Physics at LHC
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Hadronic final states and QCD studies in ep collisions

from

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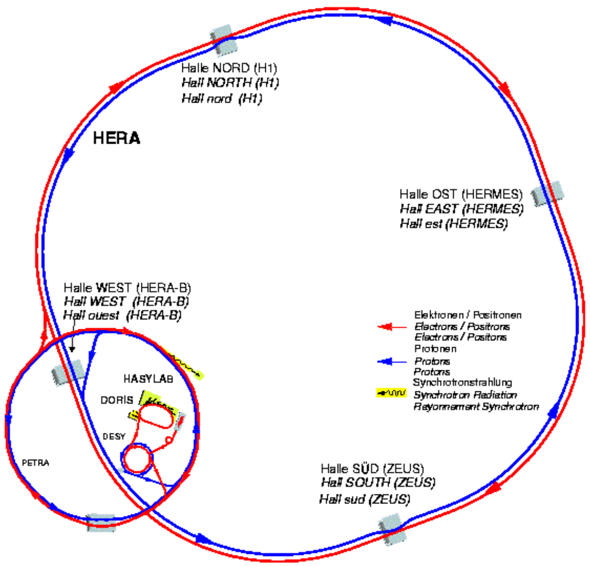
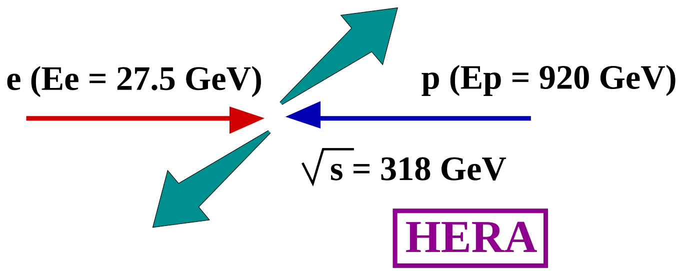
at

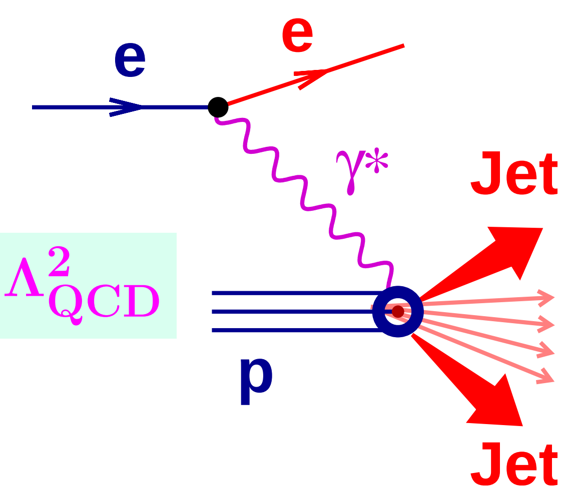


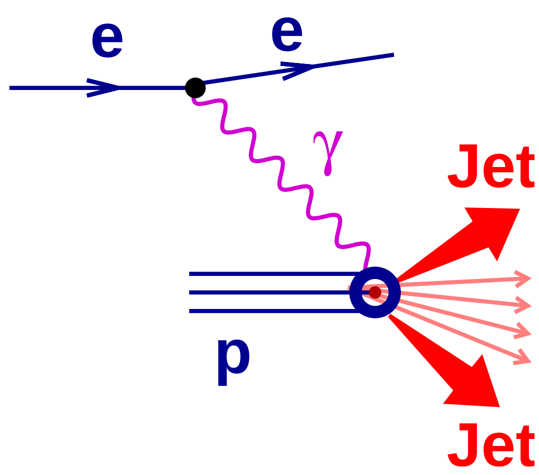


Introduction

- Jet production in pp collisions will be copious at LHC
- Main background to searches in hadronic channels: QCD multijet production
- Also, luminosity of colliding particles (partons from protons) governed by QCD (proton PDFs)
- ep collider HERA: very suitable enviroment to do precision studies of QCD
  $\longrightarrow$ tests of QCD in hadronic-induced reactions (as opposed to e^+e^- at LEP)
  $\longrightarrow$ but cleaner than $p\bar{p}$ at TeVatron
- The main sources of jets at HERA are:

$Q^2 \gg \Lambda^2_{\rm QCD}$





$Q^2 \approx 0$

NC deep inelastic scattering (DIS)

$$ep \longrightarrow e + {\rm Jet}\ (+{\rm Jet}) + X$$

photoproduction (γp)

$$ep \longrightarrow e + {\rm Jet}\ (+{\rm Jet}) + X$$

How do we study QCD at HERA ?

- We measure:

structure functions	heavy quark production	jet production	particle production
↓	↓	↓	↓
F_2^p, F_2^{CC}, F_2^D, F_2^c, ...	charm beauty	jet cross sections jet substructure forward jets	hadrons photons event shapes

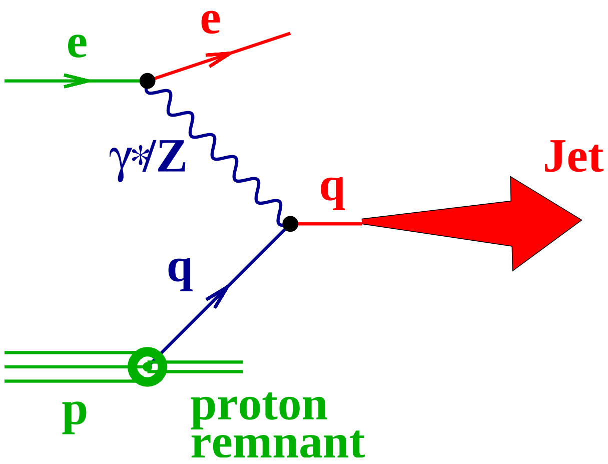
to obtain results on:

- proton, photon, pomeron structure: parton densities
- tests of pQCD: up to which extent does pQCD describe jet dynamics?
- parton dynamics at low x: breakdown of DGLAP?
- measurements of α_s: the fundamental parameter of the theory
- color dynamics: color factors, subprocesses
- non-perturbative effects: can they be described from first principles?

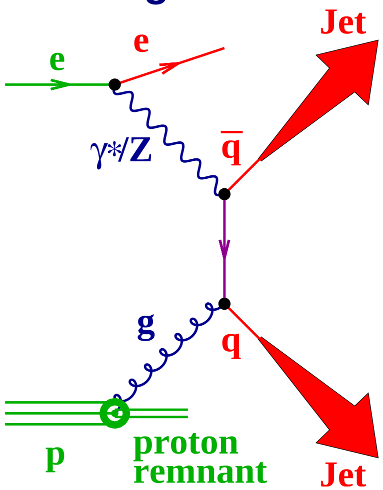
Jet production in neutral current deep inelastic ep scattering

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

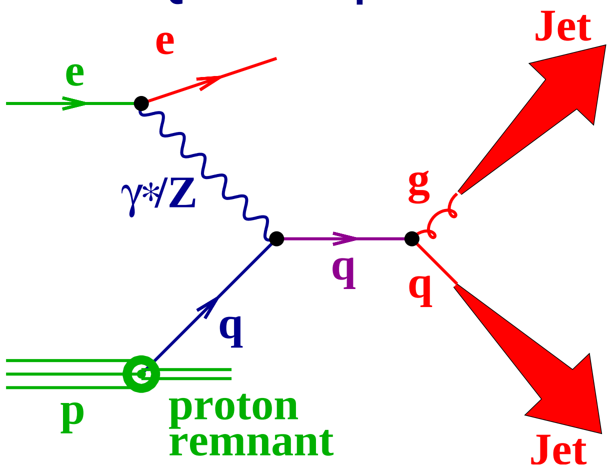
quark-parton model



boson-gluon fusion



QCD Compton



Kinematics:

– **momentum transfer:**

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

– **Bjorken x:** $x = \frac{Q^2}{2P \cdot q}$

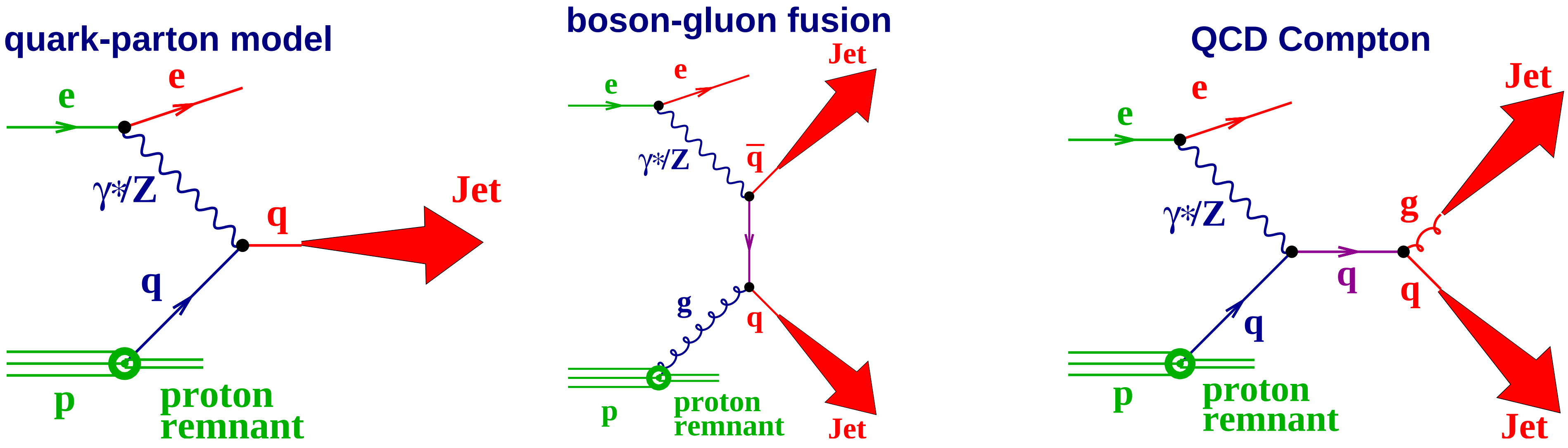
(parton momentum fraction for QPM)

– **inelasticity:**

$$y = \frac{P \cdot q}{P \cdot k} = 1 - \frac{E'_e(1 - \cos\theta_e)}{2E_e}$$

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:

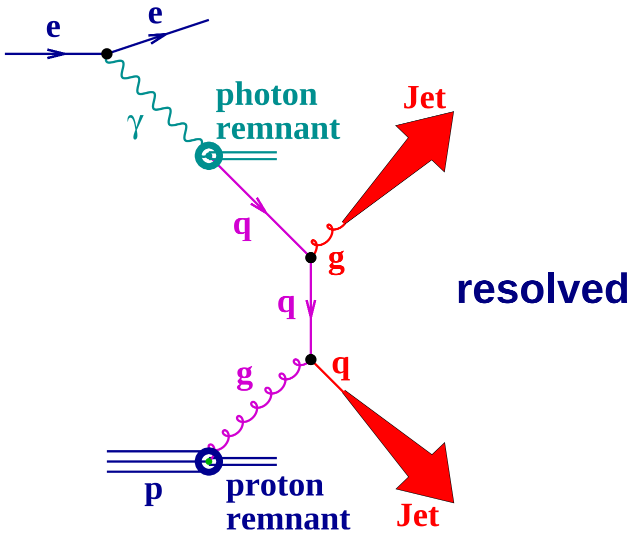
$$d\sigma_{\rm jet} = \sum_{a=q,\bar{q},g} \int dx\, f_a(x,\mu_F)\, d\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_R,\mu_F)$$

