Moscow, ICHEP 2006

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Jet cross sections and determination of α_s in ep collisions

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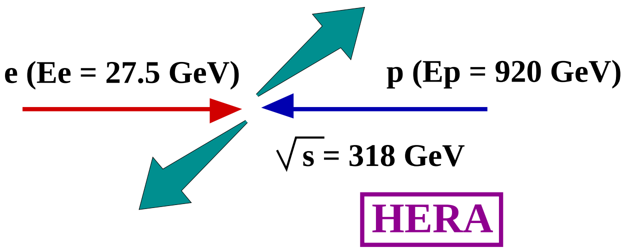
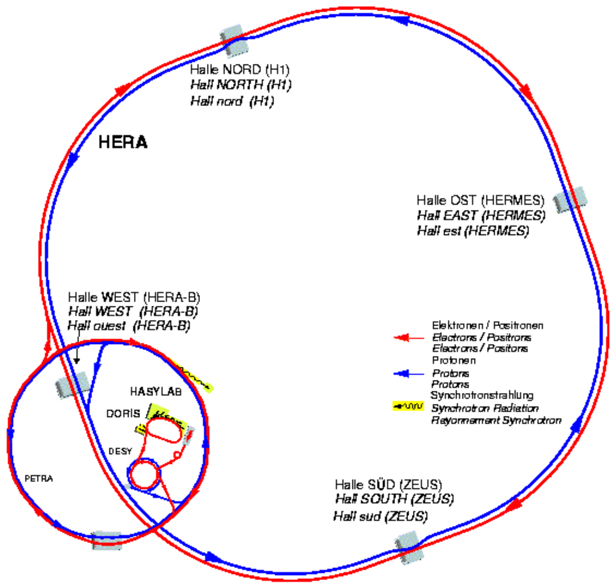
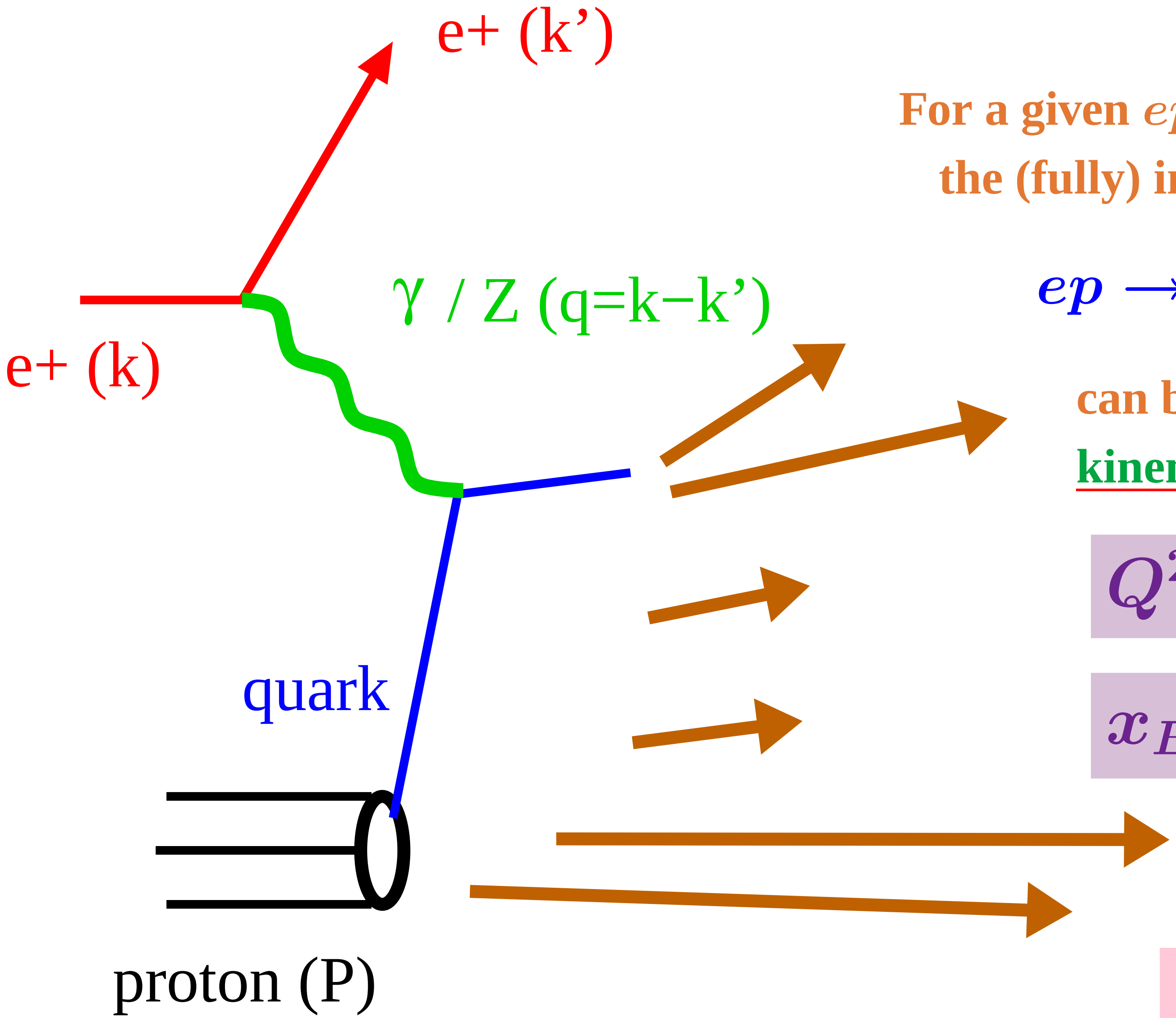




H1 and ZEUS Collaborations

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.

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

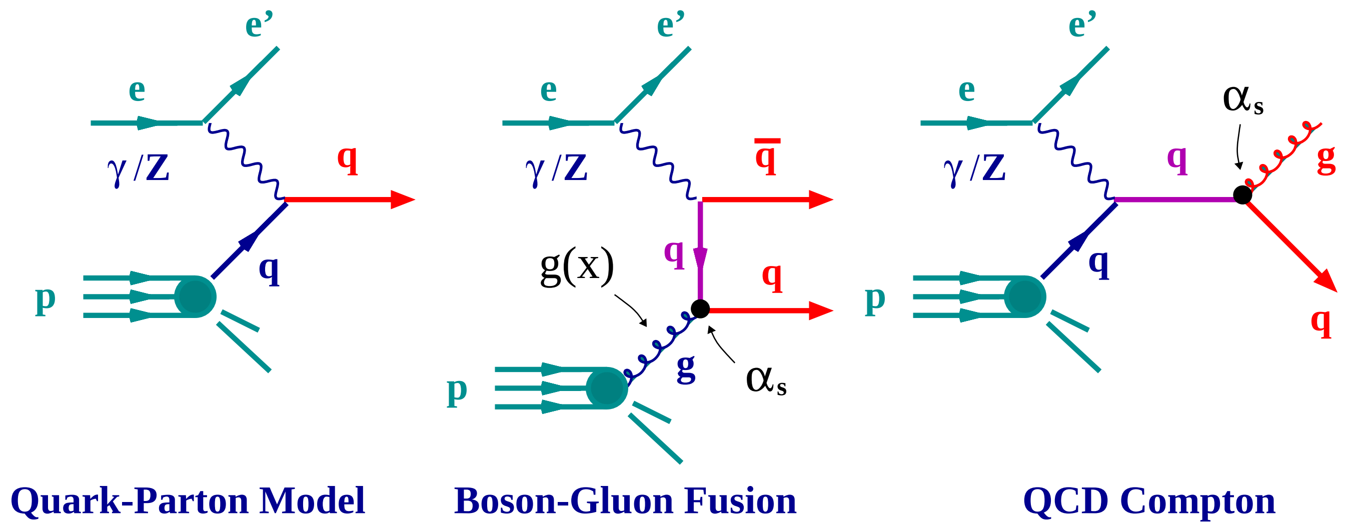
$$x_{Bj} = Q^2/(2P \cdot q)$$

→ Inelasticity variable

$$y = Q^2/(x_{Bj} s)$$

Jet Production in Neutral Current Deep Inelastic Scattering

- **Jet production in neutral current deep inelastic scattering up to $\mathcal{O}(\alpha_s)$:**



