S. Petersburg DIS-2003

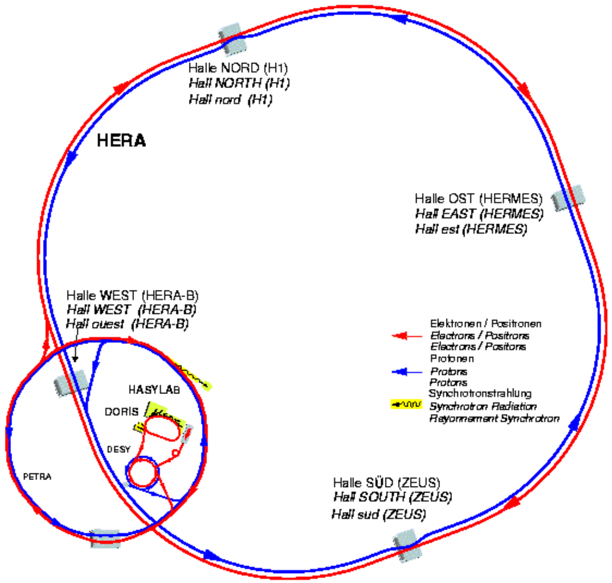
April 23^{rd}, 2003

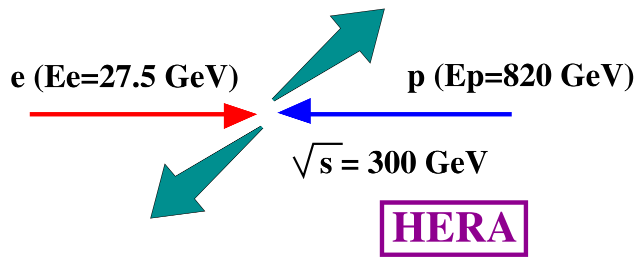
Jet Production in NC DIS with ZEUS at HERA

Juan Terrón (Universidad Autónoma de Madrid, Spain)

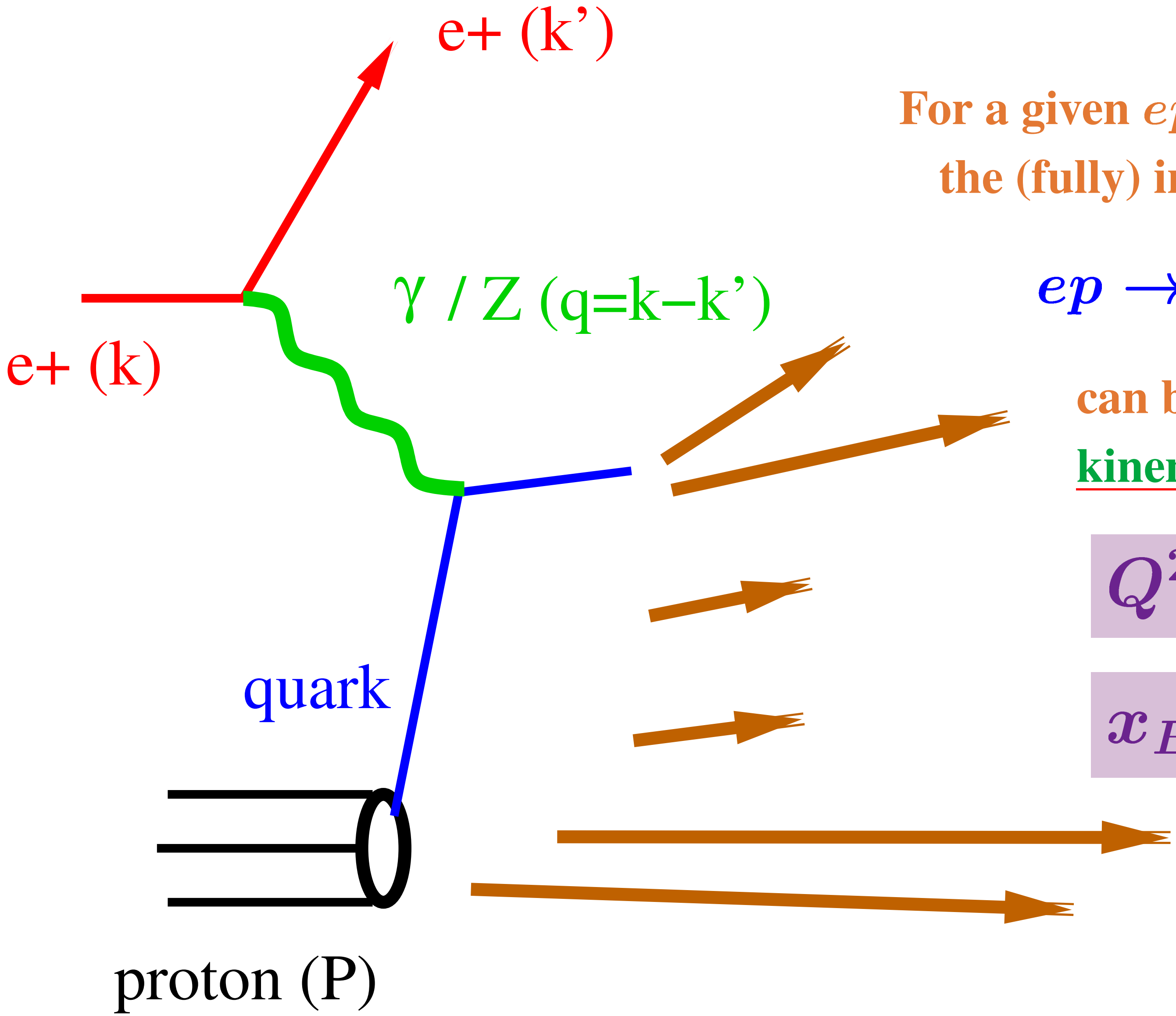
ZEUS Collab.

at





Kinematics of Neutral Current Deep Inelastic Scattering



For a given ep centre-of-mass energy, $\sqrt{s}$, the (fully) inclusive cross section for

$$ep \to e + \mathrm{X}$$

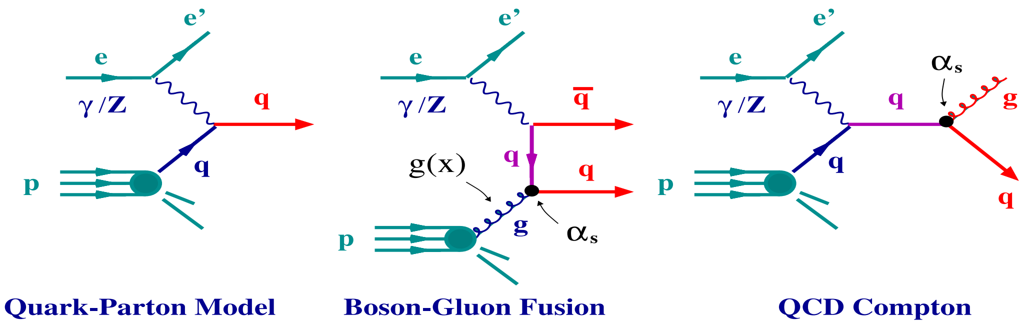
can be described by two independent kinematic variables, e.g.

$$Q^2 = -(k - k')^2$$

$$x_{Bj} = Q^2/(2P \cdot q)$$

Jet Production in Neutral Current Deep Inelastic Scattering

- Jet production in neutral current interactions up to $\mathcal{O}(\alpha_s)$:



- Jet production cross section:

$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx\, f_a(x,\mu_F^2)\, d\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_R^2,\mu_F^2)$$

  – f_a: parton a density in the proton, determined from experiment; long-distance structure of the target
  – $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD; short-distance structure of the interaction

- A wealth of data from fixed-target and collider experiments has allowed an accurate determination of the proton PDFs $\Rightarrow$ measurements of jet production in NC DIS provide

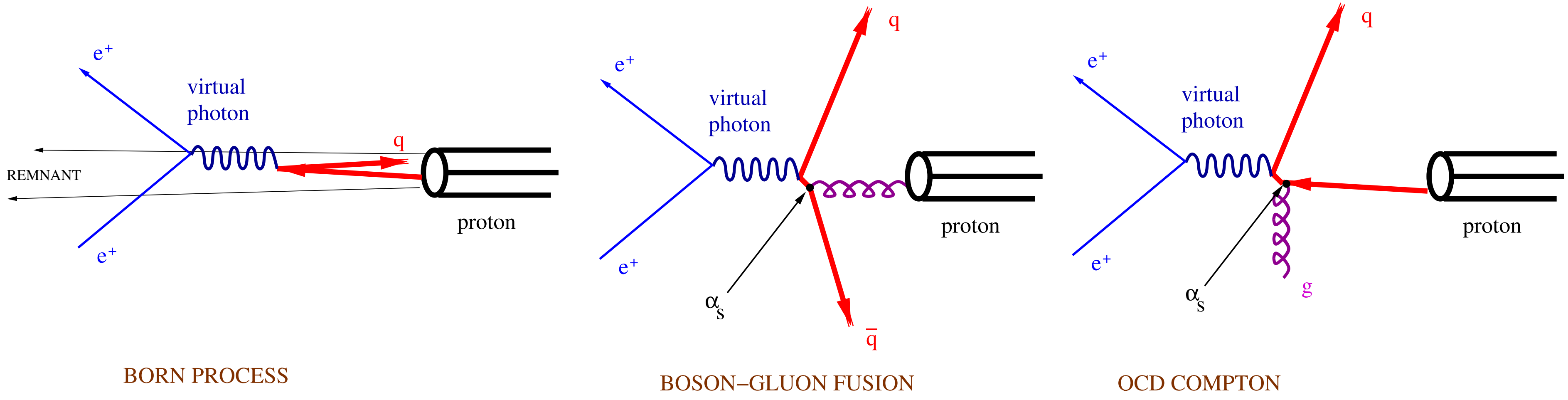
  $\rightarrow$ a sensitive test of the pQCD predictions of the short-distance structure

  $\rightarrow$ a determination of the strong coupling constant α_s

QCD Analyses of Jet Production in NC DIS

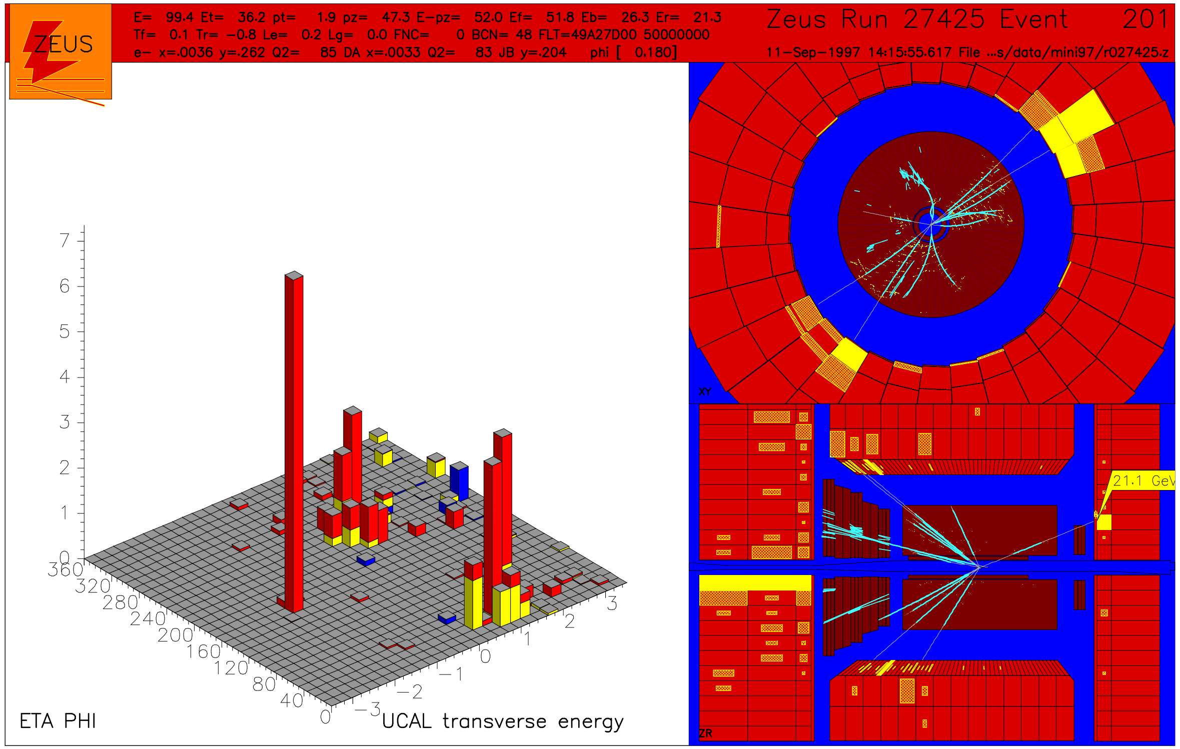
- To perform a stringent test of the pQCD predictions and a precise determination of α_s:
  - ∗ Observables for which the predictions are directly proportional to α_s
    - → Jet cross sections in the Breit frame; Jet substructure
  - ∗ Small experimental uncertainties
    - → Jets with relatively high transverse energy (uncertainty on jet energy scale!)
    - → Kinematic region in (Q^2, x) and jet variables (small detector corrections)
    - → Ratios of cross sections (partial cancellation of systematic uncertainties)
  - ∗ Small theoretical uncertainties
    - → NLO QCD calculations (reduction of higher-order contributions)
    - → Jet algorithm: longitudinally invariant k_T cluster algorithm (Catani et al)
      - ⇒ small parton-to-hadron effects
      - ⇒ less ambiguities in matching the experimental and theoretical implementations
      - ⇒ suppression of beam-remnant jet
    - → Jet selection: inclusive jet production (smaller uncertainties than for dijets)
- By fitting the data with NLO QCD calculations ⇒ extraction of α_s

