From Soft to Hard Diffraction

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Outline of the talk

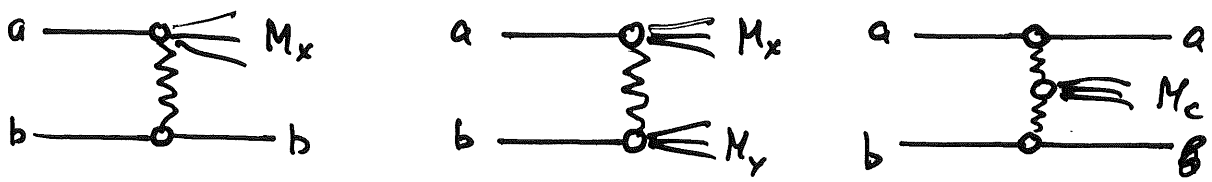
- Introduction: **Regge→QCD→Effective Field Theory ?**
- Soft Diffraction: **DL Pomeron ?**
- Hard Diffraction: **QCD Pomeron ?**
- Transition Regime: **Unitarity Corrections ?**
- Summary and Outlook

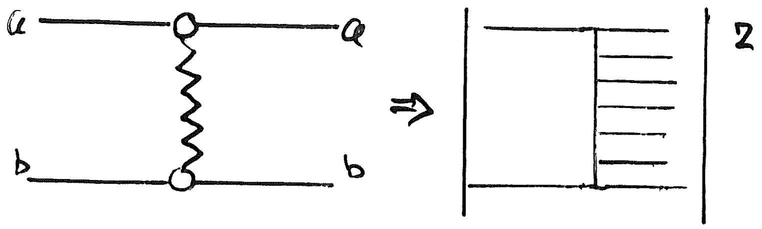
Why Diffraction ?

Convention throughout the talk:

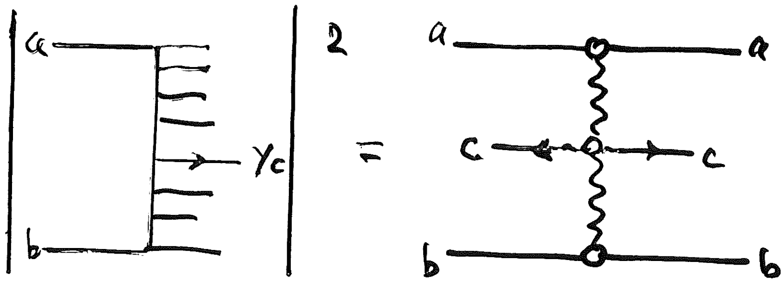
Diffraction $\equiv$ Scattering involving $I\!P$ exchange

(where $I\!P$ is a colorless object with vacuum quantum numbers)





Optical theorem for elastic and total cross sections

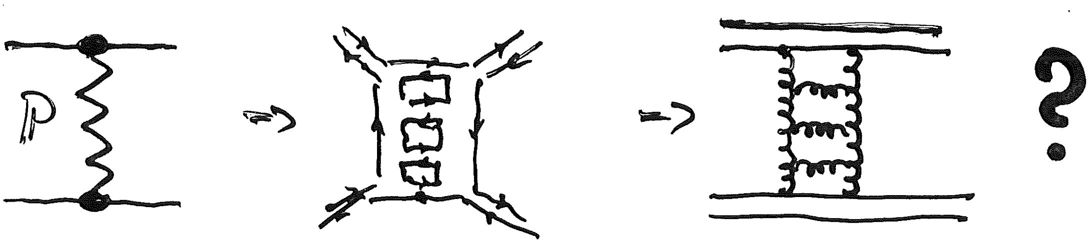


Muller's generalization of optical theorem for inclusive processes:

$ab \to cX$

⇒ Covers practically everything in high energy scattering

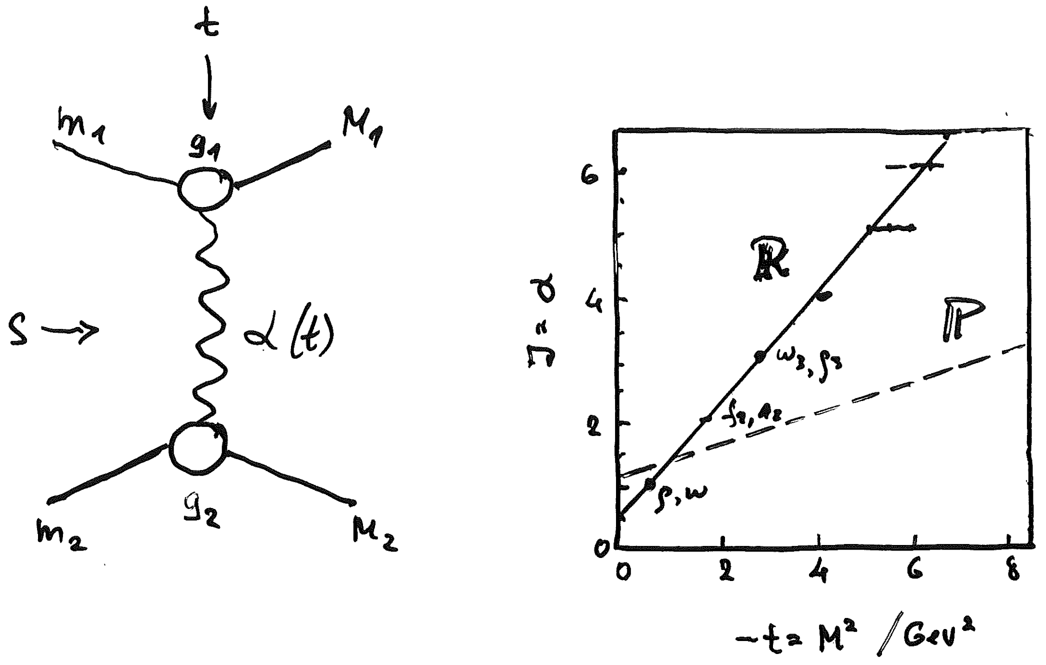
⇒ To understand the nature of the Pomeron is one of the key problems in HEP:



Hence – Diffraction

60's-70's: Regge Approach

- Simple Regge pole model



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

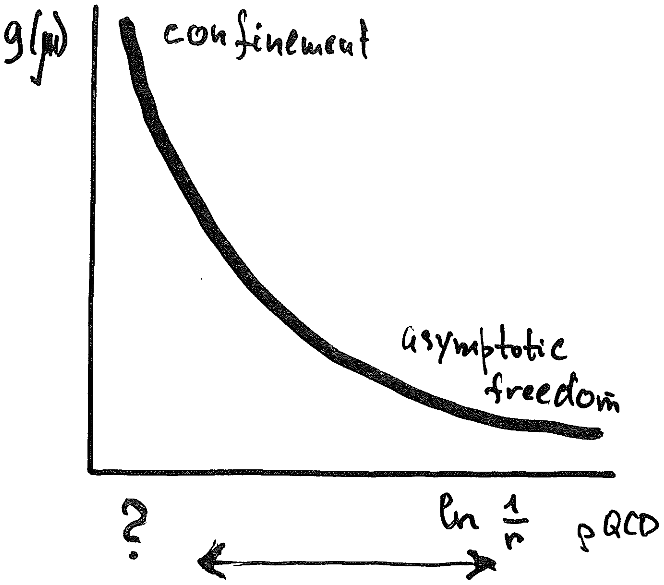
$$A(s,t) = g_1(m_1, M_1, t) g_2(m_2, M_2, t) \frac{s^{\alpha(t)} \pm (-s)^{\alpha(t)}}{sin(\pi\alpha(t))}$$

- 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)**

70's-80's: QCD Era



- Successes:
  mainly in perturbative sector
- Problems:
  in the regime of confinement
- Simplest $I\!P = 2g$ 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

$\Rightarrow$ **L. Lipatov's talk**

Experiments

- **Fixed target *hh* data** (see D. Ashery)
  - $\sqrt{s} < 20$ 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**

- **Hadron Colliders** (see A. Brandt)
  - $30 < \sqrt{s} < 1800$ GeV → high mass diffraction!
  - largest available energies → asymptotic regime
  - hard scattering (jets) in diffraction

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

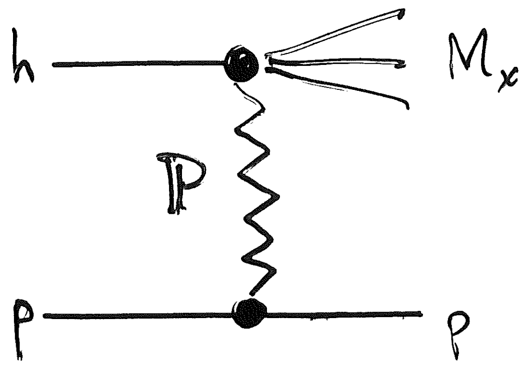
- **HERA** (see P. Marage)
  - $\gamma^*(Q^2)$ provides additional resolving power ($10^{-8} < Q^2 < 10^5$ GeV^2)
  - $x/Q^2 \geq 10^{-5}$ GeV^{-2} → low x regime → high parton densities
  - asymmetric beam configuration → excellent acceptance for γ^* diffractive dissociation system

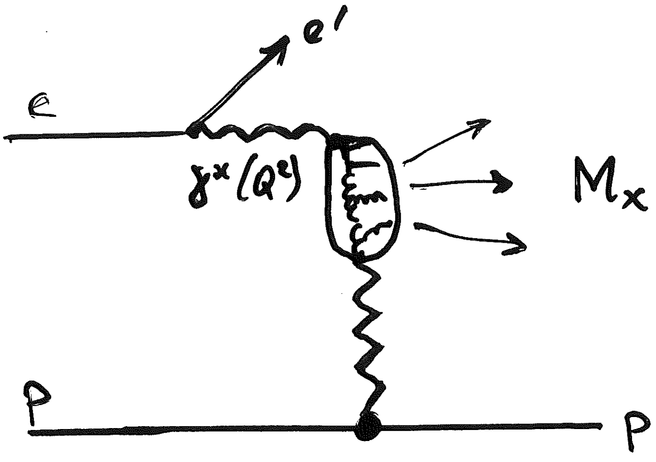
  ⇒ **unique facility**

  to probe partonic content of diffractive exchange ($I\!P$)

  to study the transition from soft to hard regime

What new can we learn at HERA?





Q's: • What is a partonic content of the $\mathbb{P}$?
(see. J. Whitmore's talk)

• How the properties of diffraction evolve with a scale (Q^2)
(soft ⟷ hard $\mathbb{P}$)

N.B! Distinguish hard and soft diffraction and hard and soft Pomeron!