- **Perturbative QCD calculations of jet cross sections:**

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

  – 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

Jet Production in Neutral Current Deep Inelastic Scattering

- In the region where the wealth of data from fixed-target and collider experiments has allowed an accurate determination of the proton PDFs, measurements of jet production in NC DIS provide

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

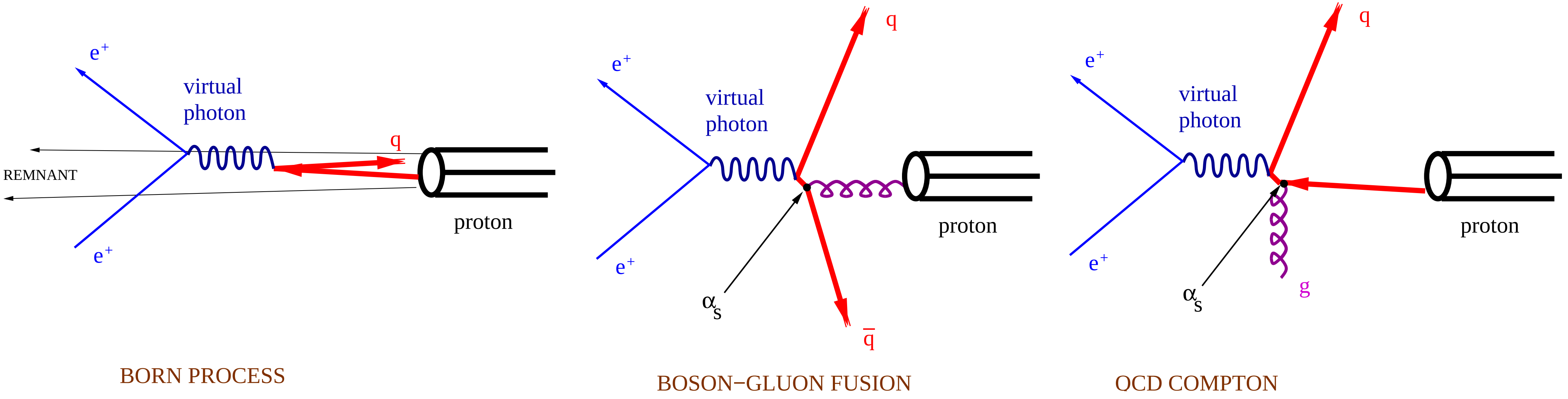
  $\longrightarrow$ a determination of the strong coupling constant α_s

- 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
    - $\longrightarrow$ Jet cross sections in the Breit frame
  - ∗ Small experimental uncertainties $\longrightarrow$ Jets with relatively high transverse energy
  - ∗ Small theoretical uncertainties $\longrightarrow$ NLO QCD calculations

  $\longrightarrow$ Jet algorithm: longitudinally invariant k_T cluster algorithm (Catani et al) (small parton-to-hadron effects, infrared safe, suppression of beam-remnant jet)

  $\longrightarrow$ Jet selection criteria

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)

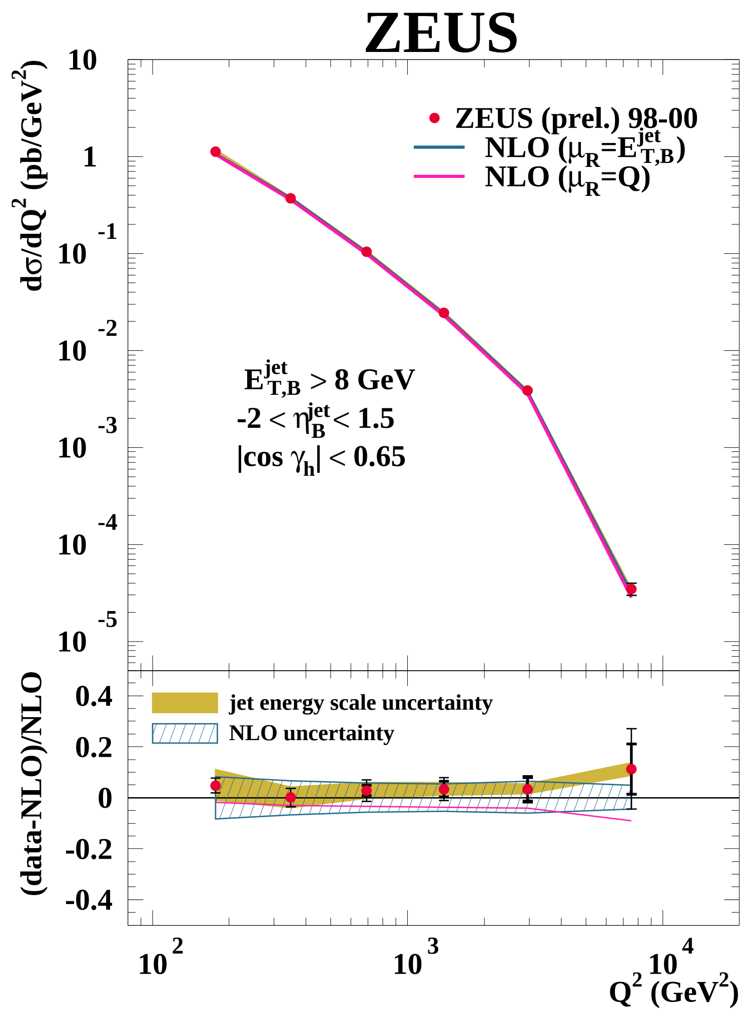
  $\rightarrow$ suppression of the beam-remnant jet (zero E_T)

  $\rightarrow$ 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)

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

- Measurement of the inclusive jet cross sections in the kinematic region defined by $Q^2 > 125$ GeV^2 and $|\cos\gamma| < 0.65$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.5$ using $\mathcal{L} = 81.7$ pb^{-1}
  $\longrightarrow$ no cut is applied in the laboratory frame
- Advantages:
  $\longrightarrow$ infrared insensitivity (no dijet cuts!)
  $\longrightarrow$ suited to test resummed calculations
  $\longrightarrow$ smaller theoretical uncertainties than for dijet
- Small experimental uncertainties:
  $\longrightarrow$ 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}): $< 10\%$



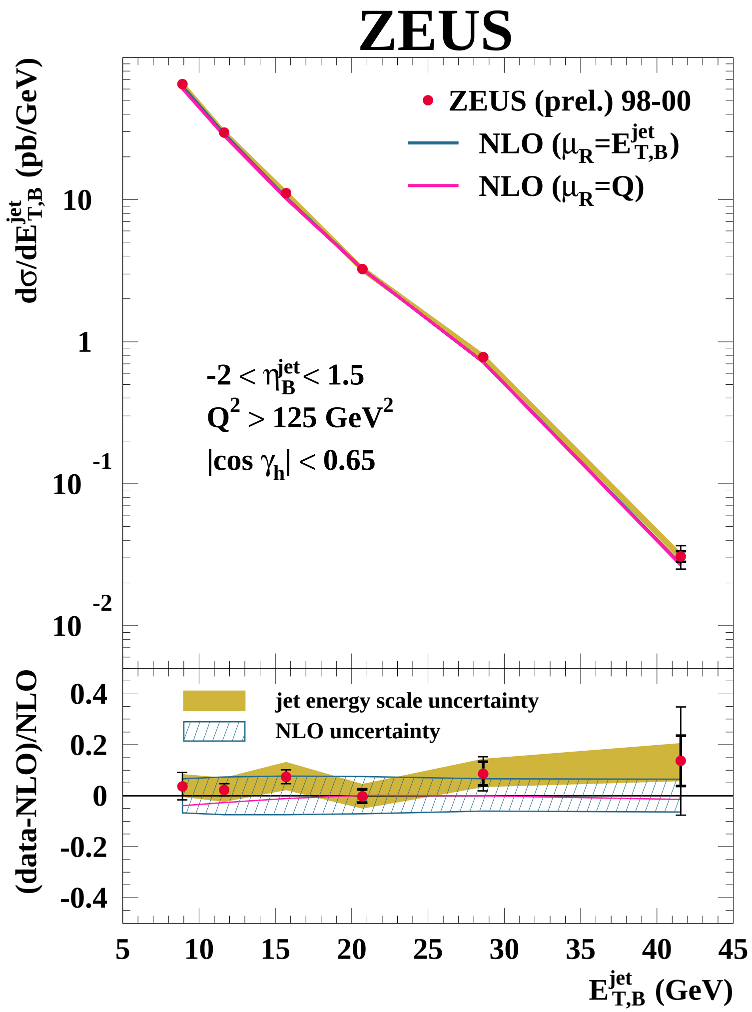
- NLO QCD calculations ($\mathcal{O}(\alpha_s^2)$) using $\mu_R = E^B_{T,jet}$, $\mu_F = Q$ and the MRST99 parametrisations of the proton PDFs describe the measurements well

