Precision measurements with jets and particles at HERA

Katharina Müller
Zurich University

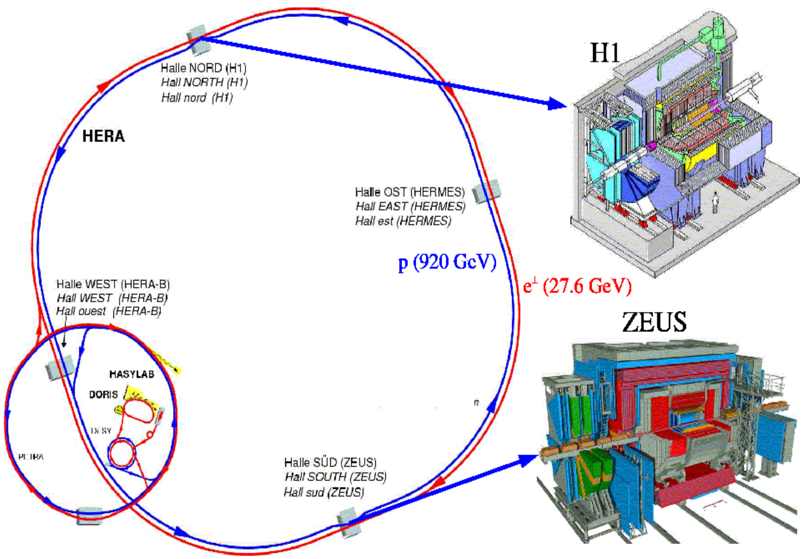
on behalf of the H1 and ZEUS collaborations

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 Q2
- Scaled Momentum Distributions
- Charge Asymmetry

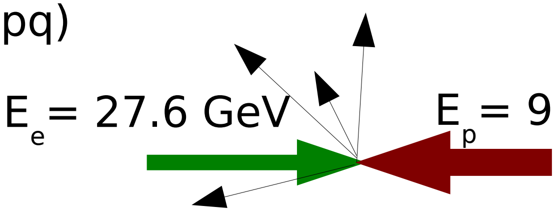
HERA- Introduction



Total integrated luminosity 0.5 fm^{-1}/experiment
Centre of mass energy: 318 GeV

$Q^2=-q^2$: photon virtuality

$x = x_{BJ} = Q^2/(2pq)$



Two kinematic regimes

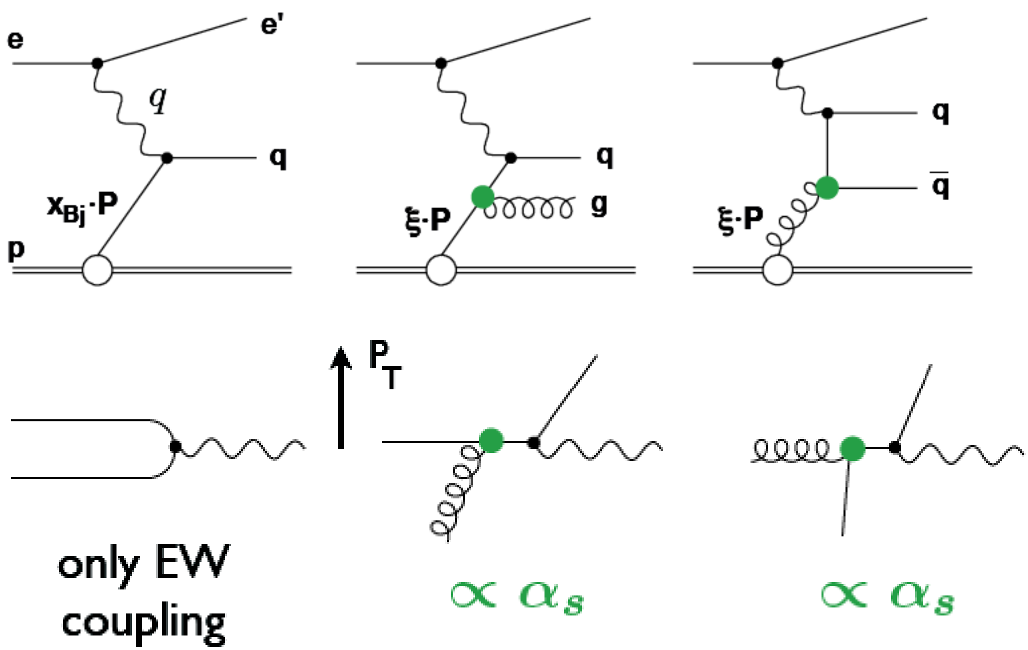
$Q^2 \cong 0$ GeV^2: Photoproduction
$Q^2 > 1$ GeV^2 : Deep Inelastic Scattering (DIS)

Jet Production

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

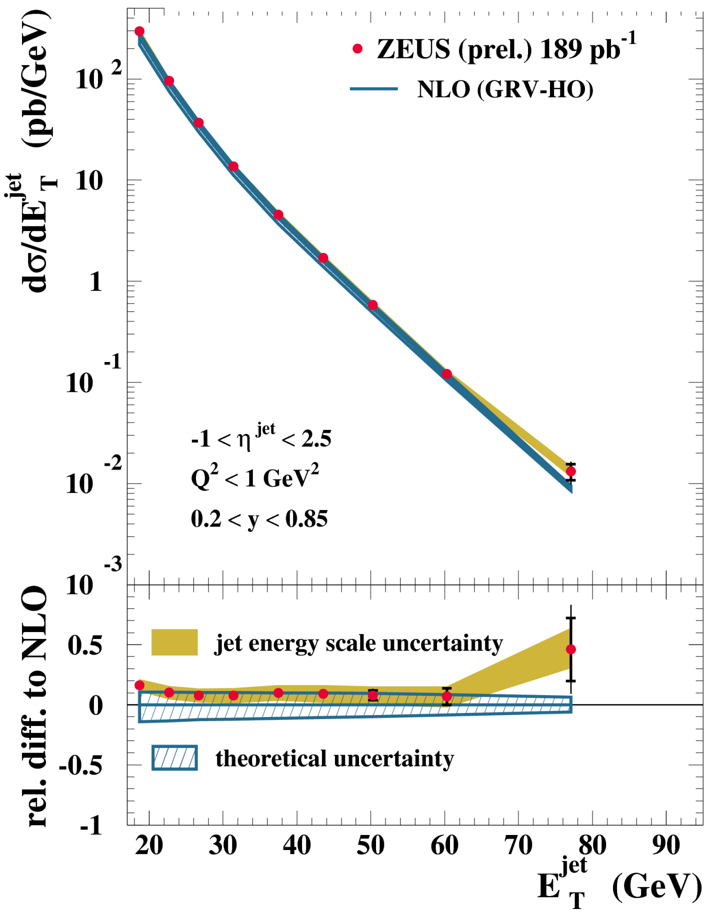
Only processes proportional to α_s generate P_T in the Breit frame

ξ: fraction of proton momentum carried by struck quark $\xi = 1+M_{12}{}^2/Q^2$

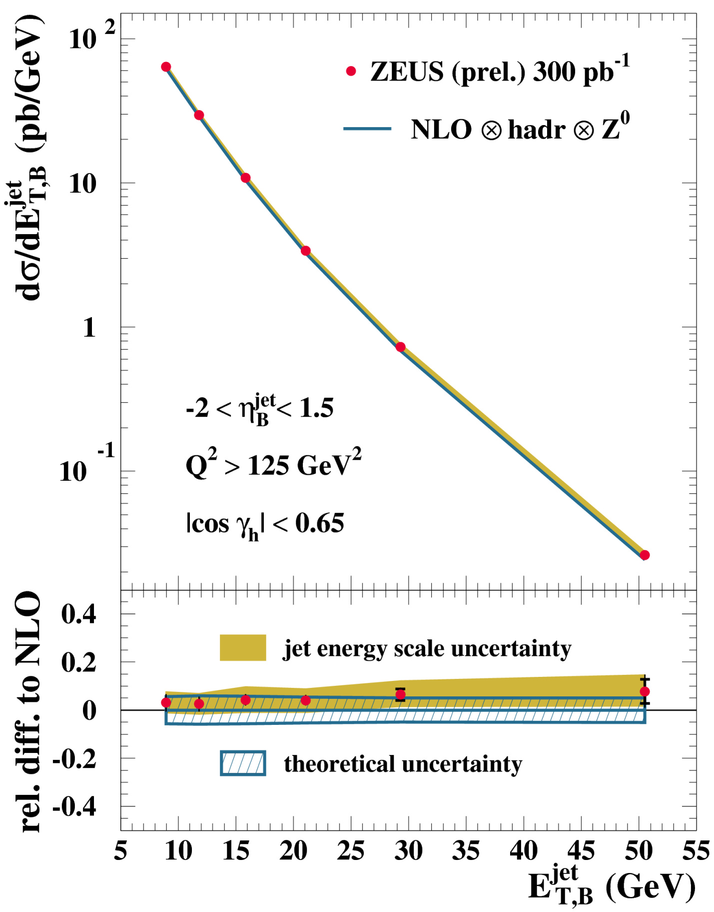


Inclusive Jet Cross Section

Photoproduction



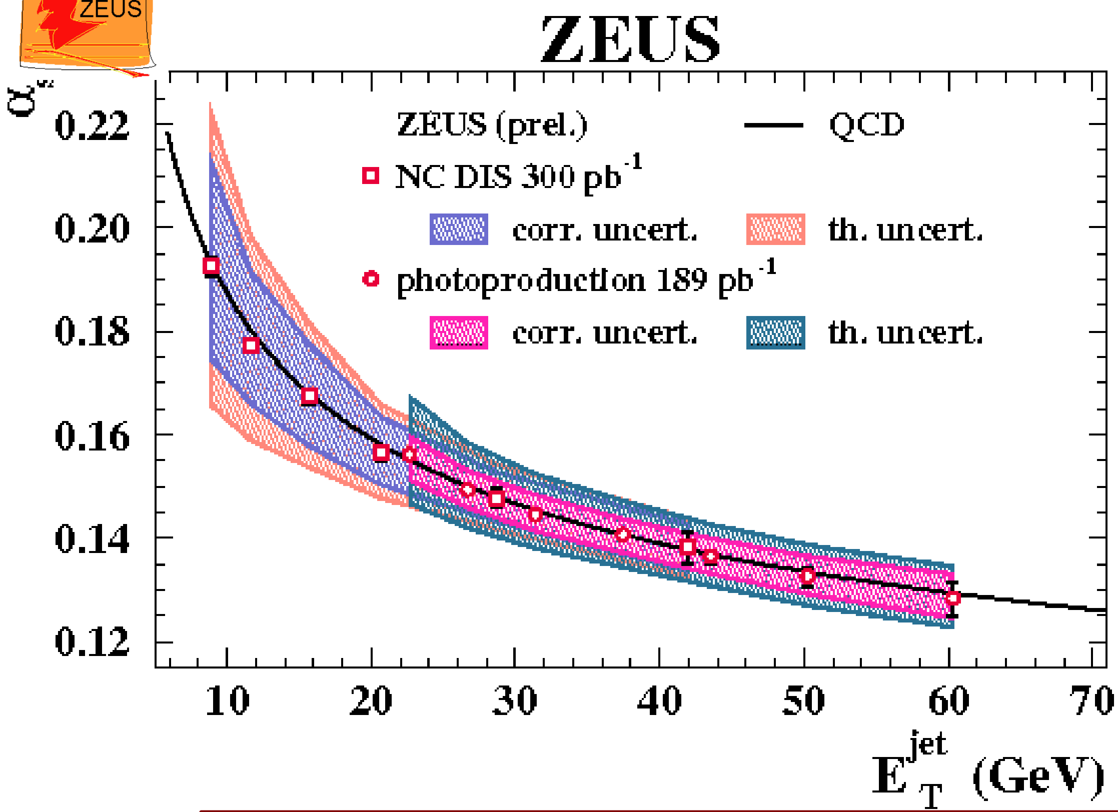
neutral current DIS



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

ZEUS-prel-10-002 ZEUS: 300 pb^{-1} ,Q^2>125GeV^2 , -2<η_B<1.5 , E_T^{Jet}>8 GeV
ZEUS-prel-10-003 ZEUS: 189 pb^{-1} ,Q^2<1GeV^2 , -1<η_B<2.5 , E_T^{Jet}>17 GeV

