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Prompt photons and multijets at HERA

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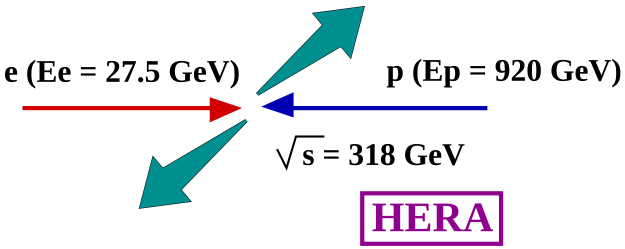
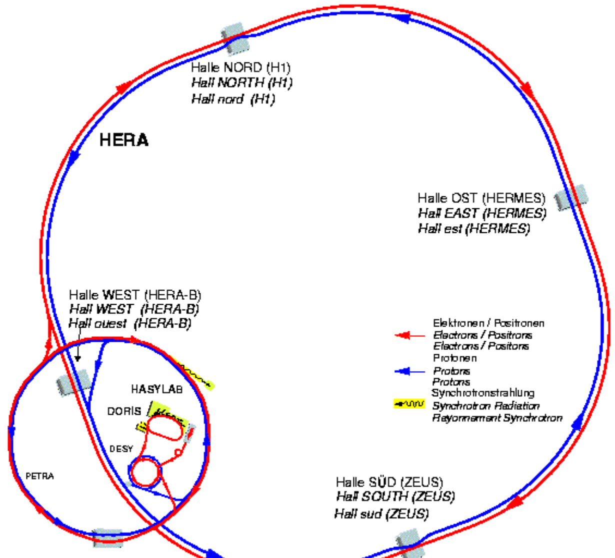


H1 and ZEUS Collaborations



- Outline

⟶ Neutral current deep inelastic scattering:

  ⟶ (multi)jet production at low x

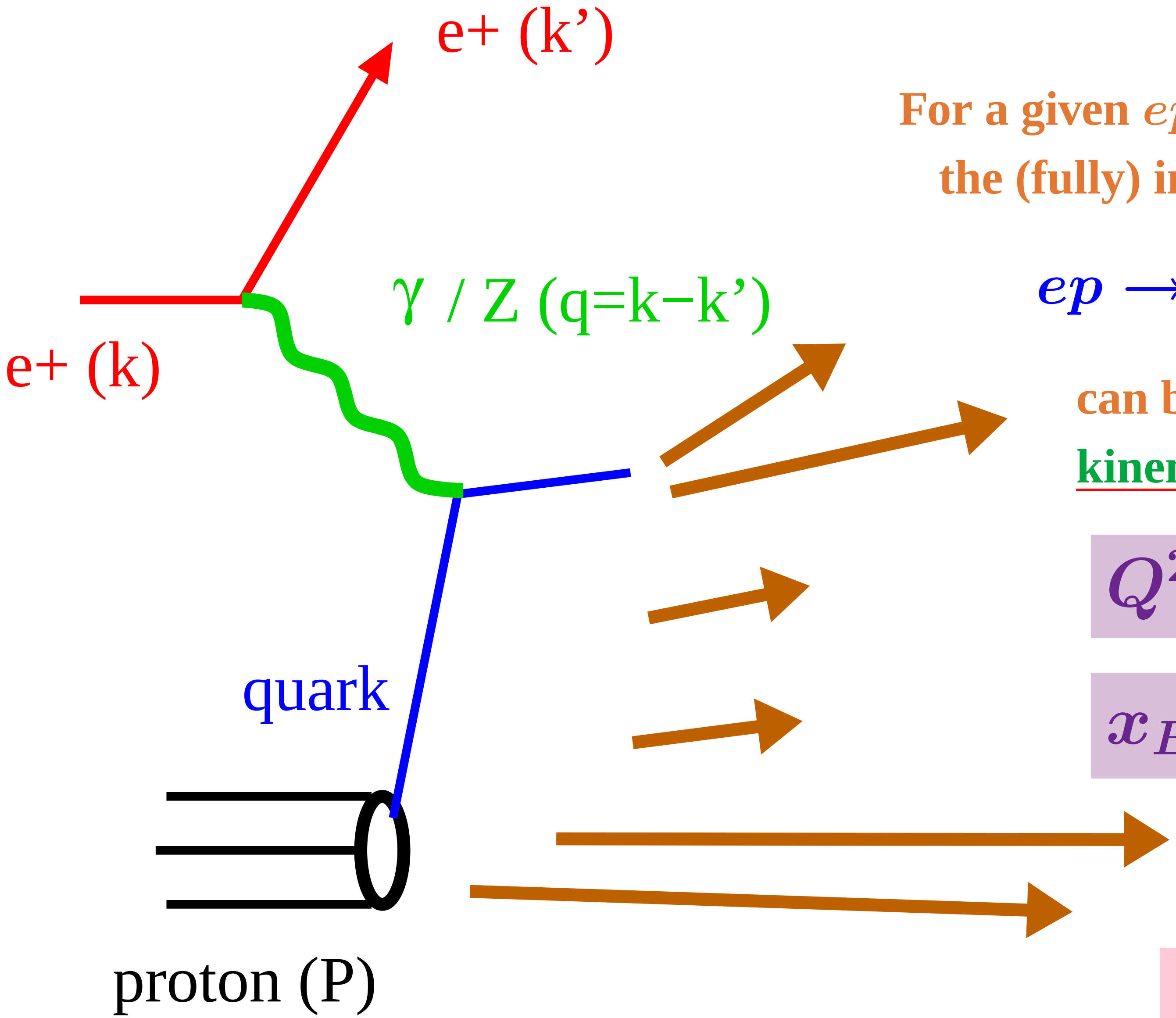
  ⟶ isolated-photon production

⟶ Photoproduction:

  ⟶ (multi)jet production

  ⟶ prompt-photon production

Kinematics of Neutral Current Deep Inelastic Scattering



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

$$ep \rightarrow e + \mathrm{X}$$

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

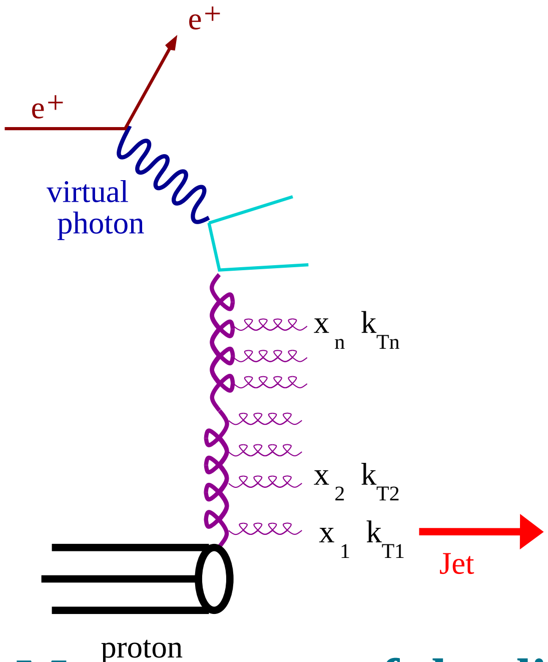
$$Q^2 = -(k - k')^2$$

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

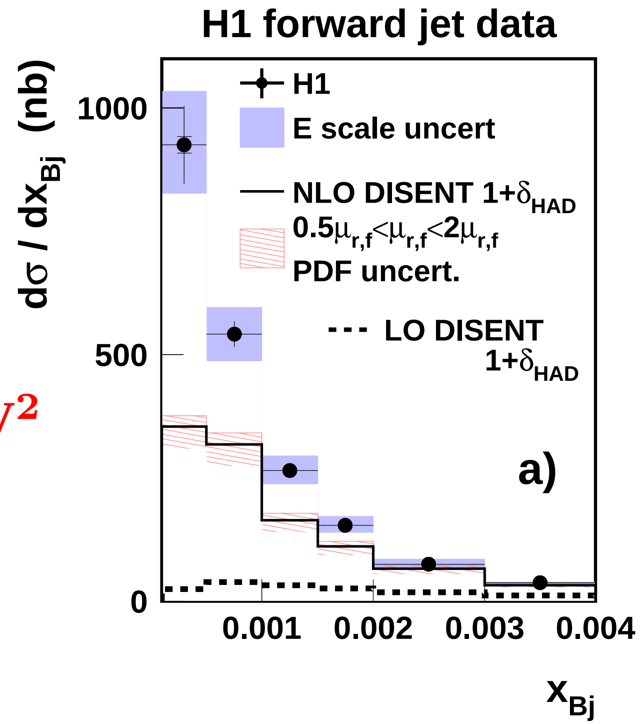
→ Inelasticity variable

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

Parton evolution at low x



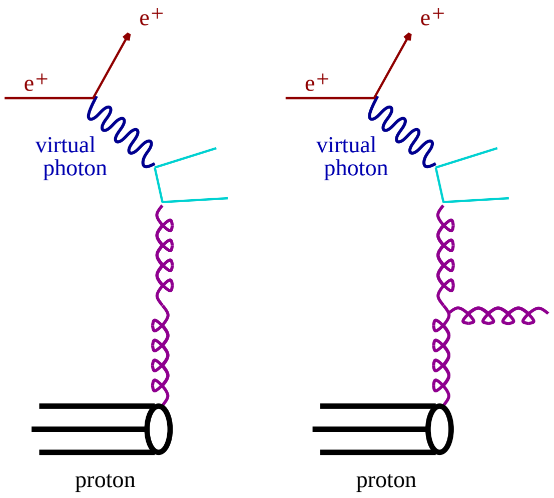
- **DGLAP equations sum the leading powers of $\alpha_s \log Q^2$ in the region $Q^2 \gg k_{Tn}^2 \gg \ldots \gg k_{T2}^2 \gg k_{T1}^2$**
- **When $\log Q^2 \ll \log 1/x \Longrightarrow \alpha_s \log 1/x$ become important; BFKL equations sum these terms $\Rightarrow$ no k_T ordering**
- **Mueller and Navelet's proposal: forward (proton's direction) jet production with x_1/x as large as possible and $k_{T1} \sim Q$**



- **Measurement of the differential cross section $d\sigma/dx$ for jet production with $p_{t,jet} > 3.5$ GeV, $7° < \theta_{\rm jet} < 20°$, $0.5 < p_{t,jet}^2/Q^2 < 2$ and $x_{jet} = E_{jet}/E_p > 0.035$ in the region $10^{-4} < x < 4 \cdot 10^{-3}$ and $5 < Q^2 < 85$ GeV^2**
- **Strong rise towards low x is observed**

$\longrightarrow$ NLO QCD (DGLAP) lies well below the data at low x ($\mu_R^2 = \langle p_{t,di-jets}^2 \rangle$)

Measurement of Forward Jet Production at low x (up to $\eta^{jet} = 4.3$)

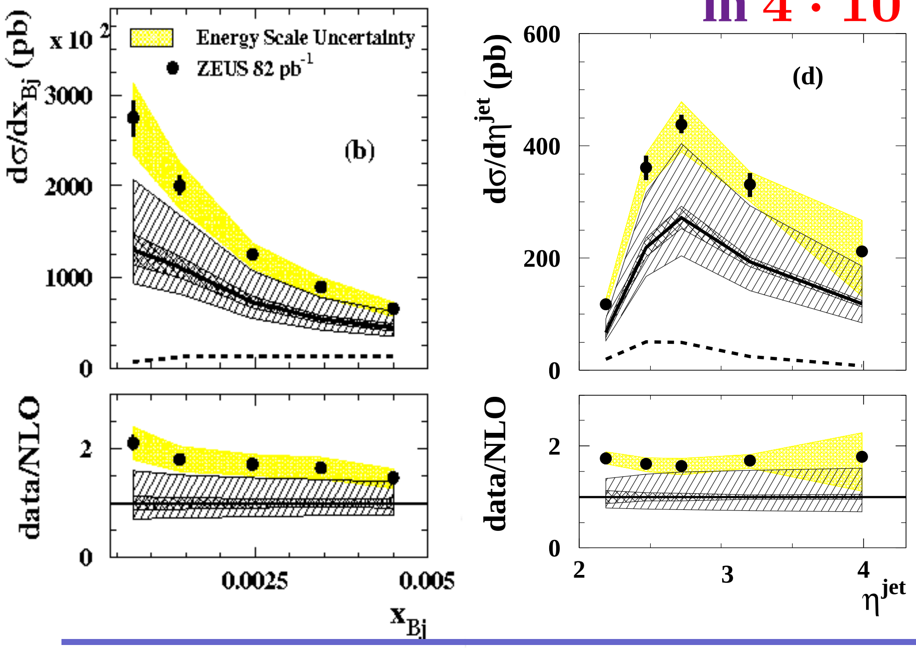


LO $\mathcal{O}(\alpha_s)$ NLO $\mathcal{O}(\alpha_s^2)$

- LO QCD ($\mathcal{O}(\alpha_s)$): hardly any phase space for forward jets
- NLO QCD ($\mathcal{O}(\alpha_s^2)$): huge increase (NLO $\gg$ LO) due to opening of new channel (gluon exchange in t-channel)

