

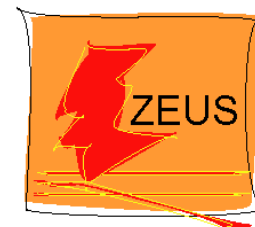
Precision measurements with jets and particles at HERA



Katharina Müller
Zurich University



on behalf of the H1 and ZEUS collaborations



Jets at HERA

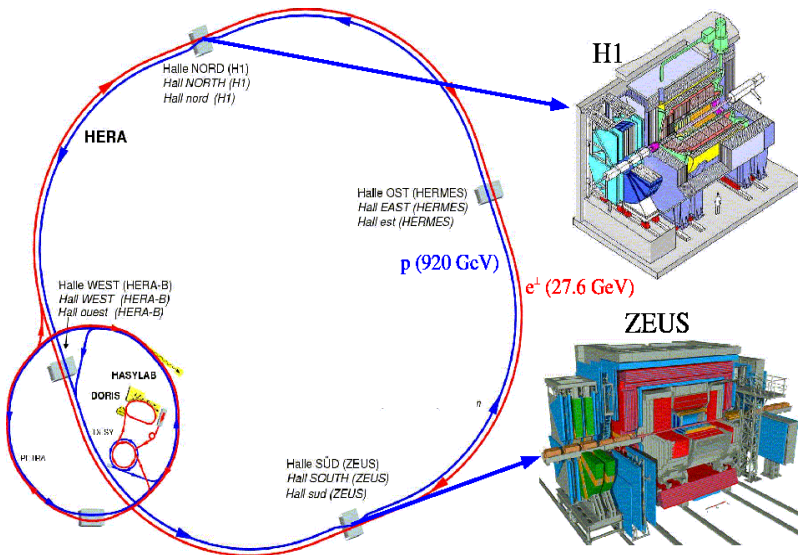
- Tests of QCD
- Sensitivity to gluon in the proton
- Measurement of $\alpha_s(M_Z)$

Prompt Photons

Final States

- Charge particle spectra at low Q^2
- Scaled Momentum Distributions
- Charge Asymmetry

HERA- Introduction

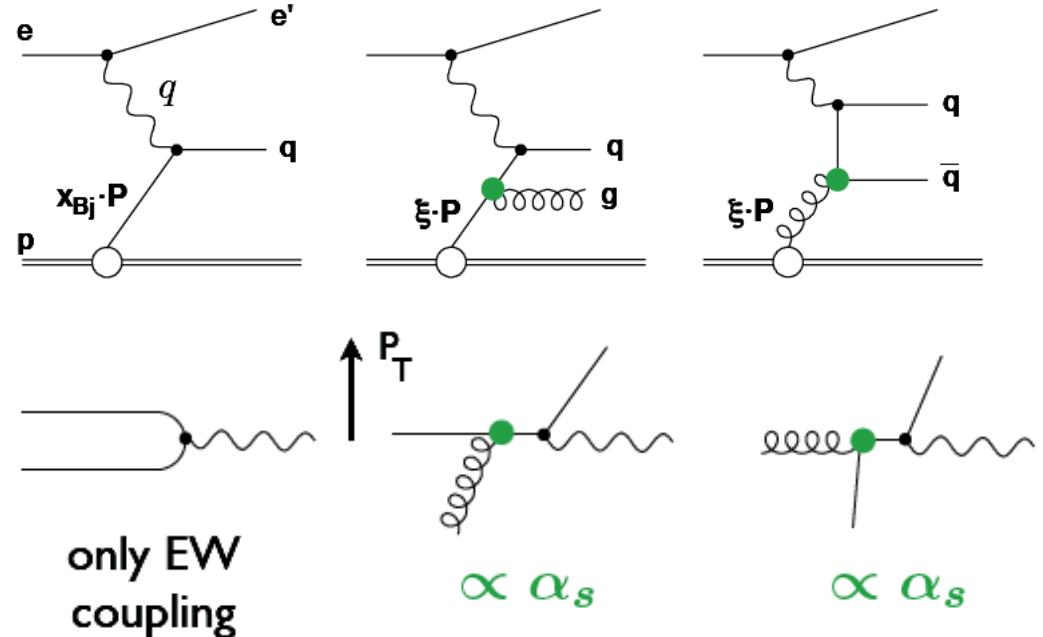


Total integrated luminosity $0.5 \text{ fb}^{-1}/\text{experiment}$
 Centre of mass energy: 318 GeV
 $Q^2 = -q^2$: photon virtuality
 $x = x_{Bj} = Q^2/(2pq)$

The kinematic diagram shows an electron beam with energy $E_e = 27.6 \text{ GeV}$ (green arrow) and a proton beam with energy $E_p = 920 \text{ GeV}$ (red arrow) colliding at a central point. Several arrows radiate from this point, representing the directions of various particles produced in the collision.

Two kinematic regimes
 $Q^2 \cong 0 \text{ GeV}^2$: Photoproduction
 $Q^2 > 1 \text{ GeV}^2$: Deep Inelastic Scattering (DIS)

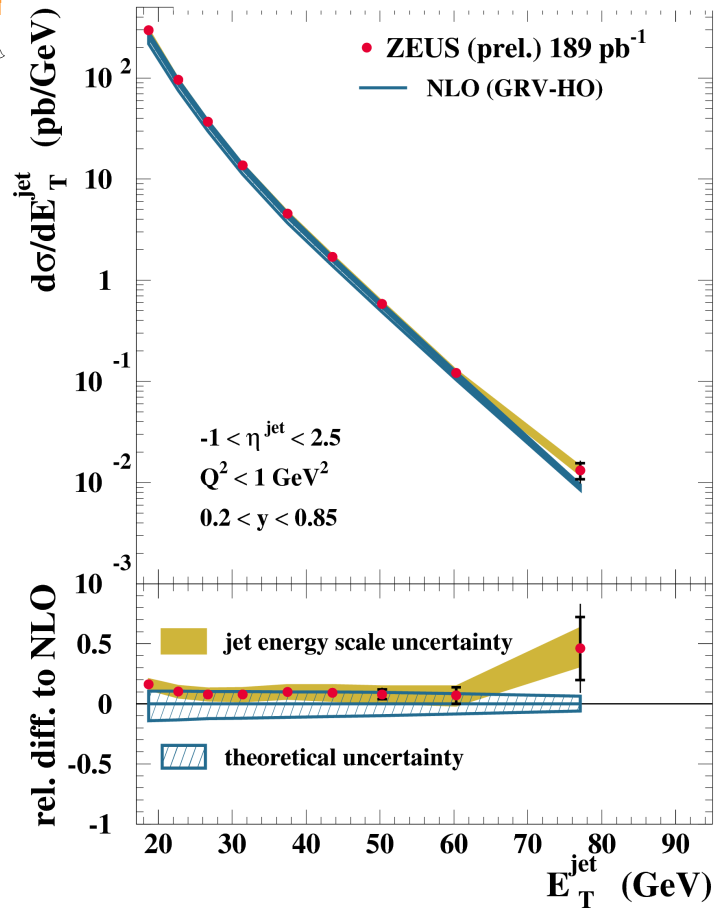
Jet Production
 Boost to Breit frame: $2x_{Bj} + q = 0$
 Only processes proportional to α_s
 generate P_T in the Breit frame
 ξ : fraction of proton momentum
 carried by struck quark $\xi = 1 + M_{12}^2/Q^2$



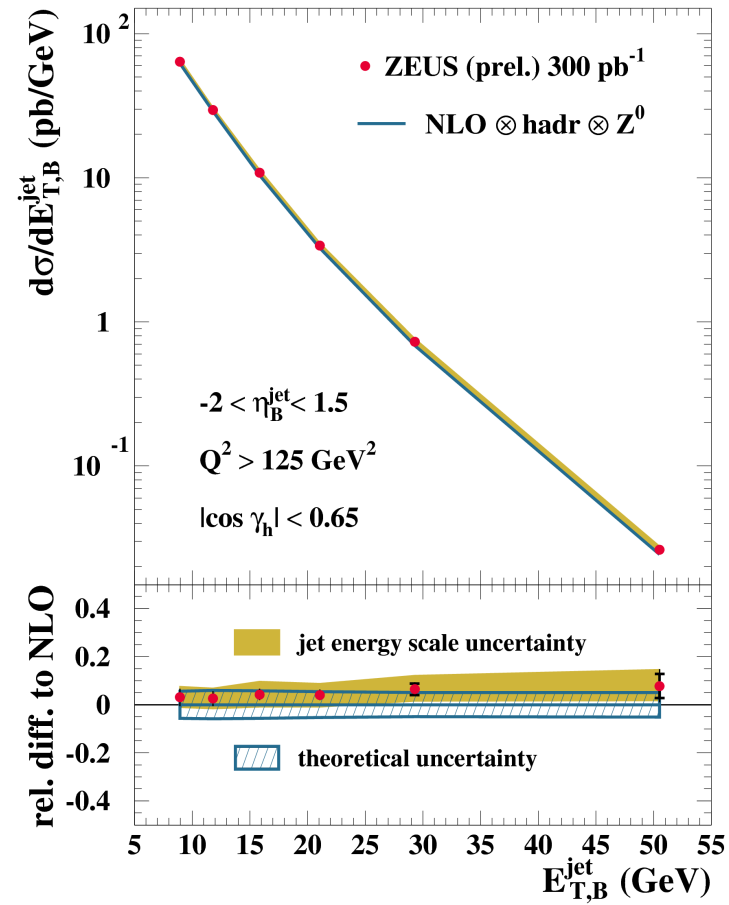
Inclusive Jet Cross Section



Photoproduction



neutral current DIS

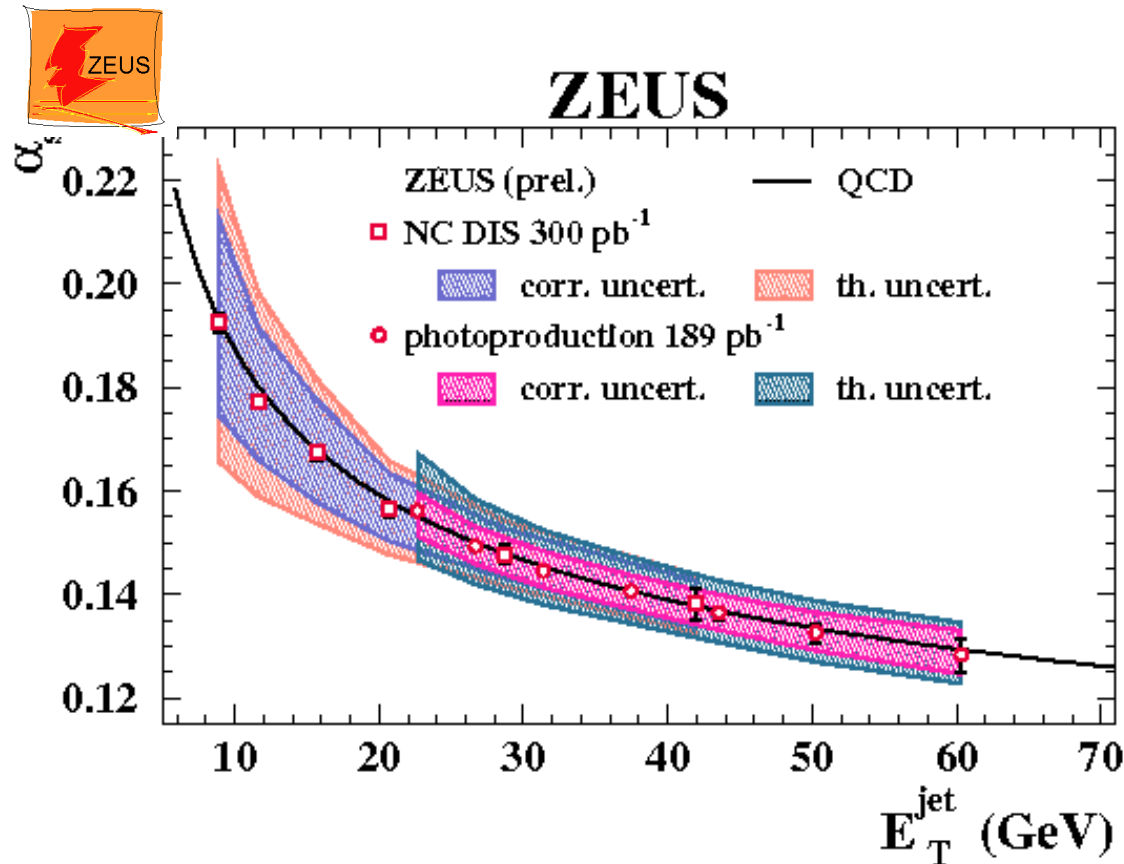


Cross section falls steeply, well described by NLO, extract α_s
 Dominant error: jet energy scale: 1% $E_T^{\text{jet}} > 10 \text{ GeV}$, 3% below
 Very precise data, stringent tests of QCD from $Q^2 \sim 0$ to 20000 GeV²