HARD $\mathbb{P}$ (QCD Pomeron) - diffractive exchange in perturbative regime

Soft $\mathbb{P}$ - non perturbative exchange

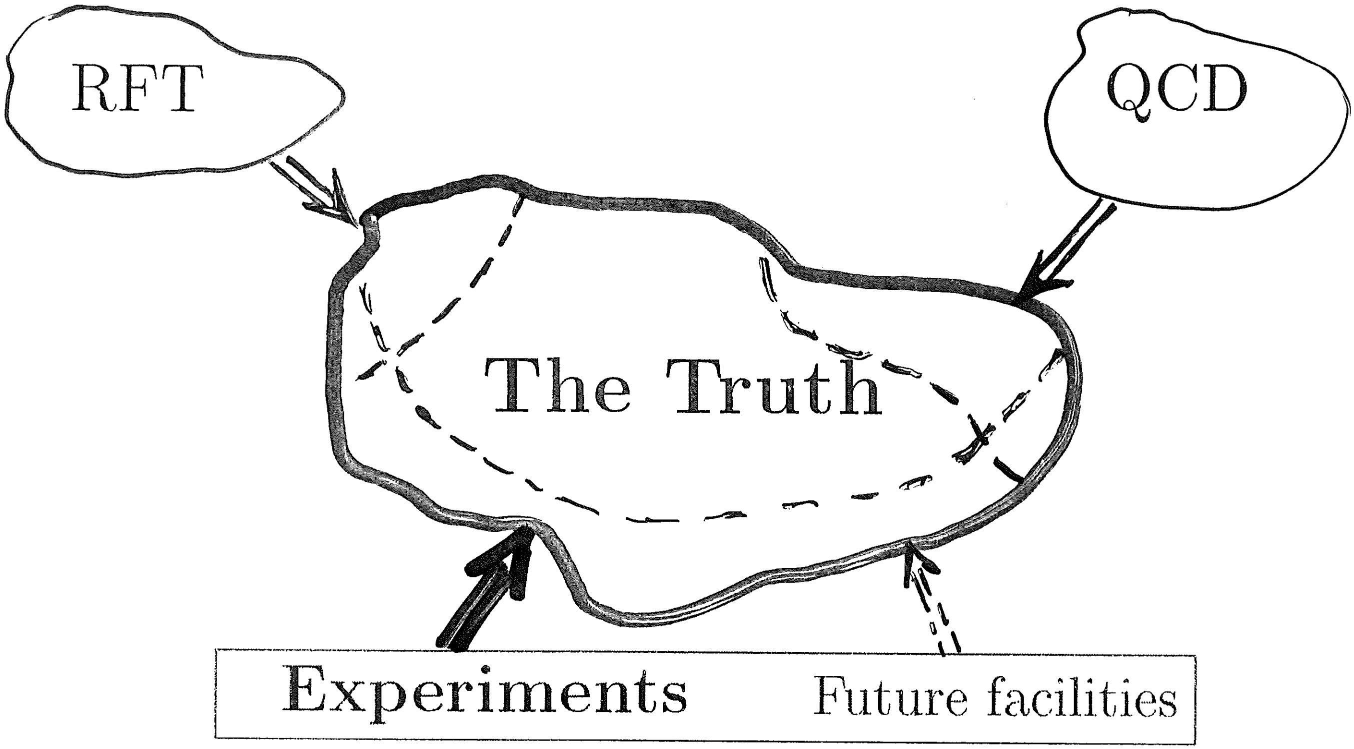
A word of caution

- **Direct comparisons of data are often difficult**
  - different treatment of non-diffractive background
  - $M_x/\sqrt{s} \ll 1$; cuts vary in $0.01 \div 0.1$ range
- **Multi-dimensional measurements are important**
  - e.g. at HERA essential variables are: M_X, t, W^2, Q^2
    → statistics limitations
- **Limited detection capabilities in rapidity space**
  - model dependencies in data corrections
  - losses of interesting and eventually novel physics

1. HERA Luminosity Upgrage is important! (Y-2000)
2. New improved experiments are desirable! (FELIX ?)

⇒ WG-2 sessions, C.Taylor, A.Santoro, H.Jung, ...

What is the Pomeron?



A.Kaidalov
(WG-1)

RFT

A. Müller,
L. Lipatov
(and WG-1)

QCD

The Truth

Experiments
(WG-3, WG-4)

Future facilities
(WG-2)

The aim of this Workshop is to get together in order **to reveal at least part of the truth and define future lines of investigations.**

Soft Diffraction: DL Pomeron ?

Consider two examples: total and diffractive hadronic cross sections.

Best described in the framework of Regge theory:

$$\sigma_{tot}(s) = X s^{\alpha_{I\!P}(0)-1} + Y s^{\alpha_{I\!R}(0)-1}$$

$$\frac{d\sigma_{el}}{dt} = g_1^2(t) \cdot g_2^2(t) \cdot s^{2(\alpha_{I\!P}(0)-1)} \cdot e^{(2\alpha'_{I\!P} \ln s)t}$$

with approximately linear trajectories

$$\boxed{\alpha_{I\!P}(t) = 1.08 + 0.25\ GeV^{-2} t} \qquad \text{('D-L Pomeron')}$$

and

$$\alpha_{I\!R}(t) = 0.55 + 0.9\ GeV^{-2} t \quad (\rho, \omega, a_2, f_2)$$

Naive expectations

$$\sigma_{tot} \propto s^{0.08} \quad \text{and} \quad \sigma_{el/diff} \propto s^{0.16+0.5\bar{t}} \quad \text{at } s \to \infty,$$

violate eventually Froissart bound: $\sigma_{tot} \leq C \ln^2 s$ and Pumplin limit: $(\sigma_{el} + \sigma_{diff})/\sigma_{tot} \leq \frac{1}{2}$

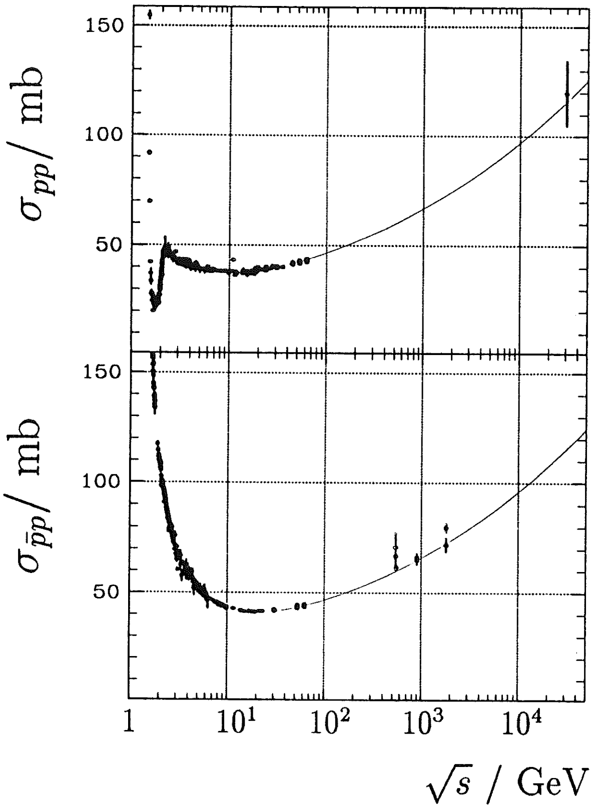
Way out gives **RFT:** unitarity corrections (multi-$I\!P$ exchanges)

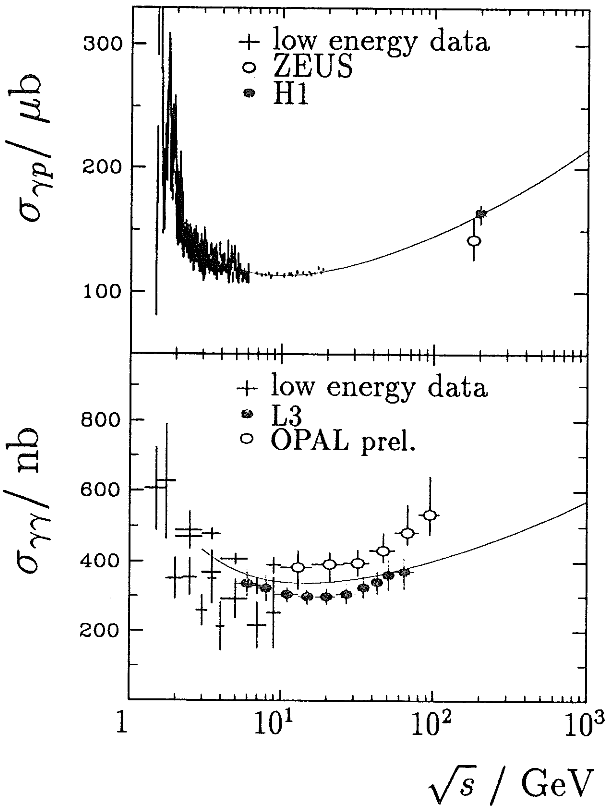
Questions:

- At which energies ?
- Do we see unitarity corrections in present data ?

Total Cross Sections

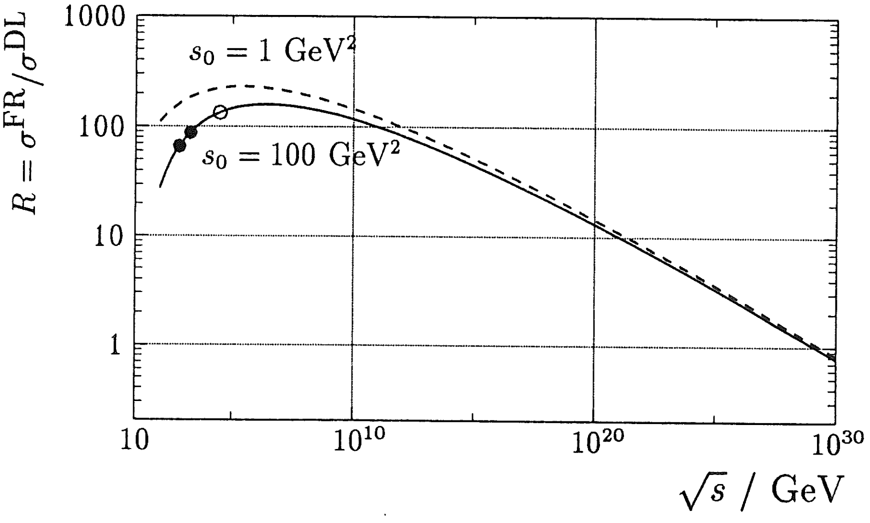
$$\sigma_{tot}^{\mathrm{DL}}(ab) = X_{ab}s^{\epsilon} + Y_{ab}s^{-\eta}$$





