Ringberg workshop: New trends in HERA Physics 2003
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# Jet production in deep inelastic $ep$ scattering at HERA

from

ZEUS Collab.

H1 Collab.


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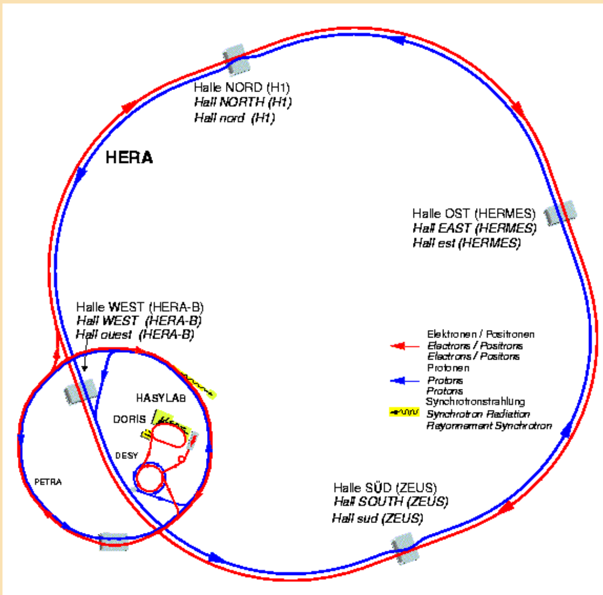
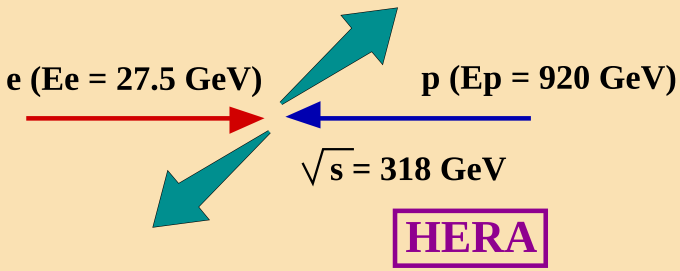
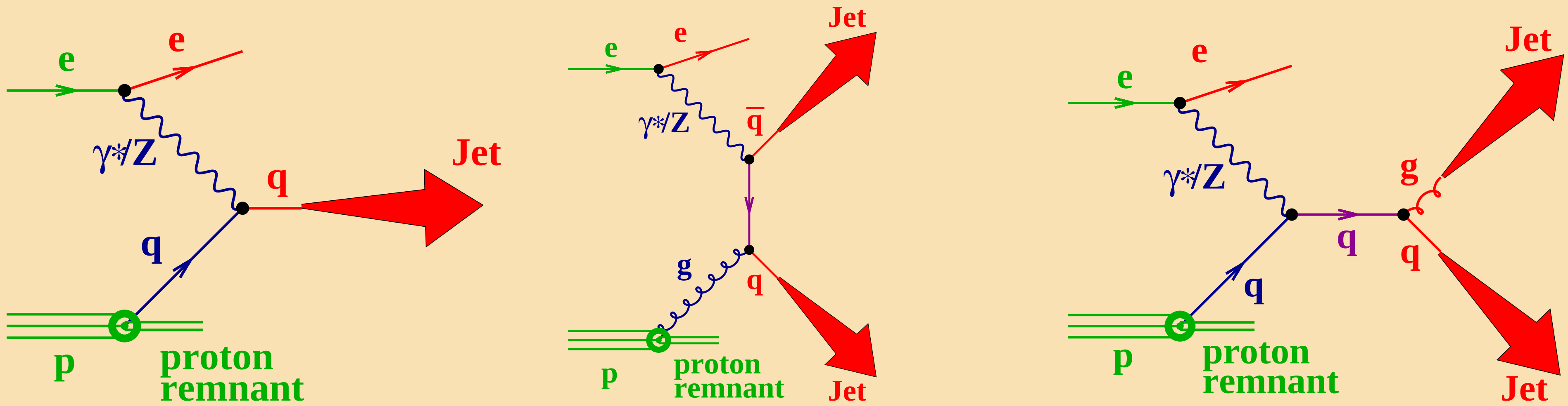


# Jet production in neutral current deep inelastic $ep$ scattering

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




- Jet production cross section:

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

– $f_a$: parton $a$ density in the proton, determined from experiment
$\longrightarrow$ long-distance structure of the target

– $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD
$\longrightarrow$ short-distance structure of the interaction

# Jet production in neutral current deep inelastic $ep$ scattering

- 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 $\alpha_s$

- To perform stringent tests of the pQCD calculations and precise determinations of $\alpha_s$ use observables for which the predictions are directly proportional to $\alpha_s$:

  jet cross sections in the Breit frame, jet substructure

$\longrightarrow$ 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)

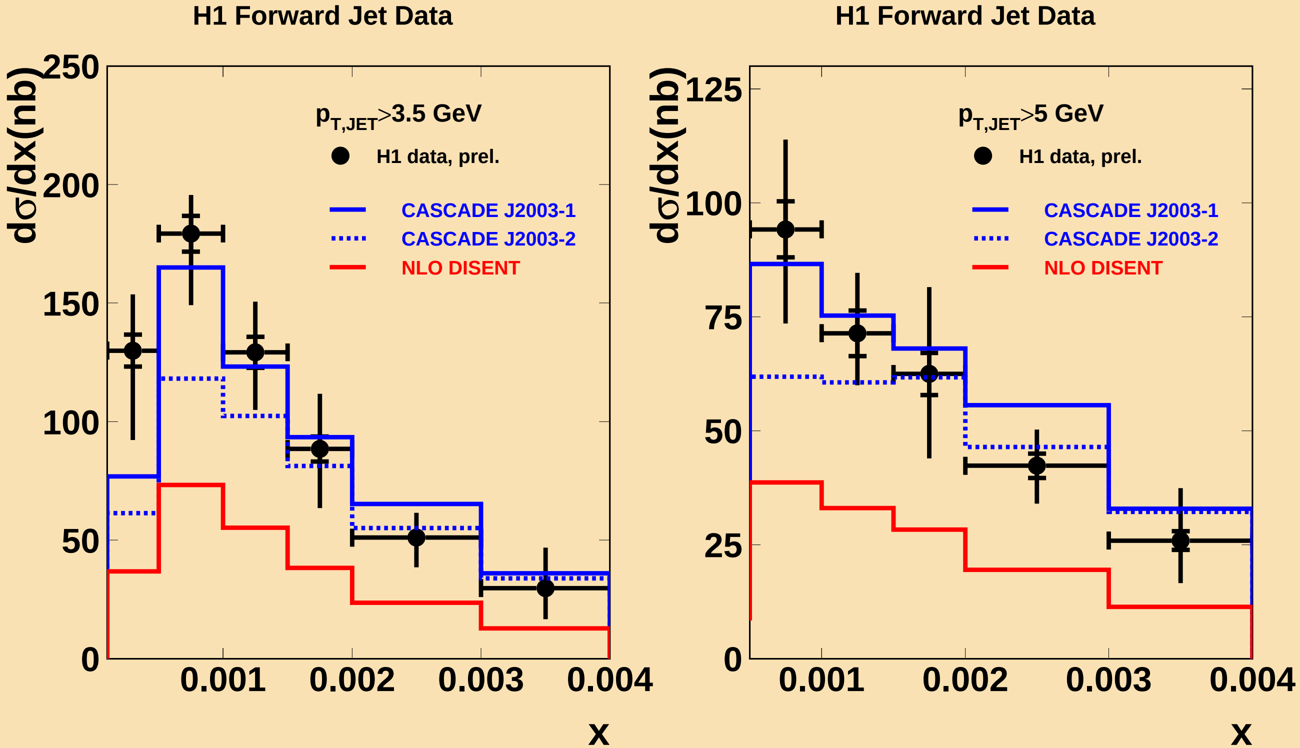
$\longrightarrow$ Small theoretical uncertainties:

- NLO QCD calculations (reduction of higher-order contributions)
- jet algorithm: longitudinally invariant $k_T$ cluster algorithm (Catani et al)
  - $>$ small parton-to-hadron effects and infrared safe to all orders
  - $>$ less ambiguities in matching the experimental and theoretical implementations
  - $>$ suppression of beam-remnant jet
- Jet selection: inclusive jet production (smaller uncertainties than for dijets)

# Jet production in neutral current deep inelastic $ep$ scattering

- At high scales ($Q^2$, $E_T^{\rm jet}$), calculations using the collinear approximation of the DGLAP evolution equations give a good description of the data at NLO
  $\longrightarrow$ by fitting the data with the NLO calculations $\longrightarrow$ extraction of $\alpha_s$ and gluon density

- For $E_T^{\rm jet} \sim Q$ and large $\eta^{\rm jet}$, large discrepancies between NLO calculations and data were observed at low $x$

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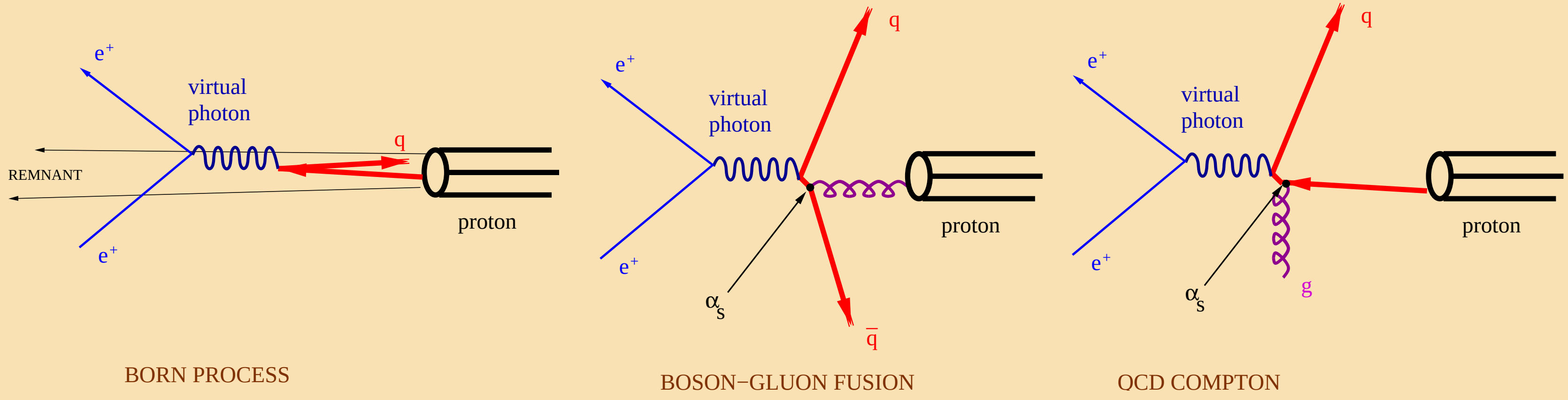
- This could indicate a breakdown of DGLAP evolution and
  $\longrightarrow$ onset of BFKL effects
  $\longrightarrow$ partonic structure of virtual photon ($(E_T^{\rm jet})^2 > Q^2$)
  $\longrightarrow$ large NNLO contributions at low $Q^2$

# NLO QCD calculations for jets in NC DIS

- Several NLO ($\mathcal{O}(\alpha_s^2)$) programs are available for performing jet cross sections calculations $\longrightarrow$ DISENT, MEPJET, DISASTER++, NLOJET
- NLO corrections $\longrightarrow$ virtual corrections with internal particle loops
  $\longrightarrow$ real corrections with a third parton in the final state
- Different methods to calculate real corrections:
  $\longrightarrow$ phase space slicing method (M)
  $\longrightarrow$ 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 $E_T^{\rm jet}$
- The calculations are for jets of partons and the measurements are done at the hadron level $\longrightarrow$ need to correct the calculations for hadronisation effects
- Theoretical uncertainties:
  $\longrightarrow$ terms beyond NLO, which are usually estimated by varying $\mu_R$ by factor 2
  $\longrightarrow$ uncertainties on $\alpha_s(M_Z)$ and the proton PDFs
  $\longrightarrow$ uncertainty coming from the hadronisation corrections

# 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:
  - $\longrightarrow$ suppression of the Born contribution (struck quark has zero $E_T$)
  - $\longrightarrow$ suppression of the beam-remnant jet (zero $E_T$)
  - $\longrightarrow$ lowest-order non-trivial contributions from $\gamma^* g \longrightarrow q\bar{q}$ and $\gamma^* q \longrightarrow qg$

$\longrightarrow$ directly sensitive to hard QCD processes ($\alpha_s$)

- Restriction of the phase space using only variables in Breit frame ($E^{\rm jet}_{T,{\rm B}}$,$\eta^{\rm jet}_{\rm B}$)
  - $\longrightarrow$ facilitates the separation of beam fragmentation and hard process in the calculations
  - $\longrightarrow$ allows the measurement of the azimuthal distribution ($\phi^B_{jet}$)

# Inclusive jet cross sections in NC DIS: $d\sigma/dQ^2$

— Jets searched with $k_T$ algorithm in the Breit frame
— At least one jet with $E_{T,\rm B}^{\rm jet} > 8$ GeV and $-2 < \eta_{\rm B}^{\rm jet} < 1.8$
— Kinematic range: $Q^2 > 125$ GeV$^2$ and $-0.7 < \cos\gamma < 0.5$
— no cut applied in the laboratory frame

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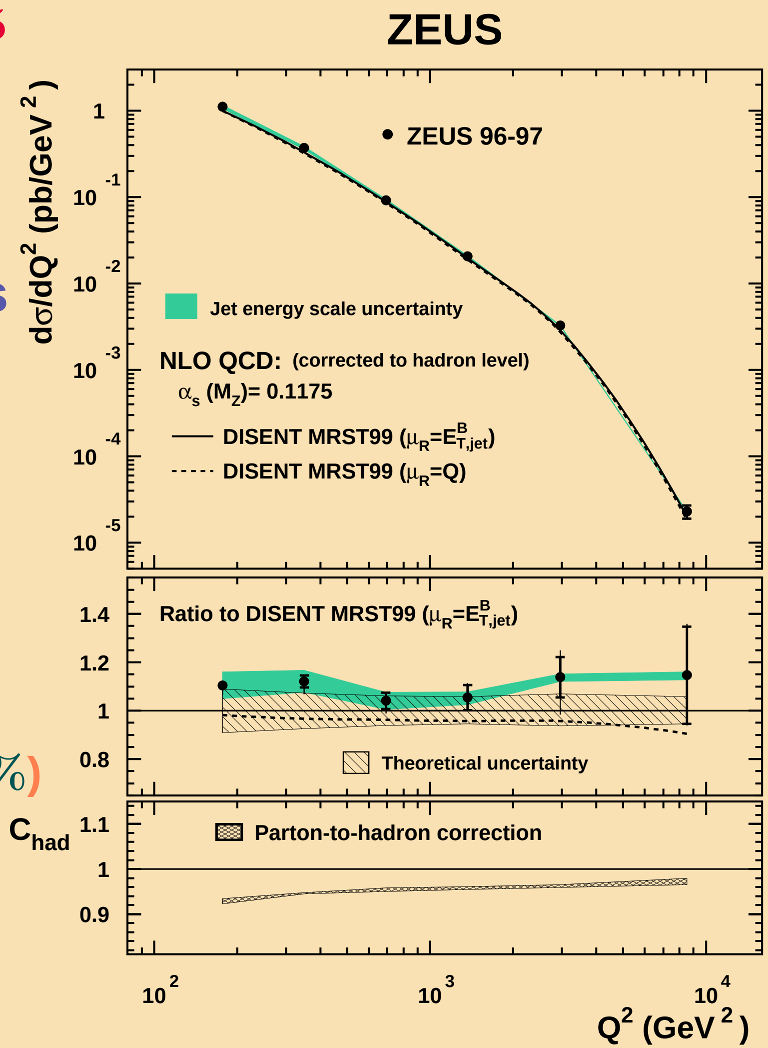


