Hadronic Final States and Diffraction at HERA
(on behalf of the H1 and ZEUS collaborations)

HERA - *ep* collider (1991-2007)
$\sim 0.5\ \mathrm{fb}^{-1}$ per experiment
$\sqrt{s} \sim 300\ GeV$

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DESY

March 26, 2011

Moriond'11, La Thuile

ep collisions: Inclusive DIS - study structure of the proton

$e(k) + p(P) \rightarrow l_e(k')X$:

$s = (k+P)^2$, ep system energy

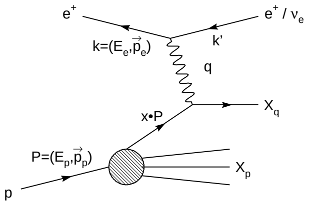
$Q^2 = -q^2$, virtuality of the photon

$Q^2 > 1$ GeV^2 - DIS

$Q^2 \approx 0$ - PHP

$x = \frac{Q^2}{2pq}$, momentum fraction of the struck parton

$y = \frac{qP}{kP}$, inelasticity

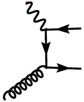


$$\frac{d^2\sigma^{ep}(x,Q^2)}{dxdQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} Y_+[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)]$$

where F_2, F_L - proton structure functions (for details see Voica's talk on Monday)

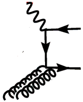
In this talk highlights of the results on processes with specific signature:

- Jets
  - α_s
  - constrain PDFs



LO - α_s^1

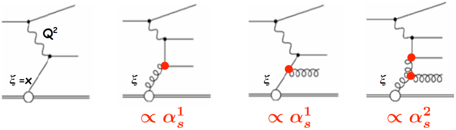
- Diffractive events
  - "gluonic" content of the prot
  - Multiparton Interactions



LO - α_s^2
2g-colorless exchange (!)

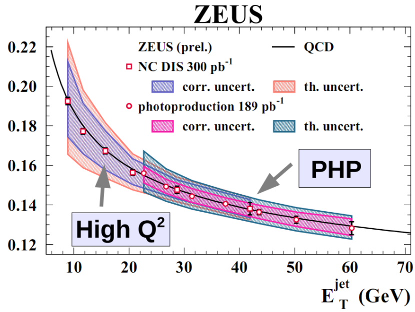
Jet cross section - Series expansion in powers of α_s

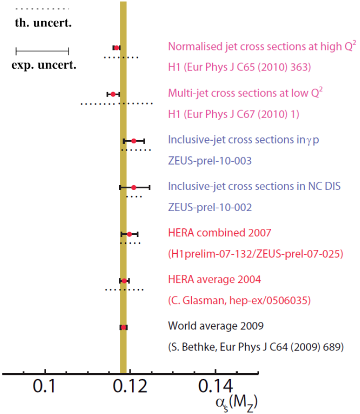
$$\sigma_{\text{jet}} = \sum_m \alpha_s{}^m(\mu_R) \sum_{a=q,\bar{q},g} f_{a/p}(x,\mu_f) \otimes \hat{\sigma}_{a,m}(x,\mu_R,\mu_F)(1+\delta_{\text{had}})$$



Coefficients are convolutions of

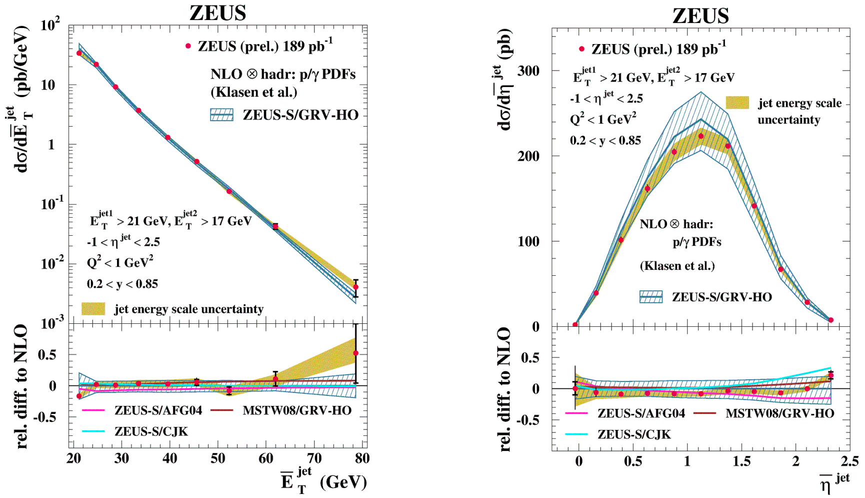
- parton distribution functions (PDFs) $f_{a/p}$ (and of γ-PDF in case of PHP)
- hard scattering matrix element $\hat{\sigma}$





Precision measurement of α_s and its running in one experiment

Dijets in Photoproduction



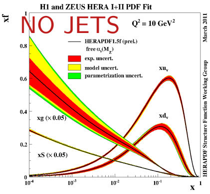
Good description of data by NLO QCD in the whole measured range

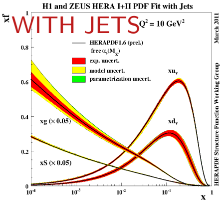
Sensitivity to proton (high E_T^{jet}) and photon (high η^{jet}) PDFs

ZEUS-prel-10-014

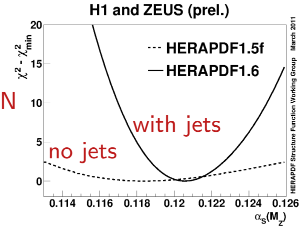
Using DIS jets in HERAPDF fit to get α_s

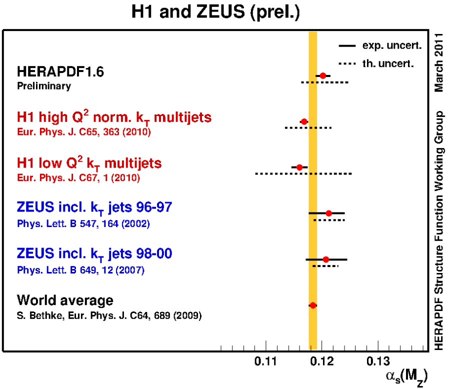
- Jet production mechanism relates the gluon PDF and α_s
- If we improve our knowledge of PDFs we can also improve it on α_s
- Perform a simultaneous fit on gluons and α_s in HERAPDF1.6 (α_s treated as free parameter)





α_s SCAN





H1prelim-11-034/ZEUS-prel-11-001

Diffractive DIS kinematics

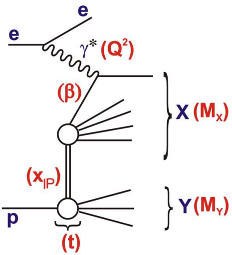
$e(k) + p(P) \rightarrow e(k')XY$:

where
X - diffractively produced system
Y - proton ($M_Y = m_p$) or a proton remnant system

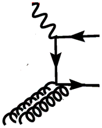
$s = (k+P)^2$, ep system energy
$|t|$ squared 4-momentum transfer at proton vertex
x_{IP} fractional momentum loss of proton (momentum fraction $\mathbb{P}/p$)
β x/x_{IP} (momentum fraction $q/\mathbb{P}$)

reduced diffractive x-section:

$$\sigma_r^{D(3)}(\beta, x, Q^2) = F_2^{D(3)}(\beta, x, Q^2) - \frac{y^2}{Y_+} F_L^{D(3)}(\beta, x, Q^2),$$



in pQCD
$\mathbb{P}\approx$ colorless "2g exchange"