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 $|\cos\gamma| < 0.65$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.5$**

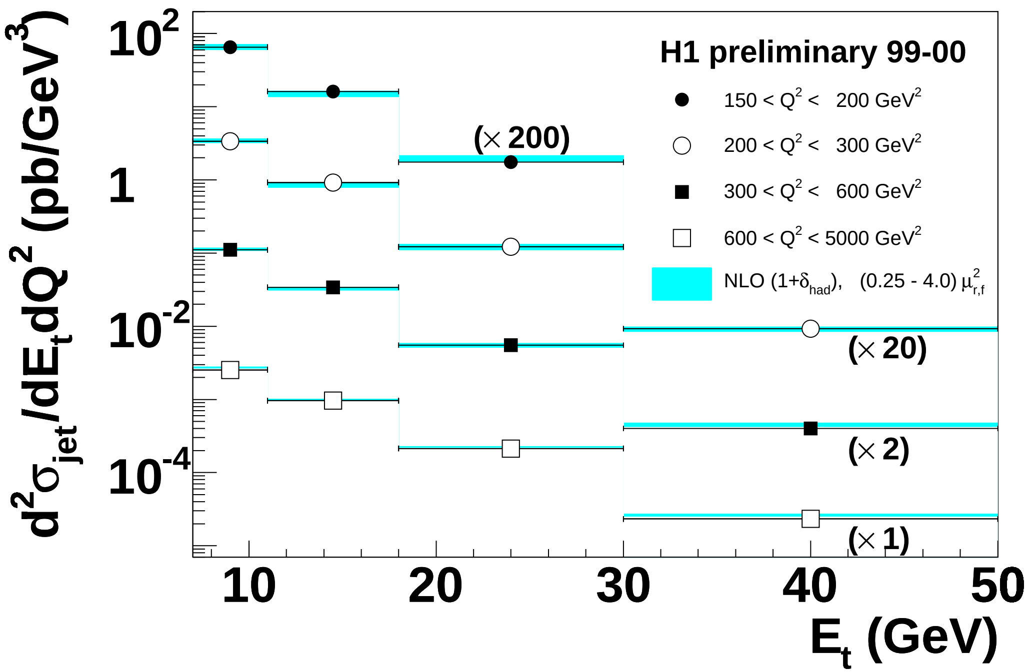
- **Small theoretical uncertainties:**
  - **$\longrightarrow$ higher-order terms ($>$ NLO); varying μ_R between $\frac{1}{2}\cdot E^B_{T,jet}$ and $2\cdot E^B_{T,jet}$ $\Rightarrow \pm5\%$**
  - **$\longrightarrow$ uncertainty on $\alpha_s(M_Z)$ (±0.0027); $\Rightarrow \pm4\%$**
  - **$\longrightarrow$ uncertainties on the proton PDFs; $\Rightarrow \pm3\%$**

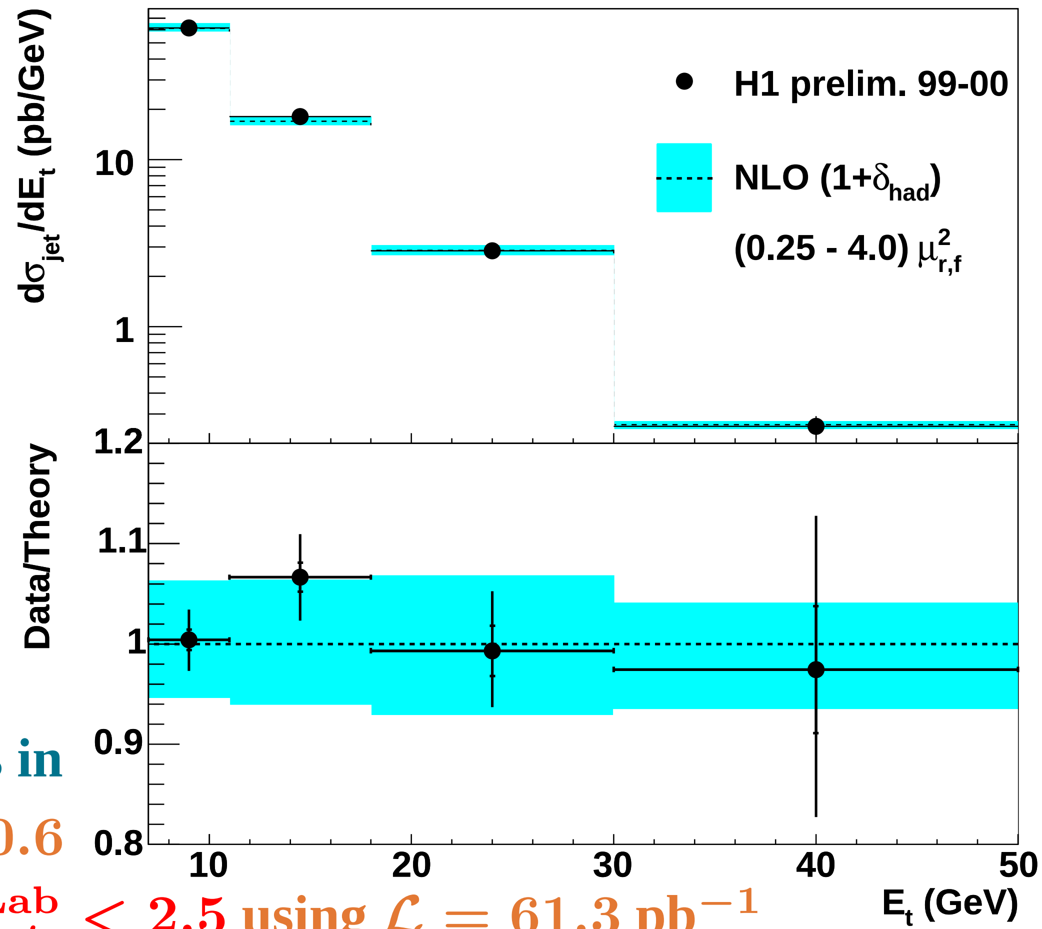
- **NLO QCD calculations provide a good description of the data $\longrightarrow$ validity of the description of the dynamics of inclusive jet production by pQCD at $\mathcal{O}(\alpha_s^2)$**



- **Inclusive jet cross sections in NC DIS in the Breit frame provide <u>direct</u> sensitivity to α_s with <u>small</u> experimental and theoretical uncertainties**

Inclusive Jet Cross Sections in NC DIS at $Q^2 > 150$ GeV^2





- Measurement of inclusive jet cross sections in $150 < Q^2 < 5000$ GeV^2 and $0.2 < y < 0.6$ for jets with $E^B_{T,jet} > 7$ GeV and $-1 < \eta^{\mathrm{Lab}}_{jet} < 2.5$ using $\mathcal{L} = 61.3$ pb^{-1}
- The data are well described by NLO QCD calculations (CTEQ5M1) corrected for hadronisation ($< 10\%$) within small theoretical uncertainties (only $\mu_{r,f}$ shown) and small experimental uncertainties ($\sim 5\%$, hadronic energy scale)