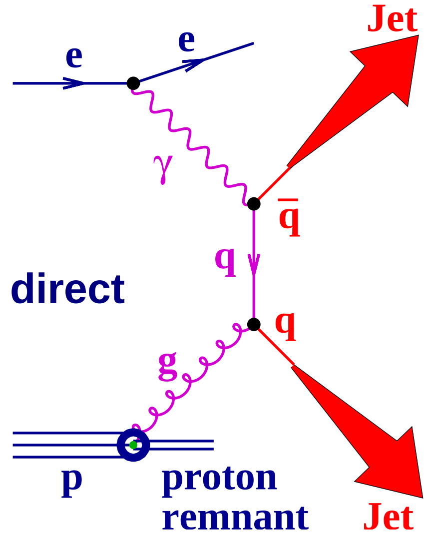
  – f_a: parton a density in the proton, determined from experiment
    $\longrightarrow$ long-distance structure of the target

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

Jet production in photoproduction

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





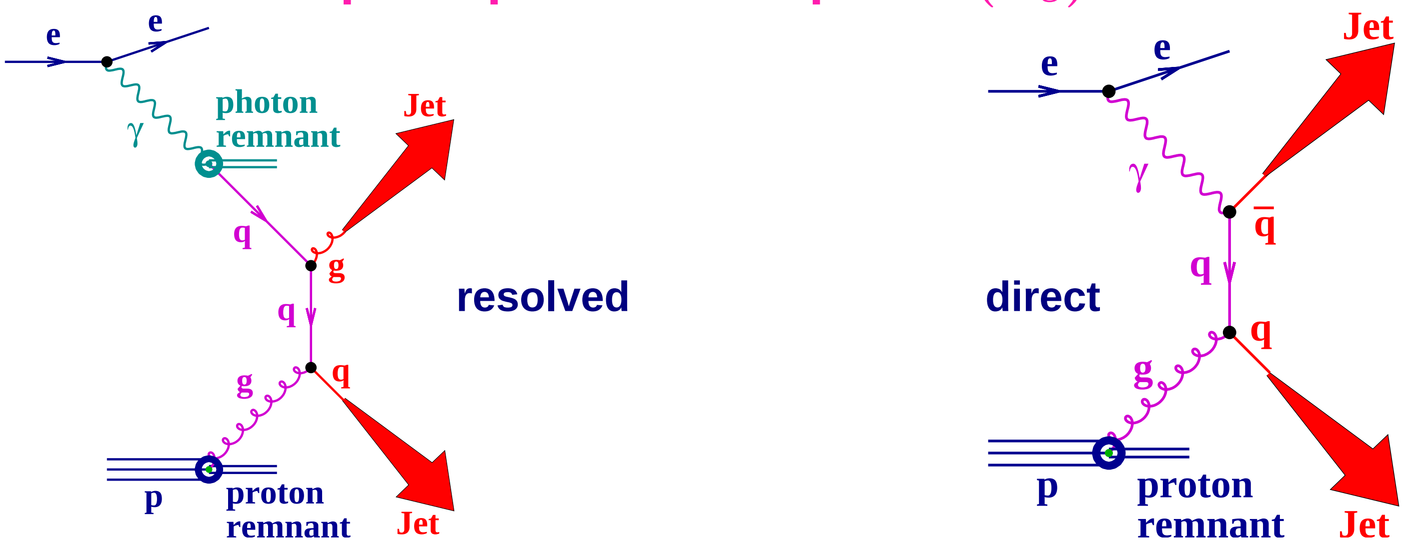
Kinematics:

– $Q^2 \approx 0$

– total hadronic cms energy:
$W^2 = ys$

Jet production in photoproduction

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



- Jet production cross section:

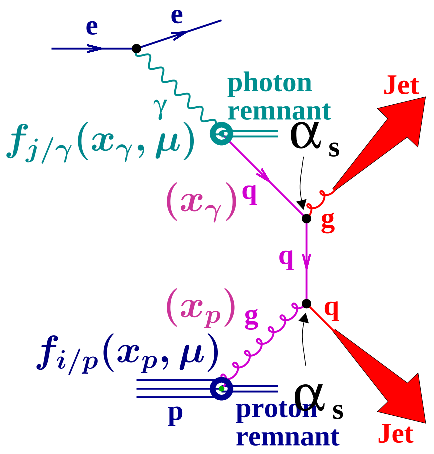
$$d\sigma_{\text{jet}} = \sum_{i,j} \int_0^1 dy\, dx_\gamma\, dx_p\, f_{\gamma/e}(y)\;\; f_{i/\gamma}(x_\gamma, \mu_{F_\gamma})\;\; f_{j/p}(x_p, \mu_{F_p})\; d\hat{\sigma}_{i(\gamma)j}(i(\gamma)j \longrightarrow \text{jet jet})$$

  – $f_{j/p}(f_{i/\gamma})$: 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

Jet search in ep collisions

- Jet search in e^+e^- annihilations is simple:
  - $\longrightarrow$ initial state: only leptons; final state: arising uniquely from short-distance interaction (all hadrons in final state associated with hard process)
  - $\longrightarrow$ best frame: centre-of-mass system = LAB
  - $\longrightarrow$ variables invariant under rotations: energies and angles
  - $\longrightarrow$ distance between hadrons: angular separation
- Jets in hadronic collisions are not as easily identified because jets carry only a fraction of the available energy and are accompanied by several soft hadrons not correlated with the hard interaction

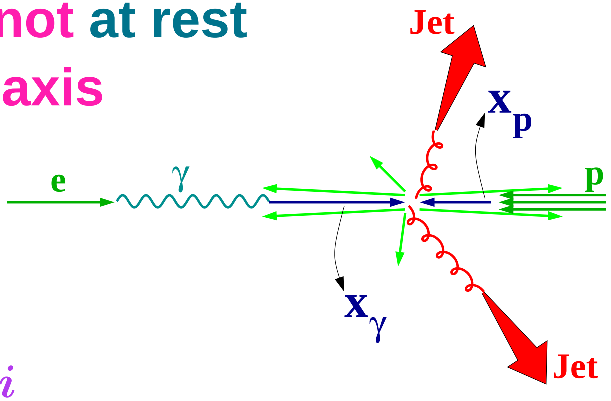


$\gamma p \rightarrow e + \text{jet} + \text{jet} + X$
(resolved photoproduction)

- Initial state: colored partons
- Initial partons carry only a fraction x_p, x_γ of the parent hadron
- Spectator partons:
  - $\longrightarrow$ remnant jets
  - $\longrightarrow$ "underlying event": soft interaction between the partons in the remnants

Jet search in ep collisions

- At HERA, ep collisions do not occur in the CM system:
  $\longrightarrow$ initial-state parton-parton or photon-parton system not at rest
  $\longrightarrow$ final-state partonic system boosted along the beam axis



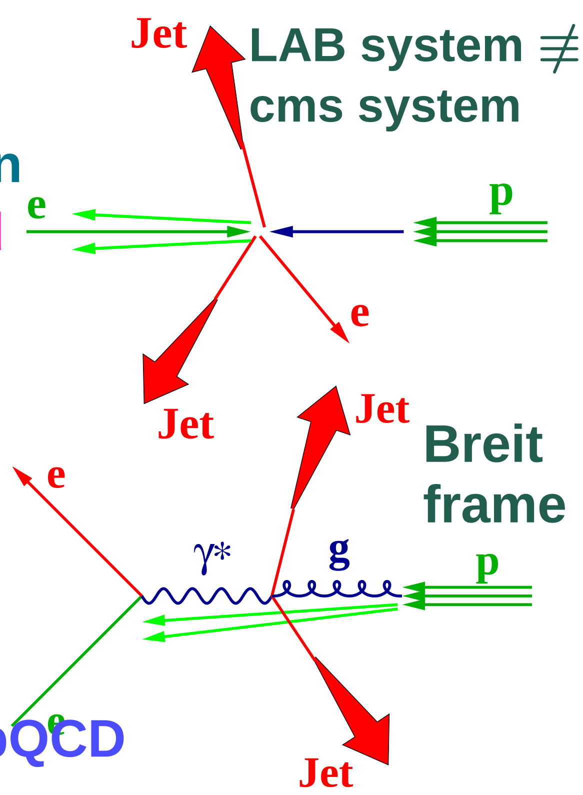
LAB system $\not\equiv$ centre-of-mass system

- To treat on equal footing all possible final-state hadronic systems $\longrightarrow$ use variables invariant under longitudinal boosts: $E_{T,i}$, $\Delta\eta_{ij}$ ($\eta = -\ln\tan\frac{\theta}{2}$) and φ_i

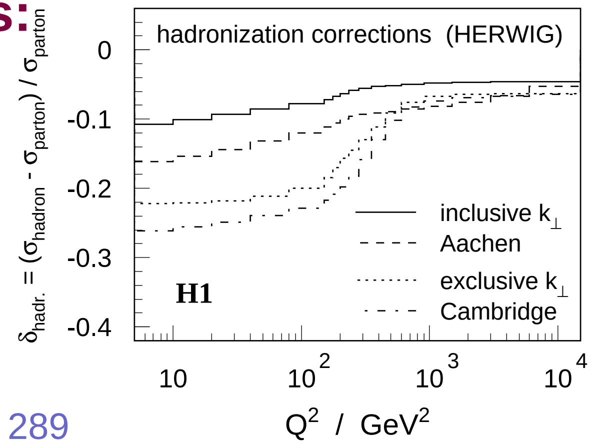
- Advantage of using transverse energies:
  $\longrightarrow$ large energy $\neq$ small distance (ie hard scattering)
  $\longrightarrow$ the beam remnant jets have huge energies, but they have not undergone a hard scattering
  $\longrightarrow$ large momentum transfer $\equiv$ small distance (hard scattering): large transverse energies $\equiv$ hard interaction
  $\longrightarrow$ the use of transverse energies helps to disentangle between the products of the hard interaction and the beam remnant jets (absent in e^+e^- annihilations)

Jet search in ep collisions

- The kinematics of NC DIS poses several challenges:
  - $\longrightarrow$ presence of beam remnant jet
  - $\longrightarrow$ the initial-state γ^*-parton system is boosted (the parton carries a fraction of the proton momentum) and rotated (the γ^* carries p_T)
- The effect of the p_T carried by the γ^* is removed by selecting a frame in which the γ^* collides head-on with the proton, eg the Breit frame



- k_T cluster algorithm in longitudinally inclusive mode:
  - $\longrightarrow$ best algorithm to reconstruct jets at HERA
  - $\longrightarrow$ in use since many years for making precision tests of pQCD
- Advantages of k_T algorithm in hadronic-type interactions:
  - $\longrightarrow$ allows transparent translation of experimental set-up to theoretical calculations (avoids ambiguities of overlapping and merging of jets (cone algorithm))
  - $\longrightarrow$ calculations using k_T are finite at all orders
  - $\longrightarrow$ smallest hadronisation corrections



