H1 & ZEUS results II

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on behalf of H1 and ZEUS Collaborations

Contents:

- ## Diffraction

Diffractive DIS dijet production with LRG — H1prelim-14-014

Diffractive dijet production with leading proton — H1prelim-14-011

Exclusive dijet production in diffractive DIS — ZEUS-prel-14-004

- ## QCD & hadronic final states

Photoproduction of Isolated Photons, Inclusively and with a Jet, at HERA
Phys Lett B 730C (2014) 293

Further studies of the photoproduction of isolated photons with a jet at HERA
JHEP08,(2014) 023

Measurement of multijet production in ep collisions at high Q^2 and determination of the strong coupling α_s — DESY-14-089

Trijet production in DIS at HERA — ZEUS-prel-14-008

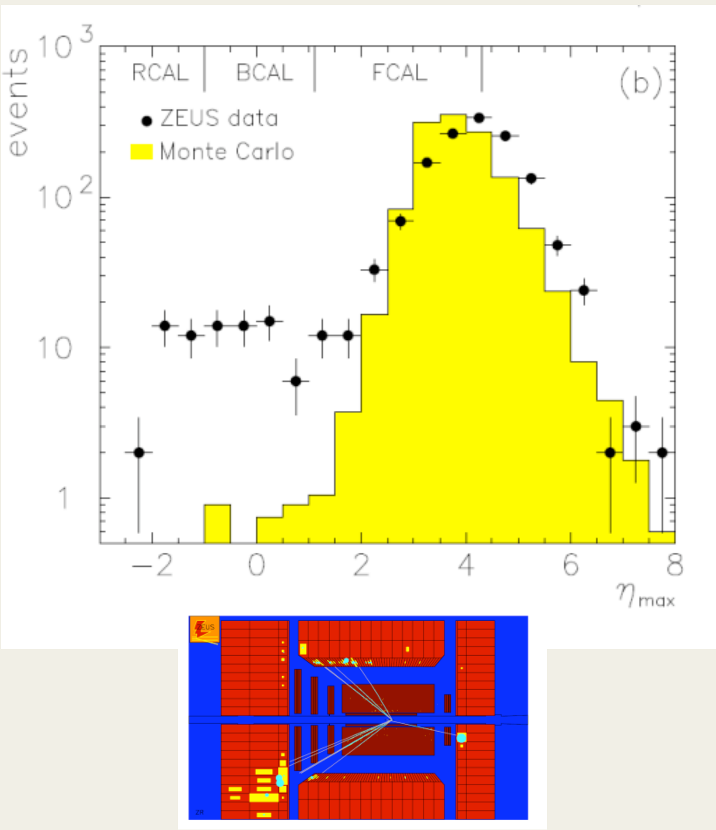
Search for instanton-induced processes in DIS at HERA — H1prelim-14-031

Diffraction -historical reminder

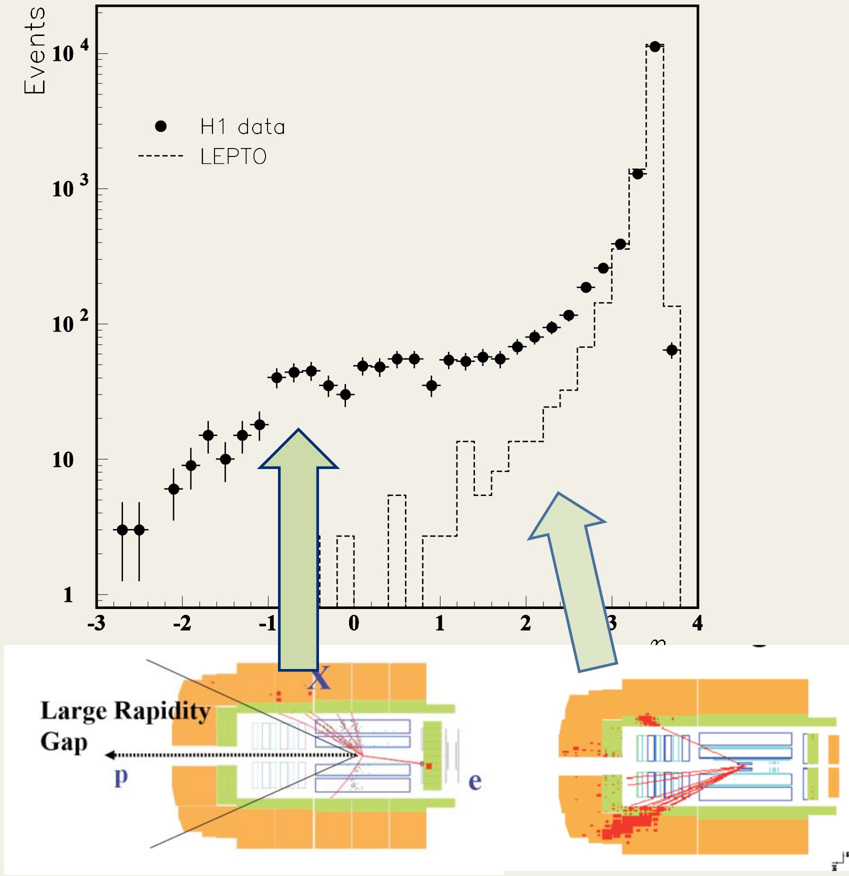
- **21 years** after the observation of diffractive DIS events at HERA!
- HERA opened **new era of diffraction studies**

1993-1994

ZEUS Collab.,Physics Letters B 315 (1993) 481-493

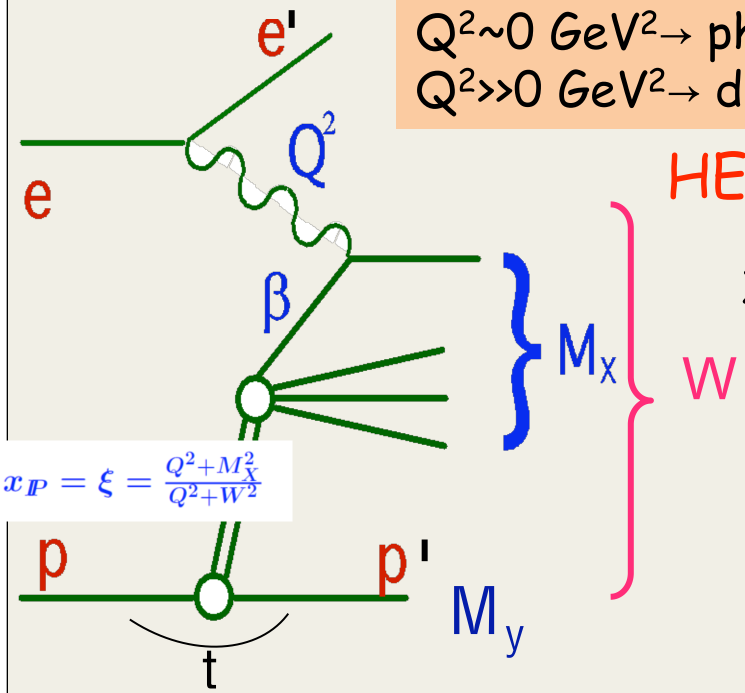


H1 Collab., Nucl. Phys. B429 (1994) 477



Diffractive kinematics

$Q^2 \sim 0\ GeV^2 \rightarrow$ photoproduction
$Q^2 >> 0\ GeV^2 \rightarrow$ deep inelastic scattering (DIS)



$$x_{I\!P} = \xi = \frac{Q^2+M_X^2}{Q^2+W^2}$$

HERA: ~10% of events diffractive

X_{IP}-momentum fraction of color singlet exchange

$M_y = m_p$ proton stays intact, needs detector setup to detect protons
$M_y > m_p$ proton dissociates, contribution should be understood

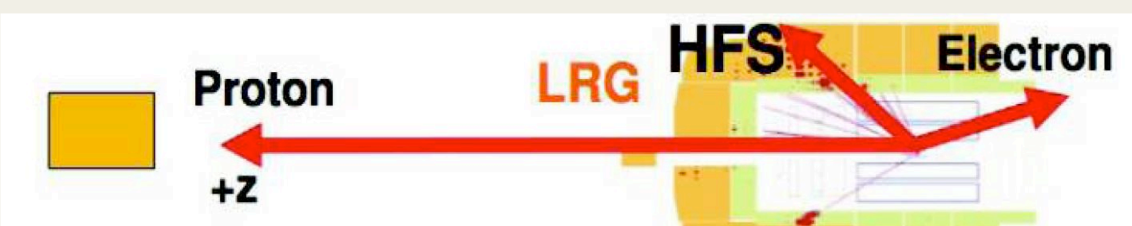
Experimental methods

Proton spectrometers

- free of p-dissociation background
- x_{IP} and t measurements
- access to high x_{IP} range (IP and IR)
- small acceptance

Large Rapidity Gap

- t not measured,integrated over $|t|<1GeV^2$
- very good acceptance at low x_{IP}
- p-diss background about 20% ☠

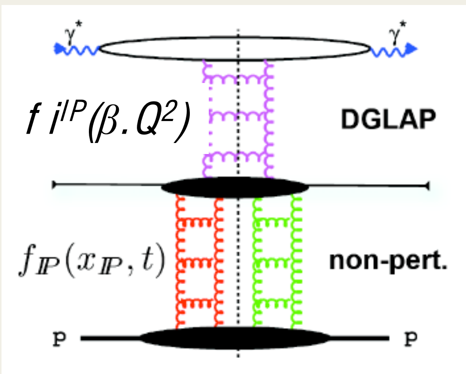


FPS, VFPS (H1), LPS (ZEUS)

Different phase space and systematics – non-trivial to compare!

Modelling of diffraction

QCD collinear factorisation theorem



Infinite momentum frame - partons

[H1 Coll. EPJC28 (2006) 715]

$$\sigma^D(\gamma^* p \to Xp) = \sum_{parton\_i} f_i^D(x, Q^2, x_{IP}, t) \cdot \sigma^{\gamma^* i}(x, Q^2)$$

Regge factorisation (conjecture, e.g. Resolved Pomeron Model by Ingelman&Schlein)

$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_i^{IP}(\beta = x/x_{IP}, Q^2)$$

$$f_{IP/p}(x_{IP}, t) = \frac{e^{Bt}}{x_{IP}^{2\alpha(t)-1}}$$

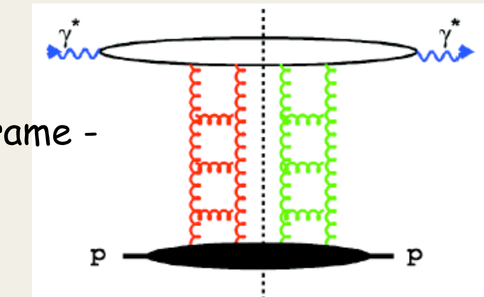
Pomeron flux factor

diffractive DPDF

DPDFs extracted from DIS data

Dipole model

Proton rest frame - dipoles

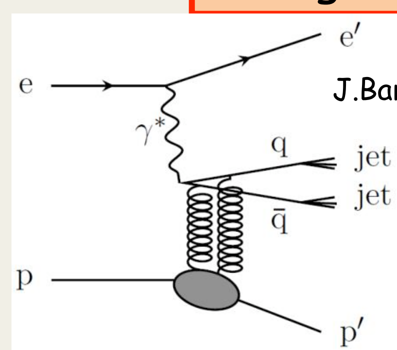


[C. Marquet PRD76 (2007) 094017]

$$d\sigma^{\gamma^* p}_{diff}/dt \propto \int dz dr^2 \Psi^* \sigma^2_{q\bar{q}}(x, r^2, t)\Psi$$

Long living quark pairs interact with gluons of the proton

Two gluon exchange model



J.Bartels et al.,Phys.Lett.B386,(1996)389

No extra parameters needed for DDIS, fully perturbative calculations based on proton PDF

Diffractive dijet production in DIS

Previous HERA results:

- **H1**, LRG measurement, JHEP 0710:042, (2007)
- **ZEUS**, LRG measurement,EPJC 52 (2007),813
- **H1**, proton tagging -FPS, EPJC 72, (2012),1970
- **H1**, proton tagging - VFPS, H1 preliminary (2014)