- **Advantages of inclusive jet cross sections in a QCD analysis:**
  - — infrared insensitivity (no dijet asymmetric cuts needed) $\longrightarrow$ wider phase-space than in dijet
  - — suited to test resummed calculations
  - — smaller theoretical uncertainties than in dijet cross sections
- **Small experimental uncertainties:**
  - $\longrightarrow$ uncorrelated uncertainties ($5\%$)
  - $\longrightarrow$ absolute energy scale, $\pm 3\ (1)\%$ for low (high) $E_T^{\rm jet}$ ($\mp 5\%$)
- **Small theoretical uncertainties:**
  - $\longrightarrow$ higher orders ($5\%$)
  - $\longrightarrow$ proton PDFs ($3\%$)
  - $\longrightarrow$ $\alpha_s(M_Z)$ ($5\%$)
  - $\longrightarrow$ parton-to-hadron corrections ($< 10\%$; uncertainty $< 1\%$)

# Inclusive jet cross sections in NC DIS: $d\sigma/dE_{T,\mathrm{B}}^{\mathrm{jet}}$

- Jets searched with $k_T$ algorithm in the Breit frame
- At least one jet with $E_{T,\mathrm{B}}^{\mathrm{jet}} > 8$ GeV and $-2 < \eta_{\mathrm{B}}^{\mathrm{jet}} < 1.8$
- Kinematic range: $Q^2 > 125$ GeV$^2$ and $-0.7 < \cos\gamma < 0.5$
- no cut applied in the laboratory frame

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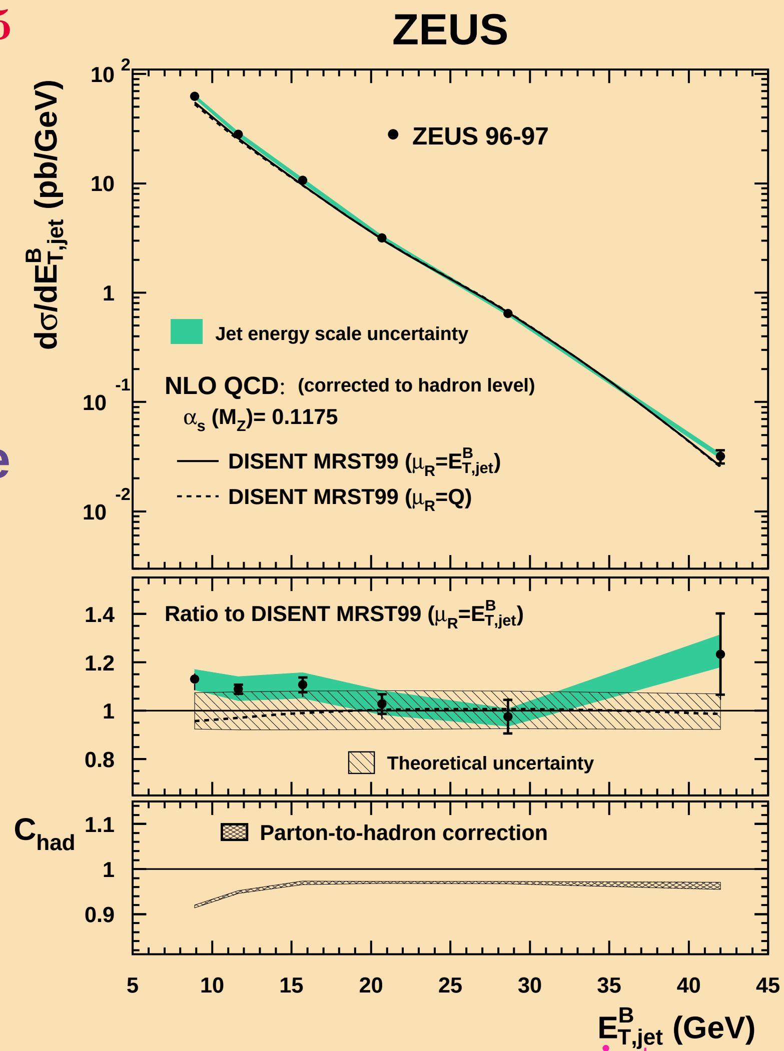



- Comparison to NLO predictions (DISENT):
  - $\longrightarrow$ $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$ and $\mu_F = Q$
  - $\longrightarrow$ $p$ PDFs: MRST99

$\longrightarrow$ The measured inclusive jet cross sections are well described by the predictions at high $Q^2$ and at high $E_{T,\mathrm{B}}^{\mathrm{jet}}$

$\longrightarrow$ At low $Q^2$ and low $E_{T,\mathrm{B}}^{\mathrm{jet}}$, the measurements of inclusive jet cross sections are above the calculations by $\sim 10\%$, of the same size as the theoretical uncertainties

$\longrightarrow$ Extraction of $\alpha_s$ from these measurements restricted to high $Q^2$ and $E_{T,\mathrm{B}}^{\mathrm{jet}}$

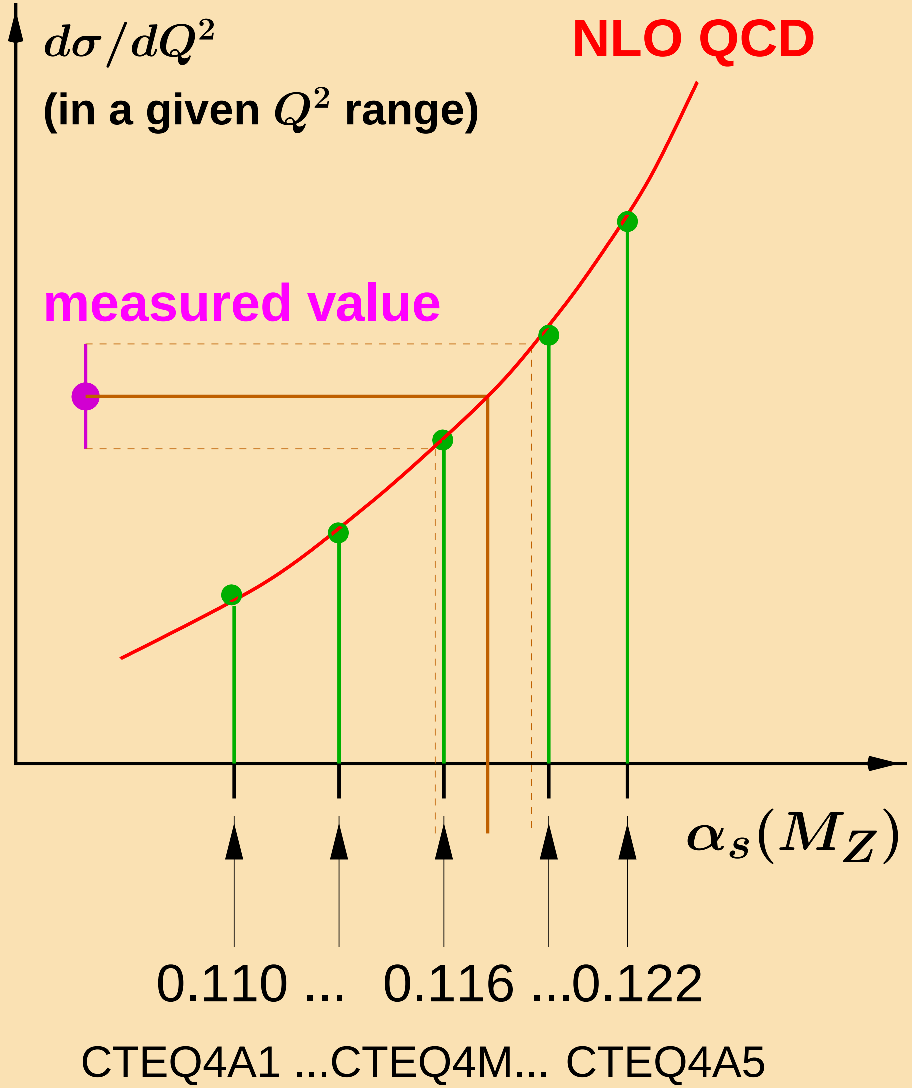
# Inclusive jet cross sections and determination of $\alpha_s(M_Z)$

- NLO QCD calculations of inclusive jet cross sections depend on $\alpha_s(M_Z)$ through
  - matrix elements ($\hat{\sigma} \sim A \cdot \alpha_s + B \cdot \alpha_s^2$)
  - proton PDFs ($\alpha_s(M_Z)$ value assumed in evolution)

- To take into account the correlation, the NLO QCD calculations were performed using various sets of proton PDFs which assume different values of $\alpha_s(M_Z)$

- The calculations were then 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 $Q^2$ region, the value of $\alpha_s(M_Z)$ and its uncertainty were extracted



# Inclusive jet cross sections and determination of $\alpha_s$

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

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

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(H1 result: $\alpha_s(M_Z) = 0.1186 \pm 0.0030\,(\mathrm{exp.})\,^{+0.0039}_{-0.0045}\,(\mathrm{th.})\,^{+0.0033}_{-0.0023}\,(\mathrm{PDF})$)
(for $Q^2 > 150$ GeV$^2$)

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- Experimental uncertainties:
  $\longrightarrow$ jet energy scale ($1\%$ for $E_T^{\mathrm{jet}} > 10$ GeV)
- Theoretical uncertainties:
  $\longrightarrow$ terms beyond NLO ($\Delta\alpha_s(M_Z) = 3\%$)
  $\longrightarrow$ uncertainties proton PDFs ($\Delta\alpha_s(M_Z) = 1\%$)
  $\longrightarrow$ hadronisation corrections ($\Delta\alpha_s(M_Z) = 0.2\%$)
- Consistent with other determinations of $\alpha_s$ and the PDG

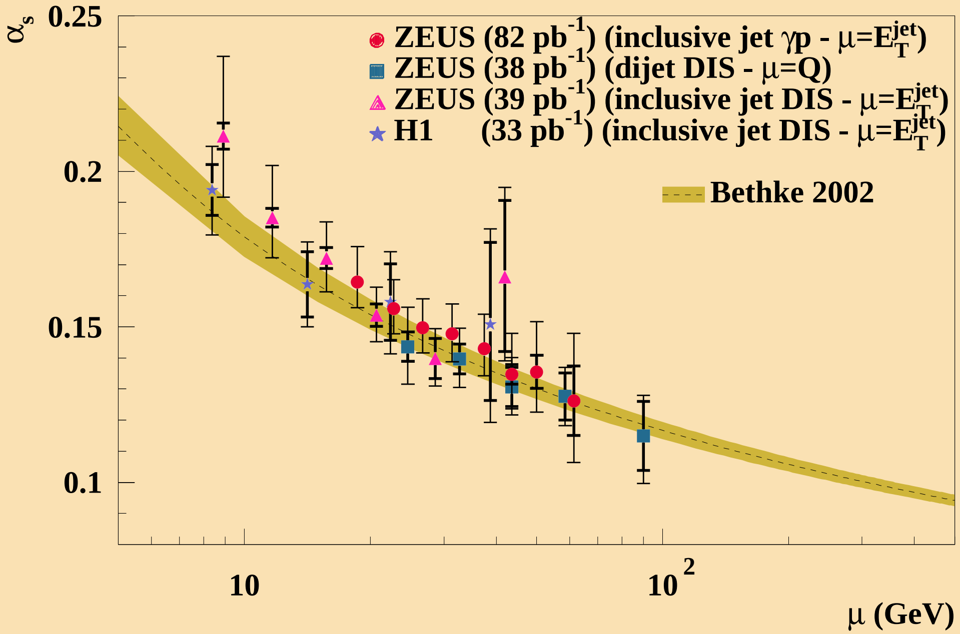
$\longrightarrow$ Very precise determination of $\alpha_s(M_Z)$!

$\longrightarrow$ Further precision depends upon further experimental and theoretical improvements

# Test of the energy-scale dependence of $\alpha_s$

- The QCD prediction for the energy-scale dependence of $\alpha_s$ has been tested by determining $\alpha_s$ from the measured differential cross sections at different scales
  $\longrightarrow$ from the measured $d\sigma/dE_{T,\rm B}^{\rm jet}$ in each $E_{T,\rm B}^{\rm jet}$ region, $\alpha_s(E_{T,\rm B}^{\rm jet})$ was extracted

$\longrightarrow$ The measurements are consistent with the running of $\alpha_s$ predicted by QCD over a large range in $E_{T,\rm B}^{\rm jet}$

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

# Inclusive jet $d\sigma/dE_{T,\mathrm{B}}^{\mathrm{jet}}$ in different $\eta_{\mathrm{LAB}}^{\mathrm{jet}}$ regions at low $Q^2$

– **Jets searched with $k_T$ algorithm in the Breit frame**

– **At least one jet with $E_{T,\mathrm{B}}^{\mathrm{jet}} > 5$ GeV and $-1 < \eta_{\mathrm{LAB}}^{\mathrm{jet}} < 2.8$**

