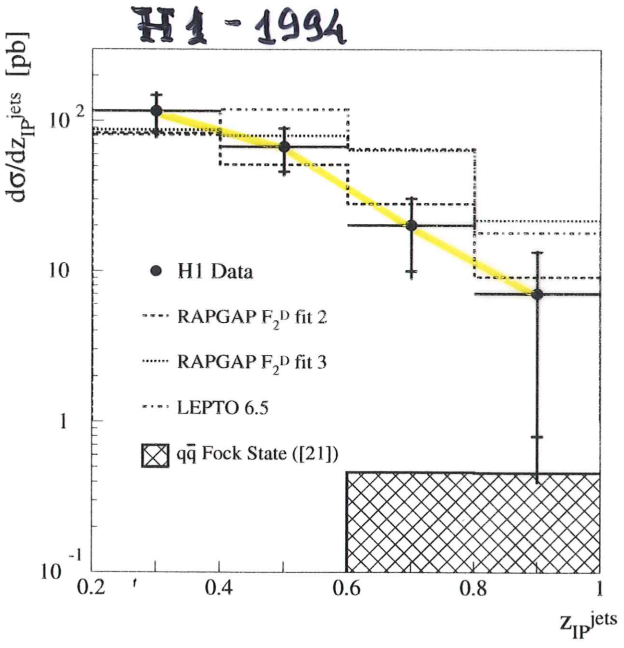
Diffractive DIS 2-Jet Event

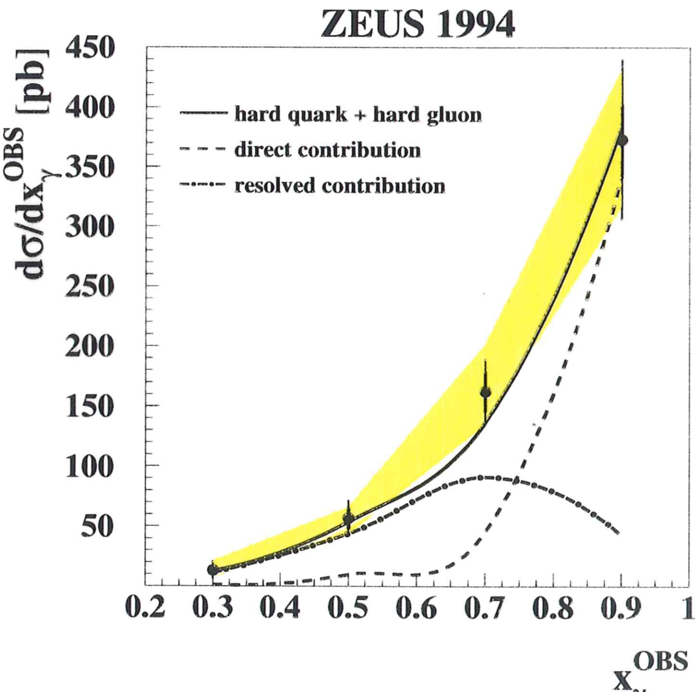


Accessing gluons in the Pomeron with jets



- Large sensitivity to gluons
- Testing the universality of IP pdf's in different kin. regime





$\gamma^* p$ ($Q^2 > 8$ GeV^2)

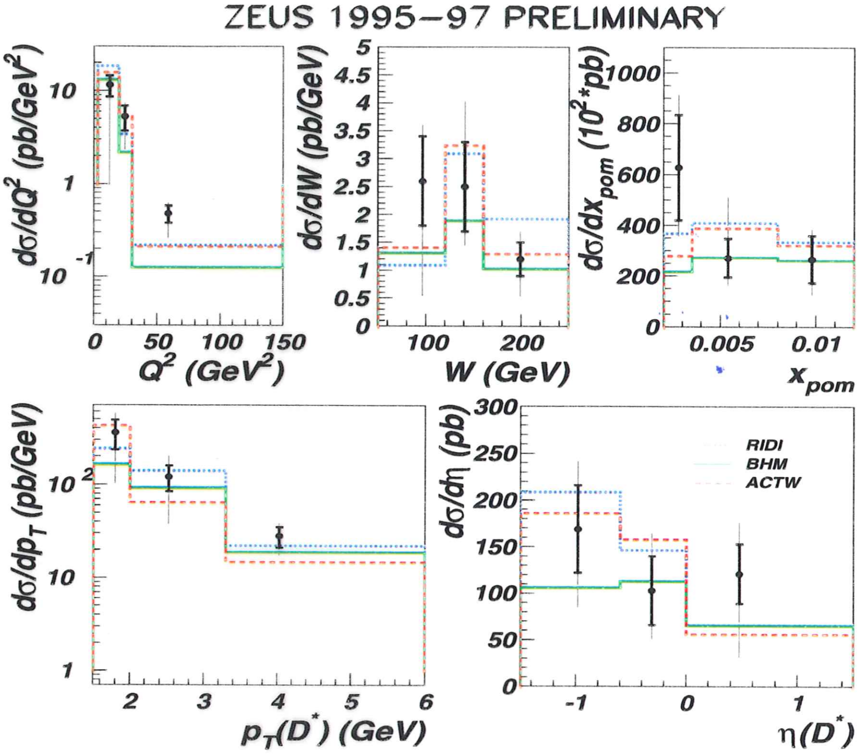
photoproduction ($Q^2 \simeq 0$)