High-E_T Jet Production in the Breit Frame

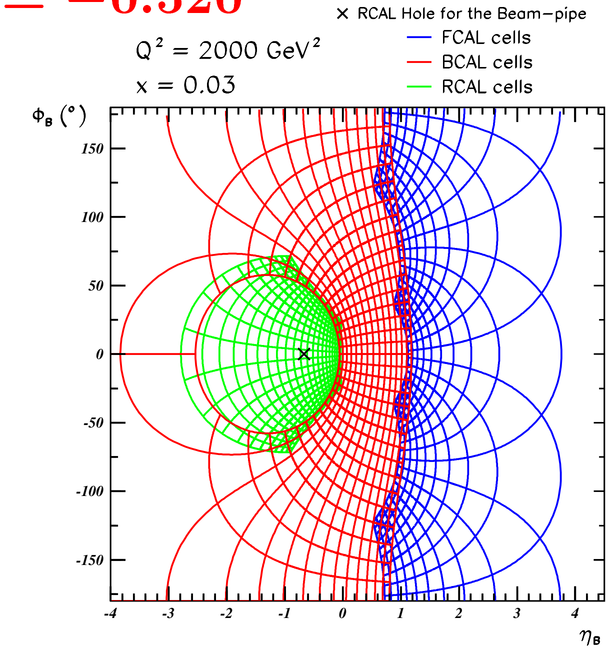


- In the Breit frame the virtual boson collides head-on with the proton
- High-E_T jet production in the Breit frame
  - $\rightarrow$ suppression of the Born contribution (struck quark has zero E_T)
  - $\rightarrow$ suppression of the beam-remnant jet (zero E_T)
  - $\rightarrow$ lowest-order non-trivial contributions from $\gamma^* g \rightarrow q\bar{q}$ and $\gamma^* q \rightarrow qg$
  - $\Rightarrow$ directly sensitive to hard QCD processes (α_s)
- Restriction of the phase space using ONLY jet variables in the Breit frame ($E^B_{T,jet}$,η^B_{jet})
  - $\rightarrow$ facilitates the separation of beam fragmentation/hard process in the calculations
  - $\rightarrow$ allows the measurement of the azimuthal distribution (ϕ^B_{jet})

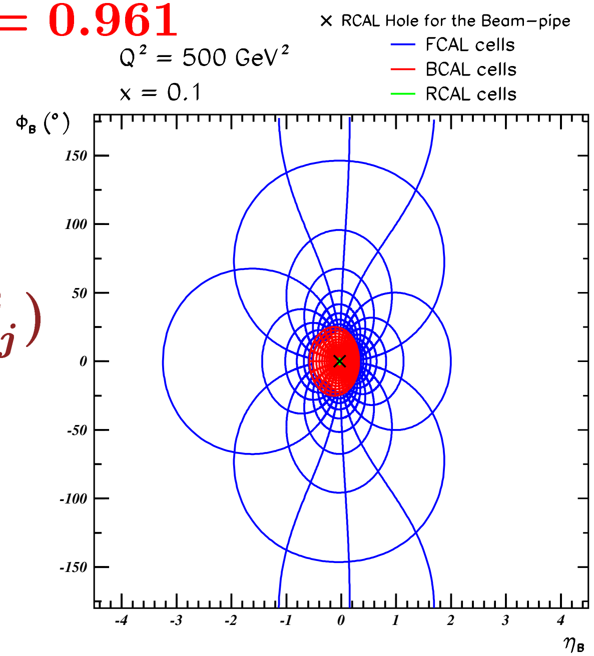
Jet Reconstrution in the Breit Frame



$\cos\gamma = -0.520$



$\cos\gamma = 0.961$



- **Longitudinally invariant k_T cluster algorithm in the η_B-ϕ_B plane of Breit frame:** $d_{ij} = min(E^2_{T,i}, E^2_{T,j}) \cdot (\Delta\eta^2_{ij} + \Delta\phi^2_{ij})$
- **Selection of the phase space to avoid large detector effects**

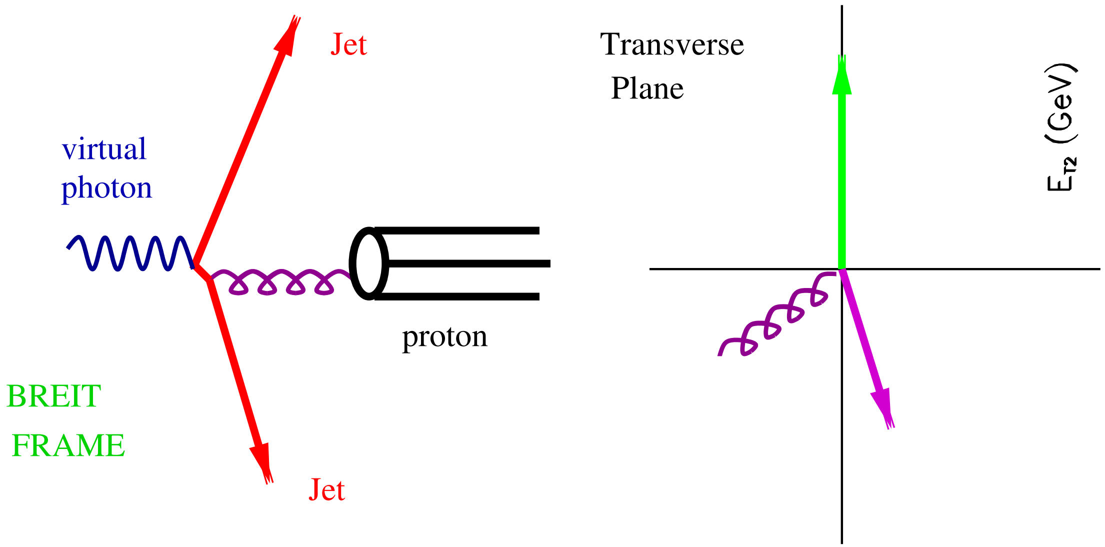
$-0.7 < \cos\gamma < 0.5$ **where** $\cos\gamma = \frac{(1-y)xE_p - yE_e}{(1-y)xE_p + yE_e}$

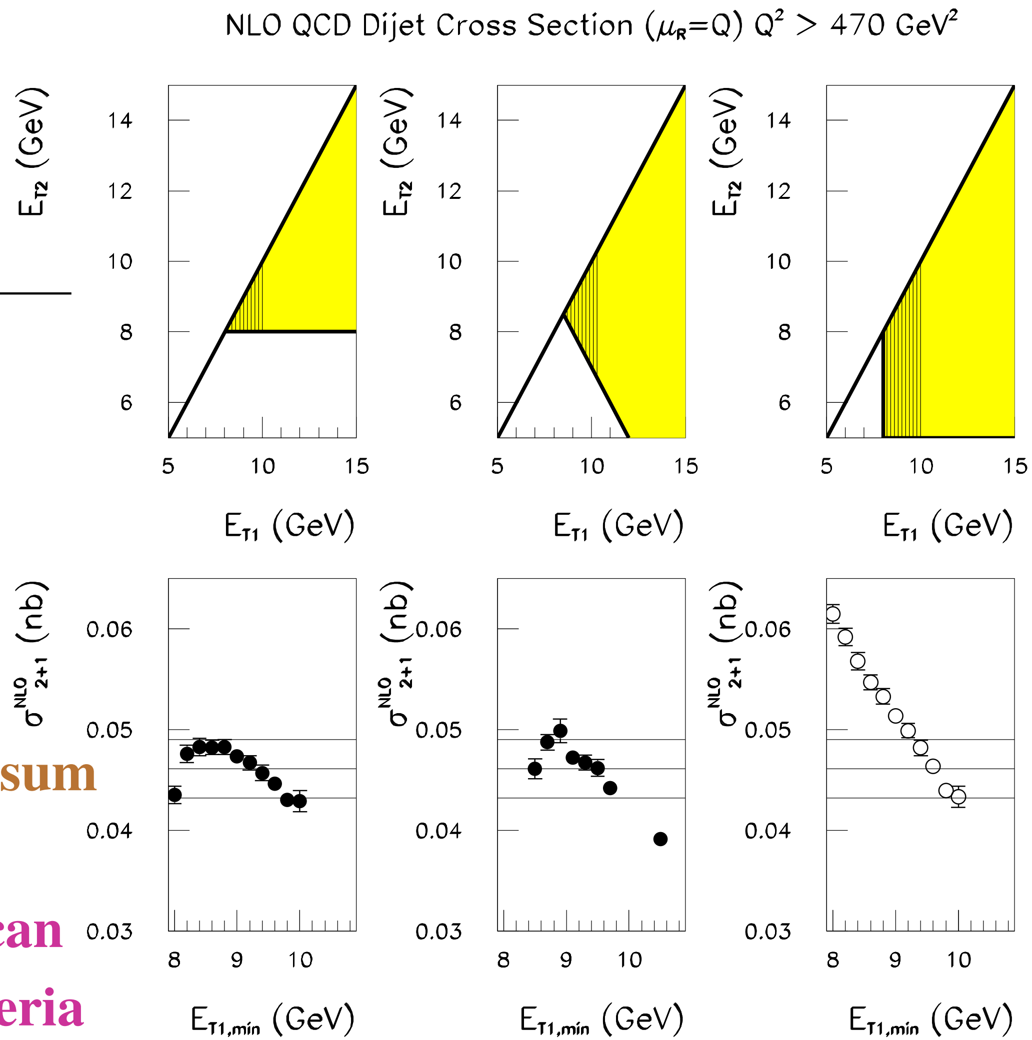
$Q^2 > 125$ GeV^2, $-2 < \eta^B_{jet} < 1.8$ **and** $E^B_{T,jet} > 8$ GeV

NLO QCD Calculations for Jets in NC DIS

- Several NLO ($\mathcal{O}(\alpha_s^2)$) programs are available for performing jet cross sections calculations → DISENT (used here), MEPJET, DISASTER++ (cross check), NLOJET
- NLO corrections → virtual corrections with internal particle loops
  → real corrections with a third parton in the final state
- Different methods to calculate real corrections:
  → phase space slicing method (M)
  → subtraction method (D, D++, NJ)
- Since there are two hard scales in jet production, the renormalisation and factorisation scales can be chosen as one of the two, $\mu_R,\ \mu_F = Q$ or $E_{T,jet}$
- The calculations are for jets of partons and the measurements are done at the hadron level → need to correct the calculations for hadronisation effects
- Theoretical uncertainties:
  → terms beyond NLO, which are usually estimated by varying μ_R by factor 2
  → uncertainties on $\alpha_s(M_Z)$ and the proton PDFs
  → uncertainty coming from the hadronisation corrections

The Infrared Sensitivity of the Selection Criteria for Dijet Events





- **Dijet selection criteria:**

→ Symmetric cuts on $E_T^{jet,1(2)}$ ⇒ danger

→ Symmetric cuts on $E_T^{jet,1(2)}$ and cut on sum

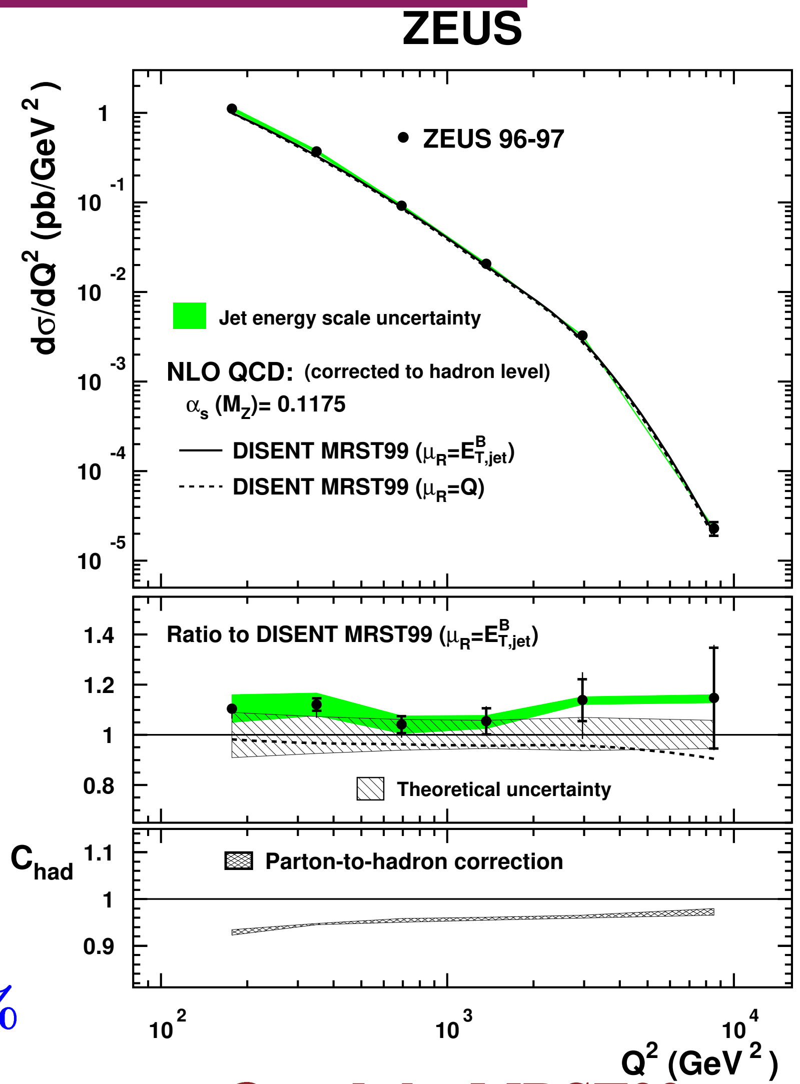
→ Asymmetric cuts on $E_T^{jet,1(2)}$

⇒ NLO calculations for dijet cross sections can be (infrared) sensitive to the selection criteria

This complication is absent for inclusive jet cross sections!

