

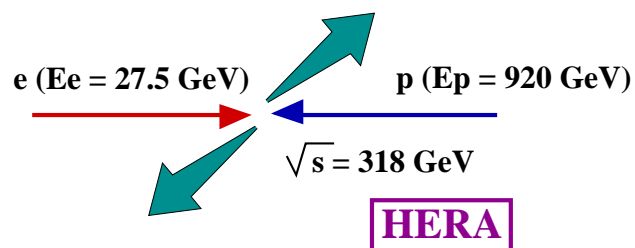
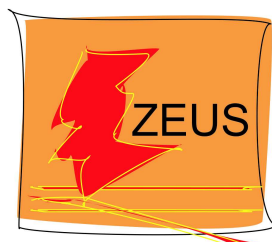
Paris, ICHEP 2010

July 24th, 2010



# Prompt photons, forward jets and subjects at HERA

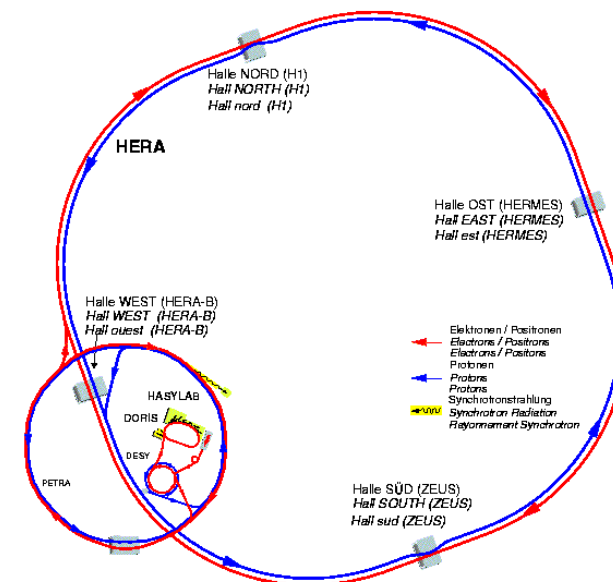
Juan Terrón (Universidad Autónoma de Madrid, Spain)



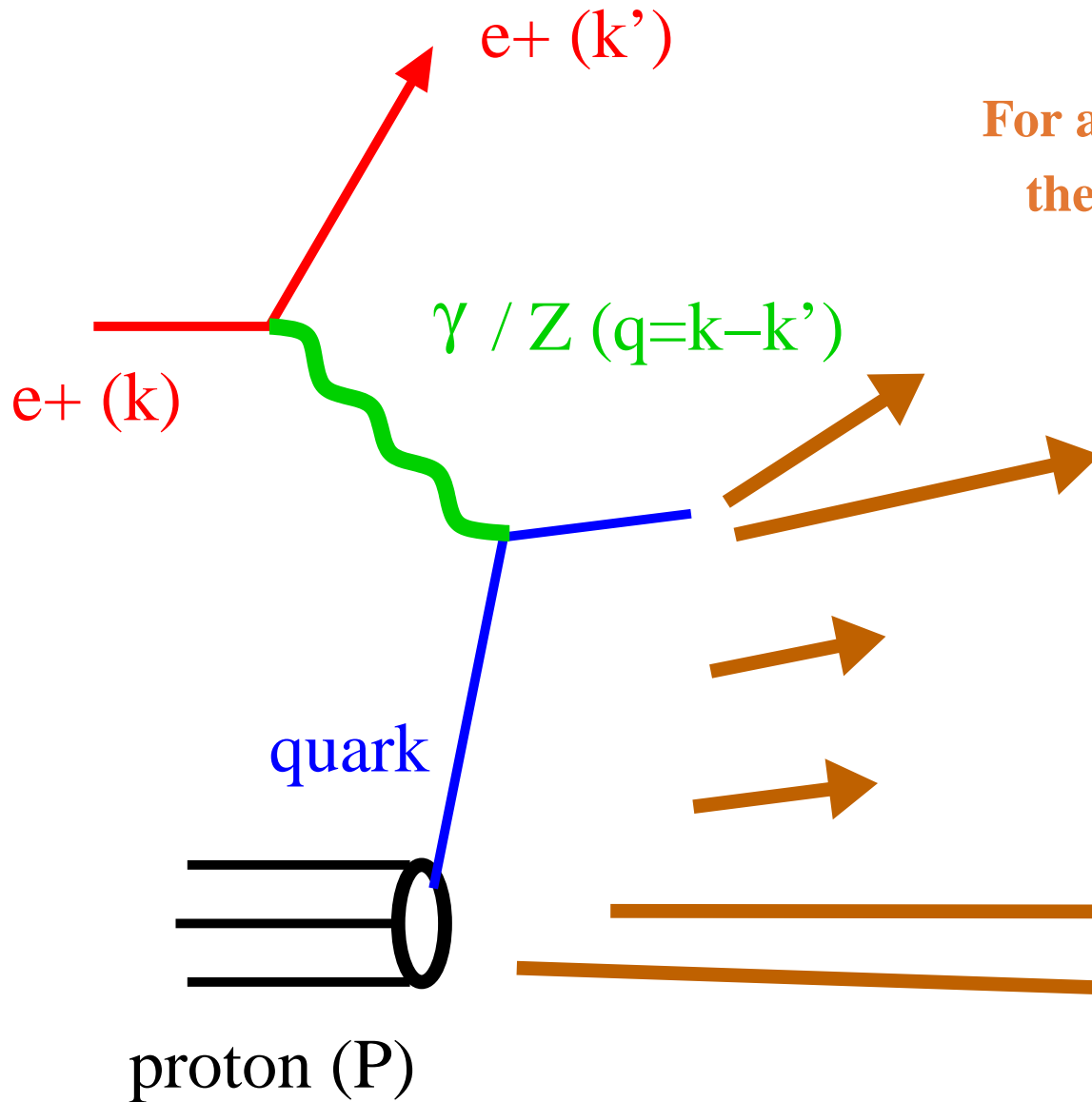
## H1 and ZEUS Collaborations

### ● Outline

- Isolated photons in neutral current DIS  $ep$
- Isolated photons in photoproduction ( $\gamma p$  collisions)
- Forward jet production in NC DIS  $ep$
- 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

