Hard diffraction at HERA

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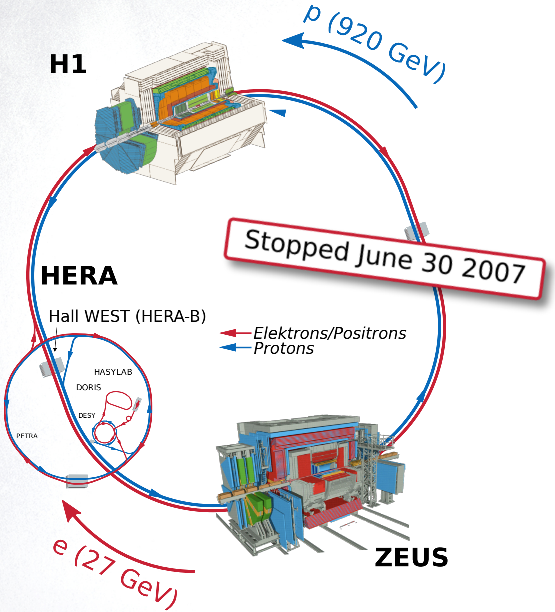
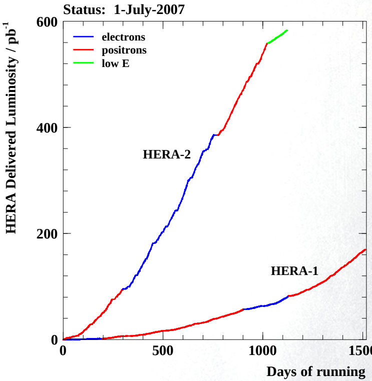
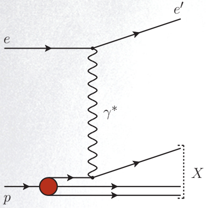


- → $E_e = 27.6$ GeV
- → $E_p = 920$ (460) GeV
- → $\sqrt{s} = 319$ GeV
- → $L_{int} \sim 0.5$ fb^{-1} per experiment



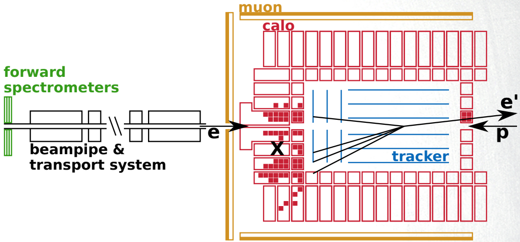
[H1 Collaboration]

deep-inelastic scattering (DIS): $ep \to e'X$



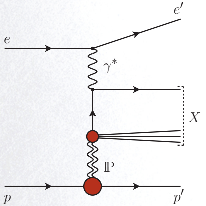
"forward" particle flow

- → proton remnant
- → colour flow



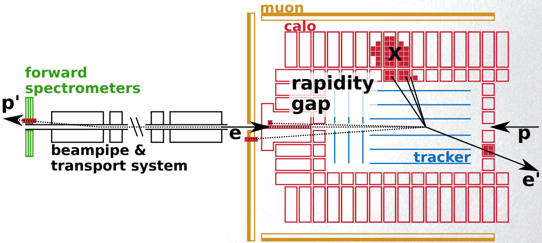
⇒ probe proton structure

diffractive scattering (DDIS): $ep \to e'Xp'$ $\sim$ 10% of DIS events



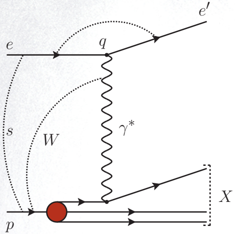
no "forward" activity

- → rapidity gap
- → $p' \to$ beampipe
- → $X \to$ "central"
- → no colour flow in between



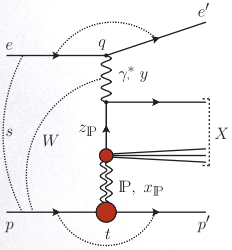
⇒ probe structure of the color singlet exchange ("Pomeron" $\mathbb{P}$)

deep-inelastic scattering (DIS): $ep \to e'X$



Q^2	virtuality of the exchanged photon: $Q^2 = -q^2$
	$Q^2 \lesssim 2$ GeV^2 photoproduction, $Q^2 > 4$ GeV^2 DIS
W	γ^*-p system energy
x	Bjorken-x: proton momentum fraction carried by the struck quark
y	γ^* inelasticity: $y = \frac{Q^2}{s\,x}$

