

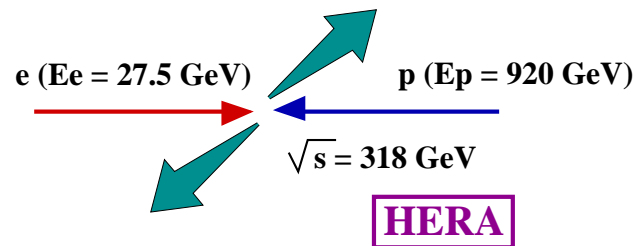
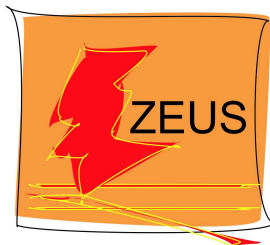
Philadelphia, ICHEP 2008

July 31st, 2008



Prompt photons and multijets at HERA

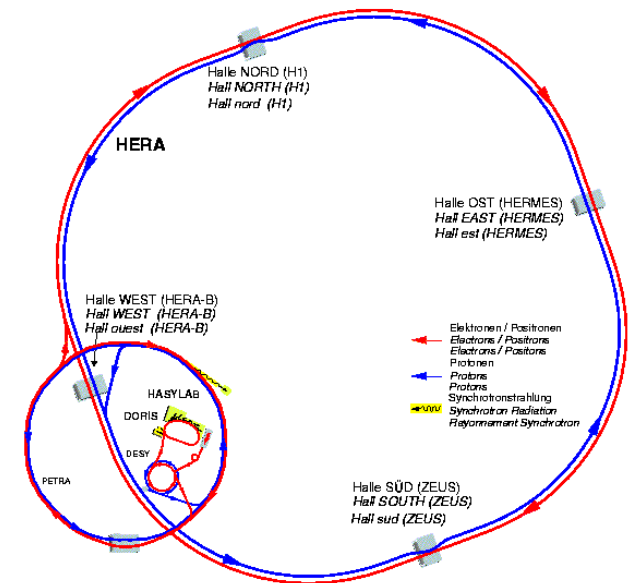
Juan Terrón (Universidad Autónoma de Madrid, Spain)



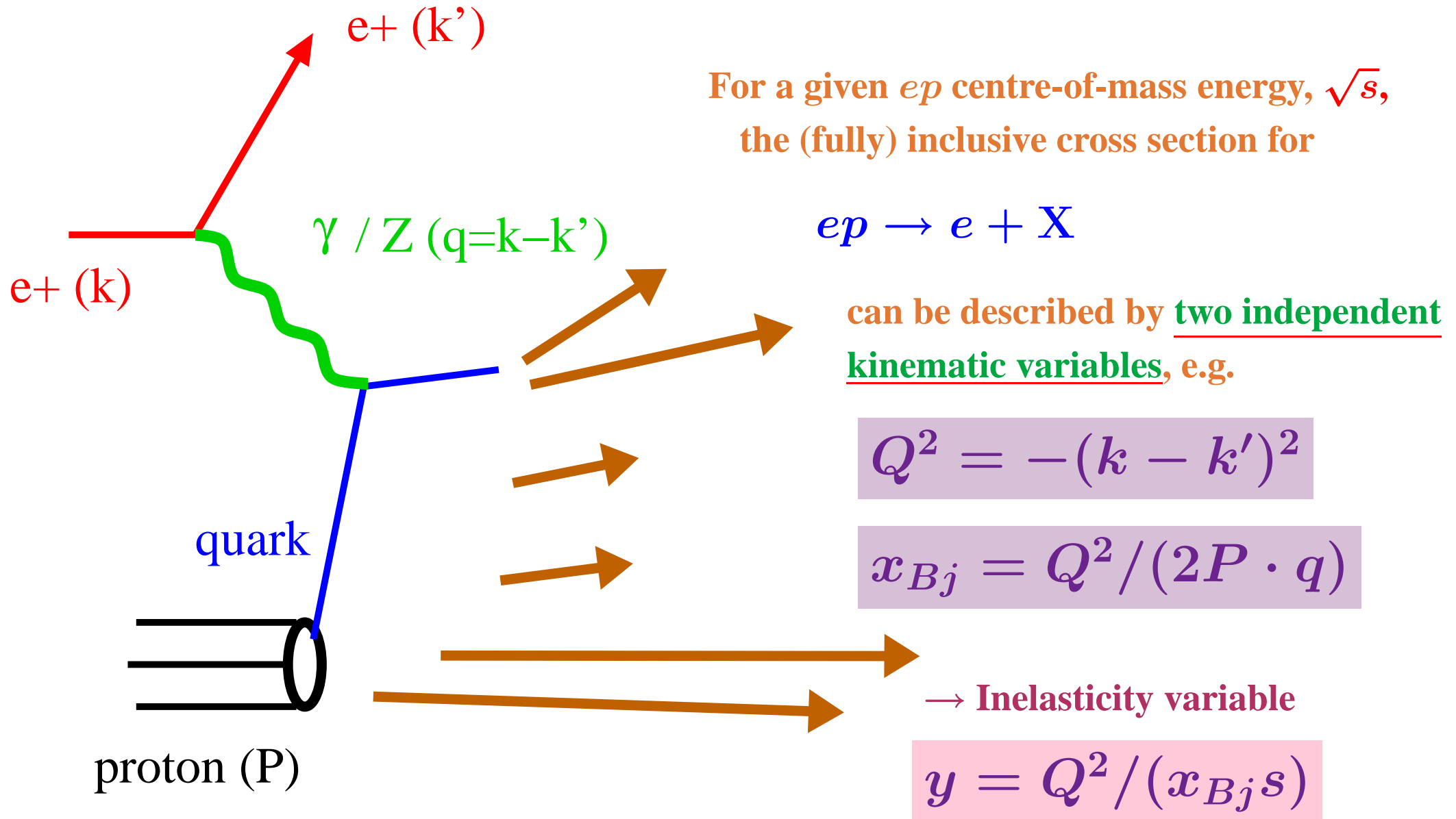
H1 and ZEUS Collaborations

● Outline

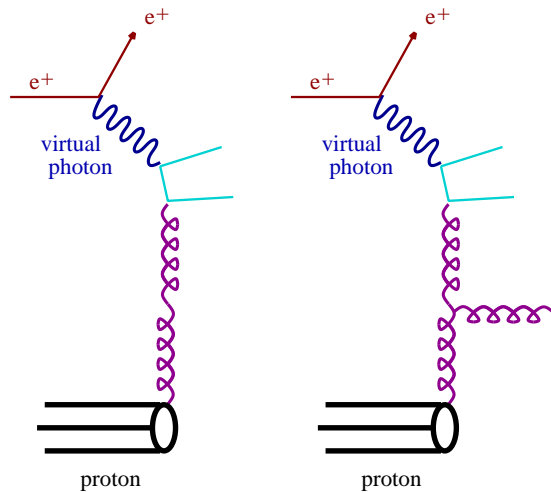
- Neutral current deep inelastic scattering:
 - (multi)jet production at low x
 - isolated-photon production
- Photoproduction:
 - (multi)jet production
 - prompt-photon production



Kinematics of Neutral Current Deep Inelastic Scattering



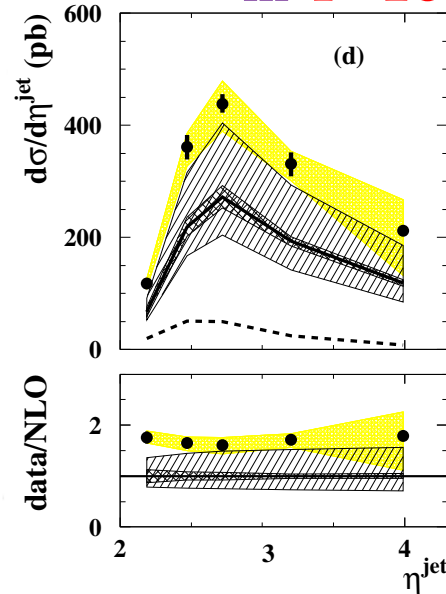
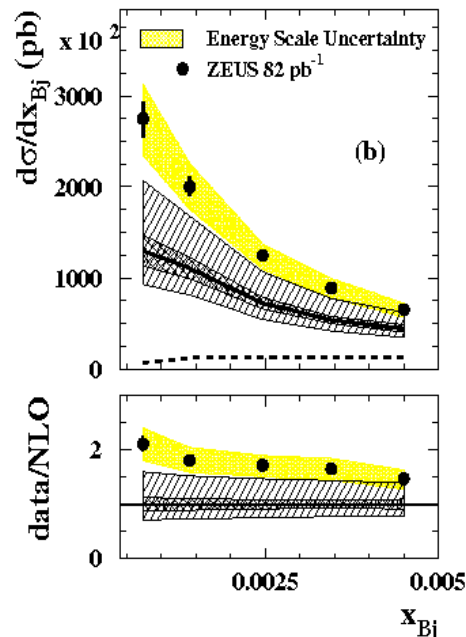
Measurement of Forward Jet Production at low x (up to $\eta^{jet} = 4.3$)



LO $\mathcal{O}(\alpha_s)$

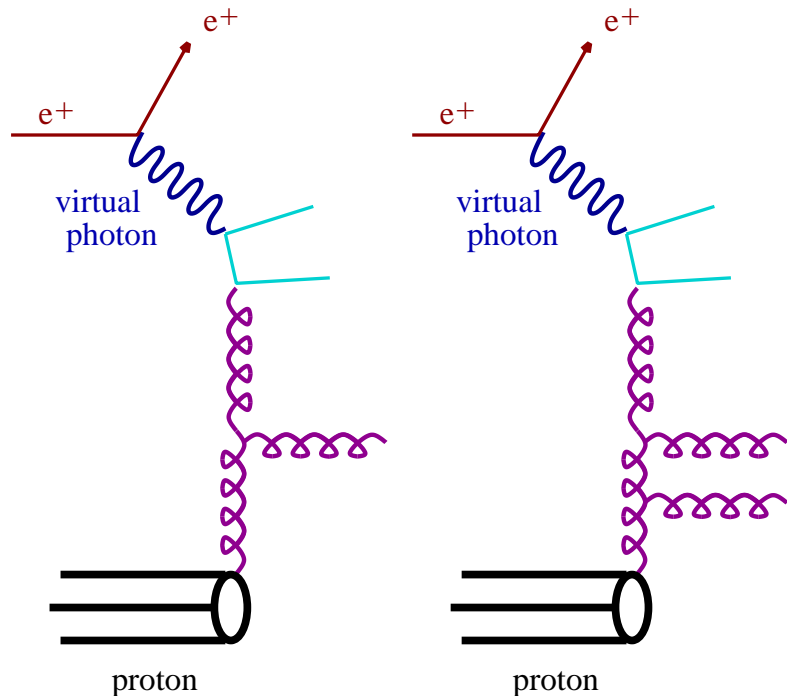
NLO $\mathcal{O}(\alpha_s^2)$

- 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)
→ NLO QCD becomes an “effective” LO, with large theoretical uncertainties
- Measurement of inclusive jet production with $E_T^{jet} > 5 \text{ GeV}$,
 $2 < \eta^{jet} < 4.3$, $0.5 < (E_T^{jet})^2/Q^2 < 2$ and $x_{jet} > 0.036$
in $4 \cdot 10^{-4} < x < 5 \cdot 10^{-3}$, $20 < Q^2 < 100 \text{ GeV}^2$