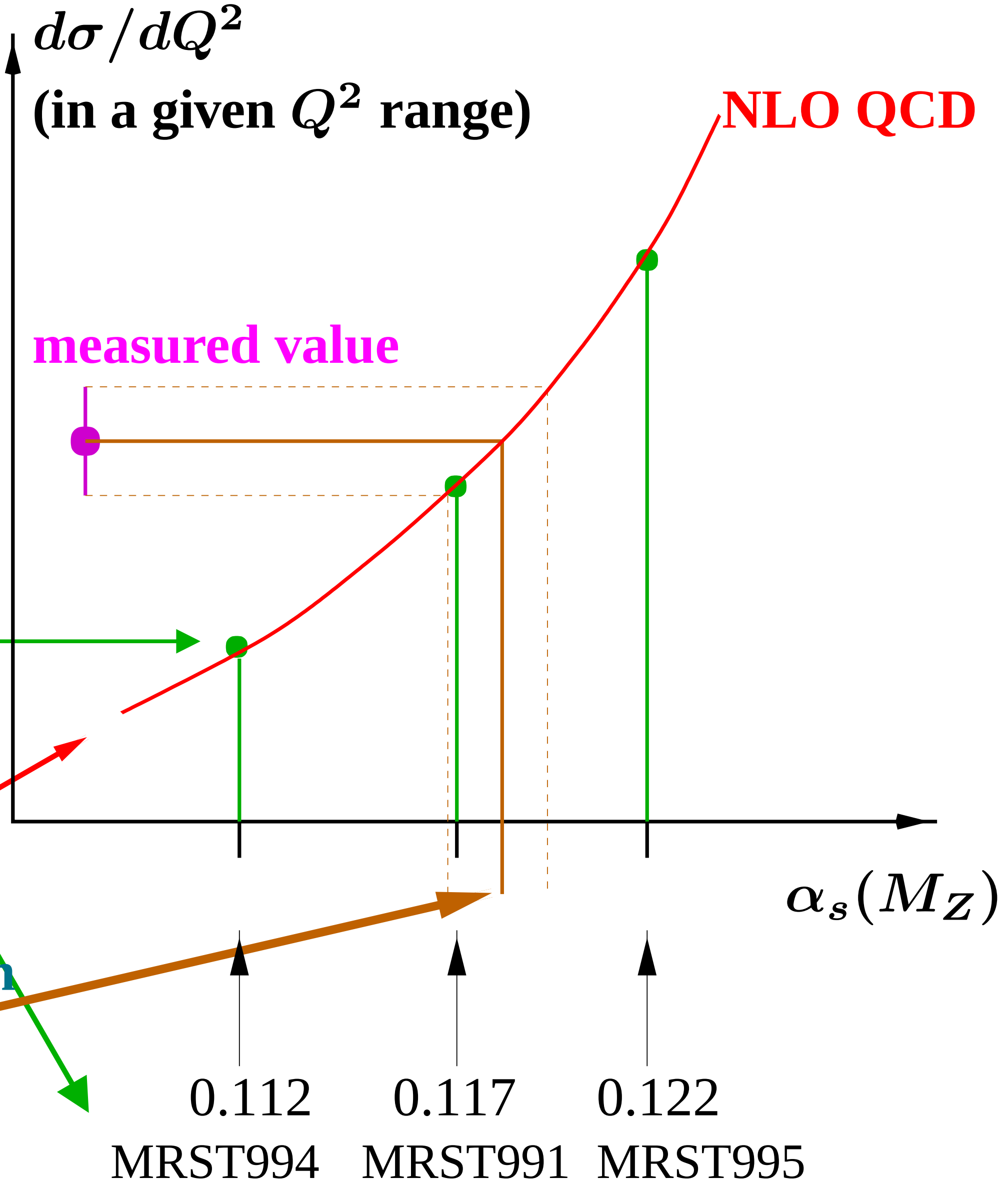
Inclusive Jet Cross Sections and extraction of $\alpha_s(M_Z)$

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

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

$\longrightarrow$ **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 (ZEUS)

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

$$\alpha_s(M_Z) = 0.1196 \pm 0.0011\ (\text{stat.})\ ^{+0.0025}_{-0.0019}\ (\text{exp.})^{+0.0017}_{-0.0029}\ (\text{th.})$$

- Precise determination of $\alpha_s(M_Z)$!
- Experimental uncertainties:

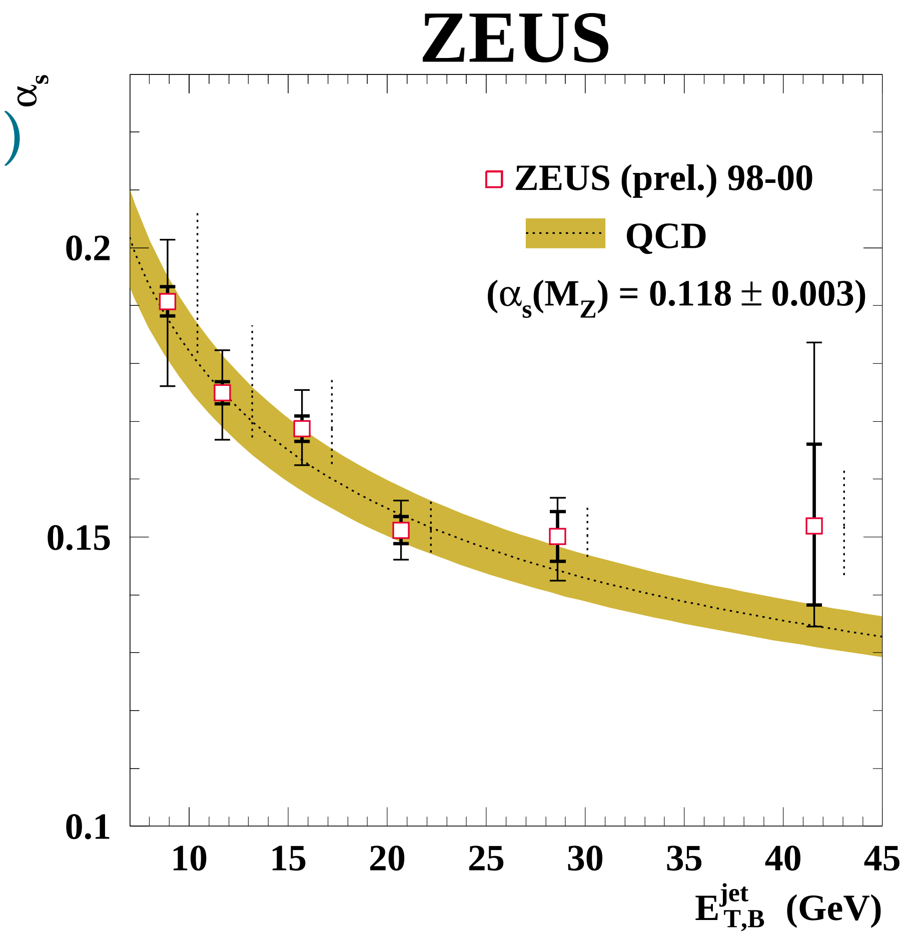
$\rightarrow$ jet energy scale (1% for $E_{T,jet} > 10$ GeV)

- Theoretical uncertainties:

$\rightarrow$ terms beyond NLO $\Delta\alpha_s(M_Z) = 1 - 2\%$

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

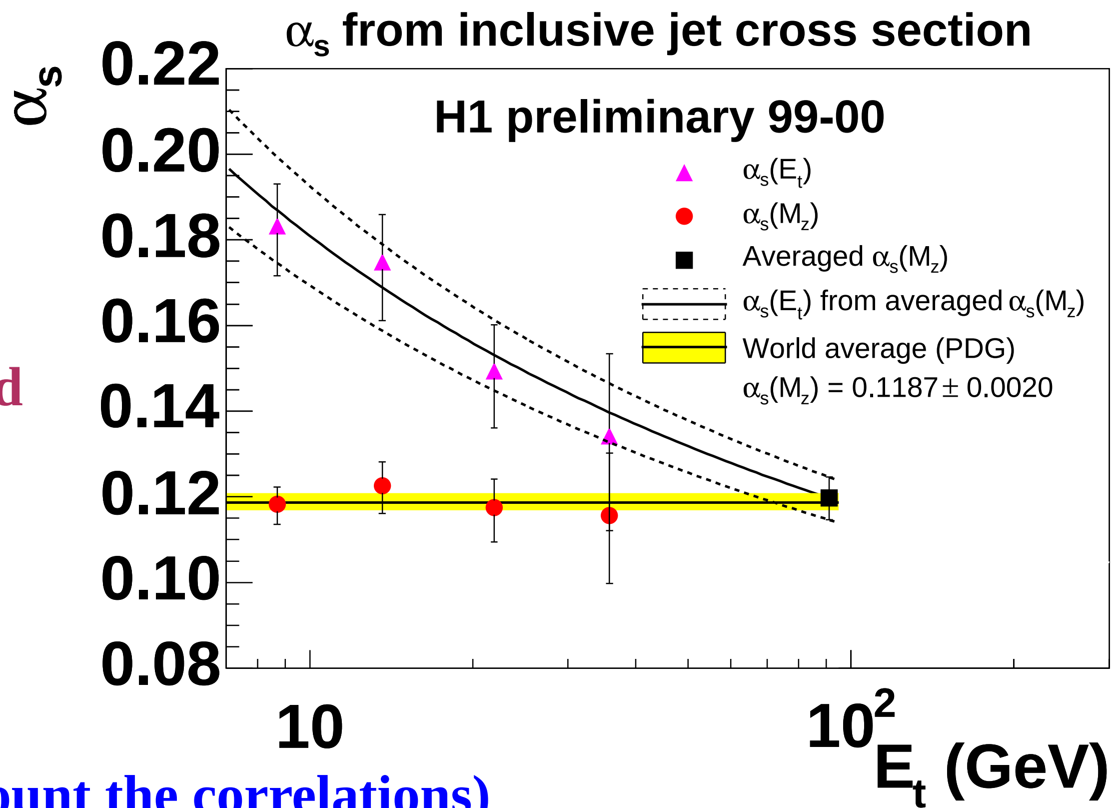
- Consistent with the world average of α_s



