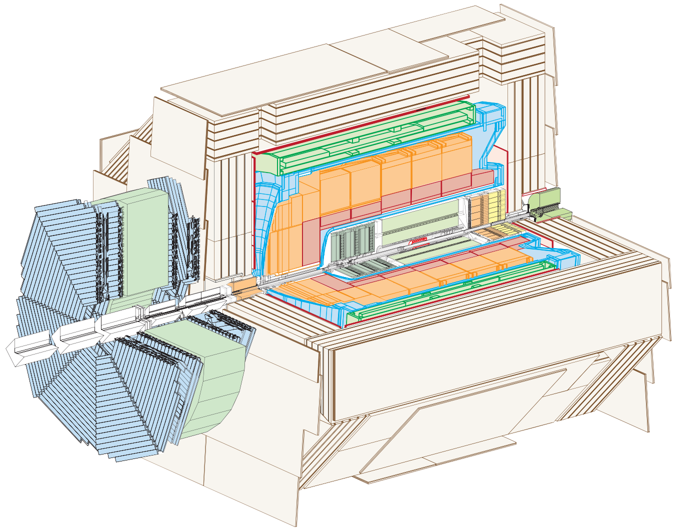
Precision Measurements, QCD and α_s

Roman Kogler

on behalf of the

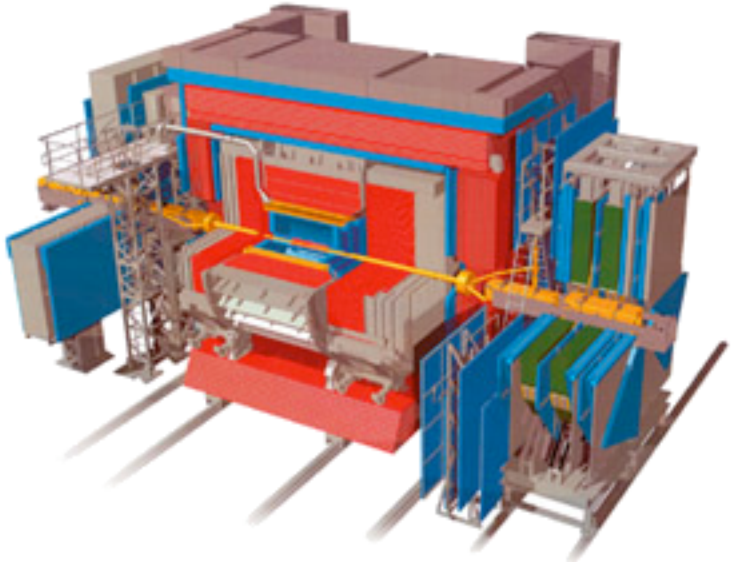
H1 and ZEUS collaborations



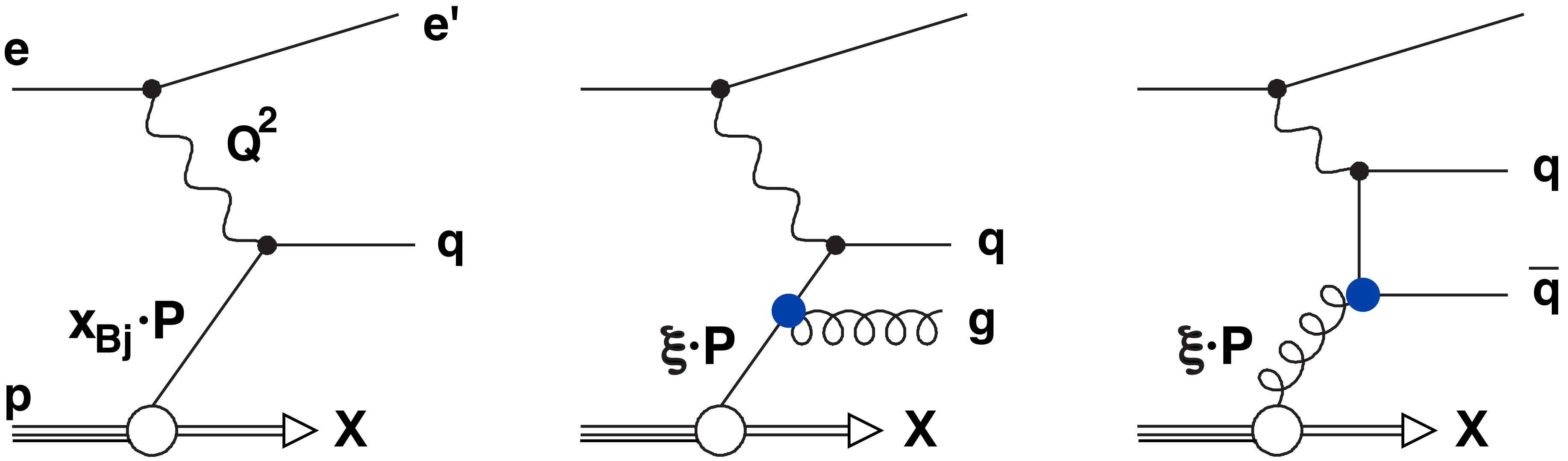
New Trends In HERA Physics

Ringberg Castle, Lake Tegernsee

September 26, 2011

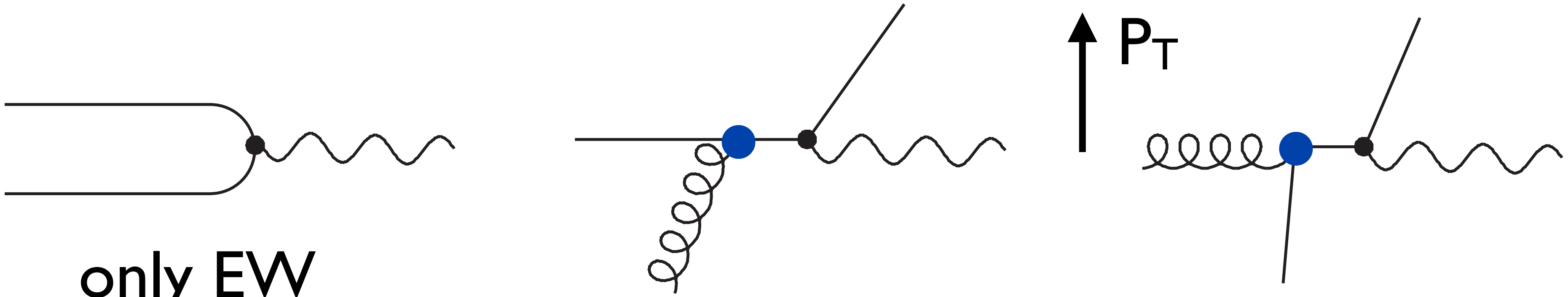


Jet Production in DIS in Leading Order



Momentum fraction of struck parton (in LO): $\xi = x\left(1+\frac{M_{12}^2}{Q^2}\right)$

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



only EW coupling

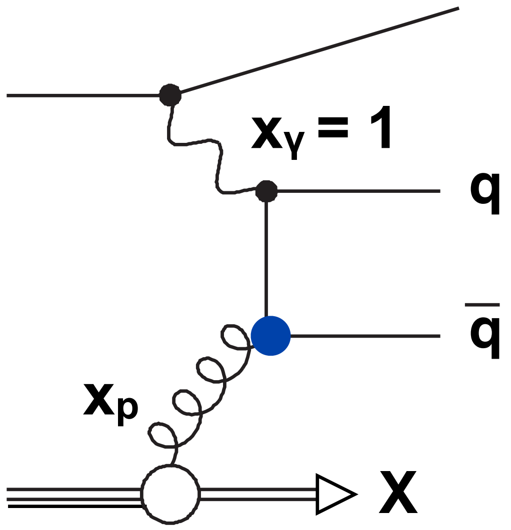
$\propto \alpha_s$

$\propto \alpha_s$

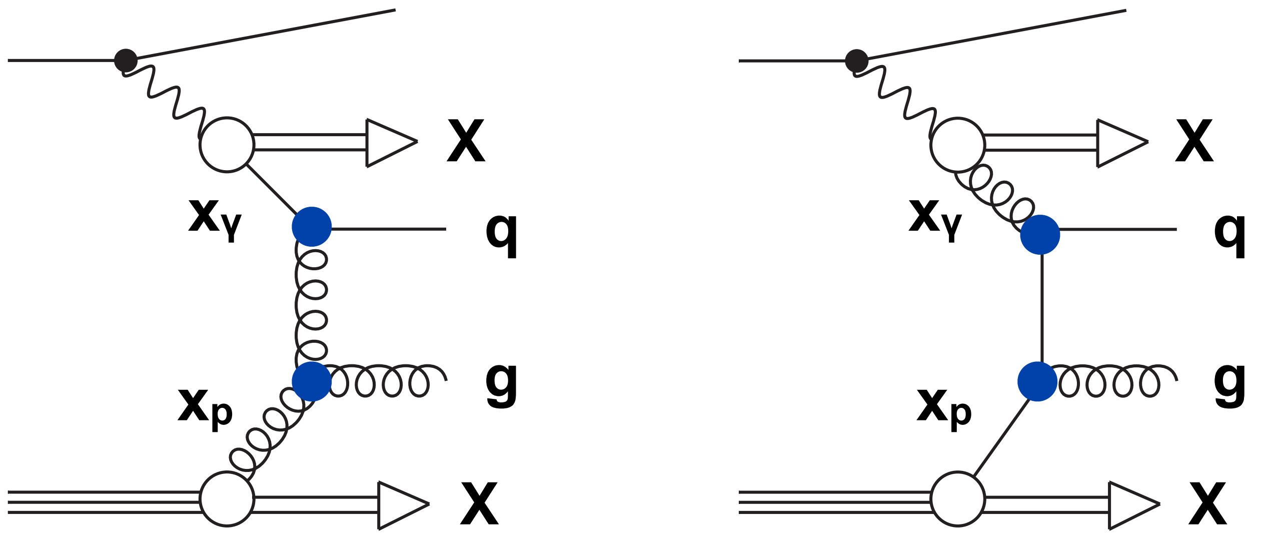
Only hard QCD processes generate considerable P_T in the Breit frame

Direct sensitivity to α_s and gluon PDF

Jet Production in γ*p in Leading Order



direct photoproduction



resolved photoproduction

Analysis in laboratory rest frame, momentum fractions x_p and x_γ not directly accessible, define LO observables:

Partonic momentum fraction of the photon: $x_\gamma^{\text{obs}} = \dfrac{E_T^{\text{jet1}} e^{-\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{-\eta^{\text{jet2}}}}{2yE_e}$

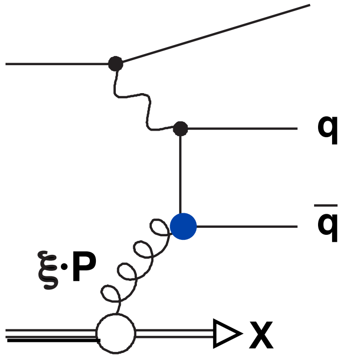
Partonic momentum fraction of the proton: $x_p^{\text{obs}} = \dfrac{E_T^{\text{jet1}} e^{\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{\eta^{\text{jet2}}}}{2E_p}$

Direct sensitivity to α_s, gluon and photon PDFs

Calculation of Jet Cross Sections

Series expansion in α_s of n-jet cross section in DIS:

$$\sigma^{ep}_{\mathrm{n-jet}} = \sum_m \alpha_s^m(\mu_r) \cdot \sum_{i=q,\bar{q},g} \int \mathrm{d}x f_{i/p}(x,\mu_f) \cdot \underline{\hat{\sigma}_i^m(x,\mu_r,\mu_f)}$$



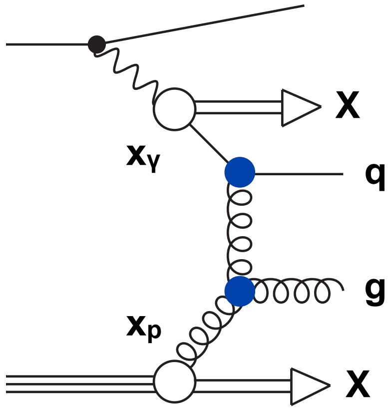
n-jet production in LO ∝ α_s^{n-1}

known up to NLO

In photoproduction:

$$\sigma^{\gamma p}_{\mathrm{n-jet}} = \sum_m \alpha_s^m(\mu_r) \sum_{i,j=q,\bar{q},g} \int \mathrm{d}x_p \int \mathrm{d}x_\gamma$$

$$f_{i/p}(x_p,\mu_f) f_{j/\gamma}(x_\gamma,\mu_f) \cdot \underline{\hat{\sigma}_{ij}^m(x_p,x_\gamma,\mu_r,\mu_f)}$$

