Paris, ICHEP 2010

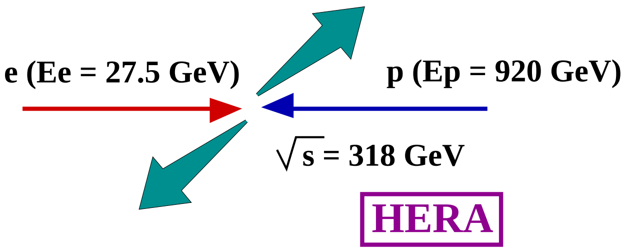
July 24th, 2010

ICHEP PARIS 2010

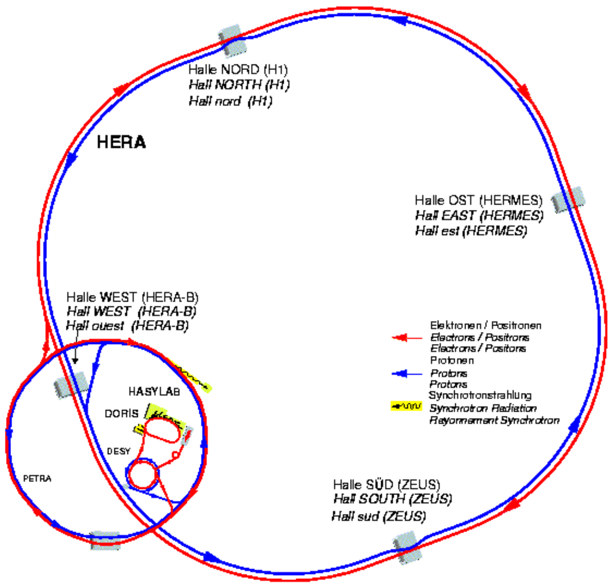
Prompt photons, forward jets and subjets at HERA

Juan Terrón (Universidad Autónoma de Madrid, Spain)

H1 ZEUS

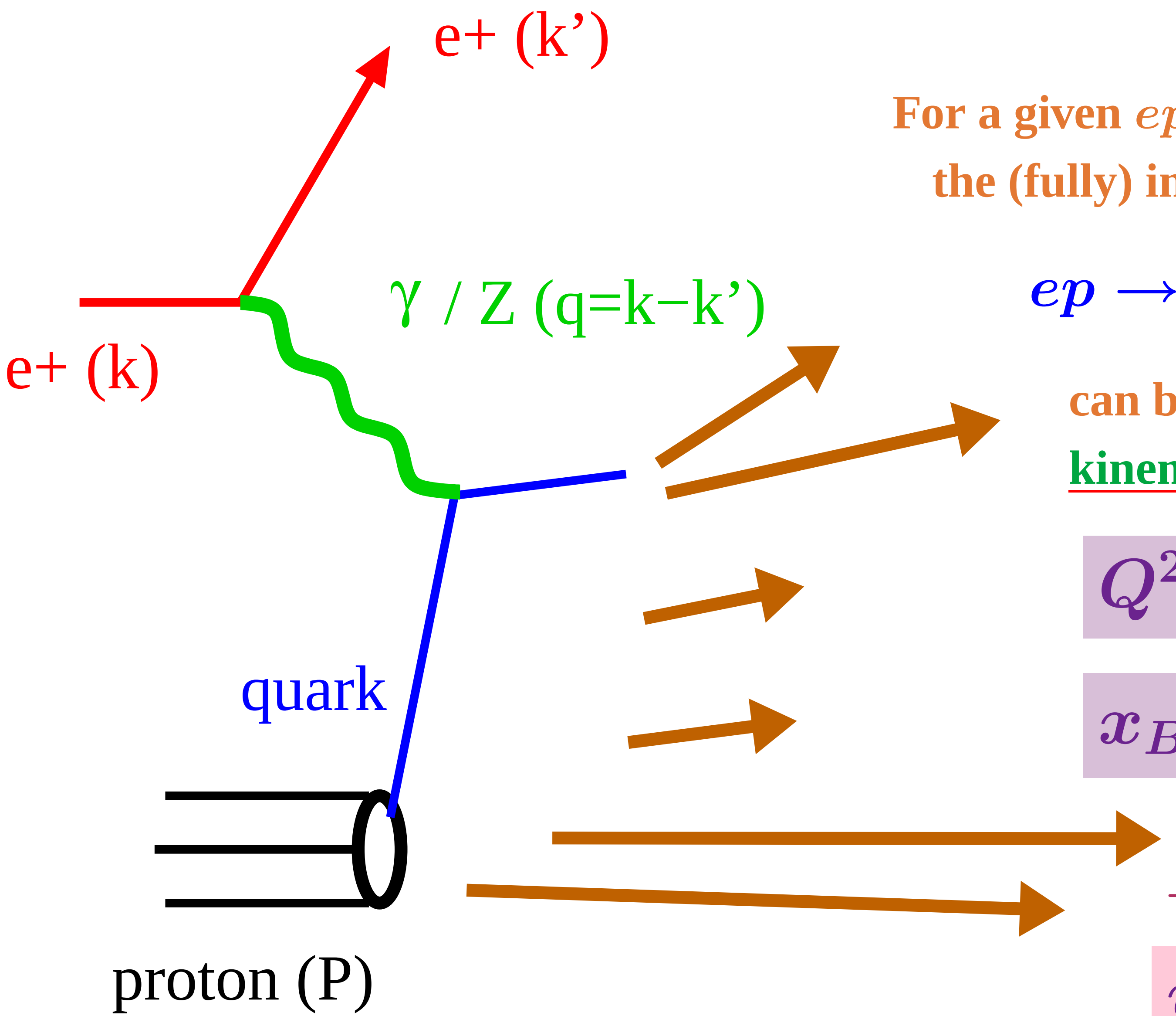


H1 and ZEUS Collaborations



- **Outline**
  - $\longrightarrow$ Isolated photons in neutral current DIS ep
  - $\longrightarrow$ Isolated photons in photoproduction (γp collisions)
  - $\longrightarrow$ Forward jet production in NC DIS ep
  - $\longrightarrow$ Three-subjet production in NC DIS ep

Kinematics of Neutral Current Deep Inelastic Scattering



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

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

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

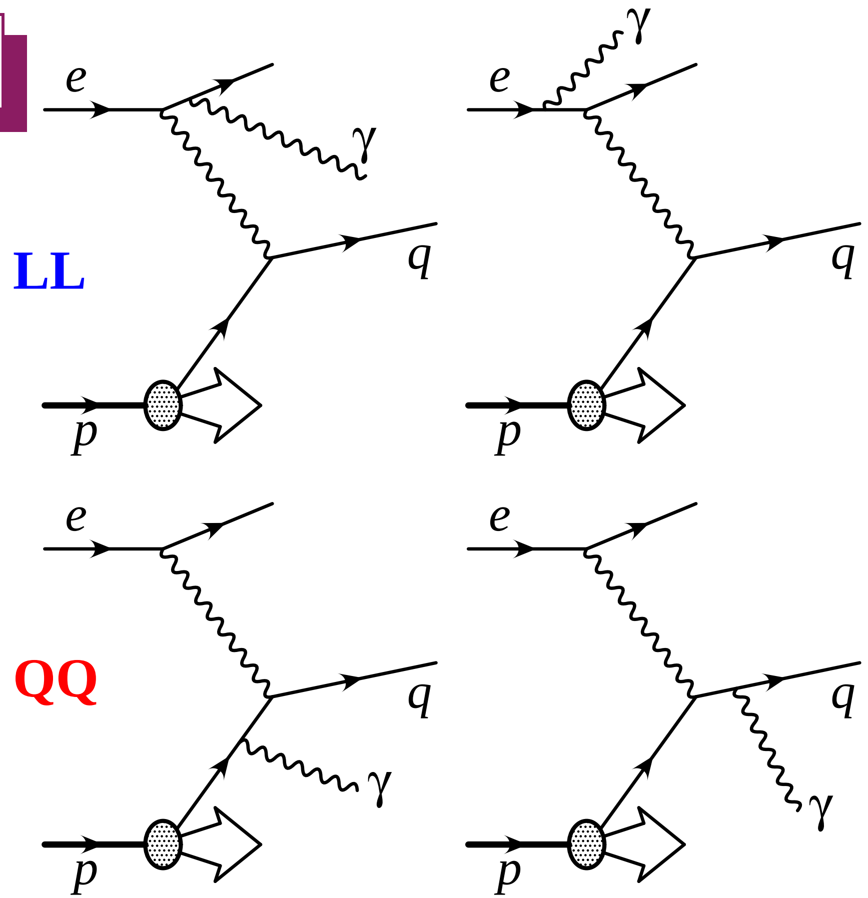
$$Q^2 = -(k - k')^2$$

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

→ Inelasticity variable

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

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 for new physics involving final-state photons

- SM calculations:

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

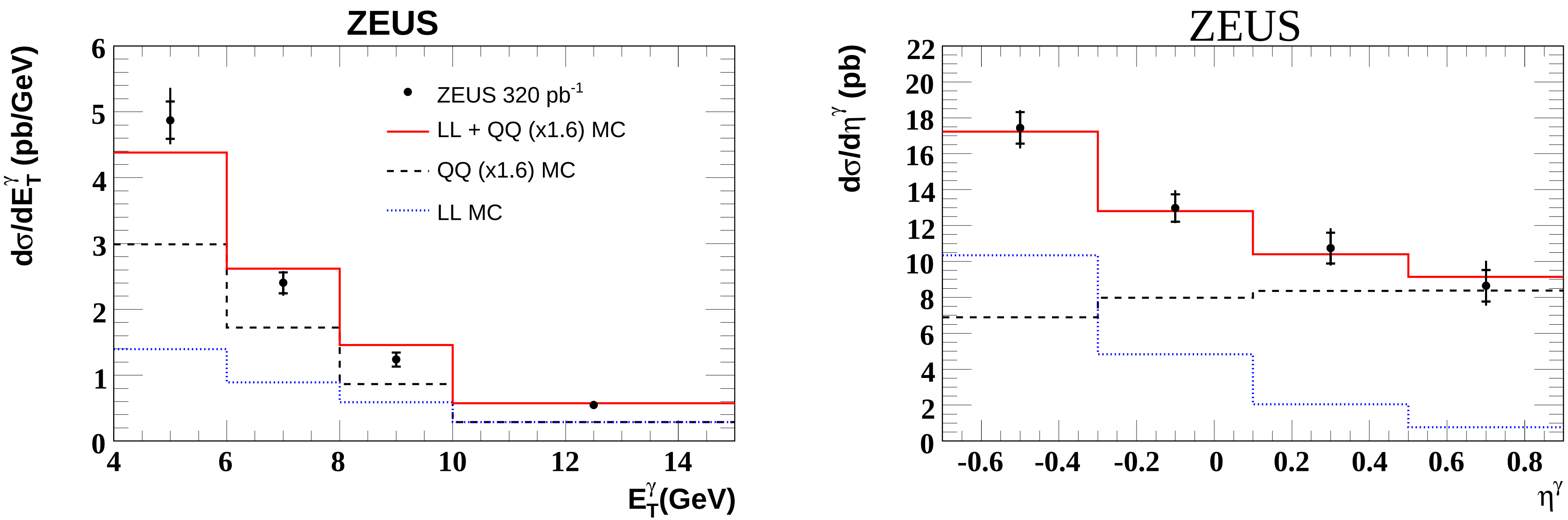
→ QQ: radiation from a quark line (direct radiation or fragmentation; fragmentation suppressed by isolation requirement)

