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Jet production at HERA

from

ZEUS Collab.

H1 Collab.

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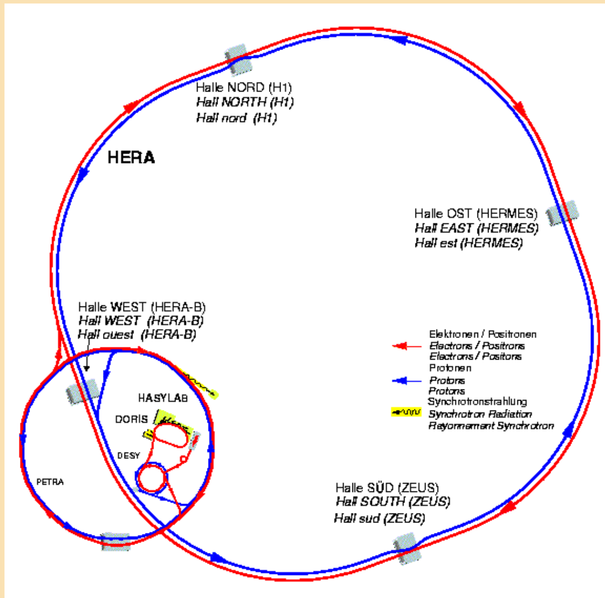
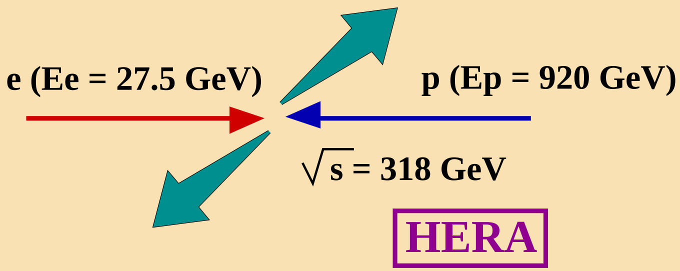
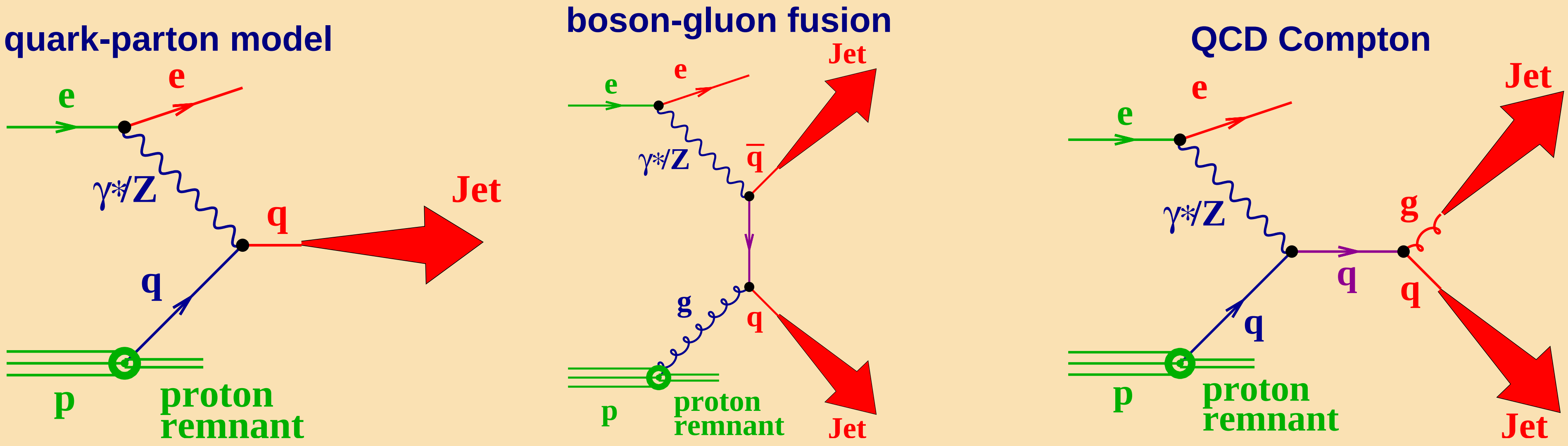
at





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:**

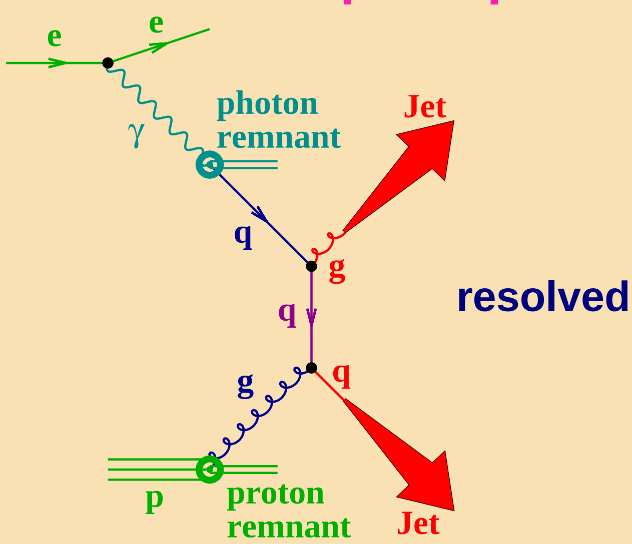
$$d\sigma_{\rm jet} = \sum_{a=q,\bar{q},g} \int dx\, f_a(x,\mu_F)\, d\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_R,\mu_F)$$

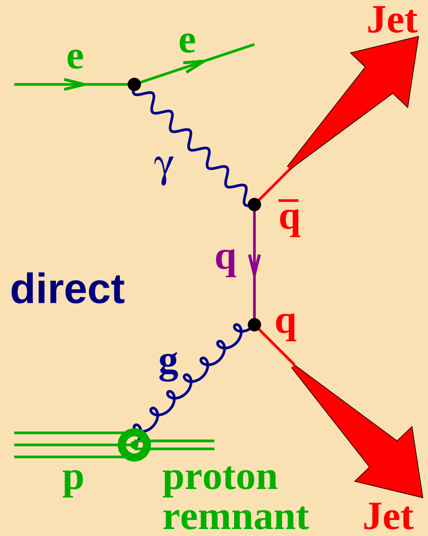
– f_a: parton a density in the proton, determined from experiment
  $\longrightarrow$ long-distance structure of the target

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

Jet production in photoproduction

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





- Jet production cross section:

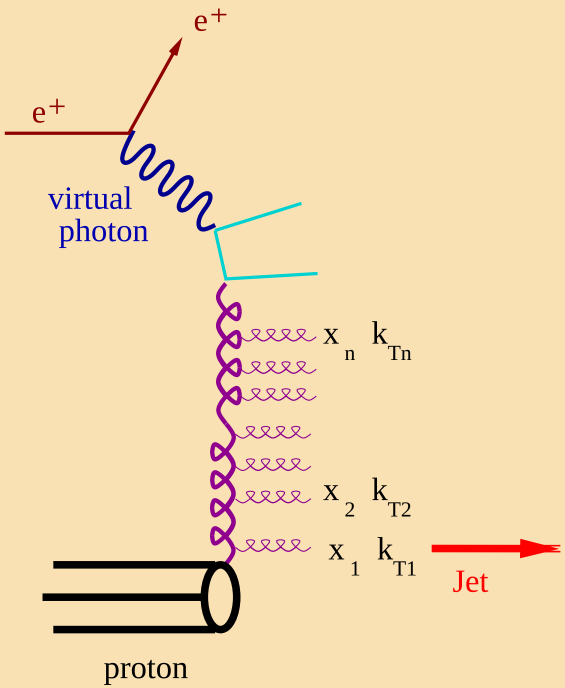
$$d\sigma_{\rm jet} = \sum_{i,j} \int_0^1 dy\; dx_\gamma\; dx_p\; f_{\gamma/e}(y)\;\; f_{i/\gamma}(x_\gamma, \mu_{F_\gamma})\;\; f_{j/p}(x_p, \mu_{F_p})\; d\hat\sigma_{i(\gamma)j}(i(\gamma)j \rightarrow {\rm jet\ jet})$$

  – $f_{j/p}(f_{i/\gamma})$: parton density in the proton (photon)
  $\longrightarrow$ long-distance structure of the target

  – $\hat\sigma_{i(\gamma)j}$: subprocess cross section, calculable in pQCD
  $\longrightarrow$ short-distance structure of the interaction

DGLAP evolution

- A wealth of data from fixed target and collider experiments has allowed an accurate determination of the proton PDFs: evolution of the PDFs with μ_F generally described by DGLAP equations