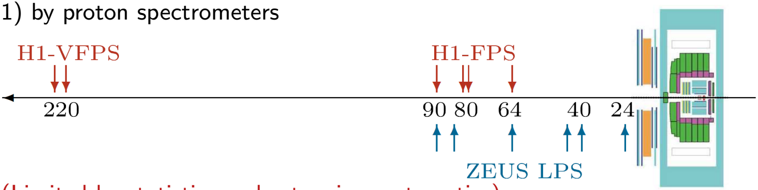
QCD factorisation theorem, proven for DDIS [Collins'98]

$$\sigma^D = \sum_i \hat{\sigma} \otimes f_i^D(x_{IP}, t, \beta, Q^2)$$

- $\hat{\sigma}$ subprocess ME
- f_i^D - DPDF, universal for diffractive DIS processes

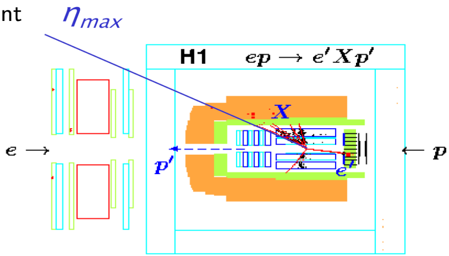
Two ways to select (define) diffractive events

1) by proton spectrometers



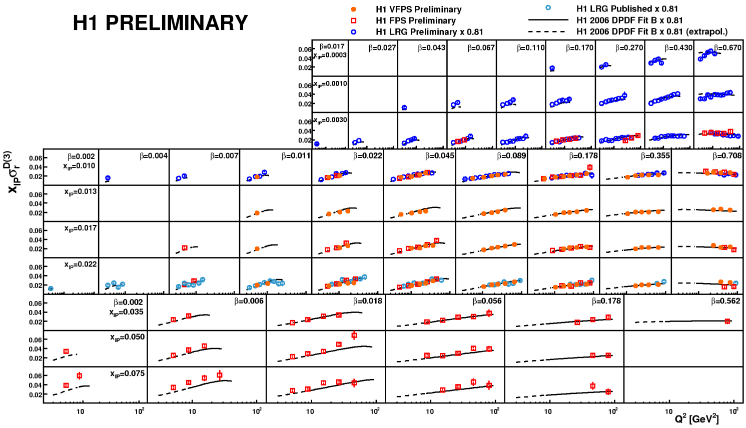
(Limited by statistics and p-tagging systematics)

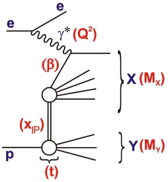
2) by 'Large rapidity gap' adjecent to outgoing (untagged) proton



(Limited by pdiss systematics)

Reduced x-section measurement: VFPS&FPS .vs.LRG





Three different detectors (two different methods) kinematic space coverage with very nice mutual agreement!

$\sigma_r \sim F_2^D$, scaling violation as in the F_2 from inclusive DIS [F_2^D is a subset of F_2]

H1prelim-10-014

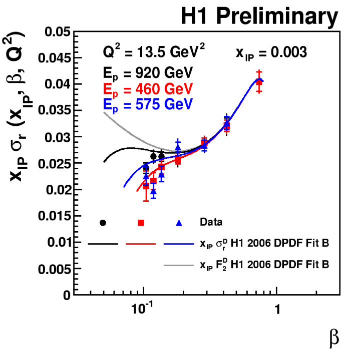
Extracting F_L^D

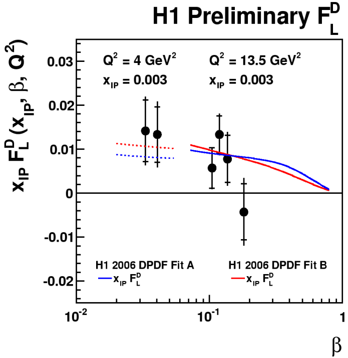
$$\sigma_r^{D(3)}(x_{IP},\beta,Q^2) = F_2^{D(3)}(x_{IP},\beta,Q^2) - \frac{y^2}{Y_+} F_L^{D(3)}(x_{IP},\beta,Q^2),$$

at high y contribution of F_L^D becomes significant $\rightarrow$ measure it

In order to extract F_L^D (F_L) must have $\sigma_r^{D(3)}$ at 3 different $\sqrt{s}$

Here, adding H1 xsection measured at $<Q^2>=4$ GeV^2



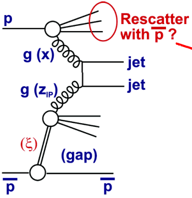


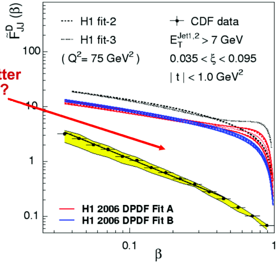
The first (& the only) measurement of $F_L^D \neq 0$ (directly see gluons!)

H1prelim-10-017

Universality of Diffractive PDFs and Rapidity Gap suppression

- Naive implementation of HERAs DPFs at $p\bar{p}$ is off by a factor of ~ 10
- Gap survival probability $S^2 \sim 0.1$
  - Suppression due to remnant rescattering on proton, i.e. Multiparton Interaction (MI)

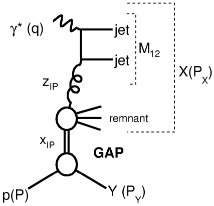


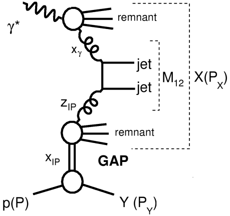


Go back to HERA and Check the Gap Survival with diJets in photoproduction

"Direct" photon ($X_\gamma \to 1$)

$S^2 = 1$





"Resolved" photon ($X_\gamma < 1$)

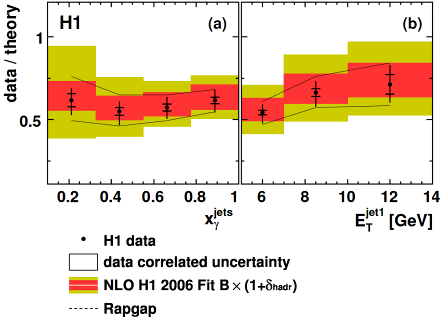
$S^2 \approx 0.34$

Diffractive dijets in γp

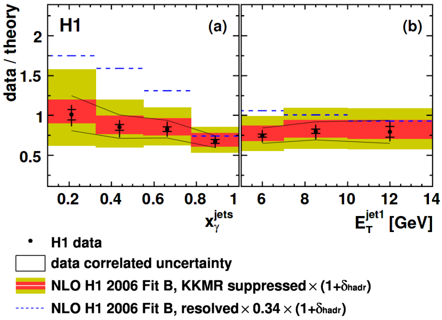
ZEUS [$E_T^1 > 7.5$ GeV] - no evidence for Gap suppression
H1 [$E_T^1 > 5$ GeV] - Gap survival probability < 1 (at 2σ)
$\sigma(H1)/\sigma(NLO) = 0.58 \pm 0.12$ (exp) ± 0.14 (scale) ± 0.09 (DPDF)

- No x_γ dependence, hint of E_T dependence?
- implement "resolved" photon suppression