$$ep \rightarrow e + X$$

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**

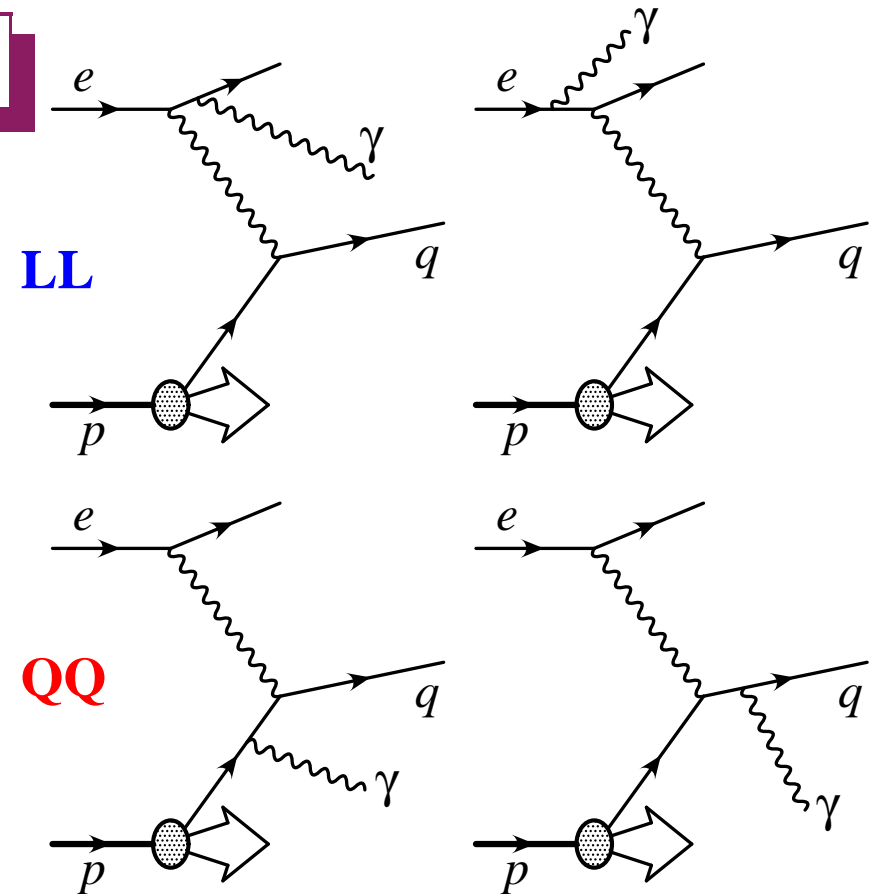
(direct radiation or fragmentation; fragmentation suppressed by isolation requirement)

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

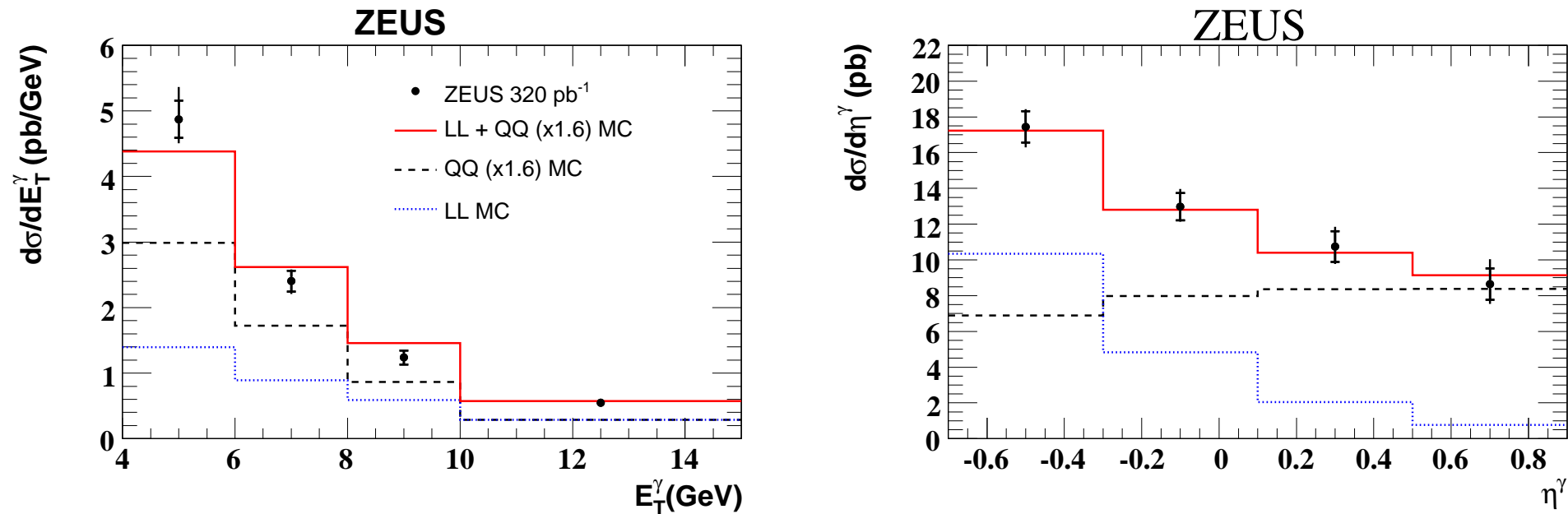
- **Photon candidates: compact EM clusters in calorimeter; no associated track; isolated.**

- 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  $\gamma$**

**should fulfill  $E_T^\gamma / E_T^{\gamma\text{-jet}} > 0.9$  ⇒ Isolated- $\gamma$  signal extracted using shower shapes**



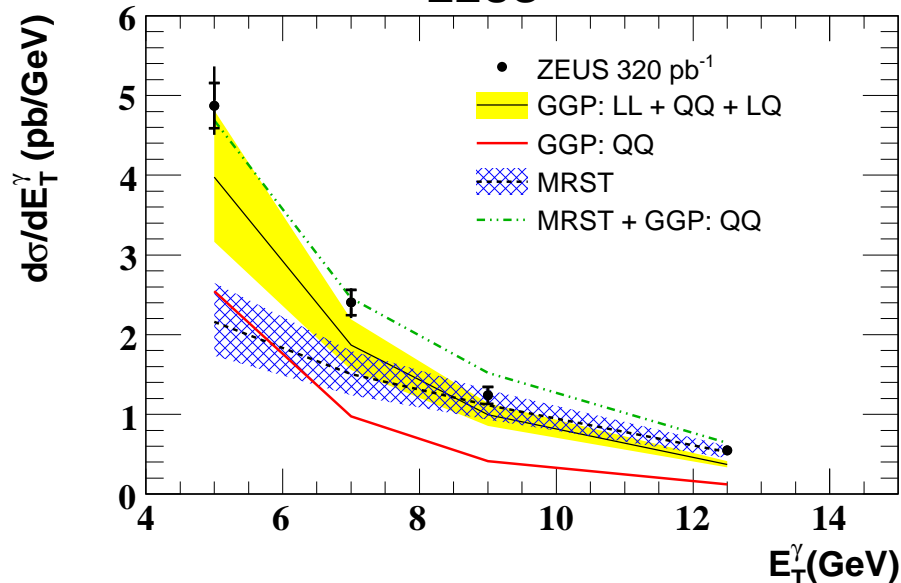
# Measurements of inclusive isolated photons in NC DIS (I)