$\longrightarrow$ NLO QCD becomes an "effective" LO, with large theoretical uncertainties

- Measurement of inclusive jet production with $E_T^{jet} > 5$ GeV, $2 < \eta^{jet} < 4.3$, $0.5 < (E_T^{jet})^2/Q^2 < 2$ and $x_{jet} > 0.036$ in $4 \cdot 10^{-4} < x < 5 \cdot 10^{-3}$, $20 < Q^2 < 100$ GeV^2



- Strong rise towards low x is observed
- Comparison to pQCD calculations ($\mu_R = Q$)

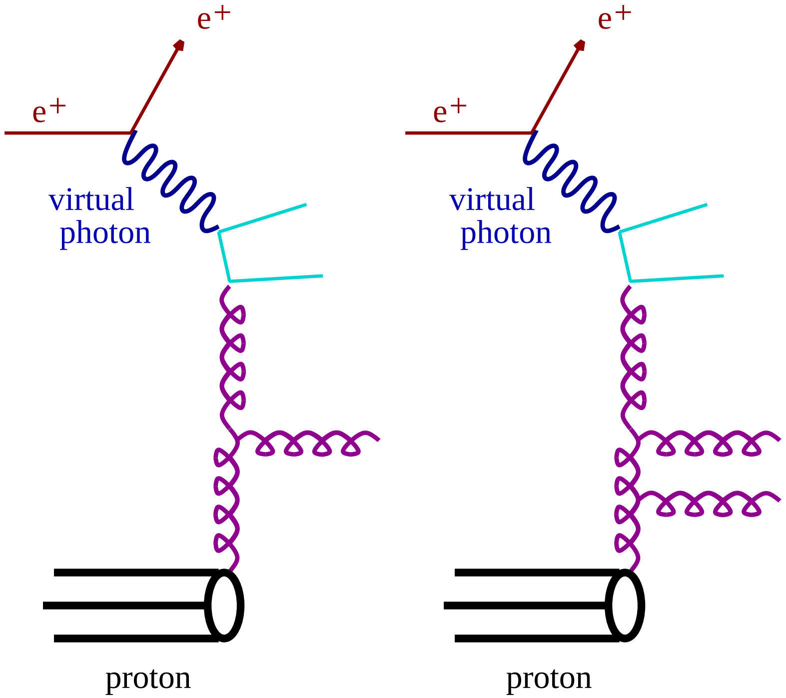
$\longrightarrow$ big jump from LO to NLO

$\longrightarrow$ large μ_R dependence (large uncertainties)

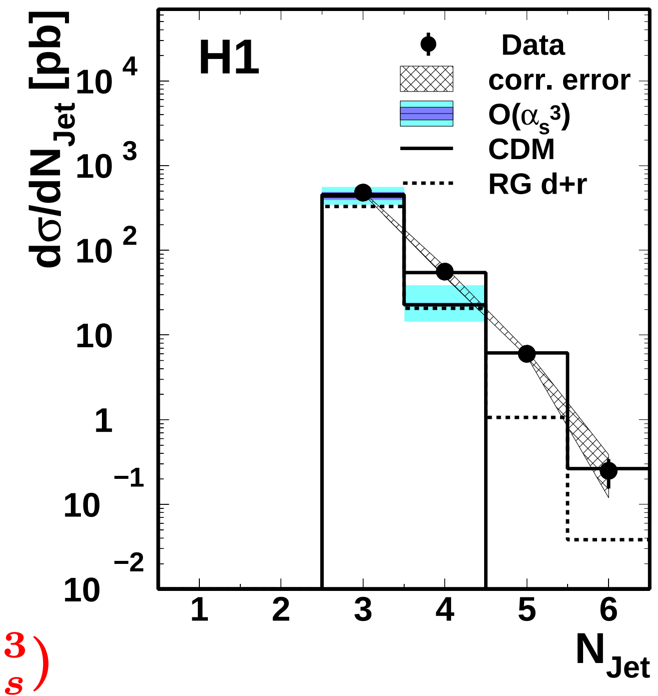
$\longrightarrow$ NLO underestimates the data by factor of ~ 2

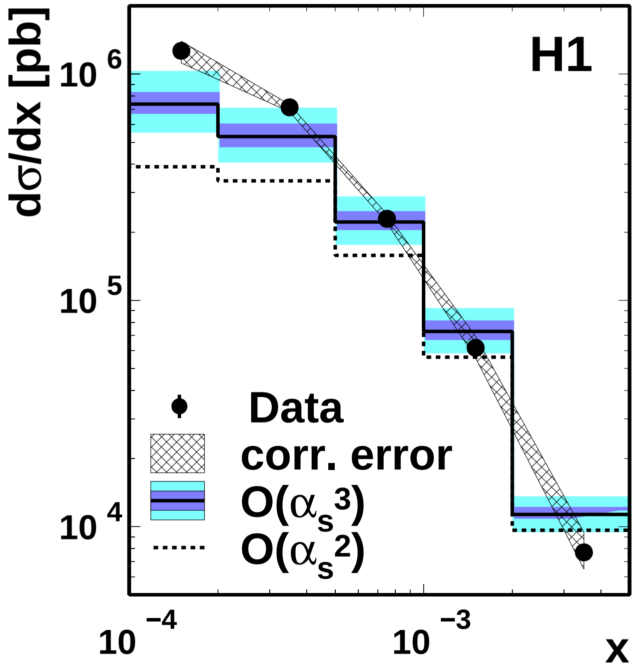
$\Rightarrow$ Large theoretical uncertainties (higher-orders) in pQCD calculations prevent firm conclusions!

Measurements of Three-jet Production at low x



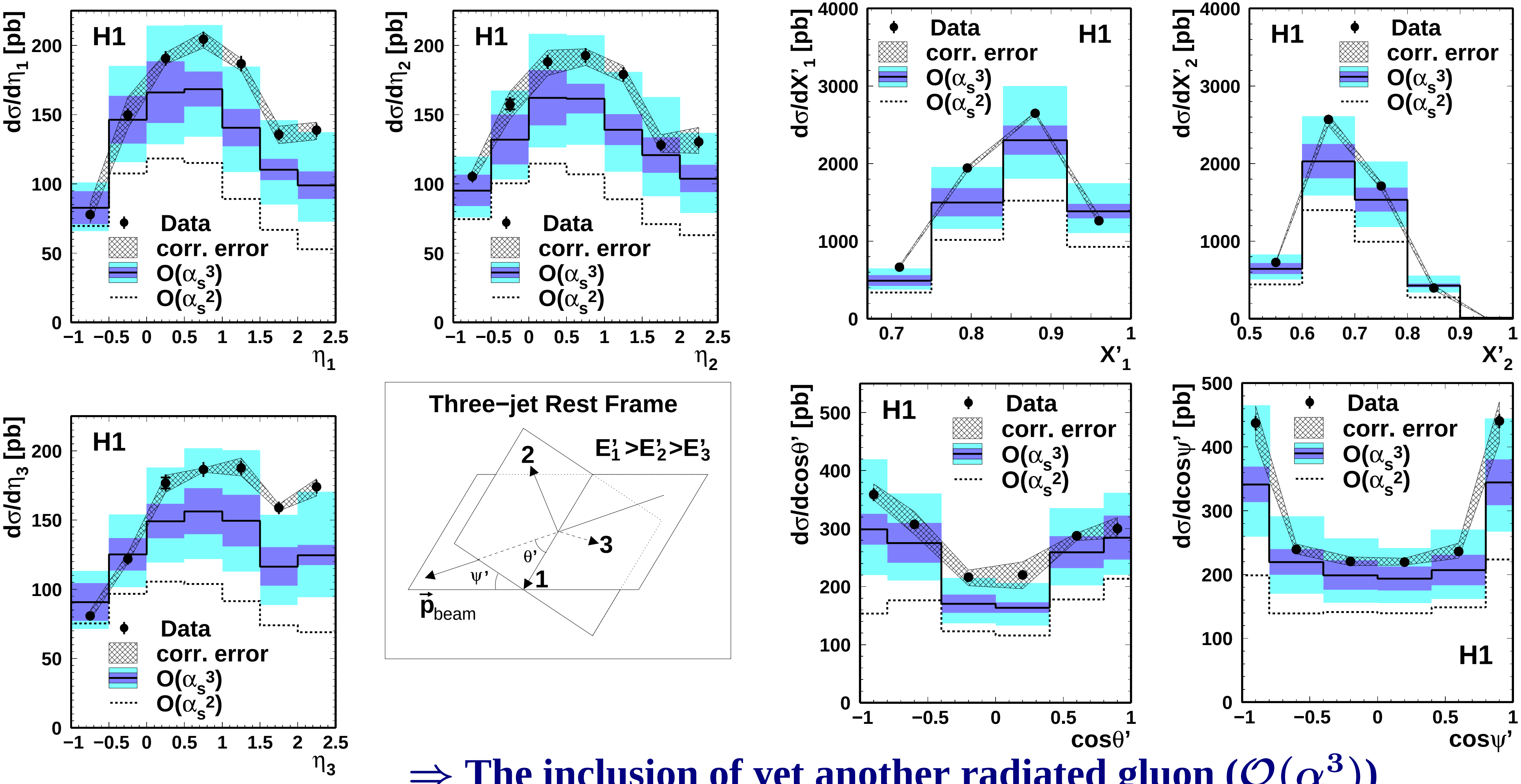
LO $\mathcal{O}(\alpha_s^2)$ **NLO** $\mathcal{O}(\alpha_s^3)$





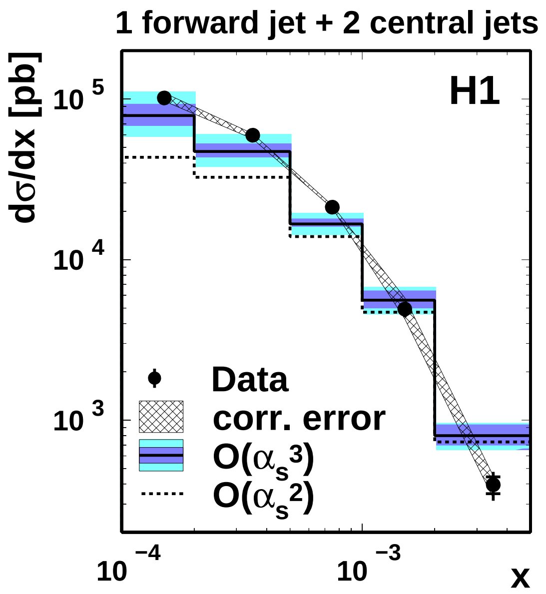
- **Measurements of three-jet production using the k_T cluster algorithm in the $\gamma^* p$ frame with $E^*_{\perp,jet} > 4$ GeV, $E^*_{\perp,jet1} + E^*_{\perp,jet2} > 9$ GeV, $-1 < \eta^{lab}_{jet} < 2.5$ (one central jet $-1 < \eta^{lab}_{jet} < 1.3$) in the kinematic region defined by $0.1 < y < 0.7$ and $5 < Q^2 < 80$ GeV^2 $\Rightarrow$ The inclusion of yet another radiated gluon ($\mathcal{O}(\alpha_s^3)$) improves dramatically the description of the data at low x**