α_s from Inclusive Jet Cross Section



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

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

In good agreement with predicted running of α_s over a large range of E_T^{jet}

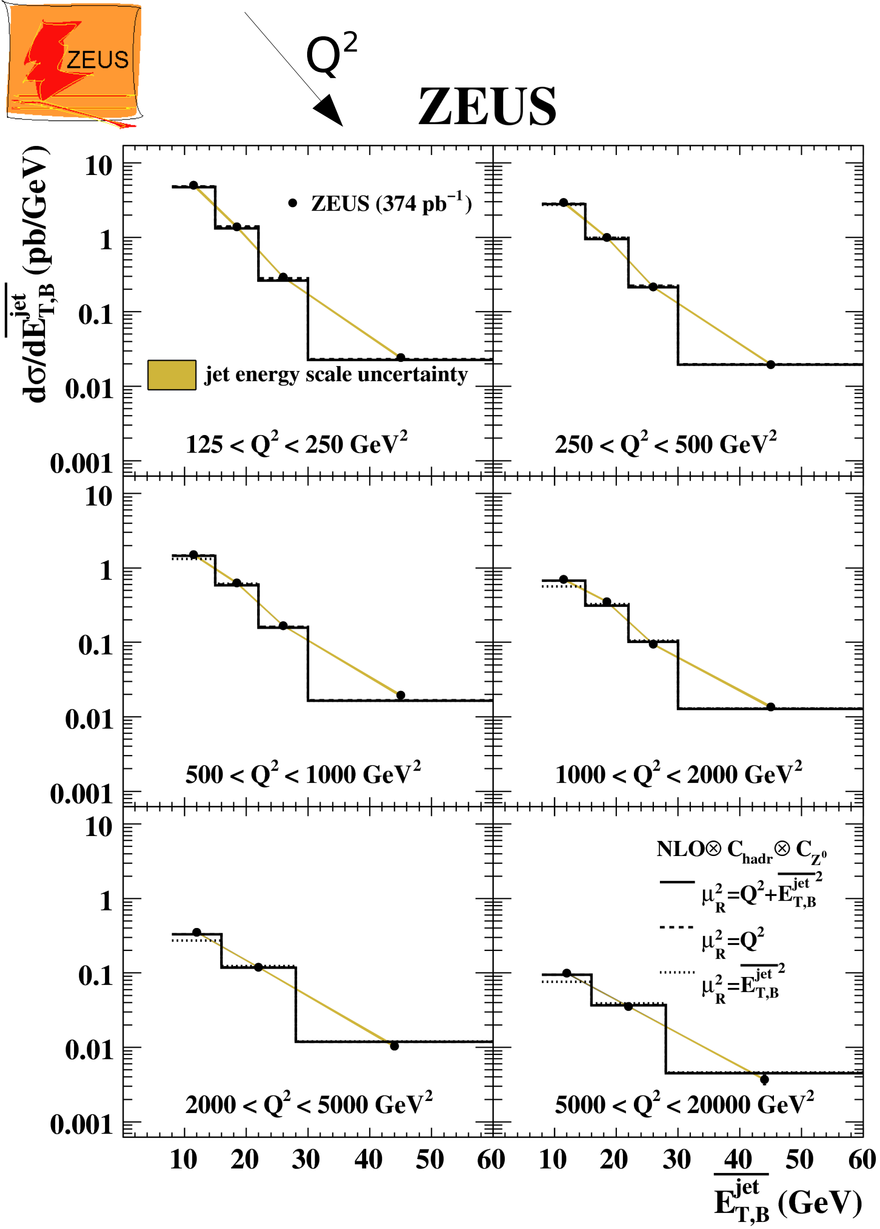
α_s measurements consistent with each other and the world average

New jet algorithms (anti-kt, SIScone) tested: similar results

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

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

Dijet Cross Sections: e+p→jet+jet+X

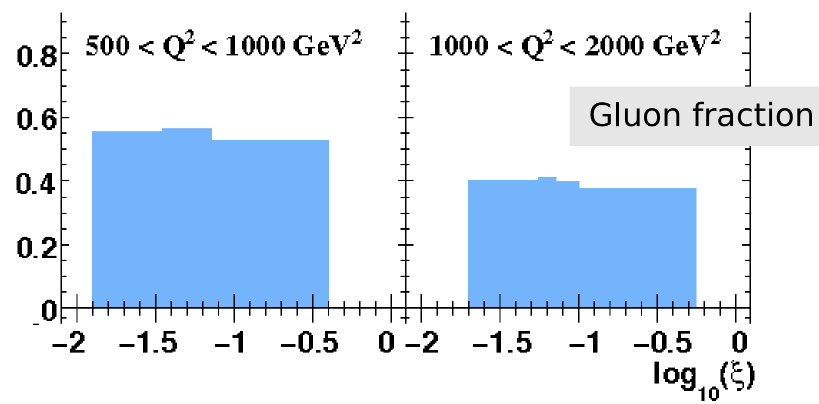


Very small statistical and systematical errors
uncorrelated ± 2(10)% at low (high) Q^2
correlated: ± 5(2)% at low (high) Q^2

Description by NLO (NLOJET++) very good

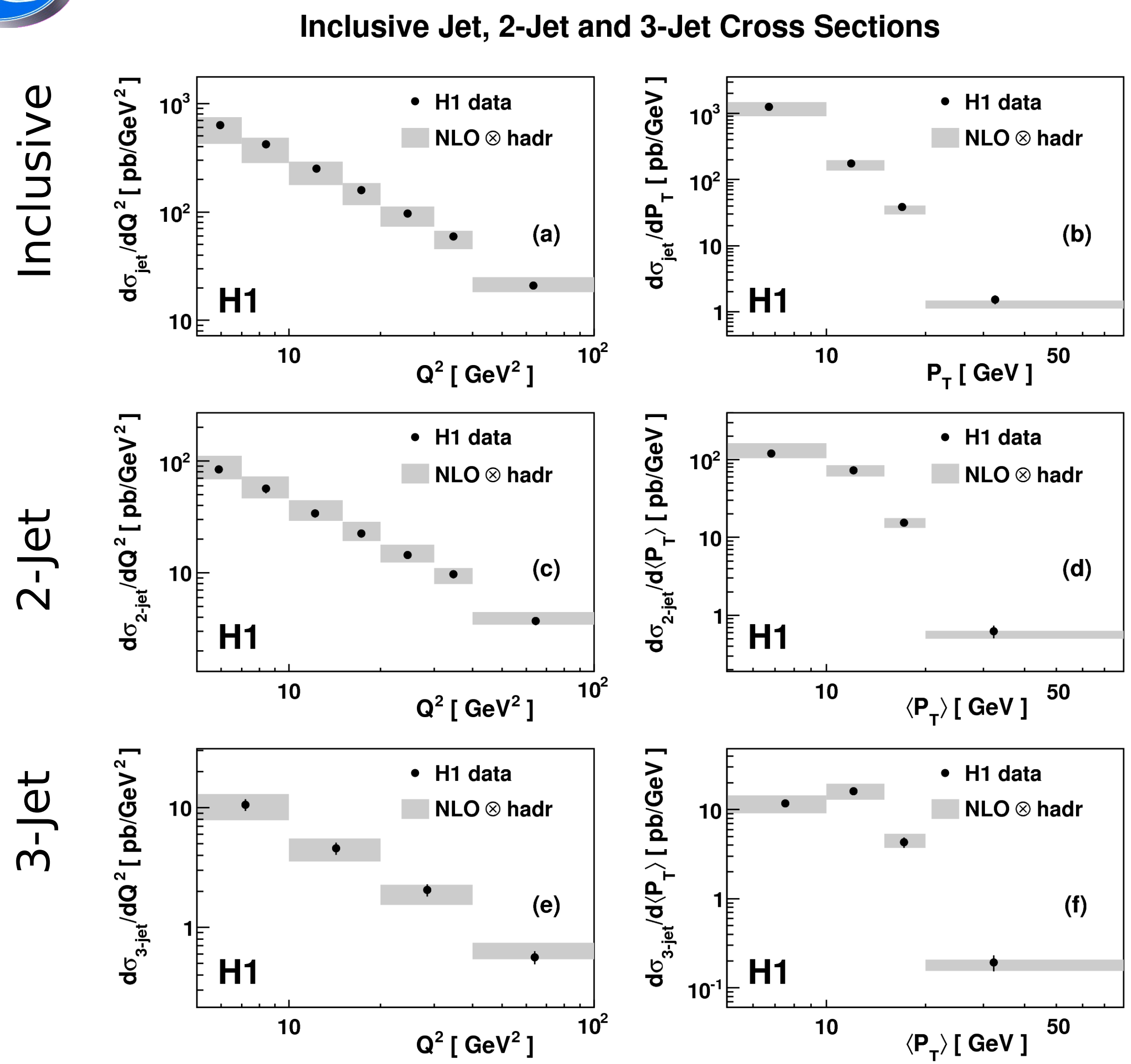
→ Important input for extraction of PDFs –

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 GeV^2 , Breit frame: E_T^{Jet}>8 GeV, Mjj>20 GeV^2



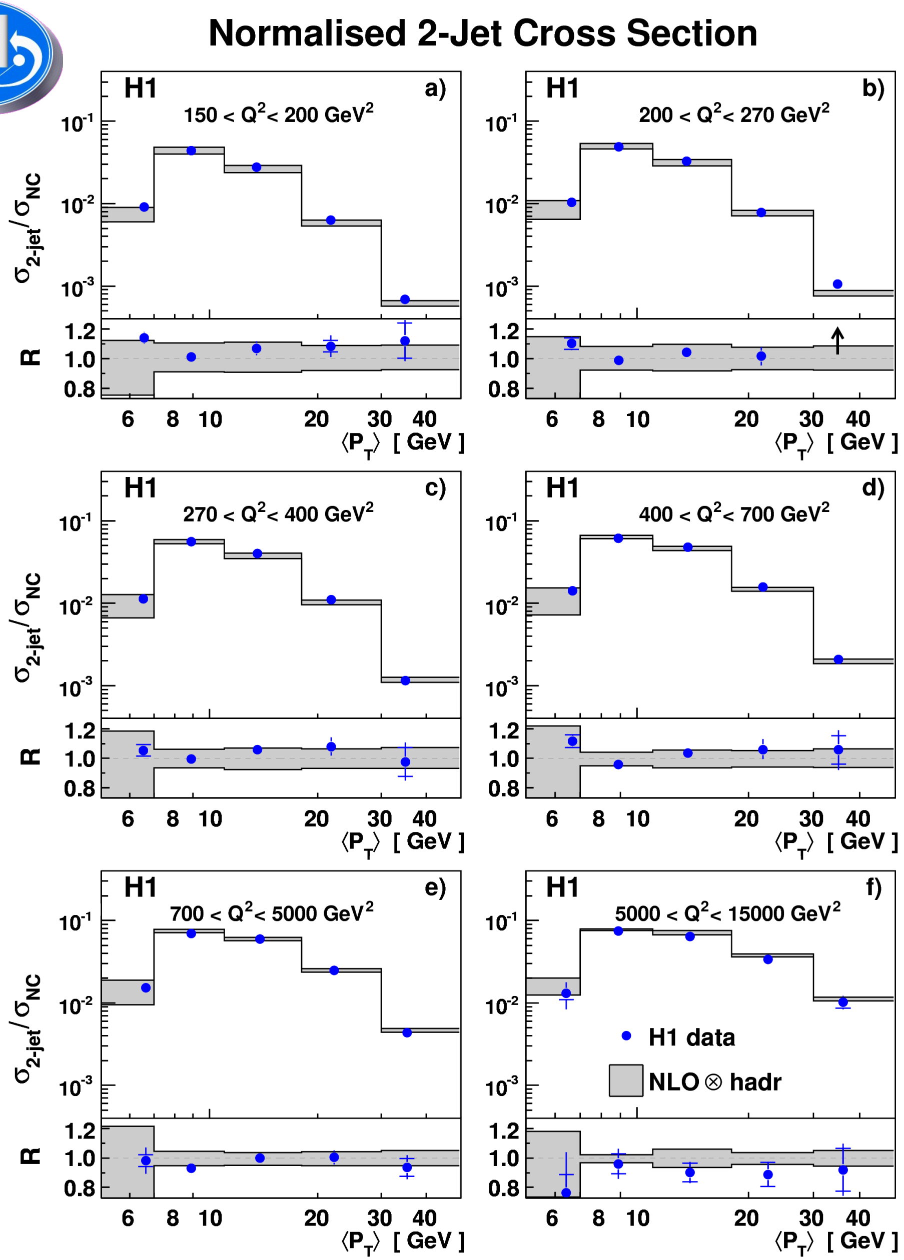
Exp. Uncertainties: 6-10%

Theoretical uncertainties
30% at low Q^2
NNLO needed

Good description by NLO

Hadronisation corrections
0.9-0.95 (0.8 3-jet)