S-channel Unitarity

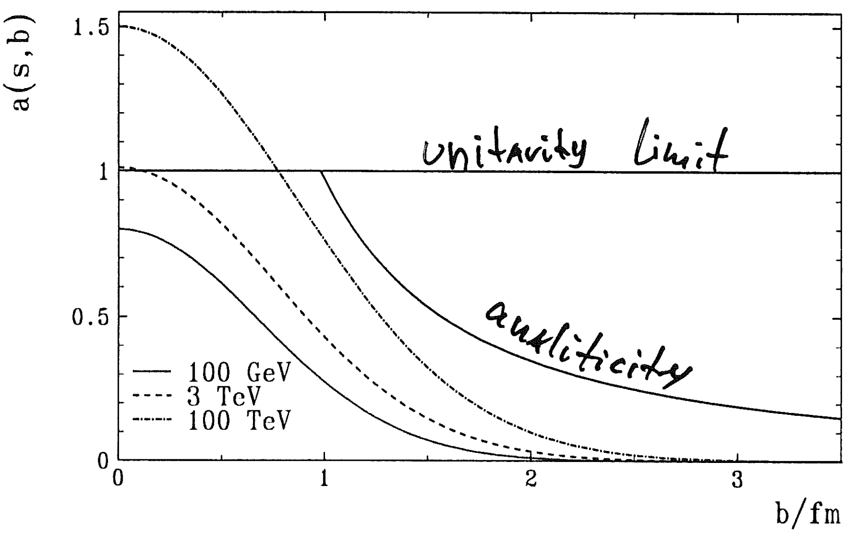
$$\sigma_{tot} \leq \sigma^{\mathrm{FR}} = \frac{\pi}{m_{\pi}^2}\ln^2\left(\frac{s}{s_0}\right)$$



Problematic area - beyond the GUT scale →
no practical importance

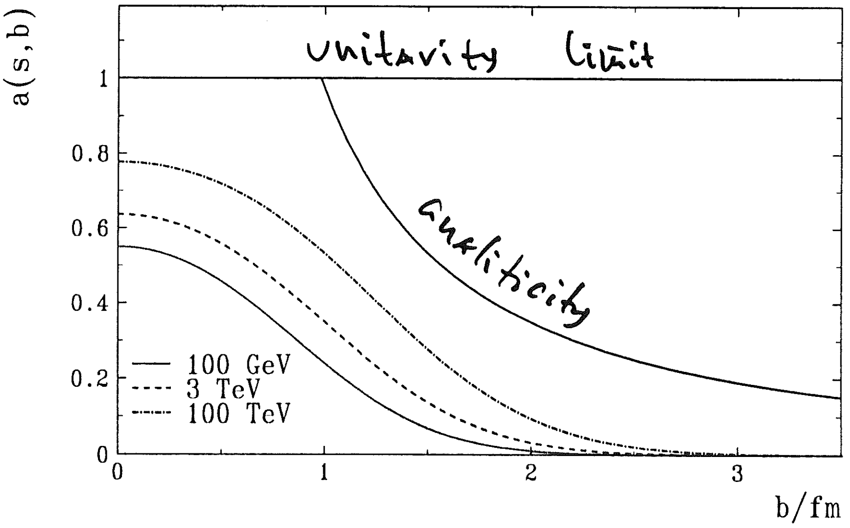
Unitarity and Screening Corrections

D-L Pomeron violates unitarity at small values of impact parameter b already at few TeV !

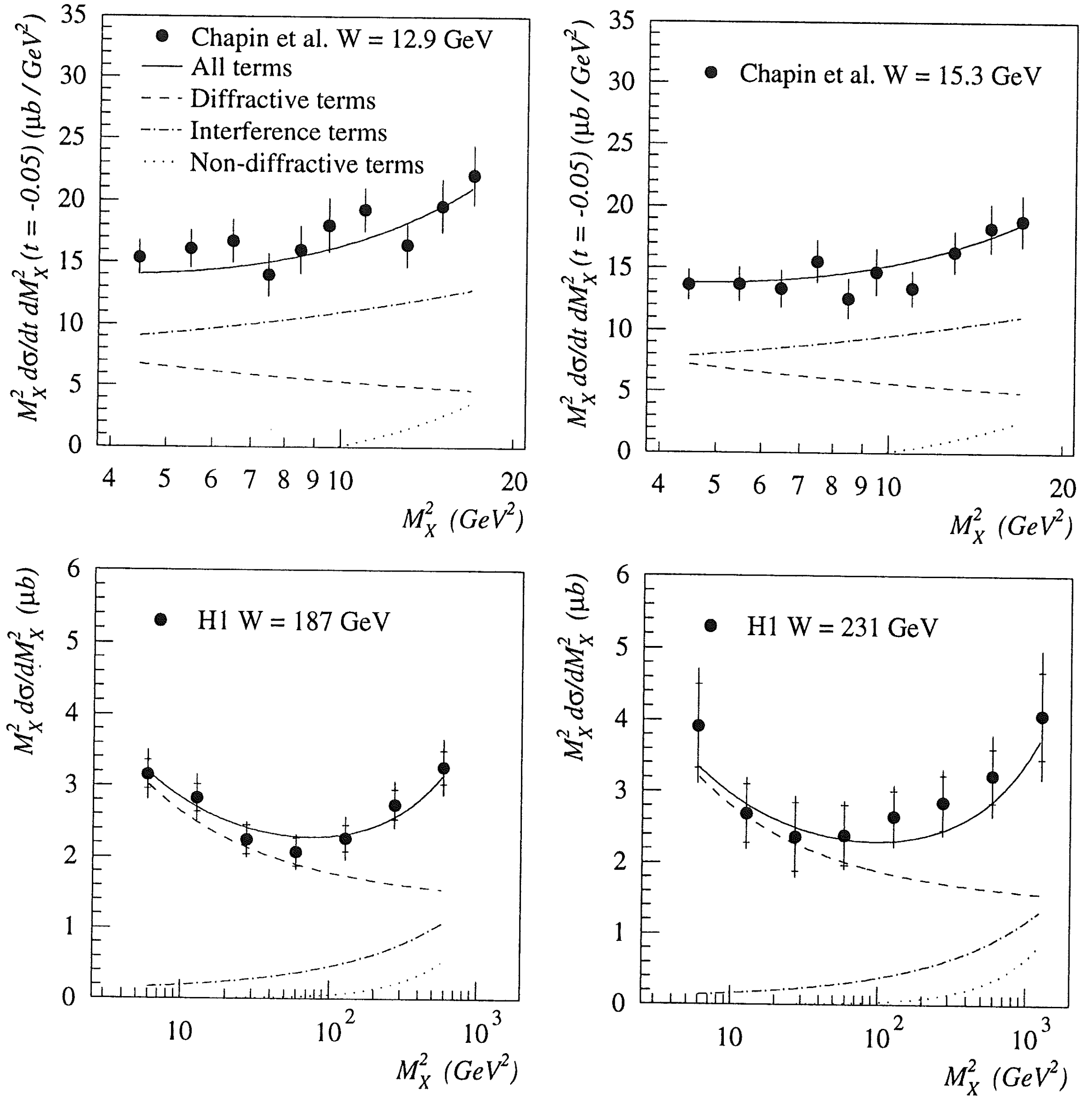


Unitarity can be restored e.g. by eikonalisation:

$$a(s,b) = i(1 - e^{-\Omega(s,b)})$$



$$\boxed{\gamma p \rightarrow M_x p}$$



$$\alpha_{I\!P}(0) = \mathbf{1.068 \pm 0.016 \pm 0.022 \pm 0.041}\ (\mathrm{H1})$$

$$\alpha_{I\!P}(0) = 1.12 \pm 0.04 \pm 0.08\ (\mathrm{ZEUS})$$

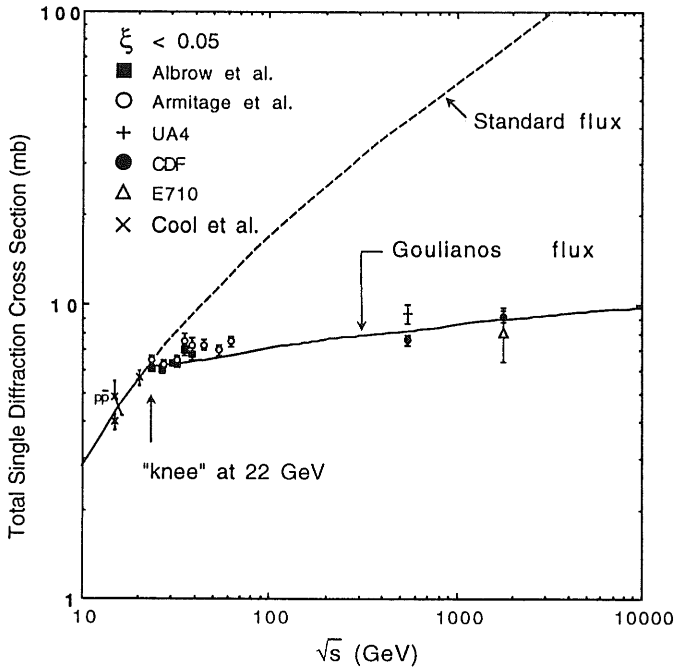
Subleading trajectory is needed in the fit

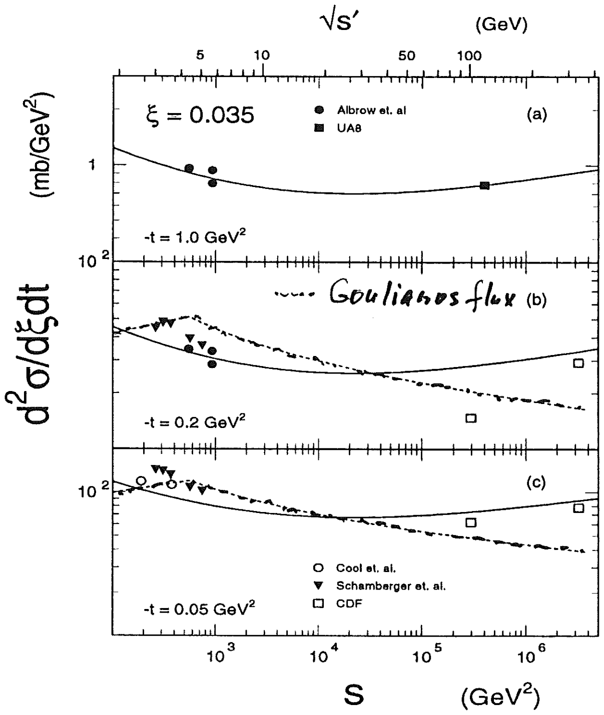
No evidence for enhanced screening w.r.t. $\sigma_{tot}(\gamma p)$

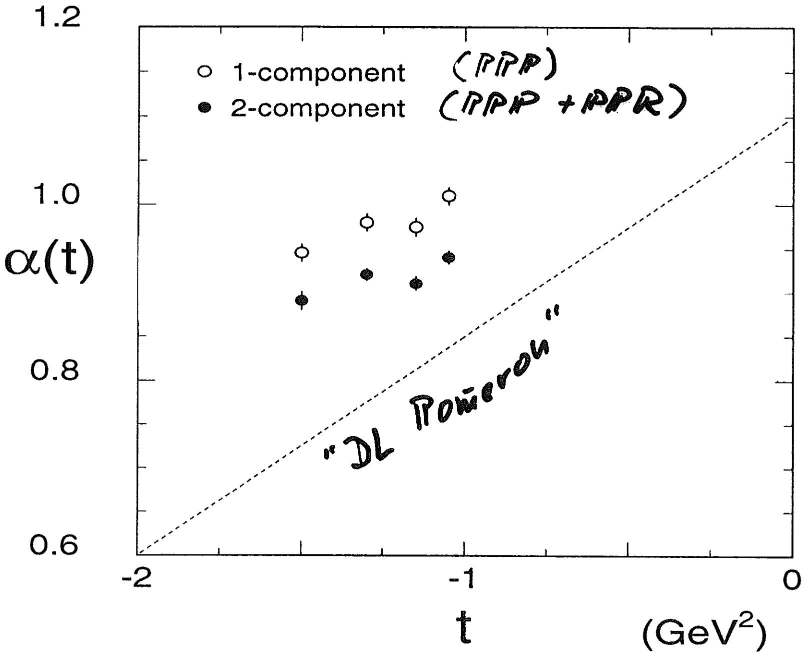
(although $\sigma_D/\sigma_{tot} \simeq 40\%$ in photoproduction at HERA)

$$\boxed{\bar{p}p \to M_x p}$$

UA8, $\sqrt{s} = 630$ GeV (A.Brandt et al., hep-ex/9710004 v2)







$$\boxed{\alpha_{I\!P}(t) = 1.10 + 0.25t + (0.079 \pm 0.012)t^2}$$

$\Rightarrow$ multi $I\!P$ exchange? Or hard scale (t) ?