All HERA results agree within errors with NLO QCD calculations

DDIS Dijet Selection
$4 < Q^2 < 80\ \mathrm{GeV}^2$
$0.1 < y < 0.7$
$p^*_{T,1} > 5.5\ \mathrm{GeV}$
$p^*_{T,2} > 4.0\ \mathrm{GeV}$
$-1 < \eta_{1,2} < 2$
$x_{I\!P} < 0.03$
$|t| < 1\ \mathrm{GeV}^2$
$M_Y < 1.6\ \mathrm{GeV}$

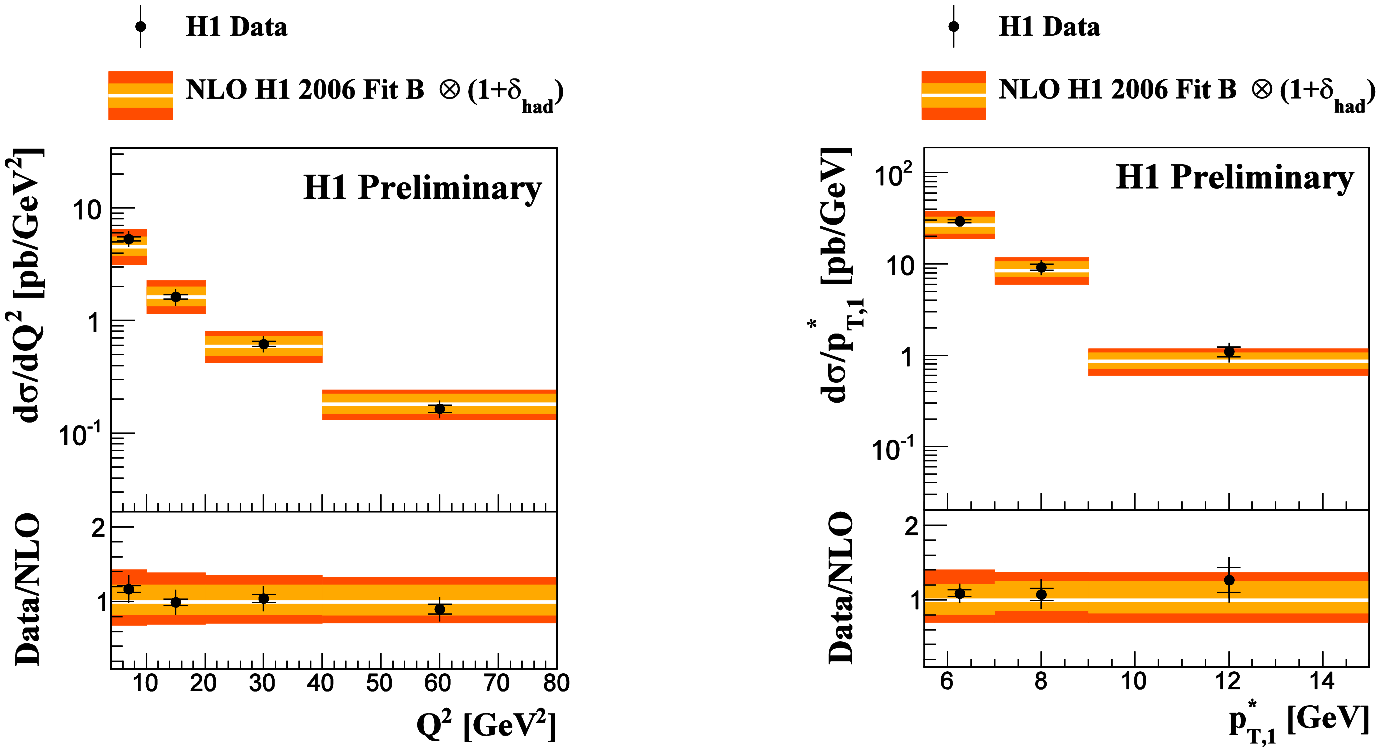
New H1 LRG measurement -
highest luminosity compared to former HERA measurements
HERA II data, luminosity ~ 290 pb^{-1}

First LRG analysis with corrections for detector effects using detector response matrix

- Measurements compared to NLO QCD predictions – program NLOJET++ using DPDF H12006 Fit B

~ 14000 events accepted

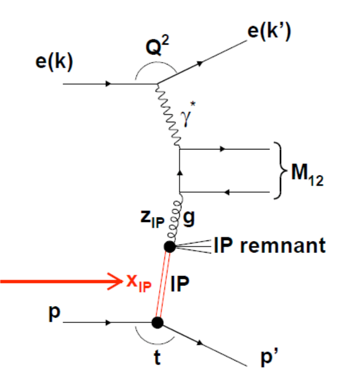
Diffractive dijet production in DIS

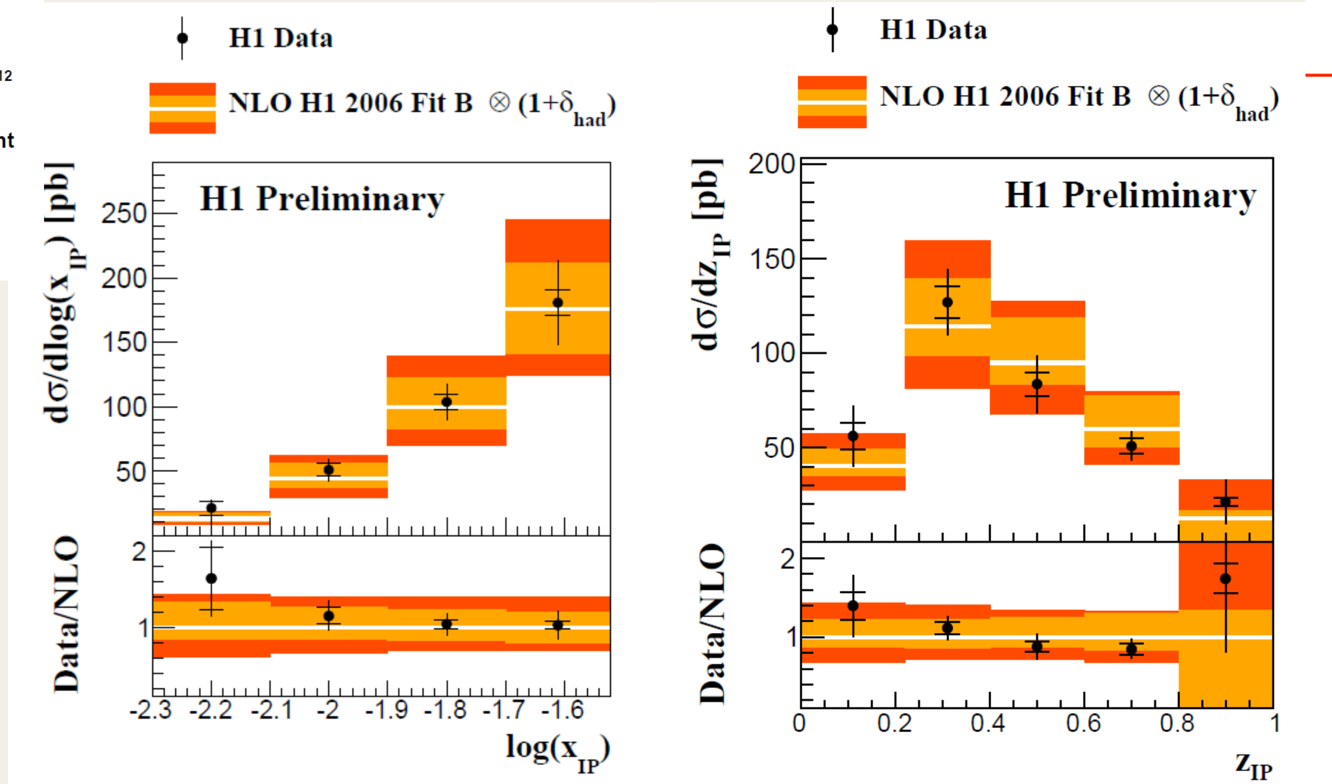


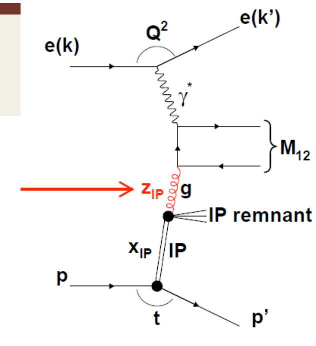
- Inner error bars of data points - statistical uncertainty, outer error bars - systematic uncertainties added in quadrature
- NLO QCD inner band - uncertainty of hadronisation and DPDF fit added in quadrature, outer band – total uncertainty (incl.QCD scale uncertainty)

- Data well described by QCD prediction within exp. and theor. uncertainties

Diffractive dijet production in DIS



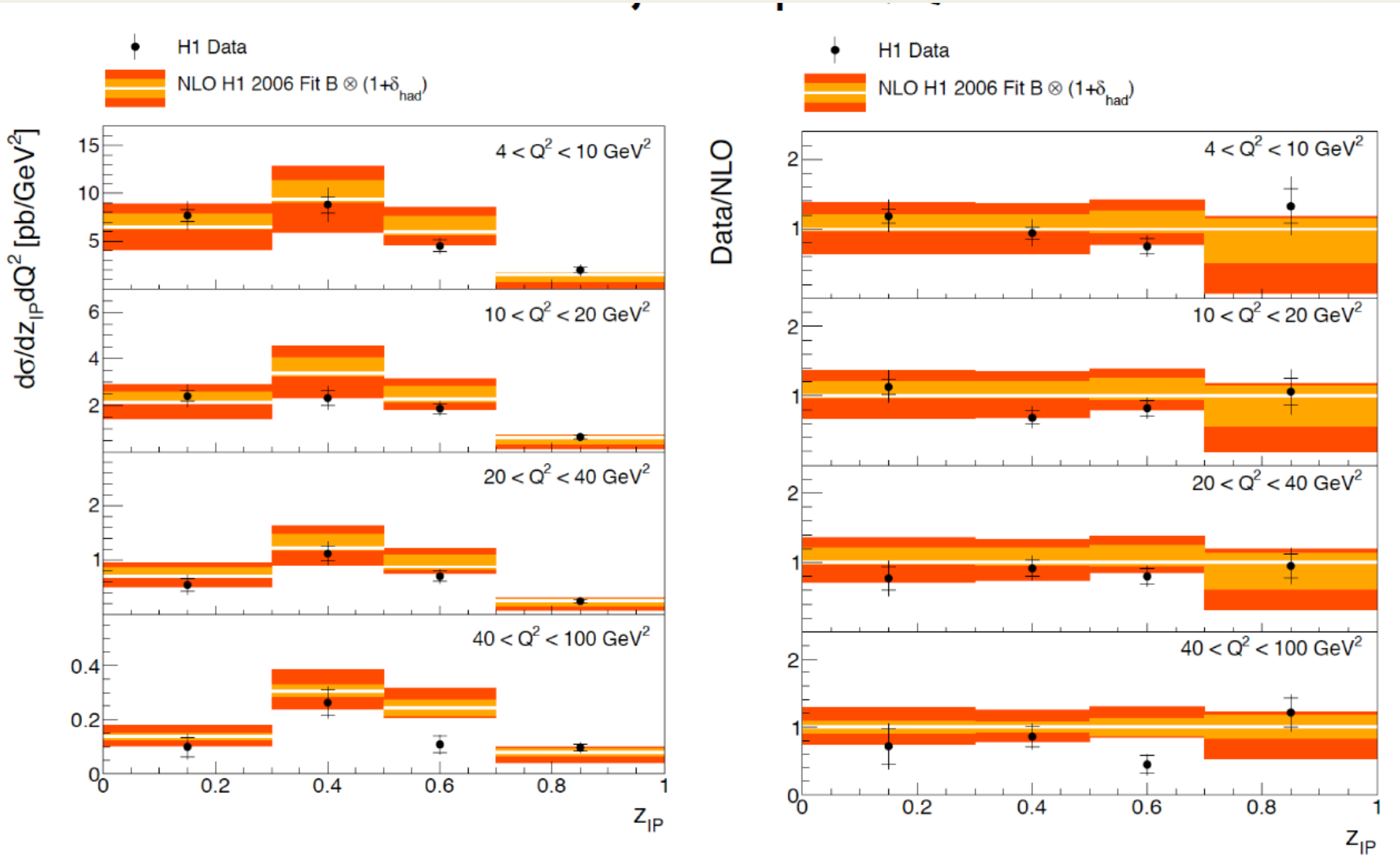




- Experimental uncertainty of measurement in z_{IP} lower than DPDF fit uncertainty, gluon DPDF might be further constrained

Measurements in agreement with NLO QCD calculations, factorisation confirmed.