ZEUS-prel-10-002 ZEUS: 300 pb⁻¹, $Q^2 > 125 \text{ GeV}^2$, $-2 < \eta_B < 1.5$, $E_T^{\text{jet}} > 8 \text{ GeV}$

ZEUS-prel-10-003 ZEUS: 189 pb⁻¹, $Q^2 < 1 \text{ GeV}^2$, $-1 < \eta_B < 2.5$, $E_T^{\text{jet}} > 17 \text{ GeV}$

α_s from Inclusive Jet Cross Section



$$\alpha_s(M_Z) = 0.1208 \pm 0.0007_{-0.0031}^{+0.0036} (\text{exp})_{-0.0022}^{+0.0022} (\text{theo}) (\text{DIS})$$

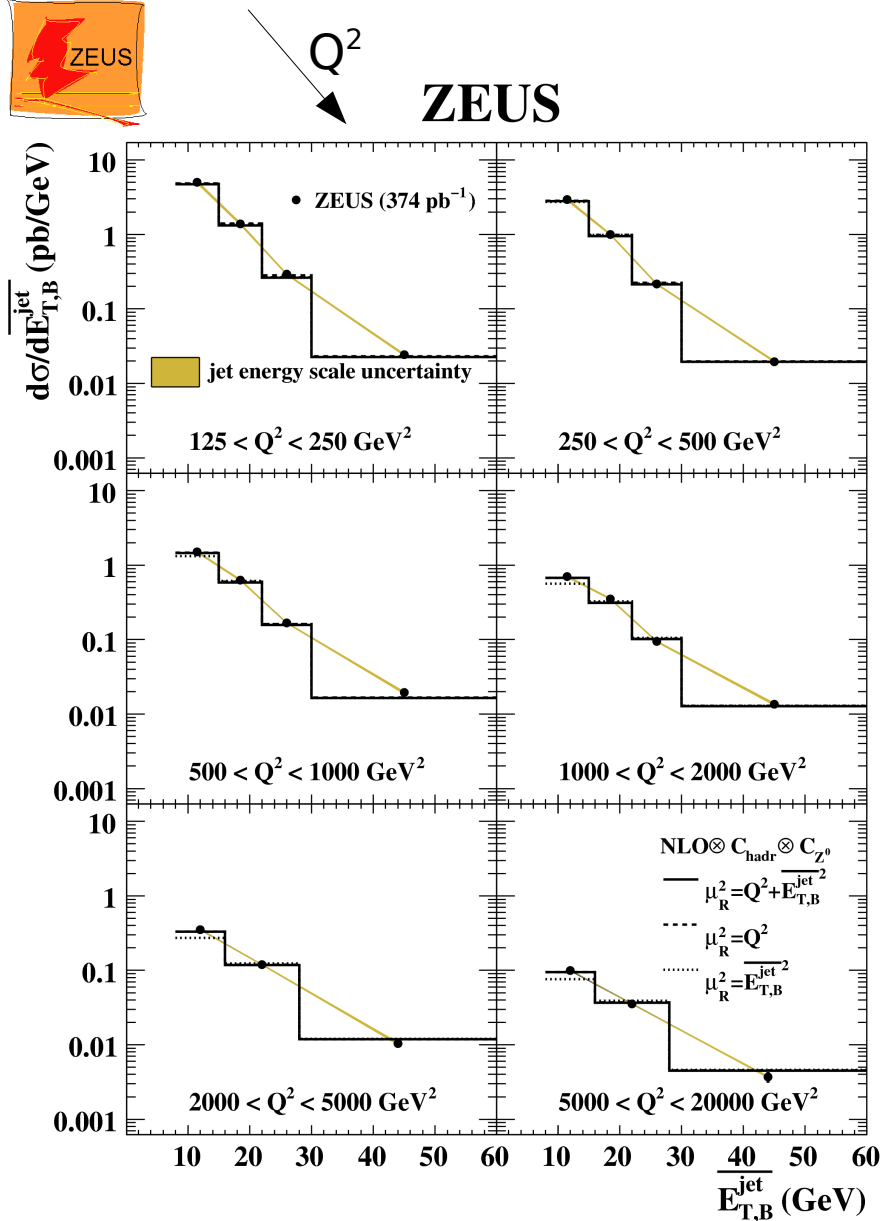
$$\alpha_s(M_Z) = 0.1208_{-0.0018}^{+0.0030} (\text{exp})_{-0.0032}^{+0.0033} (\text{theo}) (\gamma p)$$

In good agreement with predicted running of α_s over a large range of E_T^{jet}
 α_s measurements consistent with each other and the world average
 New jet algorithms (anti-kt, SIScone) tested: similar results

ZEUS-prel-10-002 ZEUS: 300 pb⁻¹, $Q^2 > 125 \text{ GeV}^2$, $-2 < \eta_B < 1.5$, $E_T^{\text{jet}} > 8 \text{ GeV}$

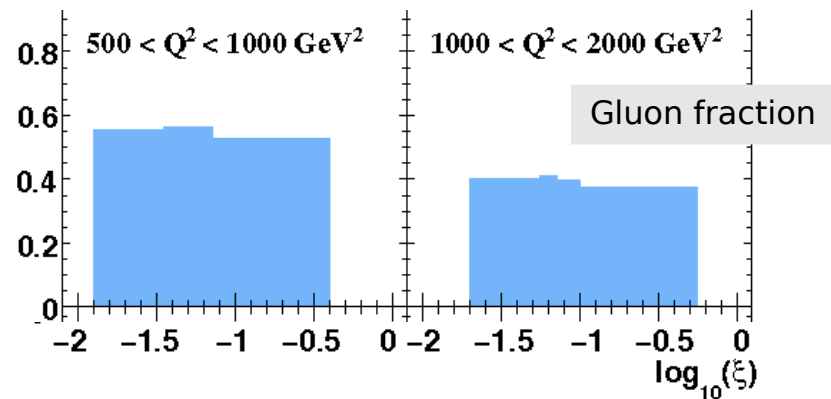
ZEUS-prel-10-003 ZEUS: 189 pb⁻¹, $Q^2 < 1 \text{ GeV}^2$, $-1 < \eta_B < 2.5$, $E_T^{\text{jet}} > 17 \text{ GeV}$

Dijet Cross Sections: $e+p \rightarrow \text{jet} + \text{jet} + X$



Very small statistical and systematical errors
 uncorrelated $\pm 2(10)\%$ at low (high) Q^2
 correlated: $\pm 5(2)\%$ at low (high) Q^2

Description by NLO (NLOJET++) very good
 → Important input for extraction of PDFs -
 especially gluon in proton - and α_s



PDF uncertainty large in regions with large
 Fraction of gluon initiated events

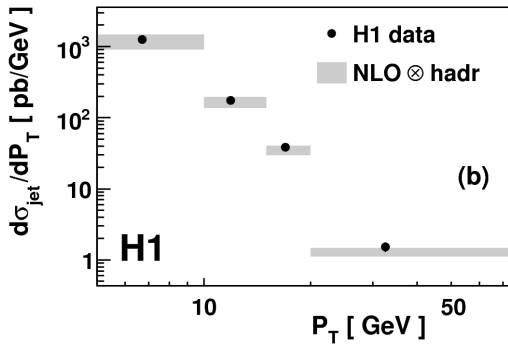
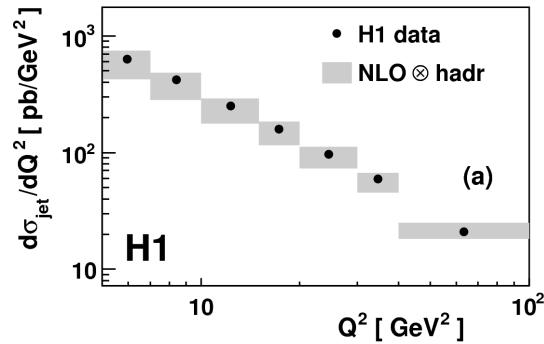
ZEUS: 374 pb⁻¹, 125 < Q^2 < 20000 GeV², Breit frame: $E_T^{\text{jet}} > 8 \text{ GeV}$, $M_{jj} > 20 \text{ GeV}^2$

Multijet Cross Sections at low Q^2

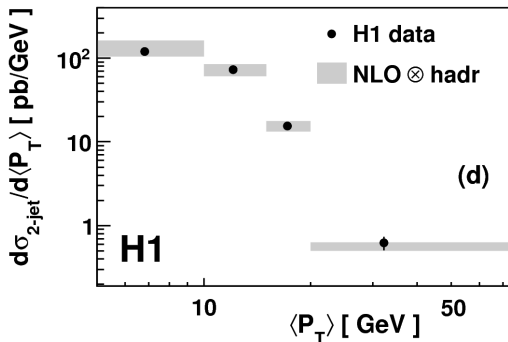
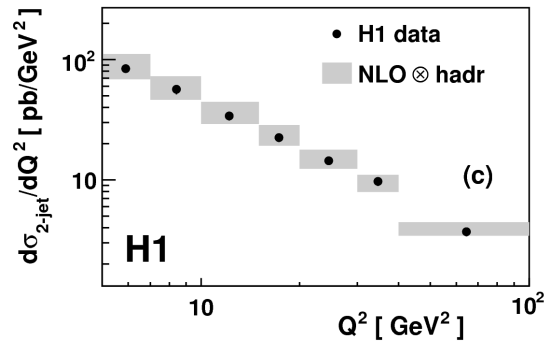


Inclusive Jet, 2-Jet and 3-Jet Cross Sections

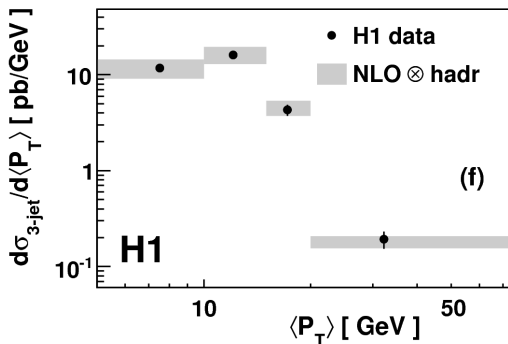
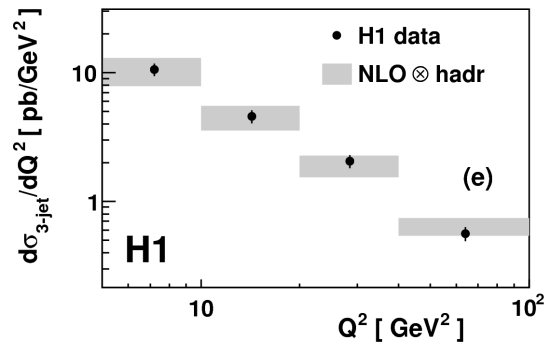
Inclusive