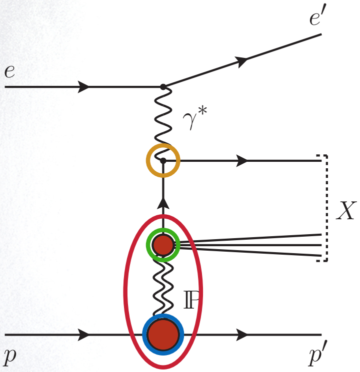
diffractive scattering (DDIS): $ep \to e'Xp'$



t	squared momentum transfer at the proton vertex: $t = (p - p')^2$
$x_{\mathbb{P}}$	proton momentum fraction of the color singlet exchange: $x_{\mathbb{P}} \simeq \frac{Q^2+M_X^2}{Q^2+W^2}$
$z_{\mathbb{P}}$	$\mathbb{P}$ momentum fraction carried by the quark "seen" by the γ^*: $z_{\mathbb{P}} = \frac{x}{x_{\mathbb{P}}}$

perturbative QCD: only if "hard scale" is present

→ diffractive factorisation theorem in analogy with proton PDFs



collinear factorisation: (proven for DDIS by J. Collins)

$$\sigma^D(\gamma^* p \to Xp) = \sum_i^{\text{partons}} \hat{\sigma}(z_{\mathbb{P}}, Q^2) \otimes f_i^D(z_{\mathbb{P}}, Q^2, x_{\mathbb{P}}, t)$$

→ hard subprocess matrix element, calculable in pQCD

→ universal diffractive parton distribution functions (DPDFs)

proton-vertex factorisation assumption: (supported by H1 and ZEUS data)

$$f_i^D(z_{\mathbb{P}}, Q^2, x_{\mathbb{P}}, t) = f_{\mathbb{P}/\mathbb{R}}(x_{\mathbb{P}}, t)\; f_i^{\mathbb{P}/\mathbb{R}}(z_{\mathbb{P}}, Q^2)$$

→ flux parametrisation, Pomeron/Reggeon PDFs

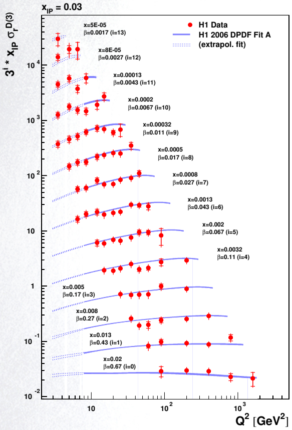
DPDFs:

→ have no firm basis in QCD, but can be extracted from inclusive DDIS data

→ test universality in semi-inclusive states

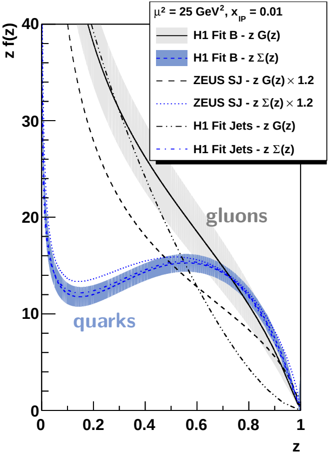
Diffractive PDFs

[EPJ C 48, 715 (2006)]



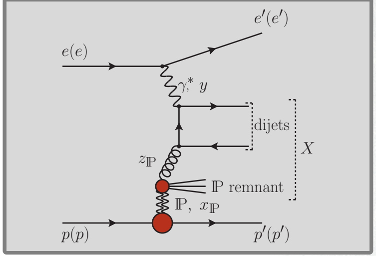
$\Rightarrow$

[EPJ C 71, 1741 (2011)]

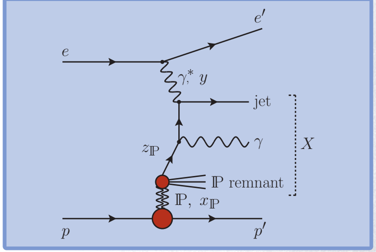


→ DPDFs obtained by H1 and ZEUS in inclusive diffractive DIS measurements and NLO QCD fits