- To leading log accuracy, DGLAP evolution is equivalent to the exchange of a parton cascade with the exchanged partons strongly ordered in virtuality:

$$Q^2 \gg k_{Tn}^2 \gg \ldots \gg k_{T2}^2 \gg k_{T1}^2$$

- At high scales (Q, $E_T^{\rm jet}$), calculations using the DGLAP evolution equations give a good description of the data at NLO

$\Rightarrow$ Measurements of jet production have provided

$\longrightarrow$ sensitive tests of pQCD (short-distance structure)

$\longrightarrow$ precise determinations of α_s

Parton evolution at low x

- DGLAP approximation expected to break down at low x since only leading logs in Q^2 are resummed and contributions from $\log 1/x$ are neglected
  $\rightarrow$ when $\log Q^2 \ll \log 1/x$, terms proportional to $\alpha_s \log 1/x$ become important

- This breakdown may have been observed in forward jet and production at HERA

- Several theoretical approaches exist which account for low-x effects:
  - BFKL evolution: resummation of large $\log 1/x$ to all orders (very low x)
    $\rightarrow$ no k_T ordering
  - CCFM evolution: angular-ordered parton emission (low and larger x)
    $\rightarrow$ equivalent to BFKL for $x \rightarrow 0$ and to DGLAP at large x
  - virtual-photon structure: higher-order QCD effects mimicked at low x by introducing a second k_T-ordered parton cascade on the photon side
    $\rightarrow$ resolved is expected to contribute for $(E_T^{\rm jet})^2 > Q^2$ and suppressed with increasing Q^2

Theoretical calculations

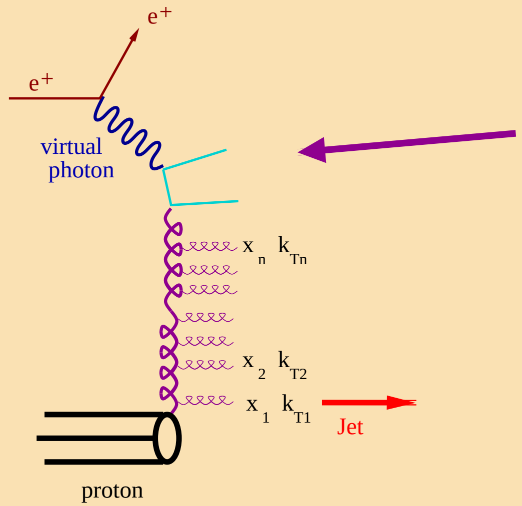
- **DGLAP evolution:**
  - NLO QCD calculations
    $\longrightarrow$ for dijets: $A\alpha_s + B\alpha_s^2$ (DISENT)
    $\longrightarrow$ for three jets: $C\alpha_s^2 + D\alpha_s^3$ (NLOJET)
  - Leading-logarithm parton-shower Monte Carlo models
    $\longrightarrow$ RAPGAP (direct or direct+resolved): generates k_T-ordered parton cascades as in DGLAP evolution

- **Monte Carlo calculations beyond DGLAP, which incorporate low-x effects:**
  - CASCADE: based on k_T factorised unintegrated parton distributions (CCFM)
  - ARIADNE: generates non-k_T ordered parton cascades based on the color dipole model (BFKL-like)

Experimental evidence for DGLAP breakdown

- Experimentally, deviations from DGLAP evolution are expected at low x and forward jet rapidity since parton emission along the exchanged gluon ladder increases with decreasing x

- In DGLAP, partons entering the hard process with negligible k_T produce a back-to-back configuration at LO ($\Delta\phi \sim 180^\circ$)
  $\rightarrow$ $\Delta\phi < 180^\circ$ occur in DGLAP due to higher-order QCD effects
- Also, $\Delta\phi < 180^\circ$ in models which predict a significant proportion of partons entering the hard process with large k_T (BFKL, CCFM): **number of events with small $\Delta\phi$ increases**



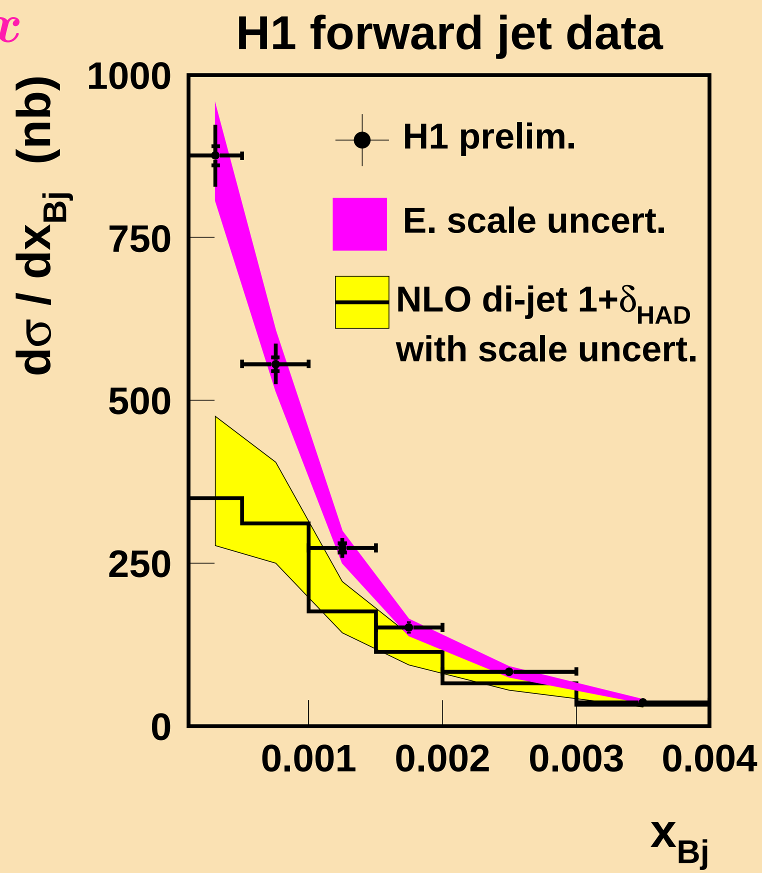
$\rightarrow$ insight into low-x dynamics can be gained also by studying the azimuthal separation between the two hardest jets: an excess of events at small $\Delta\phi$ would signal a deviation from DGLAP evolution

Forward jet production at low x in NC DIS

– Jets searched with k_T algorithm in the LAB frame
– At least one jet with $E_T^{jet} > 3.5$ GeV and $1.7 < \eta^{jet} < 2.8$; $x_{jet} = \frac{E_{jet}}{E_p} > 0.035$ and $0.5 < \frac{(E_T^{jet})^2}{Q^2} < 5$
– Kinematic range: $5 < Q^2 < 85$ GeV^2 and $0.0001 < x < 0.004$

H1 preliminary

$\longrightarrow$ Forward-jet cross section rises with decreasing x



- Comparison to NLO predictions (DISENT):
  – $\mu_R^2 = \langle (E_T^{jet})^2 \rangle = 45$ GeV^2
  – p PDFs: CTEQ6M

$\longrightarrow$ The measured forward-jet cross section is described by the prediction for large x values

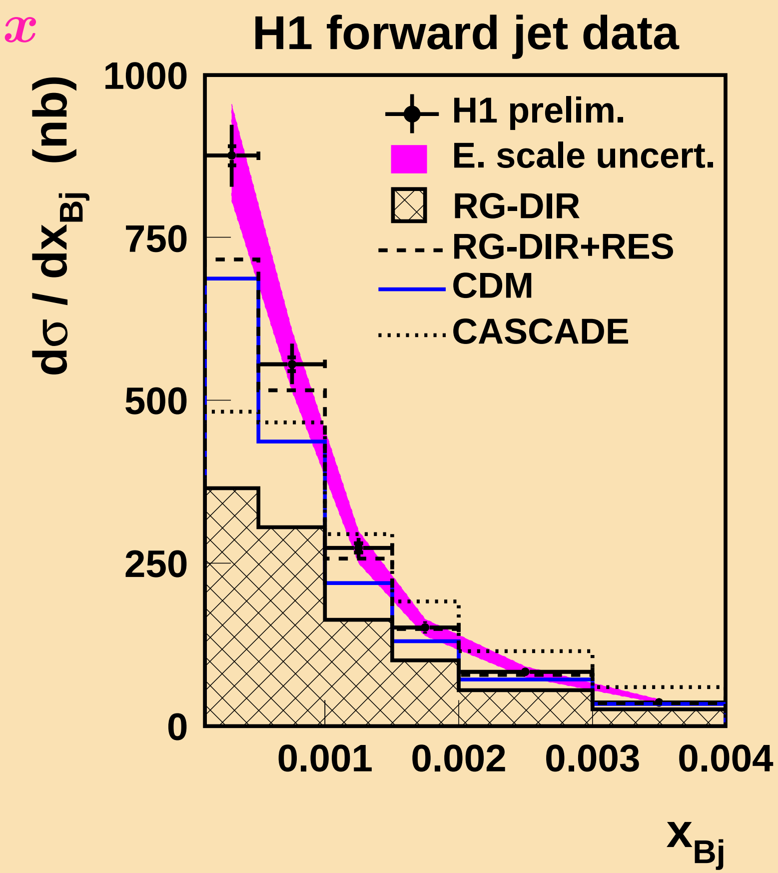
$\longrightarrow$ At low x values, there is a large excess of data wrt to NLO QCD (DGLAP)