2-Jet



3-Jet



Exp. Uncertainties: 6-10%

Theoretical uncertainties
30% at low Q^2
NNLO needed

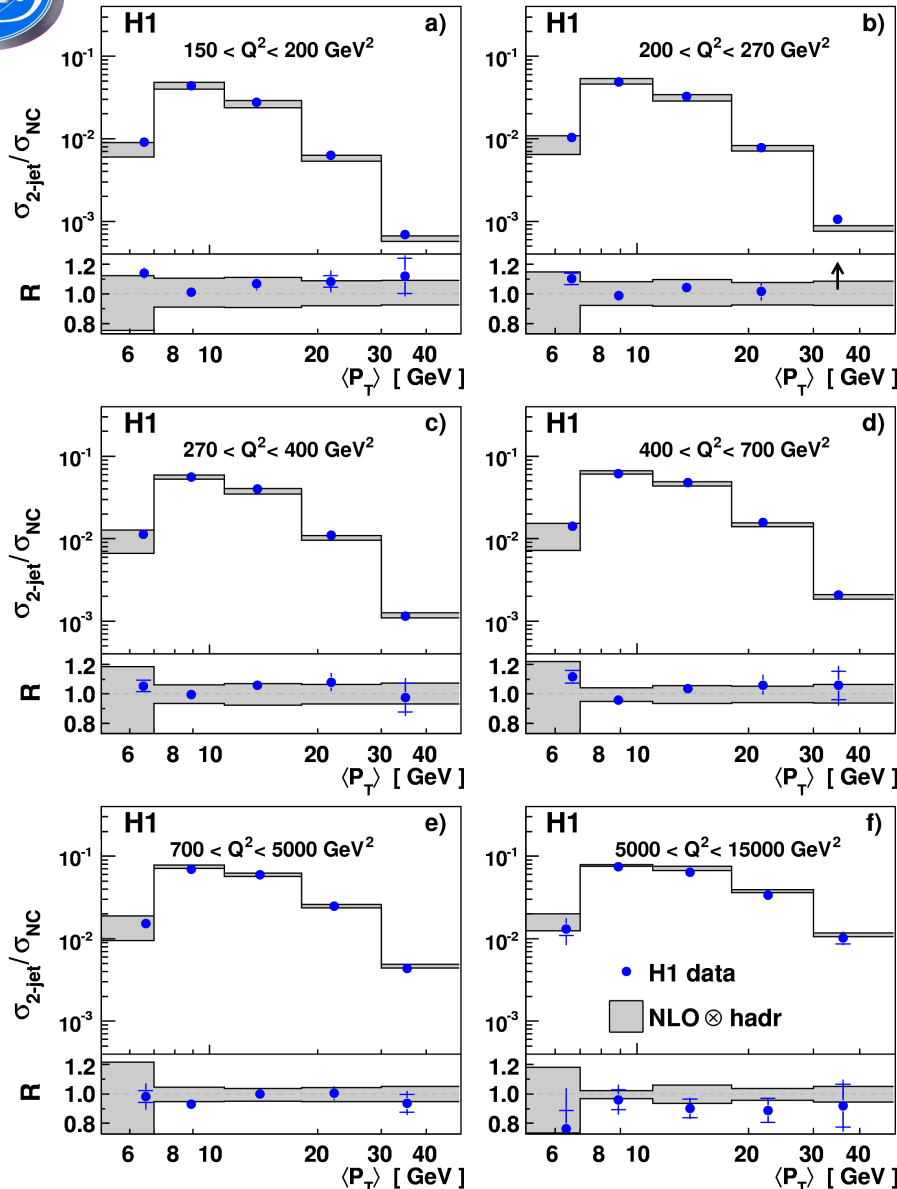
Good description by NLO

Hadronisation corrections
0.9-0.95 (0.8 3-jet)

Multijet Cross Sections at high Q^2



Normalised 2-Jet Cross Section



Normalised to NC DIS cross section
cancellation of errors

Very accurate measurement

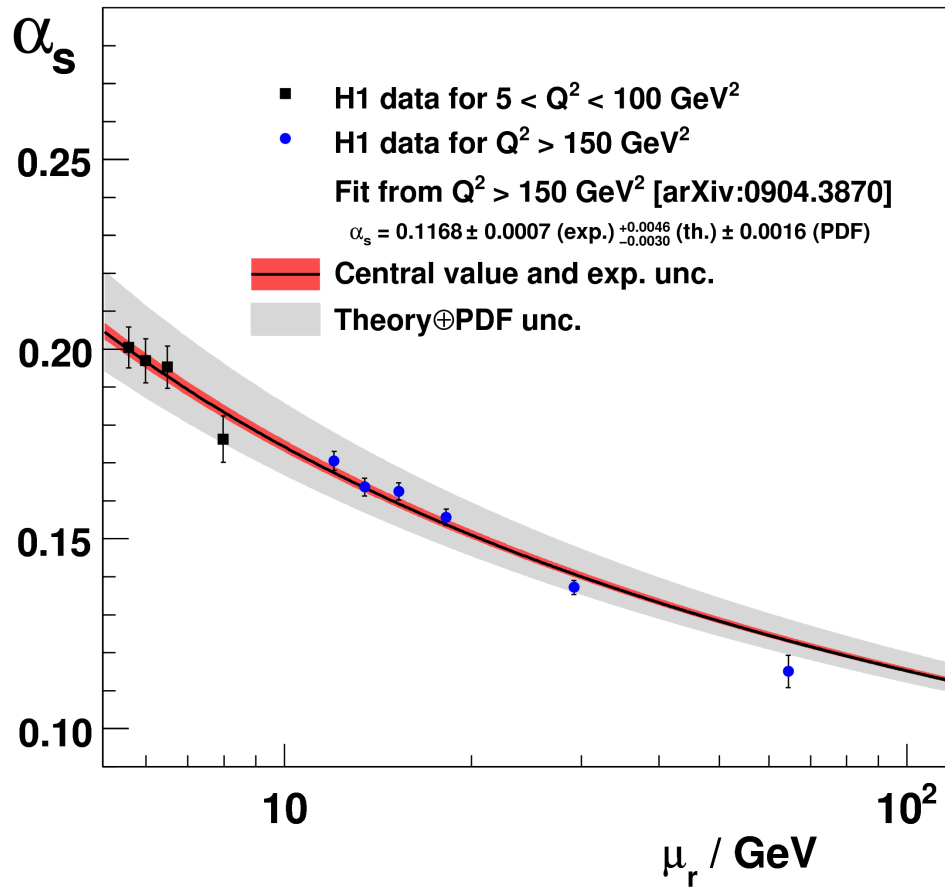
Normalised inclusive, 2-jet and 3-jet
cross sections used to extract α_s

Combination of different observables
→ improved experimental uncertainty (0.6%)

α_s : from high and low Q^2 data



α_s from Jet Cross Sections in DIS



Input inclusive, 2-jet and 3-jet cross sections

High Q^2 : fit to normalised cross sections

Low Q^2 : fit to all cross sections and 3-jet to 2-jet ratios

Running tested over wide range

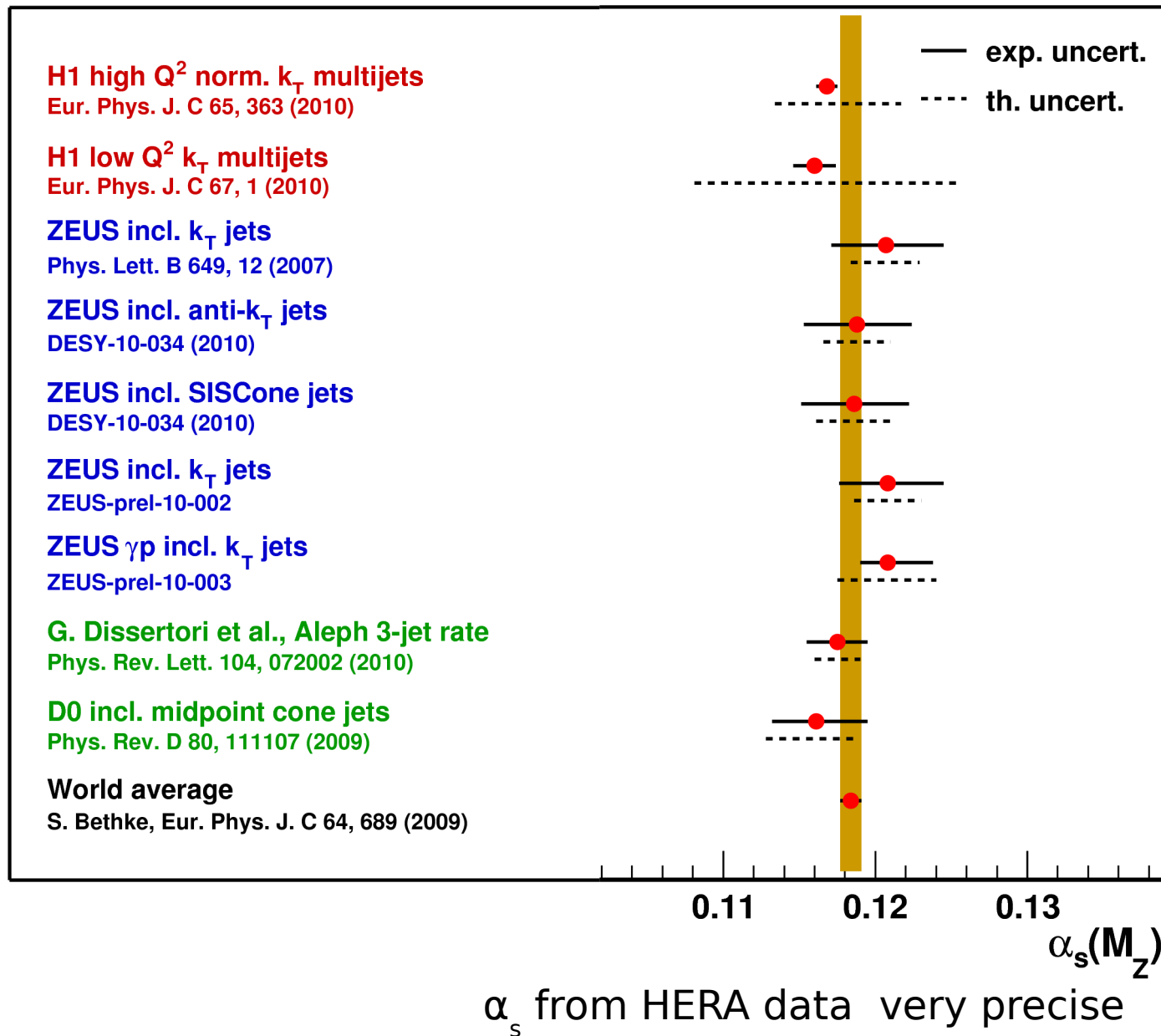
$$\mu_r = \sqrt{(q^2 + P_{T,obs}^2)}/2$$

$$\alpha_s(M_z) = 0.1160 \pm 0.0014 \text{ }^{+0.0093}_{-0.0077} \text{ (theo)} \pm 0.0016 \text{ (pdf)} \quad 5 < Q^2 < 100 \text{ GeV}^2$$

$$\alpha_s(M_z) = 0.1168 \pm 0.0007 \text{ }^{+0.0046}_{-0.0030} \text{ (theo)} \pm 0.0016 \text{ (pdf)} \quad 150 < Q^2 < 15000 \text{ GeV}^2$$

Eur.Phys.J.C65:363-383,2010. H1: 395 pb^{-1} , $150 < Q^2 < 15000 \text{ GeV}^2$, $0.2 < y < 0.7$, Breit frame: $7 < p_T^{\text{jet}} < 50 \text{ GeV}$, $M_{jj} > 16 \text{ GeV}^2$
 Eur.Phys.J.C67:1-24,2010. H1: 44 pb^{-1} , $5 < Q^2 < 100 \text{ GeV}^2$, $0.2 < y < 0.7$, Breit frame: $5 < p_T^{\text{jet}} < 80 \text{ GeV}$, $M_{jj} > 18 \text{ GeV}^2$

α_s : Summary

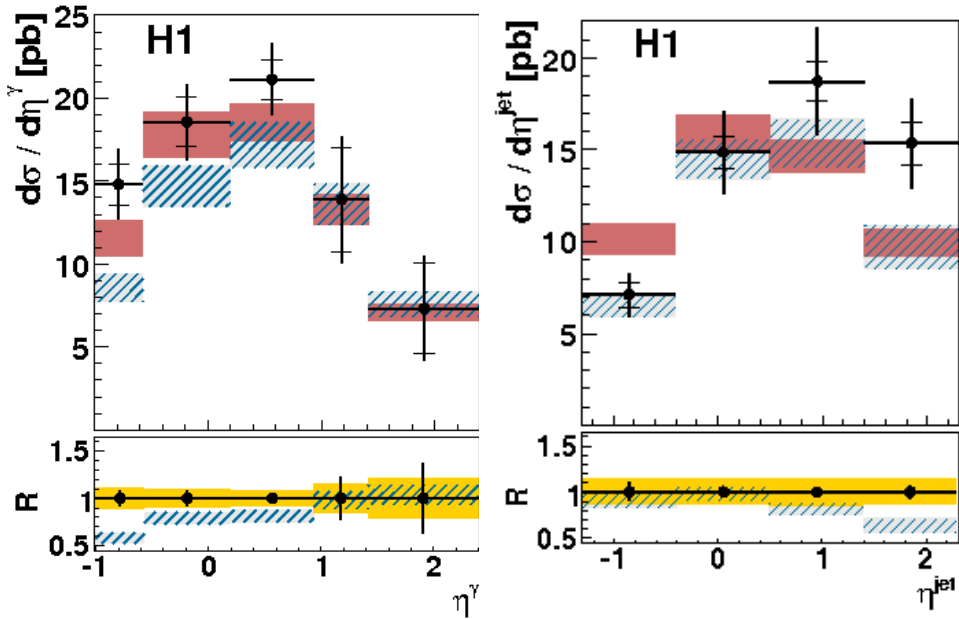


Consistent results from high and low Q^2 and different jet algorithms.

Calculations beyond NLO needed in DIS!