Inclusive Jet Cross Sections in NC DIS at $Q^2 > 125$ GeV^2

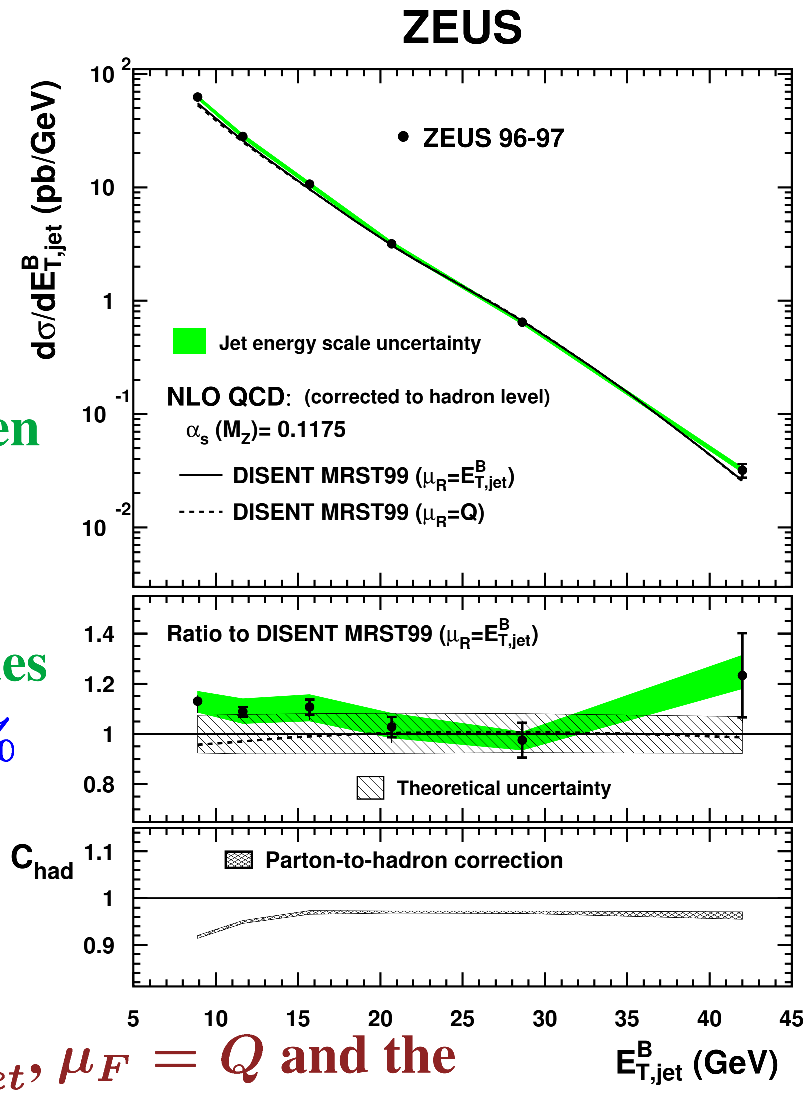
- Measurement of inclusive jet cross sections in the kinematic region defined by $Q^2 > 125$ GeV^2 and $-0.7 < \cos\gamma < 0.5$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.8$
  $\rightarrow$ no cut is applied in the laboratory frame
- Advantages:
  $\rightarrow$ infrared insensitivity (no dijet cuts!)
  $\rightarrow$ suited to test resummed calculations
  $\rightarrow$ smaller theoretical uncertainties than for dijet
- Small experimental uncertainties:
  $\rightarrow$ jet energy scale (1% for $E_{T,jet} > 10$ GeV)
  $\Rightarrow \sim \pm 5\%$ on the cross sections
- Small parton-to-hadron corrections (C_{had}): $< 10\%$



- NLO QCD calculations ($\mathcal{O}(\alpha_s^2)$) using $\mu_R = E^B_{T,jet}$, $\mu_F = Q$ and the MRST99 parametrisations of the proton PDFs describe the measurements well

Inclusive Jet Cross Sections in NC DIS at $Q^2 > 125$ GeV^2

- Measurement of the inclusive jet cross section $d\sigma/dE^B_{T,jet}$ in the kinematic region defined by $Q^2 > 125$ GeV^2 and $-0.7 < \cos\gamma < 0.5$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.8$
- Small theoretical uncertainties:
  - $\rightarrow$ higher-order terms ($>$ NLO); varying μ_R between $\frac{1}{2}\cdot E^B_{T,jet}$ and $2\cdot E^B_{T,jet} \Rightarrow \pm 5\%$
  - $\rightarrow$ uncertainty on $\alpha_s(M_Z)$ (± 0.003); $\Rightarrow \pm 5\%$
  - $\rightarrow$ hadronisation corrections; variance of C_{had} values (ARIADNE, LEPTO-MEPS, HERWIG) $\Rightarrow < 1\%$
  - $\rightarrow$ uncertainties on the proton PDFs
    - experimental uncertainties $\Rightarrow \pm 3\%$
    - theoretical assumptions $\Rightarrow \pm 3\%$



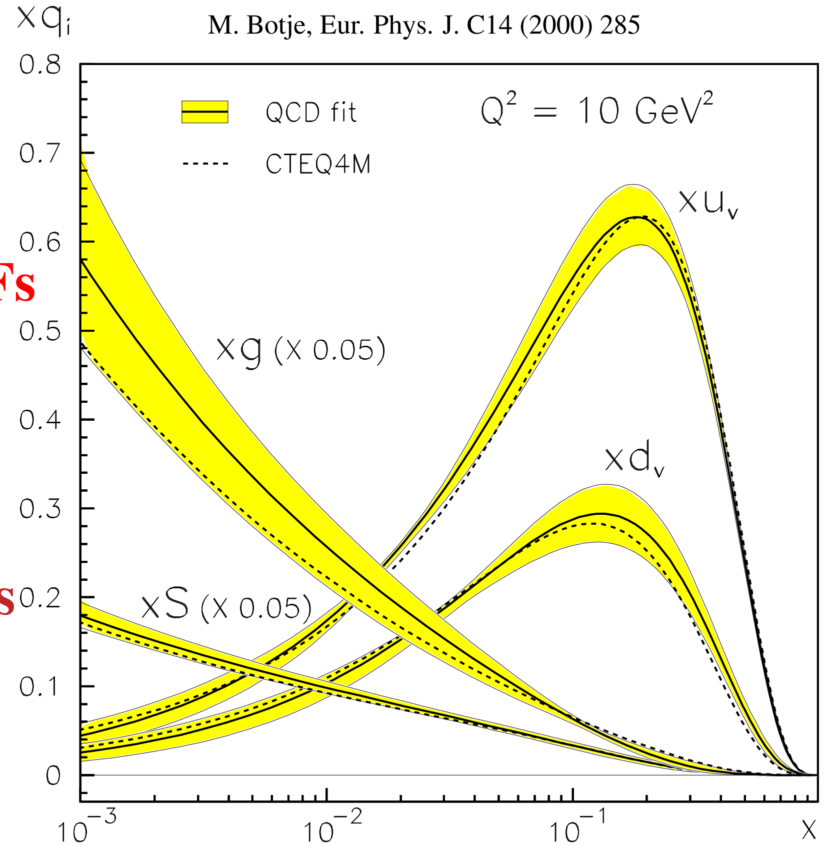
- NLO QCD calculations ($\mathcal{O}(\alpha_s^2)$) using $\mu_R = E^B_{T,jet}$, $\mu_F = Q$ and the MRST99 parametrisations of the proton PDFs describe the measurements well

Uncertainties of the Proton PDFs: effects on jet cross sections

- Comparison of jet cross-section calculations using different parametrisations of the proton PDFs (e.g. MRST vs CTEQ) DOES NOT give a reliable estimation of the uncertainties due to the proton PDFs
- Several groups have developed methods to quantify these uncertainties by accounting (properly) for

$\rightarrow$ the statistical and correlated systematic uncertainties of each data set used in the determination of the PDFs

$\rightarrow$ the theoretical uncertainties affecting the extraction of the PDFs in the DGLAP fits

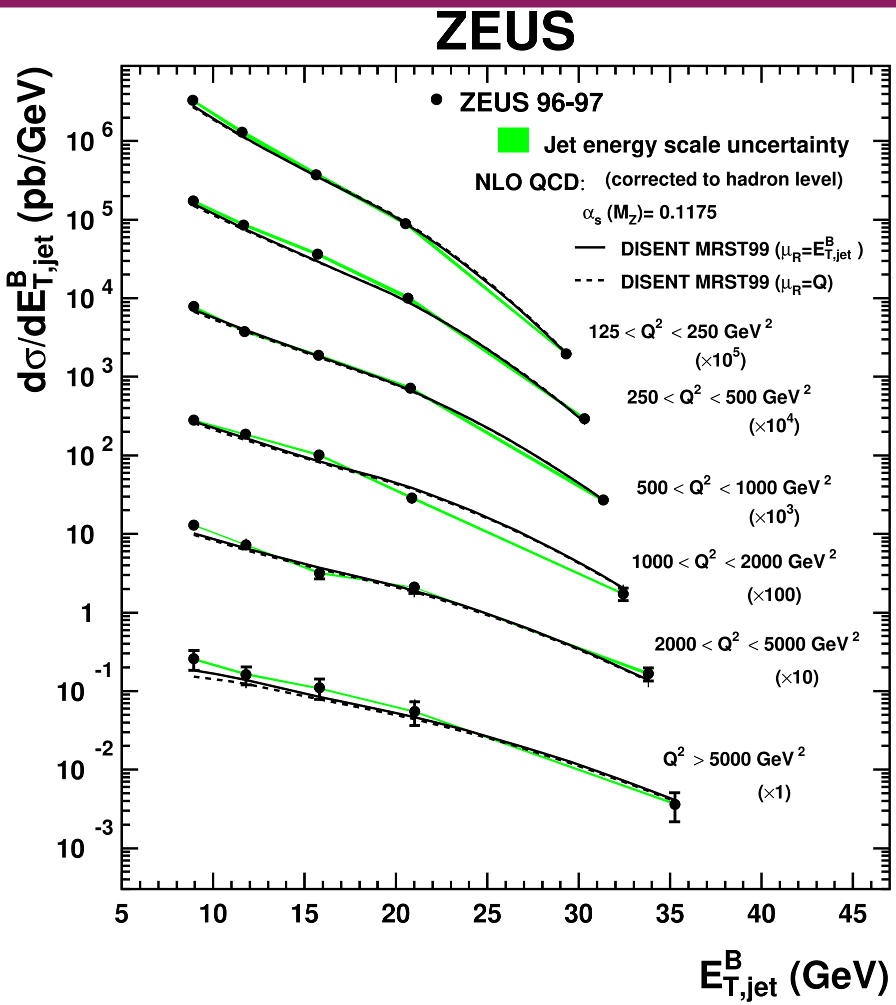


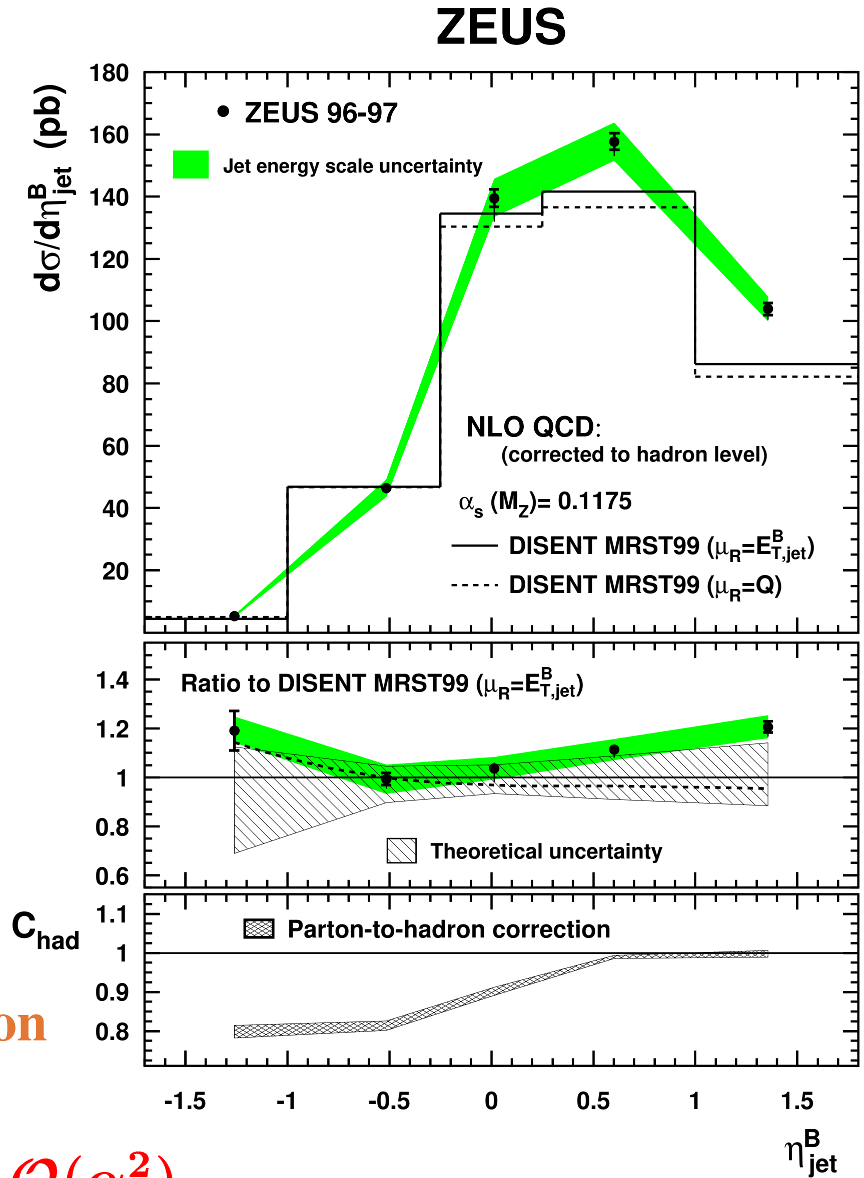
- Botje's analysis provides the covariance matrix (V_{p_μ,p_λ}) of the fitted PDF parameters ($\{p_\lambda\}$), the derivatives as functions of Q^2 and x (e.g. $\partial g(x,Q^2)/\partial p_\lambda$) and several sets obtained under different theoretical assumptions