ZEUS: C_g^{NLO} (4 GeV^2 scale) $\simeq$ 0.64 ÷ 0.94 (2 jets)

H1: (from QCD-fit of $F_2^D(\beta, Q^2)$) $\simeq$ 0.80 ÷ 0.90

Accessing gluons in the Pomeron with charm

Diffractive production of D^* in DIS regime
$\hookrightarrow K\pi\pi$



BHM Soft Colour Interaction model

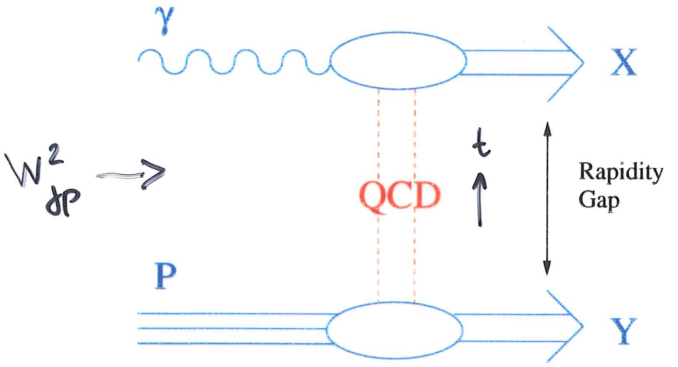
RIDI pQCD model with higher corrections

ACTW gluon-dominated resolved Pomeron model, range of HERA measurements

ZEUS: Both shapes and x-sections are in agreement with models

H1: Shapes are OK, but absolute cross-section is factor 2÷3 below MC predictions

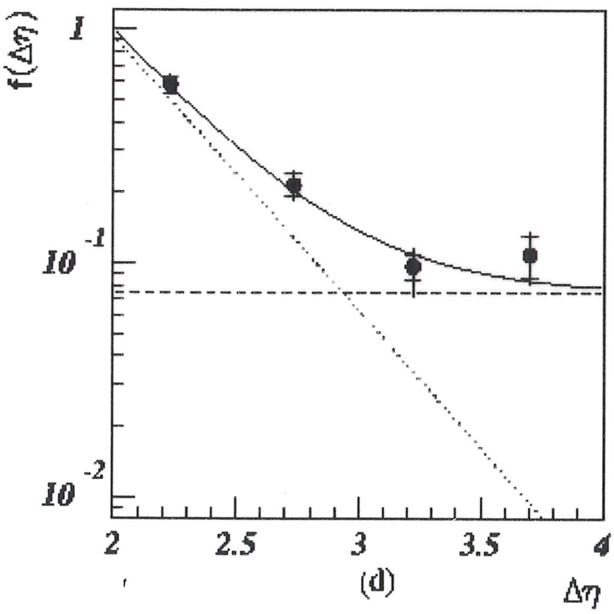
Isolating Hard Pomeron



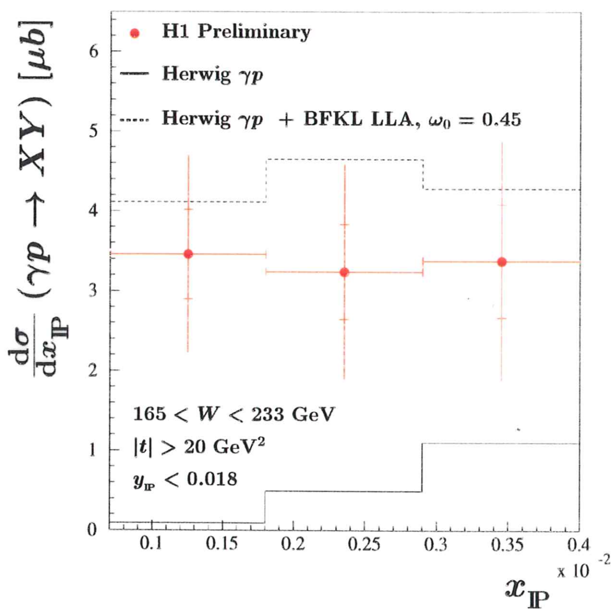
"jets"