– **Kinematic range: $5 < Q^2 < 100$ GeV$^2$**

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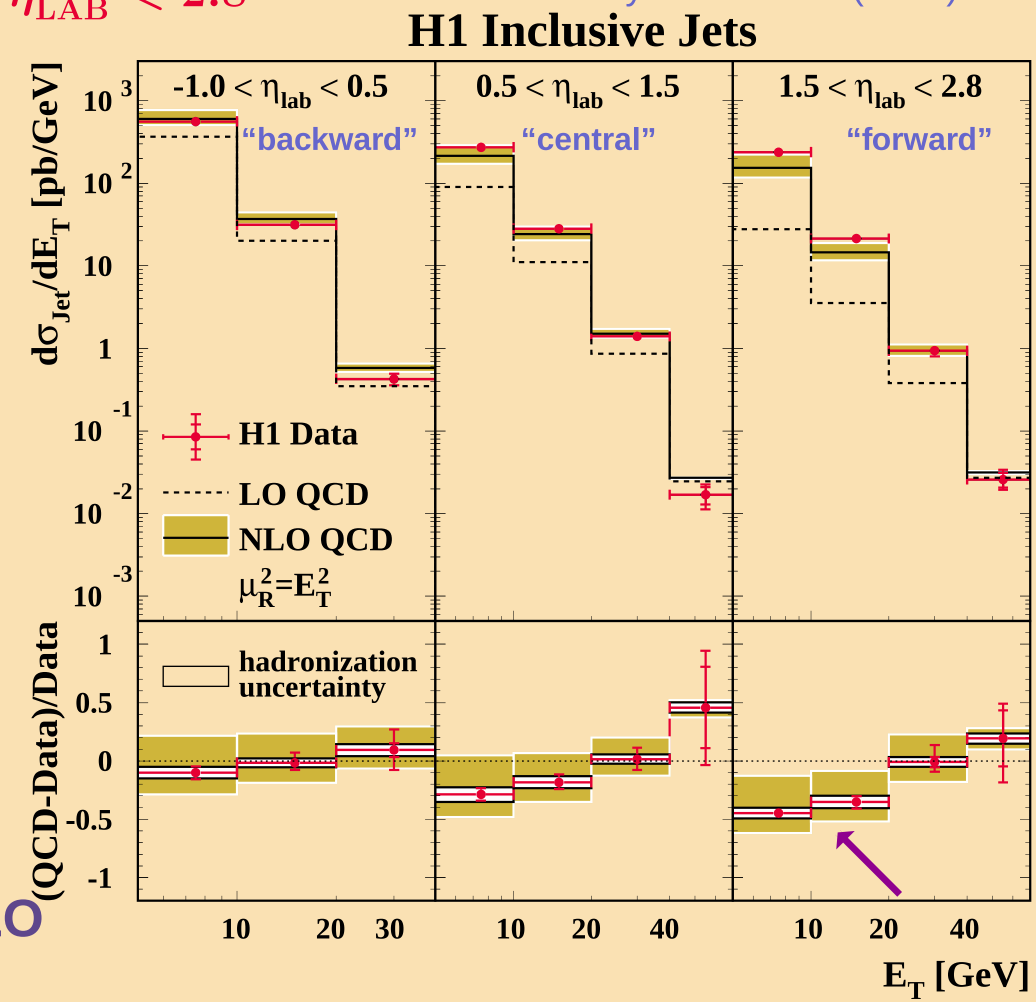


- **Experimental uncertainties:**
  - → uncorrelated uncertainties ($5-10\%$)
  - → absolute energy scale, $\pm 3\%$ ($\mp 10-15\%$)
- **Comparison to LO/NLO predictions (DISENT):**
  - → $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$, $Q$ and $\mu_F = Q$
  - → $p$ PDFs: CTEQ5L/M
- **Theoretical uncertainties:**
  - → higher orders ($20-30\%$ at low $E_{T,\mathrm{B}}^{\mathrm{jet}}$, $10\%$ at high $E_{T,\mathrm{B}}^{\mathrm{jet}}$)
  - → parton-to-hadron corrections ($5-10\%$; uncertainty $5\%$)
- **Good agreement between data and NLO in "backward" and "central" regions**
- **Large NLO corrections for low $E_{T,\mathrm{B}}^{\mathrm{jet}}$ and in "forward" region → NLO/LO $\sim 5$**
- **NLO predictions below data for $E_{T,\mathrm{B}}^{\mathrm{jet}} < 20$ GeV in "forward" region**

# Inclusive jet $d\sigma/dE_{T,\mathrm{B}}^{\mathrm{jet}}$ in different $Q^2$ regions for $1.5 < \eta_{\mathrm{LAB}}^{\mathrm{jet}} < 2.8$

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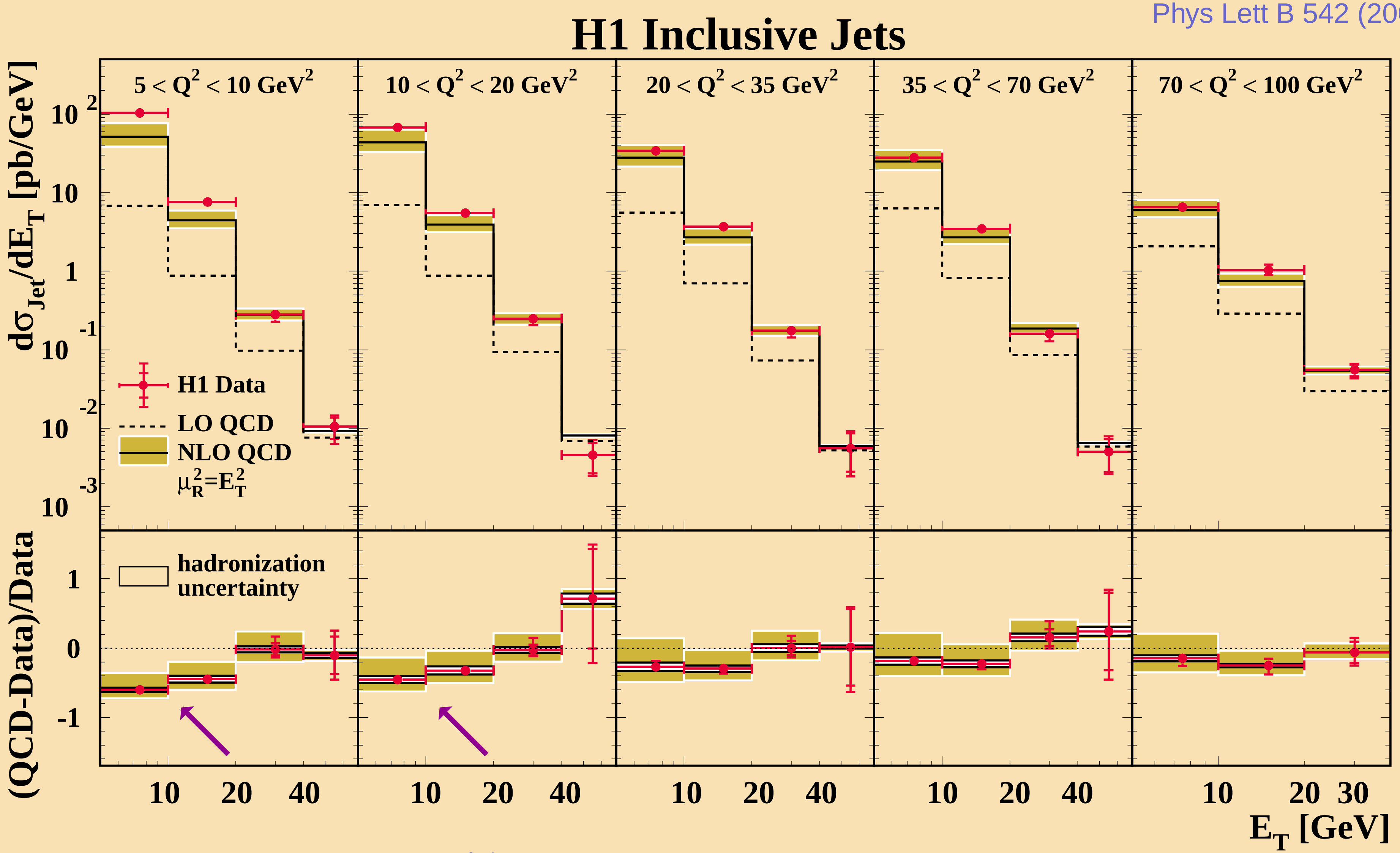
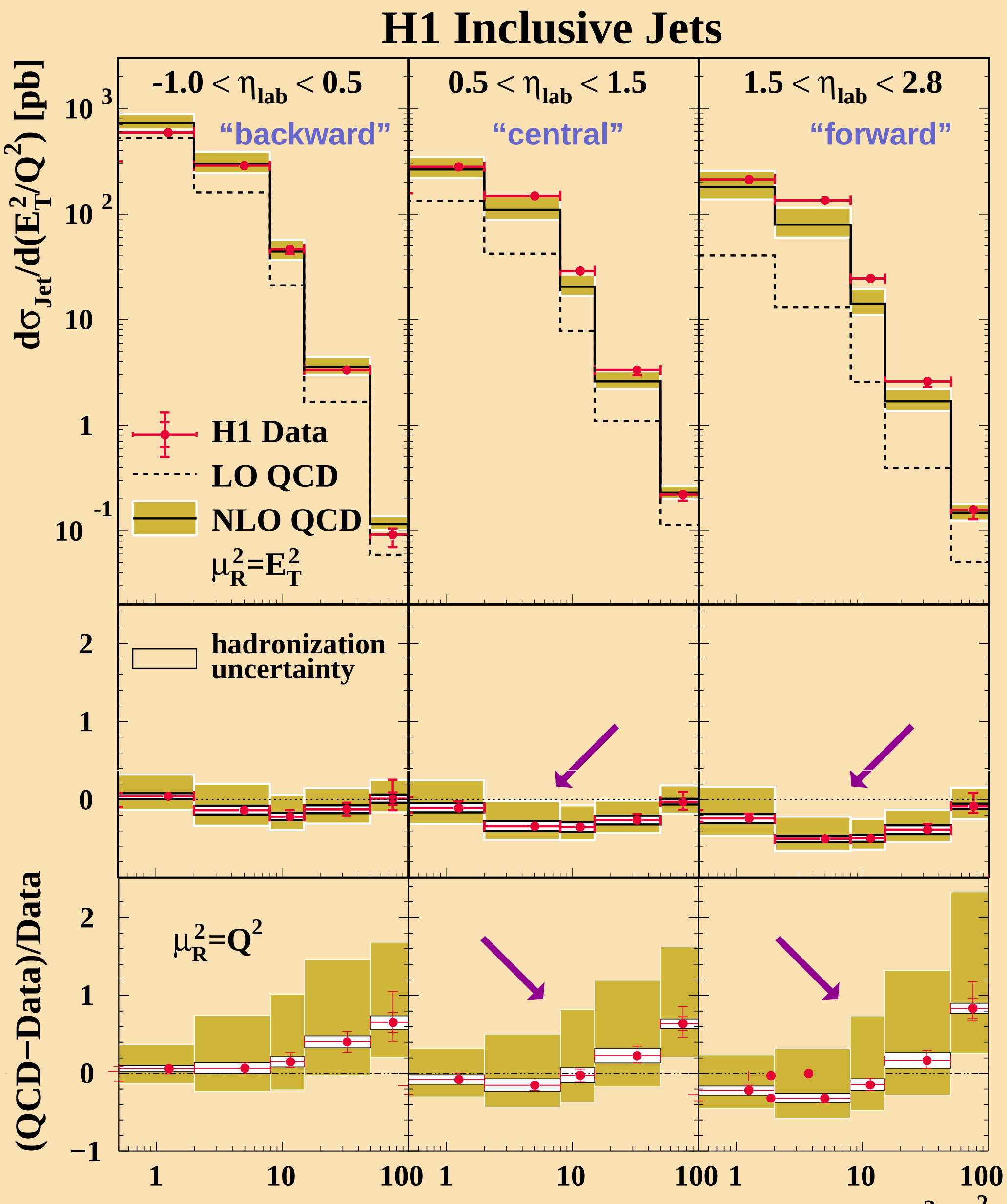



- NLO predictions up to $50\%$ lower than the data in regions where the NLO corrections are largest

# $d\sigma/d(E_{T,\mathrm{B}}^{\mathrm{jet}}/Q)^2$: interplay of the two hard scales

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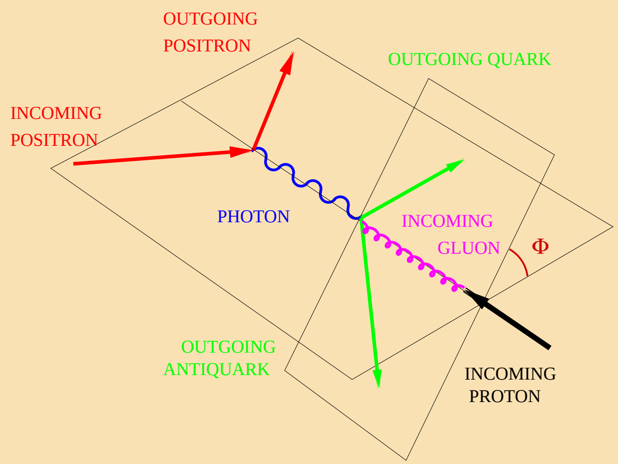
- "Backward" region well described by NLO
- NLO predictions lower than the data in "central" and "forward" regions for $2 < (E_{T,\mathrm{B}}^{\mathrm{jet}}/Q)^2 < 50$
  $\longrightarrow$ regions dominated by small values of $(E_{T,\mathrm{B}}^{\mathrm{jet}})^2$ and $Q^2$
- NLO calculations with $\mu_R = Q$
  $\longrightarrow$ disagreement for large $(E_{T,\mathrm{B}}^{\mathrm{jet}}/Q)^2$ (small $Q^2$)

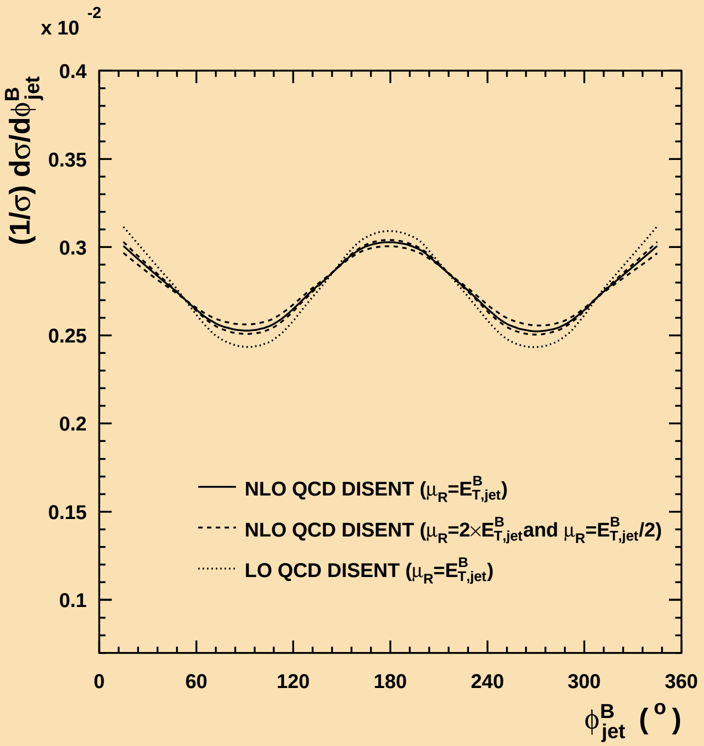
$\longrightarrow$ Improved calculations are needed to understand jet production at low $Q^2$

# Azimuthal distribution of jets in NC DIS

- The distribution of the azimuthal angle $\phi^B_{\rm jet}$ in the Breit frame between the lepton scattering plane and the plane defined by the jet and the incoming proton direction is expected to be non-uniform due to perturbative QCD effects and insensitive to non-perturbative effects




$\longrightarrow$ clean test of perturbative QCD




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

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

$\rightarrow$ In $\gamma^* q \rightarrow qg$ the outgoing $g(q)$ preferentially appears at $\phi = 0(\pi)$

