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Diffraction in Deep Inelastic Scattering at HERA

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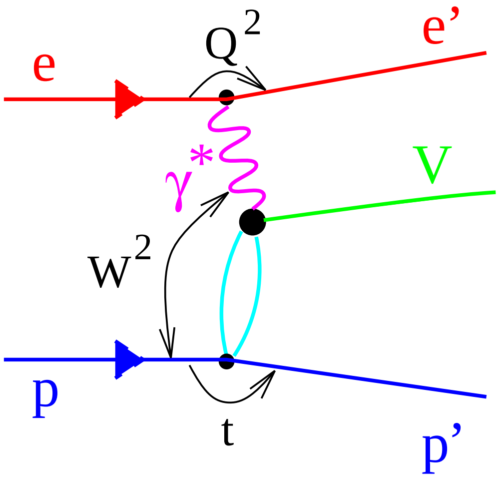
on behalf of the ZEUS and H1 Collaborations

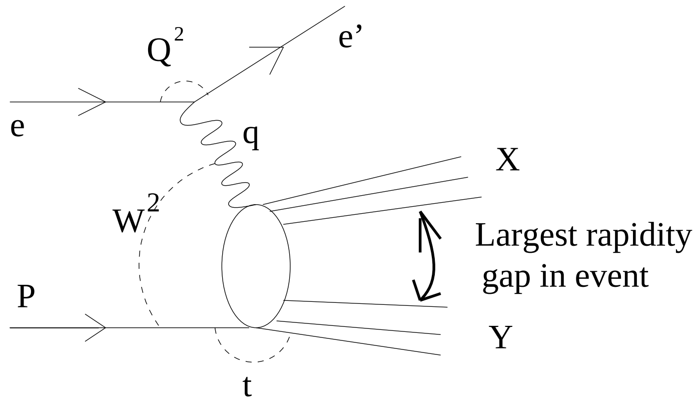
- Inclusive Diffraction
- Vector Meson Production
- Final States in Diffraction
- Summary

Inclusive diffraction (1)

Diffractive states have the same quantum numbers as the initial state $\Rightarrow$ vacuum qu. no. exchanged in the t-channel $\Rightarrow$ Pomeron ($\mathbb{P}$)

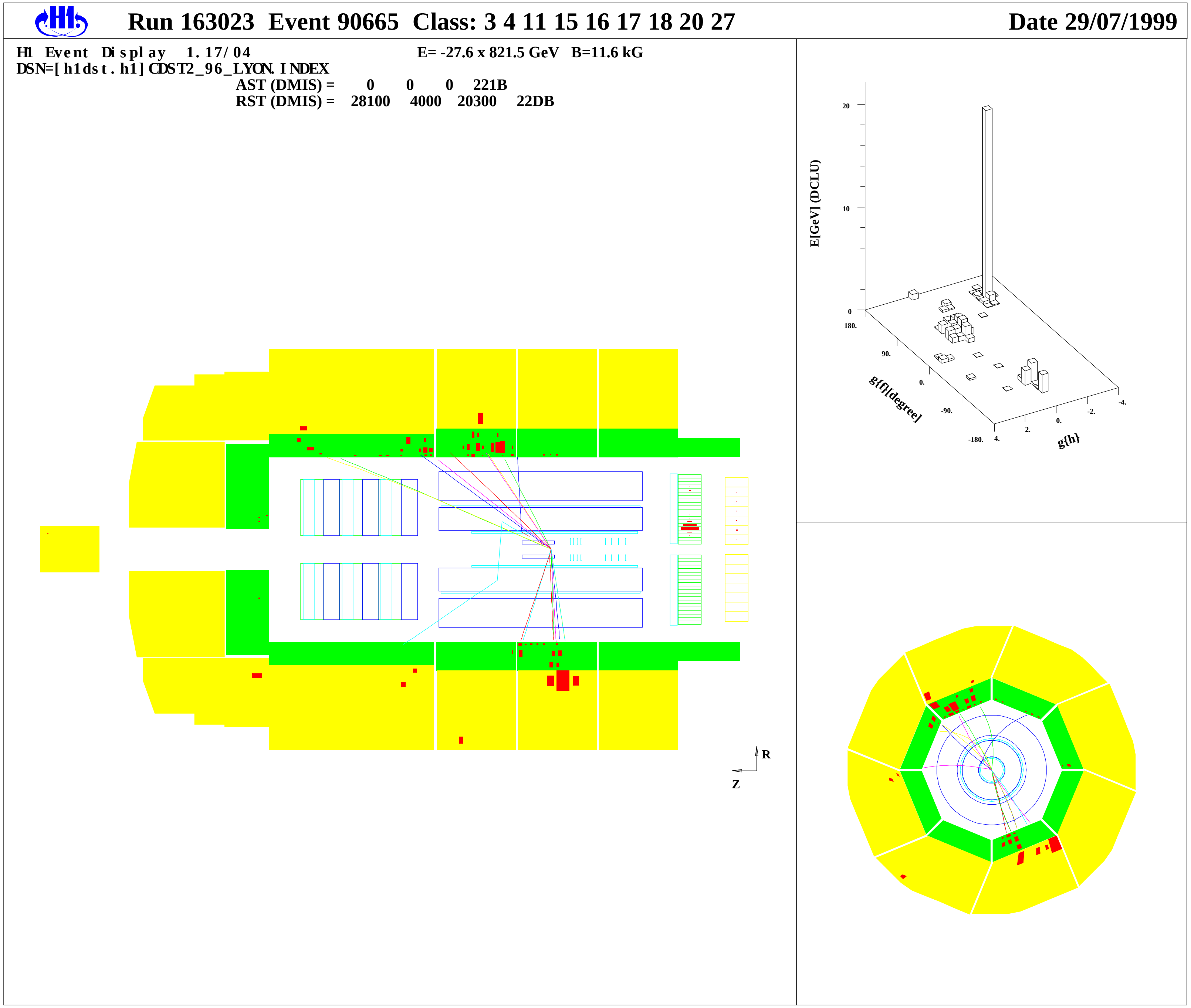
Inclusive diffractive at HERA corresponds to the diffractive excitation of a virtual γ:



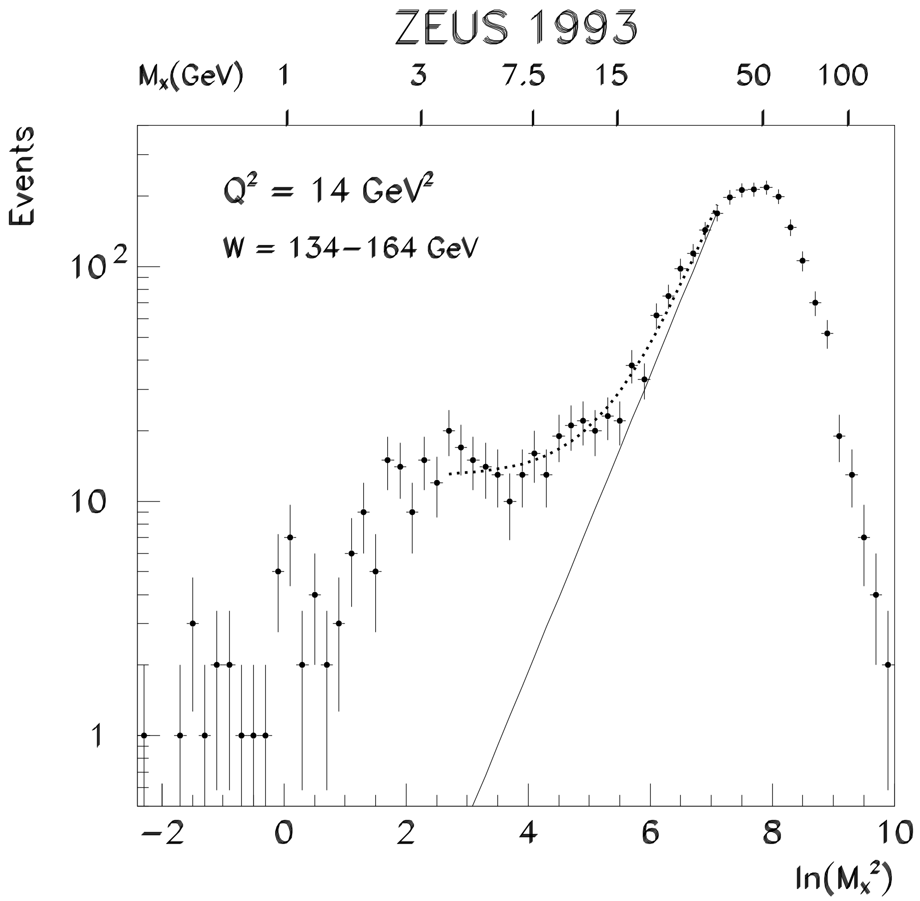


- the variables, in addition to Q^2, x and W, are
- $t = (p - p')^2$,
- $x_{\mathbb{P}} = \frac{q\cdot(p-p')}{q\cdot p} \approx \frac{M_X^2+Q^2-t}{W^2+Q^2+M_p^2}$, the fraction of the proton beam momentum carried by the $\mathbb{P}$,
- $\beta = \frac{x}{x_{\mathbb{P}}} = \frac{Q^2}{2q\cdot(p-p')} \approx \frac{Q^2}{M_X^2+Q^2-t}$, the fraction of the $\mathbb{P}$ momentum carried by the struck quark.
- Define $\frac{d^4\sigma}{d\beta dQ^2 dx_{\mathbb{P}} dt} = \frac{4\pi\alpha_{em}^2}{\beta Q^4}[1 - y + \frac{y^2}{2}]F_2^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t)$
- Factorization and integration over t: $F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}}) = f_{\mathbb{P}/p}(x_{\mathbb{P}}) \cdot F_2^{\mathbb{P}}(\beta, Q^2)$
- Three methods are used to select diffractive events: a large Rapidity Gap in the forward (proton) direction, M_X, and a leading proton spectrometer (LPS – Roman Pots)
- For VM: an additional variable is: M_V^2

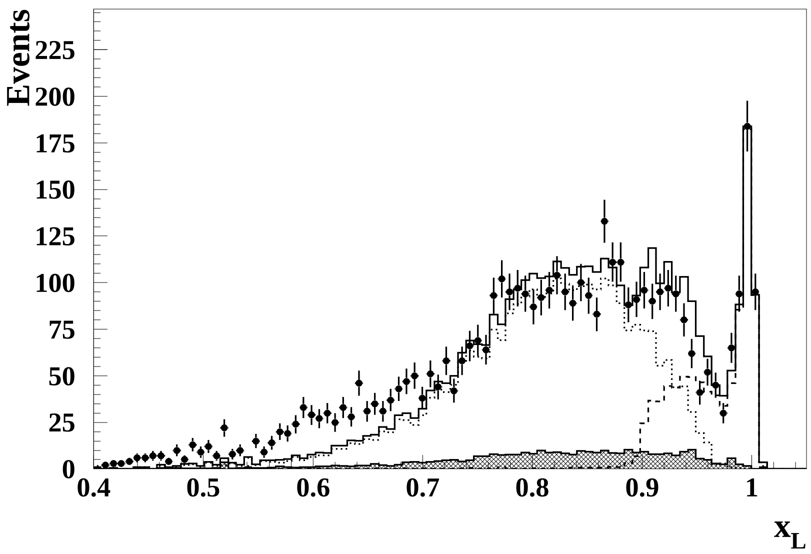
Inclusive diffraction (2)



Inclusive diffraction (3)