Diffractive dijet production in DIS



Good agreement with NLO QCD, the last bin in z_{IP} where DPDF is only extrapoled can be used further to improve DPDF fits

$$\alpha_s(M_Z) = 0.119\ (4)_{\rm exp}\ (2)_{\rm had}\ (5)_{\rm DPDF}\ (10)_{\mu_r}\ (4)_{\mu_f}$$
$$= 0.119\ (4)_{\rm exp}\ (12)_{\rm DPDF,theo}$$

The diffraction can consistently be described by NLO QCD using DPDF and factorisation!

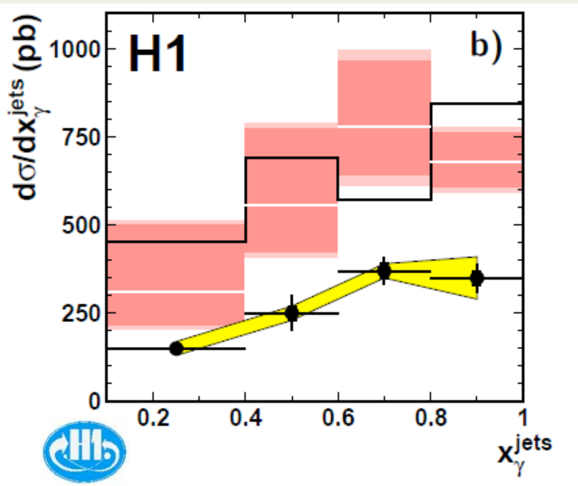
Diffractive dijet photoproduction-history

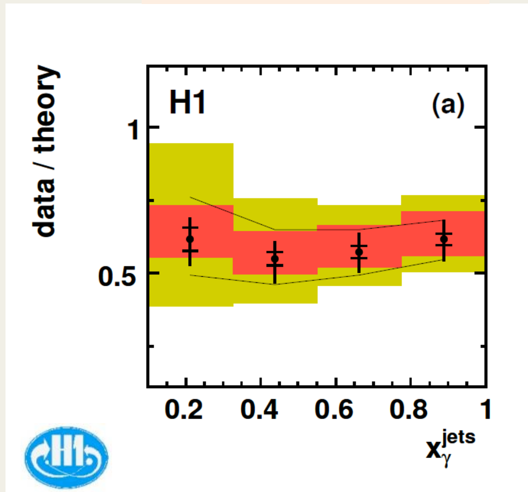
Test of QCD factorisation in diffractive photoproduction

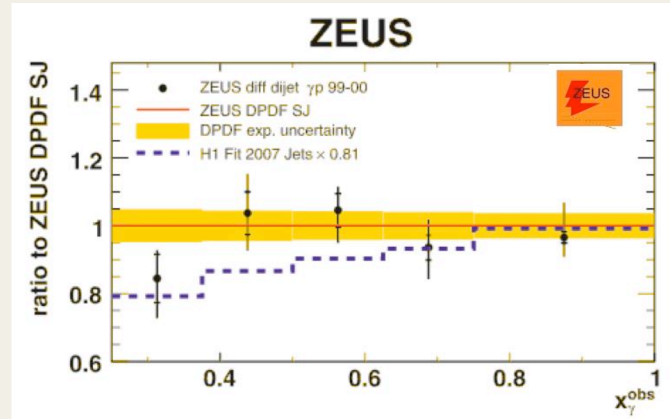
EPJC C51 (2007),549,

EPJ C68 (2010),381

Nucl.Phys. B831 (2010), 1





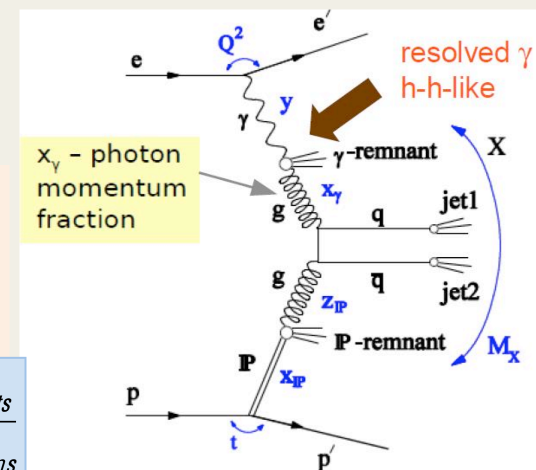


suppression $S^2 \sim 0.5 \pm 0.1$

$S^2 \sim 0.58 \pm 0.01 \pm 0.12$(exp) $\pm 0.14 \pm 0.09$(th)

$S^2 \sim 1$

$$S^2 = \frac{\sigma\,(\text{data})}{\sigma\,(\text{theory}_{(\text{NLO QCD})})}$$

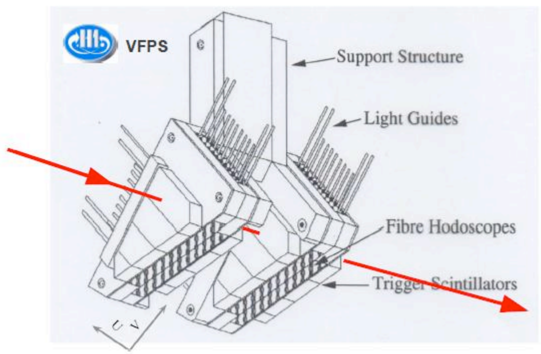


Different phase space in H1 and ZEUS analyses

- H1 tagged photoproduction, ZEUS untagged ph.,
- ZEUS larger E_T of jets, E_T dependence of suppression?
- no dependence of S^2 on x_γ!

$$x_\gamma = x_\gamma^{OBS} = \frac{\sum (E - p_z)_{jets}}{(E - p_z)_{hadrons}}$$

Diffractive dijet photoproduction & DIS



A new analysis with leading protons detected in Very Forward Proton Spectrometer

Photoproduction

$E_T^{jet1(2)} > 5.5\ (4)$ GeV

$-1 < \eta^{jet1(2)} < 2.5$

$Q^2 < 2\ \mathrm{GeV}^2$

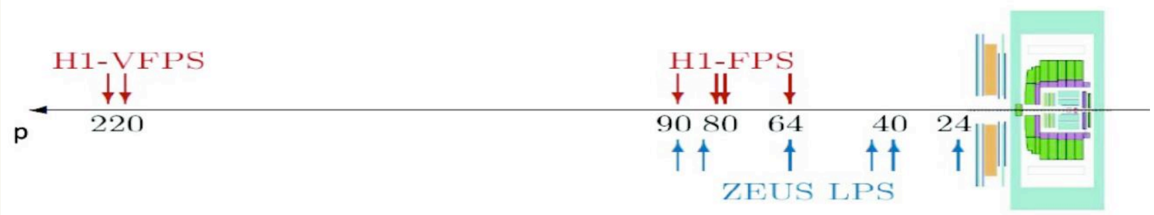
DIS

$4 < Q^2 < 80\ \mathrm{GeV}^2$

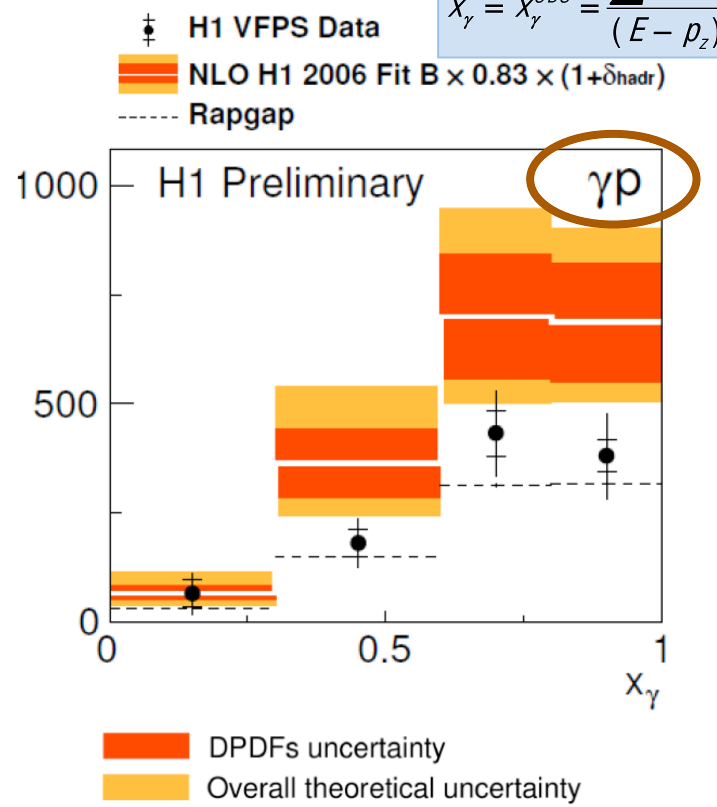
$0.2 < y < 0.7$

$|t| < 0.6\ \mathrm{GeV}^2$

Frixione-Ridolfi NLO QCD NLOJET++



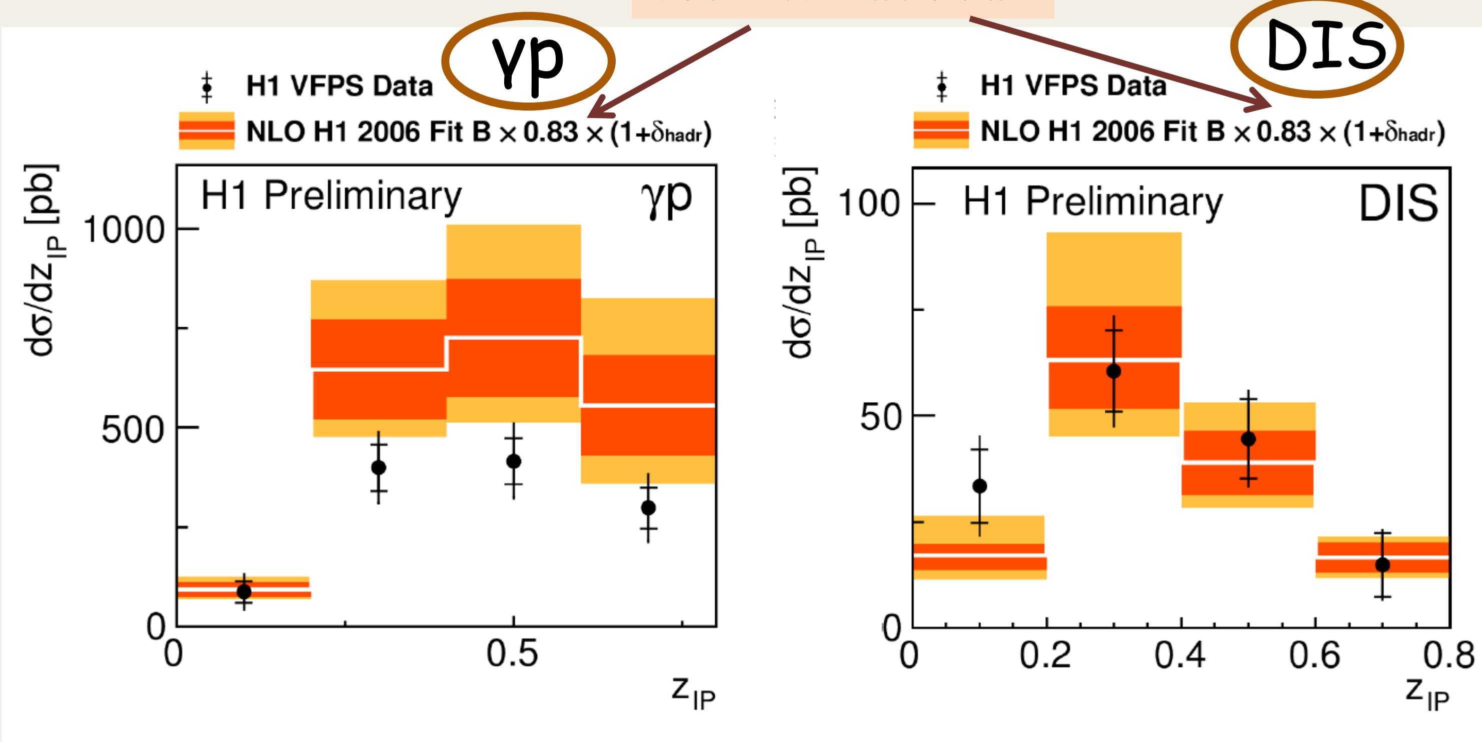
$$x_\gamma = x_\gamma^{OBS} = \frac{\sum (E - p_z)_{jets}}{(E - p_z)_{hadrons}}$$