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2

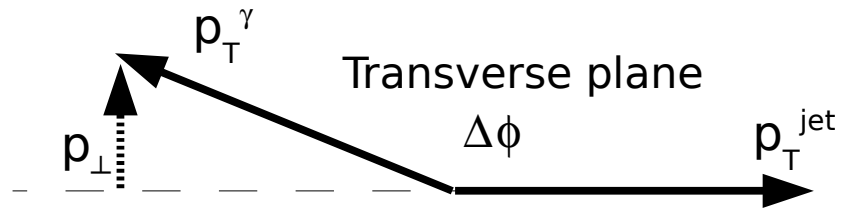
Prompt Photon plus Jet Cross Section (γp)



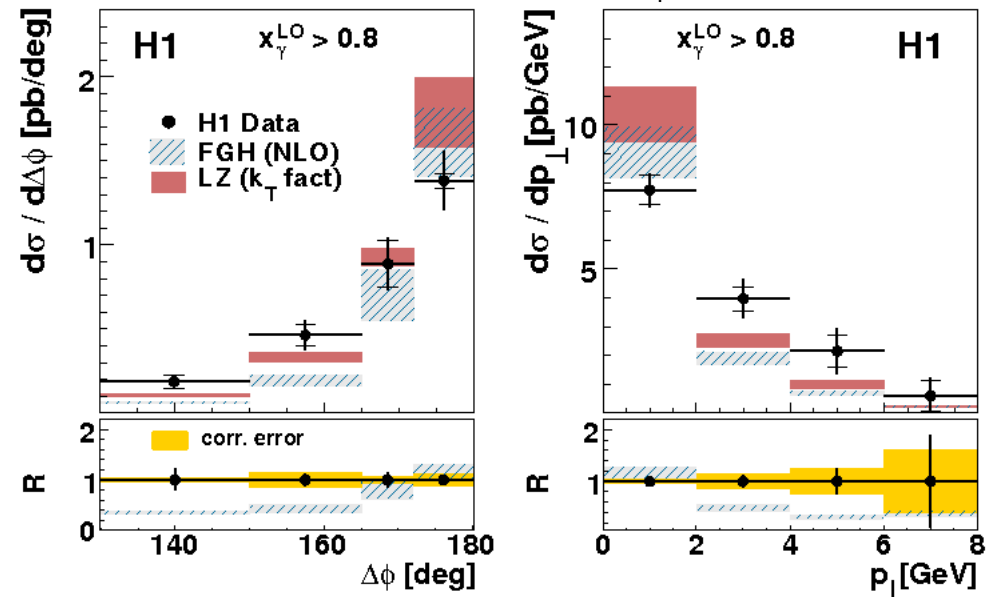
$x_\gamma > 0.8$ direct enhanced sample
 both calculations underestimate
 non back-to-back configuration
 sensitive to higher orders

Comparison to
 NLO calculation (FGH), collinear factorisation
 kt factorisation approach (LZ)

LZ favoured by η^γ but problems with η^{jet}



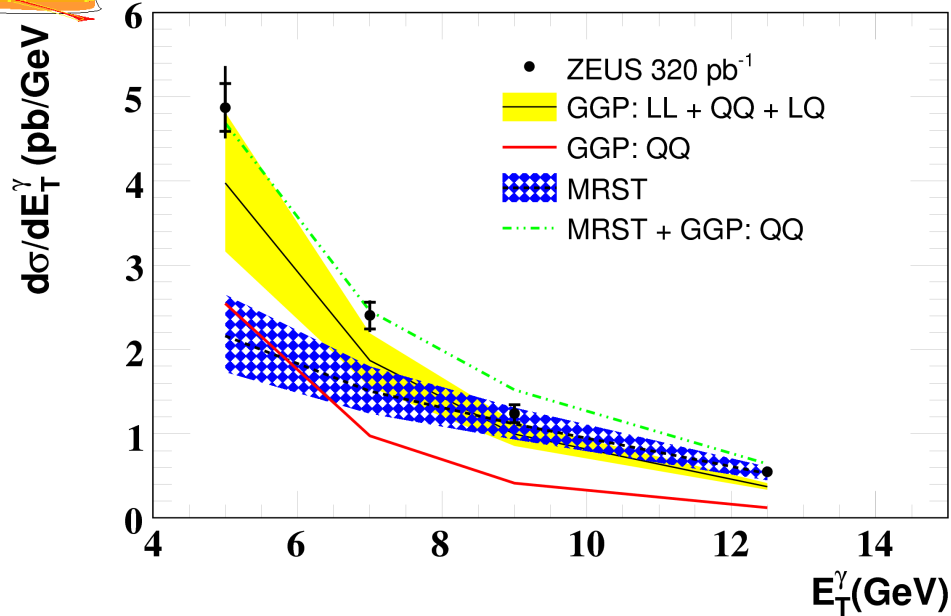
Transverse correlations, $x_\gamma > 0.8$



Prompt Photons in DIS: 2 hard scales (E_T, Q^2)



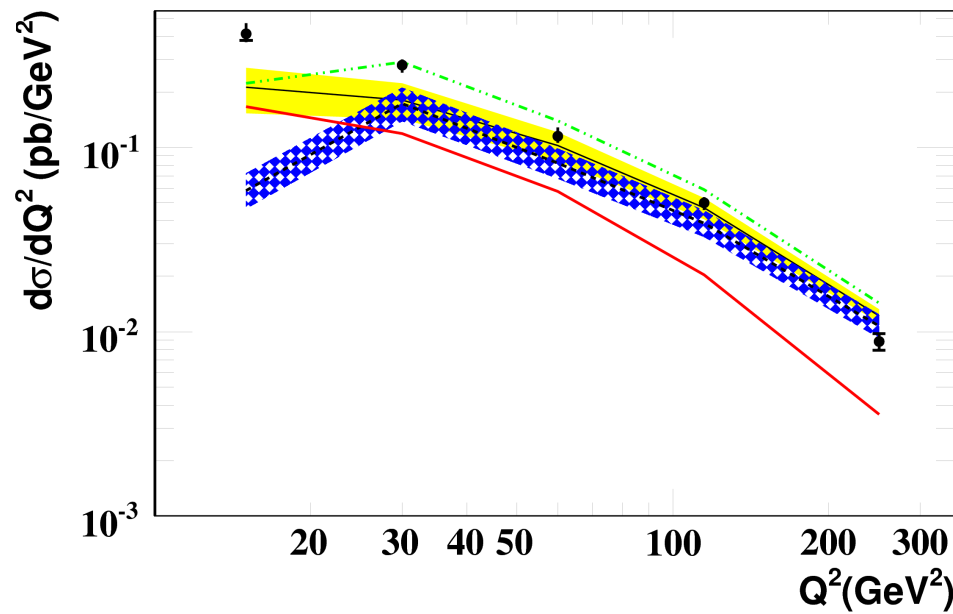
ZEUS



- GGP: shape of E_T^γ ok
normalisation 20% too low
- MRST+QQ improved overall description
- Both calculations fail to describe low Q^2 and low x

LL: hard radiation from lepton
QQ: hard radiation from quarks

GGP: LO(α^3) prediction by Gehrmann et al.
MRST: enhanced LL contribution: QED corr. in PDFs \rightarrow partonic photon component in the PDF



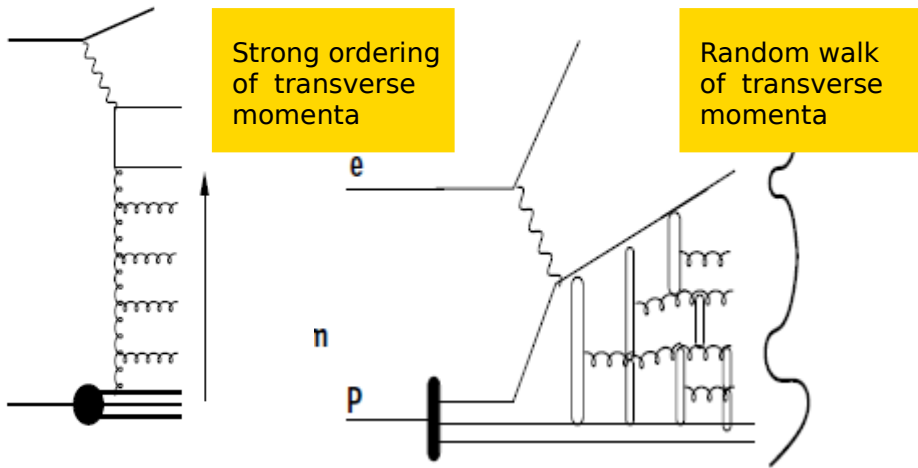


Charged Particles → Parton Dynamics

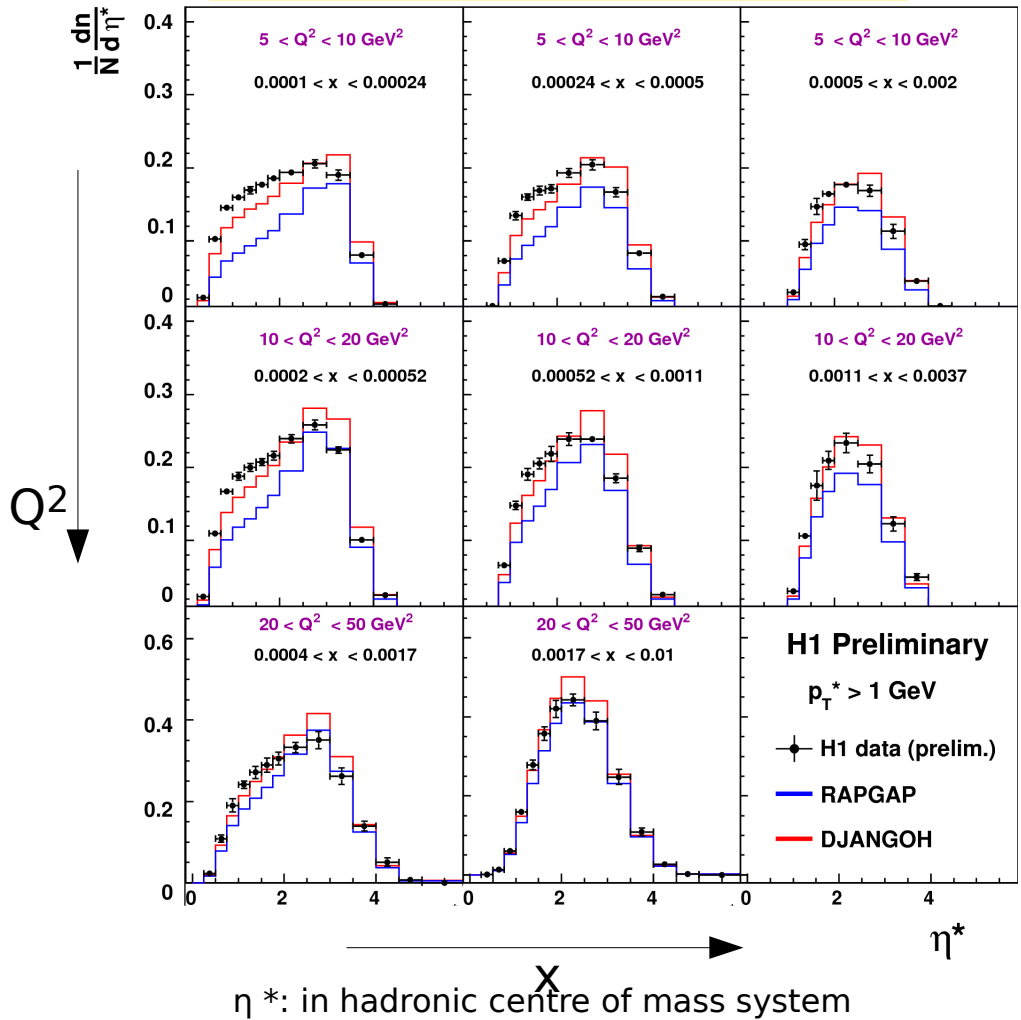
Small x : expect new parton dynamics to become important
 Structure function measurements too inclusive → measure hadronic final state

DGLAP

CDM (Color Dipole Model)



Hard p_T^* region ($p_T^* > 1$ GeV)