Measurements of Three-jet Production at low x



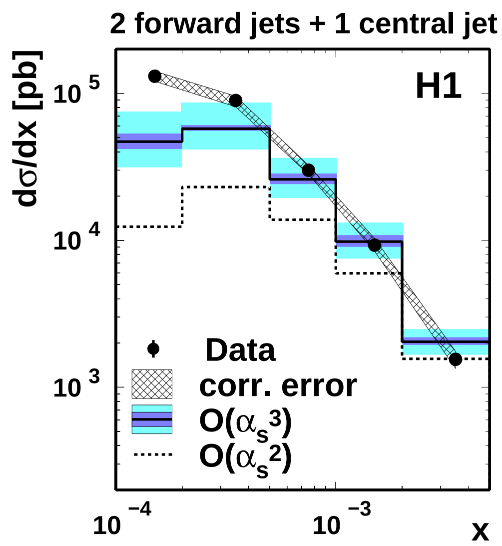
⇒ **The inclusion of yet another radiated gluon ($\mathcal{O}(\alpha_s^3)$) improves dramatically the description of the data at low x**

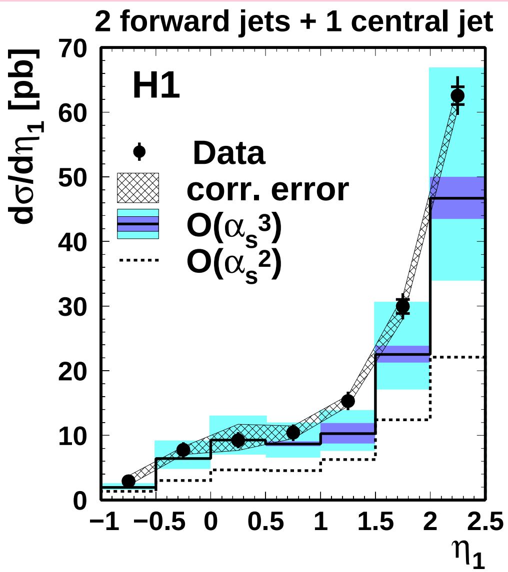
Measurements of Three-jet Production at low x

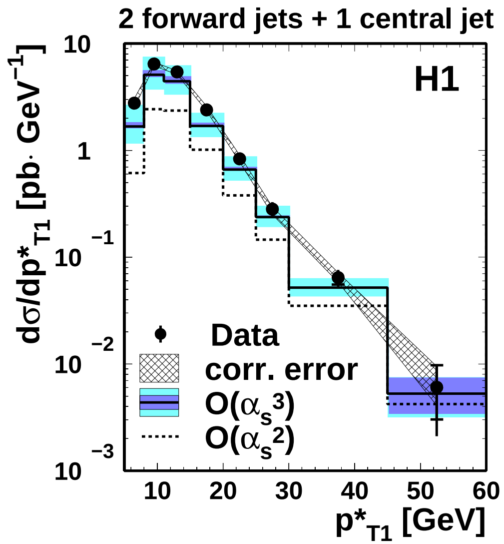


⇐ Sample of events with "2 central jets + 1 forward jet"

⇓ Sample of events with "1 central jet + 2 forward jets"







- The inclusion of $\mathcal{O}(\alpha_s^3)$ corrections provides an improved description of the data

  $\longrightarrow$ particularly dramatic for the sample with two forward jets (sample most sensitive to additional gluon radiation)

$\Rightarrow$ Success of perturbative QCD $\mathcal{O}(\alpha_s^3)$ at describing multijet production at low-x

$\longrightarrow$ almost ... still the data above NLO at $x \sim 10^{-4}$ for "1 central +2 forward jets" sample

Multijet production at low x

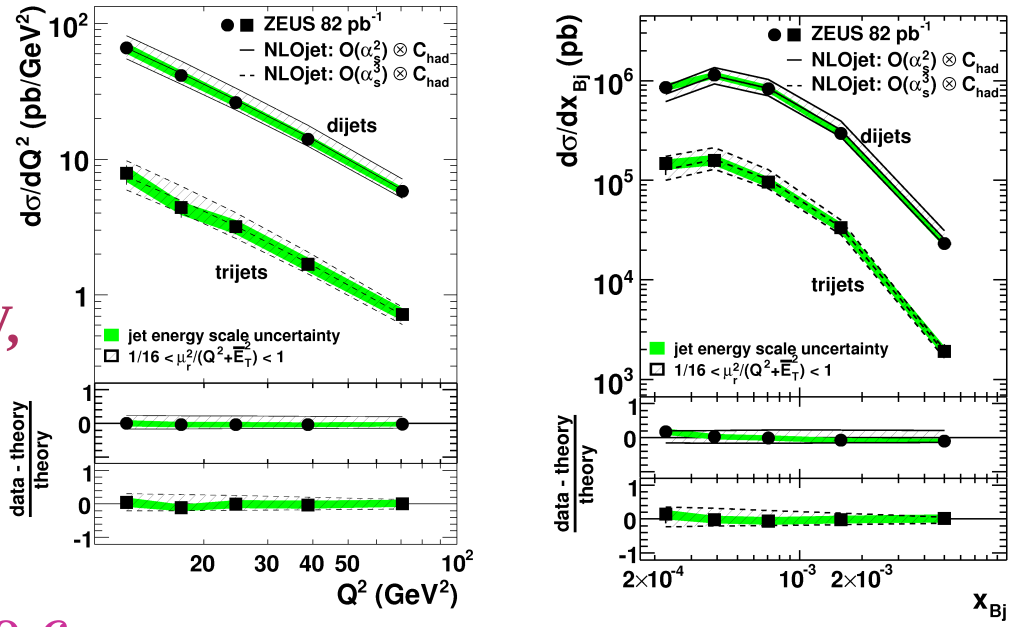
- Measurement of differential cross sections for dijet (trijet) production

  $E_{T,HCM}^{jet1} > 7$ GeV, $E_{T,HCM}^{jet2,3} > 5$ GeV, and $-1 < \eta_{lab}^{jet1,2,3} < 2.5$

  in the kinematic region defined by

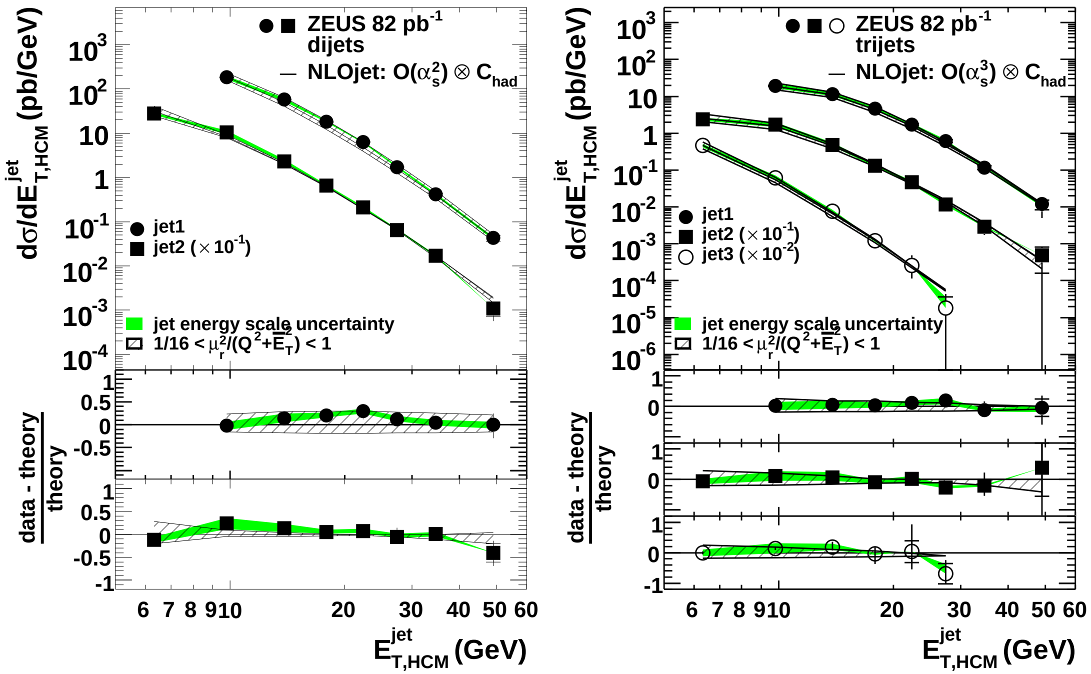
  $10 < Q^2 < 100$ GeV^2,

  $10^{-4} < x_{Bj} < 10^{-2}$ and $0.1 < y < 0.6$



- Comparison to NLO QCD calculations ($\mathcal{O}(\alpha_s^n)$ for n-jet production) corrected for hadronisation effects:

$\rightarrow$ good description of the measured distributions as functions of Q^2, x_{Bj} and $E_{T,HCM}^{jetn}$



Multijet production at low x

- Further investigation of low-x parton dynamics by studying transverse-energy and angular correlations in bins of x_{Bj}

$$d^2\sigma/d|\Delta\phi^{jet1,2}_{HCM}|dx_{Bj}$$

- Dijet events:

$\rightarrow \mathcal{O}(\alpha_s^1) \Longrightarrow \Delta\phi^{jet1,2}_{HCM} = \pi!$

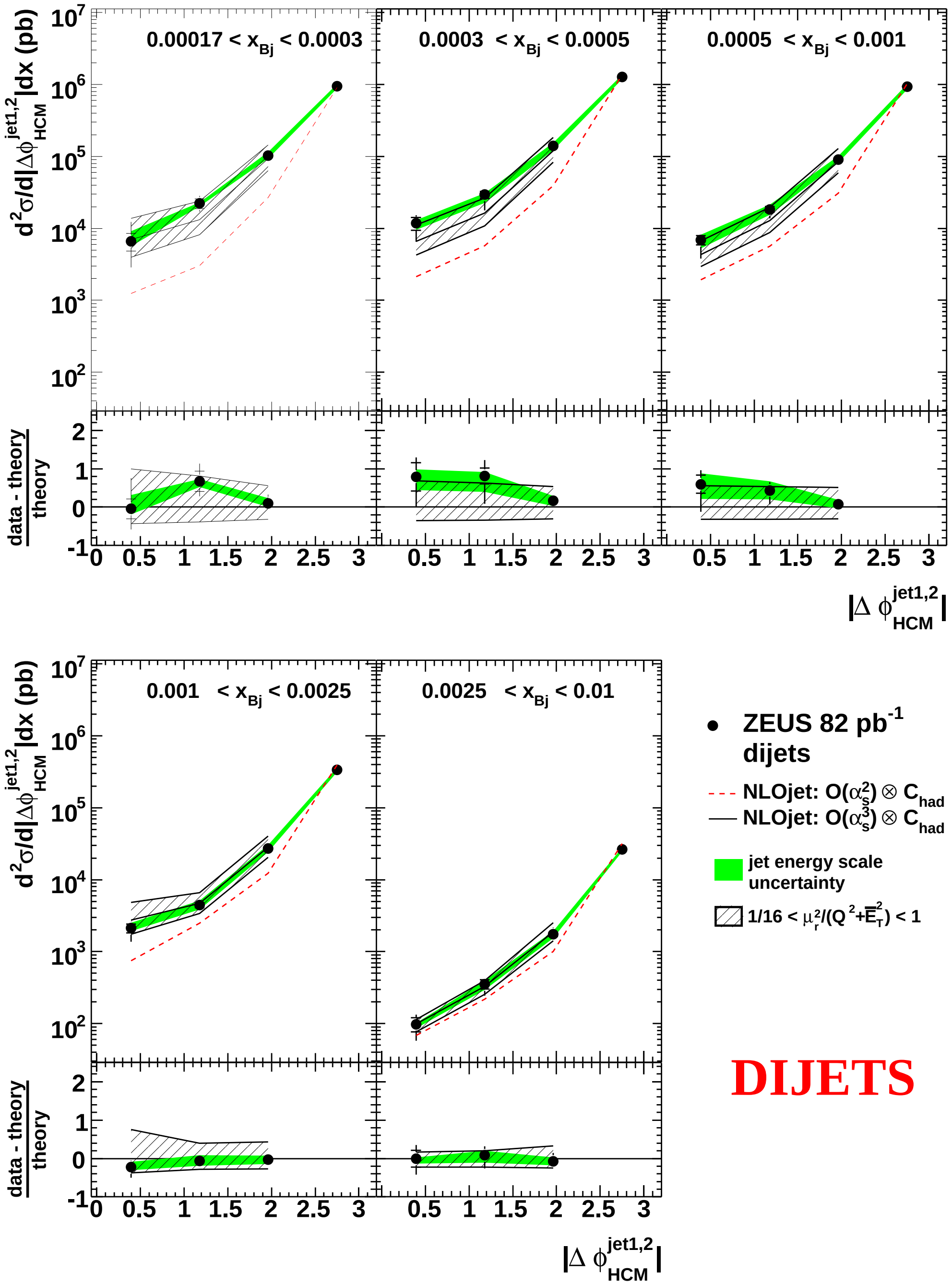
$\rightarrow \mathcal{O}(\alpha_s^2) \Longrightarrow$ first non-trivial contribution!