Eur.Phys.J.C67:1-24,2010. H1: 44 pb^{-1} ,$5<Q^2<100$ GeV^2 , $0.2<y<0.7$, Breit frame: $5<p_T^{Jet}<80$ GeV, $Mjj>18$ GeV^2



Normalised to NC DIS cross section
cancellation of errors

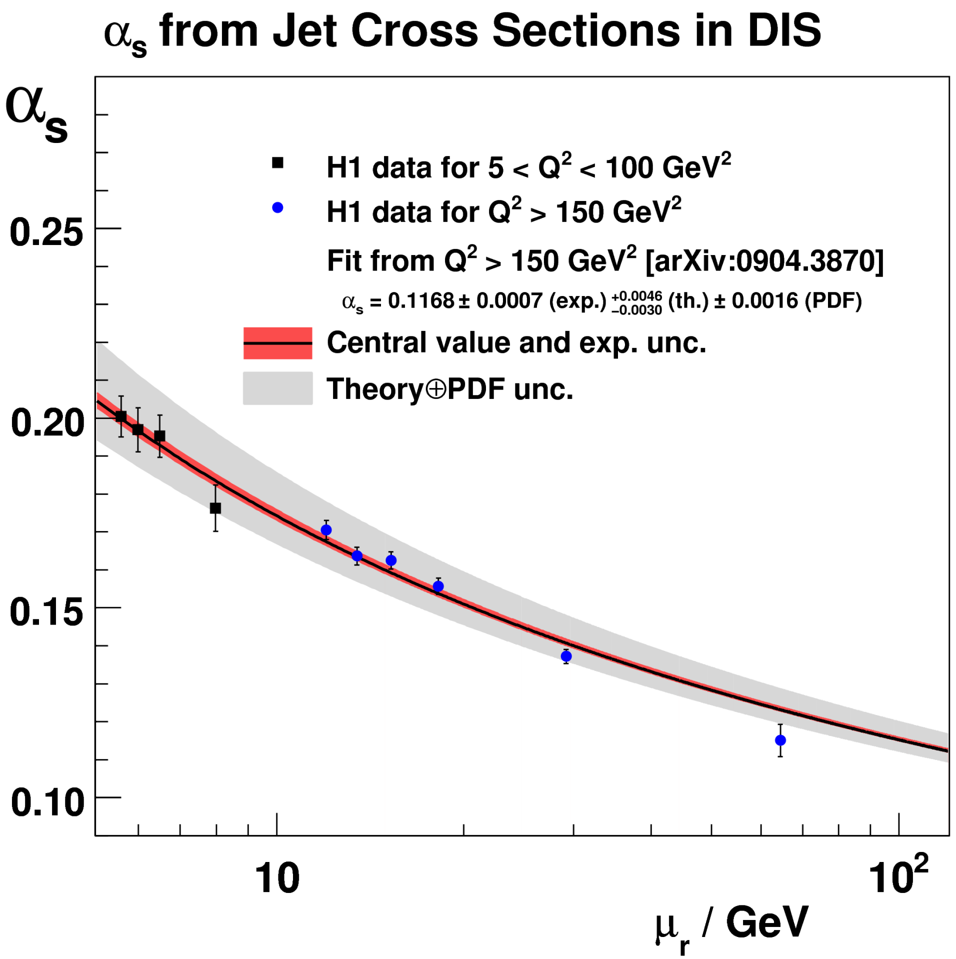
Very accurate measurement

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

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

Eur.Phys.J.C65:363-383,2010. H1: 395 pb^{-1} ,$150<Q^2<15000$ GeV^2 , $0.2<y<0.7$, Breit frame: $7<p_T^{Jet}<50$ GeV, Mjj>16 GeV^2

α_s: from high and low Q^2 data



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

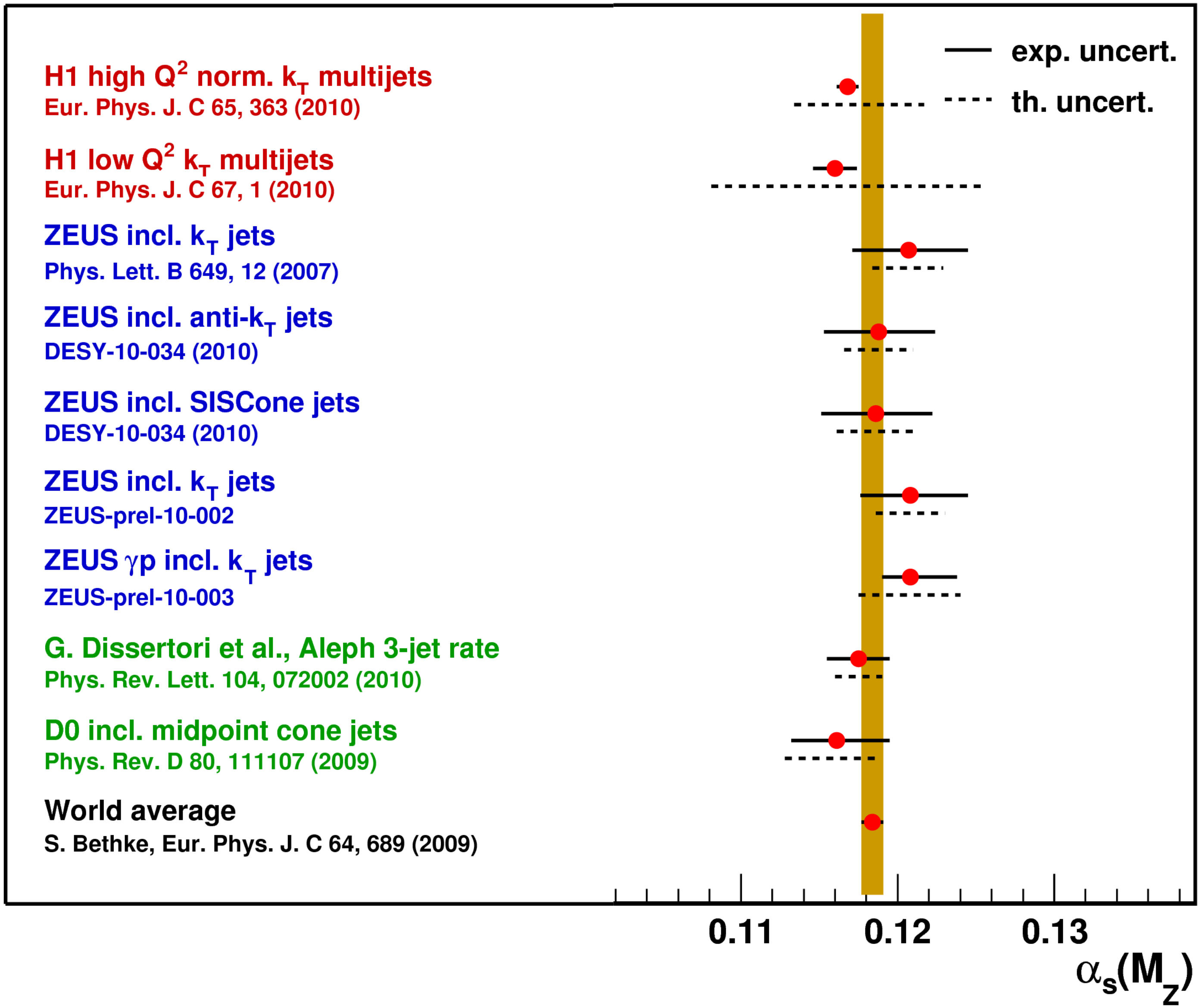
$$\mu_r = \sqrt{(q^2 + P^2_{T,obs})/2}$$

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

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

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

α_s: Summary

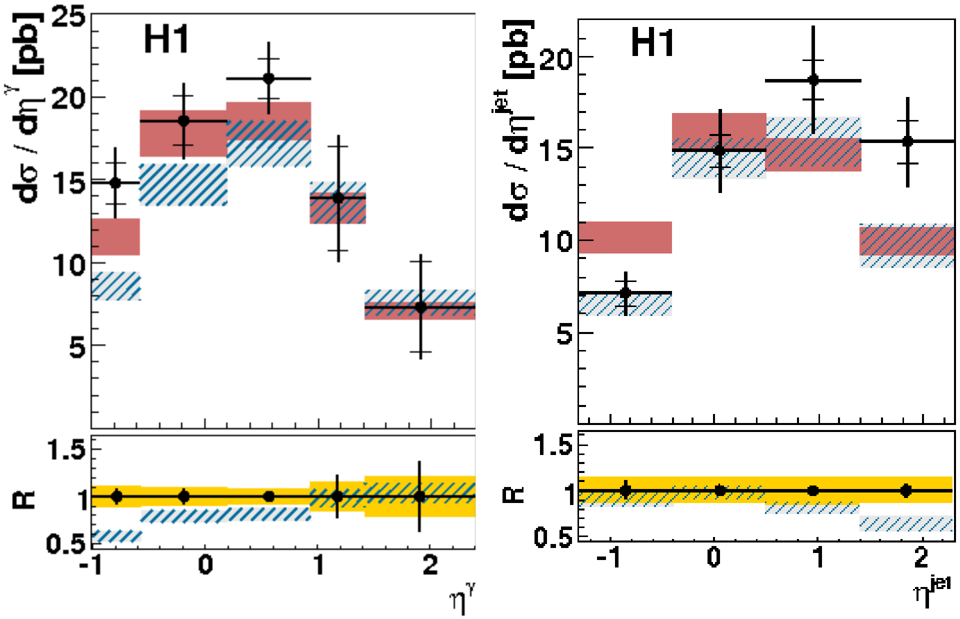


Consistent results from high and low Q^2 and different jet algorithms.

Calculations beyond NLO needed in DIS!

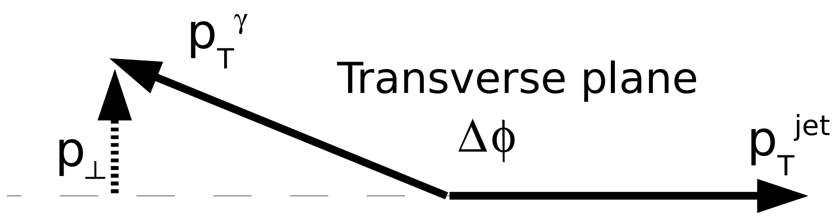
$\bar{2}$

α_s from HERA data very precise

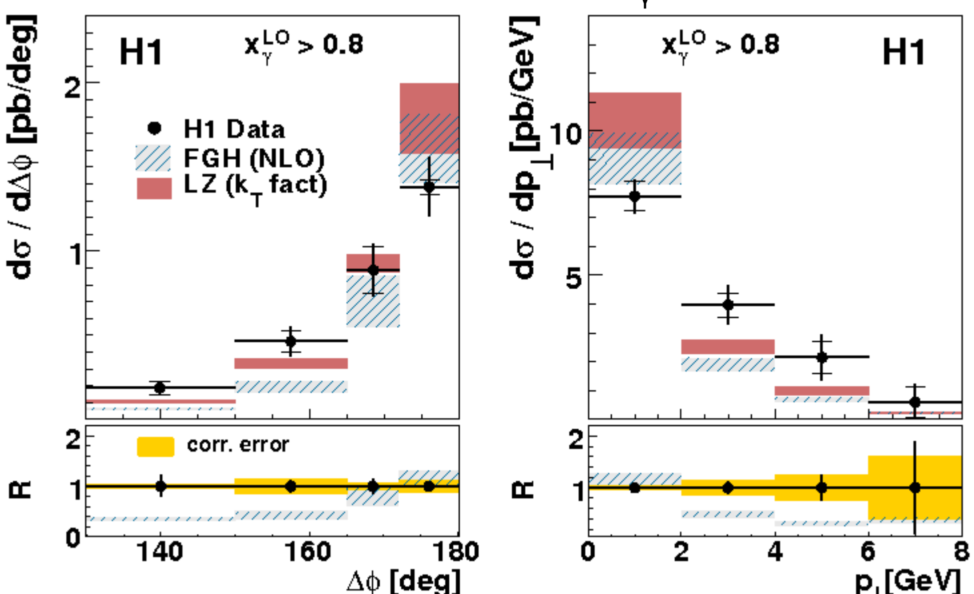


Comparison to
NLO calculation (FGH), collinear factorisation
kt factorisation approach (LZ)