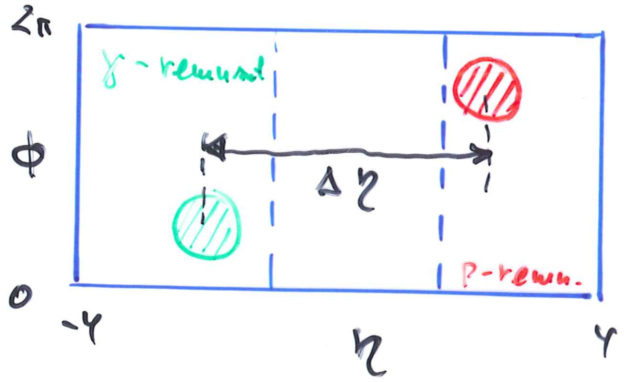
"no jets"

ZEUS-1994



H1-1996





New method!

measure γ and X only

$$t = (\gamma - X)^2$$

$$x_{I\!P} \approx \frac{M_x^2 - t}{W_{\gamma p}^2}$$

Summary on Hard Diffraction at HERA

- A relation between F_2^p at low x and Deeply Virtual Compton Scattering amplitude (or VM electroproduction) suggests the Pomeron is a gluonic ladder in DIS. For the first time HERA allows the partonic content of the Pomeron to be probed and thus to shed new light on the nature of diffractive phenomena

- Both inclusive measurements and the properties of the hadronic final states require a high gluonic content of the Pomeron, $\sim 70\% - 90\%$ (at scales $4 < Q^2 < 75$ GeV^2)

- An intercept of the Pomeron in a presence of hard scale, $\alpha_{I\!P}(0) \sim 1.2$, is found to be larger than that of the 'soft' $\alpha_{I\!P}(0) \sim 1.1$, known from hadron-hadron scattering

- The observed scale dependence of the intercept value $\alpha_{I\!P}(0)$ implies, in Regge framework, either two Pomerons, or large unitarity corrections in soft processes already at present energies

- Within the present accuracy of diffractive measurements in DIS, all three rather different theoretical approaches (Regge, pQCD, soft colour interactions) give a fair description of the HERA data

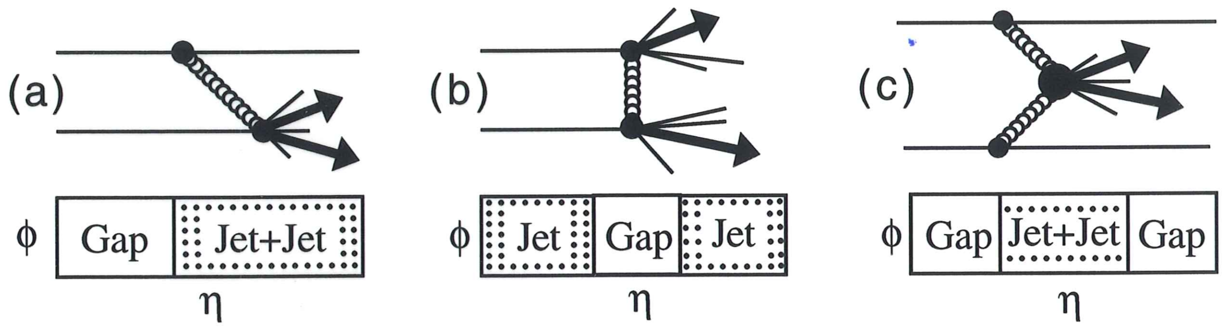
- Question: Is the Pomeron universal?

Hard Diffraction at the Tevatron

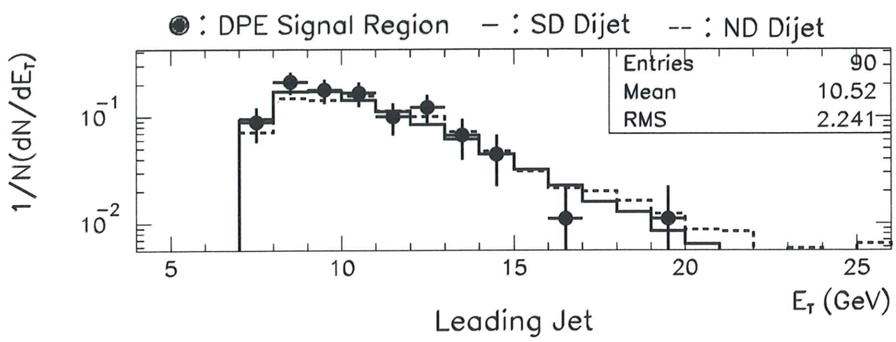
Both CDF and D0 collaborations have studied hard diffraction in $p\bar{p}$ collisions at $\sqrt{s}$ = 1800 and 630 GeV