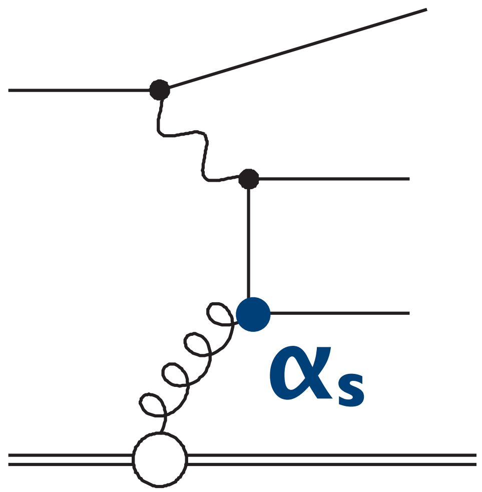


Photon flux: Weizsäcker-Williams approximation

Direct case: $f_{j/\gamma}(x_\gamma,\mu_f) = \delta(x_\gamma - 1)$

n-jet production in LO ∝ α_s^{n-1} (direct) and α_s^{n} (resolved)

Determination of $\alpha_s(M_Z)$ (H1)



NLO calculation depends on PDF and $\alpha_s(M_Z)$

⇒ Keep PDF fixed and fit $\alpha_s(M_Z)$

⇒ Neglect correlation between gluon and α_s

Hessian method: Minimise $\chi^2(\alpha_s)$

$$\chi^2 = \sum_{i=1}^{N} \frac{[d_i - t_i(1 - \sum_k \epsilon_k \Delta_{ik})]^2}{\sigma^2_{i,\mathrm{stat}} + \sigma^2_{i,\mathrm{uncorr}}} + \sum_k \epsilon_k^2$$

d_i ... measured cross section in bin i

t_i ... theoretical prediction for bin i obtained with FastNLO (based on NLOJet++)

$\sigma_{i,\mathrm{stat}}$ ... statistical uncertainty in bin i

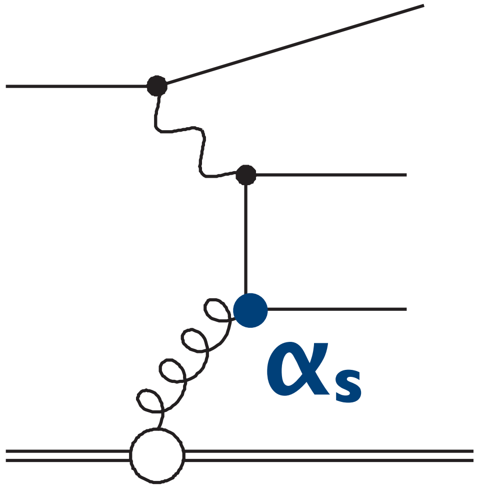
$\sigma_{i,\mathrm{uncorr}}$ ... uncorrelated systematic uncertainty in bin i

Δ_{ik} ... effect of correlated systematic uncertainty k in bin i

ε_k ... free variables of the fit, one for each correlated uncertainty

Statistical correlations taken into account in case of inclusive jet cross sections

Determination of $\alpha_s(M_Z)$ (H1)



NLO calculation depends on PDF and $\alpha_s(M_Z)$

⇒ Keep PDF fixed and fit $\alpha_s(M_Z)$

⇒ Neglect correlation between gluon and α_s

Hessian method: Minimise $\chi^2(\alpha_s)$

$$\chi^2 = \sum_{i=1}^{N} \frac{[d_i - t_i(1 - \sum_k \epsilon_k \Delta_{ik})]^2}{\sigma^2_{i,\mathrm{stat}} + \sigma^2_{i,\mathrm{uncorr}}} + \sum_k \epsilon_k^2$$

- Experimental uncertainty obtained by $\chi^2 = \chi^2_{\min} + 1$
- Theoretical uncertainty obtained by offset method:
  - Repeat fit for μ_r and μ_f varied by a factor of $1/2$ and 2
- PDF uncertainty calculated with PDF eigenvalues
- Consistency with PDF sets with varied $\alpha_s(M_Z)$ checked

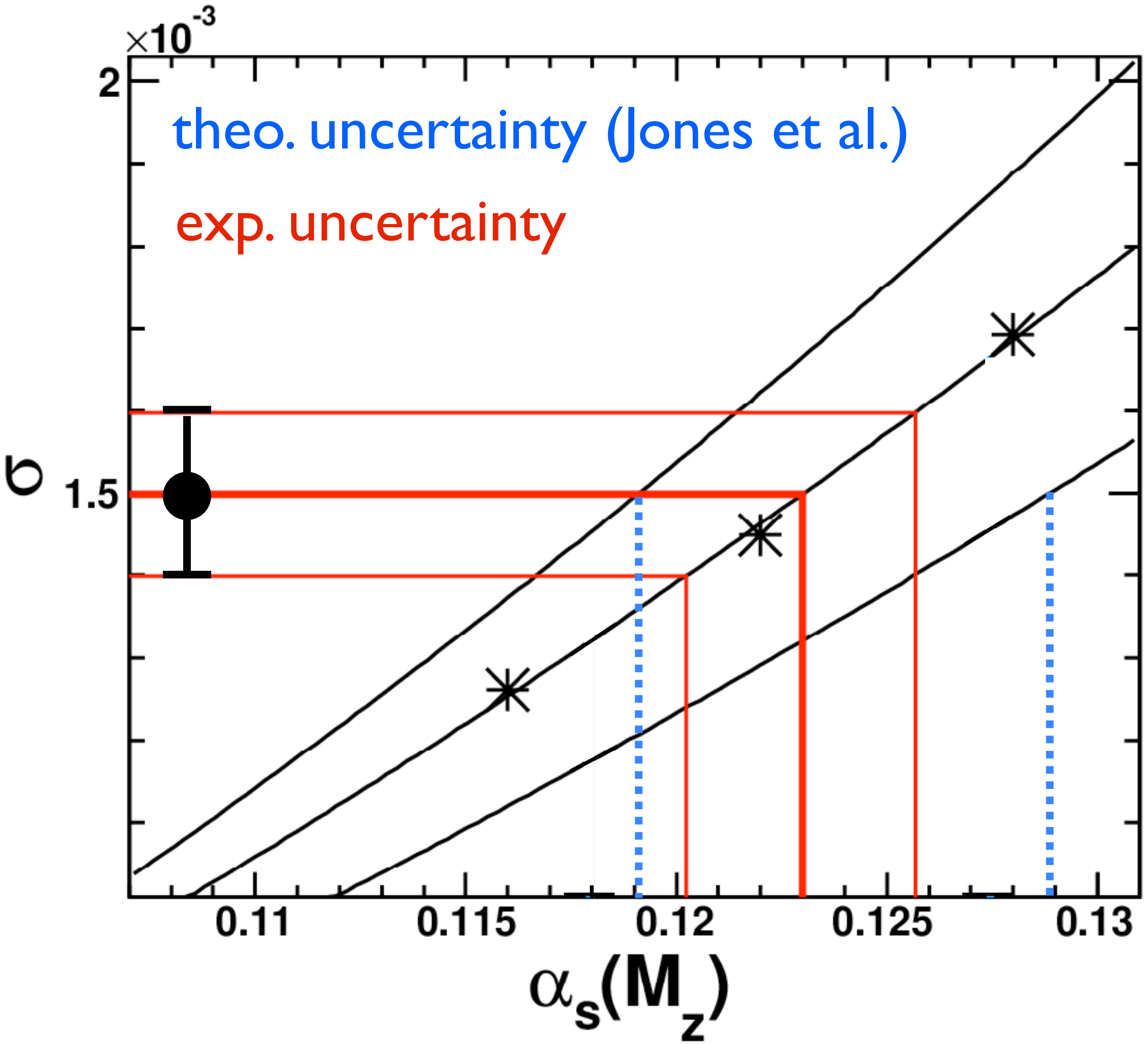
Determination of $\alpha_s(M_Z)$ (ZEUS)

⇒ Calculate cross section for different values of $\alpha_s(M_Z)$, using sets of PDFs with different assumptions on $\alpha_s(M_Z)$

⇒ Parametrise α_s dependence of cross section dσ/dA, using second order polynomials in α_s:

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}A}\right|_i = C_1\ \alpha_s(M_Z) + C_2\ \alpha_s^2(M_Z)$$

⇒ Map measured dσ/dA to parametrisation to obtain $\alpha_s(M_Z)$

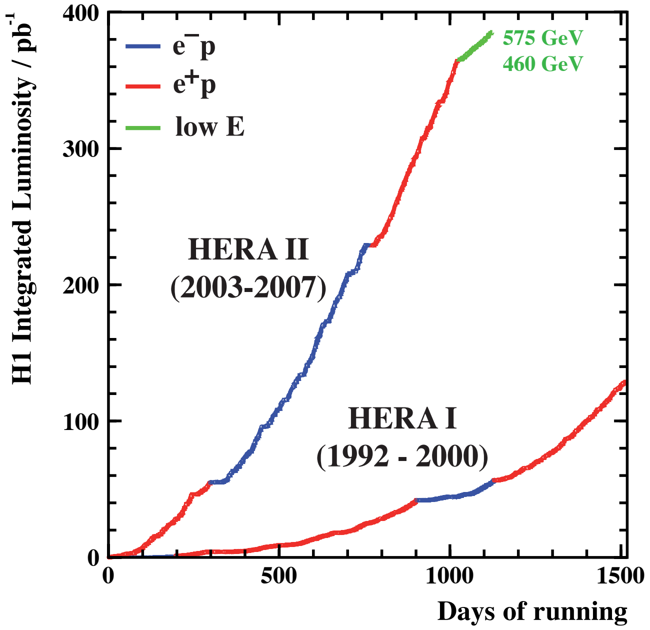


Possibility to fit many data points with χ^2 method

Theoretical uncertainties obtained with Jones et al. method

Precision Jet Measurements at HERA

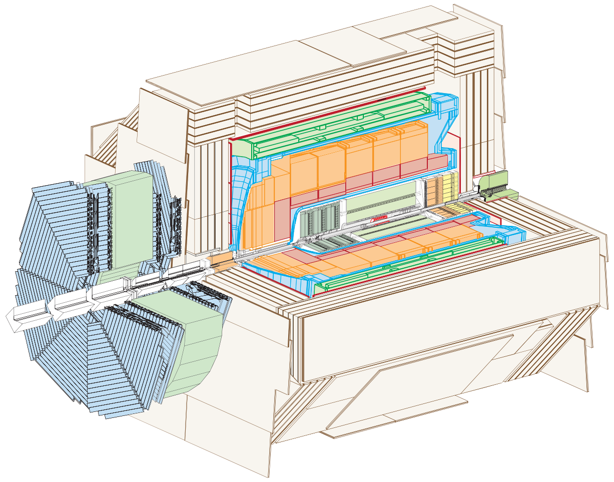
HERA-2 jet measurements



High statistics

L = 300-500 pb^{-1}: small statistical uncertainties, even at high Q^2 and high P_T