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

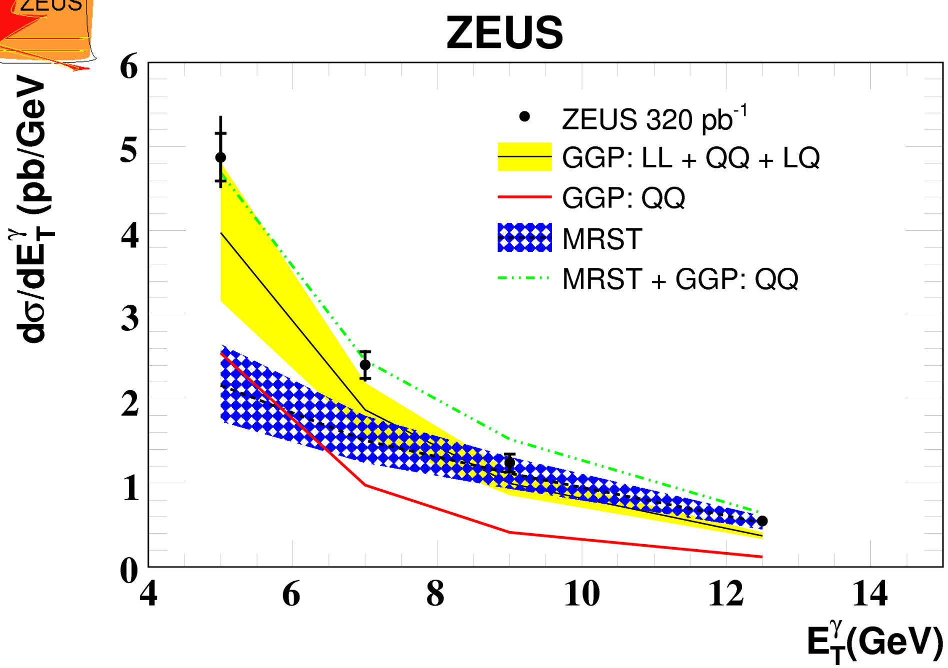


Transverse correlations, $x_{\gamma}>0.8$



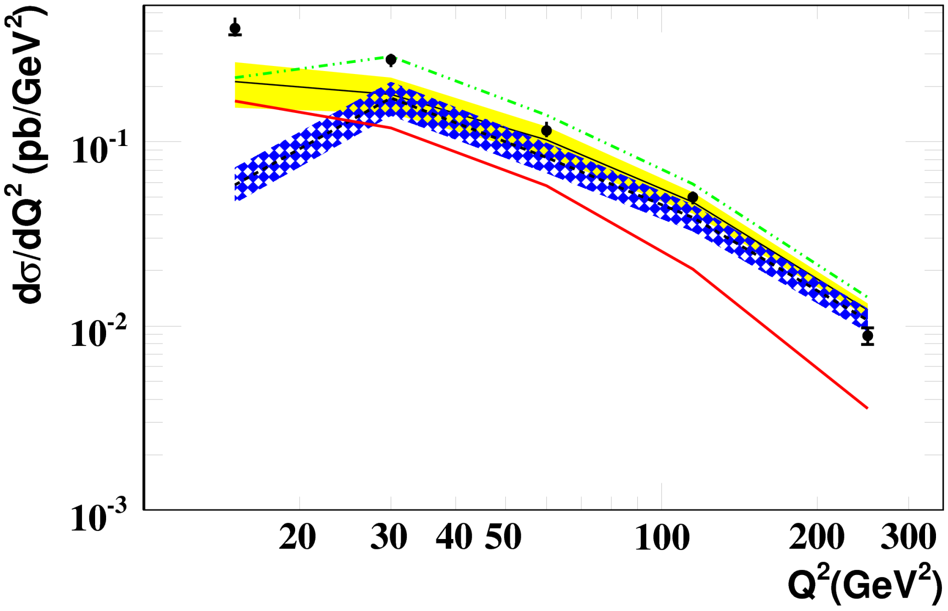
$x_{\gamma}>0.8$ direct enhanced sample
both calculations underestimate
non back-to-back configuration
sensitive to higher orders

H1 Eur Phys J C66 (2010) 17 $6<E_T^{\gamma}<15$ GeV,, $-1.0<\eta^{\gamma}<2.43$, $0.1<y<0.7$, $4.5<E_t^{jet}$, $-1.3<\eta^{jet}<2.3$



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 → partonic photon component in the PDF



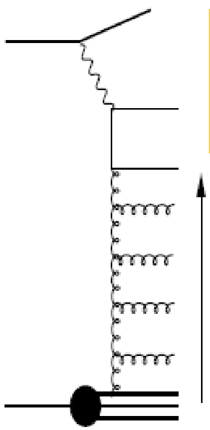
- GGP: shape of E_T^γ ok
  normalisation 20% too low
- MRST+QQ improved overall description
- Both calculations fail to describe low Q^2 and low x

ZEUS Phys Lett B687 (2010) 16 $4<E_T^\gamma < 15$ GeV, $-0.7<\eta^\gamma<0.9$, $10<Q^2<350$ GeV^2

Charged Particles → Parton Dynamics

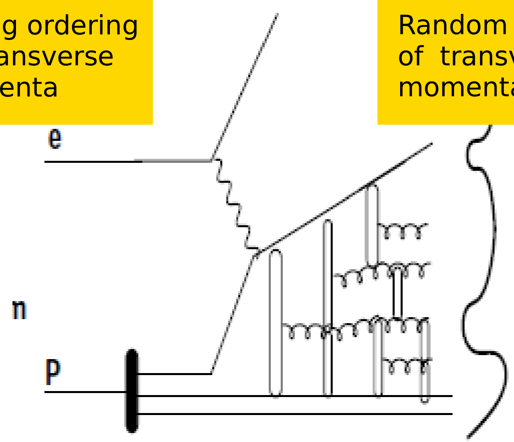
Small x: expect new parton dynamics to become important
Structure function measurements too inclusive → measure hadronic final state

DGLAP



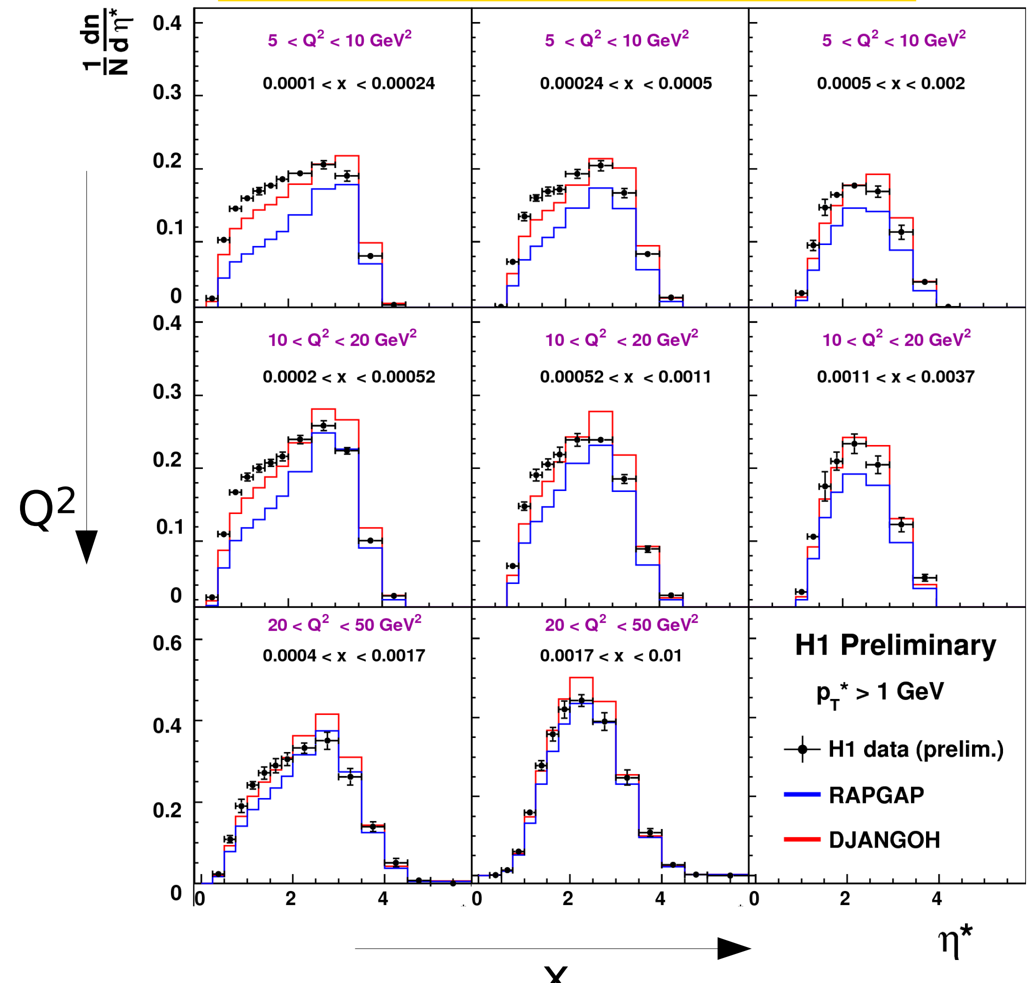
Strong ordering of transverse momenta

CDM (Color Dipole Model)



Random walk of transverse momenta

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



η *: in hadronic centre of mass system

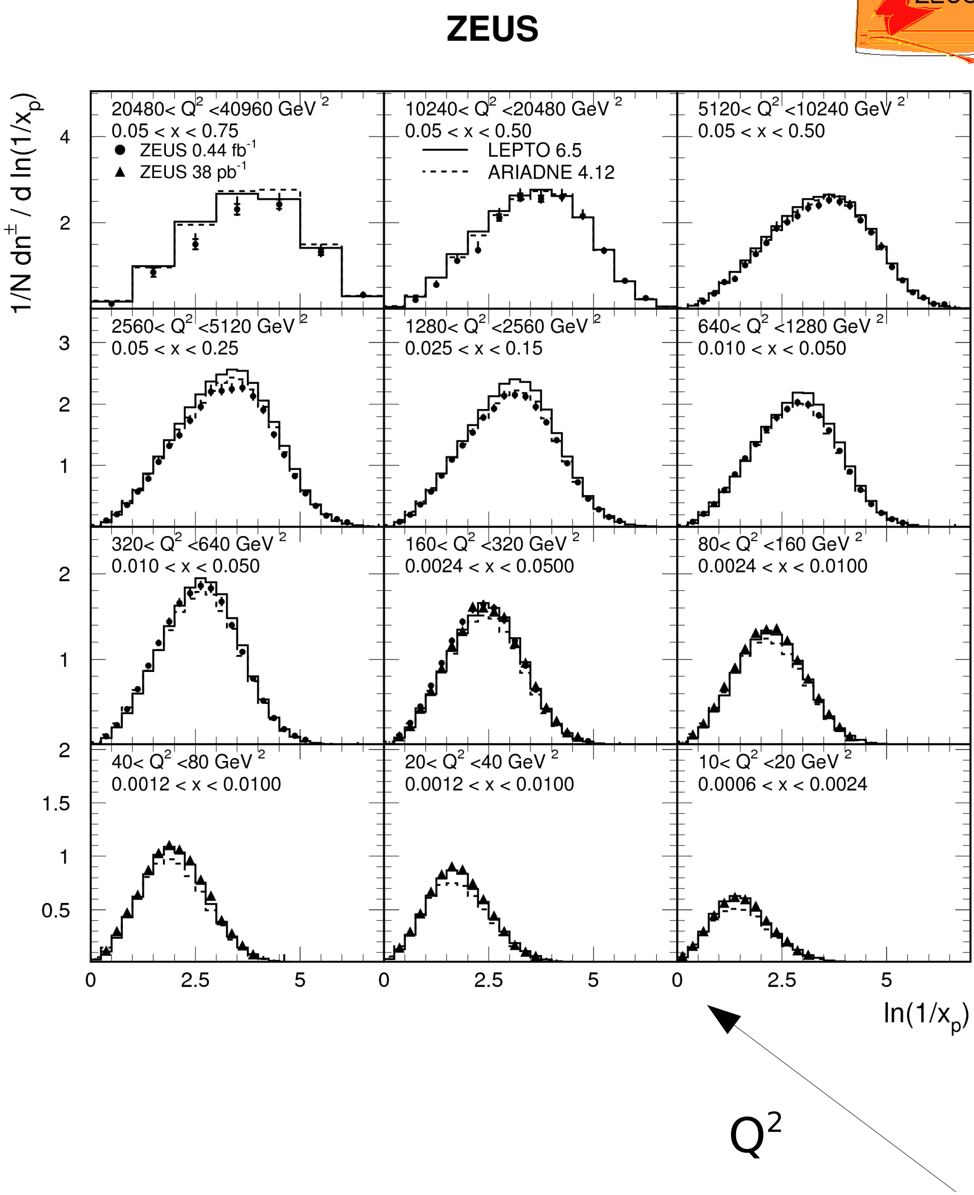
- High p_T :sensitivity to parton dynamics
- DJANGOH (CDM): reasonable description
- RAPGAP (DGLAP) significantly lower at small x, Q^2 deficit most pronounced in forward direction ($\eta^*<2$)

