Low-x and Diffractive Data from HERA, LEP and the Tevatron

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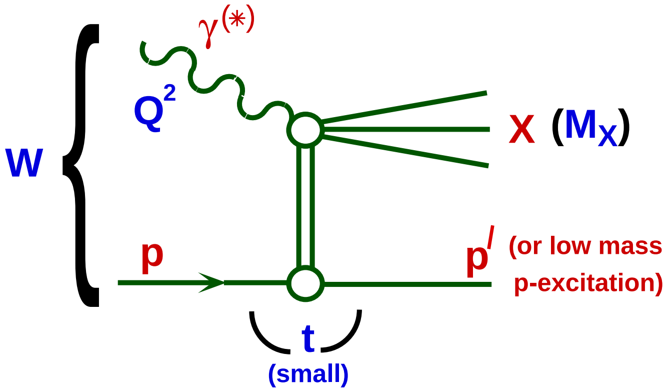
Selected topics of mutual interest ...

- Diffractive Factorisation and Parton Densities.
- Total Cross Sections.
- The search for BFKL

...focusing on Open Questions

Hard Diffractive Scattering

Lots of data on single diffractive hard processes
$\gamma^{(\star)} p \to X p$ (HERA) and $p\bar{p} \to X\bar{p}$ (Tevatron)



HERA Kinematic variables:-

- $Q^2 = -q^2$ (Photon virtuality)
- $W^2 = (q+p)^2$ ($\gamma^\star p$ centre of mass energy)
- $t = (p - p')^2$ (4-momentum transfer squared)
- $M_X^2 = X^2$ (Invariant mass of X)
- $x_{I\!P} = \frac{q.(p-p')}{q.p}$ ($x_{I\!P/\mathrm{p}}$)
- $\beta = \frac{Q^2}{q.(p-p')}$ ($x_{q/I\!P}$)

Tevatron Kinematics variables:-

- $W^2 \to s$ ($\bar{p}p$ centre of mass energy)
- $x_{I\!P} \to \xi$

Factorisation properties are very interesting!

Factorisation in Hard Diffraction

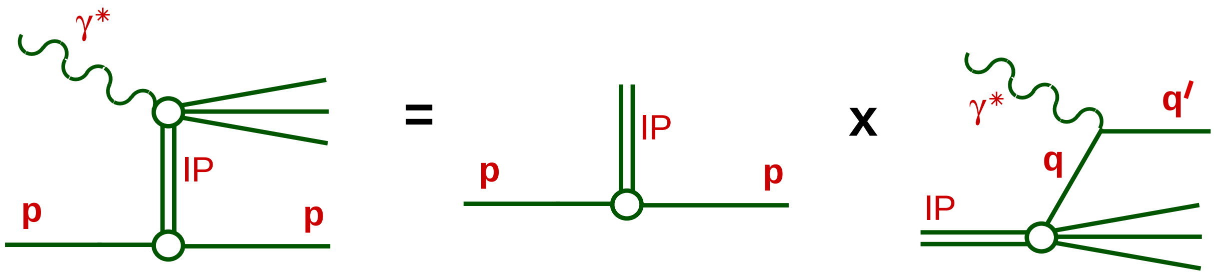
QCD Factorisation:-

QCD hard scattering factorisation theorem for diffractive DIS (Trentadue, Veneziano, Berera, Soper, Collins):
Diffractive parton distributions $f(x_{I\!P}, t, x, \mu^2)$ can be defined, expressing proton parton probability distributions with intact final state proton at particular $x_{I\!P}, t$.
Then $\sigma(\gamma^* p \to Xp) \sim f(x_{I\!P}, t, x, Q^2) \otimes \hat{\sigma}(x, Q^2)$

At fixed $x_{I\!P}$, t, diffractive partons evolve in x, Q^2 according to DGLAP equations.
QCD factorisation not proved for hadron-hadron diffraction ... non-factorisable contributions identified.

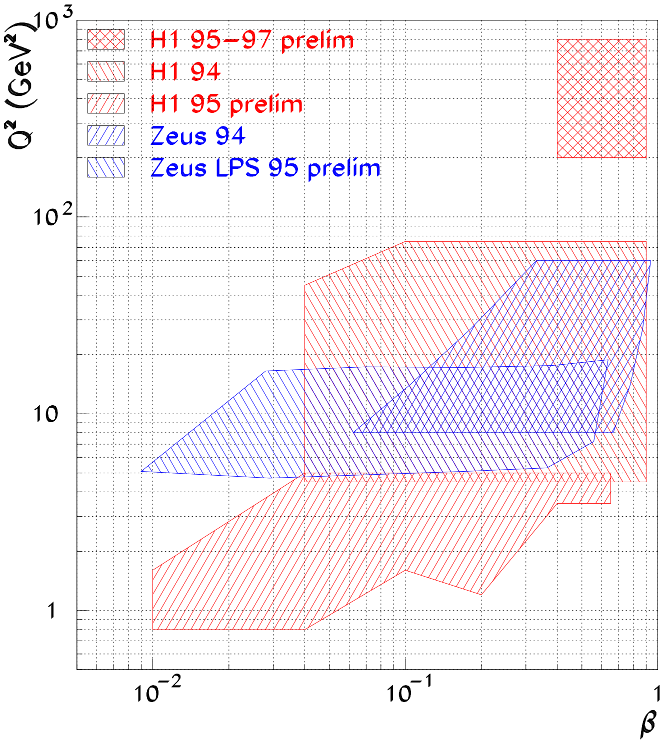
Regge Factorisation:-

Soft hadron phenomenology suggests that a universal *pomeron* ($I\!P$) exchange can be introduced, with flux dependent only on $x_{I\!P}$, t (Ingelman, Schlein).

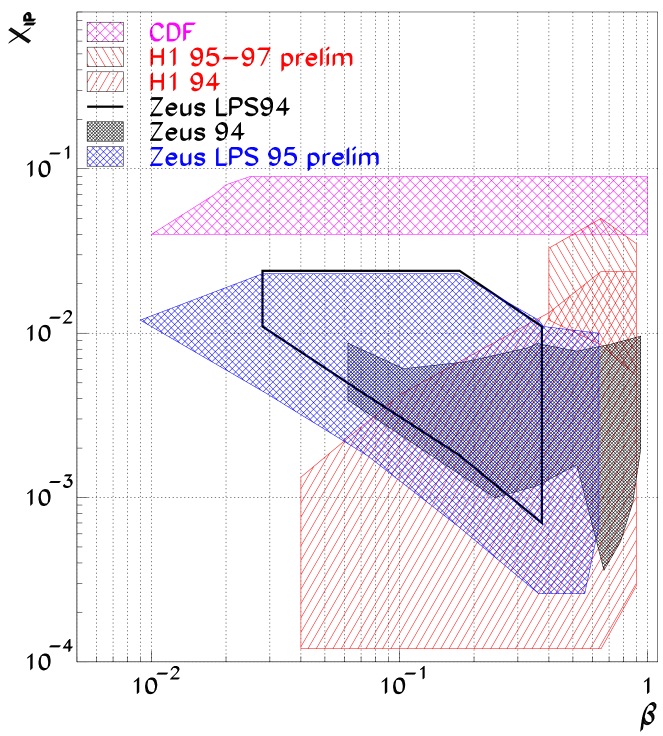


Then $\sigma(\gamma^* p \to Xp) \sim \quad f_{I\!P/p}(x_{I\!P}, t) \quad \otimes \quad F_2^{I\!P}(\beta, Q^2)$
$(\beta = x/x_{I\!P})$.

Kinematic Coverage of Diffractive Data



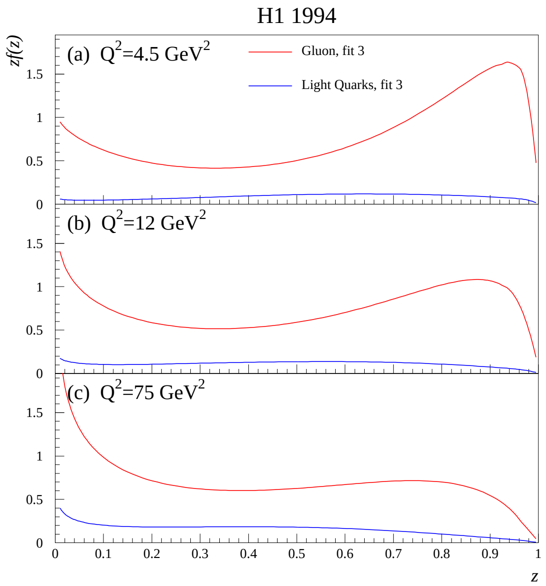
Copious $F_2^D(3)(x_{I\!P}\,\beta, Q^2)$
data spanning
$10^{-4} < x_{I\!P} < 0.05$
$10^{-2} < \beta < 0.9$
$0.8 < Q^2 < 800$



Complementary HERA and Tevatron data provide excellent testing ground for factorisation theorems / diffractive partons etc.