M_X analysis – events above an exponential background

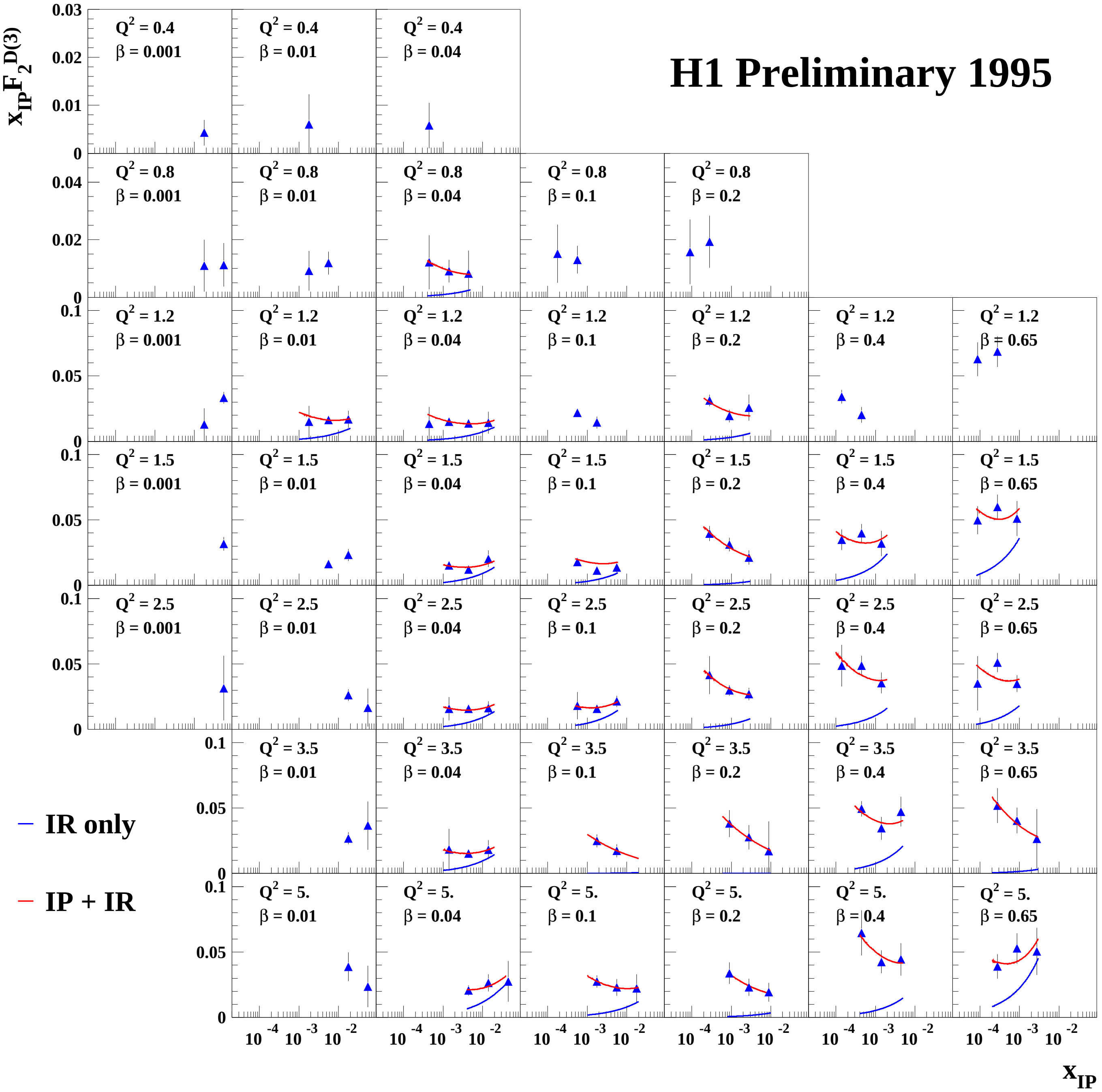


Leading proton spectrometer analysis

$x_L = \frac{p'}{p} = (1 - x_{\mathbb{P}})$

Inclusive diffraction (4)

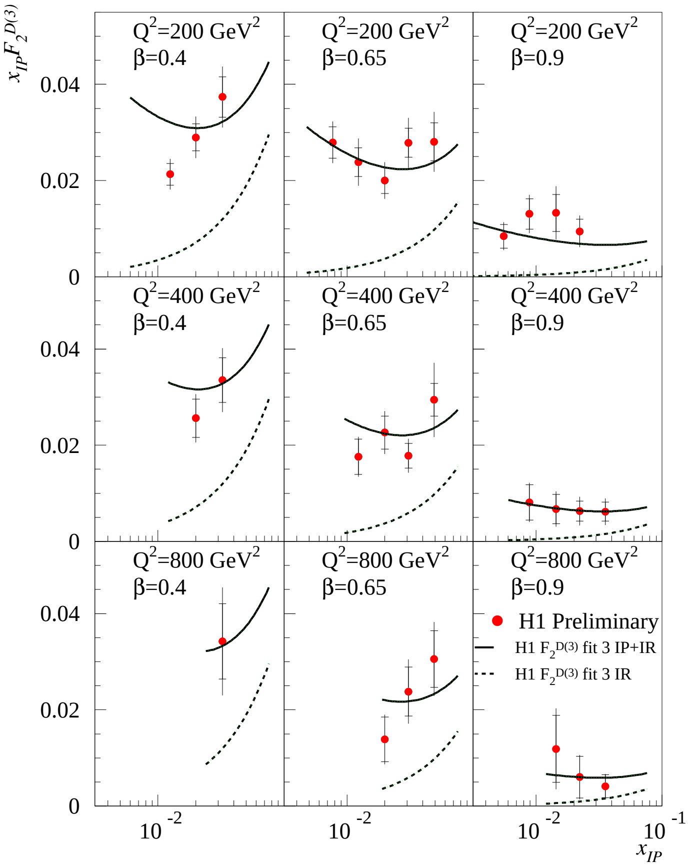
Compare H1 1995 data with their original NLO fits based on the 1994 measurements:



- Fits to diffractive ($\mathbb{P}$) and sub-leading (reggeon) trajectories
- Good agreement with the earlier fits

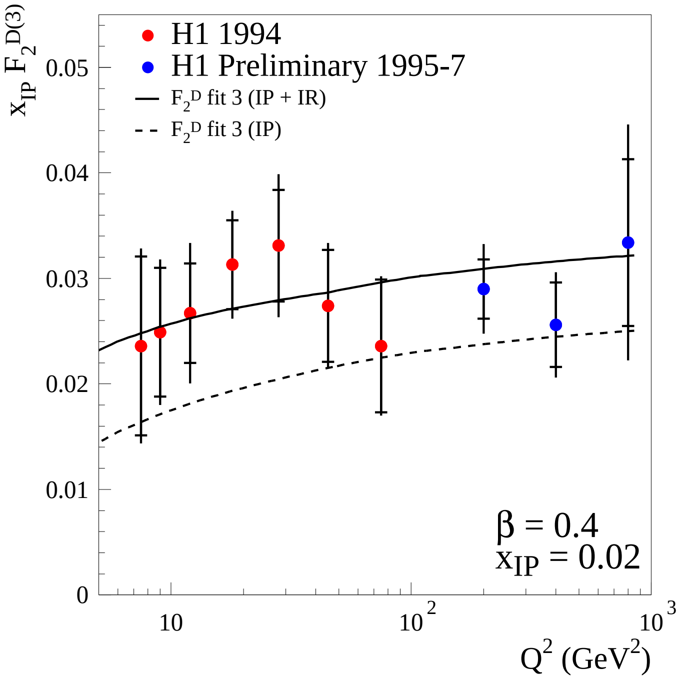
Inclusive diffraction (5): high Q^2

Study $x_{\mathbb{P}} F_2^{D(3)}$ at high Q^2 (200-800 GeV^2):



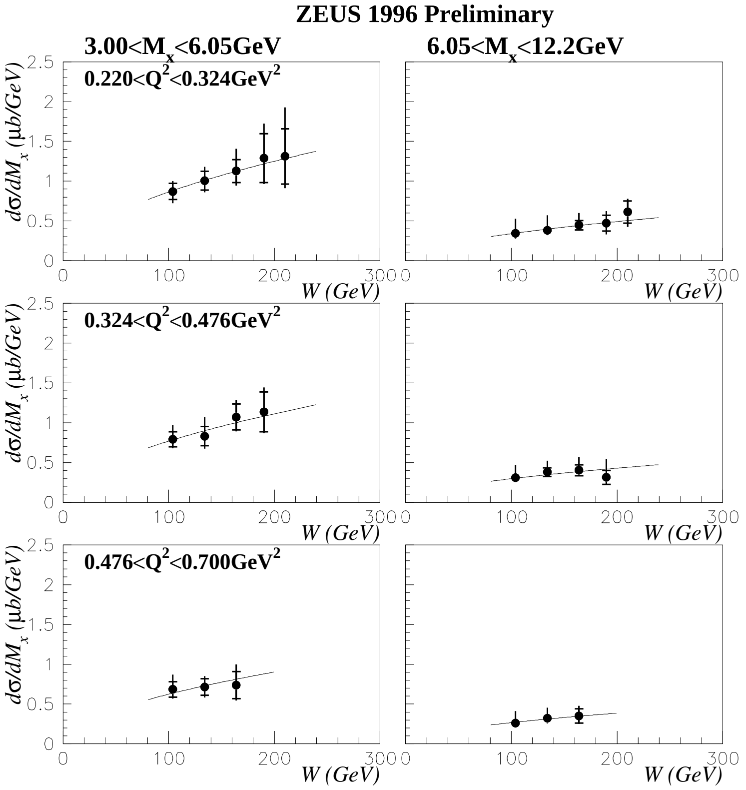
QCD fit at low Q^2 also gives a good description when extrapolated to high Q^2

Study scaling violations in diffractive F_2:



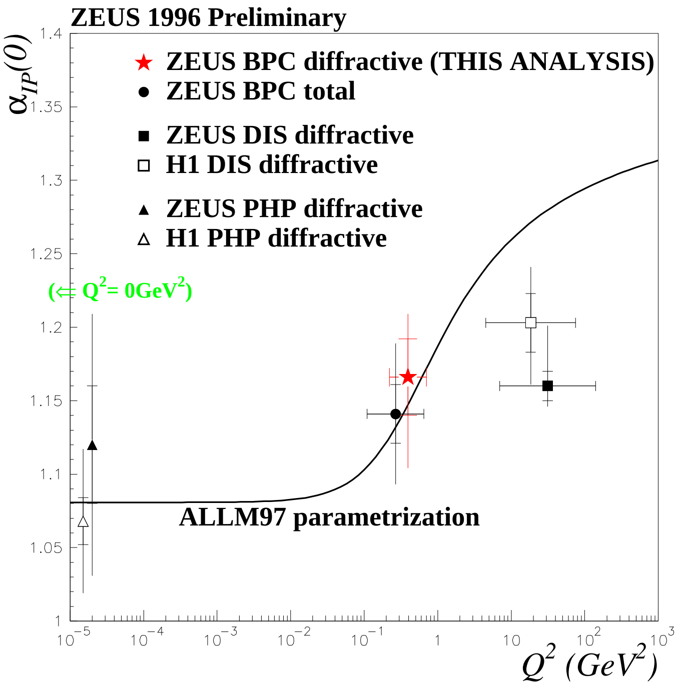
Scaling at $\beta = 0.4$, $x_{\mathbb{P}} = 0.02$ is also well described by the QCD fit

Inclusive diffraction (6): low Q^2



$$\frac{d\sigma^{\gamma^* p}}{dM_X} \sim (W^2)^{2\tilde{\alpha}_{\mathbb{P}}-2}$$

fit for $\tilde{\alpha}_{\mathbb{P}}$



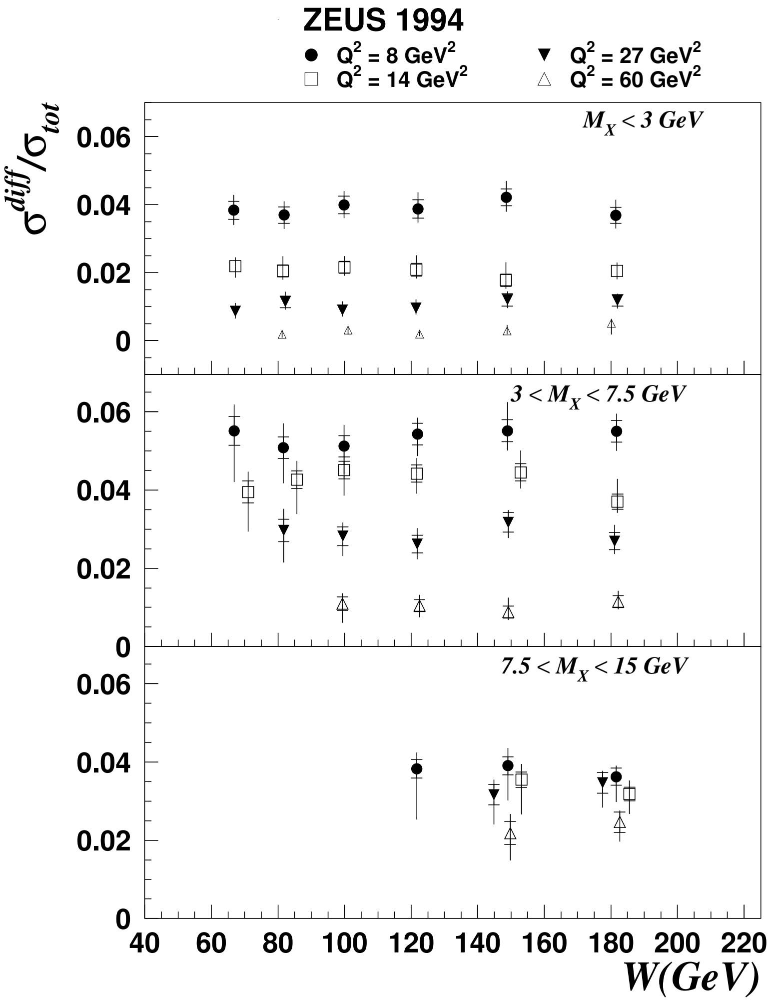
$\tilde{\alpha}_{\mathbb{P}} = \alpha_{\mathbb{P}}(0) - \frac{\alpha'}{b}$