→ Data favours beyond-DGLAP model

H1-prelim-10-035 $5<Q^2<100$ GeV^2, $0.0001<x<0.01$, $p_T^{track} > 0.15$ GeV,

Soft Particle Distribution in DIS

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



- Q^2 increase →
  mean multiplicity increase,
  peak towards lower x_p

  phase space for soft gluon emission
  increases more particles at low x_p
  → scaling violation

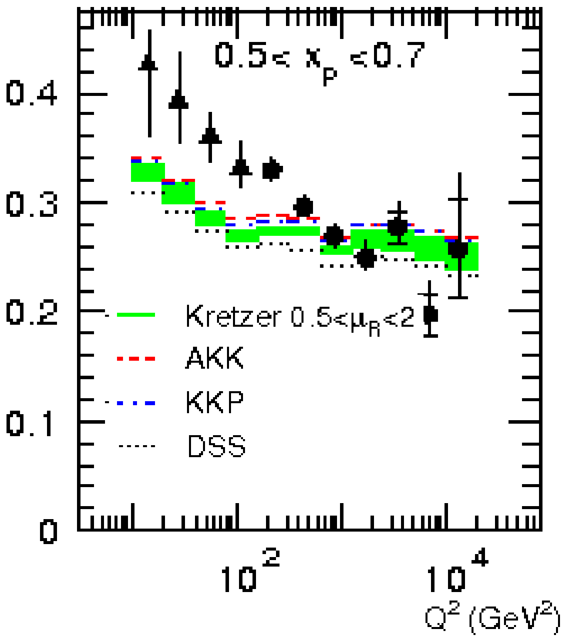
- Ariadne/ LEPTO problems at high Q^2

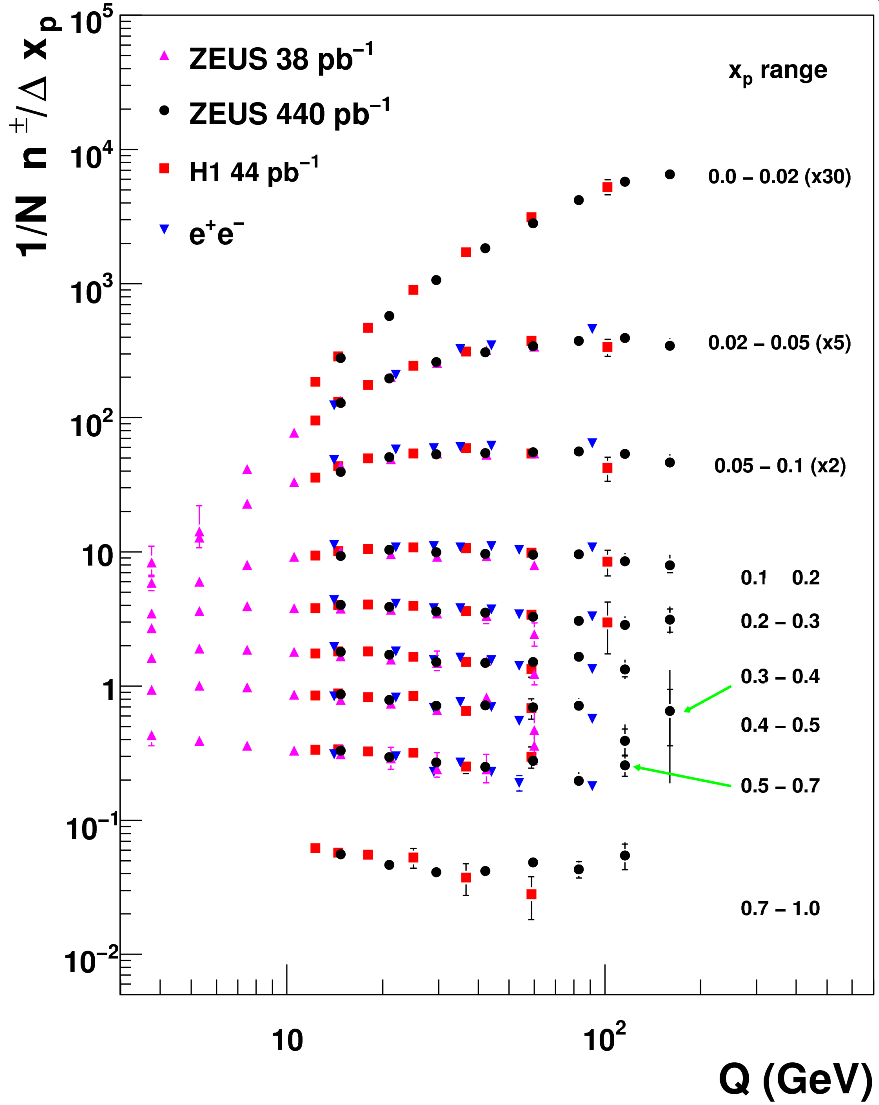
ZEUS arXiv:0904.3466v1 [hep-ex] accepted by JHEP $10<Q^2<41000$ GeV^2 , $0.002<x<0.75$, $p_T^{track} > 0.15$ GeV

Soft Particle in DIS: scaling violation

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

HERA compared to e^+e^- data

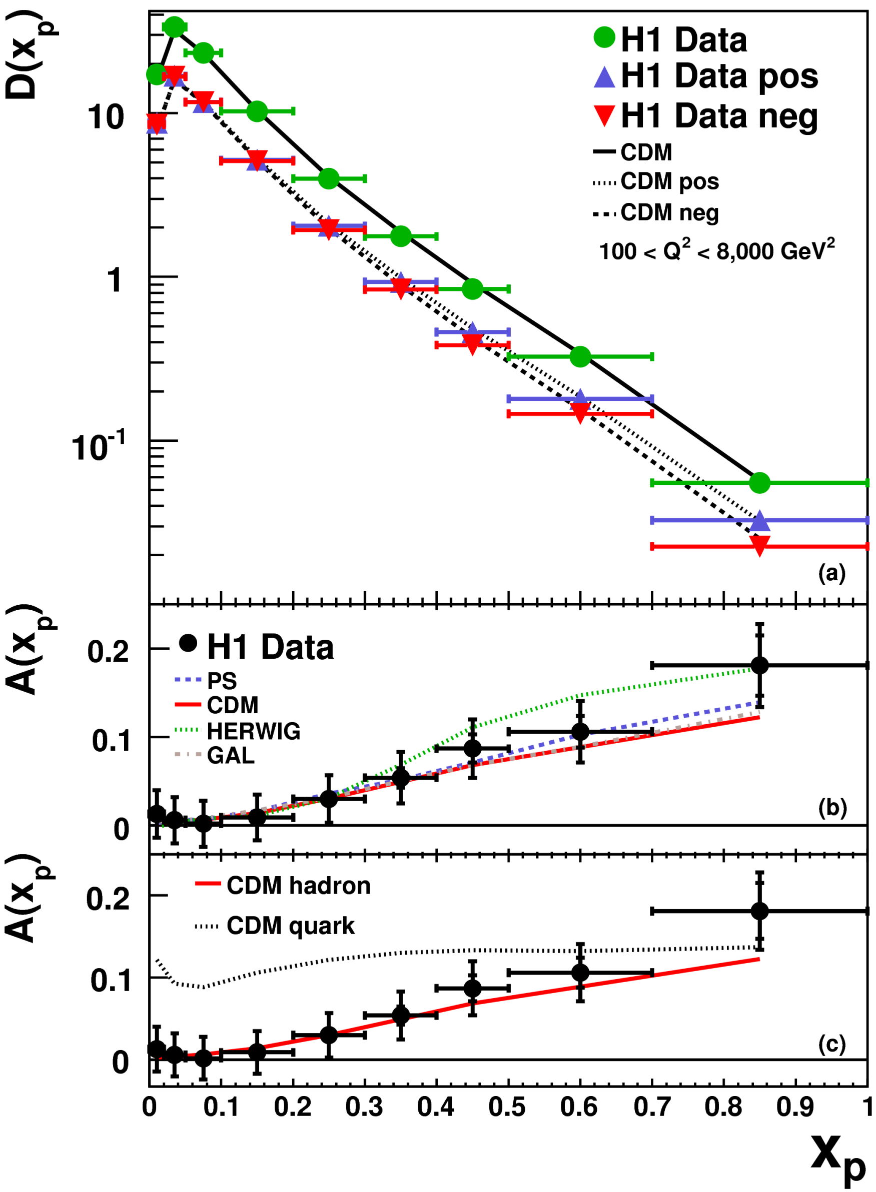




- NLO fails to describe data: predicted scaling violation too weak
- MC models better but do not describe Q^2 dependence over full range of x_p
- Data supports hypothesis of limited fragmentation

ZEUS arXiv:0904.3466v1 [hep-ex] accepted by JHEP $10<Q^2<41000$ GeV^2, $0.002<x<0.75$, $p_T^{track} > 0.15$ GeV

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

H1 arXiv:0907.2666 [hep-ex] Phys. Lett B681125-133, 2009 $100<Q^2<8000$ GeV^2, $0.002<x<0.75$, $p_T^{track} > 0.15$ GeV

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 $\alpha_s(M_Z)$

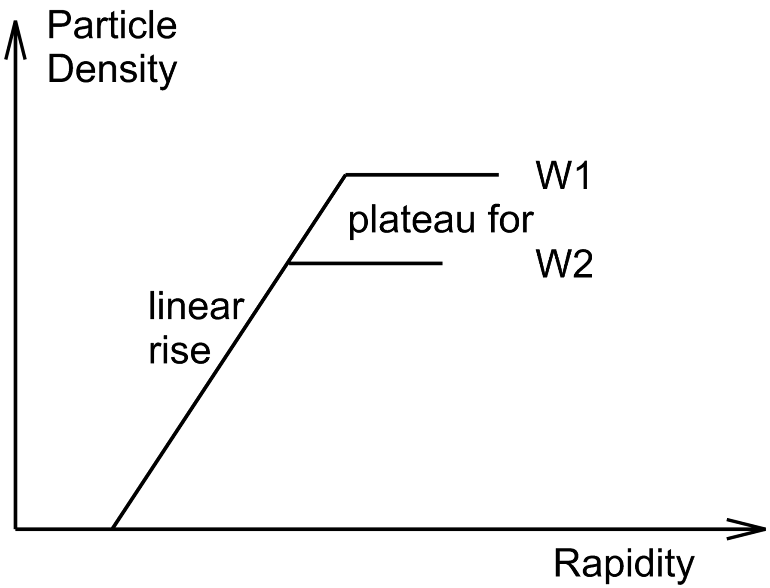
- Prompt photons in photoproduction and DIS
  Calculations generally underestimate cross section
  Fail to describe shapes in several kinematical regions