Pomeron Parton Distributions

F_2^D data consistent with universal $x_{I\!P}$ dependence.
Regge factorisation hypothesis approximately valid.
Pomeron parton distributions extracted from F2D.



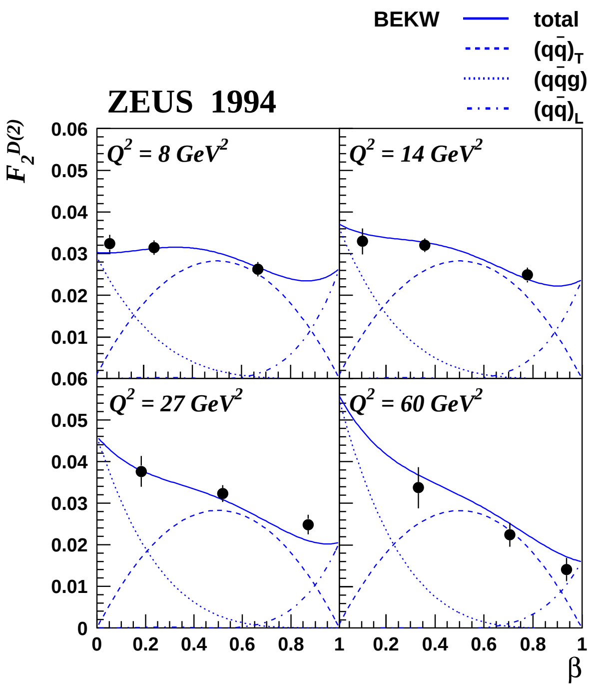
— Best fit gluon
— Best fit light quarks

All such fits suggest heavy gluon dominance with significant high x contributions.

Shape at high x v. poorly determined.

Complications . . .

- $x_{I\!P}$ dependence stronger than soft hadronic diffraction
- Sub-leading exchanges are also present (interference?)
- Fits technically difficult (high x gluon dominance.)
- Higher twist contributions likely to be present.

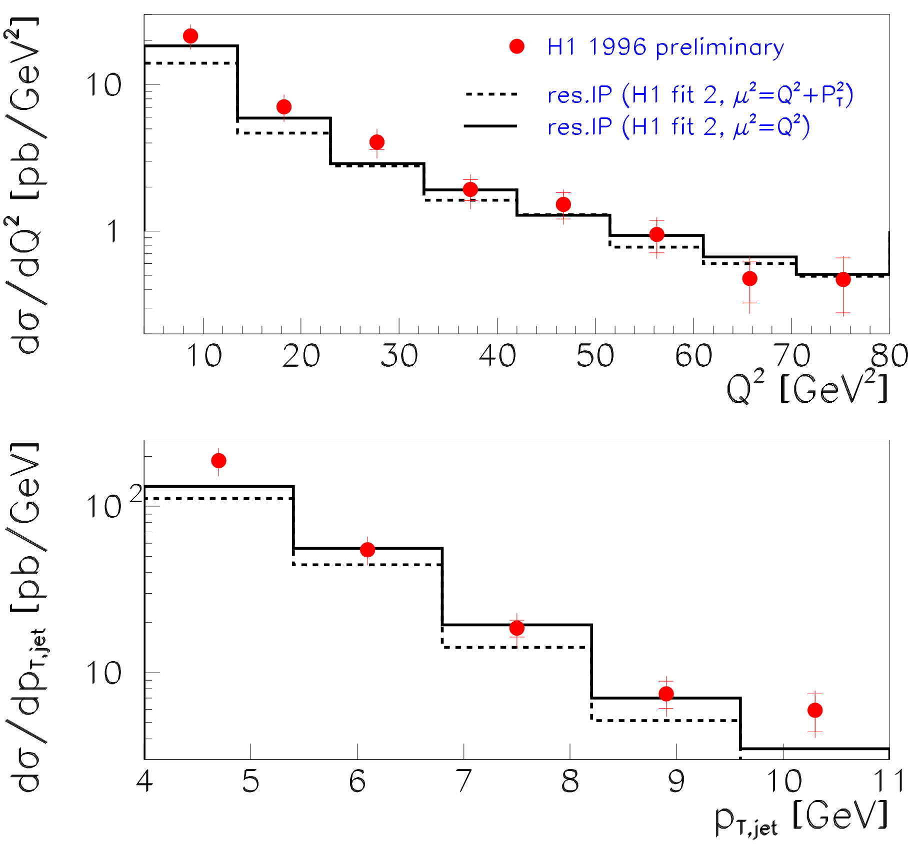


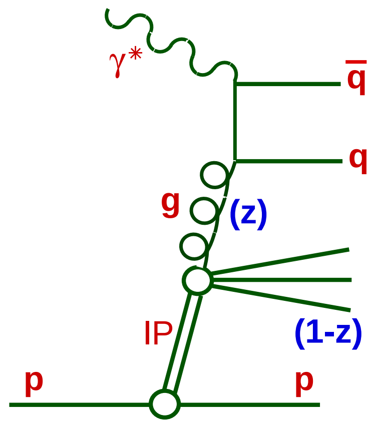
Success for Diffractive Parton Distributions

If QCD & Regge factorisation holds, IP partons extracted from F_2^D can be applied to all diffractive hard scattering.

Many hadronic final state observables at HERA well described by models based on pomeron partons (event shapes, E-flow, charged particle spectra, multiplicity . . .).

Most stringent tests come in dijet and open charm production rates and distributions.





Complications:-

Resolved γ^*?

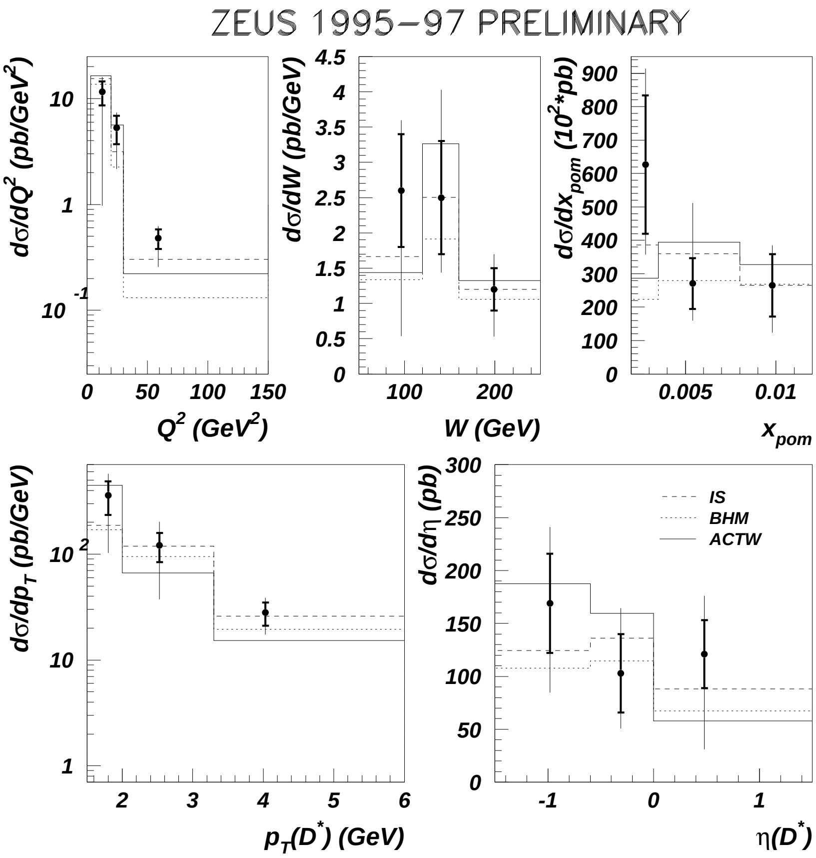
Intrinsic k_t?

Interference?

MC Modelling?

Success for Diffractive Parton Distributions?

H1 / ZEUS conclusions differ on diffractive charm . . .

