S. Petersburg DIS-2003

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Jet Production in NC DIS with ZEUS at HERA

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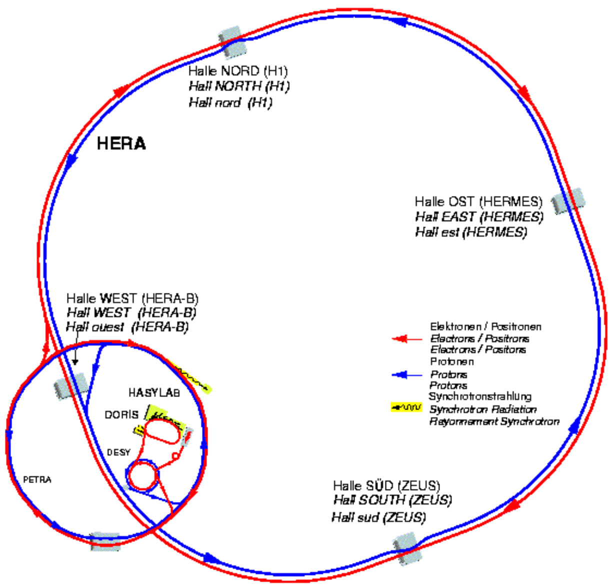
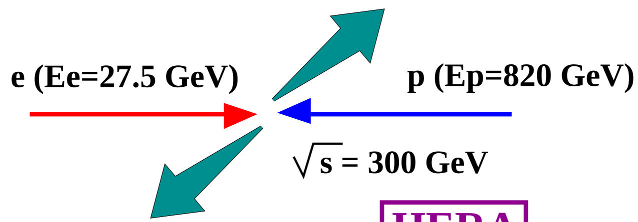
ZEUS Collab.

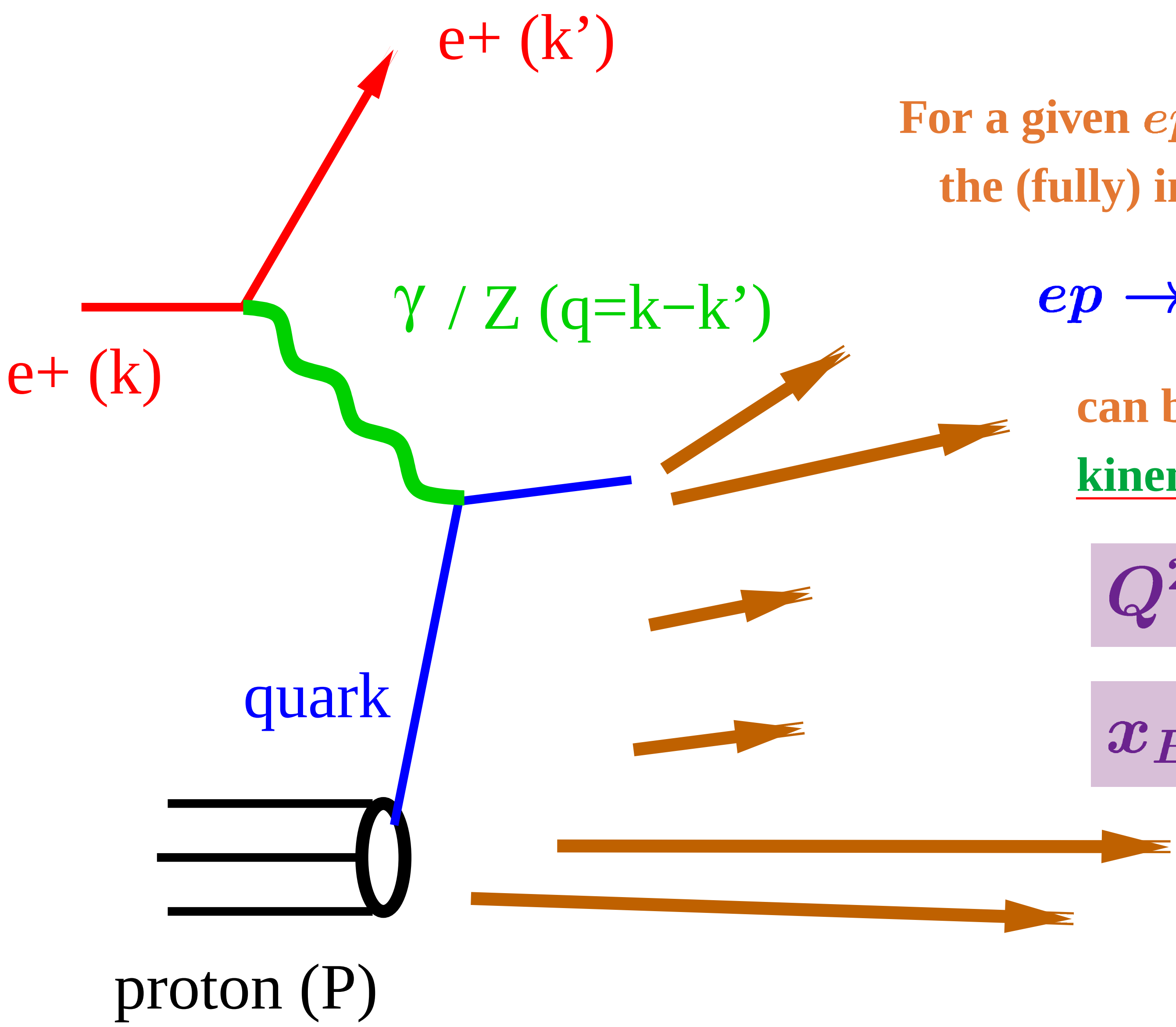
at





HERA

Kinematics of Neutral Current Deep Inelastic Scattering



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

$$ep \rightarrow e + X$$

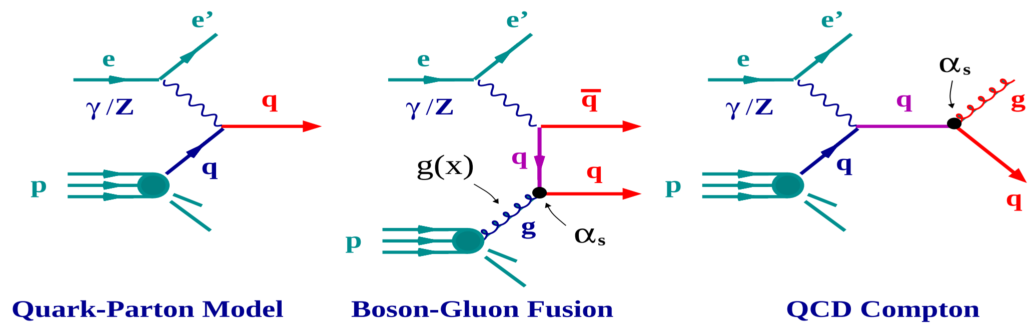
can be described by two independent kinematic variables, e.g.

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

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

Jet Production in Neutral Current Deep Inelastic Scattering

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



- Jet production cross section:

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

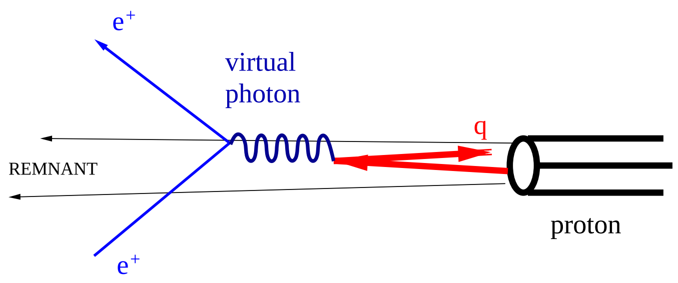
  – f_a: parton a density in the proton, determined from experiment; long-distance structure of the target
  – $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD; short-distance structure of the interaction

- 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
  $\longrightarrow$ a sensitive test of the pQCD predictions of the short-distance structure
  $\longrightarrow$ a determination of the strong coupling constant α_s

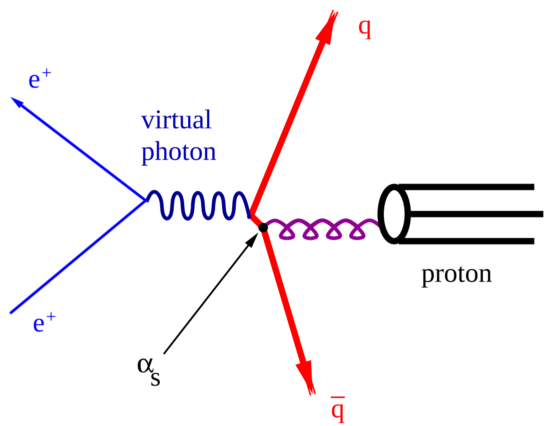
QCD Analyses of Jet Production in NC DIS

- 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

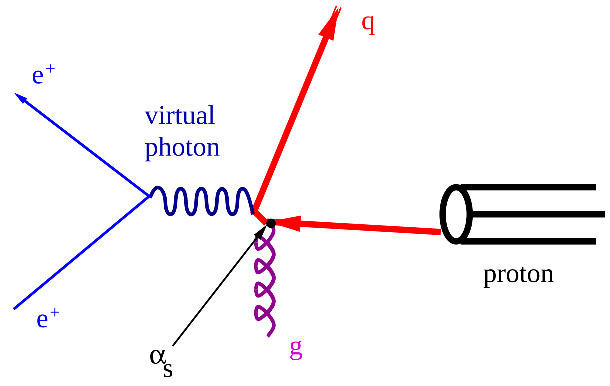
High-E_T Jet Production in the Breit Frame