Observables: di-jets (CDF,D0), $W-$bosons, $b\bar{b}$, J/ψ (CDF)

Diffractive di-jet event topologies



CDF Preliminary

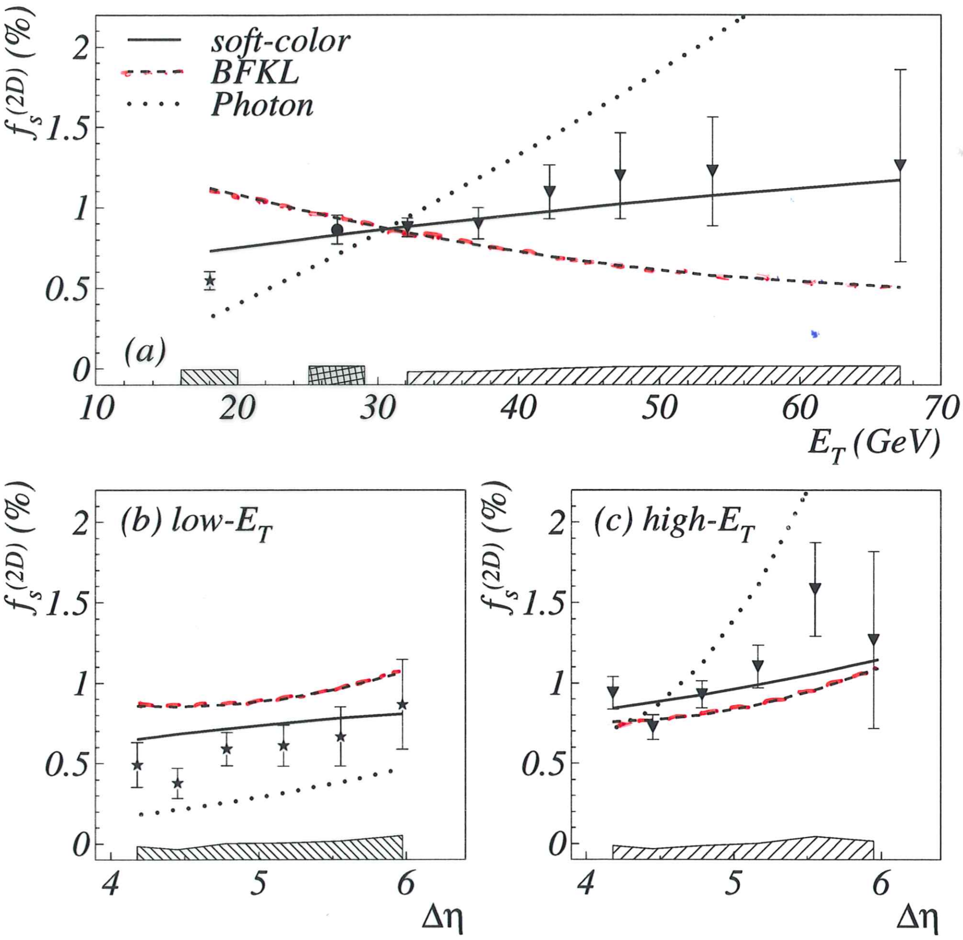


ND ($\sqrt{s}$) SD ($\sqrt{\xi s}$) DPE ($\xi\sqrt{s}$)