Data/NLO = $0.60 \pm 0.08\ (\mathrm{data}) \pm 0.21\ (\mathrm{theor.})$

Diffractive dijet photoproduction & DIS

Scaled to elastic case

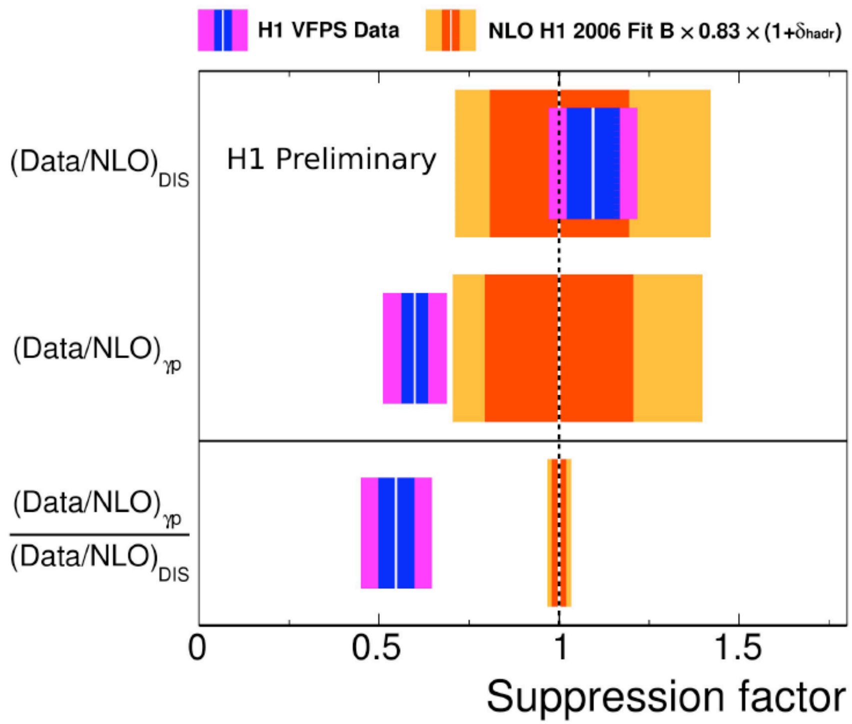


NLO QCD → Frixione-Ridolfi NLOJET++

Photoproduction – data suppressed in comparison with NLO QCD by ~ 0.6
DIS – -data satisfactorily described by NLO QCD calculations

Diffractive dijet production - double ratio

$$\frac{(\mathrm{DATA/NLO})_{\gamma p}}{(\mathrm{DATA/NLO})_{\mathrm{DIS}}} = 0.55 \pm 0.10\,(\mathrm{data}) \pm 0.02\,(\mathrm{theor.})$$



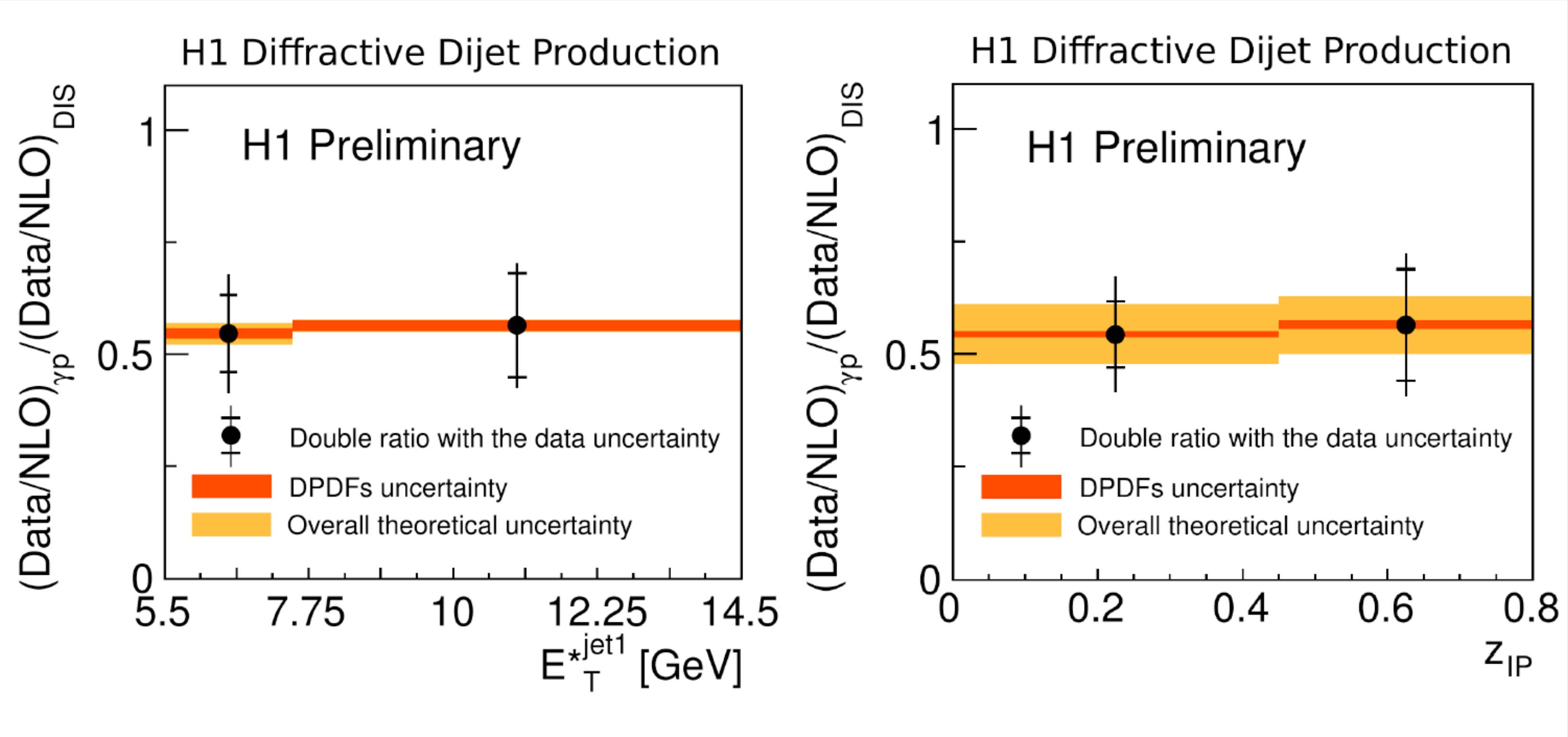
Theoretical uncertainties
- DPDFs uncertainty
- Overall theoretical uncertainty

scale - $(E_T^{*\,\mathrm{jet1}})^2 + Q^2/4$

QCD uncertainty – the scale varied simultaneously in DIS and photoproduction by factor of ½ and 2

Previous H1 measurements confirmed, factorisation breaking observed

Diffractive dijet production - double ratio

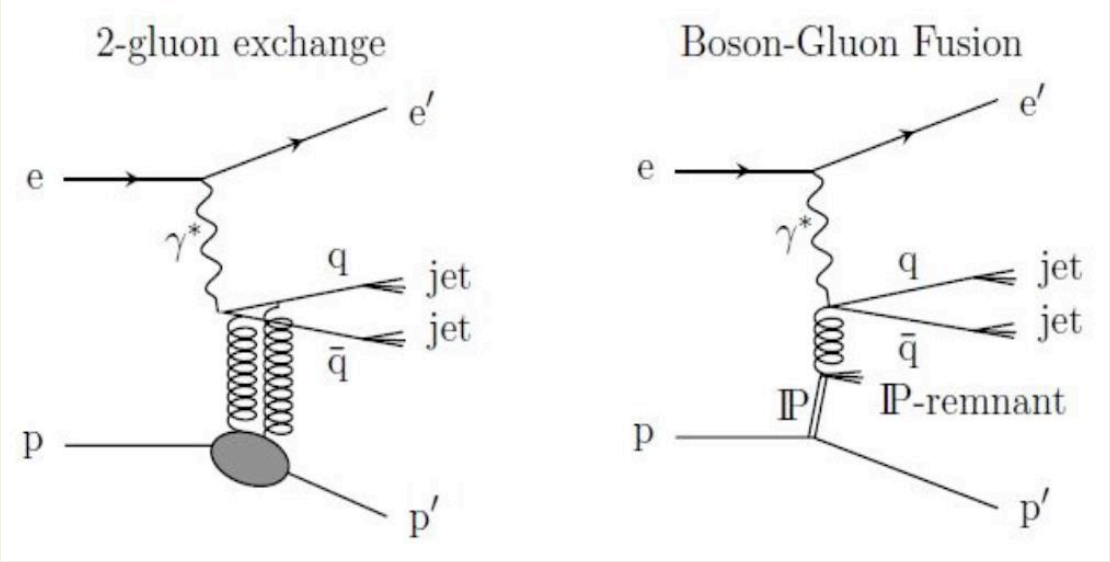


Double ratio photoproduction/DIS - uncertainites reduced!

Dependence of the suppression on E_T of the leading jet and z_{IP} not observed!

Exclusive dijet production in diffractive DIS

Aim: comparison to model predictions



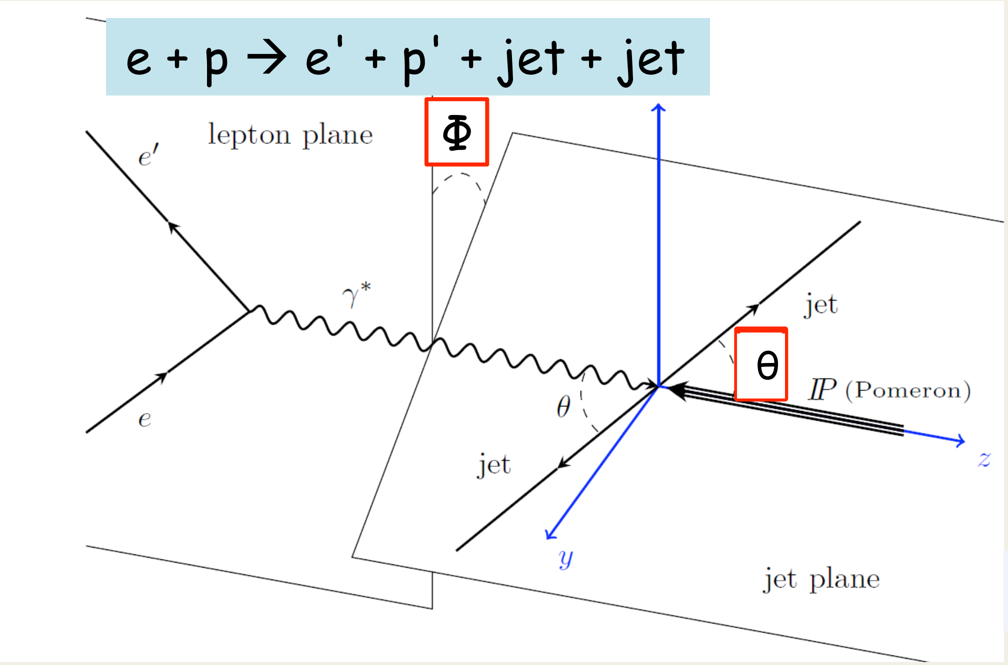
Two-gluon exchange model
(J.Bartels,H.Jung et al.)