NO SUPPRESSION



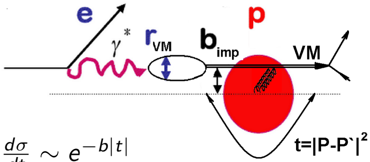
WITH SUPPRESSION

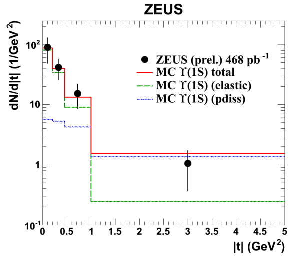


"Resolved" photon suppression factors improve data/theory agreement

H1prelim-10-017

Exclusive VM production - $|t|$-dependence





$$\frac{d\sigma}{dt} \sim e^{-b|t|}$$

b - sensitive to the transverse size of the interaction region

Geometric picture - transverse size:

$b = b_V + b_p$

transverse size:

Vector Meson: $b_V \sim \frac{1}{Q^2+M_V^2}$

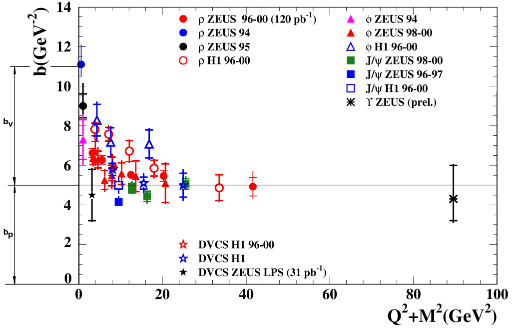
Target: $b_p \approx 5\ \mathrm{GeV}^{-2}$

b_p can be interpreted as

$r_{gluons} \approx 0.5$ fm

charge radius of the proton

$r_{em} \approx 0.8$ fm



New ZEUS measurement of $\Upsilon(1S)$ consistent with hard regime VM production.

ZEUS-prel-10-020

Summary

- A brief overview of recent results on jets and diffraction at HERA presented
  - and this is a breif overview of a tiny fraction of new results
- the HERA jets are a powerful tool
  - to increasing precision of α_s determination
  - and constraining proton PDFs
- latest results on diffractive structure functions F_2^D and F_L^D from inclusive diffractive cross section measurement presented
  - F_2^D demonstrate scaling violation, similar to F_2
  - F_L^D none zero, consistent with QCD expectations
  - diffractive dijets demonstrate Rapidity Gap Suppression
  - Exclusive Vector Mesons provide important input on gluon transverse distribution in the proton
- The unqiue data from the HERA collider experiments is crucial to understanding proton structure and plays an important role in understanding present and future data from Tevatron and LHC.

Backup slides

H1 (Diffraction)

- Measurement of the Diffractive Deep-Inelastic Scattering Cross Section with a Leading Proton at HERA
  DESY-10-095
- Diffractive Dijet Photoproduction in ep Collisions at HERA
  DESY-10-043
- Measurement of the longitudinal diffractive structure function F_L^D at low Q2 at HERA
  H1prelim-10-017
- F2D3 with VFPS
  H1prelim-10-014
- Measurement of the diffractive longitudinal structure function F_L^D at HERA II
  H1prelim-09-011
- Forward neutron PT distributions
  H1prelim-10-113
- Diffractive Jet Production in Deep-Inelastic Scattering with a Leading proton at HERA-2
  H1prelim-10-013
- F2D3 with rapidity gap
  H1prelim-10-011
- Measurement of Leading Neutron Production in Deep-Inelastic Scattering at HERA
  DESY-09-185
- Deeply Virtual Compton Scattering and its Beam Charge Asymmetry in $e^{\pm}$ p Collisions at HERA
  DESY-09-109
- Diffractive Electroproduction of rho and phi Mesons at HERA
  DESY-09-093
- A Measurement of the Pomeron Trajectory based on Elastic Rho Photoproduction
  H1prelim-09-016

H1 (Hadronic Final States)

- Measurement of the Azimuthal Correlation between the Scattered Electron and the most Forward Jet in Deep-Inelastic
  H1prelim-10-131
- Transverse Momentum of Charged Particles at low Q2 at HERA
  H1prelim-10-035
- K0s production at high Q2 at HERA II
  H1prelim-10-031
- K*+- production at low Q2
  H1prelim-08-132
- Minijet Production in Deep Inelastic Scattering at HERA
  H1prelim-07-032
- Azimuthal correlations in dijet events at low Q2 DIS
  H1prelim-06-032

ZEUS (Diffraction)

- Upsilon(1S) t-slope in PHP
  ZEUS-prel-10-019
- elastic rho/rho′
  ZEUS-prel-10-012
- Energy dependence of the total gamma p cross section
  DESY-10-178 (arXiv:1011.1652)
- QCD fits with diffraction
  DESY-09-191 (arxiv:0911.4119)
- Measurement of dijet photoproduction for events with a leading neutron at HERA
  DESY-09-139 (arXiv:0909.3032v1)
- Jψ production at large t
  DESY-09-137 (arXiv:0910.1235)
- Measurement of the Longitudinal Proton Structure Function at HERA
  DESY-09-046 (arXiv:0904.1092)
- Exclusive Photoproduction of Upsilon Mesons at HERA
  DESY-09-036 (arXiv:0903.4205)
- Leading Proton Production in Deep Inelastic Scattering at HERA
  DESY-08-176 (December 2008)
- Deep Inelastic Scattering with Leading Protons or Large Rapidity Gaps at HERA
  DESY-08-175 (December 2008)
- A Measurement of the Q^2, W and t Dependences of Deeply Virtual Compton Scattering at HERA
  DESY-08-132 (December 2008)
- Deep inelastic inclusive and diffractive scattering at Q^2 values from 25 to 320 GeV^2 with the ZEUS forward plug calorimeter
  DESY-08-011 (February 2008)
- Diffractive photoproduction of dijets in ep collisions at HERA
  DESY-07-161 (September 2007)
- Dijet production in diffractive deep inelastic scattering at HERA
  DESY-07-126 (August 2007)
- Exclusive ρ^0 production in deep inelastic scattering at HERA
  DESY-07-118 (August 2007)
- Diffractive photoproduction of Dstar(2010) at HERA
  DESY-07-039 (March 2007)

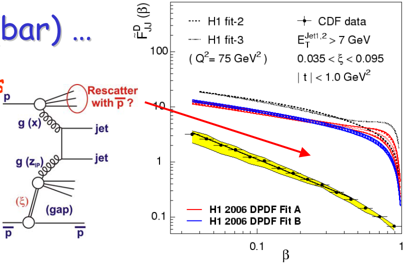
ZEUS (Hadronic Final States)

- Inclusive jet cross section in γp
  ZEUS-prel-10-003
- Inclusive jets in NC DIS + alpha$_s$
  ZEUS-prel-10-002
- Three-subjet distributions in NC DIS
  ZEUS-prel-09-007
- Dijets in PHP and constraints on p and gamma PDFs
  ZEUS-prel-10-014
- Inclusive dijet Cross Sections in Neutral Current Deep Inelastic Scattering at HERA
  DESY-10-170 (arXiv:1010.6167)
- Inclusive-jet cross sections in NC DIS at HERA and a comparison of the k$_T$, anti-k$_T$ and SIScone jet algorithms
  DESY-10-034 (arXiv:1003.2923)
- Inclusive Jets in PHP with anti-kt and SIScone + alpha$_s$
  ZEUS-prel-10-015
- Scaled momentum spectra of identified particles (K^0, Lambda) in the Breit frame
  ZEUS-prel-10-013
- elastic rho/rho$'$
  ZEUS-prel-10-012
- Measurement of isolated photon production in deep inelastic ep scattering
  DESY-09-142 (arXiv:0909.4223)
- Scaled momentum distributions of charged particles in dijet photoproduction at HERA
  DESY-09-059 (arXiv:0904.3466)
- Scaled Momenta in Breit frame
  DESY-09-229 (arXiv:1001.4026)

Diffractive dijets in PHP, 1/3

.. meanwhile in pp(bar) ...

