Soft Interactions and Diffractive Phenomena

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Outline of the Presentation

- **Total and Elastic Cross Sections**
  - Total $\gamma\gamma$ Cross Sections
  - Elastic Vector Mesons
  - Scale Dependence of W-Dependence
- **Diffraction**
  - Definition of Kinematical Variables
  - Diffractive Structure Function
  - Parton Distributions in Pomeron
  - Hard Diffraction at the Tevatron
- **Fragmentation**
  - Multiplicities in Diffraction
  - Scaling Violation of Fragmentation Functions
  - Fragmentation Properties of Gluon Jets
  - Spin Alignment in Fragmentation
- **Summary**

Energy Behaviour of Total Cross Sections

Regge theory relates poles in t-channel scattering amplitude to energy behaviour in the s-channel.
All data from $\boldsymbol{hadron - hadron}$ scattering is described by

$$\sigma_{tot}(s) = A_{IP} s^{\alpha_{IP}(0)-1} + A_{IR} s^{\alpha_{IR}(0)-1}$$

The first term dominates the high energy behaviour. The same functional form with the same exponents also fits γp and $\gamma\gamma$ data:
The Pomeron with trajectory $\alpha_{IP}(t)$ is unique in Regge theory with largest intercept and vacuum quantum numbers.

$$\alpha_{IP}(t) = 1.08 + 0.25\ GeV^{-2}\ t$$

Next leading reggeons have approximative degenerate trajectories and carry quantum numbers of ρ, ω, a_2, f_2 mesons.

$\rightarrow$ combine in effective trajectory

$$\alpha_{IR}(t) = 0.55 + 0.9\ GeV^{-2}\ t$$

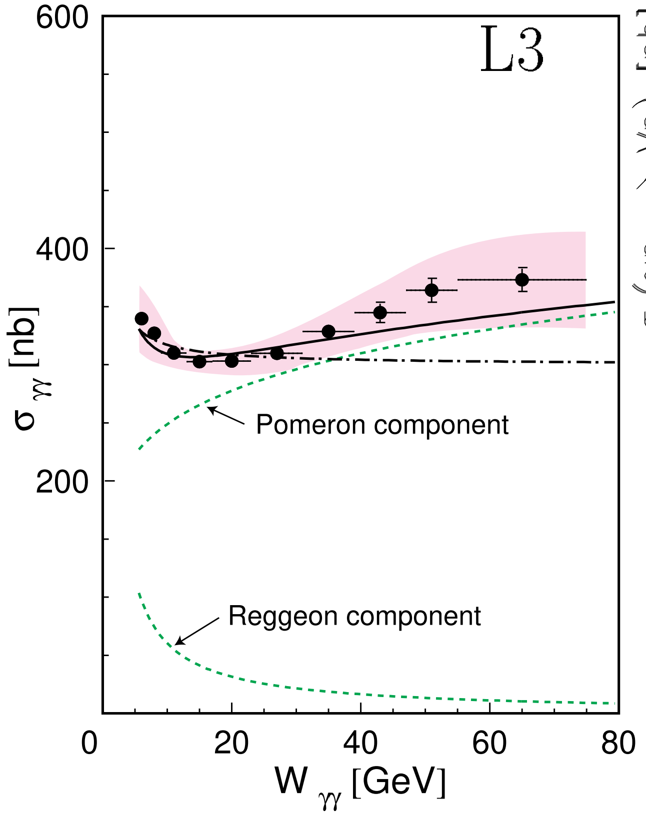
.

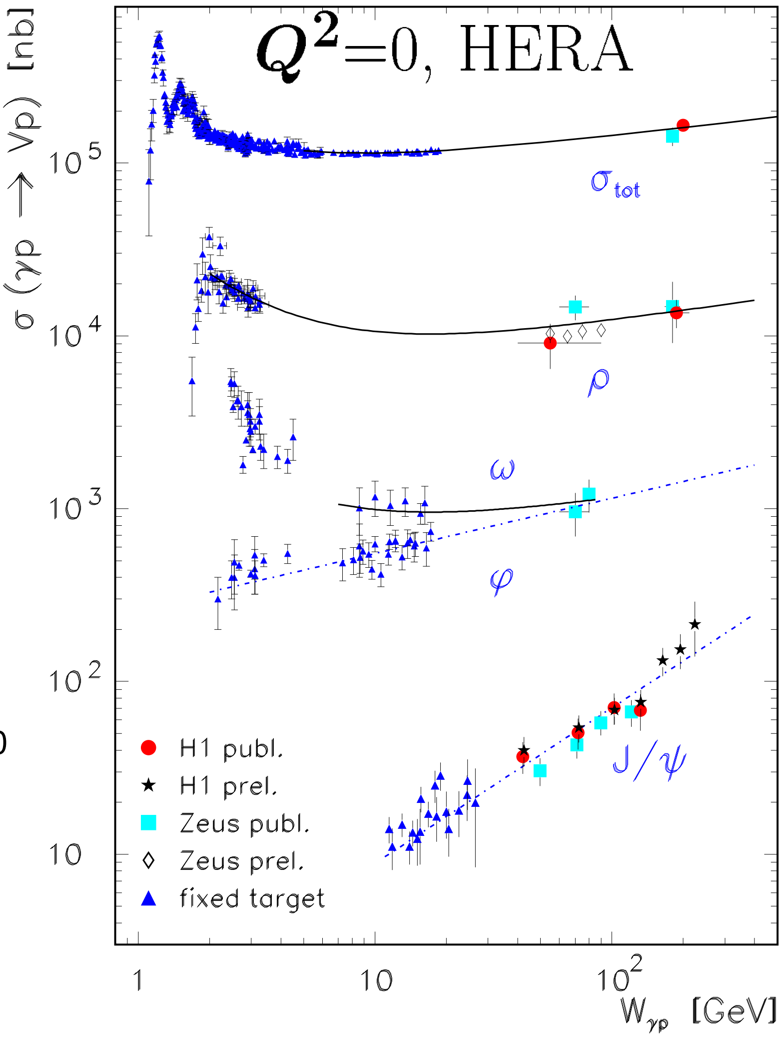
The f_2-meson and the IP have same C-parity $\rightarrow$ interference.

Even lower trajectories, the π-trajectory has

$$\alpha_{\pi}(t) = 0 + 0.7\ GeV^{2}\ t$$

Energy Dependence of Total $\gamma - \gamma$ and Elastic Vector Meson Cross Section





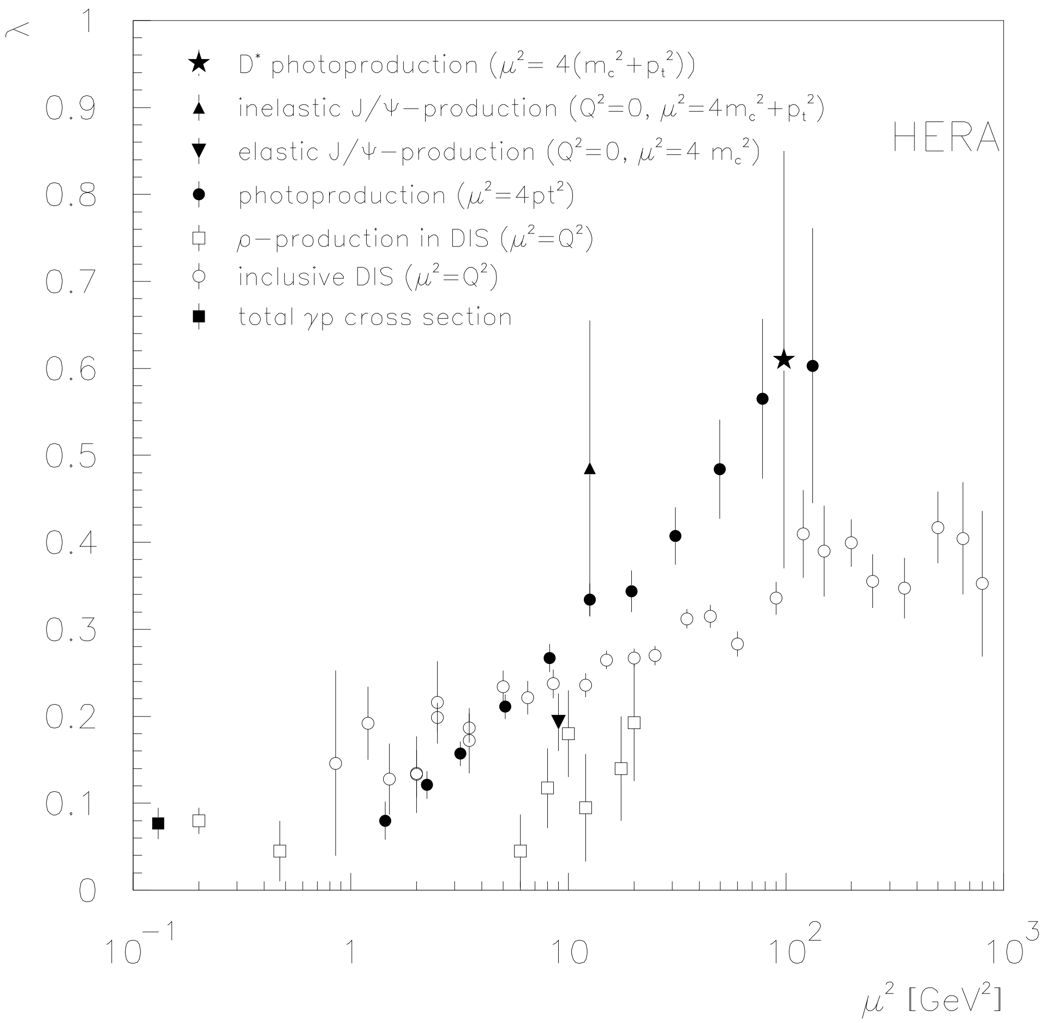
$$A_{IP} = 173 \pm 7 \; nb/GeV^2$$
$$A_{IR} = 519 \pm 125 \; nb/GeV^2$$

Total cross section and elastic forward scattering is related via optical theorem

$$\sigma \propto (W^2)^{\alpha_{IP}(0)-1}, \qquad \frac{d\sigma^{elastic}}{dt}\Big|_{t=0} \propto (W^2)^{2(\alpha_{IP}(0)-1)}$$

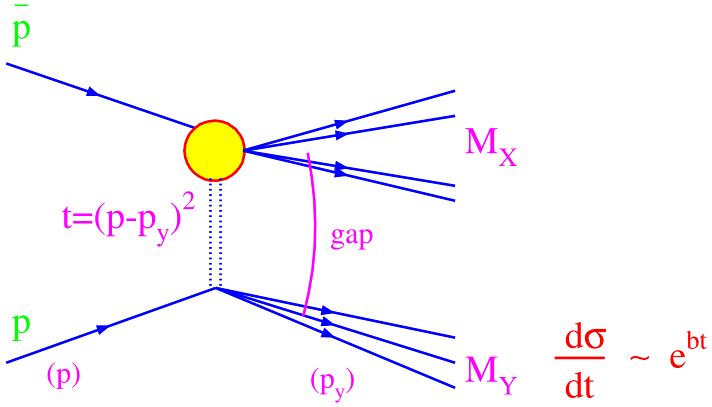
Scale Dependence of the W-dependence

$$\boldsymbol{\lambda = \alpha_{IP}(0) - 1}$$

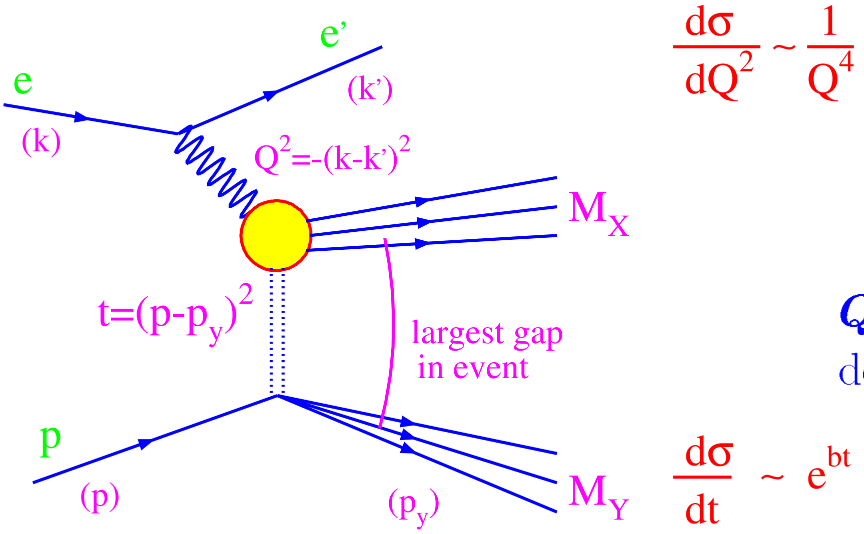


Slope $\boldsymbol{\lambda}$ larger than soft Pomeron limit $\boldsymbol{\lambda_{soft} = 0.08}$ as soon as hard scale $\boldsymbol{\mu^2}$ is involved like $\boldsymbol{\mu^2 = Q^2, p_T^2, m_c^2, ..}$