BORN PROCESS



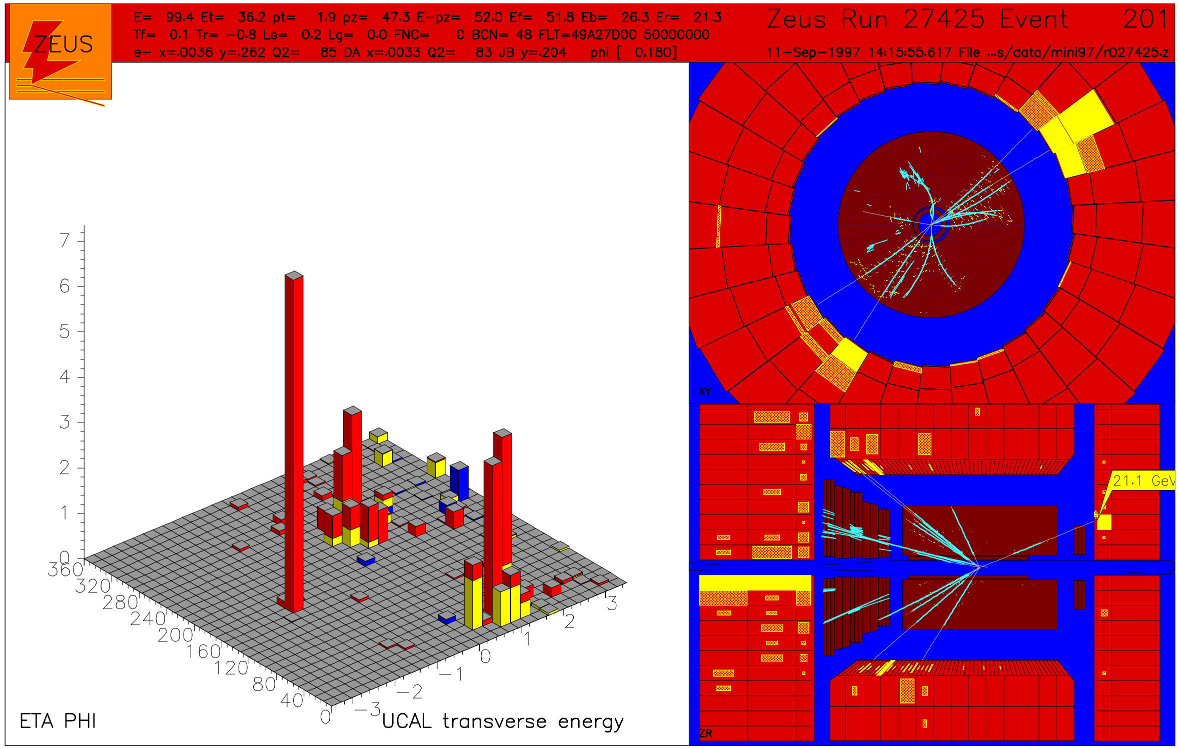
BOSON−GLUON FUSION



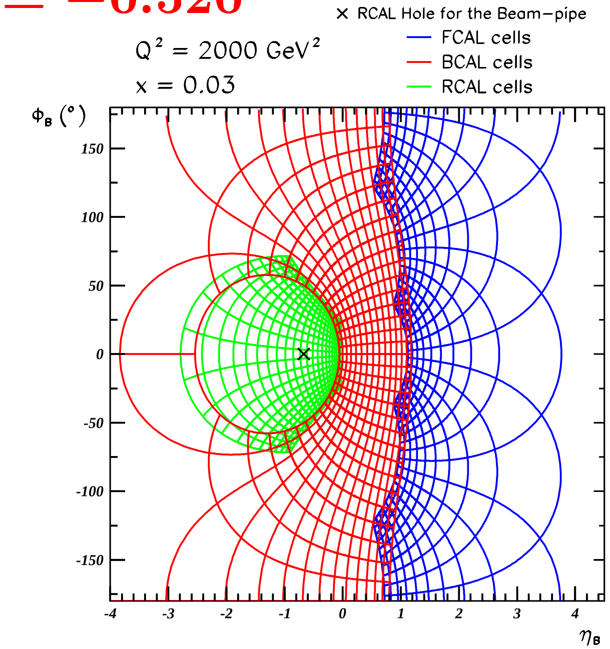
QCD COMPTON

- 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})

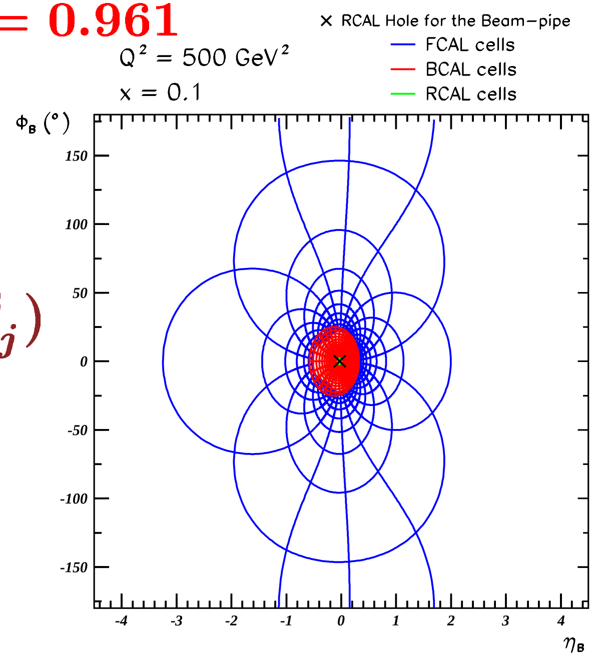
Jet Reconstrution in the Breit Frame



$\cos\gamma = -0.520$



$\cos\gamma = 0.961$



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

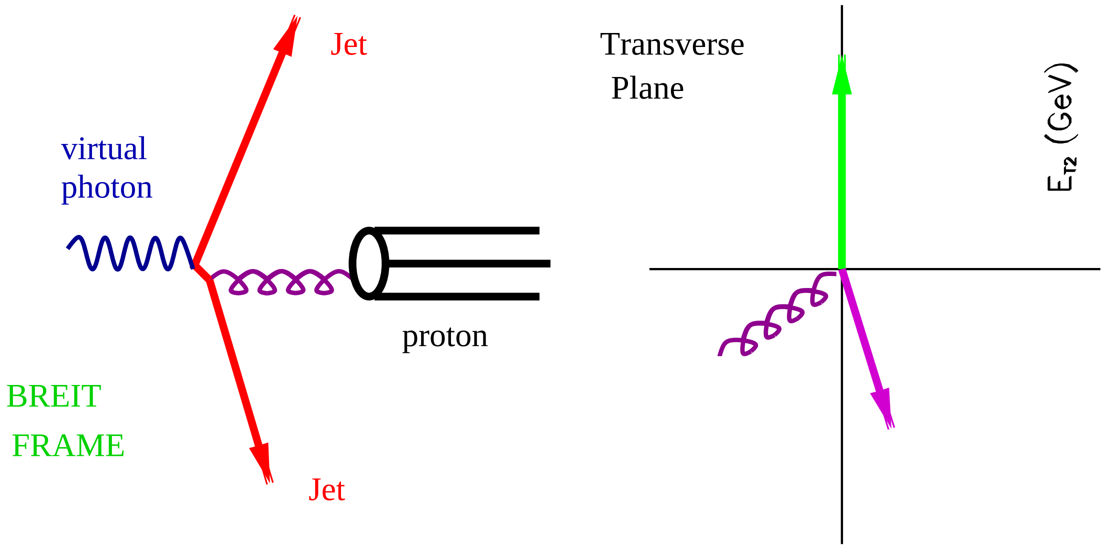
$-0.7 < \cos\gamma < 0.5$ **where** $\cos\gamma = \frac{(1-y)xE_p - yE_e}{(1-y)xE_p + yE_e}$

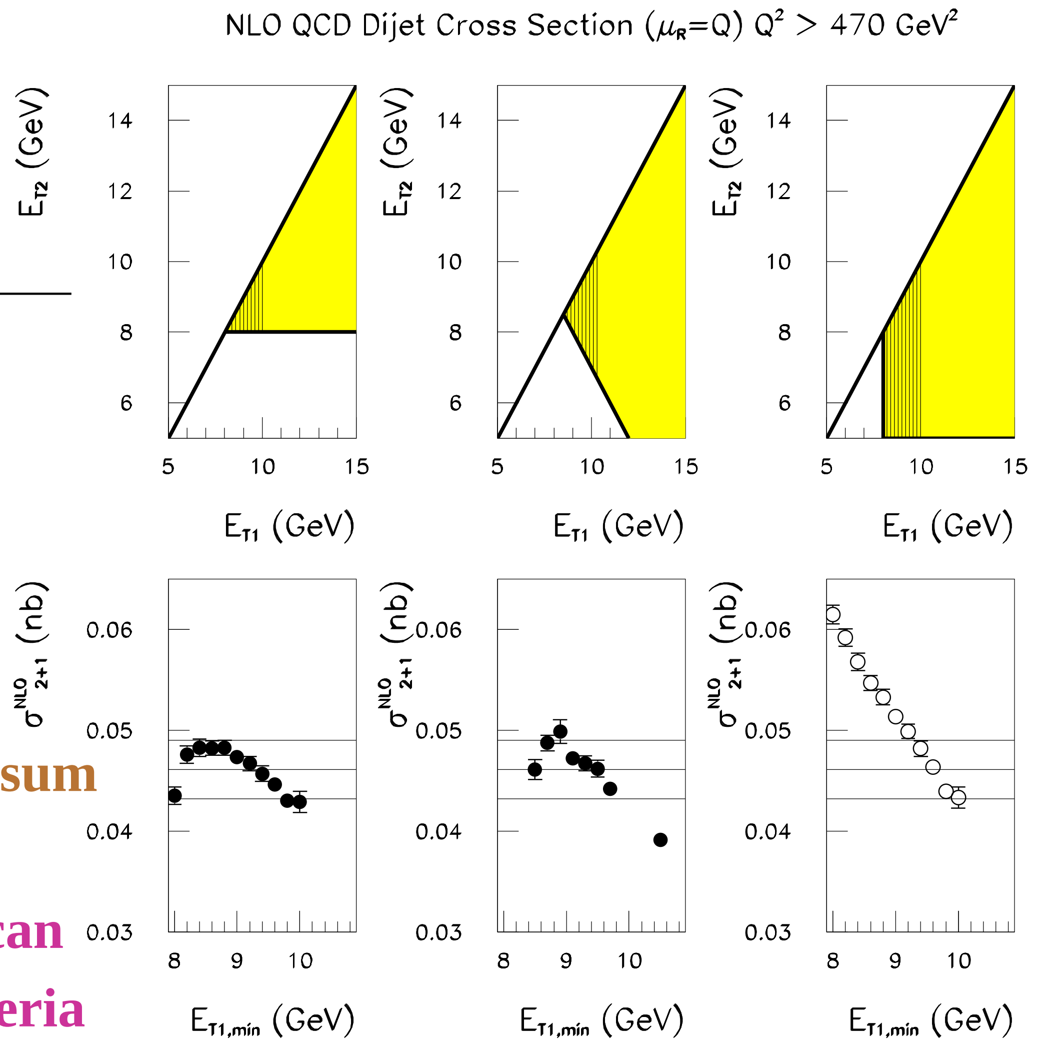
$Q^2 > 125$ GeV^2, $-2 < \eta_{jet}^B < 1.8$ **and** $E_{T,jet}^B > 8$ GeV

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**

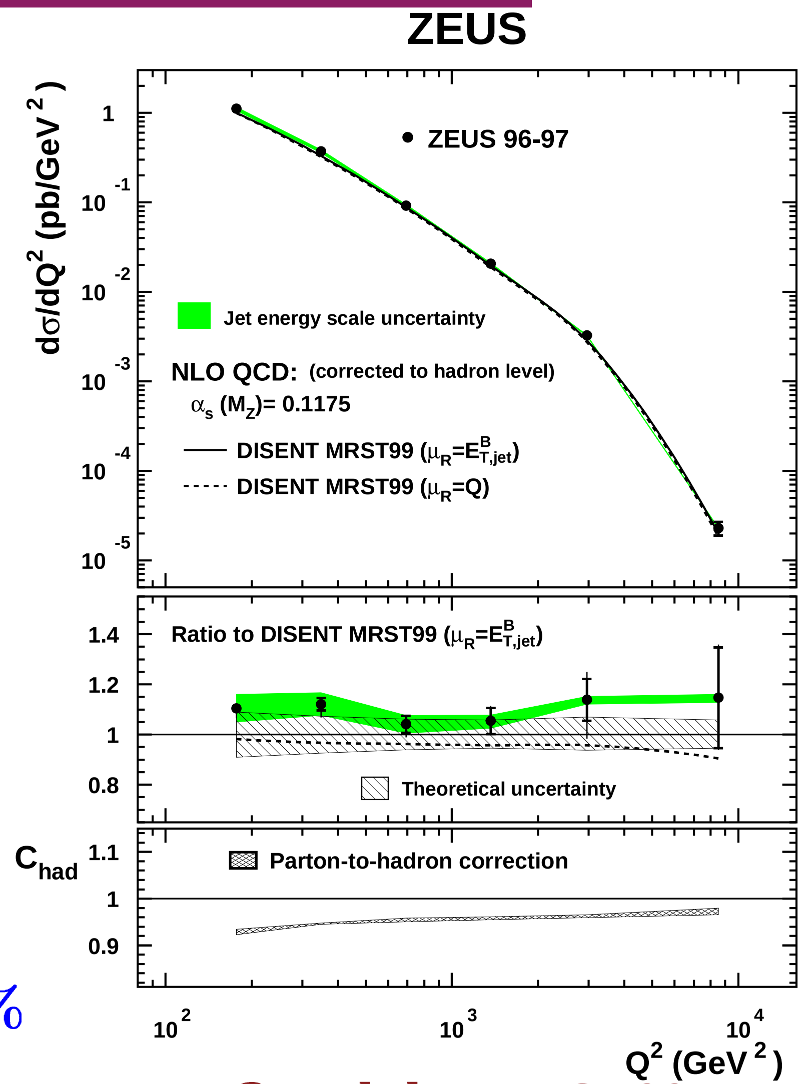
→ **Asymmetric cuts on $E_T^{jet,1(2)}$**