Tevatron effective DPDFs from dijets show strong factorisation breaking compared with HERA DPDFs ... `gap survival' factor $S^2 \sim 0.1$

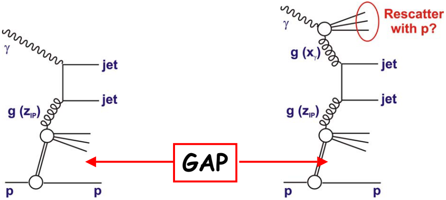


... explained by rescattering / absorption

... photoproduction jets as the perfect control experiment?...

"Direct" photon ($x_\gamma \to 1$)

"$S^2 = 1$"

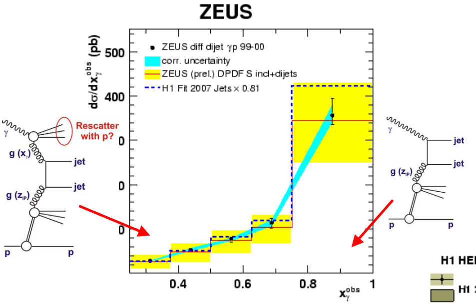


"Resolved" photon (x_γ < 1)

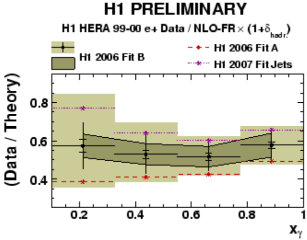
"$S^2 \sim 0.34$" (KKMR)

Diffractive dijets in PHP, 2/3

X-Section Differential in x_γ



$$x_\gamma = \frac{\sum_{jets}(E-p_z)}{\sum_{HFS}(E-p_z)}$$



- Similar quality of descriptions of high / low x_γ regions!

- H1: $E_T^{jet1} > 5$ GeV

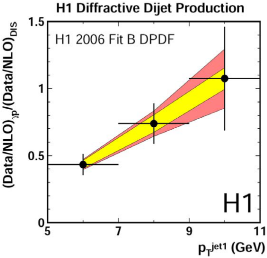
... suppression by factor ~2

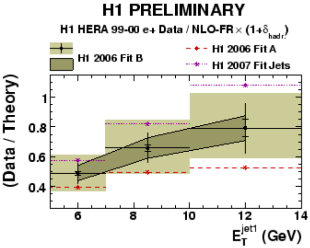
-ZEUS: $E_T^{jet1} > 7.5$ GeV

-... little or no suppression ...

Diffractive dijets in PHP, 3/3

Cross Section Differential in E_T



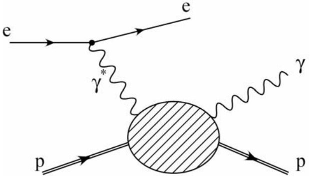


- Suggestions of harder Et dependence in data than NLO theory … thus of E_t dependent gap survival probability
- For highest E_t^{jet1}, survival probability compatible with unity (c.f. previous ZEUS results)
- Could rescattering effects for photon depend on Et, not x_γ?

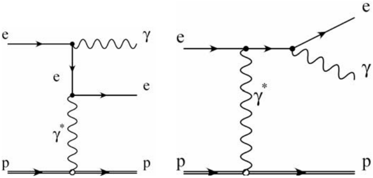
DVCS: Beam Charge Asymmetry, 1/2

H1-prelim-09-014

DVCS – Deeply Virtual Compton Scattering



BH – Bethe-Heitler



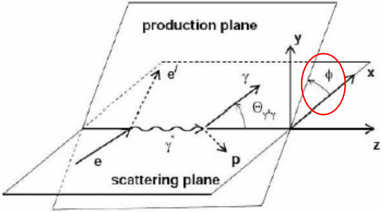
$$d\sigma = d\sigma^{BH} + d\sigma^{DVCS} \pm Interference.Term.$$

+ for beam lepton charge (+)

- for beam lepton charge (-)

$$\sigma^{+} - \sigma^{-} \sim \mathrm{Re}(Interference.Term)$$

$$BCA = \frac{\sigma^{+} - \sigma^{-}}{\sigma^{+} + \sigma^{-}} = p_1 * \cos(\phi) + \ldots\ ,\ p_1 \sim GPD$$



DVCS: Beam Charge Asymmetry, 2/2

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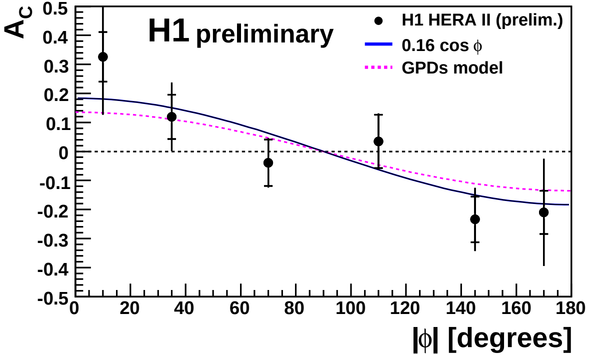
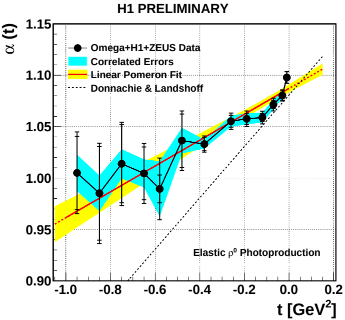


Effective ℙomeron trajectory, 1/3

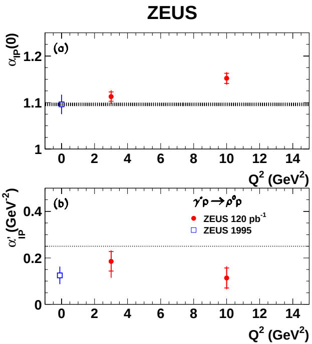
Effective Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' \cdot t$



- **Global fit:** ρ^o **Photoproduction, (Omega, H1, ZEUS)** $(1.0871 \pm 0.0026 \pm 0.003) + (0.126 \pm 0.013 \pm 0.012)\ GeV^{-2} \cdot t$
- **H1:** $(1.093 \pm 0.003^{+0.008}_{-0.007}) + (0.116 \pm 0.027^{+0.038}_{-0.046})\ GeV^{2} \cdot t$
- **ZEUS:** $(1.096 \pm 0.021) + (0.125 \pm 0.038)\ GeV^{-2} \cdot t$