→ LQ: the interference is expected to be small

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

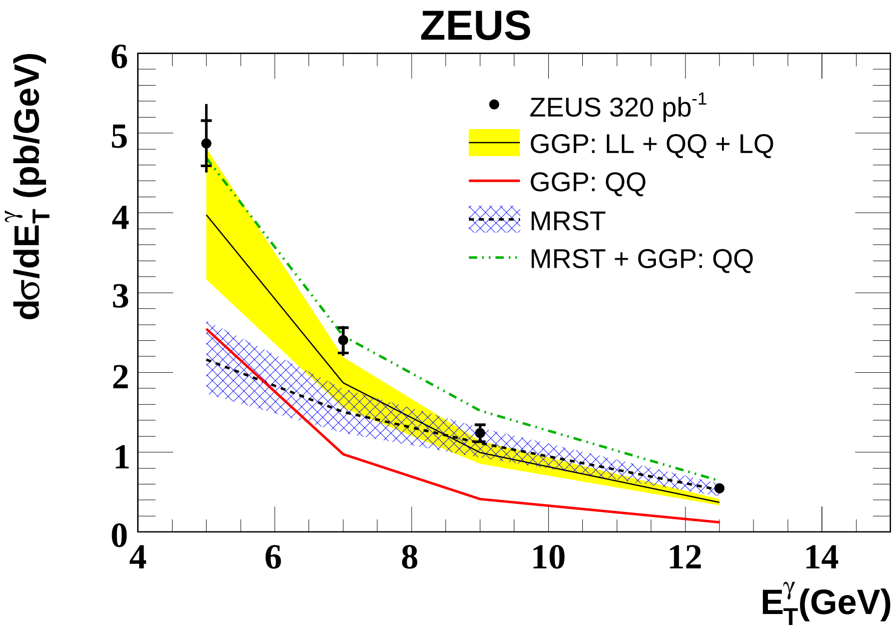
- Jets are reconstructed applying the k_T-cluster algorithm with $D = 1$ over all final-state particles, including photon candidates→ isolation condition: the jet containing the γ should fulfill $E_T^{\gamma}/E_T^{\gamma-\mathrm{jet}} > 0.9$ $\Longrightarrow$ Isolated-γ signal extracted using shower shapes

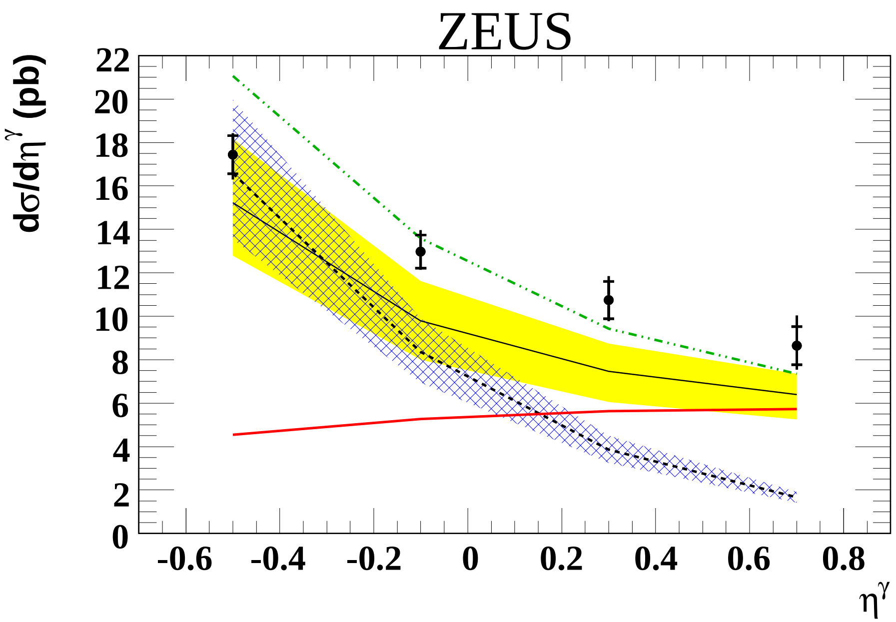
Measurements of inclusive isolated photons in NC DIS (I)



- **Measurement of inclusive isolated photon production with $4 < E_T^\gamma < 15$ GeV and $-0.7 < \eta^\gamma < 0.9$ in the kinematic region defined by $10 < Q^2 < 350$ GeV^2, $W_X > 5$ GeV, $E'_e > 10$ GeV and $139.8° < \theta_e < 171.8°$ using $\mathcal{L} = 320$ pb^{-1}**
- **Comparison to MC (DJANGOH+PYTHIA) calculations**
  $\longrightarrow$ **good description of the data**
  $\Longrightarrow$ **this is achieved by scaling the QQ contribution by a factor 1.6**

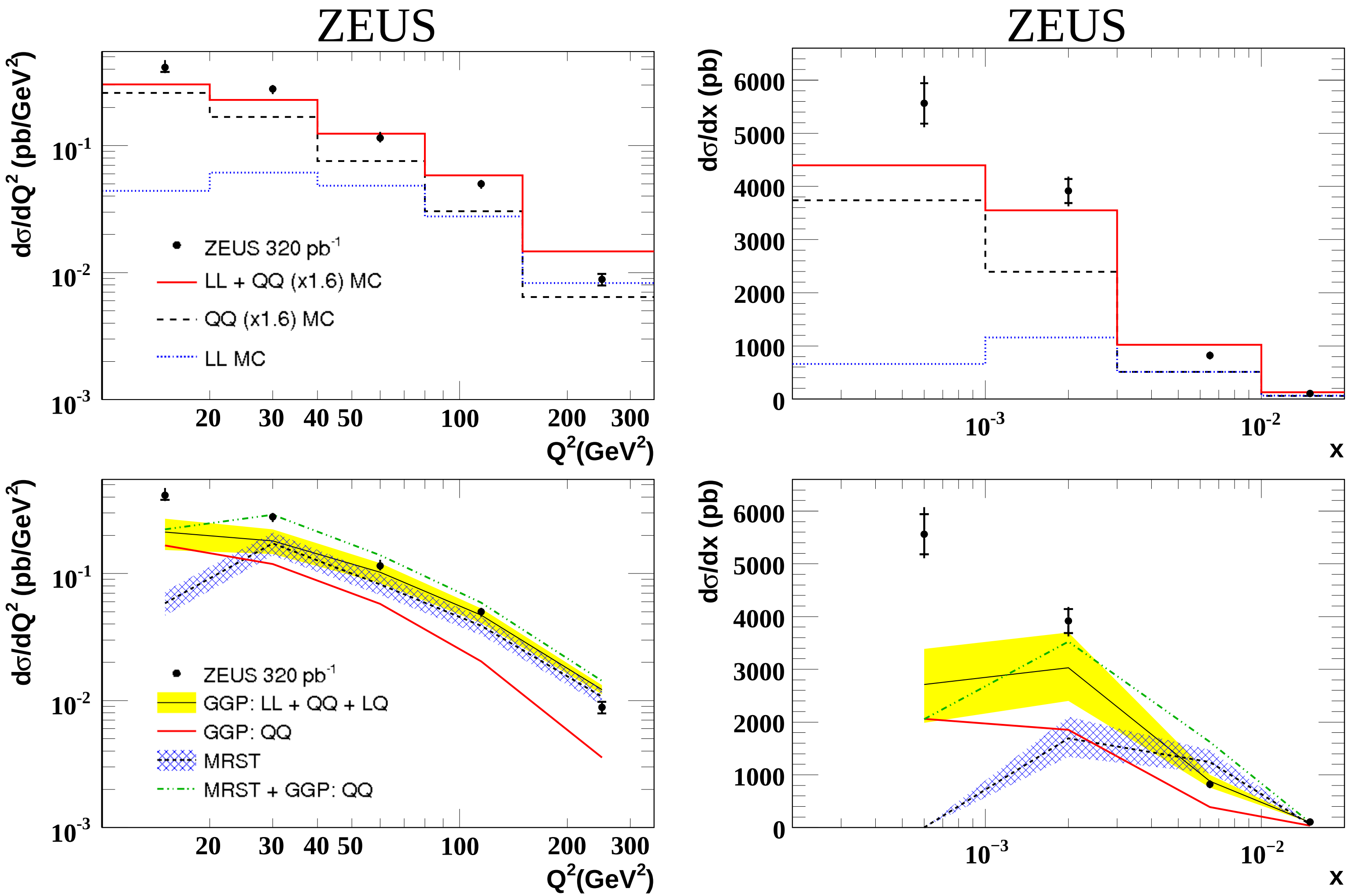
Measurements of inclusive isolated photons in NC DIS (II)





- **Comparison to theoretical calculations:**
  - **GGP (Gehrmann-De Ridder, Gehrmann, Poulsen): $\mathcal{O}(\alpha^3)$ calculations of QQ+LL+LQ. The QQ contribution includes both wide-angle emission and fragmentation**
    $\Rightarrow$ good description of shapes; normalization 20% too low
  - **MRST (Martin, Roberts, Stirling, Thorne): inclusion of QED corrections gives rise to a photonic component of the proton; LL contribution enhanced by DGLAP resummation; QQ not included. $\Rightarrow$ below data except at high E_T^γ, backward η^γ (QQ suppressed)**
  - **QQ(GGP)+MRST gives an improved description of the data**

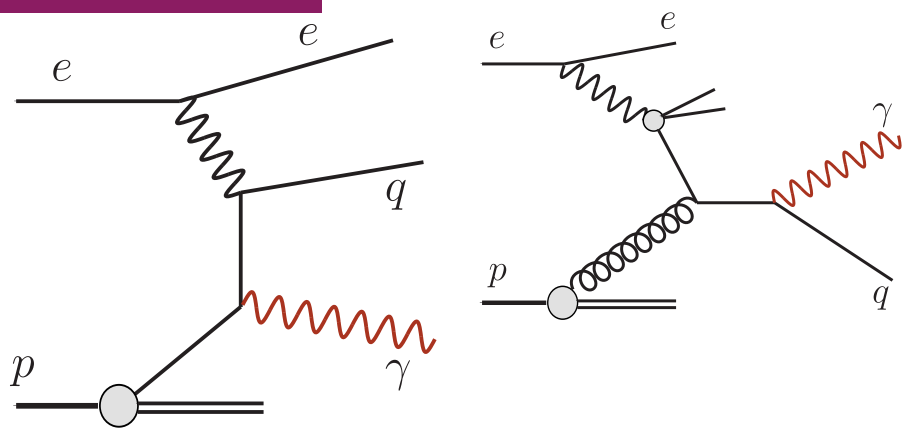
Measurements of inclusive isolated photons in NC DIS (III)



- **Comparison to theoretical calculations:** $\Rightarrow$ **failure at low Q^2 and low x**

Further theoretical investigations needed!