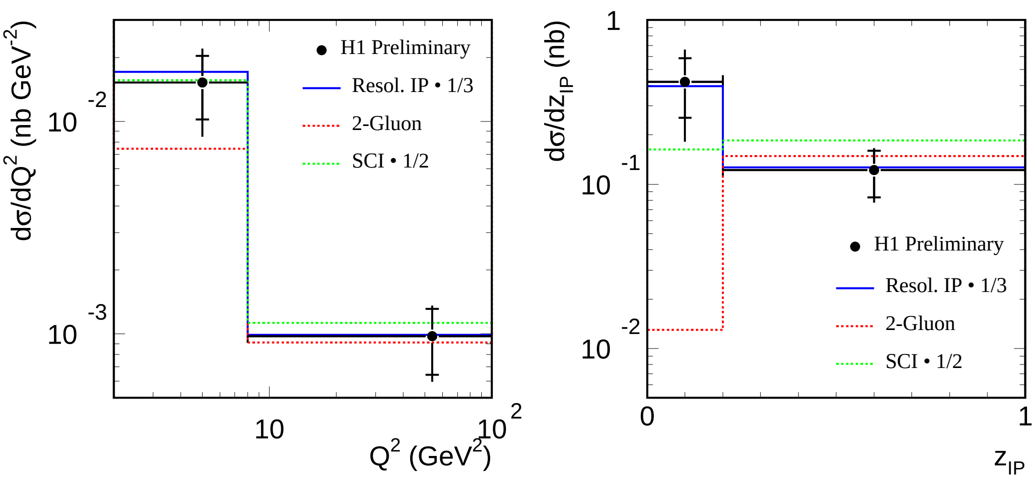


ZEUS $D^* \to K\pi\pi$ & $D^* \to K4\pi$

Rates and distributions well modelled by IP partons (ACTW)

H1 $D^* \to K\pi\pi$

Shapes well described, but normalisation difference of factor ~ 3!



Different kinematic regions? Poor statistics?

Disaster for Diffractive Parton Distributions!

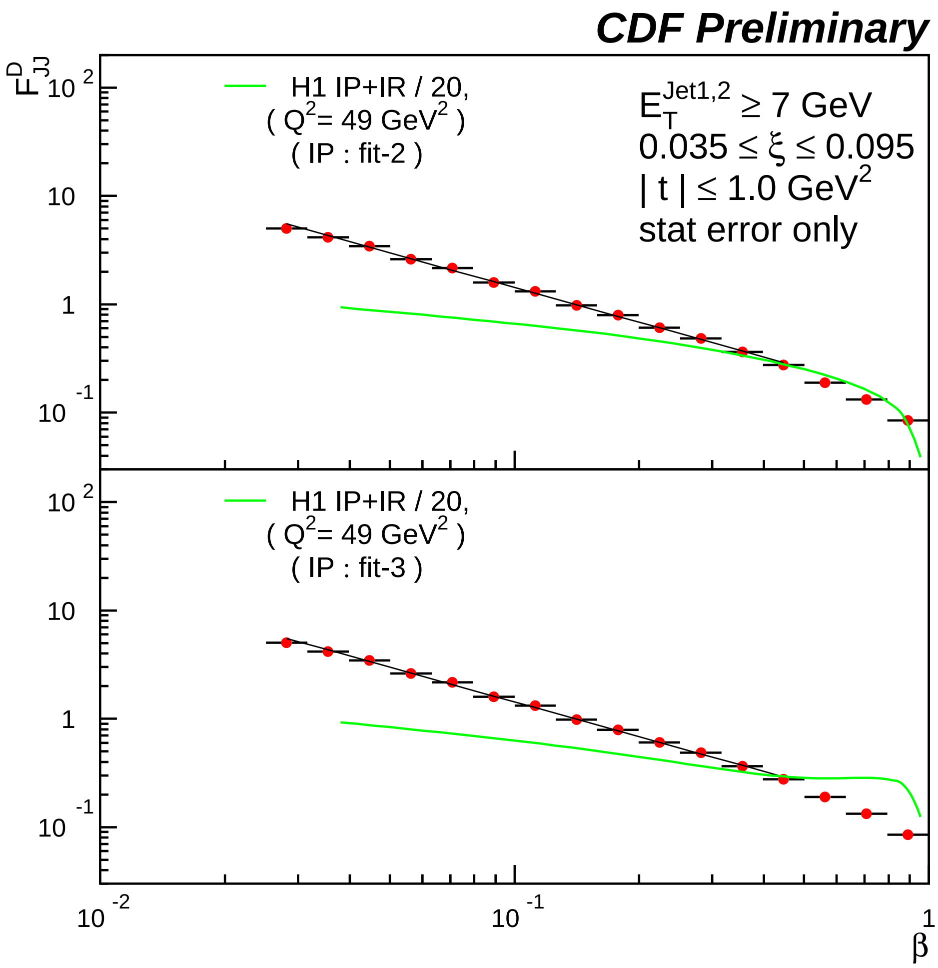
CDF Roman Pot diffractive dijet data . . . .

From diffractive / inclusive ratio, extract

$$F^D_{\rm JJ} = \frac{N^{\rm diff}}{N^{\rm incl}}(x_{\bar{p}}) \quad \left\{ x_{\bar{p}} g(x_{\bar{p}}) + \frac{4}{9}[q(x_{\bar{p}}) + \bar{q}(x_{\bar{p}})] \right\}_{\bar{p}}$$

Assuming factorisation

$$F^D_{\rm JJ} \propto \left\{ \beta g(\beta) + \frac{4}{9} x [q(\beta) + \bar{q}(\beta)] \right\}_{I\!P} \otimes f_{I\!P/{\rm p}}(\xi)$$



Comparison with $I\!P$ partons from F_2^D (standard $I\!P$ flux factor folded in) shows large β dependent discrepancy.

Inconsistent in both shape and normalisation.

Disaster for Diffractive Parton Distributions!

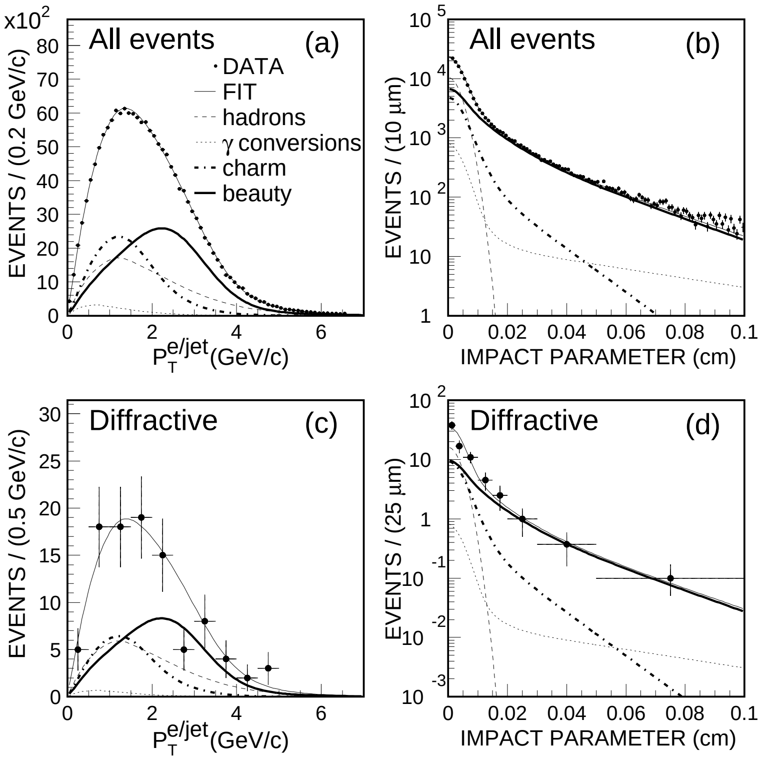
CDF measure diffractive b production ($x_{I\!P} \lesssim 0.06$).