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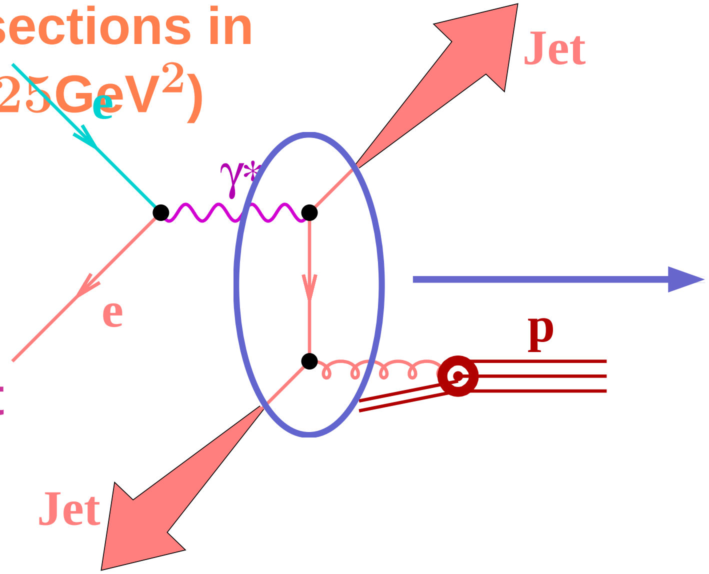
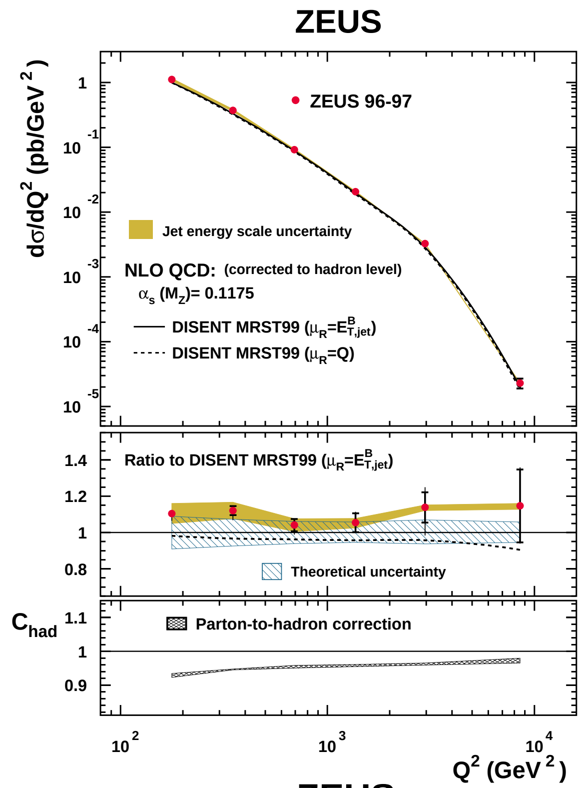
Inclusive-jet cross sections in NC DIS

- Measurements of jet cross sections in **NC DIS** at large Q^2 ($Q^2 > 125$ GeV^2) allow tests of **pQCD** and determination of α_s



- The LO prediction for the jet cross section in the Breit frame is proportional to α_s
  $\longrightarrow$ the measurements are directly sensitive to α_s:

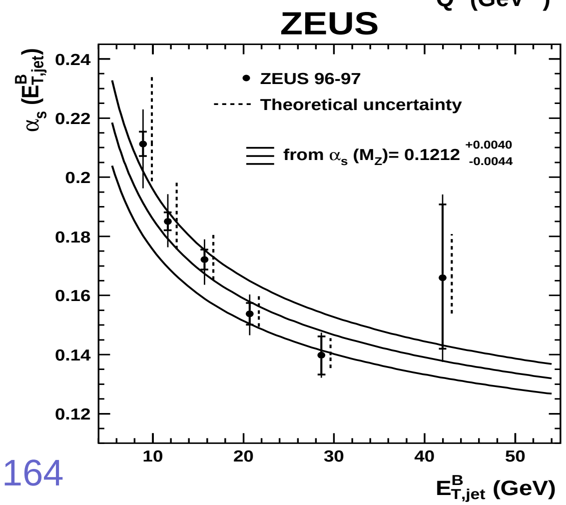


$$\alpha_s(M_Z) = 0.1212 \pm 0.0017\ (\text{stat.})\ ^{+0.0023}_{-0.0031}\ (\text{exp.})\ ^{+0.0028}_{-0.0027}\ (\text{th.})$$

$\longrightarrow$ experimental uncertainties: 2.9% ($Q^2 > 500$ GeV^2)

$\longrightarrow$ theoretical uncertainties: 2.3%

$\longrightarrow$ Test of the energy-scale dependence of α_s from $d\sigma/dE^{\text{jet}}_{T,\text{B}}$ in NC DIS



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Inclusive-jet cross sections in NC DIS

- Measurements of the differential inclusive-jet cross section at large Q^2 ($Q^2 > 150$GeV^2) as a function of $E_{T,\mathrm{B}}^{\mathrm{jet}}$ in different Q^2 regions $\longrightarrow$ harder spectrum in $E_{T,\mathrm{B}}^{\mathrm{jet}}$ as Q^2 increases

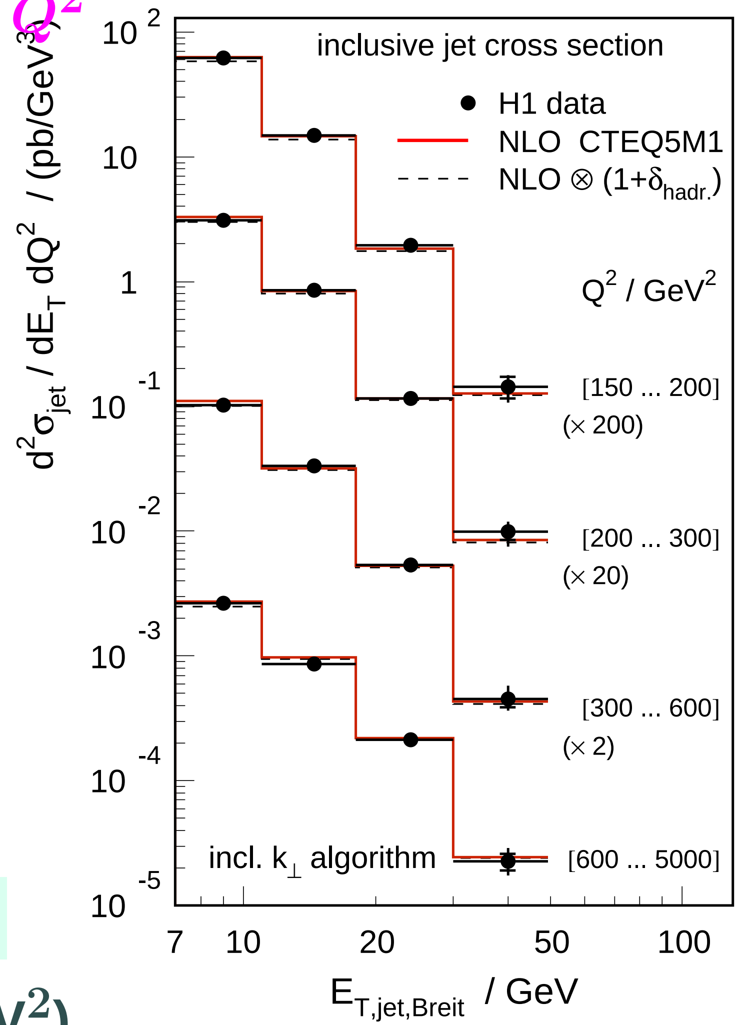
- Comparison with NLO QCD calculations:
  - $\longrightarrow$ the predictions give a good description of the data over a wide range in Q^2 and $E_{T,\mathrm{B}}^{\mathrm{jet}}$
  - $\longrightarrow$ Validity of the description of the dynamics of inclusive jet production by pQCD at $\mathcal{O}(\alpha\alpha_s^2)$ over a wide range in Q^2 and $E_{T,\mathrm{B}}^{\mathrm{jet}}$

$\longrightarrow$ The measurements are directly sensitive to α_s:

$$\alpha_s(M_Z) = 0.1186 \pm 0.0030\ (\mathrm{exp.}) \pm 0.0051\ (\mathrm{th.})$$

$\longrightarrow$ experimental uncertainties: 2.5% ($Q^2 > 150$ GeV^2)

$\longrightarrow$ theoretical uncertainties: 4.3%



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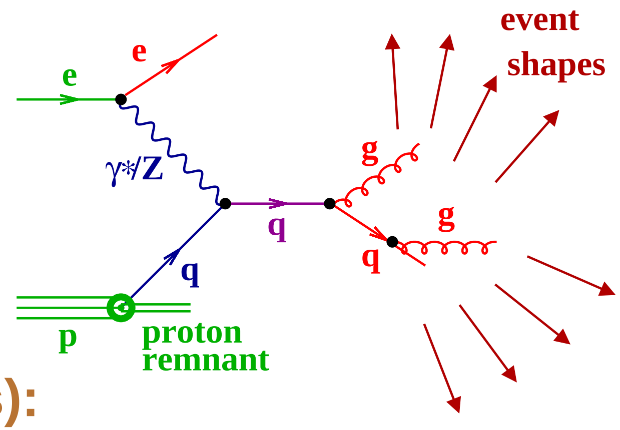
Hadronisation process

- The HFS in NC DIS has also been used to study the hadronisation process:
  $\longrightarrow$ non-perturbative effect
  $\longrightarrow$ event-shapes observables can be used to test the power-correction model: understanding of hadronisation process from first principles



- Event-shape variables (inspired by e^+e^- measurements):
  $\longrightarrow$ thrust, broadening, C parameter, jet mass

- In this type of analysis, the data are compared to a model prediction which consists of a combination of NLO QCD calculations and the expectations of the power corrections, characterised by an effective coupling $\bar{\alpha}_0$:

$$F = F_{\text{perturbative}} + F_{\text{power correction}}$$

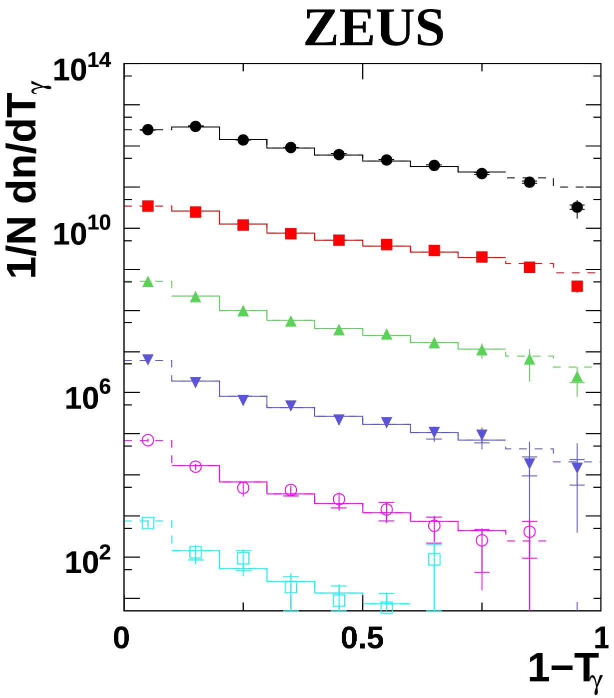
where F is an event-shape mean or distribution (NLO + matched NLL)

Test of the power-correction model

- **Extracted $\bar{\alpha}_0$ and $\alpha_s(M_Z)$ values for each event-shape observable:**