Resolved Pomeron model
(G.Ingelman,P.Schlein et al)

Models predict different shape for dijet azimuthal angular distribution

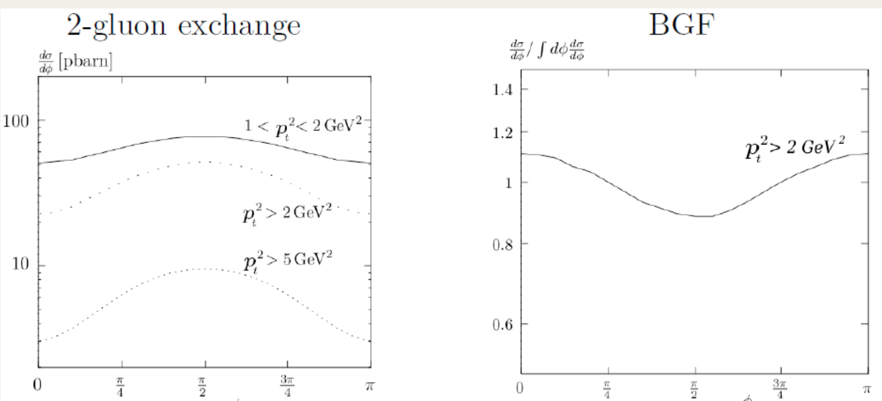
Exclusive dijet production in diffractive DIS

$e + p \rightarrow e' + p' + jet + jet$



Φ – angle between lepton and jet planes
Θ – polar angle of jet

$$d\sigma/d\phi \propto 1 + A\cos(2\phi)$$



- Two -gluon exchange – negative A
- Resolved Pomeron - positive A

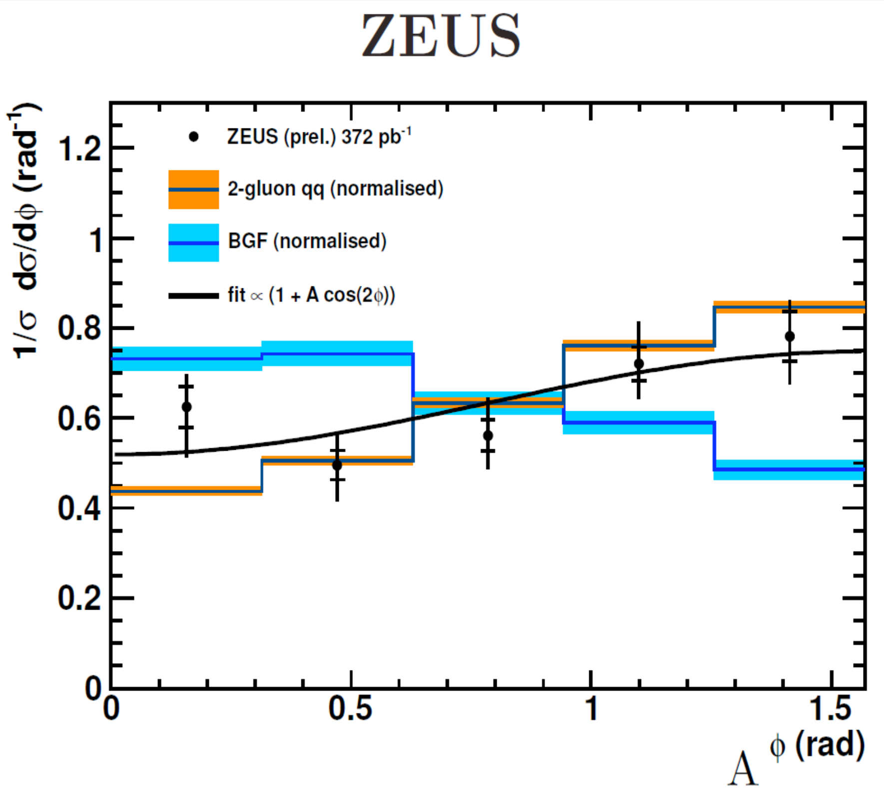
Exclusive dijet production in diffractive DIS

LRG selection of diffraction, data 2003-7

$90\ \mathrm{GeV} <$	W	$< 250\ \mathrm{GeV}$
$25\ \mathrm{GeV}^2 <$	Q^2	
	$x_{I\!P}$	< 0.01
$0.5 <$	β	< 0.7
	n_{jets}	$= 2$
$2\ \mathrm{GeV} <$	$p_{T\ jet}$	

Unfolded data compared to :

- 2-gluon exchange model – RAPGAP 3.01/26
- Boson-Gluon-Fusion model (resolved pomeron) - RAPGAP 3.01/26

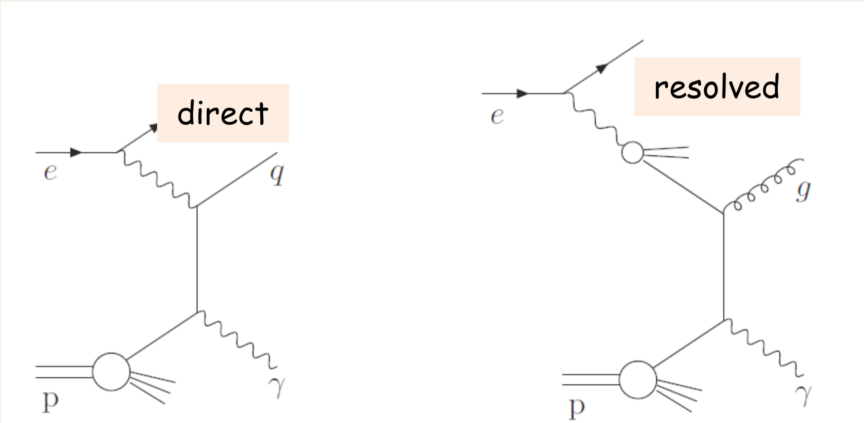


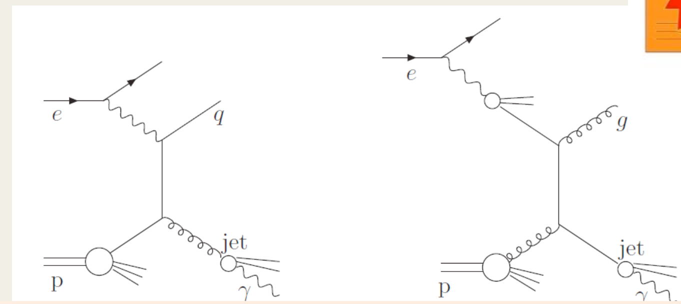
$$d\sigma \propto 1 + A\cos(2\phi)$$

A		
fit	$-0.18 \pm 0.06(\mathrm{stat.})^{+0.06}_{-0.09}(\mathrm{sys.})$
2-gluon(qq) MC	$-0.34 \pm 0.01(\mathrm{stat.})$
BGF MC	$0.21 \pm 0.02(\mathrm{stat.})$

- Negative A favours two gluon exchange model
- None of the models is able to describe the normalisation of x-section

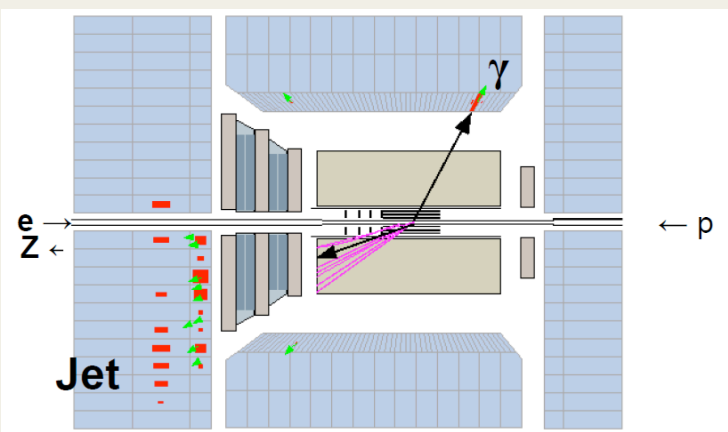
Prompt photons in photoproduction, $Q^2 < 1 GeV^2$





Direct and resolved with fragmentation, (~10% of σ)

- Measured with and without accompanying jet (ZEUS coll. Phys Lett B 730C (2014) 293)
- Measured for direct- and resolved-enhanced regions (ZEUS coll. JHEP08,(2014) 023)

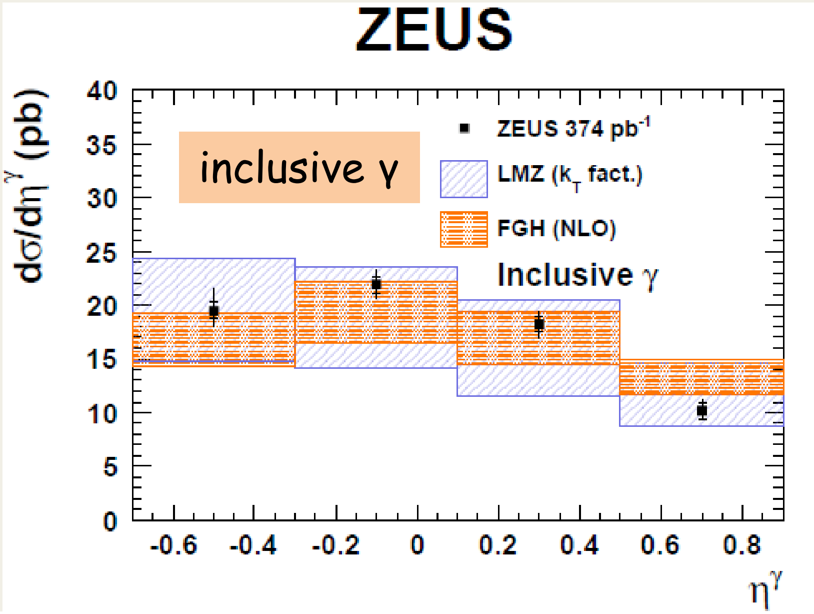


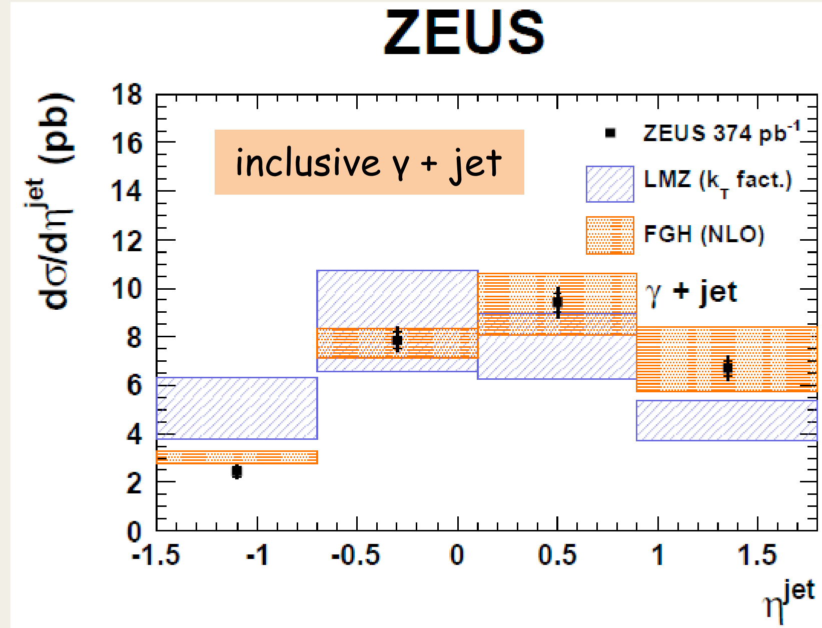
Tested models:

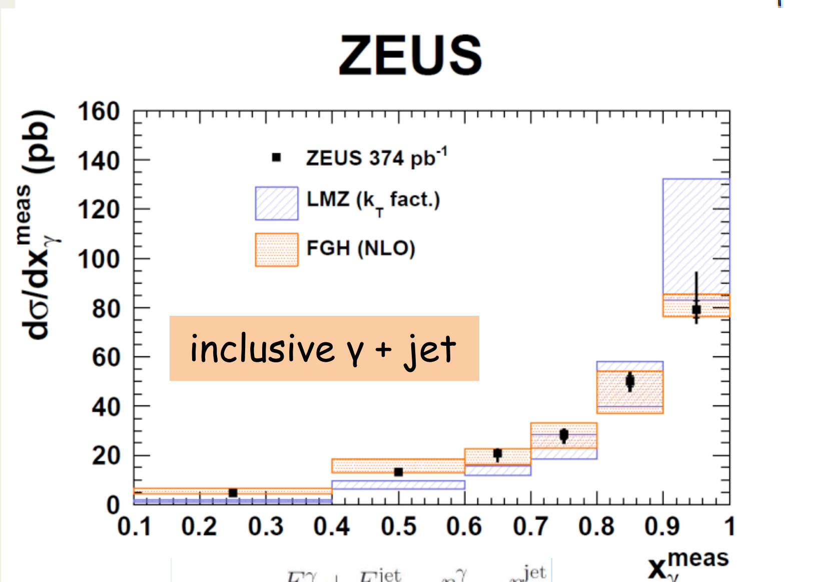
- Fontannaz,Guillet,Heinrich (**FGH**)
  NLO + box diagram+ fragmentation
- Lipatov,Malyshev,Zotov (**LMZ**)
  kt-factorisation,unintegrated PD, initial parton cascade