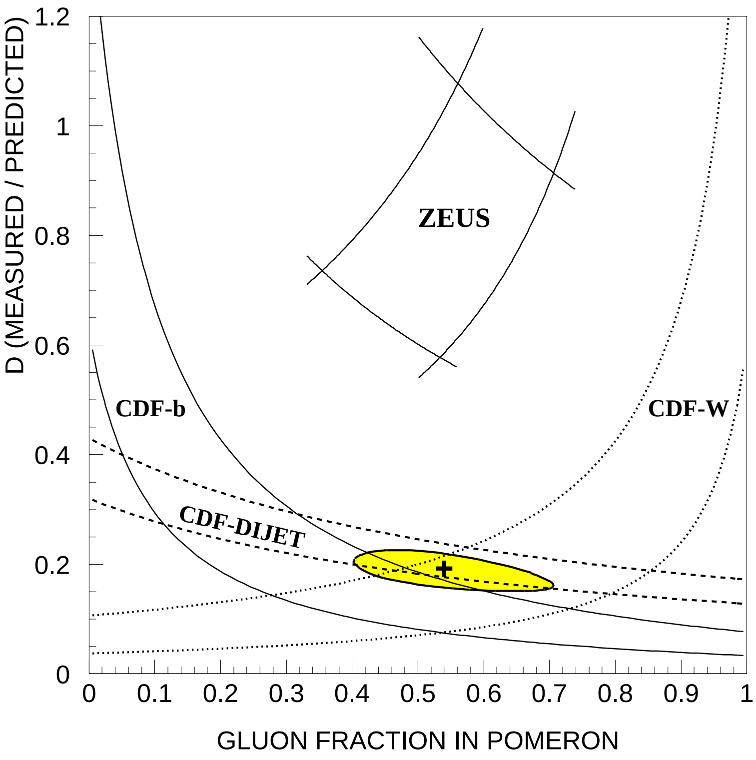
(a,c) Fit to relative p_T in $e+$ jet events.

(b,d) Fit to impact parameter distribution in silicon microvertex detector.

$$\frac{\sigma^{\rm diff}_{b\bar{b}}}{\sigma^{\rm incl}_{b\bar{b}}} = 0.62 \pm 0.19({\rm st.}) \pm 0.16({\rm sy.})\%$$

F_2^D partons predict $\sim 10\%$





Clear breaking of factorisation between HERA and Tevatron data.

From combined fits to jet, W and b data, large gluon fraction in $I\!P$ is obtained.

Extent of Factorisation Breaking

Alvero, Collins, Terron, Whitmore fit ZEUS, H1 F_2^D and ZEUS γp dijets to obtain diffractive parton distributions.

Predict diffractive / inclusive ratios at Tevatron using best fit (gluon dominated) partons . . .

Process	Data (%)	Model (%)	Model/Data
$pp \to jjX$-gap-p CDF $E_t > 10$ GeV	0.109 ± 0.016	3.7	~ 34
$pp \to jjX$-gap-p CDF $E_t > 20$ GeV	0.75 ± 0.10	16.4	~ 22
$pp \to jjX$-gap-p D0 $E_t > 12$ GeV	0.67 ± 0.05	11.8	~ 18
$pp \to WX$-gap-p CDF	1.15 ± 0.55	6.9	~ 6
$pp \to p$-jj-p CDF DPE	13.6 ± 3.4 nb	3713 nb	~ 275

Clear factorisation breaking, srongest for DPE (two $I\!P$'s)

Questions in Diffractive Factorisation

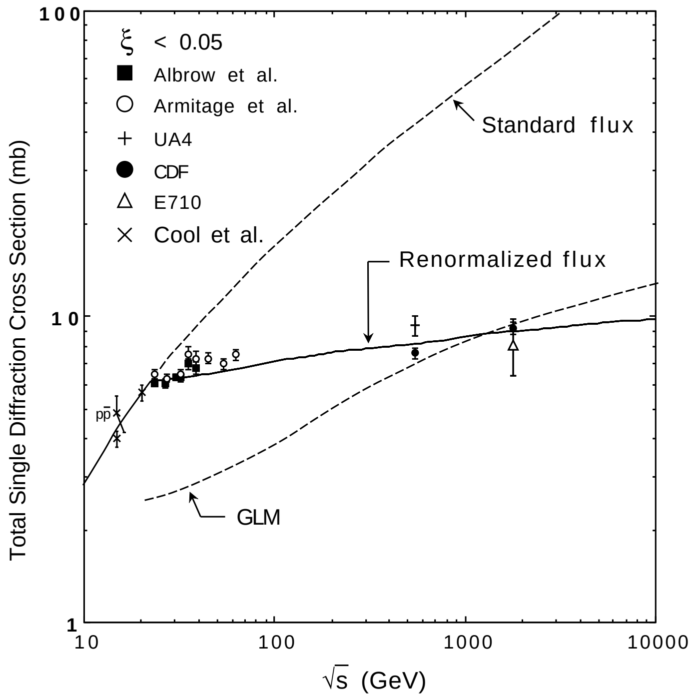
Lots of HERA and Tevatron data.
Hard scattering & Regge factorisation work well at HERA
Clear breakdown when comparing HERA with Tevatron.

- How can we improve the QCD fitting procedure for HERA DIS data?

- Can we build a phenomenological model of the factorisation breaking effects?

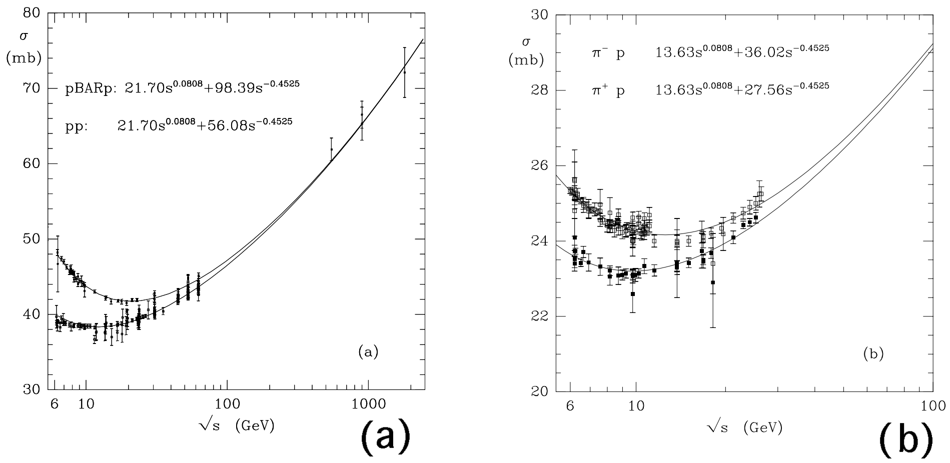
- What can be learned from photoproduction data (factorising direct photon contributions and non-factorising resolved photon contributions?)

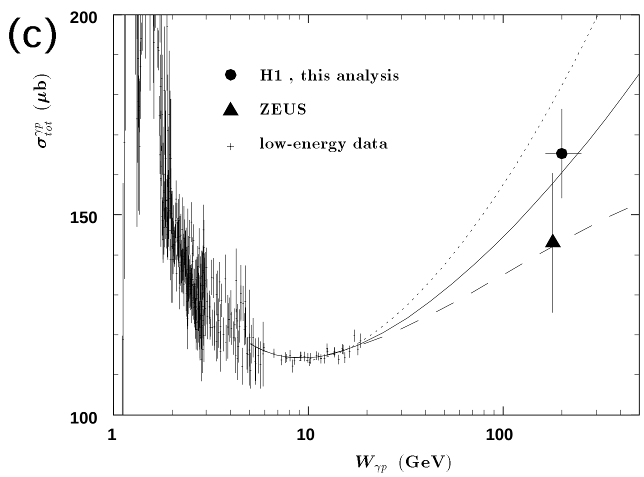
- What is the status of Regge factorisation? - Goulianos flux factor renormalisation?



Total Cross Sections

Total cross sections in hadron-hadron physics well described by 2-component ($\mathbb{P} + \mathbb{R}$) Regge models.





$$\sigma^{\rm tot} \sim A_{\mathbb{P}}\ s^{\alpha_{\mathbb{P}}(0)-1} + B_{\mathbb{R}}\ s^{\alpha_{\mathbb{R}}(0)-1}$$

$$\alpha_{\mathbb{P}}(0) \sim 1.1$$

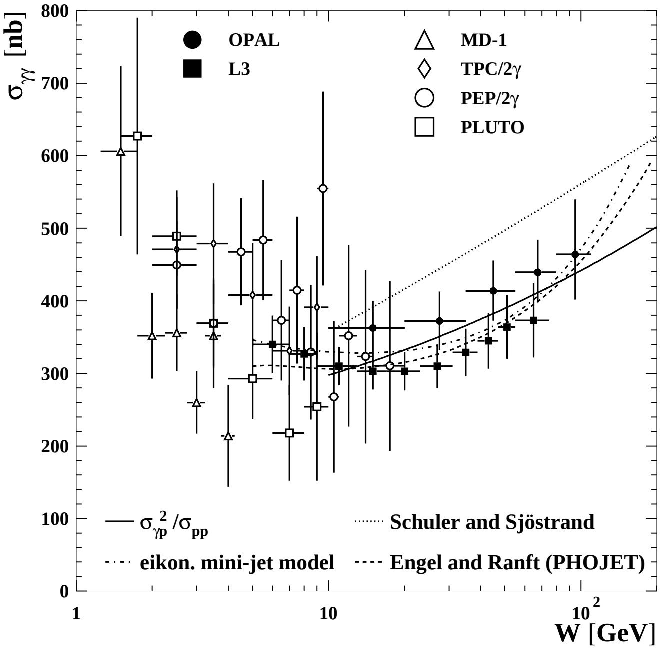
Some models predict γ induced total cross sections rise faster than in hadron-hadron physics (direct couplings).