⇒ **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

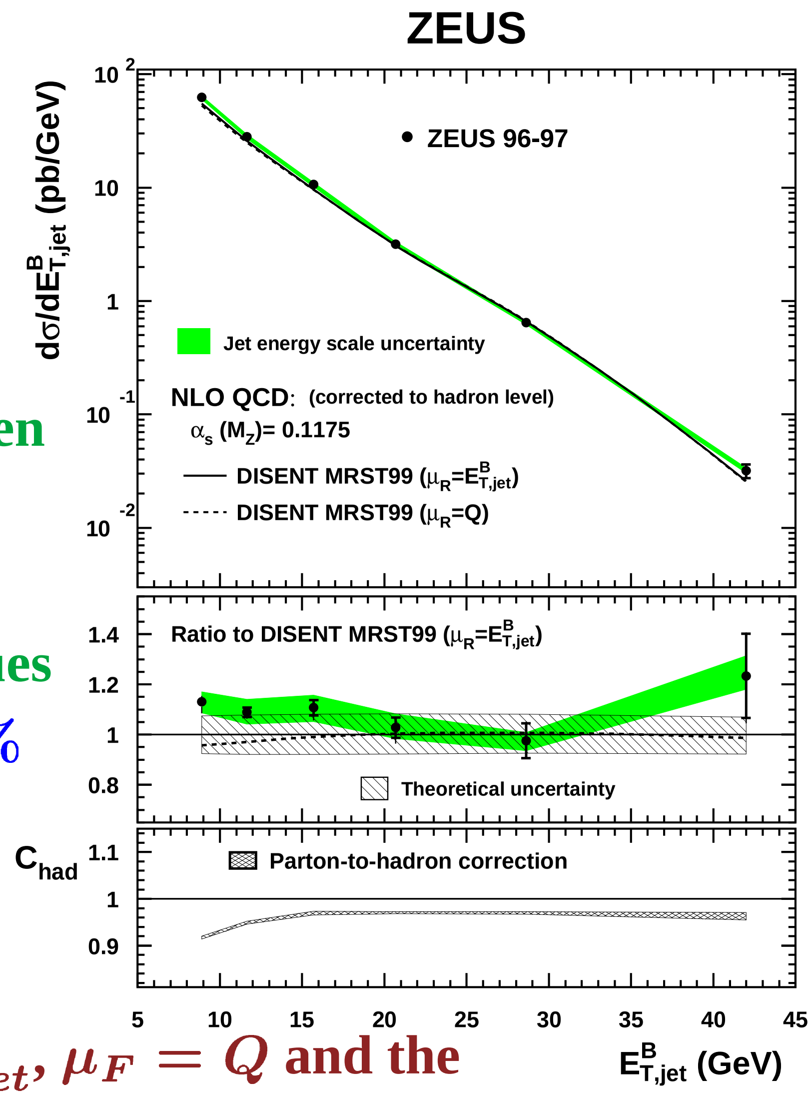
- Measurement of inclusive jet cross sections in the kinematic region defined by $Q^2 > 125$ GeV^2 and $-0.7 < \cos\gamma < 0.5$ for jets with
  $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.8$
  $\rightarrow$ no cut is applied in the laboratory frame
- Advantages:
  $\rightarrow$ infrared insensitivity (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:
  - → higher-order terms (> NLO); varying μ_R between $\frac{1}{2} \cdot E^B_{T,jet}$ and $2 \cdot E^B_{T,jet} \Rightarrow \pm 5\%$
  - → uncertainty on $\alpha_s(M_Z)$ (± 0.003); $\Rightarrow \pm 5\%$
  - → hadronisation corrections; variance of C_{had} values (ARIADNE, LEPTO-MEPS, HERWIG) $\Rightarrow < 1\%$
  - → uncertainties on the proton PDFs
    - experimental uncertainties $\Rightarrow \pm 3\%$
    - theoretical assumptions $\Rightarrow \pm 3\%$



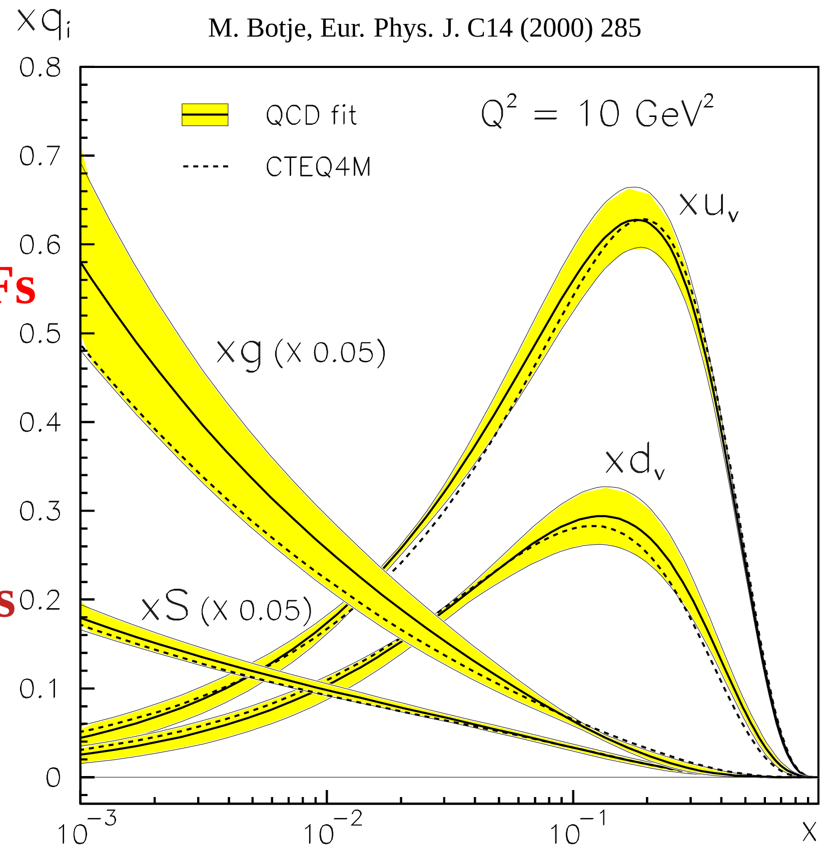
- NLO QCD calculations ($\mathcal{O}(\alpha_s^2)$) using $\mu_R = E^B_{T,jet}$, $\mu_F = Q$ and the MRST99 parametrisations of the proton PDFs describe the measurements well

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

→ the statistical and correlated systematic uncertainties of each data set used in the determination of the PDFs

→ the theoretical uncertainties affecting the extraction of the PDFs in the DGLAP fits