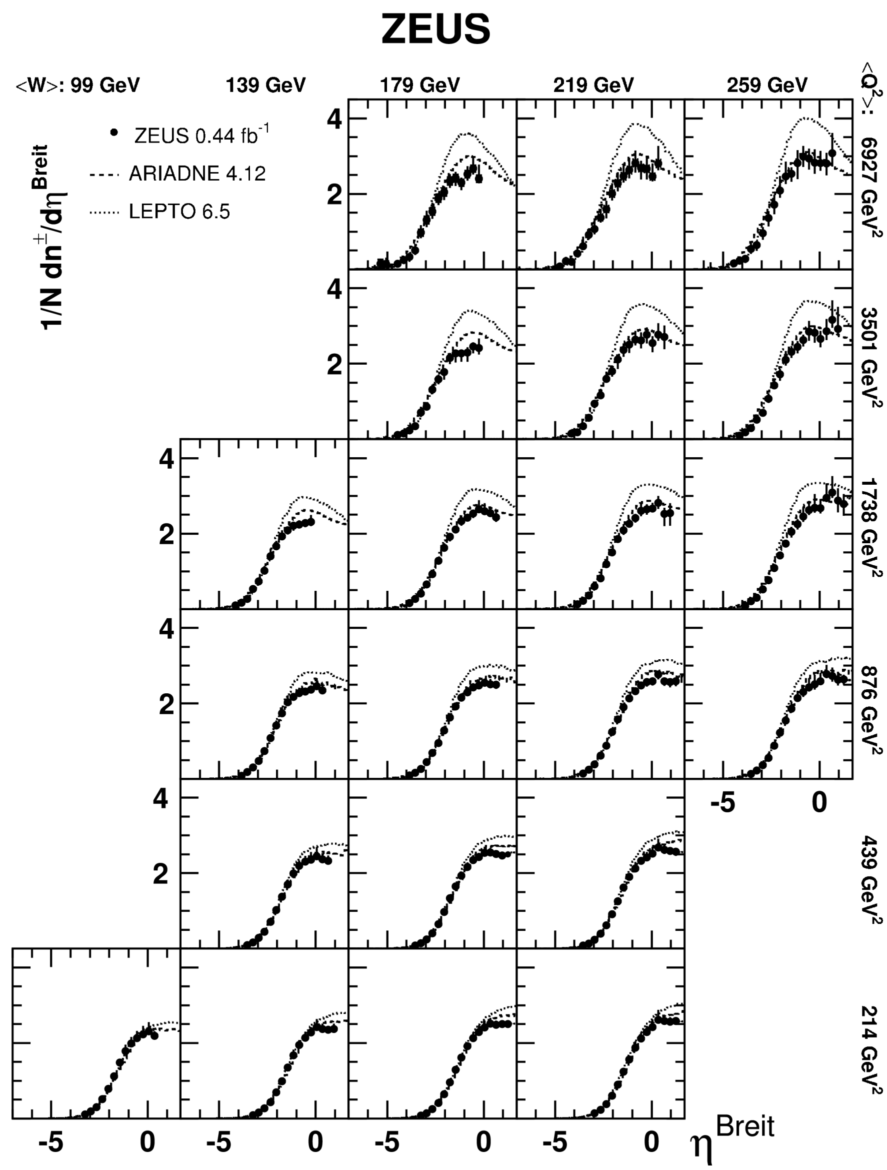
- Charged particle spectra at low Q^2, low x
  Data favours models beyond DGLAP

- Scaled momentum distributions
  NLO calculations do not describe data well, MC slightly better
  Comparison with e^+e^- supports universality of fragmentation
- Charge Asymmetry
  Aymmetry increases with scaled momentum
  Sensitivity to valence quark distribution in the proton

Backup slides

Limited fragmentation





- Density of charged particles per unit of Pseudorapidity

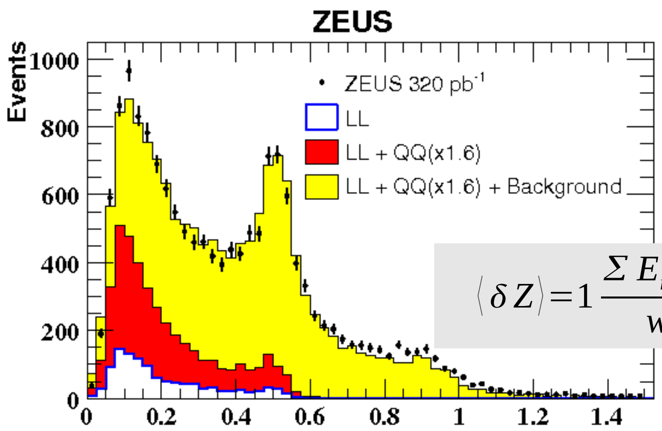
- Linear rise and plateauobserved in all bins
- Supports hypothesis of limited fragmentation
- Slopes do not depend much on Q^2 and W

ZEUS arXiv:0904.3466v1 [hep-ex] accepted by JHEP $10<Q^2<41000$ GeV^2, $0.002<x<0.75$, $p_T^{track} > 0.15$ GeV

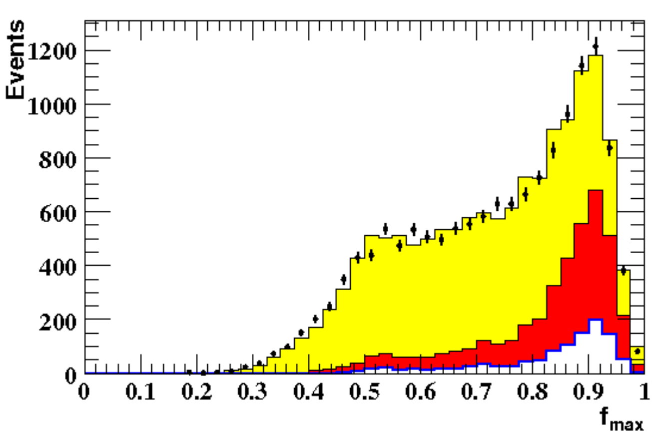
Prompt Photon Production

- 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

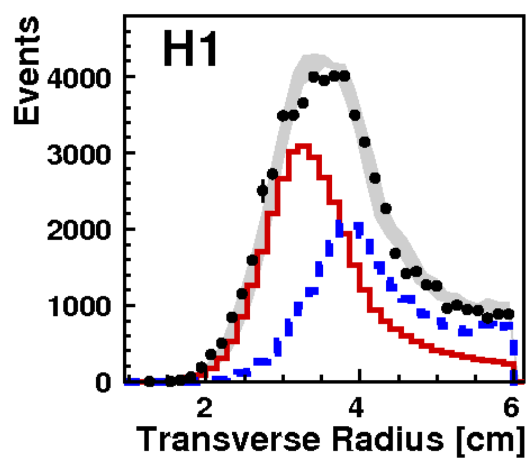
ZEUS: shower width, fit to <δZ>

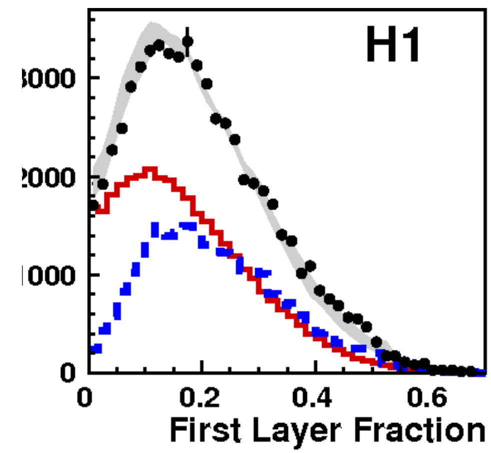


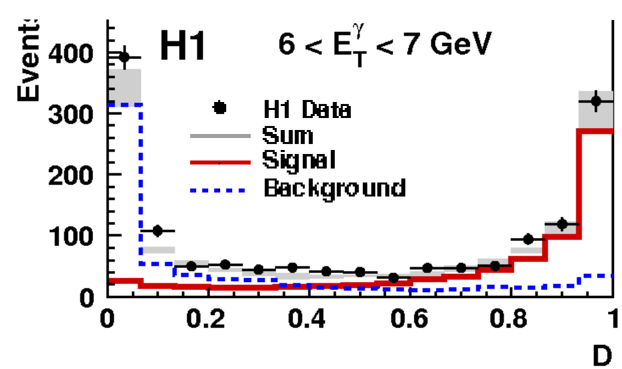
$$\langle \delta Z \rangle = 1 \frac{\Sigma E_i |z_i - z_{cluster}|}{w_{cell}\, \Sigma E_i}$$

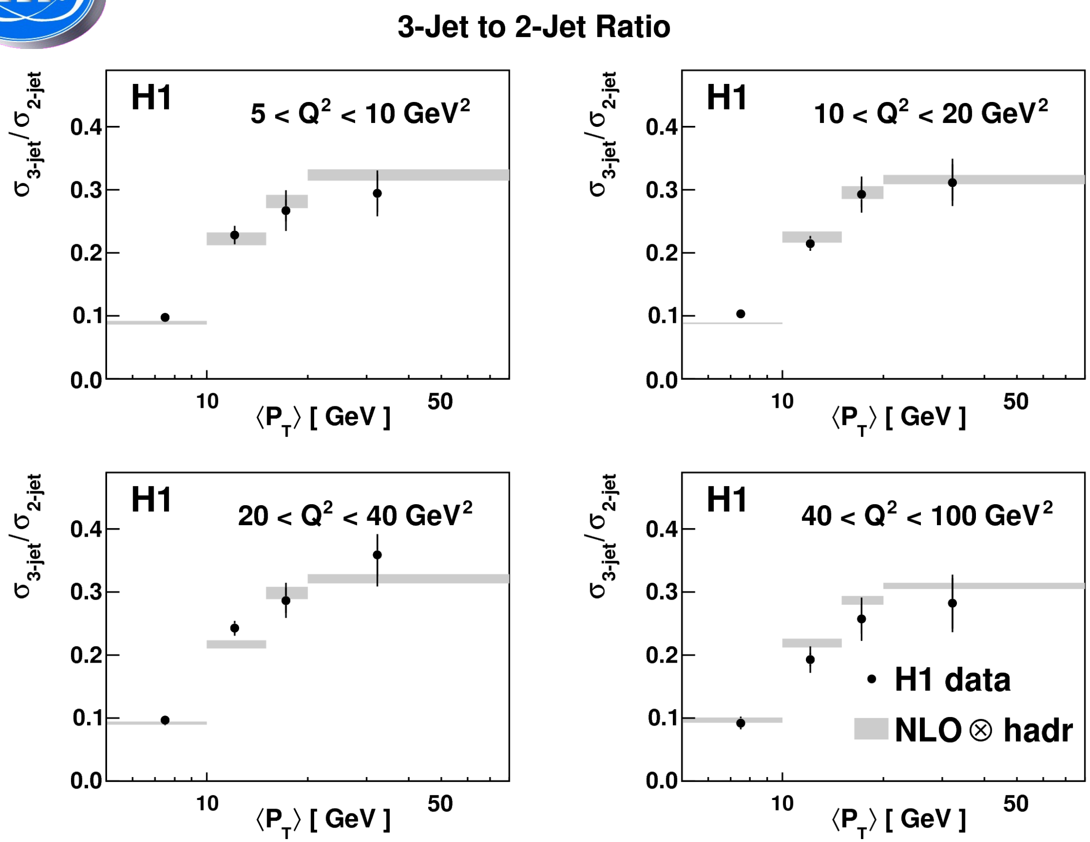


H1: six shower shapes → Discriminant

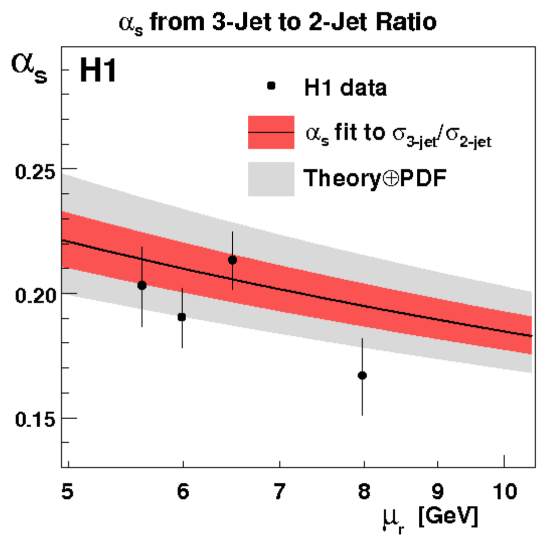








- P_T spectra of 3-jets harder
- Statistical errors dominate
- Normalisation error cancel
  Syst. errors cancel partially
  Reduced by 50%
- Reduced sensitivity to missing higher orders in NLO

