Hard QCD and the Hadronic Final State at HERA: Experimental Part

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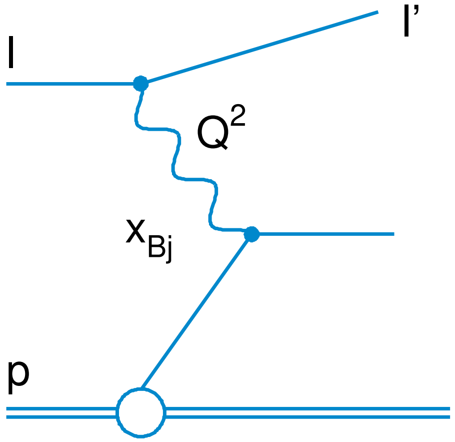
- **measurements**
- **QCD interpretation of the data**
- **prospects for progress at HERA II**

QCD Processes in DIS



Born Process (no QCD): $\mathcal{O}(\alpha_s^0)$

leading contribution to F_2: **ep** $\rightarrow$ **e + X**

directly sensitive to quark densities (only)

QCD Processes: $\mathcal{O}(\alpha_s)$

– (small) corrections to F_2

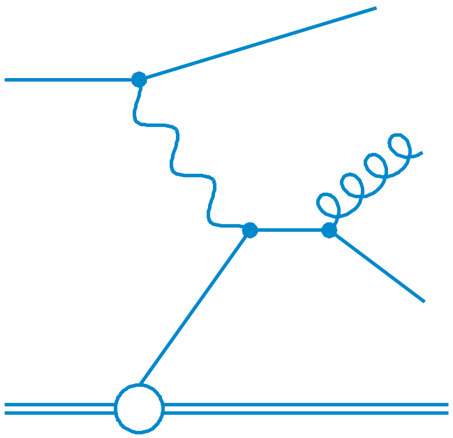
– new event signatures

ep $\rightarrow$ **e +** $E_{T,\mathrm{Breit}}$ **+ X**

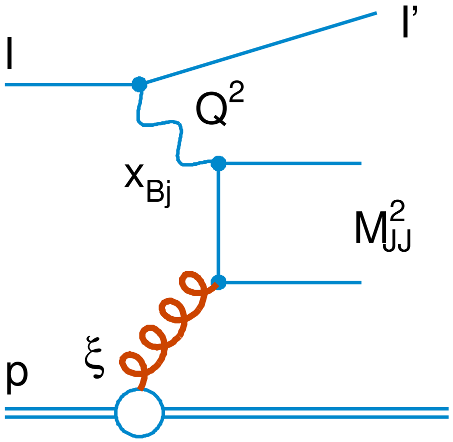
directly sensitive to:

– α_s

– gluon and quark densities



QCD-Compton



Boson-Gluon Fusion

early HERA analyses of hadronic final state

very ambitious:

- **determination of parameters:** α_s, gluon density from dijet data
  (use agreement between theory and data in local regions of phase space)

- **search of "BFKL signals"** in forward jet production where $E_T \simeq Q$
  (assume agreement in central region
  $\rightarrow$ search for deviations in forward region)

$\Rightarrow$ limited messages — no global picture

methods used in early HERA analyses

- **jet definition adopted from e^+e^- annihilation:**
  mJADE algorithm — analyses in laboratory frame

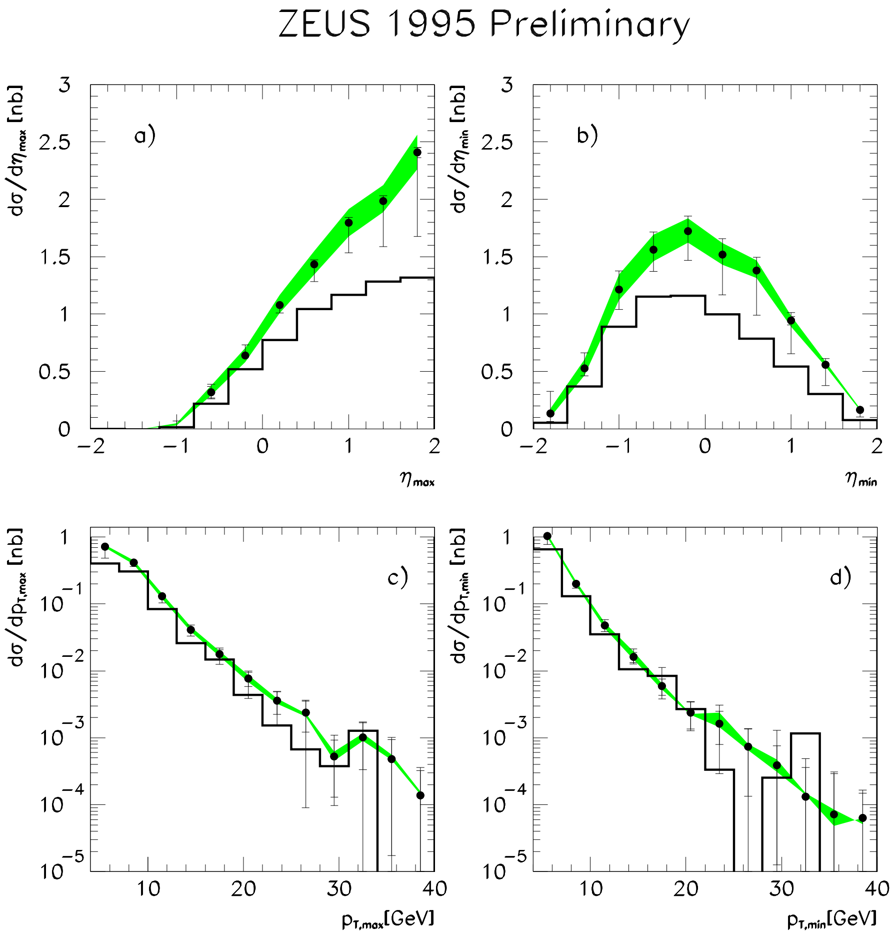
- **correcting data to "parton level"**

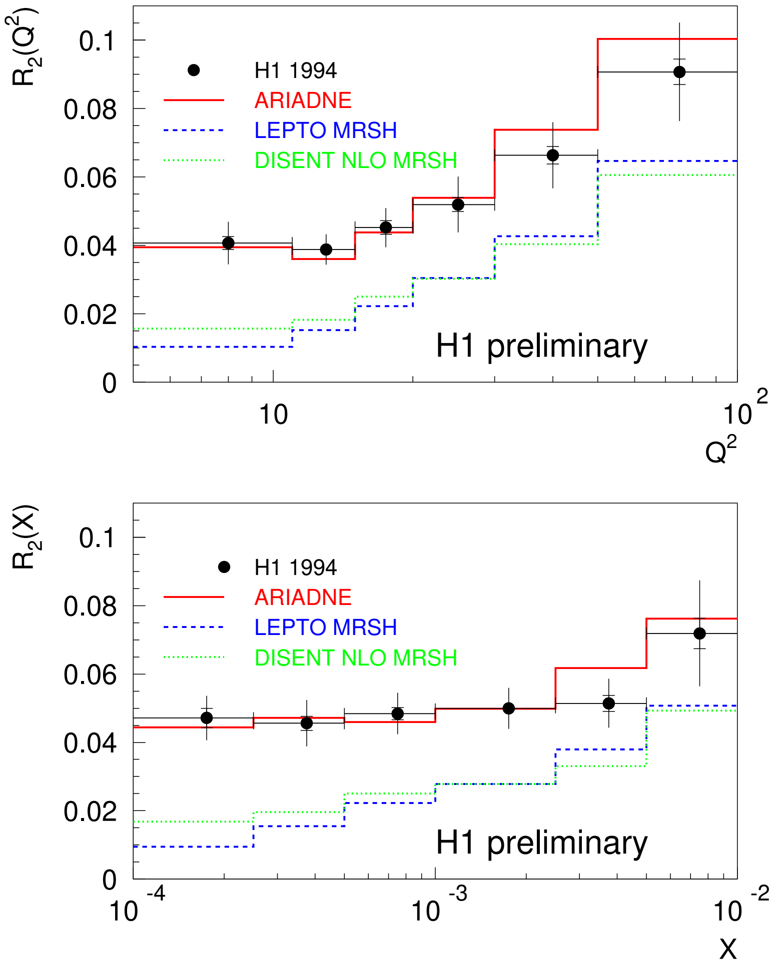
$0^{-3}]$	$f(det \to had)$	$f(det \to par)$
$^{+\,4}_{-\,9}$	$1.32 \pm 0.15 + 0.14$	$1.88 \pm 0.21 - 0.03$
$+\,9$ [illegible]	[illegible]	[illegible]