Thrust distribution in different Q^2 regions

DESY-06-042



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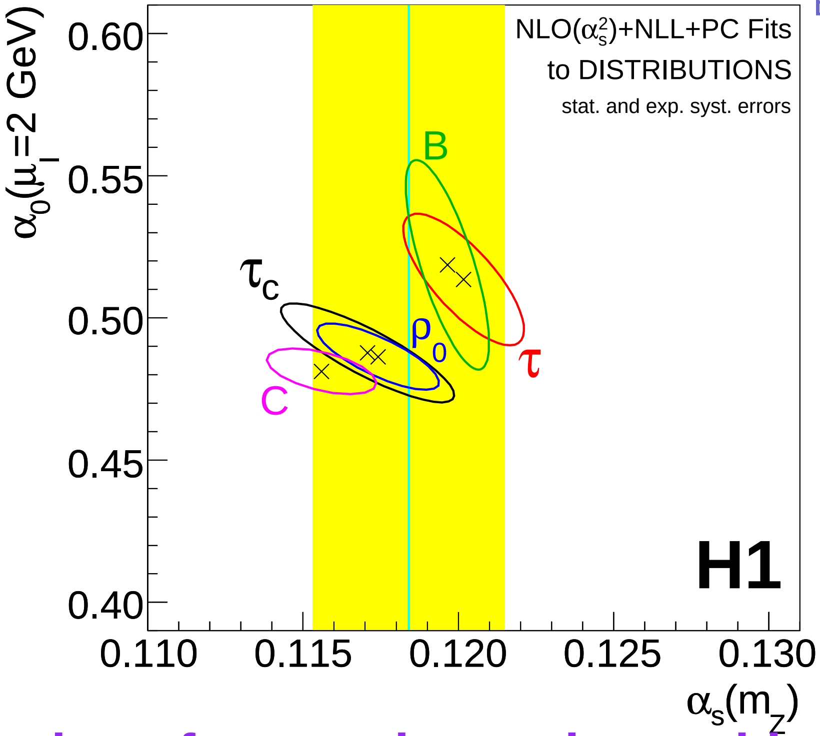


From distributions

$\longrightarrow$ **It is possible to obtain good description of event-shape observables in hadronic-induced reactions using NLO+NLL+power corrections calculations**

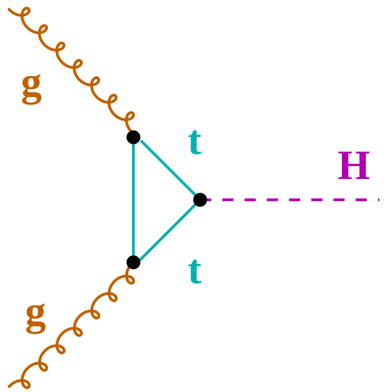
$\longrightarrow$ **Extracted value of $\alpha_s(M_Z)$ consistent for all observables and with the world average**

$\longrightarrow$ **Universal non-perturbative parameter $\bar{\alpha}_0 = 0.5 \pm 10\%$**

$\longrightarrow$ **supports concept of power corrections as appropiate alternative approach for description of hadronisation effects**

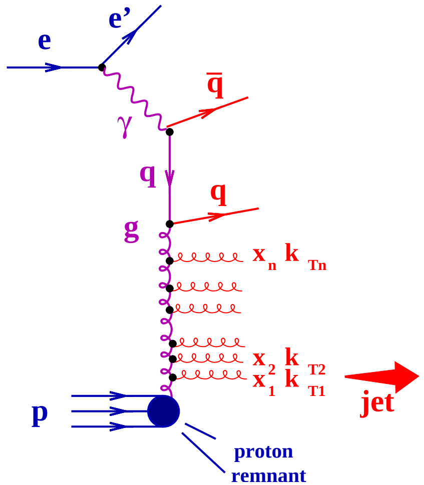
Parton evolution at low x and unintegrated PDFs

- One of the main channels of Higgs production at LHC is expected to be $gg \longrightarrow H$



- Predictions for these processes need information on
  $\longrightarrow$ parton evolution at low x
  $\longrightarrow$ unintegrated proton PDFs
  } $\longrightarrow$ forward-jet data at HERA
- 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 at HERA have provided
  $\longrightarrow$ accurate determination of the proton PDFs
  $\longrightarrow$ sensitive tests of pQCD and precise determinations of α_s



- DGLAP evolution equivalent to exchange of a parton cascade with exchanged partons strongly ordered in virtuality k_T
- But, DGLAP approximation expected to break down at low x:
  — only leading logs in Q^2 are resummed
  — contributions from $\log 1/x$ neglected (important for $\log Q^2 \ll \log 1/x$)

Parton evolution at low x and unintegrated PDFs

- HERA $\longrightarrow$ ideal testbed for theoretical approaches that account for low-x effects:
  - BFKL evolution: resummation of large $\log 1/x$ to all orders (very low x)
    $\longrightarrow$ no k_T ordering
    $\longrightarrow$ integration taken over full k_T phase space of gluons
    $\longrightarrow$ use of off-shell matrix elements together with unintegrated PDFs
  - CCFM evolution: angular-ordered parton emission (low and larger x)
    $\longrightarrow$ equivalent to BFKL for $x \rightarrow 0$ and to DGLAP at large x
    $\longrightarrow$ use of off-shell matrix elements together with unintegrated PDFs
  - virtual-photon structure: higher-order QCD effects mimicked at low x by introducing a second k_T-ordered parton cascade on the photon side
    $\longrightarrow$ resolved is expected to contribute for $(E_T^{\rm jet})^2 > Q^2$ and suppressed with increasing Q^2
- By restricting jet data to
  $\longrightarrow$ large $\eta^{\rm jet}$ (forward direction, proton side)
  $\longrightarrow$ $x_{\rm jet} = E^{\rm jet}/E_p \gg x_{\rm Bj}$ (to suppress QPM)
  $\longrightarrow$ $Q \approx E_T^{\rm jet}$ (to restrict evolution in Q^2)
  these different approaches has been investigated

Forward jet production at low x in NC DIS

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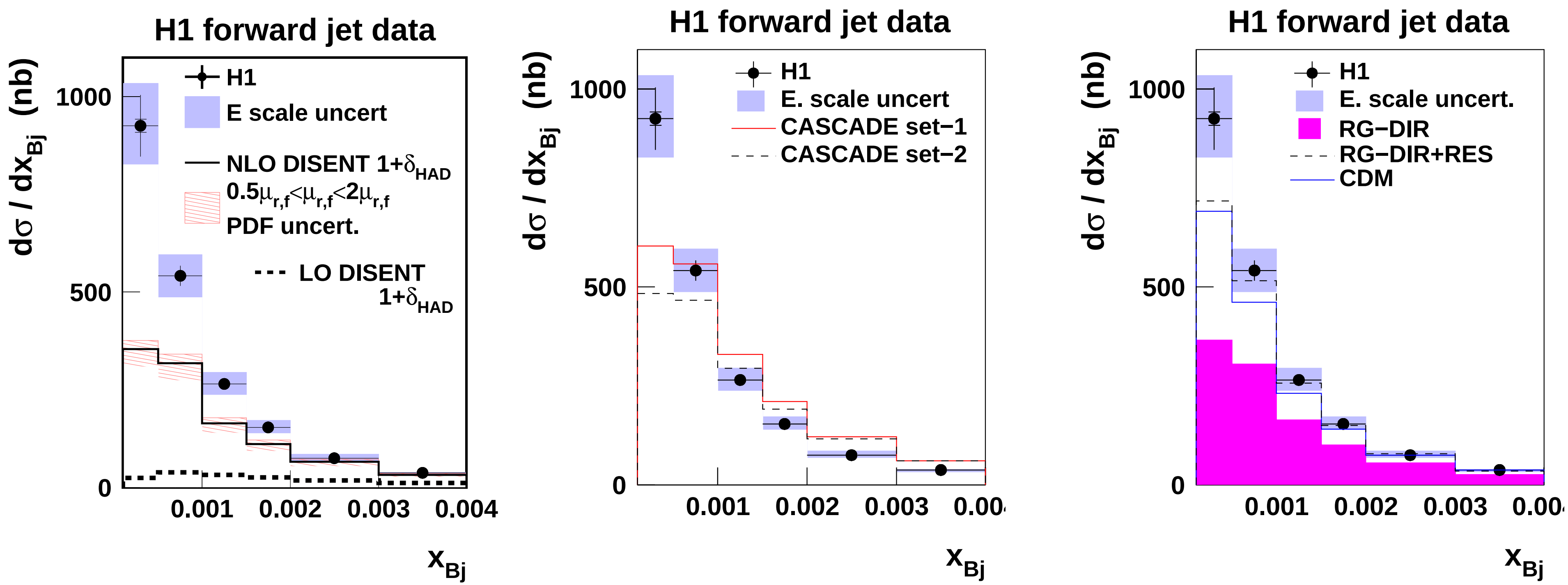


⟶ Forward-jet cross section rises with decreasing x

- Comparison to predictions:
  - ⟶ NLO pQCD (DGLAP): fails to describe the data at low x
  - ⟶ CASCADE (CCFM): improved description of data at low x (sensitivity to unintegrated PDFs)
  - ⟶ CDM (BFKL-like) and resolved-photon: better description of data

Azimuthal jet separation

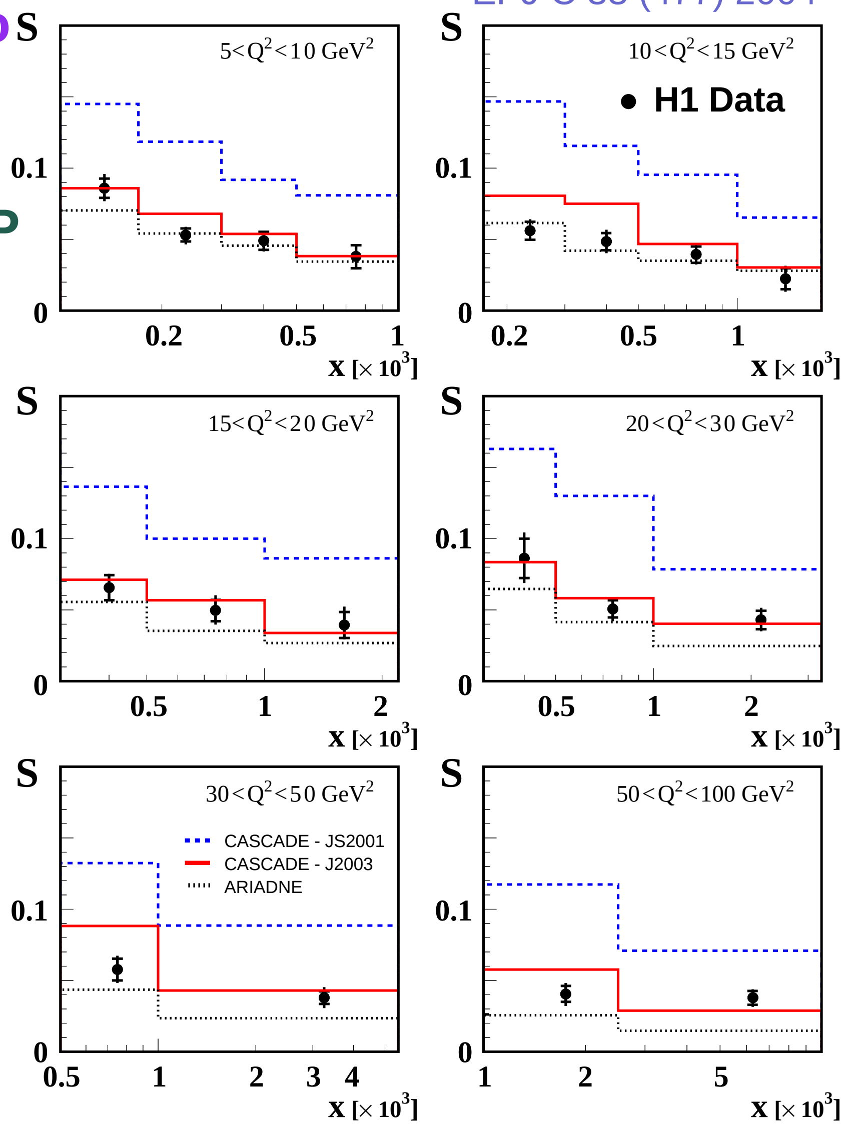
EPJ C 33 (477) 2004

- 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

- The ratio

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

is well suited to test small-x effects



- Comparison to CCFM predictions (CASCADE):
  $\longrightarrow$ calculations of S show sensitivity to the unintegrated gluon distributions