$\Rightarrow$ evaluation of the uncertainty on any function of the proton PDFs (e.g. σ_{jet})

$$(\Delta\sigma_{jet})^2 = \sum_{\lambda,\mu} \frac{\partial\sigma_{jet}}{\partial p_\mu} V_{p_\mu,p_\lambda} \frac{\partial\sigma_{jet}}{\partial p_\lambda}$$

Inclusive Jet Cross Sections in NC DIS at $Q^2 > 125$ GeV^2





- NLO QCD calculations provide a good description of the data → validity of the description of the dynamics of inclusive jet production by pQCD at $\mathcal{O}(\alpha_s^2)$

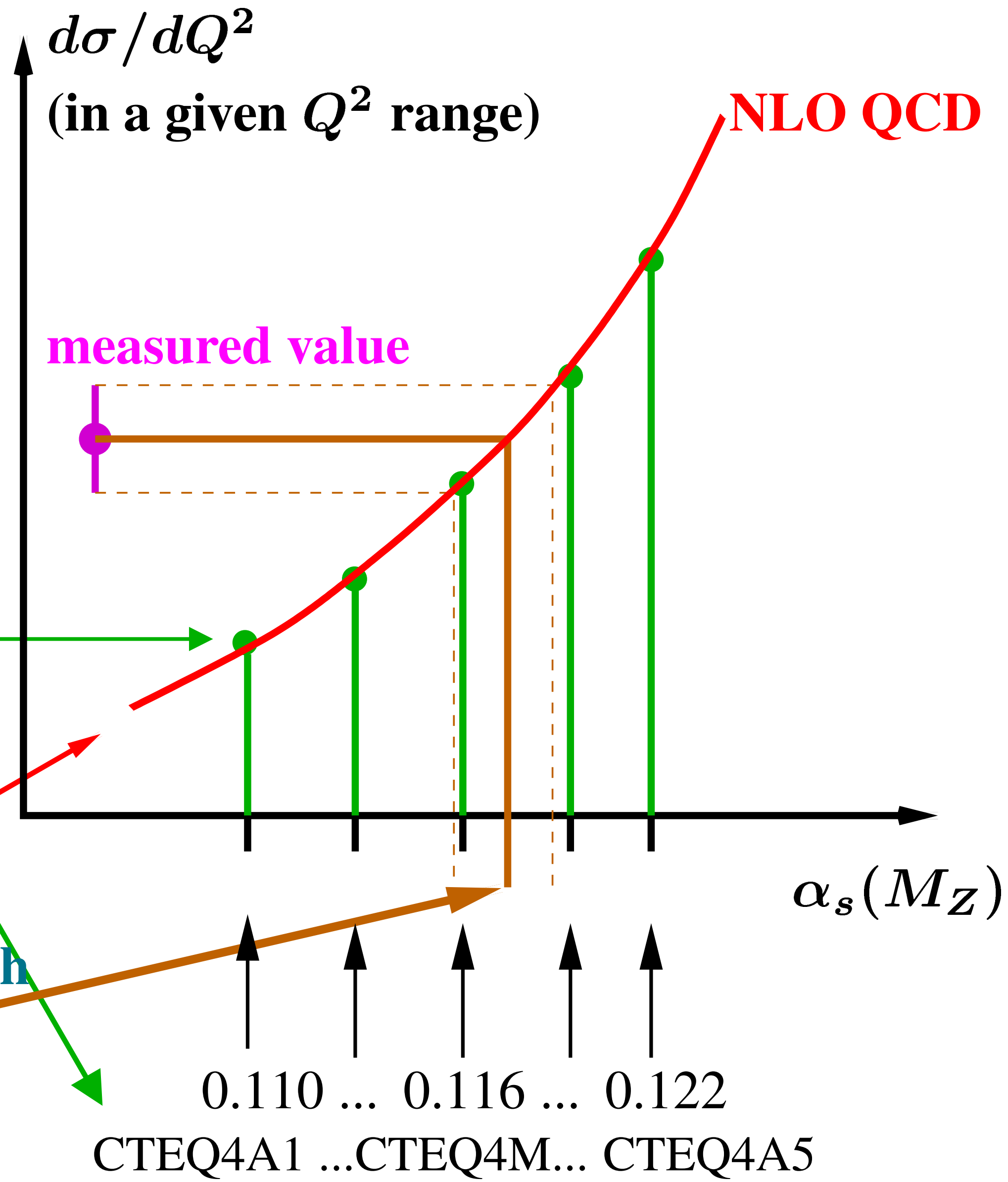
Inclusive Jet Cross Sections and extraction of $\alpha_s(M_Z)$

- NLO QCD calculations of $d\sigma/dQ^2$ depend on $\alpha_s(M_Z)$ through

$\rightarrow$ Matrix Elements: $\hat{\sigma} \sim A \cdot \alpha_s + B \cdot \alpha_s^2$

$\rightarrow$ proton PDFs: α_s assumed in evolution

- To take into account the correlation the NLO QCD calculations are performed using various sets of proton PDFs which assume different values of α_s
- The resulting NLO QCD calculations are parametrised as a function of $\alpha_s(M_Z)$ in each region of Q^2 of the measurements
- From the measured value of $d\sigma/dQ^2$ in each region of Q^2 the value of $\alpha_s(M_Z)$ and its uncertainty are extracted



Inclusive Jet Cross Sections and extraction of α_s

- The inclusive jet cross section $d\sigma/dQ^2$ at $Q^2 > 500$ GeV^2 has been used to extract $\alpha_s(M_Z)$

$$\alpha_s(M_Z) = 0.1212 \pm 0.0017\ (\text{stat.})\ ^{+0.0023}_{-0.0031}\ (\text{exp.})\ ^{+0.0028}_{-0.0027}\ (\text{th.})$$

- Experimental uncertainties:

$\rightarrow$ jet energy scale (1% for $E_{T,jet} > 10$ GeV)

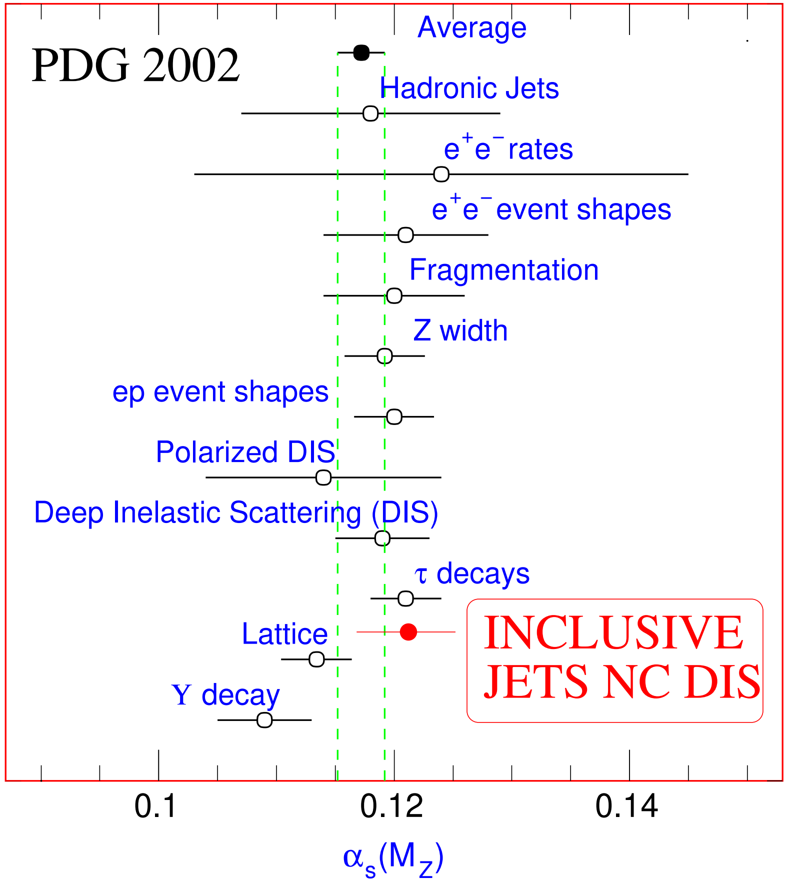
- Theoretical uncertainties:

$\rightarrow$ terms beyond NLO $\Delta\alpha_s(M_Z) = 3\%$

$\rightarrow$ uncertainties proton PDFs $\Delta\alpha_s(M_Z) = 1\%$

$\rightarrow$ hadronisation corrections $\Delta\alpha_s(M_Z) = 0.2\%$

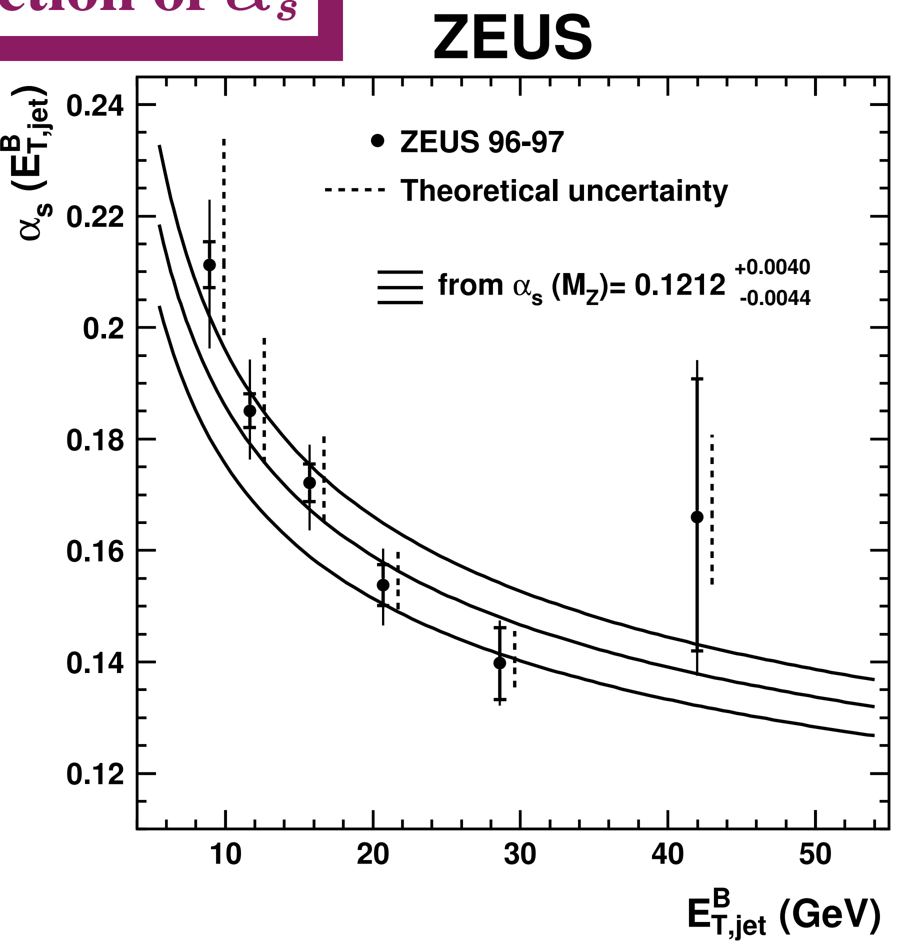
- Consistent with other determinations of α_s and PDG
- Very precise determination of $\alpha_s(M_Z)$!