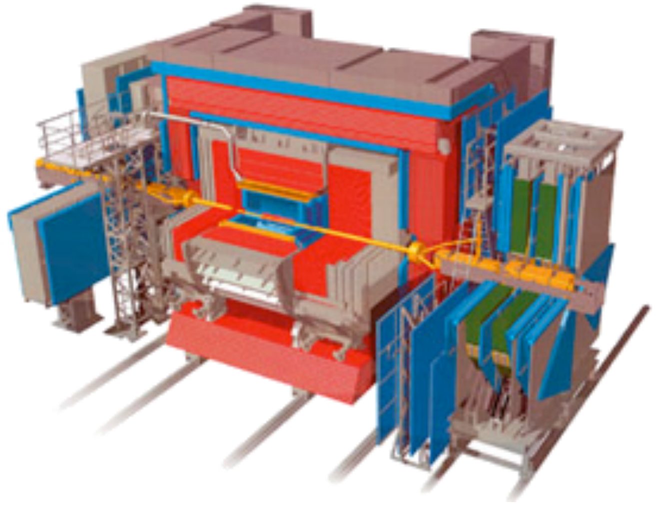
Excellent control over systematic uncertainties



electron measurement: 0.5 – 1% scale uncertainty

jet energy scale: 1% uncertainty!
effect on jet cross sections: 3 – 10%

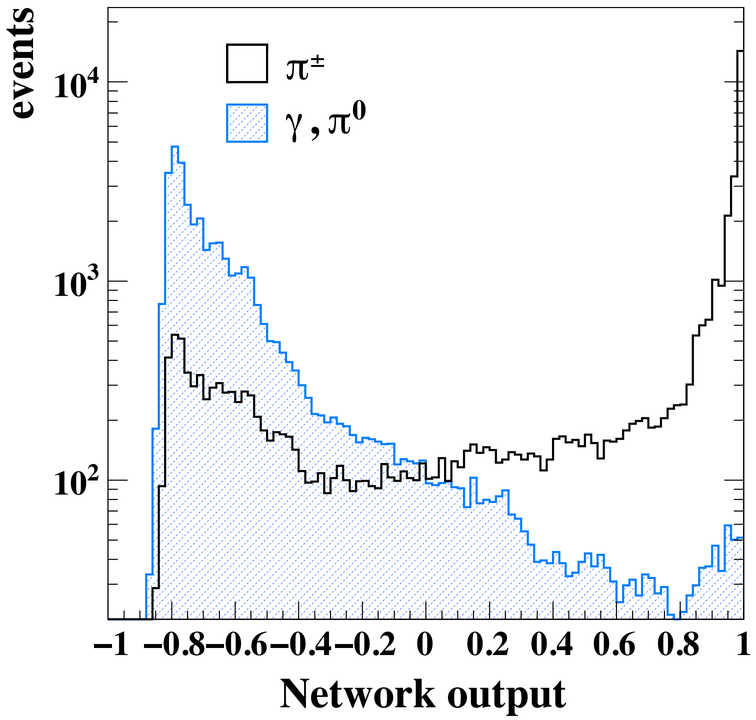
acceptance correction:
4 – 5% uncertainty



trigger: 1 – 2% normalisation uncertainty

luminosity: 2 – 2.5% normalisation uncertainty

Jet Energy Scale Uncertainty at H1

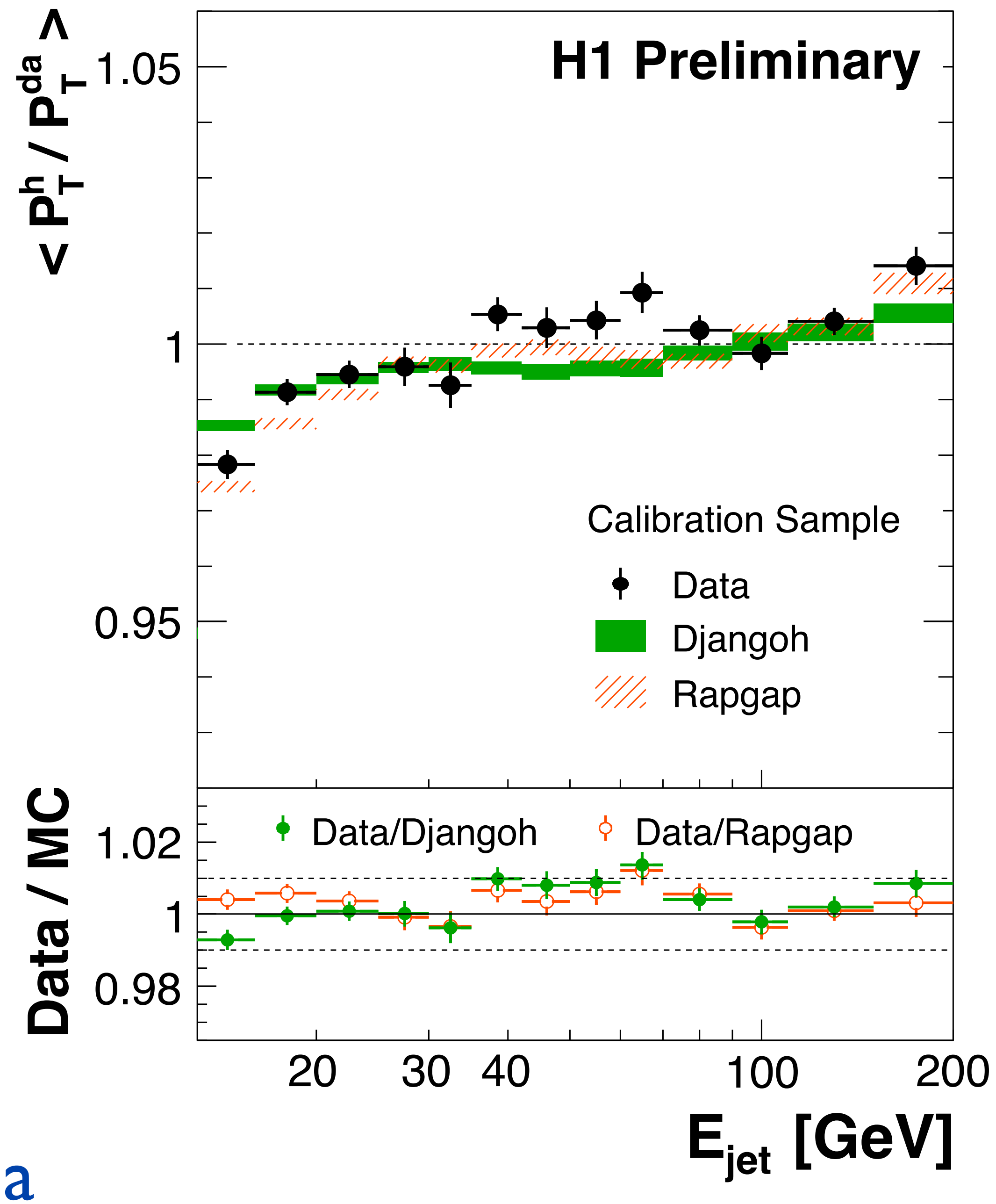


Neural networks employed to separate electromagnetic from hadronic showers in the LAr calorimeter

Calibration takes the probability of clusters to originate from electromagnetic showers into account

⇒ Improved resolutions

⇒ Jet Energy Scale uncertainty of 1% over a large range in energy and pseudorapidity



Jet Observables - Overview

Inclusive Jet

Jet-based counting, each jet satisfying phase space cuts contributes to the cross section

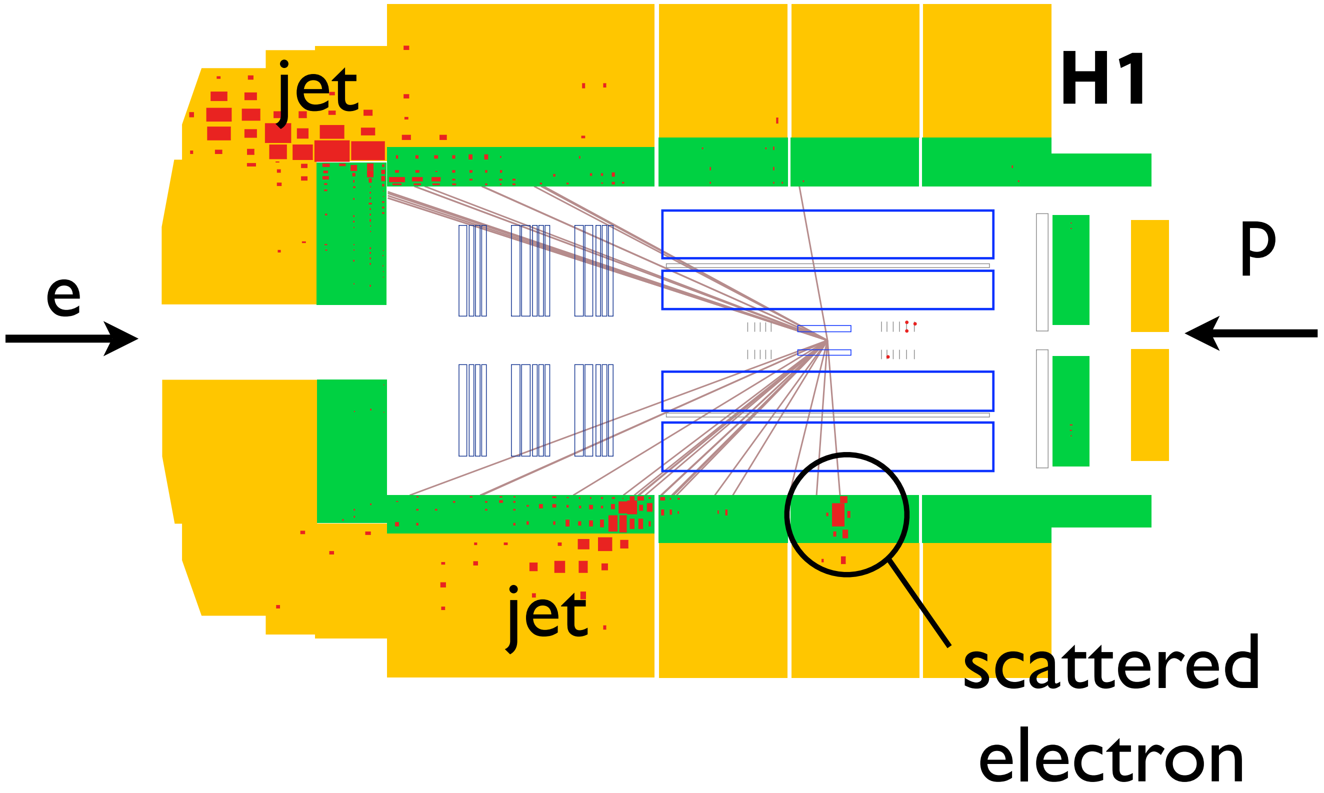
Dijet and Trijet

Event-based counting, events containing 2 (or 3) jets contribute to the cross section

Jet algorithms

Usual choice at HERA: inclusive k_T algorithm with $R_0 = 1$

Also studies with anti-k_T and SISCone performed recently



Q^2 ... virtuality of exchanged boson

y ... inelasticity

η_{lab} ... jet pseudorapidity in lab frame

P_T ... jet transverse momentum in Breit (or lab) frame

M_{12} ... invariant mass of two leading jets

Recent Jet Measurements at HERA

Photoproduction

$Q^2 \approx 0$

(no scat. electron)

$0.2 < y < 0.85$

high jet P_T:

$P_T > 17$ GeV,
up to $P_T \approx 75$ GeV

Jets at low Q^2

$5 < Q^2 < 100$ GeV^2

$0.2 < y < 0.7$

$P_T > 5$ (7) GeV

high statistics

large theoretical uncertainties

Jets at high Q^2

$125 < Q^2 < 20000$ GeV^2

$0.2 < y < 0.7$
or
$|\cos \gamma_h| < 0.65$

$P_T > 5$ (8) GeV

small theoretical uncertainties

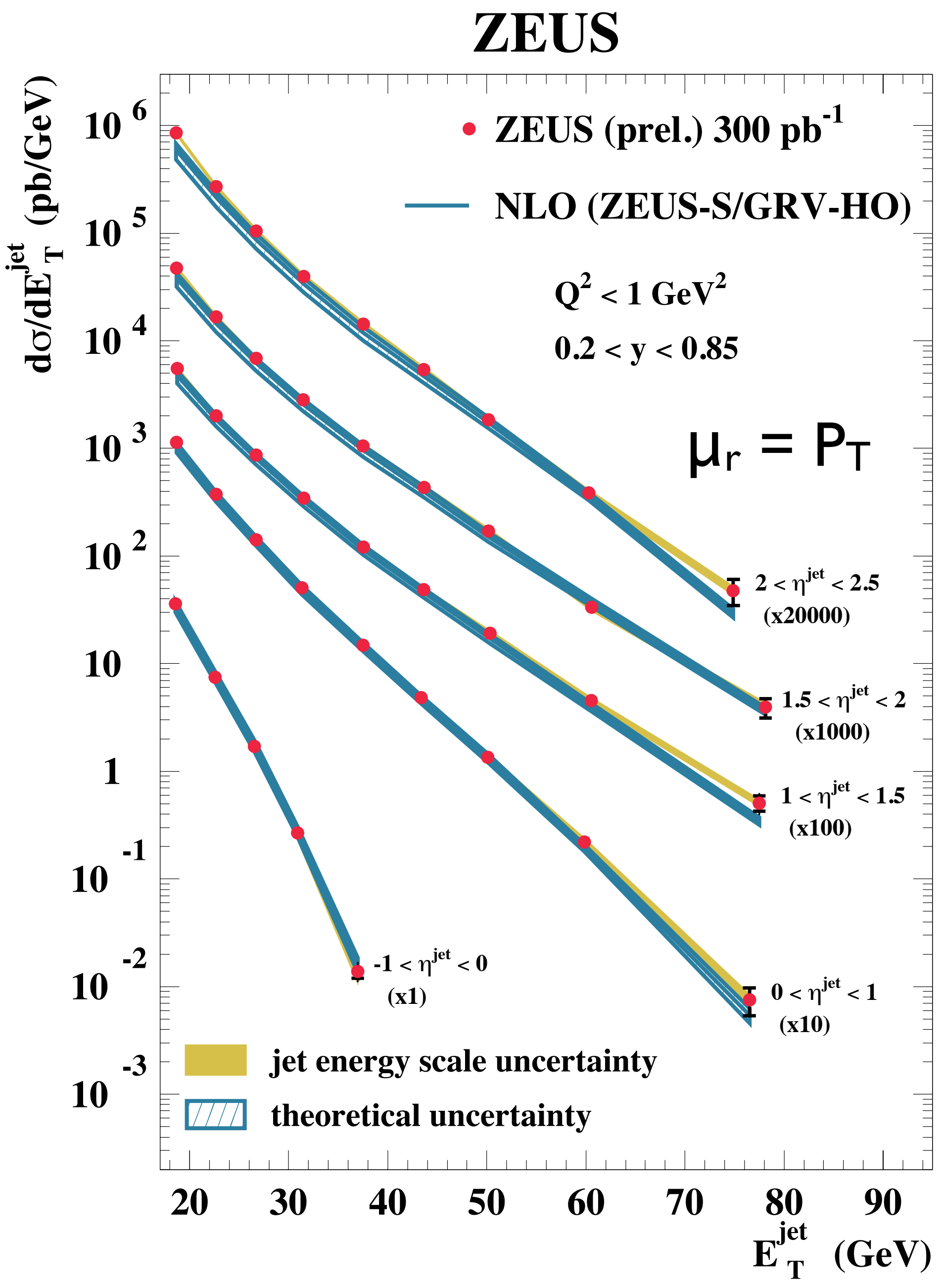
Accessible jet pseudorapidity range: $-1.0 < \eta < 2.5$