$\alpha'_{\mathbb{P}} = 0.25$ GeV^{-2}

$b = 7 \pm 1 \pm 1$ GeV^{-2}
(independent of Q^2, as measured)

- At low Q^2, diffractive data are consistent with soft Pomeron, $\alpha_{\mathbb{P}}(0) = 1.08$
- At higher Q^2, diffractive cross sections have an energy dependence similar to that found in $\sigma_{tot}(\gamma^* p)$

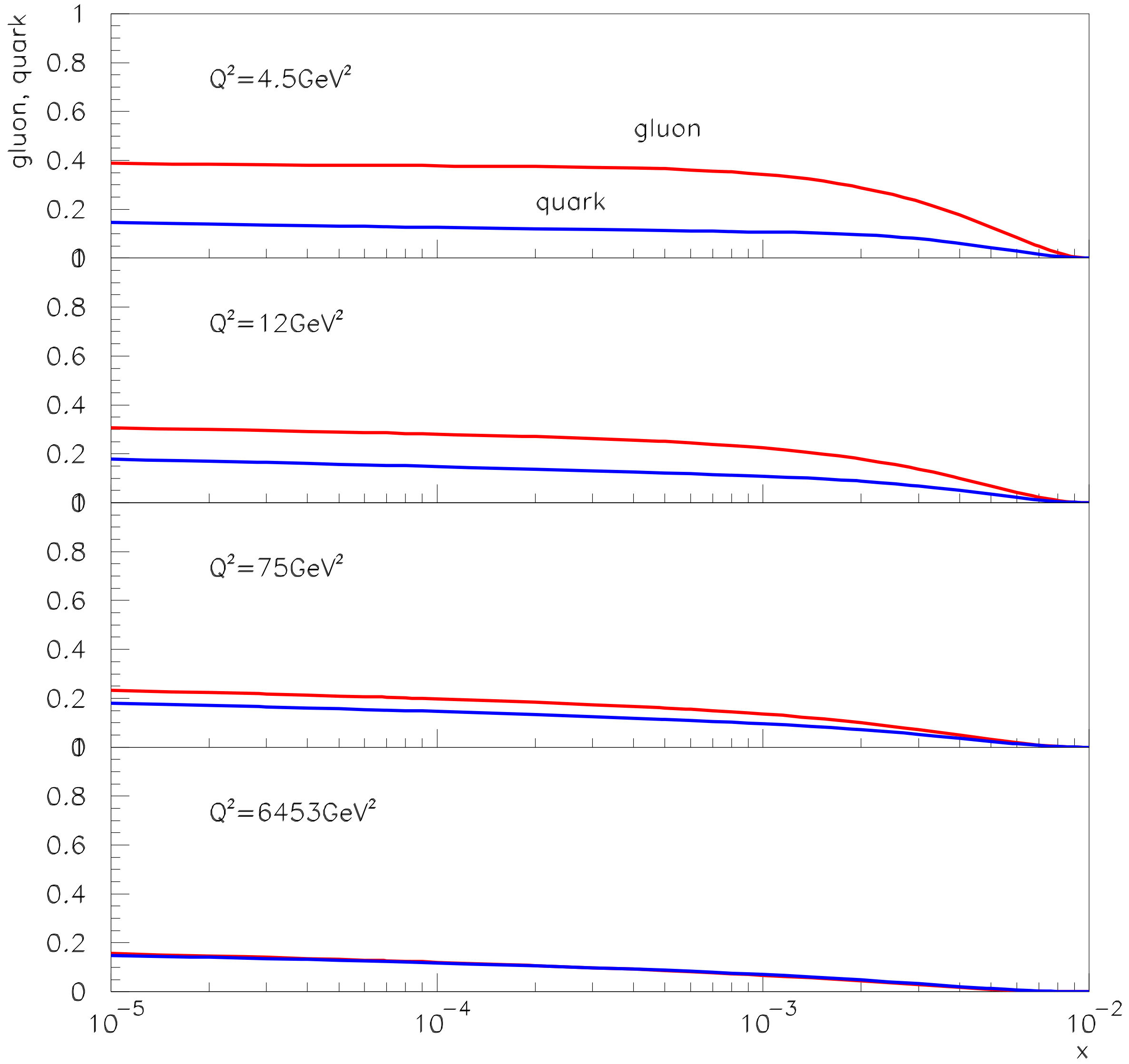
Inclusive diffraction (7): ratios



- The ratio is independent of W, and drops with increasing Q^2
- This indicates that the diffractive cross sections scales and has scaling violations just as F_2 has.
- This suggests that "diffractive parton distributions" have the same x-dependence as the inclusive proton pdf

Inclusive diffraction (8): ratios

Study the ratio of "diffractive" to total parton distributions:



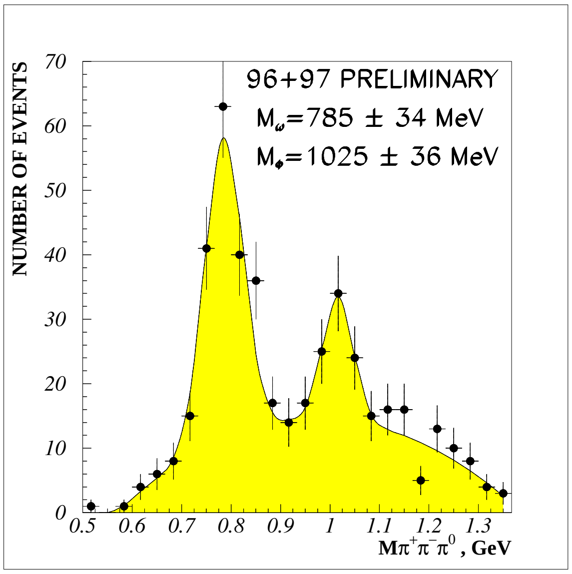
- The ratio of diffractive quark to total quark is almost independent of both x and Q^2
- The ratio of diffractive gluon to total gluon is almost independent of x, but drops with increasing Q^2

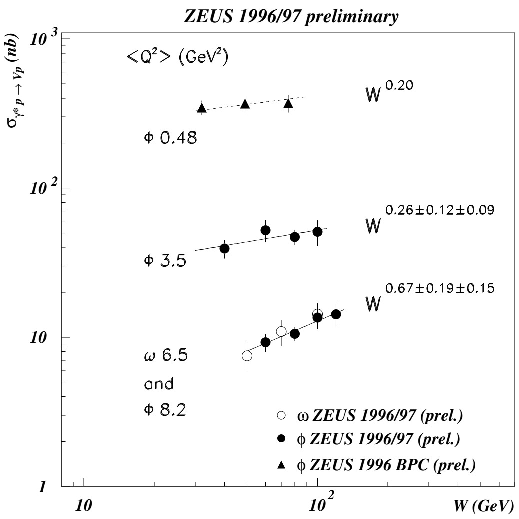
Vector Meson Production

In the plenary talk I discussed the following:

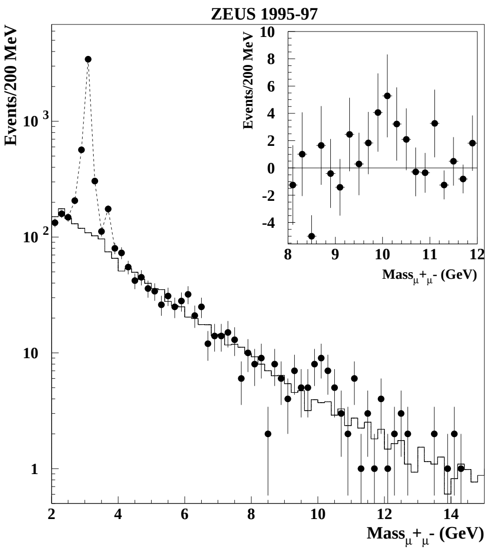
The energy dependence as $\sigma(VM) \sim W^{\delta}$:

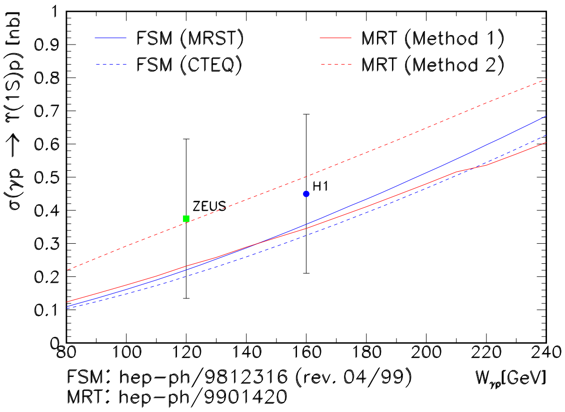
- For light VM at $Q^2 = 0$: $\sigma \sim W^{0.2}$
- For J/ψ at $Q^2 = 0$: $\sigma \sim W^{0.8}$
- For ρ^0 at $Q^2 > 2$ GeV^2: $\sigma \sim W^{0.2-0.8}$
- For J/ψ at $Q^2 > 2$ GeV^2: $\sigma \sim W^{0.8}$





- see clean ω (and ϕ) signal in $\pi^+\pi^-\pi^0$ mass plot
- for ω: $\sigma \sim W^{0.2} - W^{0.67}$ as Q^2 ranges from 0.48 to 6.5 GeV^2

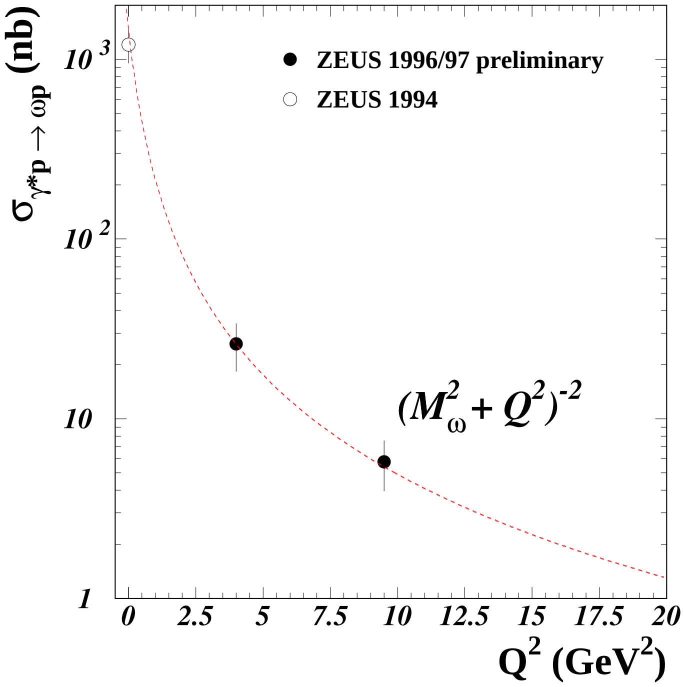




Vector Mesons: Q^2 dependence

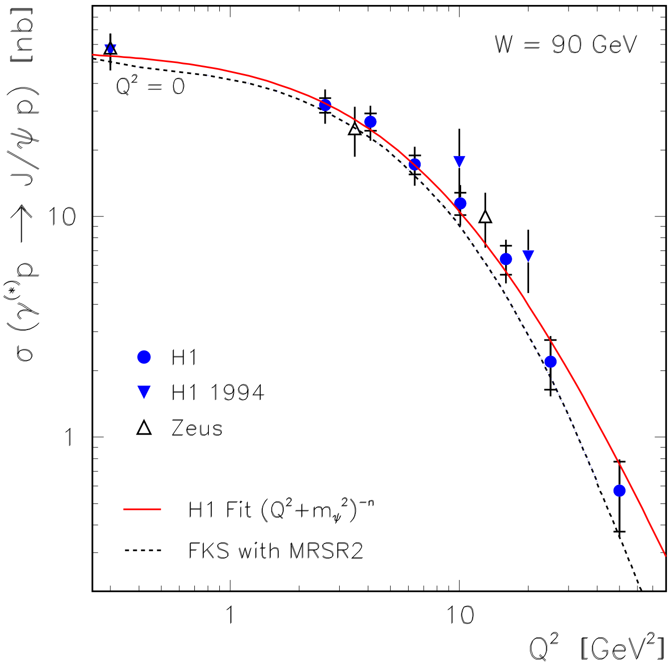
Now discuss some different topics:

(a) Dependence of the cross section on Q^2:



New data for ω:

$$\sigma \sim \frac{1}{(M_\omega^2+Q^2)^2}$$



New data for J/ψ:

$$\sigma \sim \frac{1}{(M_{J/\psi}^2+Q^2)^n}$$

$n = 2.38 \pm 0.11$

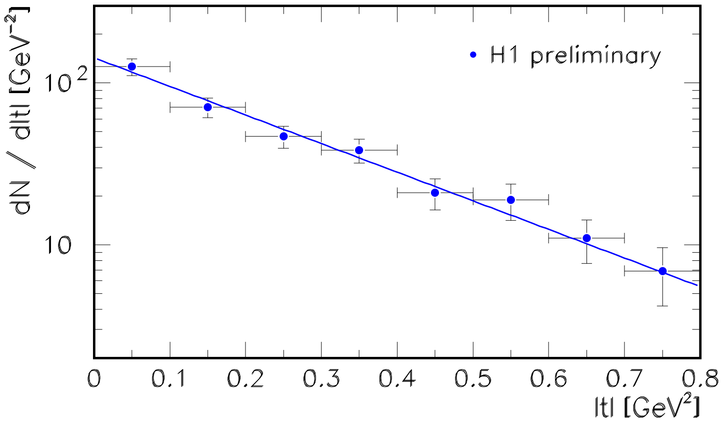
pQCD (FKS) $\sim \dfrac{\alpha_s^2(Q^2)}{Q^{4.8}}$

Vector Mesons: t-dependence

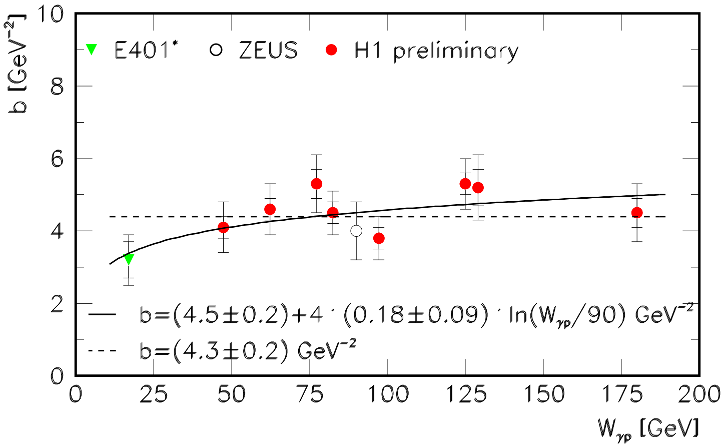
(b) Shrinkage of the diffractive t distribution:

$$\boxed{\frac{d\sigma}{dt} \sim e^{bt}}$$

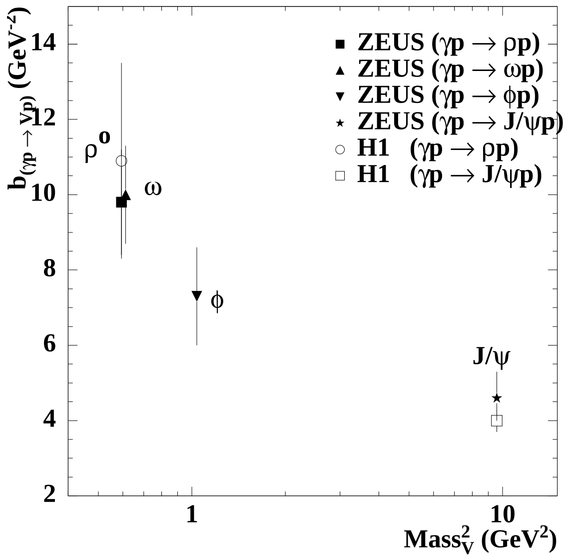
Data from J/ψ at $Q^2 = 0$:



$b = 4.3 \pm 0.2$ GeV^{-2} (averaged over W)



In fact little or no W dependence (E401 is fixed target)



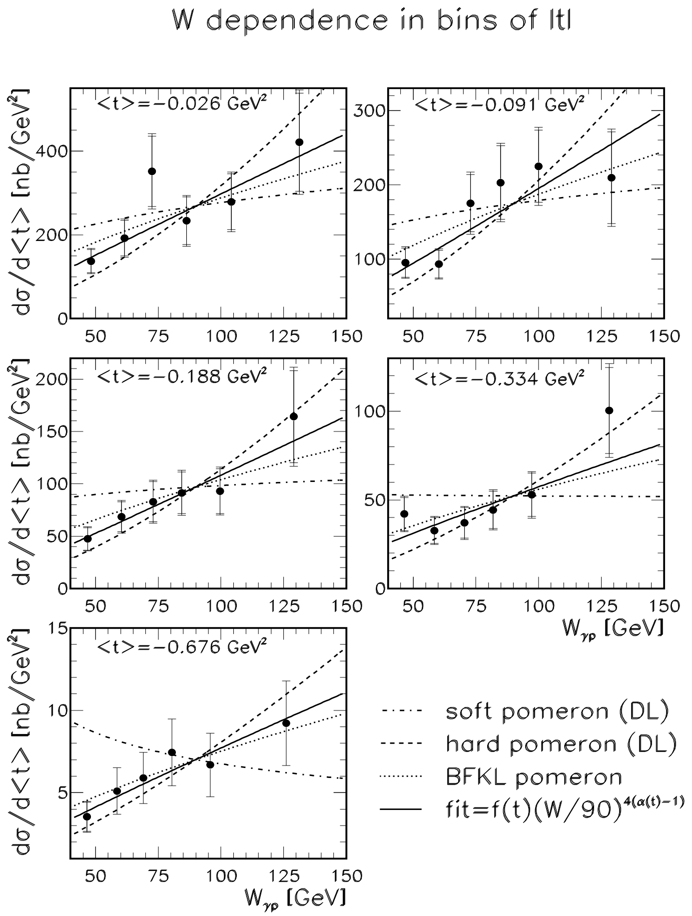
b is related to the size of the scattered particles

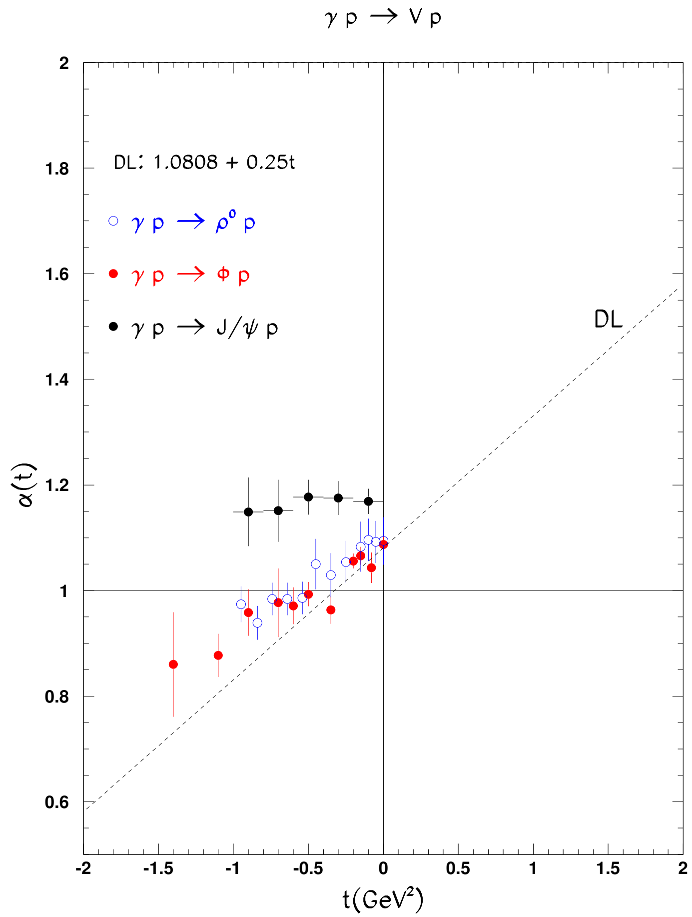
$b \propto (R_p^2 + R_{q\bar{q}}^2)$

$R_p^2 \sim 4$ GeV^{-2} $\Rightarrow$

$c\bar{c}$ system is small and probes the proton

Vector Mesons: $d\sigma/dt$

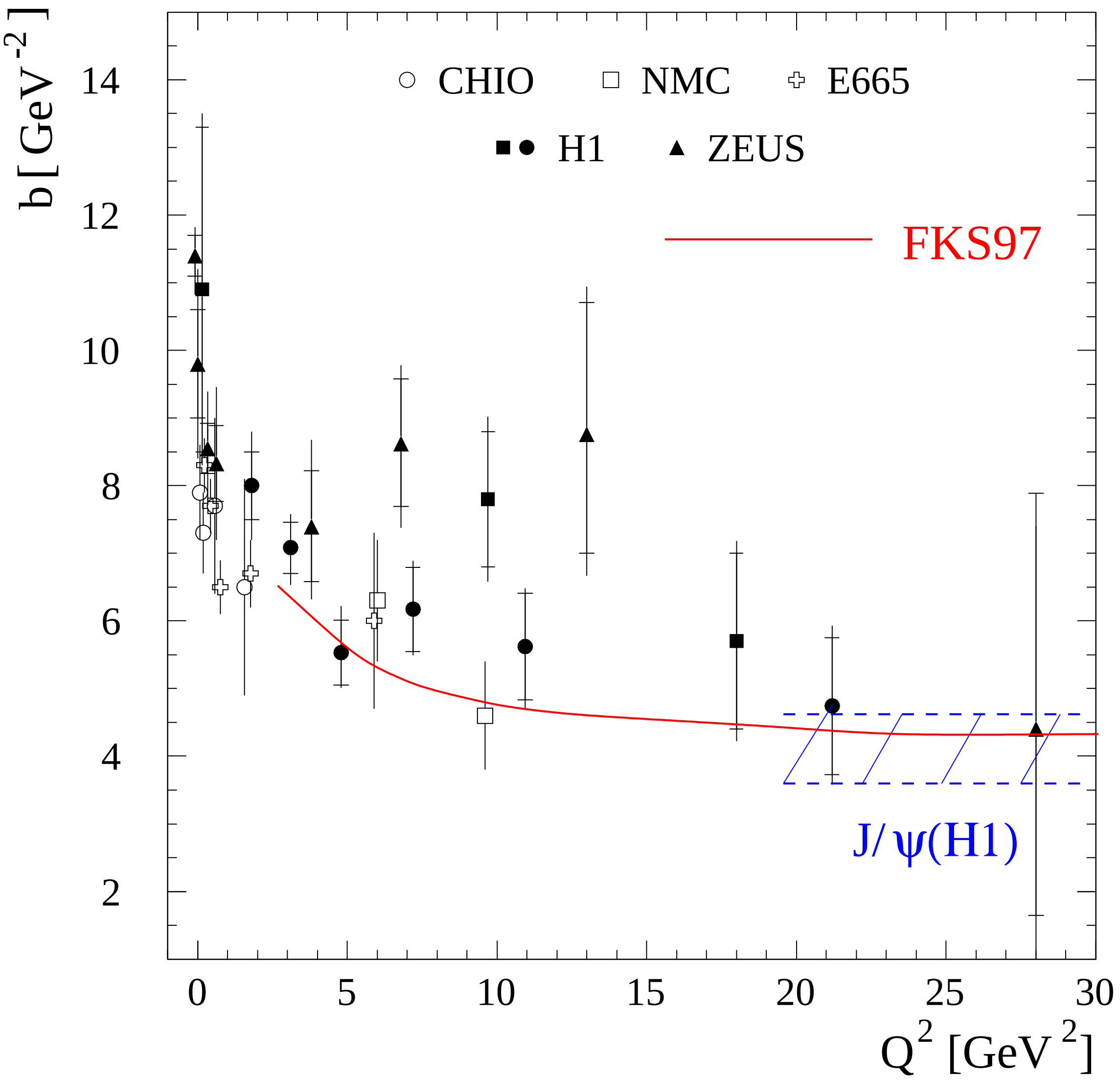




- ZEUS: ρ^0 finds $\alpha(t) = (1.096 \pm 0.021) + (0.125 \pm 0.038)t$
- ZEUS: ϕ finds $\alpha(t) = (1.081 \pm 0.010) + (0.158 \pm 0.028)t$
- H1: J/ψ finds $\alpha(t) = (1.26 \pm 0.05) + (0.05 \pm 0.15)t$
- Consistent with the value found by A. Levy:
- $\alpha(t) = (1.153 \pm 0.027) + (-0.001 \pm 0.072)t$