HERA data inconclusive. - Model dependence (correct with PHOJET or PYTHIA?) among largest systematics.

Main problem is poorly constrained diffractive channels.

Total Photon-Photon Cross Sections

LEP data with both final state electrons and many hadrons lost down beampipe. - Kinematics poorly constrained.



L3 report sharper rise of $\sigma_{\gamma\gamma}^{tot}$ than hadron-hadron σ^{tot}.

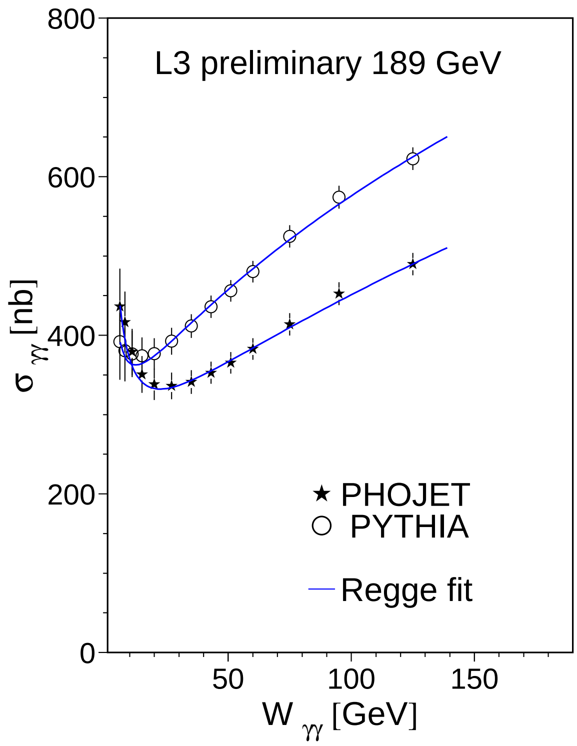
$\alpha_{\mathbb{P}}(0) \sim 1.21 \pm 0.03$

Highly correlated with $\alpha_{\mathbb{R}}(0)$

Not yet clear whether OPAL can confirm this.

$\sigma_{\gamma\gamma} = \frac{\sigma_{\gamma p}^2}{\sigma_{pp}}$ works well.

Soft + hard $\mathbb{P}$ models (Donnachie, Landshoff) work.



Model dependence of acceptance corrections large.

Large effect on cross section. W dependence is more robust.

To improve measurements, need to constrain models better!

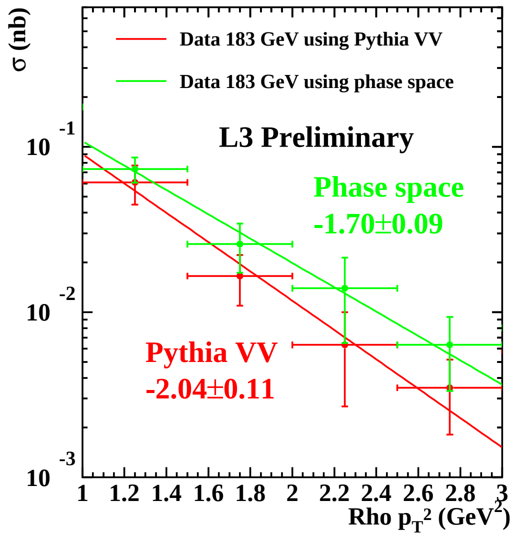
Measurements of Diffractive Channels

Soft diffractive dissociation final states display limited p_T fragmentation.

Acceptances often better in 'elastic' vector meson channels - well known decay angular distributions.

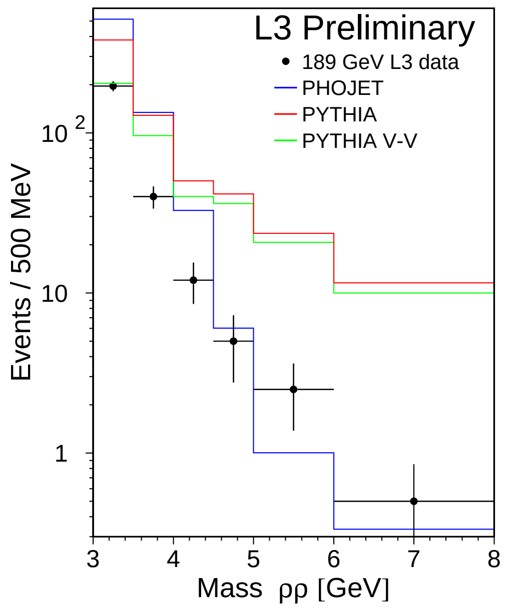
L3 measure 'elastic' $(\gamma\gamma \to \rho^0\rho^0)$ and 'single dissociation' $(\gamma\gamma \to \rho^0 X)$ channels.

Good tests of size of diffractive channels in MC.



$\sigma(\gamma\gamma \to \rho^0 X)$ well modelled in PYTHIA $\sim$ absent in PHOJET.

$|t|$ distribution measured
Slope parameter $b \sim 2$.
...useful input to
all soft physics models.



4π mass combinations not well described by either model (uncorrected data).

PYTHIA has too much $\rho\rho$.
PHOJET $m_{\rho\rho}$ dependence too steep.

Questions in Total Cross Sections

$\sqrt{s}$ dependence of $\sigma^{\rm tot}_{p\bar{p}}$ fairly well established. Lower precision in other total cross sections.

First hints of different behaviour of $\sigma^{\rm tot}_{\gamma\gamma}$.

- How can we improve our understanding of acceptance corrections?
- Can more diffractive channels be experimentally measured?
- Can the soft phenomenological models (incoprorated in PHOJET and PYTHIA) be improved. - What new data can constrain them?

Searches for BFKL Dynamics

The BFKL approximation must be valid in some region of low-x phase space

Not obvious from inclusive data $F_2(x, Q^2)$.

Where should we look? ...

1) Processes where all vertices have small transverse size.

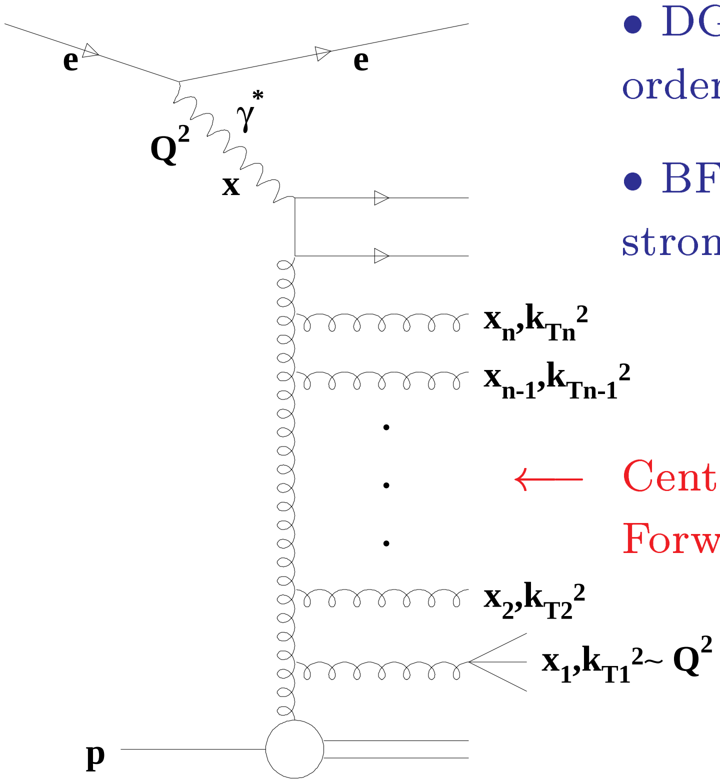
BFKL approximation most reliable where only large momentum scales are present
$\rightarrow$ $\gamma^*\gamma^*$ cross sections.
$\rightarrow$ Diffractive processes at large $|t|$.