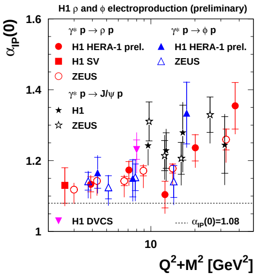
Effective IPomeron trajectory, 2/3

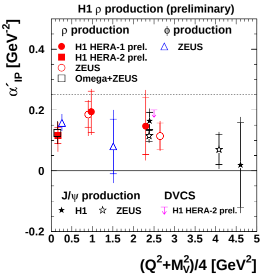
Effective Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' \cdot t$

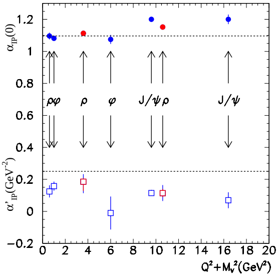


ZEUS, ρ^o electroproduction: $\alpha(0)$ and α' as a function of Q^2

Effective IPomeron trajectory, 3/3



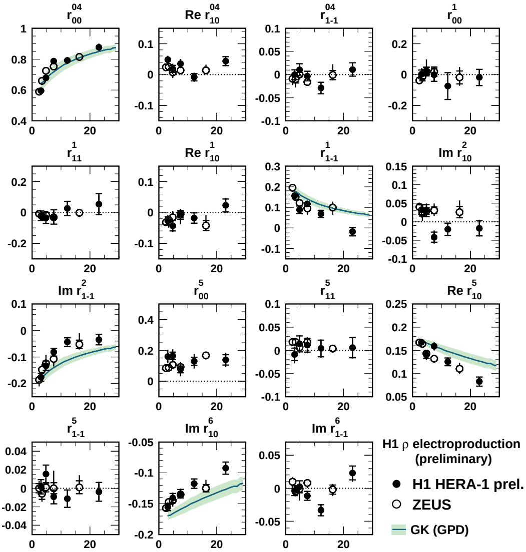




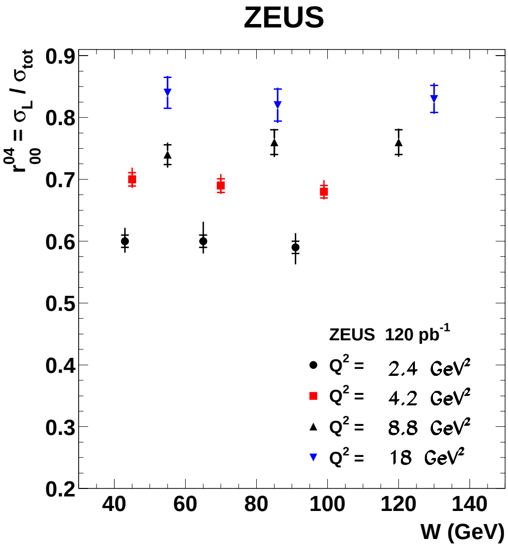
Helicity angles study, $R = \sigma_L/\sigma_T$

- **s-channel helicity conservation (SCHC)**
- **natural parity exchange $(P = (-1)^J)$ in the t-channel (NPE)**
- **5 non-zero spin-density matrix elements**
- **15 parameters fit to total angular distribution**
- r^5_{00} **deviates from zero !**
- $r^5_{00} = 0.095 \pm 0.019 \pm 0.024$ **(ZEUS) and** $r^5_{00} = 0.093 \pm 0.024^{+0.19}_{-0.10}$ **(H1)**
- $r^5_{00} \sim$ **single-flip amplitude,** $\gamma^*_T \rightarrow \rho_L$
- **if SCHC holds** $\rightarrow R = \sigma_L/\sigma_T = r^{04}_{00}/\epsilon(1 - r^{04}_{00})$
- **if not** $\rightarrow r^{04}_{00} \rightarrow r^{04}_{00} - \Delta^2$, $\Delta \propto r^5_{00}/\sqrt{2r^{04}_{00}}$
- **R(SCHC) - R(SCHNC) $\sim$ 3 %**

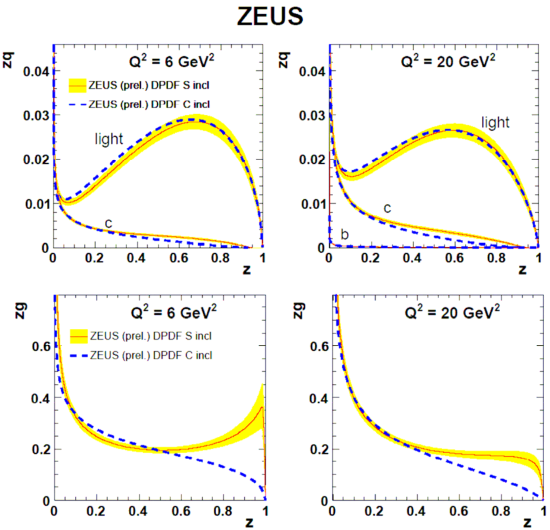
Helicity angles study, $R = \sigma_L/\sigma_T$



$R = \sigma_L/\sigma_T$ does not depend on W



QCD fits to New ZEUS LRG data



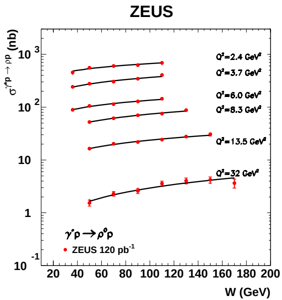
F_2^D measures quarks
$dF_2^D/d\log Q^2$ - gluons

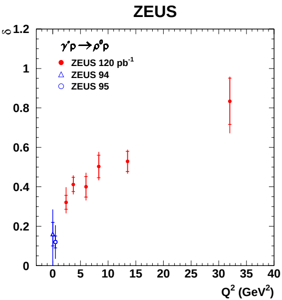
z = incoming momentum fraction of parton (=β for quarks, > β for gluons)

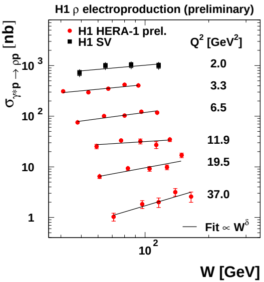
two schemes:

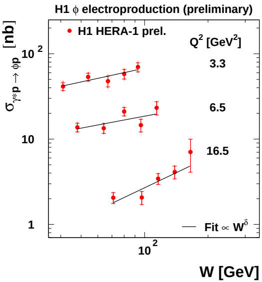
DPDF S - "Standard" scheme (flexible gluons)
DPDF C - "Constant" scheme (stiff gluons)

W-dependence, (light VM: ρ, ϕ) DIS ($Q^2 > 1$ GeV^2)







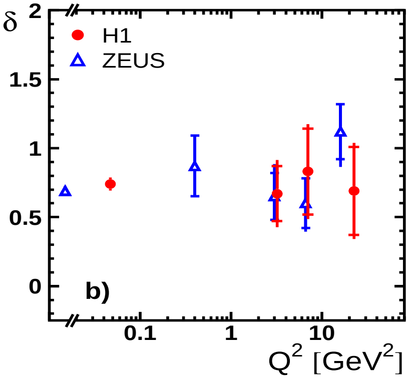


light Vector Mesons

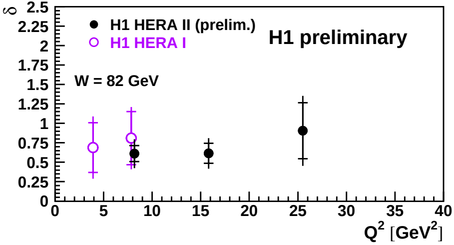
$\sigma \sim W^{\delta}$,
δ rises with Q^2
from "soft" to "hard"