$\Rightarrow$ treat hadronization as experimental effect
allow for cancelations between experimental and theoretical uncertainties

improved methods:
analyses in Breit frame;   improved jet algorithms for DIS
present measurements corrected for detector effects only;
use E_T-cut as jet selection criterion

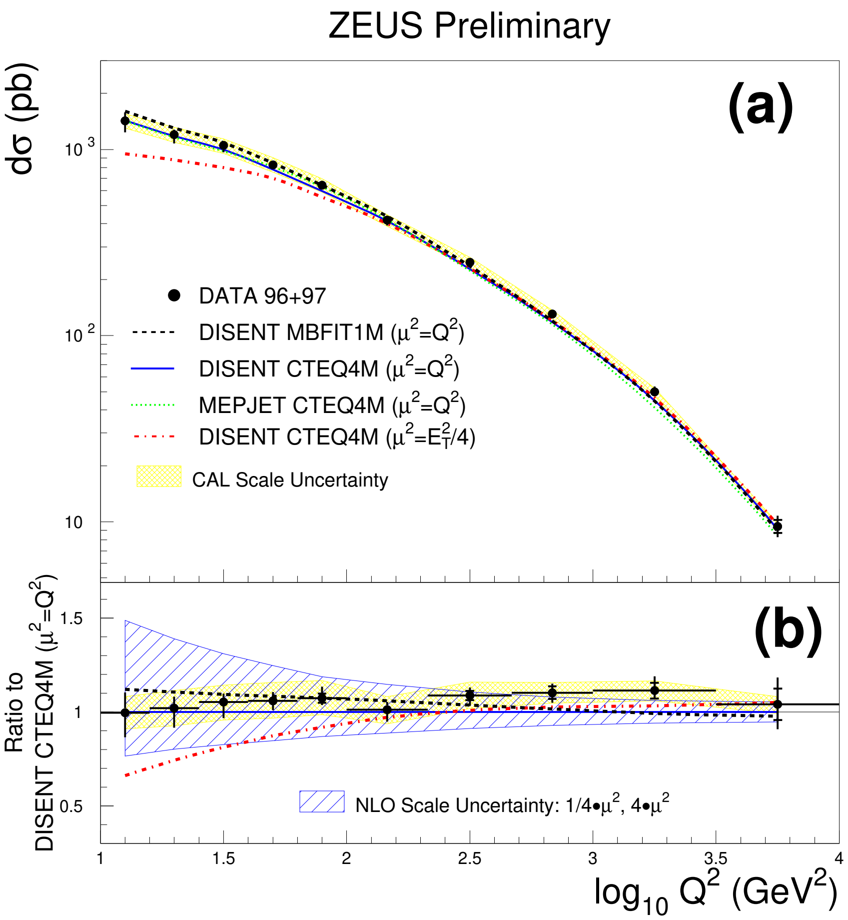
dijet production at low Q^2 — prel. results at DIS 1997

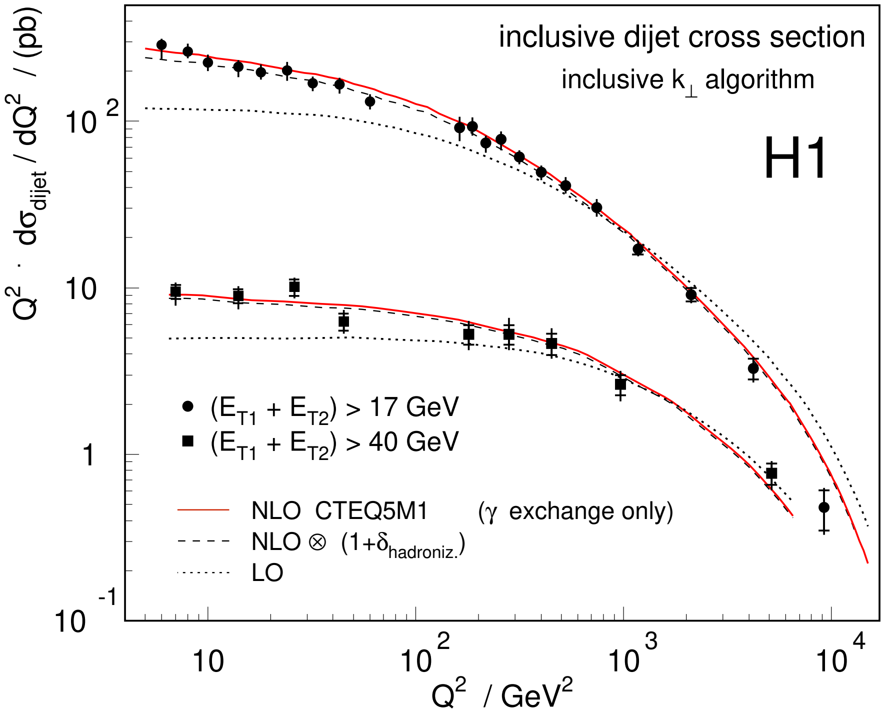




failure of NLO in describing low Q^2 data?? $\Rightarrow$ symmetric $E_{T\text{jet}}$ cuts