2) Exclusive channels sensitive to QCD cascade at central η^*.

Clear differences between BFKL and DGLAP predictions for transverse & longitudinal momentum of parton emissions away from the photon vertex at HERA.
$\rightarrow$ HERA forward region corresponds to central region in $\gamma^* p$ frame.

BFKL Searches in the HERA Final State

Can the footprints of BFKL be seen in the hadronic final state at HERA?



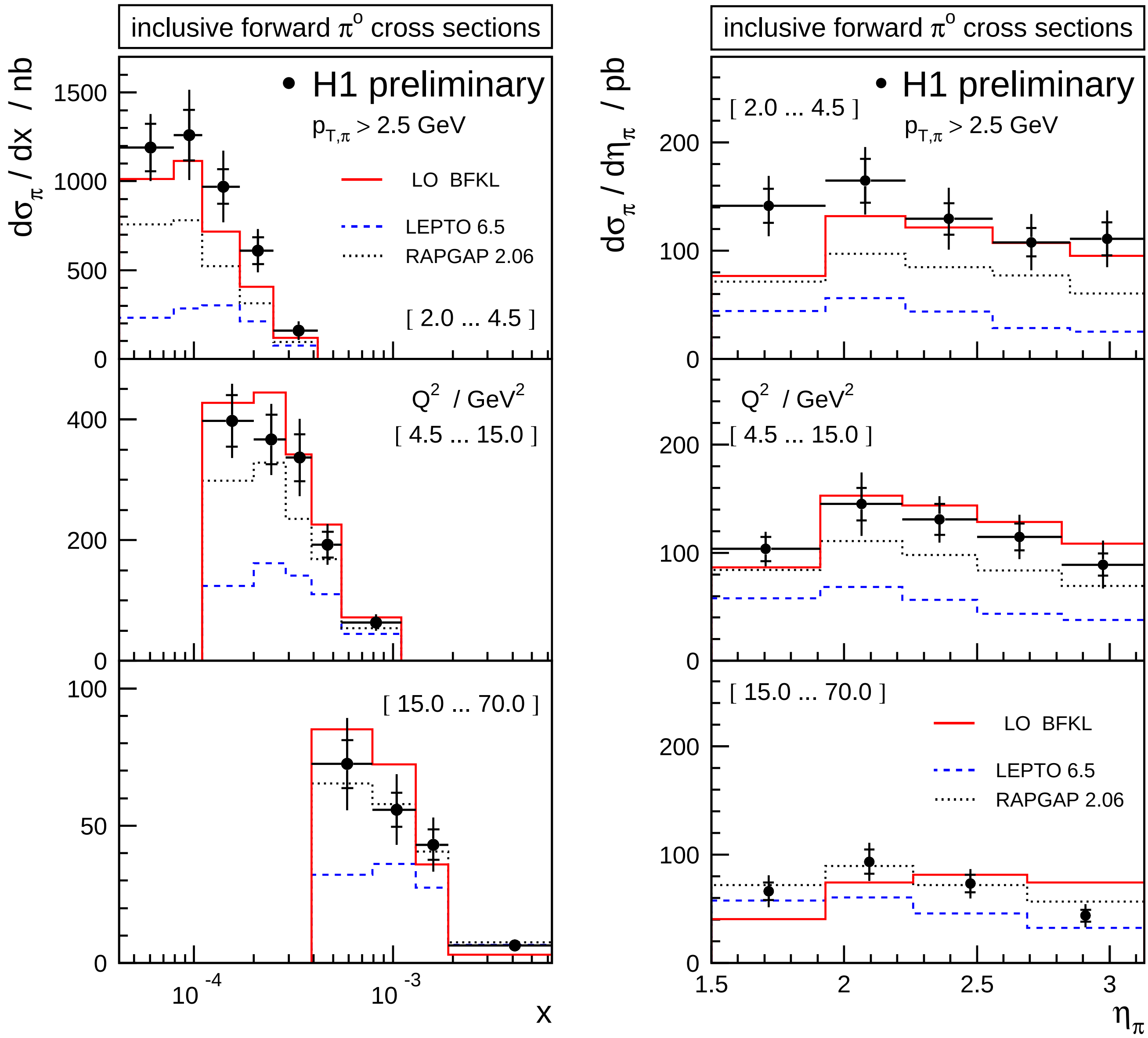
- DGLAP evolution implies k_t ordering of partons along ladder
- BFKL evolution imposes no strong k_t ordering

⟵ Central rapidity in $\gamma^* p$ lies in Forward (outgoing proton) region in HERA lab frame.

BFKL effects are expected to show up as enhanced high p_t particle production in the forward direction at HERA.
Measurements are tricky, but there are many sensitive observables . . .

Foward π^0 Production at HERA

Measure $\pi^0 \rightarrow \gamma\gamma$ with $5° < \theta(\pi^0) < 25°$, $p_t(\pi) > 2.5$ GeV



LEPTO (DGLAP) cannot reproduce the rates.

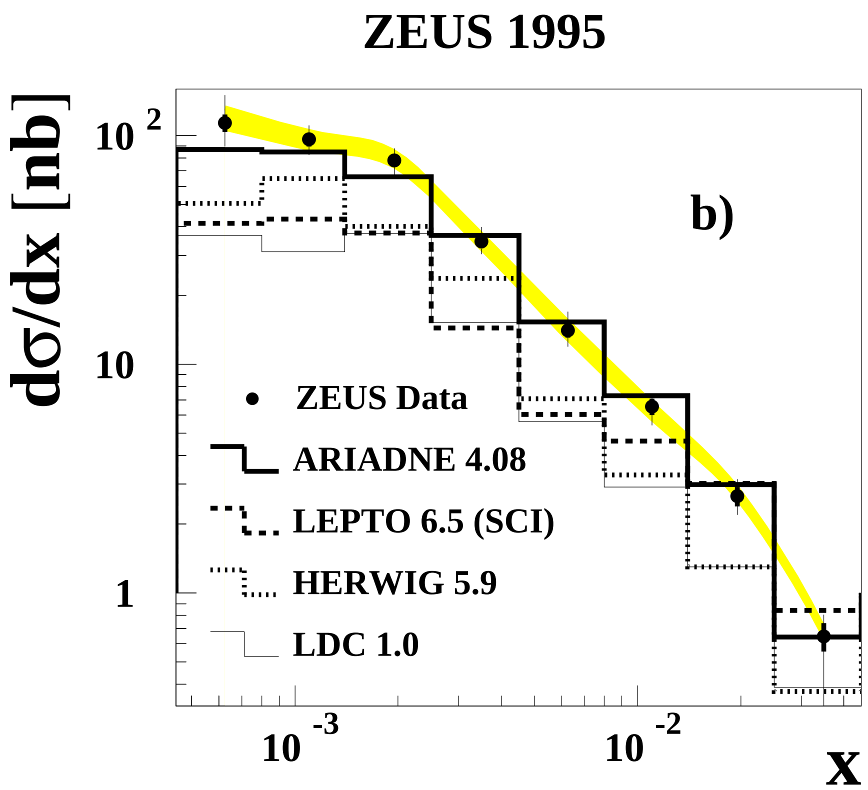
Modified LO BFKL (Kwiecinski, Martin, Outhwaite) gives a good description.

RAPGAP (DGLAP with resolved γ^*) also close to data.

Complication! - scale dependence of predictions.