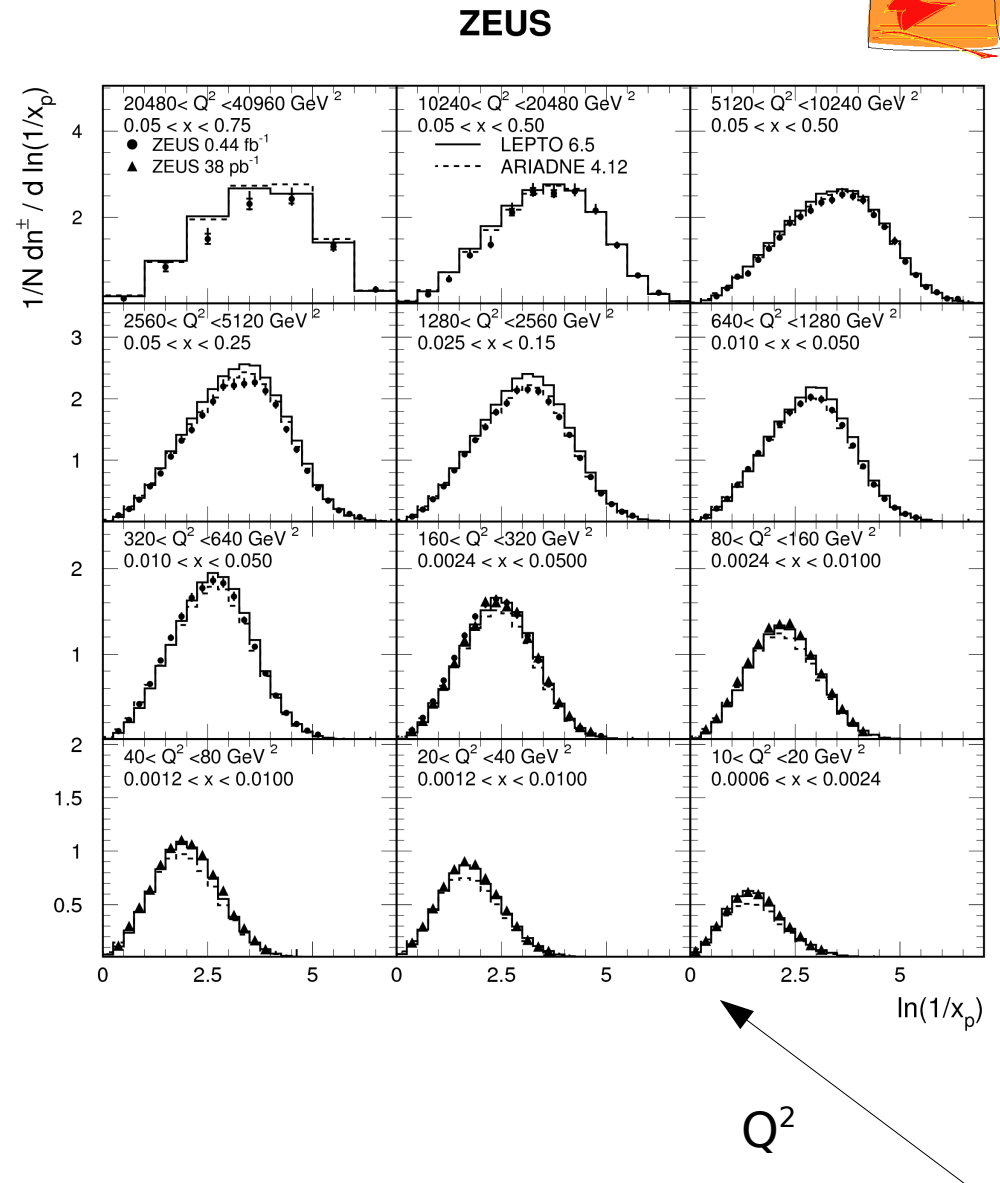
- High p_T : sensitivity to parton dynamics
 - DJANGO (CDM): reasonable description
 - RAPGAP (DGLAP) significantly lower at small x , Q^2 deficit most pronounced in forward direction ($\eta^* < 2$)
- Data favours beyond-DGLAP model

Soft Particle Distribution in DIS



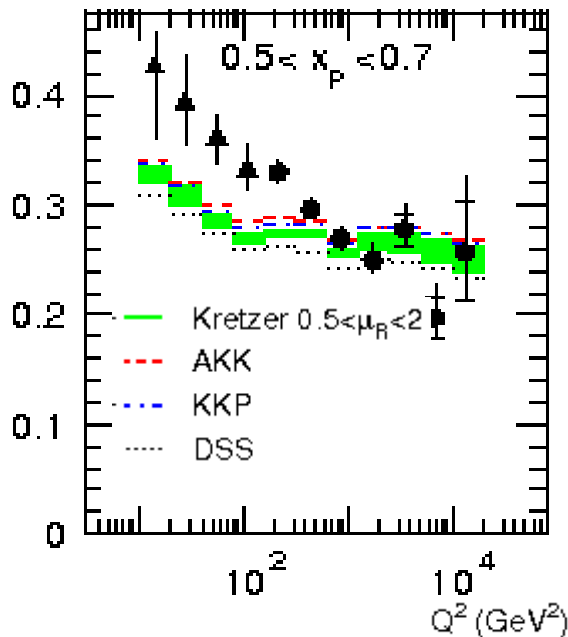
- Breit frame
- Study fragmentation
non perturbative region of QCD
- Charged hadrons in current region
 $p_t > 0.15 \text{ GeV}$ $|\eta| < 1.75$
- Scaled momentum: $x_p = 2P_{\text{Breit}}/Q$
- $10 < Q^2 < 40960 \text{ GeV}^2$

- Q^2 increase \rightarrow
mean multiplicity increase,
peak towards lower x_p
- phase space for soft gluon emission
increases more particles at low x_p
 \rightarrow scaling violation
- Ariadne/ LEPTO problems at high Q^2



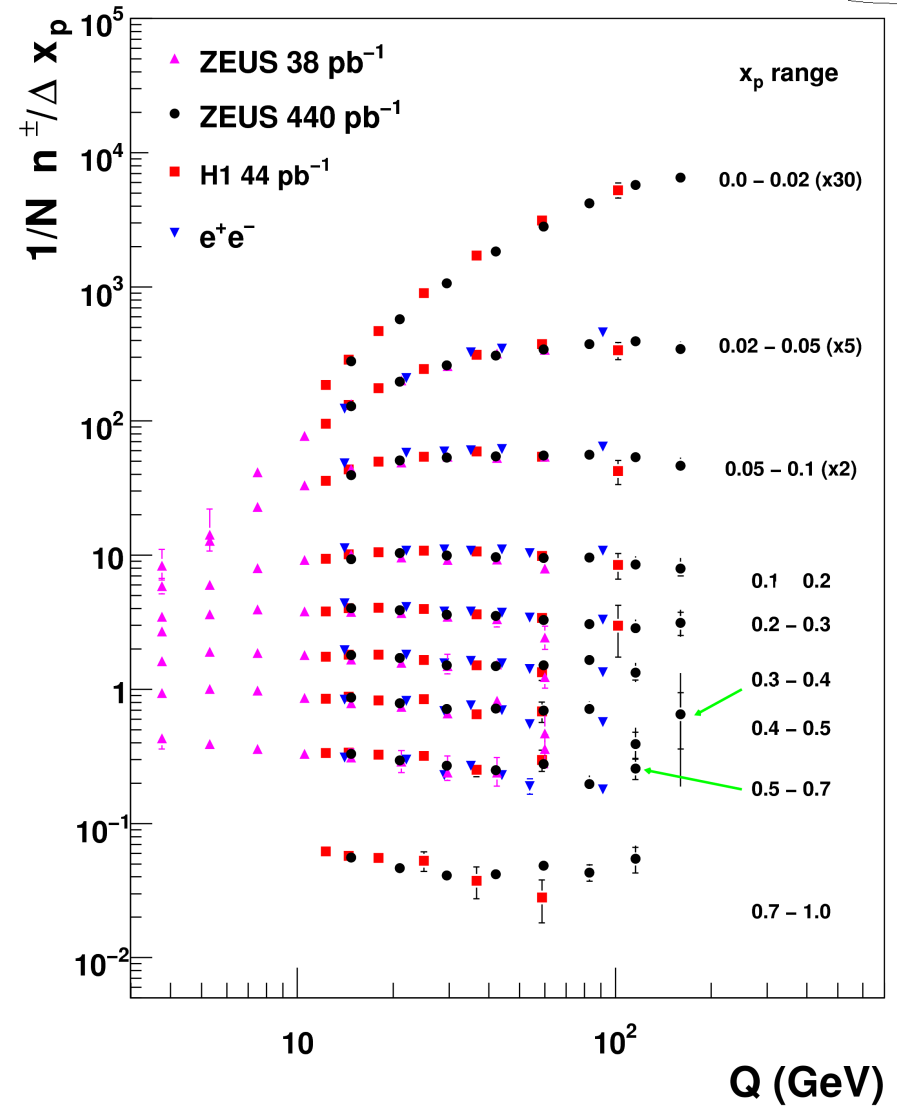
Soft Particle in DIS: scaling violation

- Large scaling violation observed
- Overall agreement between datasets
→ universality of fragmentation



- NLO fails to describe data: predicted scaling violation too weak
- MC models better but do not describe Q^2 dependence over full range of x_p
- Data supports hypothesis of limited fragmentation

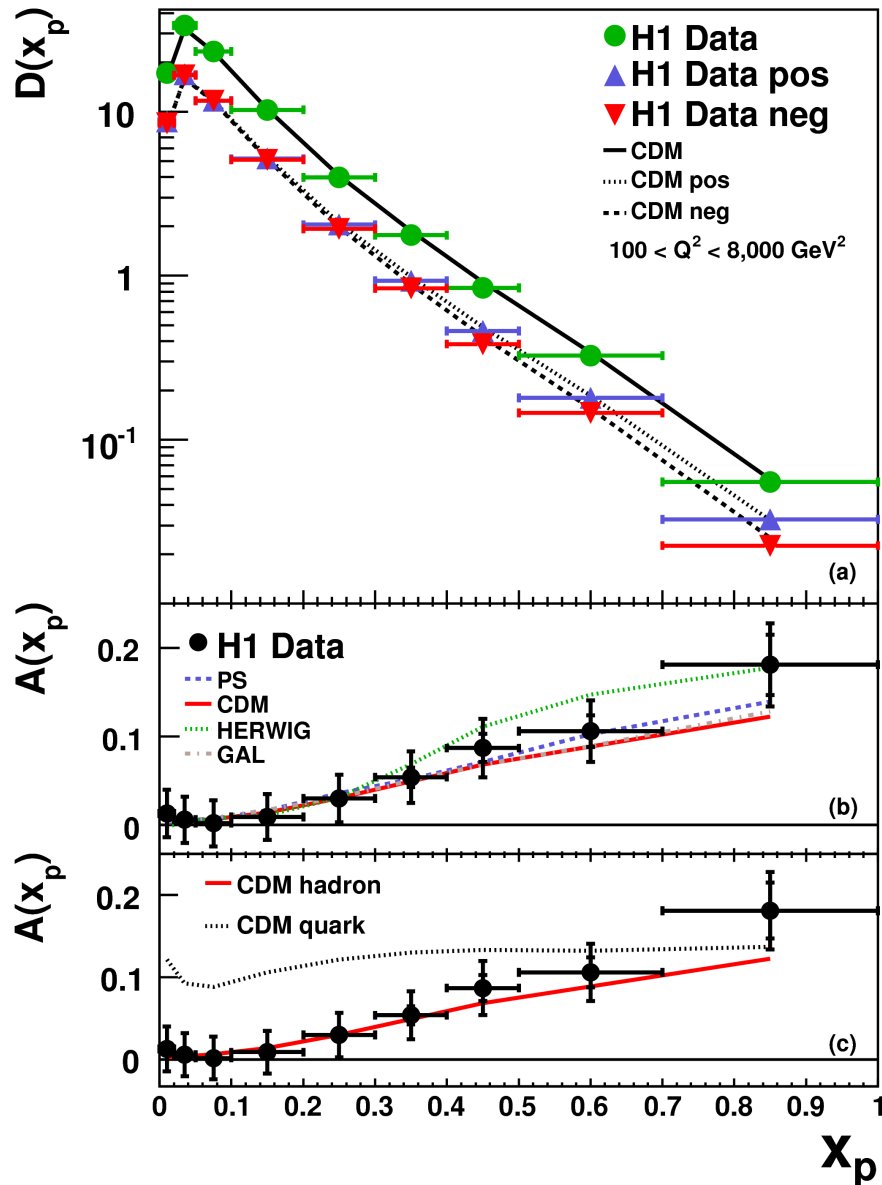
HERA compared to e^+e^- data





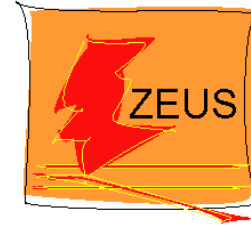
Charge Asymmetry

Scaled momentum distribution: $D = 1/N \, dn/dx_p$ for positively and negatively charged particles



- Significantly more data at low x_p
- Low x_p : distribution for positive and negative particles similar
- High x_p : excess of positively charged particles
- Charge Asymmetry 0.18 at high x_p
Described by MC and CDM
- Yields information on fragmentation functions and valence quark distribution