Vector Mesons: slope, b:

Study b (for $\frac{d\sigma}{dt} \sim e^{bt}$) for ρ^0 production vs. Q^2:

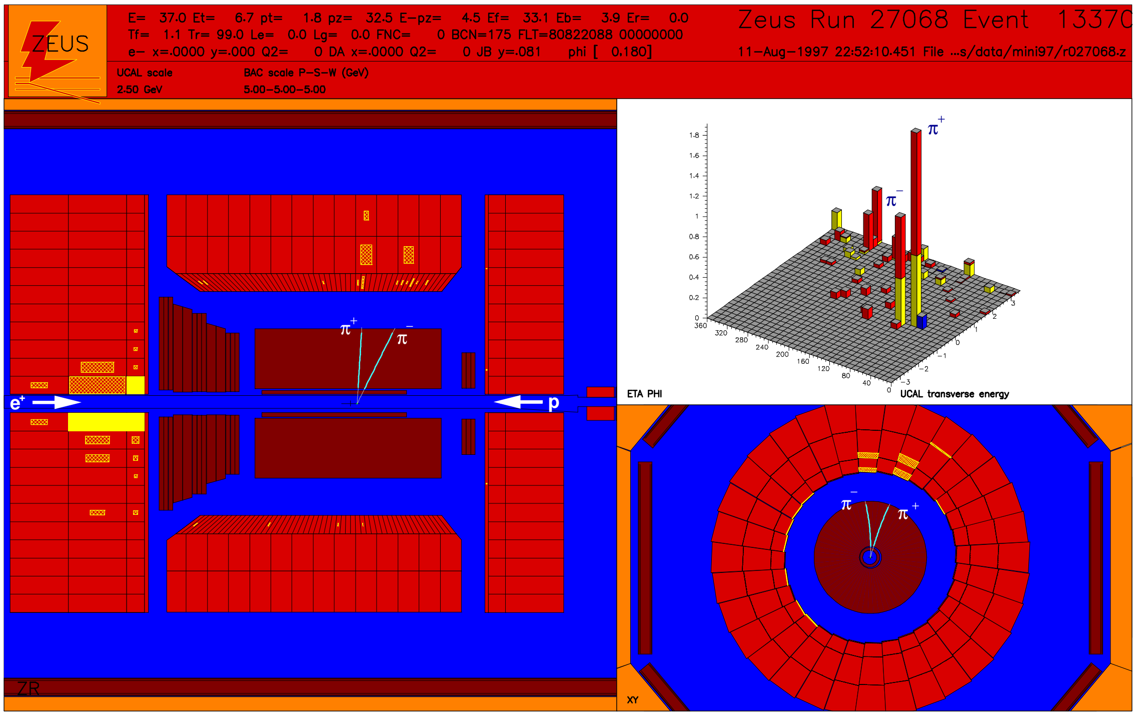


Conclusions:

- b decreases with Q^2
- $q\bar{q}$ transverse size decreases with Q^2
- reasonable agreement with pQCD model

Vector Mesons: at high $|t|$

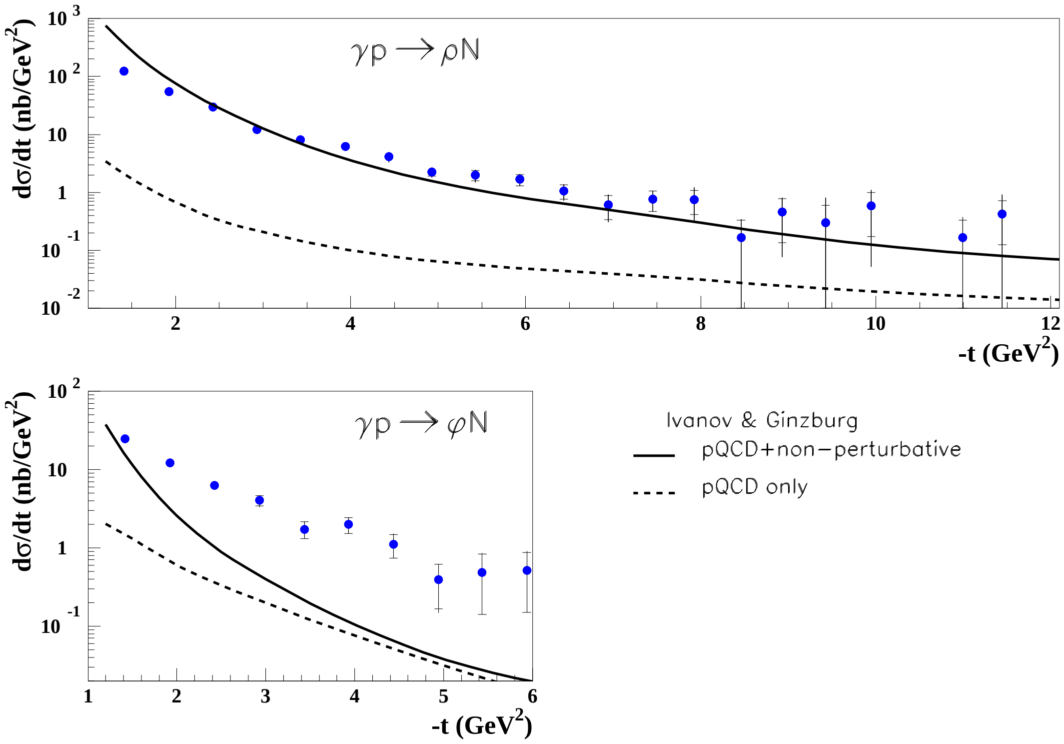
Candidate event for $\gamma p \to \rho^0$ at $t = -10$ GeV^2



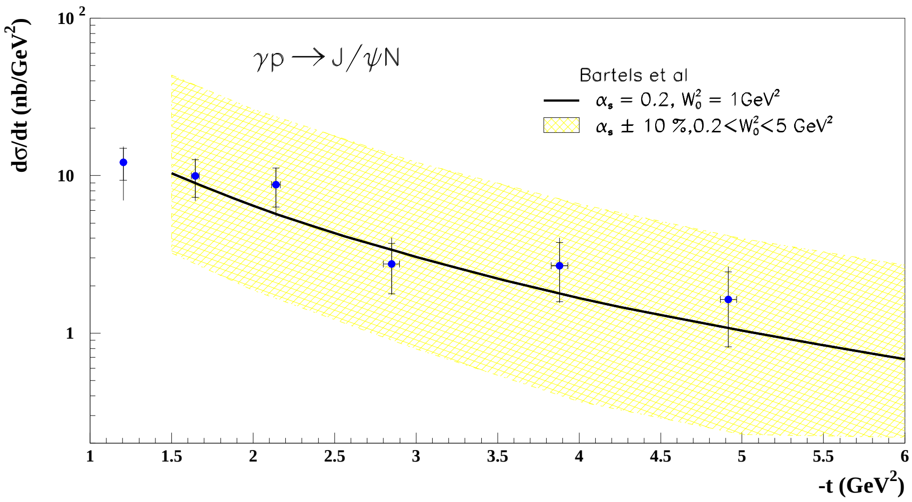
- Clean events – energy deposited around the forward beampipe $\Rightarrow$ proton dissociation

Vector Mesons: t-dependence

ZEUS Preliminary 1997



ZEUS Preliminary 1997



- data out to $t = -12$ GeV^2 for ρ^0 (not elastic!)
- data out to $t = -6$ GeV^2 for ϕ and J/ψ
- For ρ^0: non-perturbative effects dominate
- For ϕ: calculation fails
- For J/ψ: Good agreement, but large scale uncertainties

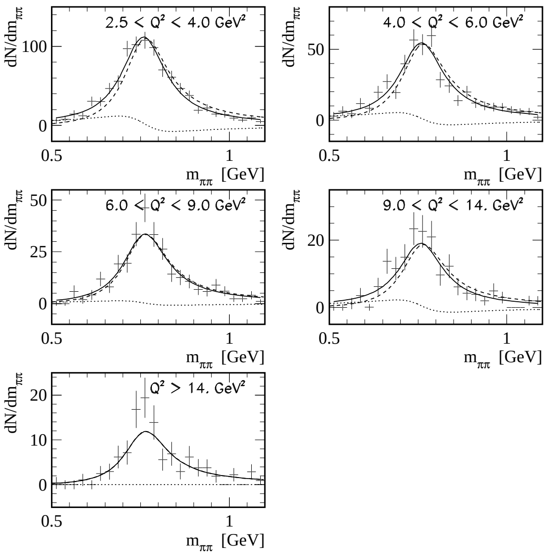
Vector Mesons: mass-skewing

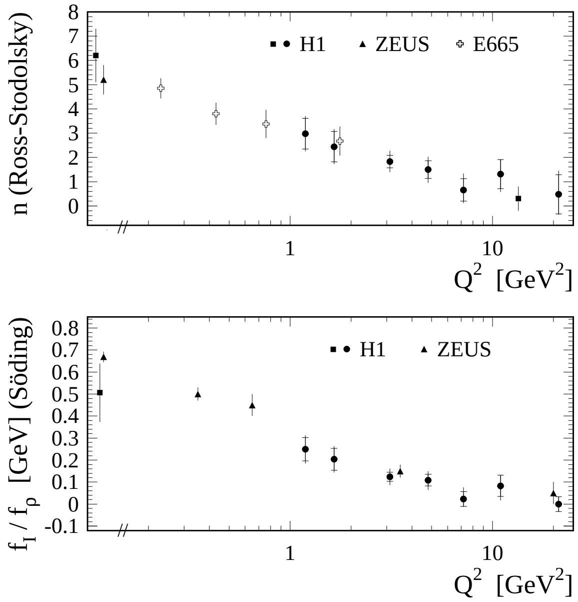
(c) Variation of the ρ^0 mass shape with Q^2, t:

- see skewing in the $\pi^+\pi^-$ mass plot

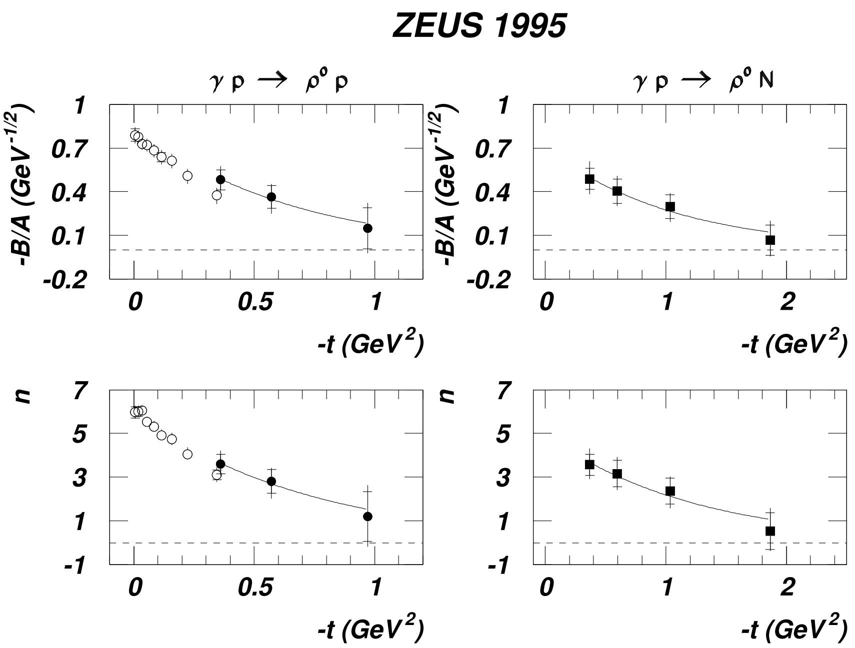
$$\boxed{\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} = f_\rho \cdot BW_\rho(M_{\pi\pi}) + f_I \cdot I(M_{\pi\pi}) + f_{NR}}$$