recent dijet results from HERA





asymmetric E_T cuts $\rightarrow$ good agreement over large Q^2 region

two kinds of analyses

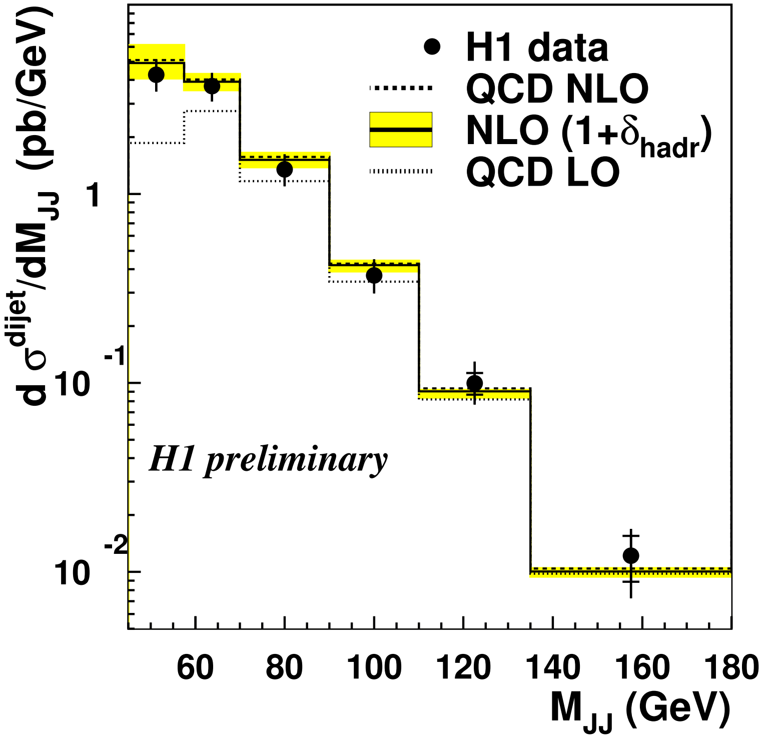
- **establish basic effects:** comparing data $\leftrightarrow$ theory
  ϕ asymmetries, prompt photon production, forward jet production,
  E_T flow, event shapes, internal structure of jets
  inclusive jet and dijet production in γp, $\gamma^* p$, low Q^2, high Q^2,
  production rates of higher jet multiplicities,
  photoproduction of jets $\leftrightarrow$ structure of the (real) photon,
  virtual photoproduction of jets $\leftrightarrow$ structure of the virtual photon,

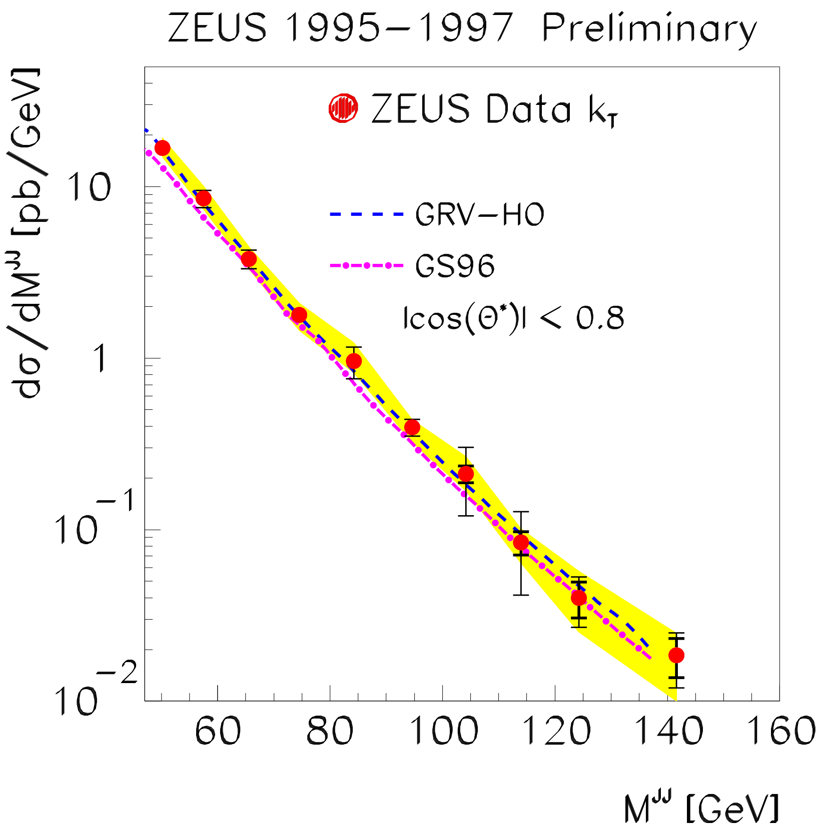
- **quantitative analyses** $\rightarrow$ determination of parameters
  inclusive jet and dijet production at **high** Q^2 — $Q^2 > 150\,\mathrm{GeV}^2$
  (where NLO pQCD makes reliable predictions)

  direct extractions of $\alpha_s(M_Z)$ and the gluon density in the proton

  urgently needed:
  concepts for extraction of photon pdfs from photoproduction data