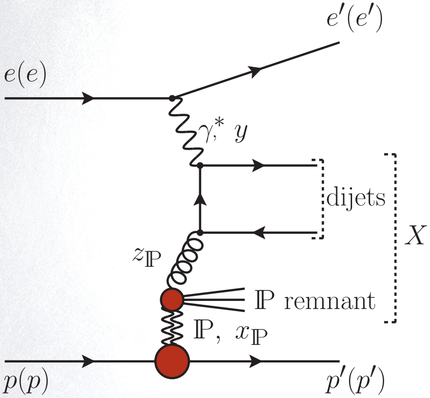
gluons: probed with dijets



quarks: probed with prompt photon



Dijets in Diffractive DIS (LRG) [JHEP 1503, 092 (2015)]

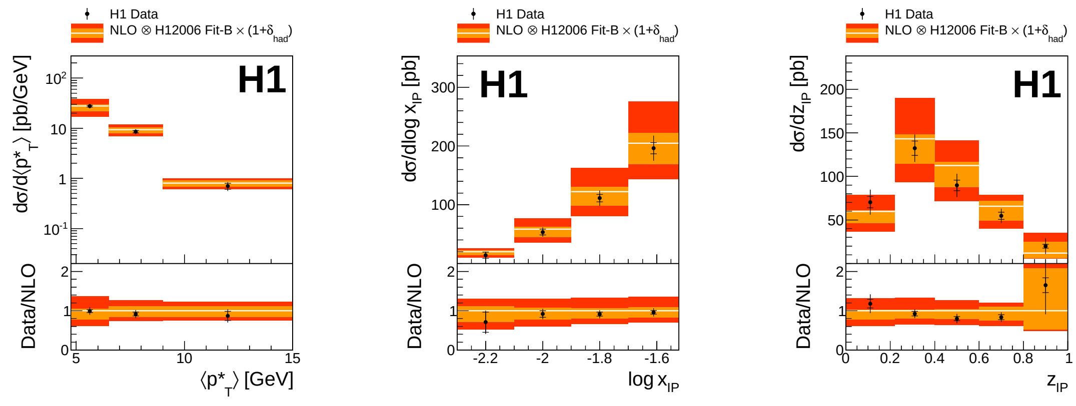


inclusive dijet production in diffractive DIS:

- → HERA-II data: $L = 290\ \text{pb}^{-1}$
- → 6 times more data than previous analysis
- → diffractive events identified by "large rapidity gap" (LRG) ($\eta_{max} < 3.2$)
- → using $R = 1$ k_T-jets
- → hadron level cross sections via regularised unfolding in extended phase space

	Extended Analysis Phase Space	Measurement Cross Section Phase Space
DIS	$3 < Q^2 < 100\ \text{GeV}^2$ $y < 0.7$	$4 < Q^2 < 100\ \text{GeV}^2$ $0.1 < y < 0.7$
Diffraction	$x_P < 0.04$ LRG requirements	$x_P < 0.03$ $\lvert t \rvert < 1\ \text{GeV}^2$ $M_Y < 1.6\ \text{GeV}$
Dijets	$p^*_{T,1} > 3.0\ \text{GeV}$ $p^*_{T,2} > 3.0\ \text{GeV}$ $-2 < \eta^{lab}_{1,2} < 2$	$p^*_{T,1} > 5.5\ \text{GeV}$ $p^*_{T,2} > 4.0\ \text{GeV}$ $-1 < \eta^{lab}_{1,2} < 2$

measurement of single differential cross sections:



NLO predictions

→ using NLOJet++ (adapted to DDIS) and H1 2006 Fit-B DPDFs

→ data well described

→ large uncertainty from PDF and theory

data precision

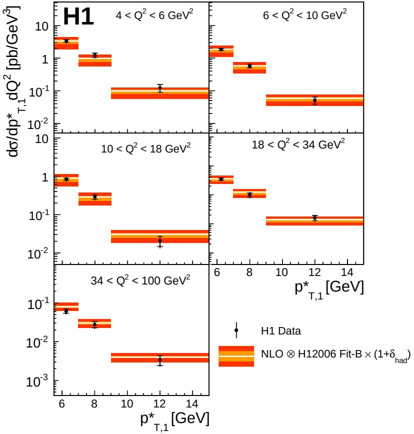
→ better than theory

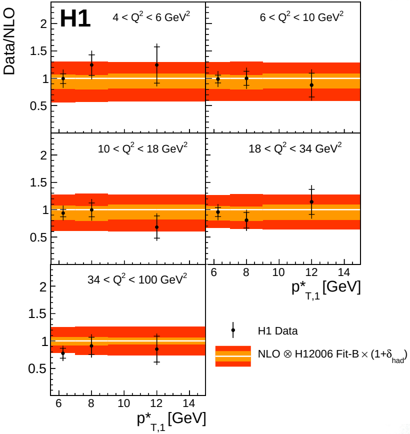
→ mostly limited by systematic effects

→ 7% normalisation uncertainty (LRG selection)

Dijets in Diffractive DIS (LRG) [JHEP 1503, 092 (2015)]

measurement of double differential cross sections: e.g. $d\sigma/d(Q^2, p^*_{T,1})$





first measurement of α_s in hard diffraction at HERA:

$\alpha_s(M_Z) = 0.119 \pm 0.004(exp) \pm 0.012(DPDF,\ theo)$

→ agreement with world average
→ not competitive with other α_s measurements
→ but supports concept of DDIS dijet calculations in pQCD

factorisation properties of diffractive dijets:

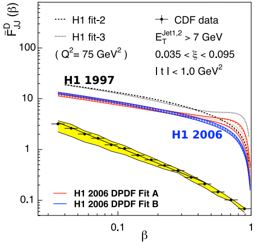
→ factorisation holds for dijets in DDIS

→ factorisation is broken in hadron-hadron scattering:

$\sigma(data)/\sigma(NLO) \sim 0.1$

at Tevatron and LHC with HERA DPDFs

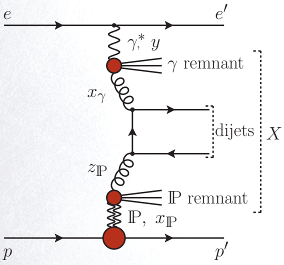
CDF: dijets in diffractive $p\bar{p}$



[PRL 84, 5043 (2000)]

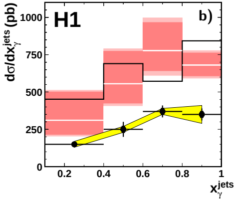
dijets in diffractive photoproduction γp:

real photon has hadronic structure

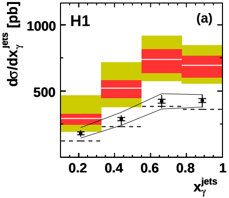


H1:

"suppression" w.r.t. NLO observed in γp



[EPJ C 51, 549 (2007)]

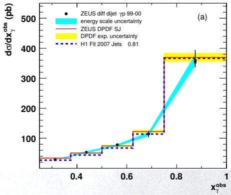


[EPJ C 70, 15 (2010)]

2 LRG+γ-tag analyses (L = 18 pb^{-1} & L = 47 pb^{-1})

ZEUS:

no indication of suppression



[Nucl.Phys. B 831, 1 (2010)]

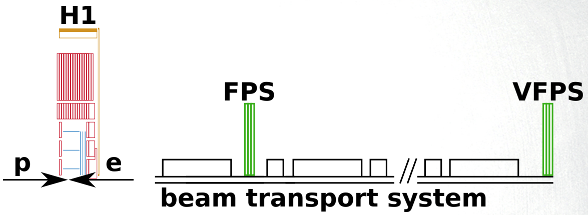
LRG analysis

⇒ could *p*-dissociative contribution be the reason?