Phase space
photon : $6 < E_T < 15$ GeV, $-0.7 < \eta < 0.9$
photon+jet: $4 < E_{Tjet} < 35$ GeV, $-1.5 < \eta < 1.8$

Prompt photons in photoproduction, $Q^2 < 1\,GeV^2$



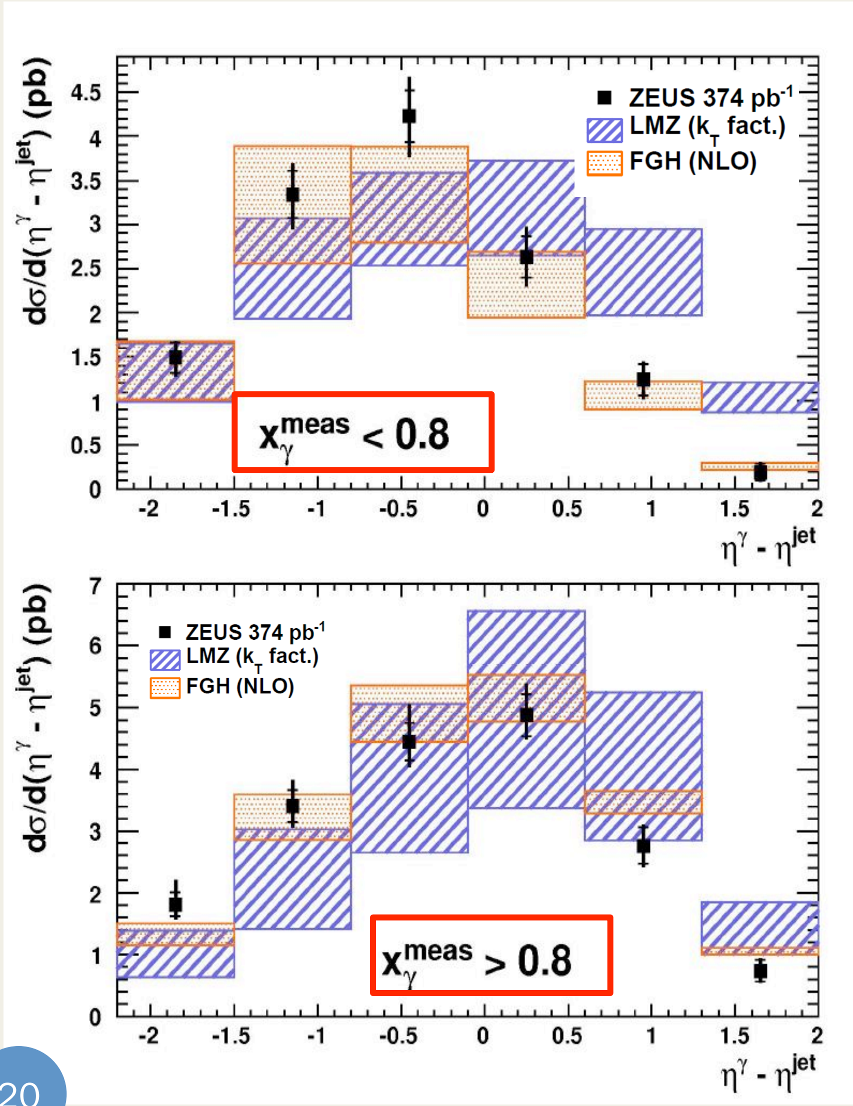




$$x_\gamma^{meas} = \frac{E^\gamma + E^{jet} - p_Z^\gamma - p_Z^{jet}}{E^{all} - p_Z^{all}}$$

- in general both predictions agree with the data
- experimental uncertainties much smaller than theoretical ones
- η_{jet} better described by FGH than LMZ

Prompt photons in photoproduction, $Q^2 < 1\,GeV^2$

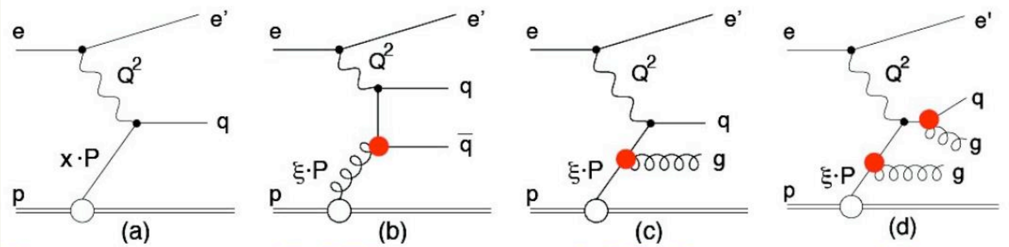


Recent analysis - cross sections measured differentially in resolved-enhanced and direct-enhanced regions

- both models are consistent within huge theoretical uncertainties with data
- FGH model gives slightly better predictions
- potential input to photon PDF fits

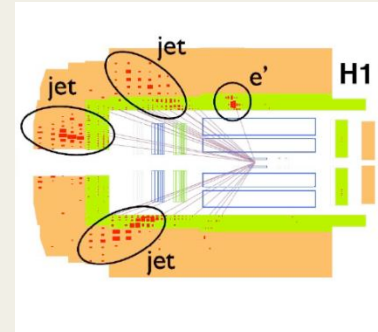
Multijets at high Q^2

Jet production in NC DIS: inclusive,dijets,trijets

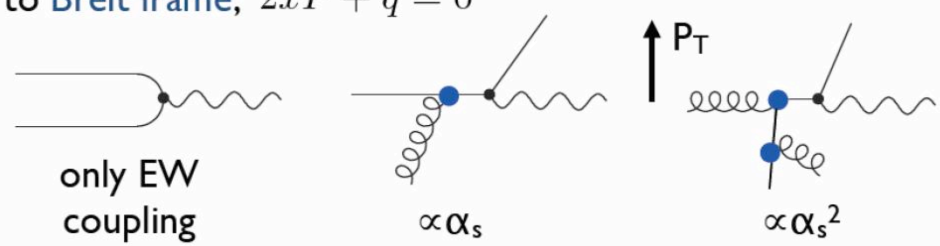


Born **BGF** $\sim\alpha_s$ **QCDC** $\sim\alpha_s$ **3-jet** $\sim\alpha_s^2$

$$\xi = x_{Bj}(1+M^2_{jj,jjj}/Q^2)$$



Boost to Breit frame, $2xP + q = 0$



- in Breit frame only hard QCD process can generate significant P_T
- direct sensitivity to α_s and gluon PDF

Neutral current phase space

$150 < Q^2 < 15000$ GeV^2

$0.2 < y < 0.7$

Jet acceptance

$-1.0 < \eta_{lab} < 2.5$

Inclusive Jet

$7 < p_T^{jet} < 50$ GeV

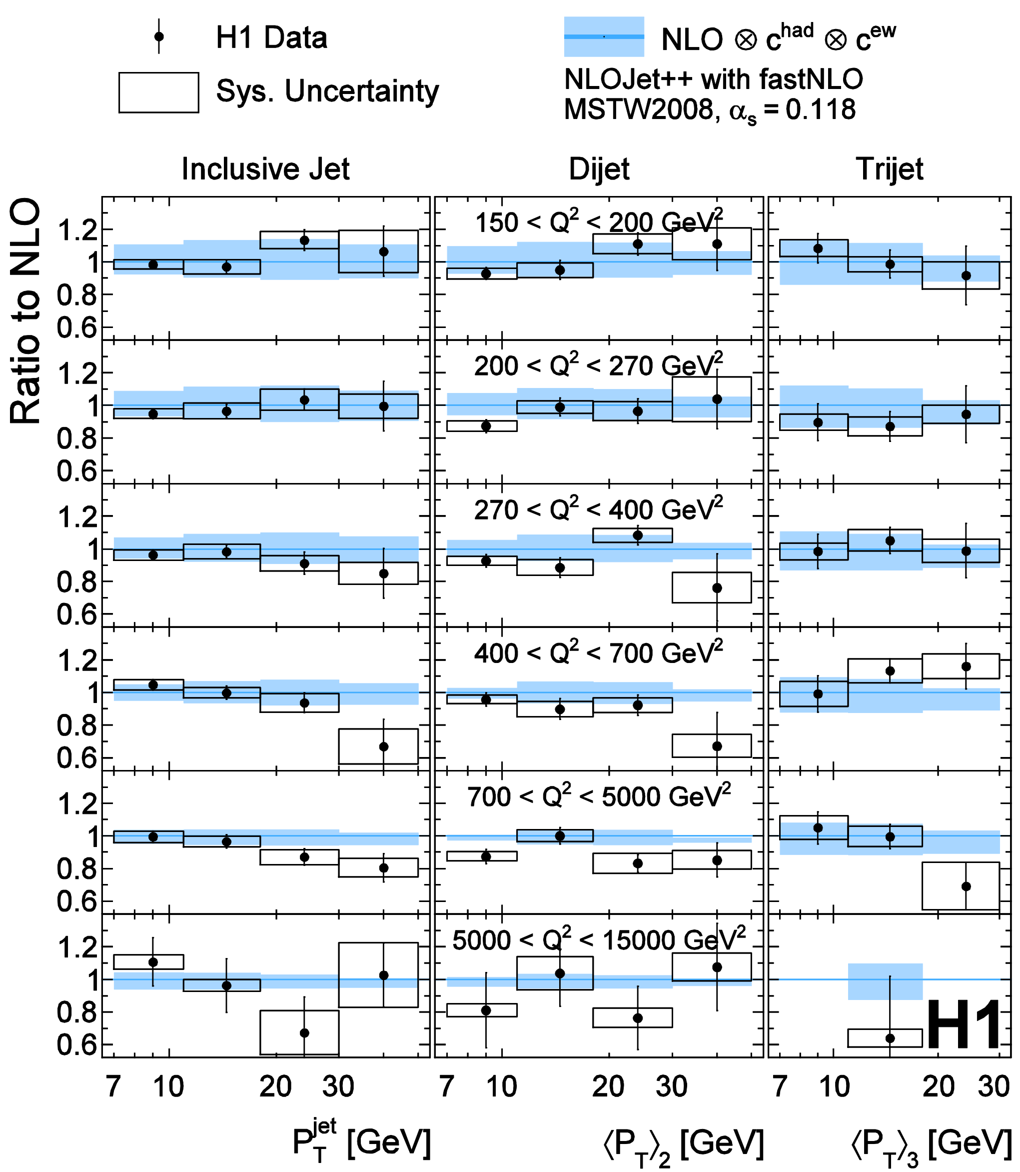
Dijet and Trijet

$5 < p_T^{jet} < 50$ GeV

$M_{12} > 16$ GeV

$7 < \langle p_T \rangle < 50$ GeV

Multijets at high Q^2



Normalised to NC DIS multijets

$N_{jet}(P_T^{jet})/N_{NC}$ in given Q^2 bin

$\langle P_T \rangle_3 = 1/3 \sum p_{Ti}$

- Data obtained using regularised unfolding
- NLO calculations – NLOJet++ corrected for hadronisation

Scales:

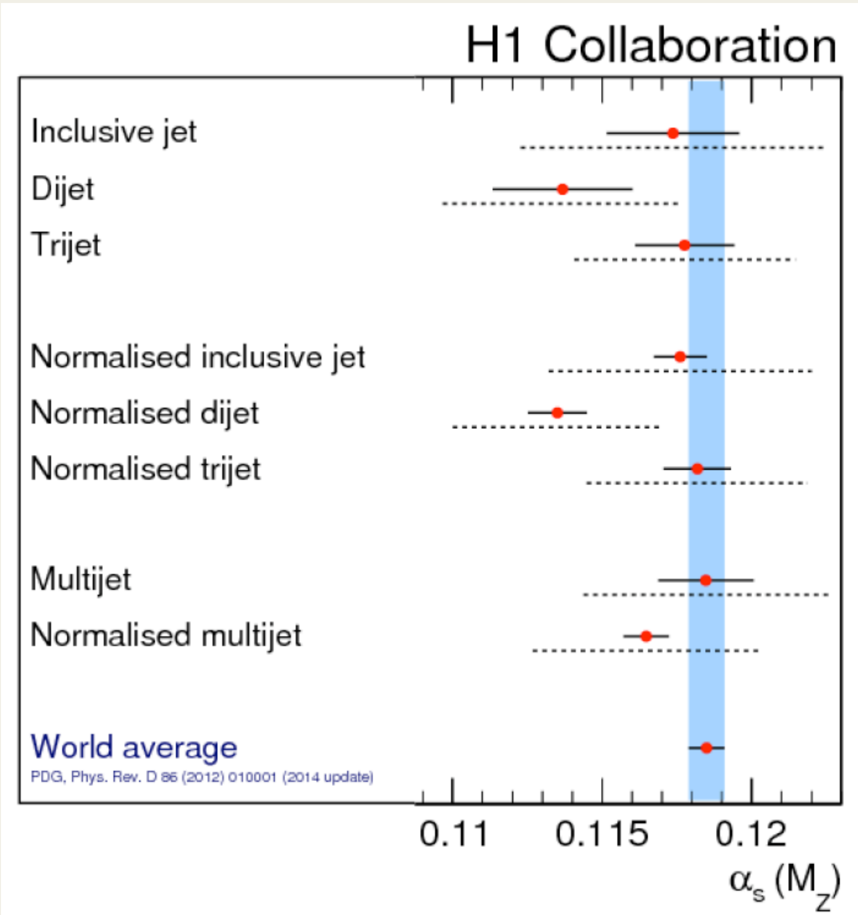
$$\mu_r^2 = \frac{1}{2}(Q^2 + P_T^2) \quad \mu_f^2 = Q^2$$

NLO QCD describes well multijet cross sections. Experimental precision better than theoretical uncertainty.