Variation of f_I/f_ρ and n with Q^2:





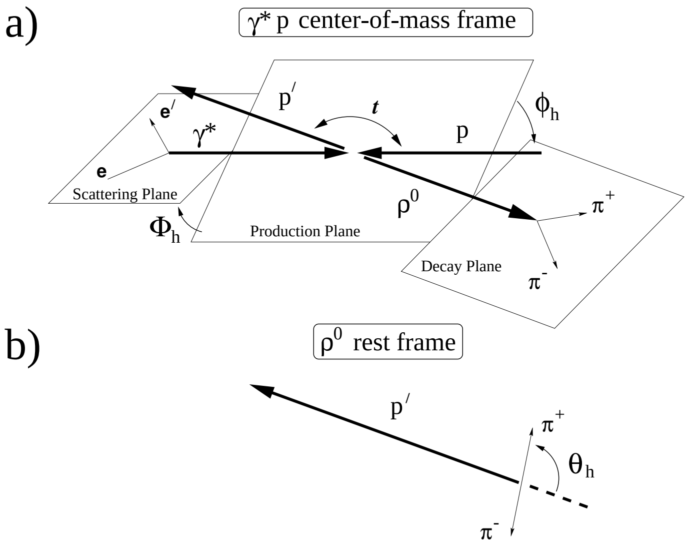
Variation of $|B|/A$ and n with t:



Vector Mesons: helicity studies

(d) Decay-angle analysis of ρ^0 electroproduction

Three angles are needed to describe the process:



Following Schilling and Wolf, the three-dimensional angular distribution $W(\cos\theta_h, \phi_h, \Phi_h) =$

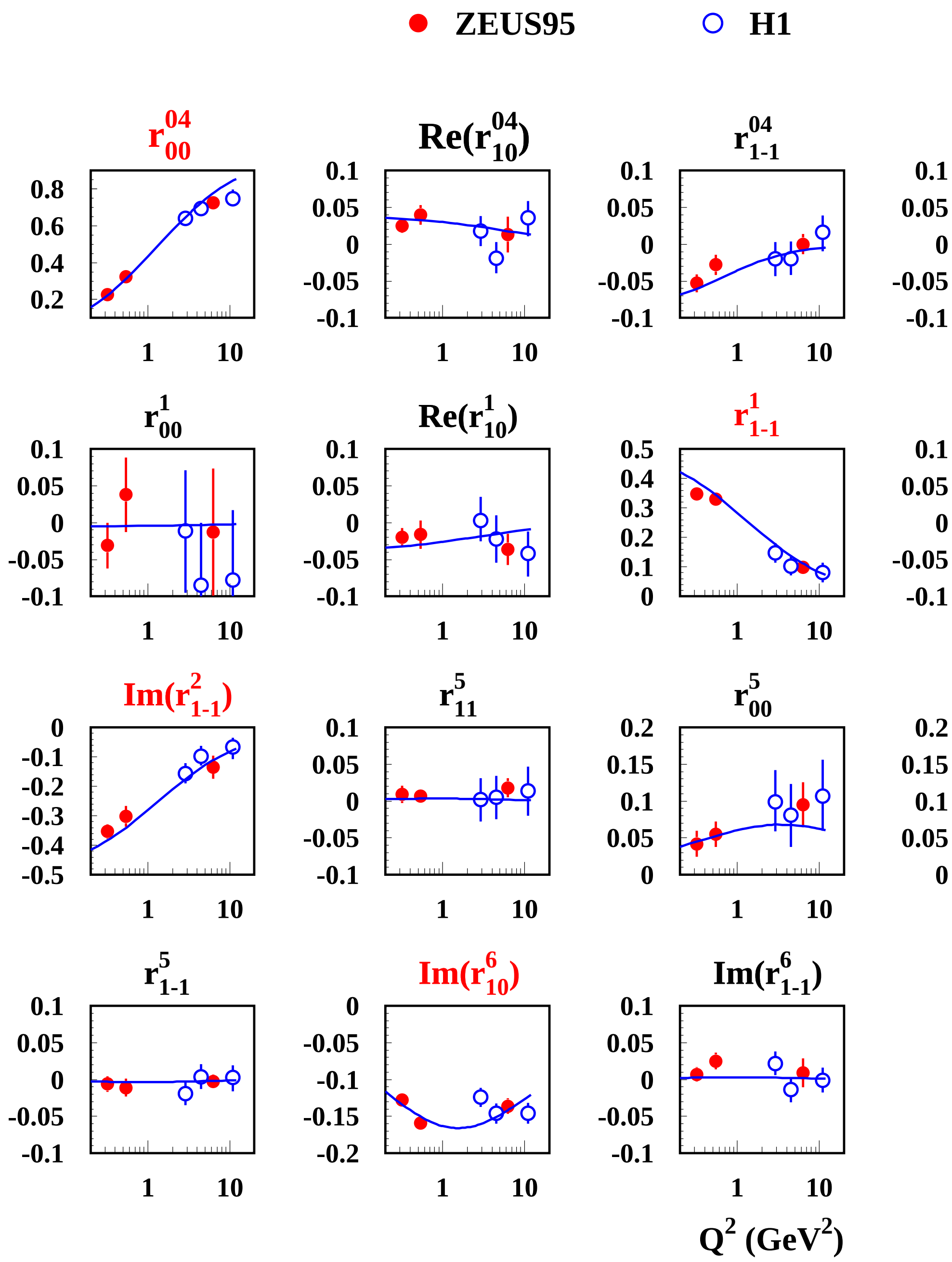
$$\begin{aligned}
&\frac{3}{4\pi}\Big[\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\theta_h \\
&-\sqrt{2}\ \mathrm{Re}\{r^{04}_{10}\}\sin 2\theta_h\cos\phi_h - r^{04}_{1-1}\sin^2\theta_h\cos 2\phi_h \\
&-\epsilon\cos 2\Phi_h(r^1_{11}\sin^2\theta_h + r^1_{00}\cos^2\theta_h - \sqrt{2}\ \mathrm{Re}\{r^1_{10}\}\sin 2\theta_h\cos\phi_h \\
&\qquad -r^1_{1-1}\sin^2\theta_h\cos 2\phi_h) \\
&-\epsilon\sin 2\Phi_h(\sqrt{2}\ \mathrm{Im}\{r^2_{10}\}\sin 2\theta_h\sin\phi_h + \mathrm{Im}\{r^2_{1-1}\}\sin^2\theta_h\sin 2\phi_h) \\
&+\sqrt{2\epsilon(1+\epsilon)}\cos\Phi_h(r^5_{11}\sin^2\theta_h + r^5_{00}\cos^2\theta_h \\
&\qquad -\sqrt{2}\ \mathrm{Re}\{r^5_{10}\}\sin 2\theta_h\cos\phi_h - r^5_{1-1}\sin^2\theta_h\cos 2\phi_h) \\
&+\sqrt{2\epsilon(1+\epsilon)}\sin\Phi_h(\sqrt{2}\ \mathrm{Im}\{r^6_{10}\}\sin 2\theta_h\sin\phi_h \\
&\qquad +\mathrm{Im}\{r^6_{1-1}\}\sin^2\theta_h\sin 2\phi_h)\Big]
\end{aligned}$$

The superscripts correspond to the helicity of the virtual photon, and the subscripts to those of the dipion state.

The fifteen coefficients r^{04}_{ik}, r^{α}_{ik} are related to various combinations of the helicity amplitudes $T_{\lambda_\rho\lambda_\gamma}$, where λ_ρ and λ_γ are the helicities of the ρ^0 meson and of the photon, respectively.

Vector Mesons: helicity studies

(d) Study of the decay angular distributions:



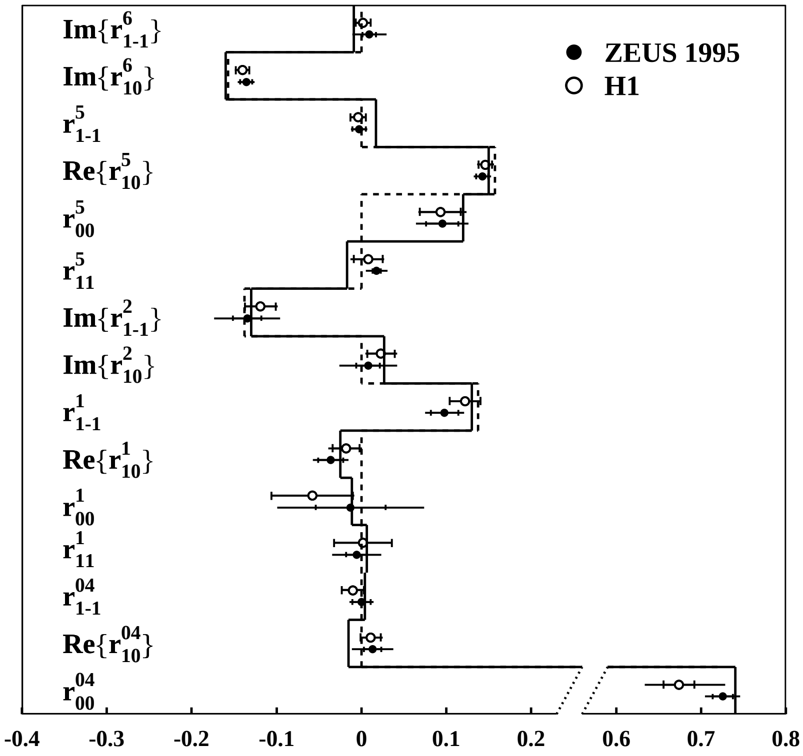
Akushevich
Ivanov
Nikolaev
Pronyaev
paper in prep.,

Nikolaev (DIS99)

Vector Mesons: helicity studies

For SCHC and natural parity exchange, only 5 combinations should be non-zero.

(d) From fits to the decay angular distributions:



$\Leftarrow r^5_{00}$

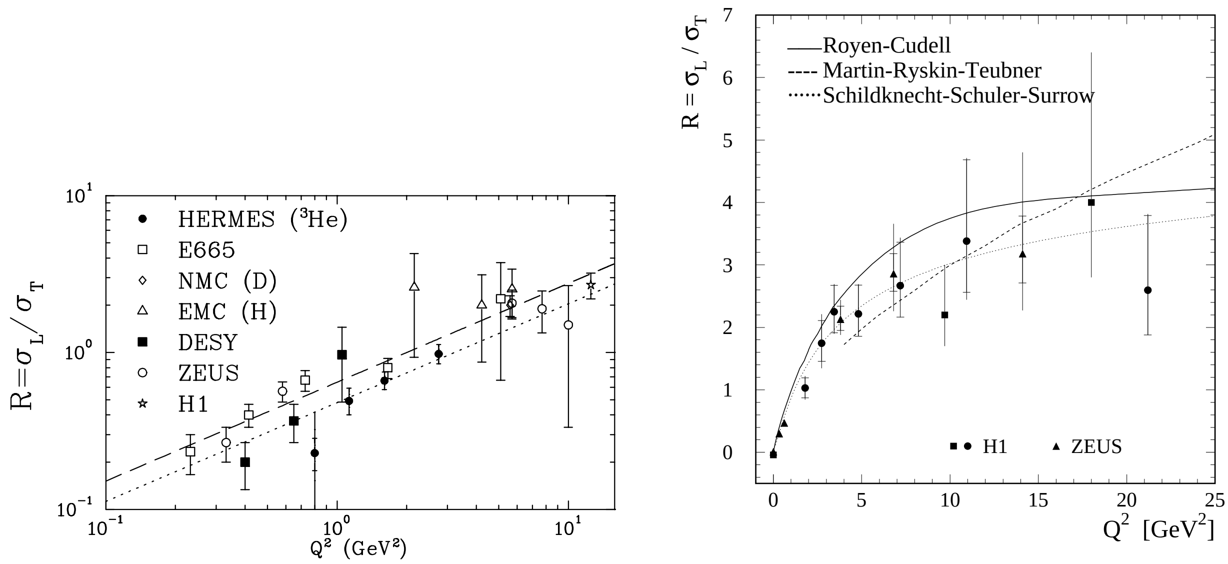
- SCHC violated in r^5_{00} (Single-helicity-flip amplitude)
- A pQCD model (Ivanov and Kirschner) describes the data well