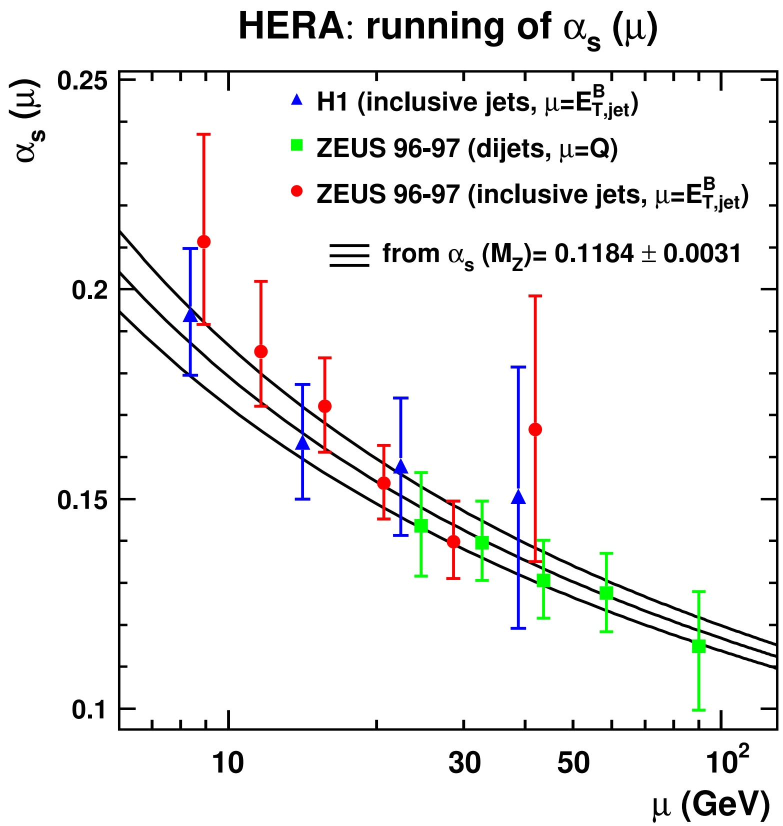


Further improvement depends upon further Experimental and Theoretical Work

Inclusive Jet Cross Sections and extraction of α_s

- Study of the scale dependence of $\alpha_s(E^B_{T,jet})$: from the measured $d\sigma/dE^B_{T,jet}$ in each $E^B_{T,jet}$ region $\rightarrow \alpha_s(< E^B_{T,jet} >)$ is extracted
- The measurements are consistent with the running of α_s predicted by perturbative QCD



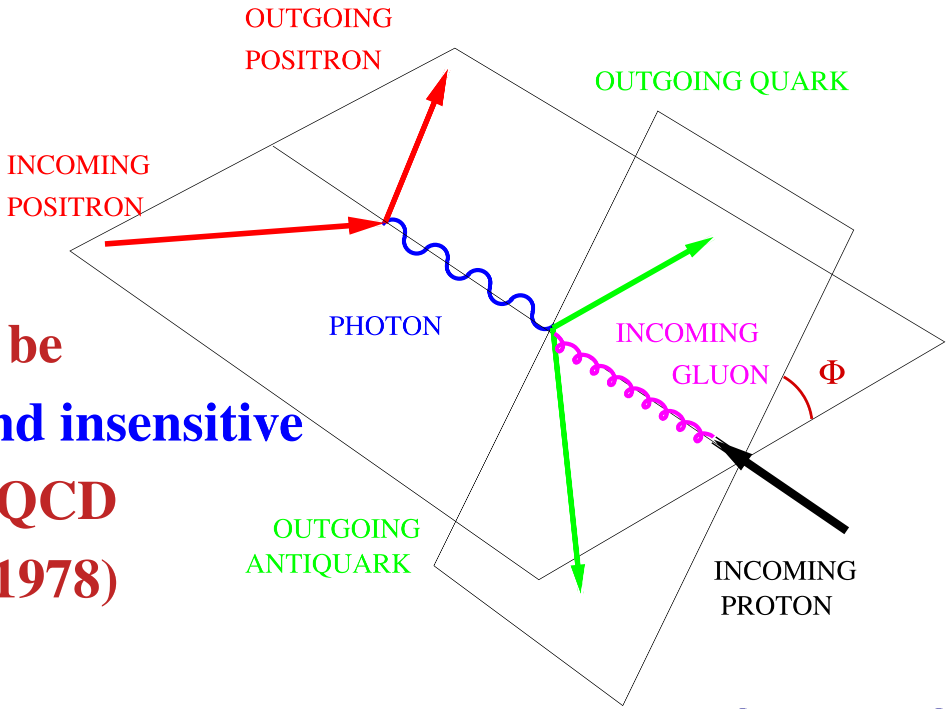


Compilation of H1 and ZEUS determinations of $\alpha_s(\mu)$ using measurements of jet production in NC DIS

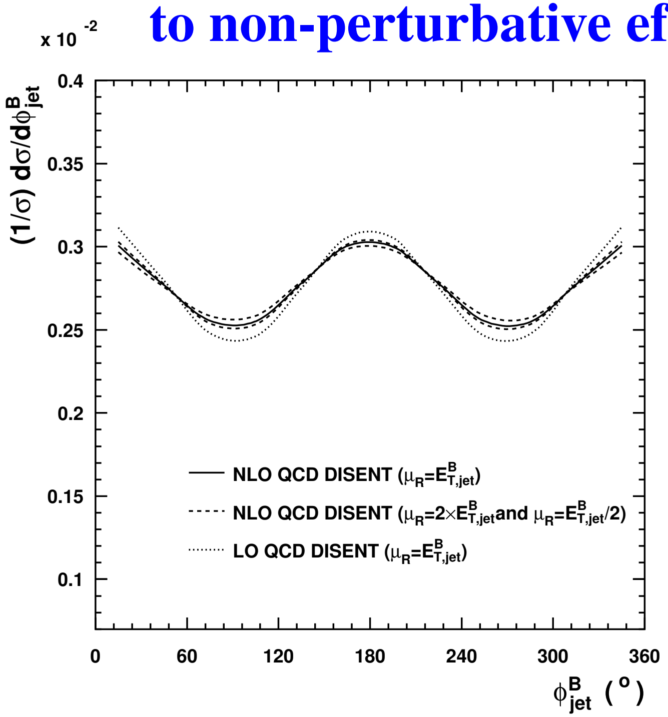
$\Rightarrow$ test of the scale dependence of $\alpha_s(\mu)$ between $\mu = 8.4$ GeV and 90 GeV

Azimuthal Distribution of Jets in NC DIS at $Q^2 > 125$ GeV^2

- Distribution of the azimuthal angle ϕ^B_{jet} in the Breit frame between the lepton scattering plane and the plane defined by the jet and the incoming proton direction



- The azimuthal distribution of jets is expected to be non-uniform due to perturbative QCD effects and insensitive to non-perturbative effects $\Rightarrow$ clean test of pQCD (Georgi and Politzer, 1978)



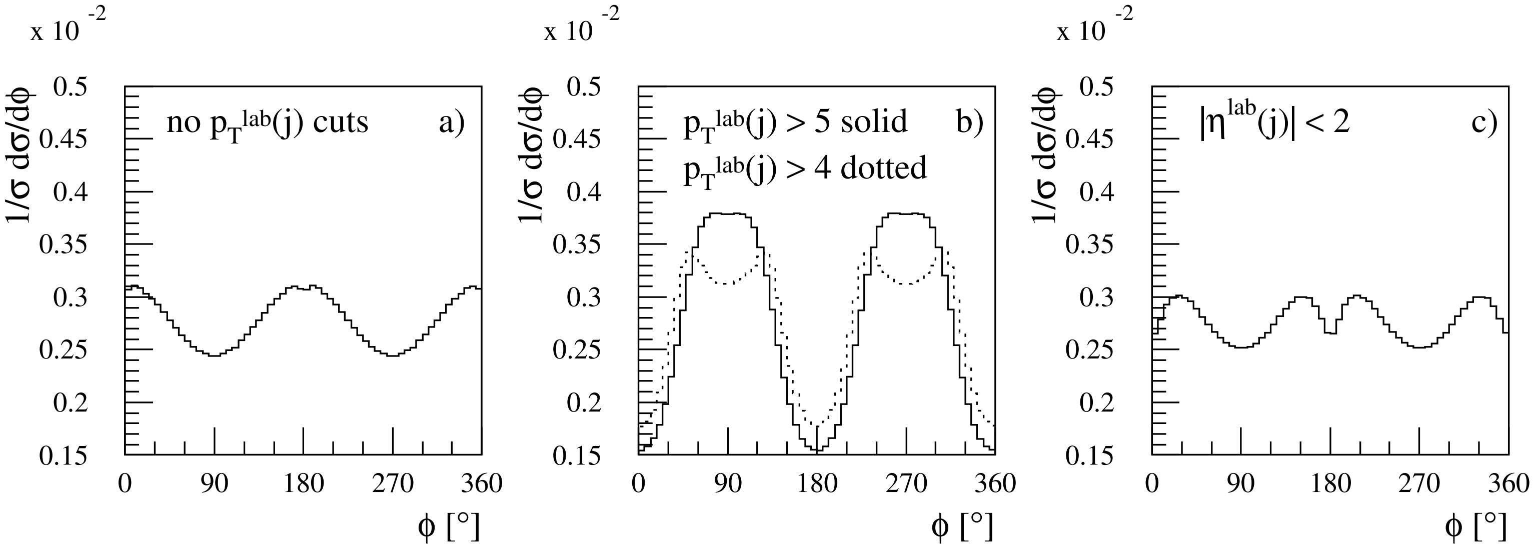
- LO pQCD prediction for unpolarised NC DIS at $Q^2 \ll M_Z^2$

$$d\sigma/d\phi^B_{jet} = A + B \cdot \cos(\phi^B_{jet}) + C \cdot \cos(2\phi^B_{jet})$$

In $\gamma^* q \to qg$ the outgoing $g(q)$ preferentially appears at $\phi = 0(\pi)$; in $\gamma^* g \to q\bar{q}$ the ϕ dependence is dominated by the $\cos 2\phi$ term. For an inclusive jet measurement

$$\Rightarrow d\sigma/d\phi^B_{jet} = A + C \cdot \cos(2\phi^B_{jet})$$

Azimuthal Distribution of Jets in NC DIS

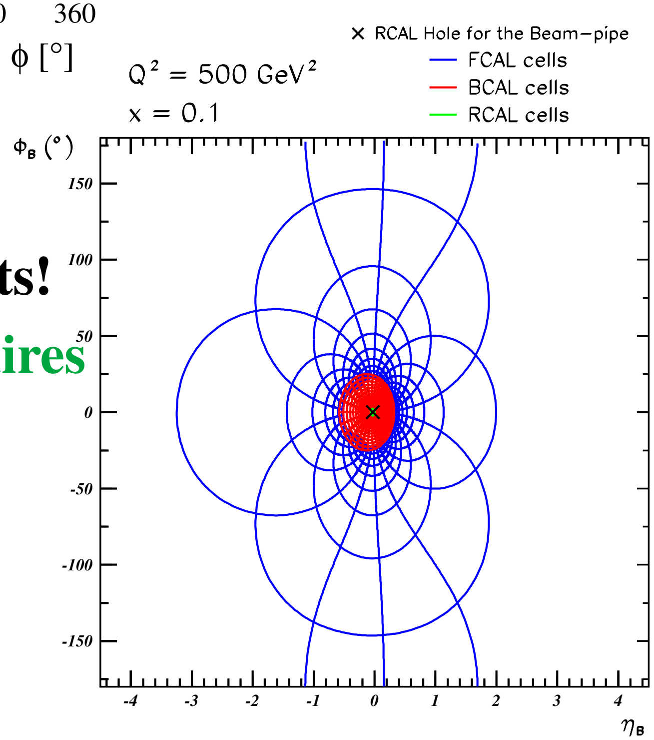


E. Mirkes and S. Willfahrt
Phys. Lett. B414 (1997) 205
(dijet production in NC DIS)

- **In the presence of cuts on the jets in the laboratory frame, e.g. $E_{T,jet}$(Lab)$>$ 5 GeV or $|\eta_{jet}(\text{Lab})| < 2$**

  ⇒ the azimuthal distribution is distorted by kinematic effects!

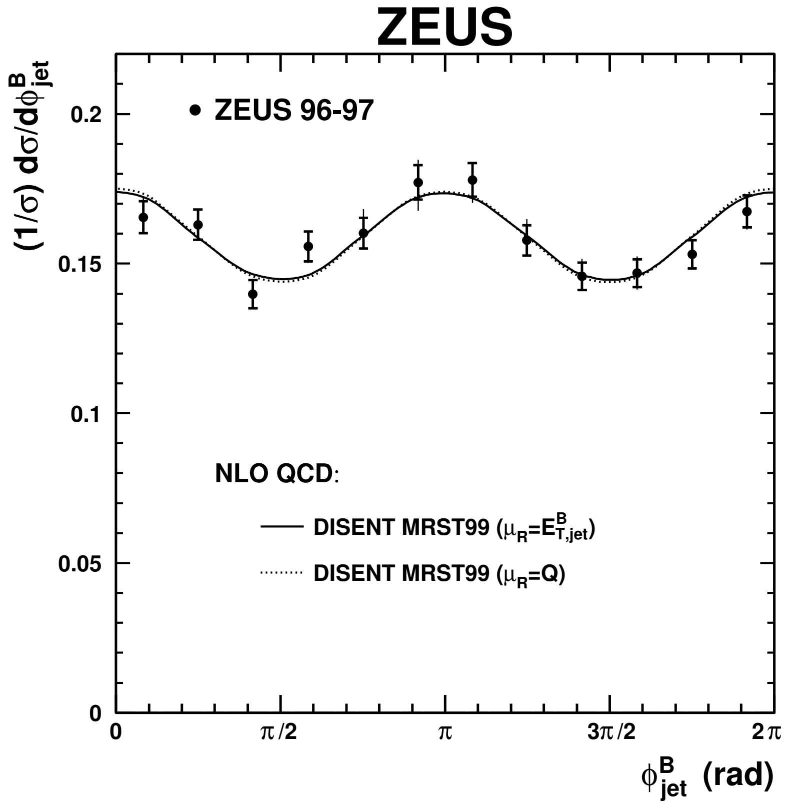
- **The measurement of the genuine azimuthal distribution requires**
  - **→ absence of cuts on the jets in the laboratory frame**
  - **→ careful design of the phase-space region to avoid large corrections for detector effects**
  - **→ cuts to suppress QED-radiation effects**



Azimuthal Distribution of Jets in NC DIS at $Q^2 > 125$ GeV^2

- Measurement of the (normalised) inclusive jet cross section $(1/\sigma)d\sigma/d\phi^B_{jet}$ in the kinematic region defined by $Q^2 > 125$ GeV^2 and $-0.7 < \cos\gamma < 0.5$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.8$
- Clear enhancements at $\phi^B_{jet} = 0$ and $\phi^B_{jet} = \pi$
- Small experimental uncertainties (normalised!)
- Negligible parton-to-hadron corrections (C_{had})
- Small theoretical uncertainties (normalised!)