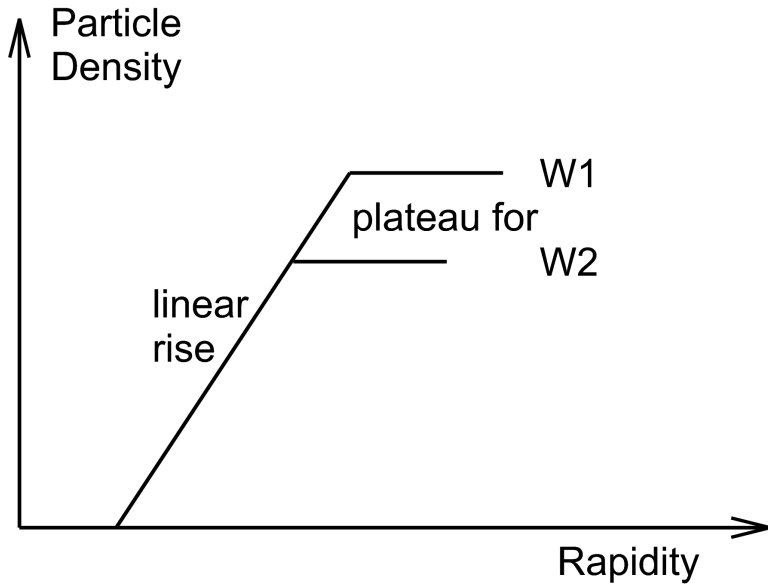
Summary



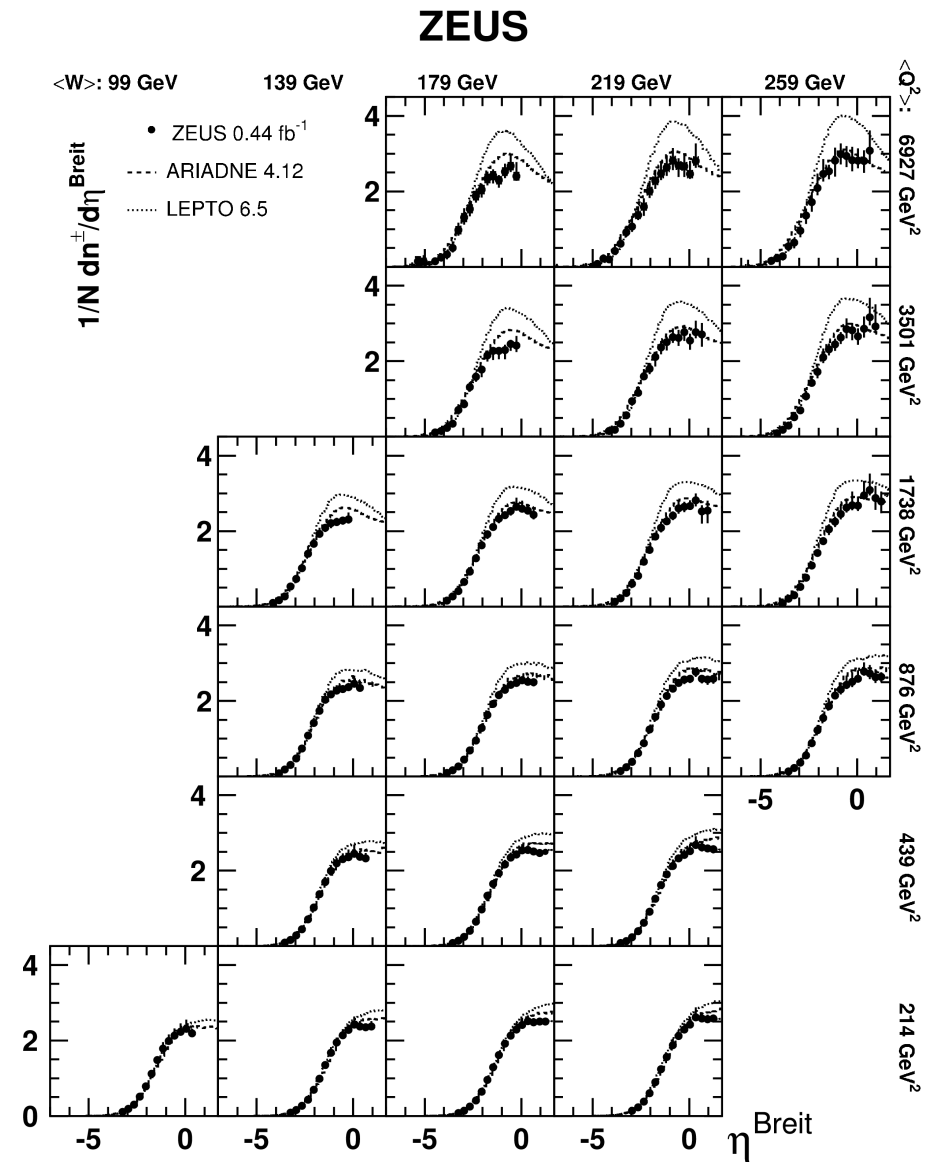
- Jets in photoproduction and DIS
accurate measurements, well described by NLO calculation
sensitivity to gluon in proton
Running of α_s measured in single experiment, extraction of $\alpha_s(M_Z)$
- Prompt photons in photoproduction and DIS
Calculations generally underestimate cross section
Fail to describe shapes in several kinematical regions
- Charged particle spectra at low Q^2 , low x
Data favours models beyond DGLAP
- Scaled momentum distributions
NLO calculations do not describe data well, MC slightly better
Comparison with e^+e^- supports universality of fragmentation
- Charge Asymmetry
Asymmetry increases with scaled momentum
Sensitivity to valence quark distribution in the proton

Backup slides

Limited fragmentation



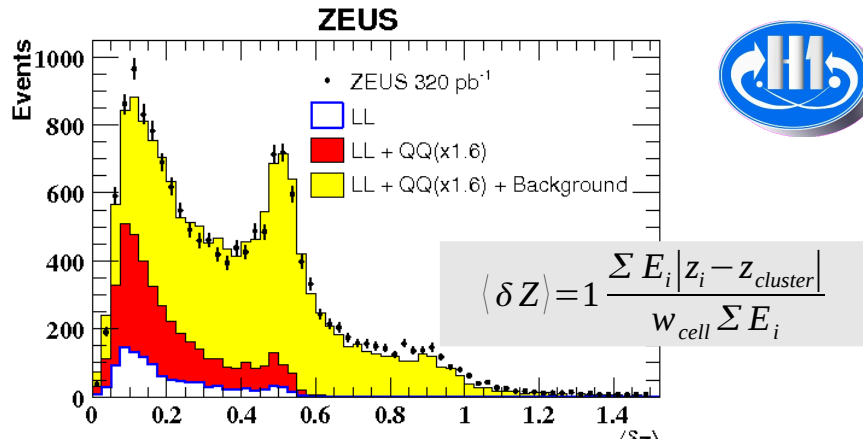
- Density of charged particles per unit of Pseudorapidity
- Linear rise and plateau observed in all bins
- Supports hypothesis of limited fragmentation
- Slopes do not depend much on Q^2 and W



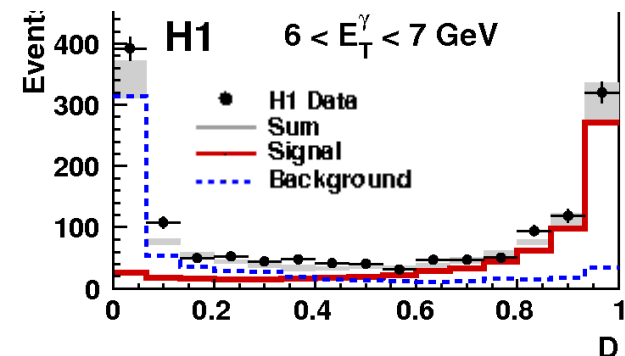
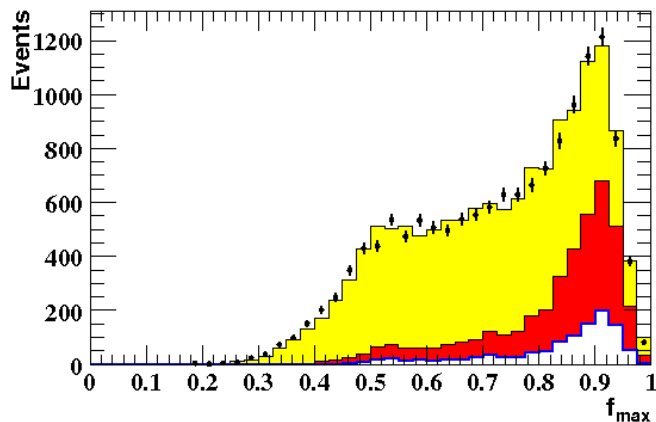
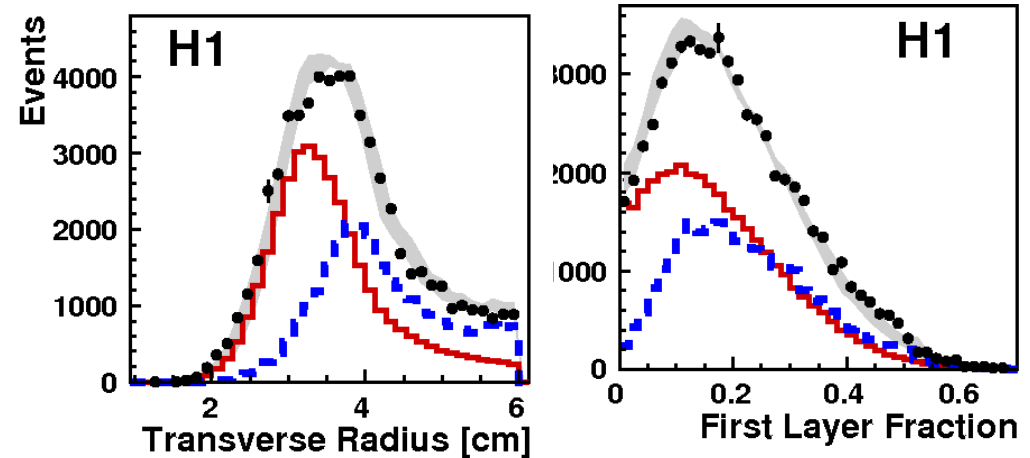
Prompt Photon Production

- Alternative access to QCD dynamics
- Different systematics
- Photoproduction (H1: Eur Phys J C66 (2010) 17)
- DIS (ZEUS: Phys Lett B687 (2010) 16)
- Background from neutral hadrons

ZEUS: shower width, fit to $\langle \delta Z \rangle$



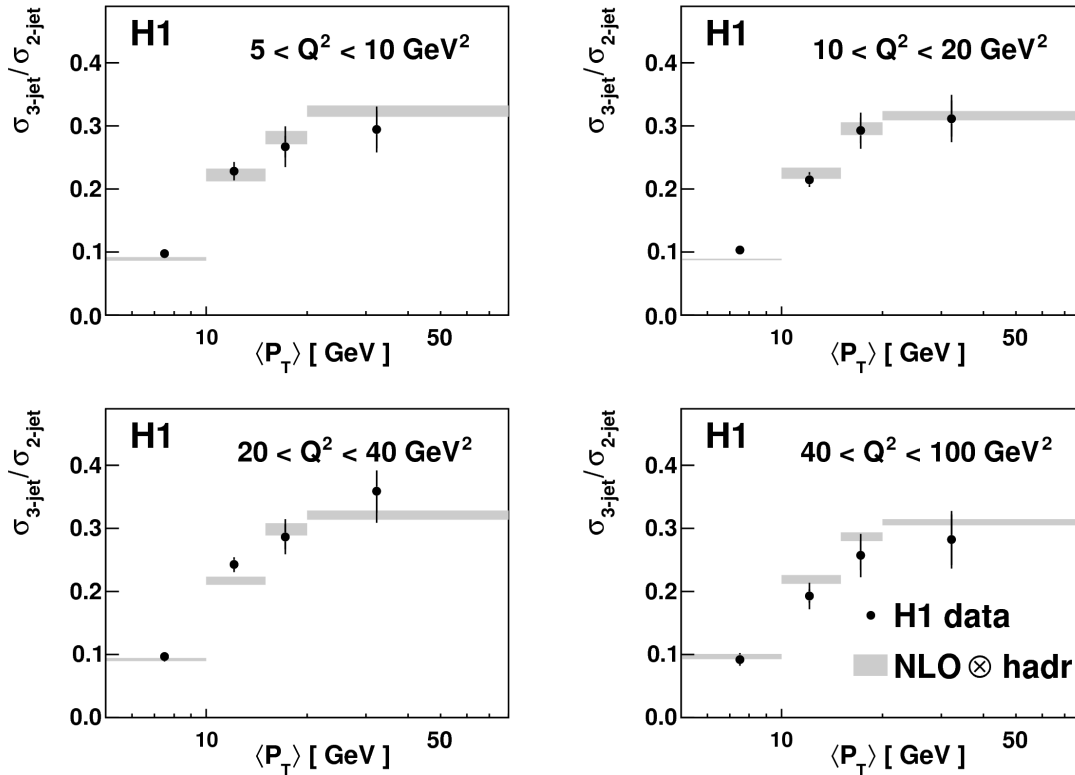
H1: six shower shapes → Discriminant



Ratio: 3-jet to 2-jet



3-Jet to 2-Jet Ratio



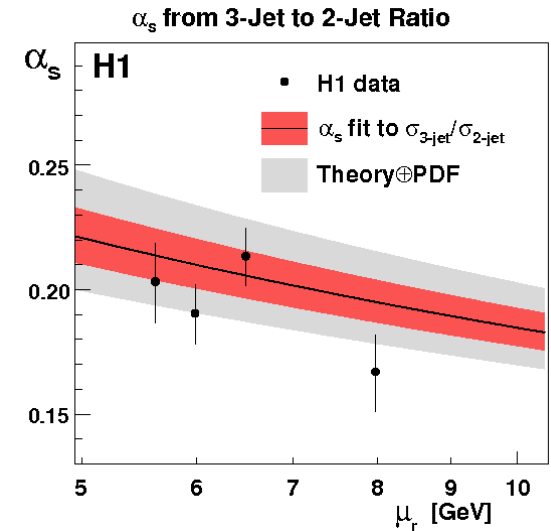
Theoretical errors smaller
 Statistical error dominates
 Expected to improve with full statistics