Hard Diffraction: QCD Pomeron ?

An intercept of the perturbative (BFKL) Pomeron in LLA corresponds to

$$\lambda_{BFKL} = \alpha_{I\!P}(0) - 1 = \frac{4N_c \ln 2}{\pi}\alpha_s \approx 0.4 \div 0.5$$

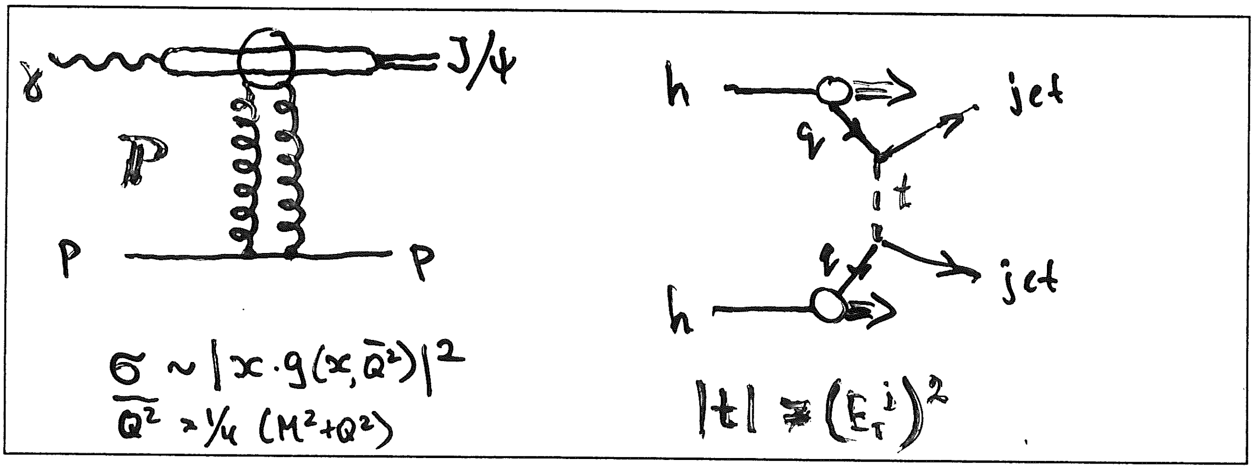
NLO corrections (**Fadin, Lipatov** – done?) are expected to reduce this value. Hence more realistic expectation for the intercept of 'hard' Pomeron is $\boldsymbol{\lambda \geq 0.2 \div 0.3}$

Hard scale is necessary for QCD Pomeron to manifest itself. It can be for example, large $\boldsymbol{t}$, $\boldsymbol{Q^2}$, $\boldsymbol{M}$, $\boldsymbol{p_t}$

Consider two clean examples:

- **Elastic photoproduction of J/ψ (scale: m_c)**
- **LR gaps between jets (scale: $t \geq (E^{jet}_{t,min})^2$)**

(attend the talks of L. West and B. Cox in WG4 for interesting details)



$$\sigma \sim |x \cdot g(x, \bar{Q}^2)|^2$$
$$\bar{Q}^2 \approx 1/4\,(M^2+Q^2)$$

$$|t| \approx (E_T^i)^2$$

Elastic Photoproduction of J/ψ

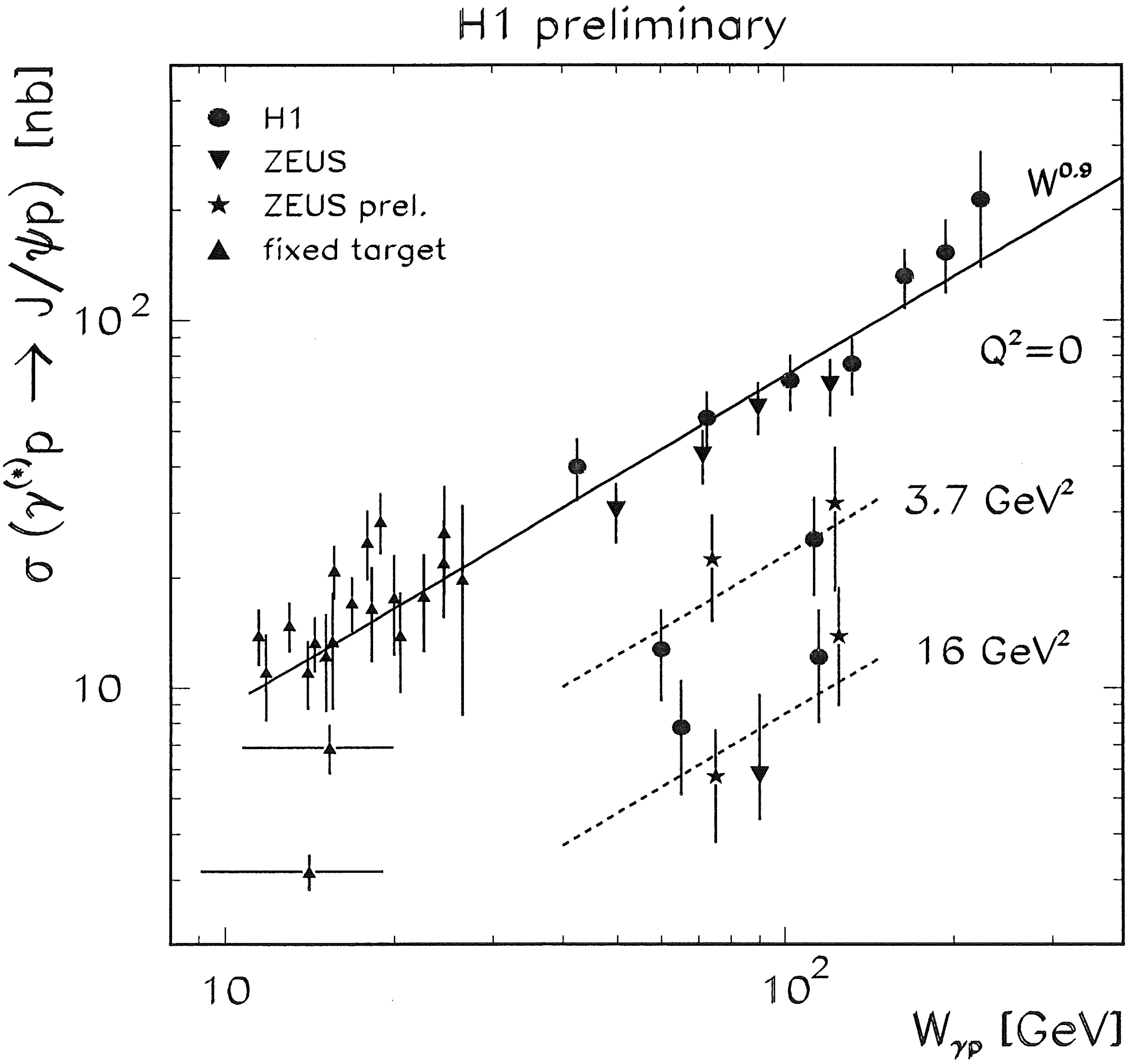
Examine Energy dependence:
$\sigma \propto W^{4(\alpha_{\mathbb{P}}(0)-1)}$
and shrinkage: $\alpha'_{\mathbb{P}} = ?$

$d\sigma/dt \sim e^{bt}$; $b = b_0 + 2\alpha'_{\mathbb{P}} \ln W^2$

$b \sim (R_p^2 + r_\perp^2)$

$r_\perp \ll R_p$ -> b -> const

$\alpha'_{\mathbb{P}}$ -> 0

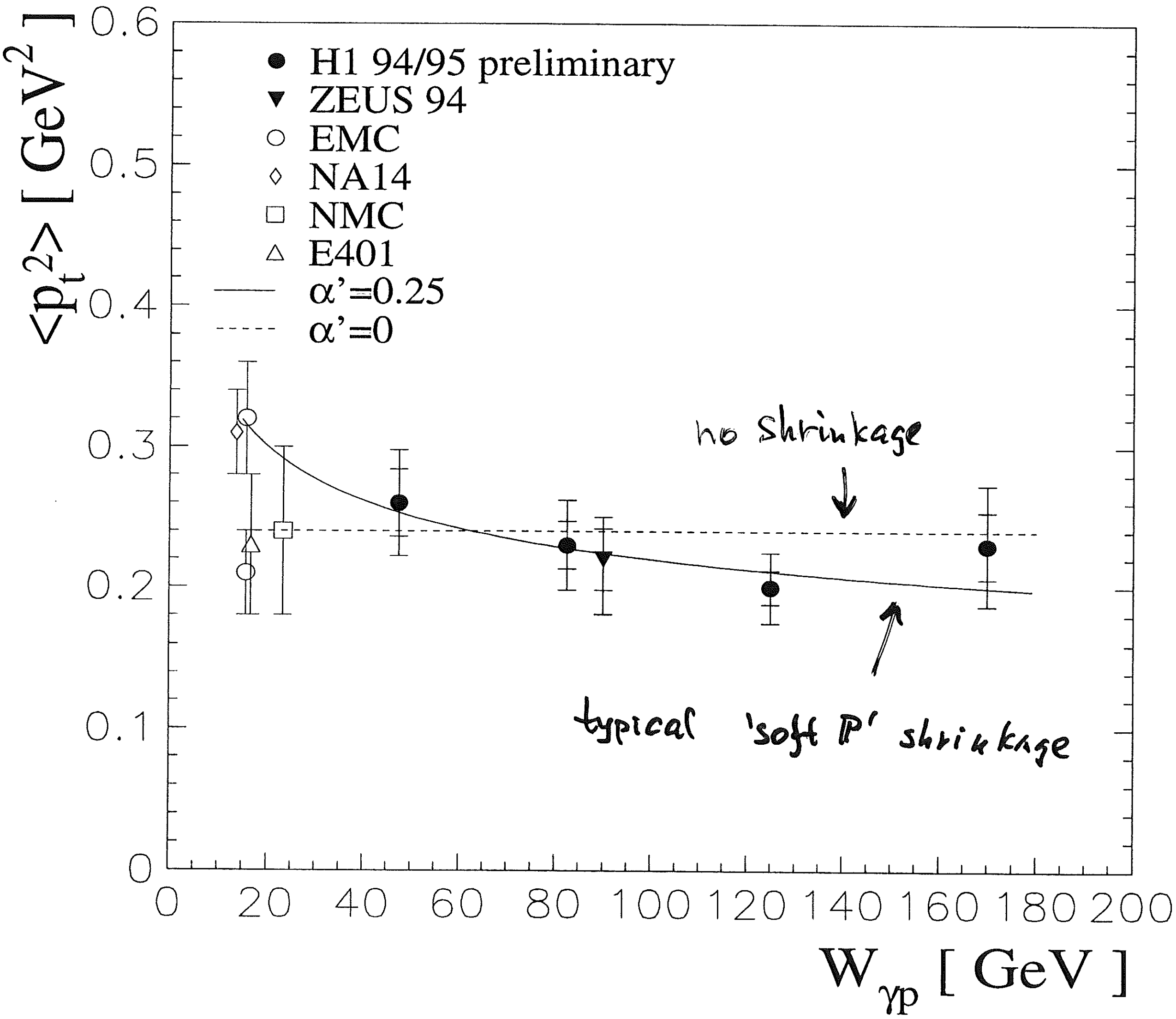


$$\alpha_{\mathbb{P}}(0) \simeq 1.22 \gg 1.08 = \alpha_{\mathbb{P}}^{DL}(0)$$

Elastic Photoproduction of J/ψ

Warnings for low energy data:

- $N \to p$ corrections
- p-dissociation background
- type of slope fit for $d\sigma/dt$ (< \ )
- real / virtual photons corr.