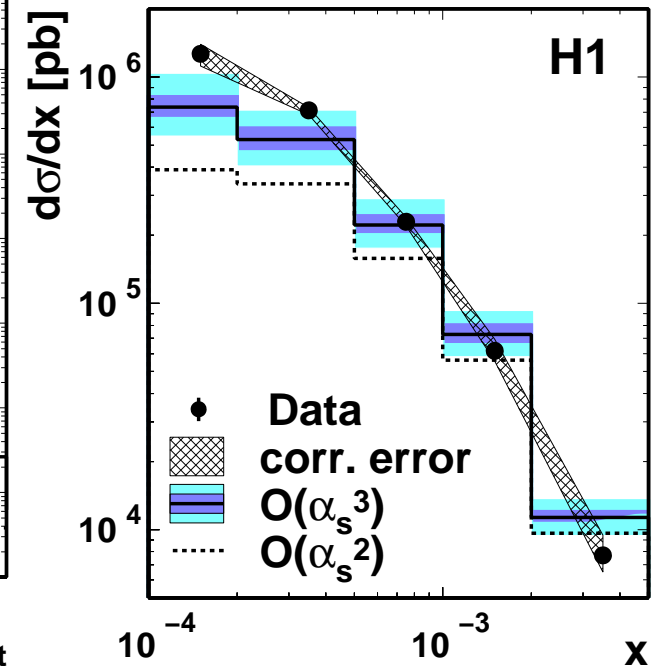
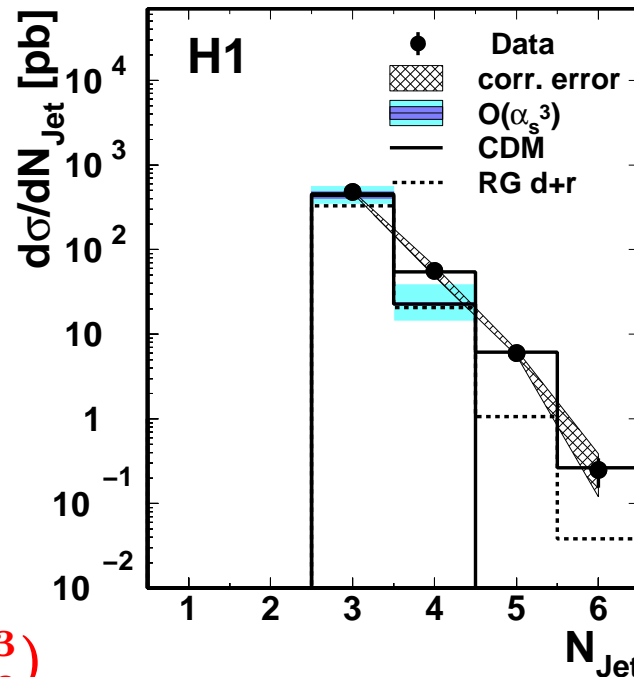


- Strong rise towards low x is observed
- Comparison to pQCD calculations ($\mu_R = Q$)
→ big jump from LO to NLO
→ large μ_R dependence (large uncertainties)
→ NLO underestimates the data by factor of ~ 2
⇒ Large theoretical uncertainties (higher-orders) in pQCD calculations prevent firm conclusions!

Measurements of Three-jet Production at low x

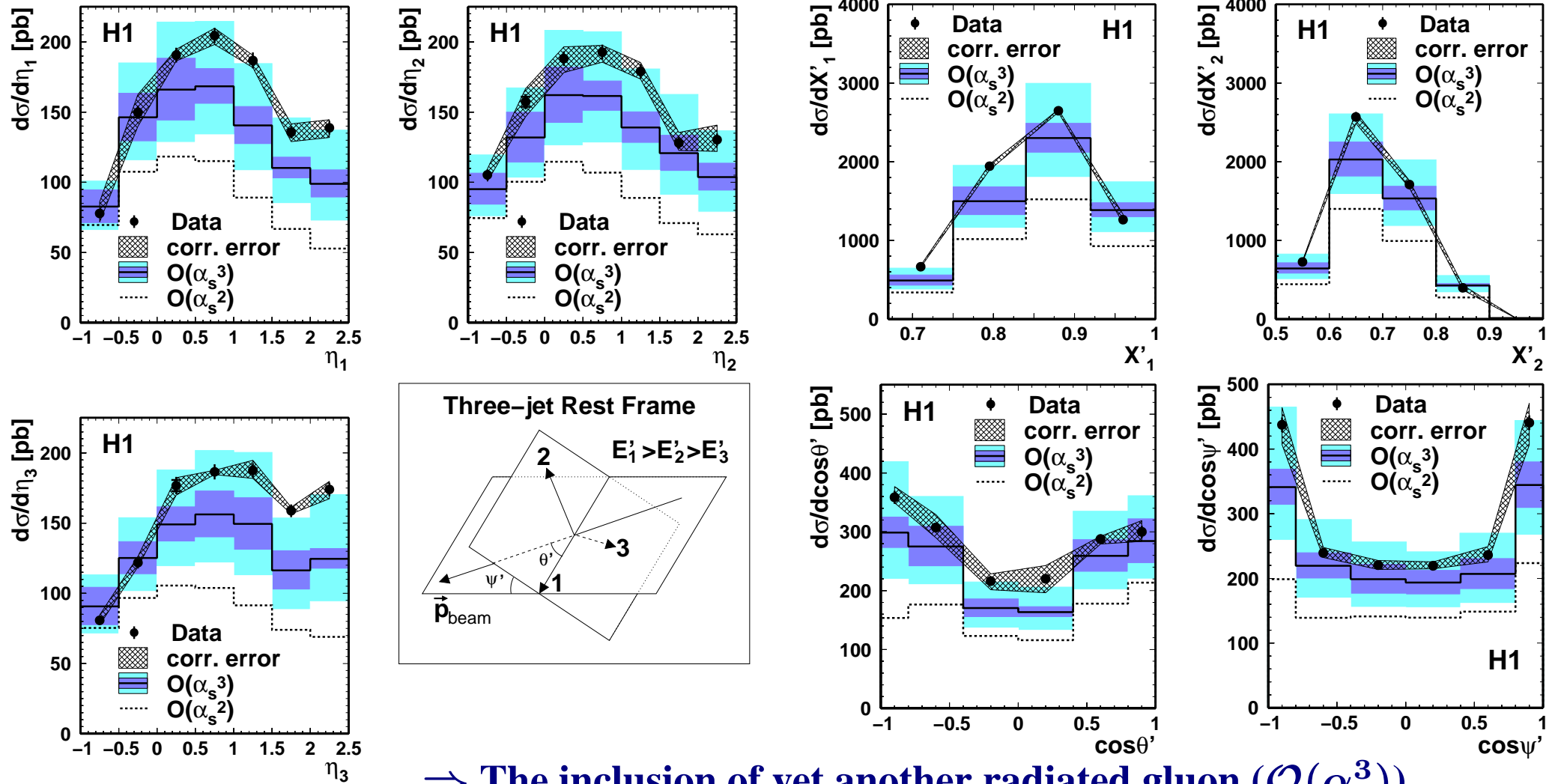


LO $\mathcal{O}(\alpha_s^2)$ NLO $\mathcal{O}(\alpha_s^3)$



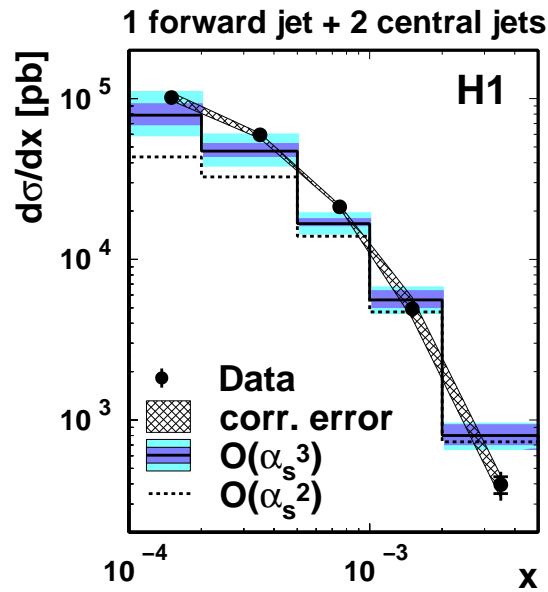
- Measurements of three-jet production using the k_T cluster algorithm in the $\gamma^* p$ frame with $E_{\perp, \text{jet}}^* > 4 \text{ GeV}$, $E_{\perp, \text{jet1}}^* + E_{\perp, \text{jet2}}^* > 9 \text{ GeV}$, $-1 < \eta_{\text{jet}}^{\text{lab}} < 2.5$ (one central jet $-1 < \eta_{\text{jet}}^{\text{lab}} < 1.3$) in the kinematic region defined by $0.1 < y < 0.7$ and $5 < Q^2 < 80 \text{ GeV}^2 \Rightarrow$ 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