W-dependence DIS ($Q^2 > 1$ GeV^2)

heavy VM: J/ψ



DVCS

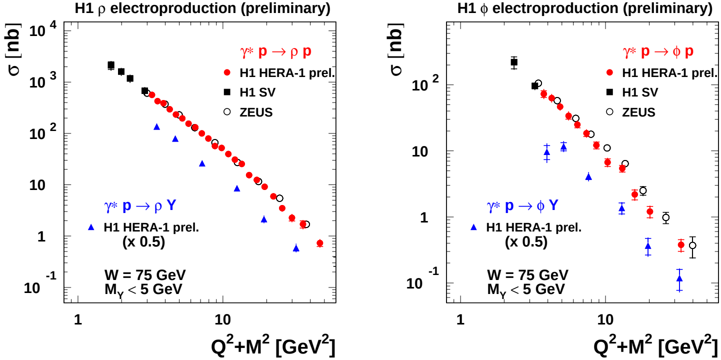


J/ψ and DVCS,

$\sigma \sim W^\delta$,
δ - flat with Q^2
the process is already "hard"

Q^2-dependence, $\sigma \sim (Q^2 + M_V^2)^{-n}$

ρ^0, $m_\rho^2 = 0.5$ GeV^2 $\qquad$ ϕ^0, $m_\phi^2 = 1.0$ GeV^2

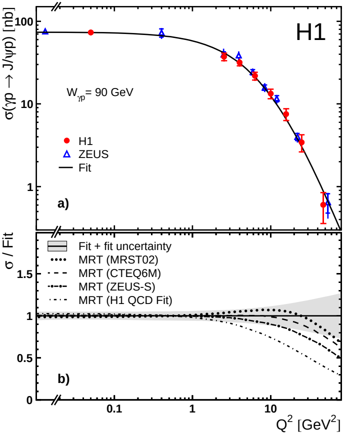


H1/ZEUS: perfect agreement

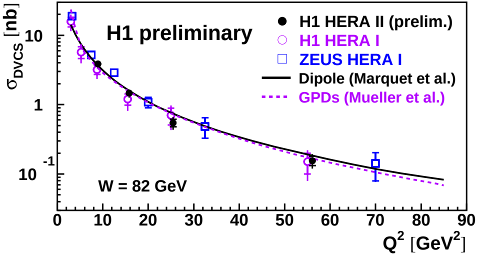
- $Q^2 \geq 0$ GeV^2, n≈2.00±0.01, $\chi^2/ndf \sim 10$
- $Q^2 \geq 10$ GeV^2, n≈2.50±0.02, $\chi^2/ndf \sim 1.5$

Q^2-dependence, $\sigma \sim (Q^2 + M_V^2)^{-n}$

J/ψ



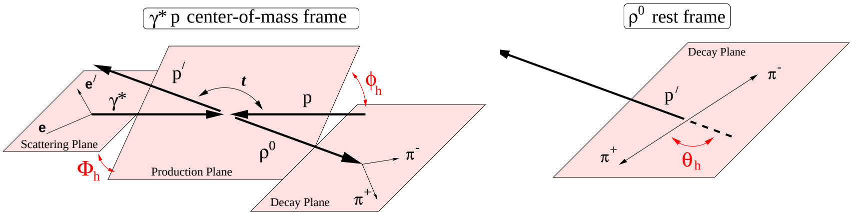
DVCS



H1/ZEUS: perfect agreement

- J/ψ n=2.49±0.08
- *DVCS* n=1.54±0.06

Helicity angles analysis, $R = \sigma_L/\sigma_T$



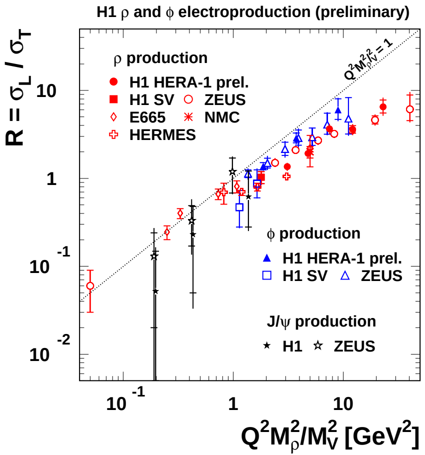
- Study angular distributions: 3 angles $(\theta_h, \phi_h, \Phi_h)$
- 15 combinationof spin-density matrix elements, r_{ij}^{kl}
- s-channel helicity conservation SCHC
  - $\gamma_T^* \to \rho_T$
  - $\gamma_L^* \to \rho_L$
- if SCHC holds $\to R = \sigma_L/\sigma_T = r_{00}^{04}/\epsilon(1 - r_{00}^{04})$
- in practive fit to $cos\theta_h$: $\frac{d\sigma}{dcos\theta_h} \sim 1 - r_{00}^{04} + (3r_{00}^{04} - 1)cos^2\theta_h$

$R = \sigma_L/\sigma_T$

$R = \xi(Q^2/M_V^2)^k$
$\xi = 0.74 \pm 0.04$
$k = 0.56 \pm 0.03$
(fit to ZEUS only)

γ_L - only small size configurations
γ_T - both, small and large, size configurations

naive interpretation:
small size configurations dominate at higher $\frac{Q^2}{M_V^2}$



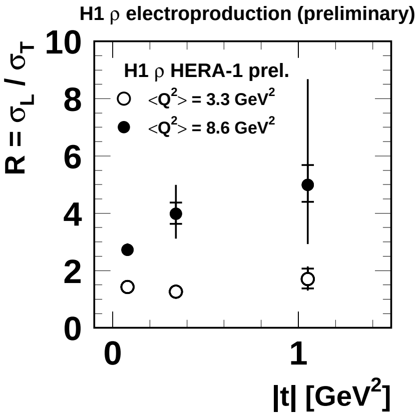
$R = \sigma_L/\sigma_T$

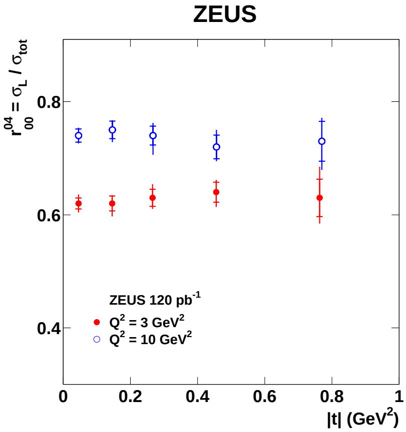
and R does not depend significantly on $|t|$!!