$\longrightarrow$ These measurements can be used to constrain the unintegrated PDFs

Dijet cross sections in photoproduction

- Measurements of jet cross sections in photoproduction allow tests of color dynamics
- At HERA, quark and gluon exchange can be studied in the same hadronic-induced reaction by separating resolved and direct processes in PHP using

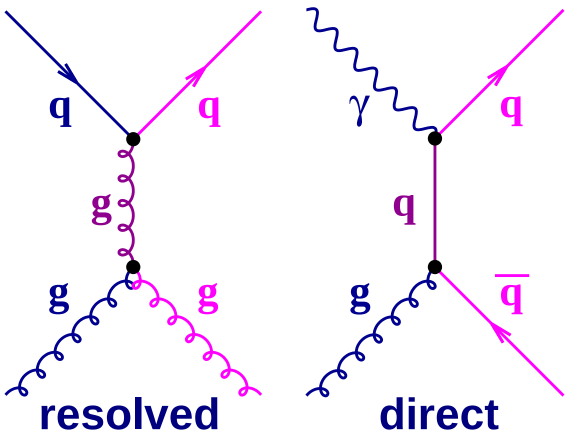
$$x_\gamma^{obs} = \frac{1}{2yE_e}(E_T^{jet1} e^{-\eta^{jet1}} + E_T^{jet2} e^{-\eta^{jet2}}) \quad \rightarrow \begin{cases} x_\gamma^{obs} < 1 \text{ for resolved} \\ x_\gamma^{obs} \sim 1 \text{ for direct} \end{cases}$$

- Resolved processes dominated by gluon exchange (like dijets in pp):

$$\theta^* \rightarrow 0, \pi: \frac{d\sigma}{d\cos\theta^*} \sim \frac{1}{(1 - |\cos\theta^*|)^2}$$

- Direct processes proceed via quark exchange (like prompt photon in pp):

$$\theta^* \rightarrow 0: \frac{d\sigma}{d\cos\theta^*} \sim \frac{1}{(1 - |\cos\theta^*|)^1}$$



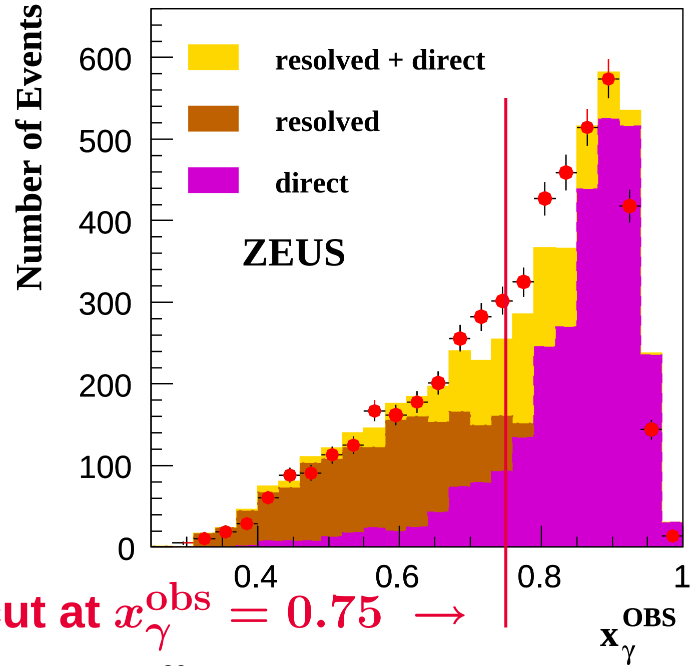
$\longrightarrow$ The $\cos\theta^*$ distribution reflects the underlying parton dynamics since it has sensitivity to the spin of the exchanged particle in two-body processes

Dijet cross sections in photoproduction

- Measurements of jet cross sections in **photoproduction** allow tests of color dynamics

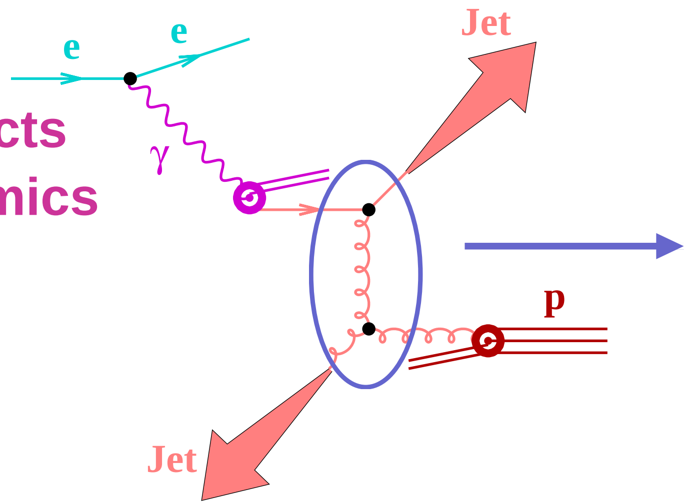
sample with $x_\gamma^{\rm obs} < 0.75 \leftarrow$ dominated by resolved processes

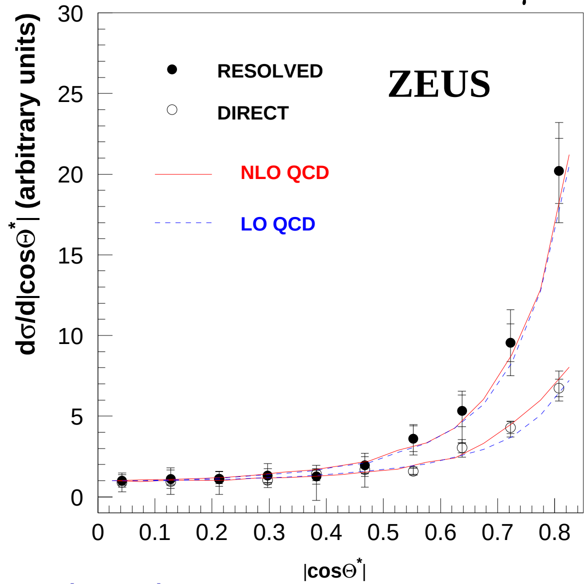
sample with $x_\gamma^{\rm obs} > 0.75 \leftarrow$ dominated by direct processes



cut at $x_\gamma^{\rm obs} = 0.75 \longrightarrow$

- The $\cos\theta^*$ distribution reflects the underlying parton dynamics





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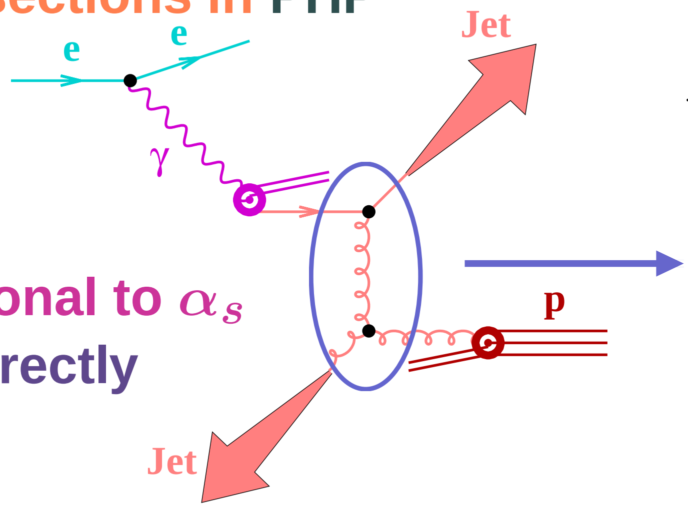
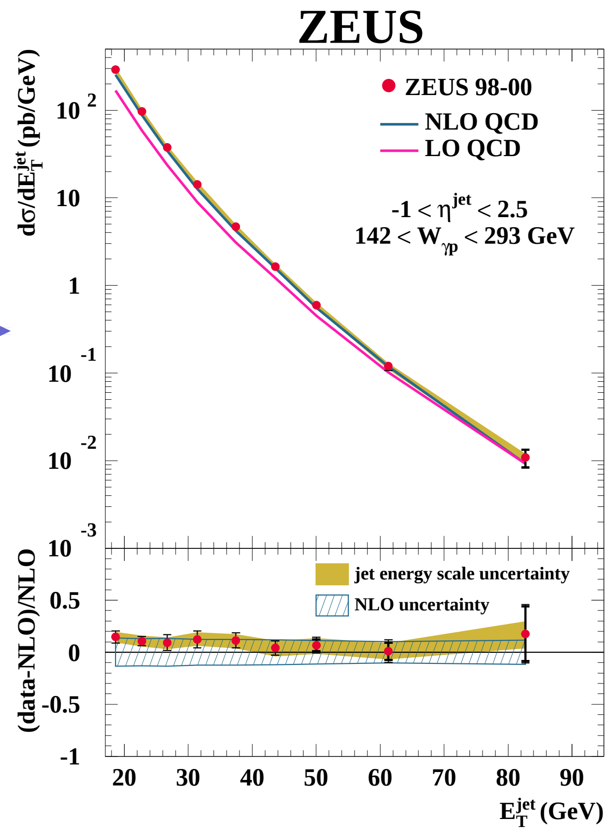
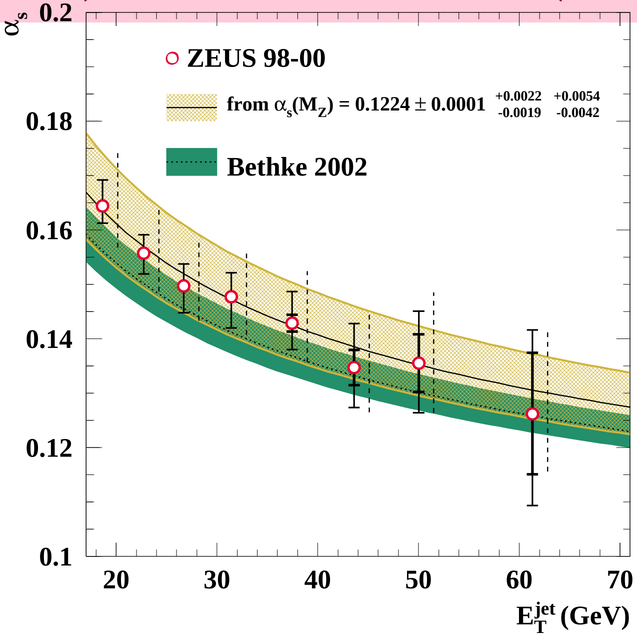
Inclusive-jet cross sections in photoproduction

- Measurements of jet cross sections in PHP at large E_T^{jet} allow tests of pQCD
- The LO prediction for the jet cross section is proportional to α_s $\longrightarrow$ the measurements are directly sensitive to α_s:





$$\alpha_s(M_Z) = 0.1224 \pm 0.0001\ (\text{stat.})\ ^{+0.0022}_{-0.0019}\ (\text{exp.})\ ^{+0.0054}_{-0.0042}\ (\text{th.})$$



experimental uncertainties: 1.8%

theoretical uncertainties: 4.4%

$\longrightarrow$ Test of the energy-scale dependence of α_s from $d\sigma/dE_T^{jet}$ in PHP