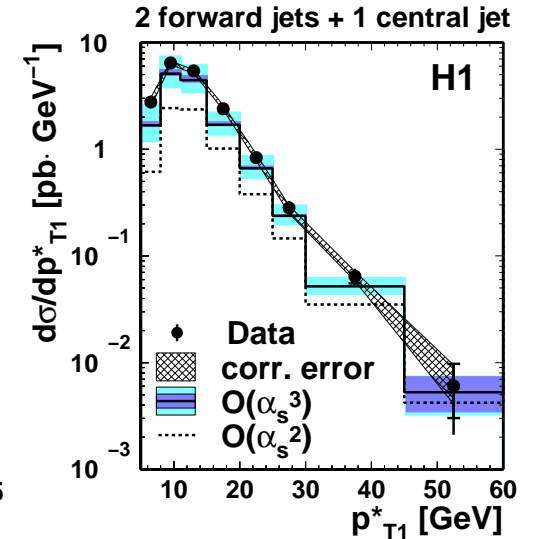
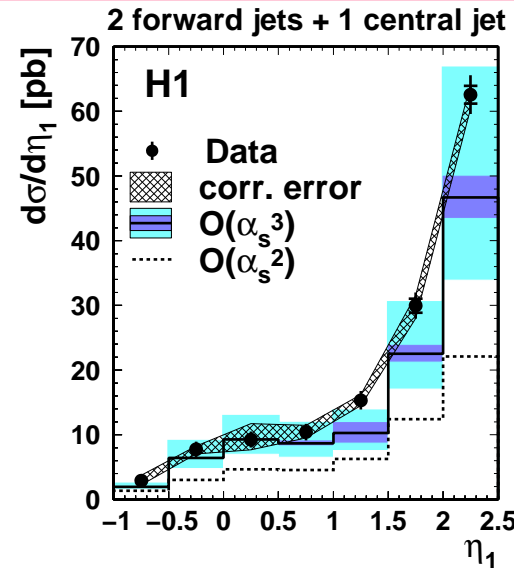
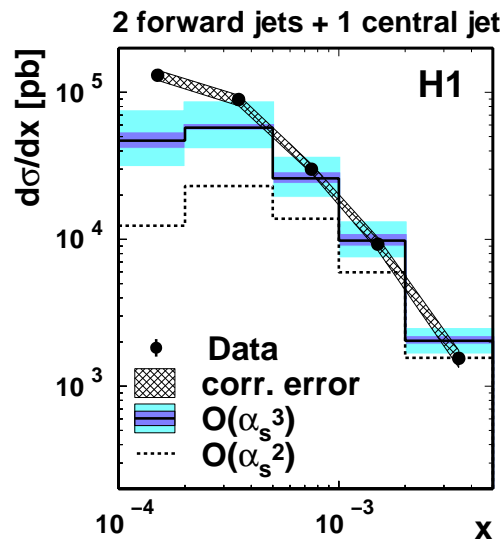
⇒ The inclusion of yet another radiated gluon ($\mathcal{O}(\alpha_s^3)$) improves dramatically the description of the data at low x

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
 - particularly dramatic for the sample with two forward jets (sample most sensitive to additional gluon radiation)
- ⇒ Success of perturbative QCD $\mathcal{O}(\alpha_s^3)$ at describing multijet production at low- x
 - 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

$$E_{T,HCM}^{jet1} > 7 \text{ GeV}, E_{T,HCM}^{jet2,3} > 5 \text{ GeV},$$

$$\text{and } -1 < \eta_{lab}^{jet1,2,3} < 2.5$$

in the kinematic region defined by

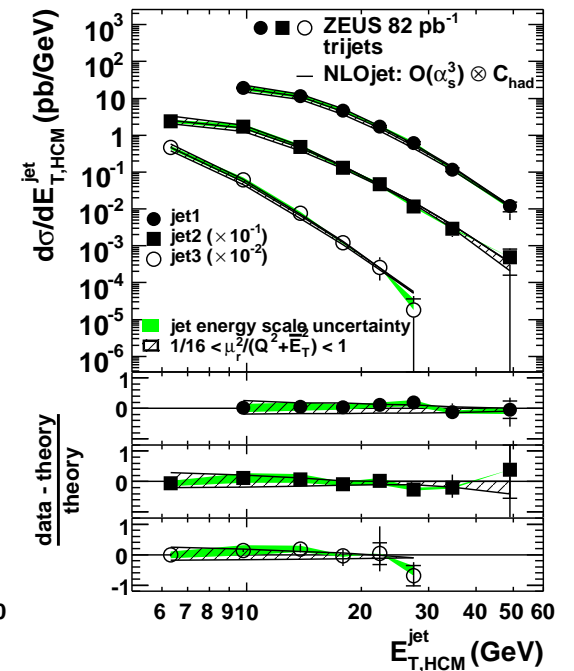
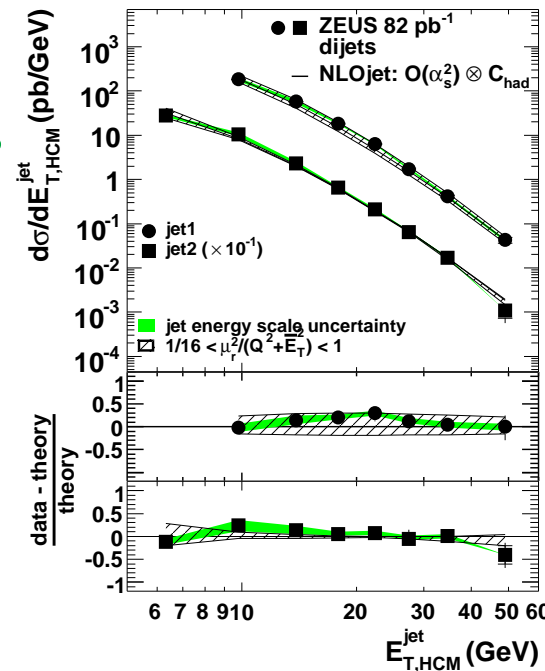
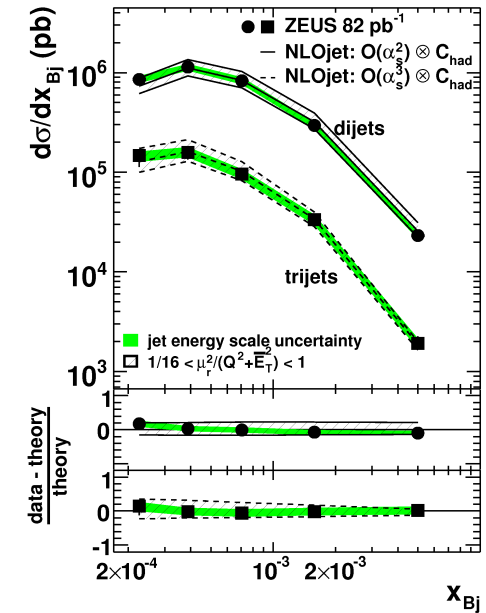
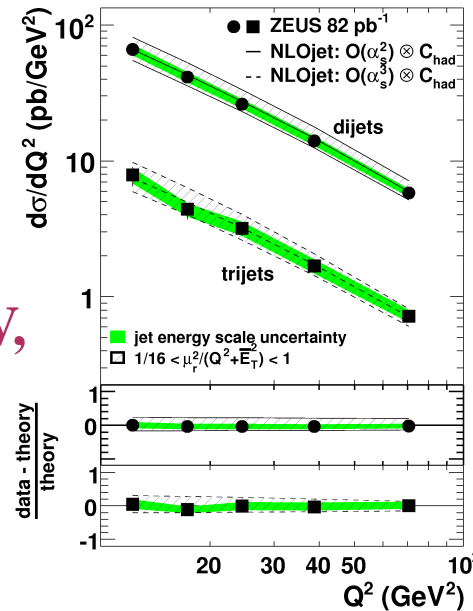
$$10 < Q^2 < 100 \text{ GeV}^2,$$

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

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

corrected for hadronisation effects:

→ 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}

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

- Dijet events:

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

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

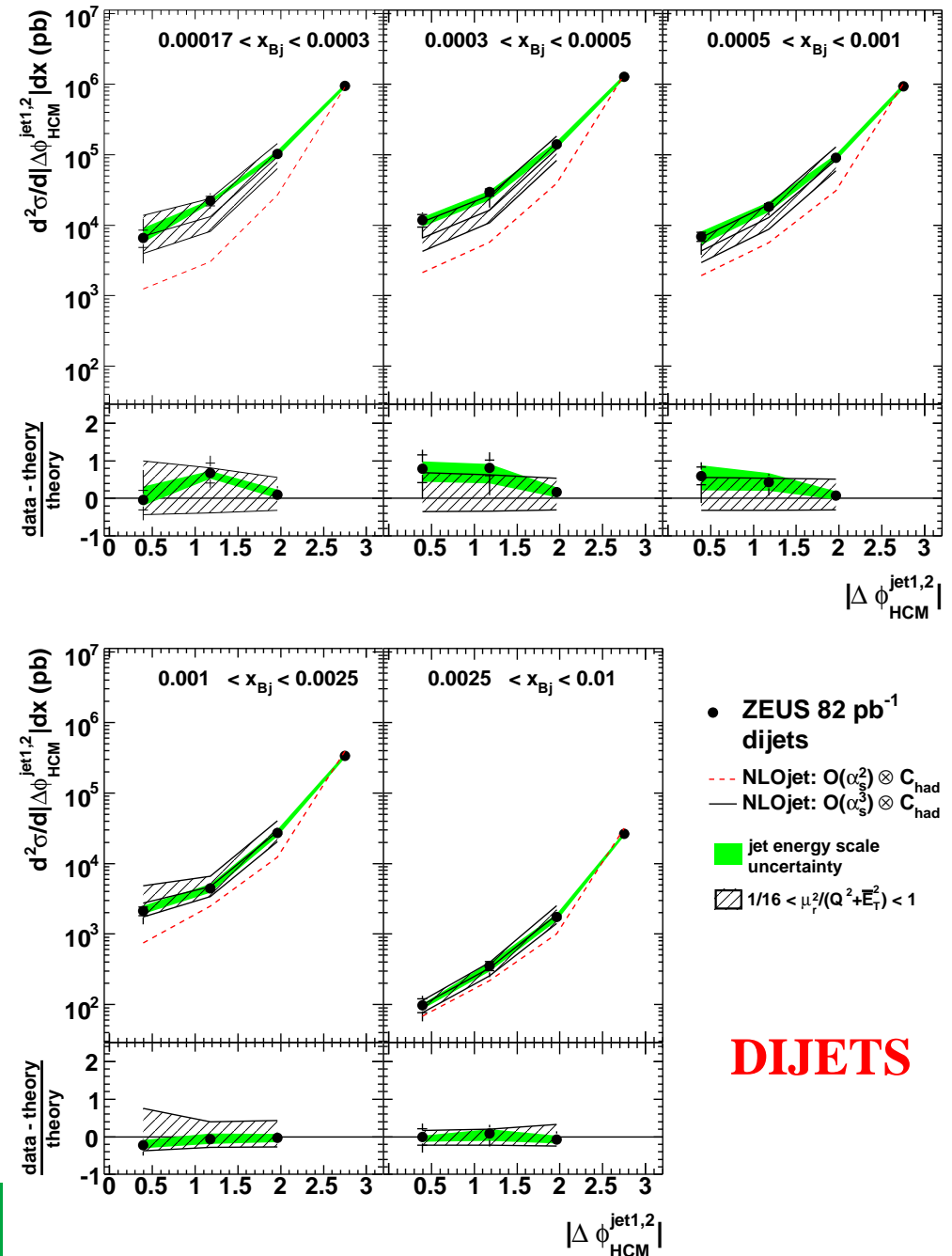
$$\rightarrow \mathcal{O}(\alpha_s^3) \Rightarrow \text{first correction!}$$

- $\mathcal{O}(\alpha_s^2)$ 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 $\Delta\phi_{HCM}^{jet1,2} = \pi$)

Importance of higher-order effects at low x !