Kinematics of Inelastic Diffraction



$t,\ M_X \rightarrow$ ***jets***
defines a hard scale



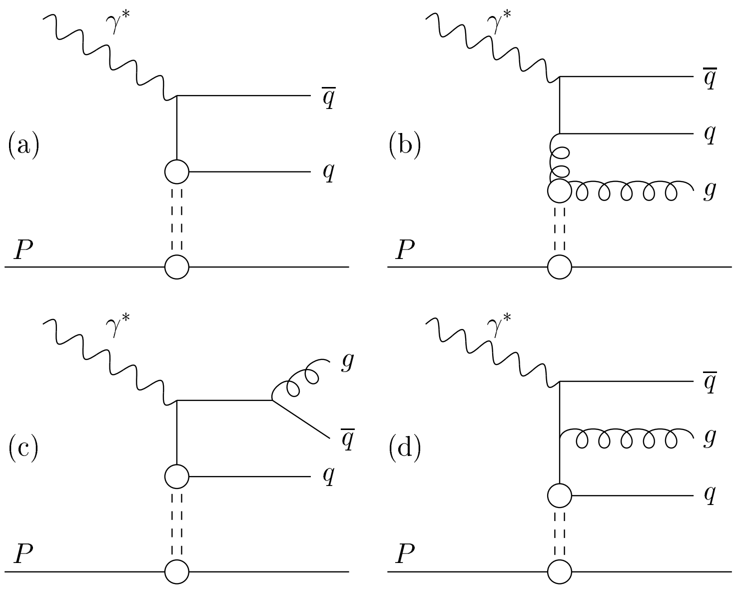
$Q^2,\ t,\ M_X \rightarrow$ ***jets***
defines a hard scale

Require no forward activity to restrict system $\boldsymbol{Y}$ to small mass and have system $\boldsymbol{X}$ well measured in detector

H1:	$3.3 \leq \eta \leq 7.5$	$\rightarrow$	$M_Y < 1.6$ GeV
ZEUS:	$3.3 \leq \eta \leq 4.3$	$\rightarrow$	$M_Y < 4$ GeV
CDF:	$2.2 \leq \eta \leq 5.9$		
D0:	$2.0 \leq \eta \leq 4.1$		

$$\boxed{x_{IP} \equiv \xi = \frac{M_X^2+Q^2}{W^2+Q^2},\ \beta = \frac{x_{Bj}}{\xi} = \frac{Q^2}{M_X^2+Q^2}}$$

Pictures of Diffraction in DIS



RAPGAP model

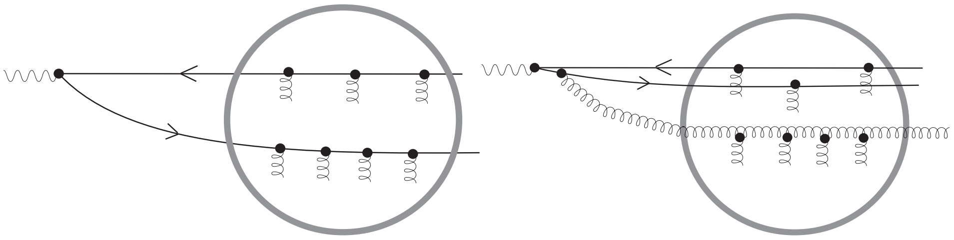
Two equivalent pictures:

- *Proton in the infinite momentum frame.* In hard scattering (e.g. large Q^2) the virtual photon "probes" partons in the diffractively exchanged object. (Ingelmann, Schlein)

  Cross section factorises into Pomeron flux times Pomeron structure function +Reggeon flux times meson structure function.

  Structure of meson-exchange: quark dominated,
  Structure of Pomeron=???

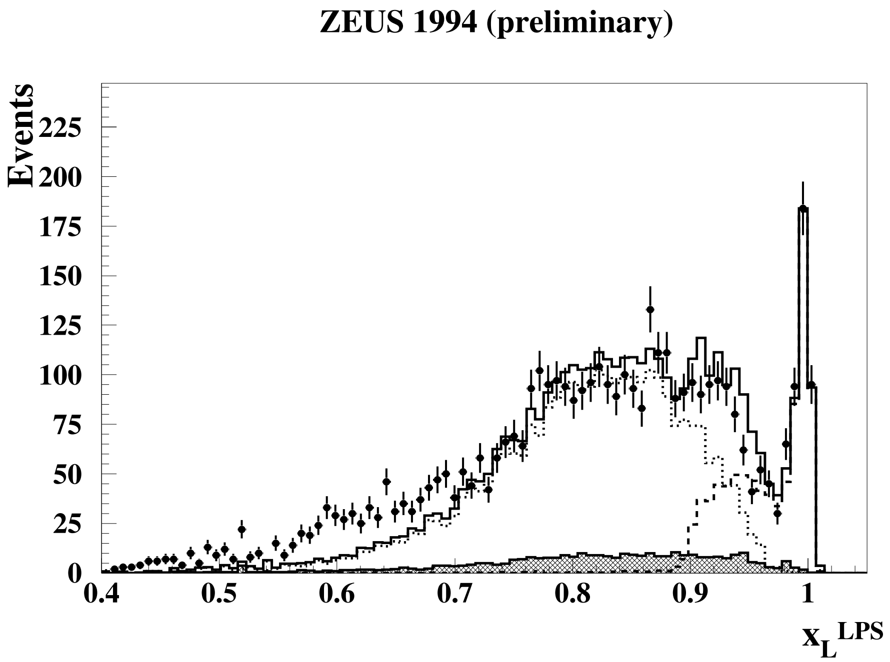
- *Proton at rest.* The Fock state of the photon $|\gamma>=|qq>, |qqg>$ is formed long before the target and interacts softly with the proton. Gap formation is a long time scale process.
  Bjorken, Buchmüller/Hebecker, Brodsky, Zacharov/Nikolaev,..



Results from Leading Proton Spectrometer

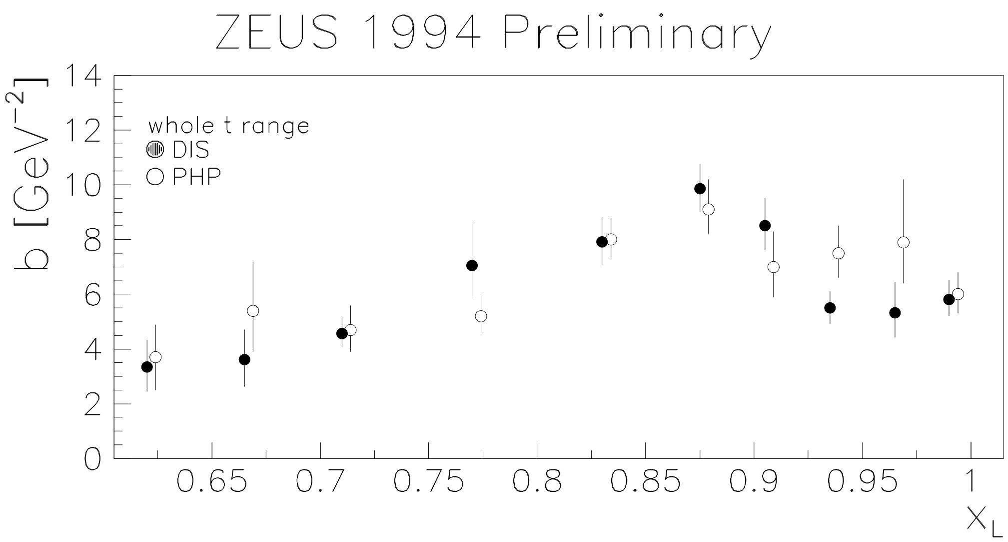
Measure energy $E_{p'}$ and p_t of scattered leading proton.

$$x_L = \frac{E_{p'}}{E_p} = 1 - \xi, \quad t = -\frac{p_t^2}{x_L} - m_p^2 \frac{(1 - x_L)^2}{x_L}$$



clearly visible diffractive peak at $x_L = 1 - \xi > 0.97$.

Now fit in bins of x_L $(-t < 0.5\ GeV^2)$ the form $\frac{dN}{dt} \propto e^{bt}$.



Definition of Diffractive Structure Function

$$\frac{d^5\sigma_{ep\to eXY}}{d\beta dQ^2 d\xi dt dM_Y} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1+(1-y)^2\right) F_2^{D(5)}(\beta,\xi,Q^2,t,M_Y)$$

The variables t and M_Y are not measured but limited by detector acceptance and therefore it is integrated over. Define cross section in analogy to DIS

H1:	$\lvert t\rvert < 1$ GeV^2	$M_Y < 1.6$ GeV
ZEUS:	$\lvert t\rvert < 1$ GeV^2	$M_Y < 4.0$ GeV

$$\frac{d^3\sigma_{ep\to eXY}}{d\beta dQ^2 d\xi} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1+(1-y)^2\right) F_2^{D(3)}(\beta,\xi,Q^2)$$

If the final state proton is measured in *leading proton spectrometer*

$$\frac{d^3\sigma_{ep\to epX}}{d\beta dQ^2 d\xi} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1+(1-y)^2\right) F_2^{LP(3)}(\beta,\xi,Q^2)$$