$|t|$-distributions are most sensitive to differences in interaction 'size'

$\rightarrow$ conclusion "small size configurations dominate at high Q^2/M_V^2" not quite correct

$\rightarrow$ one must better understand all mechanisms of "transversity" in V_T

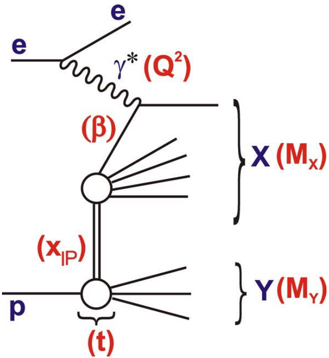




ep collisions: Inclusive Diffraction (ep$\rightarrow$ eXY)

Additional variables:

$\lvert t \rvert$	=	squared 4-momentum transfer at proton vertex
x_{IP}	=	fractional momentum loss of proton (momentum fraction $\mathbb{P}$/p)
β	=	x/x_{IP} (momentum fraction q/$\mathbb{P}$)



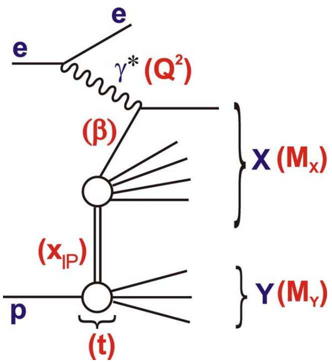
reduced diffractive x-section:

$$\sigma_r^{D(3)}(\beta, x, Q^2) = F_2^{D(3)}(\beta, x, Q^2) - \frac{y^2}{Y_+} F_L^{D(3)}(\beta, x, Q^2),$$

$$\sigma_r^{D(4)}(\beta, x, Q^2, t) = F_2^{D(4)}(\beta, x, Q^2, t) - \frac{y^2}{Y_+} F_L^{D(4)}(\beta, x, Q^2, t),$$

similar meaning of F_2^D, F_L^D to inclusive structure functions F_2 and F_L.

ep collisions: Diffraction (in general ep→ eXY)



...and also:

M_X = invariant mass of diffractively produced system

M_Y = invariant mass of proton remnant system

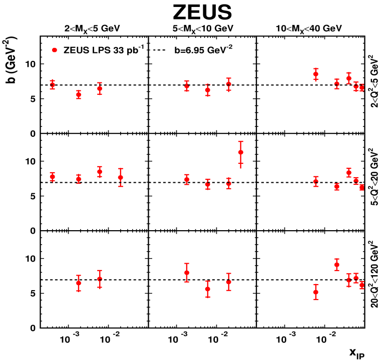
Special cases:

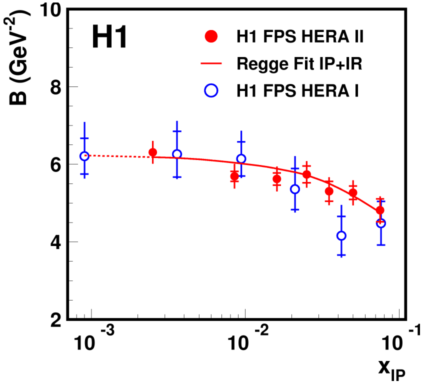
$M_Y = m_p$ - proton stays intact,
need special detector setup to detect protons
→ H1 FPS, VFPS; ZEUS LPS

$M_Y > m_p$ - proton dissociates,
the background to be understood and disantangled.
→ LRG (Large Rapidity Gap method)

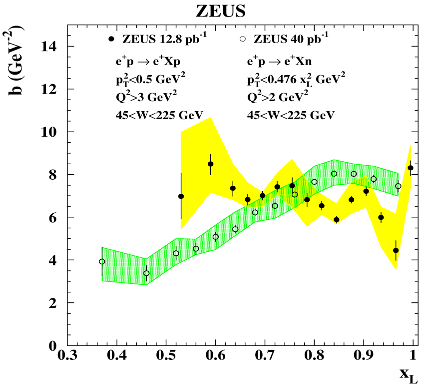
t-dependence: Leading Proton mesurement

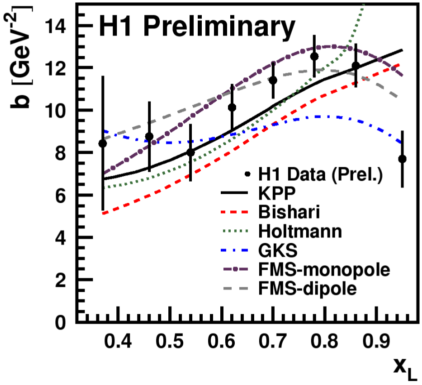
$|t|$





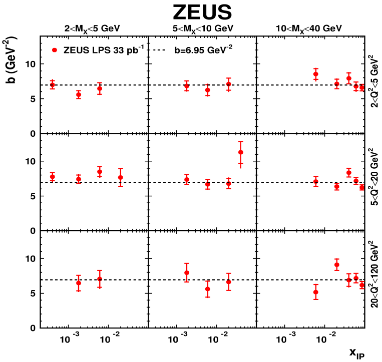
t-dependence: Leading Neutron mesurement (cf. to ZEUS proton) $|t|$

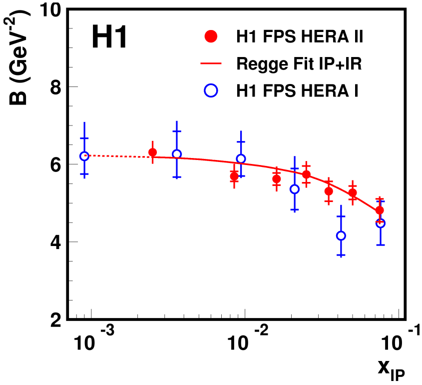




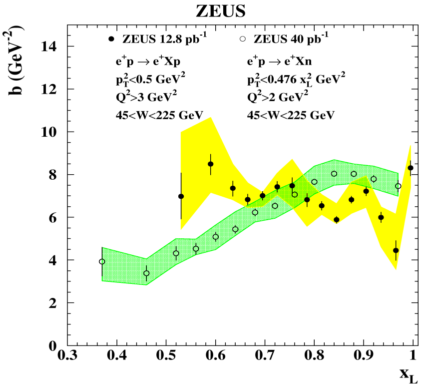
t-dependence: Leading Proton mesurement

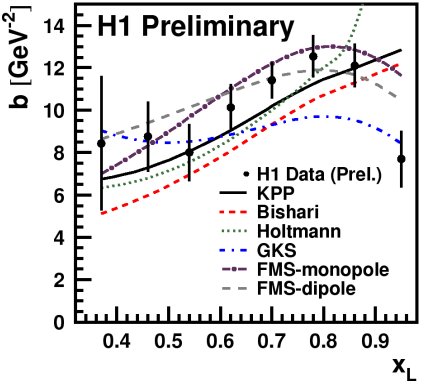
$|t|$





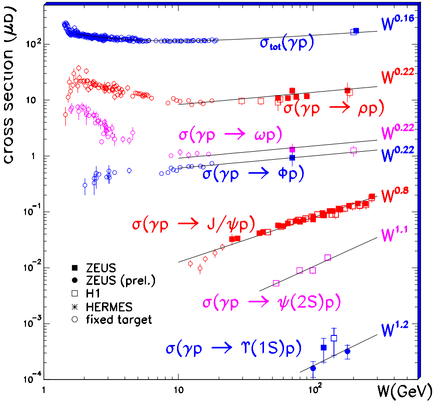
t-dependence: Leading Neutron mesurement (cf. to ZEUS proton) $|t|$



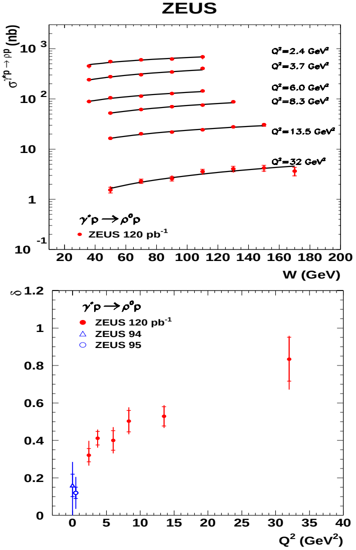


W-dependence

PHP ($Q^2 \approx 0$ GeV^2)