Multijet production at low x

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

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

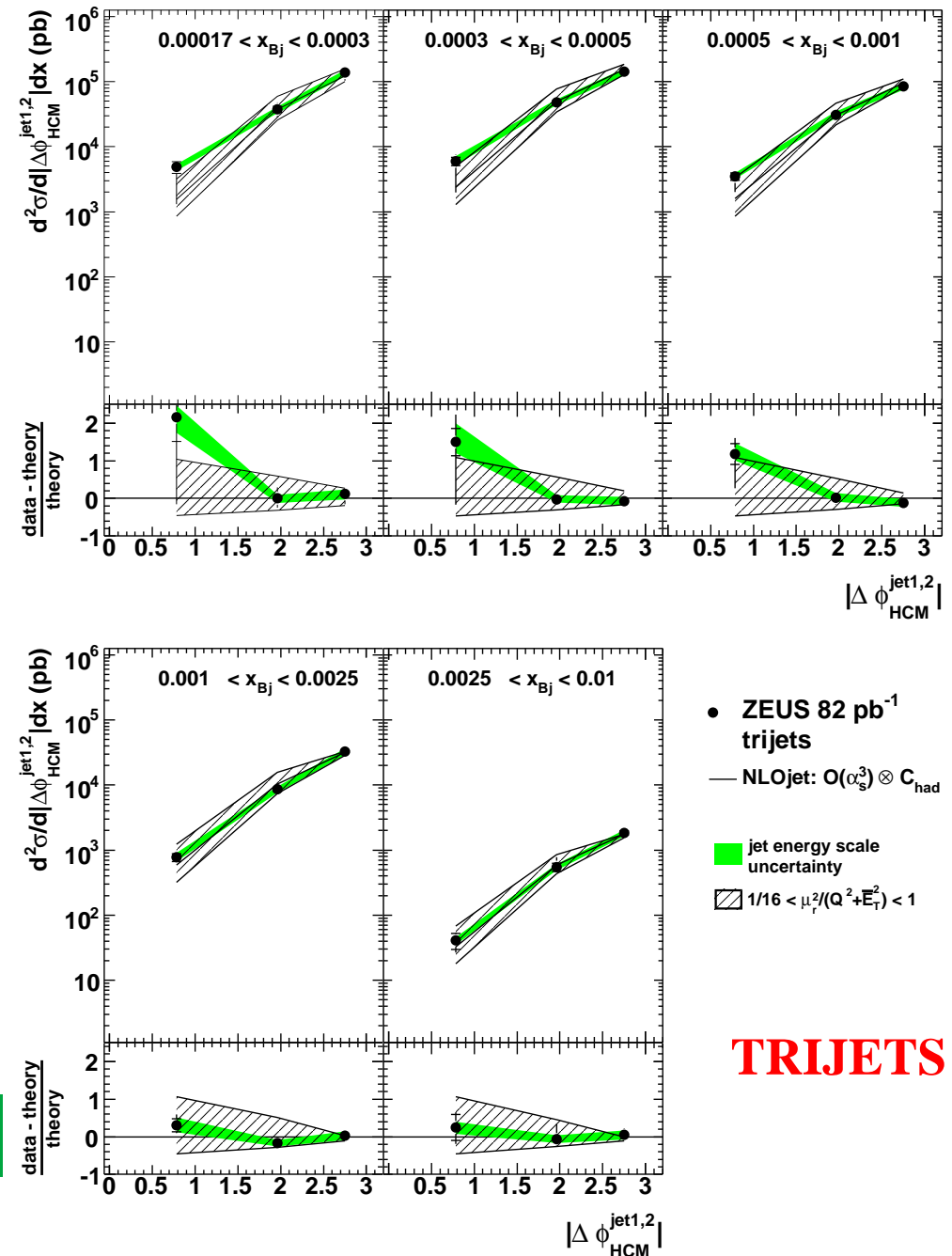
- Trijet events:

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

→ $\mathcal{O}(\alpha_s^3) \Rightarrow$ 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 !



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

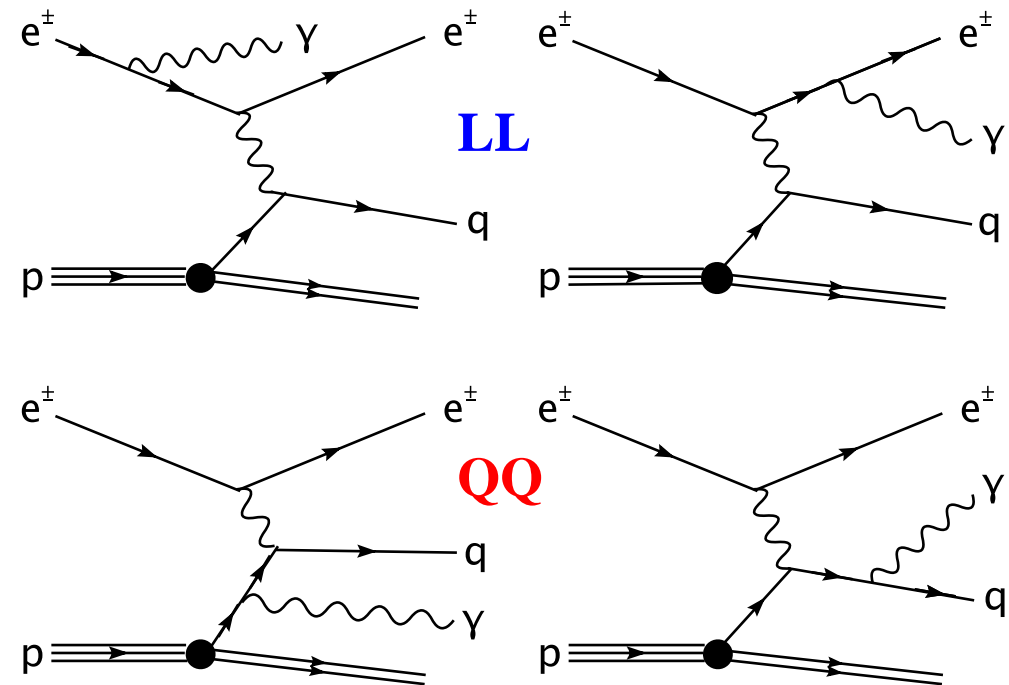
(direct radiation or fragmentation; fragmentation suppressed by isolation requirement)

- **LQ**: the interference is expected to be small

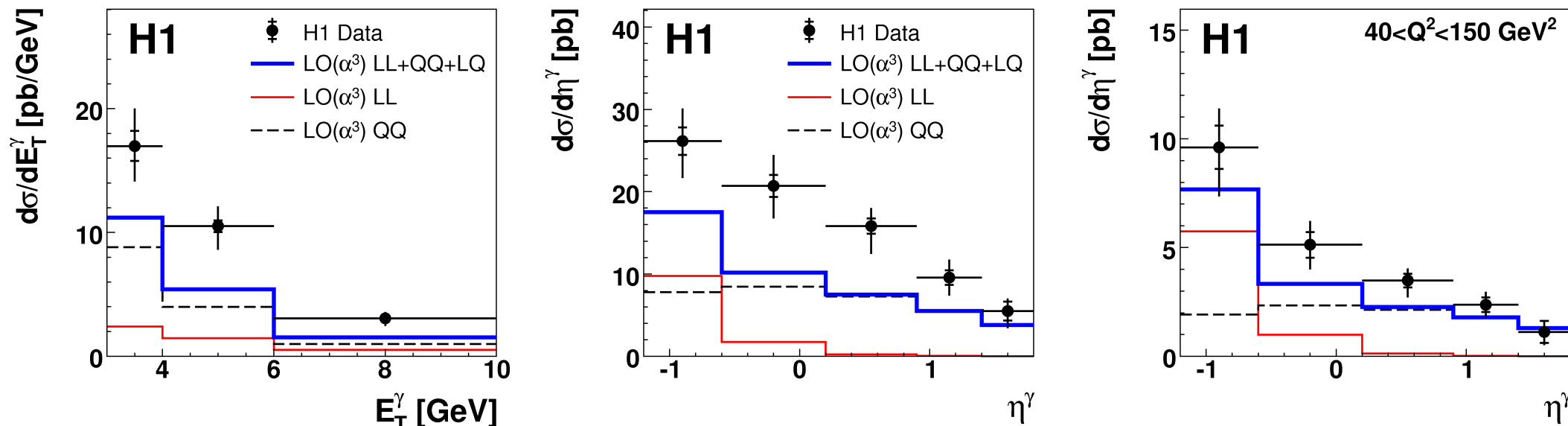
- Photon candidates: **compact EM clusters in LAr calorimeter**; **no associated track**; **isolated**.