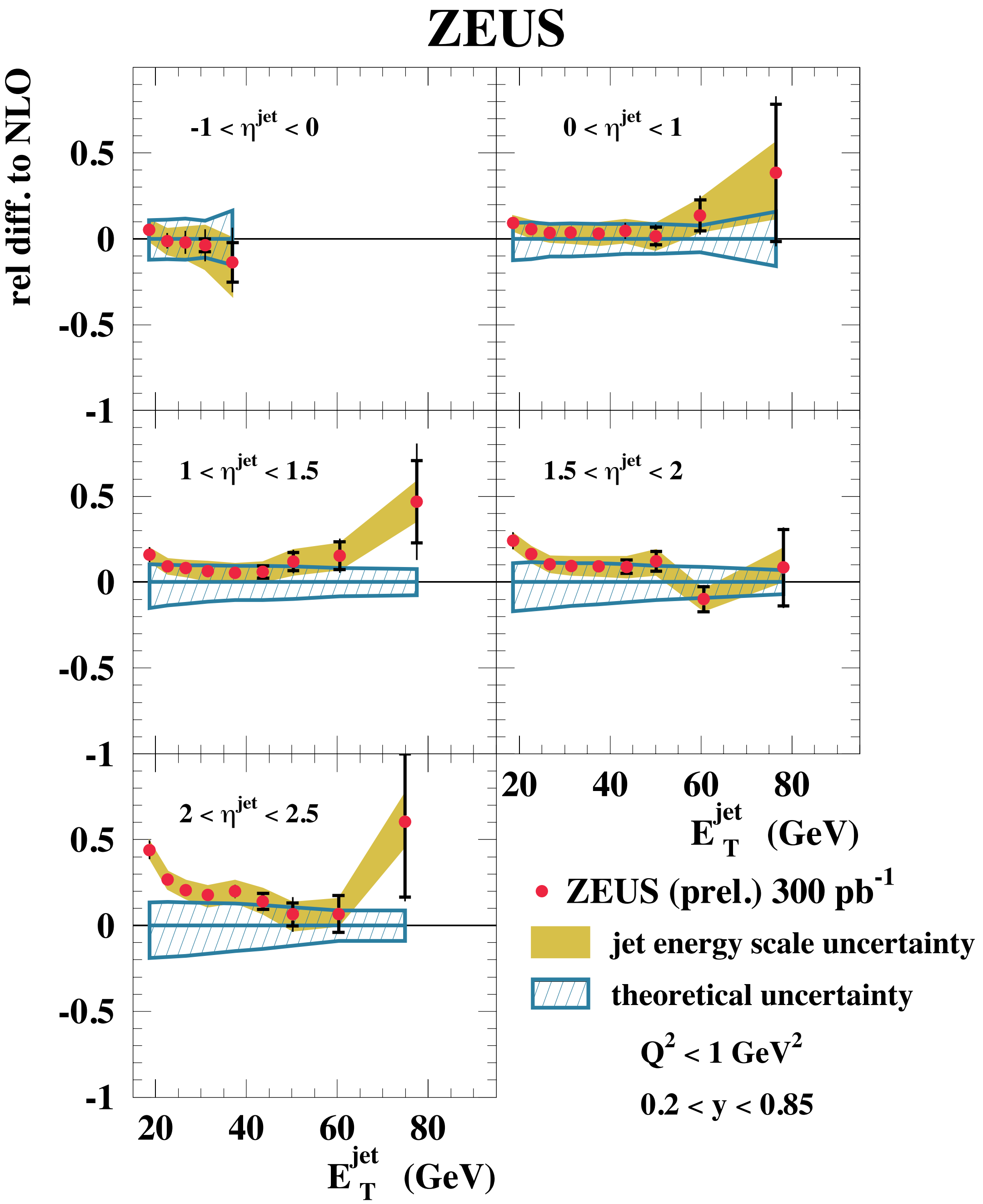
Hadronisation corrections: 5 – 10%, obtained with LO+PS MCs

pQCD calculations at NLO: NLOJet++ (DIS)
Klasen, Kleinwort, Kramer (PhP)

Inclusive Jets in Photoproduction

ZEUS-Prel-11-005

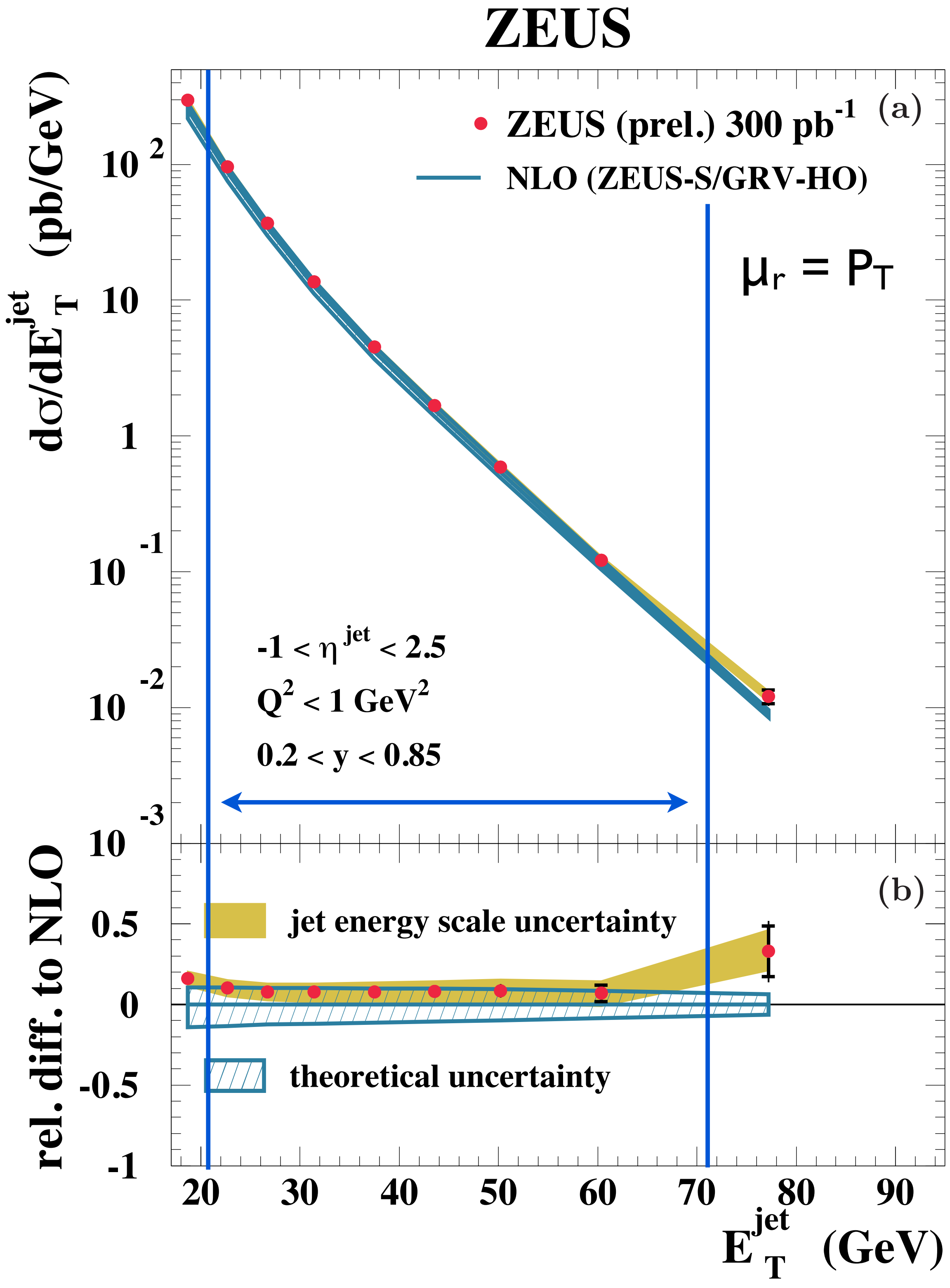




- Double-differential measurement in P_T and η
- Good description by NLO calculations, except for high η, low P_T region

α_s From Inclusive Jets in PhP

ZEUS-Prel-11-005



- Use single differential $d\sigma / dP_T$ measurement for extraction of $\alpha_s(M_Z)$
- Restricted range to avoid phase space where NLO does not describe the data: $21 < P_T < 71$ GeV

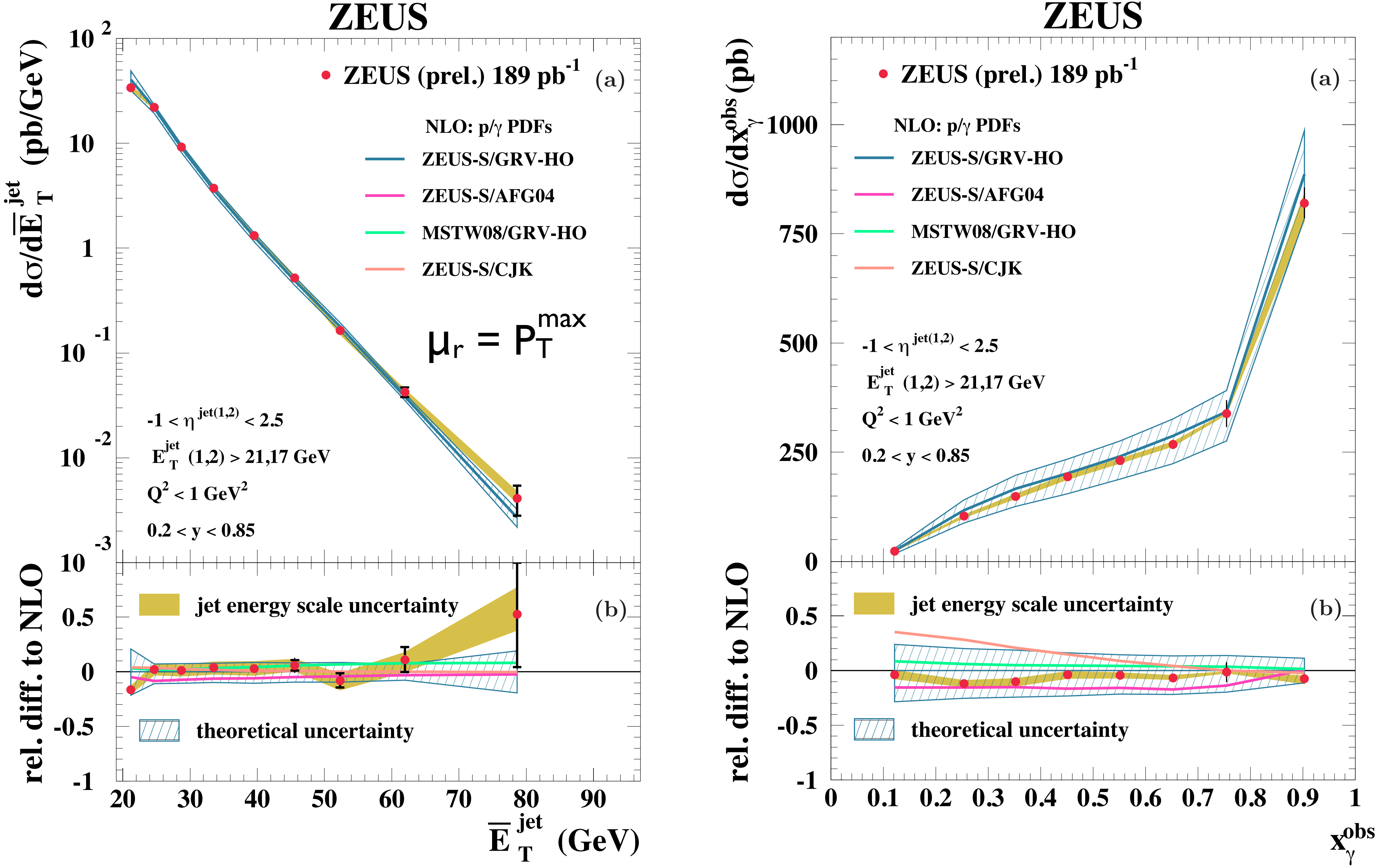
$$\alpha_s(M_Z) = 0.1206 \; {}^{+0.0023}_{-0.0022} \, (\text{exp.}) \; {}^{+0.0042}_{-0.0033} \, (\text{th.})$$

Uncertainties due to...