$\rightarrow$ In $\gamma^* g \rightarrow q\bar{q}$ the $\phi$ dependence is dominated by the $\cos 2\phi$ term

- For an inclusive jet measurement

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

# Azimuthal distribution of jets in NC DIS

- Measurement of the normalised inclusive jet cross section $(1/\sigma)d\sigma/d\phi^B_{\rm jet}$

— Jets searched with $k_T$ algorithm in the Breit frame

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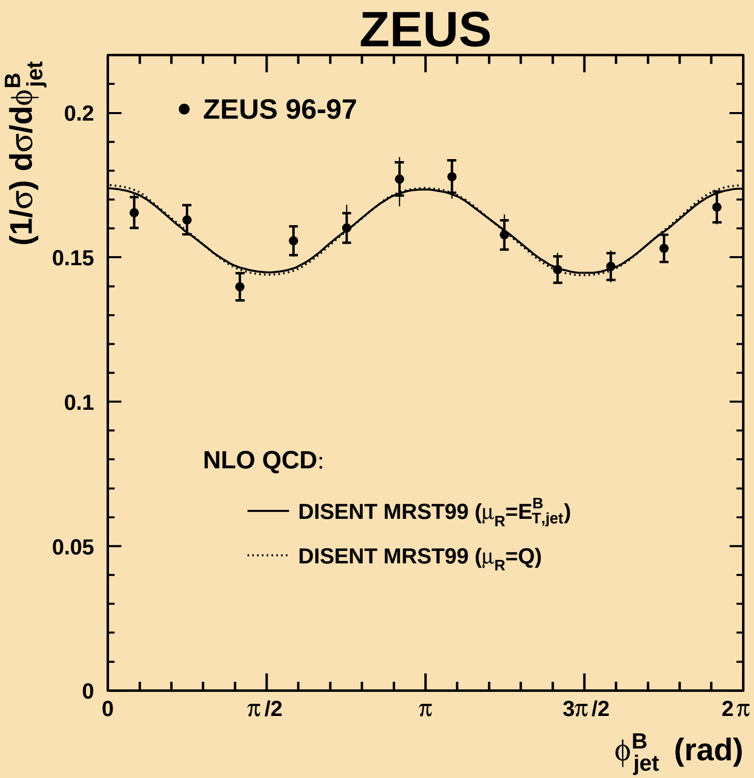
— At least one jet with $E^{\rm jet}_{T,{\rm B}} > 8$ GeV and $-2 < \eta^{\rm jet}_{\rm B} < 1.8$

— Kinematic range: $Q^2 > 125$ GeV$^2$ and $-0.7 < \cos\gamma < 0.5$

— no cut applied in the laboratory frame to avoid distorsions of the azimuthal distribution by kinematic effects




- Clear enhancements at $\phi^B_{\rm jet} = 0$ and $\phi^B_{\rm jet} = \pi$

$\longrightarrow$ Small experimental uncertainties

$\longrightarrow$ Negligible parton-to-hadron corrections

$\longrightarrow$ Small theoretical uncertainties:

— terms beyond NLO ($\pm 1\%$ on the amplitude of the modulation of the distribution)

— other uncertainties (eg intrinsic $k_T$ of partons in the proton) are smaller

- NLO QCD calculations ($\mathcal{O}(\alpha_s^2)$) using $\mu_R = E^{\rm jet}_{T,{\rm B}}$ (or $\mu_R = Q$), $\mu_F = Q$ and the MRST99 pPDF sets describe the measurements very well

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

# Azimuthal distribution of jets in NC DIS: $Q^2$ dependence

- Measurement of the normalised inclusive jet cross section $(1/\sigma)d\sigma/d|\phi^B_{\text{jet}}|$ in different regions of $Q^2$

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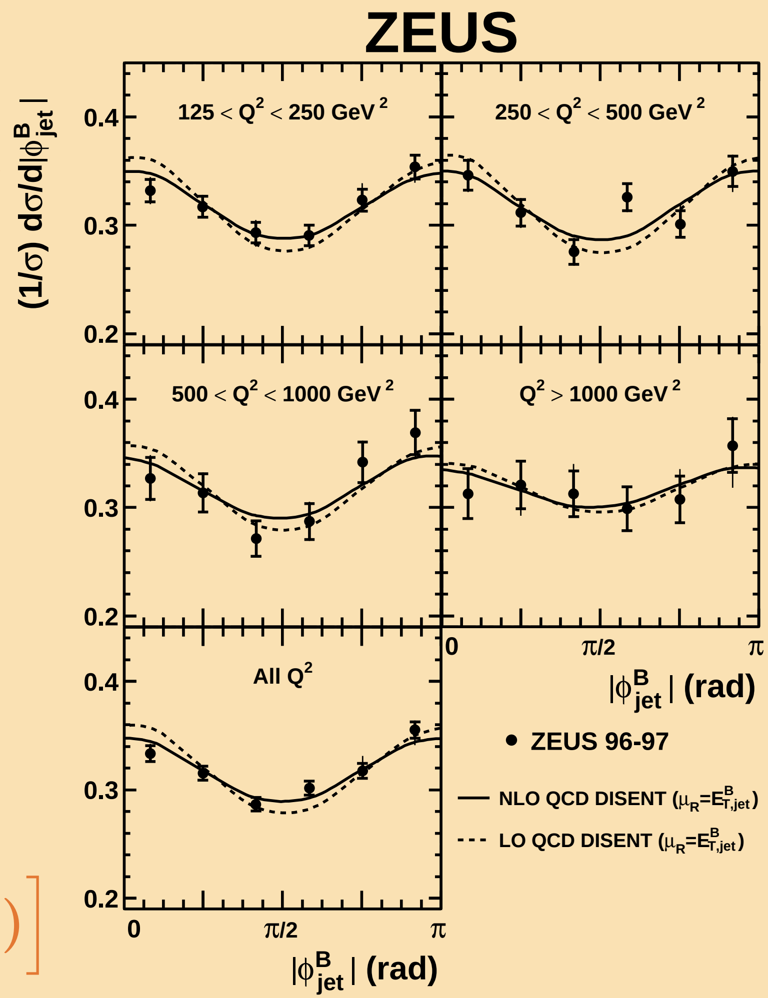


- NLO QCD calculations describe the data well
- LO QCD predicts a larger asymmetry, particularly at low $Q^2$

- The asymmetry is predicted to decrease as $Q^2$ increases due to the progressive decline of the $\gamma^* g \rightarrow q\bar{q}$ 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

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

# Azimuthal distribution of jets in NC DIS: $Q^2$ dependence

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

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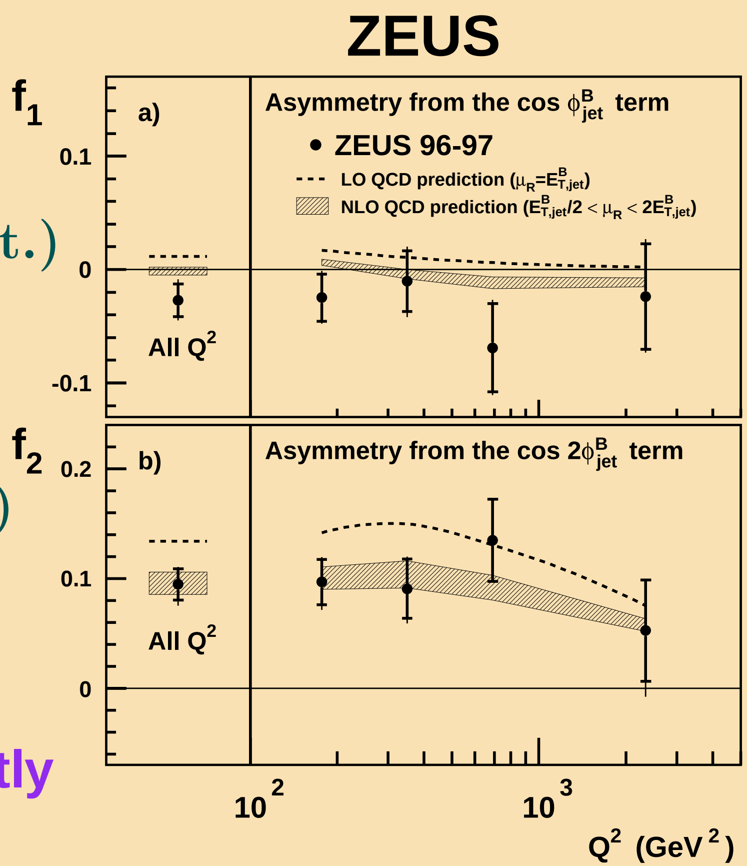
- Fitted values of $f_1$ and $f_2$ as functions of $Q^2$ and for the entire sample ($Q^2 > 125$ GeV$^2$)




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

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

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

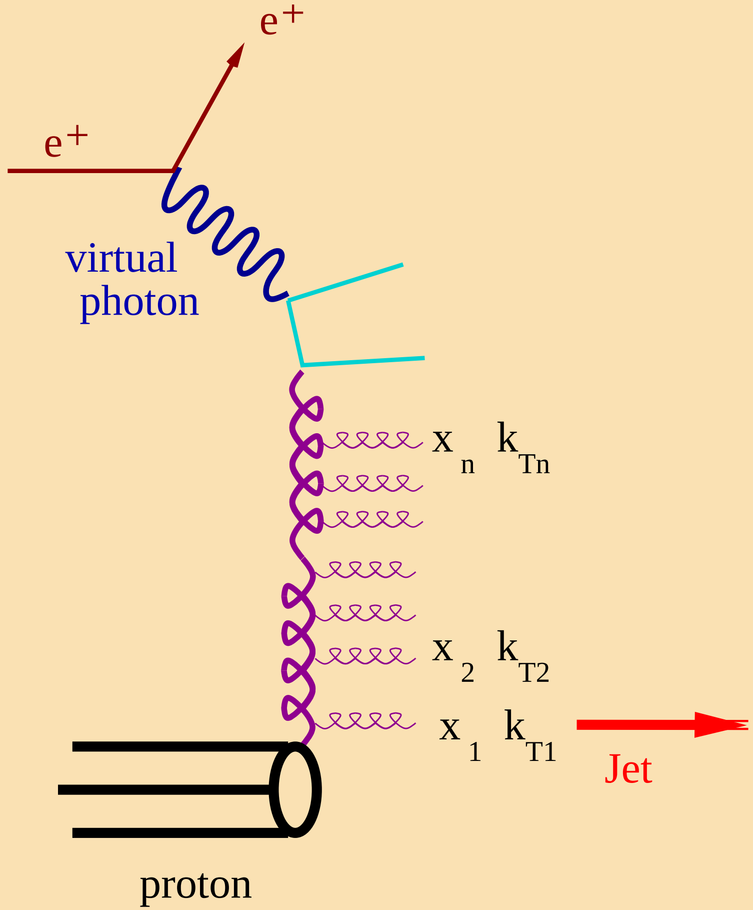
$\rightarrow$ $f_2$(NLO QCD)$= 0.0984^{+0.0074}_{-0.0131}\ (\mu_R - \text{scale})$

- 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

$\rightarrow$ **Precise test of pQCD prediction for the azimuthal asymmetry**

# Parton evolution at low $x$

- At low $x$, dijet data may be used to gain insight into parton dynamics




- The evolution of the PDFs with $\mu_F$ is described by the DGLAP evolution equations
- The DGLAP equations sum the leading powers of $\alpha_s \log Q^2$ in the region of strongly-ordered transverse momenta
  $\rightarrow Q^2 \gg k_{Tn}^2 \gg \ldots \gg k_{T2}^2 \gg k_{T1}^2$
  (LLA: strong $k_T$-ordered parton cascade)

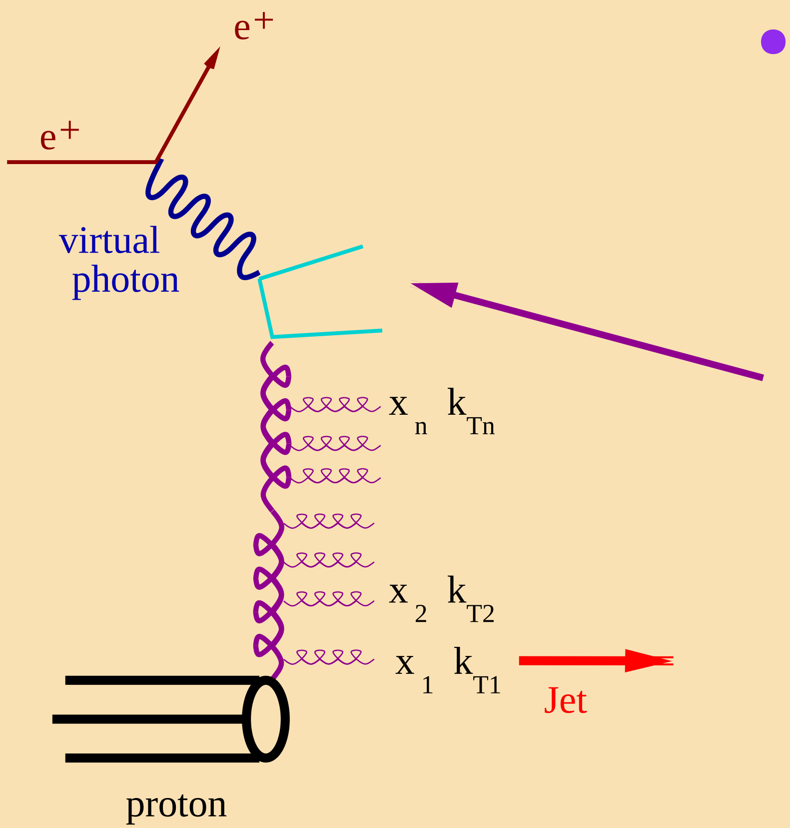
$\longrightarrow$ successful description of jet production at large scales

- DGLAP approximation expected to break down at low $x$ $\longrightarrow$ when $\log Q^2 \ll \log 1/x$, terms proportional to $\alpha_s \log 1/x$ become important and need to be summed

- The BFKL equations accomplish this:
  $\longrightarrow$ the integration is taken over the full $k_T$ phase space of the gluons
  $\longrightarrow$ no $k_T$ ordering

# Parton evolution at low $x$

- The CCFM parton evolution with angular-ordered parton emission is equivalent to the BFKL approach for $x \to 0$ and reproduces the DGLAP evolution at large $x$
- Do the properties of the dijet system depend on the dynamics of the ladder?
  $\longrightarrow$ $k_T$ ordered or unordered evolution of cascade
- Possible deviations from the DGLAP approach can be tested at small $x$, where strong $k_T$-ordering of the exchanged parton cascade is no longer strictly fulfilled