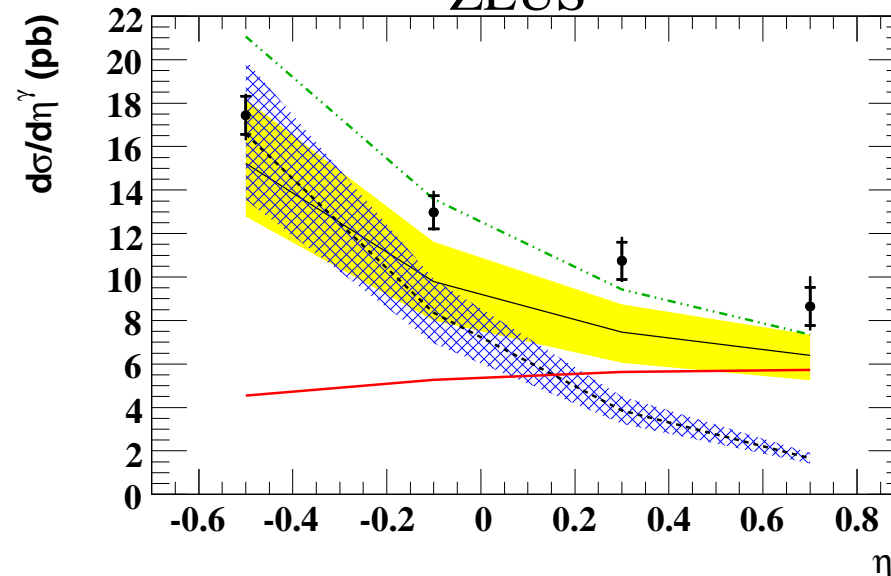
- Measurement of **inclusive isolated photon** production with  $4 < E_T^\gamma < 15$  GeV and  $-0.7 < \eta^\gamma < 0.9$  in the kinematic region defined by  $10 < Q^2 < 350$  GeV<sup>2</sup>,  $W_X > 5$  GeV,  $E'_e > 10$  GeV and  $139.8^\circ < \theta_e < 171.8^\circ$  using  $\mathcal{L} = 320$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

## Measurements of inclusive isolated photons in NC DIS (II)

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- **Comparison to theoretical calculations:**

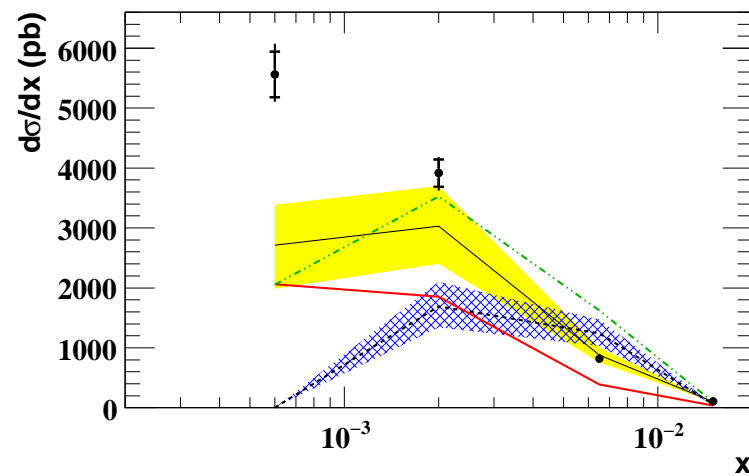
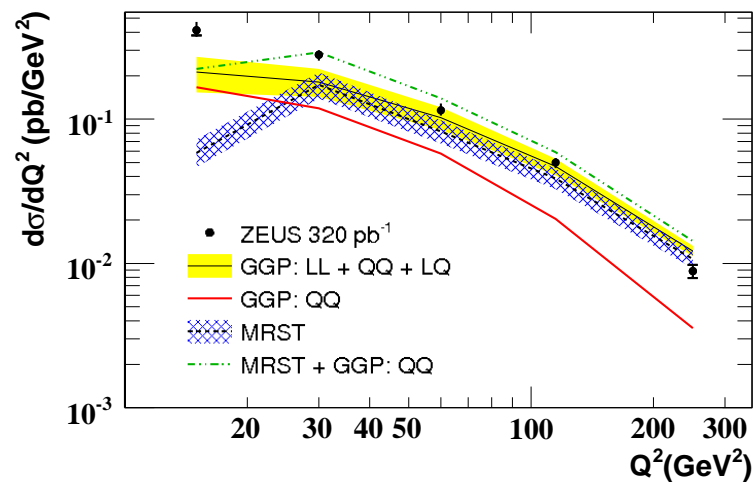
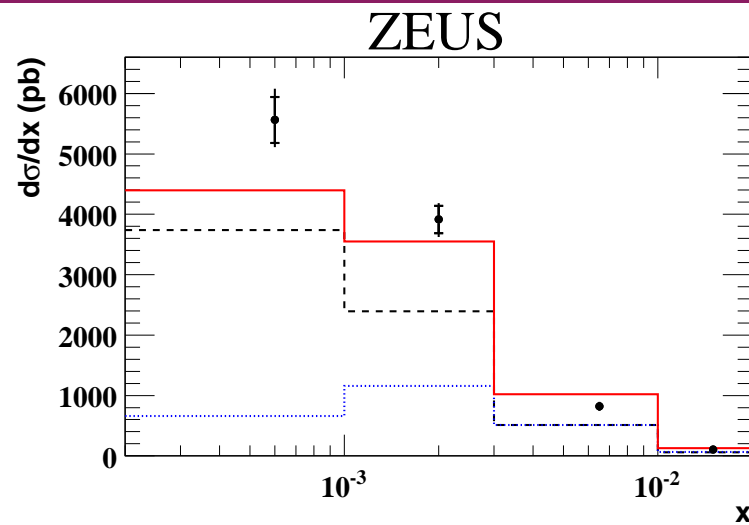
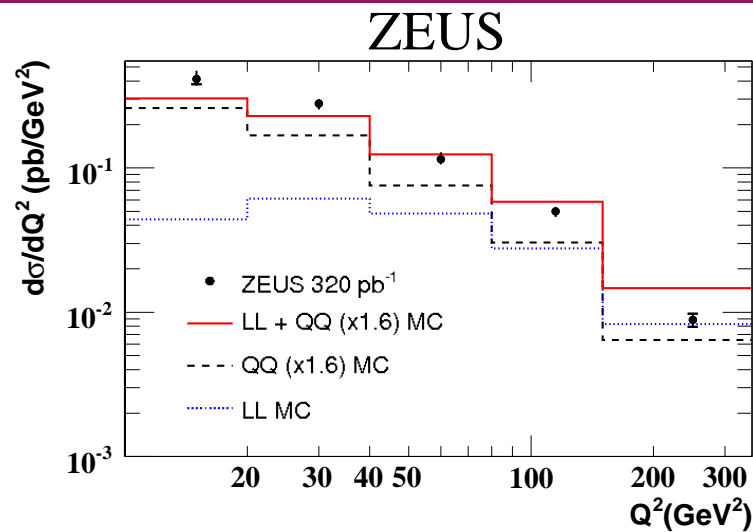
- **GGP (Gehrmann-De Ridder, Gehrmann, Poulsen):**  $\mathcal{O}(\alpha^3)$  calculations of QQ+LL+LQ. The QQ contribution includes both wide-angle emission and fragmentation