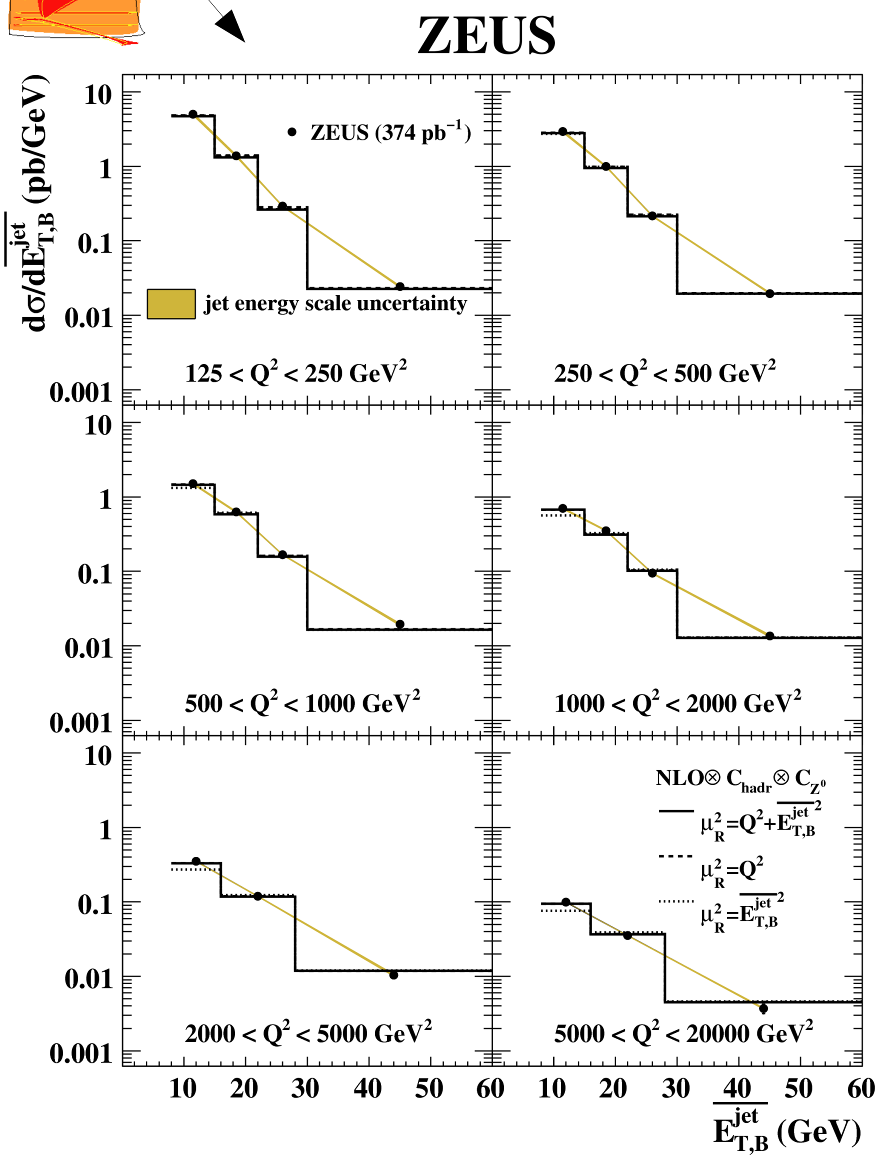


Theoretical errors smaller
Statistical error dominates
Expected to improve with full statistics

Eur.Phys.J.C67:1-24,2010. H1: 44 pb^{-1}, $5<Q^2<100$ GeV^2, $0.2<y<0.7$, Breit frame: $5<p_T^{Jet}<80$ GeV, $Mjj>18$ GeV^2

Dijet Cross Sections: e+p→jet+jet+X

Q^2

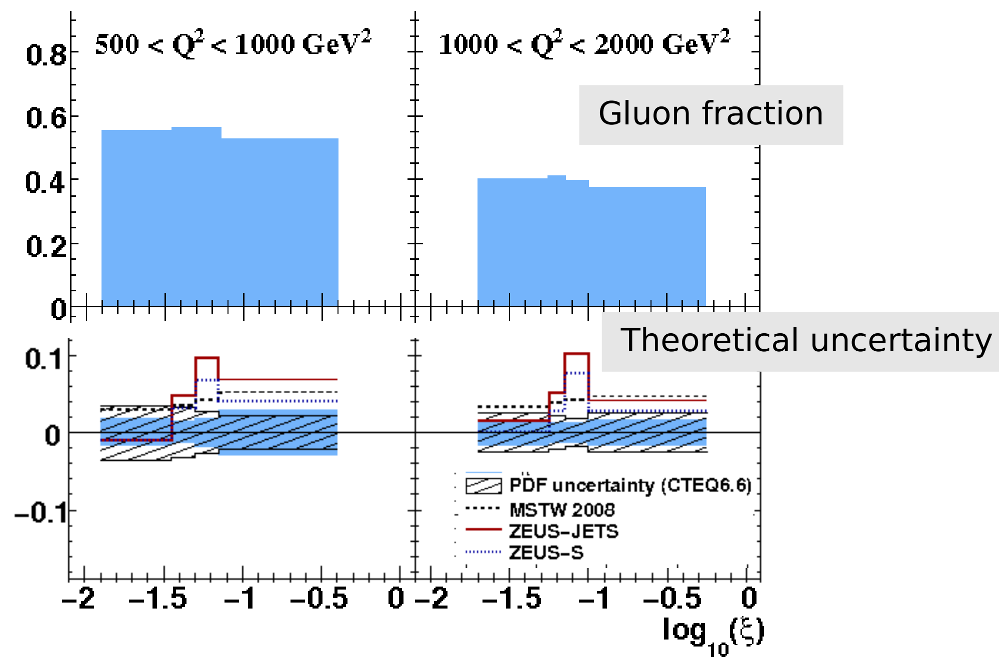


Very small statistical and systematical errors
uncorrelated ± 2(10)% at low (high) Q^2
correlated: ± 5(2)% at low (high) Q^2

Description by NLO (NLOJET++) very good

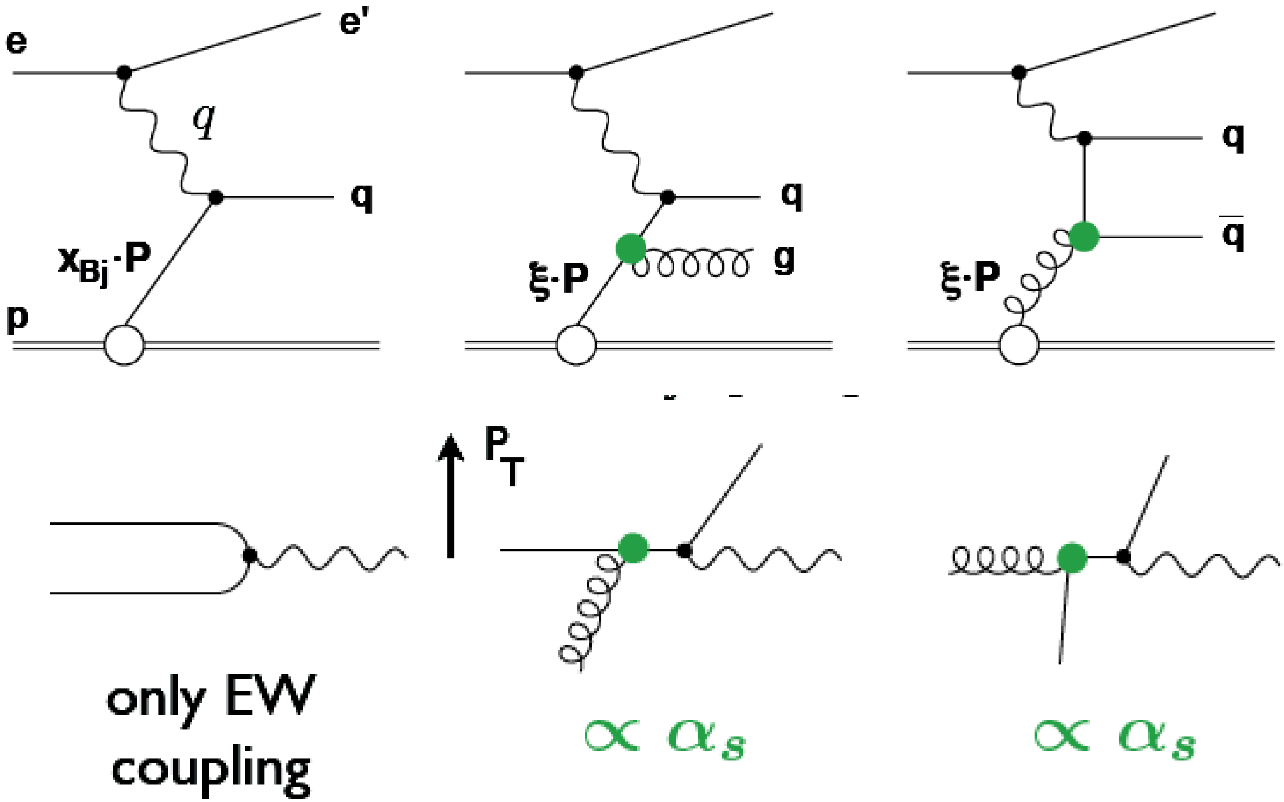
→ Important input for extraction of PDFs –

especially gluon in proton - and αs



PDF uncert. large in regions with large gluon fraction

ZEUS: 374 pb^{-1} ,$125<Q^2<20000$ GeV^2 , Breit frame: $E_T^{Jet}>8$ GeV, Mjj>20 GeV^2



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

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

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

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

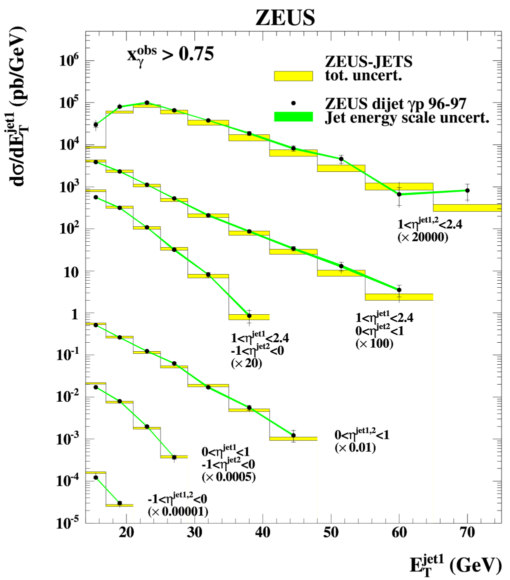
Boost to Breit frame: $2x_{Bj} + q = 0$

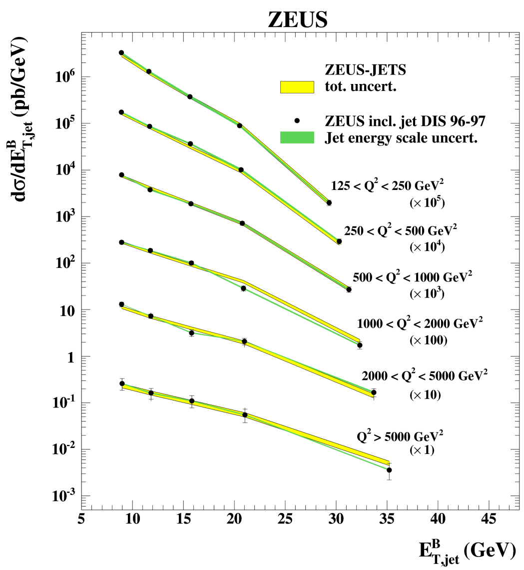
Only processes proportional to α_s generate P_T in the Breit frame