- 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 $E_T^\gamma / E_T^{\gamma\text{-jet}} > 0.9 \implies$ **Isolated- γ signal extracted using a MVA**

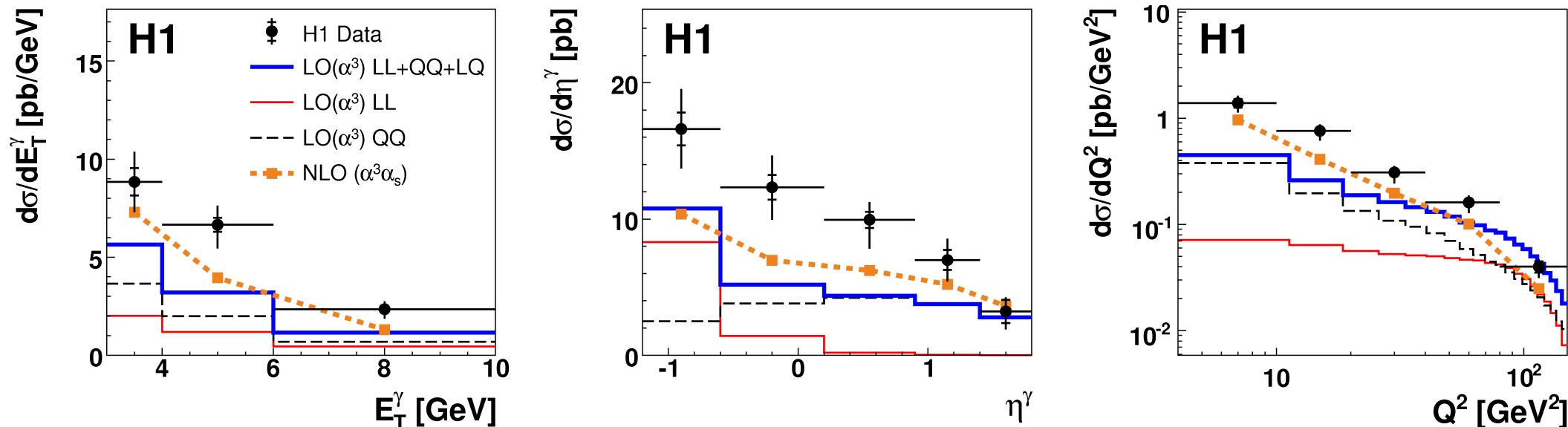


Measurements of inclusive isolated photons in NC DIS



- Measurement of inclusive isolated photon production with $3 < E_T^\gamma < 10 \text{ GeV}$ and $-1.2 < \eta^\gamma < 1.8$ in the kinematic region defined by $4 < Q^2 < 150 \text{ GeV}^2$ and $W > 50 \text{ GeV}$
- Comparison to LO ($\mathcal{O}(\alpha^3 \alpha_s^0)$) calculations corrected for hadronisation effects
 → shape of the distributions: ok → normalization: a factor 2 too low
 ⇒ a good description can be achieved by scaling the QQ contribution by a factor 2.3
- Better agreement between data and theory for $Q^2 > 40 \text{ GeV}^2$ (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

→ LO underestimates the data as for the inclusive photon measurement

→ NLO improves the description (most significantly at low Q^2),

but still below the data ($\sim 35\%$)

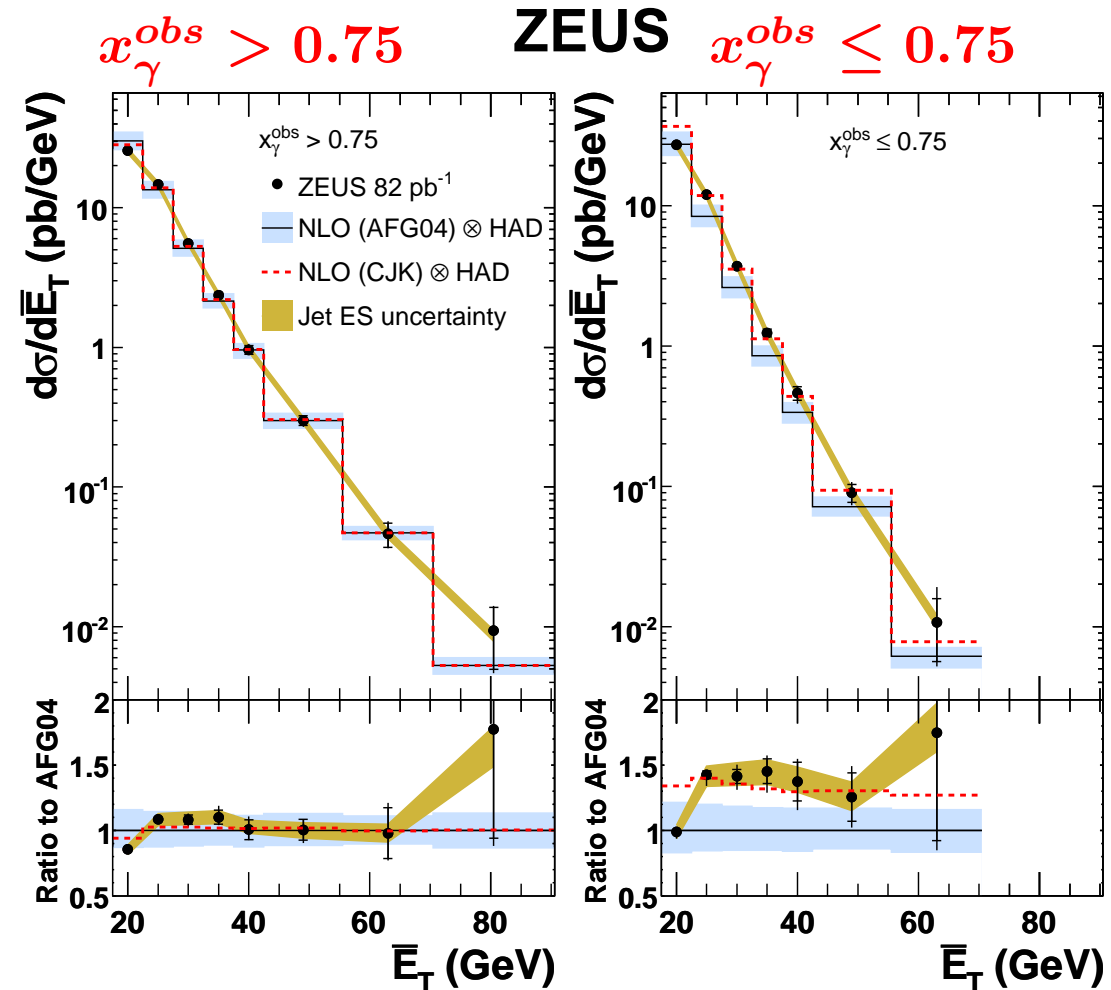
Further theoretical investigations needed!

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Dijet Photoproduction

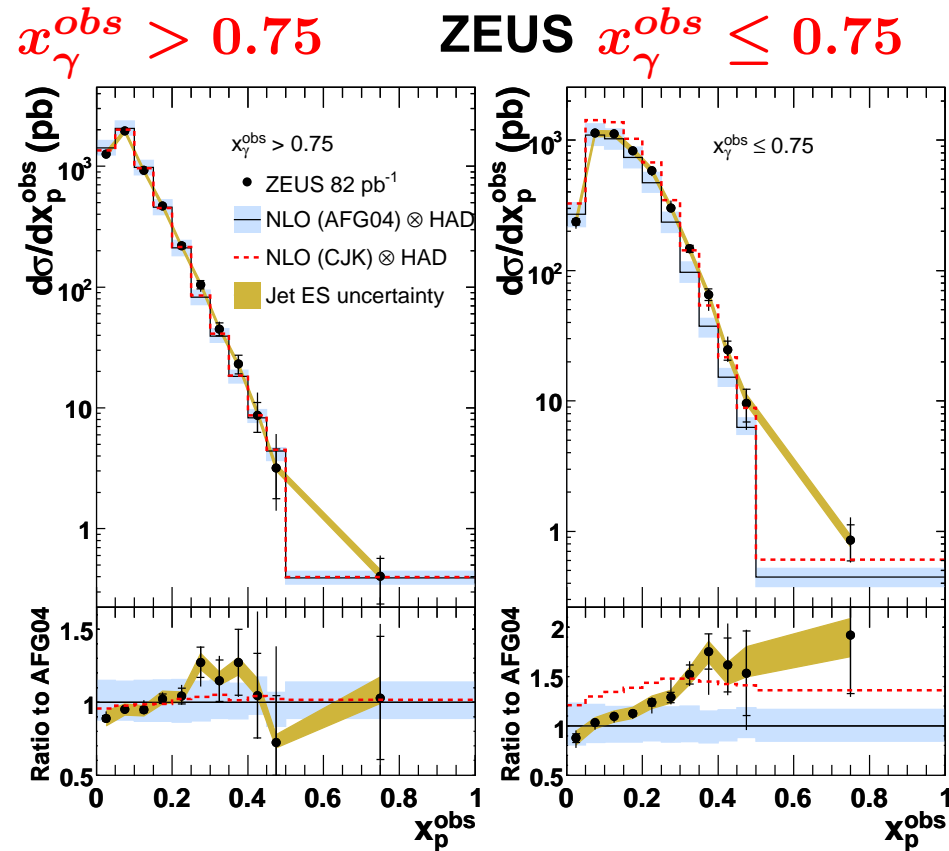
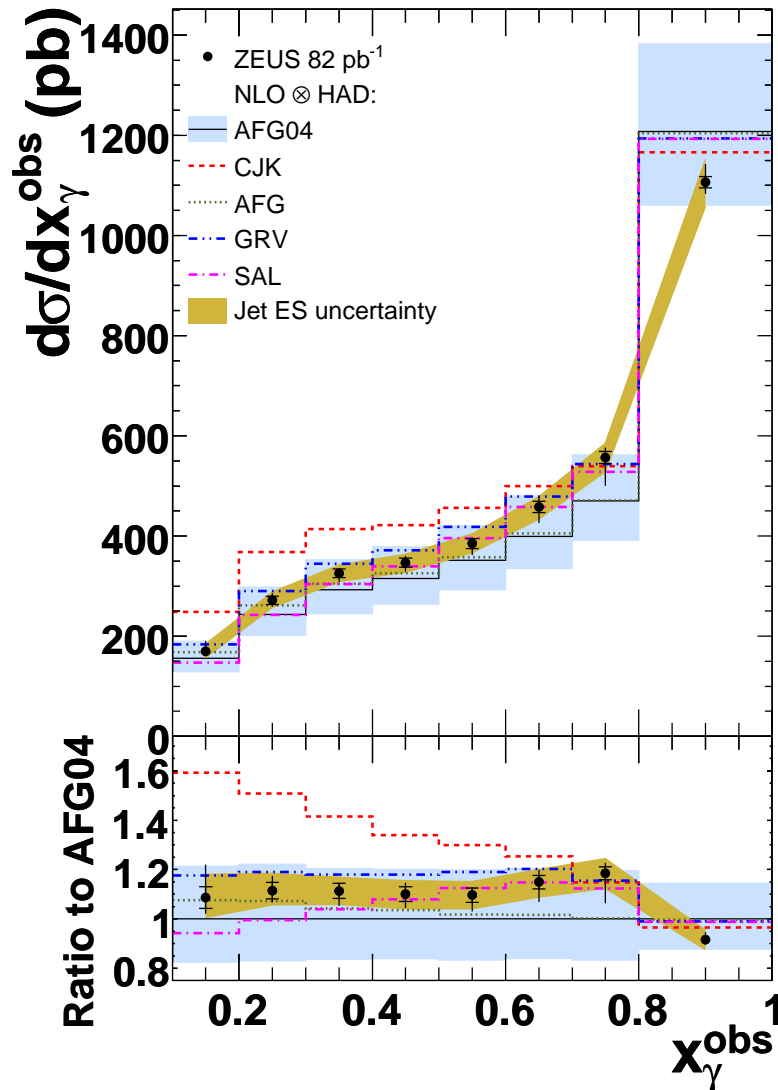
- **New** measurement of differential cross sections for dijet production $E_T^{jet1} > 20$ GeV, $E_T^{jet2} > 15$ GeV, $-1 < \eta^{jet1,2} < 3$ (and at least one of the jets within $\eta^{jet} < 2.5$) in the kinematic region $Q^2 < 1$ GeV² and $142 < W_{\gamma p} < 293$ GeV
- Measurement of $d\sigma/d\bar{E}_T$ with $\bar{E}_T = (E_T^{jet1} + E_T^{jet2})/2$
- **Small experimental uncertainties:** jet energy scale (1% for $E_T > 10$ GeV) $\rightarrow \Rightarrow \sim \pm 5\%$ 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
- \rightarrow good description of direct-photon enriched region ($x_\gamma^{obs} > 0.75$)
- \rightarrow data above NLO (AFG04) in resolved-photon enriched region ($x_\gamma^{obs} \leq 0.75$)