Prompt-photon production in γp interactions



- Production of prompt photons in γp interactions (photoproduction, $Q^2 \approx 0$) is sensitive to → proton and photon PDFs with lower hadronization corrections than in jet production
- Benchmark for pQCD calculations:

→ fixed-order (NLO) QCD calculations in the collinear approach including direct and resolved-photon processes

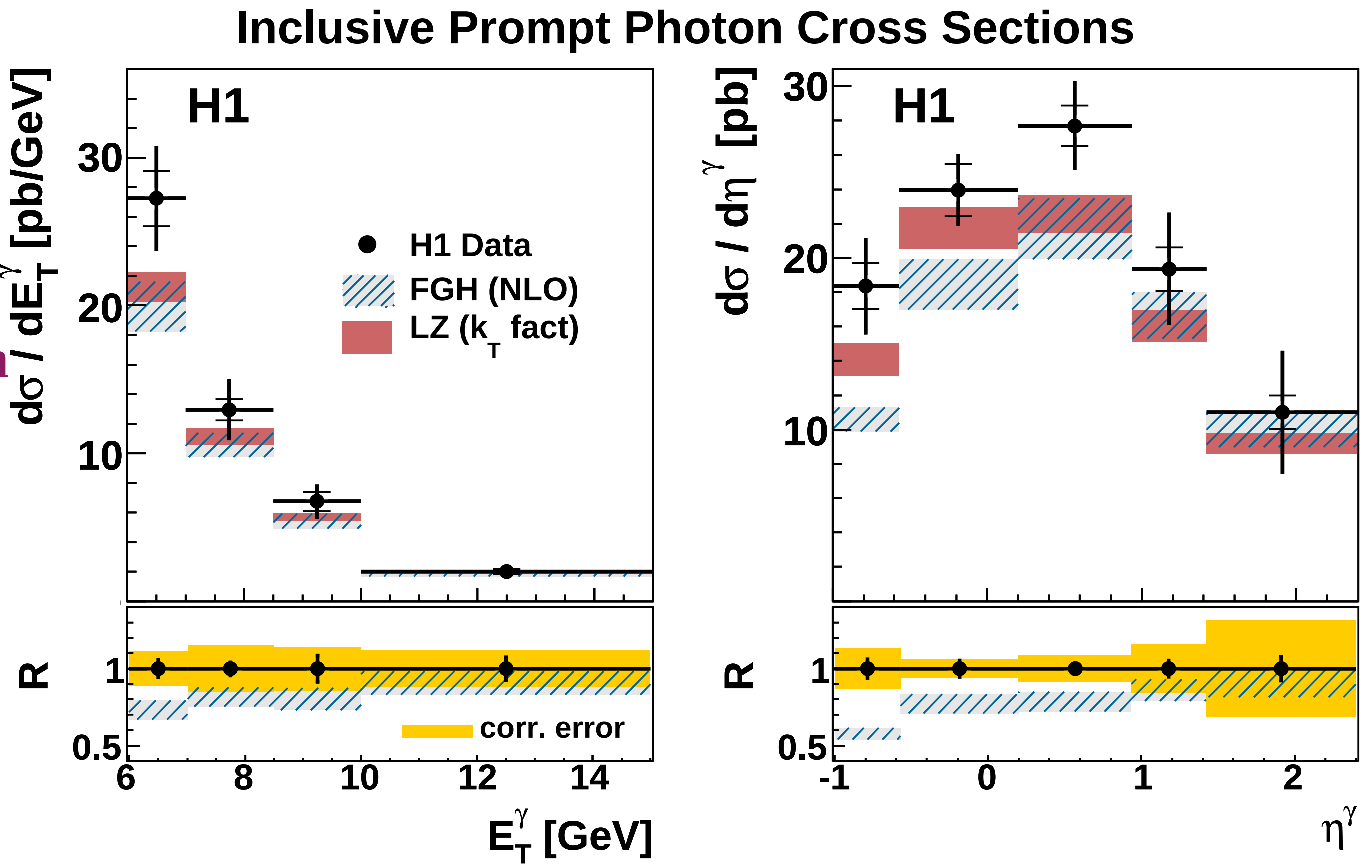
→ calculations based on k_T-factorization approach and using unintegrated PDFs; direct and resolved-photon processes included

⇒ Calculations corrected for hadronization/multiple interactions/different isolation (th.)

- Photon candidates: compact EM clusters in calorimeter; no associated track.
- 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 $E_T^{\gamma}/E_T^{\gamma-\rm jet} > 0.9$ $\Longrightarrow$ Isolated-γ signal extracted using shower shapes

Measurements of inclusive prompt-photon production

- 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 $E_T^\gamma / E_T^{\gamma-\text{jet}} > 0.9$, $6 < E_T^\gamma < 15$ GeV and $-1 < \eta^\gamma < 2.4$ using $\mathcal{L} = 340$ pb^{-1}



- Comparison to calculations:

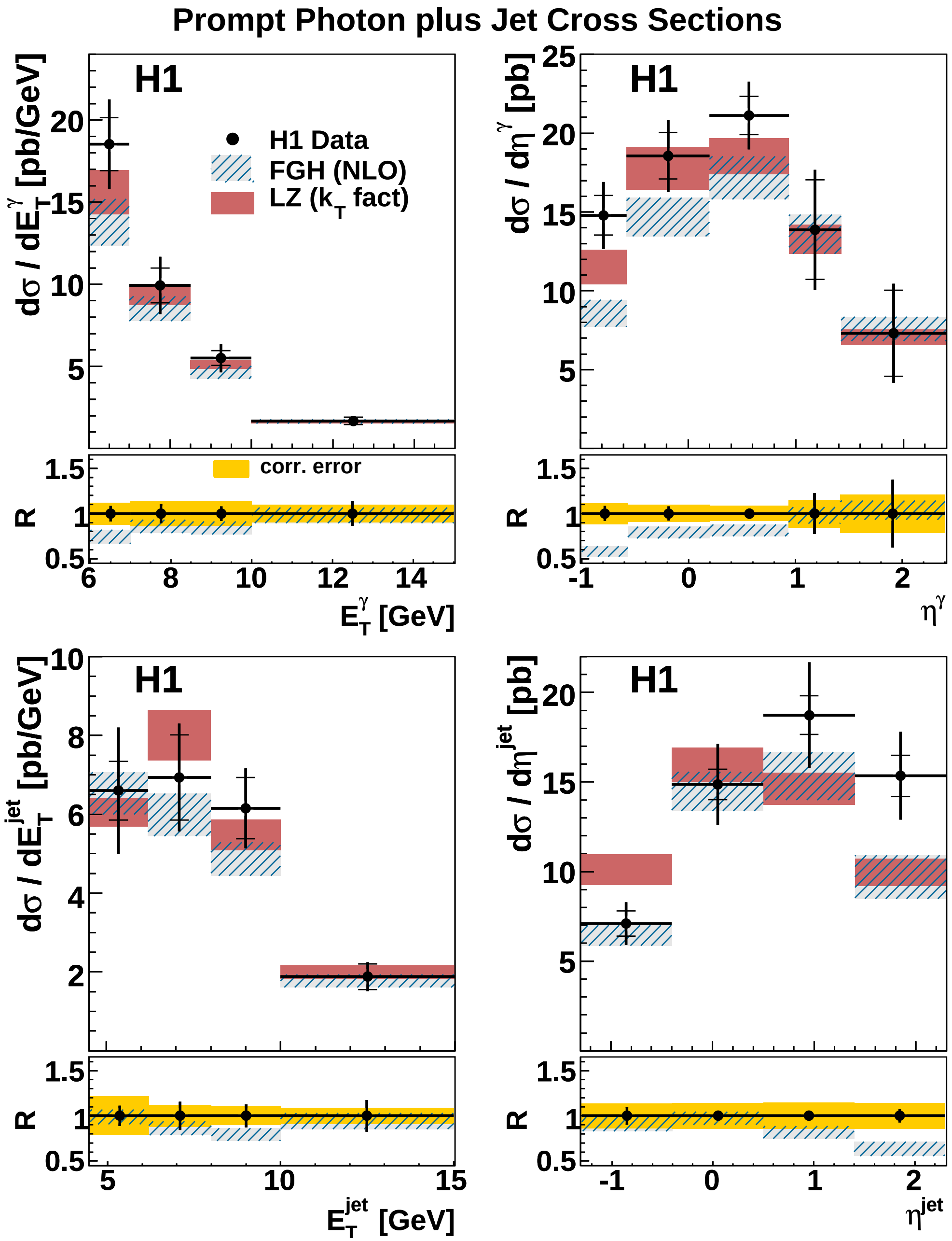
→ NLO (FGH; Fontannaz, Guillet, Heinrich) and k_T fact. (LZ; Lipatov, Zotov)

→ Data above pQCD, most significantly at low E_T^γ

→ LZ reproduces the shape in η^γ while FGH is significantly below the data for $\eta^\gamma < 0.9$

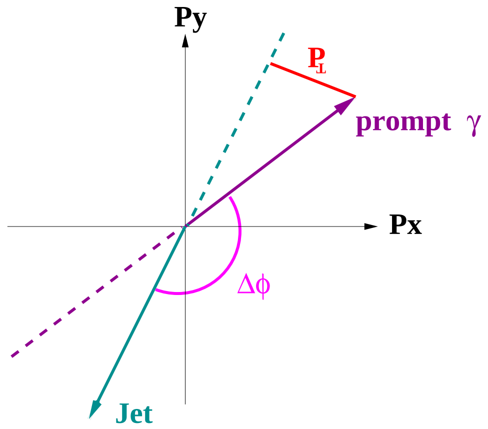
Prompt-photons + Jets (I)

- Measurement of prompt photon+jet production in the kinematic region defined by $Q^2 < 1$ GeV^2 and $0.1 < y < 0.7$ for photons with $E_T^\gamma / E_T^{\gamma-\text{jet}} > 0.9$, $6 < E_T^\gamma < 15$ GeV and $-1 < \eta^\gamma < 2.4$ and for jets with $E_T^{jet} > 4.5$ GeV and $-1.3 < \eta^{jet} < 2.3$ using $\mathcal{L} = 340$ pb^{-1}



- Comparison to calculations:
  - $\longrightarrow$ LZ and FGH give a reasonable description of the cross sections in E_T^γ and E_T^{jet}
  - $\longrightarrow$ both show deficits in the shape in η^{jet}
  - $\longrightarrow$ FGH too low for $\eta^\gamma < 0.2$

Prompt-photons + Jets (II)



- Variables describing the transverse correlation between the photon and the jet: $\Delta\Phi$ and $p_\perp$

$\longrightarrow$ sensitive to higher-order gluon emission

- Phase space divided into regions dominated by resolved/direct ($x_\gamma^{LO} < 0.8$, $x_\gamma^{LO} > 0.8$)

$\longrightarrow$ estimator momentum fraction parton from γ

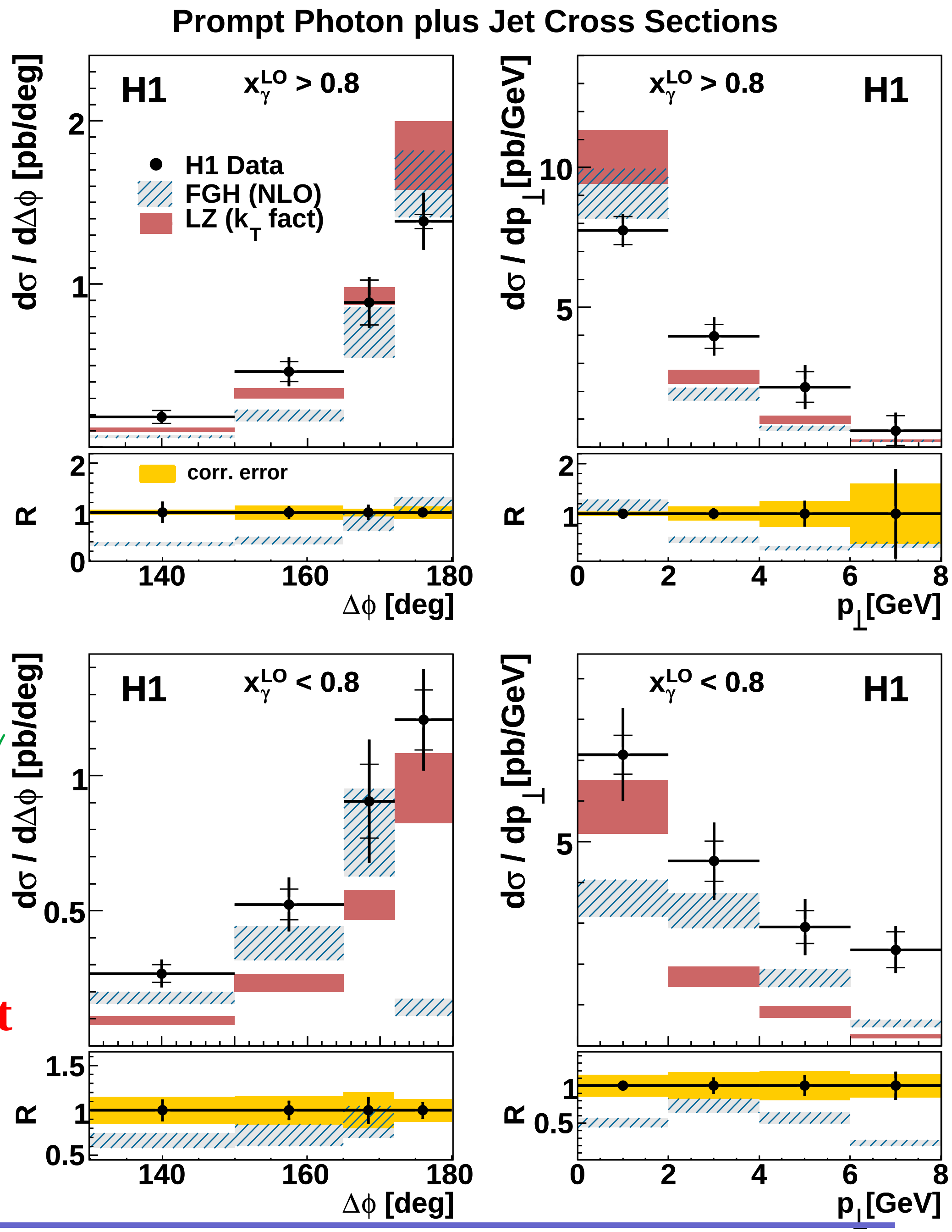
$$x_\gamma^{LO} = E_T^\gamma(e^{-\eta^{jet}} + e^{-\eta^\gamma})/(2yE_e)$$