Multijets at high Q^2

Fit NLO QCD with $\alpha_s(M_Z)$ as free parameter to absolute and norm. inclusive jet, dijet and trijet cross sections

(individually and simultaneously)



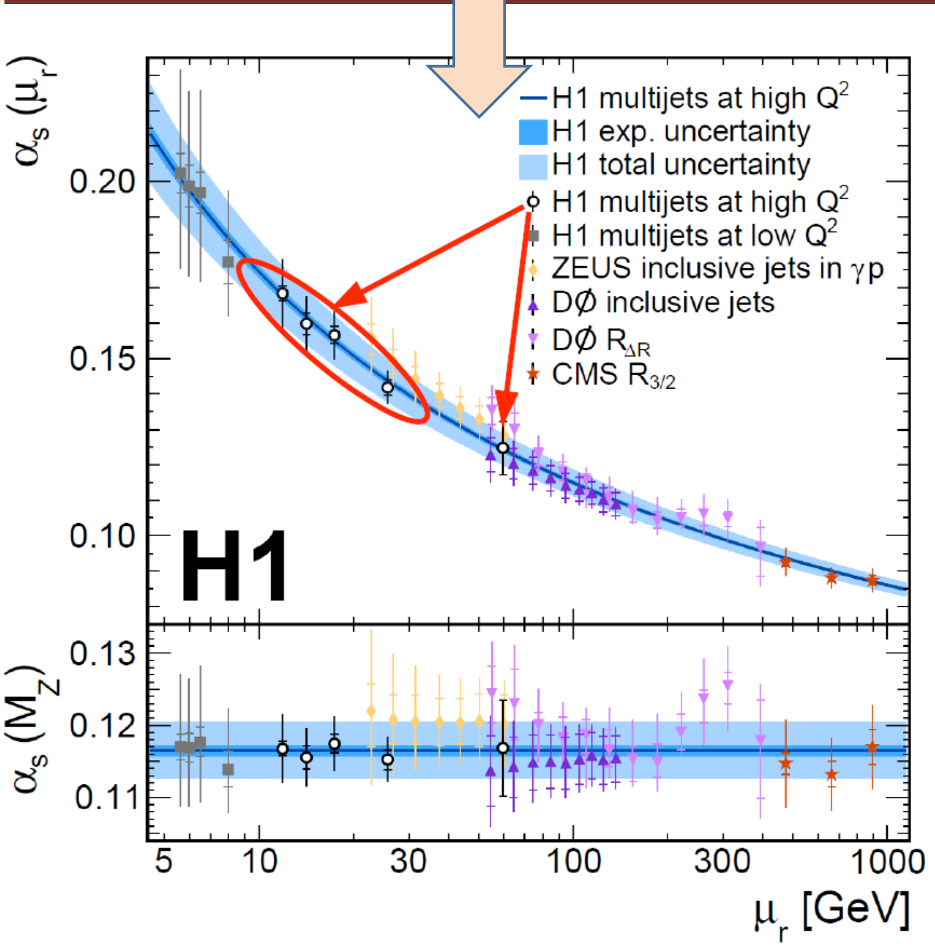
experimental uncertainties ——————

theoretical uncertainties ....

- most precise result when using norm. multijet cross section
- tension between dijet and other results within exp. uncertainties
- consistent results within uncertainties and with world average
- need NNLO calculations to match superior exp. precision ~ 0.7%

$$\alpha_s(M_Z) = 0.1165\,(8)_{exp}\,(5)_{PDF}\,(7)_{PDFset}\,(3)_{(PDF)(\alpha s)}\,(8)_{had}\,(36)_{\mu r}\,(5)_{\mu f}$$
$$= 0.1165\,(8)_{exp}\,(38)_{pdf,theo}$$

Multijets at high Q^2
running of $\alpha_s(\mu_r)$



$\alpha_s(\mu_r)$ from 5 fits using norm.multijet cross section

$\alpha_s(M_Z)$ values found to be consistent and independent of μ_r

$\alpha_s(M_Z)$ = 0.1165 $(8)_{exp}$ $(38)_{pdf,theo}$

Most precise value derived from jet data at NLO from one experiment

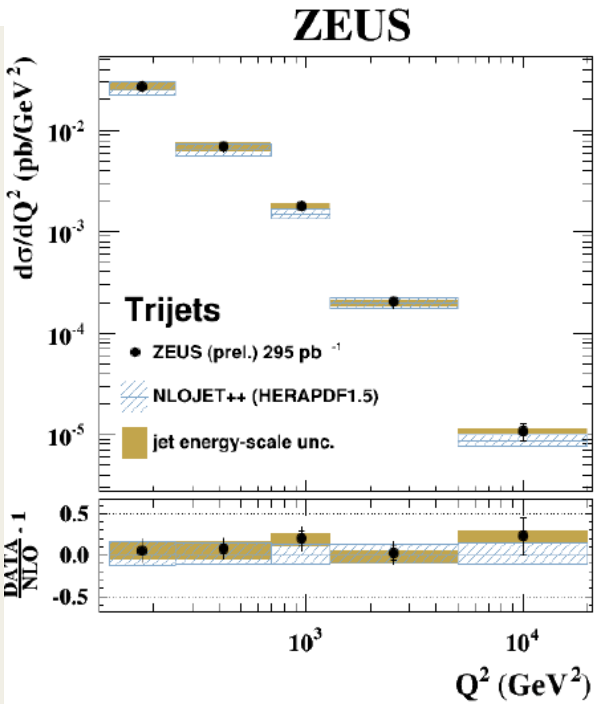
Trijet measurements in DIS

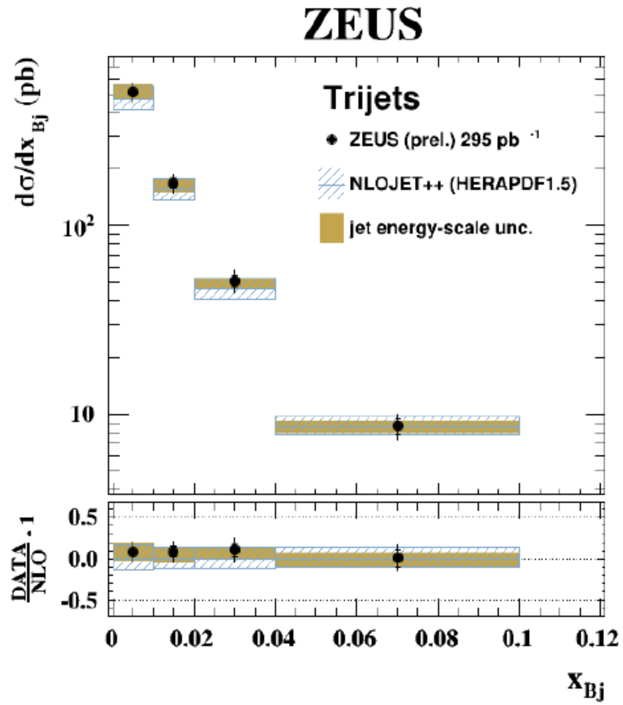
Phase space: $125 < Q^2 < 20000\ GeV^2$
$0.2 < y < 0.6$

- At least three jets with $E_{T,B}^{jet} > 8$ GeV and $-1 < \eta_{LAB}^{jet} < 2.5$
- $M_{jj} > 20$ GeV

Prediction: NLOJet++

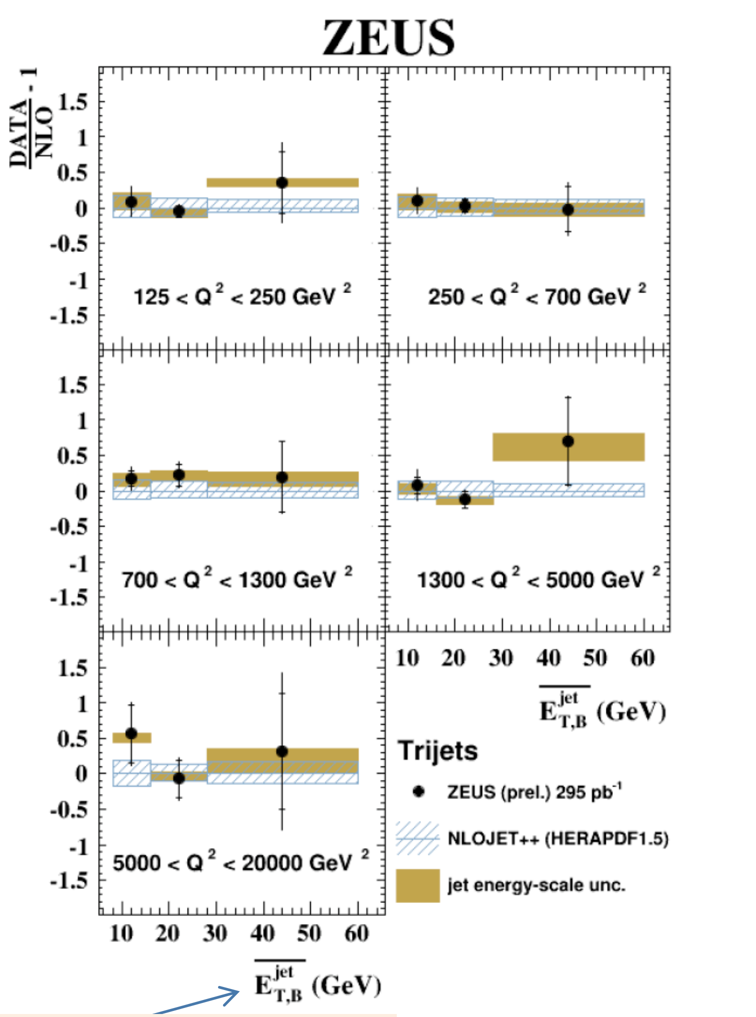
- pPDF: HERAPDF1.5
- $\mu_R^2 = Q^2 + \langle E_t^{jet} \rangle^2$
- $\mu_f^2 = Q^2$