ZEUS: $0.073 < |t| < 0.4$ GeV^2, $\xi < 0.4$

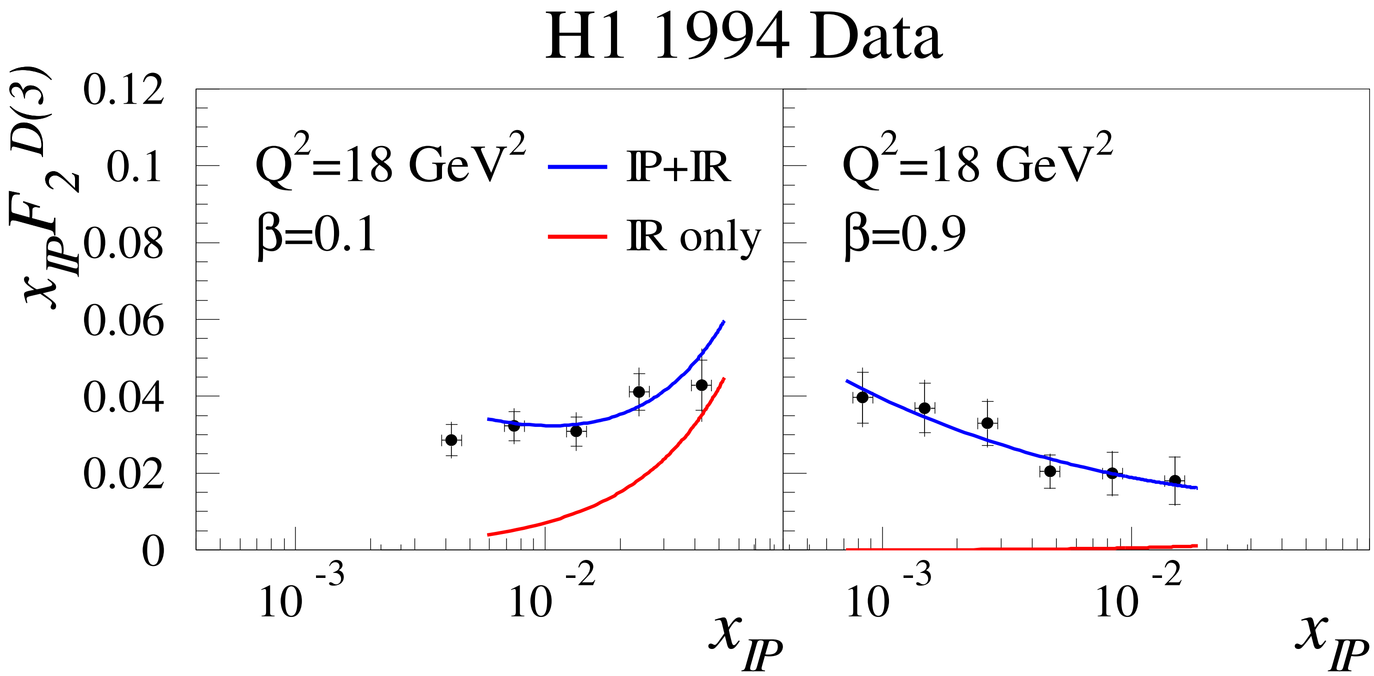
H1: $\frac{-\xi^2 m_p^2}{1-\xi} \leq t \leq \frac{-\xi^2 m_p^2 - 0.2^2\ GeV^2}{1-\xi}$, $0.1 < \xi < 0.24$

CDF: $0 < |t| < 2\ GeV^2$, $0.05 < \xi < 0.1$

Ansatz for Diffractive Structure Function

$$F_2^{D(3)}(\beta,\xi,Q^2) = \frac{e^{B_{I\!P}t}}{\xi^{2\alpha_{I\!P}(t)-1}} F_2^{I\!P}(\beta,Q^2) + C_M \frac{e^{B_{I\!R}t}}{\xi^{2\alpha_{I\!R}(t)-1}} F_2^{M}(\beta,Q^2)$$

+ possible interference term. Integrated over $|t| < 1$ GeV^2.



- contribution of meson term large at high $x_{I\!P} = \xi$ and small β
- meson intensity ∼50% at low β=0.1 and $x_{I\!P} = \xi = 0.05$

Fit of 47 bins in $4.5\ GeV^2 < Q^2 < 75\ GeV^2,\ \ 0.04 < \beta < 0.9$

$$\alpha_{I\!P}(0) = 1.203 \pm 0.02(stat) \pm 0.013(syst)^{+0.03}_{-0.035}(model)$$

$$\alpha_{I\!R}(0) = 0.50 \pm 0.11(stat) \pm 0.11(syst) \pm 0.10(model)$$

Energy Dependence of Diffractive Cross Section

Elastic scattering at fixed Q^2, M_X^2:

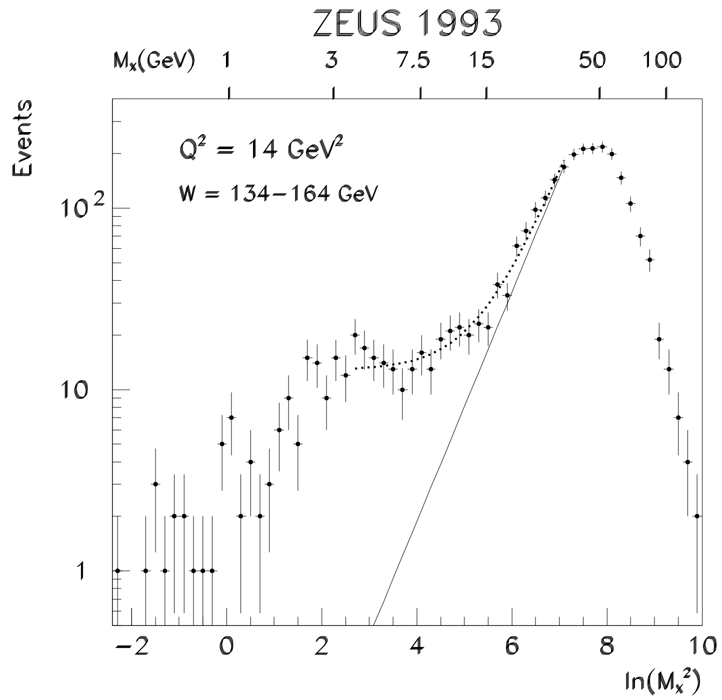
$$\frac{d^2\sigma(elastic)}{dt dM_X^2} =$$
$$f(M_X^2, t)(W^2 + Q^2)^{2\alpha_{I\!P}(t)-2} + g(M_X^2, t)(W^2 + Q^2)^{2\alpha_{I\!R}(t)-2}.$$

Transformation of variable $M_X^2 \to \xi$ yields

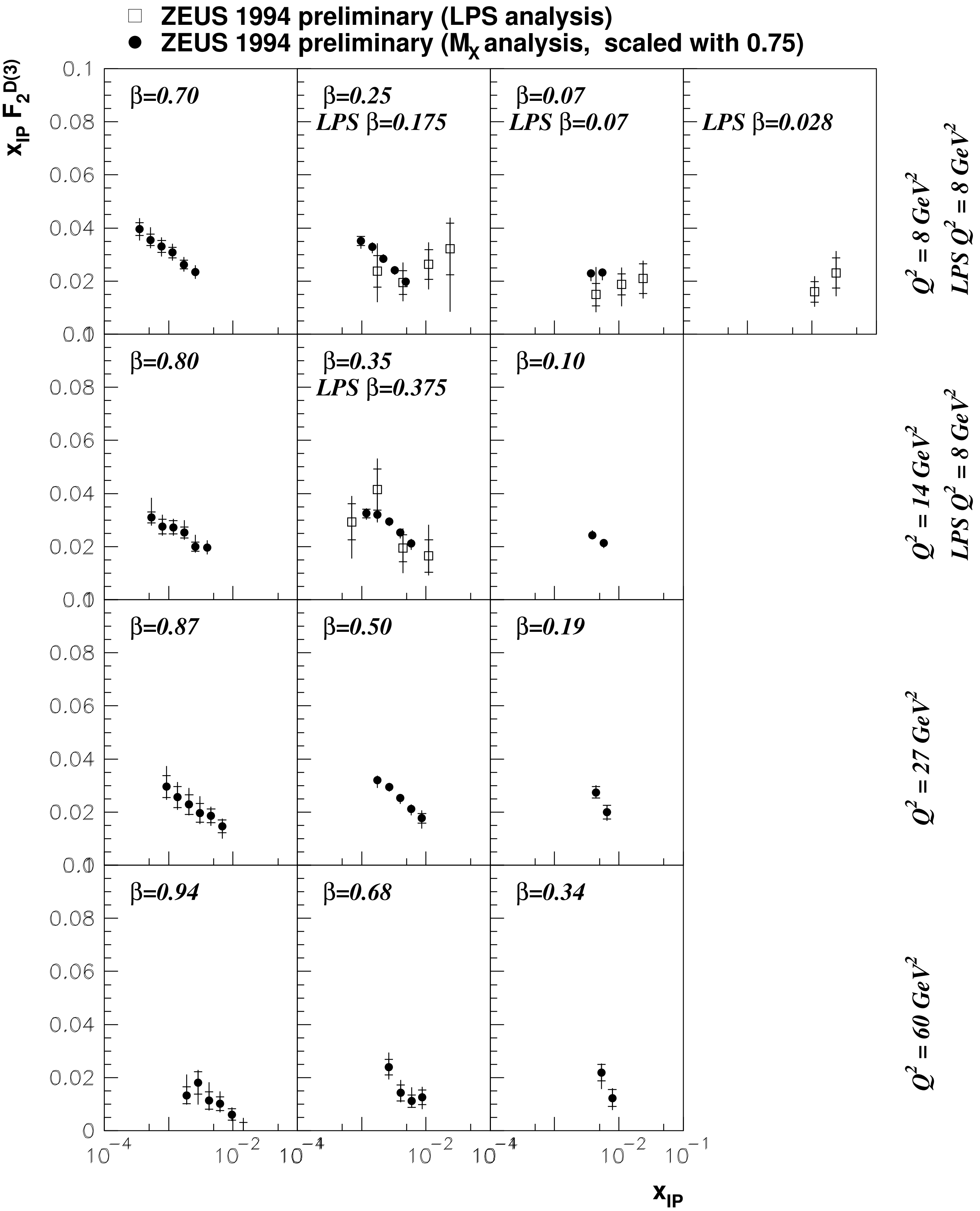
$$(W^2)^{2\alpha-2} \to \left(\frac{1}{\xi}\right)^{2\alpha-1}$$

i.e. Pomeron exchange dominates at high W^2 or low ξ.
Non-diffractive events are exponentially suppressed. ZEUS M_X-method: Fit function

$$\frac{d\mathcal{N}}{d\ln M_X^2} = D_1 + \frac{D_2}{M_X^2} + c\, e^{b\ln M_X^2}$$



$F_2^{D(3)}(\xi = x_{IP}, \beta, Q^2)$ from ZEUS



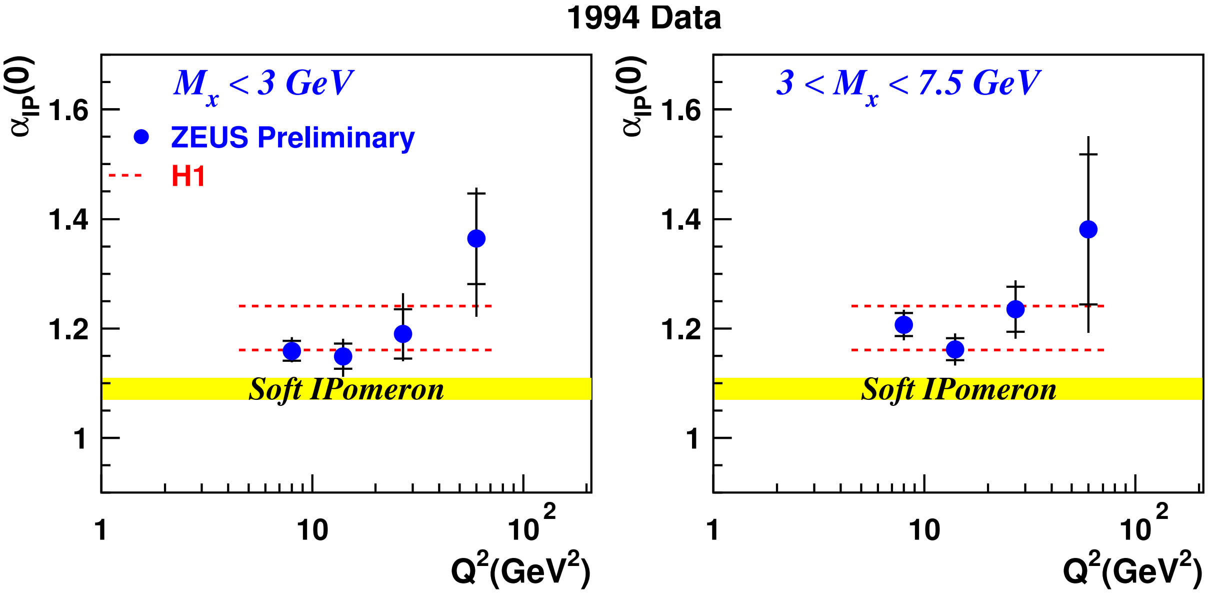
$\alpha_{IP}(0)$ in Diffractive DIS

Fit from the methods:

$$\frac{d\sigma^D_{ep\to eXY}}{dM_X} \propto (W^2)^{2\overline{\alpha_{IP}}-2} \qquad (ZEUS)$$

$$F_2^{D(3)}(\beta,\xi,Q^2) = \frac{e^{B_{IP}t}}{\xi^{2\alpha_{IP}(t)-1}} F_2^{IP}(\beta,Q^2) + C_M \frac{e^{B_{IR}t}}{\xi^{2\alpha_{IR}(t)-1}} F_2^{M}(\beta,Q^2)$$