⇒ 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. ⇒ below data except at high  $E_T^\gamma$ , backward  $\eta^\gamma$  (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:** ⇒ failure at low  $Q^2$  and low  $x$

**Further theoretical investigations needed!**

# Prompt-photon production in $\gamma p$ interactions

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

- Benchmark for pQCD calculations:

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

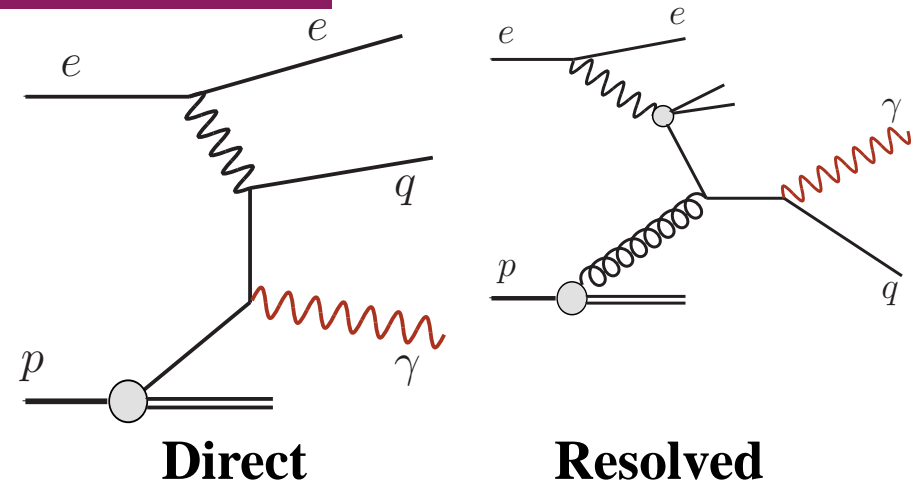
$\rightarrow$  calculations based on  $k_T$ -factorization approach and using unintegrated PDFs; direct and resolved-photon processes included

$\Rightarrow$  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  $\rightarrow$  isolation condition: the jet containing the  $\gamma$

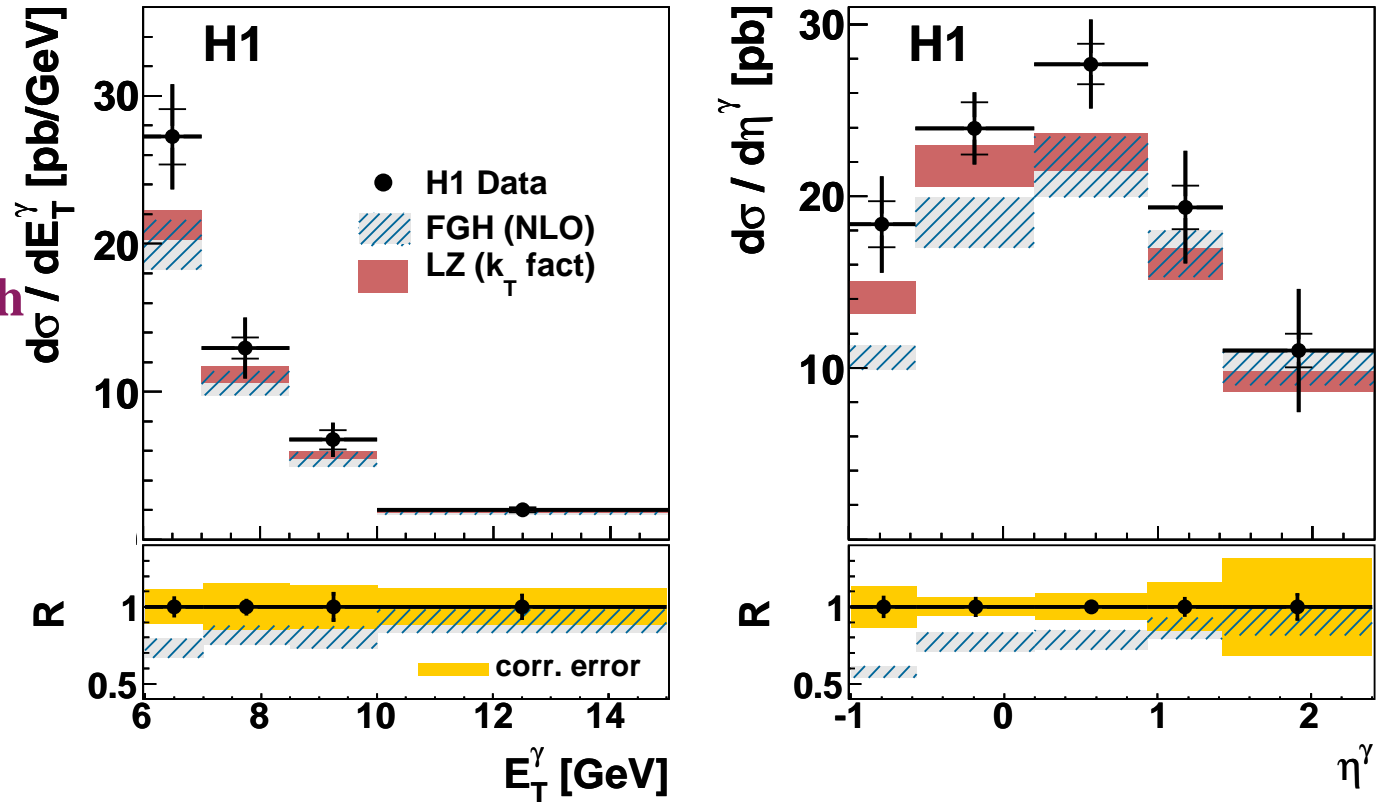
should fulfill  $E_T^\gamma / E_T^{\gamma\text{-jet}} > 0.9 \Rightarrow$  Isolated- $\gamma$  signal extracted using shower shapes



# Measurements of inclusive prompt-photon production

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

Inclusive Prompt Photon Cross Sections



- Comparison to calculations:

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

→ Data above pQCD, most significantly at low  $E_T^\gamma$

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

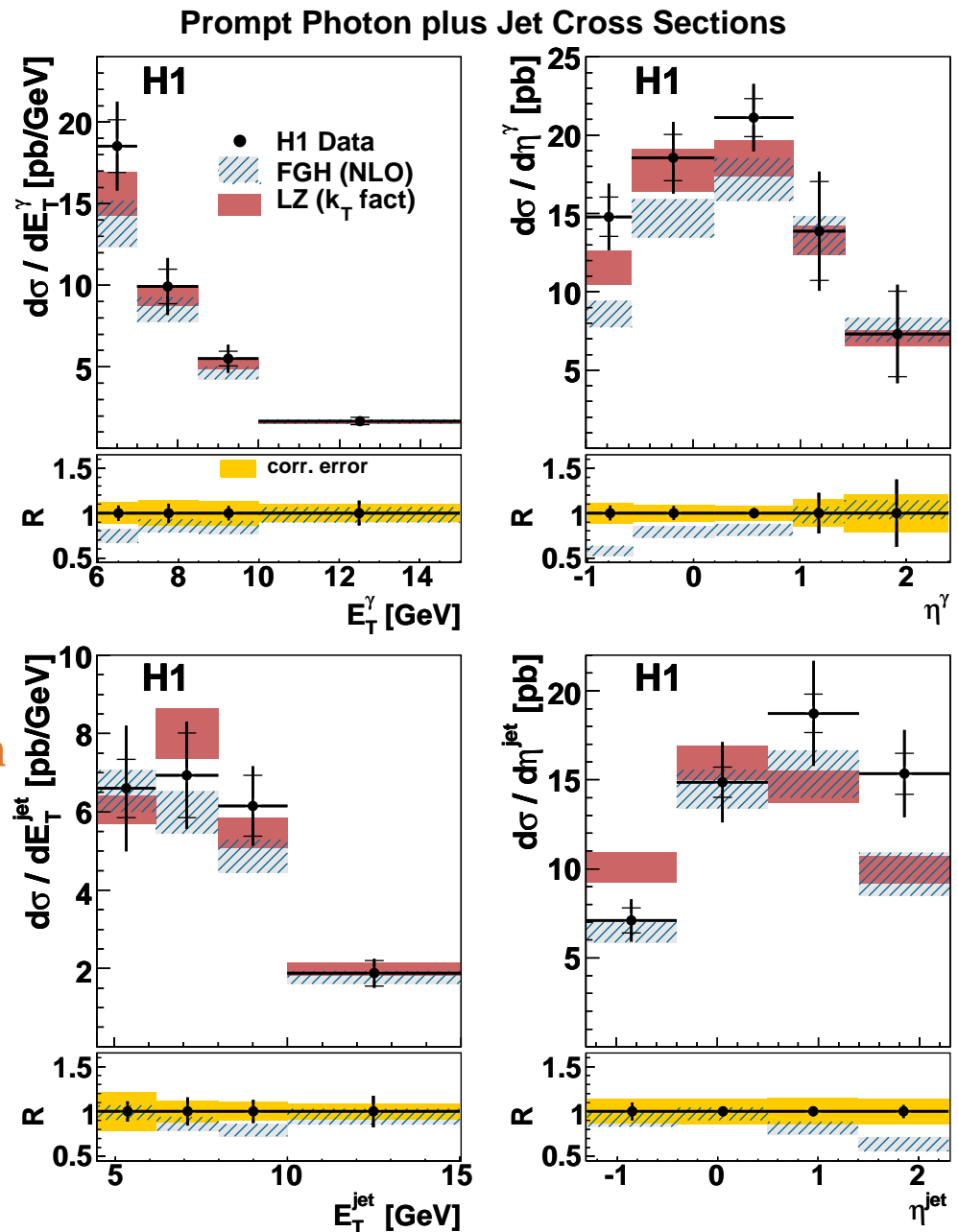


# Prompt-photons + Jets (I)

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

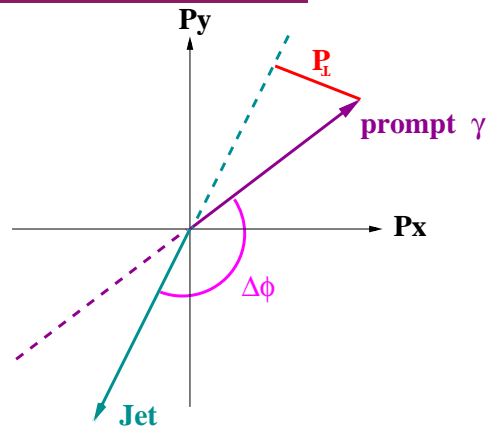
- Comparison to calculations:

- LZ and FGH give a reasonable description of the cross sections in  $E_T^\gamma$  and  $E_T^{\text{jet}}$
- both show deficits in the shape in  $\eta^{\text{jet}}$
- 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  $p_{\perp}$



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

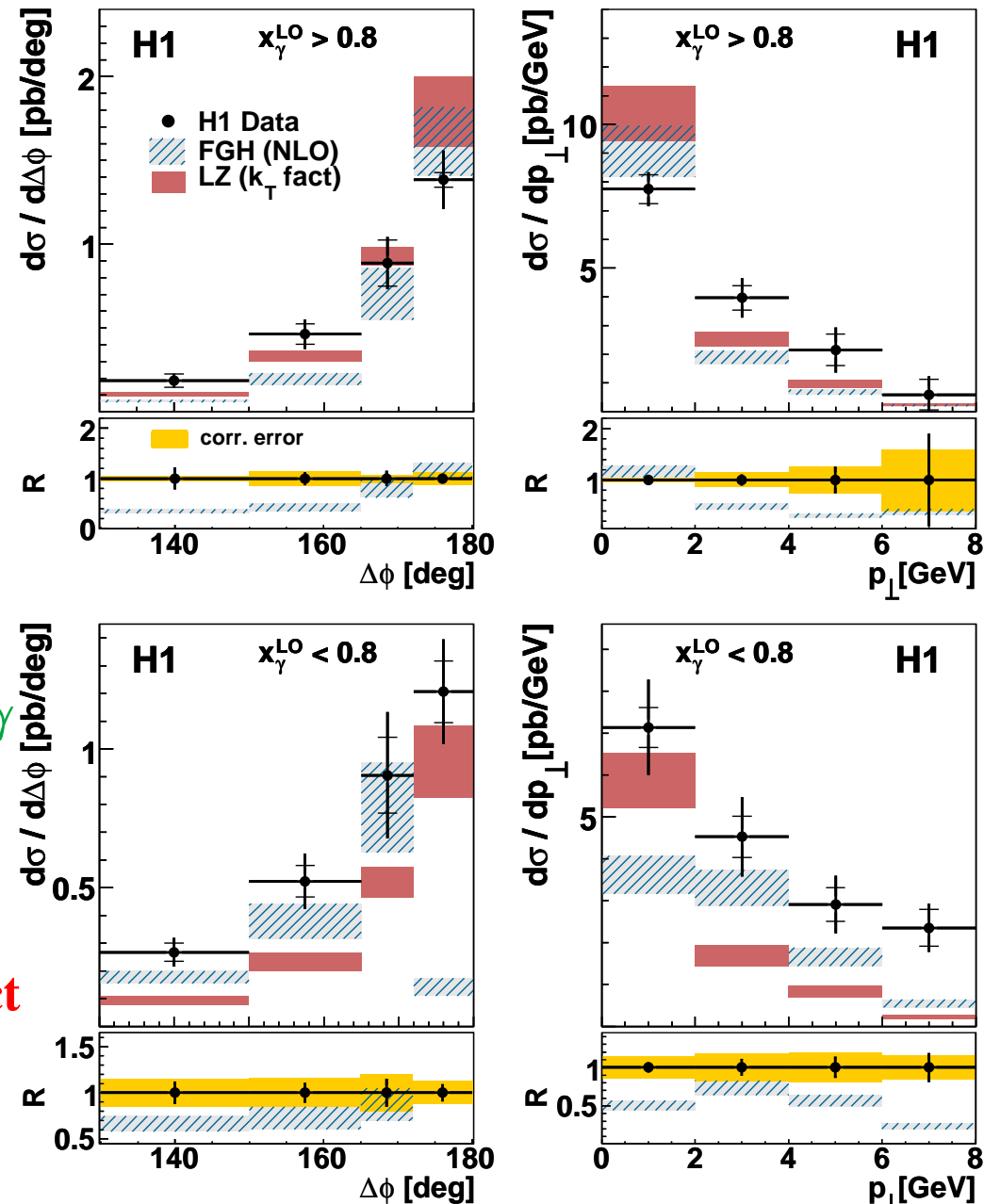
→ estimator momentum fraction parton from  $\gamma$