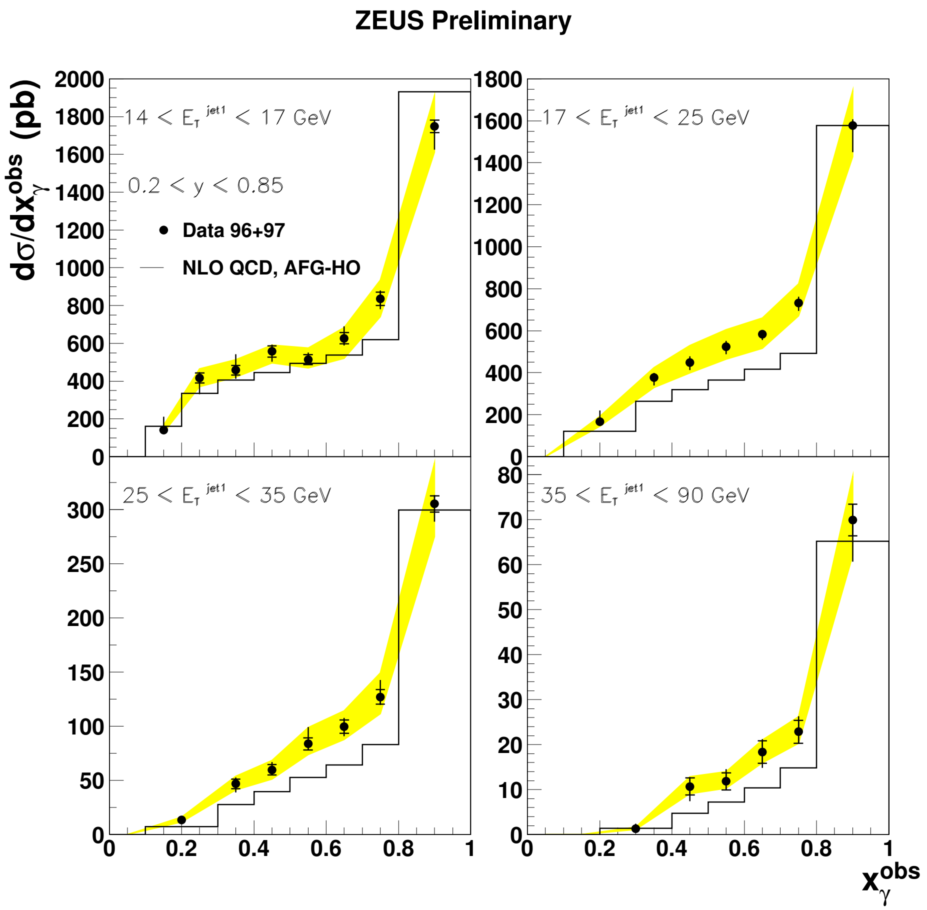
dijet cross section in photoproduction

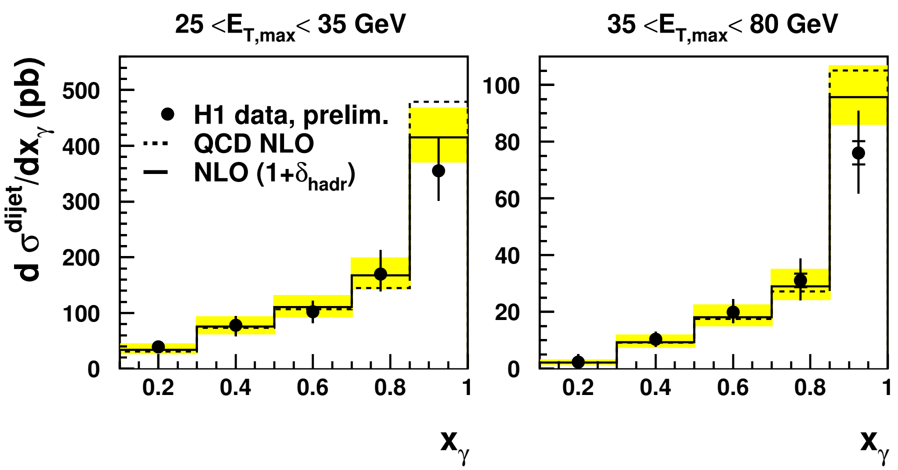




⇒ described by NLO pQCD over large range of the invariant dijet mass

dijet cross section in photoproduction → photon pdfs

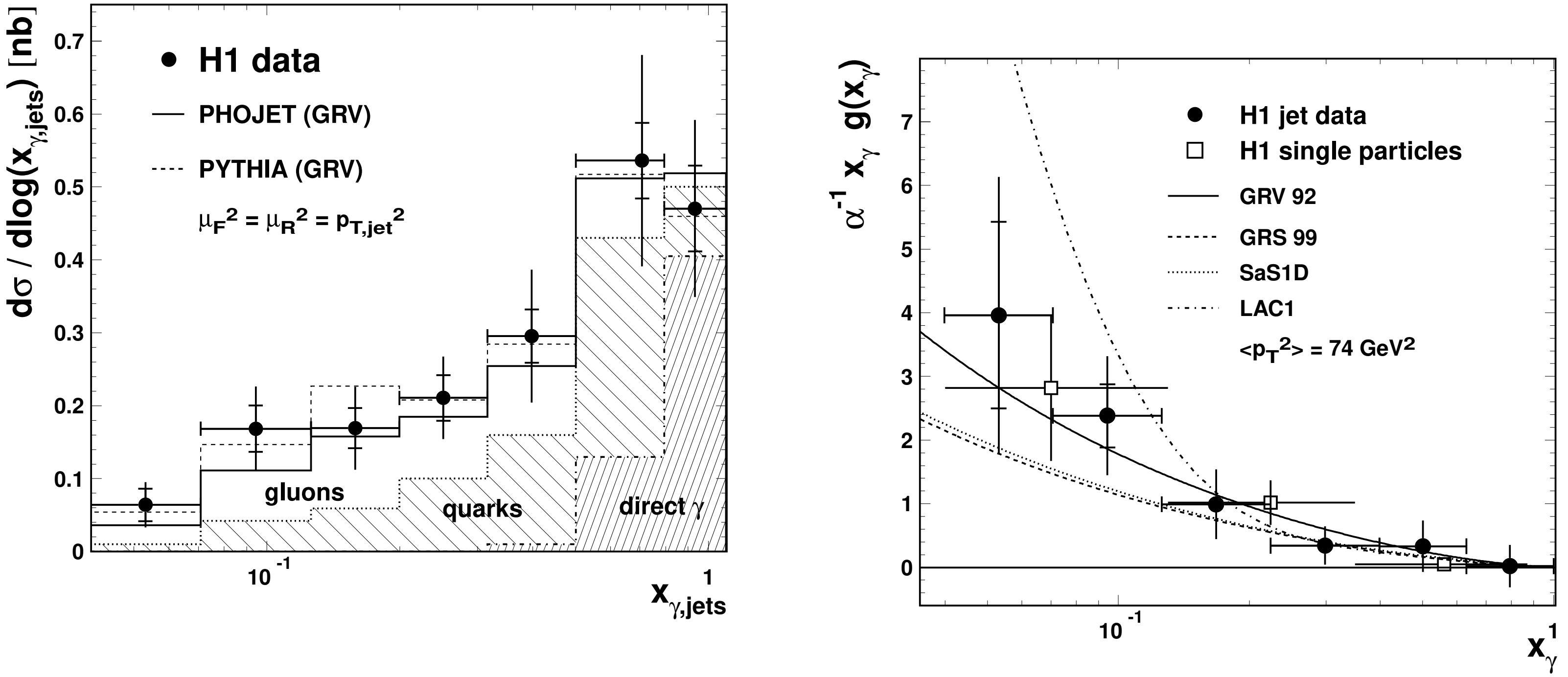




⇒ different conclusions from H1 and ZEUS — (differences in theor. calc.)