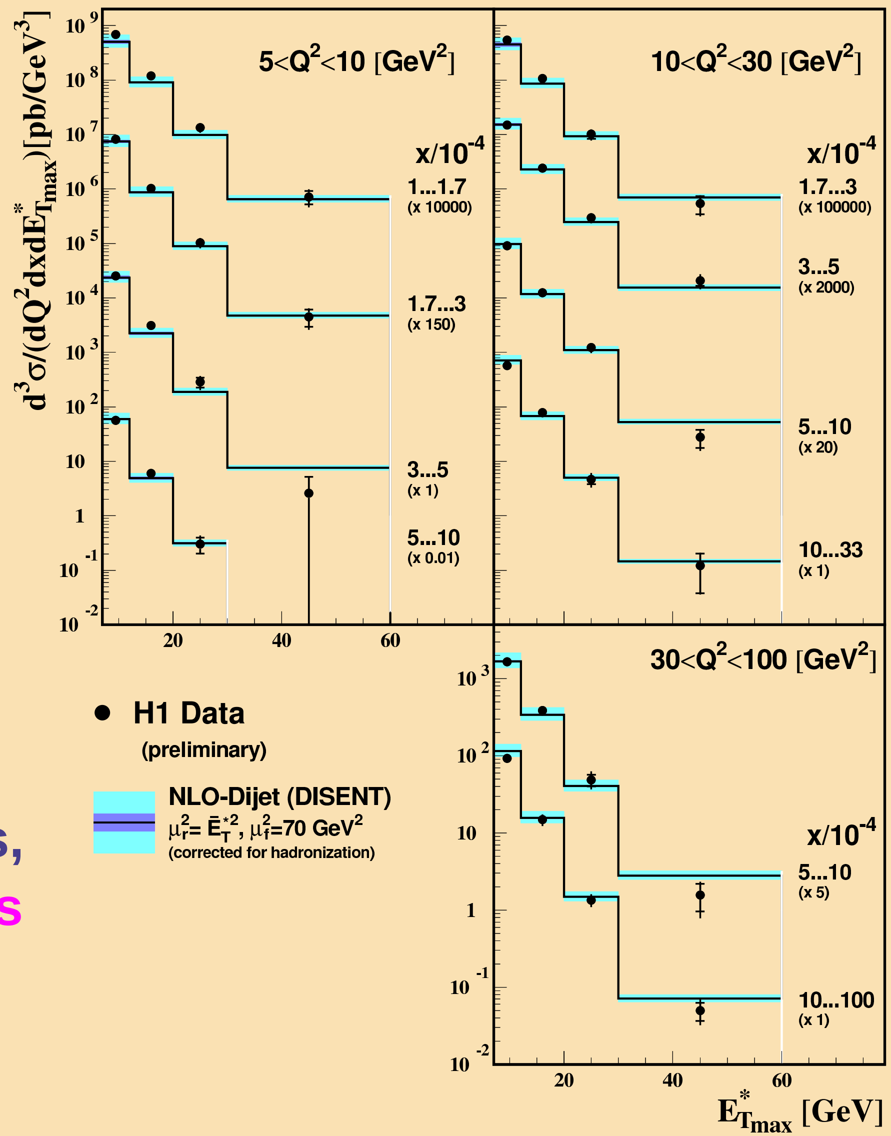



- At small $x$: parton emission along the exchanged gluon ladder increases with decreasing $x$
  $\longrightarrow$ not included in DGLAP: additional contributions have to be included when predicting cross sections at low $x$
  $\longrightarrow$ the two outgoing hard partons are no longer balanced in transverse momentum: excess of events with the hard partons no longer back-to-back in azimuth

# Triple differential cross section: $d\sigma/dQ^2dxdE_T^*$

- Jets searched with $k_T$ algorithm in the $\gamma^*p$ cms frame
- At least two jets with $E_T^* > 5$ GeV, $-1 < \eta_{\rm LAB}^{\rm jet} < 2.5$ and $E_{T,\max}^* > 7$ GeV
- Kinematic range: $5 < Q^2 < 100$ GeV$^2$ and $10^{-4} < x < 10^{-2}$

Contributed paper to EPS03




- Comparison to NLO predictions (DISENT):
  - $\rightarrow \mu_R^2 = \bar{E_T^*}^2$ and $\mu_F^2 = 70$ GeV$^2$
  - $\rightarrow p$ PDFs: CTEQ6M
- Theoretical uncertainties:
  - $\rightarrow$ higher orders ($20\%$)
  - $\rightarrow$ parton-to-hadron corrections ($10\%$)
- Good agreement between data and NLO calculations within the present uncertainties, even at small values of $E_{T,\max}^*$ where effects due to small-$x$ dynamics should be most prominent

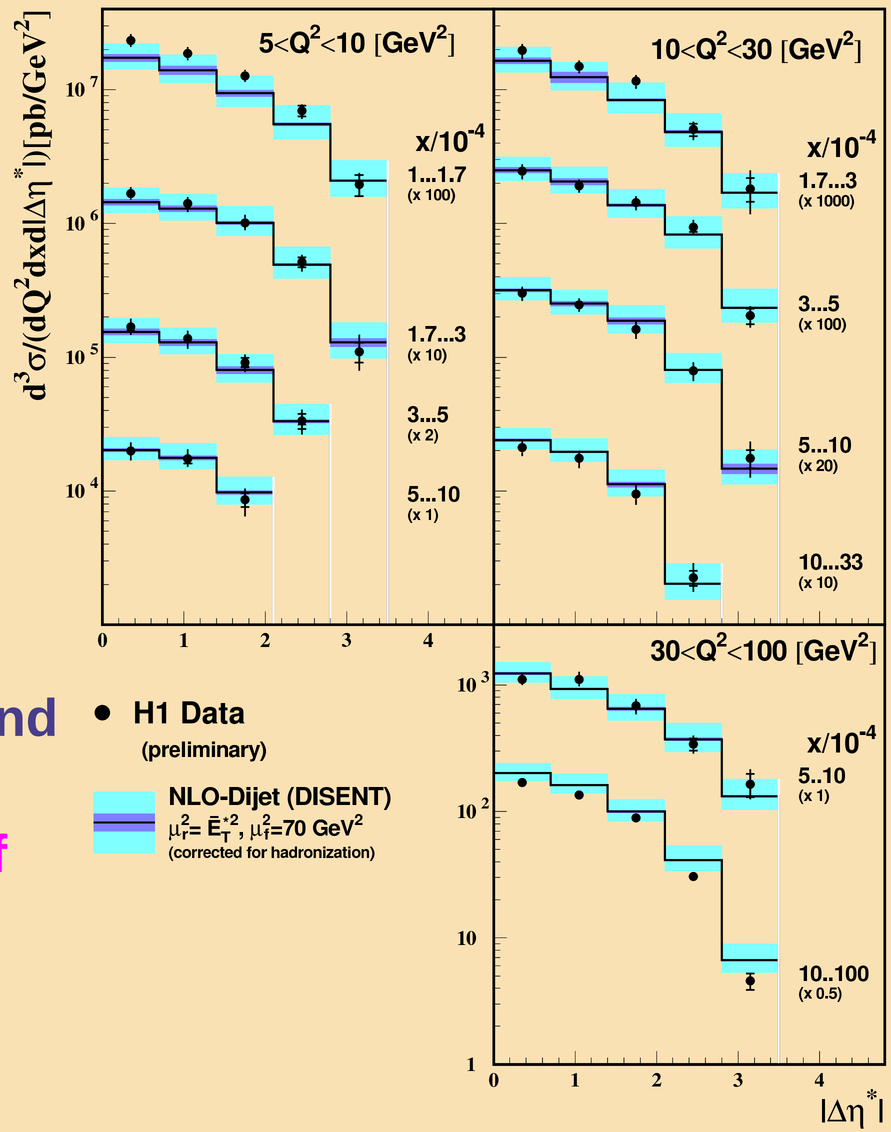
# Triple differential cross section: $d\sigma/dQ^2dx|\Delta\eta^*|$

– Jets searched with $k_T$ algorithm in the $\gamma^* p$ cms frame

– At least two jets with $E_T^* > 5$ GeV, $-1 < \eta_{\rm LAB}^{\rm jet} < 2.5$ and $E_{T,\rm max}^* > 7$ GeV

– Kinematic range: $5 < Q^2 < 100$ GeV$^2$ and $10^{-4} < x < 10^{-2}$

Contributed paper to EPS03




- Comparison to NLO predictions (DISENT):
  $\rightarrow \mu_R^2 = \bar{E_T^*}^2$ and $\mu_F^2 = 70$ GeV$^2$
  $\rightarrow p$ PDFs: CTEQ6M

- No significant disagreement between data and NLO calculations within the uncertainties, small deviations observed at small values of $x,\ Q^2$ and $|\Delta\eta^*|$

# Azimuthal jet separation

- Measurement of the azimuthal separation, $\Delta\phi^*$, of the two hardest jets in the $\gamma^* p$ cms

Contributed paper to EPS03

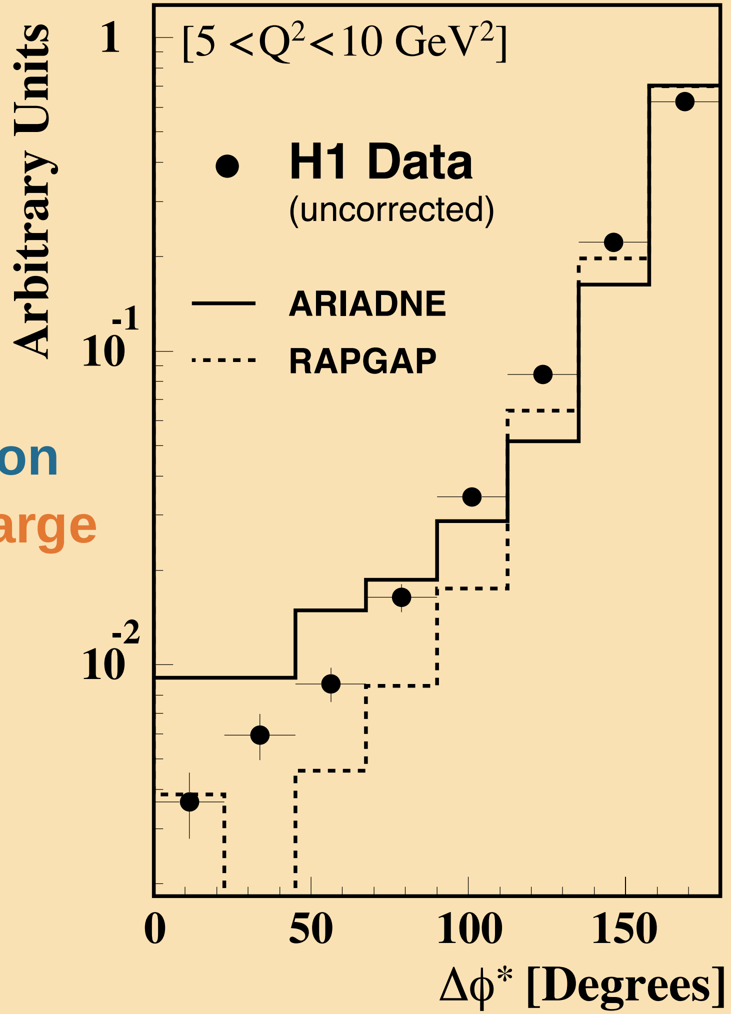
- DGLAP: $\Delta\phi^* \neq \pi$ can occur due to higher order effects
- BFKL and CCFM: number of events with $\Delta\phi^* < \pi$ should increase due to partons entering the hard process with large $k_T$

$\longrightarrow$ A significant fraction of events observed at small azimuthal separation

- The measurement of a multi-differential cross section as a function of $x$, $Q^2$ and $\Delta\phi^*$ is difficult due to large migrations
- The ratio

$$\rightarrow S = \frac{\int_0^\alpha N_{2\text{jet}}(\Delta\phi^*, x, Q^2) d\Delta\phi^*}{\int_0^\pi N_{2\text{jet}}(\Delta\phi^*, x, Q^2) d\Delta\phi^*}, \quad \alpha = \frac{2}{3}\pi$$

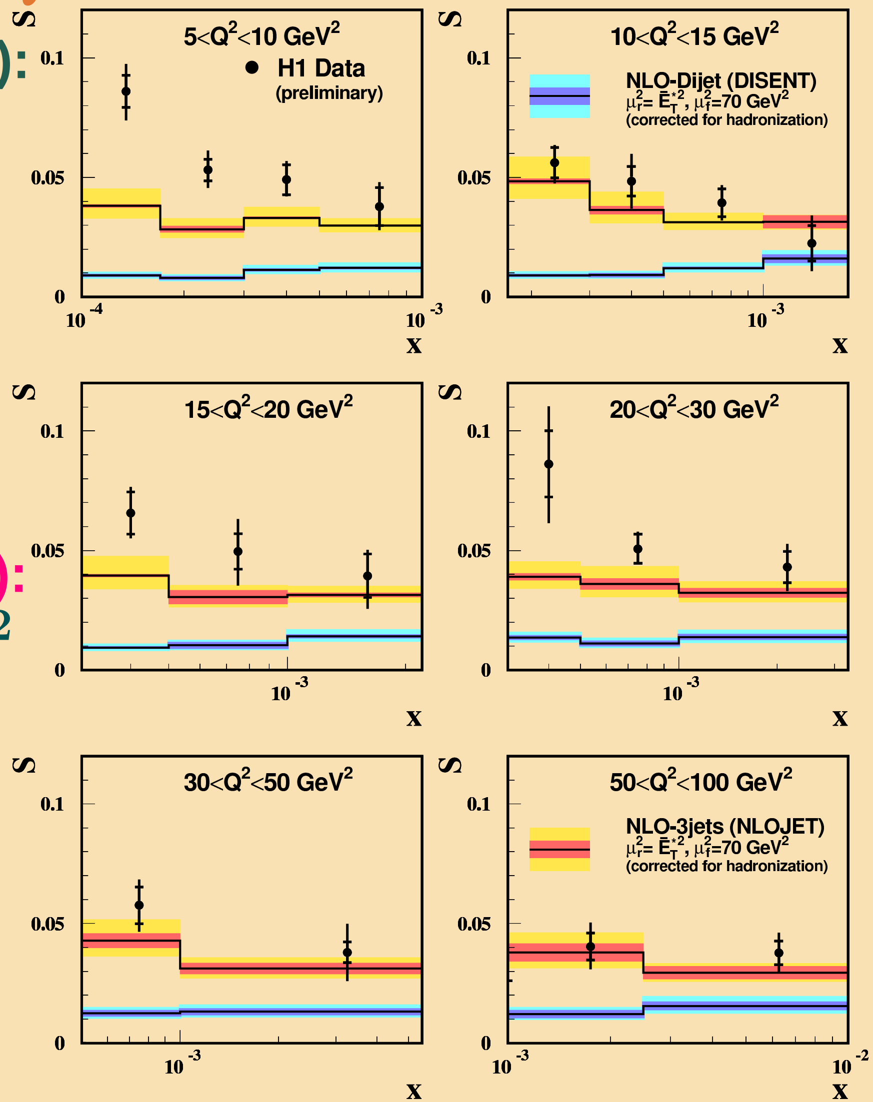
is better suited to test small-$x$ effects