Forward jet production at low x in NC DIS

H1 preliminary

$\longrightarrow$ Forward-jet cross section rises with decreasing x

- Comparison to Monte Carlo predictions:
  - $\longrightarrow$ RAPGAP (DGLAP evolution): similar to NLO prediction
  - $\longrightarrow$ RAPGAP (res+dir) and ARIADNE (CDM): good description of data for $x > 0.001$
  - $\longrightarrow$ CASCADE (J2003): lower (higher) than data at low (high) x



- No model can describe the sharp rise of the data at very low x

Azimuthal jet separation

- 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 $10^{-4} < x < 10^{-2}$

$\longrightarrow$ 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

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

is better suited to test small-x effects

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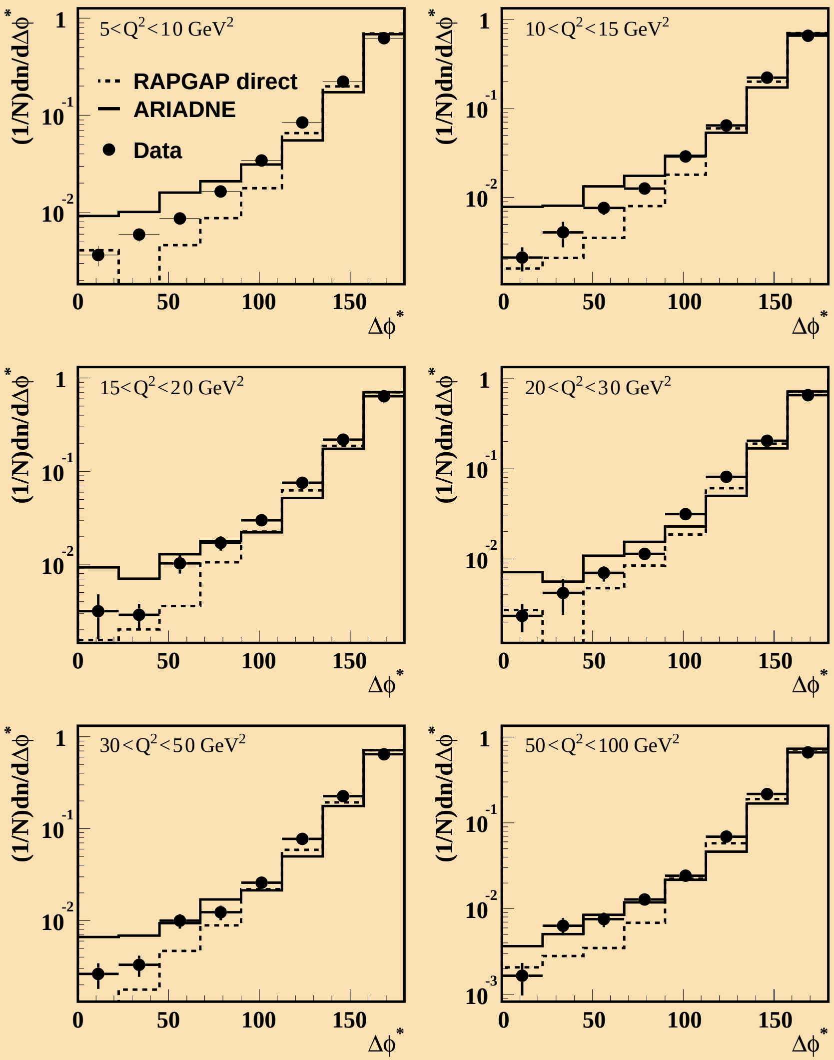
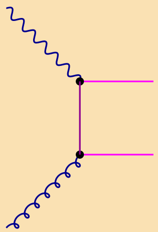


x and Q^2 dependence of S

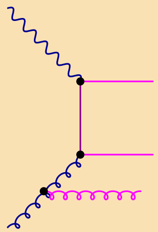
- The data rise towards low x, especially at low Q^2

- Comparison to DISENT ($\mathcal{O}(\alpha_s)$):

DISENT:



no k_T



lowest order contribution to S

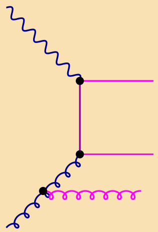
k_T

$\longrightarrow$ several standard deviations below the data

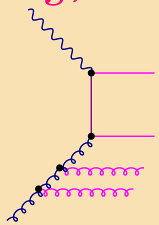
$\longrightarrow$ no rise towards low x

- Comparison to NLOJET ($\mathcal{O}(\alpha_s^2)$):

NLOJET:



k_T



NLO contribution to S

k_T

$\longrightarrow$ good description of data at large Q^2 and x

$\longrightarrow$ fail to describe the increase towards low x, especially at low Q^2

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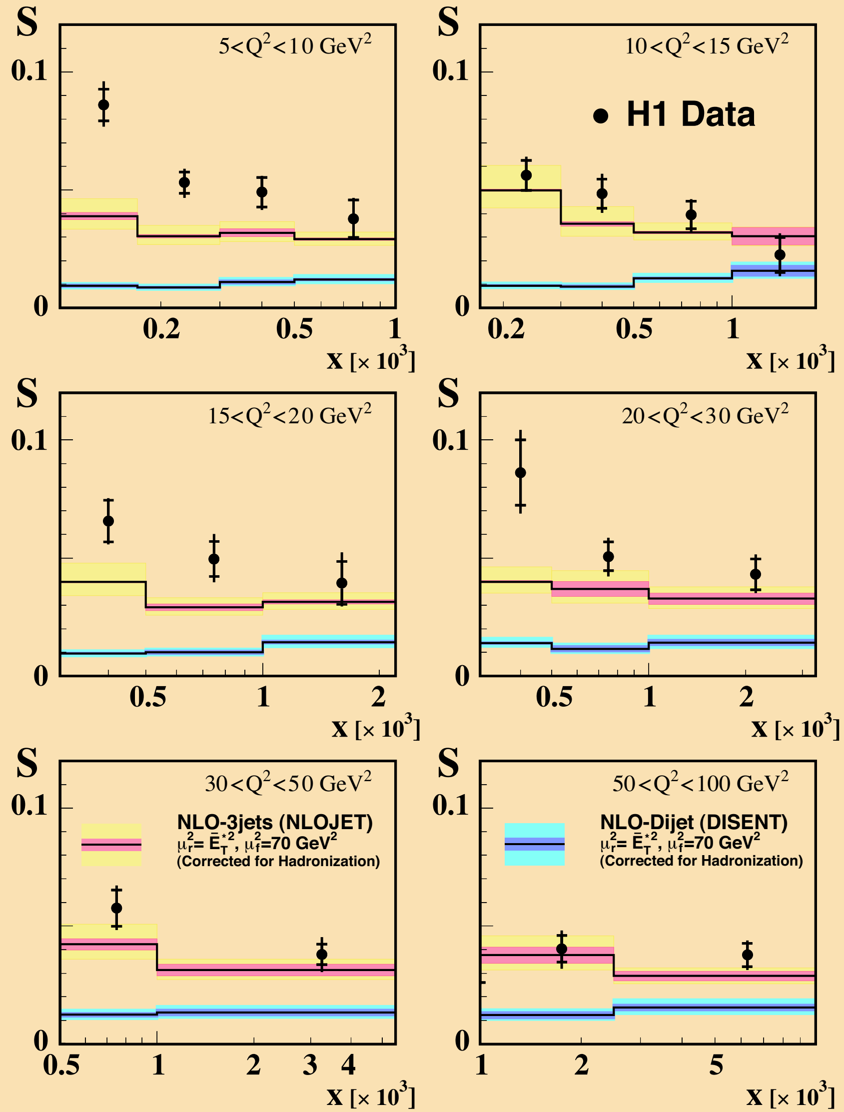