(H1)



larger than soft Pomeron

Fit from LPS-data (Zeus):

$$F_2^{LP(4)}(\xi,\beta,Q^2,t) \;=\; A\cdot\left(\frac{1}{\xi}\right)^{2\overline{\alpha_{IP}}-1}$$

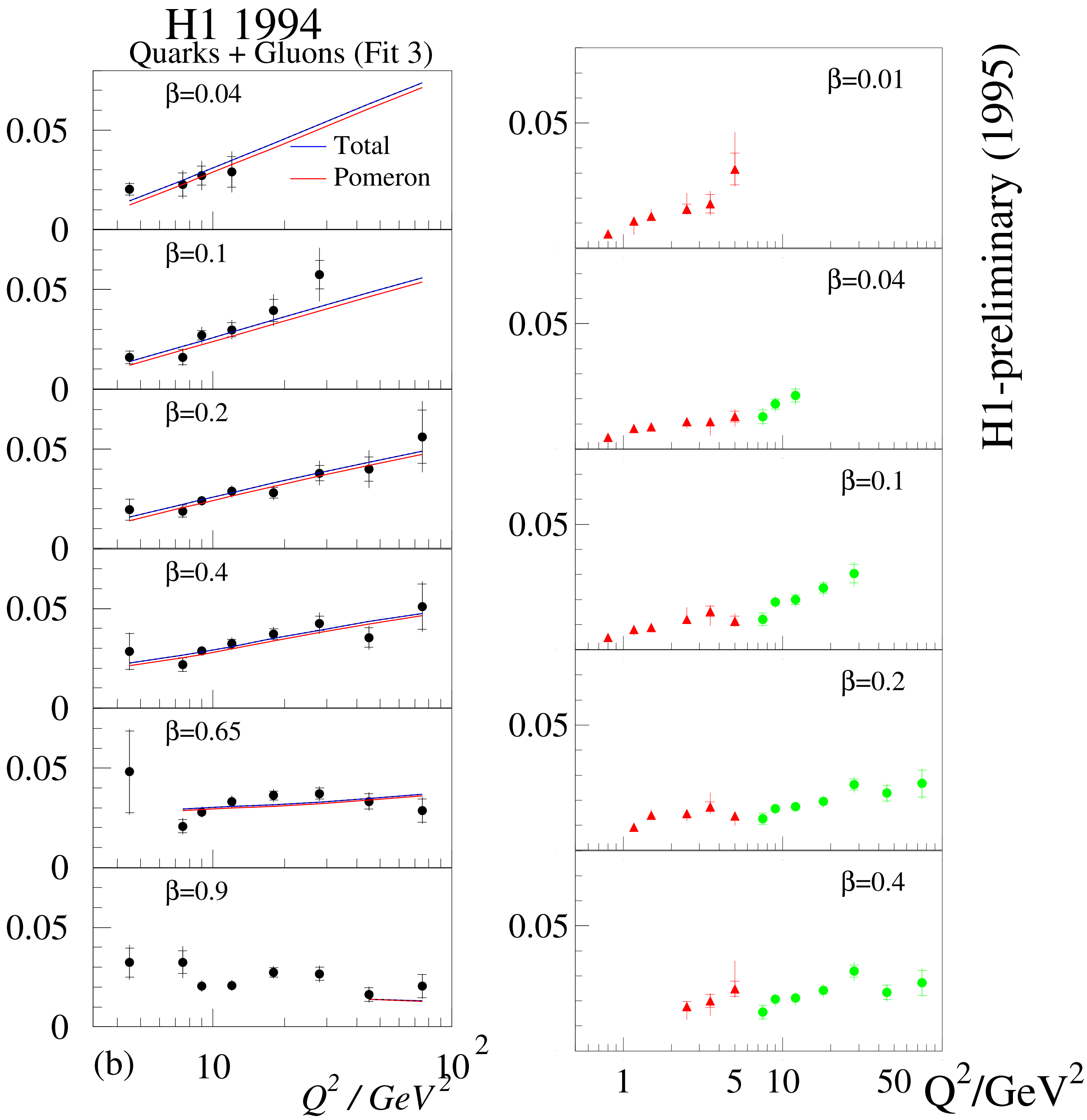
at $0.0773 < t < 0.4\ GeV^2$, $Q^2 = 5-20\ GeV^2$, $\beta < 0.35$

$$\overline{\alpha_{IP}} = 1.02 \pm 0.045^{+0.070}_{-0.065}$$

different from mass method, but different ξ range

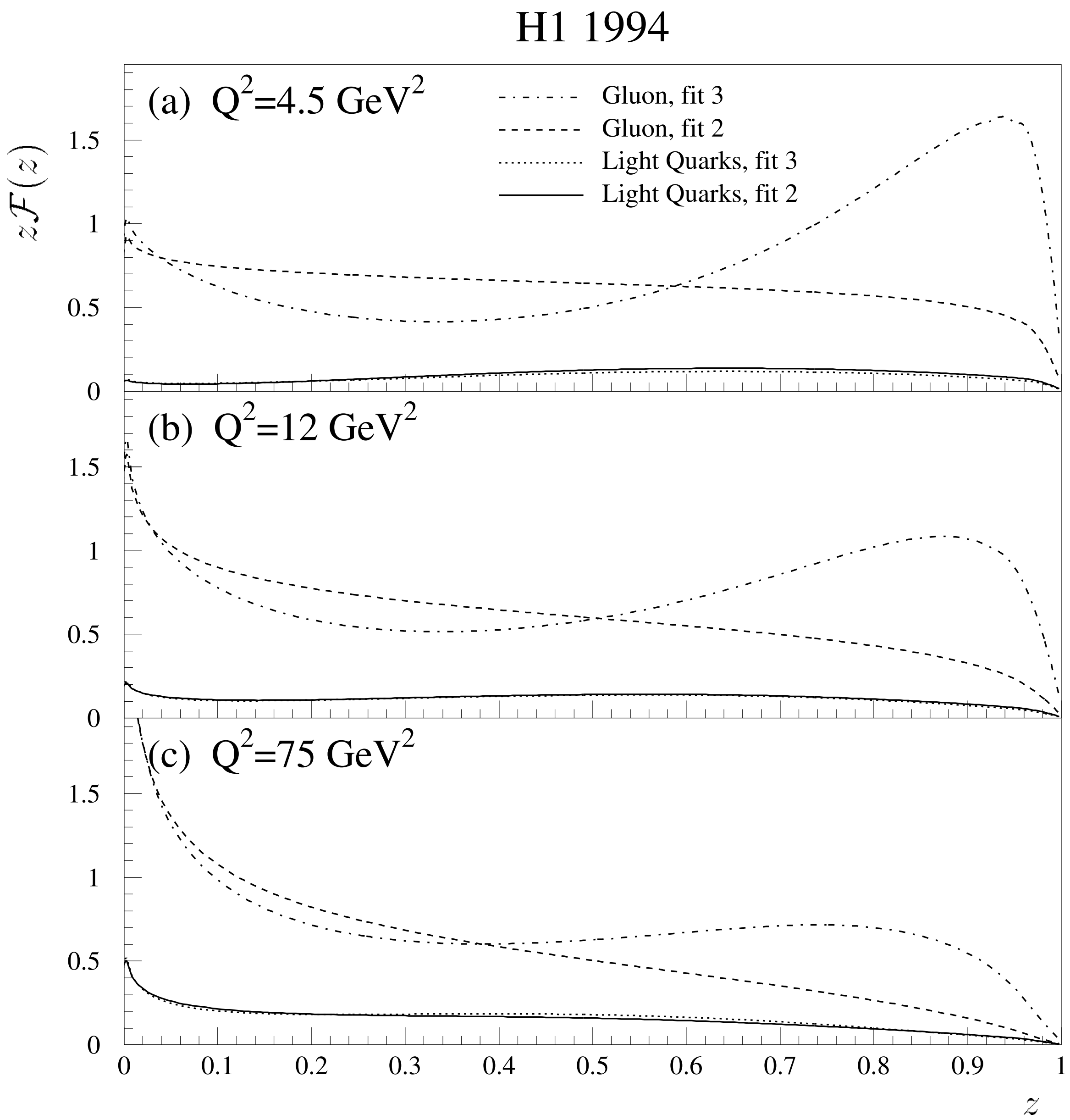
The Diffractive Structure Function

$\xi \cdot F_2^{D(3)}(\xi, \beta, Q^2)$ *at* $\xi = 0.003$ *and* 0.005



Fit fails with only quarks in Pomeron at $Q_0^2 = 3 GeV^2$, but dominant gluons describe data

Partons in the Pomeron (H1 Results)



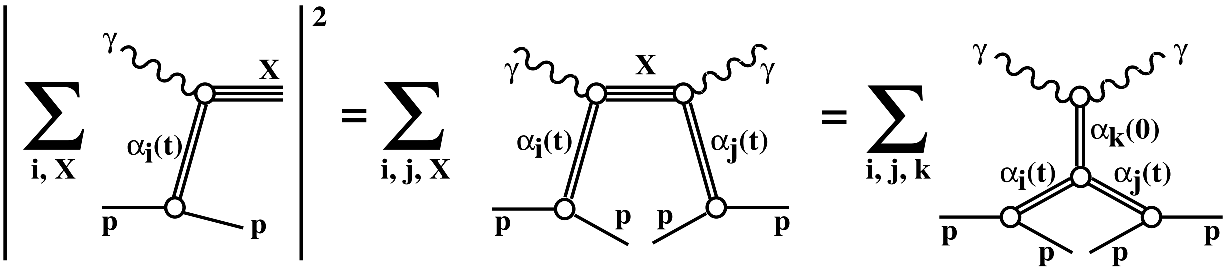
Parton parametrisation at $Q_0^2 = 3$ GeV^2:

$$z\mathcal{F}(z, Q^2 = Q_0^2) = \left[\sum C_j \cdot P_j(2z - 1)\right]^2 \; e^{\frac{a}{z-1}}$$

Fraction of momentum of Pomeron carried by gluons is 90% ($Q^2 = 4.5\ GeV^2$) and 80% ($Q^2 = 75\ GeV^2$).