Foward Jet Production at HERA

Select forward jets ($E_t > 5$ GeV) with $0.5 < E_t^2/Q^2 < 2$, $p_z^{\text{jet}}/E_p > 0.036$, target region of Breit frame

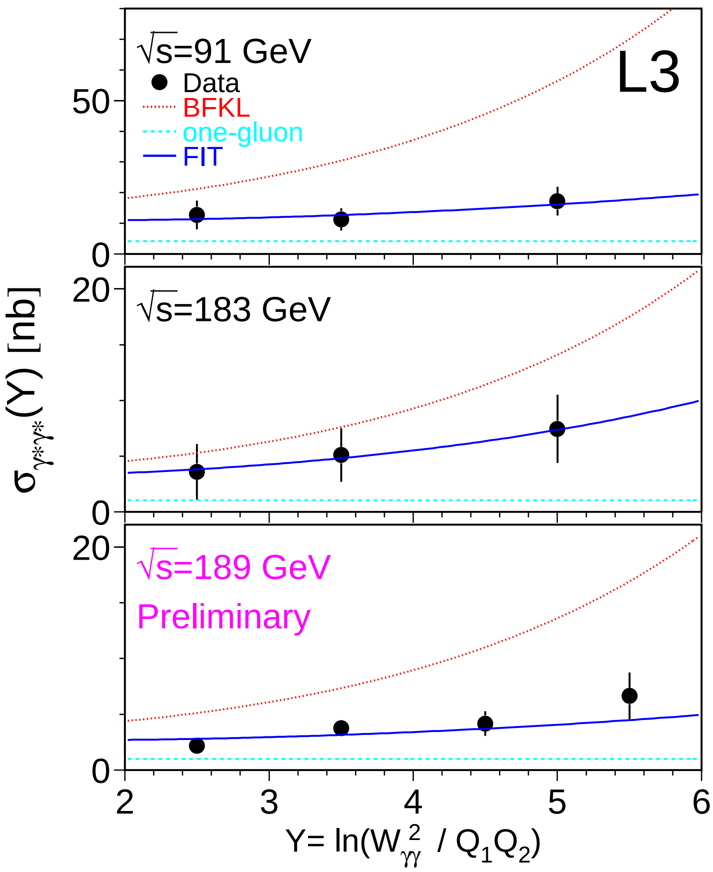


LEPTO, HERWIG (DGLAP) cannot reproduce the rates.
LDC (based on CCFM evolution, linking DGLAP and BFKL) fails to describe data.
ARIADNE (BFKL-like k_t ordering) gives a good description.
RAPGAP (DGLAP with resolved γ^*) describe similar H1 data.
Complication! - scale dependence of predictions.

$\gamma^*\gamma^*$ Scattering

$\sigma(\gamma^*\gamma^* \to X)$ is a very nice process to calculate in pQCD.
BFKL calculation expected to be valid at large
"Y"$= \ln(W^2_{\gamma^*\gamma^*}/Q_1Q_2)$.

L3 data - Both scattered electrons tagged - well reconstructed kinematics, $\langle Q^2\rangle = 14.5$ GeV^2.
QPM processes ($\mathcal{O}(\alpha_s^0)$ $\gamma^*\gamma^* \to q\bar{q}$) subtracted.



LO BFKL:
$$\sigma_{\gamma^*\gamma^*} \propto \frac{1}{Q_1Q_2\sqrt{Y}} e^{(\alpha_{\mathbb{P}}(0)-1)Y}$$

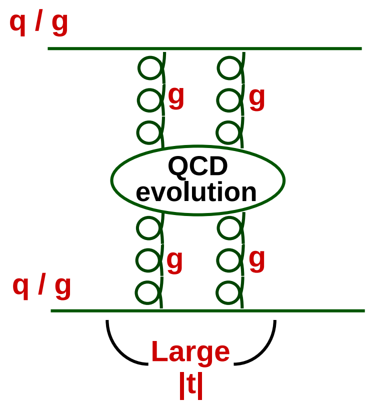
LO BFKL prediction ($\alpha_{\mathbb{P}}(0) \sim 1.5$) too high.

Free fit gives $\alpha_{\mathbb{P}}(0) = 1.29 \pm 0.03$(st.).

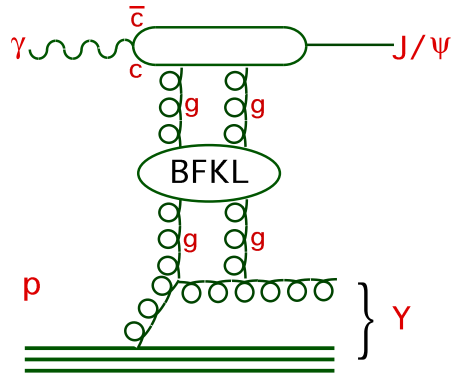
BUT!…Non BFKL models (e.g. TWOGAM) with γ^* structure also descibe data.

Diffraction at large $|t|$

Elastic parton-parton scattering at high $|t|$ has been calculated in terms of LO BFKL $I\!P$.



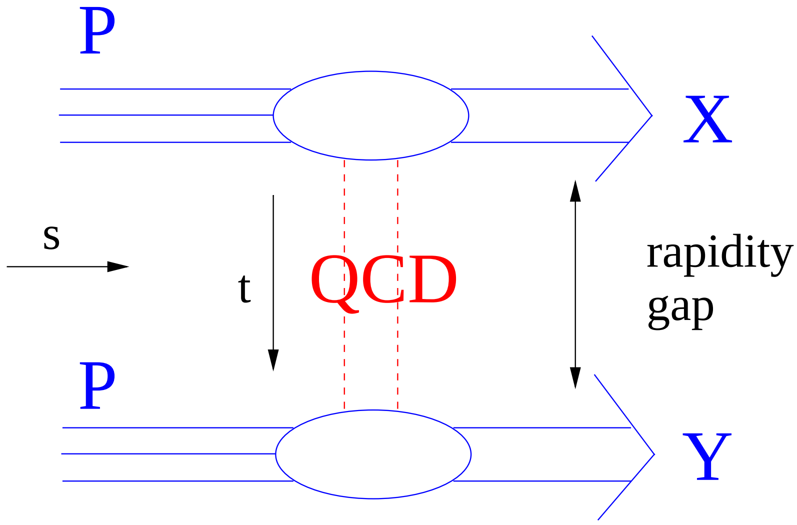
First measurements of high $|t|$ vector meson photoproduction $\gamma p \rightarrow VY$ have been made by H1 and ZEUS.



Clear high $|t|$ signal, consistent with LO BFKL calculations.

Rapidity Gaps Between Jets

The classic high $|t|$ diffractive process ...

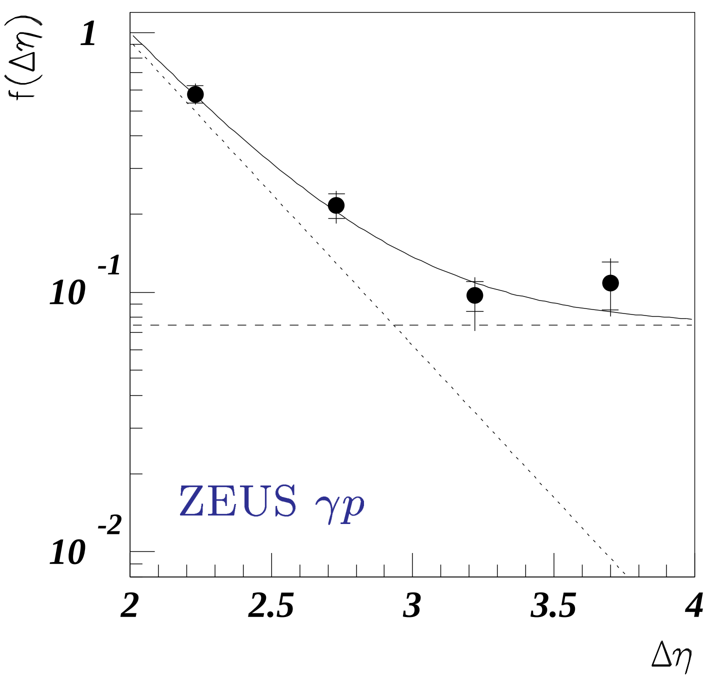


Lack of hadronic activity between jets implies net colour-singlet exchange.

Elastic parton-parton scattering at $|\hat{t}| \sim p_{t,jet}^2$

Large $|t| \rightarrow$ small spatial dimensions of interaction $\rightarrow$ pQCD treatment.

Quantified in terms of *gap fraction* $f = \frac{\text{Evts with rapgap between 2 leading jets}}{\text{All dijet events}}(\Delta\eta^{\text{jets}}, E_t^{jet}, \sqrt{s}\ldots)$



Clear excess over fluctuations in hadronisation process at large $\Delta\eta$

Magnitudes of Gap Fractions

Warning! Different experiments have different gap defns.

Experiment	$\sqrt{s}$ (GeV)	Gap Fraction
ZEUS γp	~ 200	0.11 ± 0.02 (st.) $^{+0.01}_{-0.02}$ (sy.)
H1 prel. γp	~ 200	~ 0.15
CDF $p\bar{p}$	630	0.027 ± 0.007 (st.) ± 0.006 (sy.)
D0 $p\bar{p}$	630	0.019 ± 0.001 (st.) ± 0.004 (sy.)
CDF $p\bar{p}$	1800	0.011 ± 0.001 (st.) ± 0.001 (sy.)
D0 $p\bar{p}$	1800	0.0094 ± 0.0004 (st.) ± 0.0012 (sy.)