P_T spectra of 3-jets harder

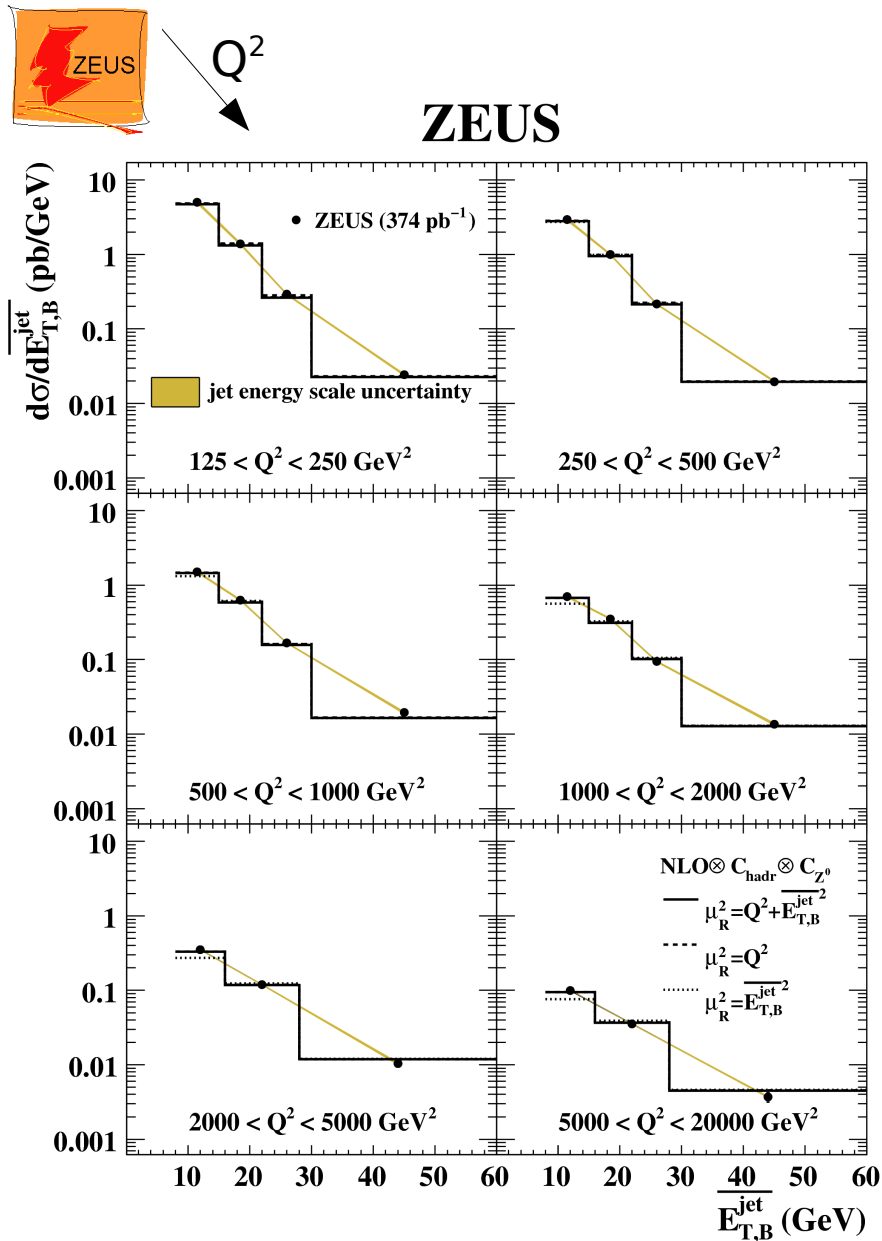
Statistical errors dominate

Normalisation error cancel
 Syst. errors cancel partially
 Reduced by 50%

Reduced sensitivity to missing
 higher orders in NLO

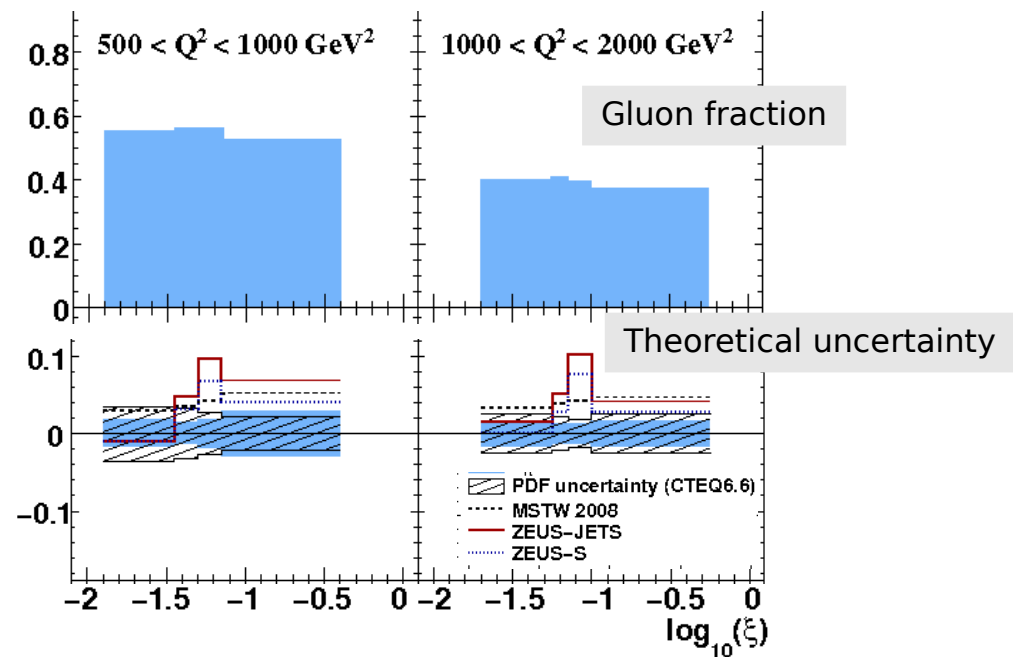


Dijet Cross Sections: $e+p \rightarrow \text{jet} + \text{jet} + X$



Very small statistical and systematical errors
 uncorrelated $\pm 2(10)\%$ at low (high) Q^2
 correlated: $\pm 5(2)\%$ at low (high) Q^2

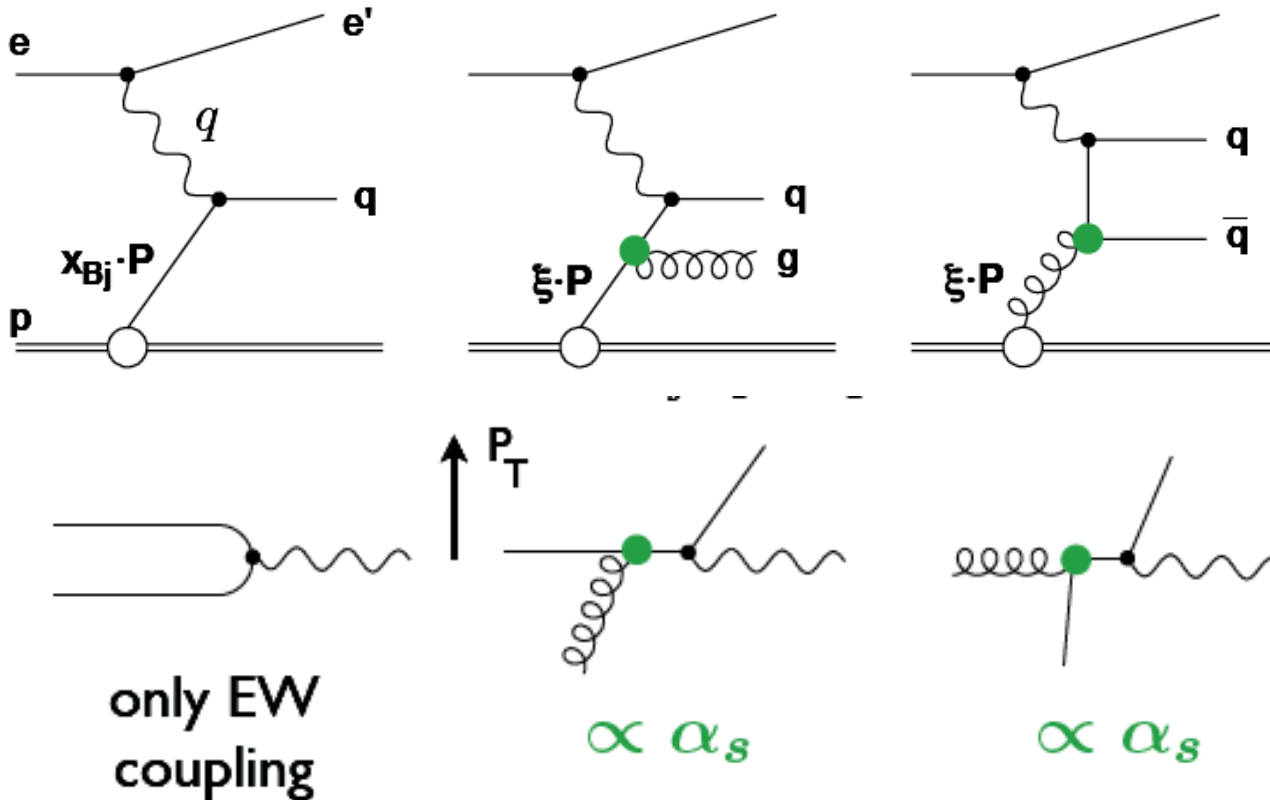
Description by NLO (NLOJET++) very good
 → Important input for extraction of PDFs -
 especially gluon in proton - and α_s



PDF uncert. large in regions with large gluon fraction

ZEUS: 374 pb⁻¹, 125 < Q² < 20000 GeV², Breit frame: E_T^{Jet} > 8 GeV, M_{jj} > 20 GeV²

Jet Production



Virtuality $Q^2 = -q^2 = -(e-e')^2$

Inelasticity $y = \frac{p \cdot q}{p \cdot k}$

Bjorken scaling variable $x_{Bj} = \frac{Q^2}{2pq}$

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

Boost to Breit frame: $2x_{Bj} + q = 0$

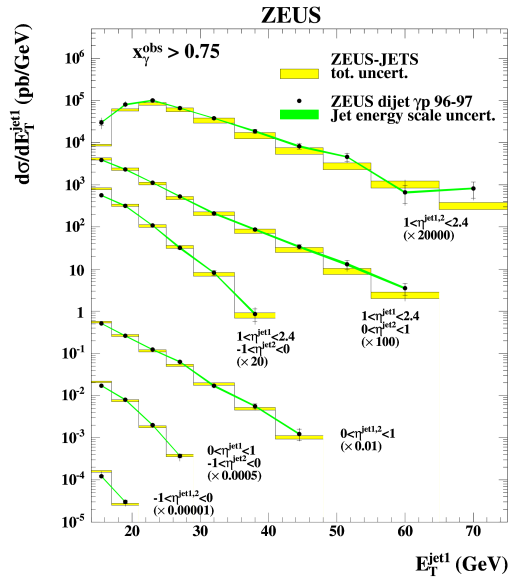
Only processes proportional to α_s generate P_T in the Breit frame