H1 Very Forward Proton Spectrometer (VFPS):

→ VFPS is 220m from interaction point:
- ⇒ 2 stations at 218 and 220m
- ⇒ high acceptance (90%) and efficiency (95%)
- ⇒ low background ($< 1\%$)

→ directly measure scattered proton:
- ⇒ exclude *p* dissociation
- ⇒ directly reconstruct $x_{\mathbb{P}}$ and t



new cross section measurement:

→ tag scattered proton in VFPS

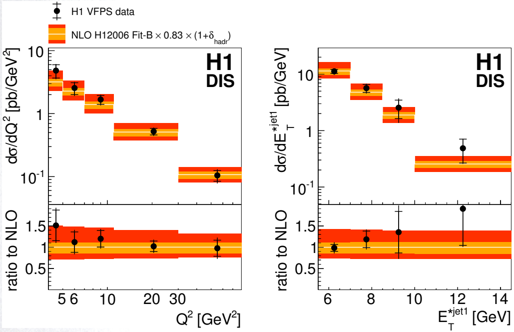
→ simultaneously performed in
- ⇒ photoproduction and
- ⇒ DIS

→ regularised unfolding to hadron level in extended phasespace

	Photoproduction	DIS
Event kinematics	$Q^2 < 2\,\mathrm{GeV}^2$	$4\,\mathrm{GeV}^2 < Q^2 < 80\,\mathrm{GeV}^2$
	$0.2 < y < 0.7$	
Diffractive phase space	$0.010 < x_{\mathbb{P}} < 0.024$	
	$\lvert t\rvert < 0.6\,\mathrm{GeV}^2$	
	$z_{\mathbb{P}} < 0.8$	
Jet phase space	$E_T^{*\mathrm{jet1}} > 5.5\,\mathrm{GeV}$	
	$E_T^{*\mathrm{jet2}} > 4.0\,\mathrm{GeV}$	
	$-1 < \eta^{\mathrm{jet1,2}} < 2.5$	

dijets in **DDIS**:

$\Rightarrow$ shape and normalisation well described by NLO



$\rightarrow$ luminosity: $L \sim 50$ pb^{-1}

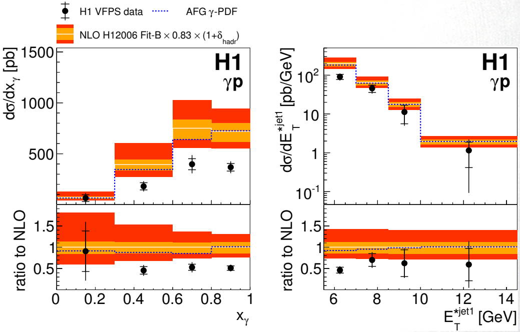
$\rightarrow$ NLO by NLOJet++

$\rightarrow$ H1 2006 Fit-B DPDFs

dijets in diffractive γp:

$\Rightarrow$ shape well described by NLO

$\Rightarrow$ normalisation overestimated $\sim \times 2$



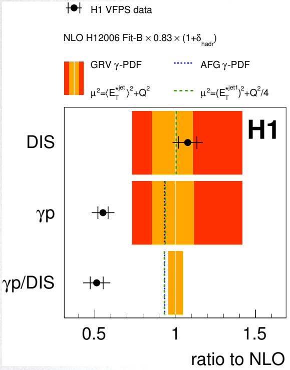
$\rightarrow$ luminosity: $L \sim 30$ pb^{-1}

$\rightarrow$ NLO by FKS (Frixione et al.)

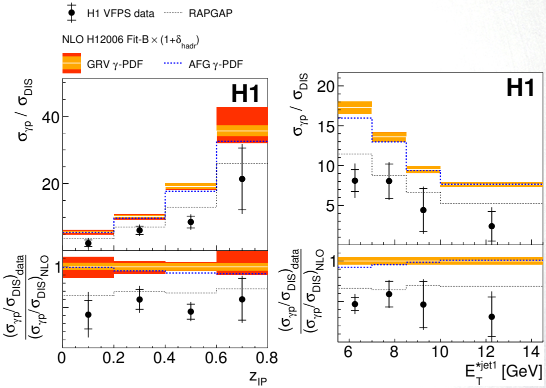
$\rightarrow$ H1 2006 Fit-B DPDFs

$\rightarrow$ GRV and AFG γ-PDFs

double ratios of cross section γp/DIS : $\rightarrow$ much reduced theory uncertainties



$$\frac{(\text{data}/\text{NLO})_{\gamma p}}{(\text{data}/\text{NLO})_{\text{DIS}}}$$