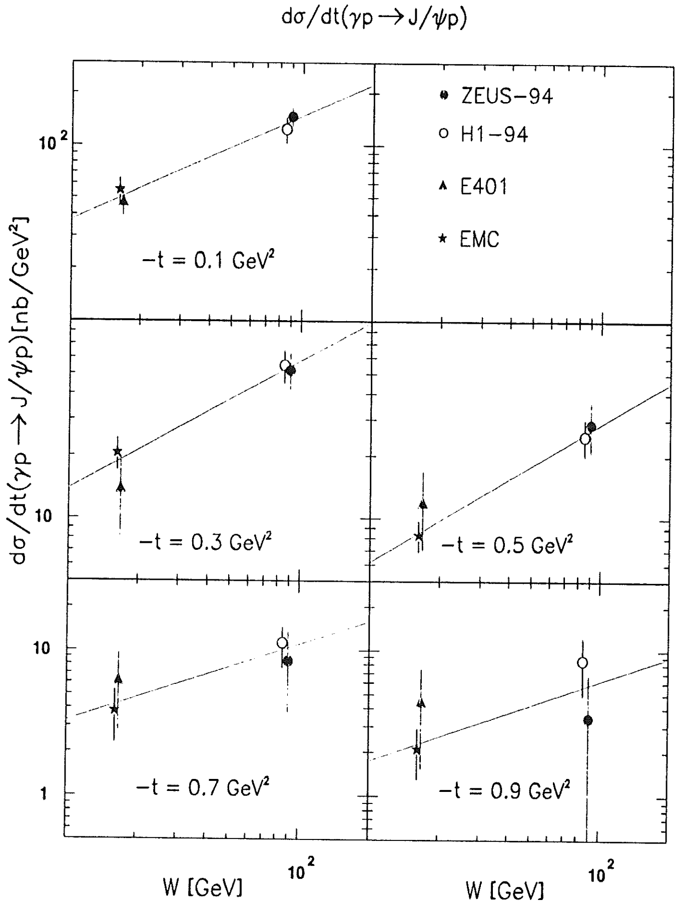
→ Extend HERA measurements to full $W_{\gamma p}$ range (~40 ÷ 290 GeV)

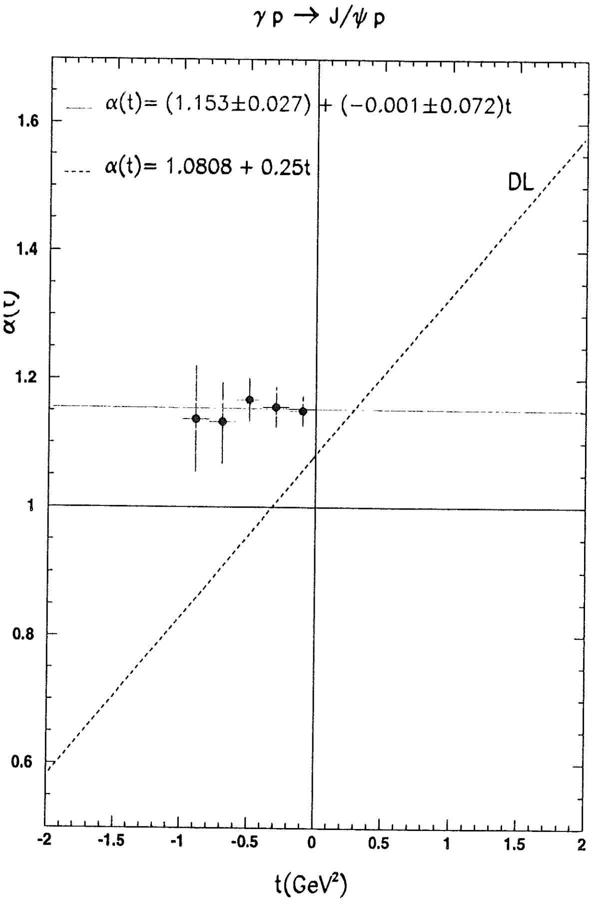
→ High statistics will allow to define $\alpha_{I\!P}(t)$ from HERA data alone

Elastic Photoproduction of J/ψ

A.Levy, hep-ph/9712519

$$\frac{d\sigma}{dt} = f(t) \cdot W^{2(2\alpha(t)-2)}$$; common fit for 20 exp. points in the range $|t| = 0.1 \div 0.9$ GeV^2





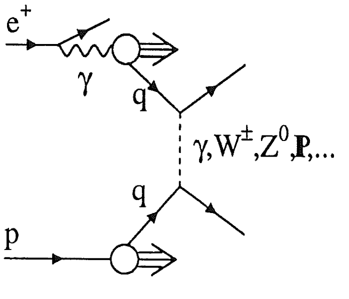
$$\boxed{\alpha_{I\!P}(t) = (1.153 \pm 0.027) + (-0.001 \pm 0.072)t}$$

LRG between jets - the idea

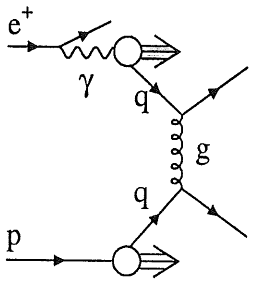
Detailes on Tevatron data see later in the talk of A.Brandt

Here mainly HERA results are presented

Motivation: hard $I\!P \rightarrow$ new QCD dynamics?



(a)



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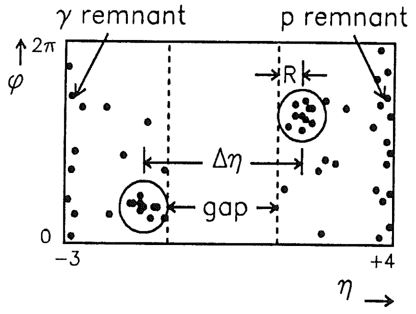

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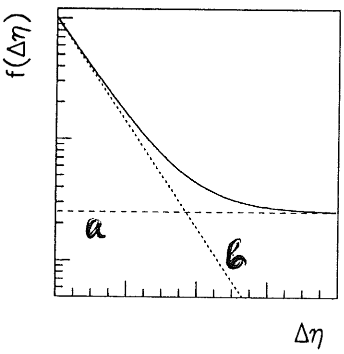
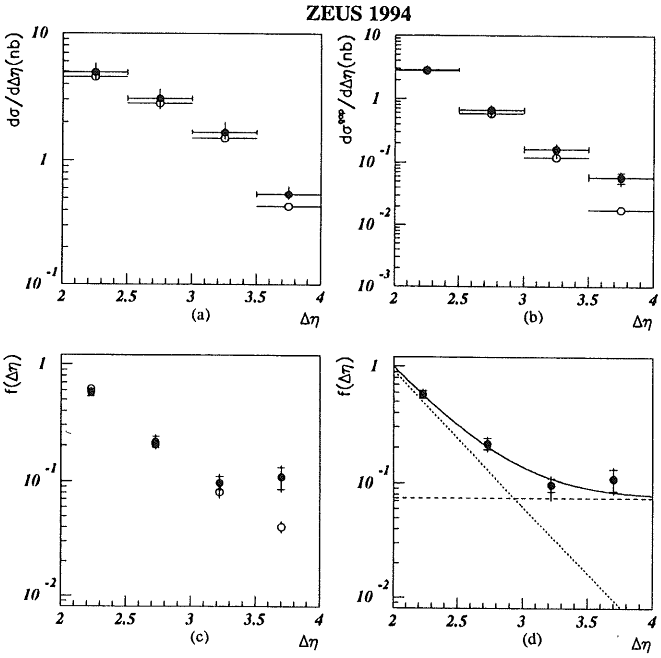


(d)

At HERA LRG sample is dominated by $I\!P$ exchange

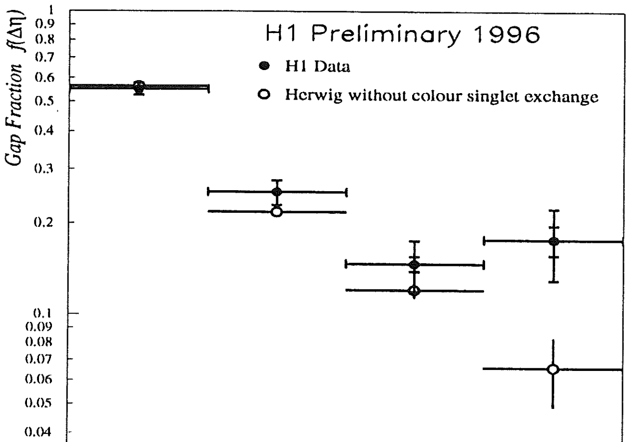
Complication: additional (non-perturbative) activity in the event may fill the gap (Survival Probability < 1)

LRG between jets - Results



● data

○ PYTHIA MC



$$
\begin{aligned}
f(\Delta\eta) &\simeq 12\% \text{ (H1)} \\
&\simeq 7\% \text{ (ZEUS)} \\
&\simeq 1\% \text{ (Tevatron)}
\end{aligned}
$$