$\rightarrow$ terms beyond NLO $\Rightarrow \pm1\%$ on the amplitude of the modulation of the distribution



$\rightarrow$ other uncertainties (e.g. intrinsic k_T of partons in the proton) are small in comparison

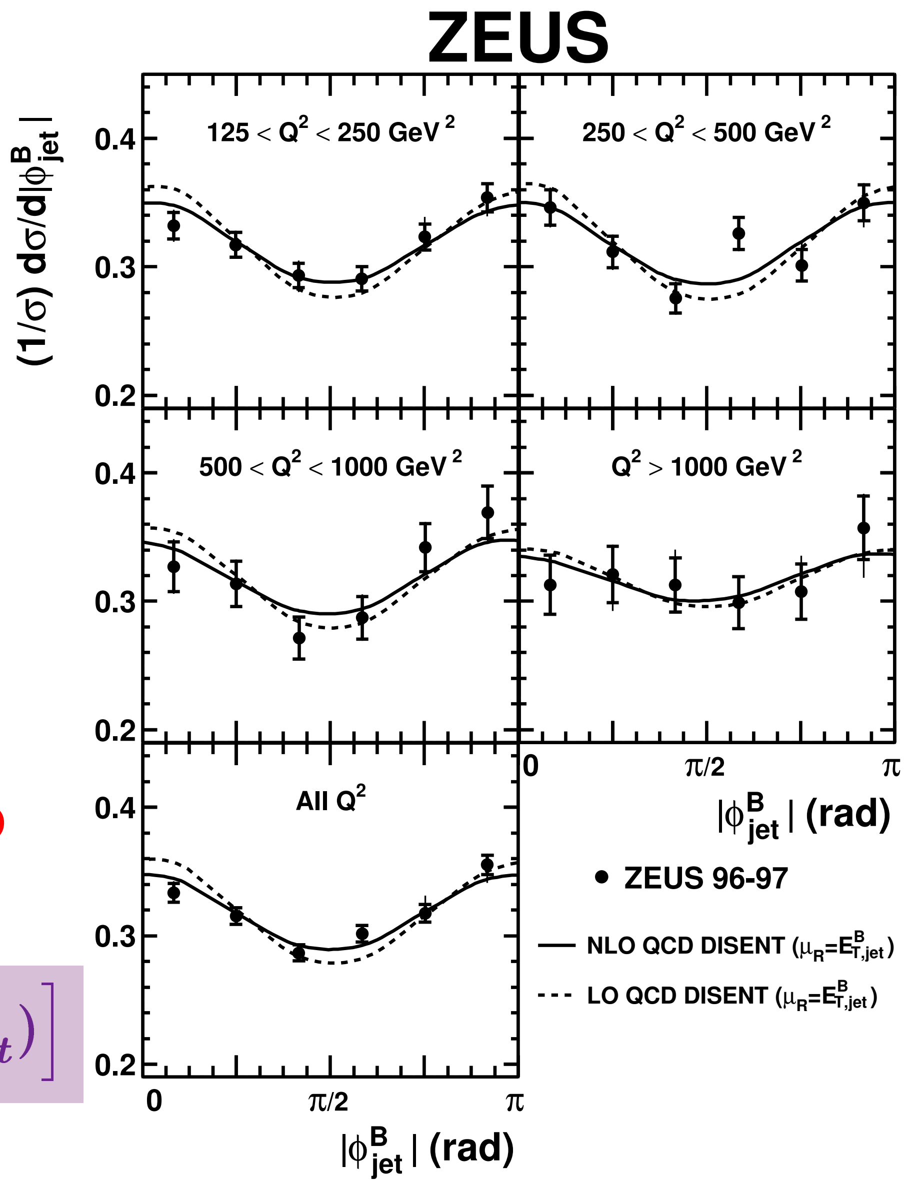
- NLO QCD calculations ($\mathcal{O}(\alpha_s^2)$) using $\mu_R = E^B_{T,jet}$ (or $\mu_R = Q$), $\mu_F = Q$ and the MRST99 parametrisations of the proton PDFs describe the measurements very well

$\Rightarrow$ precise test of the perturbative QCD prediction for the azimuthal distribution

Q^2 Dependence of the Azimuthal Distribution of Jets in NC DIS

- Measurement of the (normalised) inclusive jet cross section $(1/\sigma)d\sigma/d|\phi^B_{jet}|$ (folded about π) in different regions of Q^2
- NLO QCD calculations describe the data well whereas LO QCD predicts a larger asymmetry, particularly in the lower Q^2 intervals
- The asymmetry is predicted to decrease as Q^2 increases due to the progressive decline of the photon-gluon fusion ($\gamma^* g \to q\bar{q}$) process
- To quantify the asymmetry and its dependence on Q^2, a fit was performed to the data and QCD calculations using the functional form

$$\frac{1}{\sigma}\frac{d\sigma}{d|\phi^B_{jet}|} = \frac{1}{\pi}\left[1 + f_1 \cos\left(\phi^B_{jet}\right) + f_2 \cos\left(2\phi^B_{jet}\right)\right]$$



Q^2 Dependence of the Azimuthal Asymmetry of Jets in NC DIS

$$\frac{1}{\sigma}\frac{d\sigma}{d|\phi^B_{jet}|} = \frac{1}{\pi}\left[1 + f_1 \cos\left(\phi^B_{jet}\right) + f_2 \cos\left(2\phi^B_{jet}\right)\right]$$

- Fitted values of f_1 and f_2 as functions of Q^2 and for the entire sample ($Q^2 > 125$ GeV^2)

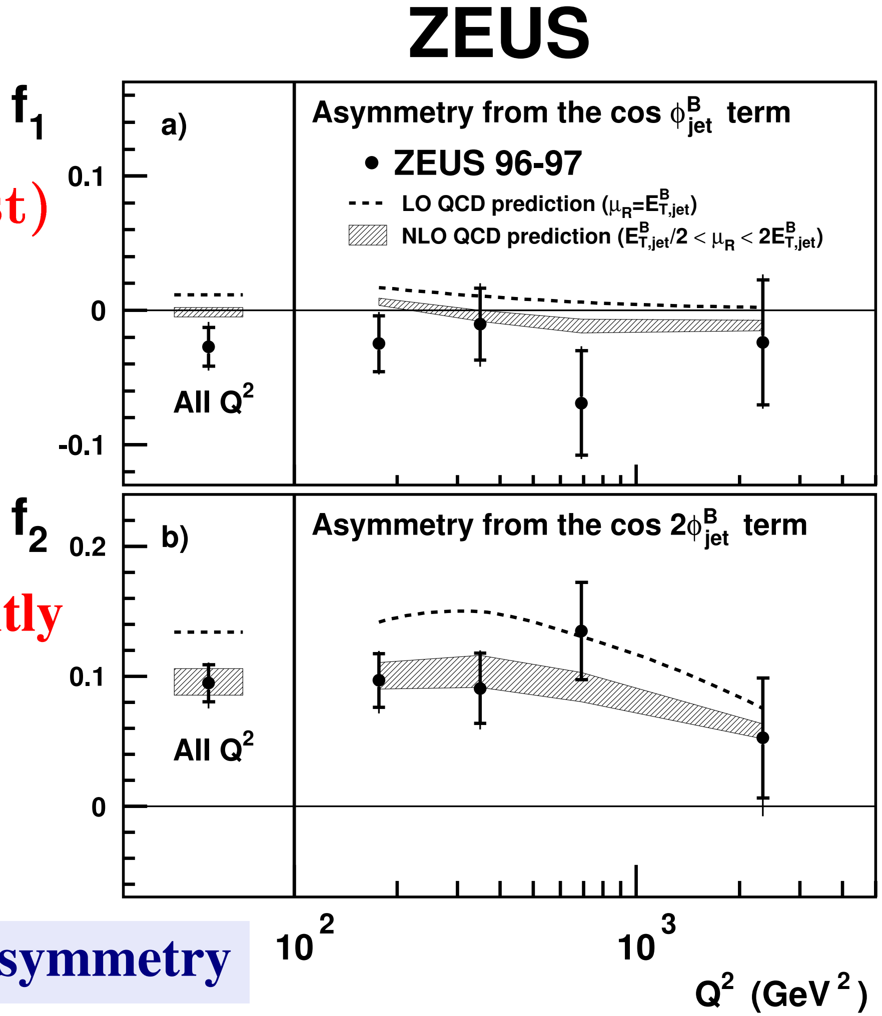
f_1(Data)$= -0.0273 \pm 0.0144(\text{stat})^{+0.0121}_{-0.0099}(\text{syst})$

f_1(NLO QCD)$= -0.0003^{+0.0025}_{-0.0044}(\mu_R - \text{scale})$

f_2(Data)$= 0.0947 \pm 0.0143(\text{stat})^{+0.0068}_{-0.0133}(\text{syst})$

f_2(NLO QCD)$= 0.0984^{+0.0074}_{-0.0131}(\mu_R - \text{scale})$

- For f_1, the observed asymmetry tends to be slightly larger and more negative than that of the NLO
- The NLO QCD calculations of f_2 are in good agreement with the measured values



Precise test of pQCD prediction for the azimuthal asymmetry

Jet Substructure

- The investigation of the internal structure of jets gives insight into the transition between a parton produced in a hard process and the experimentally observable spray of hadrons
- At sufficiently high E_T^{jet}, where fragmentation effects become negligible, the jet structure is expected to be calculable by pQCD

$\rightarrow$ At $\mathcal{O}(\alpha_s^0)$ a jet consists of one parton (no structure)

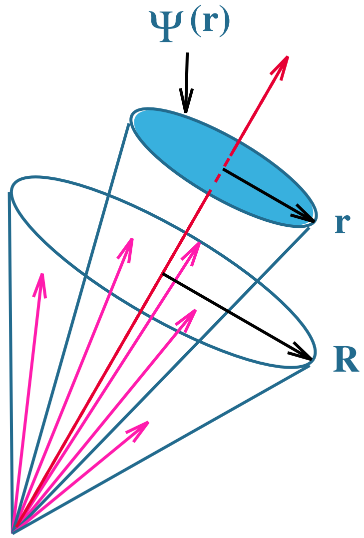
$\rightarrow$ $\mathcal{O}(\alpha_s)$ calculations give the lowest non-trivial order contribution (2 partons in a jet)

$\rightarrow$ Monte Carlo generators (ARIADNE, HERWIG, LEPTO) approximate the jet structure by using parton showers

- Gluons are predicted to be broader than quarks
- Integrated jet shape $\langle\Psi(r)\rangle$:

Average fraction of the jet's transverse energy that lies inside a cone in the η-ϕ plane of radius r concentric with the jet axis

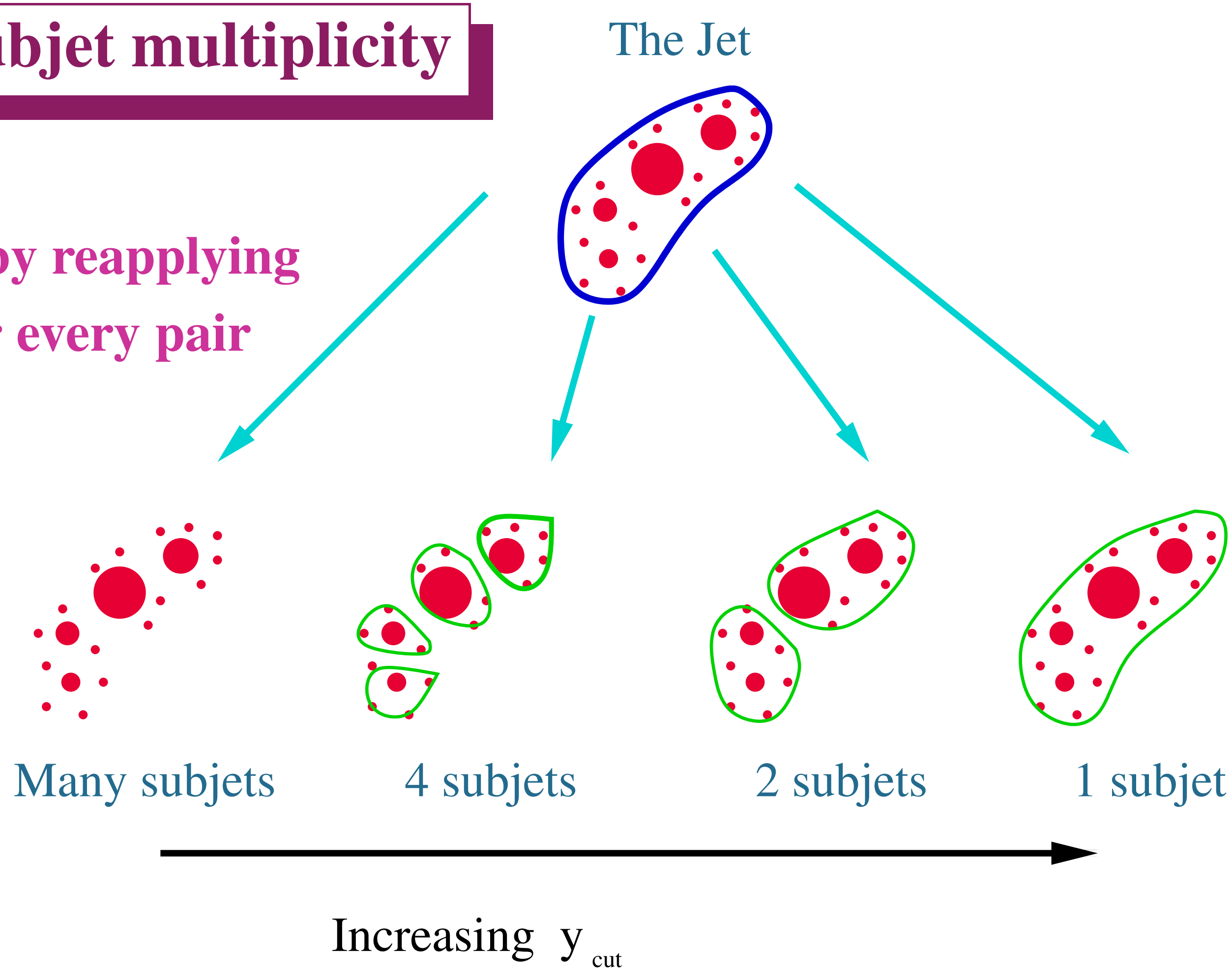
$$\langle\Psi(r)\rangle = \frac{1}{N_{jets}} \sum_{jets} \frac{E_T(r)}{E_T(r=1)}$$



Jet Substructure: the subjet multiplicity

- **Subjet multiplicity $\langle n_{sbj} \rangle$:**

Subjets are resolved within a jet by reapplying the k_T-cluster algorithm until for every pair of particles the quantity d_{ij} is above $y_{cut} \cdot (E_T^{jet})^2$.