- 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

Inclusive Jet Cross Sections and extraction of α_s (H1)

- A value of $\alpha_s(M_Z)$ has been extracted from each data point of $d\sigma/dQ^2dE_t$ and $d\sigma/dE_t$.
- The results are consistent with the world average of $\alpha_s(M_Z)$.
- The results obtained from $d\sigma/dE_t$ are used to determine $\alpha_s(E_t)$ $\Rightarrow$



- An average is obtained (taking into account the correlations)

$$\alpha_s(M_Z) = 0.1197 \pm 0.0016\ (\text{exp.})^{+0.0046}_{-0.0048}\ (\text{th.})$$

$\Rightarrow$ precise determination of $\alpha_s(M_Z)$; consistent with the world average

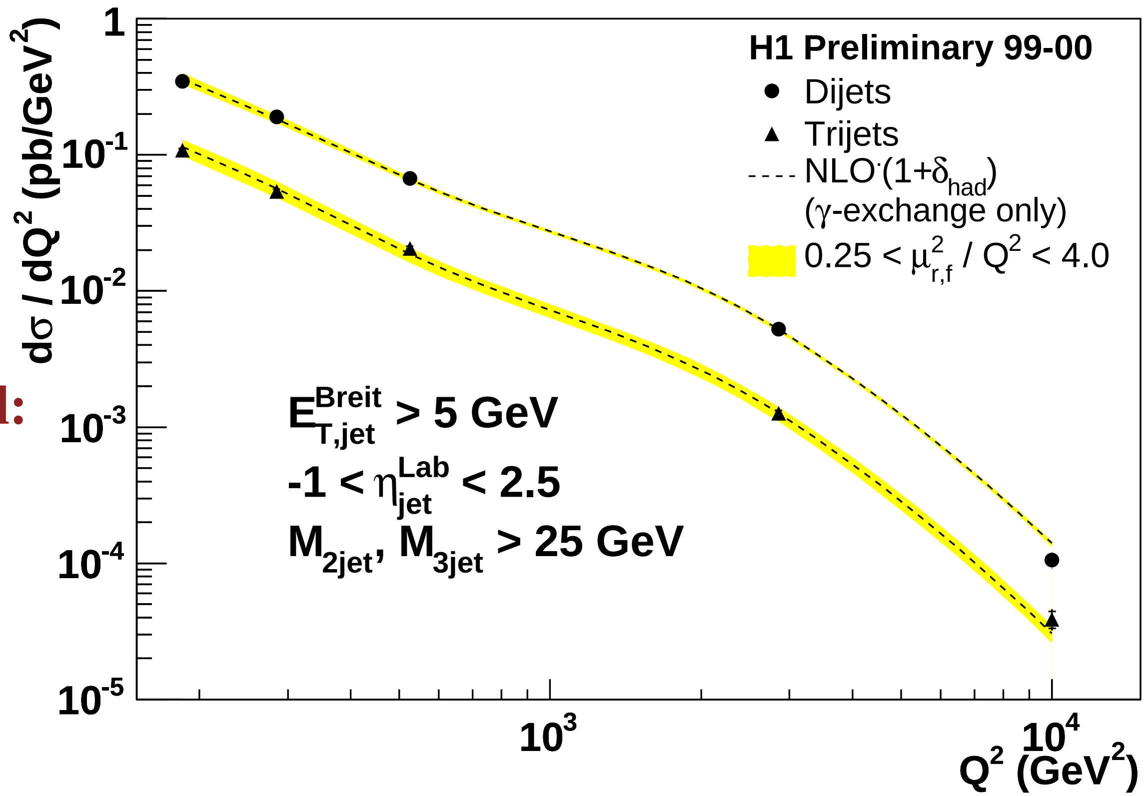
$\longrightarrow$ theoretical uncertainty dominant (major contributions from $\mu_{r,f}$ variations)

Dijet and Trijet Cross Sections in NC DIS ($150 < Q^2 < 15000$ GeV^2)

- Measurement of dijet and trijet cross sections over a wide range in $Q^2 \rightarrow$ $150 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.6$ for jets with
  E_T^{jet}(Breit)> 5 GeV, $-1 < \eta^{jet}$(Lab)< 2.5, $M_{jj} > 25$ GeV ($M_{jjj} > 25$ GeV)
  using $\mathcal{L} = 65.4$ pb^{-1}
- Trijet cross sections test QCD beyond LO directly $\rightarrow \sigma_{3jet} \propto \alpha_s^2$

- Comparison with NLO QCD calculations:
  - $\rightarrow \mu_R = \mu_F = Q$
  - $\rightarrow$ CTEQ5M set of proton PDFs
  - $\rightarrow$ parton-to-hadron corrections applied: $\sim 7\%$ (25%) for dijets (trijets)

- NLO QCD gives a good description of the data over a wide range in Q^2



Dijet and Trijet Cross Sections in NC DIS ($150 < Q^2 < 15000$ GeV^2)