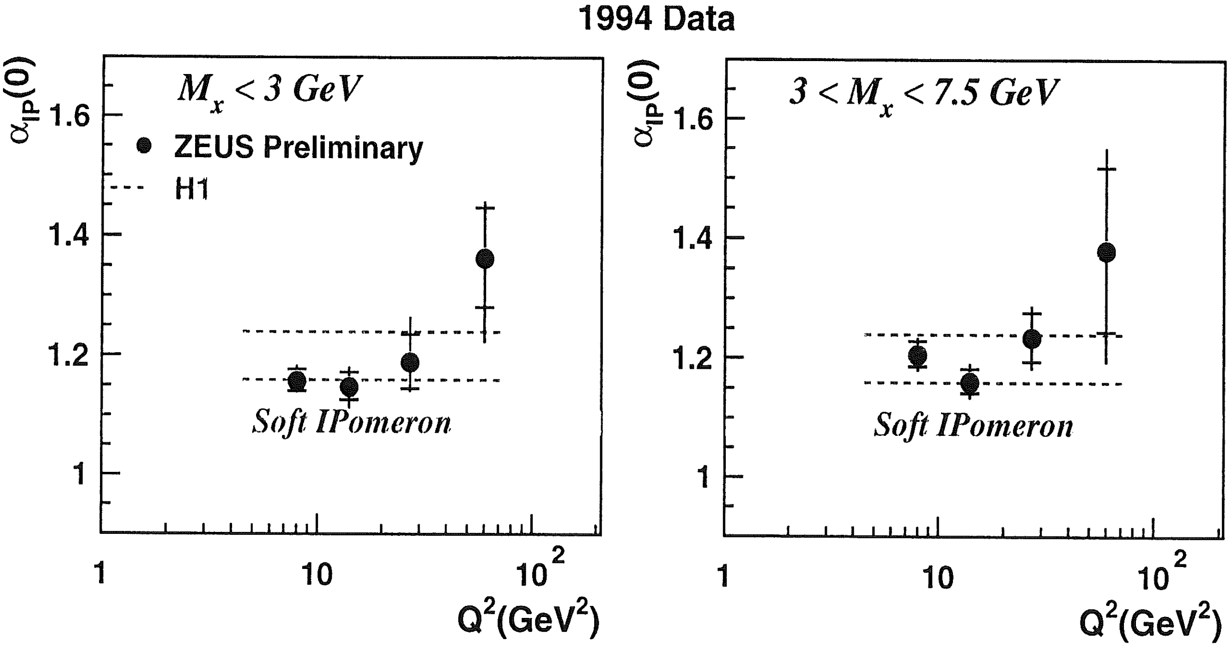
1. $f_{HERA} \gg f_{Tevatron}$

2. Difficult measurement (limited $\Delta\eta$, $SP<1$) $\rightarrow$ new suggestion (S. Cox at WG-4!)

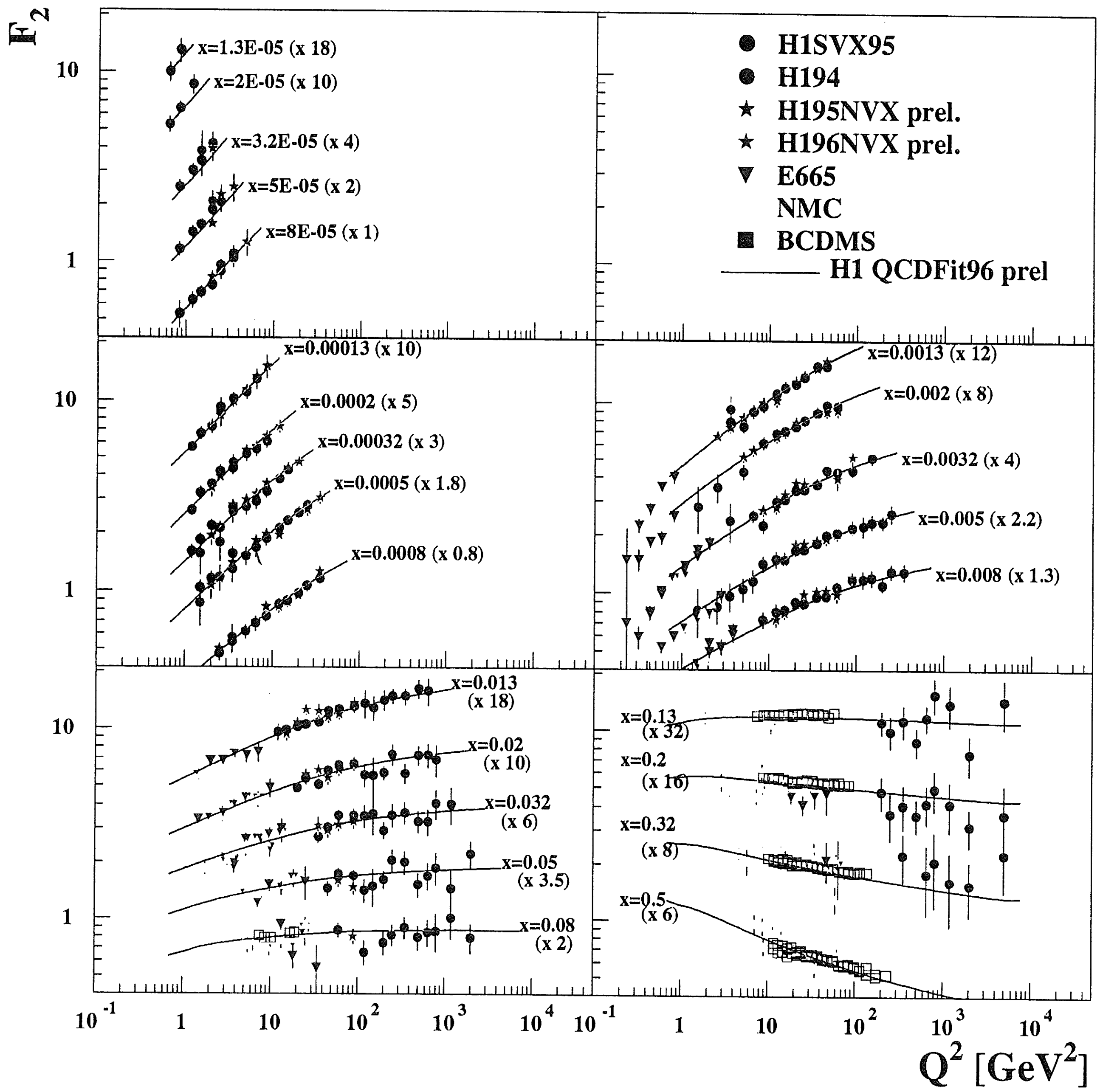
Transition Regime: Unitarity Corrections ?

- **Do we see a Q^2 dependence of the Pomeron intercept $\alpha_{I\!P}(0, Q^2)$?**
- **If yes, what is the reason for this ?**

$\Rightarrow$ **study $\sigma^{tot}_{\gamma^* p}(W, Q^2)$ and Deep Inelastic diffraction at HERA**



Result of prel. H1 NLO QCD fit:

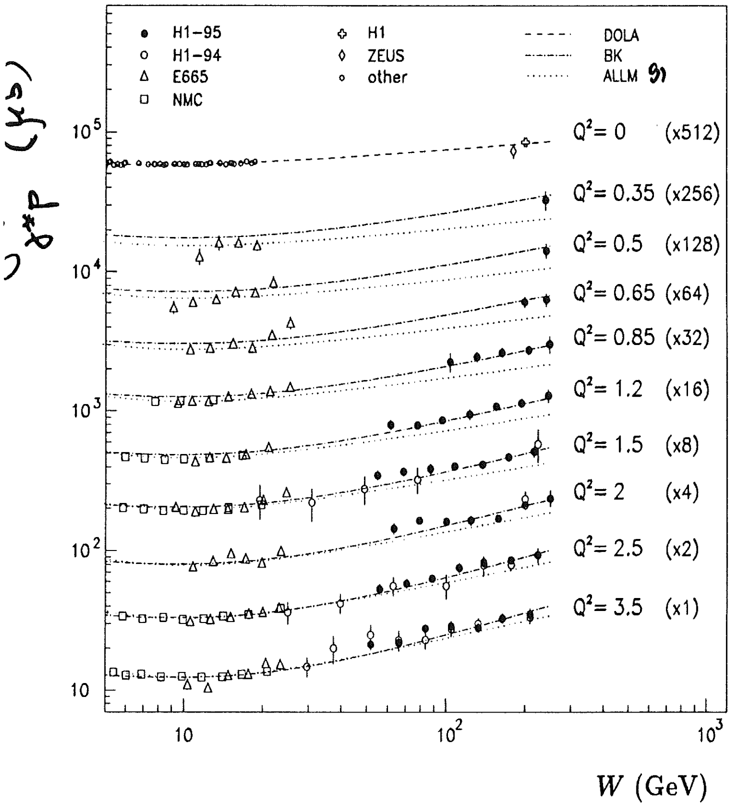


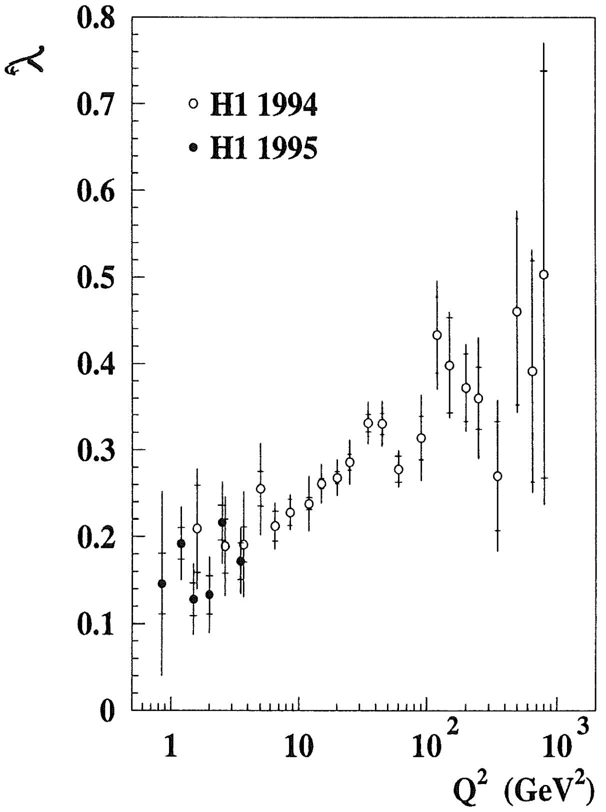
NLO DGLAP fit provides good description of F_2 for $10^{-5} \leq x \leq 0.5$ and $1.2 \leq Q^2 \leq 5000$ GeV^2

Transition regime – $\sigma^{tot}_{\gamma^* p}$

New high precision HERA data at low Q^2 allow for a detailed study of the transition region!

$$\sigma^{tot}_{\gamma^* p} \simeq \frac{4\pi^2\alpha}{Q^2} F_2(x, Q^2) \qquad F_2 \sim x^{-\lambda} \quad (\sim W^{2\lambda} \text{ at fixed } Q^2)$$