Triple Regge Exchange Model

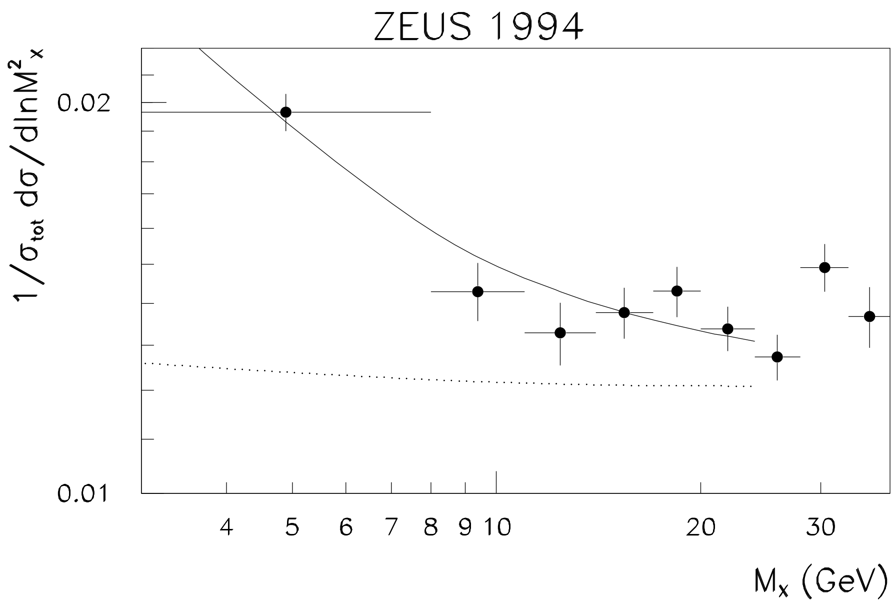
Triple Regge Limit: $\frac{M_X^2}{Q^2} = \frac{1-\beta}{\beta} >> 1$, following Q^2=0.



$$\frac{d\sigma}{dt dM_X^2} = \Sigma \frac{G_{ijk}(t)}{W^4} \left(\frac{W^2}{M_X^2}\right)^{\alpha_i(t)+\alpha_j(t)} \left(\frac{M_X^2}{s_0}\right)^{\alpha_k(0)} \cos\Delta\phi_{ij}$$

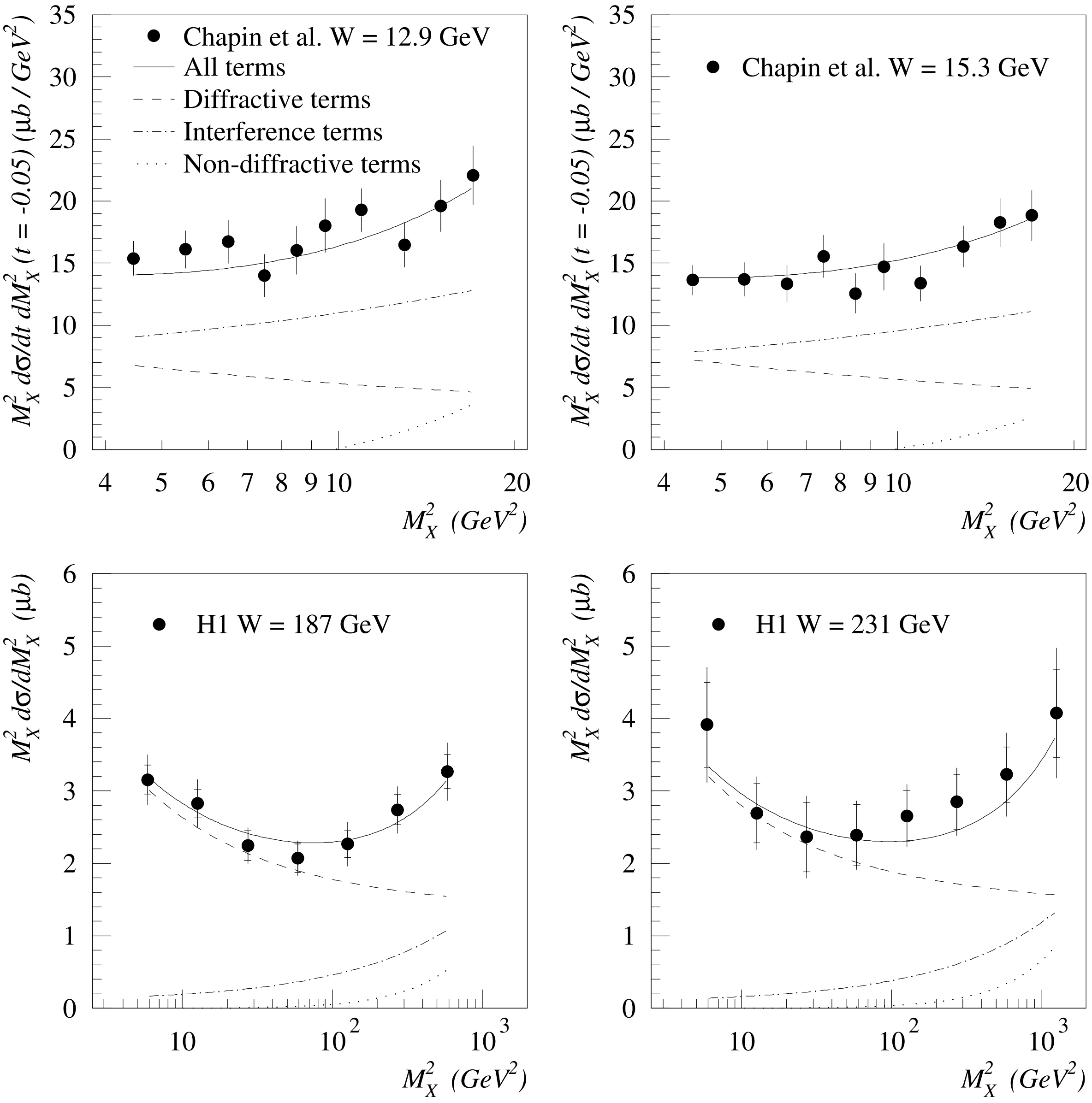
Use the functional form

$$G_{ijk}(t) = e^{b_{ijk}t} G_{ijk}(0), \quad \alpha_i(t) = \alpha_i(0) + \alpha_i' \cdot t$$



fit of Pomeron trajectory only.

Pomeron and Meson Fit



Results from fit with maximal interference and fit-parameters $G_{IPIPIP}(0), G_{IPIPIR}(0), G_{IPIRIR}(0), G_{IRIRIR}(0)$ and

- $\alpha_{IP}(0) = 1.068 \pm 0.016 \pm 0.022 \pm 0.041 (model)\ H1$
- $\alpha_{IP}(0) = 1.12\ \pm 0.04\ \pm 0.08\ ZEUS$
- Subleading trajectory needed in fit. Confirms result of diffractive structure function in DIS, $F_2^{D(3)}(\xi, Q^2, \beta)$.

Hard Diffraction at Tevatron

Measure

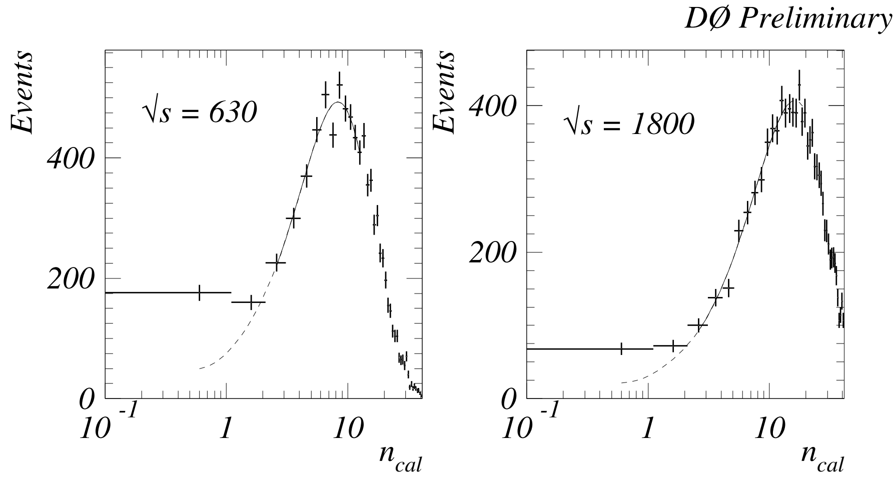
$$p + \bar{p} \to p + (X \to jet1 + jet2 + X')$$

$$p + \bar{p} \to jet1 + gap + jet2$$

and

$$p + \bar{p} \to p + (W \to e\nu + X')$$

Require rapidity gap on proton side (see page 5), i.e. cut on multiplicity of calorimeter towers with $E_T > 200$ MeV



Correct for loss of rapgap events due to random overlap of min. bias events with activity in the gap region ($\mathcal{O}(0.15 \pm 0.02)$).
Analysed in the Ingelmann-Schlein model (POMPYT-MC) with a factorised Pomeron flux

$$f_{I\!P/p}(\xi, t) = \frac{K}{\xi^{2\alpha_{I\!P}(t)-1}} F^2(t)$$

and a hard Pomeron structure function

$$\beta G(\beta) = 6\beta(1 - \beta)$$

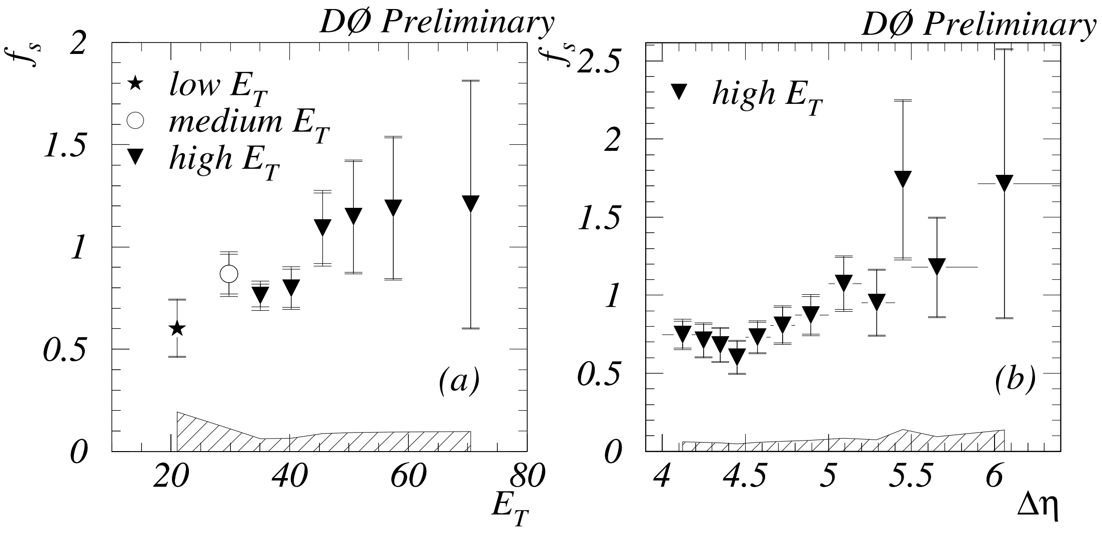
Note: ξ can not be measured without leading proton spectrometer and is taken from the MC model. Majority of events have $\xi < 0.05$.

Results on hard Diffraction at CDF/D0

Goal is to measure relative ratio of quarks and gluons in Pomeron in hard scattering.

process	sensitivity to
diff. W - production	quarks (gluons are suppressed by $\boldsymbol{\alpha_s}$)
diff. dijets	quarks and gluons
energy dep. of diff. dijets	colour singlet fraction rises with quark content

1. Ratio of diffractive to non-diffractive dijets with $\boldsymbol{E_T}$ >20 GeV, $\mathbf{0.005 < \xi < 0.015}$,
   $\boldsymbol{R_{JJ} = 0.75 \pm 0.05(stat) \pm 0.09(syst)\%}$ (CDF)
   $\boldsymbol{0.67 \pm 0.05(stat)\%}$ (D0)
2. Ratio of diffractive to non-diffractive W-production,
   $\boldsymbol{R_W = 1.15 \pm 0.55(stat) \pm 0.20(syst)\%}$ (CDF)
3. Fraction $\boldsymbol{f_s}$[%] of events with rapidity gap between jets (D0)

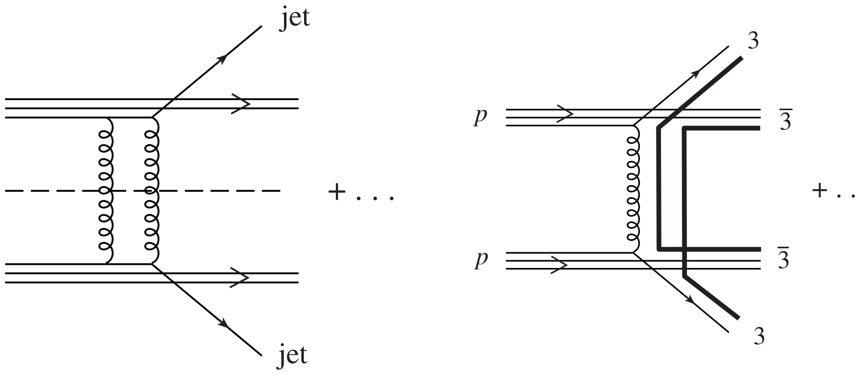


$$\boldsymbol{R = \frac{f_s(630\ GeV)}{f_s(1800\ GeV)} = 2.6 \pm 0.6(stat)}\ \text{(D0)}$$
$$\boldsymbol{f_s(1800\ GeV) = 1.13 \pm 0.12(stat) \pm 0.11(syst)\%}\ \text{(CDF)}$$