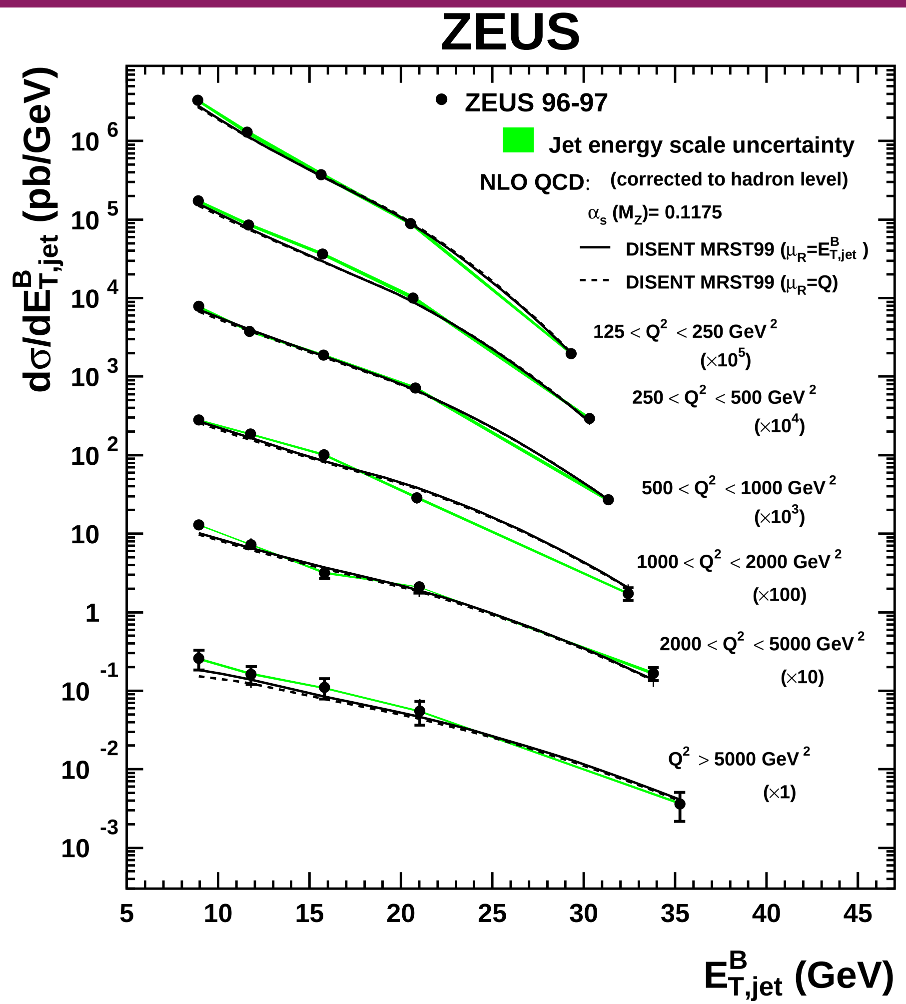


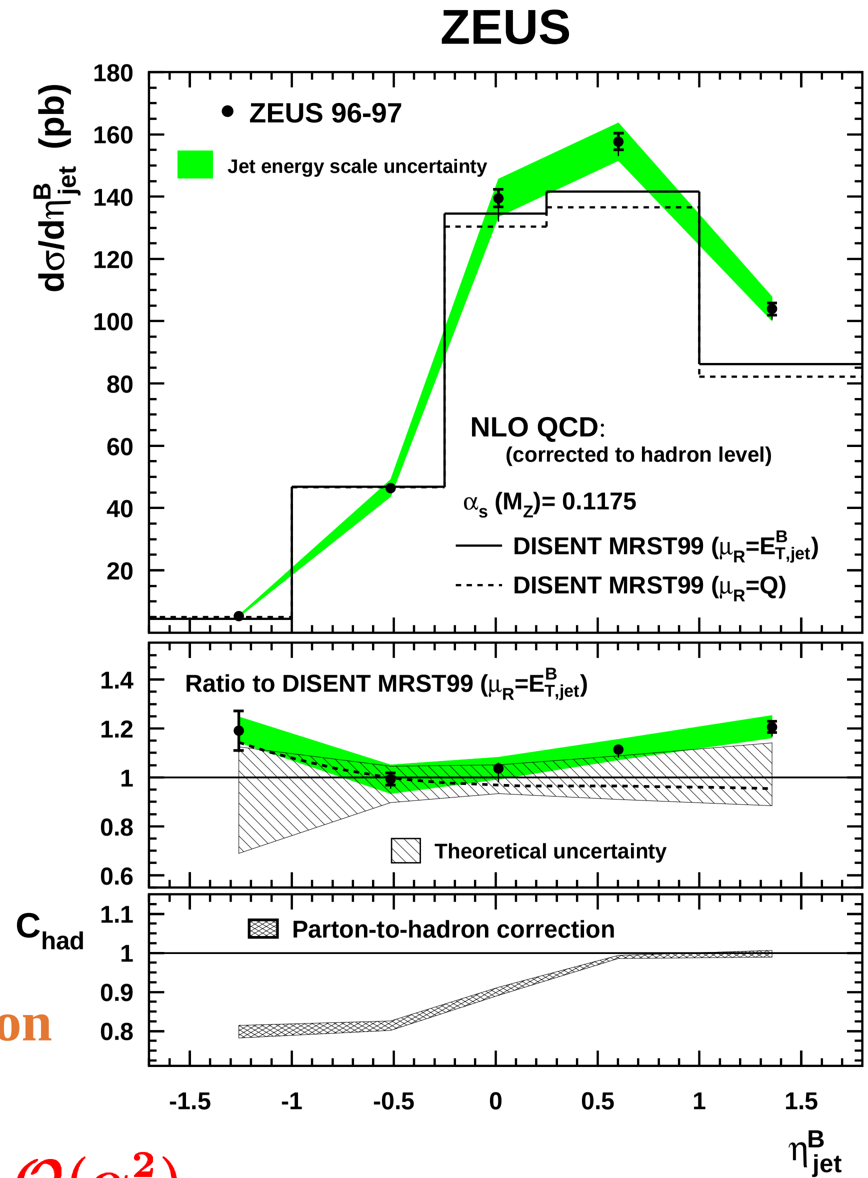
- Botje's analysis provides the covariance matrix (V_{p_μ,p_λ}) of the fitted PDF parameters ($\{p_\lambda\}$), the derivatives as functions of Q^2 and x (e.g. $\partial g(x,Q^2)/\partial p_\lambda$) and several sets obtained under different theoretical assumptions

$\Rightarrow$ 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 $\rightarrow$ validity of the description of the dynamics of inclusive jet production by pQCD at $\mathcal{O}(\alpha_s^2)$

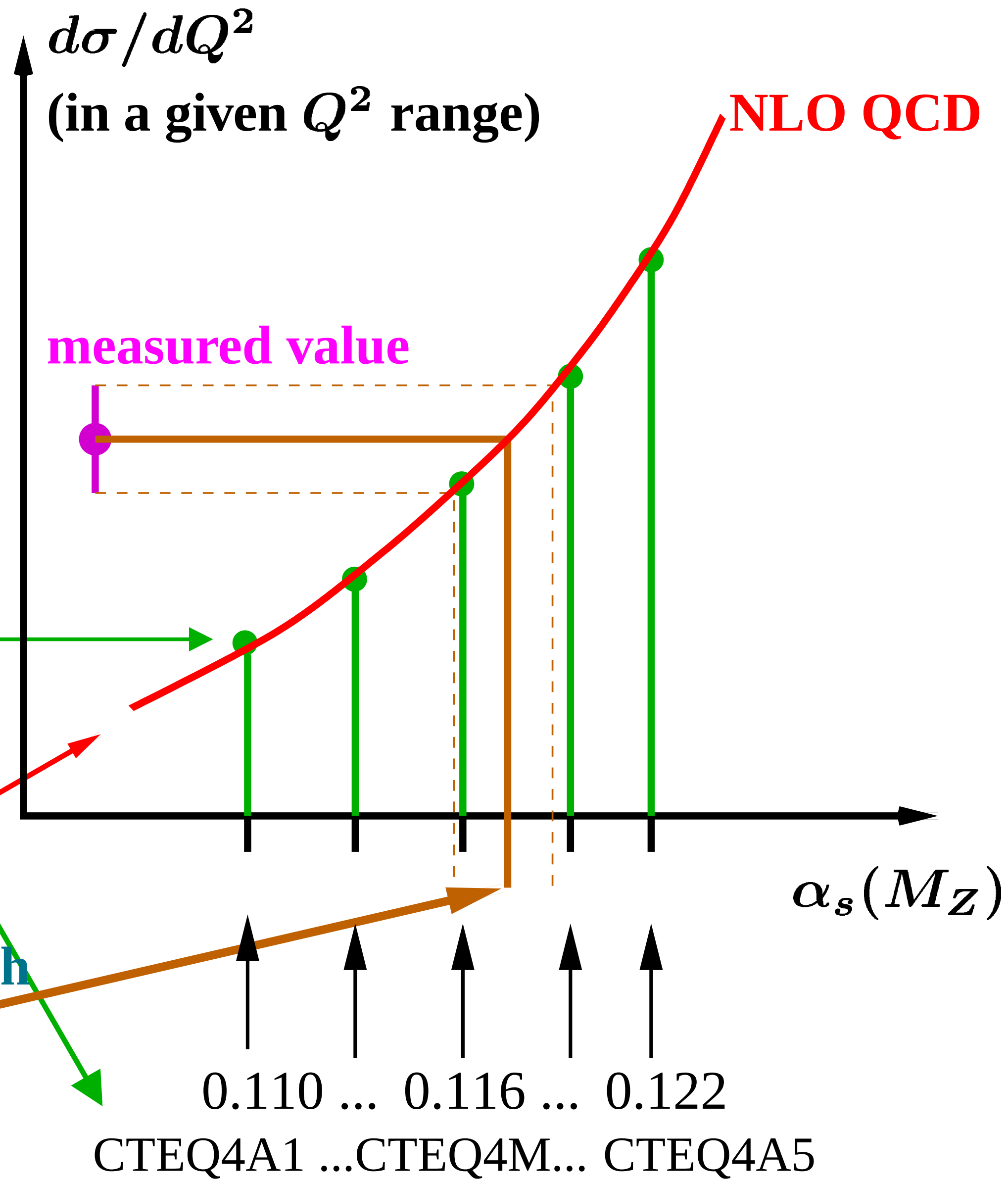
Inclusive Jet Cross Sections and extraction of $\alpha_s(M_Z)$

- 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:

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

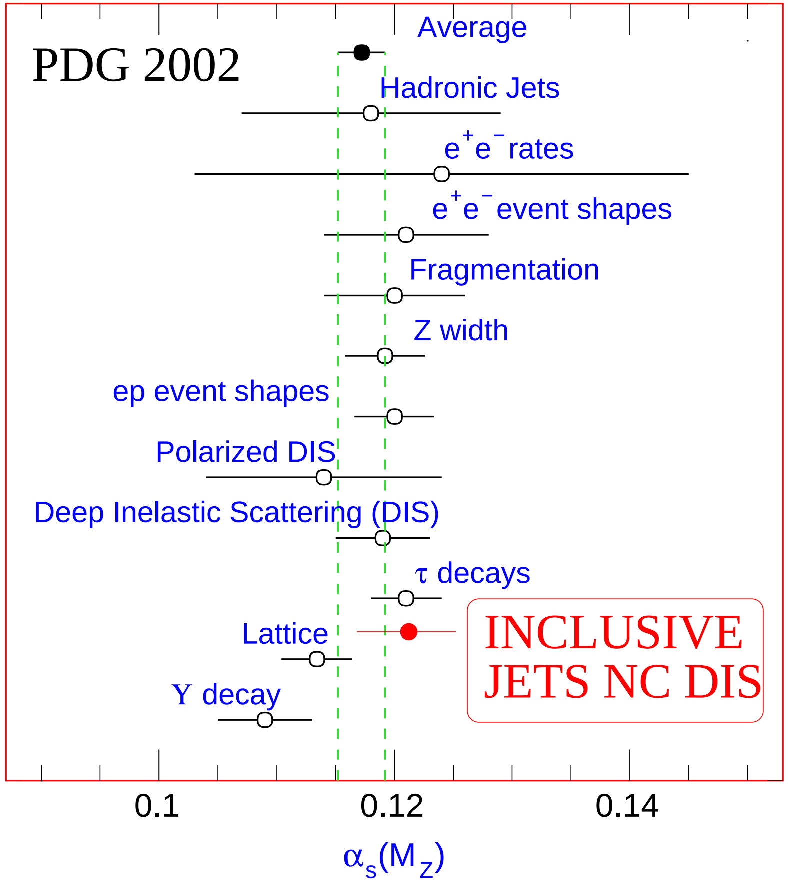
- Theoretical uncertainties:

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

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

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

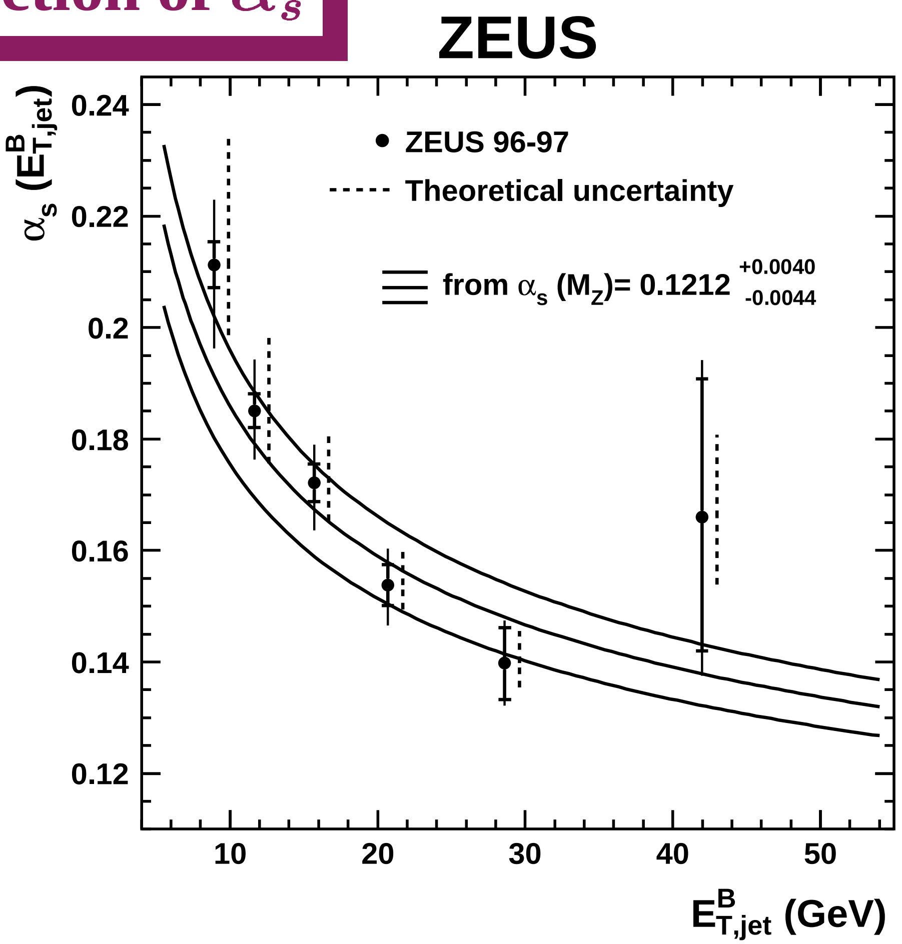
- Consistent with other determinations of α_s and PDG
- Very precise determination of $\alpha_s(M_Z)$!