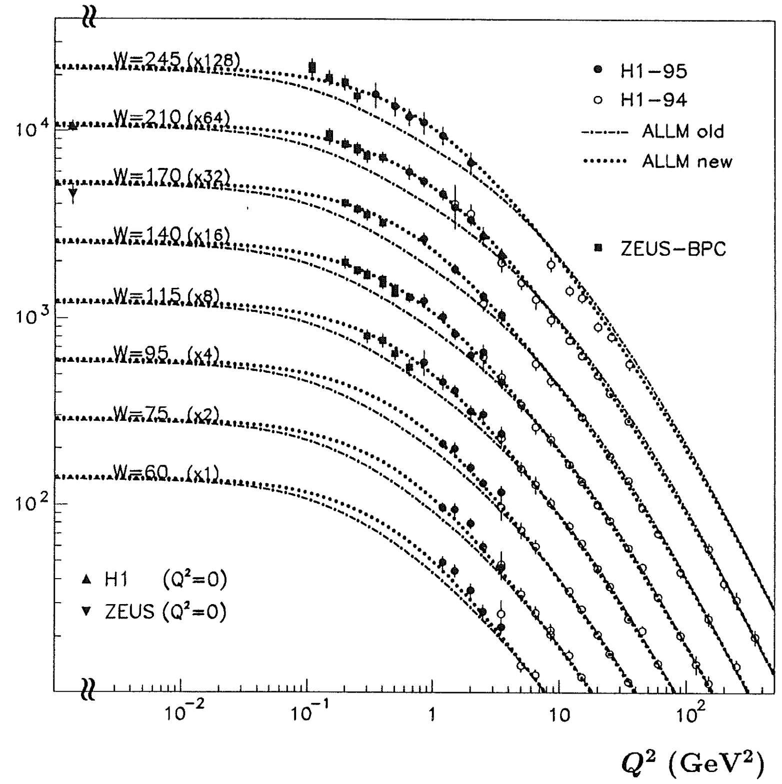
- Soft DL Pomeron model fails at $Q^2 \gtrsim 0.35$ GeV^2
- pQCD description is OK down to $Q^2 \simeq 1.2$ GeV^2? But then it goes too high
- Smooth transition between 'soft' and 'hard' regimes $\lambda(Q^2)$ (rises with Q^2)

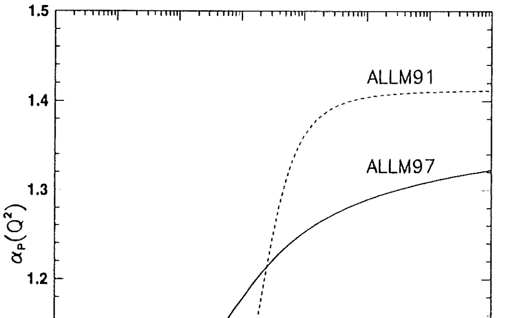
Transition regime – $\sigma^{tot}_{\gamma^* p}$

(H.Abramowitz and A.Levy, hep-ph/9712415)

An update of empirical parametrization (23 parameters)

$0 < Q^2 < 5000$ GeV^2; $3\cdot 10^{-6} < x < 0.85$





- Good data description, but 23 param..!
- Transition is smooth, but what is the dynamics behind that?
- $\alpha_{I\!P}(Q^2)$ dependence is very similar to CKMT model picture

$$\alpha_{I\!P}^{eff}(Q^2) = \alpha_{I\!P}^{bare}\cdot f\left(\frac{s}{Q^2}\right) = \underbrace{\alpha_{I\!P}^{0}\left(1+\frac{2Q_0^2}{d+Q_0^2}\right)}_{\text{for D.I.S.}}$$

→ Screening corrections at work ?!

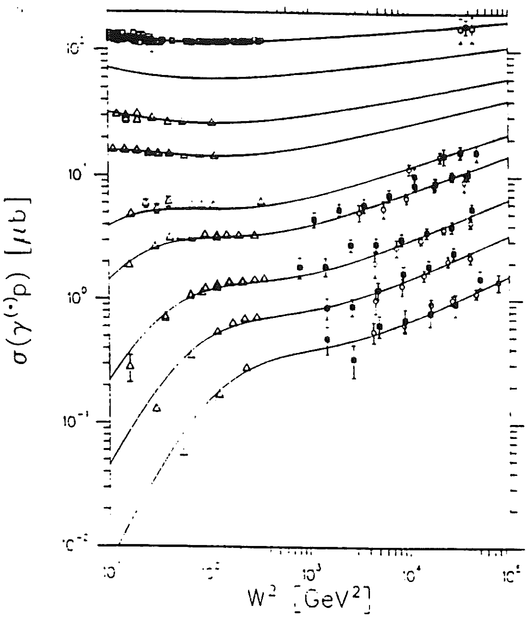
CKMT model [A. Capella et al., PL B337 (1994) 358]

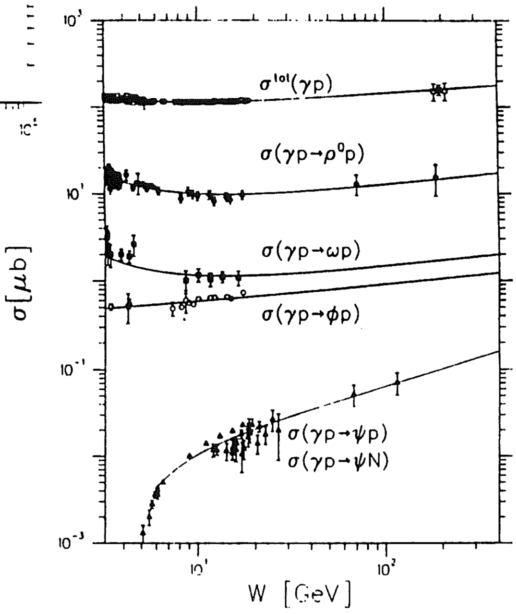
- Multi-Pomeron exchanges give screening (absorbtive) corrections to one $\mathbb{P}$-pole amplitude → unitarization

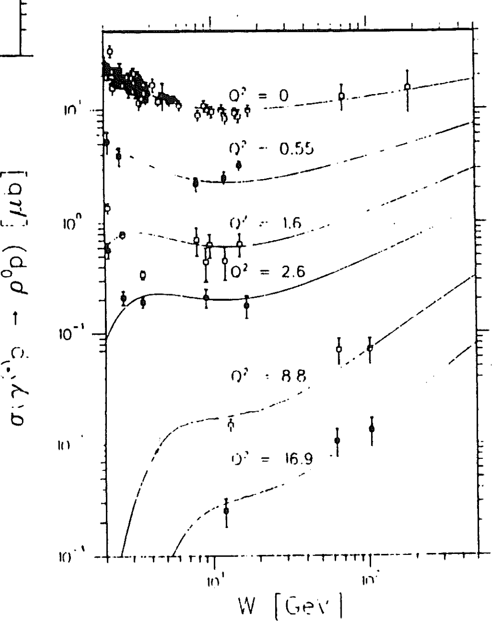
Bare Pomeron : $\Delta(0) \simeq 0.2 \div 0.25$

"Effective" Pomeron :

$$\boxed{\Delta(Q^2) = \Delta(0)\left(1 + \frac{2Q^2}{d+Q^2}\right)}$$







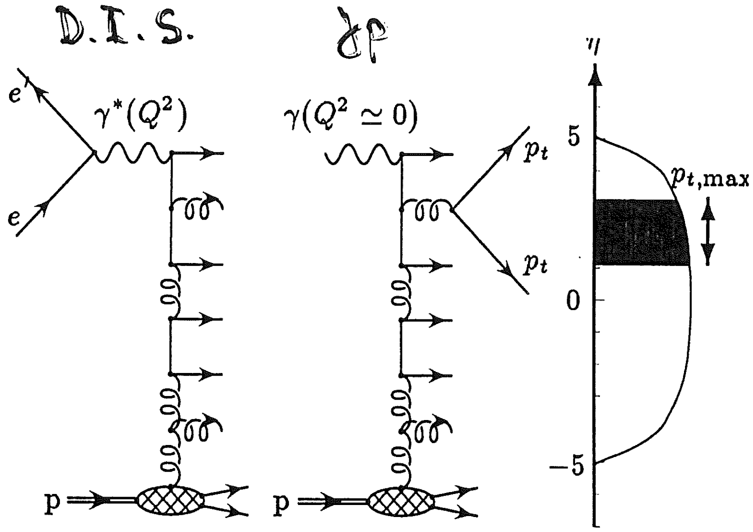
↳ Works quite well

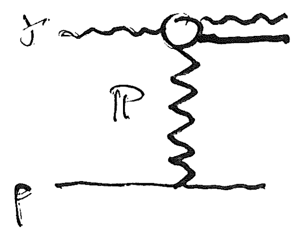
Important consequence :

absorbtive corrections are quite large in γp (and hh) interactions already at present energies.

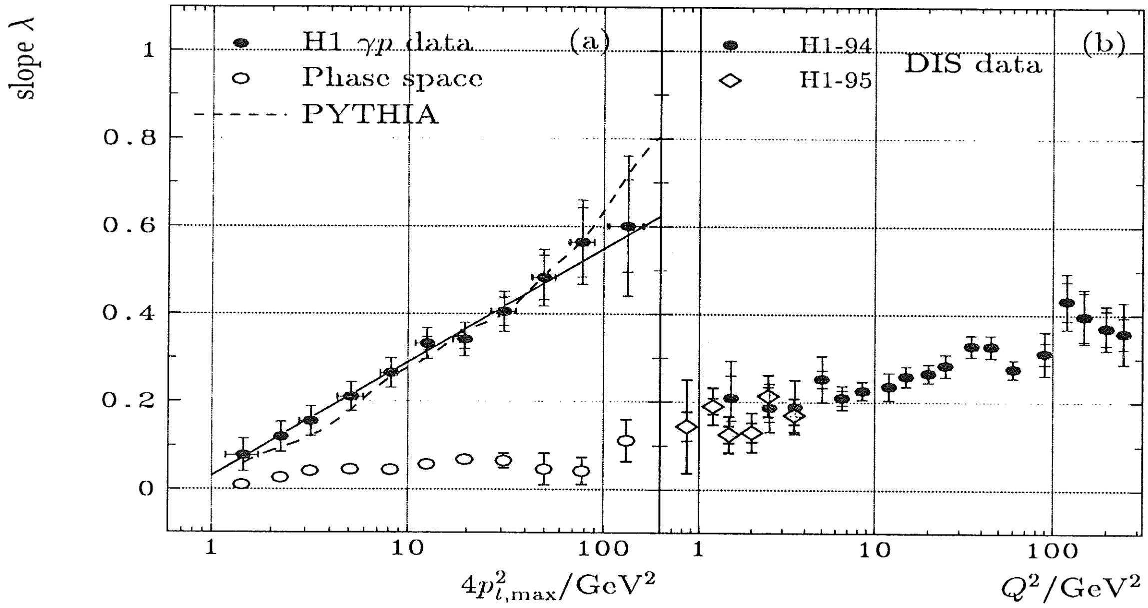
Transition regime – γp vs $\gamma^* p$

$$\sigma_{\gamma^* p}(W,Q^2) \sim W^{2\lambda(Q^2)} \quad \Longleftrightarrow \quad \sigma_{\gamma p}(W,p_t^2) \sim W^{2\lambda(p_t^2)}$$





(Müller-Regge Optical Th.)