sensitivity to photon pdfs — **urgently needed:** concepts for the extraction

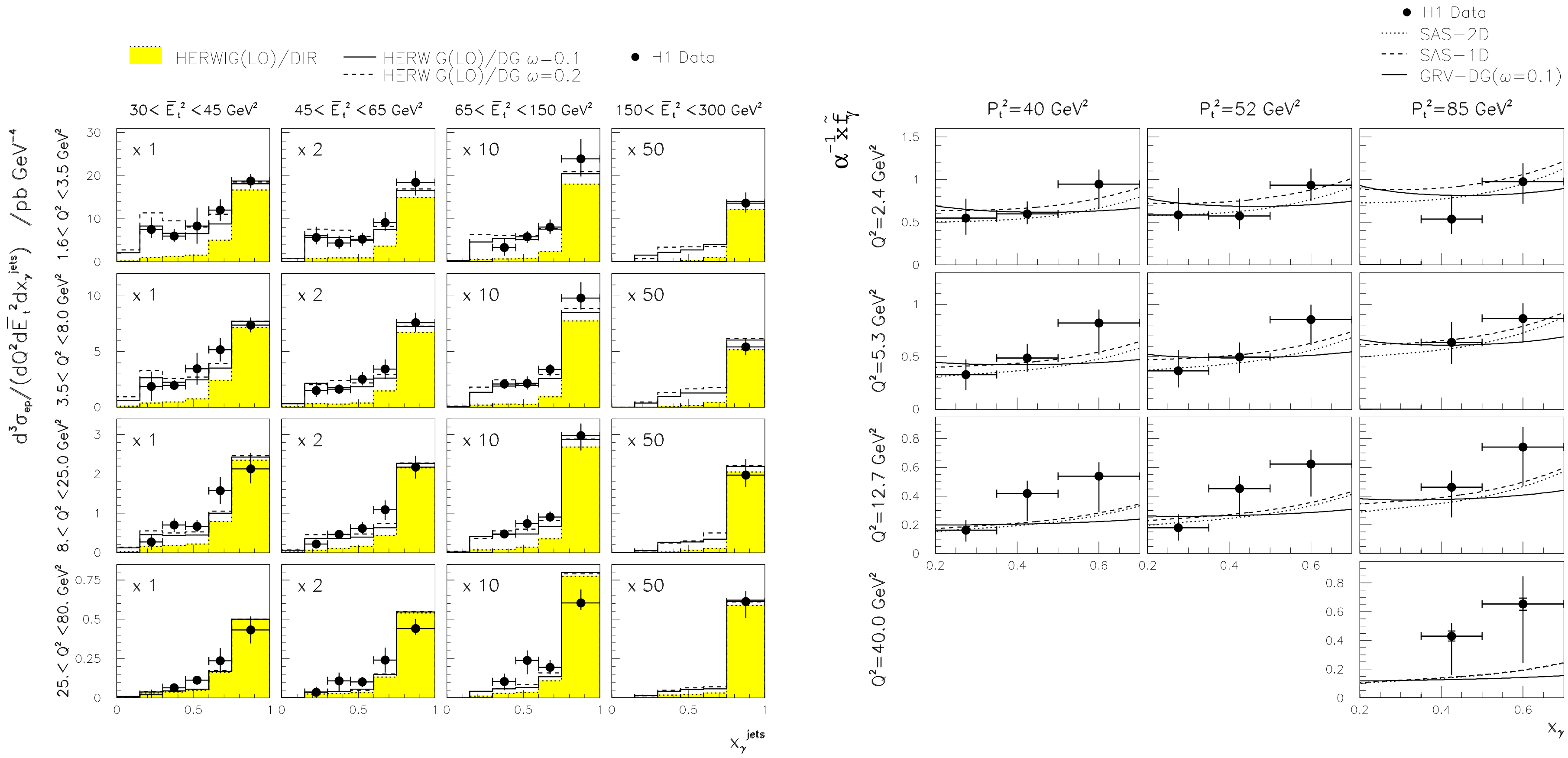
dijet cross section in photoproduction



extraction of effective photon pdf   using leading order calculation

$\Rightarrow$ demonstrate sensitivity — but quantitatively not reliable

dijet cross section in virtual photoproduction

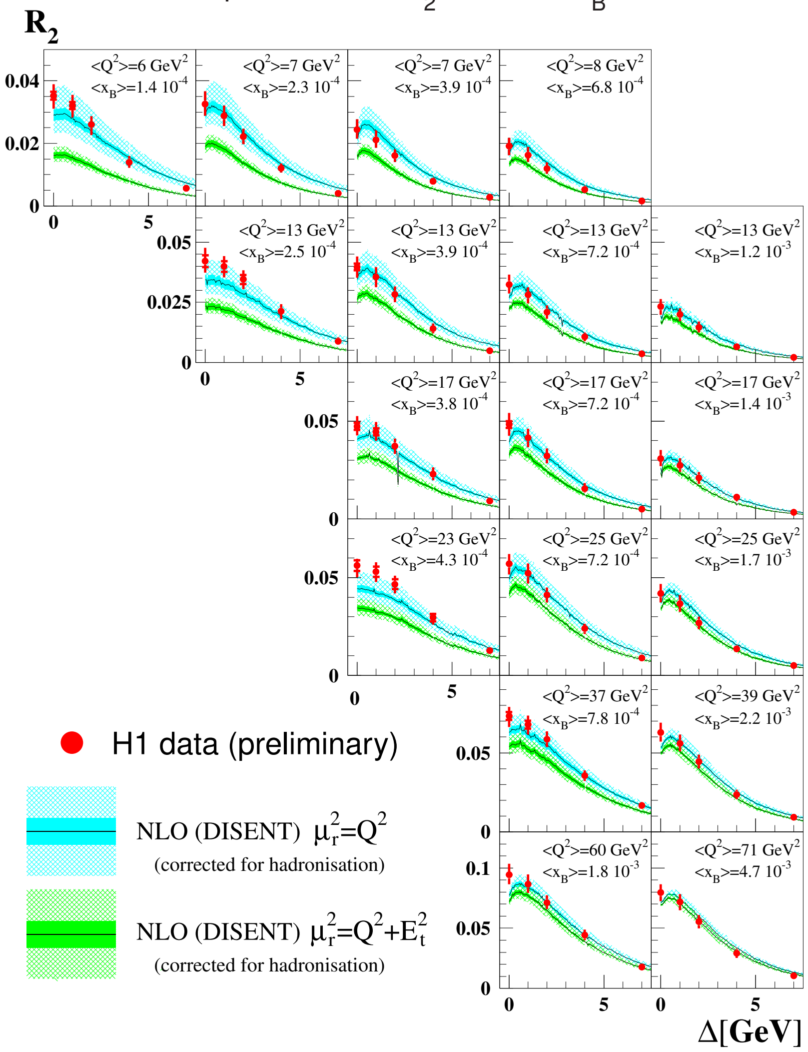


extraction of effective photon pdf   using leading order calculation

⇒ demonstrate sensitivity — but quantitatively not reliable

extension of dijet rate analysis

Δ dependence of R_2 in bins of x_B and Q^2



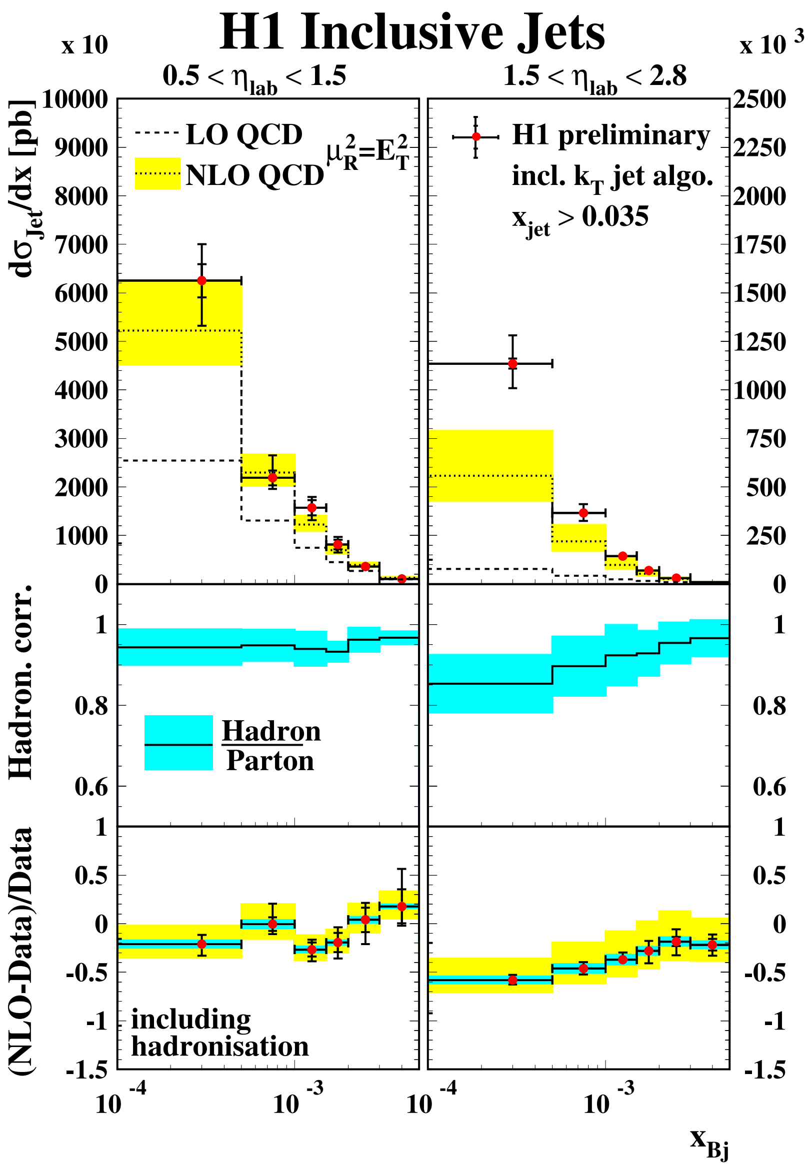
$R_2(x, Q^2) =$
$\sigma_{\text{dijet}}(x, Q^2)/\sigma_{\text{incl.DIS}}(x, Q^2)$

problem in interpretation of prev. analysis: symmetric E_T cuts

here:
explicitly demonstrate effect of cut asymmetry: $\Delta = E_{T,1,\text{cut}} - E_{T,2,\text{cut}}$