Vector Mesons: helicity studies

(d) Study of the decay angular distributions:

Study $R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$ **(although SCHC is violated at** $\sim 8 \pm 3$**%, influence on** R **is 2-3%):**

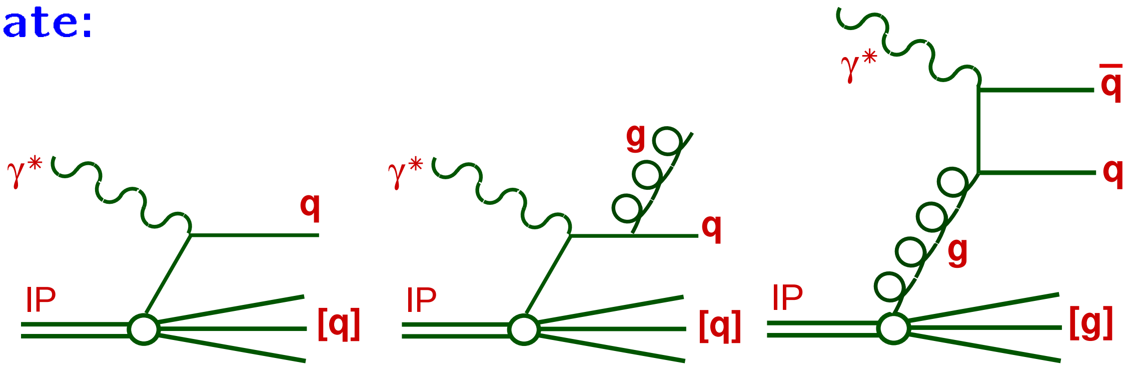
$R \sim (Q^2)^{0.63 \pm 0.04}$



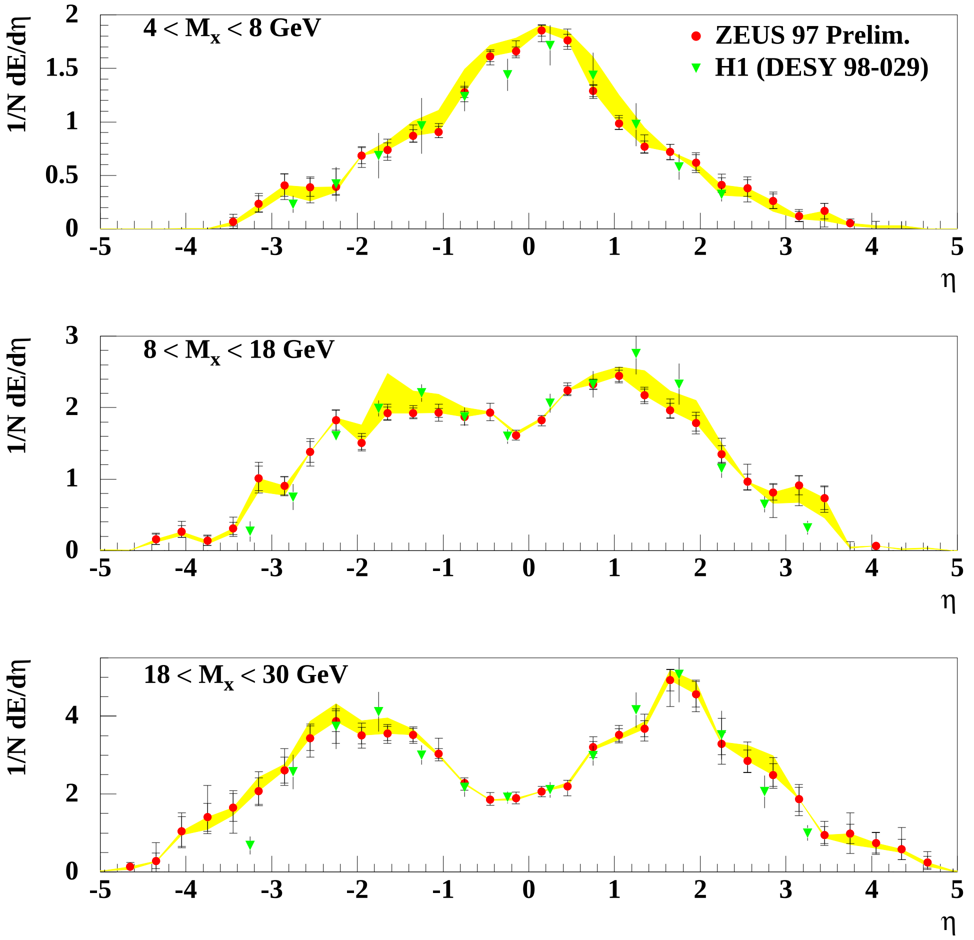
- $r^{04}_{00} \sim$ prob. to produce longitudinally polarized ρ^0 from either transverse or longitudinal γ^*
- dependence of R on Q^2 is well described by QCD models

Final States in Diffraction

Look at the properties of the diffractive final state:



For ZEUS, select a leading proton with $x_L > 0.97$ in proton spectrometer; for H1 use a rapidity gap selection:

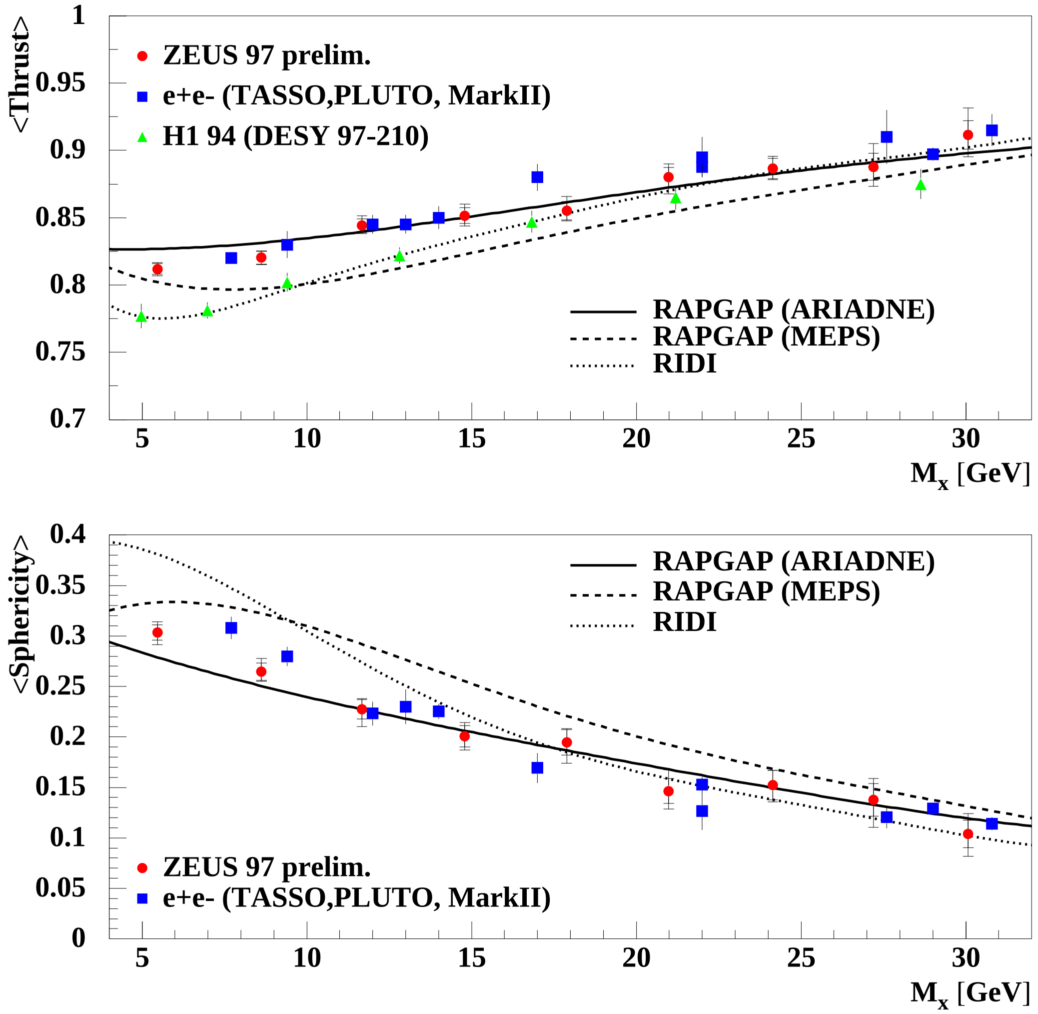


- Good agreement between H1 and ZEUS
- As M_X increases, start to see a 2-peak structure

Final States in Diffraction

Study of event-shape variables in diffraction:

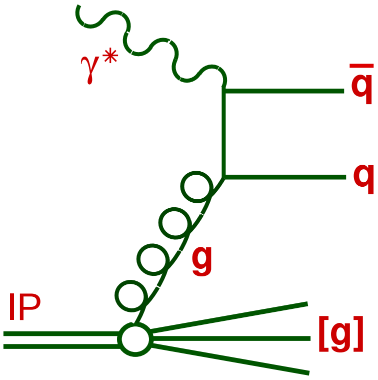
ZEUS: select a leading proton with $x_L > 0.97$ in proton spectrometer; H1: uses a rapidity gap cut:



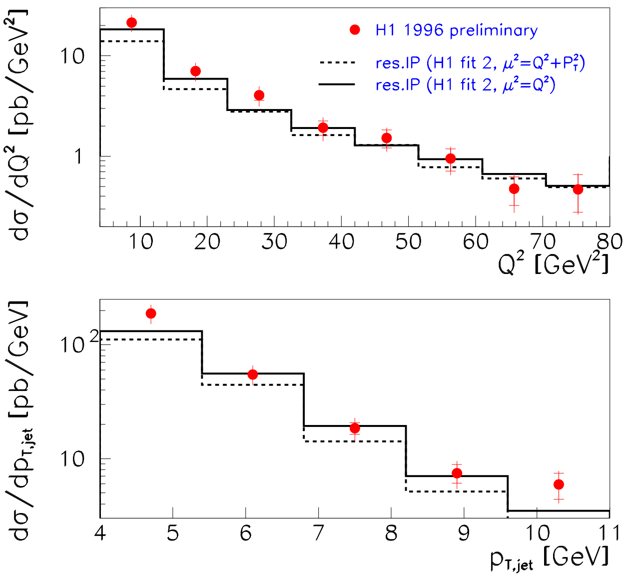
- $< T >$ increases and $< S >$ decreases as M_X increases:
- suggesting more 2 back-to-back jet topology ($T \to 1,\ S \to 0$)
- disagreement between H1 and ZEUS at lower M_X values

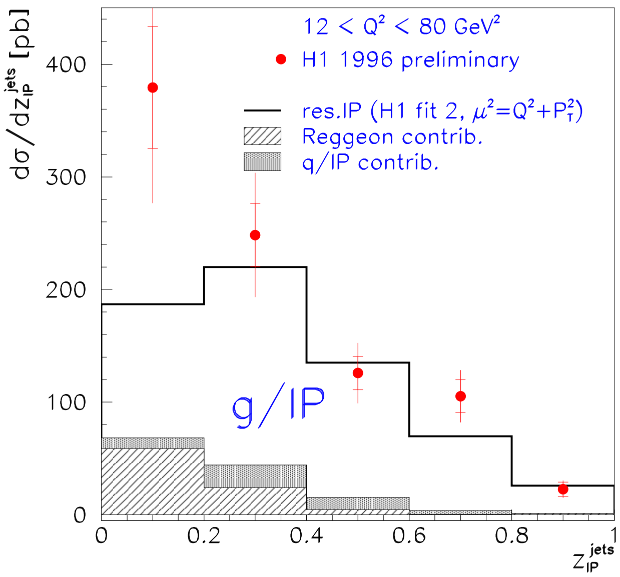
Diffractive Jet Production

Look at the properties of the diffractive final state; again, the BGF process dominates:



expect 2 jets+remnant
$4 < Q^2 < 80$ GeV^2
$x_{\mathbb{P}} < 0.05$
$p_{T,jet} > 4$ GeV
$N_{jets} = 2$