... jet energy scale:	1.8%
... terms beyond NLO:	2.5%
... photon PDF:	2.3%
... proton PDF:	1.0%

Dijets in Photoproduction

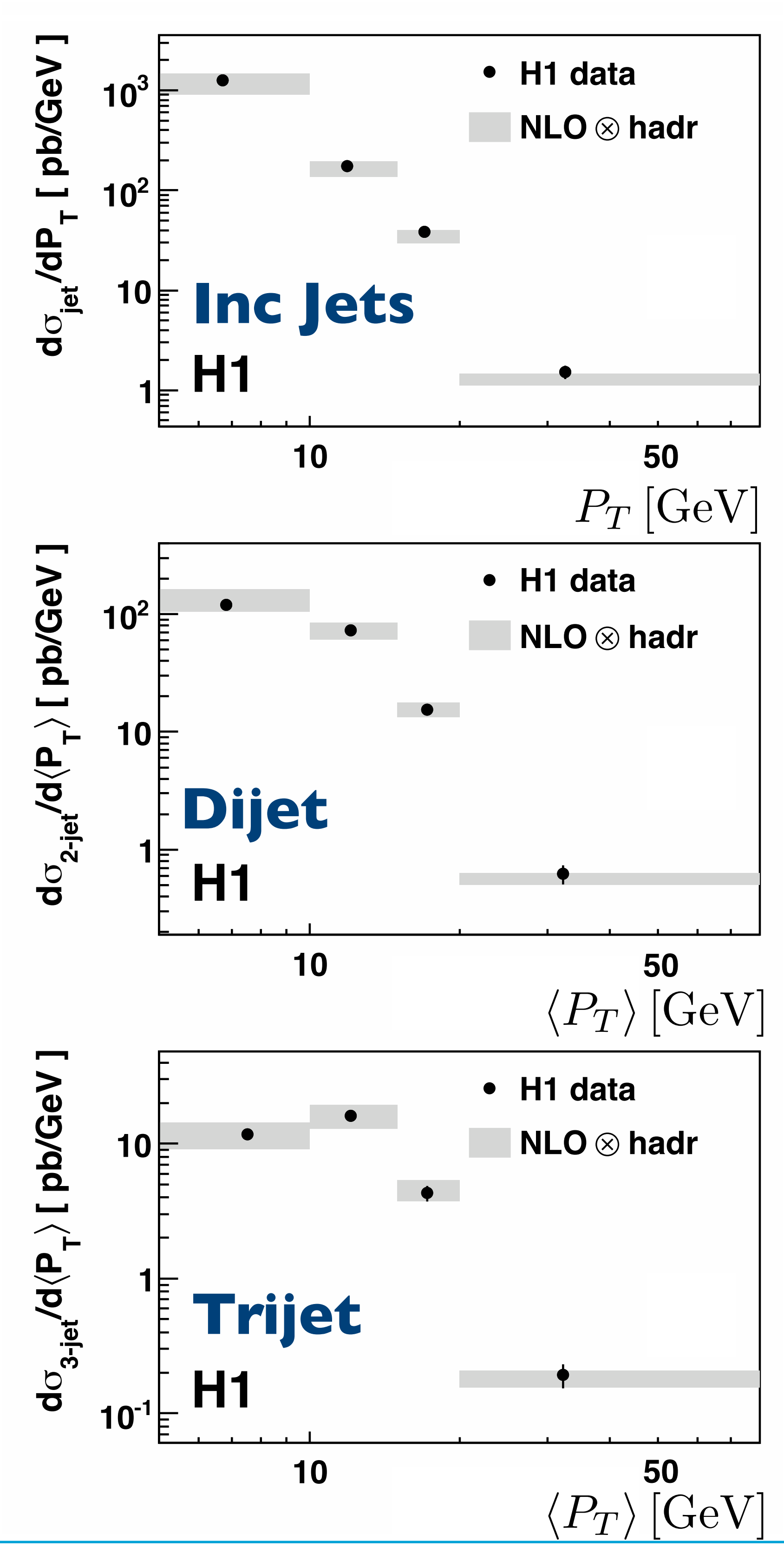
ZEUS-Prel-10-014



- Single-differential measurement in $\langle P_T \rangle$, $\langle \eta \rangle$, x_γ, M_{jj} and $|\cos\theta^*|$
- Good description by NLO calculations, no $\alpha_s(M_Z)$ determination yet
- Possibility to constrain photon PDFs

Multi-Jet Cross Sections At Low Q^2

EPJ C67, 1 (2010)

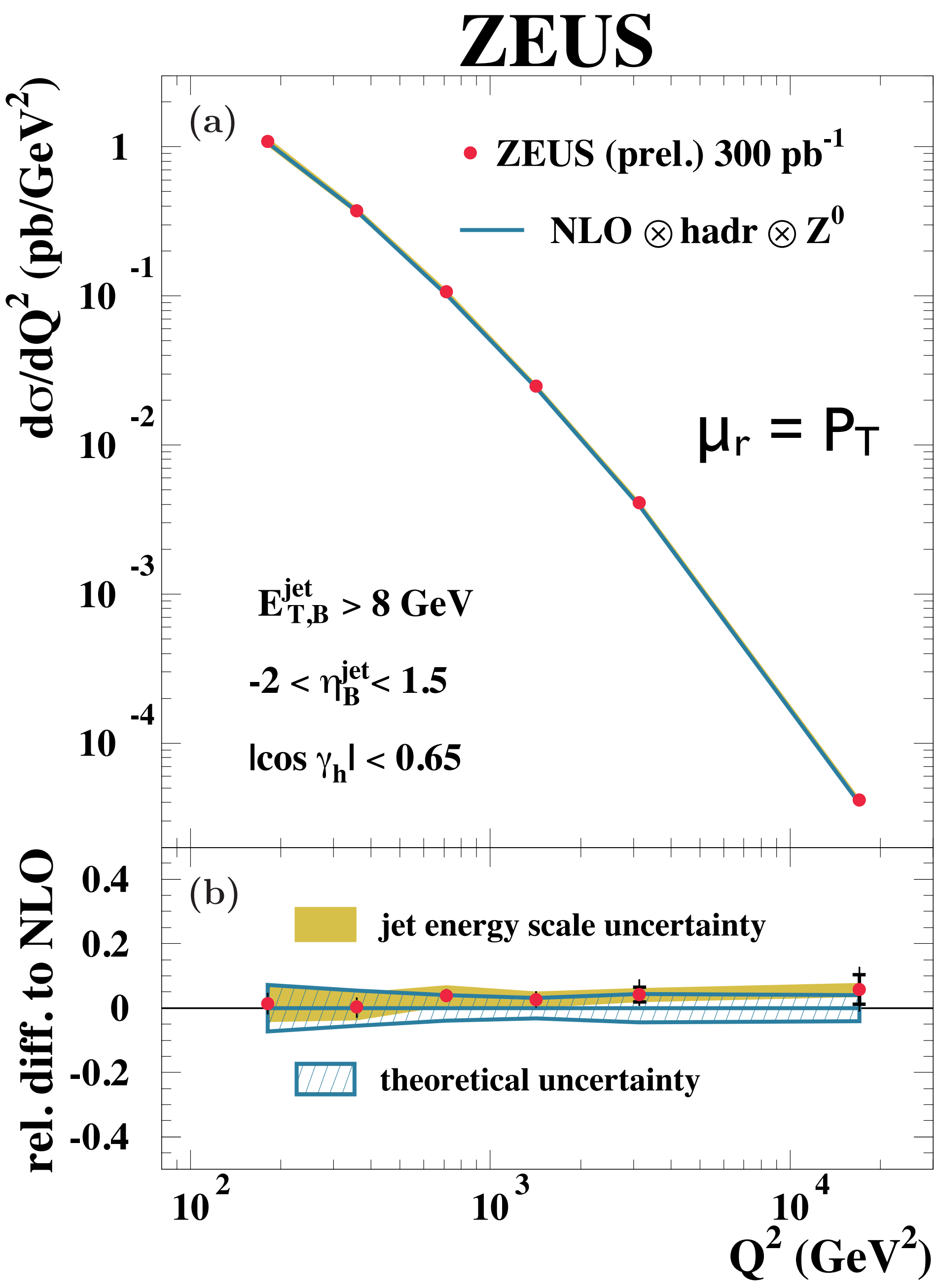


- Measurement based on HERA-1 data
- Double-differential inclusive jet, dijet and trijet measurement, small experimental uncertainties of 6 – 10 %
- Data well described by NLO, $\mu_r = \sqrt{(Q^2 + P_T^2)/2}$ theoretical uncertainties dominated by missing higher orders:
  30% at low Q^2, P_T and 10% at high Q^2, P_T
- choice of $\mu_r = \langle P_T \rangle$ disfavoured by data
- Simultaneous $\alpha_s(M_Z)$ fit to 62 data points:

$$\boxed{\alpha_s(M_Z) = 0.1160 \pm 0.0014(\text{exp.})\ {}^{+0.0093}_{-0.0077}(\text{th.}) \pm 0.0016(\text{pdf})}$$

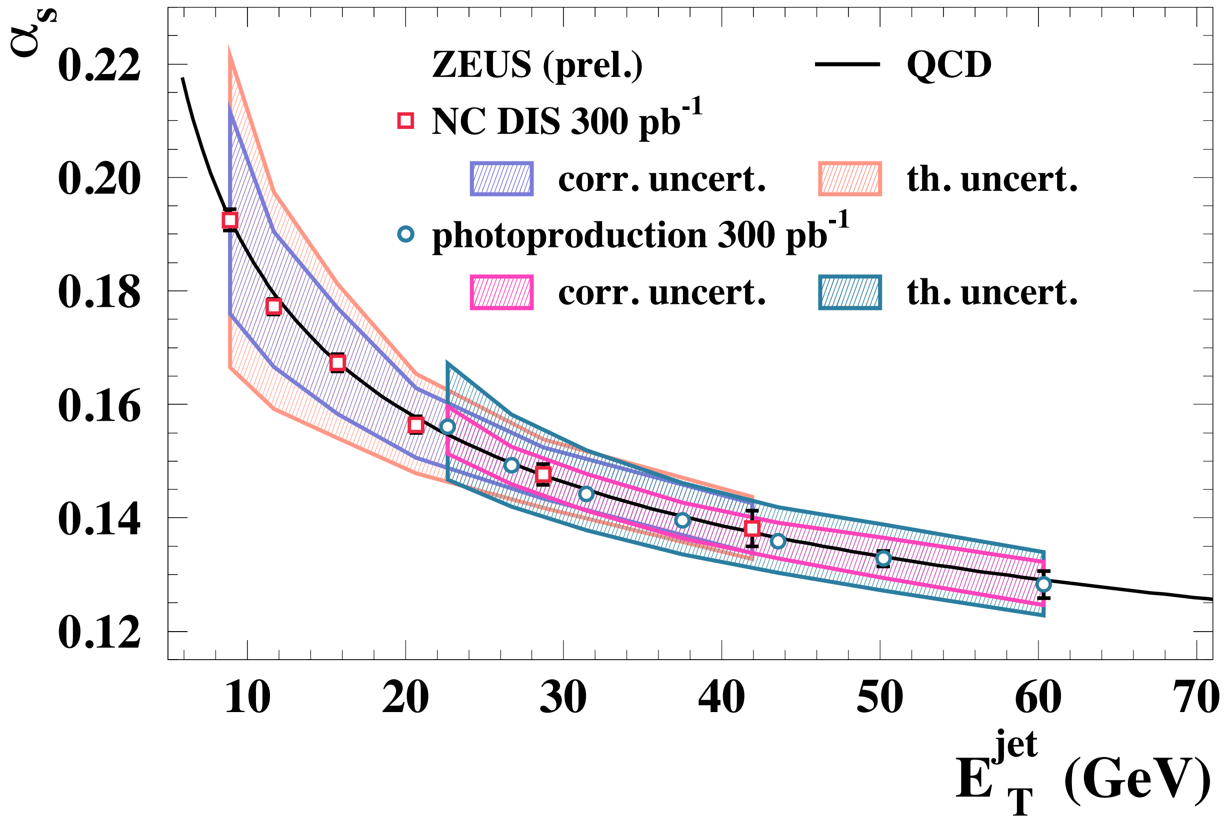
Inclusive Jet Production At High Q²

ZEUS-prel-10-002



- single- and double-differential cross sections as function of Q^2 and P_T
- $\alpha_s(M_Z)$ fit to data 4 points with $Q^2 > 500$ GeV^2