Dijet Cross Sections: PDF extraction

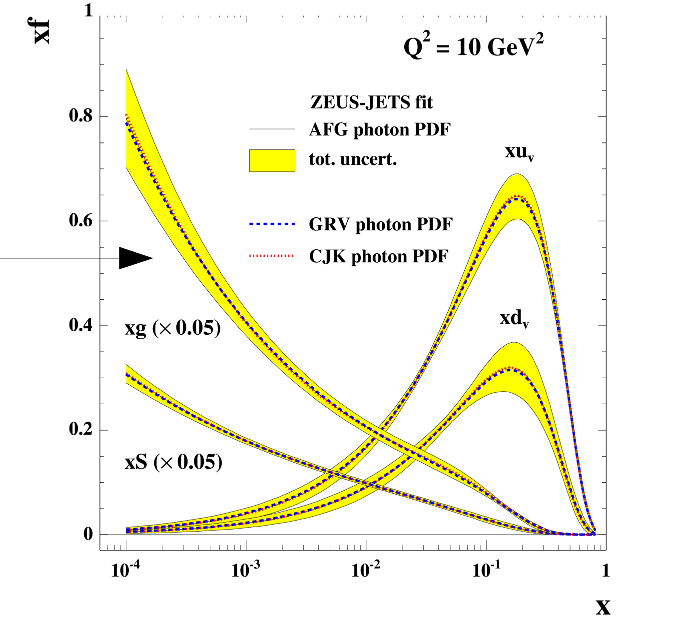
Photoproduction + NC DIS

40 pb^{-1}

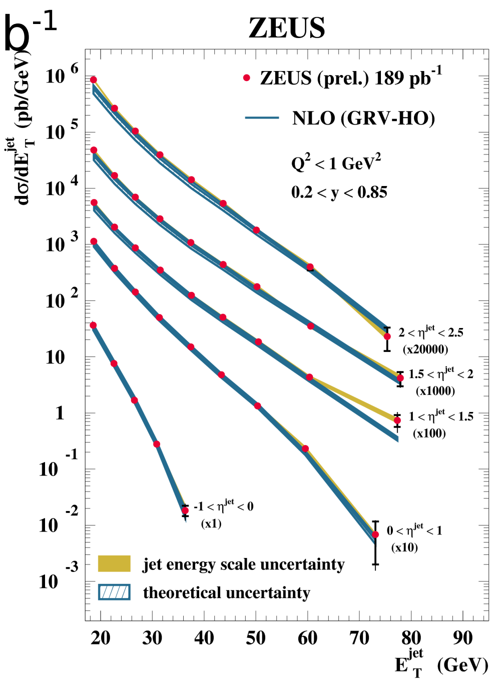


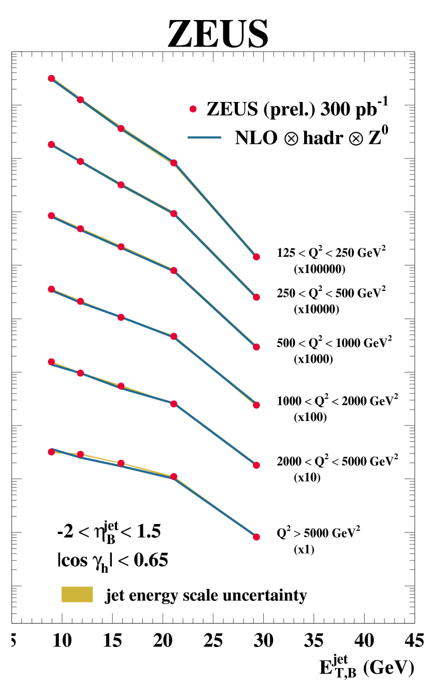


Parton Density functions



200 -400 pb^{-1}



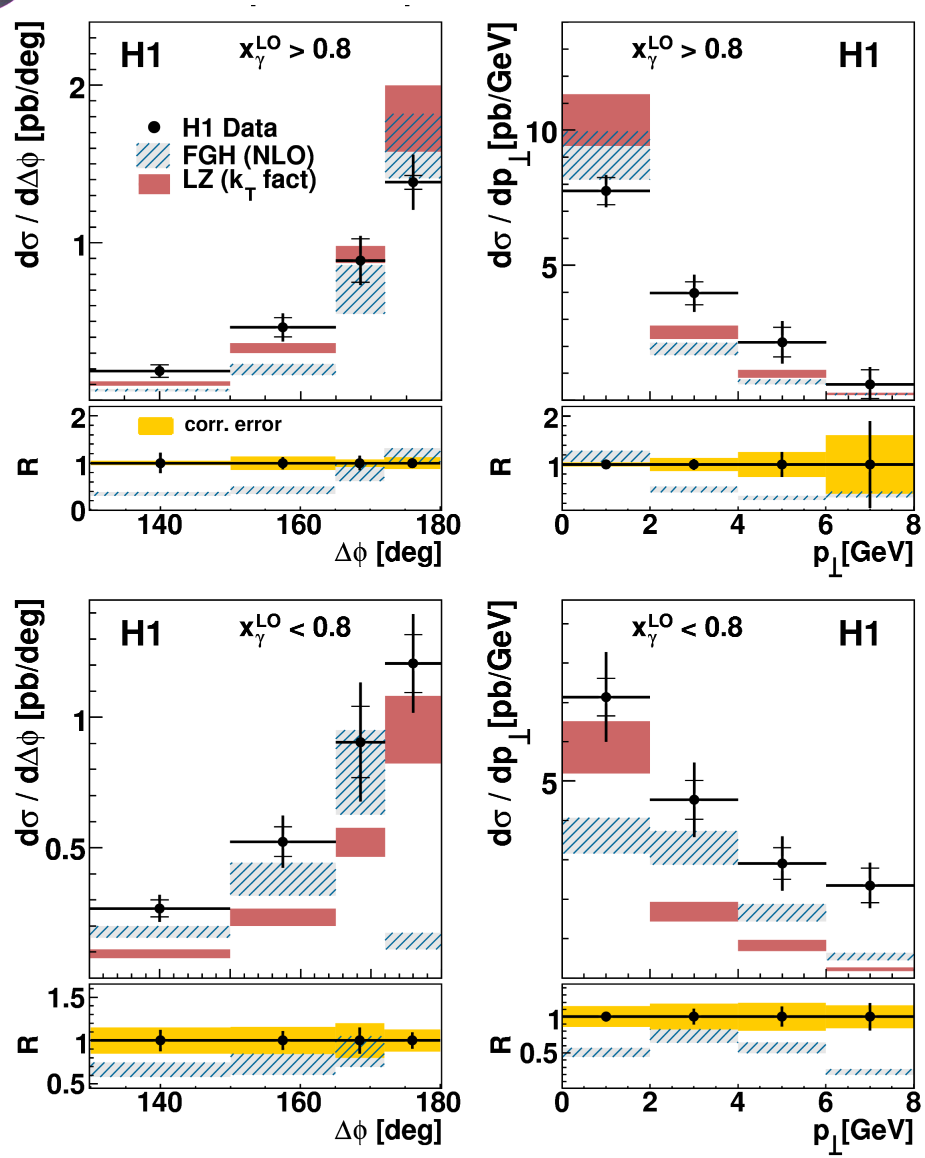


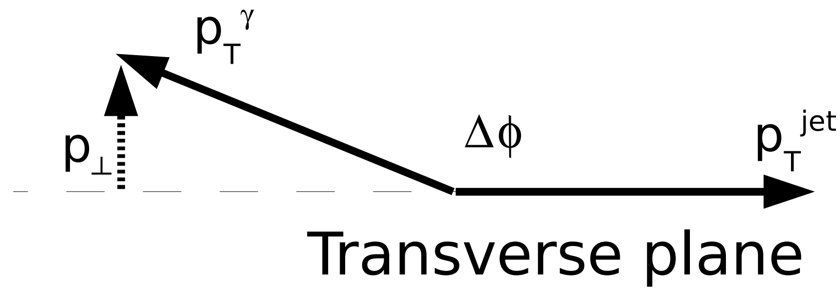
ZEUS EPJ C 42(2005) 1

Prompt Photon and Jet: Transverse Correlation

Direct enhanced

Resolved enhanced

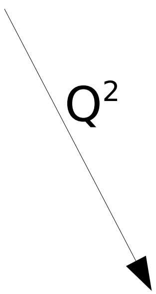


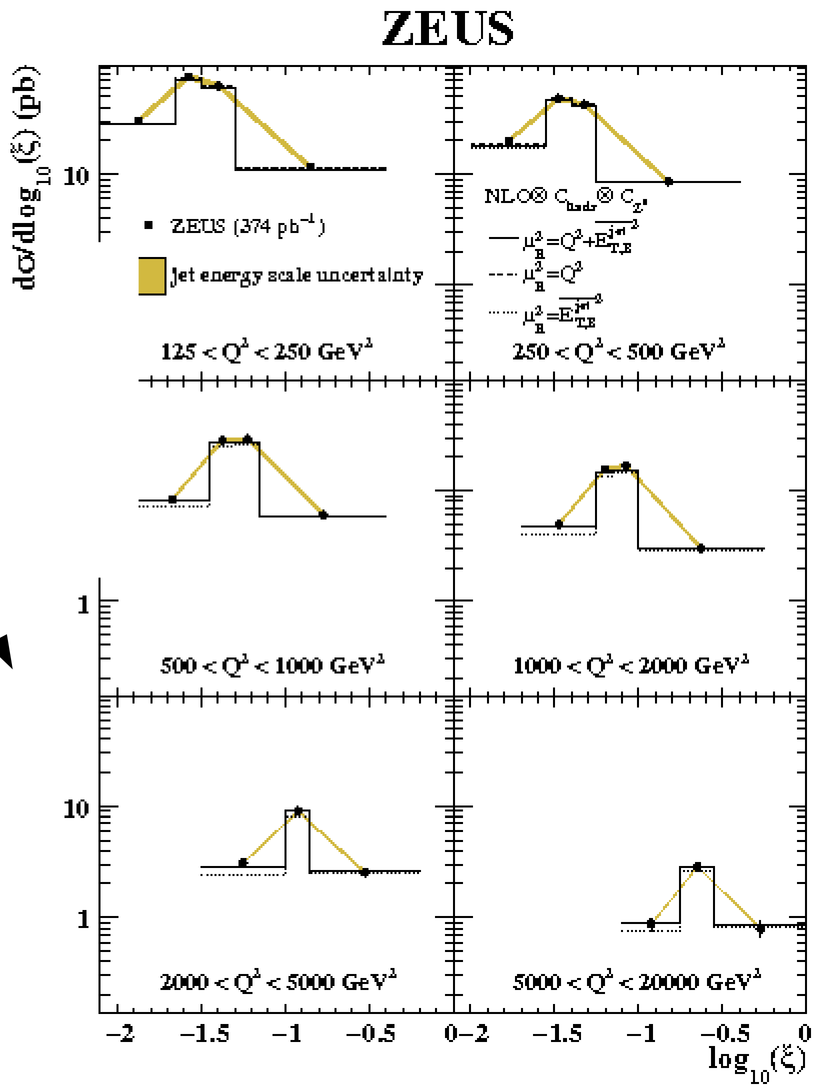


- Data not well described
- $x_\gamma > 0.8$
  Both calculations underestimate non back-to-back configuration
- $x_\gamma < 0.8$
  Sensitivity to multiple soft gluon emission for $\Delta\Phi \rightarrow 180$
  Fixed order calculation not reliable
  kt factorisation aborbs soft gluons in PDFs
  Tails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

H1 Eur Phys J C66 (2010) 17 $6 < E_T^{\gamma} < 15$ GeV, $-1.0 < \eta^{\gamma} < 2.43$, $0.1 < y < 0.7$, $4.5 < E_t^{jet}$, $-1.3 < \eta^{jet} < 2.3$

Dijets: Sensitivity to PDFs and αs





Very small statistical and systematical errors

Description by NLO very good

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

ZEUS: 374 pb^{-1} ,125<Q^2<20000 GeV^2 , Breit frame: E_T^{Jet}>8 GeV, Mjj>20 GeV^2