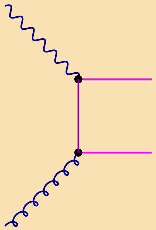
# $x$ and $Q^2$ dependence of $S$

- Measurement of the $S$ distribution as a function of $x$ in bins of $Q^2$
- The data rise towards low $x$, especially at low $Q^2$
- Comparison to NLO-dijet predictions (DISENT):
  - $\longrightarrow$ the calculations are several standard deviations below the data and show no rise towards low $x$

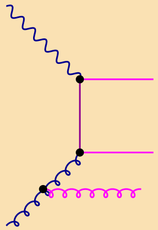
Contributed paper to EPS03




**DISENT:**



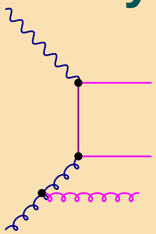
no $k_T$



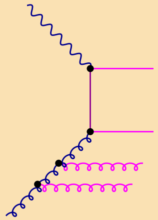
$k_T$

- Comparison to NLO-3jet predictions (NLOJET):
  - $\longrightarrow$ accurate description of the data at large $Q^2$ and large $x$
  - $\longrightarrow$ fail to describe the increase towards low $x$, especially at low $Q^2$

**NLOJET:**



$k_T$

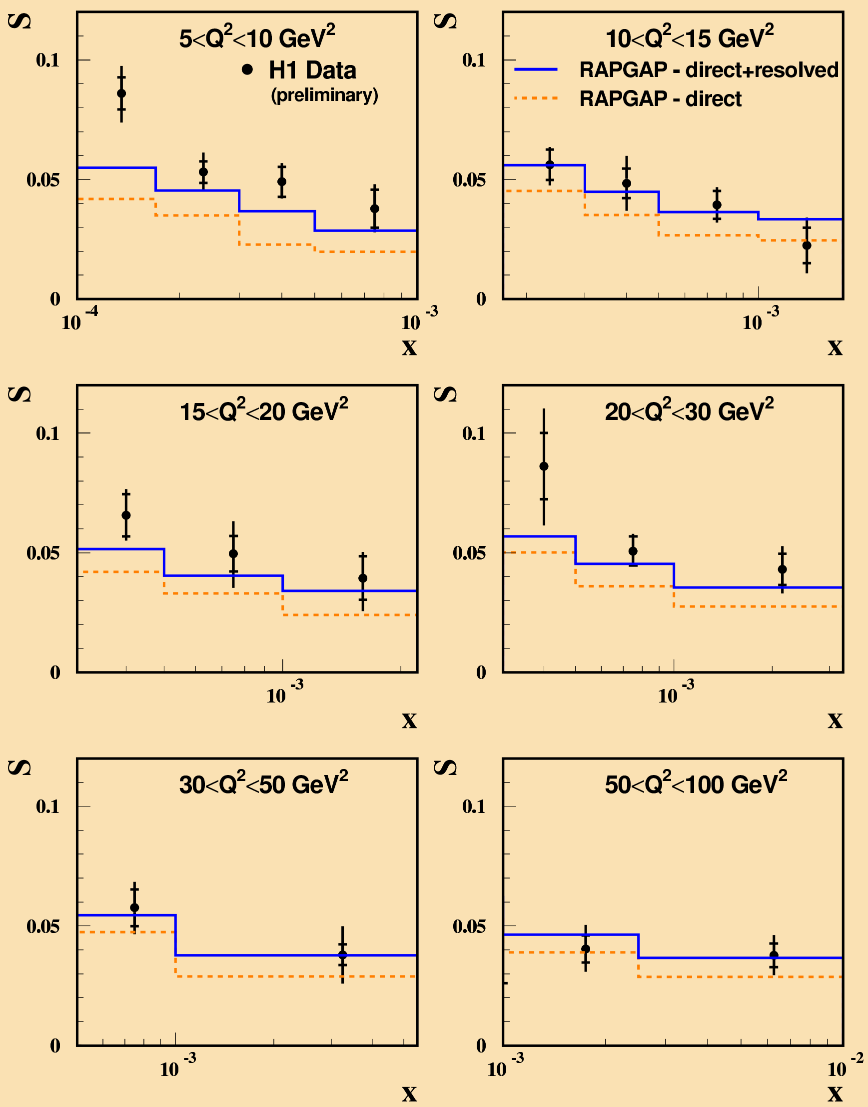


$k_T$

# $x$ and $Q^2$ dependence of $S$

- Measurement of the $S$ distribution as a function of $x$ in bins of $Q^2$

Contributed paper to EPS03



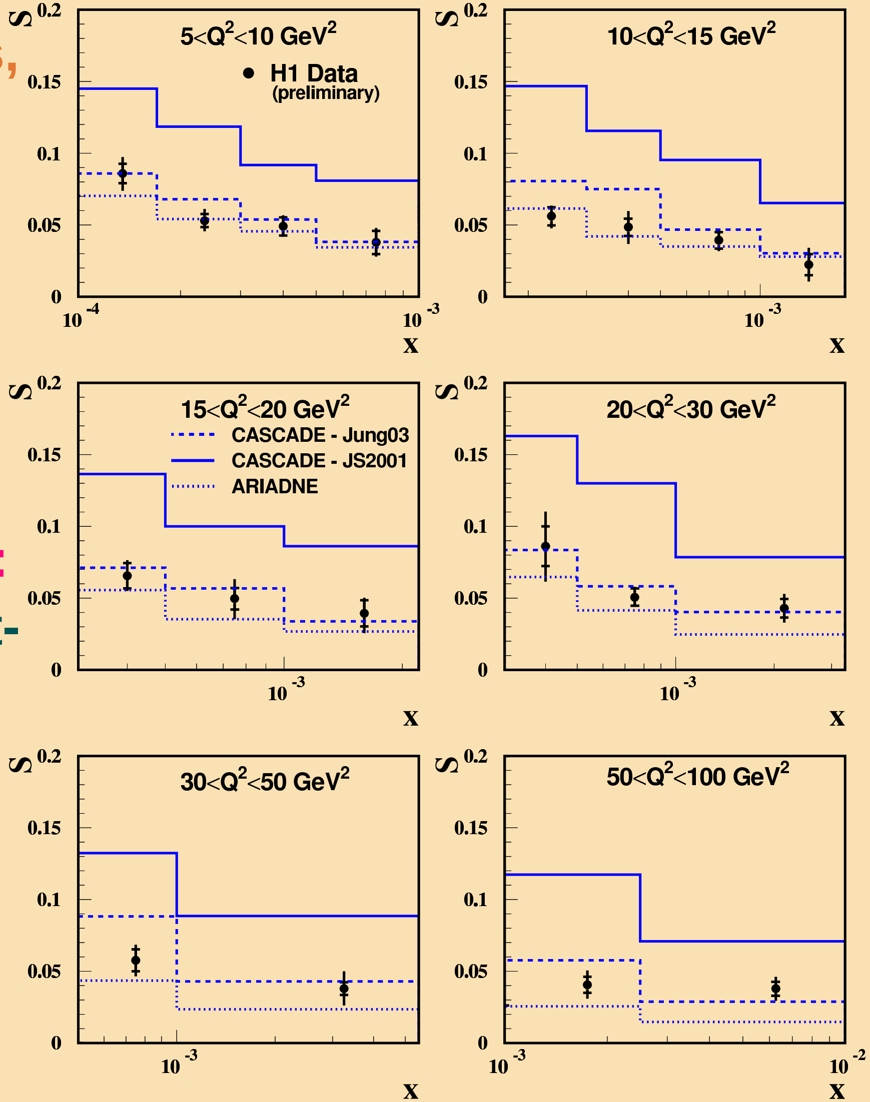

→ A useful comparison is only provided by models which incorporate higher order effects beyond NLO

- Comparison to RAPGAP predictions (DGLAP approach):
  - → good description of data at large $Q^2$ and large $x$
  - → fail to describe the increase towards low $x$, especially at low $Q^2$
  - → improved description of data when incorporating resolved photons, but still prediction too low at low $x$

# $x$ and $Q^2$ dependence of $S$

- Measurement of the $S$ distribution as a function of $x$ in bins of $Q^2$

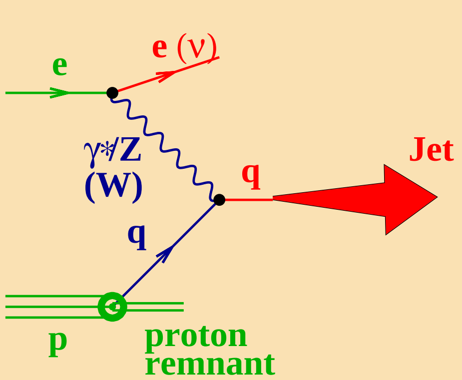
Contributed paper to EPS03




- If the observed discrepancies are due to the influence of non-$k_T$-ordered parton emissions, models based on the color dipole model or the CCFM evolution equations, may provide a much better description of the ratio $S$
- Comparison to CDM predictions (ARIADNE):
  $\longrightarrow$ good description of data at low $x$ and $Q^2$
  $\longrightarrow$ fail to describe the data at high $Q^2$
- Comparison to CCFM predictions (CASCADE):
  $\longrightarrow$ the prediction using JS2001 lies significantly above the data
  $\longrightarrow$ the prediction using the set 2 of Jung2003 closer to the data

$\longrightarrow$ The measurement of the ratio $S$ is sensitive to the details of the unintegrated gluon distribution

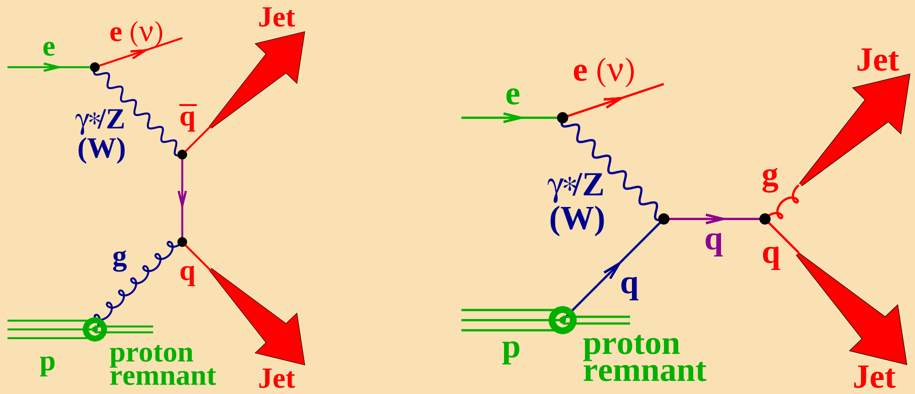
# Multijet production in NC DIS




**jet production in the QPM:**

$$\gamma^* \longrightarrow q$$

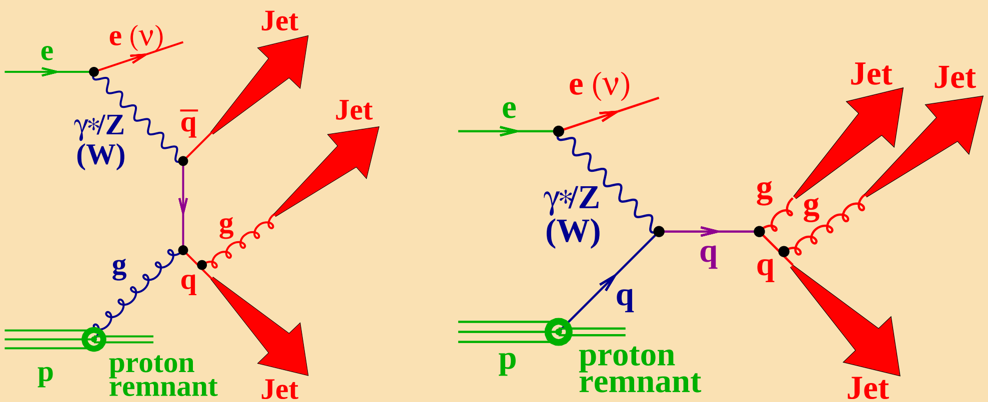
**one-jet events**




**jet production at $\mathcal{O}(\alpha_s)$:**

$$\gamma^* g \longrightarrow q\bar{q}, \gamma^* q \longrightarrow qg$$

**two-jet events**




**jet production at $\mathcal{O}(\alpha_s^2)$:**

$$\gamma^* g \longrightarrow q\bar{q}g, \gamma^* q \longrightarrow qgg$$

**three-jet events**

$\longrightarrow$ **Events with three jets can be seen as dijet processes with additional gluon radiation or splitting of a gluon in a $q\bar{q}$ pair**

$\longrightarrow$ **Direct tests of QCD beyond LO:**

$$\sigma_{3\text{jet}} \propto \alpha_s^2$$

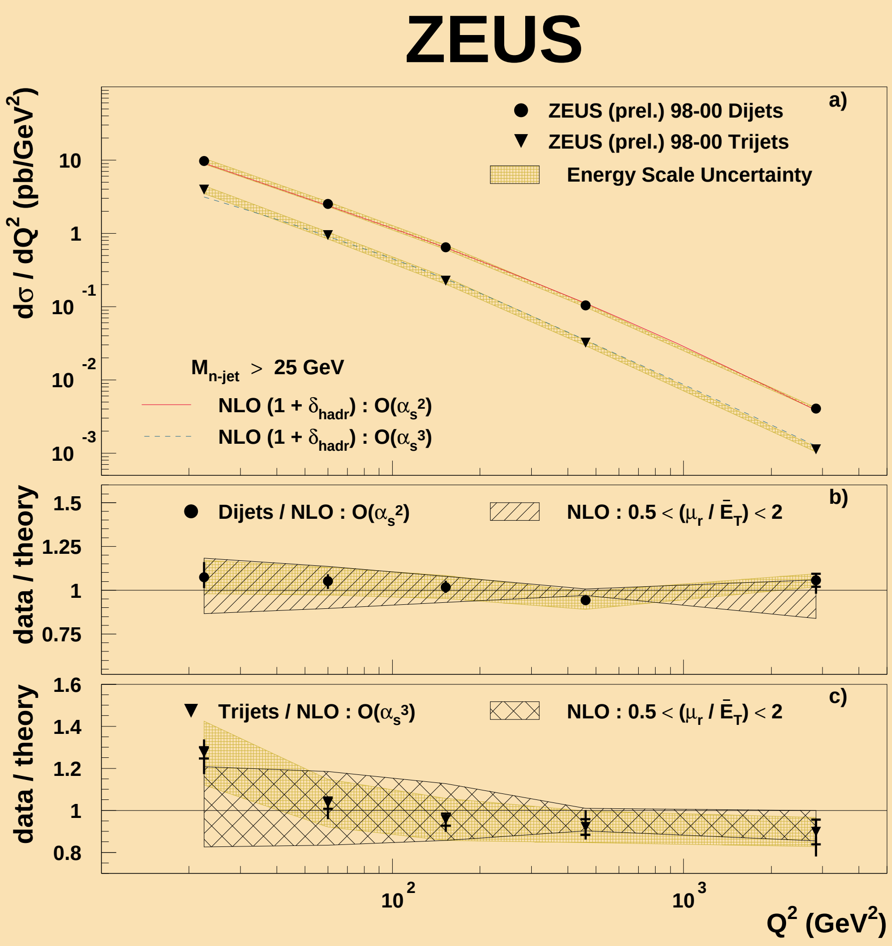
# Dijet and three-jet cross sections in NC DIS: $d\sigma/dQ^2$