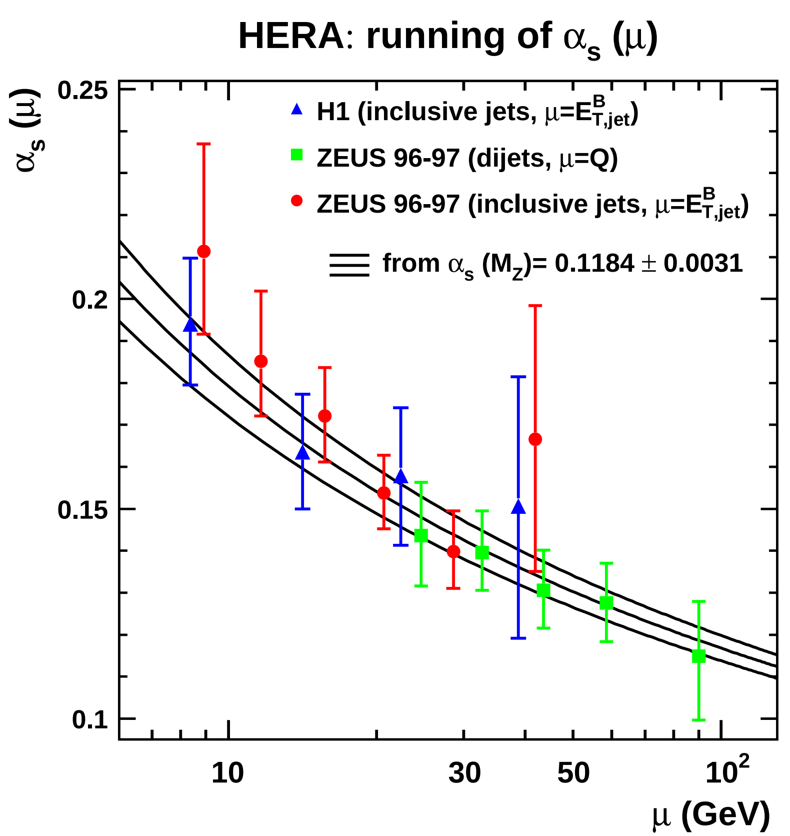


Further improvement depends upon further Experimental and Theoretical Work

Inclusive Jet Cross Sections and extraction of α_s

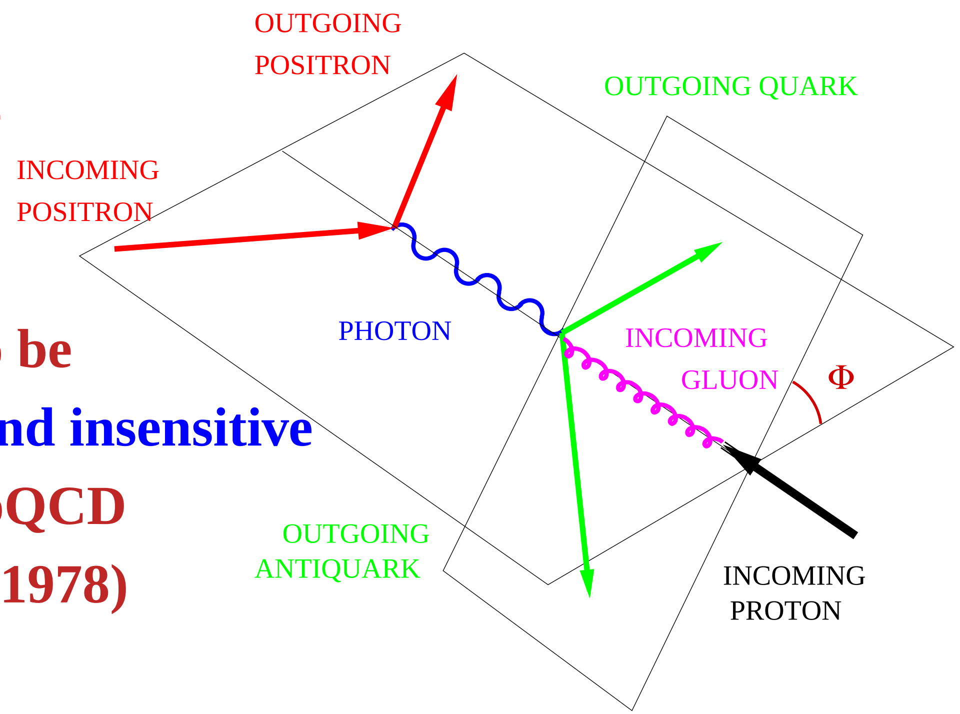
- Study of the scale dependence of $\alpha_s(E^B_{T,jet})$: from the measured $d\sigma/dE^B_{T,jet}$ in each $E^B_{T,jet}$ region $\rightarrow \alpha_s(< E^B_{T,jet} >)$ is extracted
- The measurements are consistent with the running of α_s predicted by perturbative QCD



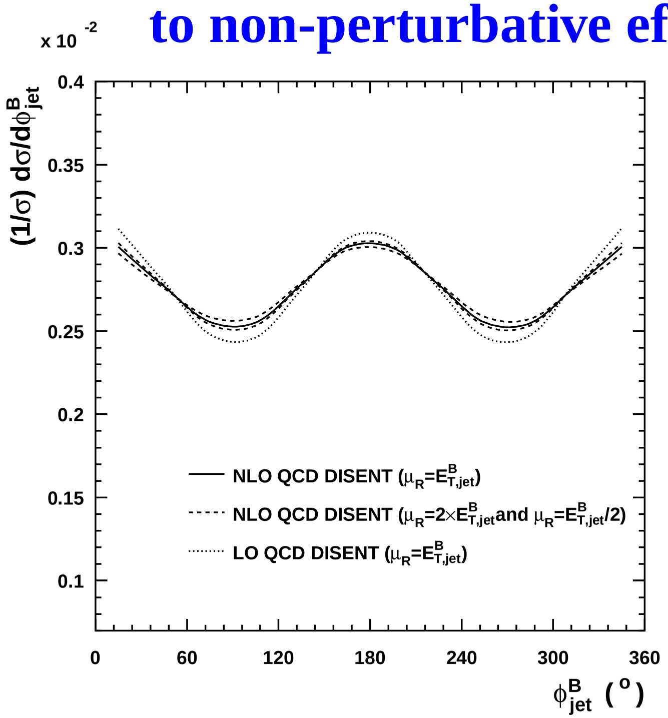


Compilation of H1 and ZEUS determinations of $\alpha_s(\mu)$ using measurements of jet production in NC DIS
$\Rightarrow$ test of the scale dependence of $\alpha_s(\mu)$ between $\mu = 8.4$ GeV and 90 GeV

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 ⇒ clean test of pQCD (Georgi and Politzer, 1978)**



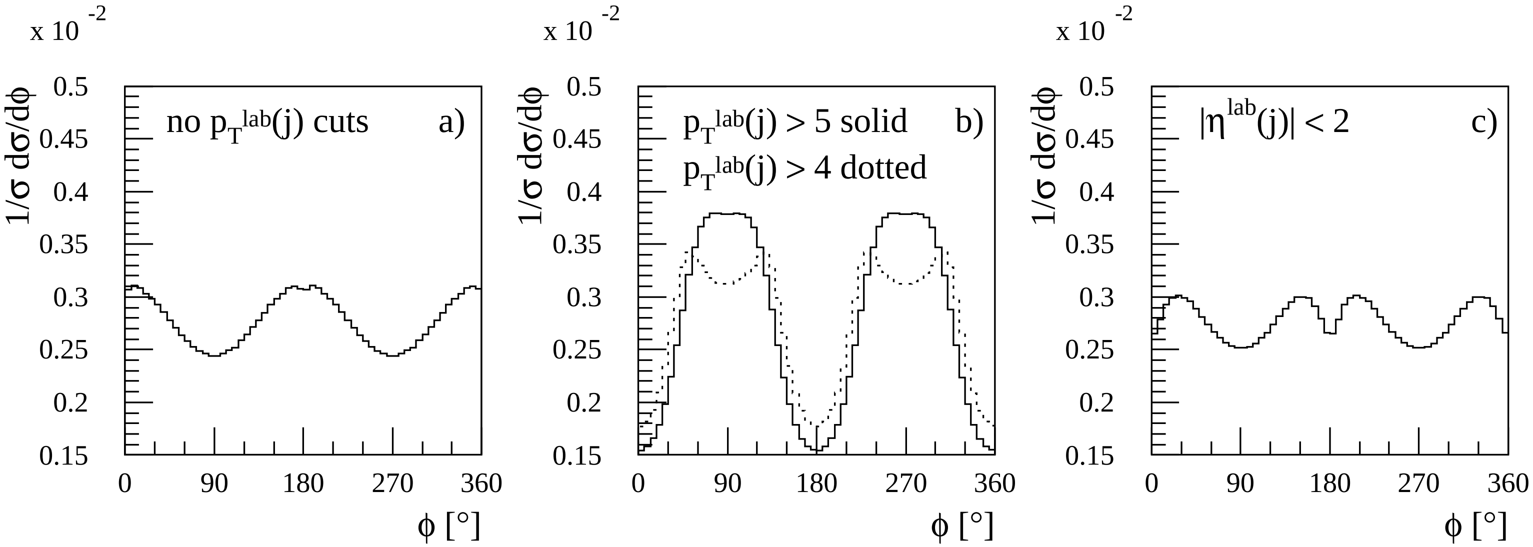
- **LO pQCD prediction for unpolarised NC DIS at $Q^2 \ll M_Z^2$**

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

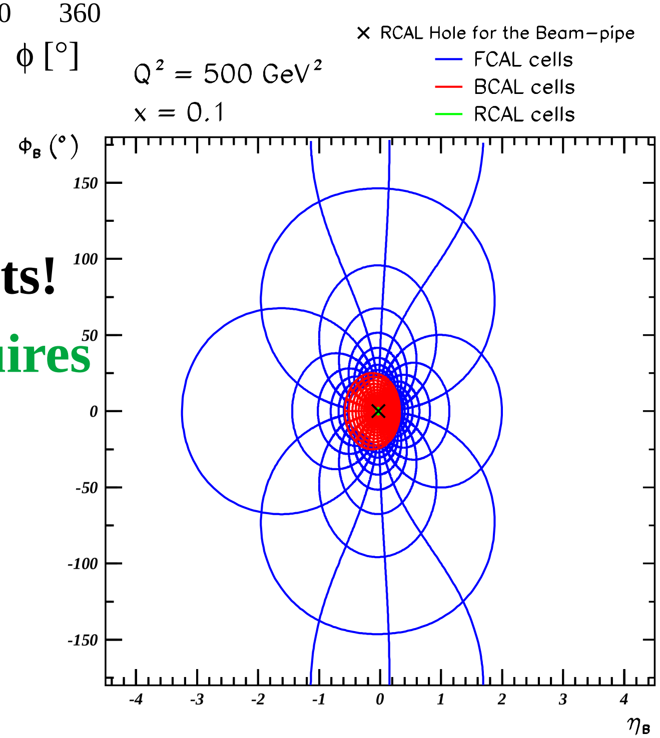
In $\gamma^* q \to qg$ the outgoing $g(q)$ preferentially appears at $\phi = 0(\pi)$; in $\gamma^* g \to q\bar{q}$ the ϕ dependence is dominated by the $\cos 2\phi$ term. For an inclusive jet measurement