⇒ suggests hard partons in the Pomeron

Jet-Gap-Jet topology

$|t| \sim (E_t^{jet})^2 \quad \rightarrow$ **pQCD should be applicable**



'Photon' model (color singlet coupling to quarks only) – excluded

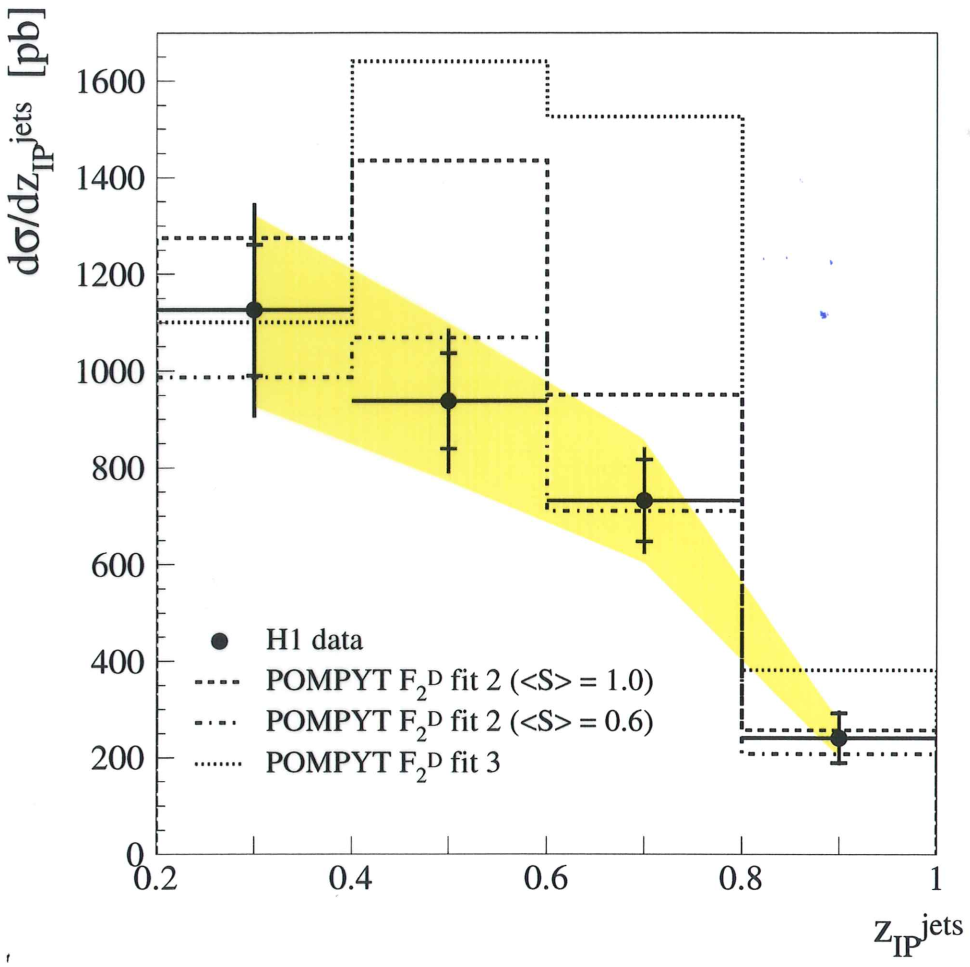
'BFKL' model (two hard gluons) – fails to describe E_T behavior

SCI model (one 'leading' gluon) – gives best description of the data

Gap Survival Probability

HERA: $\gamma p \rightarrow jet + jet + Gap + M_Y(< 1.6GeV)$

Estimated value of $< S > \approx 0.6$ **at** $W_{\gamma p} = 200$ **GeV**



Tevatron: $p\bar{p} \rightarrow jet + Gap + jet$ **measurement**

$$\frac{S(630)}{S(1800)} = 2.2 \pm 0.8$$

Calculations (*Gotsman, Levin, Ryskin, Maor, Martin*) **gives** 2.2 ± 0.2

Rates of Hard Diffractive Processes

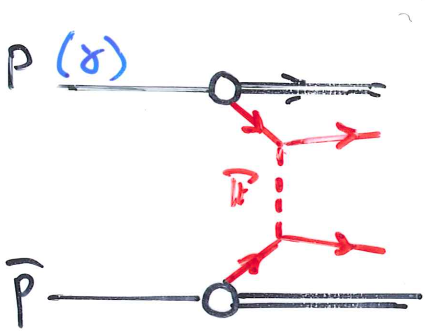
Table 1: Diffractive to total production ratios at the Tevatron (G≡rapidity gap).