x and Q^2 dependence of S

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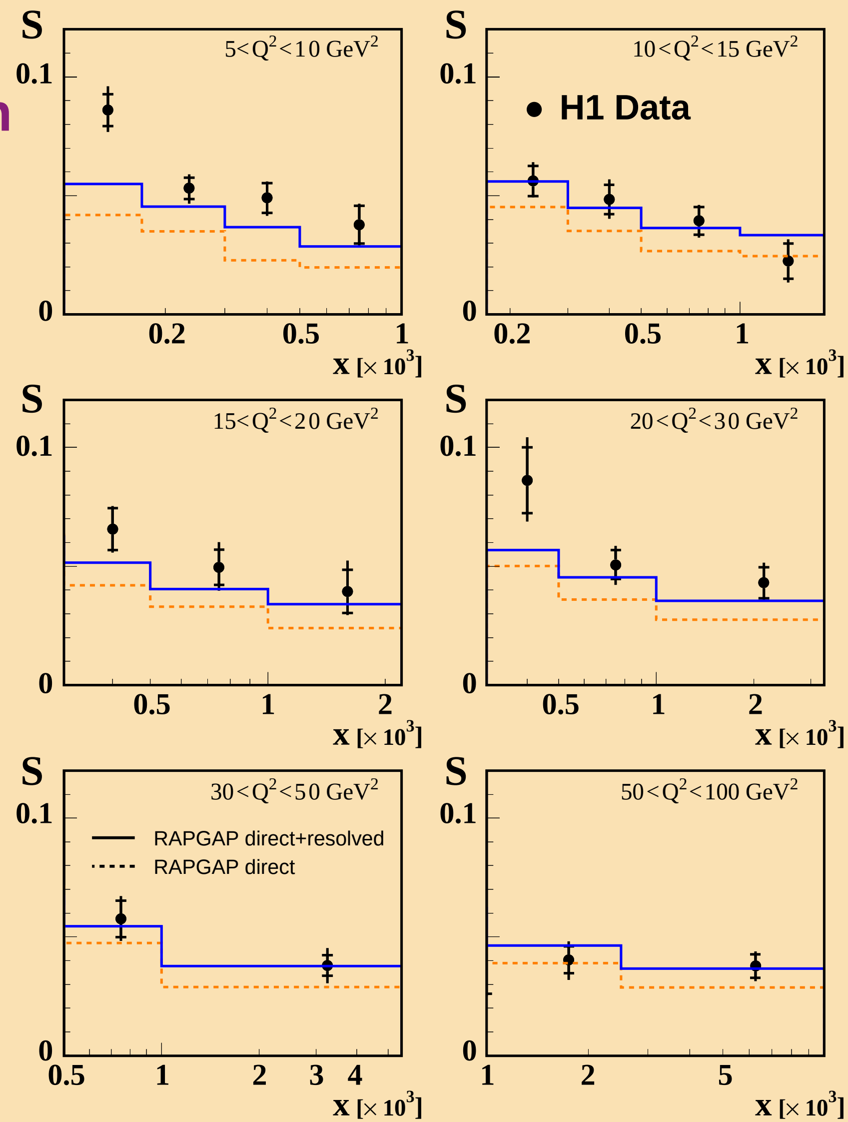
→ Useful comparison provided by models with higher-order effects: parton-shower approach in Monte Carlo models



- Comparison to RAPGAP predictions: (DGLAP)
  - → good description of data at large Q^2 and 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 and low Q^2

x and Q^2 dependence of S

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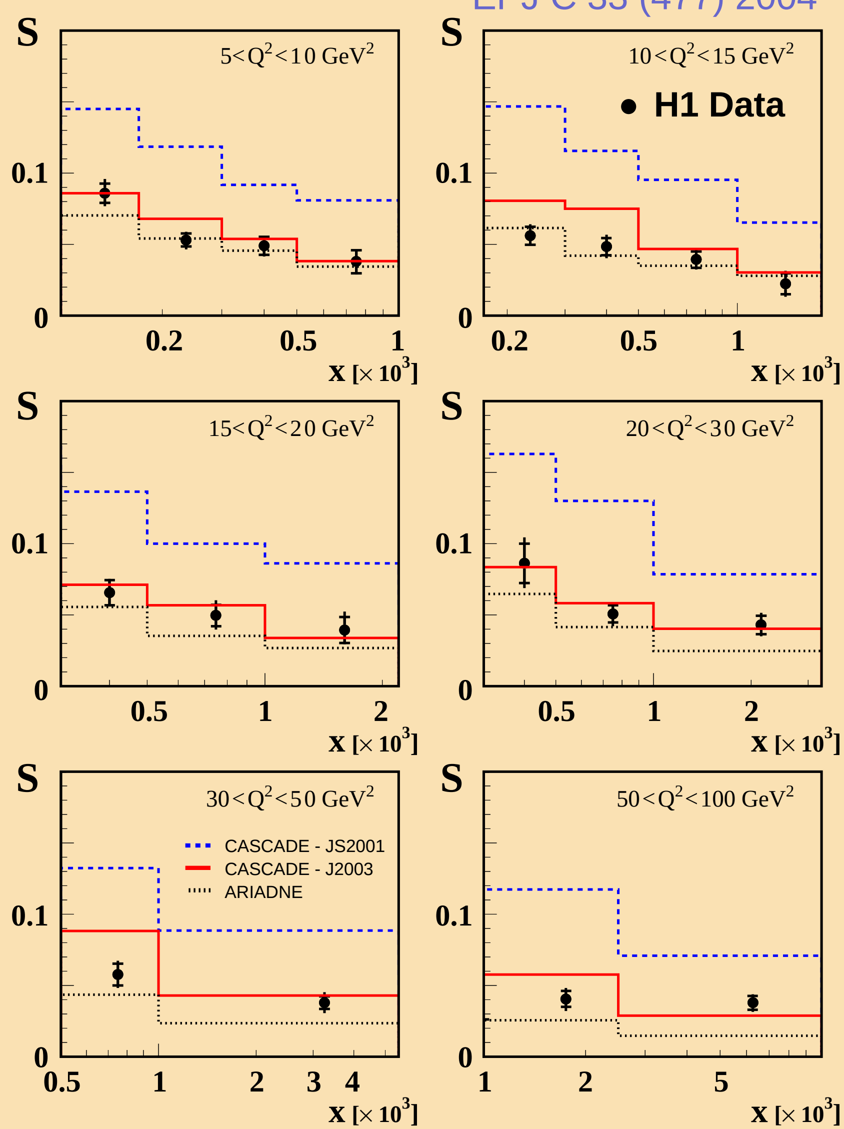
- If discrepancies are due to influence of non-k_T-ordered parton emissions, models based on the CDM or CCFM may give a better description

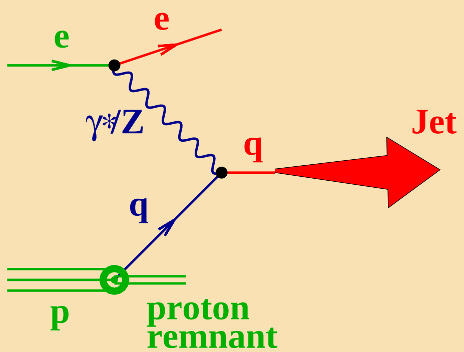
- Comparison to CDM predictions (ARIADNE):
  $\longrightarrow$ good description of data at low x and Q^2
  $\longrightarrow$ prediction below the data at high Q^2

- Comparison to CCFM predictions (CASCADE):
  $\longrightarrow$ JS2001: significantly above the data
  $\longrightarrow$ Jung2003-set 2: closer to the data



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

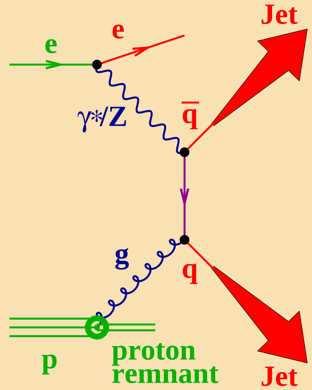
Multijet production in NC DIS

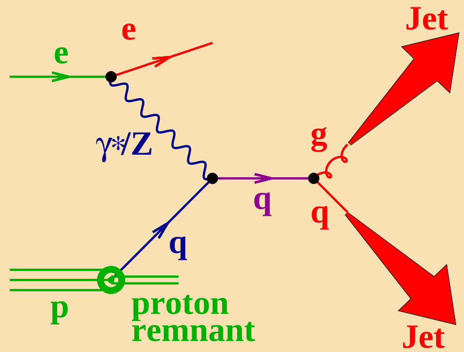


jet production in the QPM:

$$\gamma^* \to q$$

one-jet events

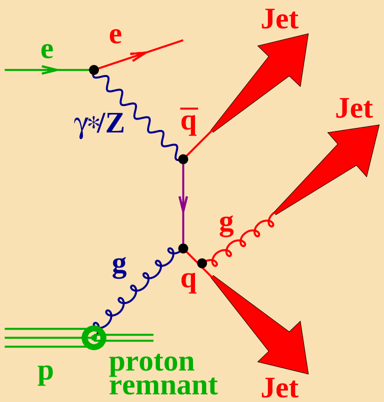


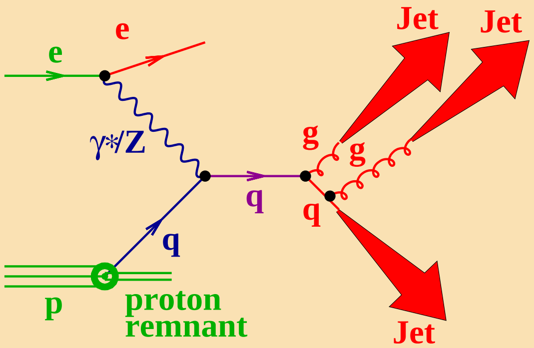


jet production at $\mathcal{O}(\alpha_s)$:

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

two-jet events





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

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

three-jet events

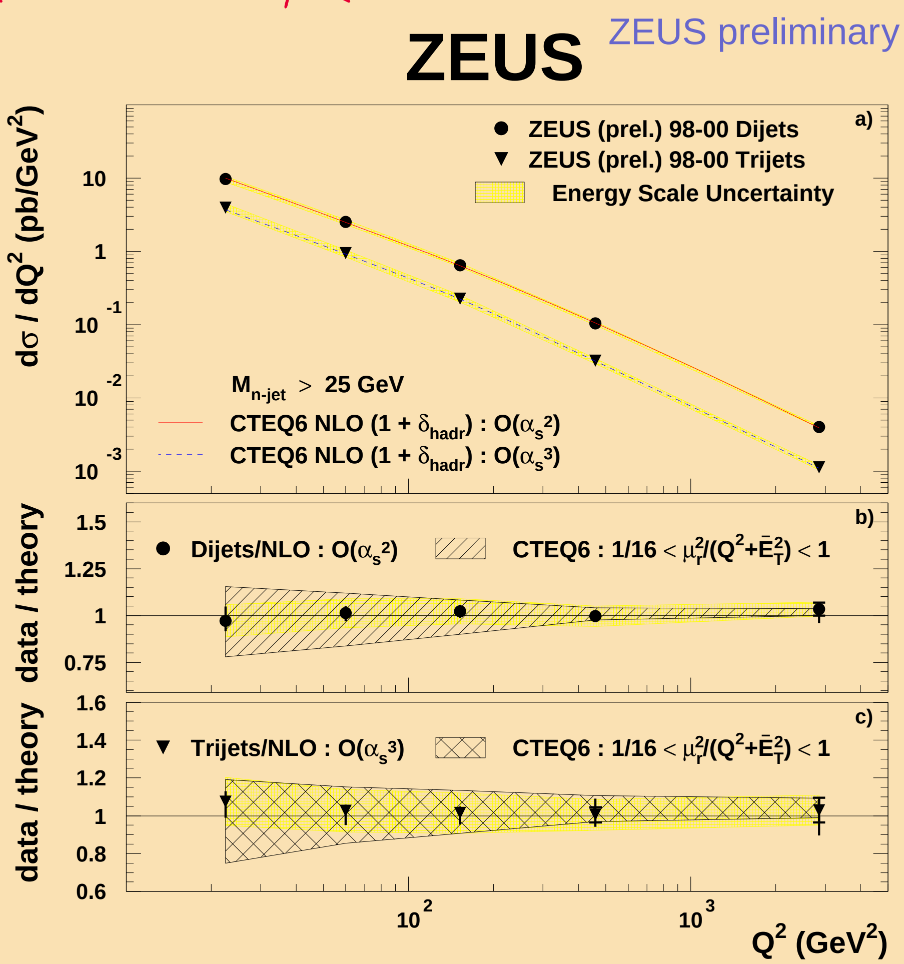
→ Events with three jets can be seen as dijet processes with additional gluon radiation or splitting of a gluon in a $q\bar{q}$ pair

→ Direct tests of QCD beyond LO:

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

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

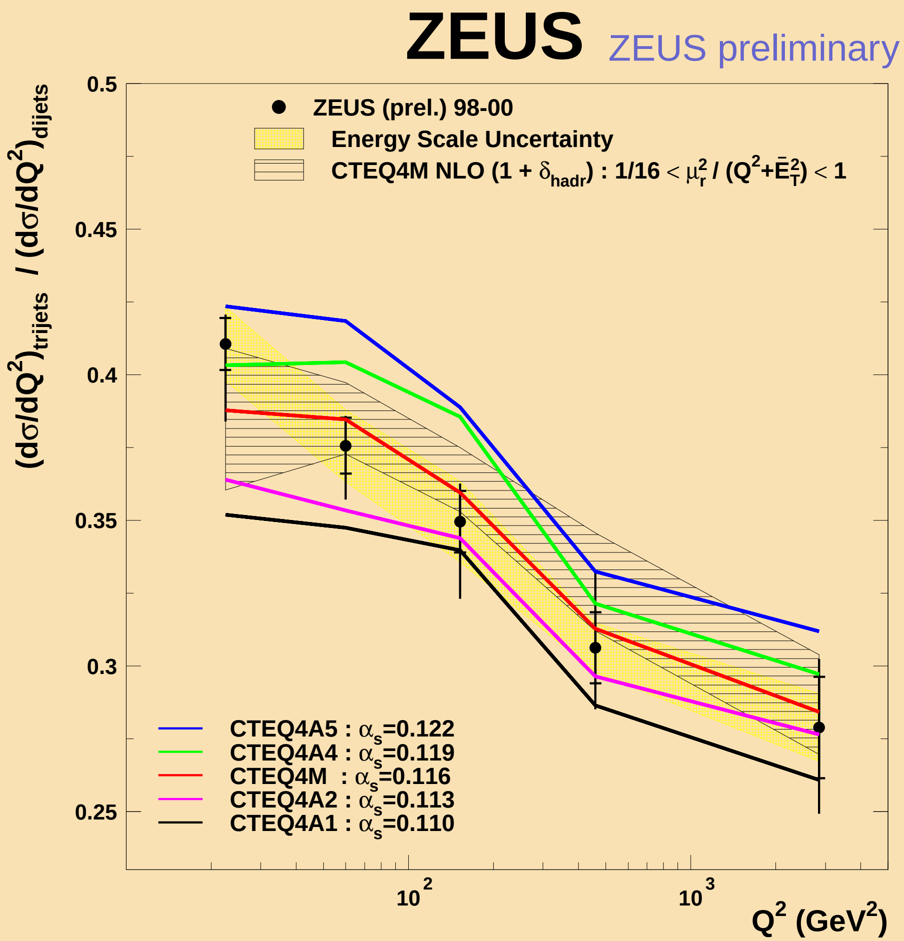
- Jets searched with k_T algorithm in the Breit frame
- At least two jets with $E_{T,B}^{\rm jet} > 5$ GeV and $-1 < \eta_{\rm LAB}^{\rm jet} < 2.5$
- Kinematic range: $10 < Q^2 < 5000$ GeV^2,$0.04 < y < 0.6$ and $\cos\gamma < 0.7$
- Events with $M^{3j}(M^{jj}) > 25$ GeV were selected



- Comparison to NLO ($\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$) predictions (NLOJET):
  - $\rightarrow \mu_R^2 = Q^2 + \bar{E}_T^2$
  - $\rightarrow \mu_F^2 = Q^2$
  - $\rightarrow p$ 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 α_s

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



- 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

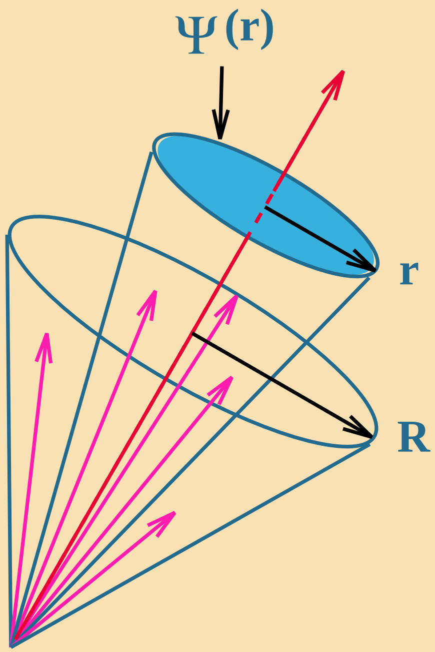
- Observable sensitive to value of $\alpha_s(M_Z)$
  $\longrightarrow$ possibility to extract α_s from the ratio:

$$\rightarrow \alpha_s(M_Z) = 0.1179 \pm 0.0013\ (\text{stat.})\ {}^{+0.0028}_{-0.0046}\ (\text{exp.})\ {}^{+0.0061}_{-0.0047}\ (\text{th.})$$