Interpretation of RapGaps at Tevatron

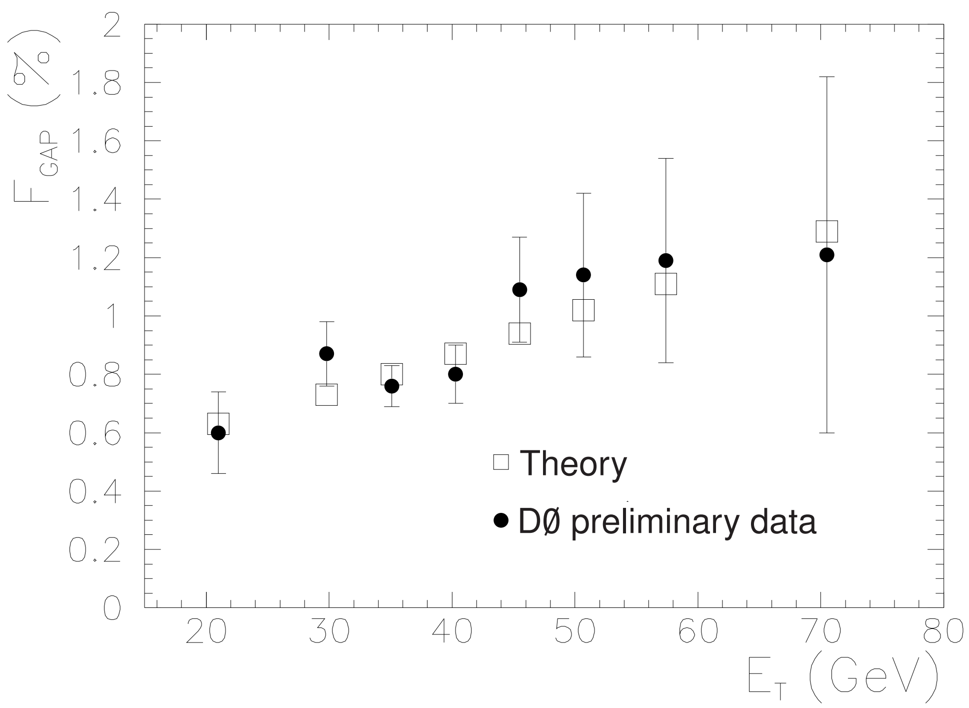
Conclusion: all results cannot consistently be described with the POMPYT model with only Pomeron exchange.

paper by Eboli, Gregores, Halzen, hep-ph/9708283



Pomeron as a 2-gluon system

colour bleaching by soft final state interactions. Gap survival prob.=?



Squares are fit by soft interaction model. Rules out the simple 2-gluon model.

HERA: $\boldsymbol{f_s = 15\%}$ (H1), $\boldsymbol{= 8\%}$ (ZEUS) larger gap survival prob.?

Fragmentation Studies

The Lund string model or cluster fragmentation models are well tuned to data. They describe the gross features of fragmentation.
Fragmentation gives the link between cross section on the parton level and observed particles in the detector. Special interest has to go to the fragmentation of heavy quarks. The b-fragmentation function has not really been measured.

At this conference results from

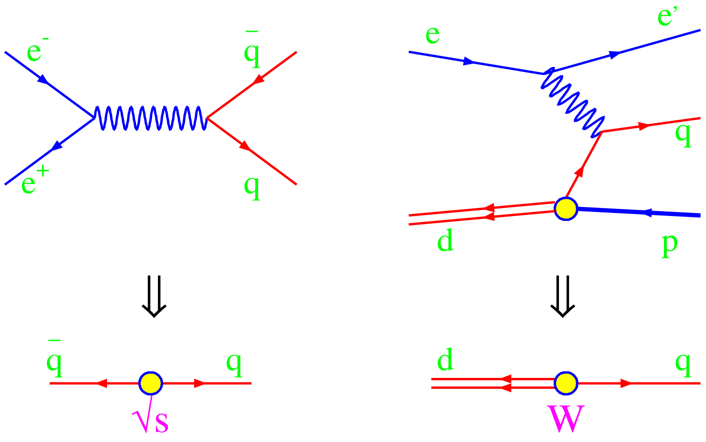
- charged multiplicity in diffractive DIS
- charged multiplicity in gluon jets
- particle species as a function of scaled jet momentum x_p
- scaling violation in quark and gluon jets, measurement of C_A/C_F
- leading baryons and vector mesons
- spin alignment

For the identification of gluon jets select 3-jet events.
Quark jets in $q\bar{q}\gamma$ topology
Gluon jets in $q\bar{q}g$ topology with q = heavy quark.

Reach purity of gluon jets of 75-95%.

Fragmentation of Diffractive System M_X

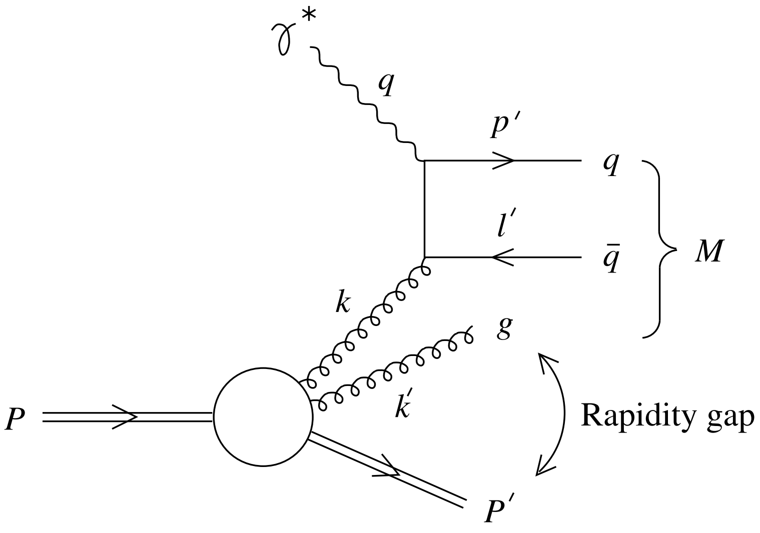
String fragmentation model (Lund model) is very successful.



LUND model: fragmentation of colour triplet string $q\bar{q}$ *or* dq.

Expect charged particle multiplicity to rise with $\sqrt{s}$ in e^+e^-, but with W in ℓp - independent of Q^2. (H1:Z.Phys.C72(1996)573)

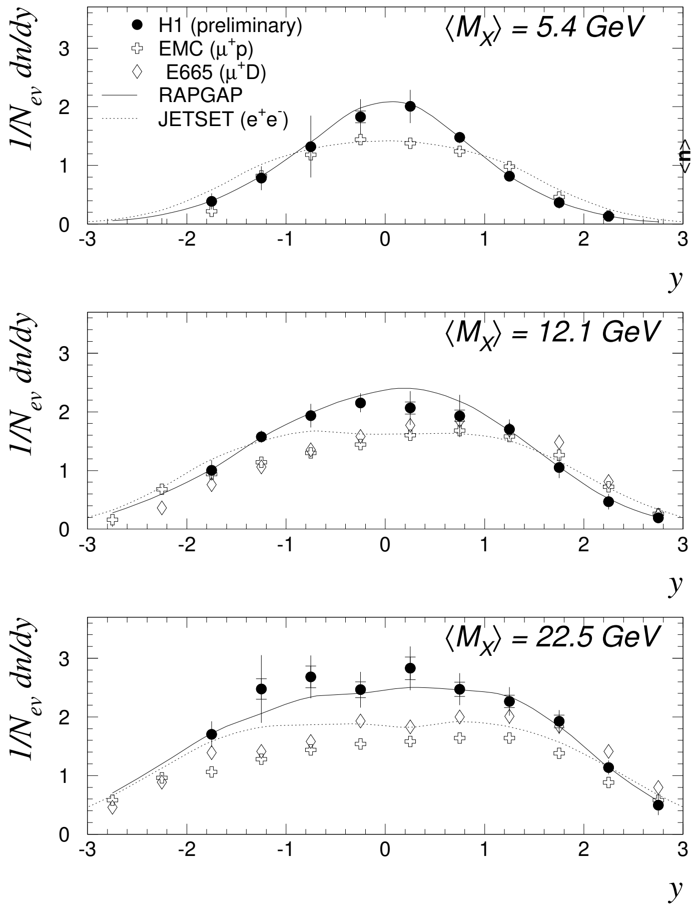
Does the diffractive system X fragment as an "independent" object, i.e. is the multiplicity governed by M_X or still by W?



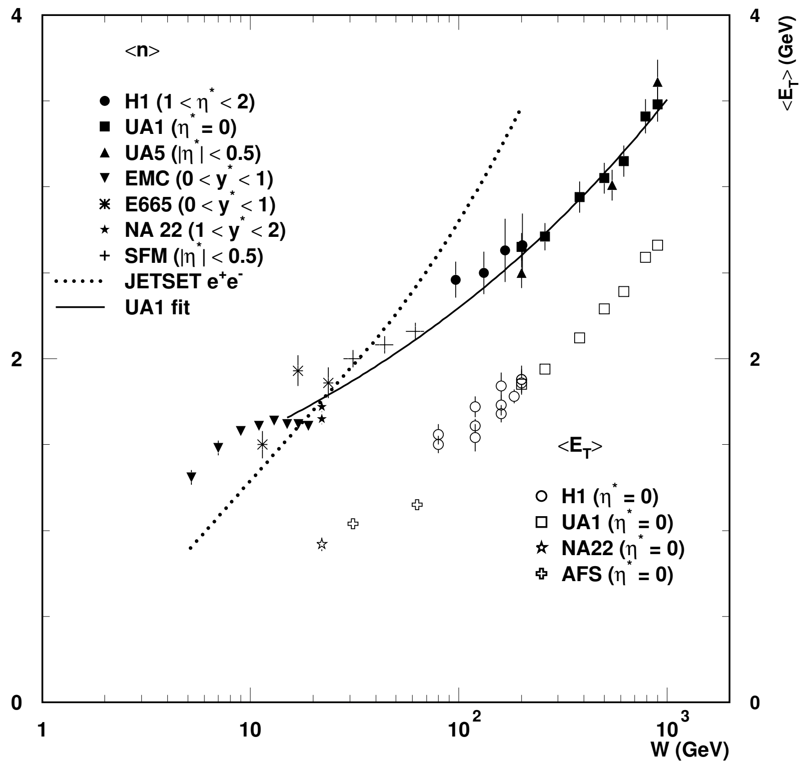
Buchmueller, McDermott, and Hebecker, dominant diagram

Fragmentation of a colour octet string in Diffractive DIS.