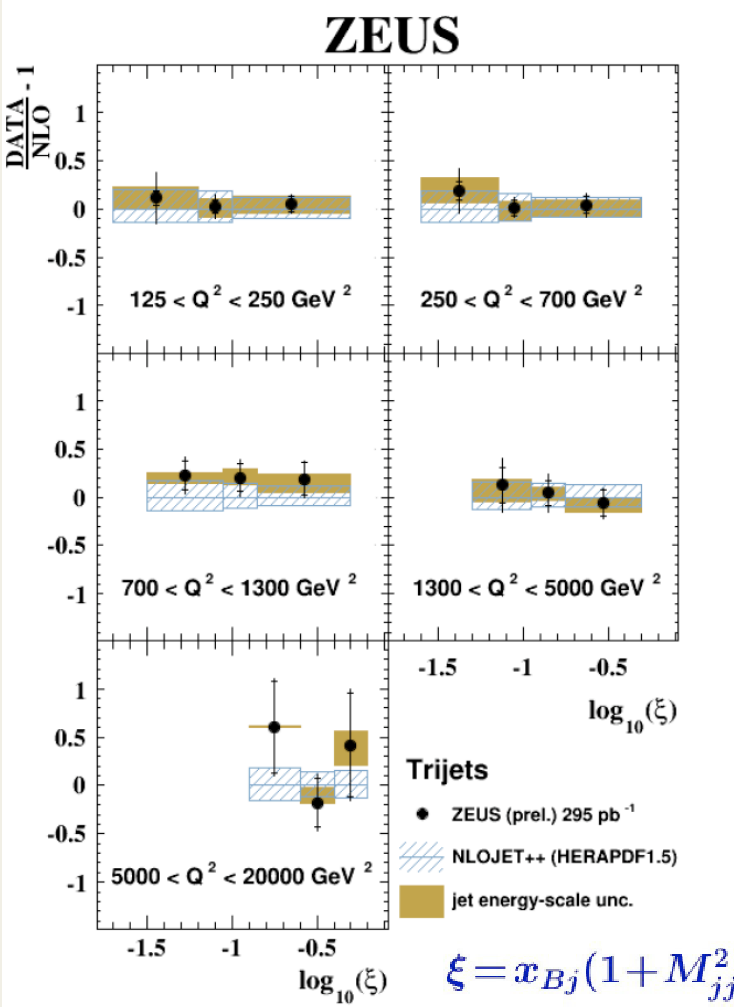




Data well described by NLO QCD calculations

Trijet measurements in DIS





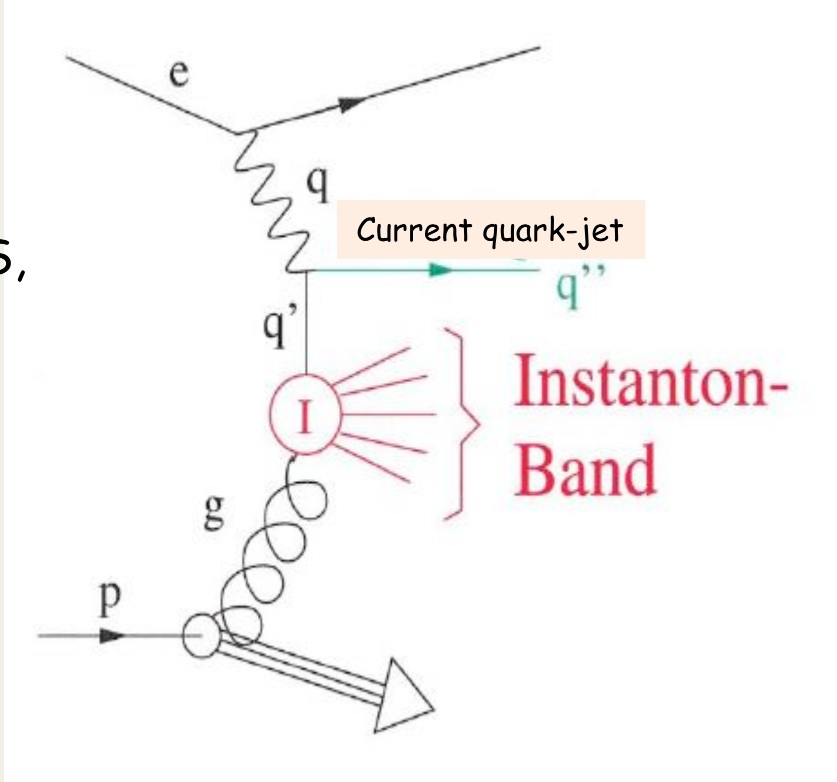
$$\xi = x_{Bj}(1 + M_{jjj}^2/Q^2)$$

the average transverse momentum of the three leading jets

Good agreement between data and NLO calculations

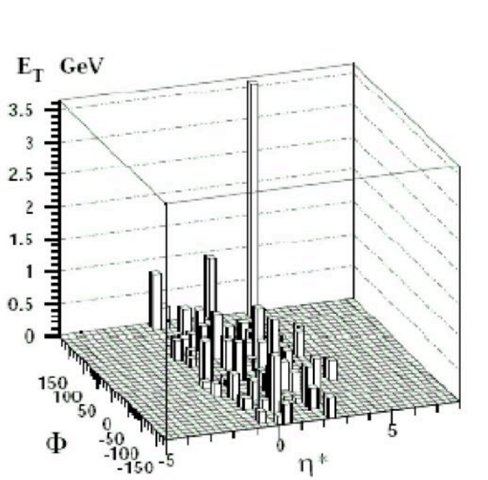
Search for Instantons

Confirmation of the non-perturbative QCD of SM?
Theory: for HERA σ ~ 10-100 pb
A.Ringwald,F.Schrempp a.o.



HERA I data – not observed by H1 and ZEUS, upper limits compatible with theory

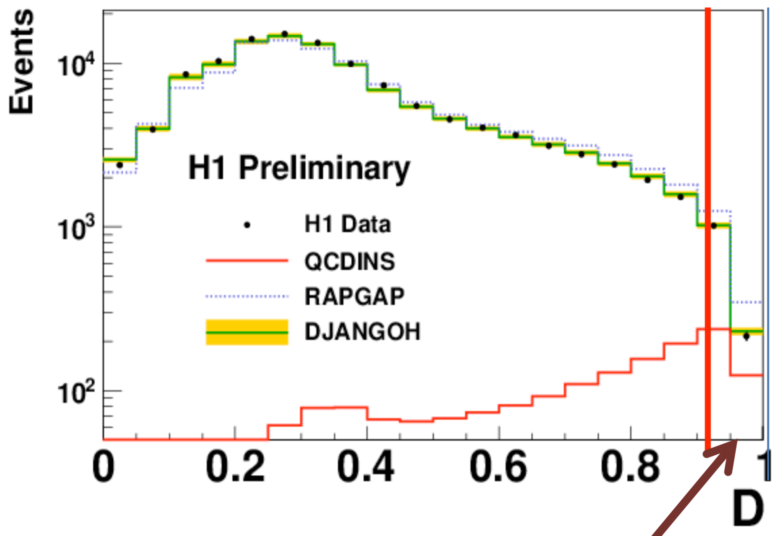
Signature:
- Hard current jet
- Instanton band – high multiplicity
- Isotropy in I rest frame
- Parton (u,d,s) democracy



Background needs to be reduced by at least 2 orders of magnitude

MultiVariate analysis
→ 5 variables
- good signal/background separation
- reasonable background description

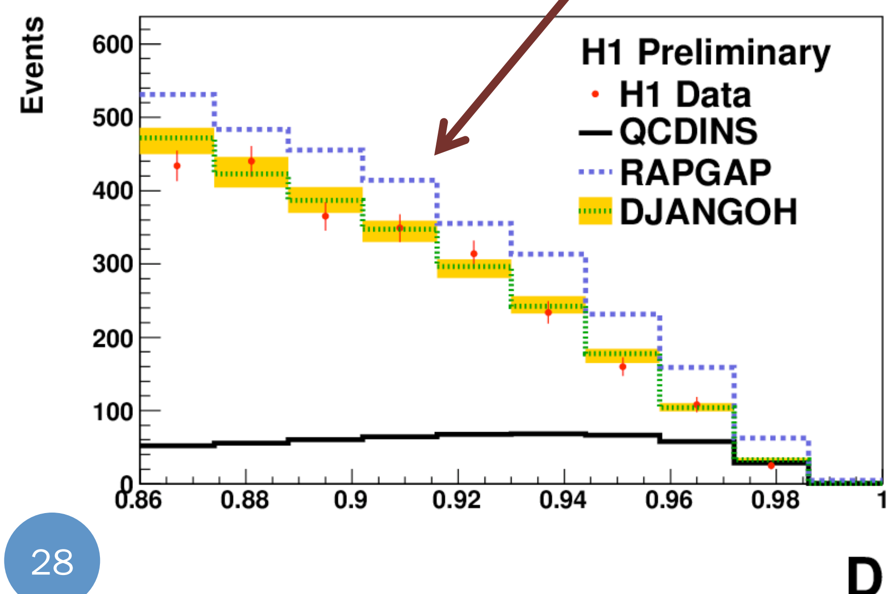
Search for Instantons



Multivariate analysis
Probability Density Estimator with Range Search (PDERS)

Training:
- RAPGAP, DJANGO - background
- QCDINS (Ringwald, Schremmp)-signal

Good description of discriminator in background region
Signal region
D > 0.86

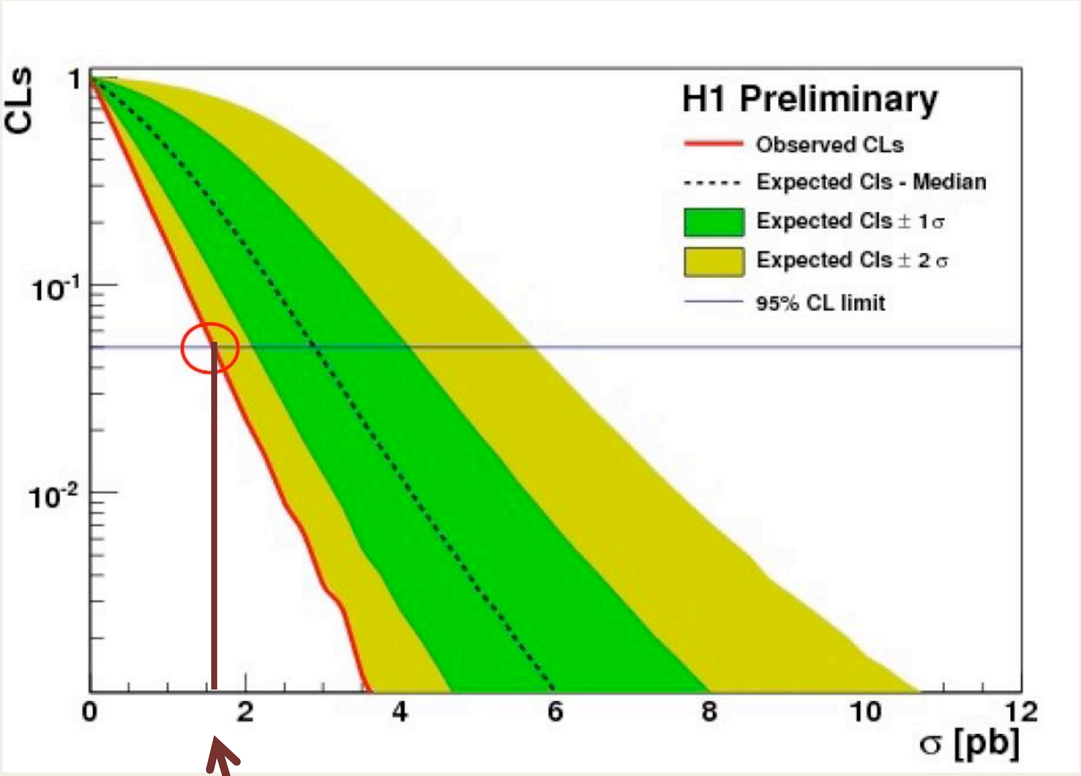


Expected Instanton signal >500 events corresponding to σ_{QCDINS}= 10 ± 2pb not seen

Upper limit?????

Search for Instantons

Confidence level distribution CLs & upper limit on the instanton cross section



Upper limit on the QCD instanton cross section obtained with PDERS method is

1.6 pb **at 96% C.L.**

QCD instanton cross section in the PS of the analysis 10±2pb

Conclusions

- Diffractive dijet DIS cross section agree well with QCD NLO calculations, QCD factorisation confirmed
- Diffractive dijet DIS and photoproduction (PH) with a leading proton compared to NLO, QCD factorisation breaking of ~ 0.5 observed in PH.
- The measurement of the shape of the azimuthal angular distributions of exclusive dijets in diffractive DIS prefers 2-gluon exchange model of $q\bar{q}$ production over Resolved Pomeron model.
- Prompt photon cross sections (measured with and without jet)described within large theoretical uncertainties by NLO and k_t factorisation
- Multijets DIS cross sections described by QCD NLO, the most precise value of α_s from jet cross sections obtained
- Trijet cross sections satisfactorily described by NLO QCD
- No evidence for instantons, upper limit <1.6 pb at 95%CL, Ringwald-Schrempp's solution appears to be excluded