$\rightarrow \mathcal{O}(\alpha_s^3) \Longrightarrow$ first correction!

- $\mathcal{O}(\alpha_s^2)$ calculations deviate more and more from the data as x_{Bj} decreases
- $\mathcal{O}(\alpha_s^3)$ calculations provide a good description of the data even at low x

(calculations not possible close to $\Delta\phi^{jet1,2}_{HCM} = \pi$)

Importance of higher-order effects at low x!



DIJETS

Multijet production at low x

- Further investigation of low-x parton dynamics by studying transverse-energy and angular correlations in bins of x_{Bj}

$$d^2\sigma/d|\Delta\phi^{jet1,2}_{HCM}|dx_{Bj}$$

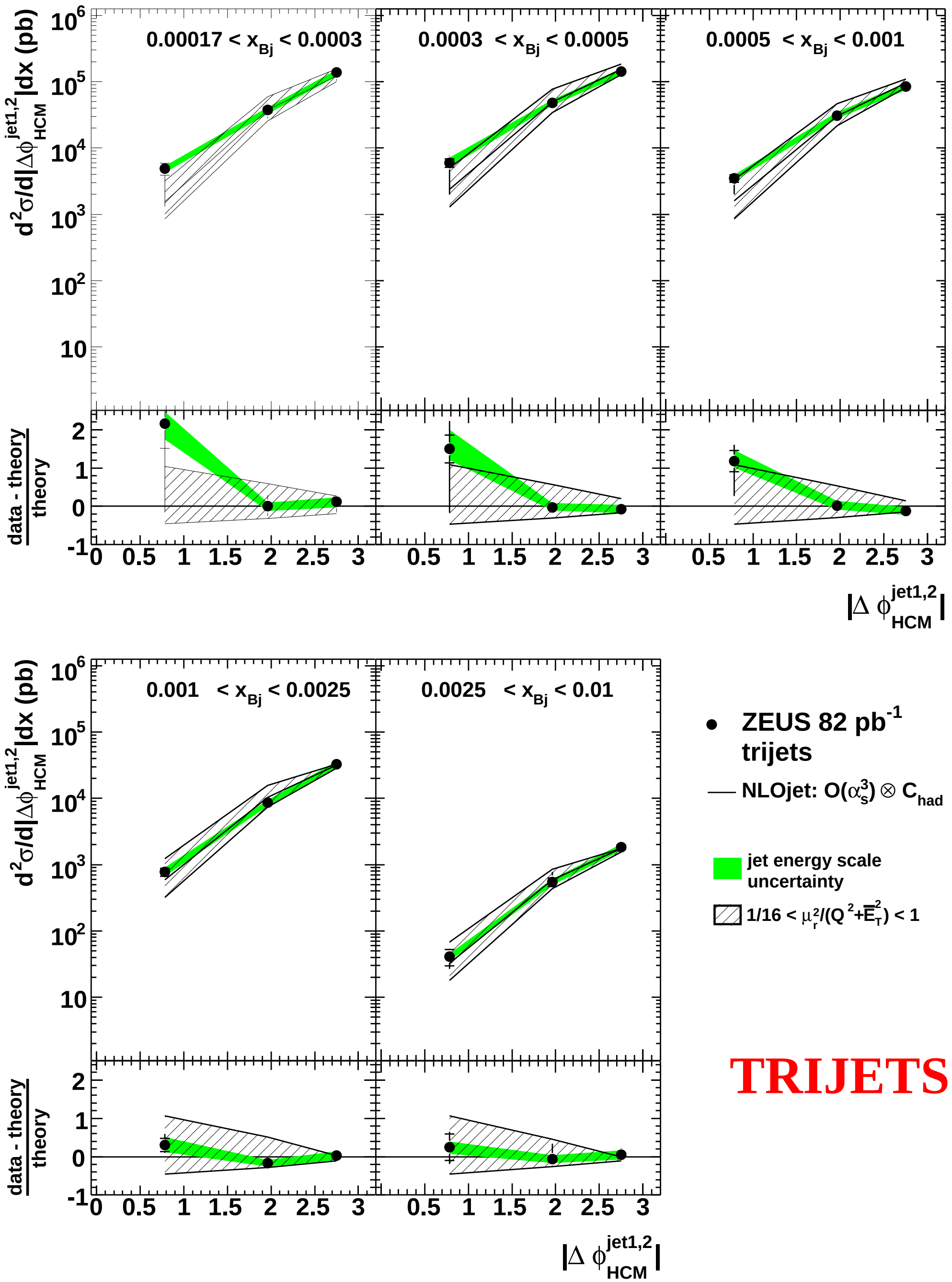
- Trijet events:

$\rightarrow \mathcal{O}(\alpha_s^2) \Longrightarrow$ non-trivial contribution!

$\rightarrow \mathcal{O}(\alpha_s^3) \Longrightarrow$ first correction!

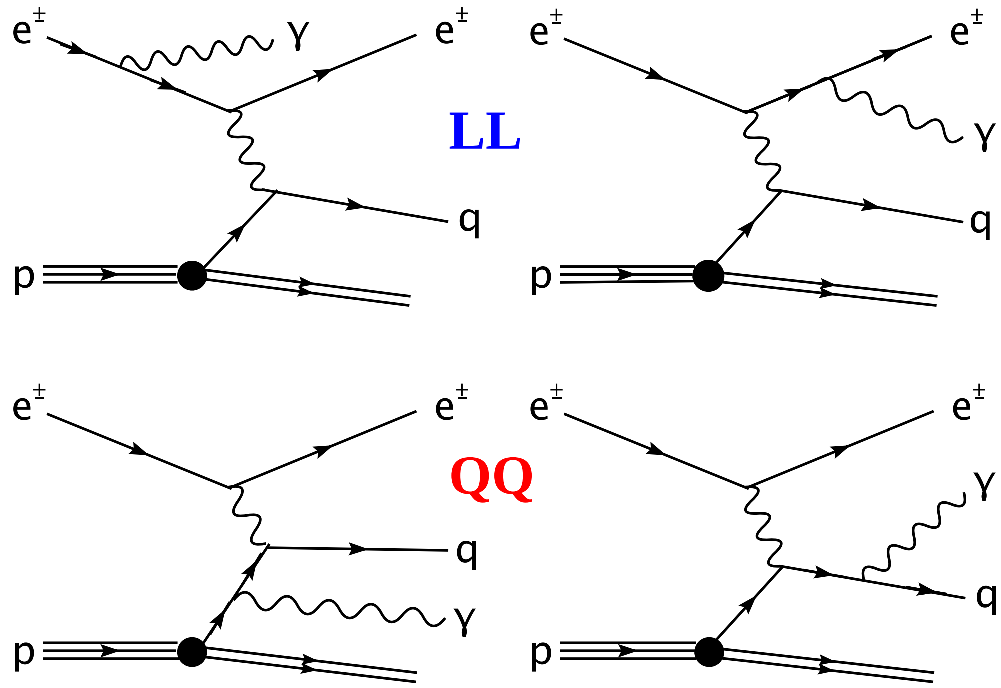
- $\mathcal{O}(\alpha_s^3)$ calculations provide a good description of the data even at low x

Importance of higher-order effects at low x!



TRIJETS

Isolated-photon production in NC DIS



- Production of isolated photons in NC DIS constitutes a clean probe of pQCD and a benchmark for SM-background calculations in the search of new physics involving final-state photons
- SM calculations:

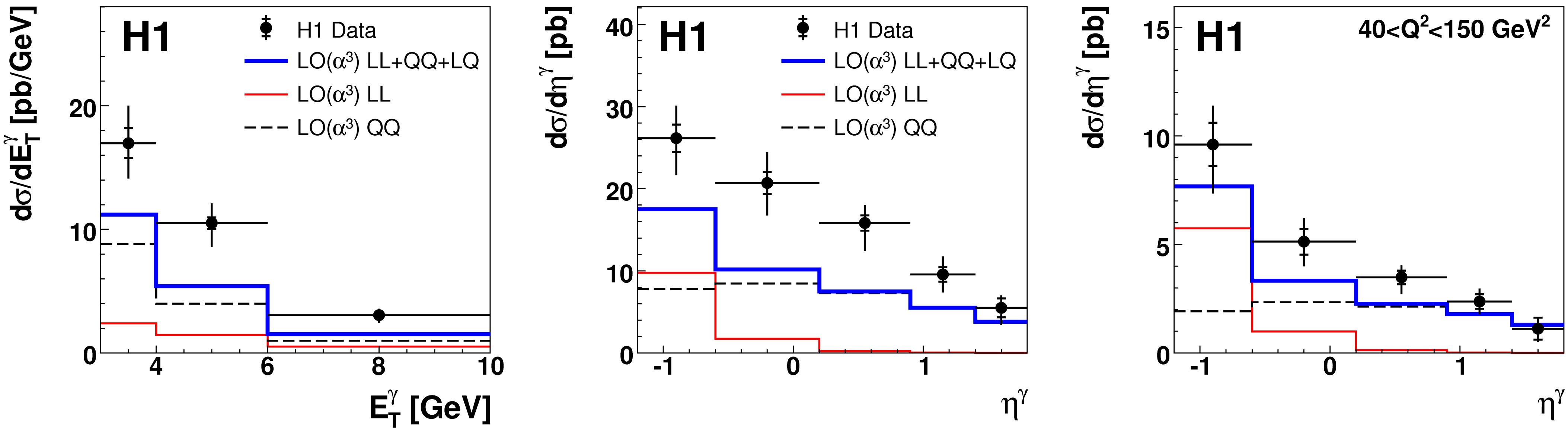
→ LL: wide-angle radiation from the electron line (low-angle radiation suppressed)

→ QQ: radiation from a quark line (direct radiation or fragmentation; fragmentation suppressed by isolation requirement)

→ LQ: the interference is expected to be small

- Photon candidates: compact EM clusters in LAr calorimeter; no associated track; isolated.
- Jets are reconstructed applying the k_T-cluster algorithm with $D = 1$ over all final-state particles, including photon candidates→ isolation condition: the jet containing the γ should fulfill $E_T^{\gamma}/E_T^{\gamma-\mathrm{jet}} > 0.9$ $\Longrightarrow$ Isolated-γ signal extracted using a MVA