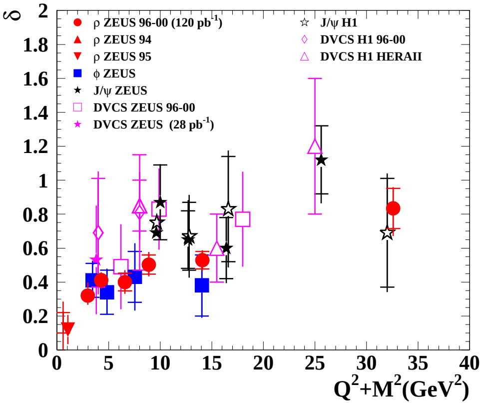
DIS ($Q^2 > 1$ GeV^2)



$\sigma \sim W^\delta$, δ rises with M_V^2 and Q^2
from "soft" ($\delta = 0.22$) to "hard" ($\delta \approx 1.0$)

W-dependence summary

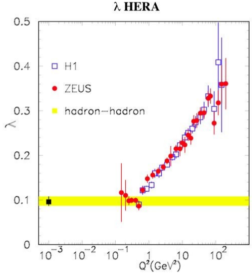
PHP+DIS



$\sigma \sim W^{\delta}$,
δ rises with $Q^2_{eff} = Q^2 + M^2_V$

consistent within pQCD

- experiment gives $\sigma \sim W^{\delta}$
- two gluon exchange: $\sigma \sim \alpha_s |xg(x, Q^2)|^2$
- remember: $F_2(x, Q^2) \sim xg(x, Q^2) \sim x^{-\lambda(Q^2)}$ and $W^2 \sim 1/x$
- so, $\delta \sim 4\lambda(Q^2)$



HERA

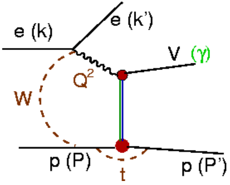
HERA - *ep* collider (1991-2007),
HERA-I in $\leq$ 2000, afterwards: HERA-II
located at DESY, Hamburg
$E_e = 27.5 GeV$
$E_p =$ different:

820 GeV ($\sqrt{s} = 300$), 95p-97p : 42 pb^{-1}
920 GeV ($\sqrt{s} = 320$), 98e-07p : 455 pb^{-1}
575 GeV ($\sqrt{s} = 252$), 07p : 11 pb^{-1}
460 GeV ($\sqrt{s} = 225$), 07p : 6 pb^{-1}

H1 and ZEUS: colliding beams experiments with similar physics analysis program.

luminosity collected: $\approx 0.5 fb^{-1}$ per experiment

An important subset of diffractive reactions - Exclusive Diffraction

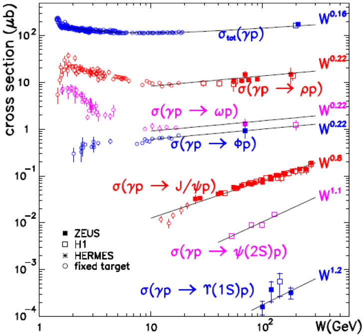


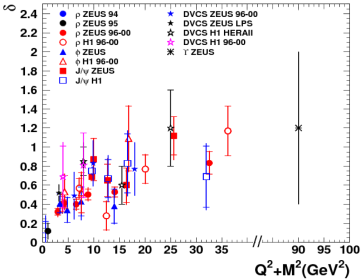
- vector mesons ($J^{PC} = 1^{--}$, $\rho, \phi, J/\psi, \Upsilon$)
- photon (DVCS)

Kinematics: $\mathbf{M_V^2}, \mathbf{Q^2}, \mathbf{W}, |\mathbf{t}|$

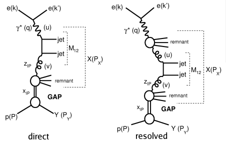
M_V^2, Q^2 provide hard scale to apply pQCD,

- two gluon exchange: $\sigma \sim \alpha_s |xg(x,Q^2)|^2 \sim W^\delta$
- remember: $F_2(x,Q^2) \sim xg(x,Q^2) \sim x^{-\lambda(Q^2)}$ and $W^2 \sim 1/x$, so, $\delta \sim 4\lambda(Q^2)$

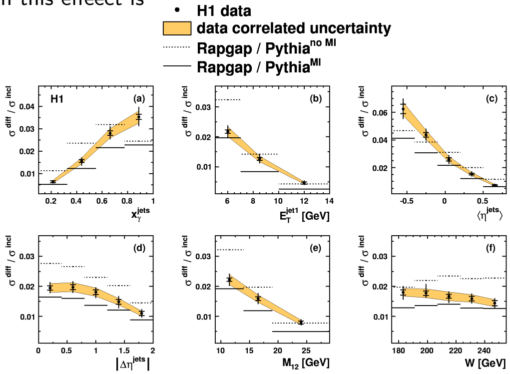




Diffractive to Inclusive dijets comparison



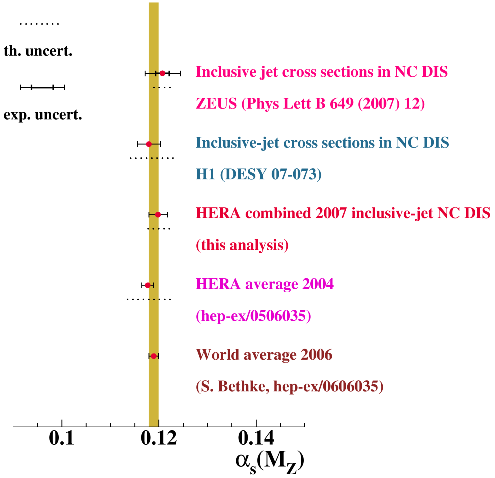
- further tests of gap survival issues
- some experimental systematics and theoretical uncertanties (e.g. photon structure) cancel out in the ratio
- GAP suppression (due to Multiple Interactions) can be really large, but the uncertainty on this effeect is also large



from jets to α_s

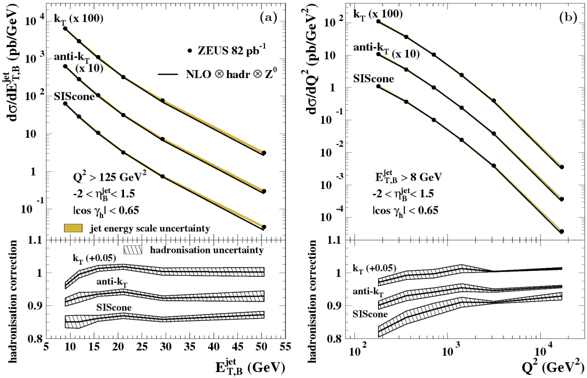
Jets can be used to determine the strong coupling constant α_s

Consistent with the world average.
Simultaneous fit to inclusive, dijet, and trijet allowed to reduce experimental uncertainty.
Precision limited by the NLO calculation



Jet algorithms comparison

Performance test for new algorithms developed for LHC (anti-k_T, SIScone) applied for the first time to inclusive DIS



- k_T and anti-k_T perform similar
- SIScone hadronisation correction somewhat higher

all three algorithms perform well and are consistent with each other!