Hard process	$\sqrt{s}$ (GeV)	$R = \frac{\text{DIFF}}{\text{TOTAL}}$ (%)	Comments	Exp't
SD				
$W(\to e\nu)$+G	1800	1.15 ± 0.55	E_T^e, $\not{E}_T > 20$ GeV	CDF [1]
Jet+Jet+G	1800	0.75 ± 0.1	$E_T^{jet} > 20$ GeV, $\eta^{jet} > 1.8$	CDF [2]
Jet+Jet+G	1800	0.76 ± 0.08	$E_T^{jet} > 12$ GeV, $\eta^{jet} > 1.6$	DØ *
Jet+Jet+G	630	1.11 ± 0.23	$E_T^{jet} > 12$ GeV, $\eta^{jet} > 1.6$	DØ *
$b(\to e + X)$+G	1800	0.62 ± 0.24	$\lvert\eta^e\rvert < 1.1$, $p_T^e > 9.5$ GeV	CDF*
$J/\psi(\to \mu\mu)$+G	1800	$(0.64 \pm 0.12)/\mathcal{A}^{\dagger}$	$\lvert\eta^\mu\rvert < 0.6$, $p_T^\mu > 2$ GeV	CDF*
DD				
Jet-G-Jet	1800	1.13 ± 0.16	$E_T^{jet} > 20$ GeV, $\eta^{jet} > 1.8$	CDF [3]
Jet-G-Jet	1800	0.54 ± 0.17	$E_T^{jet} > 12$ GeV, $\eta^{jet} > 1.6$	DØ [4]
Jet-G-Jet	630	2.7 ± 0.9	$E_T^{jet} > 8$ GeV, $\eta^{jet} > 1.8$	CDF [5]
Jet-G-Jet	630	1.85 ± 0.37	$E_T^{jet} > 12$ GeV, $\eta^{jet} > 1.6$	DØ [4]
DPE				
$\bar{p}$-(Jet+Jet)-G	1800	$\sim 10^{-3}/\mathcal{A}_{DPE}^{\ddagger}$	$E_T^{jet} > 7$ GeV, $0.04 < \xi_{\bar{p}} < 0.1$	CDF*
G-(Jet+Jet)-G	1800	$\sim 10^{-3}/\mathcal{A}_{DPE}^{\ddagger}$	$E_T^{jet} > 12$ GeV	DØ *
G-(Jet+Jet)-G	630	$\sim 10^{-3}/\mathcal{A}_{DPE}^{\ddagger}$	$E_T^{jet} > 12$ GeV	DØ *

* Preliminary
† $\mathcal{A}\sim 0.4$ (estimated rapidity gap acceptance)
‡ $\mathcal{A}_{DPE}\sim 0.1$ (estimated double-gap acceptance for DPE)

at HERA :

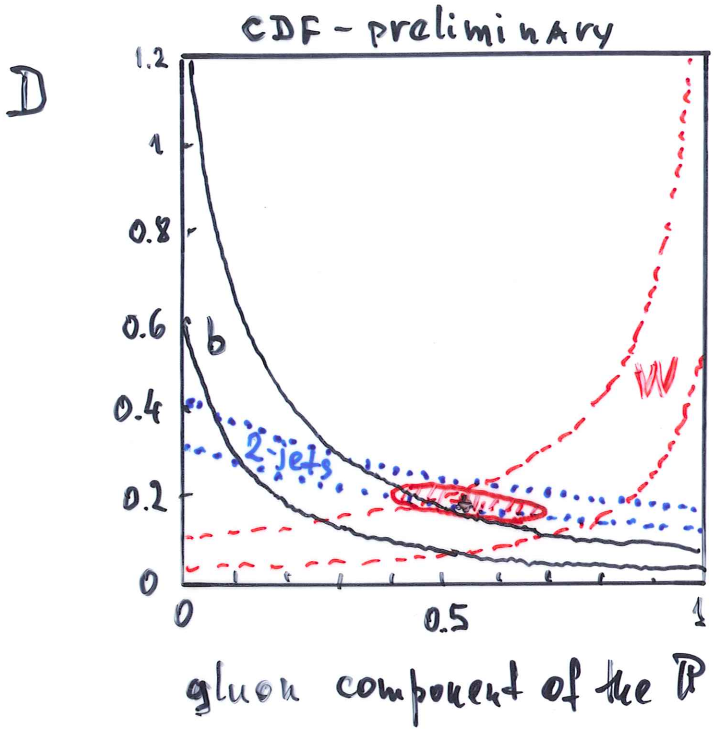
Jet-G-Jet 200 ~10% ($E_t > 5$ GeV) H1, ZEUS



Gap can be destroyed by additional interact. between the remnants

→ Gap "S"

Evidence of Factorization Breaking



$$f_g^{\mathbb{P}} = 0.54^{+0.16}_{-0.14}$$

↓

consistent with HERA

(taking into account scale)

The ratio of measured to 'predicted' diffractive rates at the Tevatron:

$$D = 0.18 \pm 0.04$$

→ Flux renormalization? (D.G., 1995-98)

HERA $F_2^D(\beta, Q^2, x_{\mathbb{P}}) * D$ → SD at Tevatron

–||– $* D^2$ → DPE at Tevatron

Summary on Hard Diffraction at the Tevatron

- Tevatron data are consistent with the hard partonic structure of the Pomeron, as measured at HERA

- Models involving dominant gluonic component in the diffractive exchange give best description of the data

- An energy dependence of the diffractive di-jet rates is in a good agreement with gap survival probability calculations