Measurements of inclusive isolated photons in NC DIS



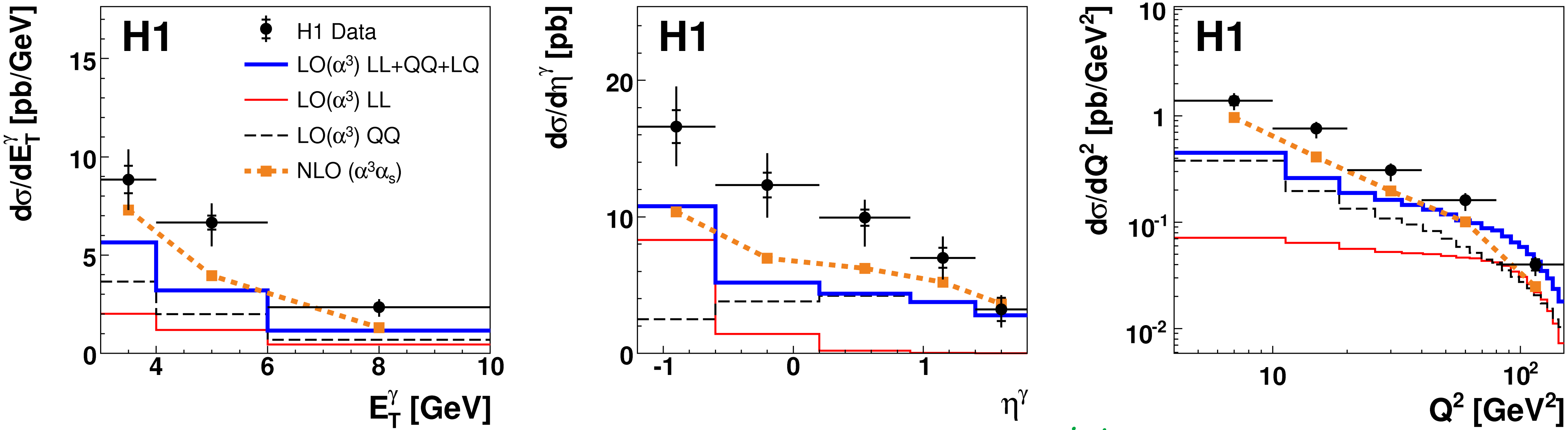
- Measurement of inclusive isolated photon production with $3 < E_T^\gamma < 10$ GeV and $-1.2 < \eta^\gamma < 1.8$ in the kinematic region defined by $4 < Q^2 < 150$ GeV^2 and $W > 50$ GeV
- Comparison to LO ($\mathcal{O}(\alpha^3\alpha_s^0)$) calculations corrected for hadronisation effects

$\longrightarrow$ shape of the distributions: ok $\longrightarrow$ normalization: a factor 2 too low

$\Longrightarrow$ a good description can be achieved by scaling the QQ contribution by a factor 2.3

- Better agreement between data and theory for $Q^2 > 40$ GeV^2 (LL contribution larger)

Isolated photons with an accompanying jet in NC DIS



- Measurement of isolated photon plus jet production with $E_T^{jet} > 2.5$ GeV and $-1.0 < \eta^{jet} < 2.1$
- Comparison to LO ($\mathcal{O}(\alpha^3\alpha_s^0)$) and NLO ($\mathcal{O}(\alpha^3\alpha_s)$) calculations corrected for hadronisation effects

$\longrightarrow$ LO underestimates the data as for the inclusive photon measurement

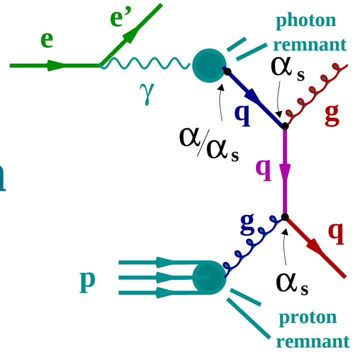
$\longrightarrow$ NLO improves the description (most significantly at low Q^2), but still below the data ($\sim 35\%$)

Further theoretical investigations needed!

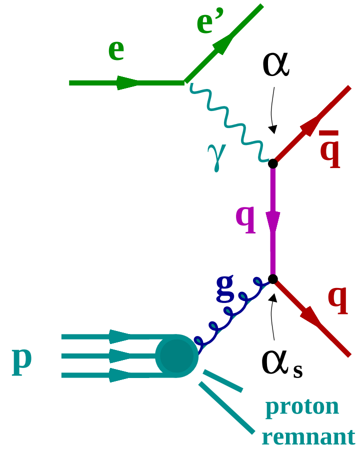
Photoproduction of Jets

• Production of jets in γp collisions has been measured via ep scattering at $Q^2 \approx 0$

• At lowest order QCD, two hard scattering processes contribute to jet production ⇒



Resolved process



Direct process

• pQCD calculations of jet cross sections

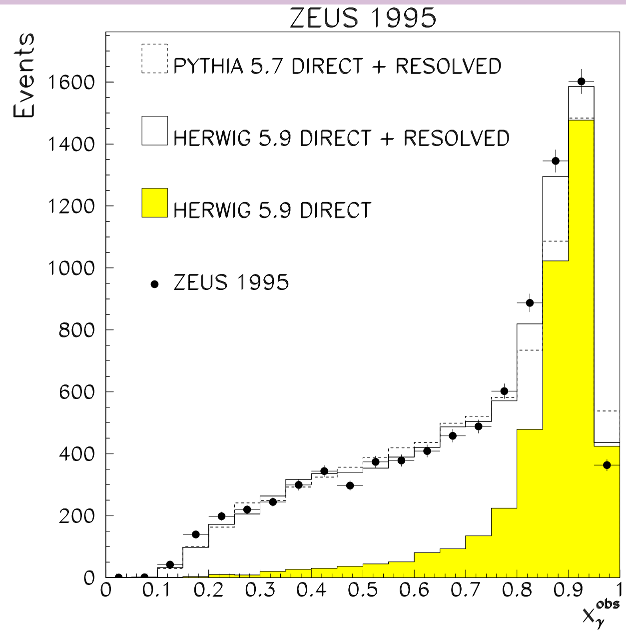
$$d\sigma_{jet} = \sum_{a,b} \int_0^1 dy\, f_{\gamma/e}(y) \int_0^1 dx_\gamma\, f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma}) \int_0^1 dx_p\, f_{b/p}(x_p, \mu^2_{Fp})\; d\hat{\sigma}_{ab\to jj}$$

→ Photon structure: jet cross sections in γp probe quark and gluon γ-PDFS at $\mu^2_{F\gamma} \sim E^2_{T,jet}$ $(200 - 10^4\ \mathrm{GeV}^2)$

→ Proton structure: jet cross sections in γp probe quark and gluon p-PDFs at x_p up to ~ 0.75

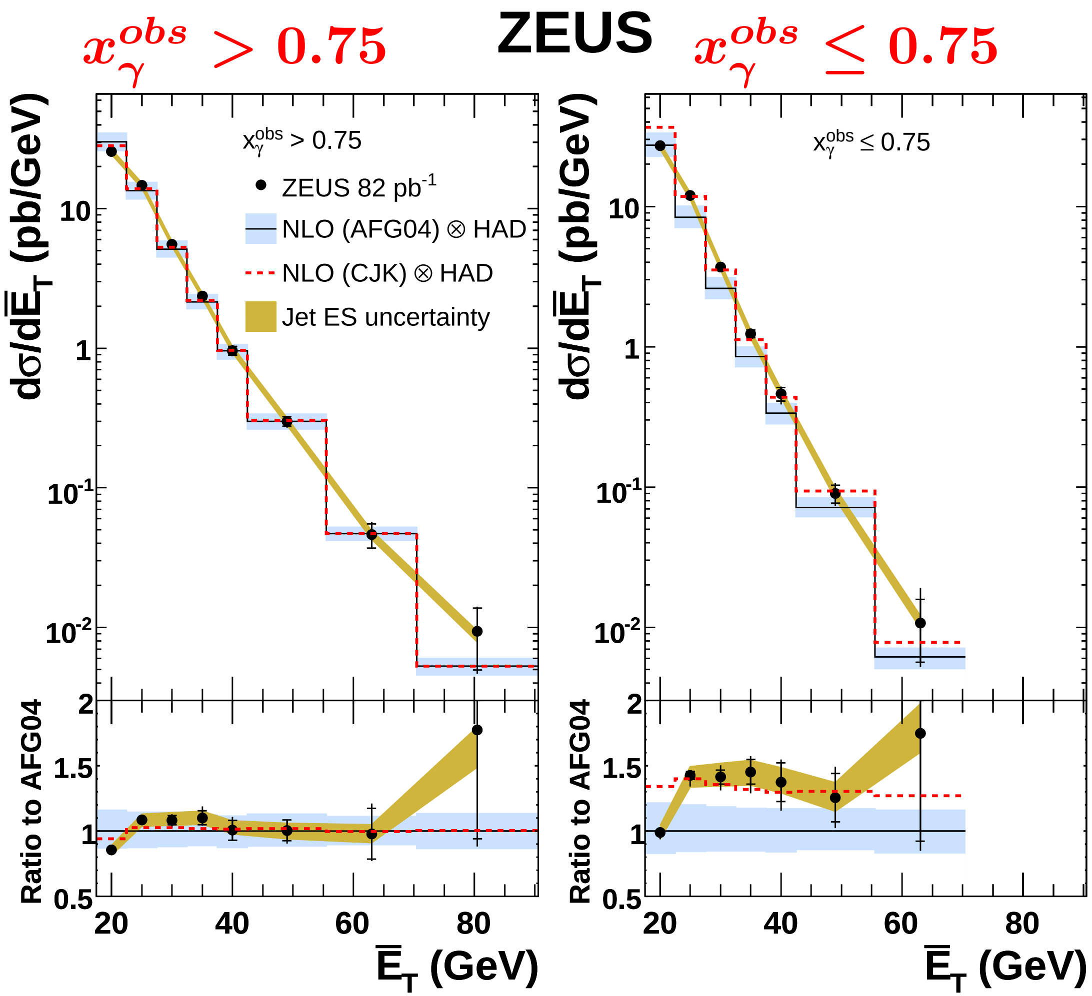
• Observable to separate the contributions: the fraction of the photon's energy participating in the production of the dijet system

$$x_\gamma^{OBS} = \frac{1}{2E_\gamma} \sum_{i=1}^{2} E_T^{jet_i} e^{-\eta^{jet_i}}$$



Dijet Photoproduction

- New measurement of differential cross sections for dijet production $E_T^{jet1} > 20$ GeV, $E_T^{jet2} > 15$ GeV, $-1 < \eta^{jet1,2} < 3$ (and at least one of the jets within $\eta^{jet} < 2.5$) in the kinematic region $Q^2 < 1$ GeV^2 and $142 < W_{\gamma p} < 293$ GeV
- Measurement of $d\sigma/d\overline{E_T}$ with $\overline{E_T} = (E_T^{jet1} + E_T^{jet2})/2$
- Small experimental uncertainties: jet energy scale (1% for $E_T > 10$ GeV) $\longrightarrow \Rightarrow \sim \pm 5\%$ on the cross sections

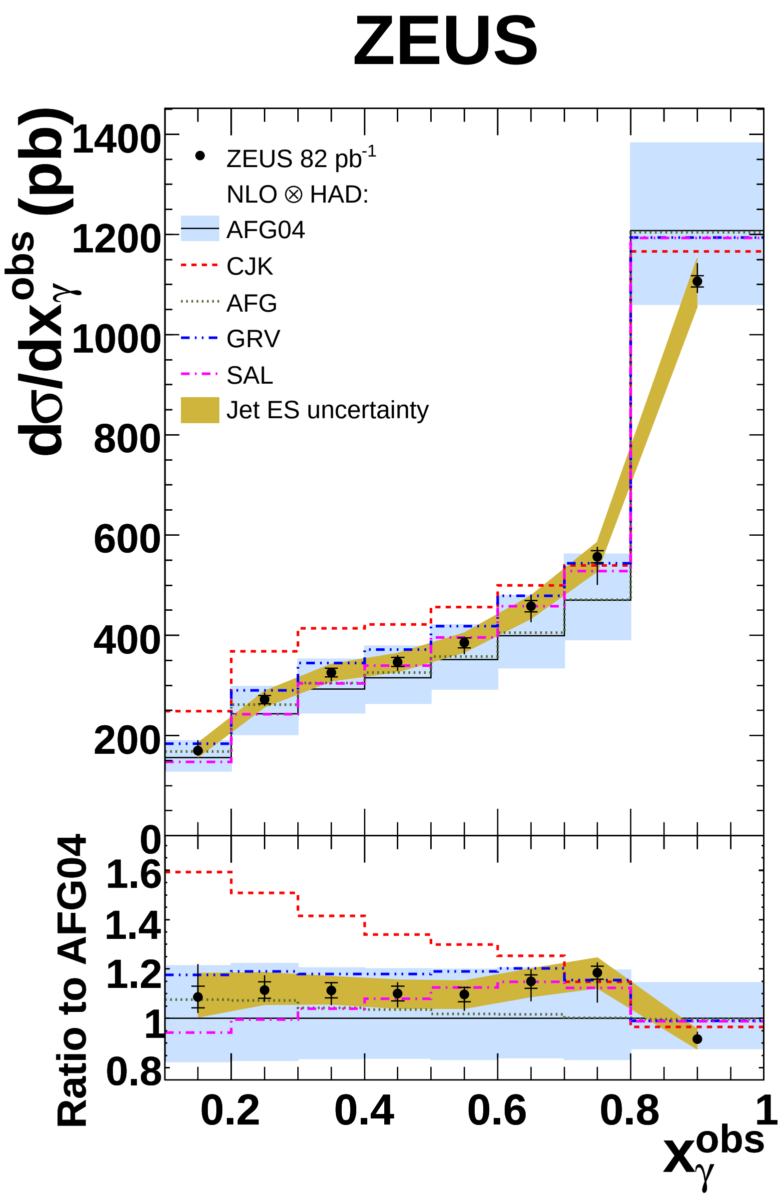


- Comparison with NLO QCD calculations (corrected for hadronisation effects, $< \mathcal{O}(10\%)$) using CTEQ5M1 for the proton PDFs and AFG04 for the photon PDFs