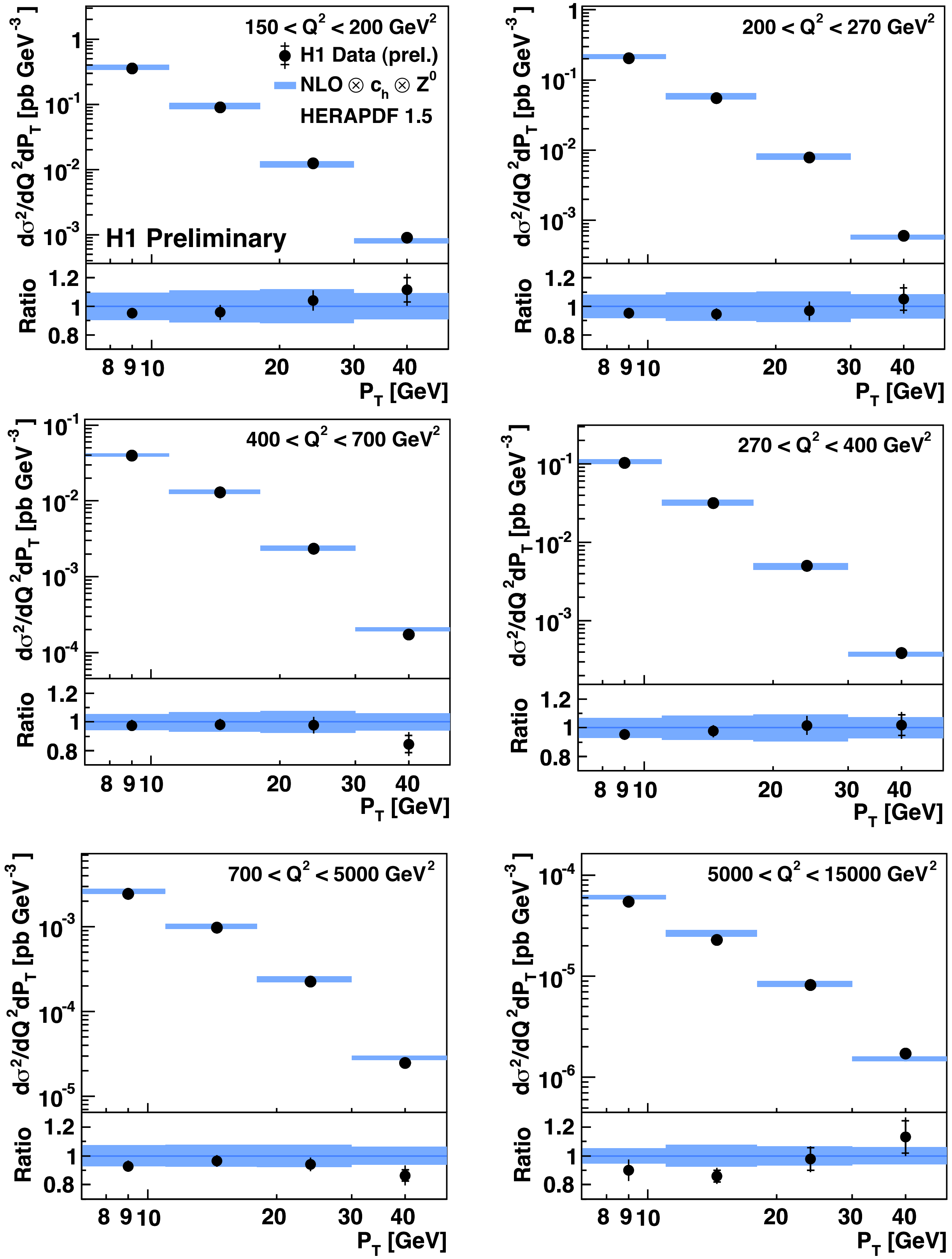
$$\alpha_s(M_Z) = 0.1208 \begin{array}{l} +0.0036 \\ -0.0031 \end{array} (\mathrm{exp.}) \begin{array}{l} +0.0022 \\ -0.0022 \end{array} (\mathrm{th.})$$



Running of $\alpha_s(\mu_r)$ from NC DIS and photoproduction from a single experiment

Inclusive Jet Production At High Q^2

H1prelim-11-032



- Data are well described by NLO calculations over large range in Q^2 and P_T with $\mu_r = \sqrt{(Q^2 + P_T^2)/2}$

- Independent test of gluon PDF in HERAPDF1.5

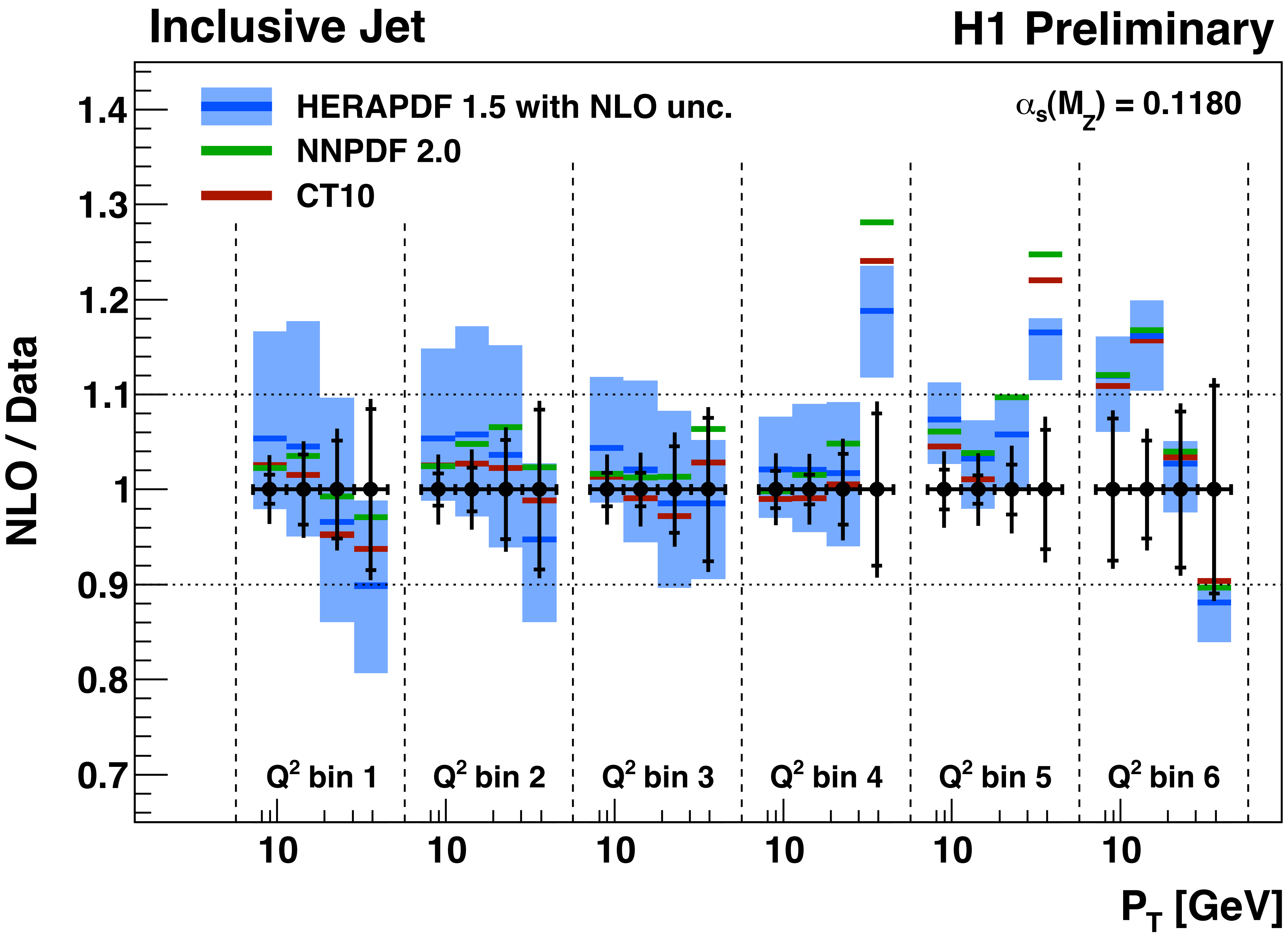
- Experimental uncertainty about half the size of theoretical uncertainty

- $\alpha_s(M_Z)$ fit to all 24 data points

$$\boxed{\begin{aligned}\alpha_s(M_Z) = 0.1190 &\pm 0.0021\ (\text{exp.})\\ &\pm 0.0020\ (\text{pdf})\\ &{}^{+0.0050}_{-0.0056}\ (\text{th.})\end{aligned}}$$

Comparison With Different PDFs

H1prelim-11-032



Central predictions for different PDFs shown

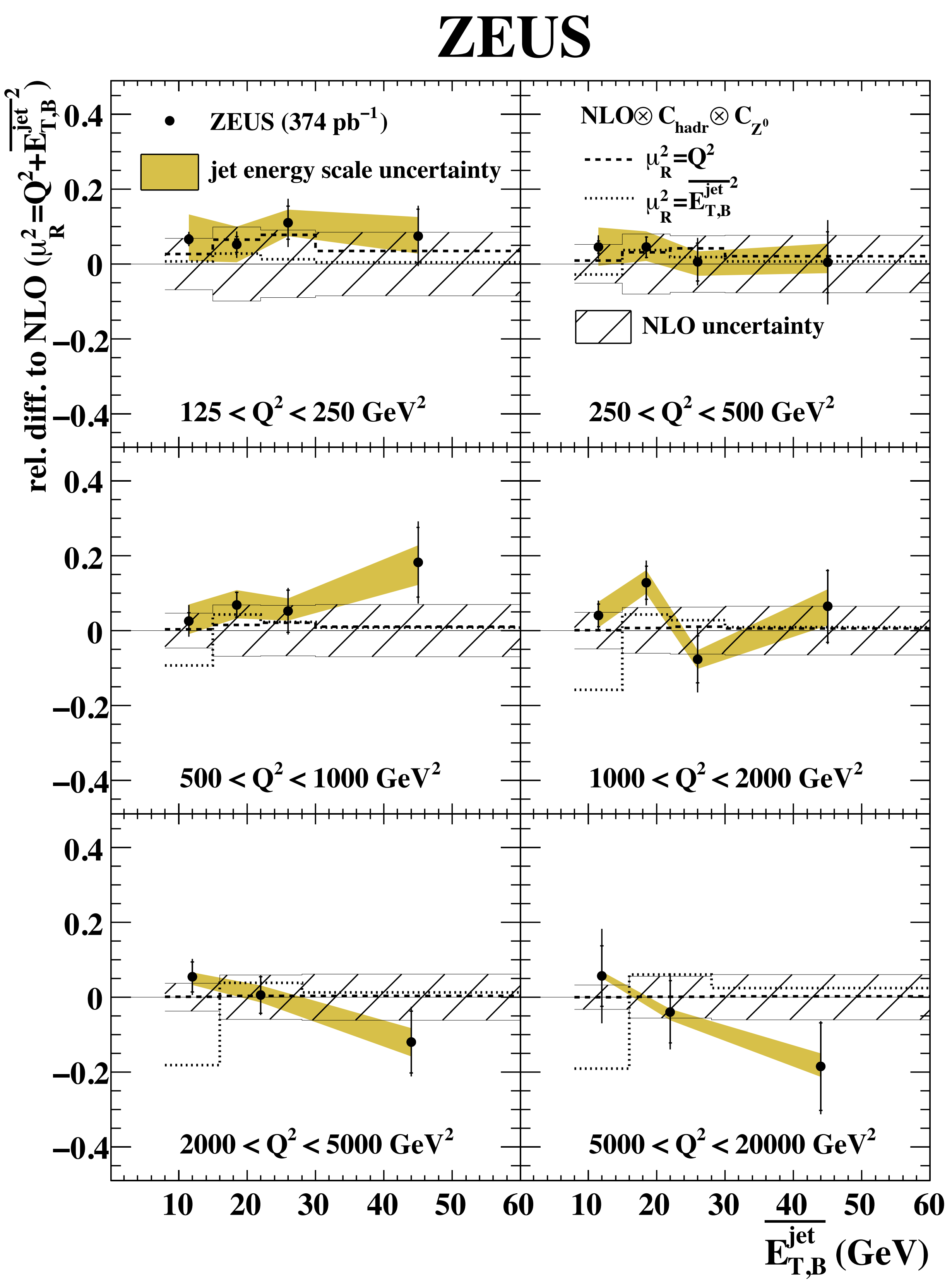
Different x regions of gluon and valence distributions probed in different regions of Q^2 and P_T