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

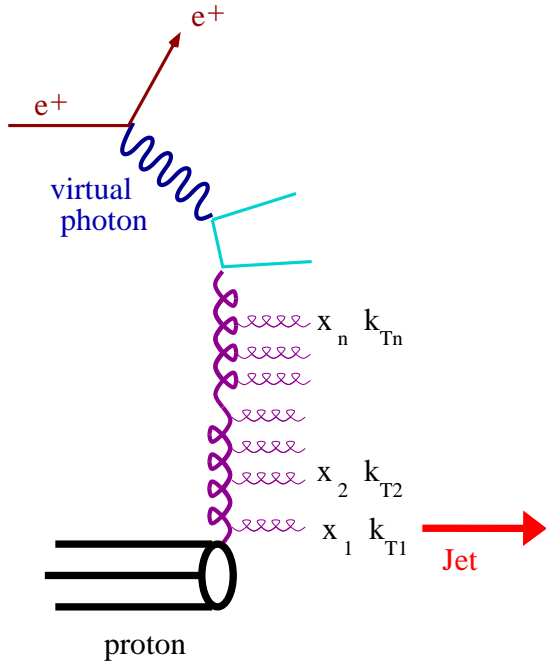
- ⇒ Significant fraction of events with a topology which is NOT back-to-back
- ⇒ Harder  $p_{\perp}$  spectrum in resolved than in direct
- ⇒ More decorrelation in the data than in theory

**Challenge to theory!**

Prompt Photon plus Jet Cross Sections



# Parton evolution at low $x$

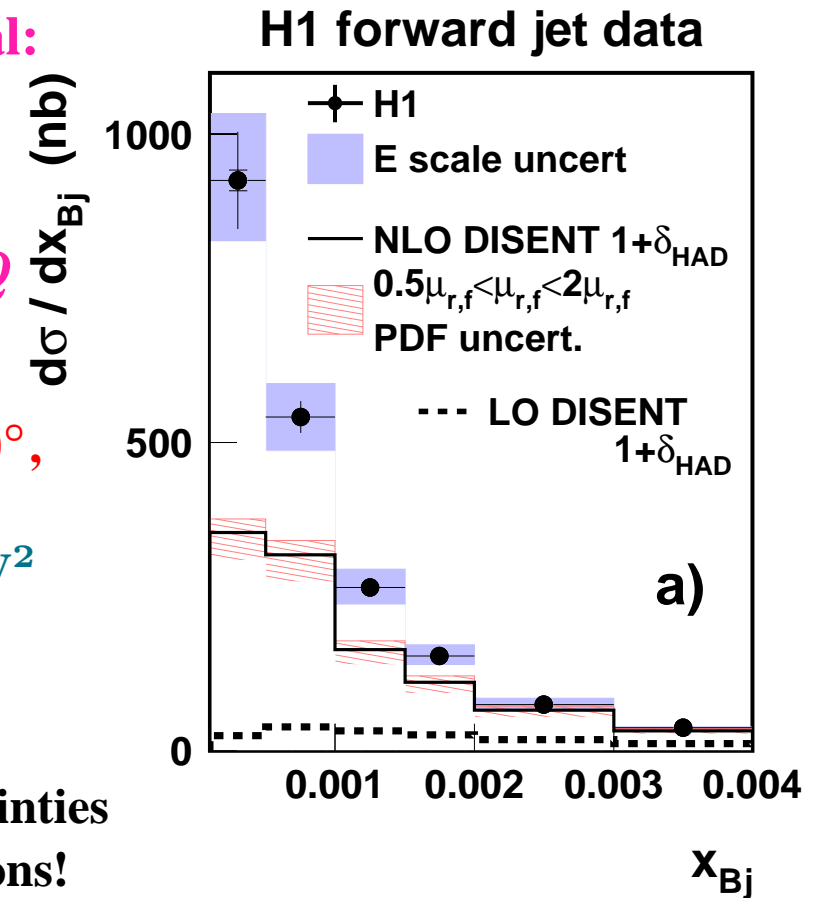


- DGLAP equations sum the leading powers of  $\alpha_s \log Q^2$  in the region  $Q^2 \gg k_{Tn}^2 \gg \dots \gg k_{T2}^2 \gg k_{T1}^2$
- When  $\log Q^2 \ll \log 1/x \implies \alpha_s \log 1/x$  become important; BFKL equations sum these terms  $\implies$  no  $k_T$  ordering
- Mueller and Navelet's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