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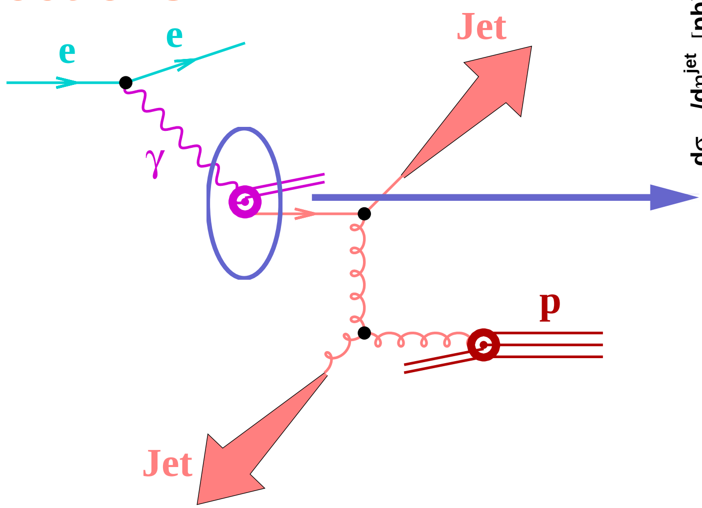
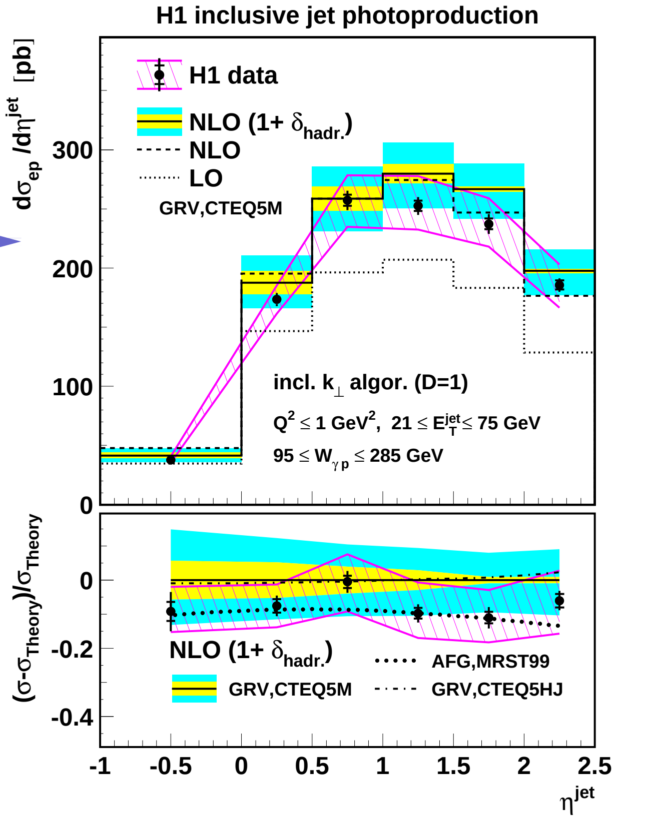
Inclusive-jet cross sections in photoproduction

- Measurements of jet cross sections in photoproduction allow tests of γPDFs





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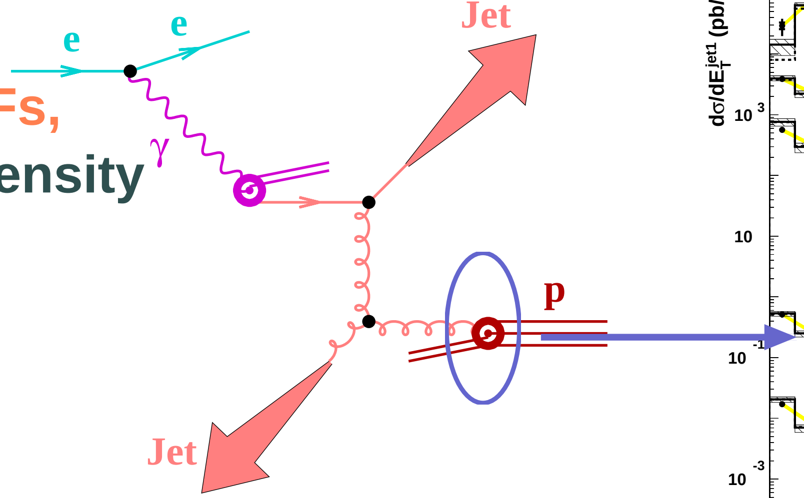
$$x_\gamma^{\rm obs} = \frac{1}{2yE_e}(E_T^{\rm jet1}e^{-\eta^{\rm jet1}} + E_T^{\rm jet2}e^{-\eta^{\rm jet2}})$$

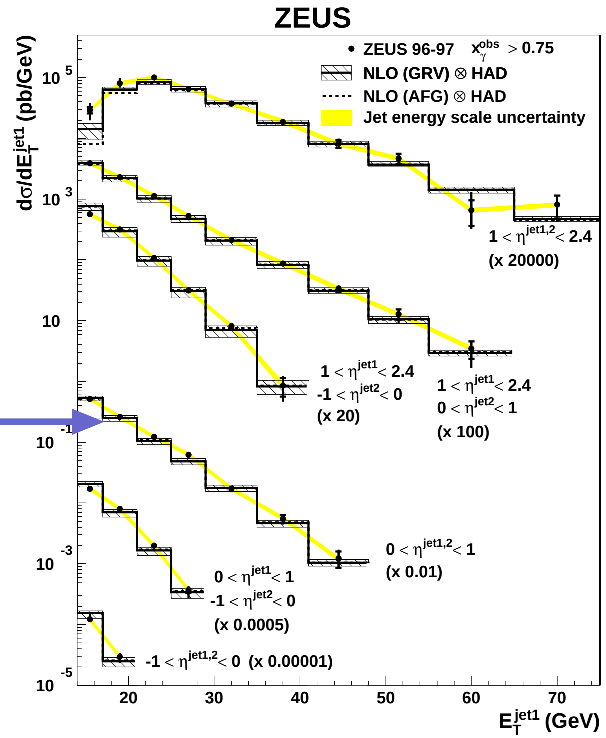
($x_\gamma^{\rm obs} < 1$ for resolved and $x_\gamma^{\rm obs} \sim 1$ for direct)

- The structure of the photon is investigated by measuring jet cross sections most sensitive to the γPDF's, eg $d\sigma/d\eta^{\rm jet}$ or $d\sigma/dx_\gamma^{\rm obs}$, and comparing the measurements to predictions based on different parametrisations of the γPDF's
  $\longrightarrow$ the measurements can be used to discriminate among different parametrisations or used in a global fit to constrain them

Dijet cross sections in photoproduction

- Measurements of jet cross sections in **photoproduction** provide a useful constrain of the pPDFs, in particular, on the **gluon density**





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- **This is achieved by measuring jet cross sections less sensitive to the γPDF's, eg $d\sigma/dE_T^{\rm jet}$ for $x_\gamma^{\rm obs} > 0.75$**

- **These measurements have been incorporated in a global fit of the pPDFs to improve the determination of the gluon density in the proton**

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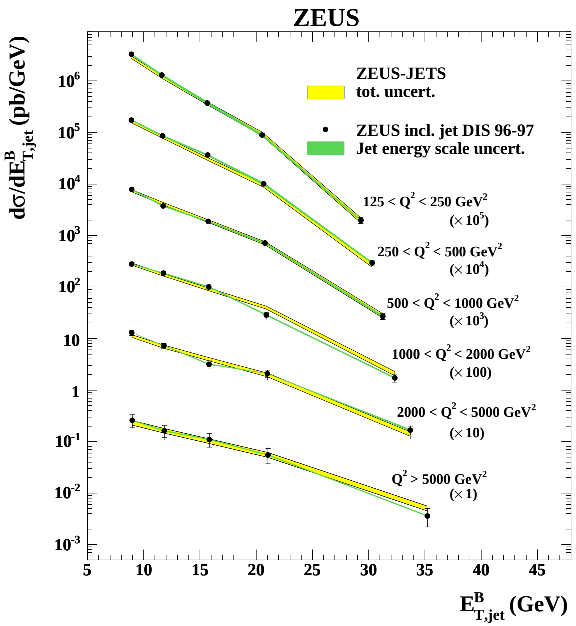
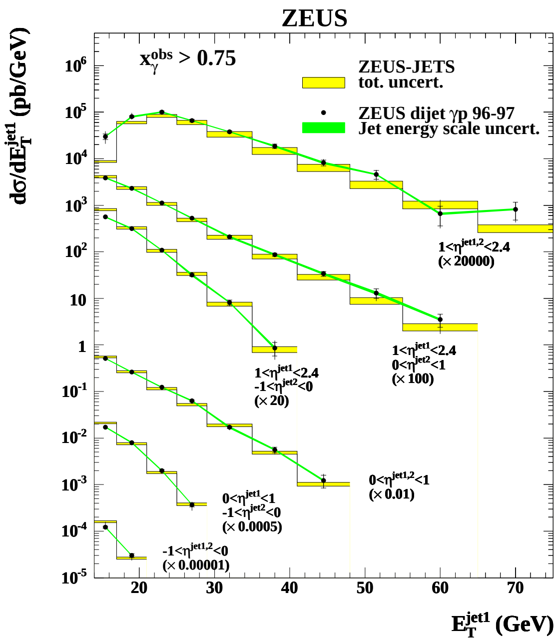
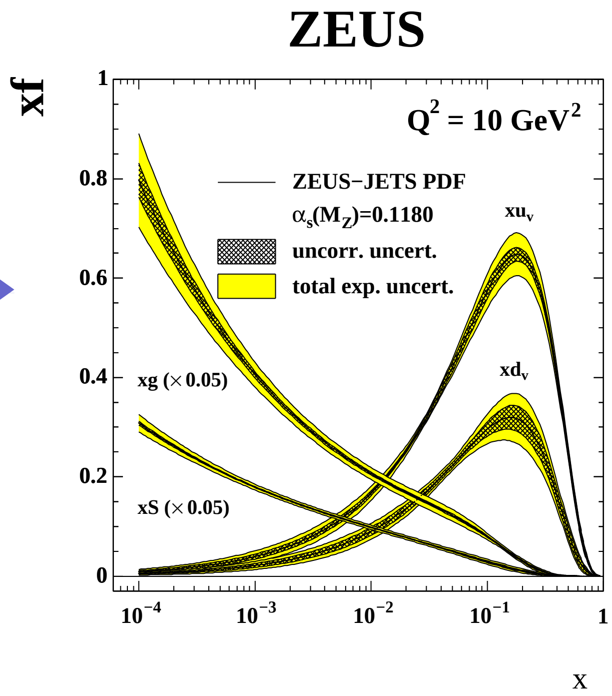
Conclusions: jets and PDFs

- Very precise jet cross sections in NC DIS and PHP that are directly sensitive to the gluon content of the proton: useful to constrain gluon density, especially at mid- to high-x (most relevant at LHC energies)
- Measurements incorporated in a QCD fit to determine PDFs parametrisations:







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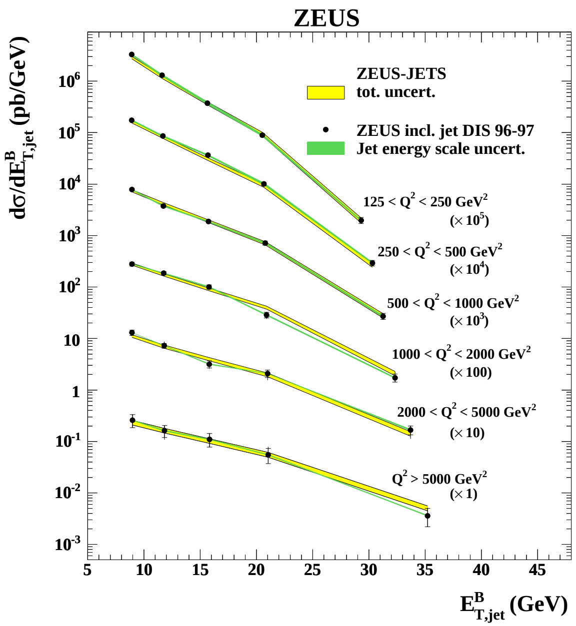
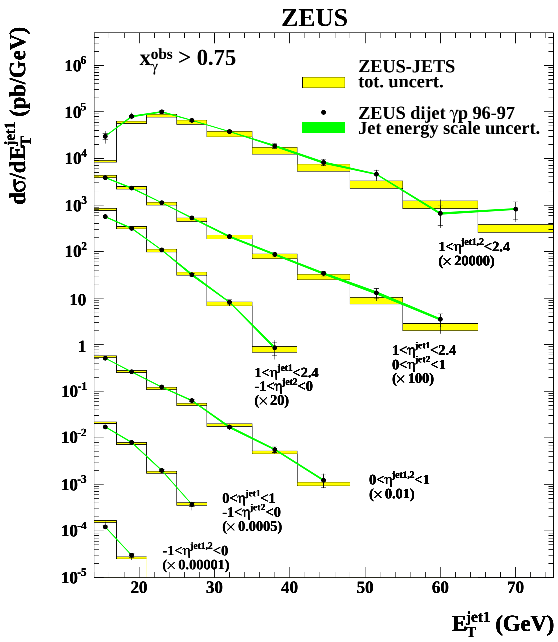
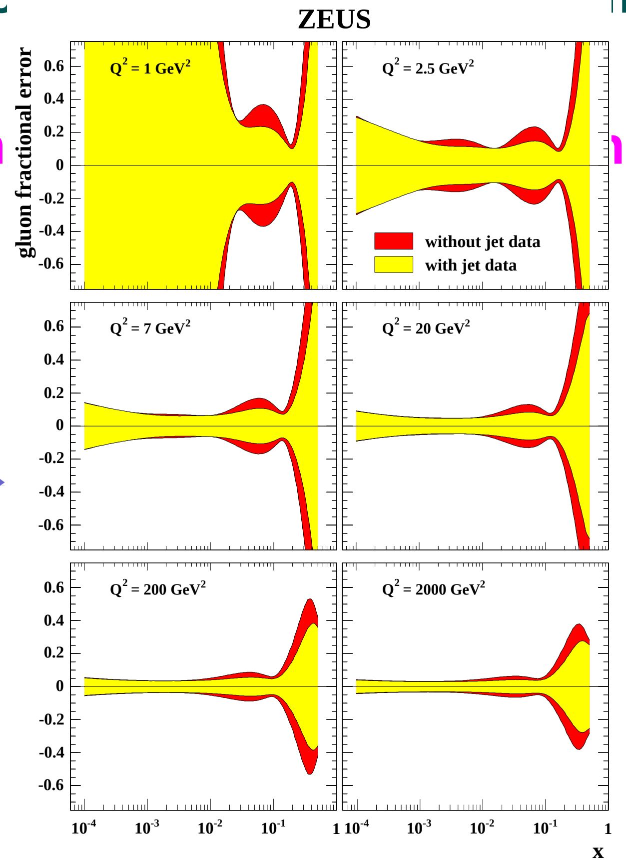
Conclusions: jets and PDFs

- Very precise jet cross sections in NC DIS and PHP are directly sensitive to the gluon content of the proton: useful to constrain gluon density, especially at mid- to high-x (most relevant at LHC energies)
- Measurements incorporated in a QCD fit to determin ns:







- The result is an improvement on the determination of the gluon density in the proton $\longrightarrow$ the uncertainty in the gluon density decreases for mid- to high-x by up to a factor of 2

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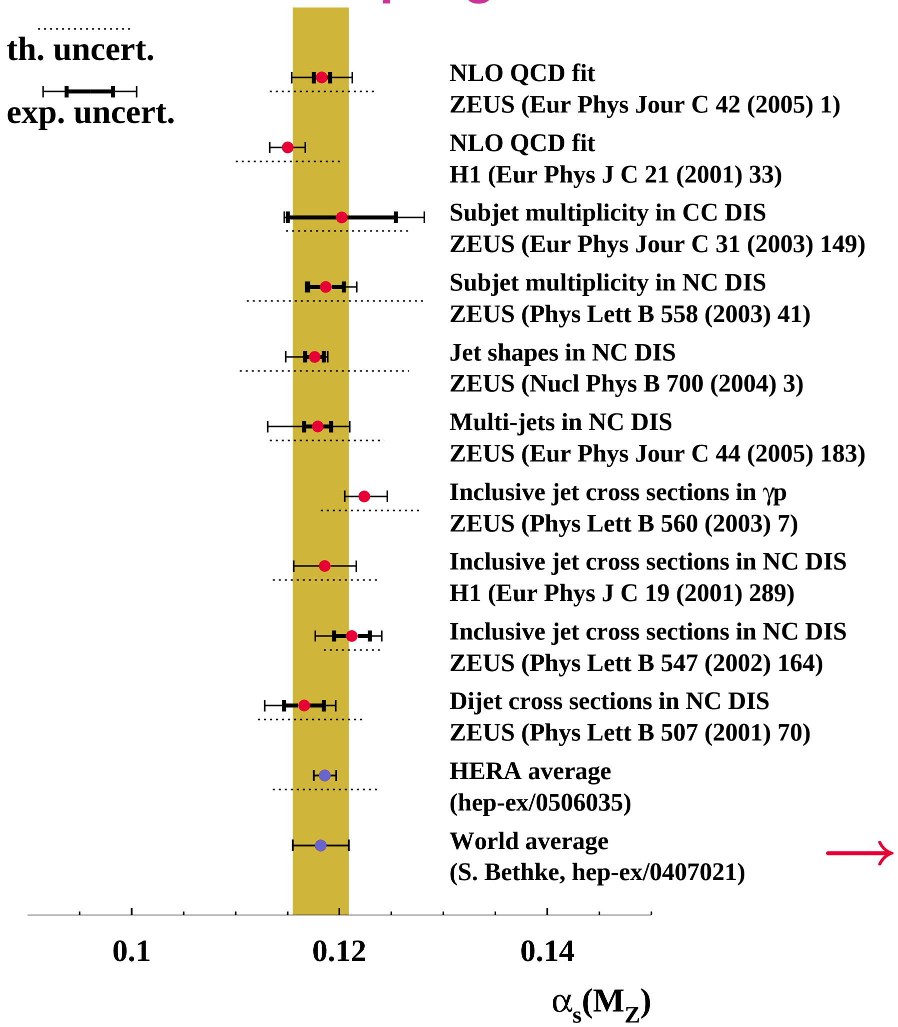
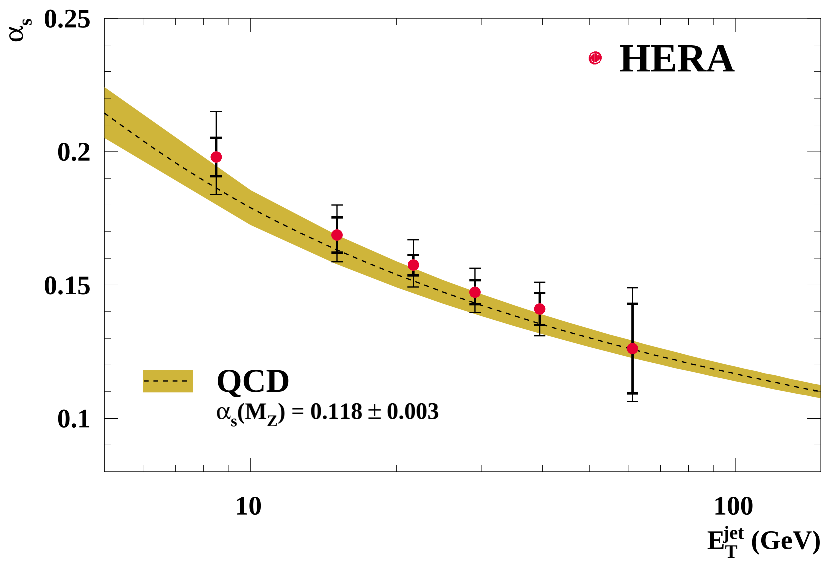
Conclusions: α_s

- **HERA has become a unique QCD-testing machine:** very useful for understanding multijet production in "clean" hadronic-induced reactions

→ considerable progress in understanding and reducing uncertainties led to very precise determinations of α_s

⇒ improved calculations needed for better accuracy





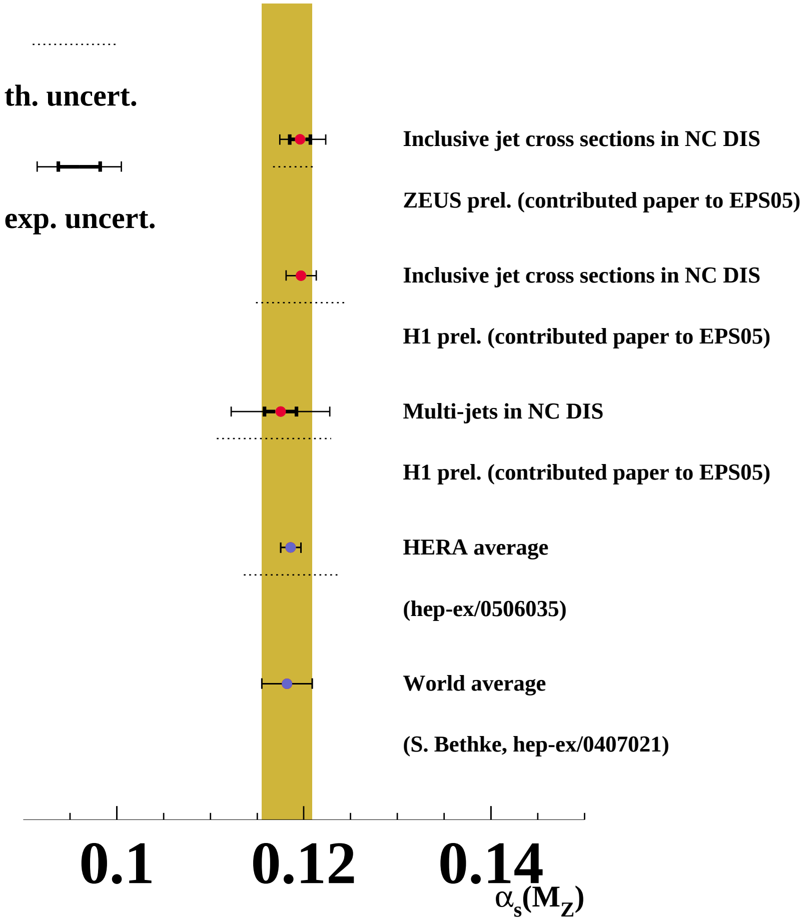
→ **Observation of the running of α_s from HERA jet data alone**