$\Rightarrow$ Significant fraction of events with a topology which is NOT back-to-back

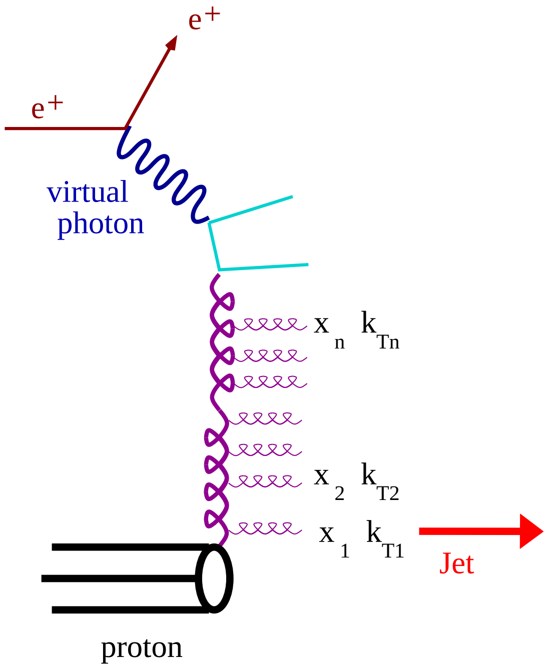
$\Rightarrow$ Harder $p_\perp$ spectrum in resolved than in direct

$\Rightarrow$ More decorrelation in the data than in theory

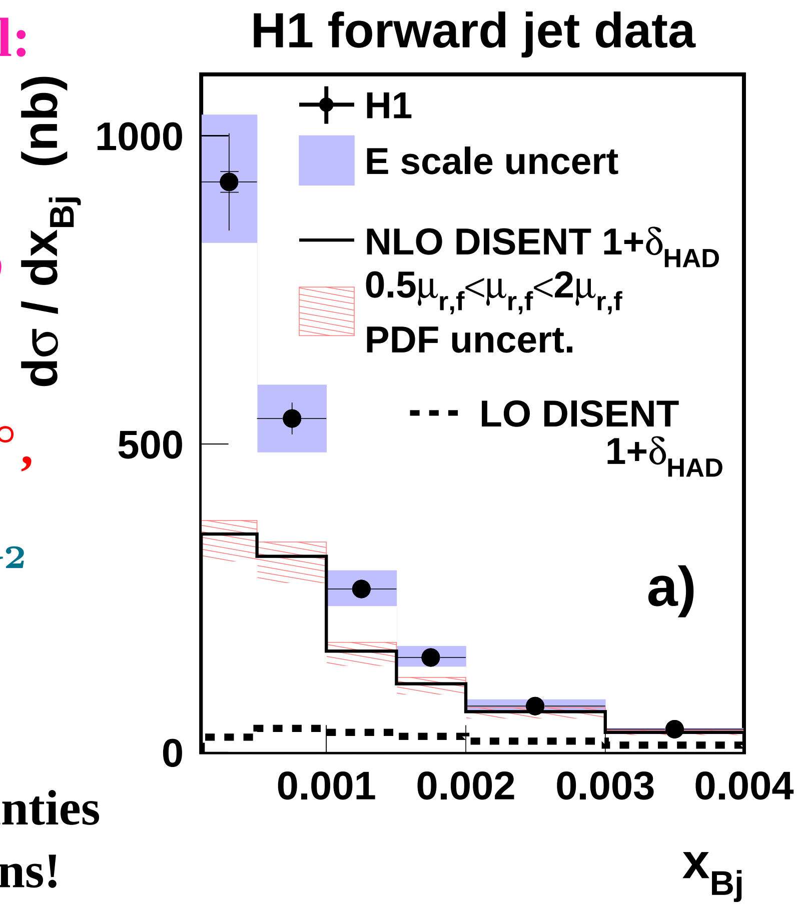
Challenge to theory!



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 $k_{T1} \sim Q$



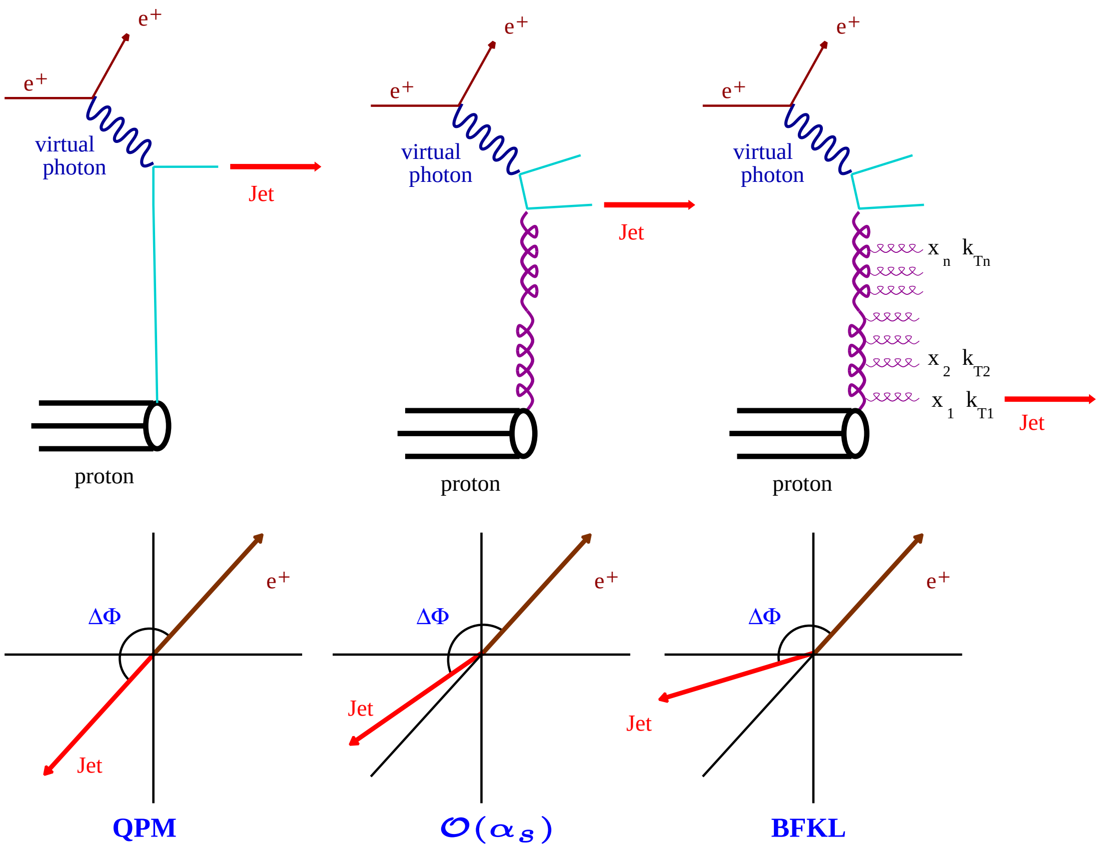
- Measurement of the differential cross section $d\sigma/dx$ for jet production with $p_{t,jet} > 3.5$ GeV, $7^\circ < \theta_{\rm jet} < 20^\circ$, $0.5 < p_{t,jet}^2/Q^2 < 2$ and $x_{jet} = E_{jet}/E_p > 0.035$ in the region $10^{-4} < x < 4 \cdot 10^{-3}$ and $5 < Q^2 < 85$ GeV^2

- Strong rise towards low x is observed

$\longrightarrow$ NLO QCD (DGLAP) lies well below the data at low x

$\longrightarrow$ big jump from LO to NLO $\Rightarrow$ Large theoretical uncertainties (higher-orders) in pQCD calculations prevent firm conclusions!

Azimuthal correlations between the scattered positron and forward jets



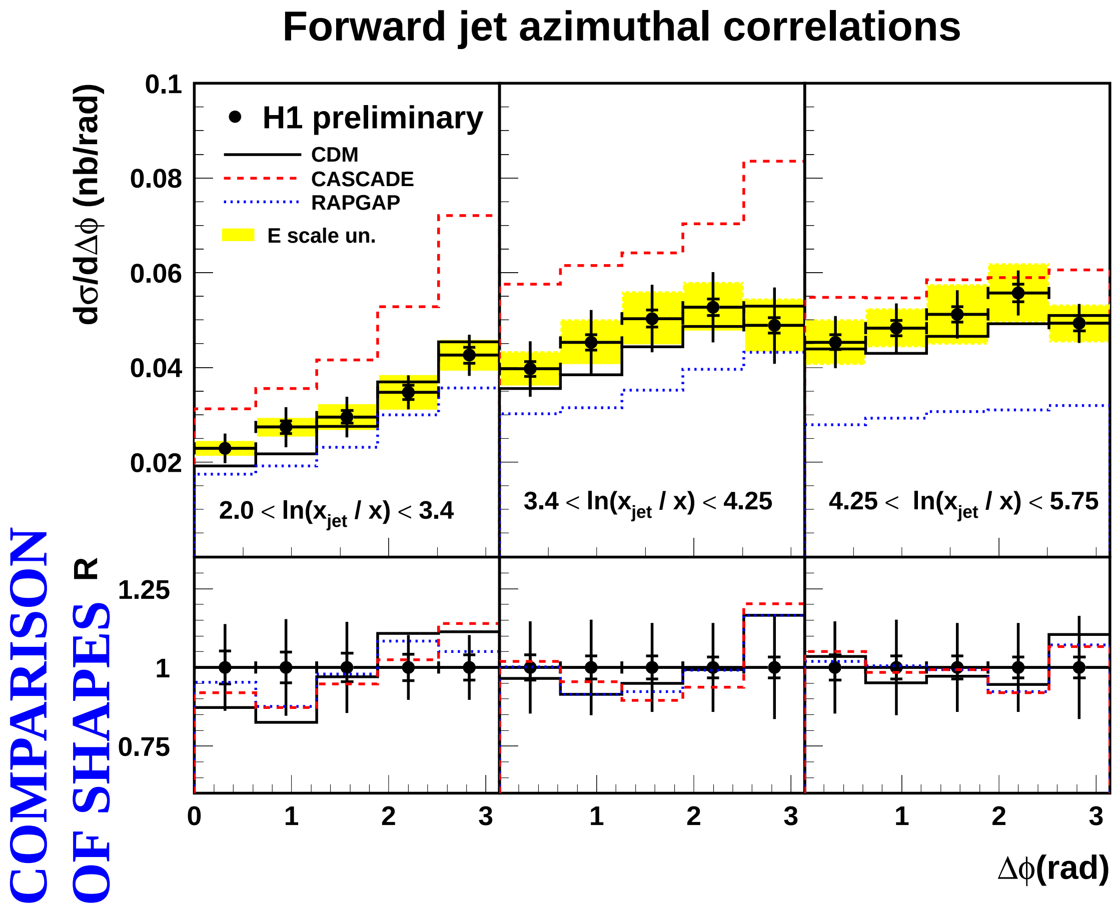
- **Quark Parton Model:**
  $\rightarrow \Delta\Phi = \pi$
- **$\mathcal{O}(\alpha_s)$ corrections:**
  $\rightarrow \Delta\Phi \leq \pi$ **(decorrelation)**
- **BFKL-induced effects:**
  $\rightarrow \Delta\Phi \leq \pi$ **(stronger decorrelation)**
  $\rightarrow$ **stronger decorrelation as x_{jet}/x increases**