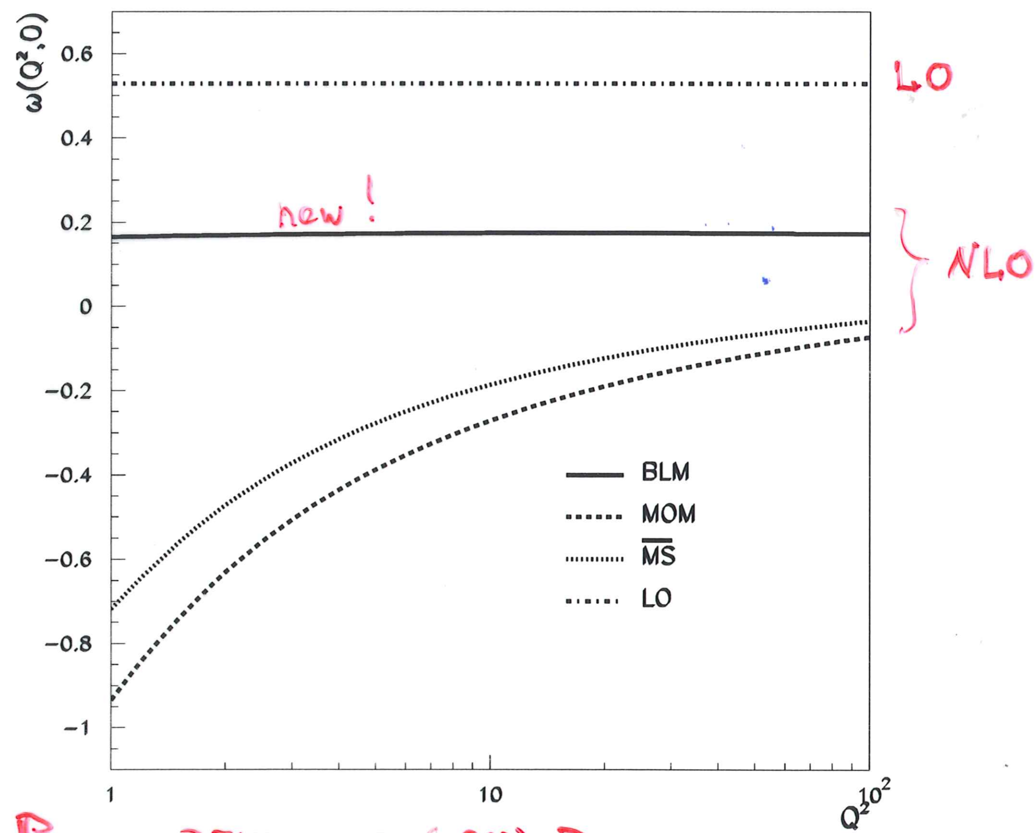
- A clear factorization breaking is observed when comparing rates of diffractive processes at HERA and Tevatron colliders

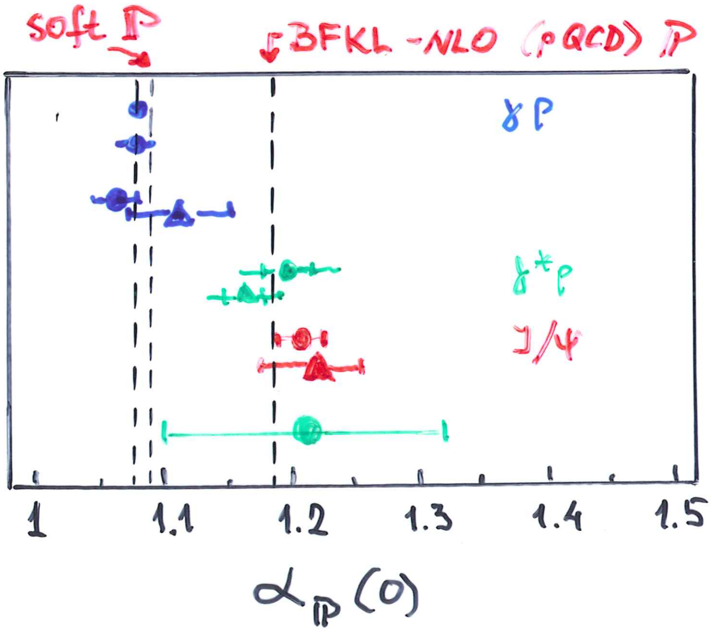
- A simple empirical Pomeron flux renormalization a'la D.Goulianos works so far fine, although theorists expect more complicated unitarity corrections mechanisms to be responsible for the factorization, breaking

Recent progress in Theory

NLO corrections to BFKL Pomeron intercept

(S.J.Brodsky, V.S.Fadin, V.T.Kim, L.N.Lipatov and G.B.Pivovarov, **hep-ph/9901229)**





- It works!?
- Q: Transition?