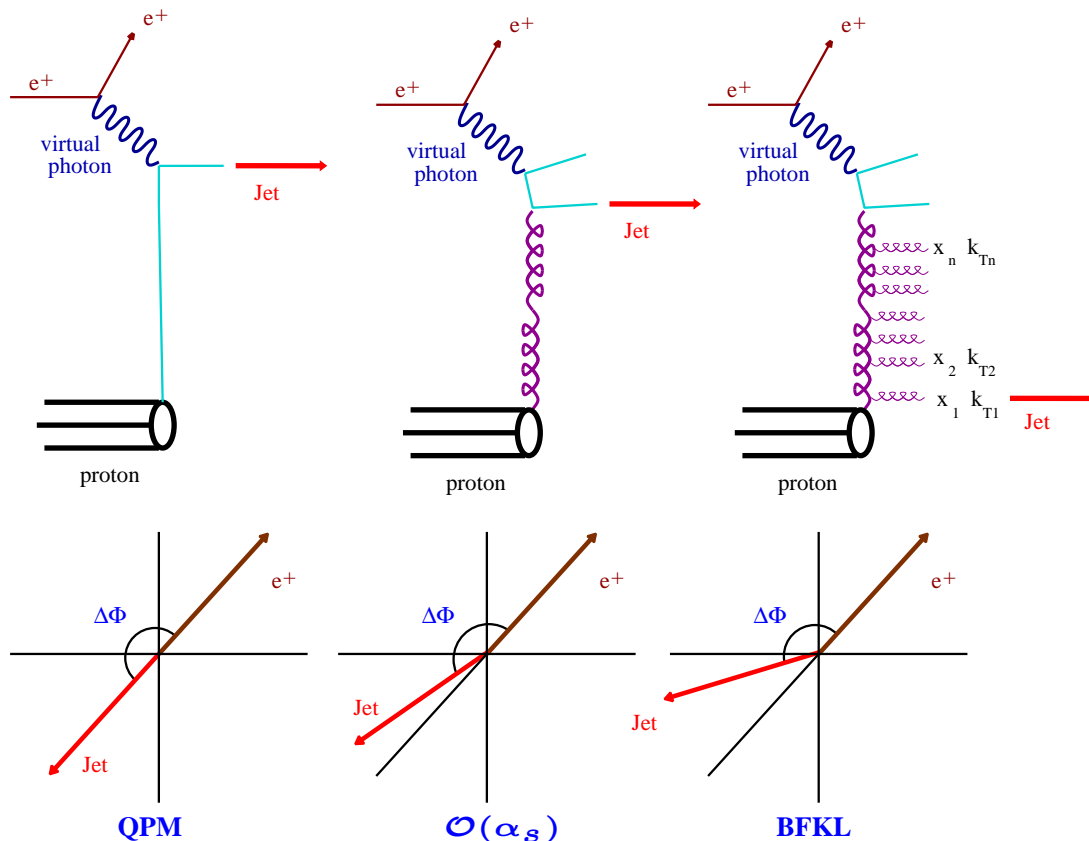
- Measurement of the differential cross section  $d\sigma/dx$  for jet production with  $p_{t,jet} > 3.5 \text{ GeV}$ ,  $7^\circ < \theta_{jet} < 20^\circ$ ,  $0.5 < p_{t,jet}^2/Q^2 < 2$  and  $x_{jet} = E_{jet}/E_p > 0.035$  in the region  $10^{-4} < x < 4 \cdot 10^{-3}$  and  $5 < Q^2 < 85 \text{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

- Strong rise towards low  $x$  is observed

- $\rightarrow$  NLO QCD (DGLAP) lies well below the data at low  $x$
- $\rightarrow$  big jump from LO to NLO  $\implies$  Large theoretical uncertainties (higher-orders) in pQCD calculations prevent firm conclusions!



# Azimuthal correlations between the scattered positron and forward jets



- **Quark Parton Model:**

→  $\Delta\Phi = \pi$

- $\mathcal{O}(\alpha_s)$  corrections:

→  $\Delta\Phi \leq \pi$  (decorrelation)

- **BFKL-induced effects:**

→  $\Delta\Phi \leq \pi$  (stronger decorrelation)

→ stronger decorrelation as  $x_{jet}/x$  increases

- **Jets are reconstructed using the inclusive  $k_T$  algorithm in the Breit frame and boosted**

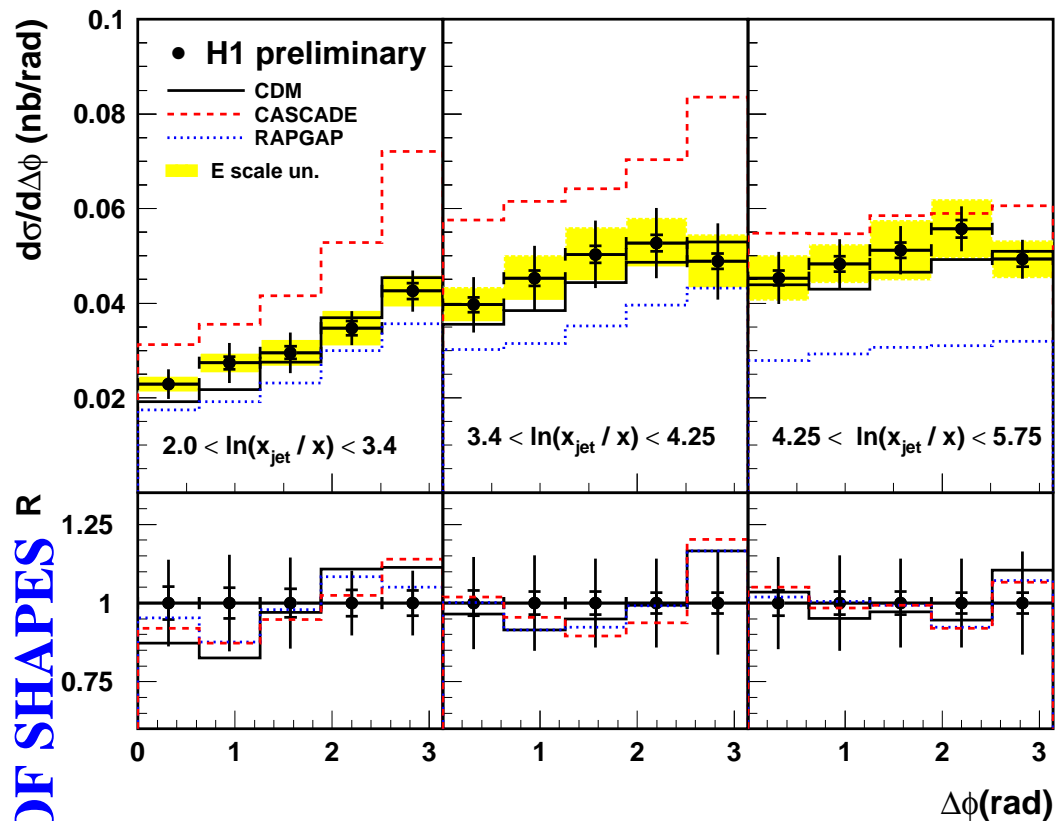
**back into the LAB:  $7^\circ < \theta_{jet} < 20^\circ$ ,  $p_{t,jet} > 6$  GeV and  $x_{jet} = E_{jet}/E_p > 0.035$**

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

→ **suppression of DGLAP evolution:  $0.5 < p_{t,jet}^2/Q^2 < 6$**

# Azimuthal correlations between the scattered positron and forward jets

Forward jet azimuthal correlations



COMPARISON OF SHAPES R

- 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:
  - RAPGAP (DGLAP evolution)
  - CDM (no  $k_T$  ordering; BFKL-like)
  - CASCADE (CCFM evolution)