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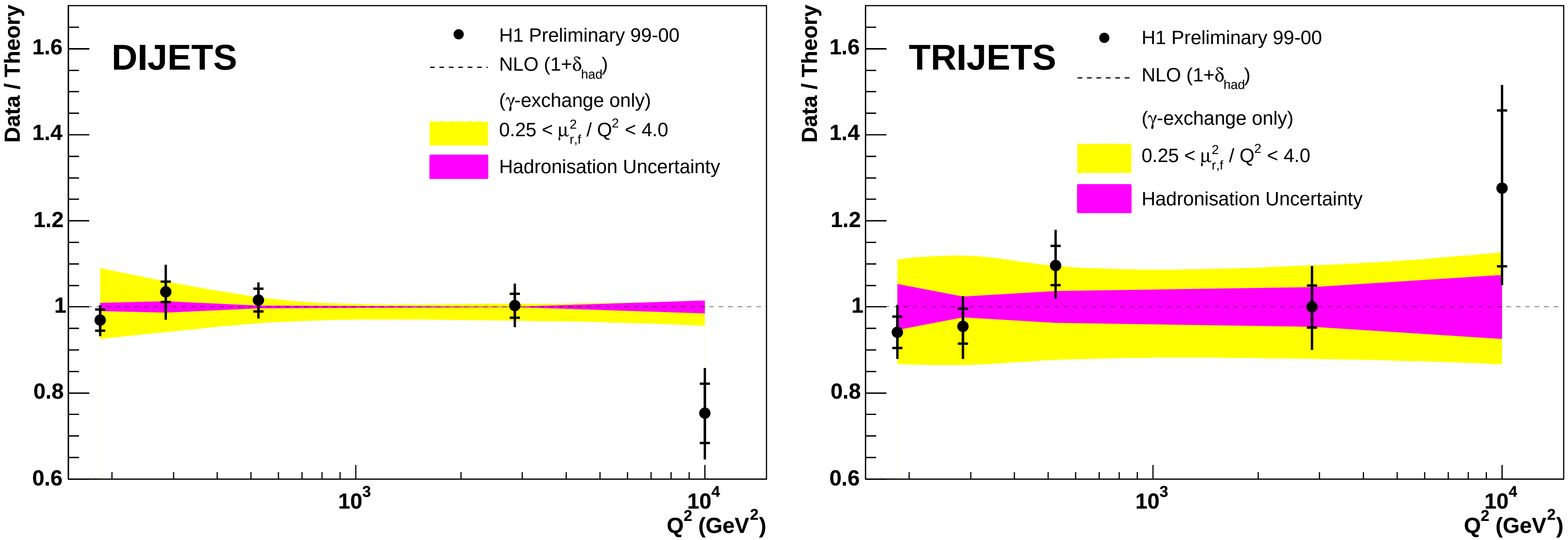
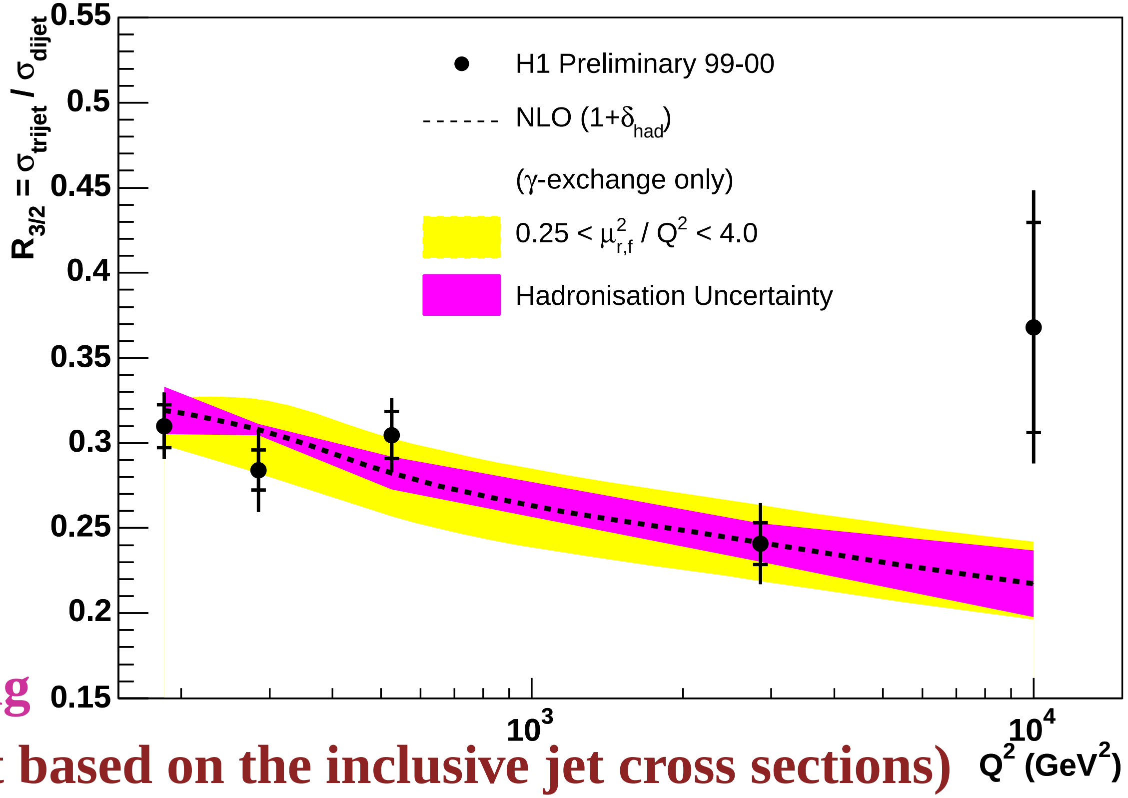


- NLO QCD gives a good description of the data over a wide range in Q^2 (Z^0-exchange effects not included in NLO; significant only for the highest Q^2 point)

Dijet and Trijet Cross Sections in NC DIS ($150 < Q^2 < 15000$ GeV^2)

- Measurement of the ratio of the trijet to dijet cross section over a wide range in Q^2

$\rightarrow$ $R_{3/2} \equiv \frac{\sigma_{\text{trijet}}(Q^2)}{\sigma_{\text{dijet}}(Q^2)}$



- Small experimental uncertainties.
- Small theoretical uncertainties:
  - $\rightarrow$ uncertainties on the proton PDFs
  - $\rightarrow$ higher-order terms ($>$ NLO) (reduced to $\sim 5\%$)
- Since $R_{3/2} \propto \alpha_s$ at LO it allows a determination of the strong coupling constant (in a different way than that based on the inclusive jet cross sections)
- The measured values of $R_{3/2}$ have been fitted with NLO QCD calculations to extract a combined value of $\alpha_s(M_Z)$:

$$\alpha_s(M_Z) = 0.1175 \pm 0.0017\ \text{(stat.)} \pm 0.0050\ \text{(syst.)}^{+0.0054}_{-0.0068}\ \text{(th.)}$$

α_s from Event Shapes in NC DIS ($196 < Q^2 < 40000$ GeV^2)

- **Determination of α_s from measurements of event shape distributions in NC DIS**

→ **kinematic region: $196 < Q^2 < 40000$ GeV^2 and $0.1 < y < 0.7$**

→ **For details see talk by S. Levonian**

- **Fit to each event shape distribution using NLO + NLL + Power Corrections**

  ⇒ $\alpha_s(M_Z)$ **and** α_0

- **Average of the results for various event shapes**

$$\alpha_s(M_Z) = 0.1198 \pm 0.0013\ (\text{exp.})^{+0.0056}_{-0.0043}\ (\text{th.})$$

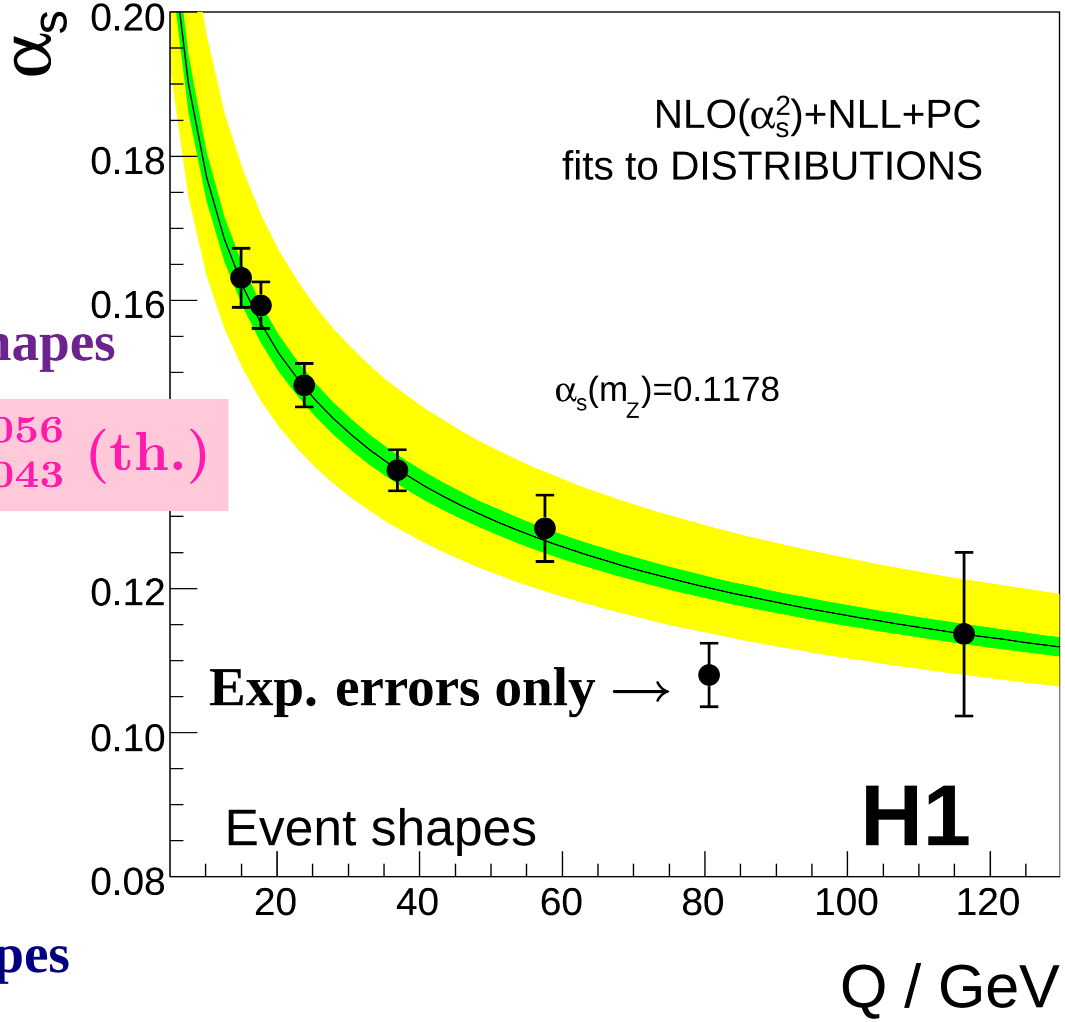
→ **Consistent with jet-based extractions**