Jet substructure

- 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
- At sufficiently high jet transverse energy, where fragmentation effects become negligible, the jet substructure is expected to be calculable in pQCD
- pQCD predicts that gluon-initiated jets are broader than quark-initiated jets due to the larger colour charge of the gluon
- The jet substructure can be studied using the jet shape:

$\psi(r)$: fraction of the jet transverse energy that lies inside a cone in the $\eta - \varphi$ plane of radius r, concentric with the jet axis



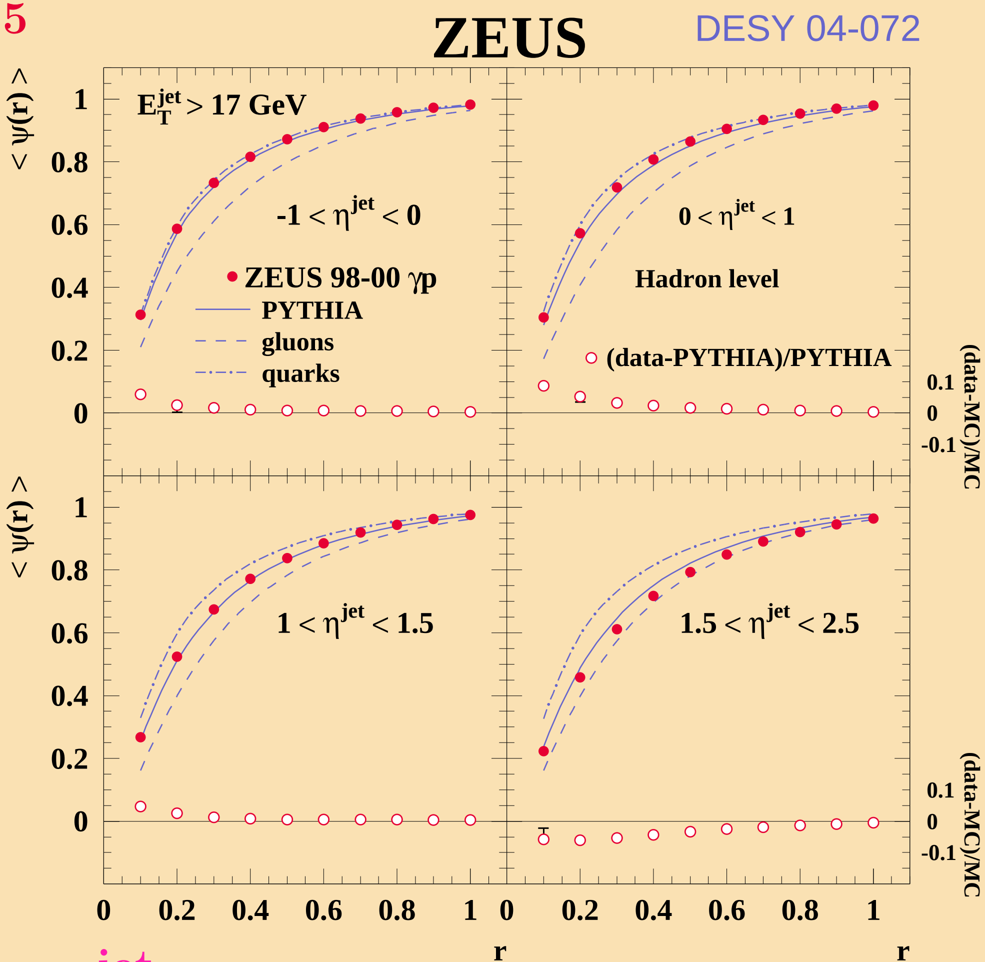
$$\psi(r) = \frac{E_T(r)}{E_T^{\rm jet}} \longrightarrow \langle\psi(r)\rangle = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_T(r)}{E_T^{\rm jet}}$$

mean integrated jet shape

Mean integrated jet shape: $\eta^{\rm jet}$ regions (γp)

– Jets searched with k_T algorithm in the LAB frame
– At least one jet with $E_T^{\rm jet} > 17$ GeV and $-1 < \eta^{\rm jet} < 2.5$
– Kinematic range: $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$

→ $\langle \Psi(r) \rangle$ in different $\eta^{\rm jet}$ regions:
jets become broader as $\eta^{\rm jet}$ increases



- **Comparison to QCD predictions:**

→ Models including initial and final state QCD radiation (PYTHIA):
– good description of the data for $-1 < \eta^{\rm jet} < 1.5$

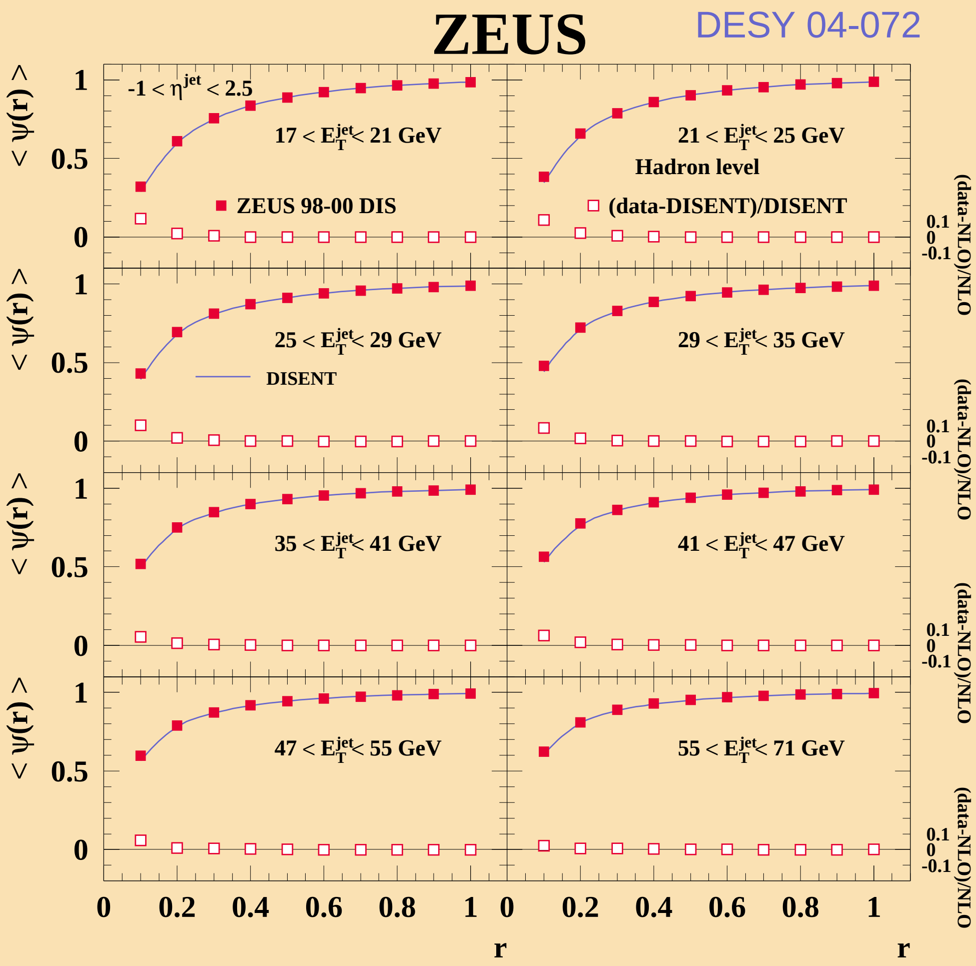
→ For $1.5 < \eta^{\rm jet} < 2.5$: the measured jets are slightly broader than the predictions

→ The measured jets are quark-like for $-1 < \eta^{\rm jet} < 0$ and become increasingly more gluon-like as $\eta^{\rm jet}$ increases

Mean integrated jet shape: $E_T^{\rm jet}$ regions (NC DIS)

– Jets searched with k_T algorithm in the LAB frame
– At least one jet with $E_T^{\rm jet} > 17$ GeV and $-1 < \eta^{\rm jet} < 2.5$
– Kinematic range: $Q^2 > 125$ GeV^2

→ $\langle\Psi(r)\rangle$ in different $E_T^{\rm jet}$ regions: the jets become narrower as $E_T^{\rm jet}$ increases



- **Comparison to NLO QCD predictions:**

→ The data are well described by the NLO QCD calculations: the fractional differences between the measurements and the predictions amount to less than 0.2% for $r = 0.5$