- **Jets are reconstructed using the inclusive k_T algorithm in the Breit frame and boosted back into the LAB: $7^\circ < \theta_{jet} < 20^\circ$, $p_{t,jet} > 6$ GeV and $x_{jet} = E_{jet}/E_p >$0.035**

$\rightarrow$ **kinematic region: $5 < Q^2 < 85$ GeV^2, $0.1 < y < 0.7$, $10^{-4} < x < 4 \cdot 10^{-3}$**

$\rightarrow$ **suppression of DGLAP evolution: $0.5 < p^2_{t,jet}/Q^2 < 6$**

Azimuthal correlations between the scattered positron and forward jets



- Measurement of the differential cross-section $d\sigma/d\Delta\phi$ as a function of $\Delta\phi$, the difference in azimuth between the scattered positron and the most forward jet in three regions of $\ln(x_{jet}/x)$ (increasing lengths for BFKL evolution)

- Comparison to MC predictions:

$\rightarrow$ RAPGAP (DGLAP evolution)

$\rightarrow$ CDM (no k_T ordering; BFKL-like)

$\rightarrow$ CASCADE (CCFM evolution)

$\Rightarrow$ A stronger decorrelation in $\Delta\phi$ as $\ln(x_{jet}/x)$ increases is observed!

$\rightarrow$ The models predict similar shapes (!), all of them consistent with the data

$\rightarrow$ Significant differences in normalization between the models

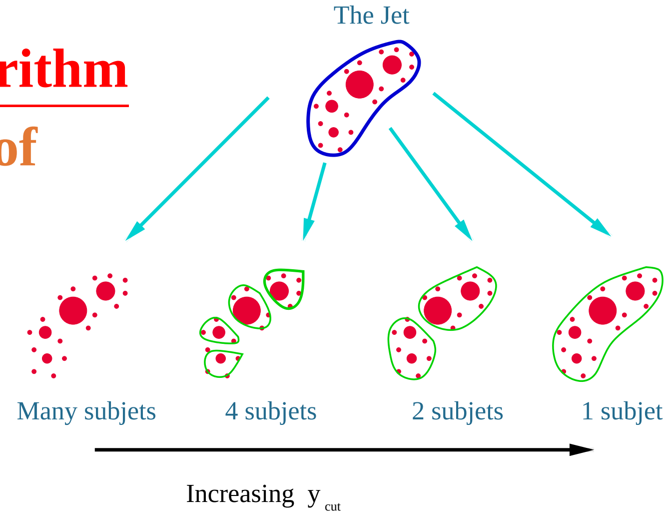
$\Rightarrow$ Comparison to higher-order QCD calculations needed to draw firm conclusions

Subjets

⇒ **Understanding jet substructure is becoming more and more relevant for boosted systems such as hadronic top decays, Higgs and supersymmetric final states at the LHC**

- **Subjets are resolved within a jet by reapplying the k_T algorithm on all the particles belonging to the jet until for every pair of particles the distance betwen clusters is above**

$$d_{cut} = y_{cut} \cdot (E_T^{jet})^2$$

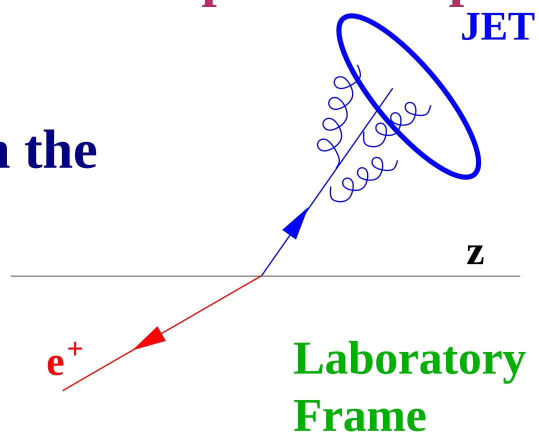


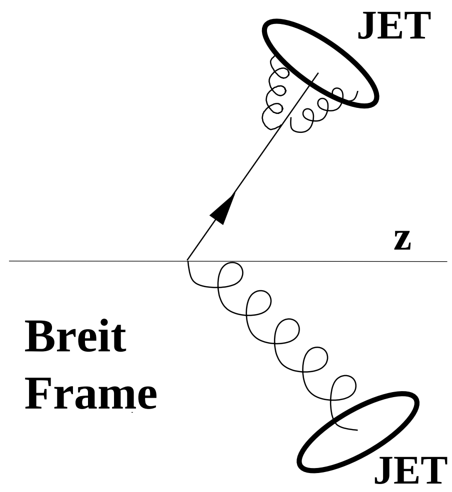
⟶ **all remaining clusters are called subjets**

⟶ **the subjet multiplicity depends upon y_{cut}**

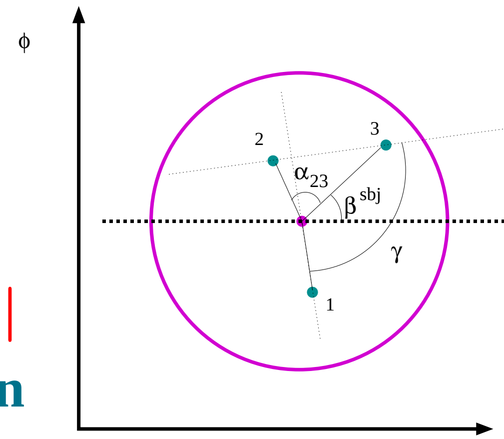
⟶ **the distributions of subjets are sensitive to the pattern of parton radiation**

- **Jets (and subjets) are reconstructed in the laboratory frame since NLO QCD calculations are possible.**
  At $\mathcal{O}(\alpha_s^3)$, up to 4 partons can be in the same jet (not possible in the Breit frame)





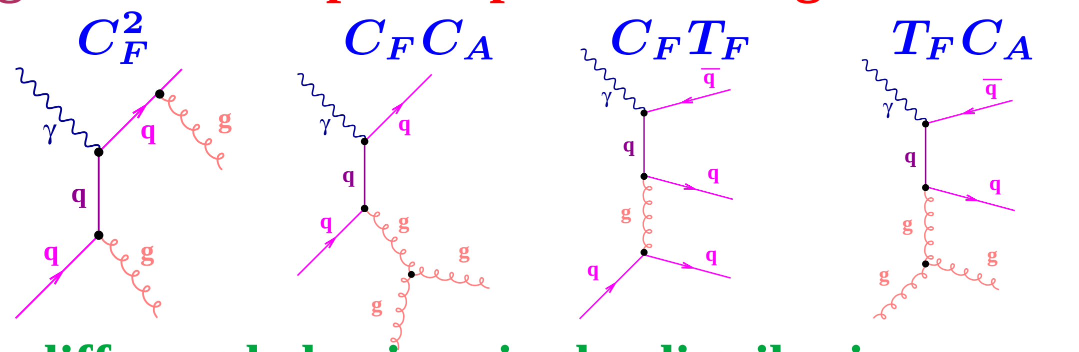
Three-Subjet Variables in NC DIS

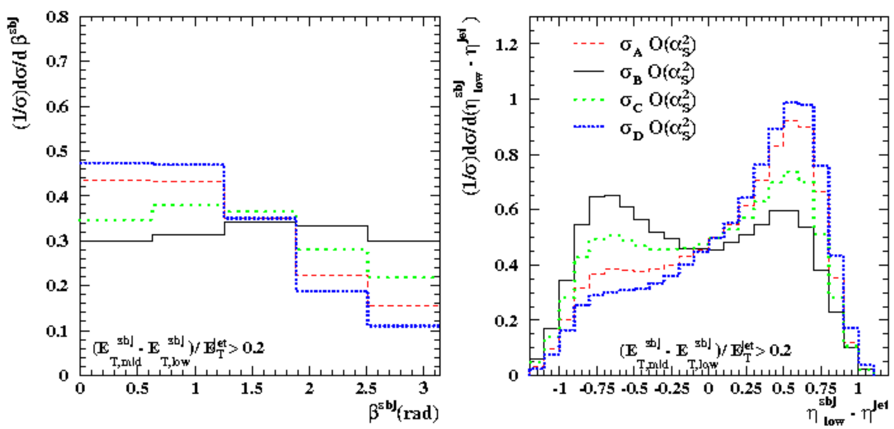


- The pattern of QCD radiation from a primary parton has been studied by measuring normalised cross sections as functions of the subjet variables E_T^{sbj}/E_T^{jet} , $\eta^{sbj}-\eta^{jet}$, $|\phi^{sbj}-\phi^{jet}|$ and the angle β^{sbj} in the η-ϕ plane of the laboratory frame between the subjet with lowest E_T and the proton beam direction, as viewed from the jet centre
- Predicted cross section at $\mathcal{O}(\alpha_s^2)$ for three-subjet production (colour configurations)

$$\sigma_{ep\to 3\,\text{subjets}} = C_F^2\cdot\sigma_A + C_F C_A\cdot\sigma_B + C_F T_F\cdot\sigma_C + T_F C_A\cdot\sigma_D$$

- Since the couplings qqg and ggg have different spin structures, the color factors give rise to a specific pattern of angular correlations between the subjets





$\longrightarrow$ different behaviour in the distributions

$\longrightarrow$ Relative contributions predicted by SU(3):

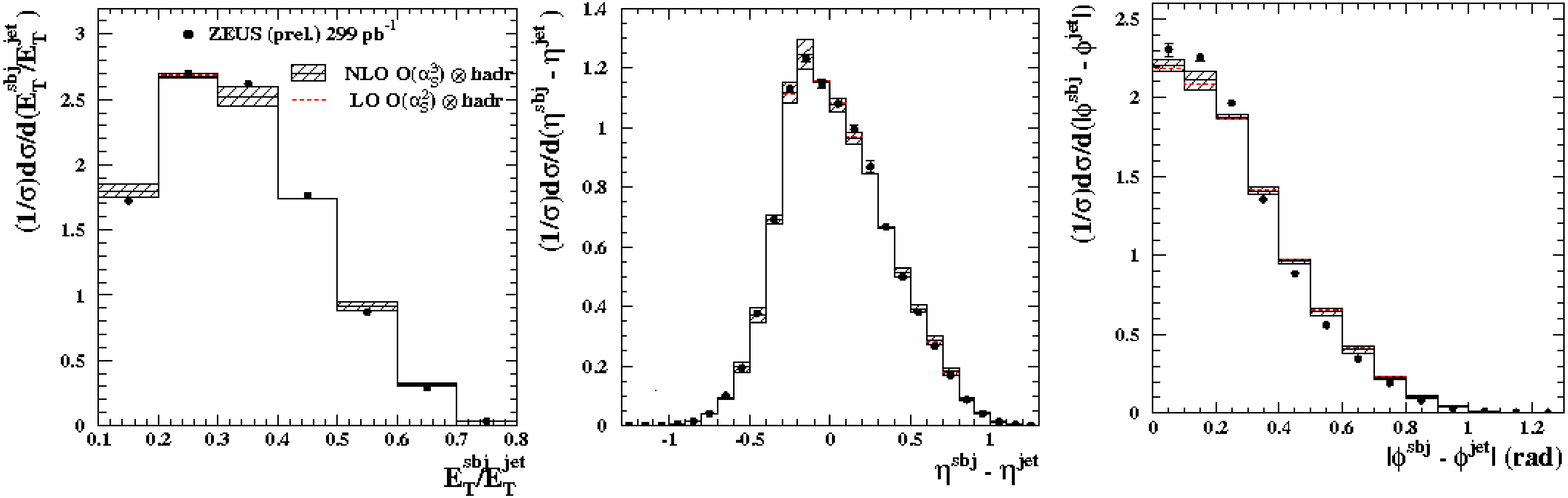
A(C_F^2): 54-57%, B($C_F C_A$): 14-15%, C($C_F T_F$): 21-23%, D($T_F C_A$): 8-9%