Dijet Cross Sections: PDF extraction

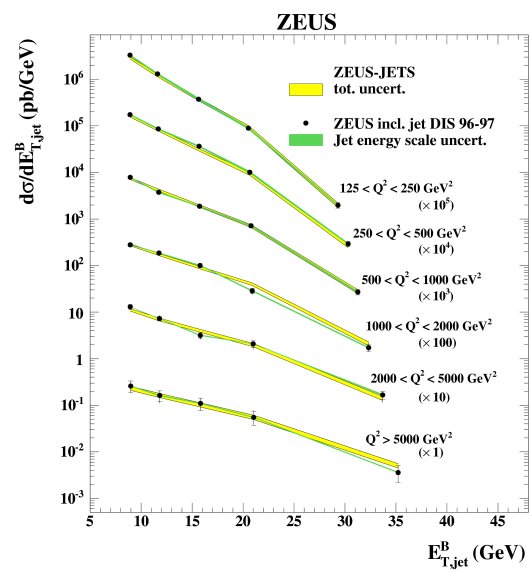


40 pb⁻¹

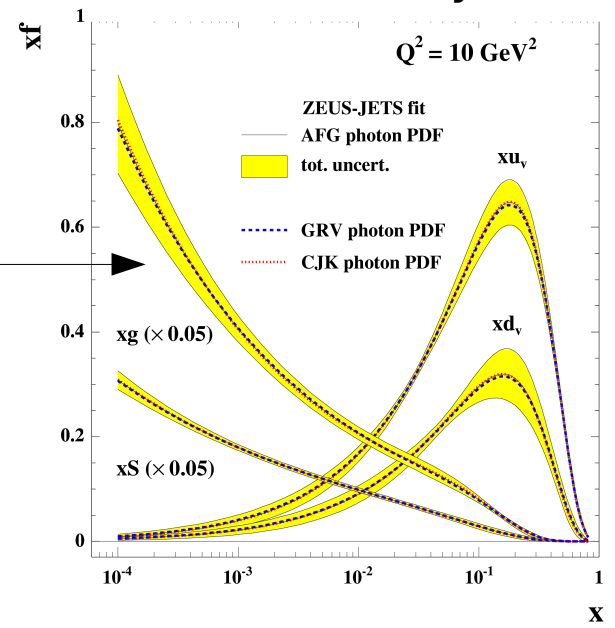
Photoproduction



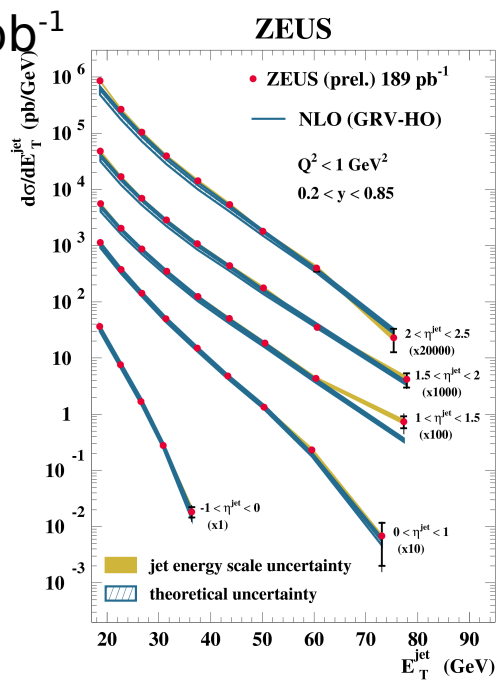
+ NC DIS



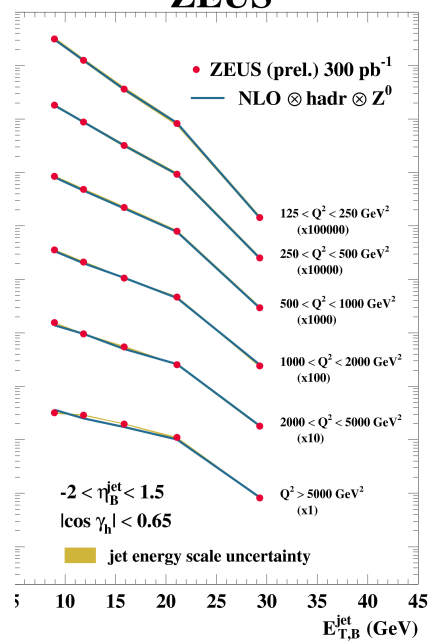
Parton Density functions



200 -400 pb⁻¹

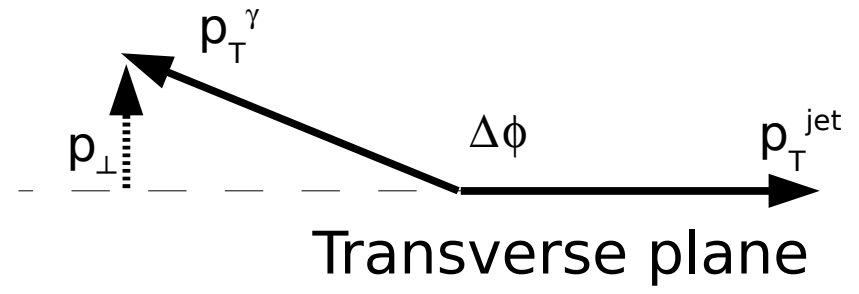
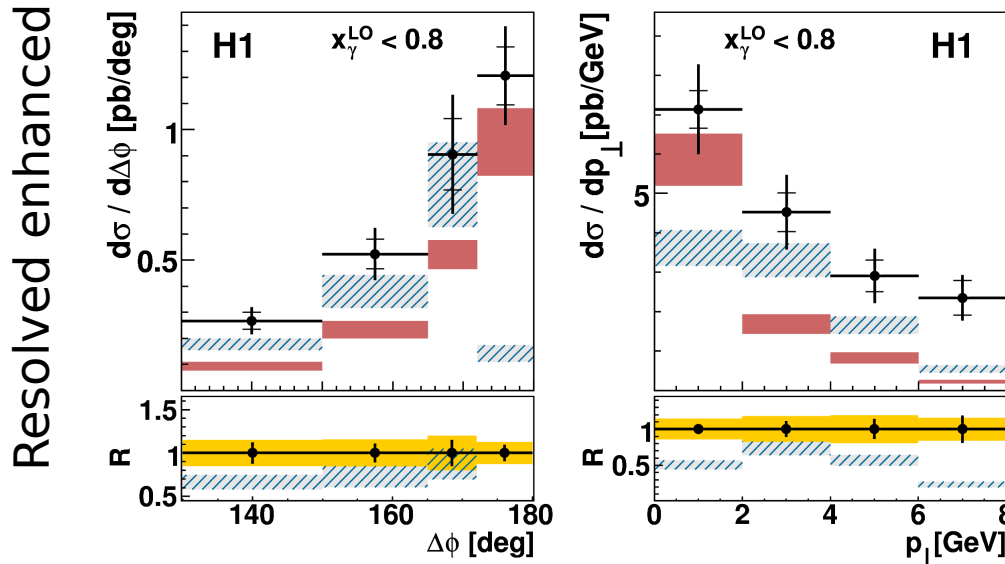
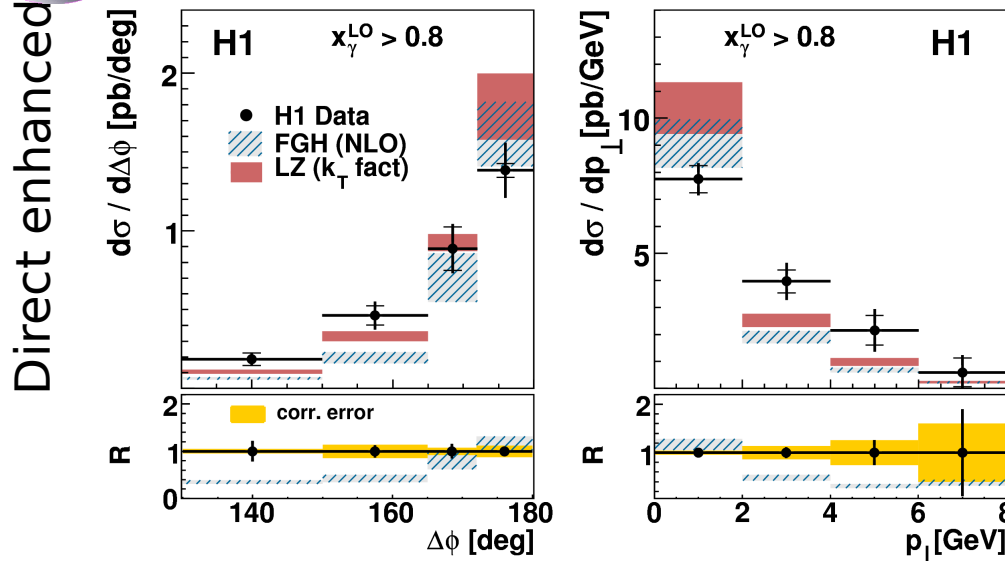


ZEUS



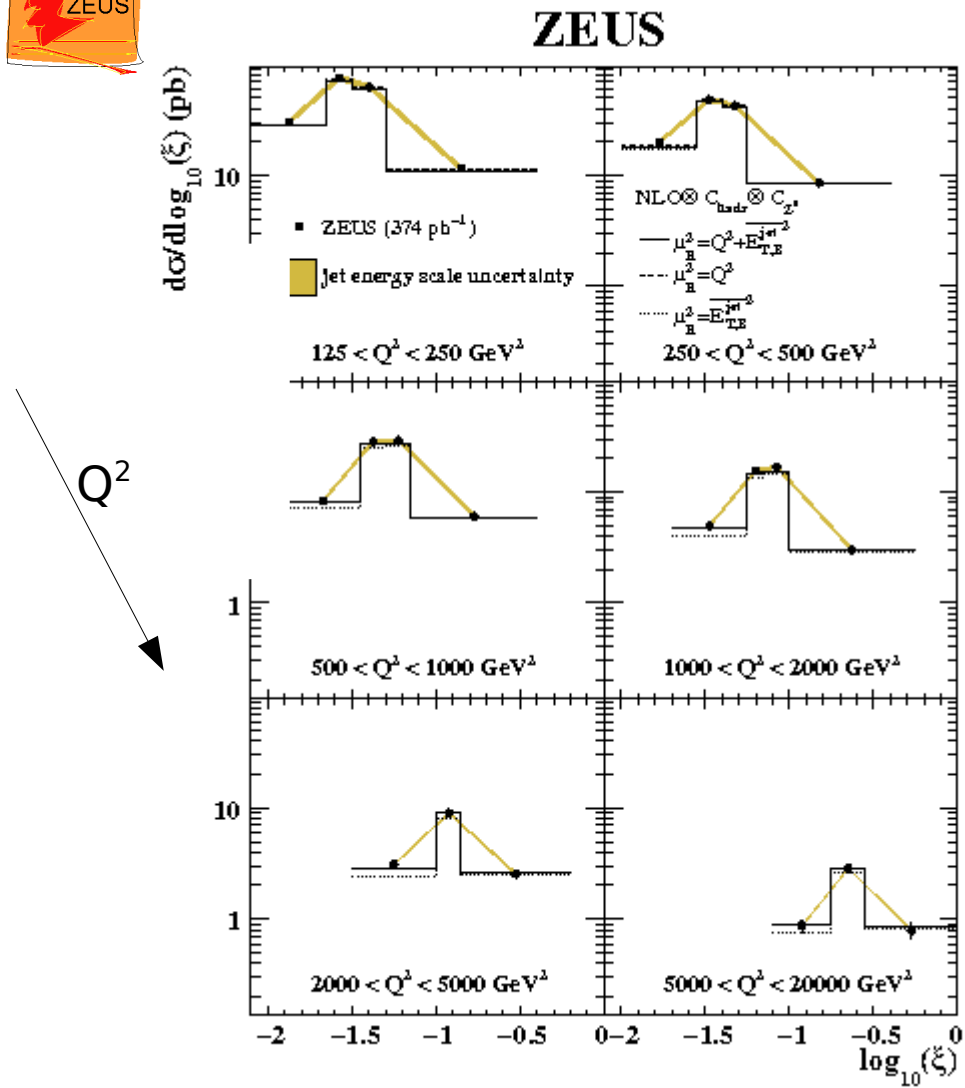
ZEUS EPJ C 42(2005) 1

Prompt Photon and Jet: Transverse Correlation



- Data not well described
- $x_{\gamma} > 0.8$
 Both calculations underestimate non back-to-back configuration
- $x_{\gamma} < 0.8$
 Sensitivity to multiple soft gluon emission for $\Delta\Phi \rightarrow 180$
 Fixed order calculation not reliable
 k_T factorisation absorbs soft gluons in PDFs
 Tails underestimated (higher orders)

Dijets: Sensitivity to PDFs and α_s



Very small statistical and systematical errors

Description by NLO very good

→ Important input for extraction of PDFs, especially gluon in proton, and α_s

ZEUS: 374 pb⁻¹, 125 < Q² < 20000 GeV², Breit frame: E_{T,jet} > 8 GeV, M_{j,j} > 20 GeV²