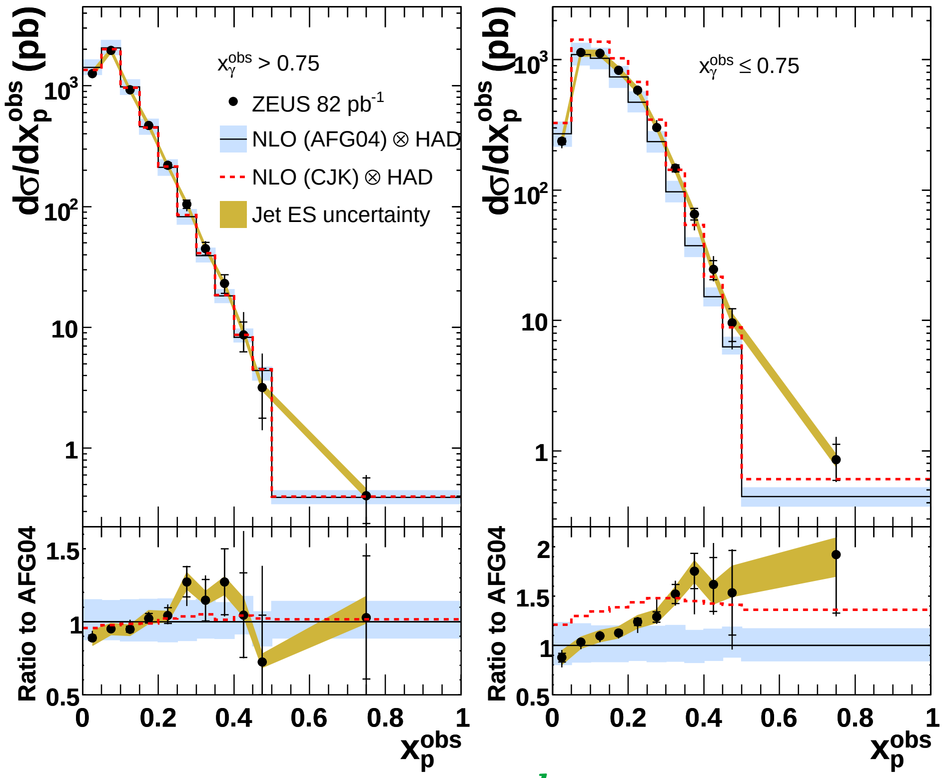
$\longrightarrow$ good description of direct-photon enriched region ($x_\gamma^{obs} > 0.75$)

$\longrightarrow$ data above NLO (AFG04) in resolved-photon enriched region ($x_\gamma^{obs} \leq 0.75$)

Dijet Photoproduction



$x_\gamma^{obs} > 0.75$ ZEUS $x_\gamma^{obs} \leq 0.75$



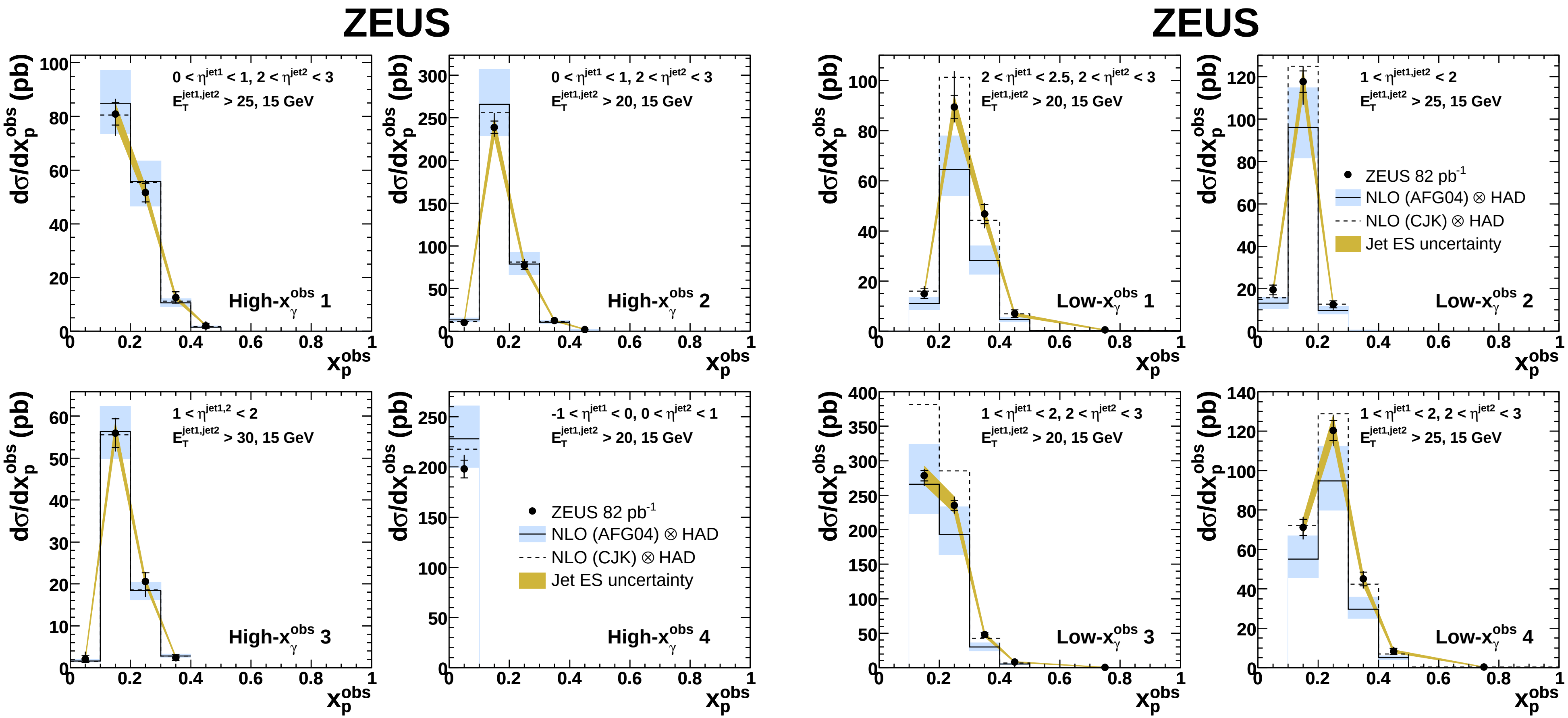
- **Measurement of $d\sigma/dx_\gamma^{obs}$: comparison with different sets of photon PDFs (most deviant: CJK)**
- **Measurement of $d\sigma/dx_p^{obs}$, $x_p^{obs} = \frac{1}{2E_p}\sum E_T^{jet_i} e^{\eta^{jet_i}}$**

→ reasonable description of direct-photon enriched region

→ poor description of resolved-photon enriched region

⇒ None of the photon PDFs describe low-x_γ^{obs} data

Dijet Photoproduction: optimized cross sections

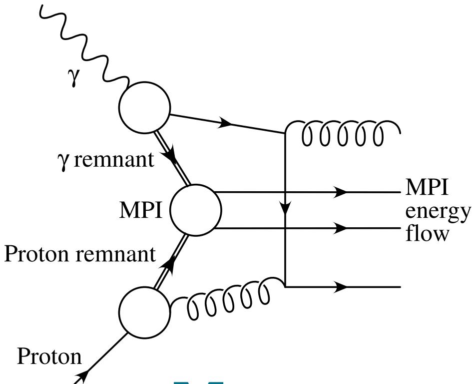


- High-x_γ^{obs} optimized cross sections: major sensitivity to proton PDFs
- Low-x_γ^{obs} optimized cross sections: major sensitivity to photon PDFs

$\Rightarrow$ useful constrains in a global determination of proton and photon PDFs

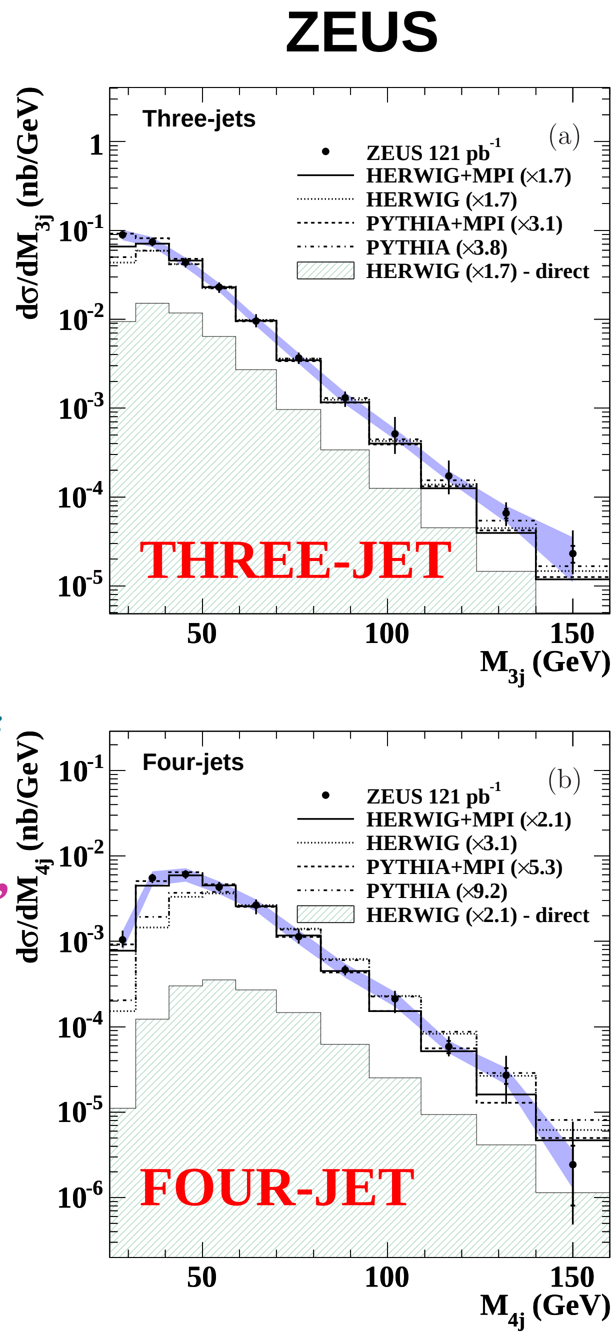
Three- and Four-jet Photoproduction

- Benchmarks for higher-order QCD calculations
- Testing ground for models of multi-parton interactions (MI)



- Comparison to PYTHIA and HERWIG predictions:
  →without MI
  → with MI: PYTHIA
  HERWIG+JIMMY (tuned)

- Measurement of differential cross-sections $d\sigma/dM_{nj}$ for three(four)-jet production $E_T^{jet} > 6$ GeV, $|\eta^{jet}| < 2.4$ in the kinematic region $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$,
- HERWIG and PYTHIA without MI (normalised to $M_{nj} > 50$ GeV data), underestimate the data at low M_{nj}
  → dramatically for four-jet production
- The inclusion of multi-parton interactions provides a good description of the data over the full range in M_{nj}