Measurements of Three-Subjet Distributions in NC DIS (I)

- **Measurements of the normalised cross sections for three-subjet production as functions of E_T^{sbj}/E_T^{jet}, $\eta^{sbj} - \eta^{jet}$ and $|\phi^{sbj} - \phi^{jet}|$ in NC DIS for $Q^2 > 125$ GeV^2 for jets with $E_T^{jet} > 14$ GeV and $-1 < \eta^{jet} < 2.5$ and exactly THREE subjets at $y_{cut} = 0.01$**

$\rightarrow \mathcal{L} = 299$ pb^{-1} $\Rightarrow$ 80 000 jets

LO and NLO QCD calculations using NLOJET++



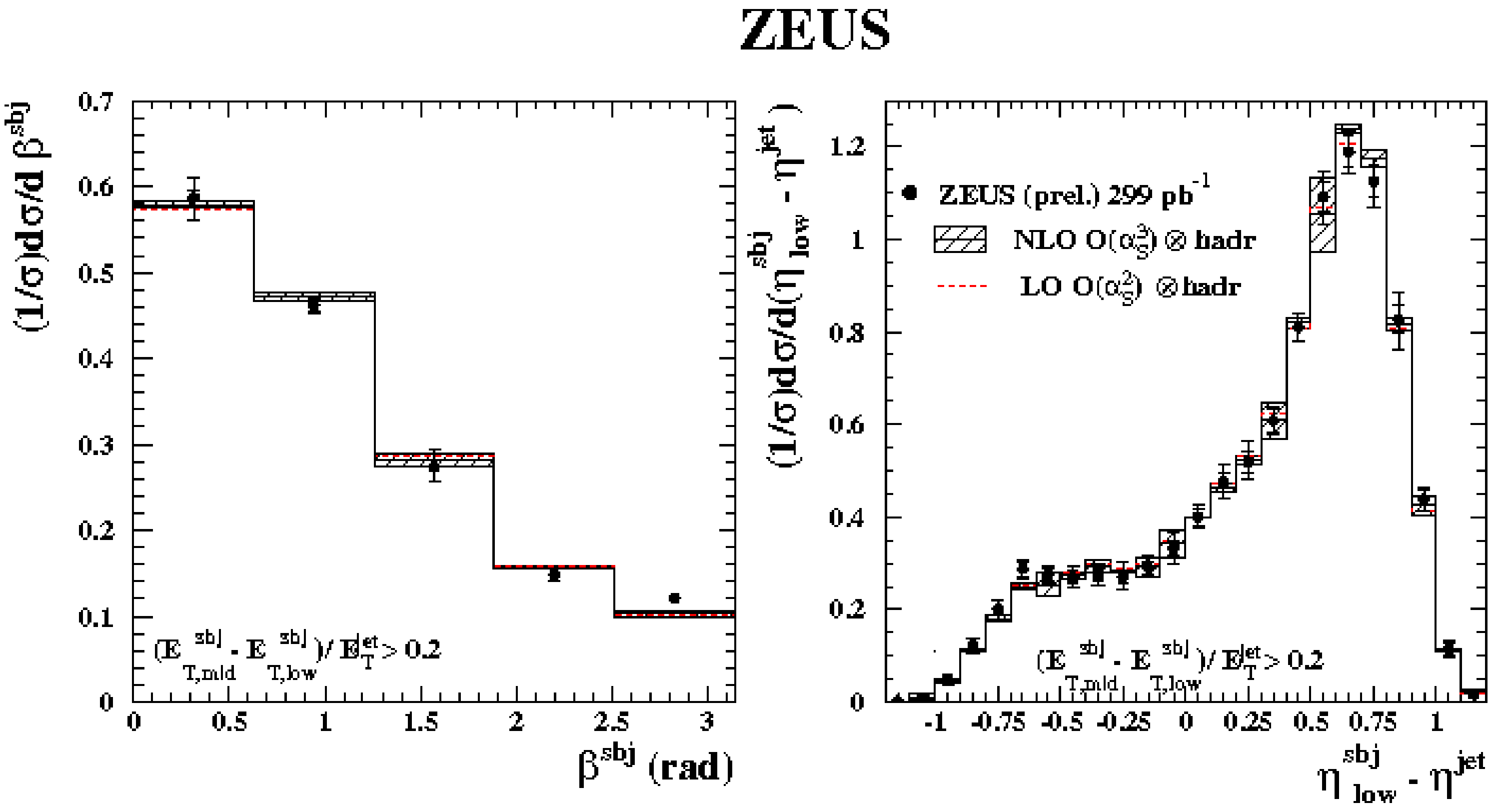
$\rightarrow$ Good description of the measured distributions in E_T^{sbj}/E_T^{jet} and $\eta^{sbj} - \eta^{jet}$ by NLO

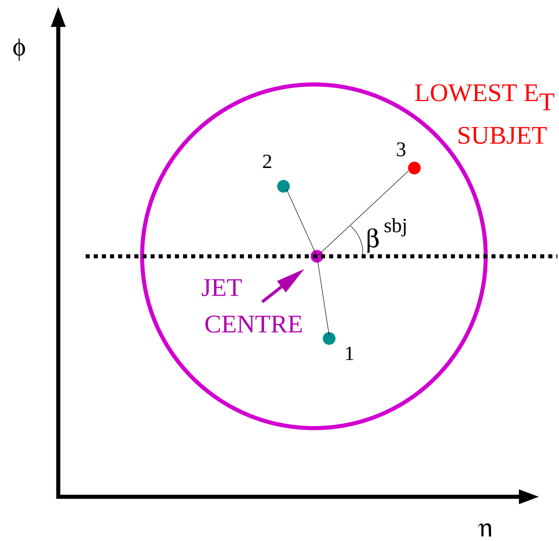
$\rightarrow$ Reasonable description of the measured distribution in $|\phi^{sbj} - \phi^{jet}|$ by NLO

Measurements of Three-Subjet Distributions in NC DIS (II)

- Measurements of the normalised cross sections for three-subjet production as functions of β^{sbj} and $\eta^{sbj}_{low} - \eta^{jet}$ vs LO and NLO QCD calculations

  → Additional cut to "separate" lowest-E_T subjet: $(E^{sbj}_{T,mid} - E^{sbj}_{T,low})/E^{jet}_T > 0.2$

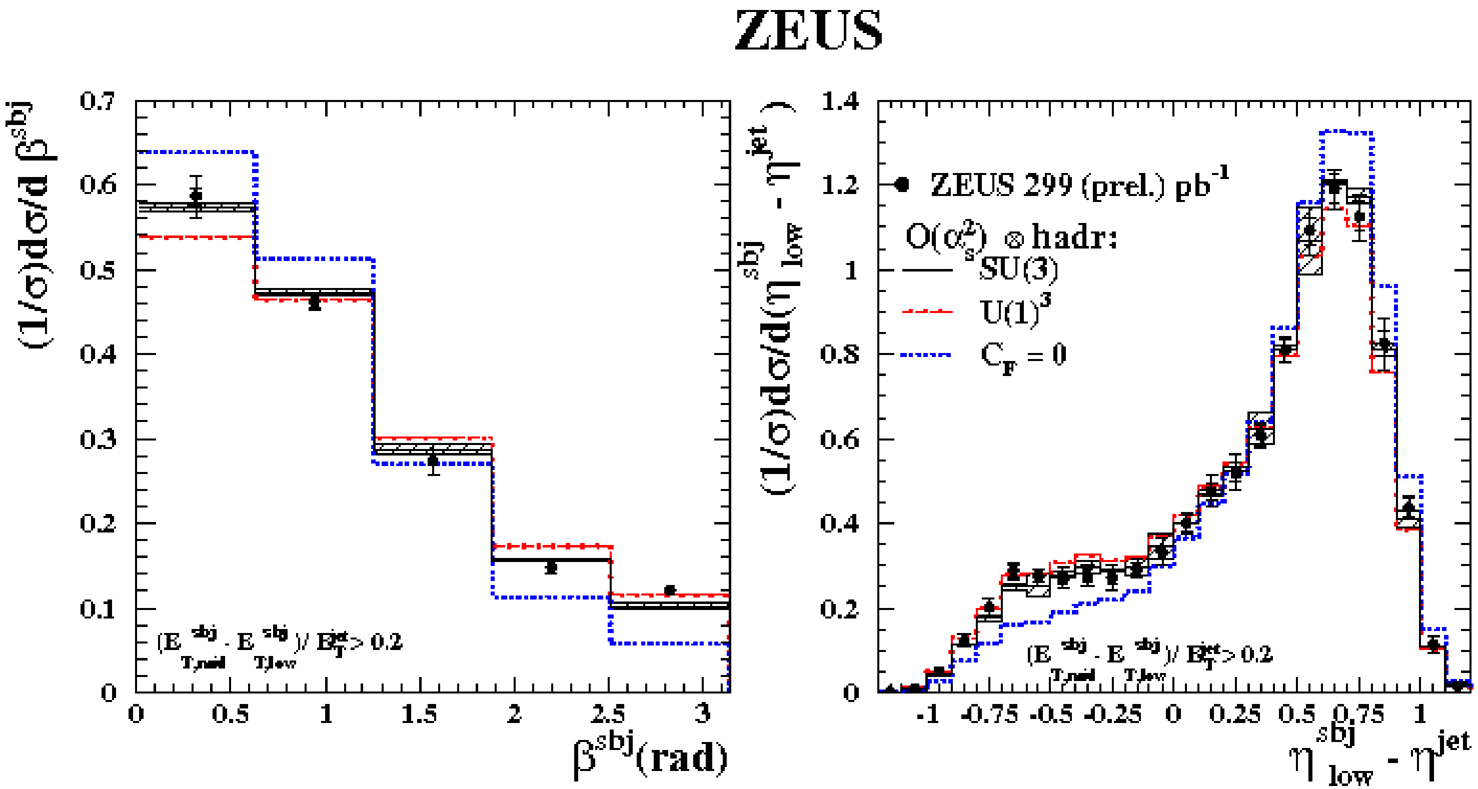


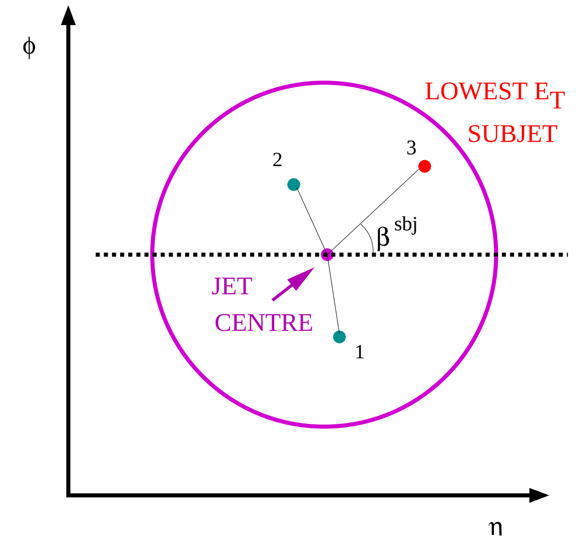


→ Good description of the measured distributions by NLO QCD

Measurements of Three-Subjet Distributions in NC DIS (III)