Abnormal Multiplicity in Diffraction?



diffractive sample



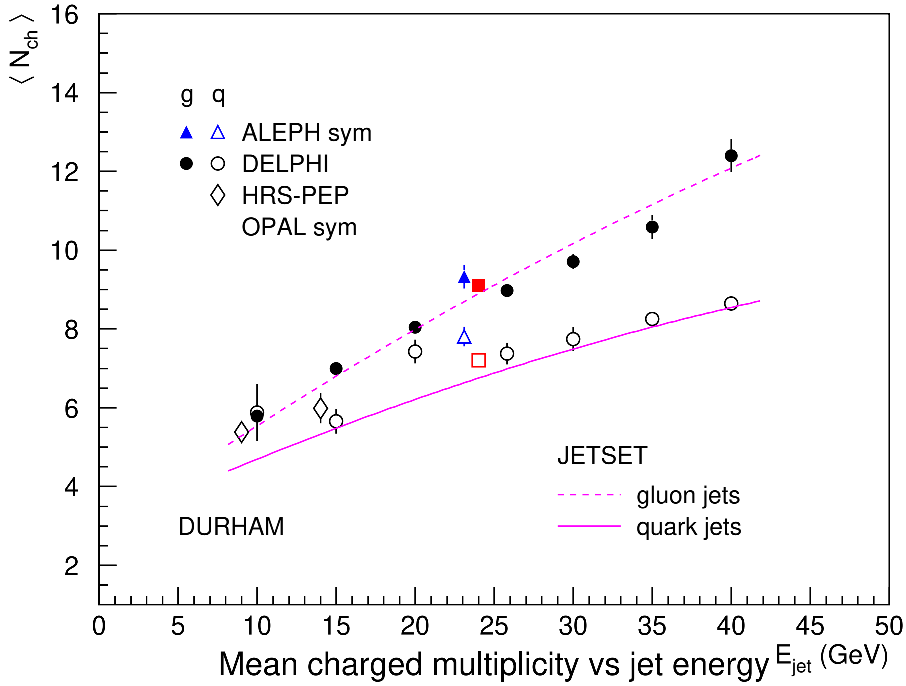
non-diffractive DIS

Rapidity plateau in diffraction scales with M_X. It is about 0.6 units higher than in non-diffractive events at $W = M_X$.

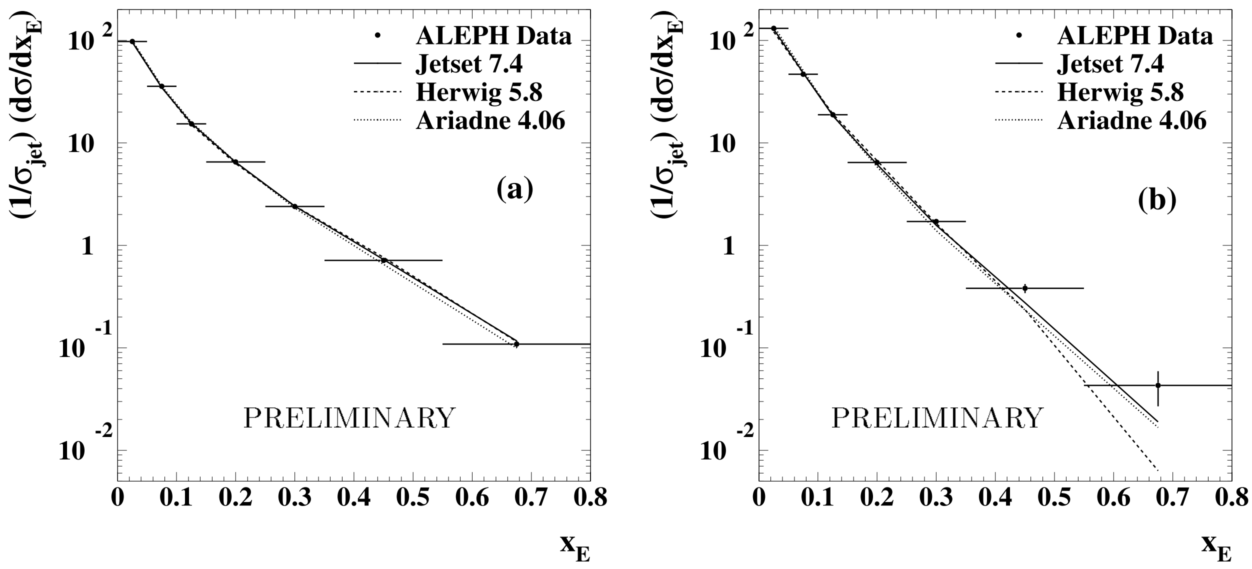
Hadronisation in diffraction not described by fragmentation of a single colour triplet string..

Fragmentation of Quark vs Gluon Jets

Expect a larger multiplicity in gluon jets, because of stronger effective $\boldsymbol{g \rightarrow gg}$ than $\boldsymbol{q \rightarrow qg}$ coupling.



The gluon fragmentation function is expected to be softer. The gluon jet has no valence quark at high $\boldsymbol{x_E}$. This analysis is at an energy scale of $\boldsymbol{Q = \sqrt{y_{cut}} \cdot E_{CM} = 30\ GeV}$, harder than in previous analyses of OPAL, ALEPH and DELPHI.



Scaling Violation in Fragmentation Function

Fragmentation functions can not be calculated in QCD, their evolution follows the DGLAP equation. As a scale use the Dokshitzer, Diakonov, Trojan (DDT) scale. For each jet in 3-jet event:

$$\kappa^i_{DDT} = \sqrt{s}\frac{\sin\theta_i}{\sin\theta_1 + \sin\theta_2 + \sin\theta_3}\sin\frac{\theta_{min}}{2}$$

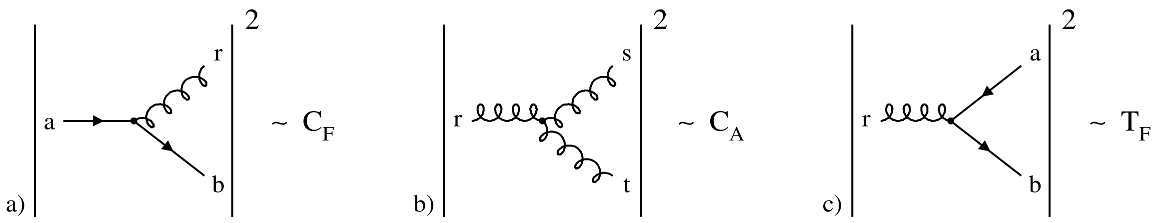
Make Ansatz

$$D_p(x_E) = p_3 x_E^{p_1}(1 - x_E)^{p_2} e^{-p_4 ln x_E^2}$$

and use (for large x_E)

$$\frac{dD_g(x_E,\kappa)}{d\ln\kappa} = \frac{\alpha_s(\kappa)}{2\pi}\int_{x_E}^1 \frac{dy}{y} P_{g\to gg}\left(\frac{x_E}{y}\right) D_g(y,\kappa)$$

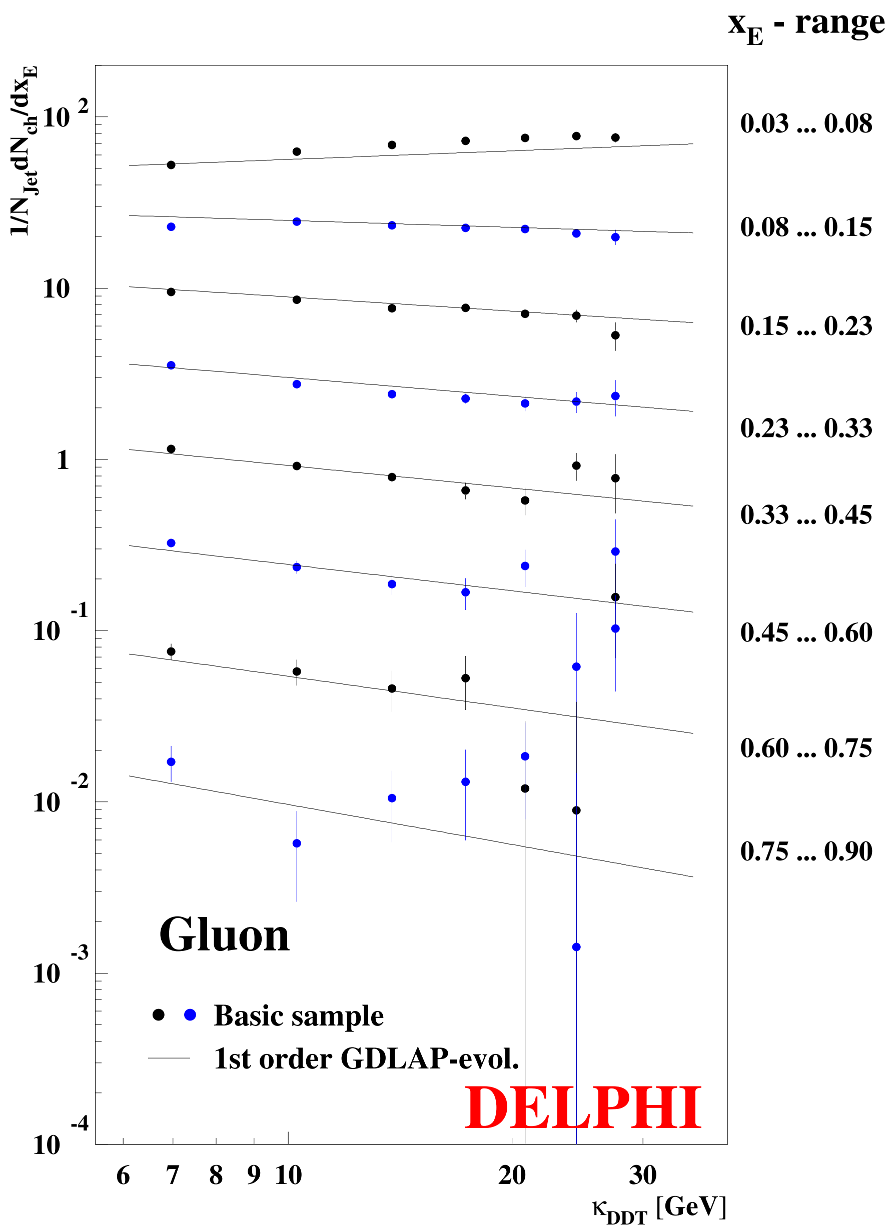
$$\frac{dD_q(x_E,\kappa)}{d\ln\kappa} = \frac{\alpha_s(\kappa)}{2\pi}\int_{x_E}^1 \frac{dy}{y} P_{q\to qg}\left(\frac{x_E}{y}\right) D_q(y,\kappa)$$



$C_F = 4/3$ $\quad$ $C_A = 3$ $\quad$ $T_F = 1/2$

$$\lim_{x_E\to 1}\frac{\frac{d\ln D_p(x_E,\kappa)}{d\ln\kappa}}{\frac{d\ln D_q(x_E,\kappa)}{d\ln\kappa}} = \frac{C_A}{C_F}$$

Scaling Violation in Gluon Fragmentation

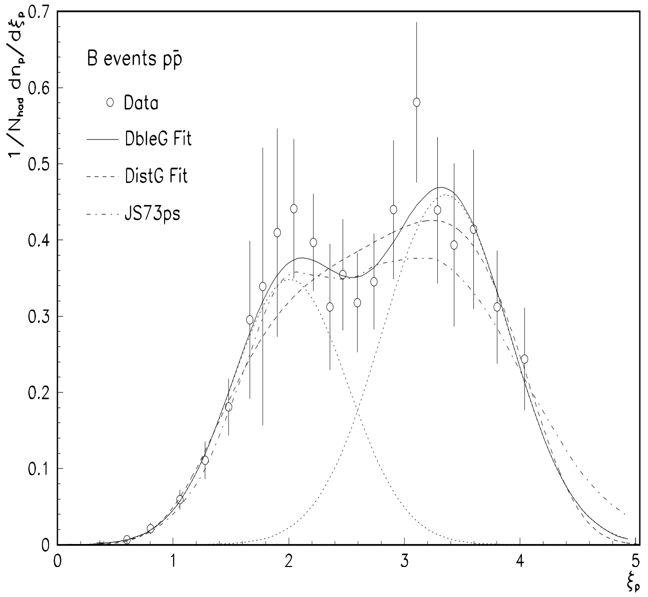


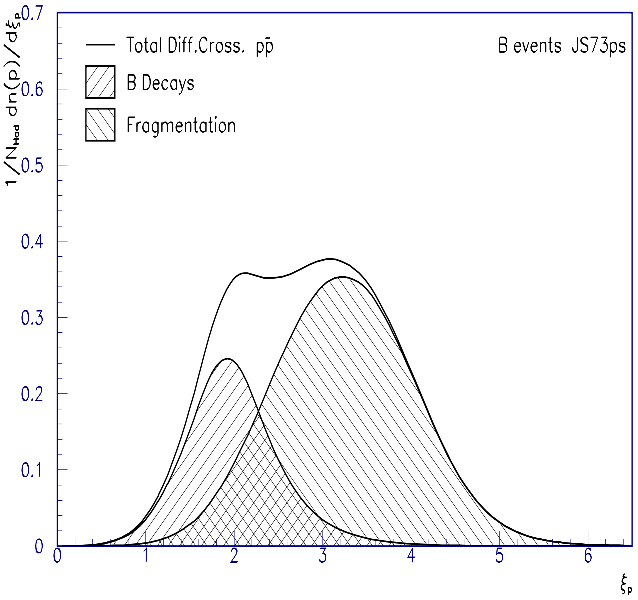
$$\frac{C_A}{C_F} = 2.7 \pm 0.7(stat.) \quad (QCD : 9/4 = 2.25)$$

κ_{DDT}=9.8 GeV	Quark jets	Gluon jets
p_1	-3.08	-4.20
p_2	1.05	1.65
p_3	0.18	0.07
p_4	0.40	0.63

Baryons from B Events (DELPHI)

Fragmentation function plotted in variable $\boldsymbol{\xi_p = \ln \frac{1}{x_p}}$ exhibits for most particles a (distorted) gaussian distribution. The integral is multiplicity. Baryons in events with a b-quark show a different shape.