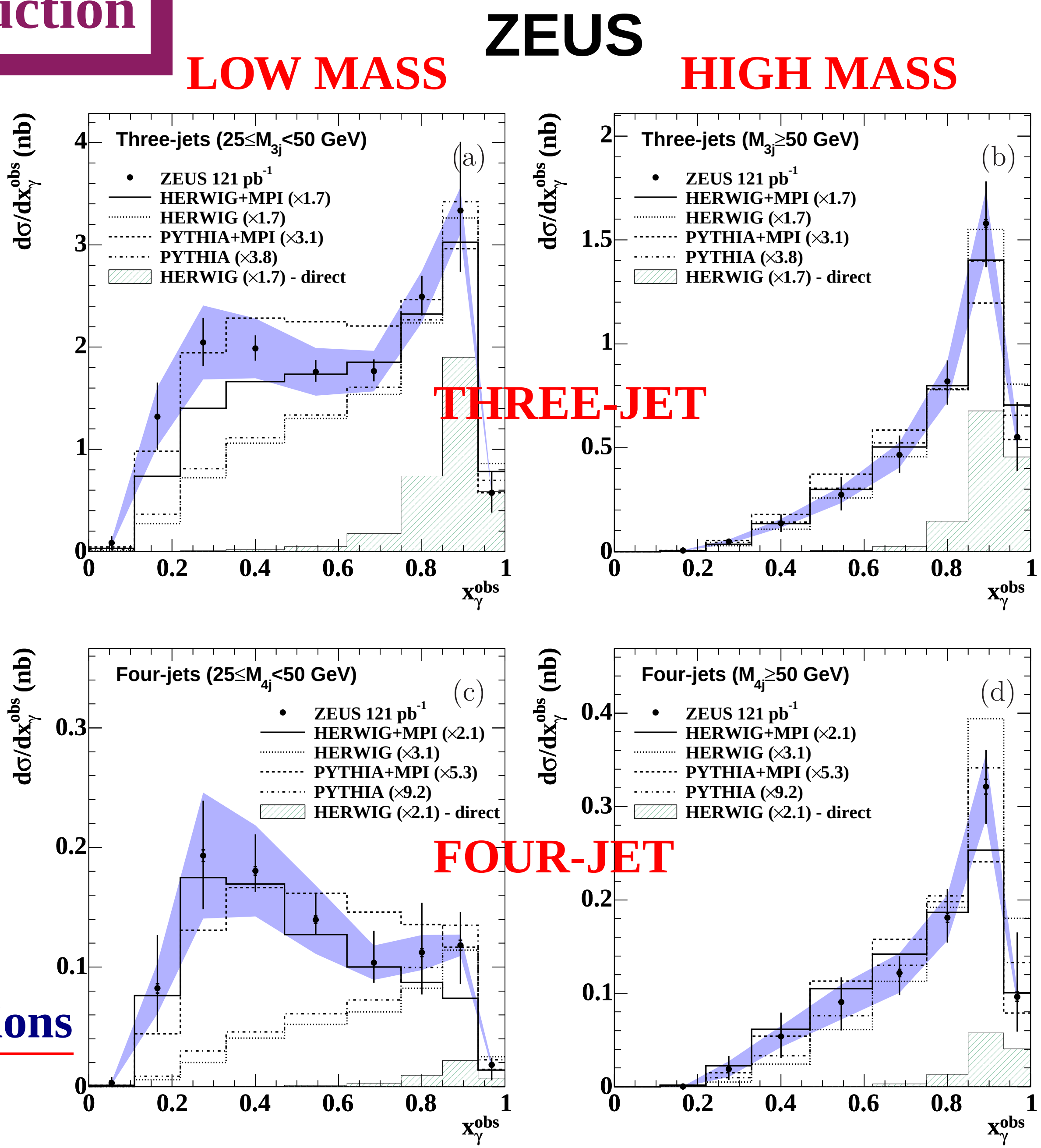


Three- and Four-jet Photoproduction

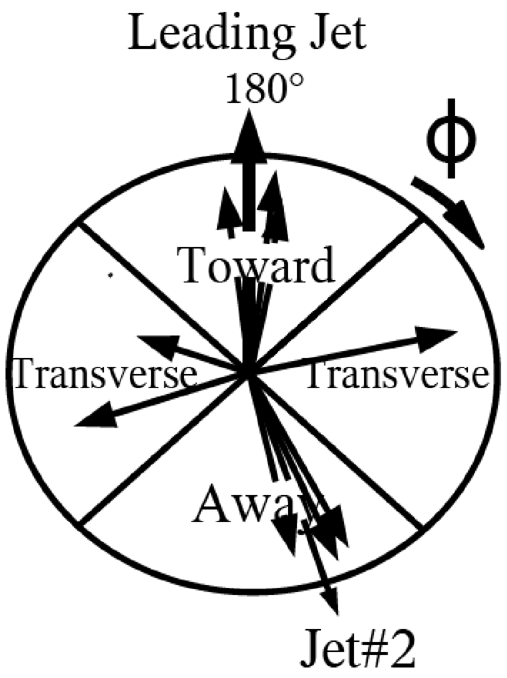
- Measurement of differential cross section $d\sigma/dx_\gamma^{obs}$ for three(four)-jet production in two regions of M_{nj}:
  $\rightarrow$ low mass: $25 < M_{nj} < 50$ GeV
  $\rightarrow$ high mass: $M_{nj} > 50$ GeV

$$x_\gamma^{obs} = \frac{1}{2E_\gamma} \sum_{i=1}^{3(4)} E_T^{jet_i} e^{-\eta^{jet_i}}$$

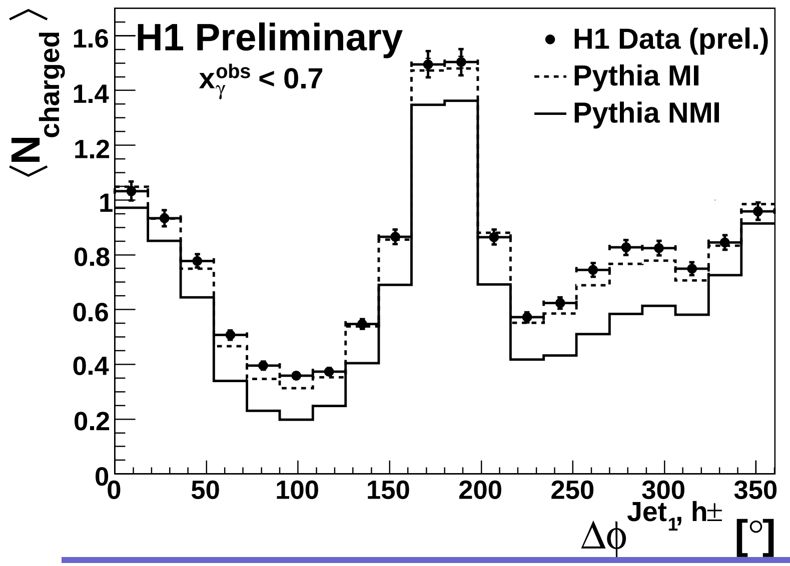
- High mass: HERWIG and PYTHIA (with or without MI) describe the data
- Low mass: HERWIG and PYTHIA without MI fail to describe the observed enhancement at low x_γ^{obs}
- The inclusion of multi-parton interactions improves the description of the data



Study of multi-parton interactions using dijet photoproduction



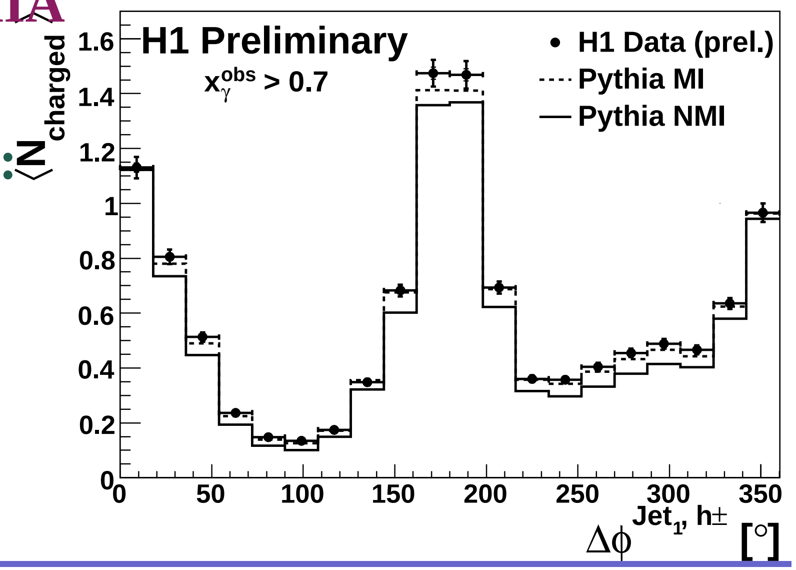
- Study of multi-parton interactions in photoproduction by measuring the charged-particle multiplicity in dijet events $P_T^{jet} > 5$ GeV and $-1.5 < \eta_{lab}^{jet} < 1.5$
- Kinematic region: $Q^2 < 0.01$ GeV^2, $0.3 < y < 0.65$
- Jets are reconstructed using the k_T-cluster algorithm in the LAB frame: leading jet at $\phi = 180°$
- Measurement of $\langle N_{charged} \rangle$ in four regions: "Toward", "Away", "High-activity" and "Low-activity"



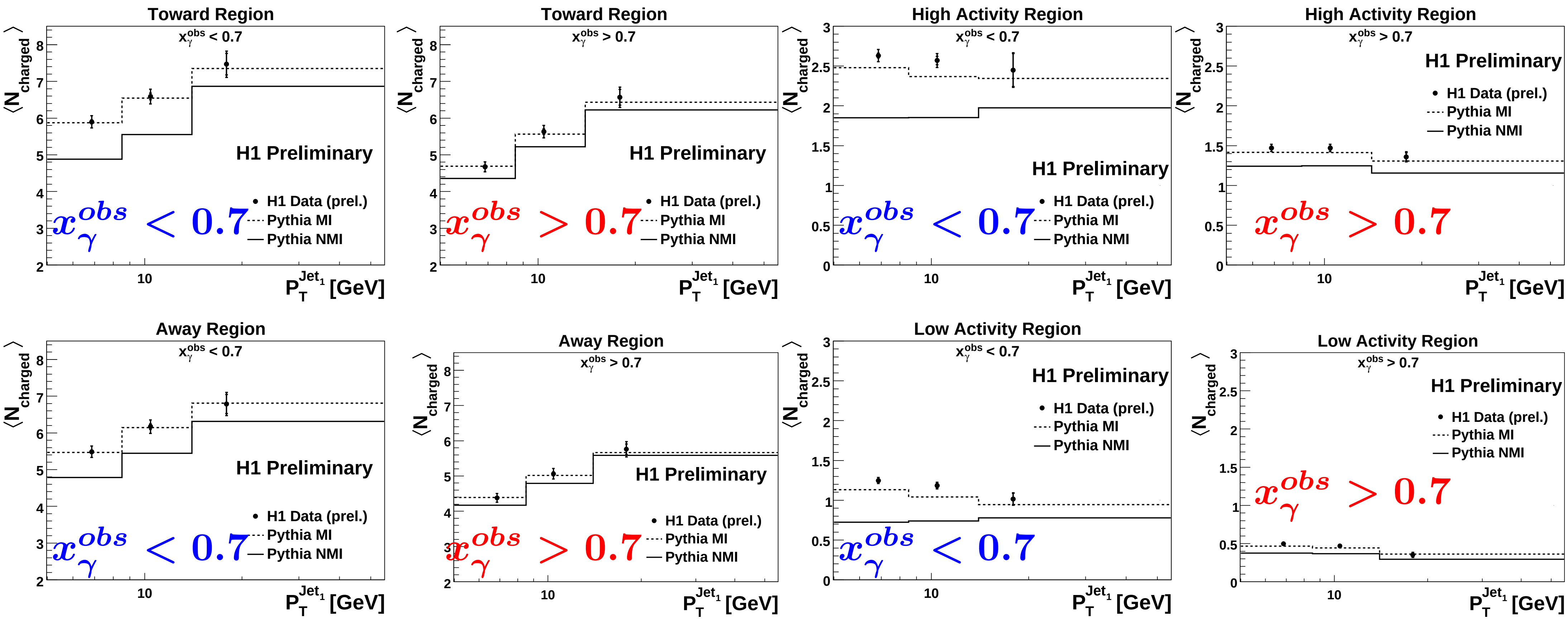
Comparison to PYTHIA with/without MI in two regions in x_γ^{obs}:

← resolved-photon $x_\gamma^{obs} < 0.7$

direct-photon → $x_\gamma^{obs} > 0.7$



Study of multi-parton interactions using dijet photoproduction

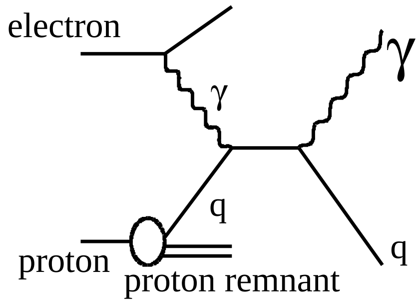


- Direct-photon: reasonably well described by PYTHIA with parton showers and no MI
- Resolved-photon: excess observed in the data with respect to PYTHIA without MI

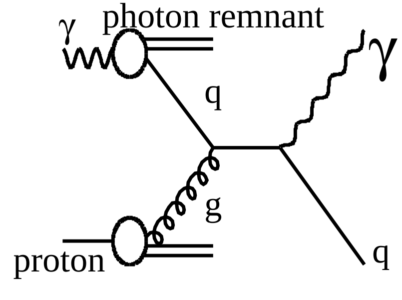
  $\longrightarrow$ inclusion of multi-parton interactions describes the data well

Prompt-photon production in γp interactions

- Production of prompt photons in γp interactions (photoproduction, $Q^2 \approx 0$) is sensitive to $\longrightarrow$ proton and photon PDFs with lower hadronization corrections than dijet production



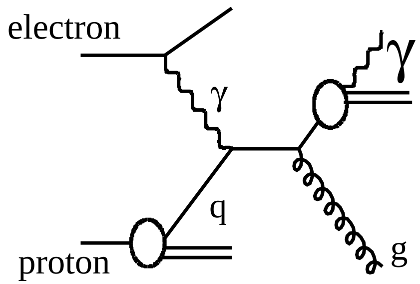
(a) direct non-fragmentation



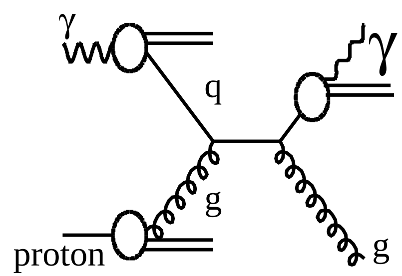
(b) resolved non-fragmentation

- Benchmark for pQCD calculations:

$\longrightarrow$ fixed-order (NLO) QCD calculations in the collinear approach including direct and resolved-photon processes, quark-to-photon fragmentation and the box diagram $\gamma g \longrightarrow \gamma g$



(c) direct fragmentation



(d) resolved fragmentation

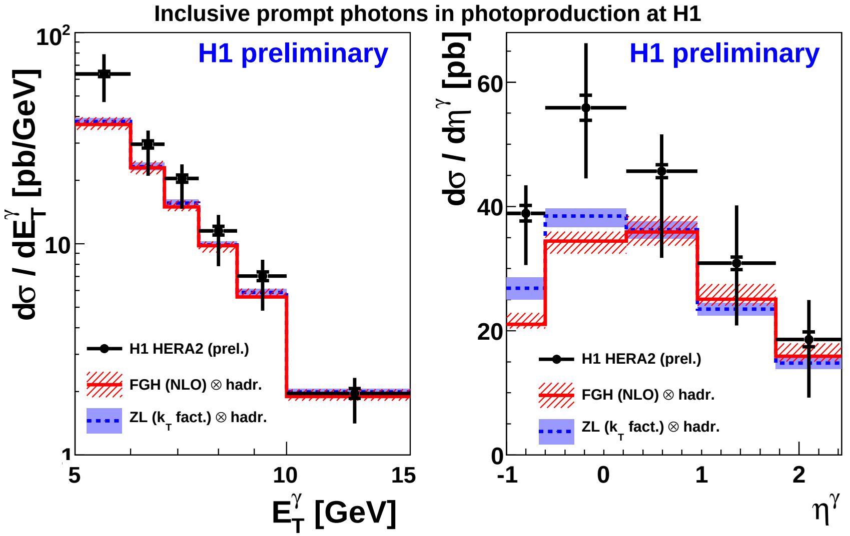
$\longrightarrow$ calculations based on k_T-factorization approach and using unintegrated PDFs; direct and resolved-photon processes included

$\Longrightarrow$ Calculations corrected for hadronization and multi-parton interaction effects

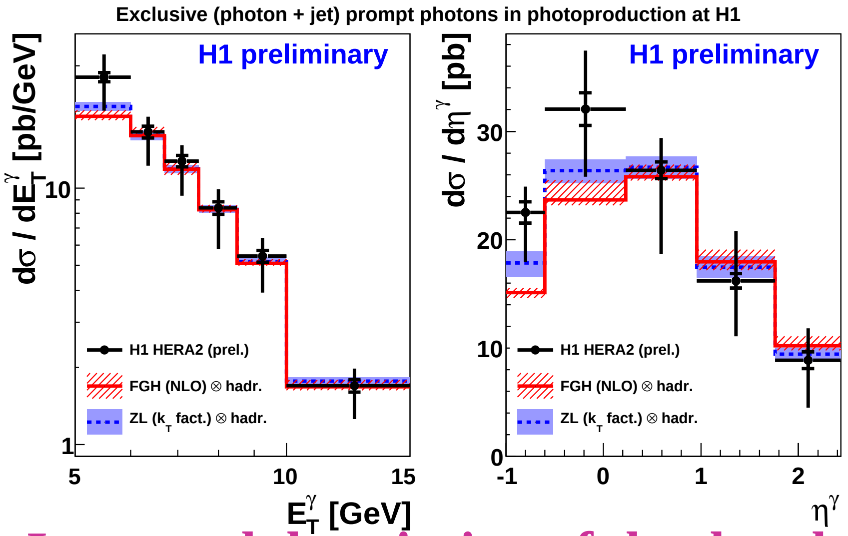
Measurements of inclusive prompt photon and prompt-photon+jets

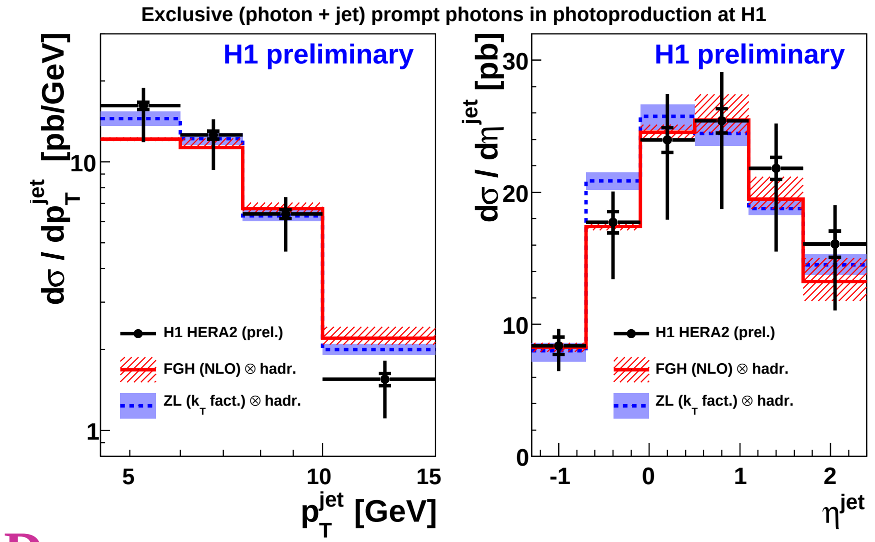
- Measurement of inclusive prompt photon production in the kinematic region defined by $Q^2 < 1$ GeV^2 and $0.1 < y < 0.7$ for photons with $E_T^\gamma / E_T^{\gamma-\rm jet} > 0.9$, $5 < E_T^\gamma < 15$ GeV and $-1 < \eta^\gamma < 2.4$ using $\mathcal{L} = 340$ pb^{-1} (HERA II data)

  $\longrightarrow$ Data above pQCD at low E_T^γ and low η^γ



- Prompt-photon+jet production for jets with $E_T^{jet} > 4.5$ GeV, $-1.3 < \eta^{jet} < 2.4$



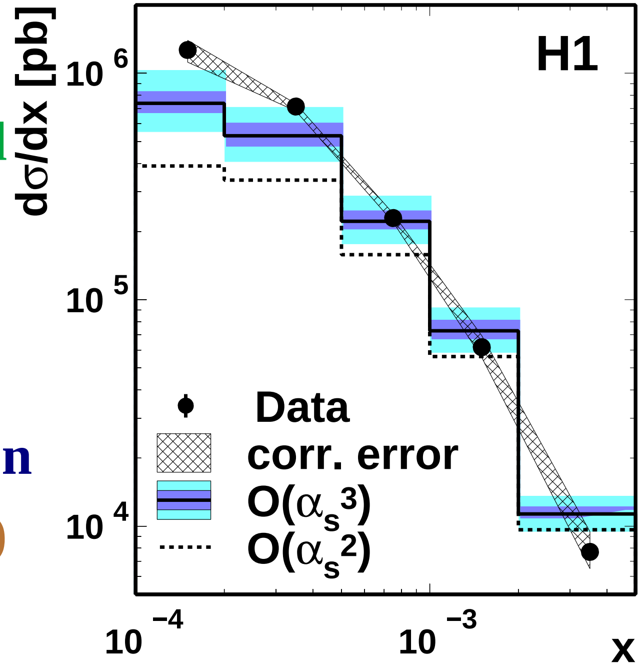


$\longrightarrow$ Improved description of the data by pQCD

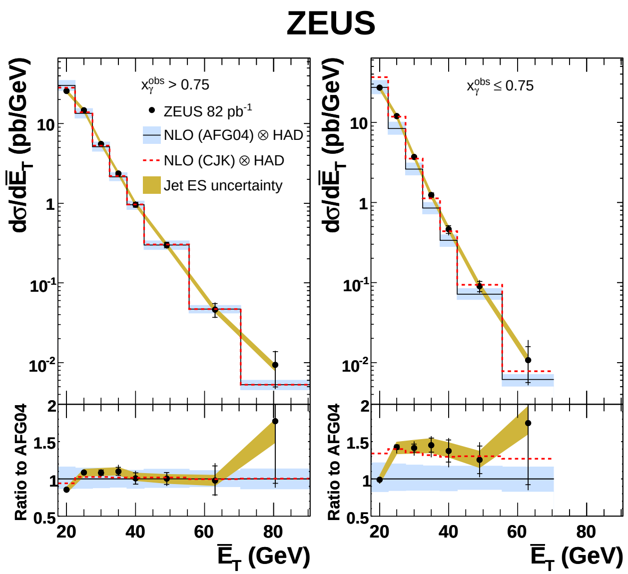
Summary

- Exploration of parton dynamics at low x vigorously pursued
  $\longrightarrow$ particularly relevant for LHC physics
  Precise measurements of (multi)jet production in NC DIS down to $x \sim 10^{-4}$ in terms of jet rates, topologies and correlations demonstrates the big impact of initial-state gluon radiation: pQCD at $\mathcal{O}(\alpha_s^3)$ reproduces successfully (almost) all data, albeit with significant theoretical uncertainties

  $\Longrightarrow$NNLO corrections needed!!



- Precise measurements of (multi)jet photoproduction provide useful information on the quark and gluon densities in the proton and photon



- Prompt-photon production:

$\longrightarrow$ the theory describes photoproduction data

$\longrightarrow$ but fails to reproduce DIS data (?)