$\sqrt{s}$ dependence may be explained by rapgap destruction
... secondary scattering from (coloured) beam remnants.

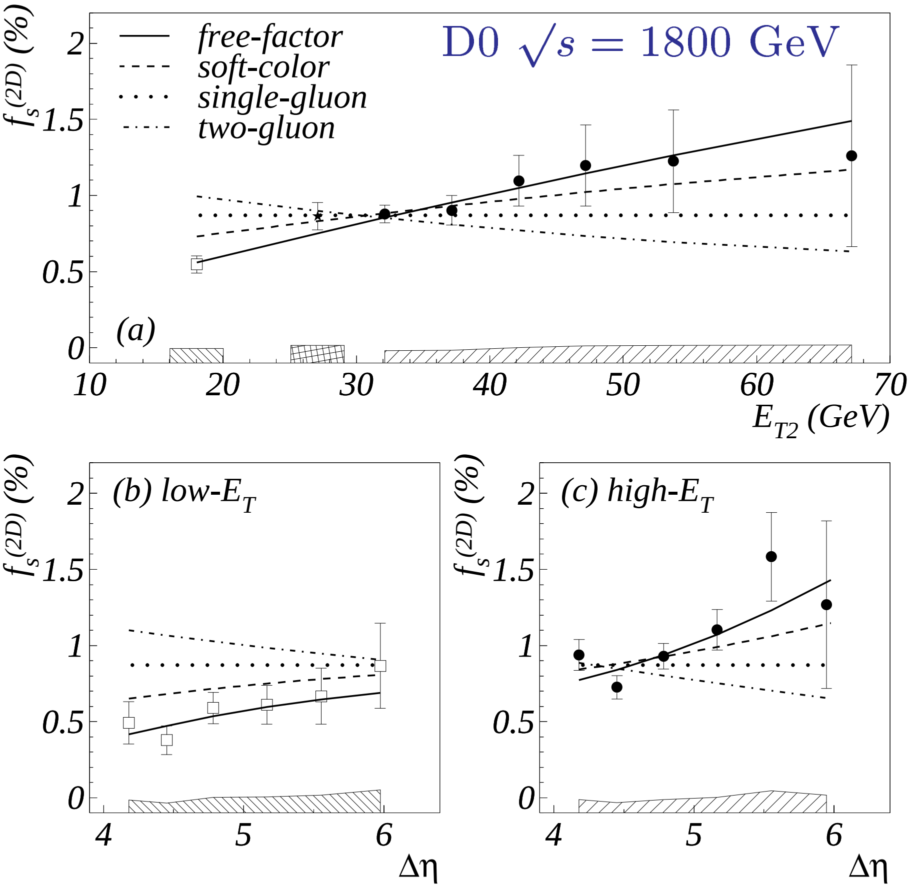
Re-interaction probability depends on density of partons?
... increasing as $\sqrt{s}$ incerases and $\langle x \rangle$ decreases

Toy model based on pQCD multiple interaction prob's in PYTHIA (Cox, Forshaw, Lönnblad) reproduces trend ...

$\sqrt{s}$ (GeV)	Gap Survival Probability
200 (γp)	0.67
630 ($\bar{p}p$)	0.35
1800 ($\bar{p}p$)	0.22

Eikonal model (GLM) gives similar conclusions
Survival Probability $\sim 13\%$ (630 GeV), $\sim 6\%$ (1800 GeV)

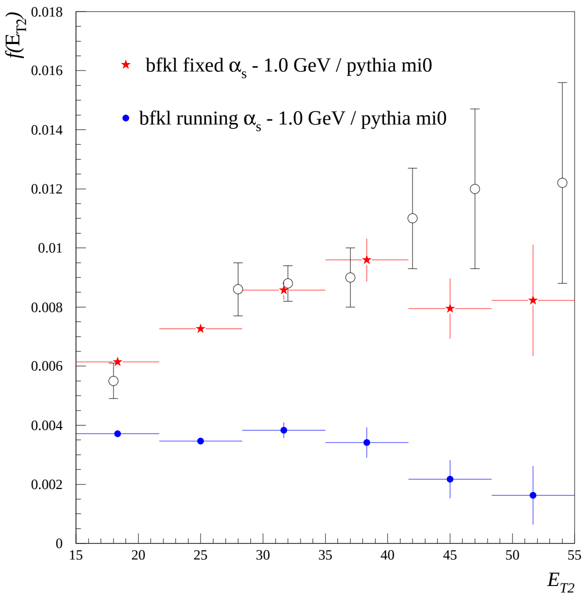
E_t, $\Delta\eta$ Dependence and Model Comparisons



Gap fraction flat or slowly rising with E_t and $\Delta\eta$.

Good description from soft colour interactions creating rapidity gaps in standard dijet events.

Can a good description be obtained with BFKL?



Analysis (Cox, Forshaw, Lönnblad) with leading log BFKL, fixed α_s, survival probability corrections ...

- ○ D0 data
- ● BFKL fixed α_s
- ● BFKL running α_s

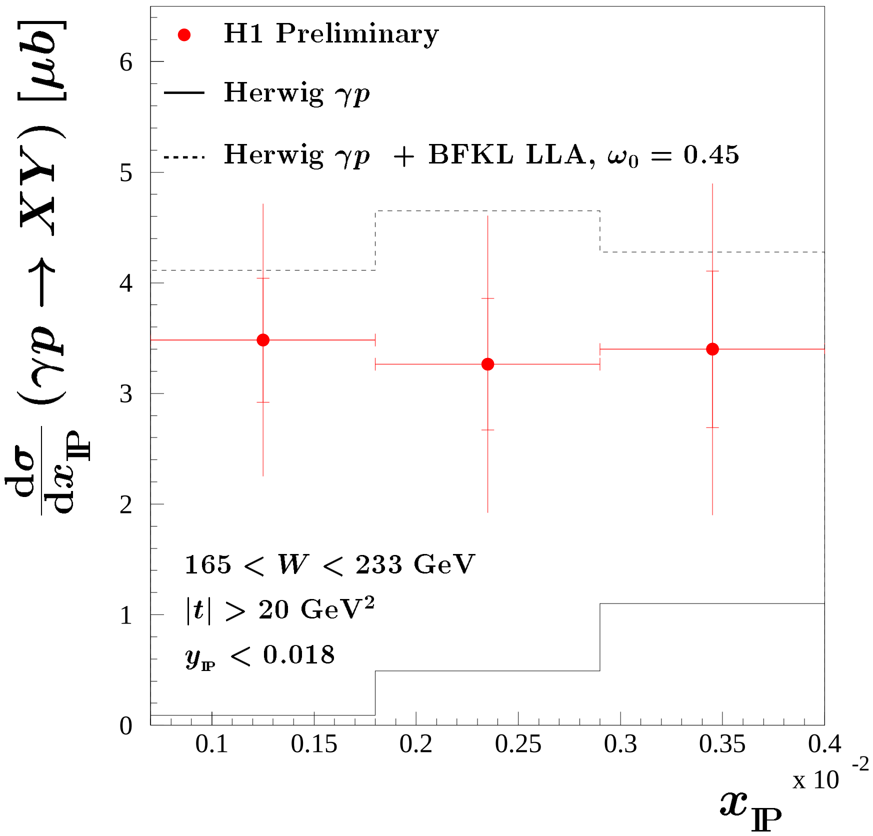
Relaxing the Jet Requirement

Is it really necessary to require jets? ...

Large $\Delta\eta$ is needed to see signal (at limits of acceptance at HERA).

What does the data look like for $|t| < 25$ GeV^2?

H1 measure inclusive diffractive process $\gamma p \to XY$ at high $|t|$ ...



Precision limited by poor $|t|$ resolution.

Data consistent with leading log BFKL prediction.

Questions in the search for BFKL

Now lots of data ... high $|t|$ diffraction in $\bar{p}p$ and γp, forward particle production at HERA, $\sigma^{\rm tot}_{\gamma^*\gamma^*}$ ...

- Comparisons beyond LO BFKL are beginning - how do we proceed?
- Do we have a common definition of rapidity gaps between jets?
- Can we develop a full phenomenological description of rapidity gap survival probabilities?
- Which new high $|t|$ measurements will help most? ... $\gamma^{(*)}p \to \gamma p$?
- Forward particle measurements look promising. Scale dependence of predictions limits strength of conclusions.
- What about resolved virtual photon models? - Should these contributions be included anyway?
- What are the next steps for CCFM-type models?
- Can BFKL evolution be seen in $\gamma^*\gamma^*$ at less than linear collider energies?