Dijet Photoproduction

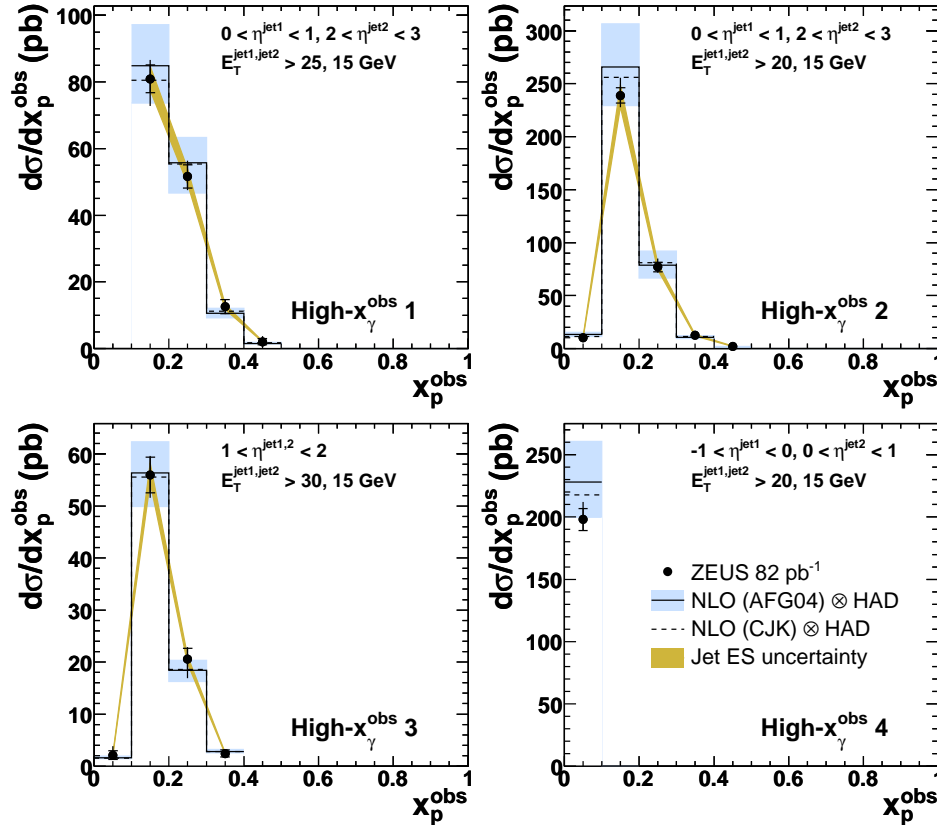
ZEUS



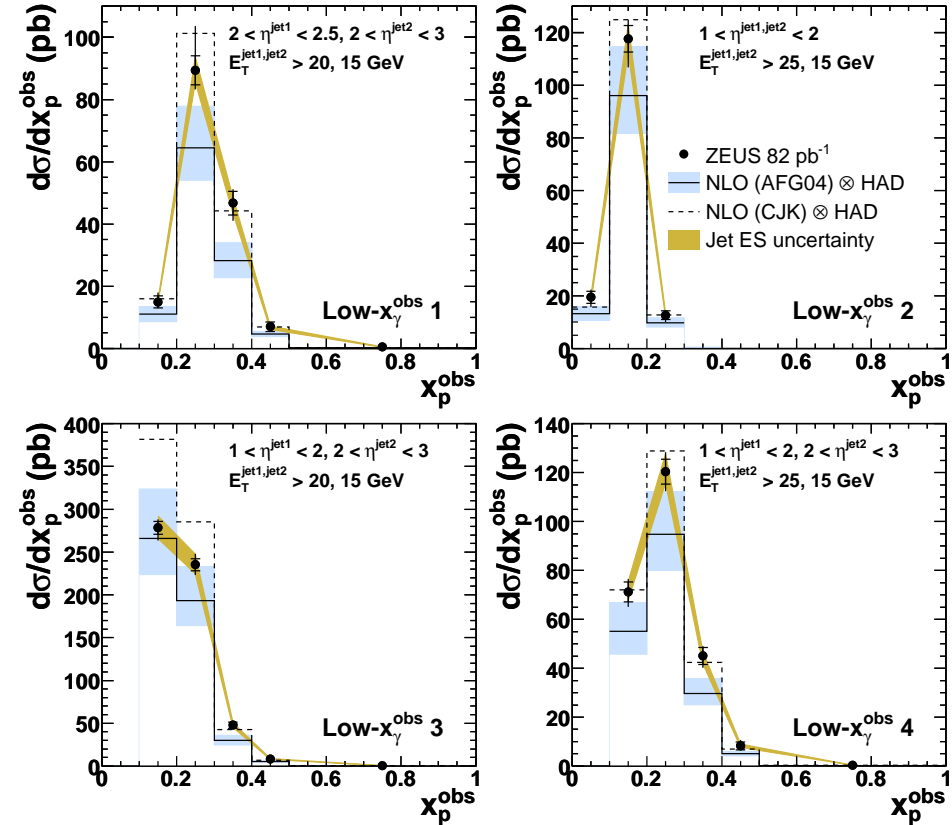
- Measurement of $d\sigma/dx_\gamma^{obs}$: comparison with different sets of photon PDFs (most deviant: CJK)
 - Measurement of $d\sigma/dx_p^{obs}$, $x_p^{obs} = \frac{1}{2E_p} \sum E_T^{jet_i} e^{\eta^{jet_i}}$
 - reasonable description of direct-photon enriched region
 - poor description of resolved-photon enriched region
- ⇒ None of the photon PDFs describe low- x_γ^{obs} data

Dijet Photoproduction: optimized cross sections

ZEUS



ZEUS

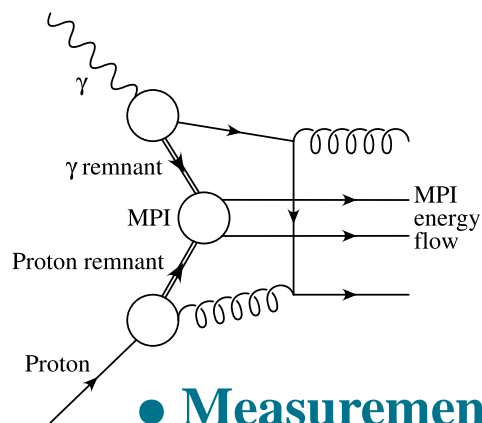


- High- x_{γ}^{obs} optimized cross sections: major sensitivity to proton PDFs
- Low- x_{γ}^{obs} optimized cross sections: major sensitivity to photon PDFs

⇒ 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:

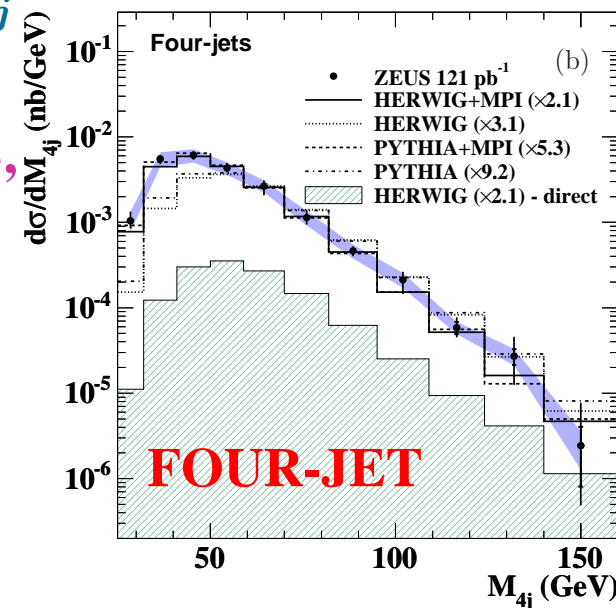
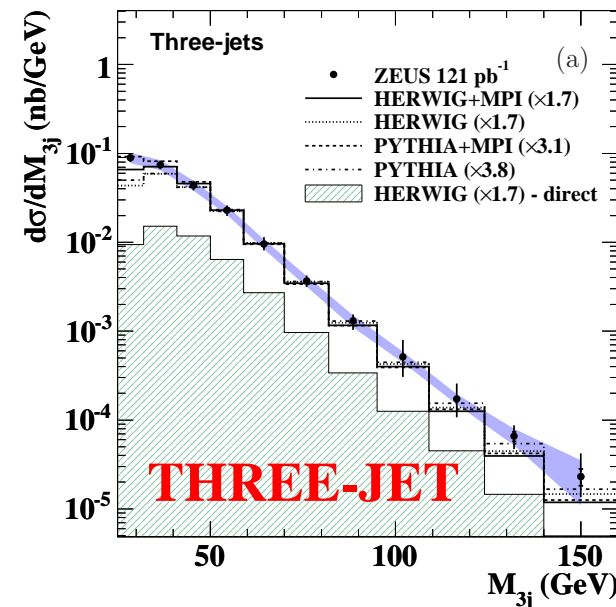
→ without MI