hep-ex/0506035

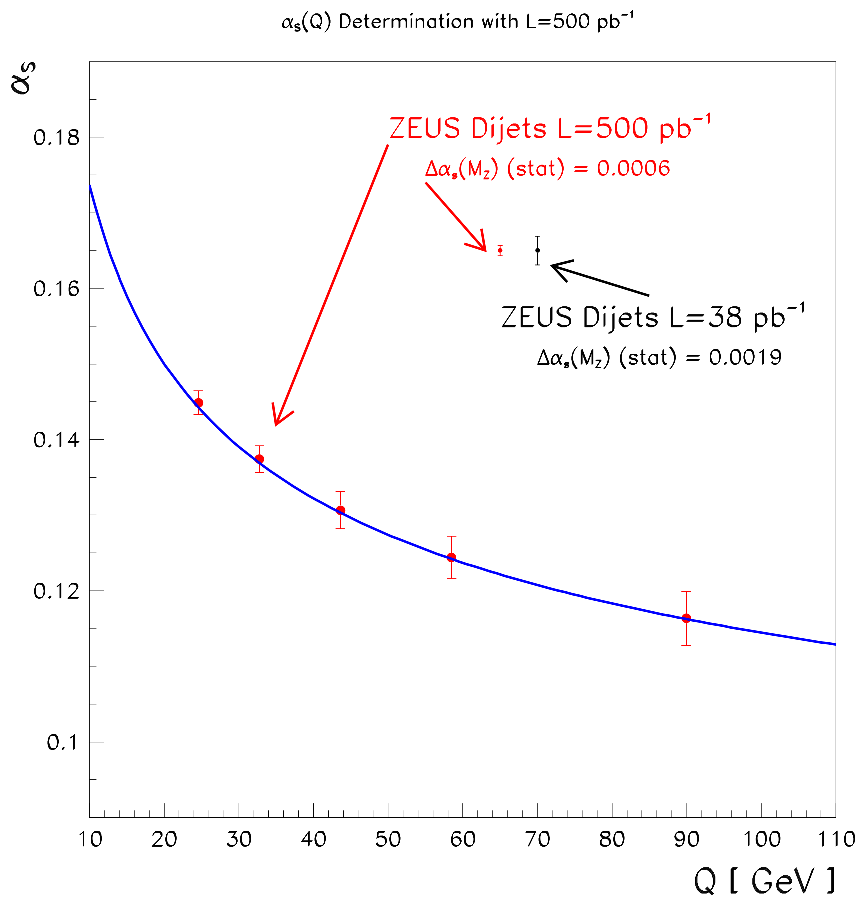
The future of HERA

- **HERA is still running:** wealth of data already available to test **new MC models**, **MC@NLO** and **NNLO pQCD calculations** if they are made available for ep collisions

$\longrightarrow$ **new HERA I results still coming:**



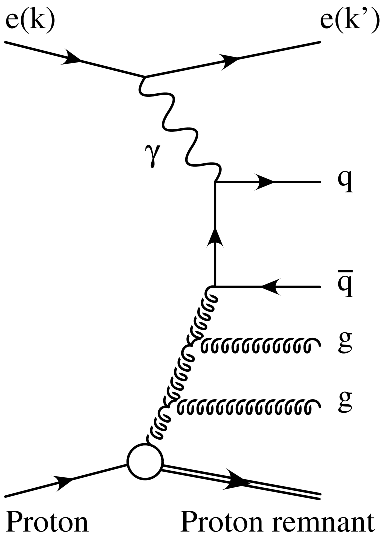
$\longrightarrow$ **85 pb^{-1} e^+p and 300 pb^{-1} e^-p HERA II data being analysed:**

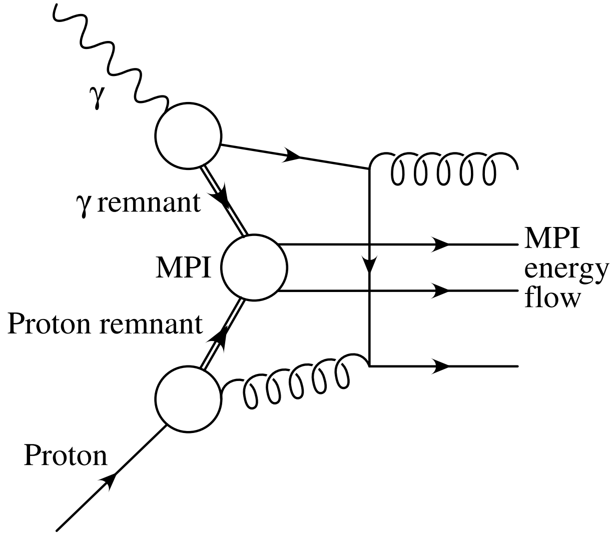


Back-up slides

Multijet cross sections in photoproduction

- Measurements of jet cross sections in photoproduction allow tests of hard multijet production, multiparticle interactions and "underlying event"

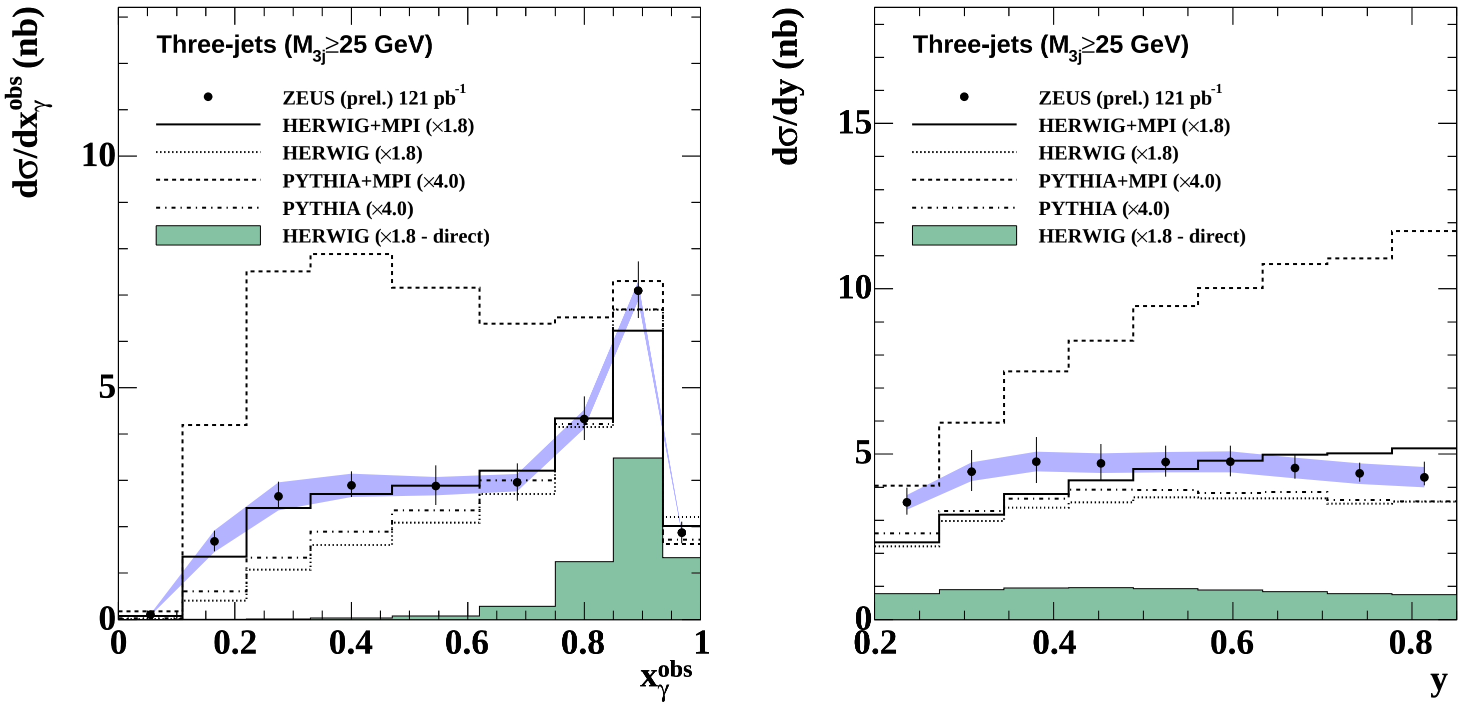




- Multijet production is directly sensitive to high orders: $\sigma_{3\mathrm{jet}} \propto \alpha_s^2$
- Test of parton showers in Monte Carlo models
- Sensitivity to multiparton interactions/underlying event $\longrightarrow$ test/tune models

Multijet cross sections in photoproduction

DIS06 preliminary



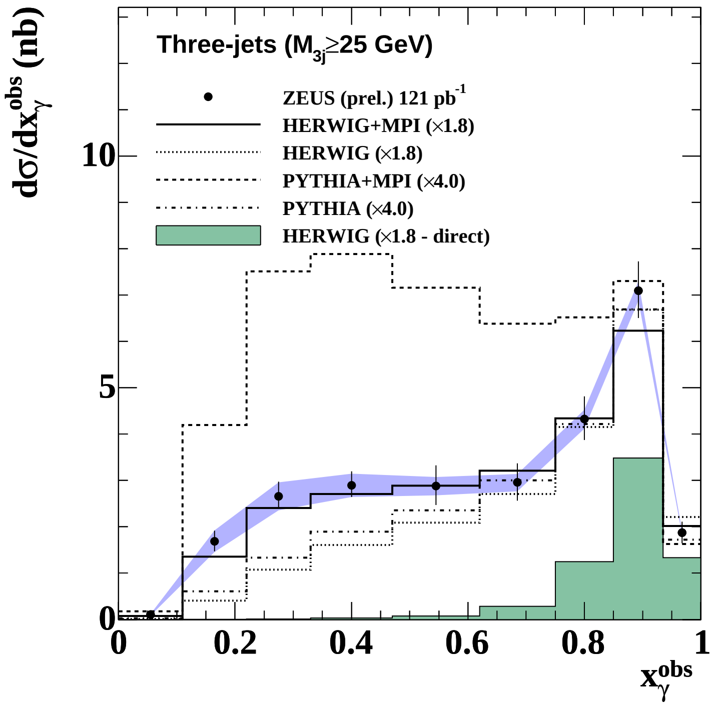
PYTHIA MPI tuned to generic collider data **HERWIG MPI tuned to $x_\gamma^{\rm obs}$ data**

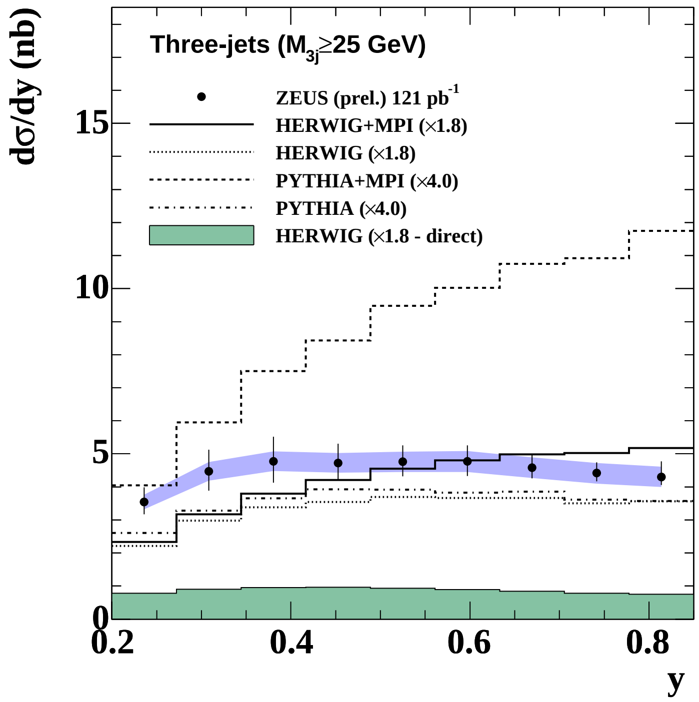
- **Monte Carlo models without multiparton interactions describe the y ($= \sqrt{W s}$) but fail describe the shape of the measured $x_\gamma^{\rm obs}$ distribution**
- **PYTHIA MPI fails to describe the data**
- **HERWIG MPI describes the $x_\gamma^{\rm obs}$ but the description of y gets spoiled**

$\rightarrow$ **$x_\gamma^{\rm obs}$ and y distributions: ideal ground for tuning and testing models**

Multijet cross sections in photoproduction

DIS06 preliminary





→ **very precise hadronic data can be used as testing ground for hadronisation and multiparton interaction models**