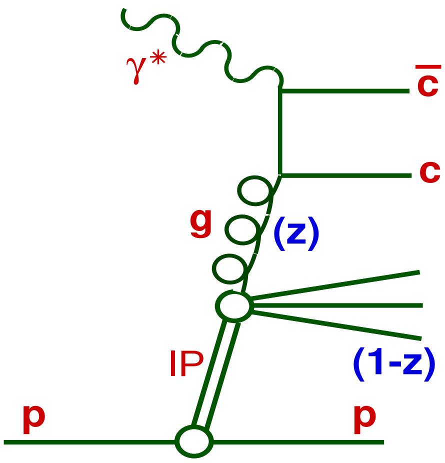
$$z_{\mathbb{P}}^{\text{jets}} = \frac{Q^2+M_{JJ}^2}{Q^2+M_X^2}$$

- Rates are in reasonable agreement with diffractive parton distributions from $F_2^{D(3)}$ measurements

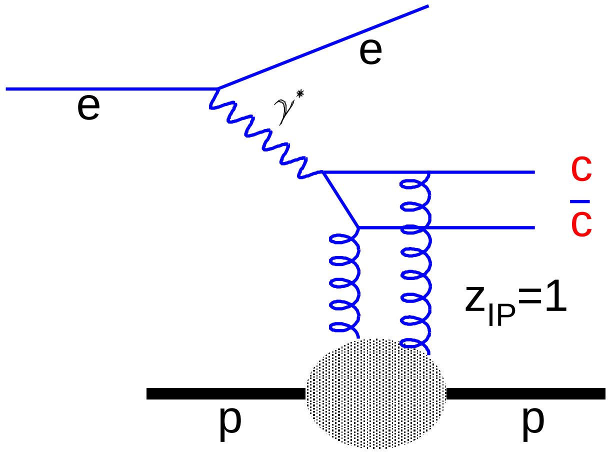
- Jet production driven by diffractive gluons

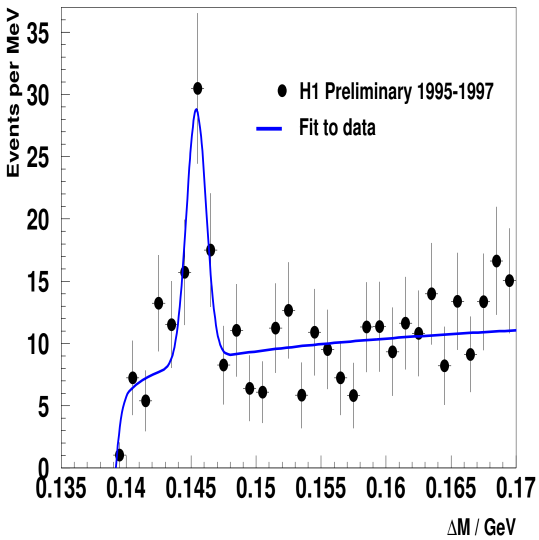
Diffractive Charm Production

Look at diffractive charm ($D^{*\pm}$):

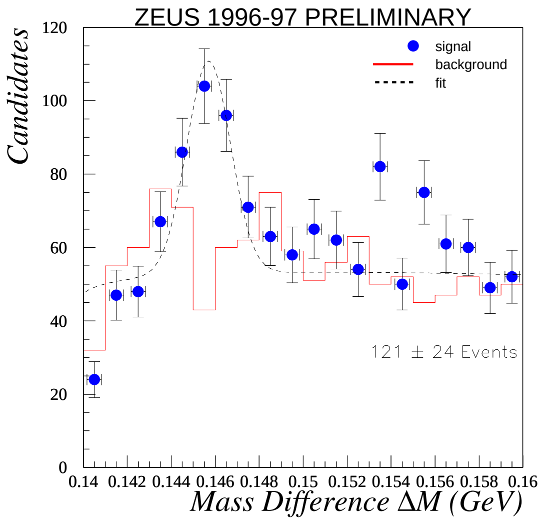


vs





$D^{*+} \rightarrow (D^0 \rightarrow K^-\pi^+)\pi^+_{\rm slow}$



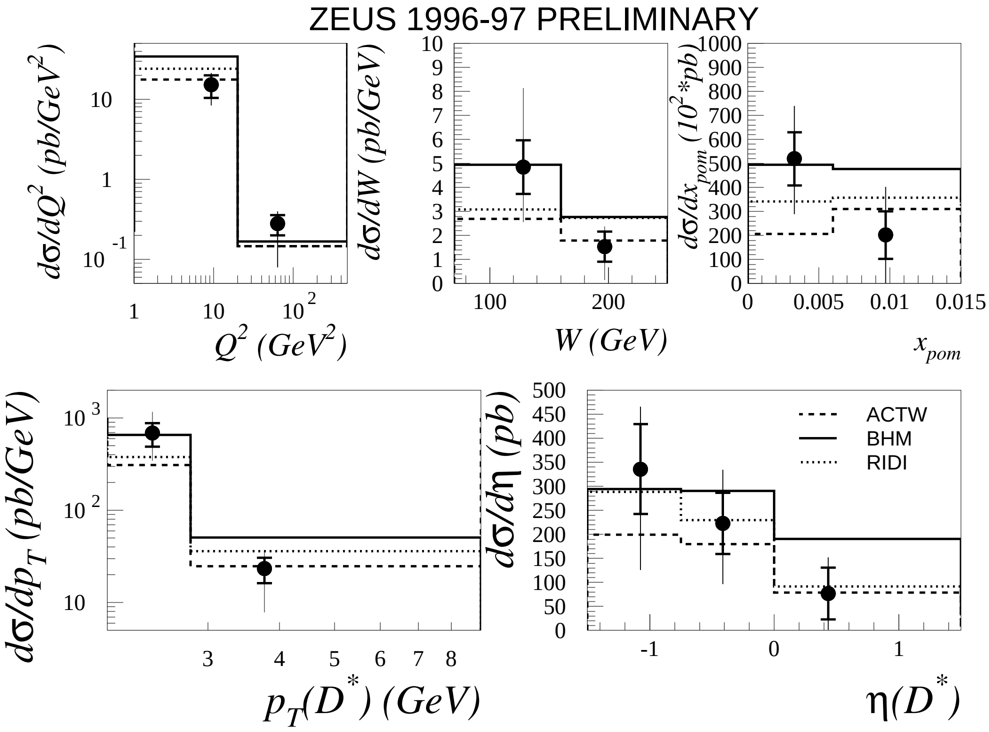
$D^{*+} \rightarrow (D^0 \rightarrow K^-\pi^+\pi^-\pi^+)\pi^+_{\rm slow}$

- Clear $D^{*\pm}$ signals observed in both experiments
- H1: $38 \pm 10 \pm 4$ events
- ZEUS: 121 ± 24 events

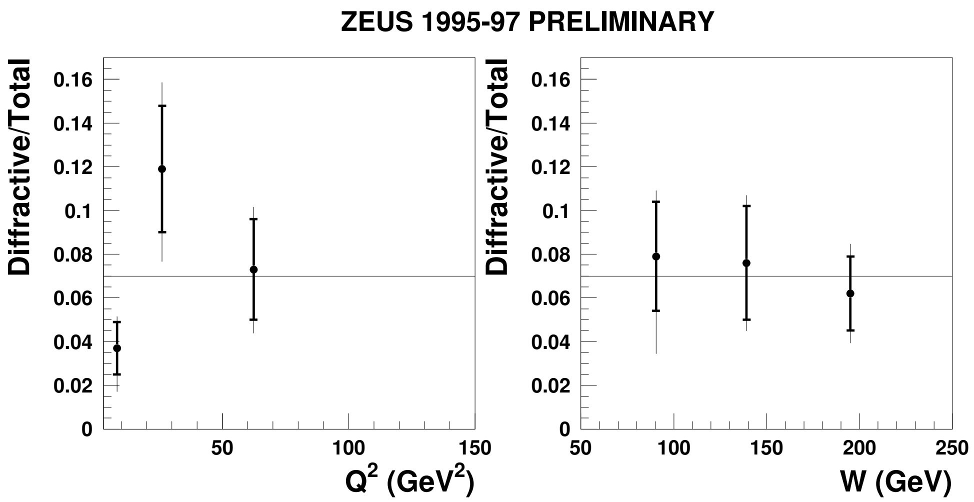
Diffractive Charm (2)

Look at the kinematic distributions:

ZEUS – $K4\pi$



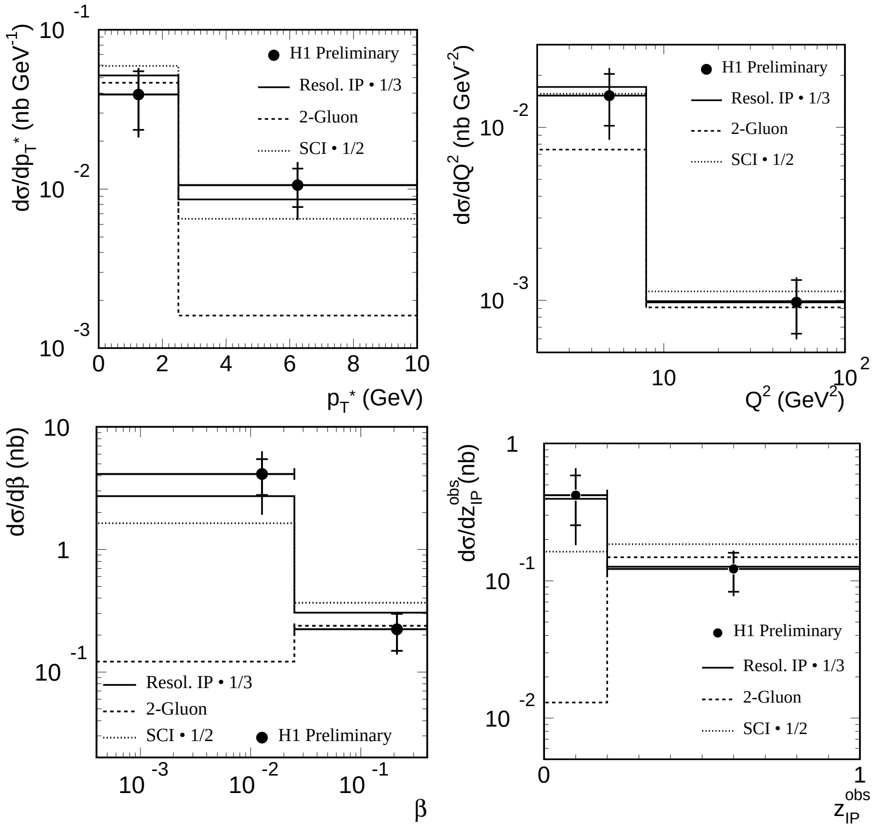
ZEUS –$K2\pi$



- diffractive/total $\sim 7\%$, independent of Q^2 or W
- ZEUS rates agree with all three calculations

Diffractive Charm (3)

H1 – $K2\pi$



Comparison between H1 and ZEUS:

ZEUS $(K\pi\pi)$	H1 $(K\pi\pi)$
$3 < Q^2 < 150$ GeV^2	$2 < Q^2 < 100$ GeV^2
$0.02 < y < 0.7$	$0.05 < y < 0.7$
$0.002 < x_{\mathbb{P}} < 0.012$	$x_{\mathbb{P}} < 0.04$
$p_T^{D^*} > 1.5$ GeV	$p_T^{D^*} > 2$ GeV
$\lvert\eta^{D^*}\rvert < 1.5$	$\lvert\eta^{D^*}\rvert < 1.5$
$\beta < 0.8$	
σ_{ep}(pb)	σ_{ep}(pb)
$398 \pm 83(\text{stat})^{+154}_{-180}(\text{syst})$	$154 \pm 40(\text{stat}) \pm 35(\text{syst})$
agrees with $(K4\pi)$ and RapGap	$\sim 1/3$ of Rapgap
ACTW: 360 pb	ACTW: 650 pb

Experimental disagreement between H1 and ZEUS:

Summary

What have we learned from diffraction in Deep Inelastic Scattering at HERA:

- A hard gluon component exists; DGLAP works well here also.

- Evidence that Q^2, t or M_V^2 can all serve as a hard scale in exclusive vector meson production:
  1. Fast rise of $\sigma(W)$
  2. Decreasing slope of the t-distribution
  3. SU(4) restoration

- $R = \frac{\sigma_L}{\sigma_T}$ increases with Q^2, and is well described by pQCD

- Evidence for a small but significant SCHC violation