- Measurements of the normalised cross sections for three-subjet production as functions of β^{sbj} and $\eta_{low}^{sbj} - \eta^{jet}$ vs LO calculations assuming different gauge symmetry groups



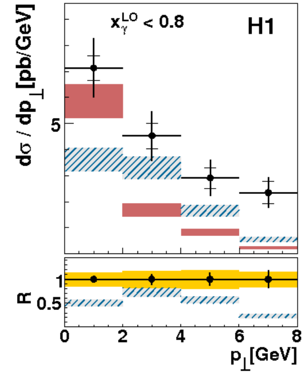


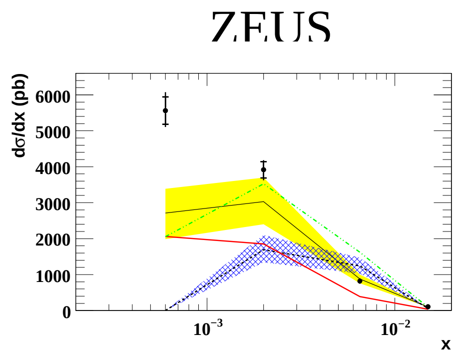
→ The data disfavours the predictions based on $C_F = 0$

→ U(1)^3 vs SU(3): some differences are observed in the β^{sbj} distribution

→ The predictions of SU(3) describe reasonably well the data

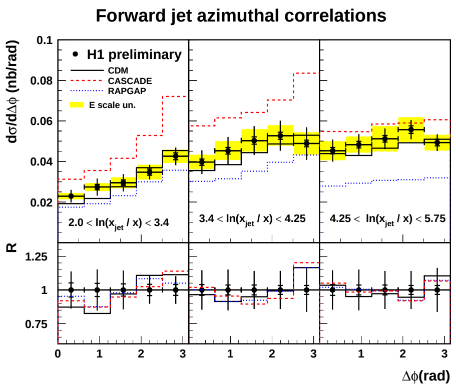
Summary: exploration of parton dynamics at low x and in jet substructure





- Measurements of prompt-γ and prompt-γ+jet in NC DIS and photoproduction $\longrightarrow$ Theoretical approaches fail in some regions, particularly at low x and correlations in the transverse plane

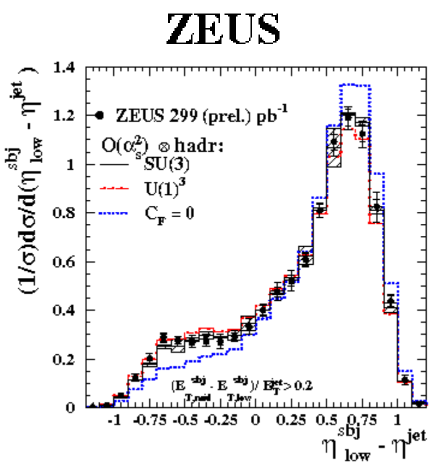
$\longrightarrow$ Challenge to theory



- Measurements of azimuthal correlations between the scattered positron and the most forward jet at low x

$\longrightarrow$ A stronger decorrelation in $\Delta\phi$ as $\ln(x_{jet}/x)$ increases is observed!

$\longrightarrow$ CCFM, DGLAP and CDM predict similar shapes, all consistent with the data $\Rightarrow$ higher-order QCD calculations needed!



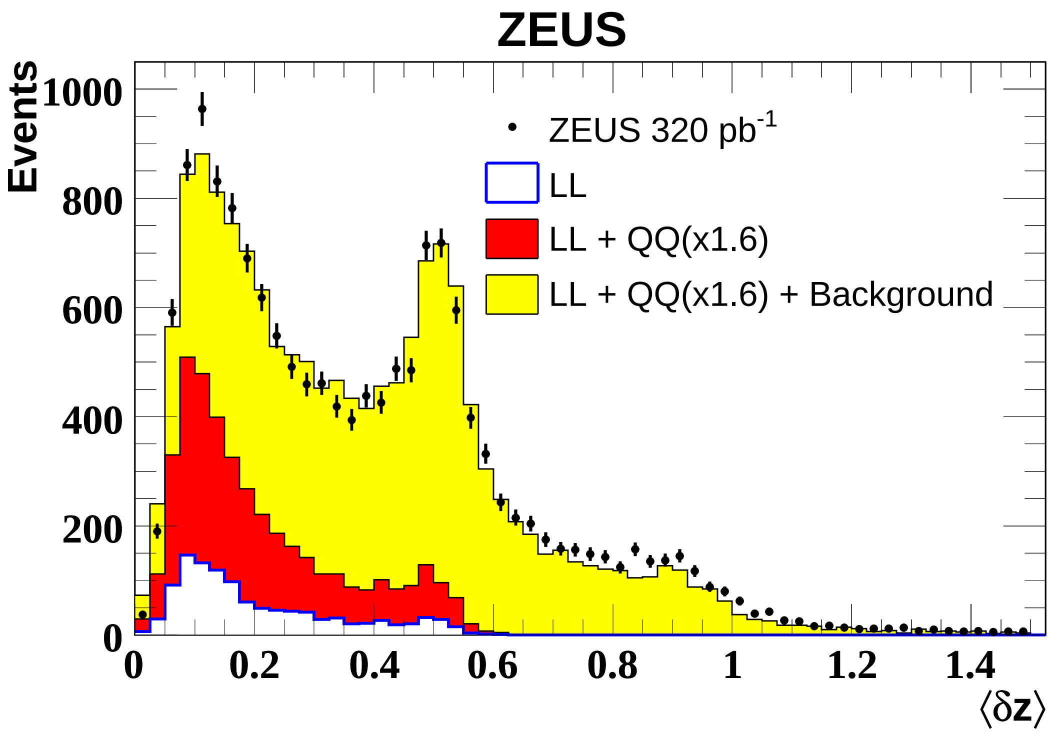
- Measurements of three-subjet production in NC DIS for jets with $E_T^{jet} > 14$ GeV using $\mathcal{L} = 299$ pb^{-1}

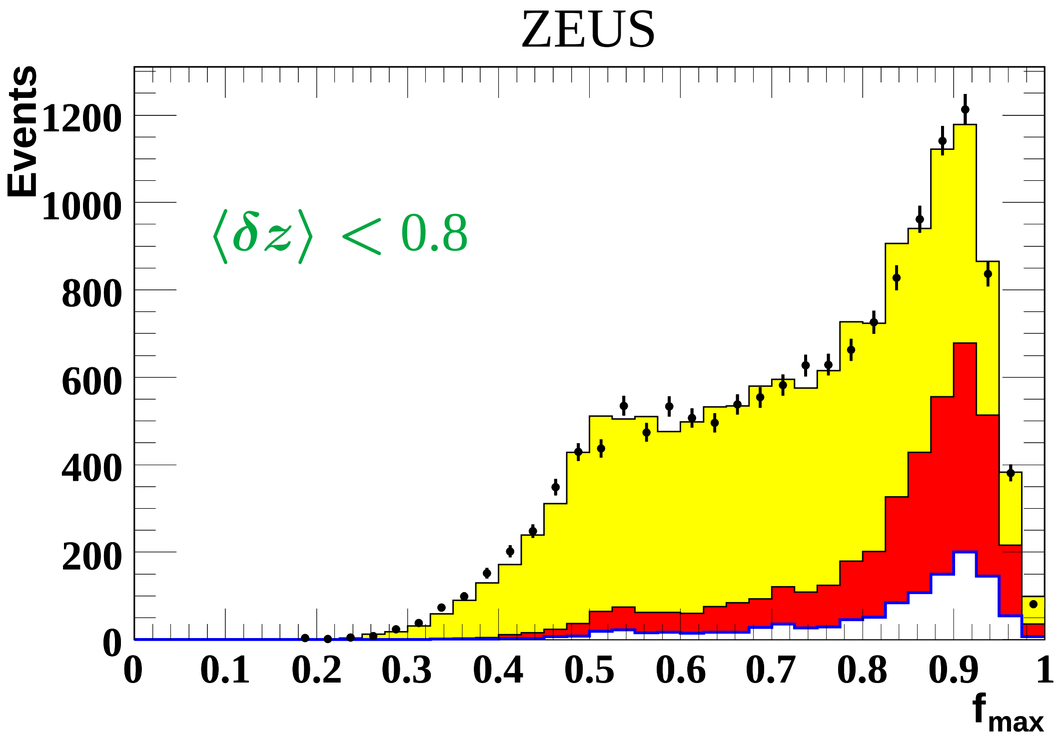
$\longrightarrow$ the pattern of QCD radiation as implemented in the NLO calculations reproduces the measured subjet distributions

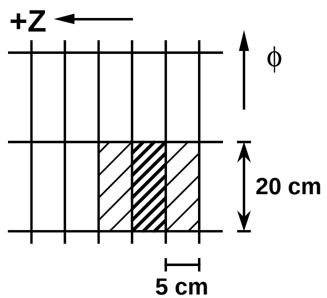
$\longrightarrow$ the subjet distributions are sensitive to the colour configurations and are found to be consistent with the predictions of SU(3)

Backup

Extraction of the isolated-photon signal







- Variable $\langle \delta z \rangle$: width of the cluster in the barrel EMC (BEMC)

  $\langle \delta z \rangle = \sum_i E_i |Z_i - Z_{\text{cluster}}| / (w_{\text{cell}} \sum_i E_i)$ (in units of 5 cm)

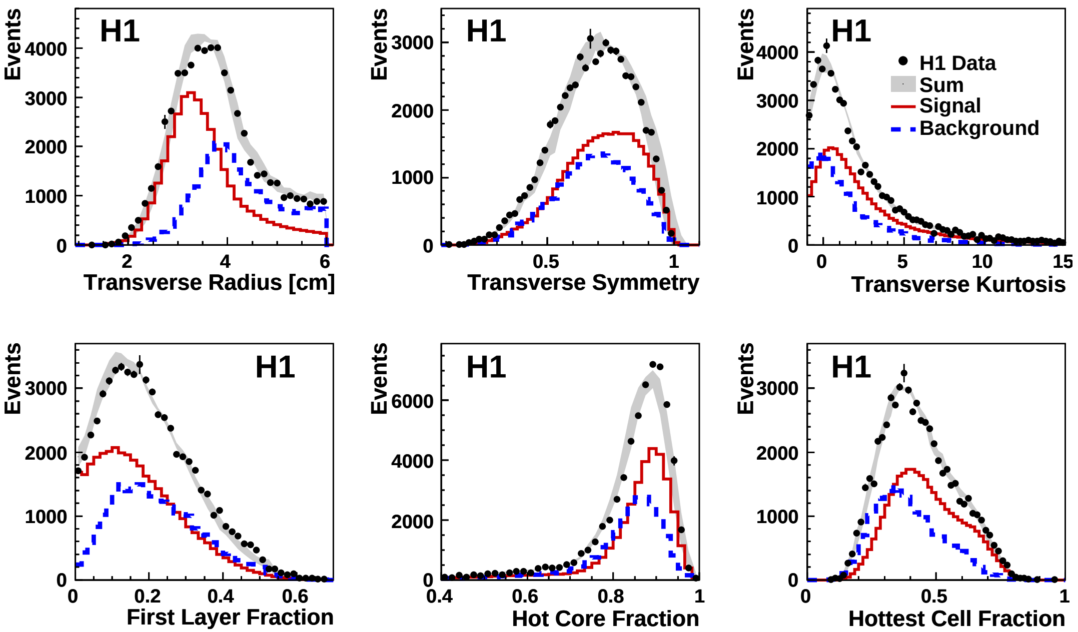
  $\rightarrow$ Peaks due to γ's and π^o's clearly visible