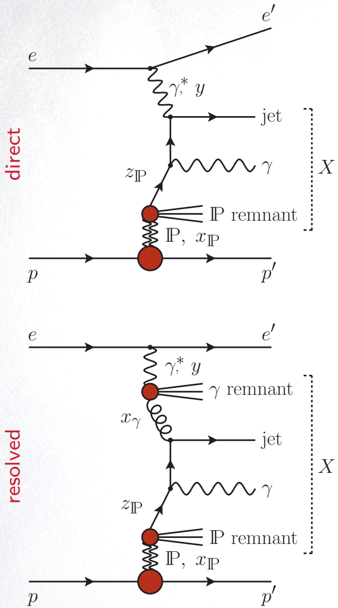
$\rightarrow$ suppression factor:

$0.511 \pm 0.085(\text{data}) \pm 0.022(\text{theo})$

$\rightarrow$ confirms previous results
w/ complimentary experimental method

$\rightarrow$ no hint for suppression dependence on $z_{\mathbb{P}}$, E_T^{*jet1}, ...

Prompt Photons in Diffractive Photoproduction (LRG) [ZEUS-PREL-15-001]



→ HERA I+II data: luminosity $L = 374\ \text{pb}^{-1}$

→ LRG selection

→ measure prompt photon with and without accompanying jet

→ photon must couple to charged particle
⇒ explore quark structure of the Pomeron

→ channel sensitive to factorisation breaking

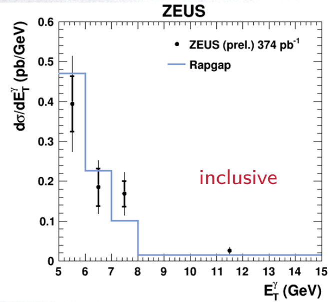
analysis phasespace:				
		$Q^2[\text{GeV}^2]$	$<$	1
		$x_{\mathbb{P}}$	$<$	0.03
5	$<$	$E_{T,\gamma}[\text{GeV}]$		
-0.7	$<$	η_γ	$<$	0.9
4	$<$	$E_{T,jet}[\text{GeV}]$		
-1.5	$<$	η_{jet}	$<$	1.8

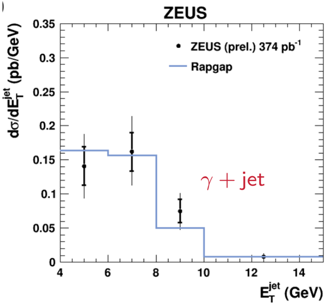
→ bin by bin detector corrections

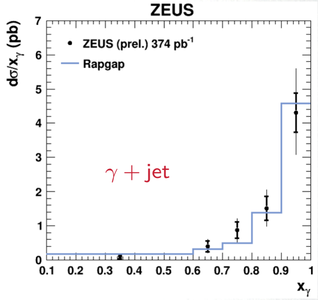
→ data compared to RAPGAP with H1 2006 Fit-B DPDFs

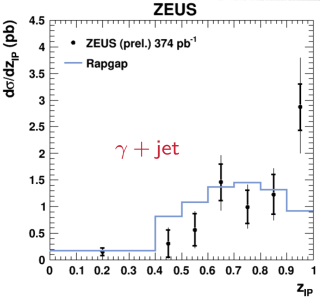
→ normalized to data

Prompt Photons in Diffractive Photoproduction (LRG) [ZEUS-PREL-15-001]

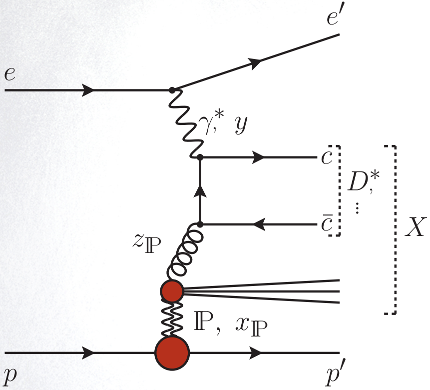








- → RAPGAP normalized to data gives reasonable description of most variables within uncertainties
- → not at $z_{\mathbb{P}} \sim 1$, where H1 2006 Fit-B was not fitted
- → most photons are accompanied by a hard jet
- → further studies ongoing