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

Azimuthal Distribution of Jets in NC DIS



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

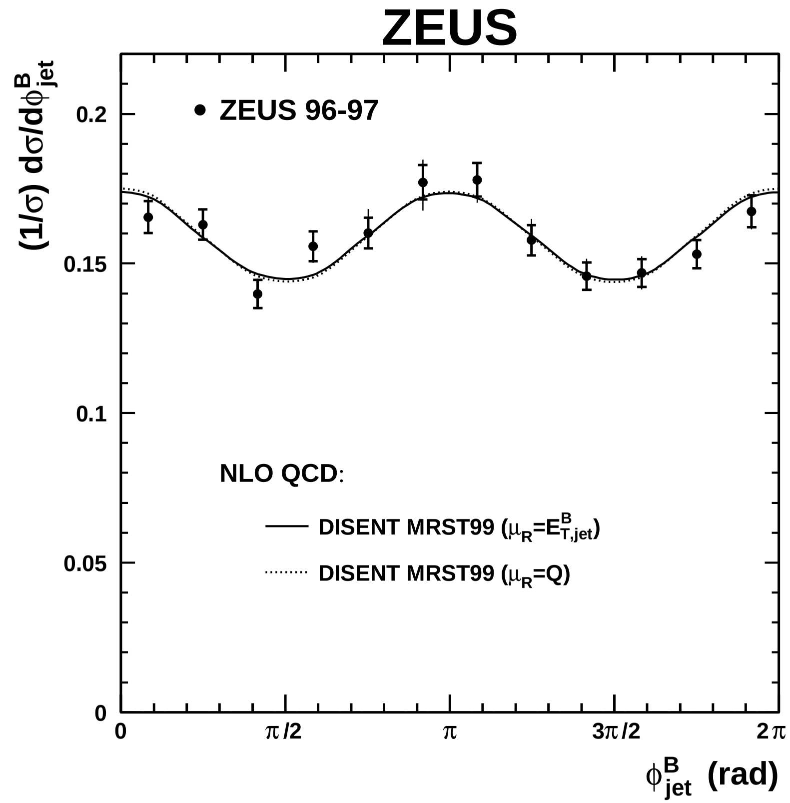


- **In the presence of cuts on the jets in the laboratory frame, e.g. $E_{T,jet}$(Lab)> 5 GeV or $|\eta_{jet}$(Lab)$| < 2$**

⇒ 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 $\Rightarrow \pm 1\%$ 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

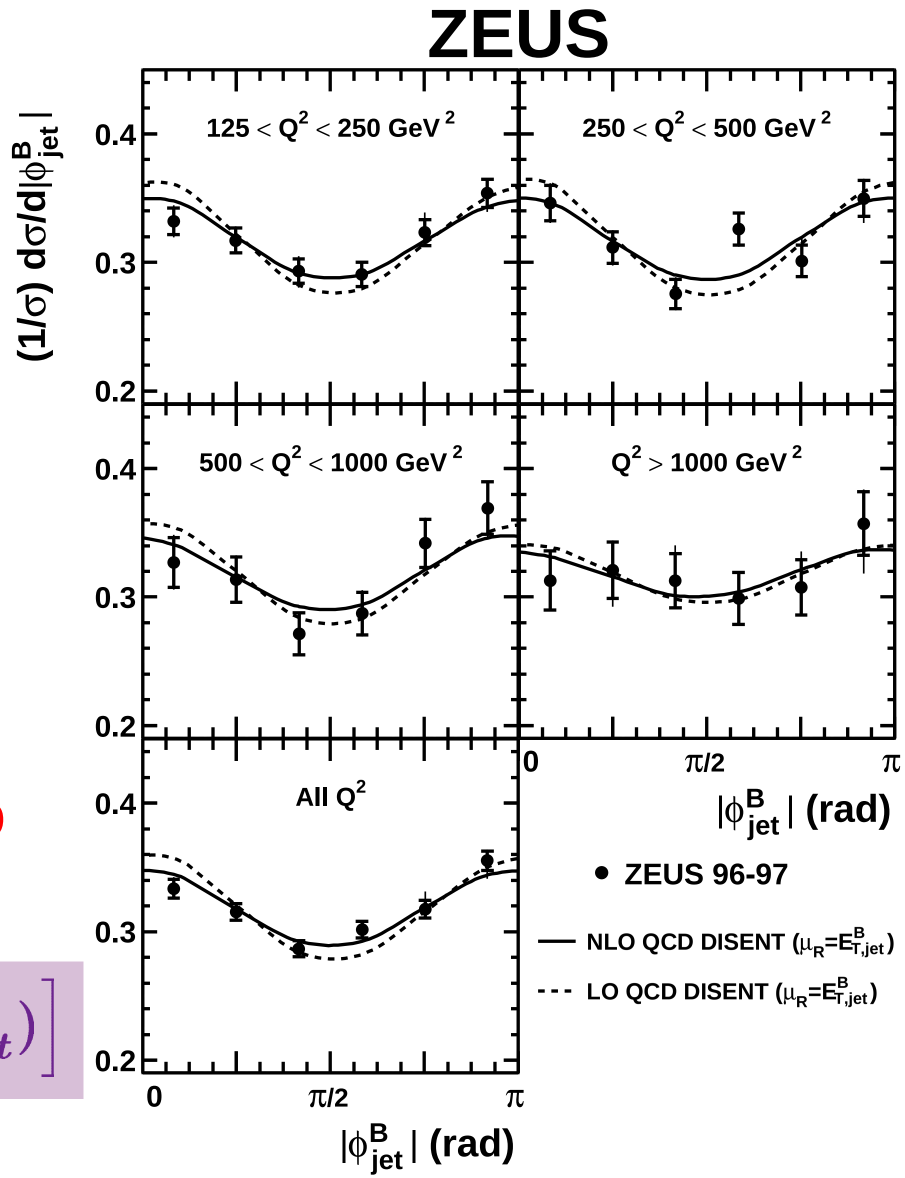
- NLO QCD calculations ($\mathcal{O}(\alpha_s^2)$) using $\mu_R = E^B_{T,jet}$ (or $\mu_R = Q$), $\mu_F = Q$ and the MRST99 parametrisations of the proton PDFs describe the measurements very well

$\Rightarrow$ 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)**

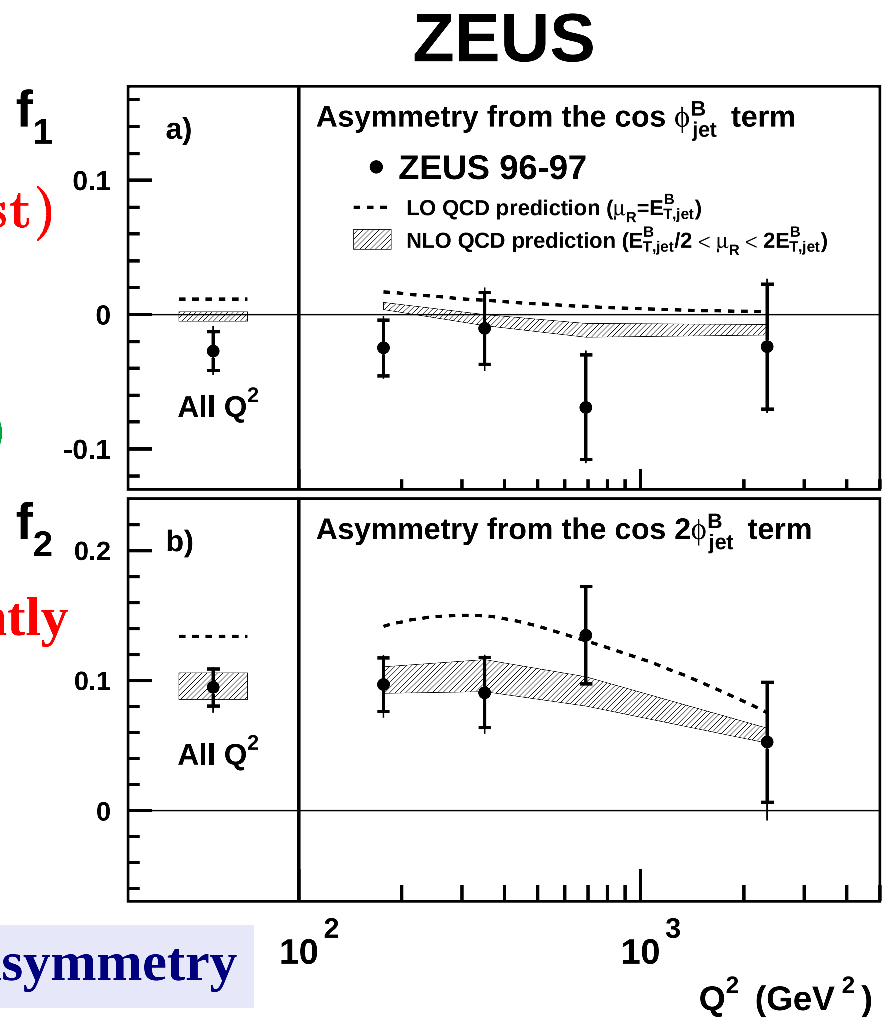
f_1(Data)$= -0.0273 \pm 0.0144(\mathrm{stat})^{+0.0121}_{-0.0099}(\mathrm{syst})$

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

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

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

- **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)

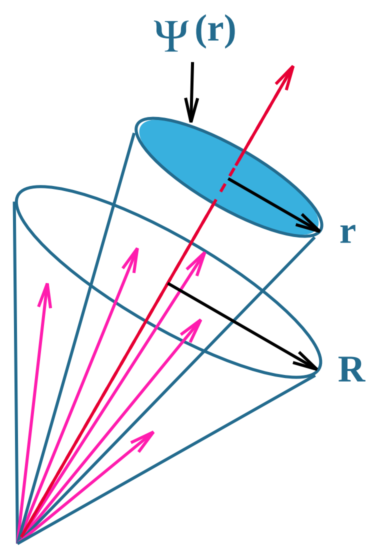
$\rightarrow$ $\mathcal{O}(\alpha_s)$ calculations give the lowest non-trivial order contribution (2 partons in a jet)