– Jets searched with $k_T$ algorithm in the Breit frame
– At least two jets with $E^{\rm jet}_{T,\rm B} > 5$ GeV and $-1 < \eta^{\rm jet}_{\rm LAB} < 2.5$
– Kinematic range: $10 < Q^2 < 5000$ GeV$^2$, $0.04 < y < 0.6$ and $\cos\gamma < 0.7$
– Events with $M^{3j}(M^{jj}) > 25$ GeV were selected

Contributed paper to EPS03

- Comparison to NLO ($\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$) predictions (NLOJET):
  $\longrightarrow \mu_R = \mu_F = \bar{E}_T$
  $\longrightarrow p$ PDFs: CTEQ6
- The measured dijet and three-jet cross sections are well described by the predictions

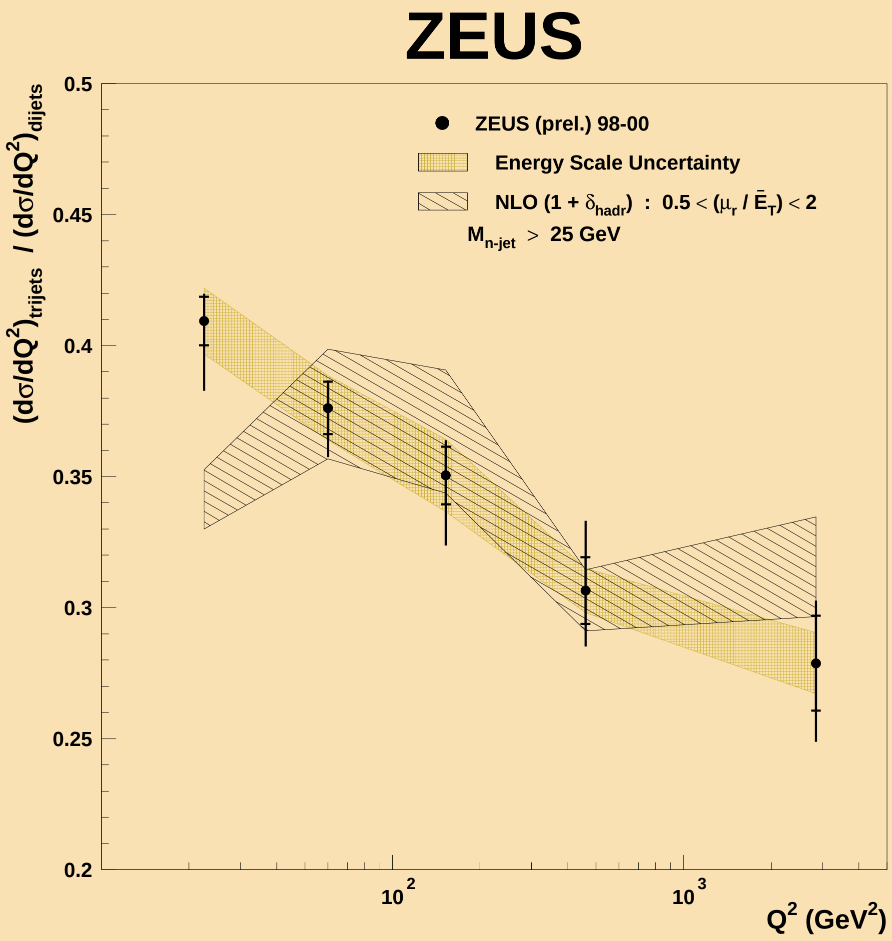
$\longrightarrow$ Potentially useful observable to make an accurate determination of $\alpha_s$



# $Q^2$ dependence of the dijet to three-jet cross section ratio

Contributed paper to EPS03

- Measurement of the dijet to three-jet cross sections ratio as a function of $Q^2$
- Many experimental and theoretical uncertainties cancel out in the ratio $\longrightarrow$ more accurate test of color dynamics
- The measured ratio is well described by the NLO calculations for $Q^2 > 50$ GeV$^2$



# Internal structure of jets

- 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 jet of hadrons
- The internal structure of a jet is expected to depend mainly on the type of primary parton, quark or gluon, from which it originated and to a lesser extent on the particular hard scattering process
- QCD predictions:

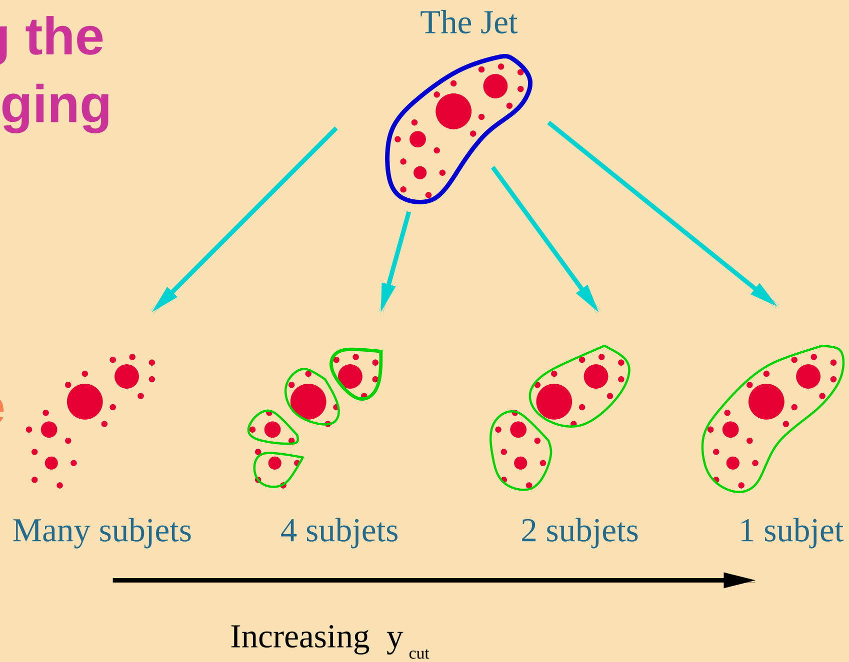
  $\longrightarrow$ At sufficiently high $E_T^{\rm jet}$, where fragmentation effects become negligible, the jet structure is expected to be driven by gluon emission off the primary parton, and therefore, calculable by pQCD

  $\longrightarrow$ Gluon jets are predicted to be broader than quark jets due to the larger colour charge of the gluon
- The lowest non-trivial-order contribution to the jet substructure is given by $\mathcal{O}(\alpha\alpha_s)$ calculations for $ep$ in LAB frame

  $\longrightarrow$ Measurements of jet substructure provide a stringent test of pQCD calculations directly beyond LO

# Internal structure of jets: subjet multiplicity

- Subjets are resolved within a jet by reapplying the $k_T$-cluster algorithm on all the particles belonging to the jet until for every pair of particles the quantity $d_{ij}$ is above $d_{\rm cut} = y_{\rm cut} \cdot (E_T^{\rm jet})^2$
- All remaining clusters are called subjets
- The subjets structure depends upon the value chosen for the resolution parameter $y_{\rm cut}$




- In pQCD, the mean subjet multiplicity, $\langle n_{\rm subjet}\rangle$ is calculated as the ratio of the cross section for $n_{\rm subjet} - 1$ subjets over that of the inclusive jet production

$$\langle n_{\rm subjet} - 1\rangle = \frac{\sigma_{n_{\rm subjet}-1}(E_T^{\rm jet})}{\sigma_{\rm jet}(E_T^{\rm jet})} \approx \frac{A_{n_{\rm subjet}-1}\cdot\alpha_s + B_{n_{\rm subjet}-1}\cdot\alpha_s^2}{C_{\rm jet} + D_{\rm jet}\cdot\alpha_s}$$

# $y_{\mathrm{cut}}$ dependence of $n_{\mathrm{subjet}}$

– Jets searched with $k_T$ algorithm in the LAB frame

– At least one jet with $E_T^{\mathrm{jet}} > 15$ GeV and $-1 < \eta^{\mathrm{jet}} < 2$

– Kinematic range: $Q^2 > 125$ GeV$^2$

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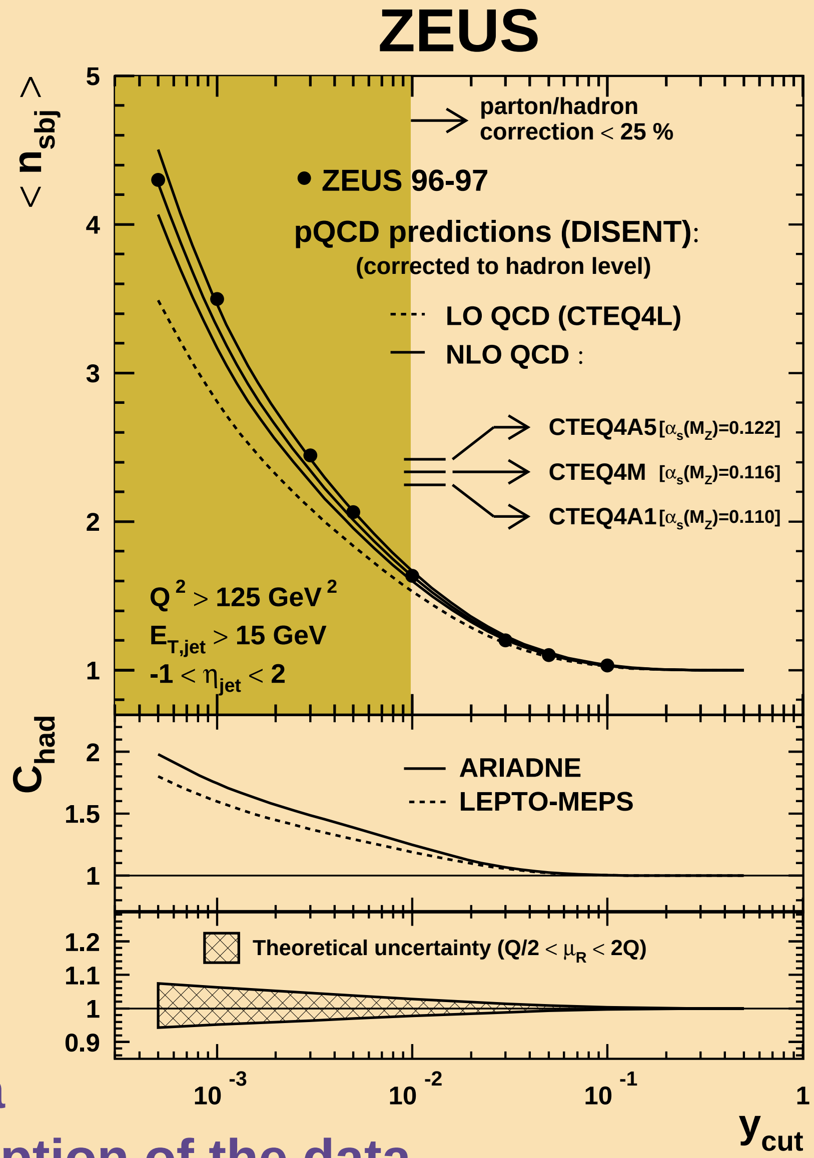


- Small experimental uncertainties for $y_{\mathrm{cut}} \geq 10^{-2}$
  - fragmentation model dependence: $< 3\%$
  - jet energy scale: $\sim 1\%$
- Small corrections for $y_{\mathrm{cut}} \geq 10^{-2}$
  - Data (detector effects): $< 10\%$
  - NLO (parton-to-hadron effects): $< 17\%$ for $E_T^{\mathrm{jet}} > 25$ GeV
- Comparison to LO/NLO predictions (DISENT):
  - $\rightarrow \mu_R = \mu_F = Q$
  - $\rightarrow p$ PDFs: CTEQ4L/M
- Comparison with QCD calculations:
  - $\rightarrow$ The LO calculations fail to describe the data
  - $\rightarrow$ The NLO calculations provide a good description of the data

# $E_T^{jet}$ dependence of $n_{subjet}$

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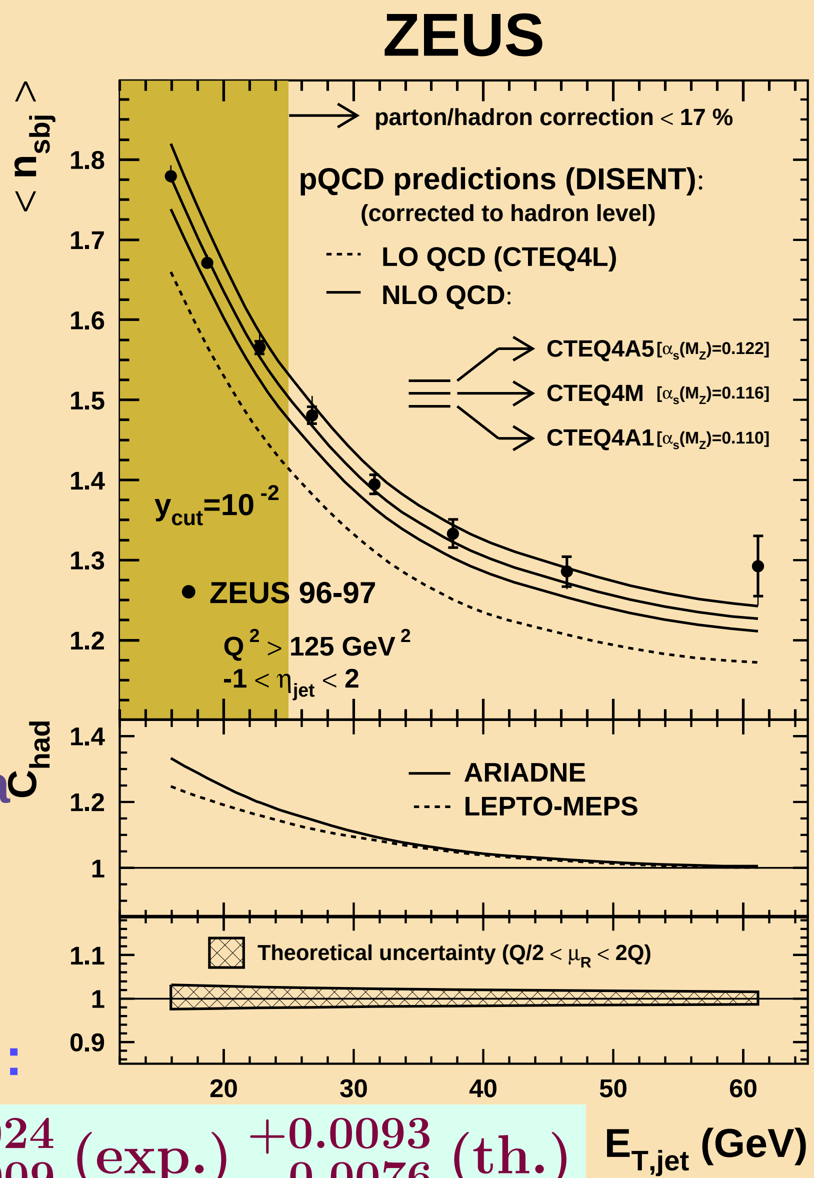
- The mean subjet multiplicity at a fixed value of $y_{cut}$, $\langle n_{subjet}(y_{cut} = 10^{-2})\rangle$, decreases as $E_T^{jet}$ increases: the jets become more collimated
- This observable is sensitive to $\alpha_s$
- The sensitivity of $\langle n_{subjet}(y_{cut} = 10^{-2})\rangle$ as a function of $E_T^{jet}$ to the value of $\alpha_s(M_Z)$ is seen by comparing the measurement to QCD calculations using three different values of $\alpha_s(M_Z)$
- Comparison with QCD calculations:
  - $\rightarrow$ The LO calculations fail to describe the data
  - $\rightarrow$ The NLO calculations provide a good description of the data: thus, it can be used to determine $\alpha_s(M_Z)$ for $E_T^{jet} > 25$ GeV