Two Pomerons ?

Regge fit of hh- and low-x DIS data with two Pomerons

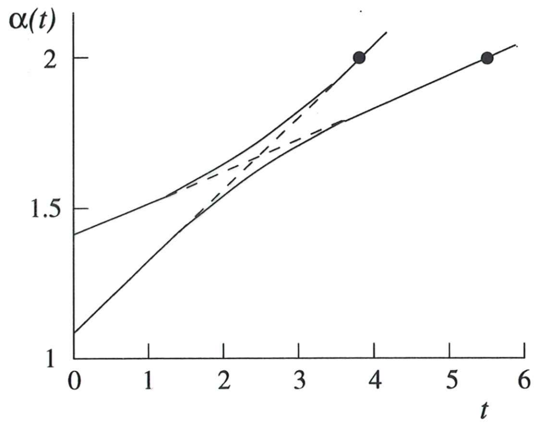
(A. Donnachie and P.V. Landshoff **hep-ph/9806344)**

Regge theory is expected to be applicable to DIS, even for large Q^2, if $x \sim Q^2/W^2 << 1$

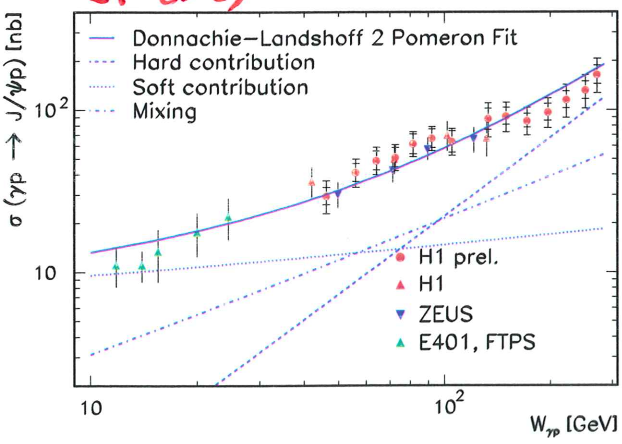
Fit is performed of the form

$$F_2(x, Q^2) = \sum_{i=0}^{2} f_i(Q^2) x^{-\epsilon_i}$$

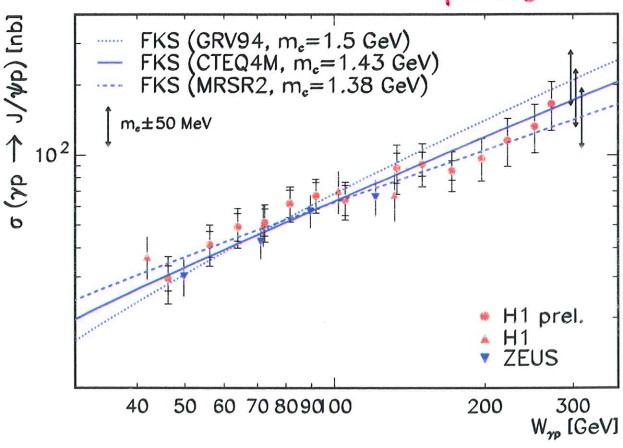
to $x < 0.07$ F_2 data (χ^2/ndf = 1.016) yielding $\boxed{\epsilon_0 = 0.435}$



2P (D-L)



pQCD



Summary

- For the first time HERA provides the possibility to study a structure of diffration at the microscopic level

- An experimental evidence is found of the 'hard Pomeron' with gluon dominated structure both in ep and $p\bar{p}$ collisions at high energies

- A clear evidence of factorization breaking is established, by comparing HERA and Tevatron data. The details of the underlying mechanism of that phenomenon is still to be revealed

- A fundamental question:
  What is the relation between 'soft' and 'hard' Pomerons?
  How many Pomerons are there after all? Two? Or just one, with scale dependent properties (intercept, slope)?

Outlook

- Presently released results on diffraction at HERA correspond to $2 \div 35$ pb^{-1}. Until the shutdown, in total of about 100 pb^{-1} per experiment will be available
- Luminosity Upgrades at the Tevatron and HERA (by 2001) will bring yet a lot more data, allowing for precision measurements of hard diffraction
- Heavy nuclei option at HERA (for 2006) would allow to extend QCD studies in DIS in the environment of strong color field. To make this possible an active support from HEP community is necessary
- QCD at LHC ($\geq$ 2006) – New insights into the hadronic sector of the Standard Model

An ultimate goal: To formulate an effective field theory for high energy particle scattering, bridging pQCD and RFT