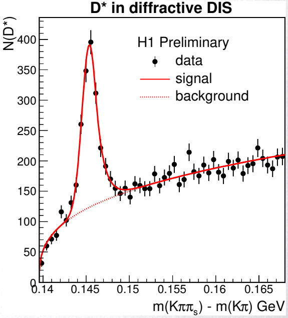
→ charm mass → "natural" hard scale
→ NLO by HVQDIS in FFNS
→ H1 2006 Fit-B DPDFs

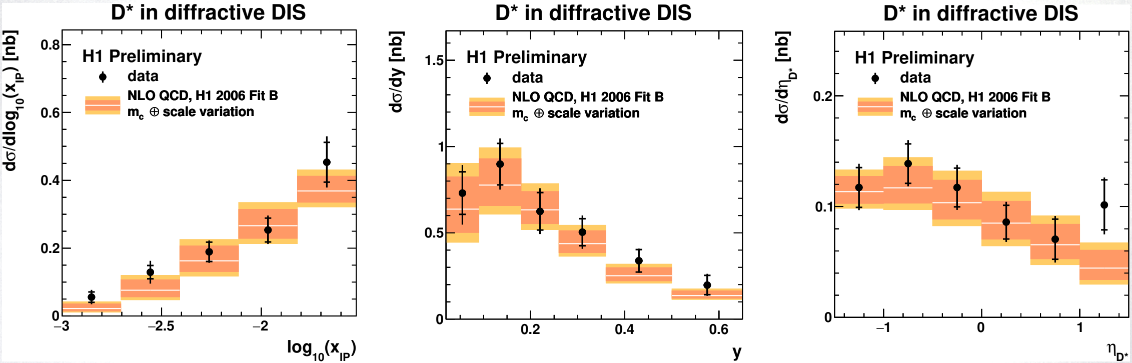
→ HERA II data: luminosity: $L \sim 280\ \text{pb}^{-1}$
→ LRG selection
→ open charm tagged with D^* in

$$D^{*+} \to D^0\pi^+_{\text{slow}} \to (K^-\pi^+)\pi^+_{\text{slow}} + c.c.$$

→ signal extraction via mass fit
→ binwise efficiency/acceptance correction

analysis phasespace:				
5	$<$	$Q^2\,[\text{GeV}^2]$	$<$	100
1.5	$<$	$p_{t,D^*}\,[\text{GeV}]$		
		$x_{\mathbb{P}}$	$<$	0.03
0.02	$<$	y	$<$	0.65
		$\lvert\eta_{D^*,\ \text{lab}}\rvert$	$<$	1.5





⇒ shape and normalisation well described by NLO + DPDFs

→ exp. uncertainties dominated by gap selection and proton dissociative contribution

Summary

inclusive dijets in diffractive DIS:

data well described by NLO+H1 DPDFs,
data precision overshoots theory precision,
first α_s extraction in diffraction,

inclusive dijets in γp (and DIS):

measurement using VFPS proton spectrometer
DIS: VFPS data well described by NLO + H1 DPDFs
γp: cross sections overestimated by NLO + H1 DPDFs
confirms previous H1 observations of factorisation breaking
ZEUS: no suppression observed

prompt photons in diffractive γp:

another hard process sensitive to factorisation breaking,
data compared to RAPGAP,
agreement in most cross section shapes,

open charm production in diffractive DIS:

well suited for factorisation tests due to hard charm mass scale,
data well described by NLO in normalisation and shape,
may be used to further constrain DPDFs,
H1 analysis ongoing