testing ground
for resummed calculations

extension of forward jet analysis: incl. jet cross section

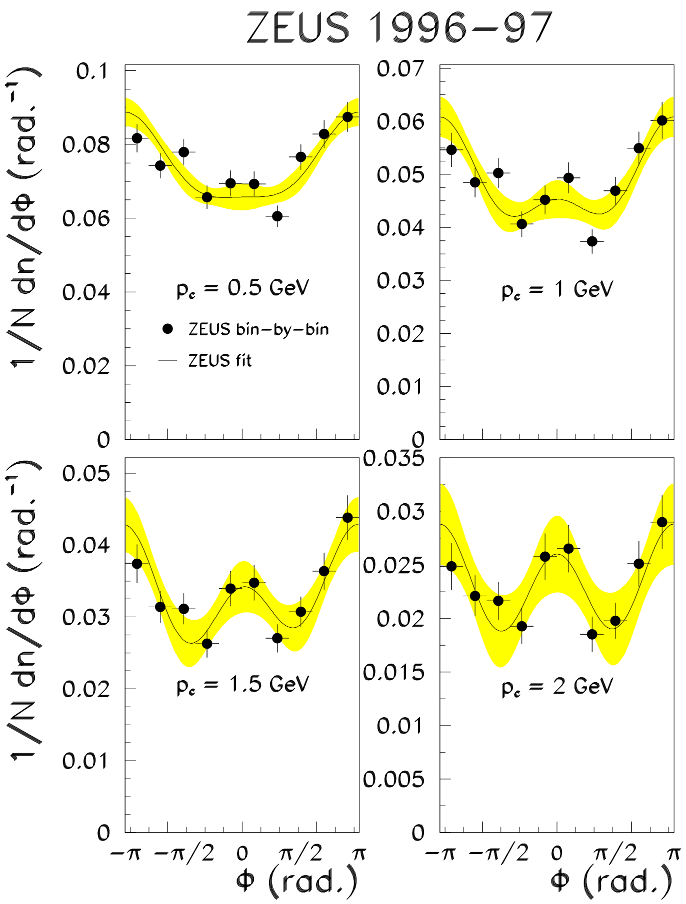


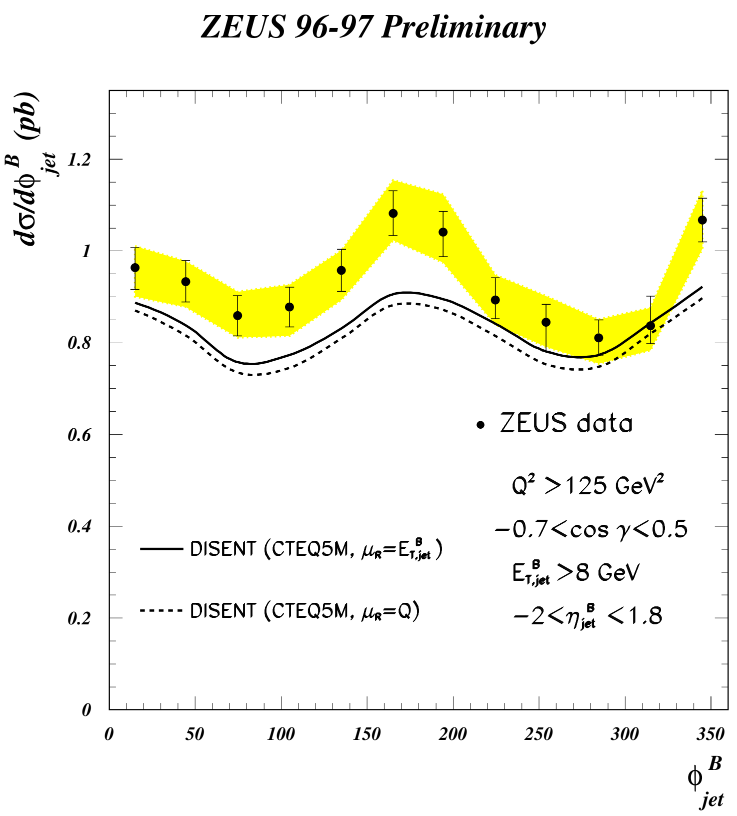
obtain a more global picture:

measure multi-differential distributions

in: Q^2, $x_{\rm Bj}$, E_T, E_T^2/Q^2, $\eta_{\rm jet}$

Phi Asymmetries in inclusive particle and jet production

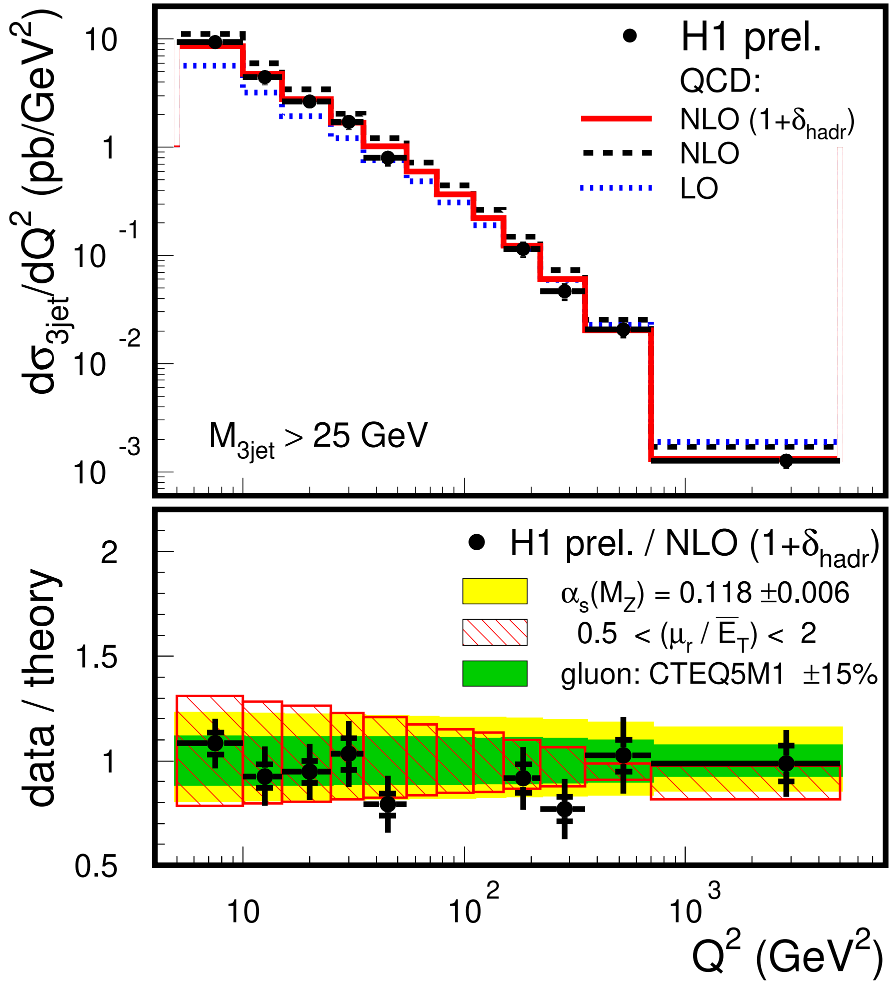




$d\sigma/d\phi = A + B\cos\phi + C\cos 2\phi$ different for QCD-C and BGF

potential: use dijet events — independent handle on BGF fraction: $xg(x)$

three-jet cross section in DIS $\sigma_{\text{3jet}} \propto \alpha_s^2$



recent theoretical progress:
brandnew NLO calculation (Z. Nagy)

good agreement theory / data

σ_{3jet}: high sensitivity to $\alpha_s(M_Z)$

currently limited by statistics
($\rightarrow$ go to higher E_T, M_{3jet})
($\rightarrow$ double differential distributions)