- **Theoretical advantadges:**

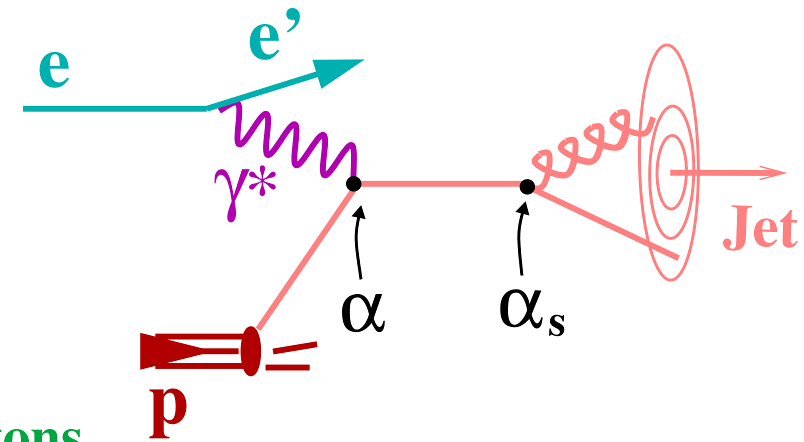
→ "safe" observables can be defined at any order in pQCD

→ allowance for "resummed" calculations

→ useful tool to investigate colour dynamics (eg quark/gluon differences)

→ small hadronisation corrections (for not too low y_{cut})

Jet Substructure in Neutral Current Deep Inelastic Scattering



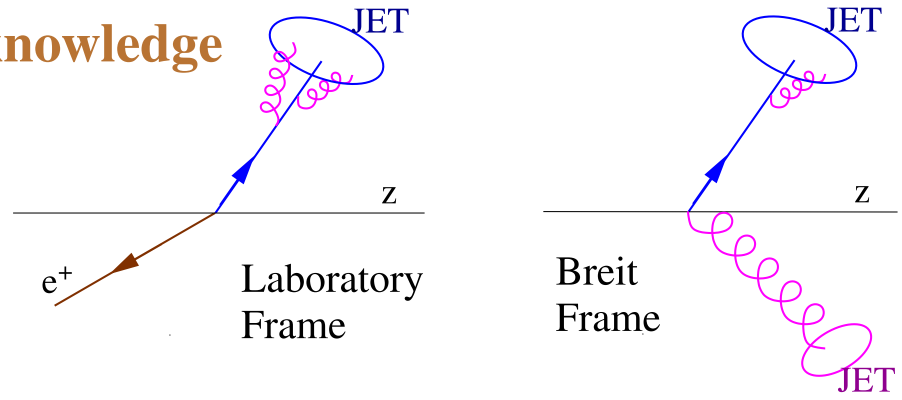
- The lowest non-trivial-order contribution to the measurements is given by $\mathcal{O}(\alpha\alpha_s)$ pQCD calculations

$$\boxed{\langle 1-\Psi(r)\rangle = \frac{\int dE_T\ E_T[d\sigma(ep\rightarrow 2\text{partons})/dE_T]}{E_T^{jet}\ \sigma_{\text{jet}}(E_T^{jet})}}$$

- NLO QCD calculations of jet substructure can be made in the laboratory frame since it is possible to have 3 partons in the same jet (not possible in the Breit frame)
- The dependence of the pQCD calculations on the knowledge of the proton PDFs is reduced
- Measurements of jet substructure provide:

$\rightarrow$ a stringent test of pQCD calculations beyond LO

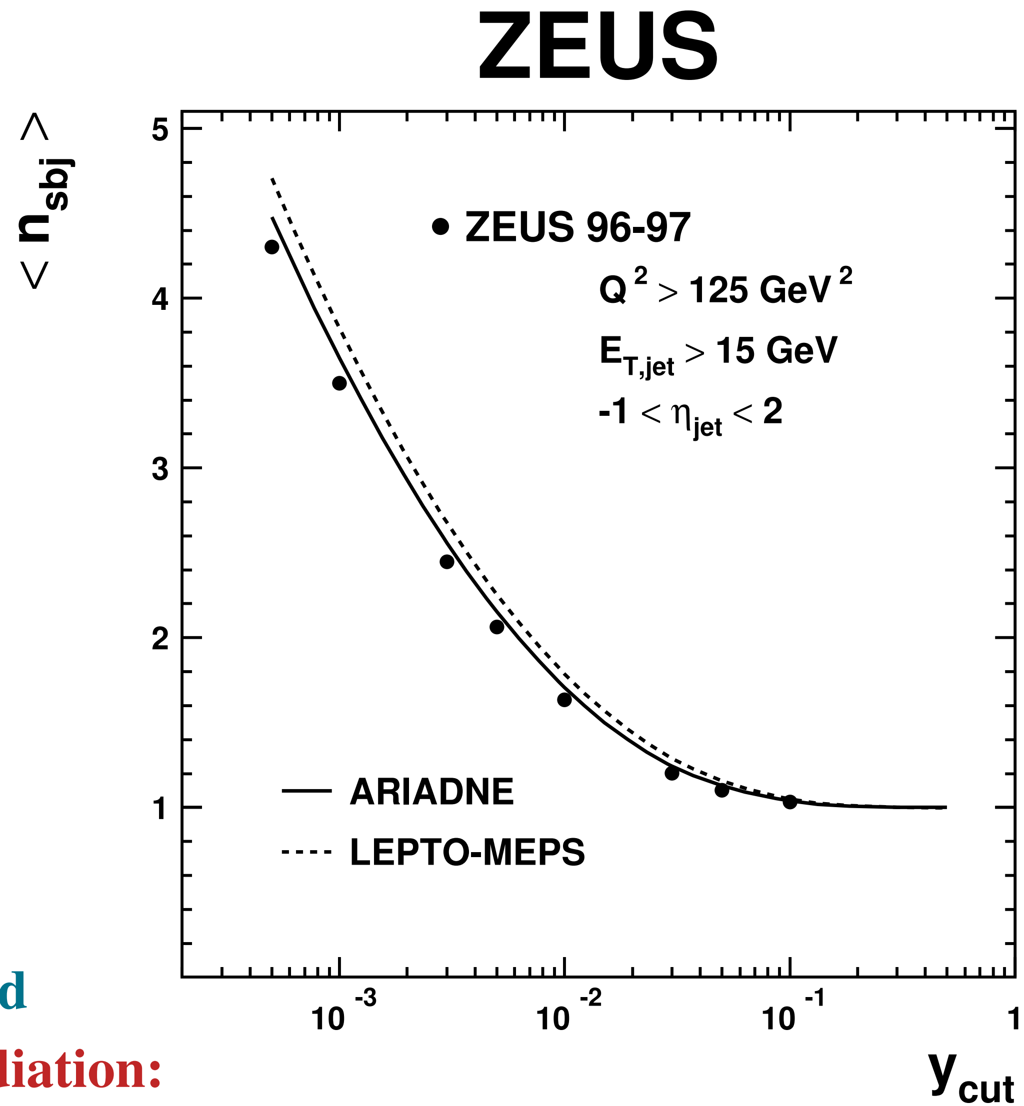
$\rightarrow$ a determination of α_s



$$\boxed{\langle n_{sbj}-1\rangle = \frac{\sigma_{n_{sbj}-1}(E_T^{jet})}{\sigma_{jet}(E_T^{jet})} \approx \frac{A_{n_{sbj}-1}\cdot\alpha_s + B_{n_{sbj}-1}\cdot\alpha_s^2}{C_{jet}+D_{jet}\cdot\alpha_s} + \mathcal{O}(\alpha_s^3)}$$

Jet Substructure in Neutral Current DIS ($Q^2 > 125$ GeV^2)

- Measurement of the mean subjet multiplicity $\rightarrow < n_{sbj} >$ for an inclusive sample of jets with
  E_T^{jet}(Lab)> 15 GeV
  $-1 < \eta^{jet}$(Lab)< 2
  in NC DIS at $Q^2 > 125$ GeV^2
- Study of the dependence of $< n_{sbj} >$ on
  $\rightarrow$ resolution parameter y_{cut}
  $\rightarrow$ jet variables E_T^{jet}(Lab) and η^{jet}(Lab)
- Small experimental uncertainties.
- Small theoretical uncertainties:
  $\rightarrow$ uncertainties on the proton PDFs
- Comparison with model predictions based on different approximations to parton radiation: matrix elements + parton shower (MEPS) and colour dipoles (ARIADNE)



Jet Substructure in Neutral Current DIS

- Comparison with fixed-order QCD calculations for $< n_{sbj} >$ as a function of y_{cut}:

$\rightarrow$ DISENT program (subtraction method)

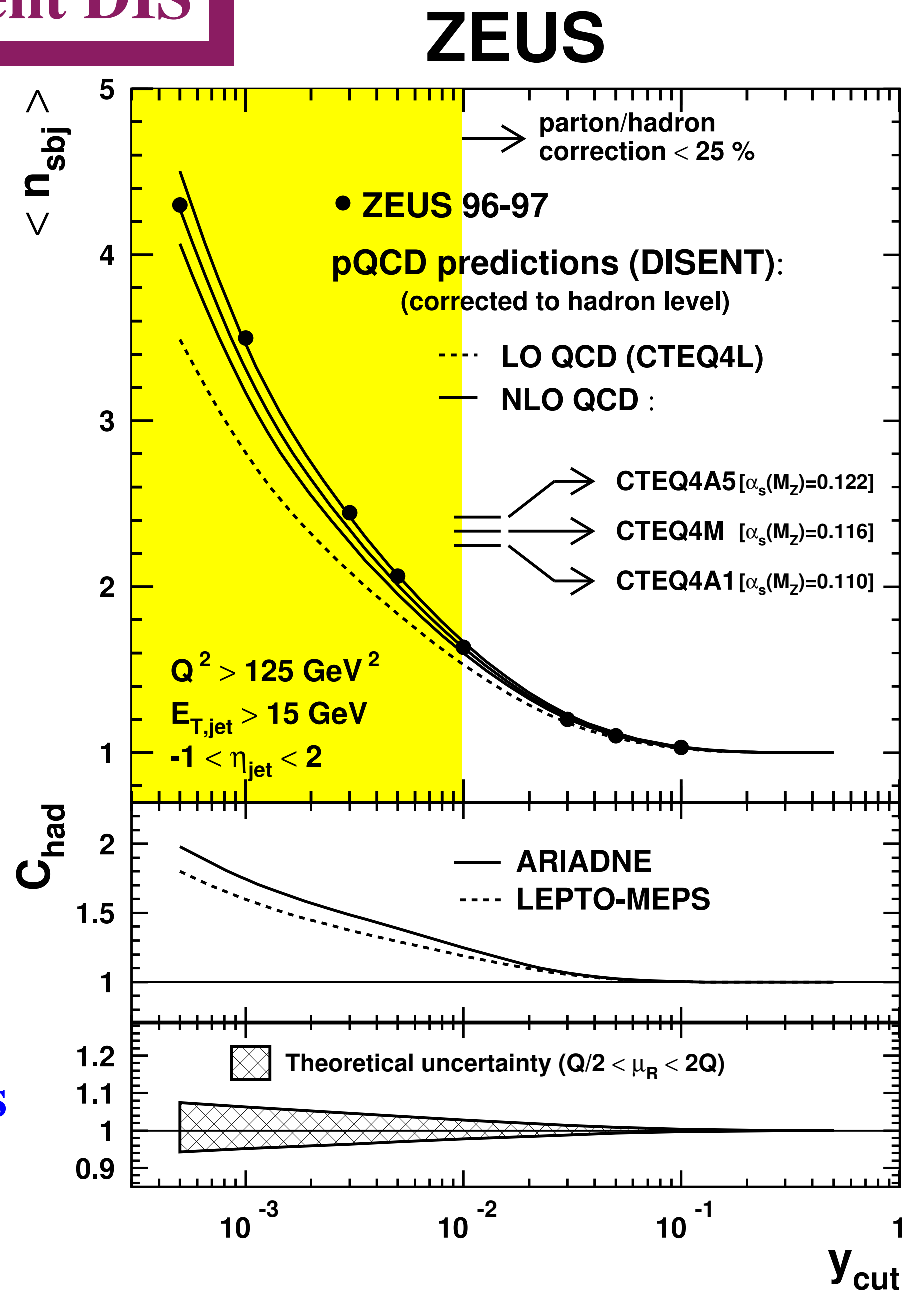
$\rightarrow$ up to 3 partons in a jet at $\mathcal{O}(\alpha_s^2)$

$\rightarrow$ $\mu_R = \mu_F = Q$

$\rightarrow$ parton-to-hadron corrections applied (smaller than 25% for $y_{cut} \geq 10^{-2}$)

- LO calculations fail to describe the data
- NLO calculations describe the data well

$\rightarrow$ for very small values of y_{cut} fixed-order QCD calculations are affected by large uncertainties and a resummation of terms enhanced by $\ln y_{cut}$ would be required for a precise comparison with the data