Mean integrated jet shape: $\eta^{\rm jet}$ and $E_T^{\rm jet}$ dependence (DIS and γp)

- $\eta^{\rm jet}$ dependence:
  - $\longrightarrow$ DIS: no dependence
  - $\longrightarrow$ γp: jets become broader as $\eta^{\rm jet}$ increases
- Comparison with QCD:
  - $\longrightarrow$ DIS: consistent with being dominated by quark-initiated jets
  - $\longrightarrow$ γp: broadening of data consistent with increase of fraction of gluon-initiated jets

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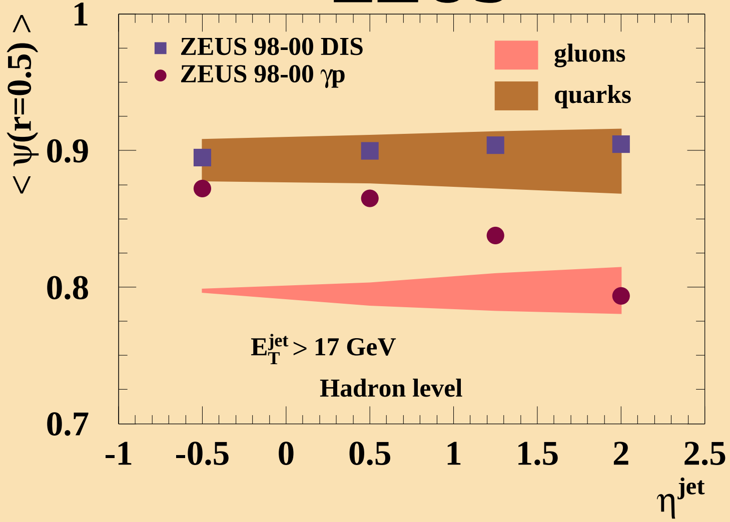
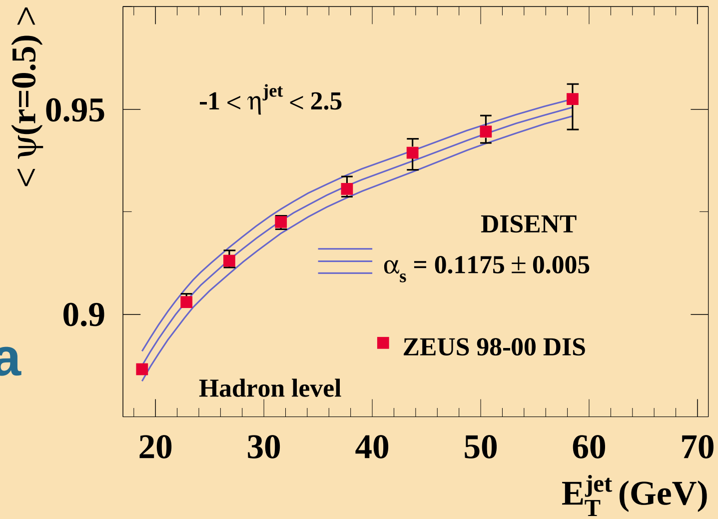




- $E_T^{\rm jet}$ dependence:
  - $\longrightarrow$ DIS and γp: jets become narrower as $E_T^{\rm jet}$ increases
- Comparison with QCD: the calculations provide a good description of the data: thus, it can be used to determine $\alpha_s(M_Z)$:

$$\longrightarrow \alpha_s(M_Z) = 0.1176 \pm 0.0009\,(\text{stat.})\,{}^{+0.0009}_{-0.0026}\,(\text{exp.})\,{}^{+0.0091}_{-0.0072}\,(\text{th.})$$

Selection of quark- and gluon-initiated jets

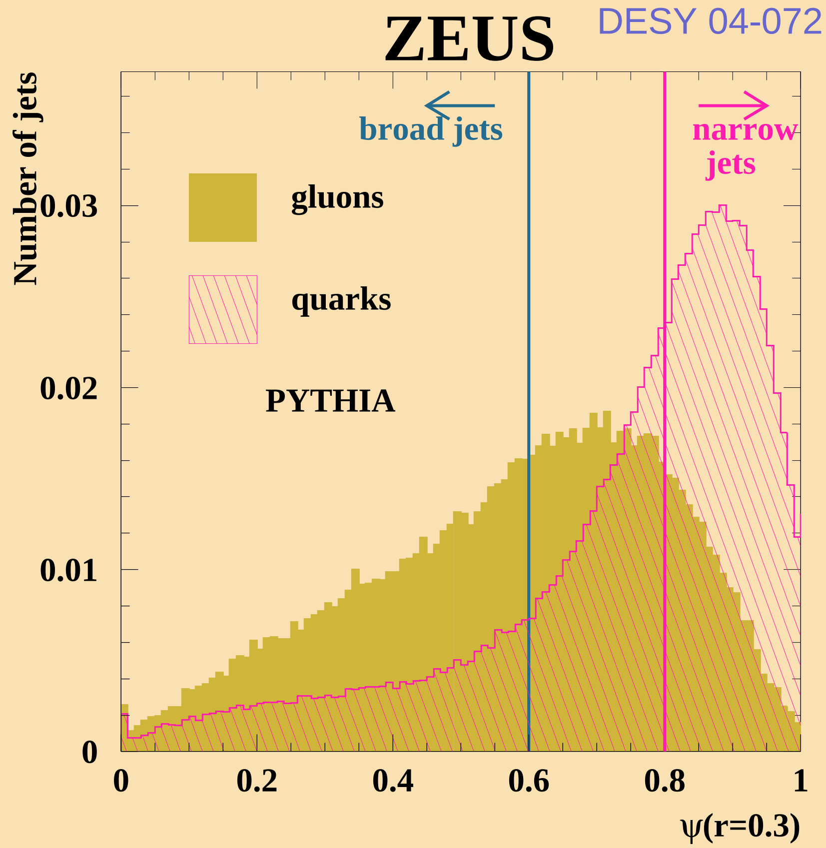
- To study the dynamics of the hard subprocesses in detail:

⟶ Separation of quark- and gluon-initiated jets on a statistical basis assuming

gluon jets ↔ "broad" jets

quark jets ↔ "narrow" jets

⟶ Sample enriched in gluon- (quark-) initiated jets: $\psi(r=0.3) < 0.6 (> 0.8)$



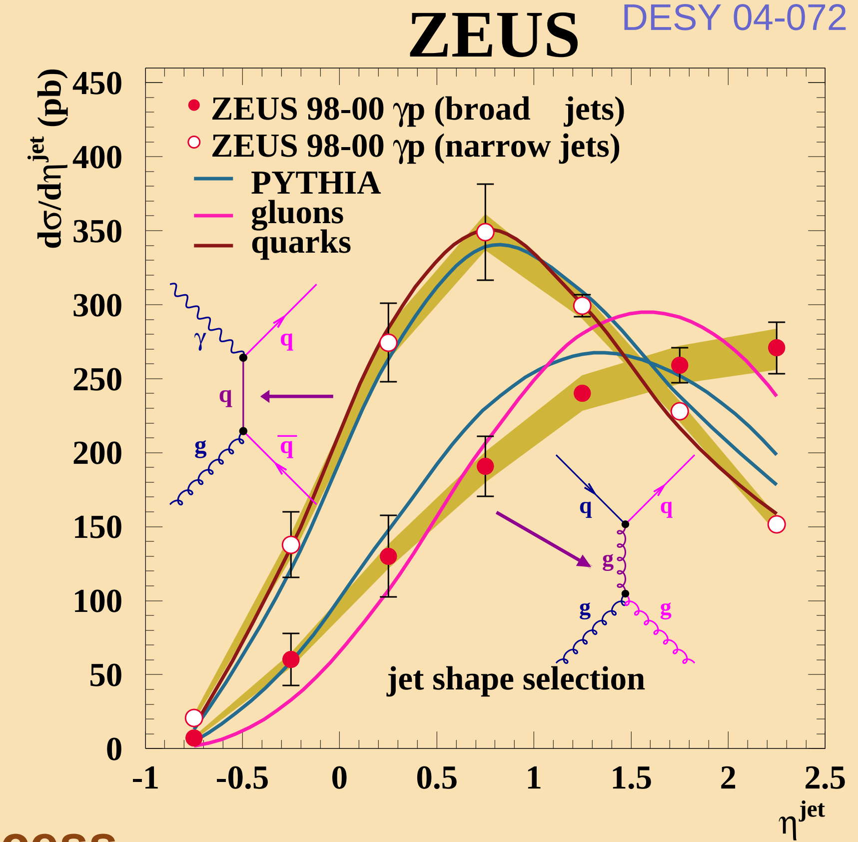
- Purity/Efficiency:

	PYTHIA	HERWIG
gluons	57/58 %	50/43 %
quarks	84/51 %	85/55 %

Measurement of $d\sigma/d\eta^{\rm jet}$ in inclusive jet γp

- $d\sigma/d\eta^{\rm jet}$ separated in broad and narrow jets show different shape

- Comparison with leading-logarithm parton shower MC calculations:
  - * MC area-normalised to data of each type
  - → same selection as data: good description of shape of data by PYTHIA
  - → quark/gluon selection: good description of shape of data by PYTHIA for narrow jets and similar for broad jets



→ broad jets dominated by $q_\gamma g_p \to qg$ subprocess

→ narrow jets dominated by $\gamma g \to q\bar{q}$ subprocess

Measurement of $d\sigma/d\cos\theta^*_{\rm broad}$ in dijet γp

- $d\sigma/d\cos\theta^*_{\rm broad}$ for a sample of broad-narrow dijet events measured wrt the broad jet shows different behaviour on the negative and positive sides:

$\longrightarrow$ $d\sigma/d\cos\theta^*_{\rm broad}$ at 0.7 is approximately two times larger than at -0.7

- Comparison with MC:
  - * same selection cuts as the data for broad-narrow sample

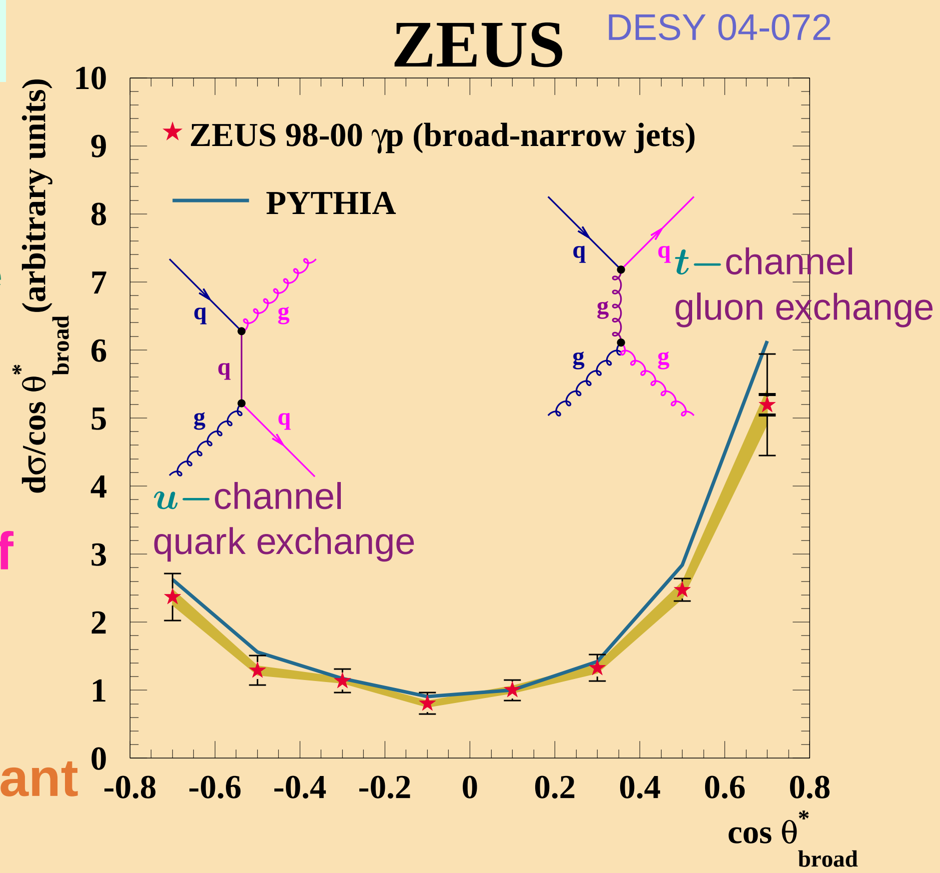
  $\longrightarrow$ PYTHIA gives a reasonable description of the shape of the data

$\longrightarrow$ Observed asymmetry understood in terms of the dominant resolved subprocess:

$$q_\gamma g_p \longrightarrow qg$$

$\longrightarrow$ The asymmetry is due to the different dominant diagrams for $\cos\theta^*_{\rm broad} \rightarrow \pm 1$:

* Data and MC normalised to unity at $\cos\theta^*_{\rm broad} = 0.1$



- * $t-$channel gluon exchange at $\cos\theta^*_{\rm broad} = +1$
- * $u-$channel quark exchange at $\cos\theta^*_{\rm broad} = -1$

Conclusions

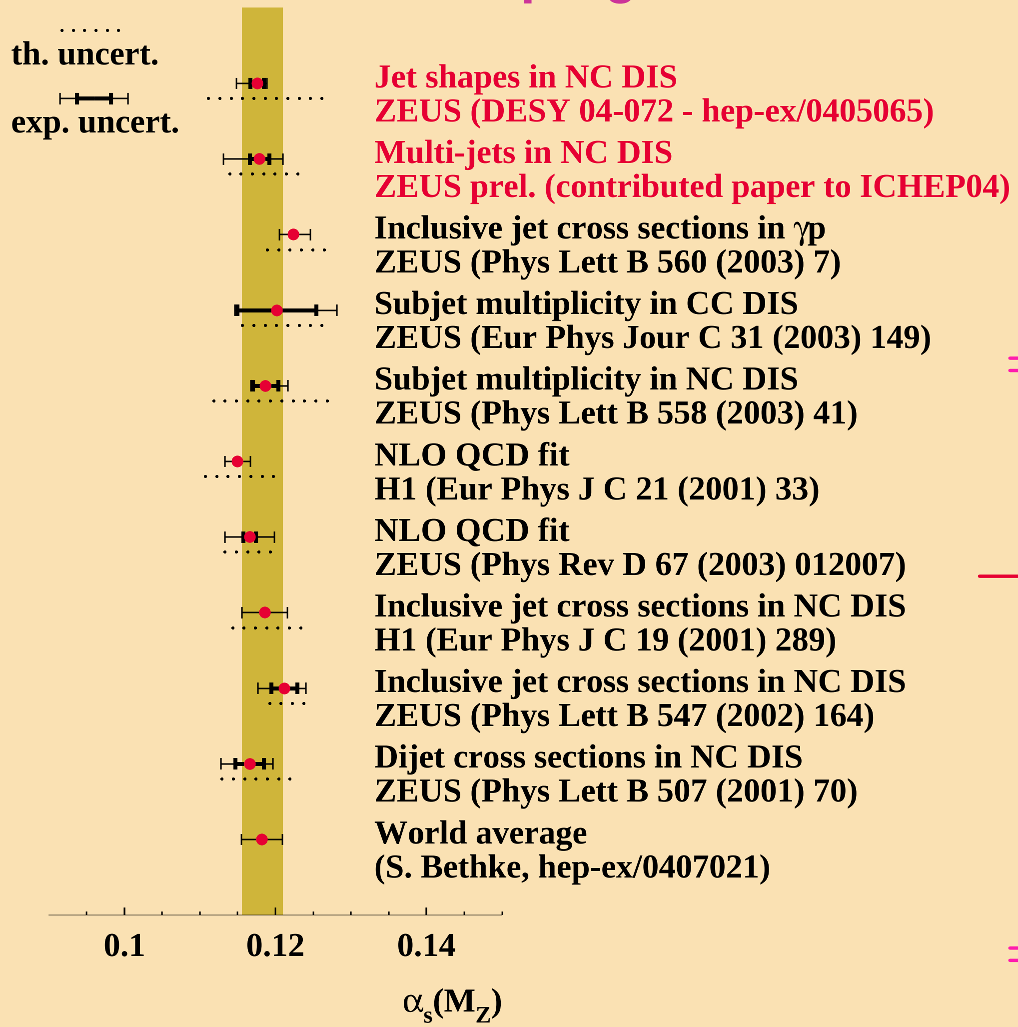
- **HERA has become a unique QCD-testing machine due to**

  $\longrightarrow$ **at large scales:**

  – considerable progress in understanding and reducing uncertainties led to very precise measurements of the fundamental parameter of the theory

  – jet observables give determinations of α_s as precise as those from more inclusive measurements (eg τ decay)

  $\Rightarrow$ Improved calculations needed for better accuracy



  $\longrightarrow$ **at low x and low Q^2:**

  – considerable progress in understanding the mechanisms for parton emission has been achieved

  – interplay of DGLAP $\leftrightarrow$ BFKL $\leftrightarrow$ CCFM dynamics has still to be fully worked out

  $\Rightarrow$ Further progress needs more experimental and theoretical work