→ with MI: PYTHIA

HERWIG+JIMMY (tuned)

- Measurement of differential cross-sections $d\sigma/dM_{nj}$ for three(four)-jet production $E_T^{jet} > 6 \text{ GeV}$, $|\eta^{jet}| < 2.4$ in the kinematic region $Q^2 < 1 \text{ GeV}^2$ and $0.2 < y < 0.85$,
- HERWIG and PYTHIA without MI (normalised to $M_{nj} > 50 \text{ GeV}$ 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}

ZEUS



Three- and Four-jet Photoproduction

ZEUS

LOW MASS

HIGH MASS

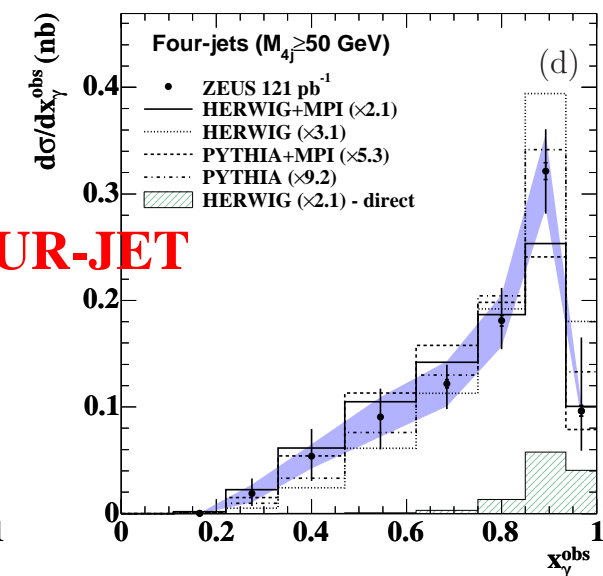
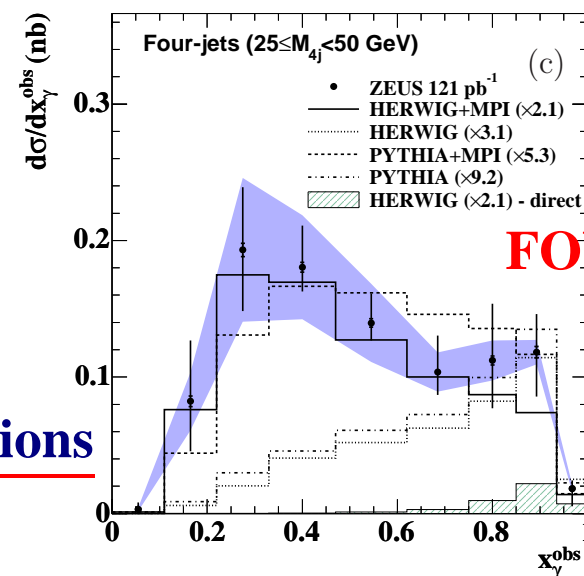
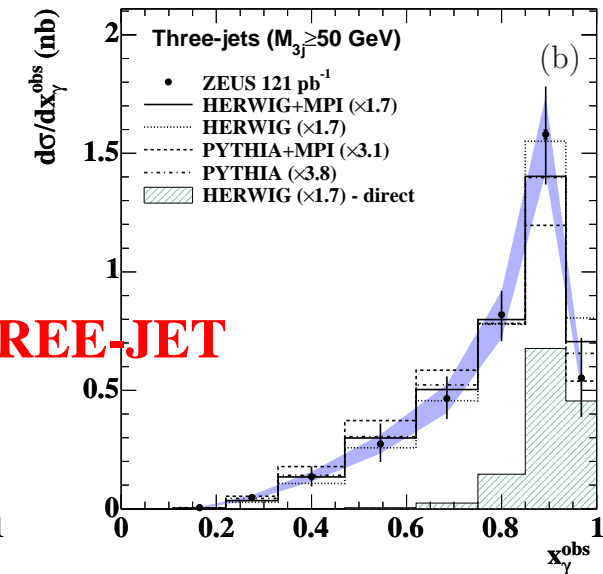
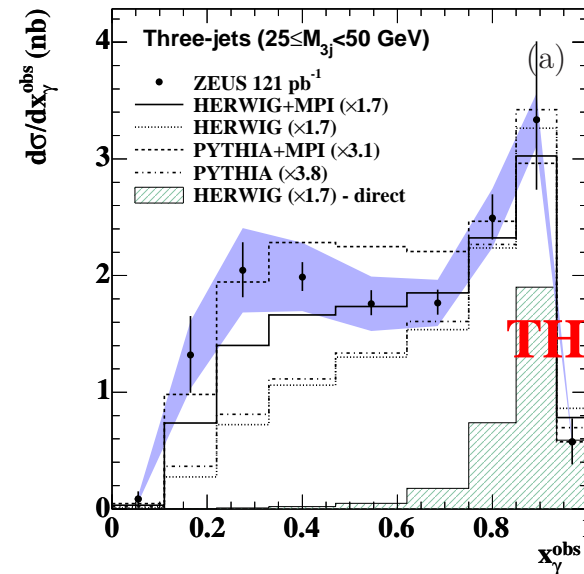
- Measurement of differential cross section $d\sigma/dx_\gamma^{obs}$ for three(four)-jet production in two regions of M_{nj} :

→ low mass: $25 < M_{nj} < 50$ GeV

→ high mass: $M_{nj} > 50$ GeV

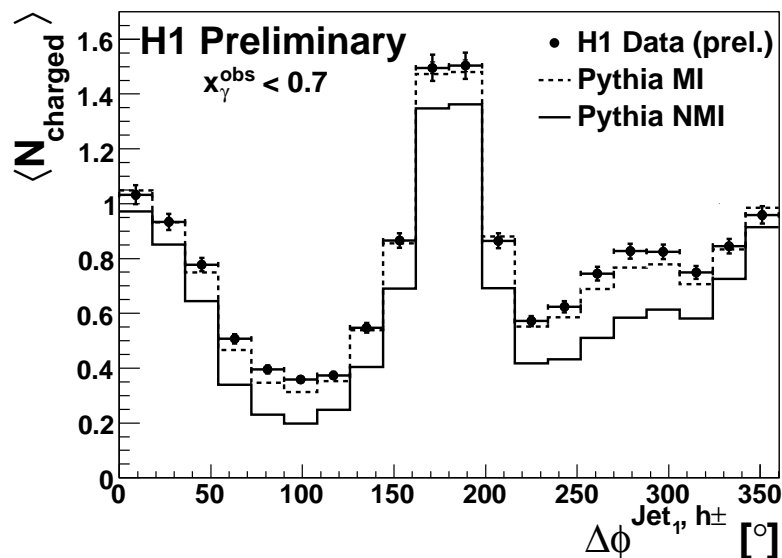
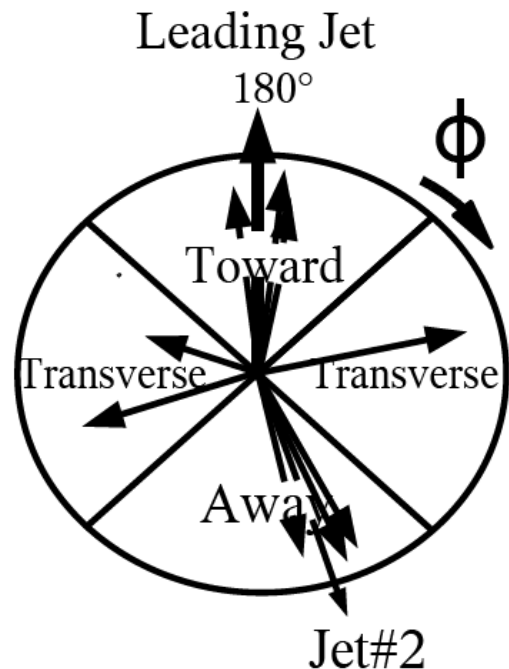
$$x_\gamma^{obs} = \frac{1}{2E_\gamma} \sum_{i=1}^{3(4)} E_T^{jet_i} e^{-\eta^{jet_i}}$$

- 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
 $P_T^{jet} > 5 \text{ GeV}$ and $-1.5 < \eta_{lab}^{jet} < 1.5$
- Kinematic region: $Q^2 < 0.01 \text{ GeV}^2$, $0.3 < y < 0.65$
- Jets are reconstructed using the k_T -cluster algorithm in the LAB frame: leading jet at $\phi = 180^\circ$
- Measurement of $\langle N_{charged} \rangle$ in four regions: “Toward”, “Away”, “High-activity” and “Low-activity”



Comparison to PYTHIA
 with/without MI

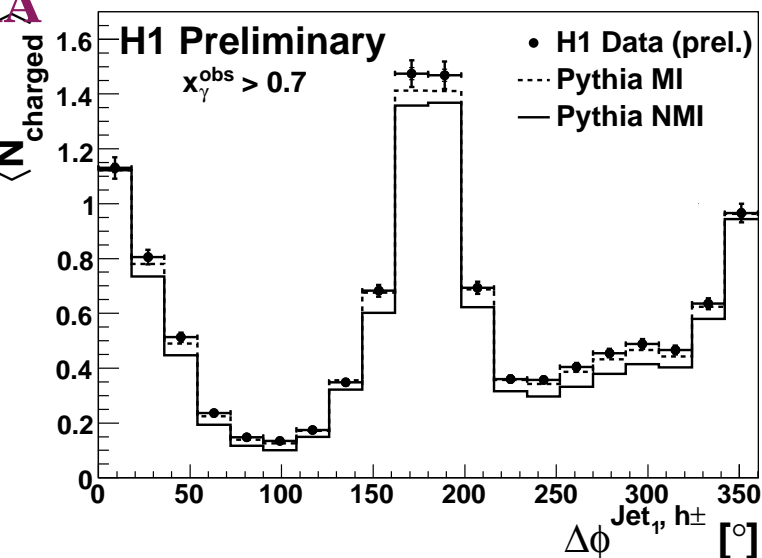
in two regions in x_γ^{obs} :