Angular Jet Distributions in the 3-Jet CM Frame

angles:

in 3-jet CM frame

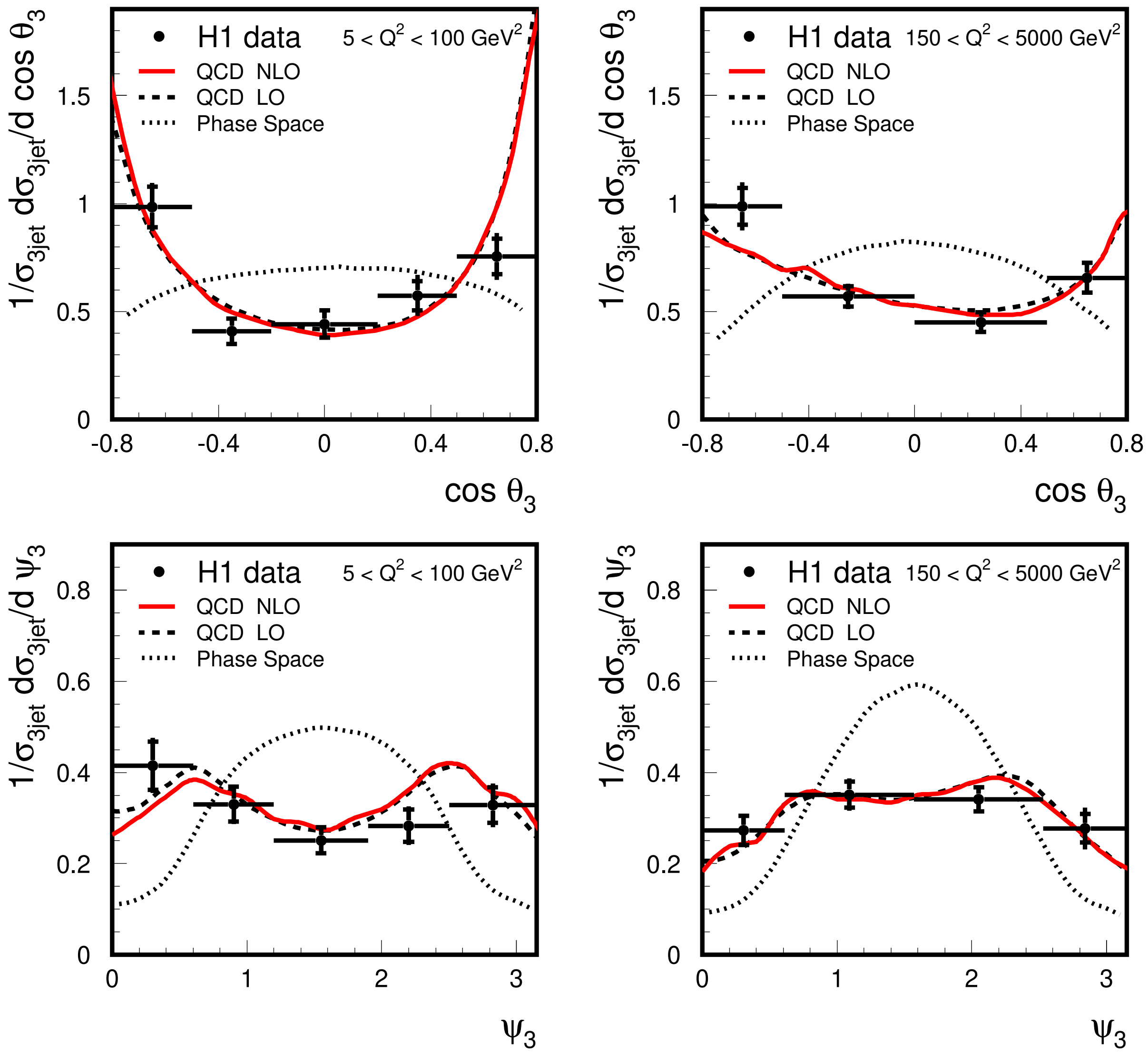
$$\cos\theta_3 = \frac{\vec{p}_B \cdot \vec{p}_3}{|\vec{p}_B|\;|\vec{p}_3|}$$

$$\cos\psi_3 = \frac{(\vec{p}_3 \times \vec{p}_B)\cdot(\vec{p}_4 \times \vec{p}_5)}{|\vec{p}_3 \times \vec{p}_B|\quad|\vec{p}_4 \times \vec{p}_5|}$$

add. cuts:

$X_3 < 0.95$
$|\cos\theta_3| < 0.8$

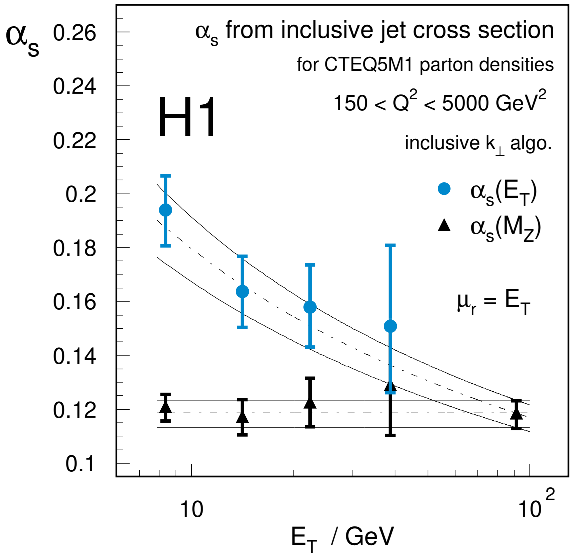
$M_{3\text{jet}} > 40\,\text{GeV}$
(only at $Q^2 < 100\,\text{GeV}^2$)

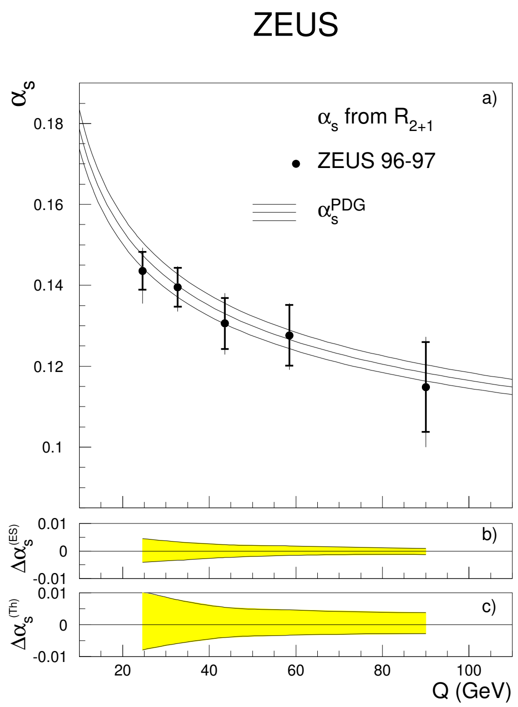


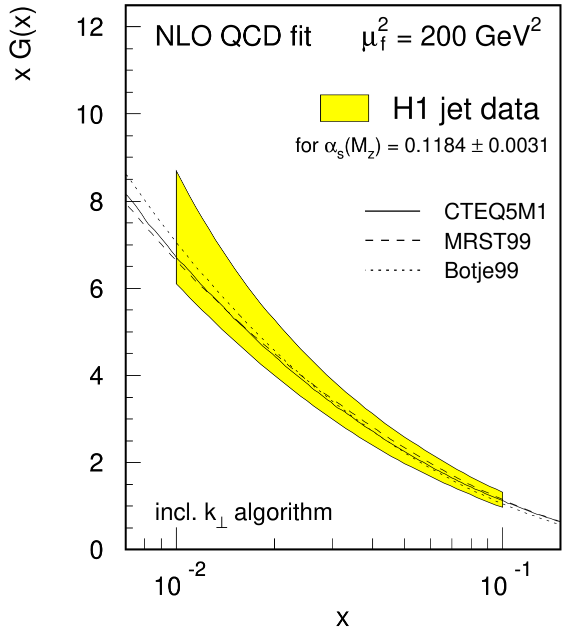
⇒ strong dynamic effects visible — good description by NLO pQCD