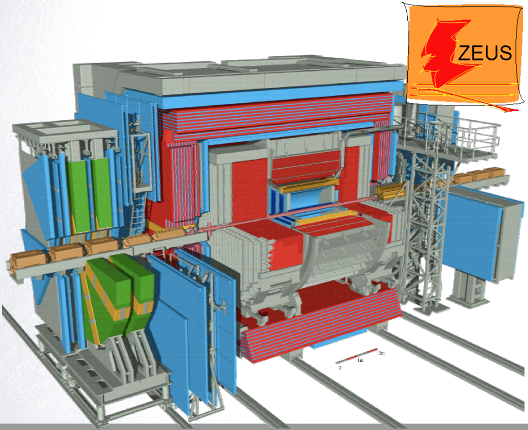
see also talk on exclusive production at HERA by Mariusz Przybycien

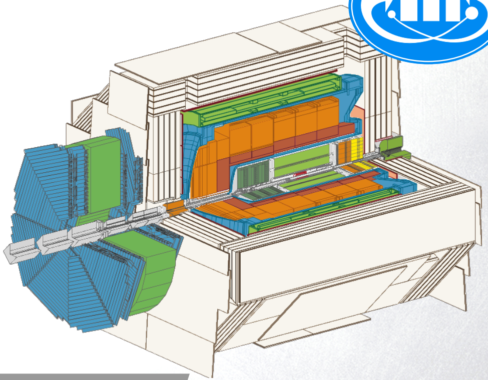
BACKUP

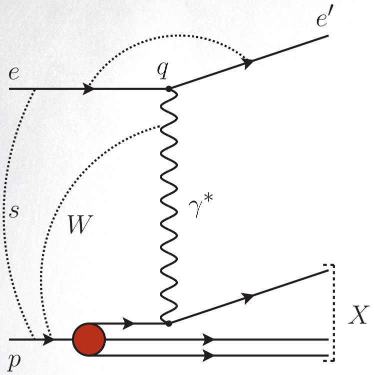
The H1 and ZEUS Multi Purpose Experiments

→ recorded integrated luminosity: $\sim 0.5\ \mathrm{fb}^{-1}$ per experiment

→ excellent control over experimental uncertainties:
- ⇒ over-constrained system in deep inelastic scattering
- ⇒ electron measurement scale uncertainty: 0.5 - 1%
- ⇒ jet energy scale uncertainty: 1%
- ⇒ trigger and normalisation uncertainty: 1-2%
- ⇒ luminosity uncertainty: 1.8 - 2.5%





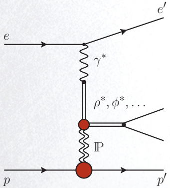


ep scattering mainly via γ^* exchange:

- → γ^* virtual photon: Deep Inelastic Scattering (DIS)
  ⇒ reconstruct e': $Q^2 = -q^2 \gtrsim 4$ GeV^2
- → γ real photon: photoproduction
  ⇒ don't reconstruct e': $Q^2 \lesssim 2$ GeV^2

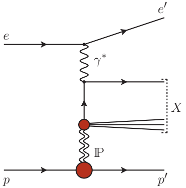
diffractive scattering:

- → a kind of strong interaction with "vacuum quantum number" exchange
- → outside the reach of perturbative QCD
- → phenomenological model: Regge theory
- → illustration: Pomeron $\mathbb{P}$ exchange
- → also affects γp interactions



i) hadronic structure of the γ:

- → quantum fluctuations:
  $\gamma \to q\bar{q}$: vector mesons $\rho, \phi, \ldots$
- → effective $h + h$ scattering
- → "whole" $\mathbb{P}$ participates
- → mostly in photoproduction



ii) hard diffraction:

- → $\mathbb{P}$ is composite object
- → hard scattering with $\mathbb{P}$ "parton"
- → only "part" of $\mathbb{P}$ participates
- → this talk: recent HERA results

[1] H1 Collaboration, "Measurement of Dijet Production in Diffractive Deep-Inelastic ep Scattering at HERA," JHEP **1503**, 092 (2015) [arXiv:1412.0928 [hep-ex]].

[2] H1 Collaboration, "Diffractive Dijet Production with a Leading Proton in *ep* Collisions at HERA," JHEP **1505**, 056 (2015) [arXiv:1502.01683 [hep-ex]].

[3] ZEUS Collaboration, "Studies of the diffractive photoproduction of isolated photons at HERA," ZEUS-prel-15-001.

[4] H1 Collaboration, "D^* Meson Production in diffractive DIS," H1-prel-16-011.

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