Jet Substructure in Neutral Current DIS

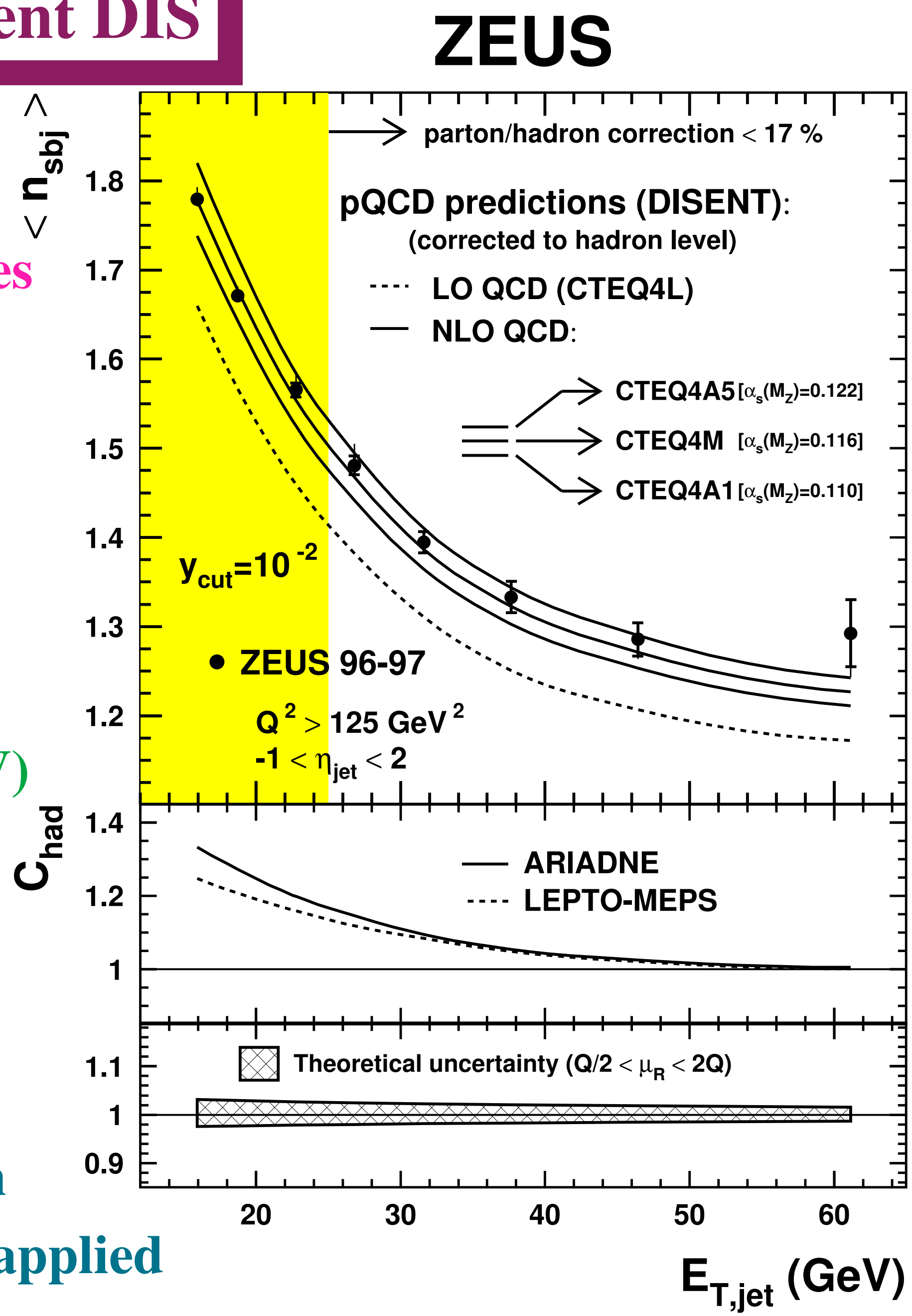
- At a fixed value of $y_{cut} = 10^{-2}$
  $< n_{sbj} >$ decreases as E_T^{jet}(Lab) increases
  $\rightarrow$ the jets become narrower

- Comparison with fixed-order QCD calculations for $< n_{sbj} >$ as a function of E_T^{jet}(Lab) at fixed $y_{cut} = 10^{-2}$:
  $\rightarrow$ parton-to-hadron corrections applied (smaller than 17% for E_T^{jet}(Lab)$>$ 25 GeV)

- LO calculations fail to describe the data

- NLO calculations describe the data well
  $\rightarrow$ sensitivity of the measurements to α_s

- The method used to extract $\alpha_s(M_Z)$ from the inclusive jet cross sections has also been applied



Jet Substructure in Neutral Current DIS ($Q^2 > 125$ GeV^2)

- **Measurement of the integrated jet shape**

  $\rightarrow \langle\Psi(r)\rangle$ for an inclusive sample of jets with E_T^{jet}(Lab)> 21 GeV and $-1 < \eta^{jet}$(Lab)< 2 in NC DIS

- **Study of the dependence of $\langle\Psi(r)\rangle$ on distance from jet axis $r = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$**

- Small experimental uncertainties ($r \geq 0.5$)

  $\rightarrow$ **model dependence ($< 0.8\%$)**

  $\rightarrow$ **jet energy scale ($< 0.4\%$)**

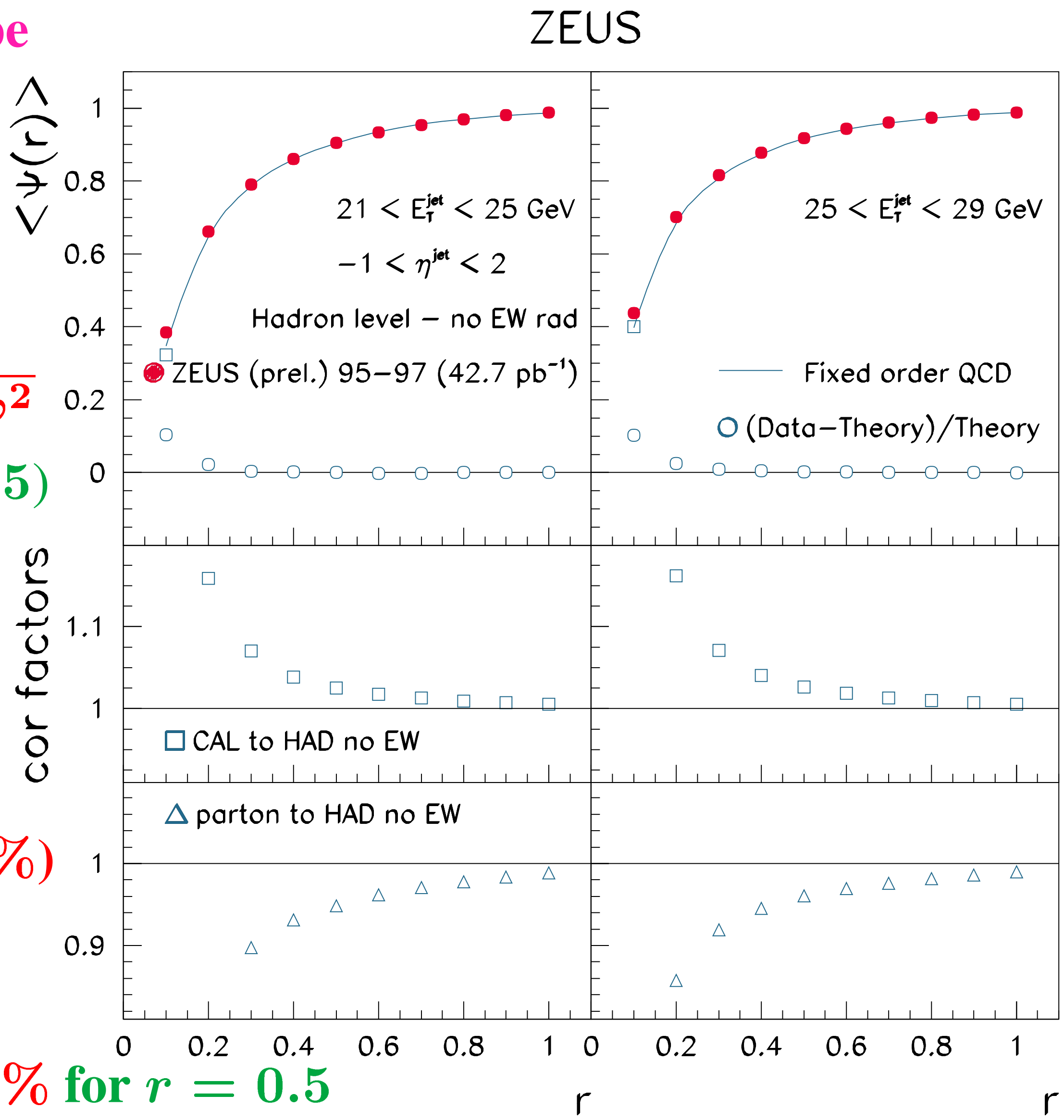
- **Small corrections (for $r \geq 0.5$) to**

  $\rightarrow$ **DATA: detector effects ($< 3\%$)**

  $\rightarrow$ **NLO: parton-to-hadron effects ($< 5\%$)**

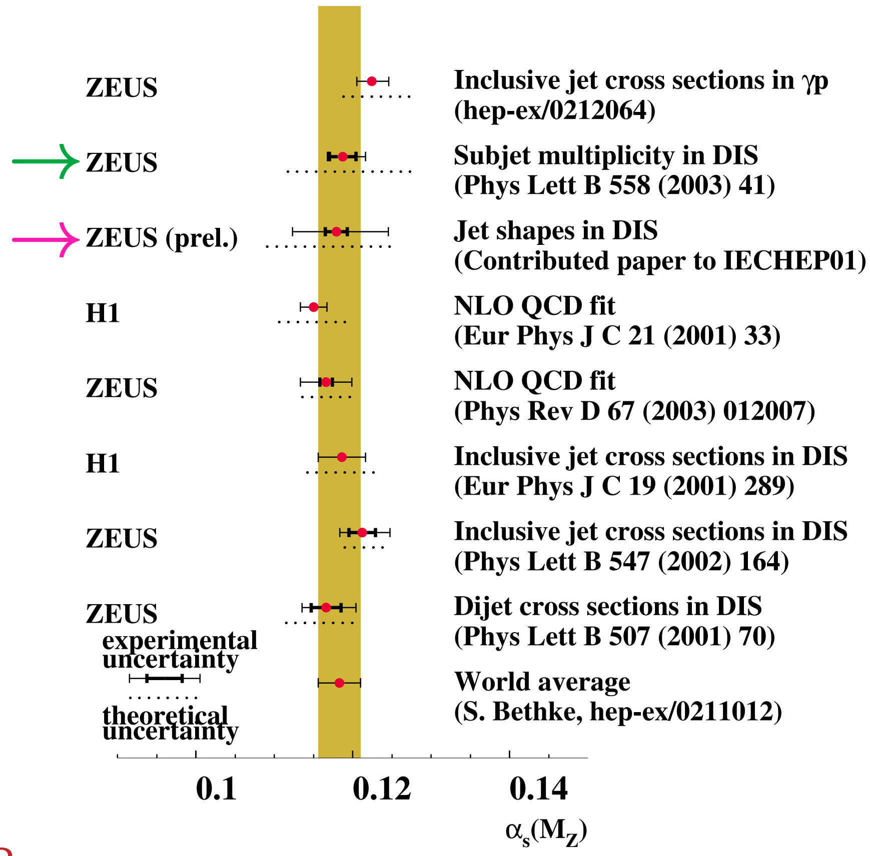
- **NLO QCD calculations provide a good description of the data:**

  $\rightarrow$ **(DATA-NLO)/NLO smaller than 1.3% for $r = 0.5$**



Jet Substructure in NC DIS and extraction of $\alpha_s(M_Z)$

- The measurements of $\langle\Psi(r=0.5)\rangle$ for E_T^{jet}(Lab)$>$ 21 GeV and of $\langle n_{sbj}\rangle(y_{cut}=10^{-2})$ for E_T^{jet}(Lab)$>$ 25 GeV have been used to extract the value of $\alpha_s(M_Z)$:



From $\Psi \rightarrow \alpha_s(M_Z) = 0.1179 \pm 0.0014\,(\text{stat.})\,{}^{+0.0054}_{-0.0065}\,(\text{exp.})\,{}^{+0.0094}_{-0.0073}\,(\text{th.})$

From $n_{sbj} \rightarrow \alpha_s(M_Z) = 0.1187 \pm 0.0017\,(\text{stat.})\,{}^{+0.0024}_{-0.0009}\,(\text{exp.})\,{}^{+0.0093}_{-0.0076}\,(\text{th.})$

- The theoretical uncertainties dominate: for n_{sbj}
  - $\rightarrow$ terms beyond NLO $\Delta\alpha_s(M_Z) = {}^{+0.0089}_{-0.0071}$
  - $\rightarrow$ parton-to-hadron effects $\Delta\alpha_s(M_Z) = \pm 0.0028$
  - $\rightarrow$ uncertainty due to that of the gluon density in the proton (negligible)

Improvements depend upon further Theoretical Work

Summary

- Measurements have been presented of inclusive jet cross sections and jet substructure in neutral current deep inelastic ep scattering at $Q^2 > 125$ GeV^2 with the ZEUS detector
- These measurements have provided

$\rightarrow$ precise tests of perturbative QCD at $\mathcal{O}(\alpha_s^2)$

$\rightarrow$ precise determinations of $\alpha_s(M_Z)$

thanks to

* a good knowledge of the proton parton distribution functions
* a reduction of experimental uncertainties (jet energy scale known to 1% for $E_T > 10$ GeV)
* a reduction of theoretical uncertainties (NLO, jet algorithm and jet selection)

- Very competitive determination of $\alpha_s(M_Z)$ from $d\sigma/dQ^2$ at $Q^2 > 500$ GeV^2

$$\alpha_s(M_Z) = 0.1212 \pm 0.0017\ (\text{stat.})^{+0.0023}_{-0.0031}\ (\text{exp.})^{+0.0028}_{-0.0027}\ (\text{th.})$$

- The measurements have reached a level of precision such that the theoretical uncertainties due to terms beyond NLO dominate in the accuracy of the final results
- To improve the accuracy of the determination of the fundamental parameters of QCD and of the tests at higher orders $\Rightarrow$ further theoretical work is needed