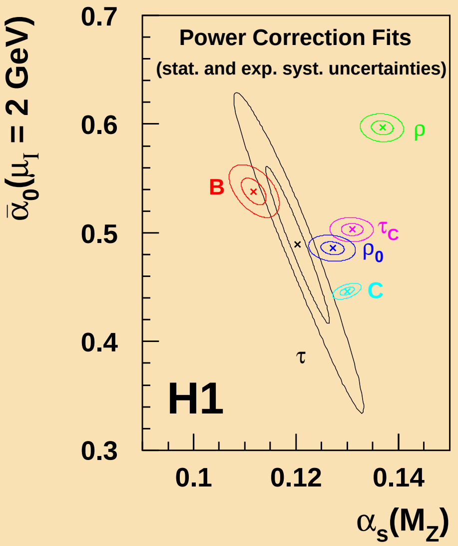
$\rightarrow$ Extraction of $\alpha_s$ from $\langle n_{subjet}(y_{cut} = 10^{-2})\rangle$:

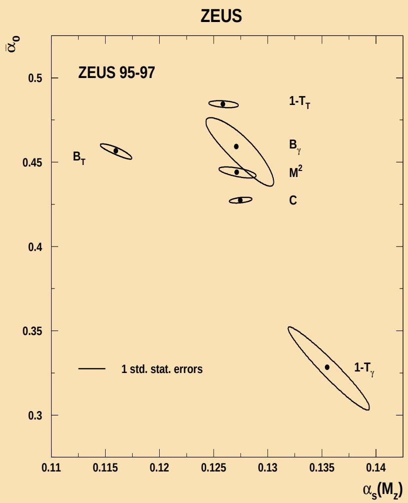
$$\rightarrow \alpha_s(M_Z) = 0.1187 \pm 0.0017\ (\text{stat.})\ ^{+0.0024}_{-0.0009}\ (\text{exp.})\ ^{+0.0093}_{-0.0076}\ (\text{th.})$$



# Event shapes

- Extraction of $\alpha_s$ from measurements of event shape variables (thrust, jet broadening) is complementary to the one from jet cross sections
- Event shape variables are particularly sensitive to the details of the non-perturbative effect of hadronisation
- Recently, new developments on the model of power-law corrections have prompted revived interest in the understanding of hadronisation within the framework of pQCD
- In this type of analysis, the data are compared to a model prediction which consists of a combination of NLO QCD calculations and the theoretical expectations of the power corrections, characterised by an effective coupling $\bar{\alpha}_0$
- Previous results give support to the concept of power corrections in the approach of Dokshitzer et al.




→ but a large spread in the fitted values for $\alpha_s$ suggested higher orders QCD needed

→ resummed NLL calculations matched to NLO, are now available

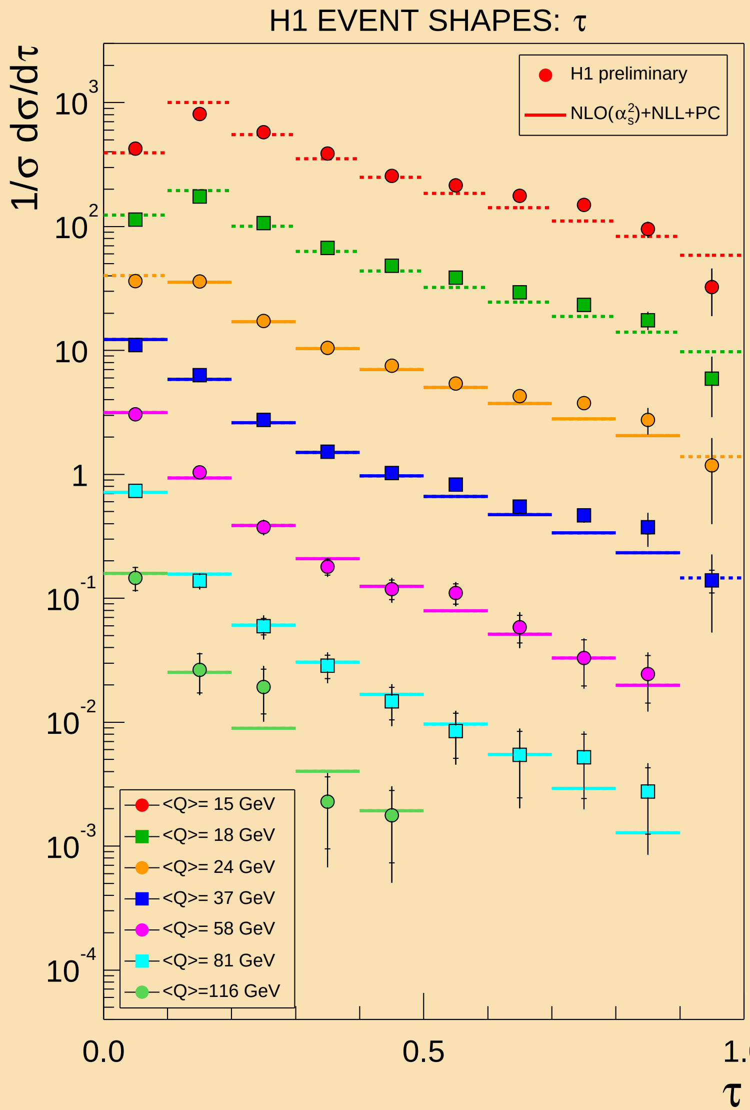
→ and it is possible to study event shape distributions instead of only mean values

# Event shape distributions: thrust

- A suitable frame in which to study event shapes at HERA is the Breit frame
  $\longrightarrow$ the separation between the current jet and the proton remnant is maximal

Contributed paper to EPS03

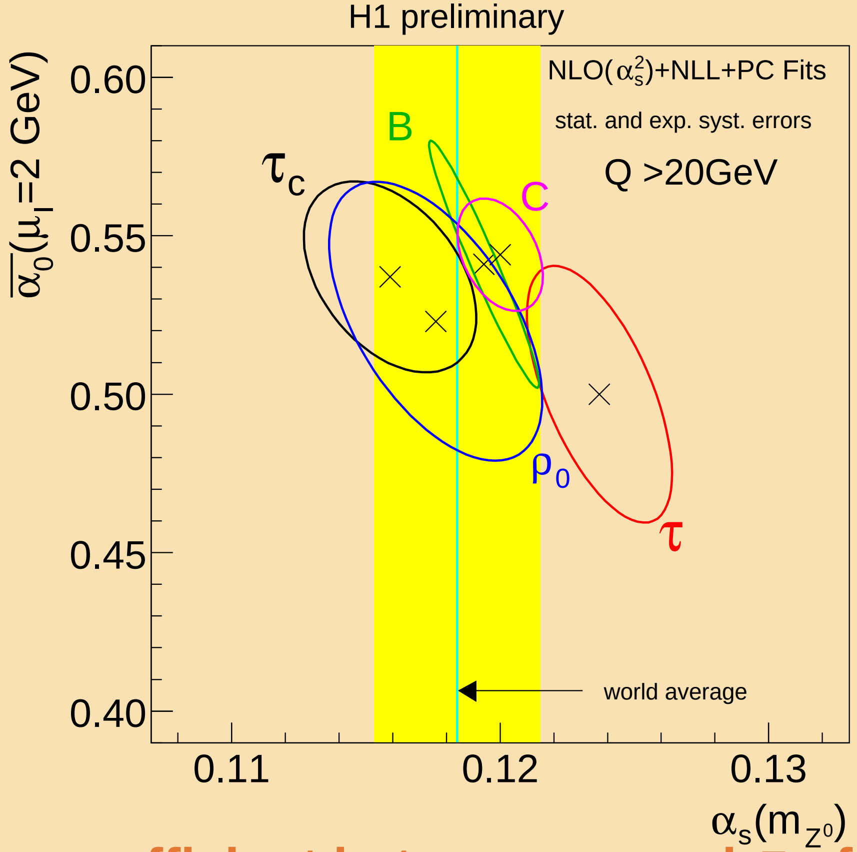
- Measurement of event shape distributions for $14 < Q < 200$ GeV and $0.1 < y < 0.7$:
  $\longrightarrow$ thrust $\tau$ and $\tau_C$, jet broadening $B$, jet mass $\rho$ and $C$ parameter are defined for particles in the current hemisphere ($\eta < 0$)
  $\longrightarrow$ jet rates are defined using the $k_T$ algorithm for all hadrons in both hemispheres
- Example: corrected measured distribution for thrust and fitted theory prediction
- Theory:
  - DISASTER++ (CTEQ5M1 pPDFs)
  - resummation matched to NLO and power corrections
  - $\chi^2$ fit to data
  - free parameters: $\alpha_s(M_Z)$ and $\bar{\alpha}_0$
- A good description of the data by the QCD predictions is obtained at high $Q^2$
- The description of the data at low $Q^2$ is poorer



# Test of the power corrections model

- The $1\sigma$ contours of the results of $\bar{\alpha}_0$ and $\alpha_s$:

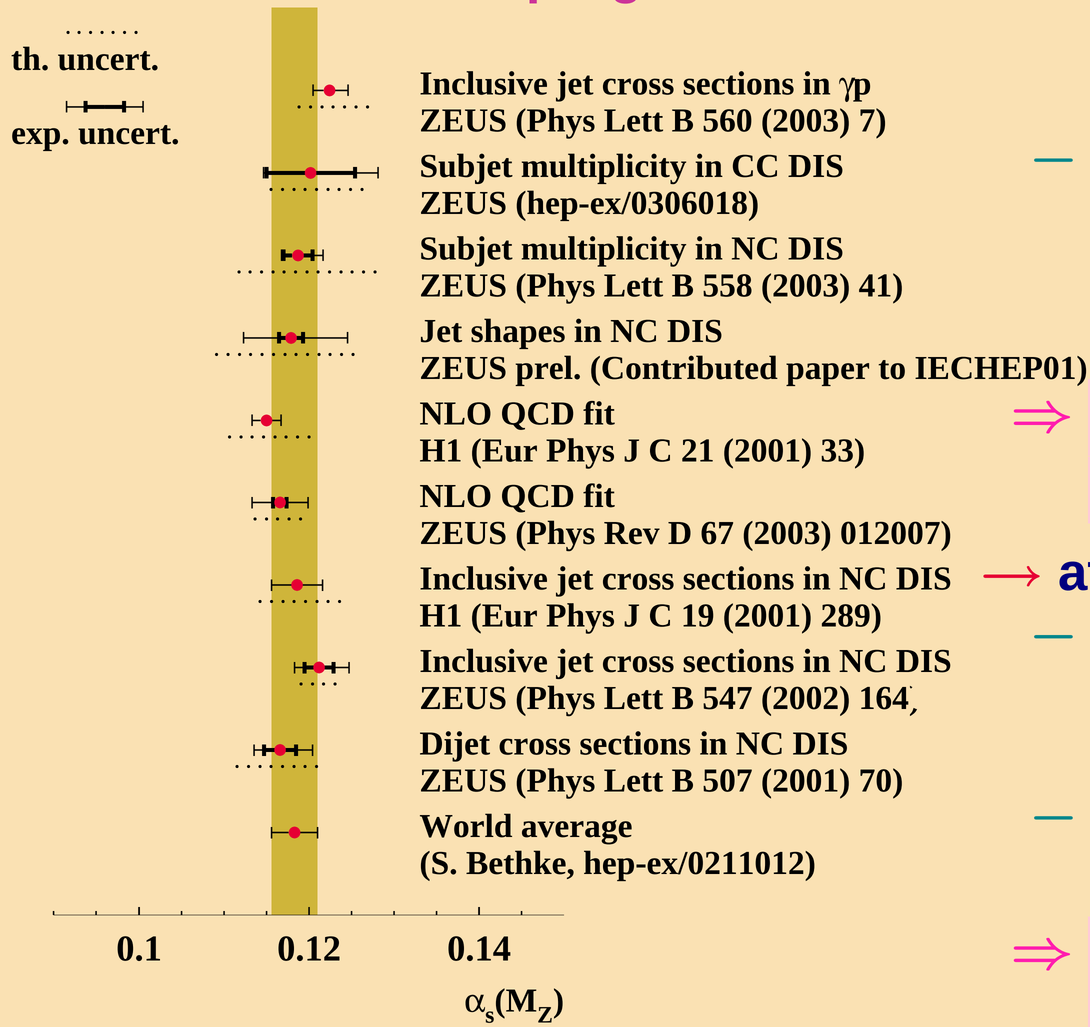
Contributed paper to EPS03




- Negative correlation coefficient between $\alpha_s$ and $\bar{\alpha}_0$ found for all variables
- Universal non-perturbative parameter $\bar{\alpha}_0 = 0.5$ at the $10\%$ level in agreement with previous results but with smaller spread
- Sizeable theoretical uncertainty coming from higher orders ($\sim 5\%$ for both $\bar{\alpha}_0$ and $\alpha_s$, as large as experimental uncertainty)

# Conclusions

- **HERA has become a unique QCD-testing machine due to**
  - → **at large scales:**
    - – considerable progress in understanding and reducing uncertainties led to very precise measurements of the fundamental parameter of the theory
    - – the use of observables resulting from jet algorithms leads to determinations of $\alpha_s$ as precise as those from more inclusive measurements (eg $\tau$ decay)




⇒ **Improved calculations needed for better accuracy**

  - → **at low $x$ and low $Q^2$:**
    - – considerable progress in understanding the mechanisms for parton emission has been achieved
    - – interplay of DGLAP ↔ BFKL ↔ CCFM dynamics has still to be fully worked out

⇒ **Further progress needs more experimental and theoretical work**