→ **Theoretical uncertainty dominant**

- **Energy scale dependence of α_s:**

→ $\alpha_s(Q)$ **and** α_0 **extracted for each event shape and each bin in** Q

→ **Average of** $\alpha_s(Q)$ **for various event shapes**

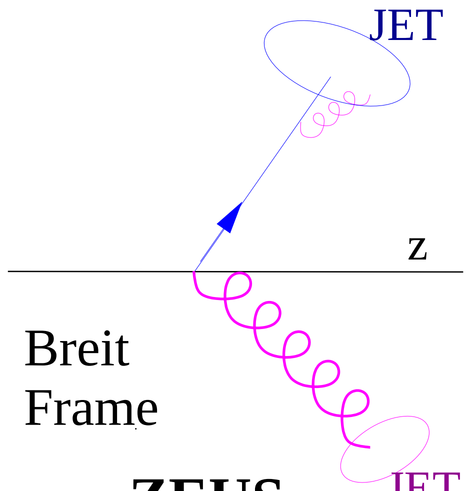


Jet-Radius Dependence of Inclusive Jet Cross Sections in NC DIS

- So far, all the measurements of jet production in NC DIS with the k_T cluster algorithm have been done with the jet radius $R = 1$

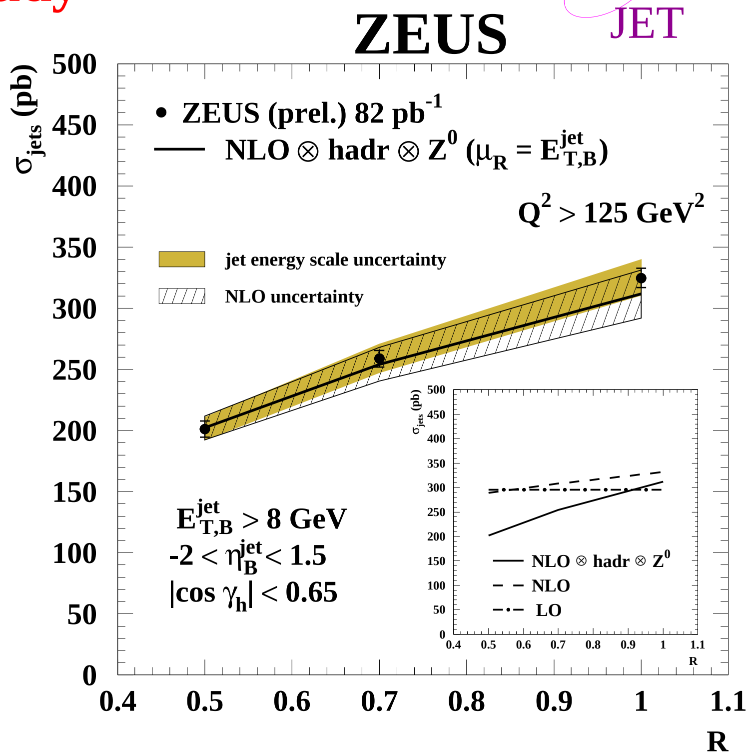
$\Rightarrow$ Smaller values of the jet radius R are of particular interest for the identification of heavy particles decaying into jets

$\rightarrow$ NC DIS provides a well understood environment to study the dependence of jet production on R



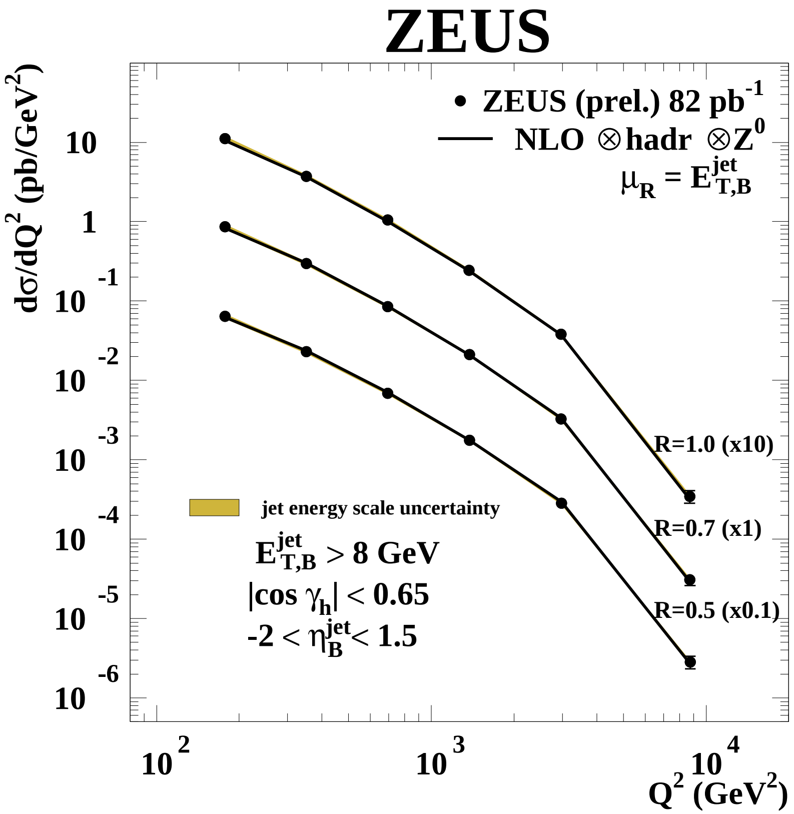
- New measurements of the inclusive jet cross sections in the kinematic region defined by $Q^2 > 125$ GeV^2 and $|\cos\gamma| < 0.65$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.5$ using $\mathcal{L} = 81.7$ pb^{-1}

$\Rightarrow$ for different R values: 0.5, 0.7 and 1.0

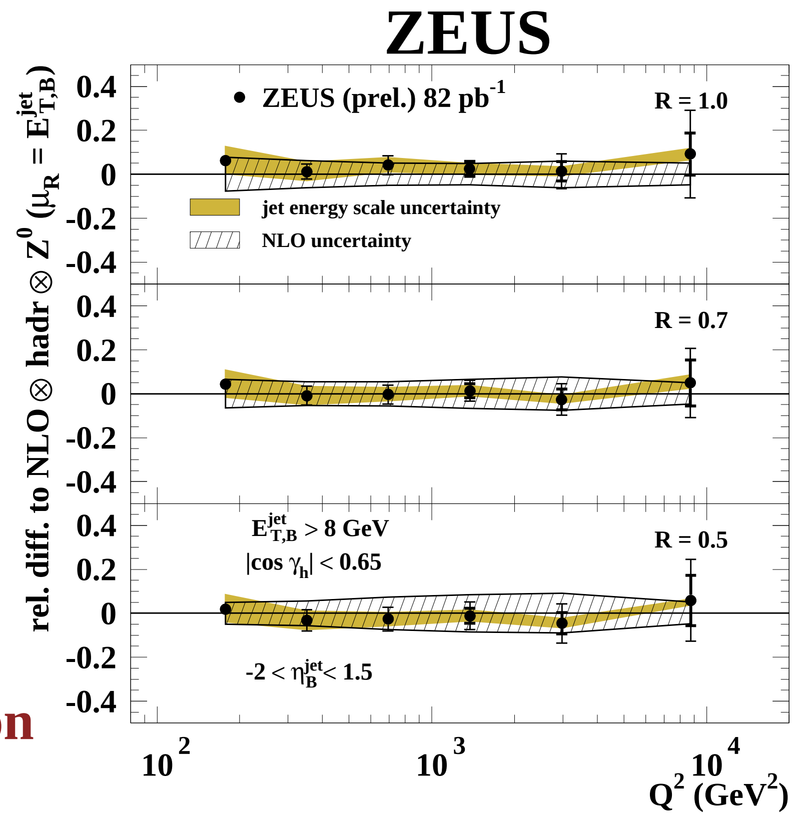


- NLO QCD calculations (corrected for hadronisation) provide a good description of the data