Differences small in most regions of phase space, visible differences at high P_T

HERA jet data will provide important input for PDF determinations

Dijet Production At High Q^2

EPJ C70, 965 (2010)



- high-precision measurement, experimental uncertainty about half the size of theoretical uncertainties
- NLO calculations for three different choices of scale shown:

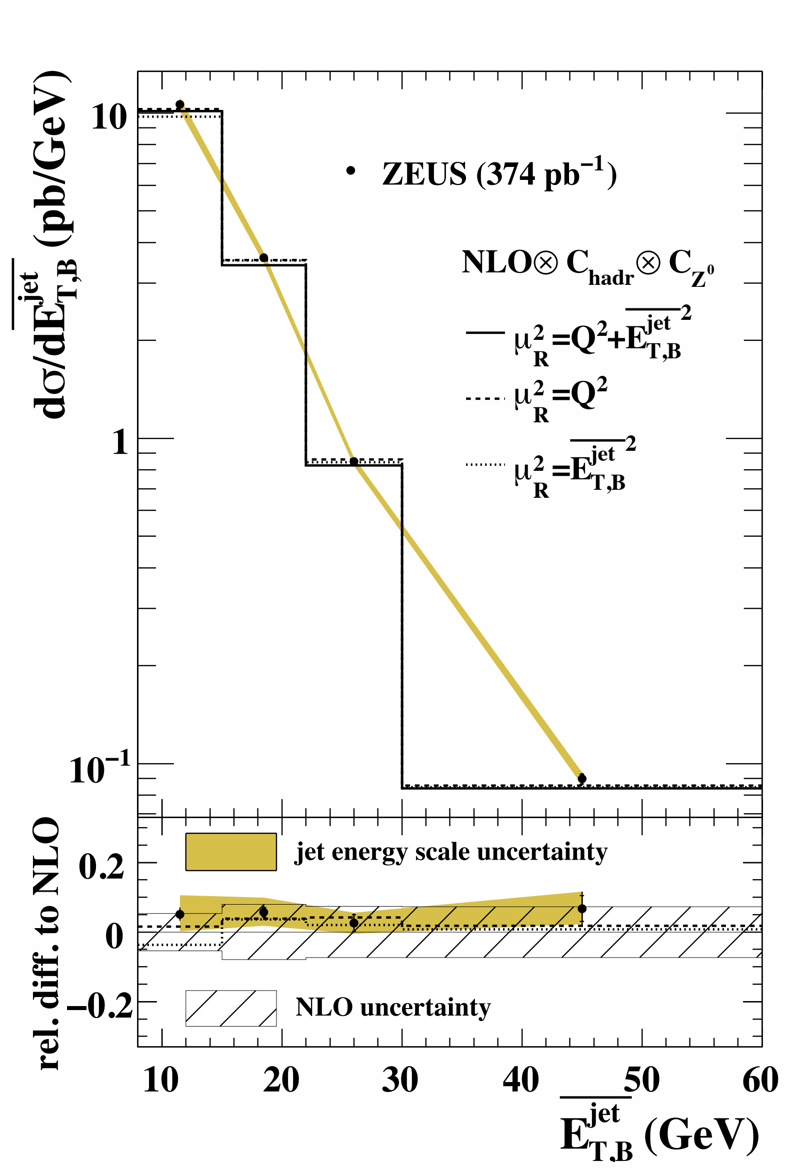
  $\mu_r^2 = \langle P_T \rangle^2$

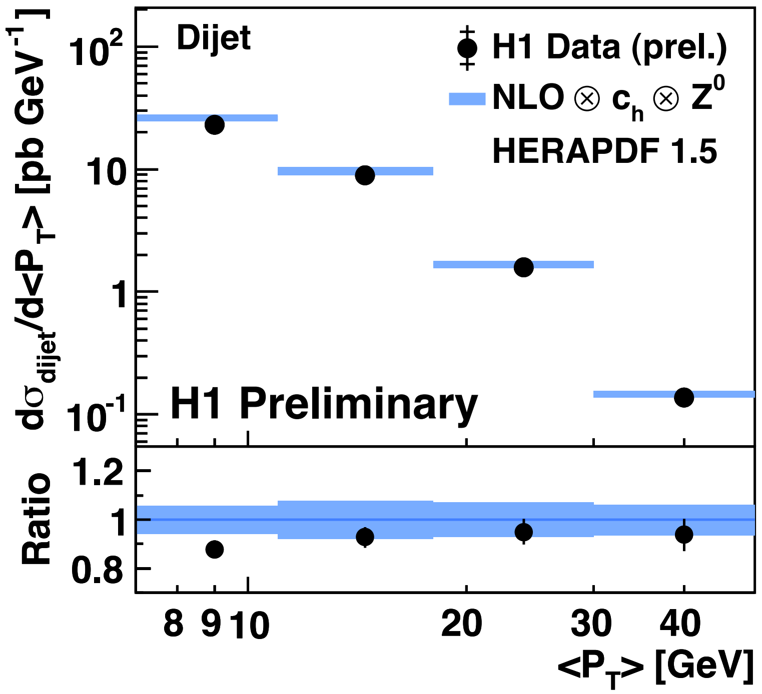
  $\mu_r^2 = Q^2$

  $\mu_r^2 = Q^2 + \langle P_T \rangle^2$
- NLO with $\mu_r = \langle P_T \rangle$ does not describe the data at high Q^2 and low P_T
- double-differential measurement as function of Q^2 and ξ: valuable input for PDF determinations

Dijet Production At High Q²

H1prelim-11-032, EPJ C70, 965 (2010)





- ☑ very similar measurements by H1 and ZEUS, slightly different phase space and different binning
- ☑ size of uncertainties very similar

☐ different choices of scale in QCD analyses:

$$\mu_r^2 = Q^2 + \langle P_T\rangle^2 \qquad \text{(ZEUS)}$$

$$\mu_r^2 = (Q^2 + \langle P_T\rangle^2)/2 \qquad \text{(H1)}$$

☐ slightly different phase space and bin sizes

☐ corrected to different QED Born-level: no running / running of α_{em}

no direct comparison possible

α_s From Dijet Data At High Q^2

Work carried out by a DESY summer student: Junwu Huang

NLO calculations with NLOJet++ / FastNLO

Consistent settings for H1 and ZEUS analysis:

HERAPDF1.5 with $\mu_f^2 = Q^2$ and $\mu_r^2 = (Q^2 + \langle P_T \rangle^2)/2$

Fit to 22 ZEUS dijet data points:

$\alpha_s(M_Z) = 0.1162 \pm 0.0028$ $\chi^2 / \mathrm{ndf} = 1.212$

Fit to 24 preliminary H1 dijet data points:

$\alpha_s(M_Z) = 0.1160 \pm 0.0021$ $\chi^2 / \mathrm{ndf} = 1.333$

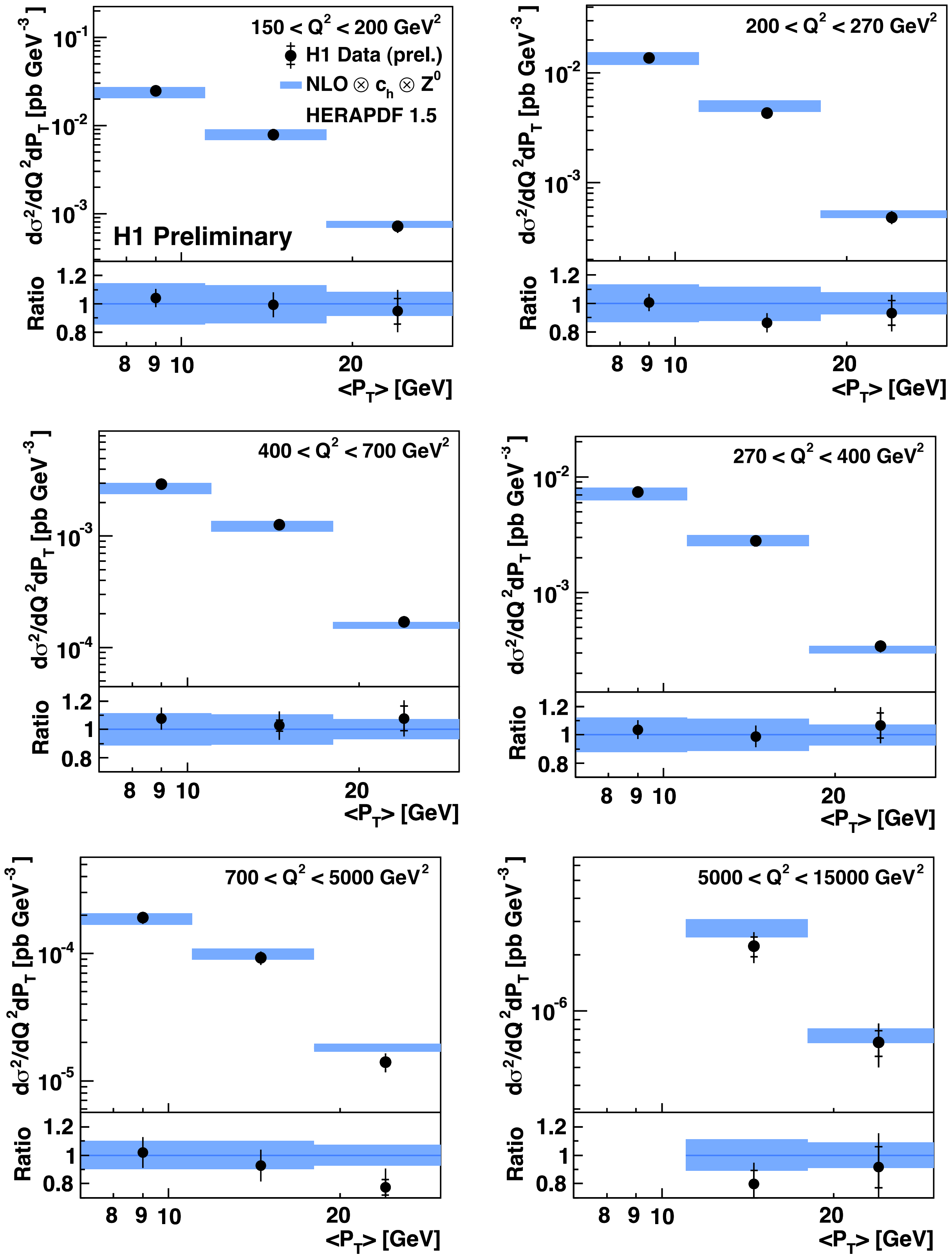
Remarkable agreement

Datasets are consistent, combination will prove valuable

Combined α_s determination from HERA jet data alone feasible

Trijet Production At High Q^2

H1prelim-11-032



- First double-differential trijet cross section measurement at high Q^2
- Experimental uncertainty of 6% (low $\langle P_T \rangle$) and 15% (high $\langle P_T \rangle$)
- Experimental uncertainty dominated by model uncertainty: matrix unfolding under investigation
- $\alpha_s(M_Z)$ fit to all 17 data points

$$\alpha_s(M_Z) = 0.1196 \pm 0.0016\ (\text{exp.}) \\ \pm 0.0010\ (\text{pdf}) \\ {}^{+0.0055}_{-0.0039}\ (\text{th.})$$

- smaller experimental uncertainty than for inclusive or dijet case: higher sensitivity to α_s

Normalised Jet Cross Sections

EPJ C65, 363 (2010), EPJ C67, 1 (2010)