A double Gaussian (DbleG) fit describes the data much better than a distorted Gaussian (DistG) fit. The origin of the two Gaussian is shown in JETSET Monte Carlo model of fragmentation originating from *fragmentation* and from *B-decays*. The decay protons are at low $\boldsymbol{\xi}$, i.e. at high momentum where we expect decay products from heavy quarks.

Data shows 40% protons/antiprotons from B-decays as compared to 30% from JETSET.

Leading Particles in Fragmentation

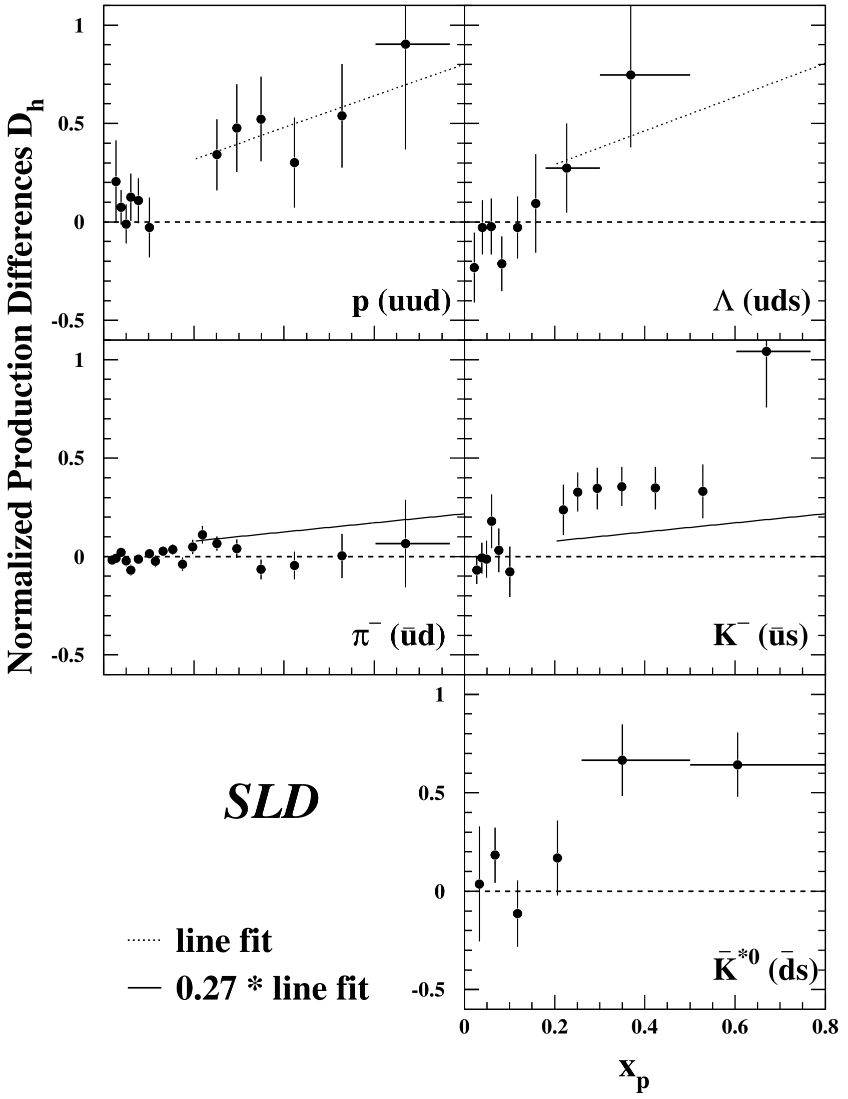
Define $N(q \to h)$ the number of hadrons of type h in uds-jets. Production rate per uds-quark jet R_h^q and difference between hadron and anti-hadron differential X-section D_h:

$$R_h^q = \frac{1}{2N_{evts}} \frac{d}{dx_p} \left[N(q \to h) + N(\bar{q} \to \bar{h}) \right], \qquad D_h = \frac{R_h^q - R_{\bar{h}}^q}{R_h^q + R_{\bar{h}}^q}$$

Baryons

Pseudoscalars

Vector meson



- Clear evidence for the production of leading baryons at high x_p.
- Excess of K^- over K^+, and $\overline{K^{*0}}$ over K^{*0} at high x_p. Leading kaons predominantly produced in $s\bar{s}$ events rather than in $d\bar{d}, u\bar{u}$ events.

Spin Alignment of Vector Mesons in Fragmentation

Quarks from $Z^0 \rightarrow q\bar{q}$ are polarised. Polarisation transferred to first rank baryons $(\Lambda, \Lambda_c, \Lambda_b)$.

$$P_\Lambda = -32.9 \pm 7.6\%(OPAL), = -32 \pm 7\%(ALEPH)$$

In $J^P = 1^-$ (vector)mesons any spin alignment must arise from hadronisation. Measure angle θ_H of decay meson with respect to the spin quantisation axis ($\vec{p}(V)$ in LEP frame.)

$$W(\cos\theta_H) = \frac{3}{4}\left[(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta_H\right]$$

Spin-alignment parameter is defined

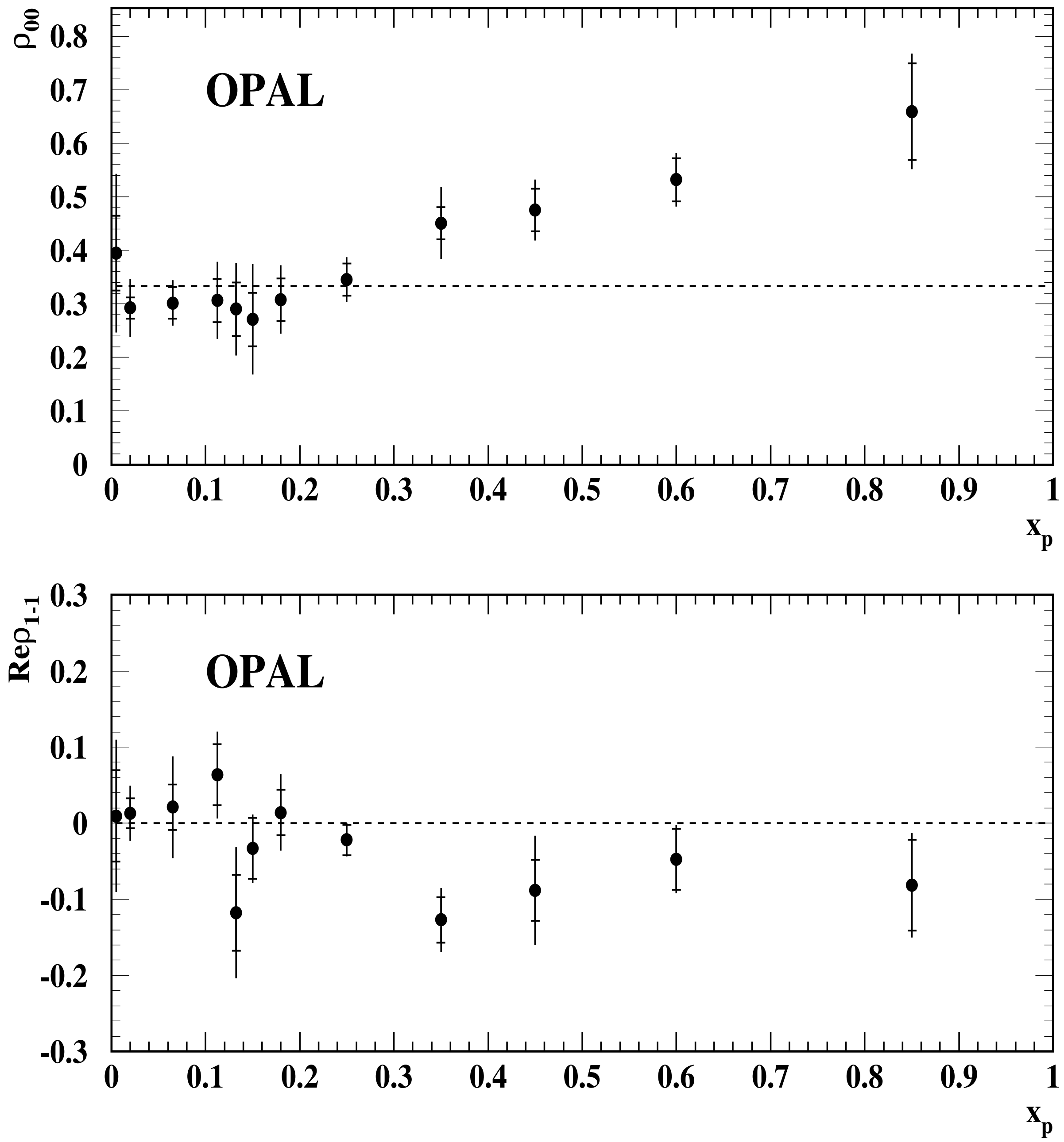
$$\eta = \frac{1}{2}(2\rho_{00} - \rho_{11} - \rho_{-1-1}) = \frac{1}{2}(3\rho_{00} - 1)$$

In a statistical model $\rho_{00} = \frac{1}{2}(1 - P/V)$ with P/V ratio of pseudoscalar to vector mesons in fragmentation. In this model $\rho_{00} \leq 0.5$ and $\rho_{00} = 0$ for $P/V = 1$, $\rho_{00} = 1/3$ for $P/V = 1/3$.

Results from CLEO, HRS, TPC-2γ, ALEPH, DELPHI, OPAL

- $\rho_{00} \sim 1/3$ for ρ, D^*, B^*-mesons
- $\rho_{00} > 1/3$ for D^*, Φ, K^*-mesons at large fractional momentum
- $\rho_{00} > 0.5$ for K^* (see figure)

Large Spin Alignment for K^*-Mesons



Interesting observation,
rules out simple statistical model.

Summary

- Semi-inclusive cross sections rise with energy proportional $(W^2)^\lambda$ where λ grows with the hard scale involved
- Multi-dimensional distributions in diffraction at HERA and Tevatron help understanding of diffractive phenomena
- Inelastic diffraction in DIS described by sum of Pomeron exchange (80% gluons) and meson exchange (quarks). Only Pomeron exchange breaks factorisation.
- $\alpha_{IP}(0) \sim 1.20$ in diffractive DIS slightly larger than in total cross section or diffractive photoproduction (α_{IP}(0)=1.08)
- particle density $dn/d\eta$ at fixed M_X larger in diffractive DIS than in non-diffractive DIS at corresponding W.
- Factorisation breaking also in hard diffraction at Tevatron
- Fragmentation properties of gluon jets well measured at LEP. Scaling violation of fragmentation function as expected from DGLAP .$C_A/C_F = 2.7 \pm 0.7$
- Large spin alignment of leading vector mesons at Z^0.