$\rightarrow$ 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

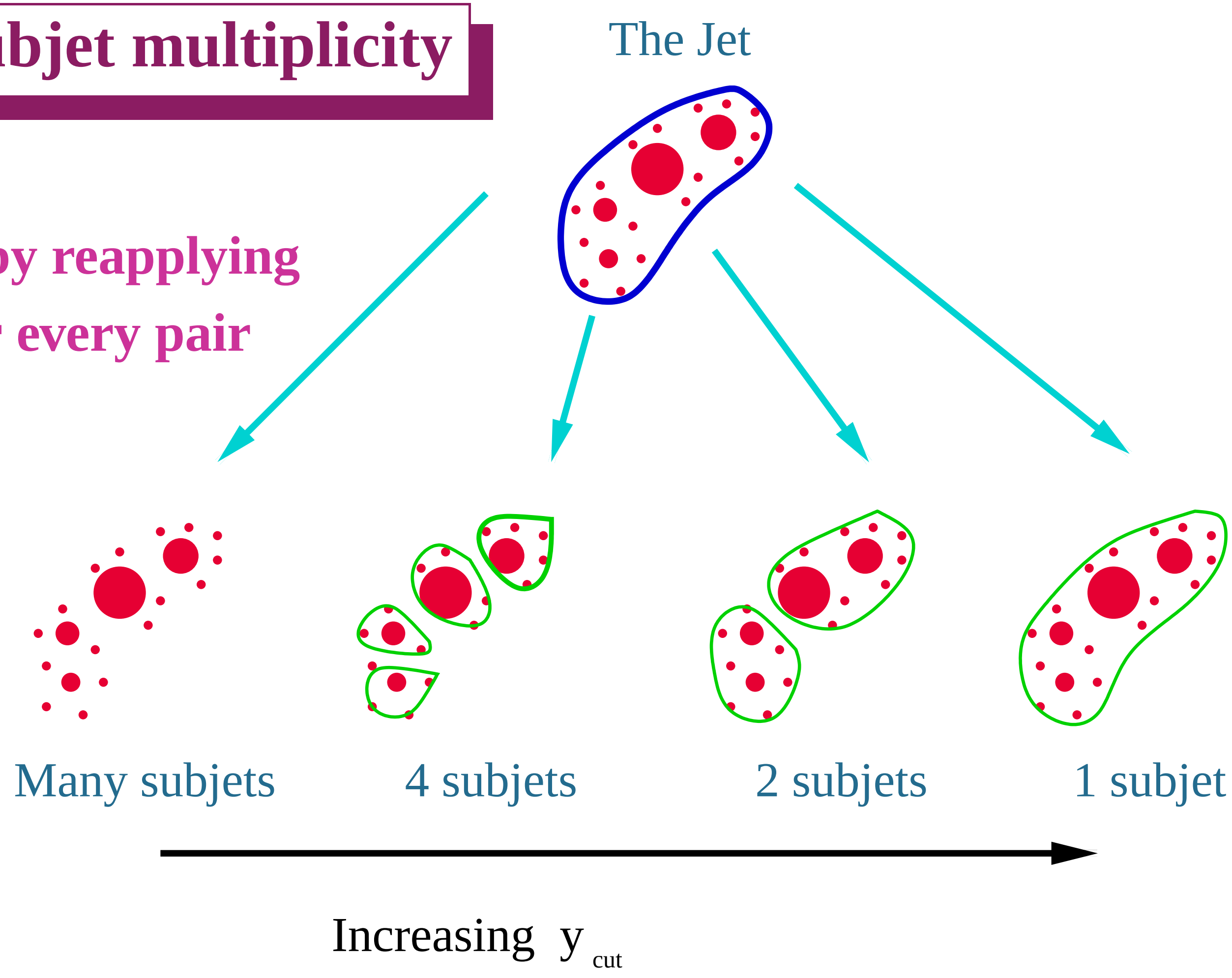
$$\langle\Psi(r)\rangle = \frac{1}{N_{jets}} \sum_{jets} \frac{E_T(r)}{E_T(r=1)}$$



Jet Substructure: the subjet multiplicity

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

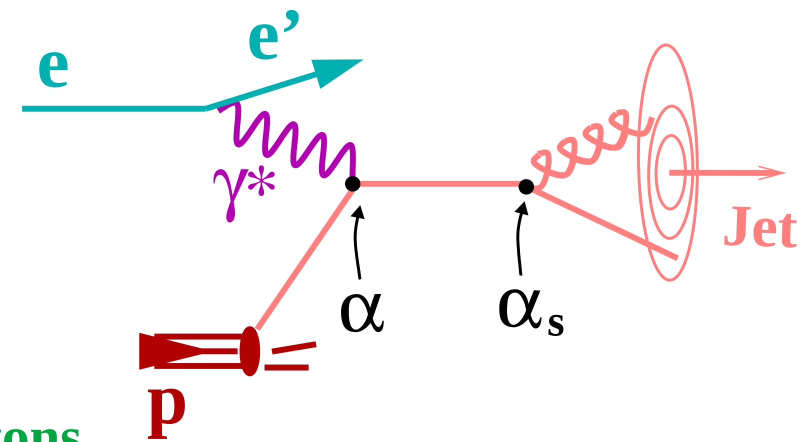
Subjets are resolved within a jet by reapplying the k_T-cluster algorithm until for every pair of particles the quantity d_{ij} is above $y_{cut} \cdot (E_T^{jet})^2$.



- **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



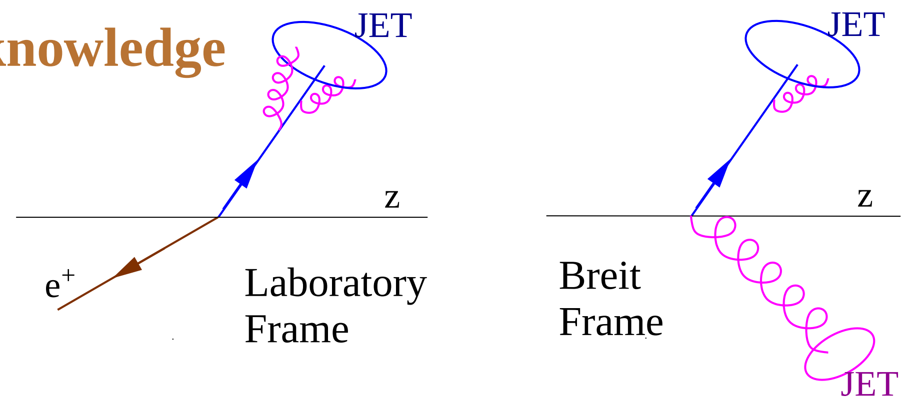
- The lowest non-trivial-order contribution to the measurements is given by $\mathcal{O}(\alpha\alpha_s)$ pQCD calculations

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

- 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:

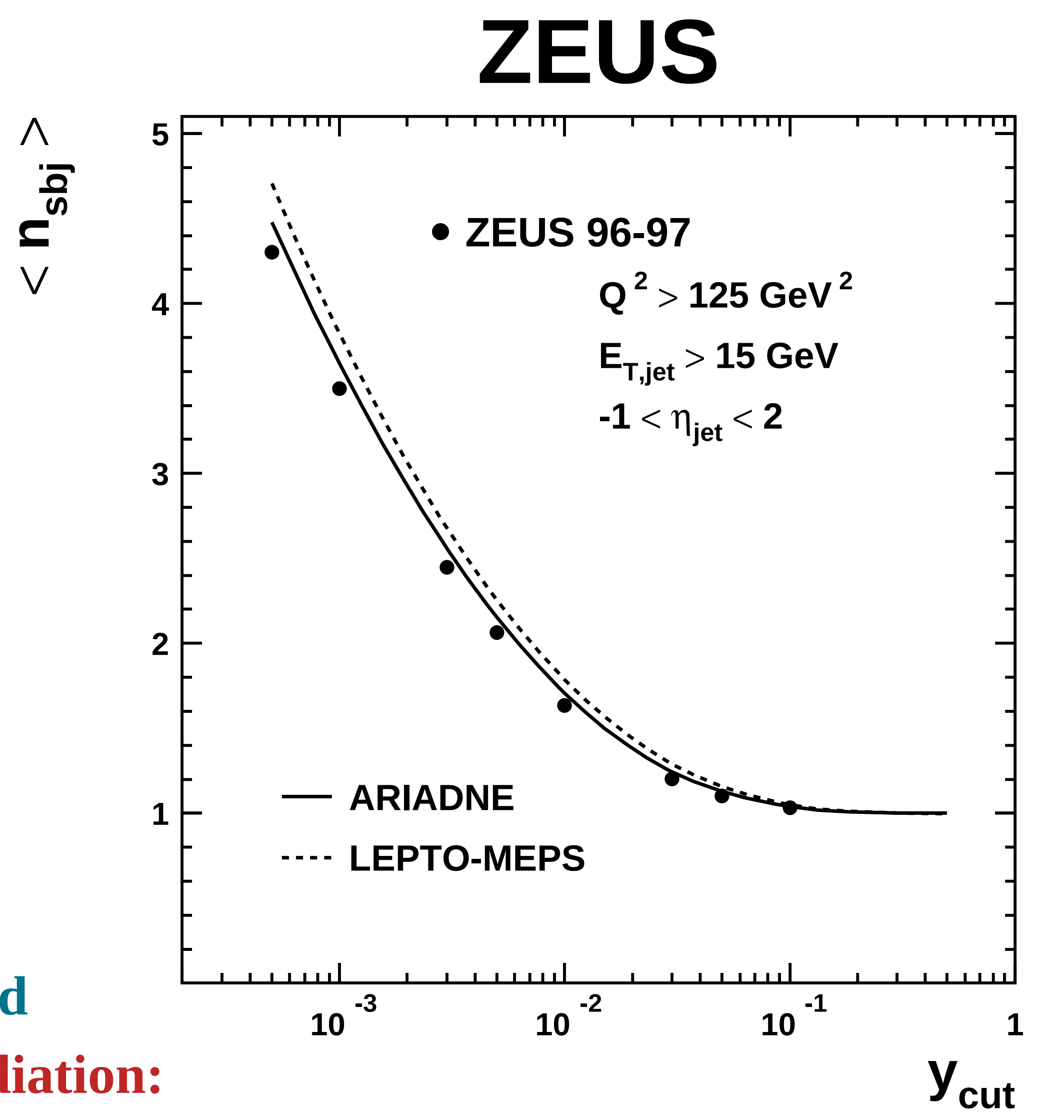
→ a stringent test of pQCD calculations beyond LO

→ 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}:

→ DISENT program (subtraction method)

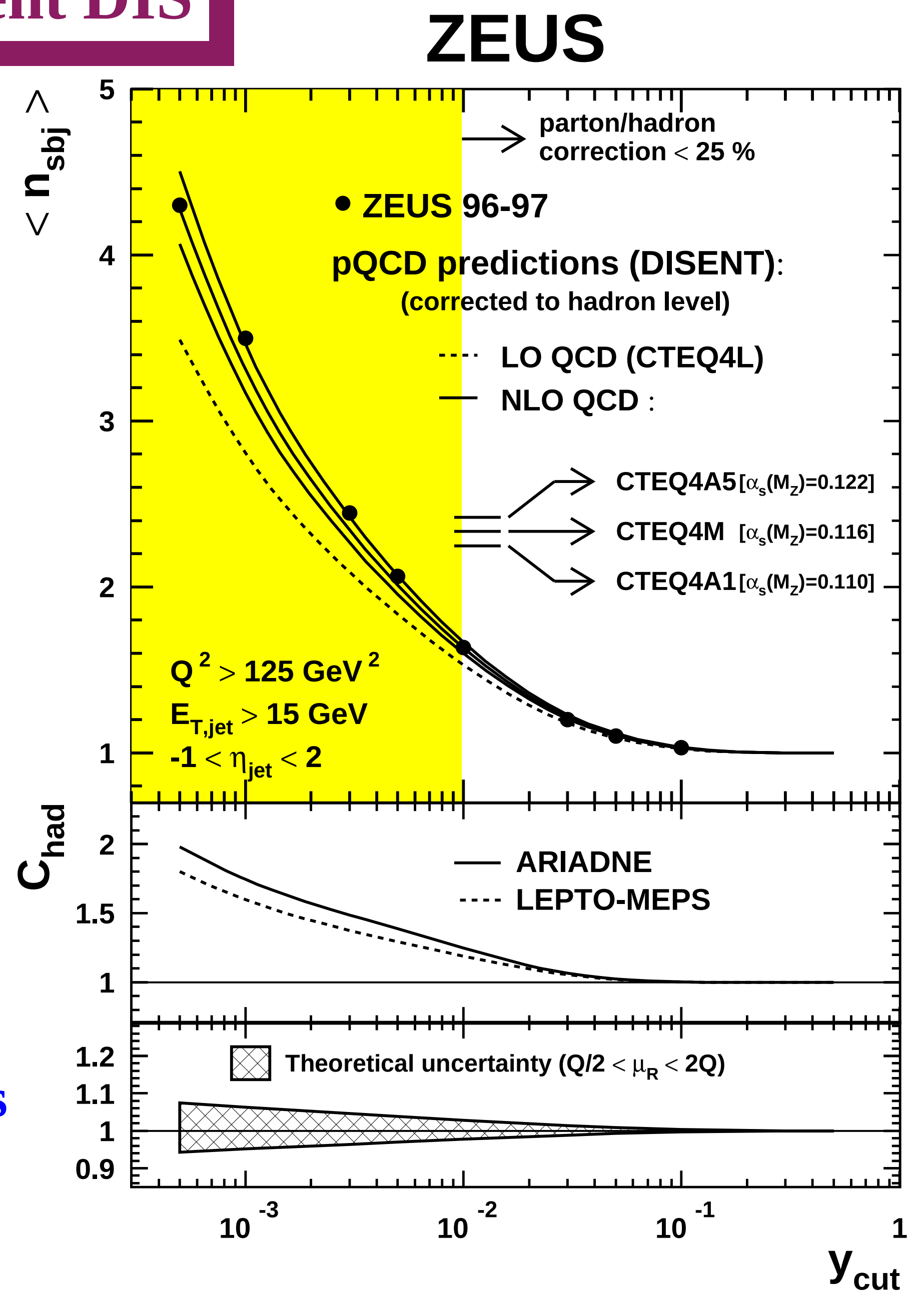
→ up to 3 partons in a jet at $\mathcal{O}(\alpha_s^2)$