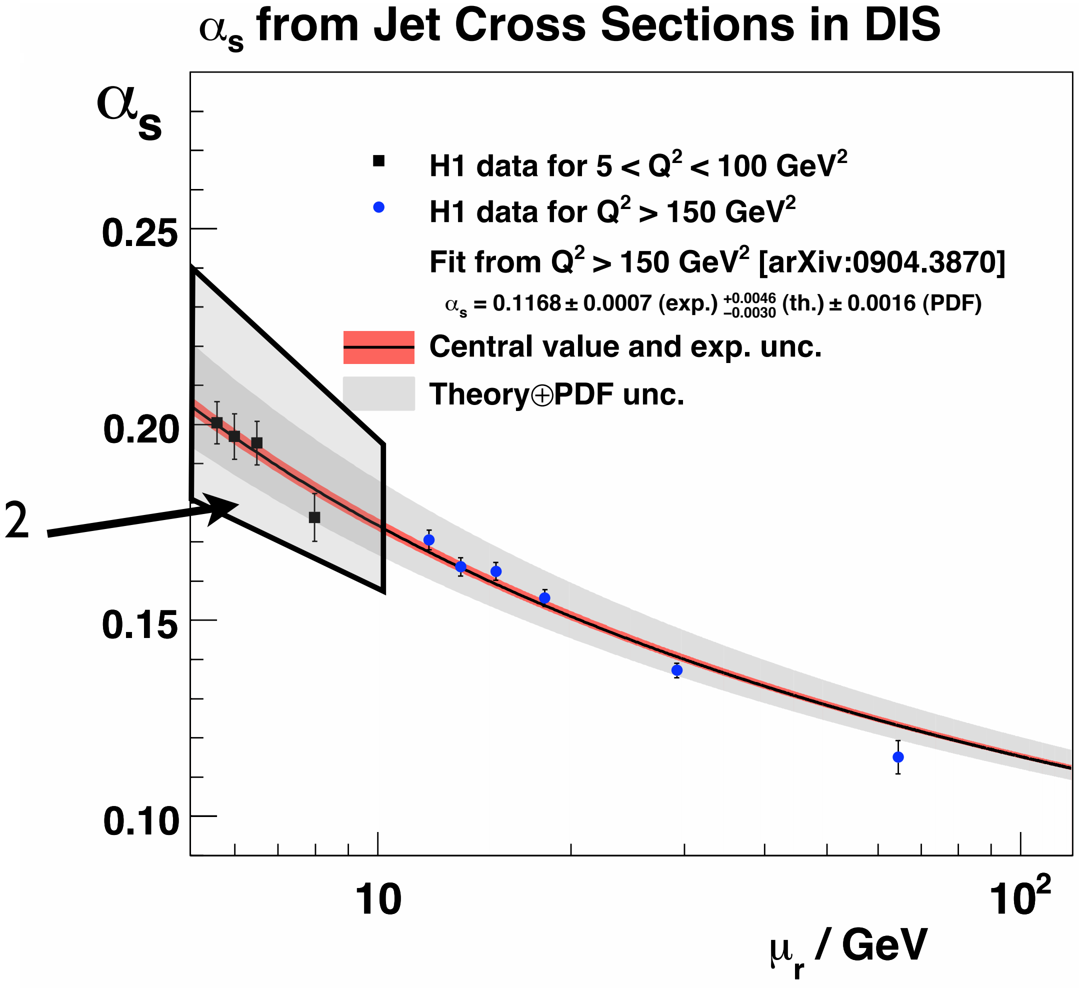
- Measurement of σ_{jet} / σ_{NC} or σ_{trijet} / σ_{dijet} to reduce experimental uncertainties: all normalisation uncertainties cancel
- $\alpha_s(M_Z)$ fit to 54 data points from normalised multijet cross sections

$$\boxed{\alpha_s(M_Z) = 0.1168 \pm 0.0007(\text{exp.})^{+0.0046}_{-0.0030}(\text{th.}) \pm 0.0016(\text{pdf})}$$

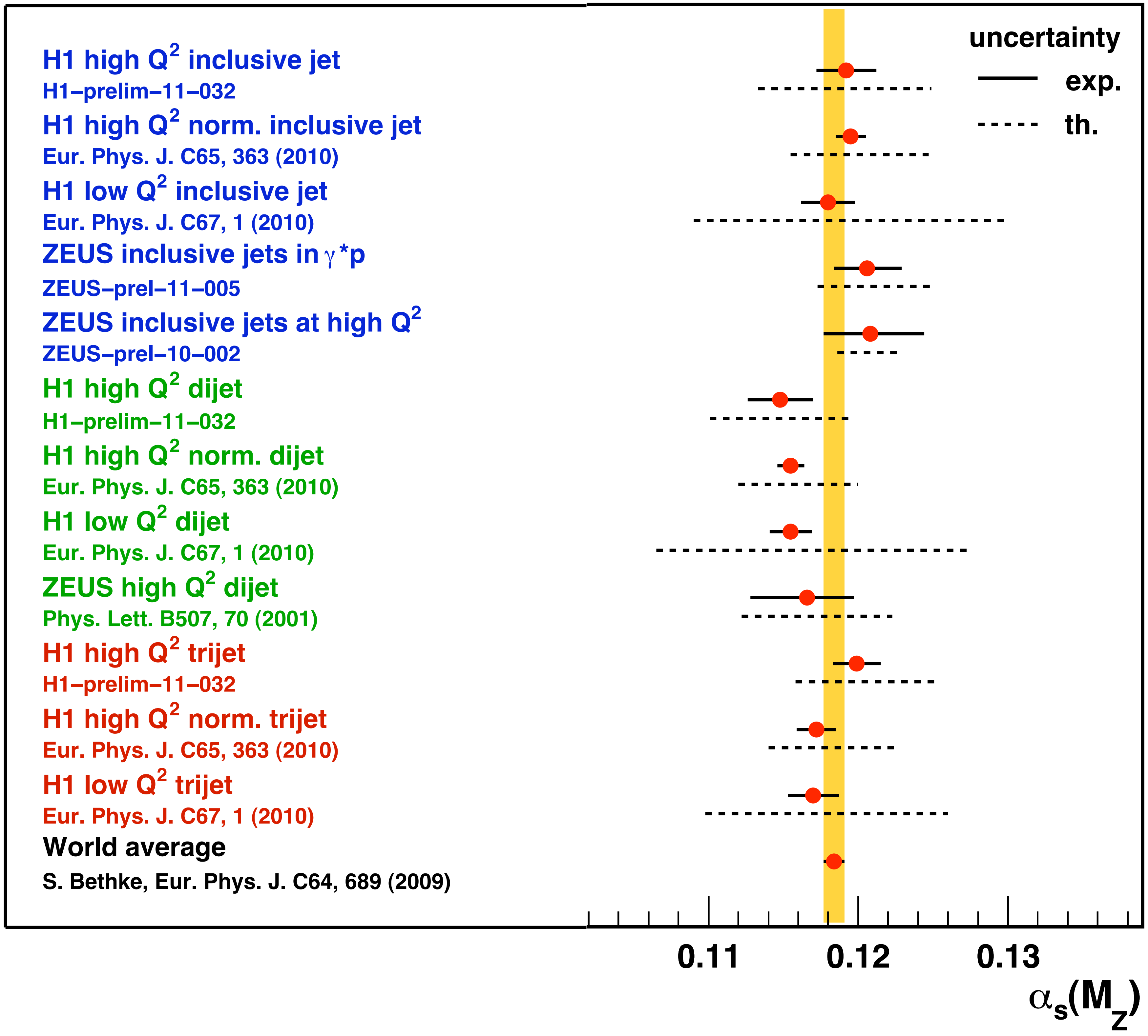
Running of $\alpha_s(\mu_r)$ from NC DIS at low and high Q^2 from H1 alone

Remarkable agreement, considering the large theoretical uncertainties at low Q^2

Running of the strong coupling tested for scales between 6 - 70 GeV



α_s From HERA Jet Data

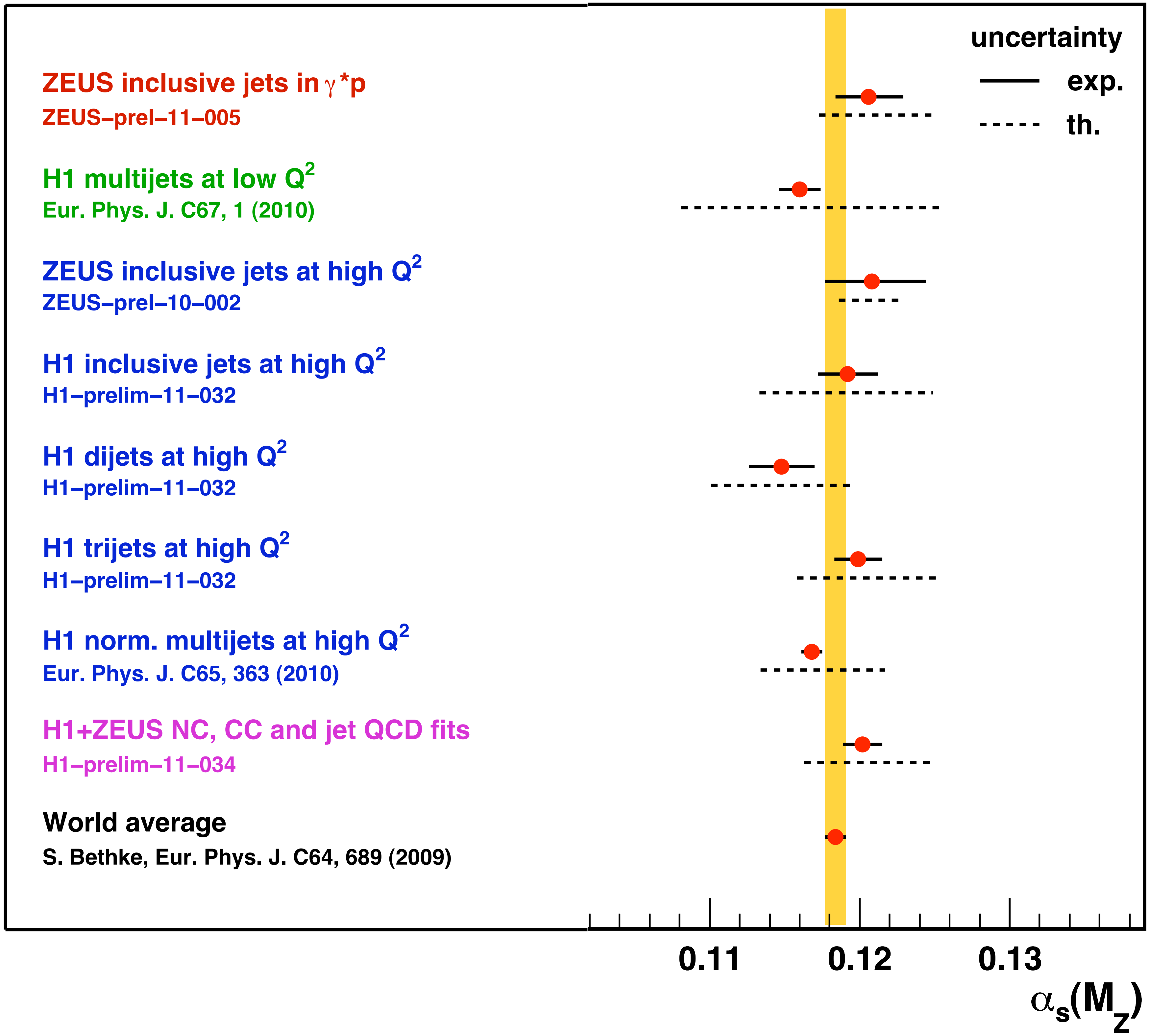


α_s values grouped by observable, incomplete list

Values of $\alpha_s(M_Z)$ are consistent, but $\alpha_s(M_Z)$ from dijet data have the tendency towards a smaller value

How large are the correlations between the theoretical uncertainties?

α_s From HERA Jet Data



Summary of α_s values shown in this talk

Dominated by theoretical uncertainties

Combination of $\alpha_s(M_Z)$ from jet data at HERA needed

First common QCD analysis with ZEUS and H1 jet data: HERAPDF1.6

Summary

HERA provides the most precise measurements of jet cross sections at e^+e^-, ep and hadron colliders up to date

Many active analyses of inclusive jet, dijet and trijet production in DIS and photoproduction

- Stringent test of pQCD
- Tests of available PDFs
- Important for future combined PDF and α_s determinations

Extracted values of $\alpha_s(M_Z)$ compatible between H1 and ZEUS and competitive with other determinations, dominated by theoretical uncertainties

A combination of jet data from H1 and ZEUS will provide best precision for future QCD analyses

Looking forward to eventual NNLO calculations or resummation corrections as calculated for the Tevatron