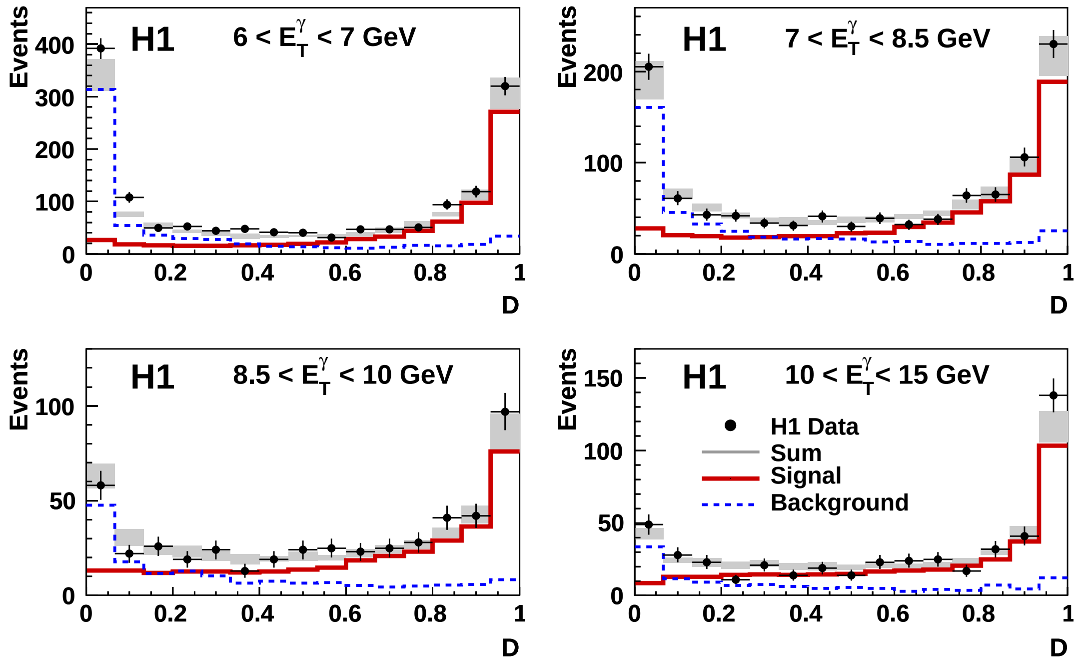
- f_{max}: ratio of hottest BEMC-cell energy to candidate total-BEMC energy

- Extraction of signal by a χ^2 fit to the $\langle \delta z \rangle$ distribution in each cross-section bin

Extraction of the prompt-photon signal

- Photon candidates: compact EM clusters in calorimeter; no associated track.
- Jets are reconstructed applying the k_T-cluster algorithm with $D = 1$ over all final-state particles, including photon candidates$\longrightarrow$ 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 shower shapes
- Probability density functions are defined and a discriminator is formed
- A regularised unfolding procedure is used to determine the corrected variables and the fractions of signal and background

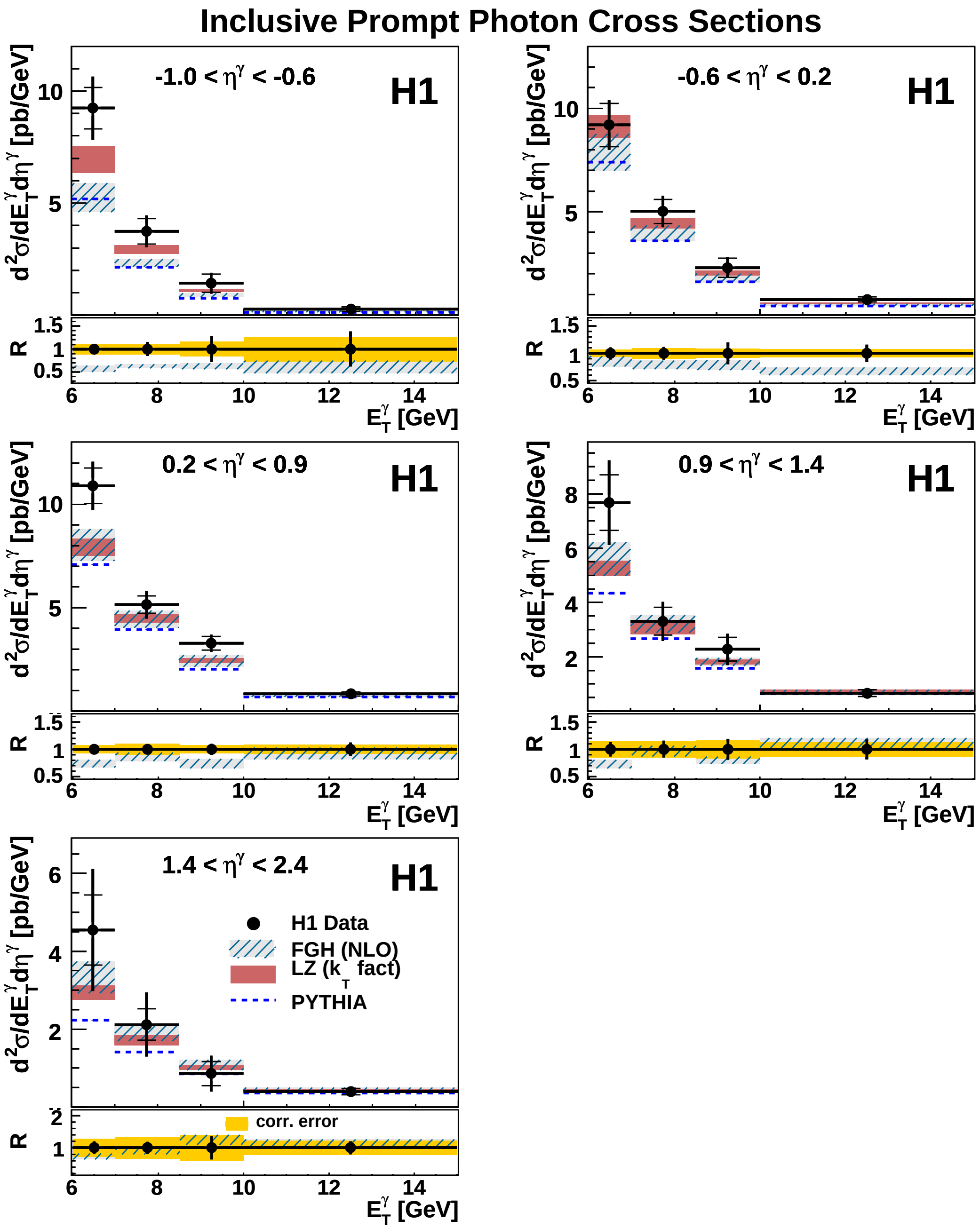




Inclusive prompt-photons (II)

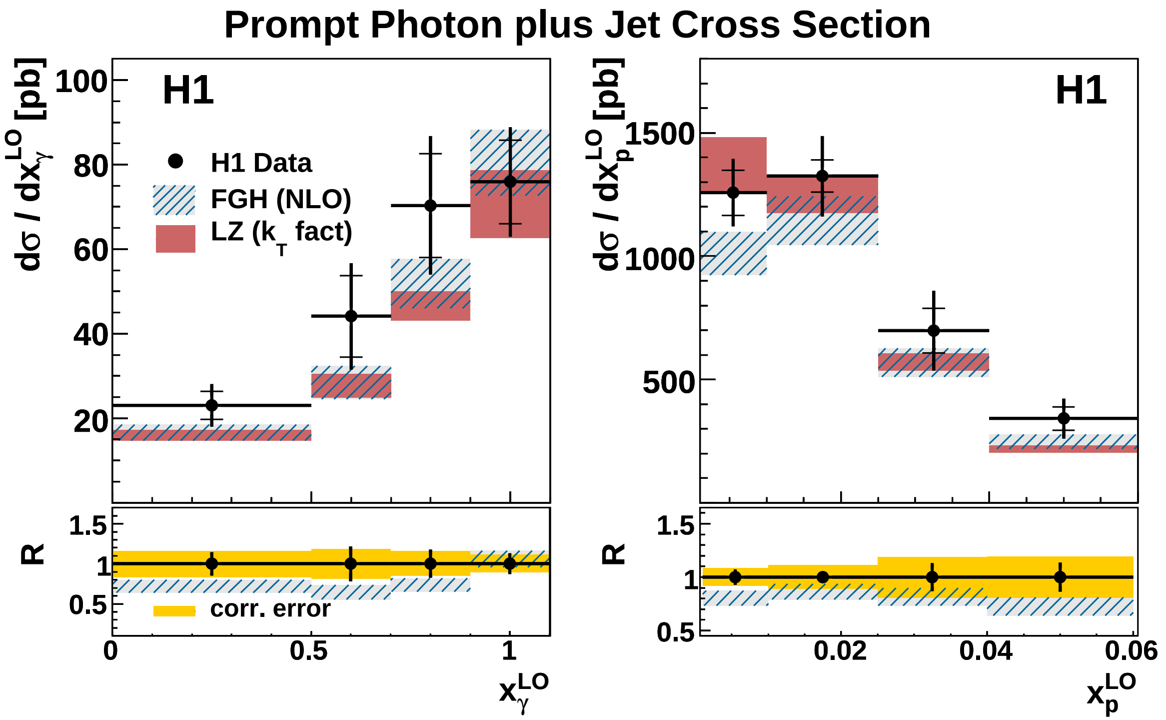
- Measurement of inclusive prompt photon production in the kinematic region defined by $Q^2 < 1$ GeV^2 and $0.1 < y < 0.7$ for photons with $E_T^\gamma / E_T^{\gamma-\text{jet}} > 0.9$, $6 < E_T^\gamma < 15$ GeV and $-1 < \eta^\gamma < 2.4$ using $\mathcal{L} = 340$ pb^{-1}

- Comparison to calculations:
  $\rightarrow$ LZ provides a reasonable description of the data except for the lowest E_T^γ bin in the central region ($0.2 < \eta^\gamma < 0.9$)
  $\rightarrow$ FGH underestimates the data in the central and backward regions ($\eta^\gamma < -0.6$)



Prompt-photons + Jets (III)

- Measurement of prompt photon+jet production in the kinematic region defined by $Q^2 < 1$ GeV^2 and $0.1 < y < 0.7$ for photons with $E_T^\gamma / E_T^{\gamma-\mathrm{jet}} > 0.9$, $6 < E_T^\gamma < 15$ GeV and $-1 < \eta^\gamma < 2.4$ and for jets with $E_T^{jet} > 4.5$ GeV and $-1.3 < \eta^{jet} < 2.3$ using $\mathcal{L} = 340$ pb^{-1}



- Estimators of the momentum fractions of the partons in the incoming photon and proton:

$\longrightarrow$ parton in the incoming photon: $x_\gamma^{LO} = E_T^\gamma (e^{-\eta^{jet}} + e^{-\eta^\gamma})/(2yE_e)$

$\longrightarrow$ parton in the incoming proton: $x_p^{LO} = E_T^\gamma (e^{\eta^{jet}} + e^{\eta^\gamma})/(2E_p)$

- LZ and FGH describe the data within errors

Measurements of Three-Subjet Distributions in NC DIS

- Measurements of the normalised cross sections in NC DIS for $Q^2 > 125$ GeV^2:

$\longrightarrow$ Jets with $E_T^{jet} > 14$ GeV and $-1 < \eta^{jet} < 2.5$

$\longrightarrow$ Selected sample of jets: jets with exactly THREE subjets at $y_{cut} = 0.01$

$\longrightarrow$ $\mathcal{L} = 299$ pb^{-1} $\Rightarrow$ 80 000 jets