determination of $\alpha_s(M_Z)$ and the gluon density

using inclusive jet and dijet data



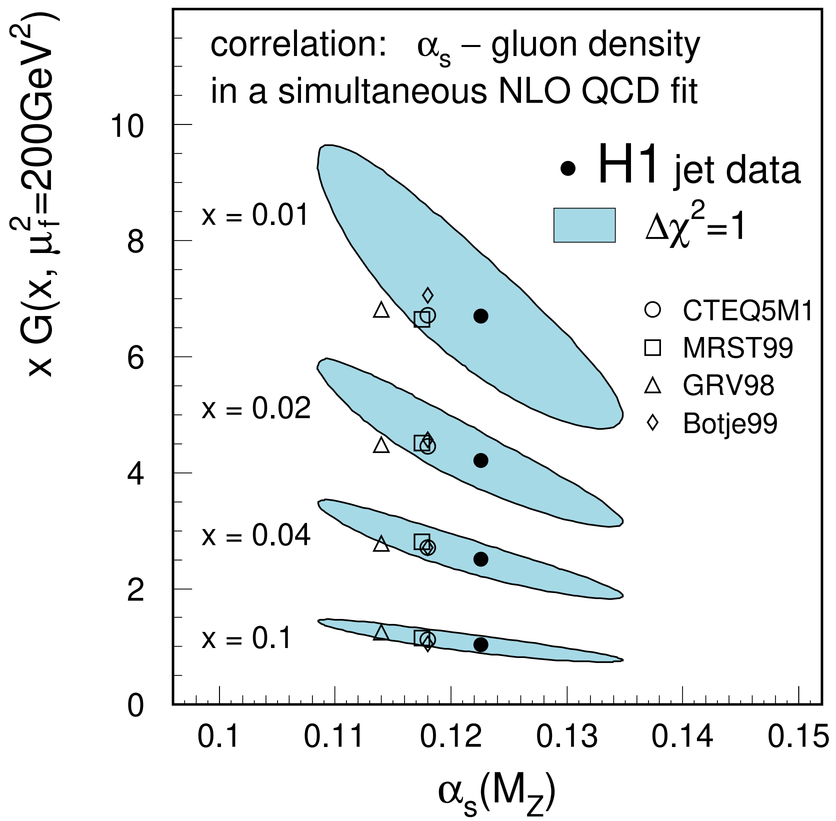




$\Rightarrow$ improved methods: consistent propagation of pdf uncertainties

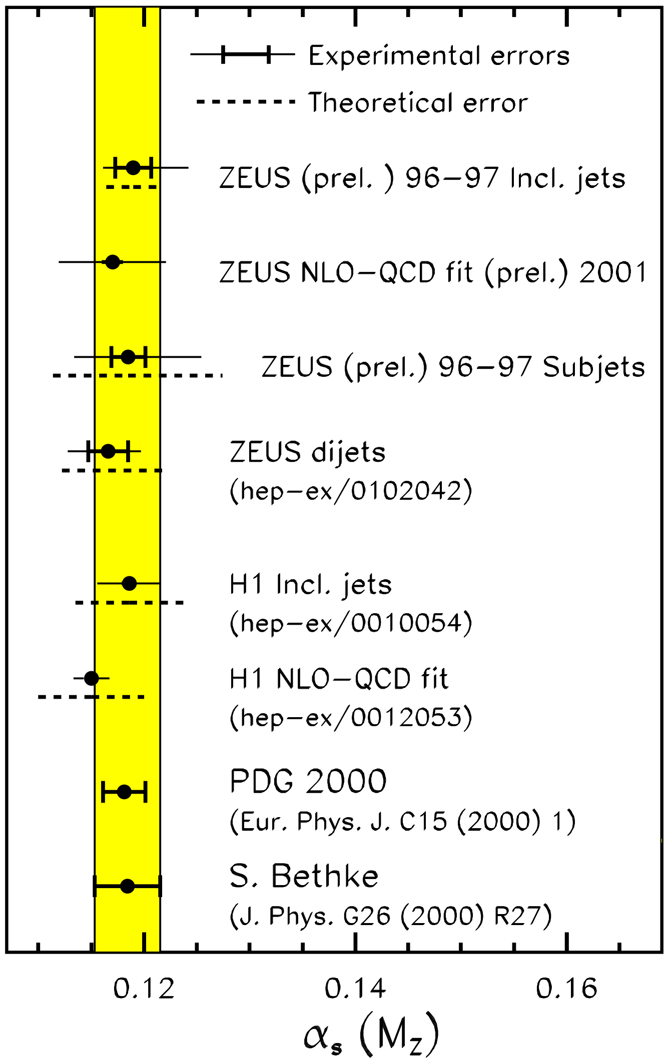
results consistent with each other and with world knowledge

aim for consistency: simultaneous determination of $\alpha_s(M_Z)$ and the gluon density



clear demonstration of anti-correlation

determination of $\alpha_s(M_z)$ from HERA data



outcome at HERA I:
collection of individual results

consistency:
between different processes
between both experiments
with world average

competitive
$\Rightarrow$ impact on world average

Summary

- recent HERA analyses of the hadronic final state cover a large field of physics topics $\Rightarrow$ leading to global picture

- agreement of theory and data over wide ranges of phase space; reasons for disagreement in local regions are basically understood

- starting to make quantitative QCD tests & extraction of parameters (serious & competitive level $\rightarrow$ contribute to world knowledge)

- experimental uncertainties dominated by hadronic energy scale (work in progress)

- QCD interpretation of data often limited by theoretical uncertainties
  $\Rightarrow$ cross check of (existing) NLO calculations (to better than 1%)
  $\Rightarrow$ extensions: matching of NLO & parton showers
  $\Rightarrow$ need theoretical progress: NNLO, resummation $(\alpha_s \ln(E_T/Q))^n$

HERA II

- $\Rightarrow$ challenges at HERA II:
  extend previous analyses to high precision measurements

- unlikely that e.g. new α_s determination from single observable
  will lead to significantly (& reliably) reduced uncertainties

coherent analysis strategies:

- high precision $\leftrightarrow$ quantitative comparisons between H1 and ZEUS
  propose: jet analyses in identical phase space $\leftrightarrow$ <u>direct</u> comparisons

- global picture: need efforts for the interpretation of combined data sets
  $\rightarrow$ HERA QCD working group

- progress at HERA II:
  new concepts — improved methods — much individual creativity