- Clear similarity (although quantitatively difficult to compare: different scales)

- In both cases the transition from 'soft' to 'hard' regime proceeds smoothly

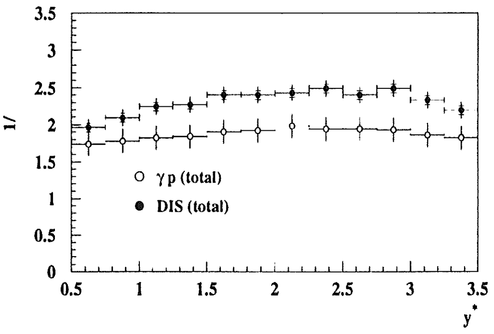
Transition regime – γp vs $\gamma^* p$

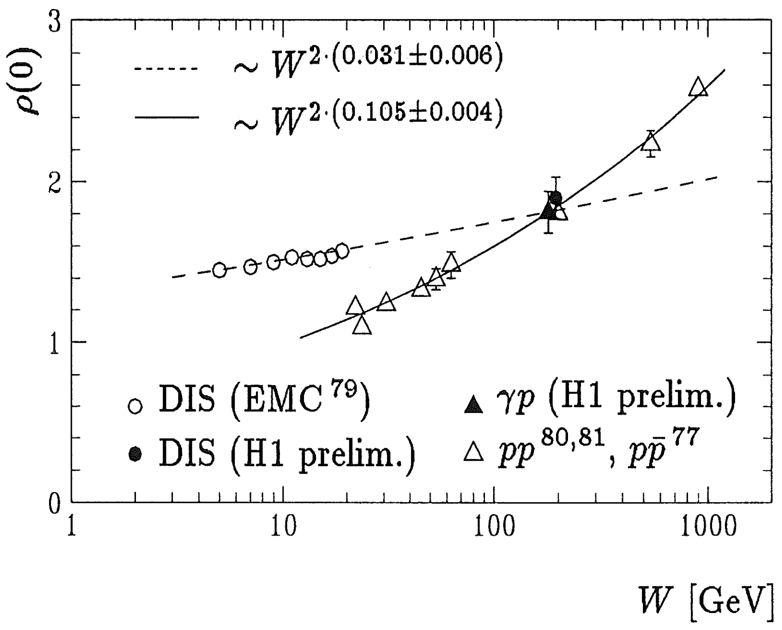
Let's test another remarkable property of **RFT**:

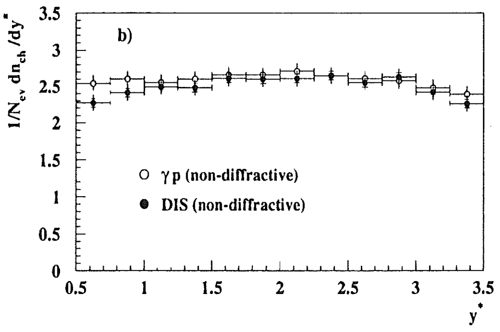
Unitarity correction contributions <u>cancel</u> in the incl. part. spectra in the central rapidity region (AGK cutting rules)

$$\left.\frac{d\sigma_{ch}}{d\eta}\right|_{\eta\approx 0} \overset{AGK}{=} \sigma^{(1)} \left.\frac{dN_{ch}^{(1)}}{d\eta}\right|_{\eta\approx 0}$$

→ universal in all types of high energy reactions (→ bare de-P exchange)







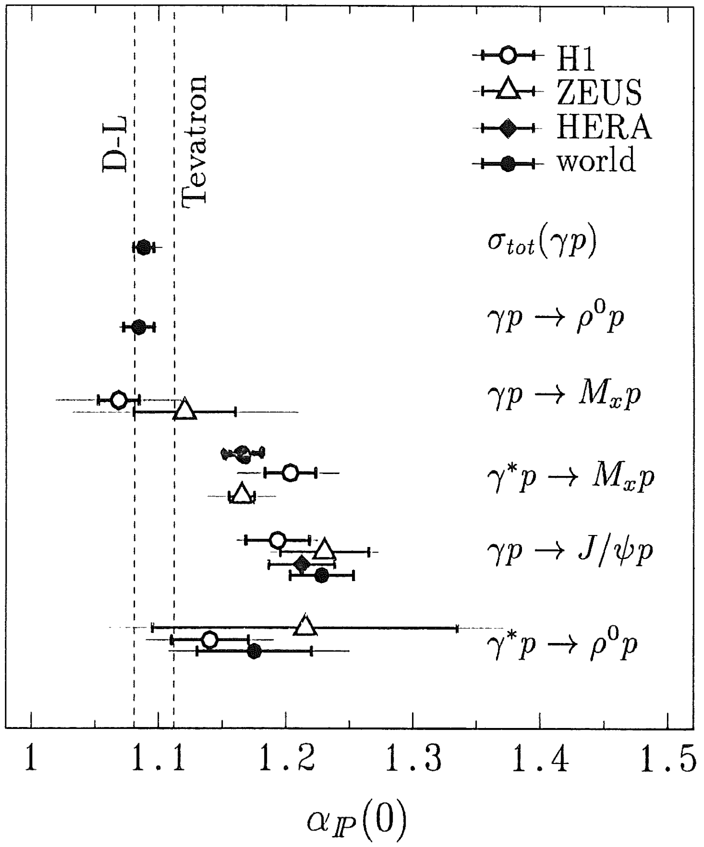
$$\rho(0) = \frac{1}{\sigma_{tot}}\frac{d\sigma_{ch}}{d\eta} \quad (\eta=0)$$

$$\rho(0)\cdot\sigma_{tot} = \begin{cases} W^{2\cdot\epsilon_{\gamma p}} \cdot W^{2(\alpha_{I\!P}^{\gamma p}-1)} \\ W^{2\epsilon_{\gamma^* p}} \cdot W^{2(\alpha_{I\!P}^{\gamma^* p}-1)} \end{cases} \Rightarrow \alpha_{I\!P}^{\gamma^* p} - \alpha_{I\!P}^{\gamma p} = 0.073 \pm 0.007$$

$$\Rightarrow \overline{\alpha_{I\!P}(0)}_{DIS} \simeq 1.16 \pm 0.01$$

SUMMARY

Pomeron Intercept Measurements at HERA



The data clearly show the departure

from ‘soft’ **Pomeron**

towards larger values of $\boldsymbol{\alpha_{I\!P}(0)}$

whenever a *hard scale* is present

SUMMARY

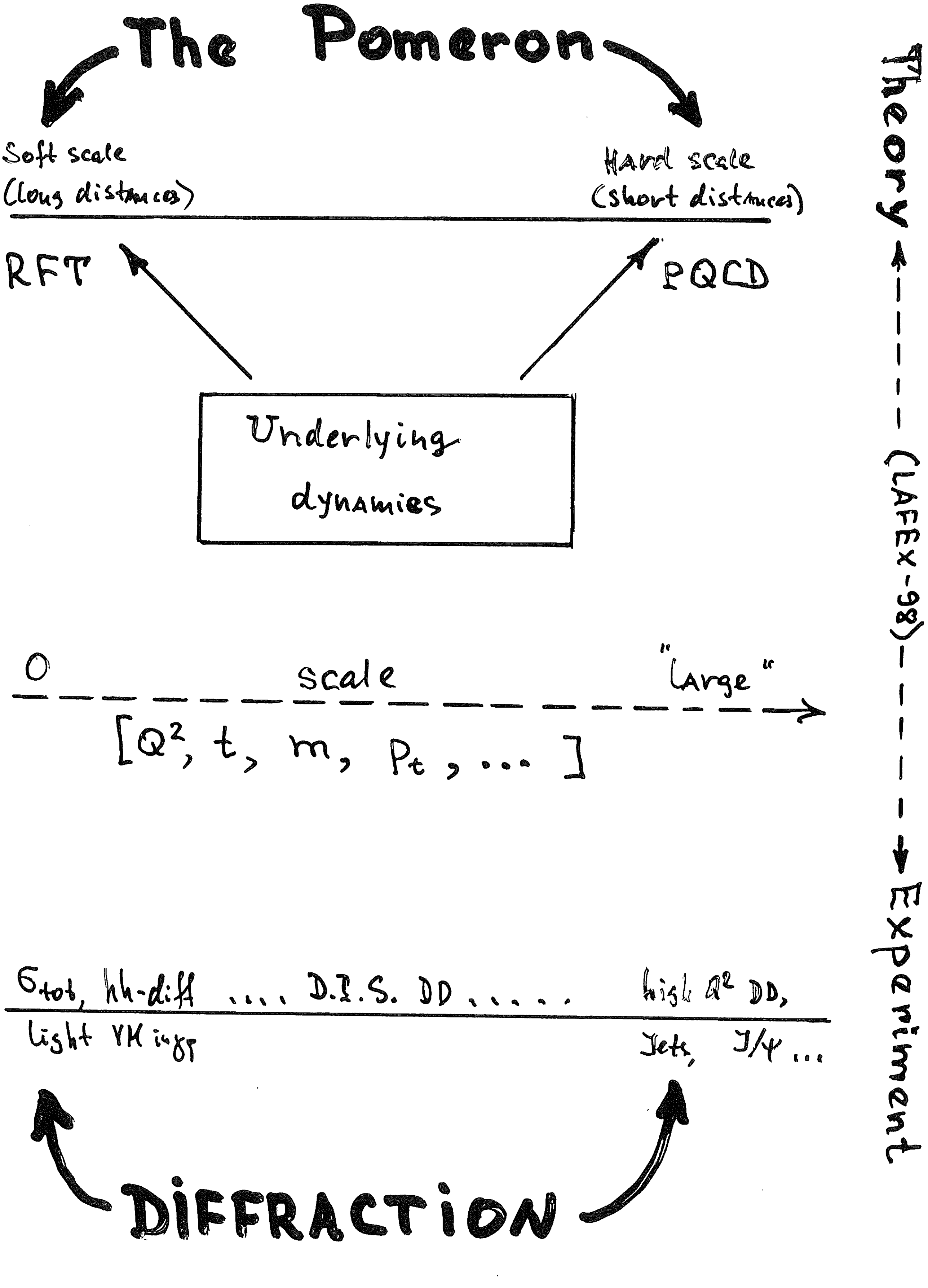
- We have seen the Pomeron at work both in soft and hard regimes, as well as in the transition region.

- All experimental data are consistently described by the universal Pomeron concept with an intercept value $\alpha_P(0) \approx 1.2 \div 1.3$

- The reduced value of $\alpha_{I\!P}^{eff}(0) \approx 1.08 \div 1.12$ observed in soft periferal collisions can be explained by the unitarity correction effects.

- A precise mechanism of this dumpening of $\alpha_{I\!P}(0)$ value is connected to non-perturbative QCD effects, and remains to be revealed

- The underlying dynamics must be able to reproduce all remarkable **RFT** features observed in the experiment


The Pomeron
Soft scale
(long distances)
Hard scale
(short distances)
RFT
PQCD
Underlying dynamics
0
scale
"Large"
[Q^2, t, m, P_t, ...]
σ_{tot}, hh-diff .... D.I.S. DD ..... high Q^2 DD,
light VM in γp
Jets, J/ψ ...
DIFFRACTION
Theory
(LAFEX-98)
Experiment