Jet-Radius Dependence of Inclusive Jet Cross Sections in NC DIS

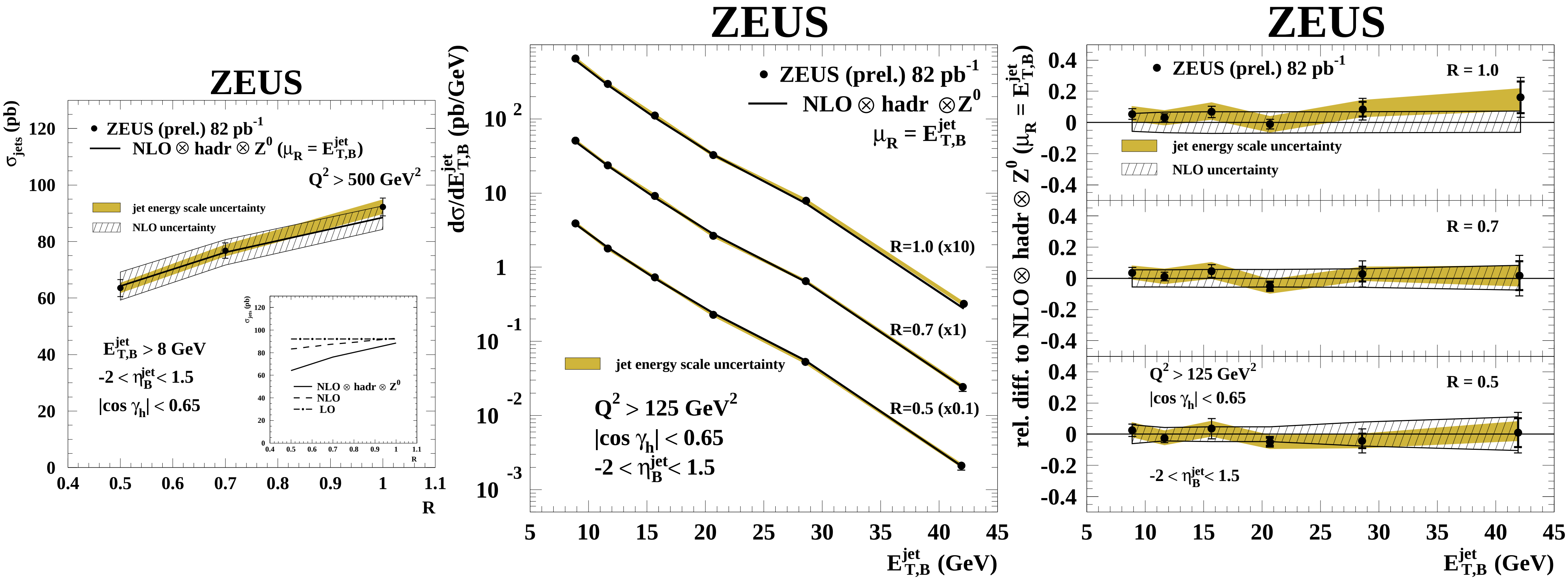


- **Experimental uncertainties:** $\sim 5\%$ **(jet energy scale)**
- **Theoretical uncertainties: higher-order terms ($>$ NLO) 7% at low Q^2, below 5% for $Q^2 > 250$ GeV^2 ($R = 1$); for smaller R, it is reduced (increased) at low (high) Q^2**



- **Hadronisation corrections: below 5%, 15%, 25% for $R = 1, 0.7, 0.5$ (in the region $Q^2 > 500$ GeV^2)**
- **NLO QCD calculations ($\mathcal{O}(\alpha_s^2)$) using $\mu_R = E^B_{T,jet}$, $\mu_F = Q$ and the MRST01 parametrisations of the proton PDFs describe the measurements well for all jet radii**

Jet-Radius Dependence of Inclusive Jet Cross Sections in NC DIS



- NLO QCD calculations corrected for hadronisation effects provide **an equally good description of the** measured $d\sigma/dE^B_{T,jet}$ and $d\sigma/dQ^2$ over a wide range of $E^B_{T,jet}$ and Q^2 for $R = 0.5, 0.7$ and 1

- The measured jet cross section integrated above $Q^2 > 500$ GeV^2 increases linearly with R in the range considered and is well described by the calculations

Summary

- HERA I has made possible precise measurements of inclusive jet cross sections in NC DIS

$\longrightarrow$ precise determinations of α_s:

ZEUS, $d\sigma/dQ^2$, $Q^2 > 500$ GeV^2 $\alpha_s(M_Z) = 0.1196^{+0.0032}_{-0.0040}$

H1, $d\sigma/dQ^2 dE_t$, $Q^2 > 150$ GeV^2 $\alpha_s(M_Z) = 0.1197^{+0.0049}_{-0.0051}$

$\Rightarrow$ Limited by theoretical uncertainties $\longrightarrow$ NNLO calculations will be of great help

$\longrightarrow$ accuracy comparable to e.g. α_s from $\Gamma(Z \rightarrow \text{hadrons})$ in e^+e^-

$\longrightarrow$ consistent with world average (Bethke, 2006):
$\alpha_s(M_Z) = 0.1189 \pm 0.0010$

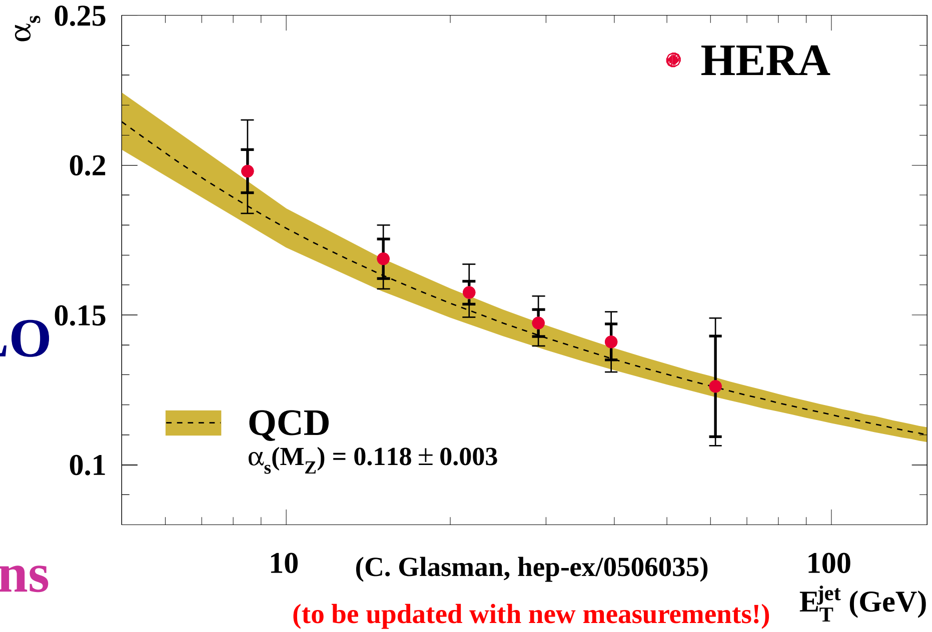
- Measurements of multijet production in NC DIS

$\Rightarrow$ alternate method of extracting α_s

$\longrightarrow$ it will benefit from HERA II statistics and NNLO

- New measurements of inclusive jet production with smaller jet radius ($R = 0.5, 0.7, 1$)

$\longrightarrow$ equally well described by NLO QCD calculations



(C. Glasman, hep-ex/0506035)

(to be updated with new measurements!)