← resolved-photon

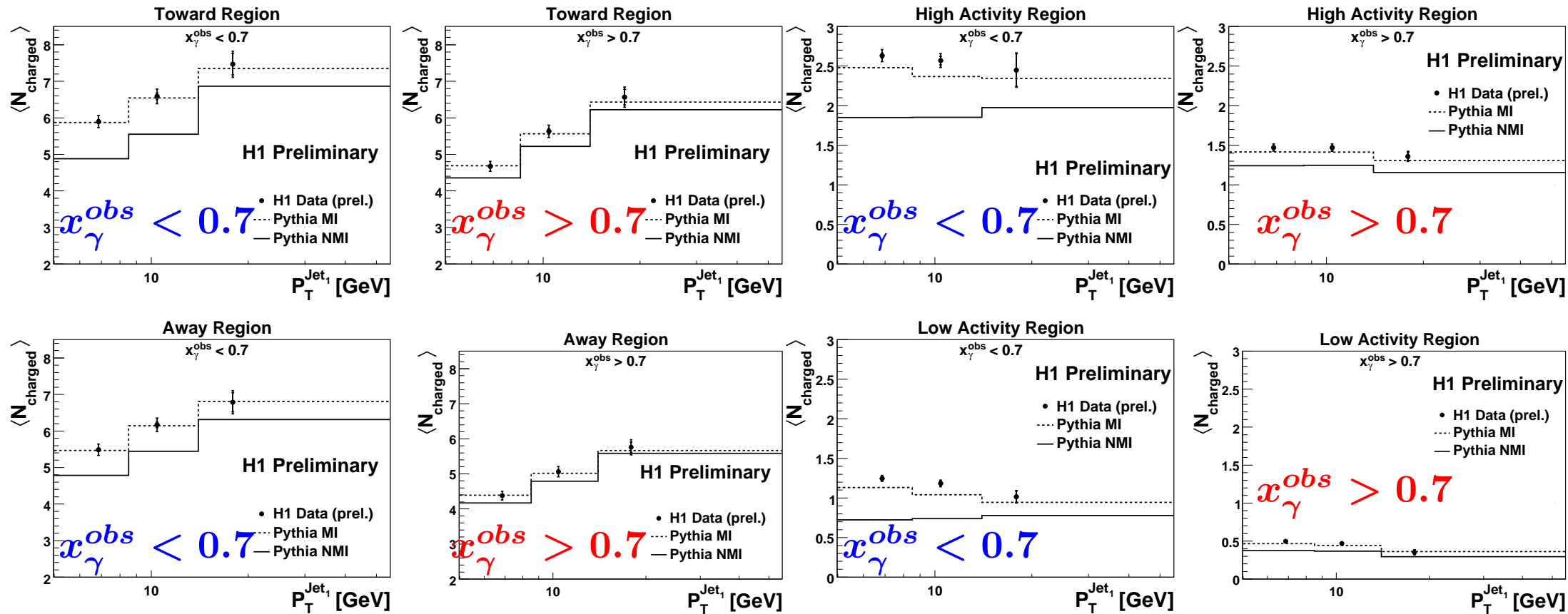
$x_\gamma^{obs} < 0.7$

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
→ inclusion of multi-parton interactions describes the data well

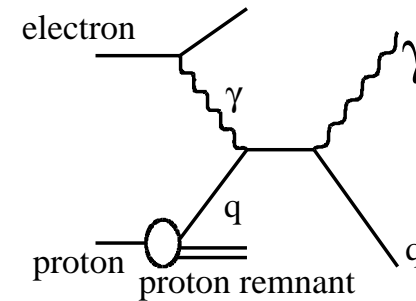
Prompt-photon production in γp interactions

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

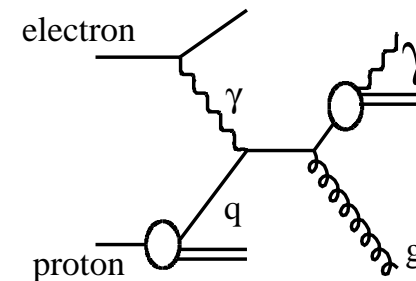
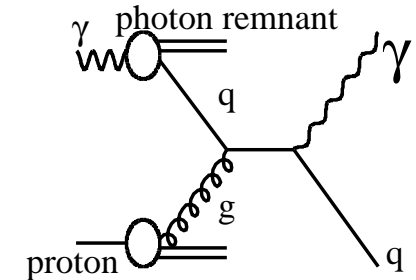
- Benchmark for pQCD calculations:
 \rightarrow fixed-order (NLO) QCD calculations in the collinear approach including direct and resolved-photon processes, quark-to-photon fragmentation and the box diagram $\gamma g \rightarrow \gamma g$

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

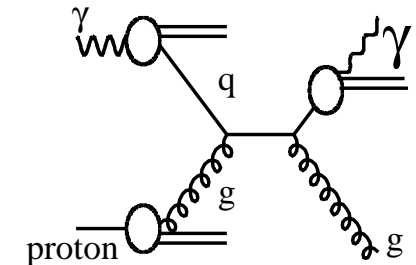
- \Rightarrow Calculations corrected for hadronization and multi-parton interaction effects



(a) direct non-fragmentation (b) resolved non-fragmentation



(c) direct fragmentation



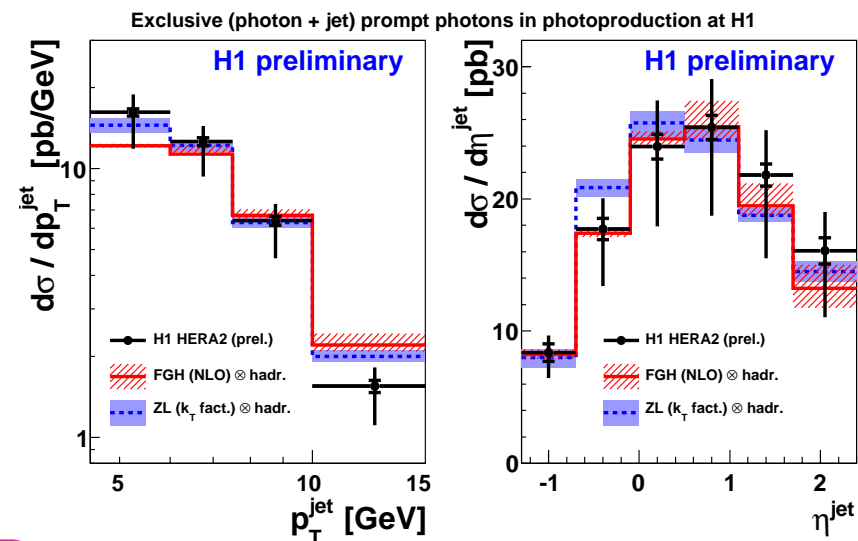
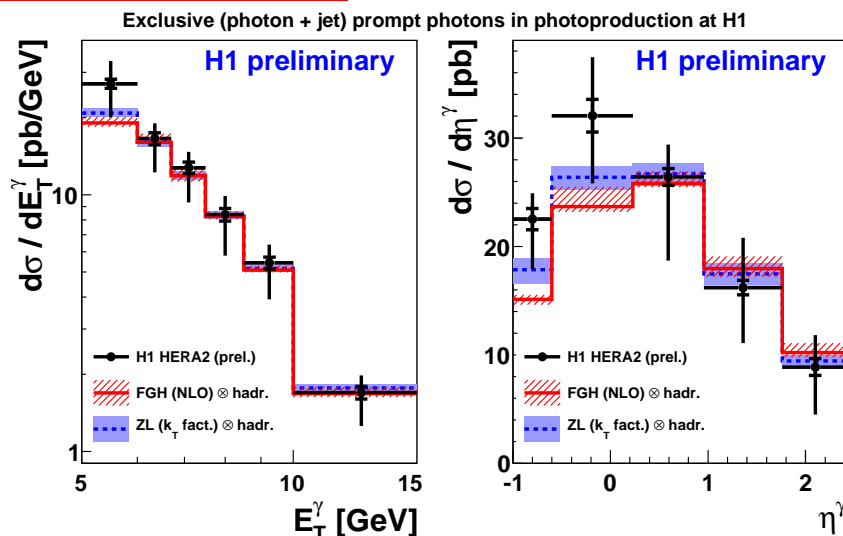
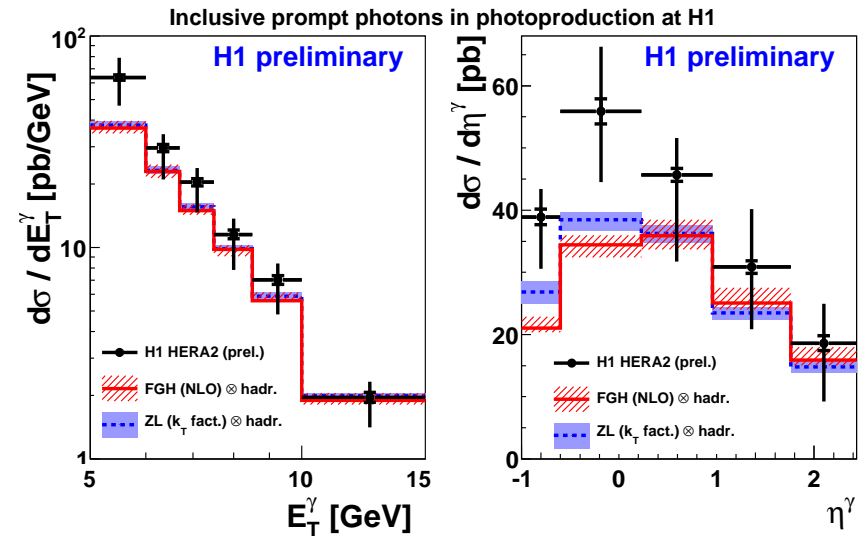
(d) resolved fragmentation

Measurements of inclusive prompt photon and prompt-photon+jets

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

→ Data above pQCD at low E_T^γ and low η^γ

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



→ Improved description of the data by pQCD

Summary

- Exploration of parton dynamics at low x vigorously pursued
→ 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

⇒ 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:
→ the theory describes photoproduction data
→ but fails to reproduce DIS data (?)