→ $\mu_R = \mu_F = Q$

→ 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

→ 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

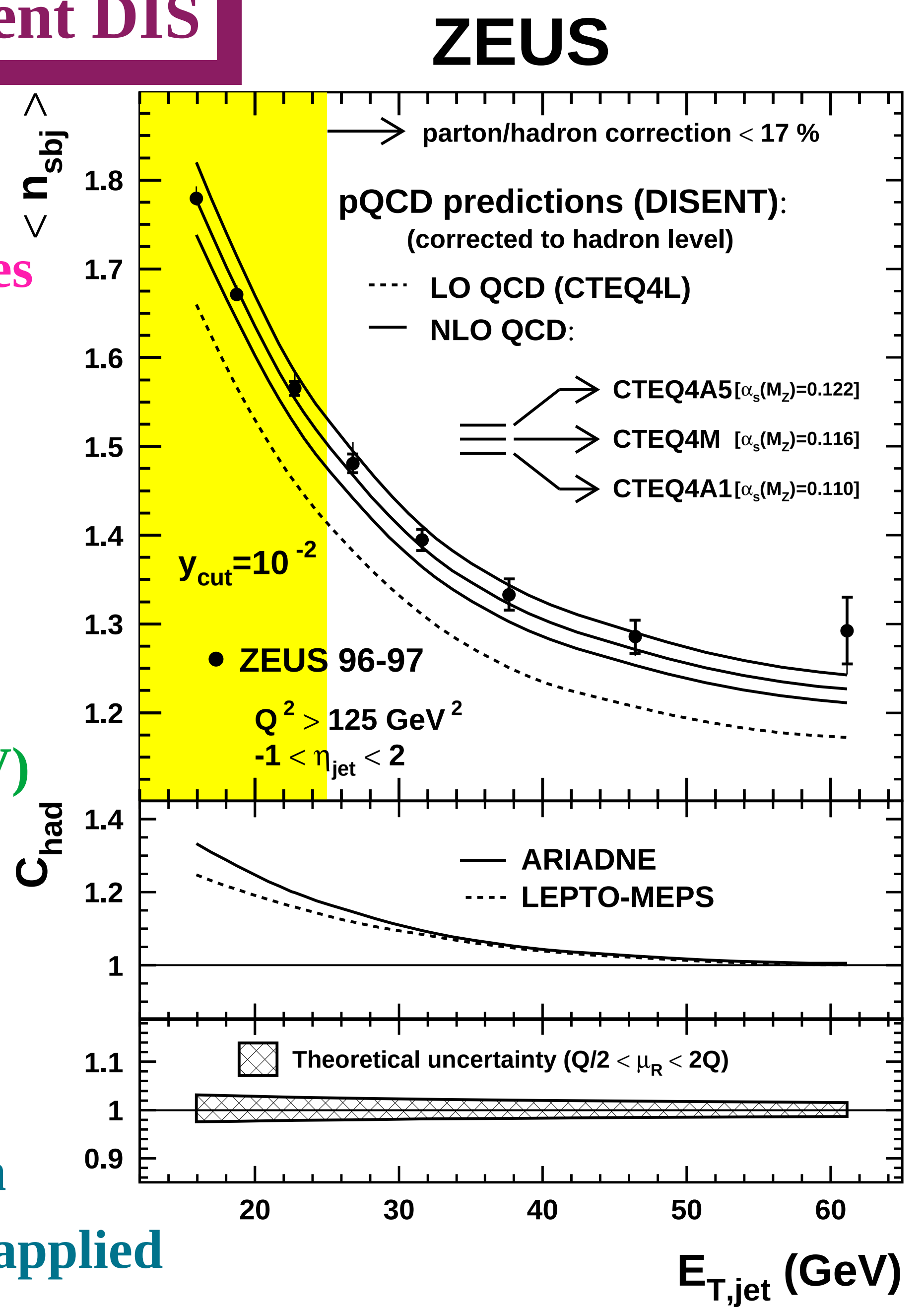
- At a fixed value of $y_{cut} = 10^{-2}$
  $< n_{sbj} >$ decreases as E_T^{jet}(Lab) increases
  $\rightarrow$ the jets become narrower

- 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

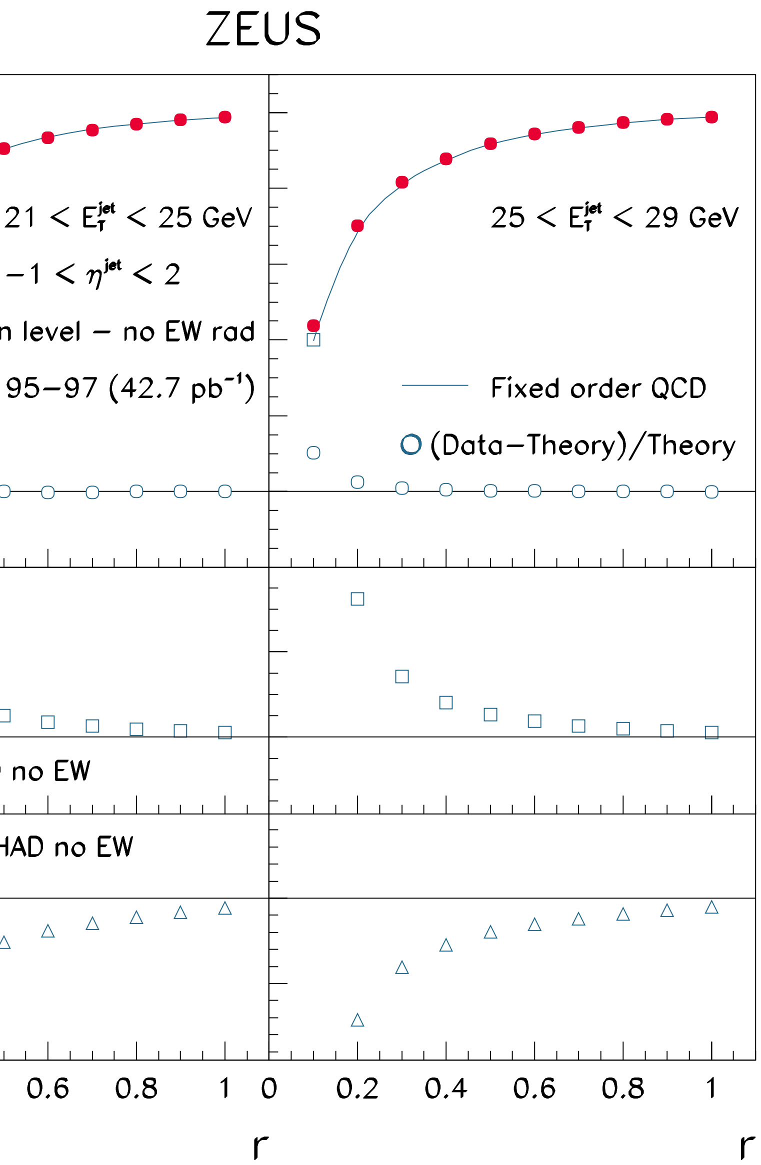
- NLO calculations describe the data well
  $\rightarrow$ sensitivity of the measurements to α_s

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



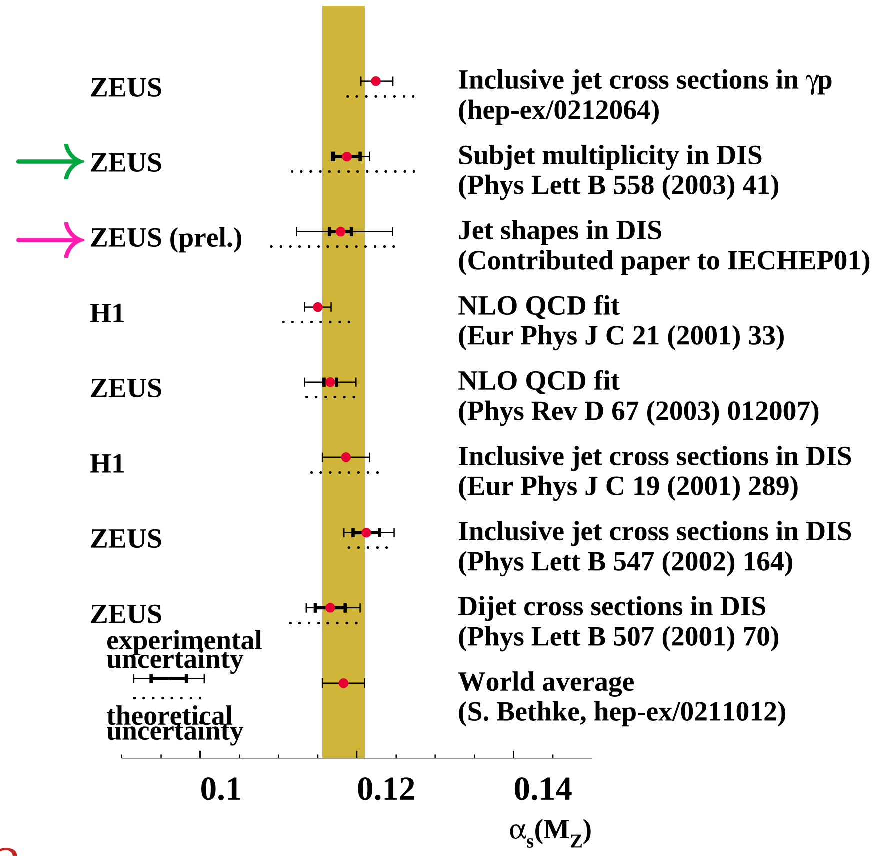
Jet Substructure in Neutral Current DIS ($Q^2 > 125$ GeV^2)

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

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

- The theoretical uncertainties dominate: for n_{sbj}

$\to$ terms beyond NLO $\Delta\alpha_s(M_Z) = ^{+0.0089}_{-0.0071}$

$\to$ parton-to-hadron effects $\Delta\alpha_s(M_Z) = \pm 0.0028$

$\to$ 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

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

$\longrightarrow$ 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