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

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

→ Significant differences in normalization between the models

⇒ Comparison to higher-order QCD calculations needed to draw firm conclusions

# Subjects

⇒ 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**

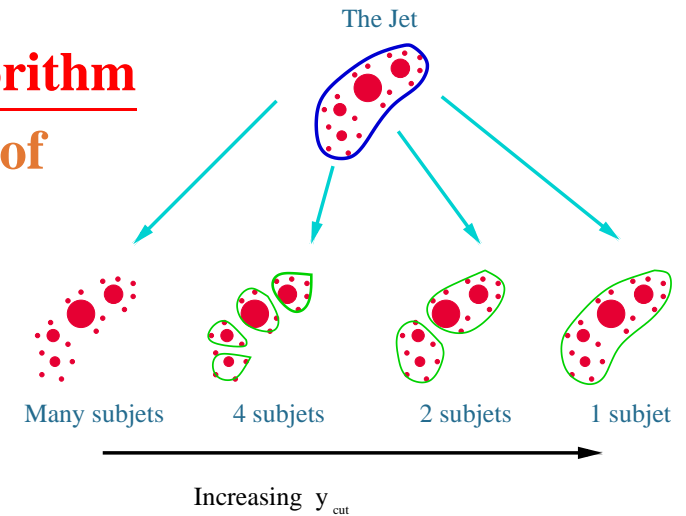
- Subjects are resolved within a jet by reapplying the  $k_T$  algorithm on all the particles belonging to the jet until for every pair of particles the distance between clusters is above

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

→ all remaining clusters are called **subjects**

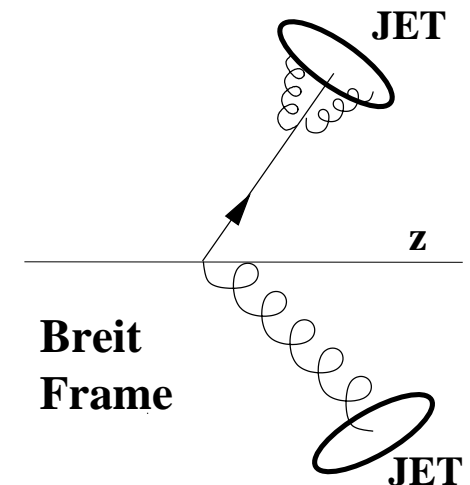
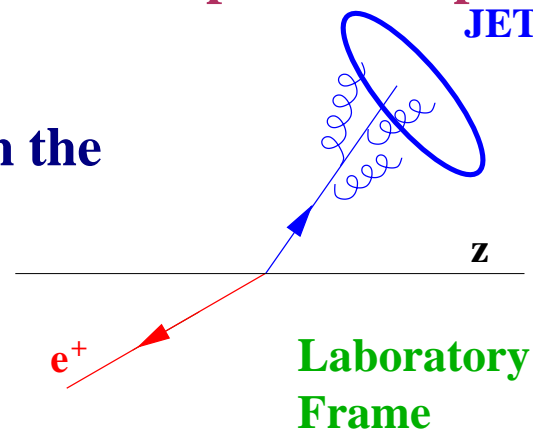
→ the **subject multiplicity depends upon  $y_{cut}$**

→ the distributions of subjects are sensitive to the pattern of parton radiation



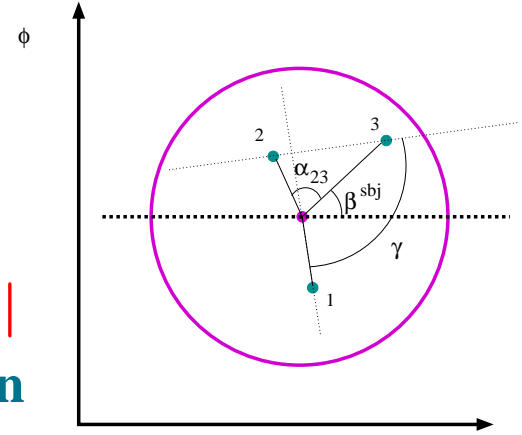
- Jets (and subjects) are reconstructed in the laboratory frame since NLO QCD calculations are possible.

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

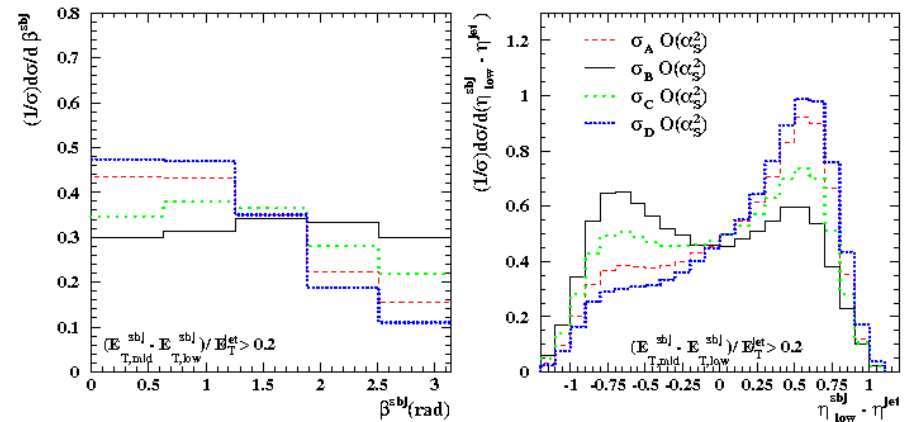
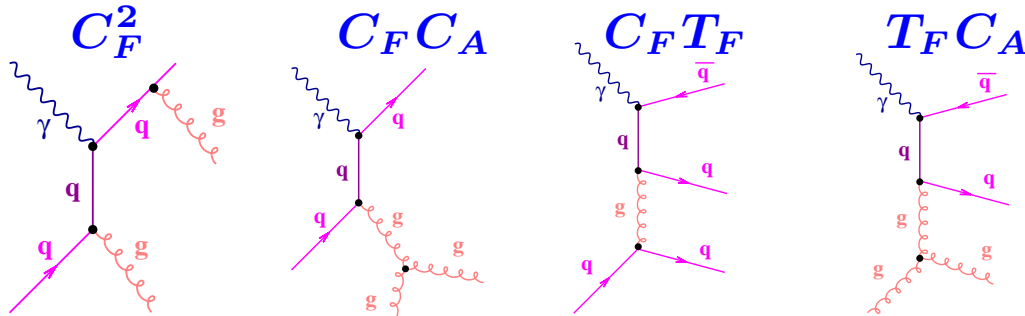
• The pattern of QCD radiation from a primary parton has been studied by measuring normalised cross sections as functions of the subjet variables  $E_T^{sbj} / E_T^{jet}$ ,  $\eta^{sbj} - \eta^{jet}$ ,  $|\phi^{sbj} - \phi^{jet}|$  and the angle  $\beta^{sbj}$  in the  $\eta$ - $\phi$  plane of the laboratory frame between the subjet with lowest  $E_T$  and the proton beam direction, as viewed from the jet centre  $\eta$



• Predicted cross section at  $\mathcal{O}(\alpha_s^2)$  for three-subjet production (colour configurations)

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

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



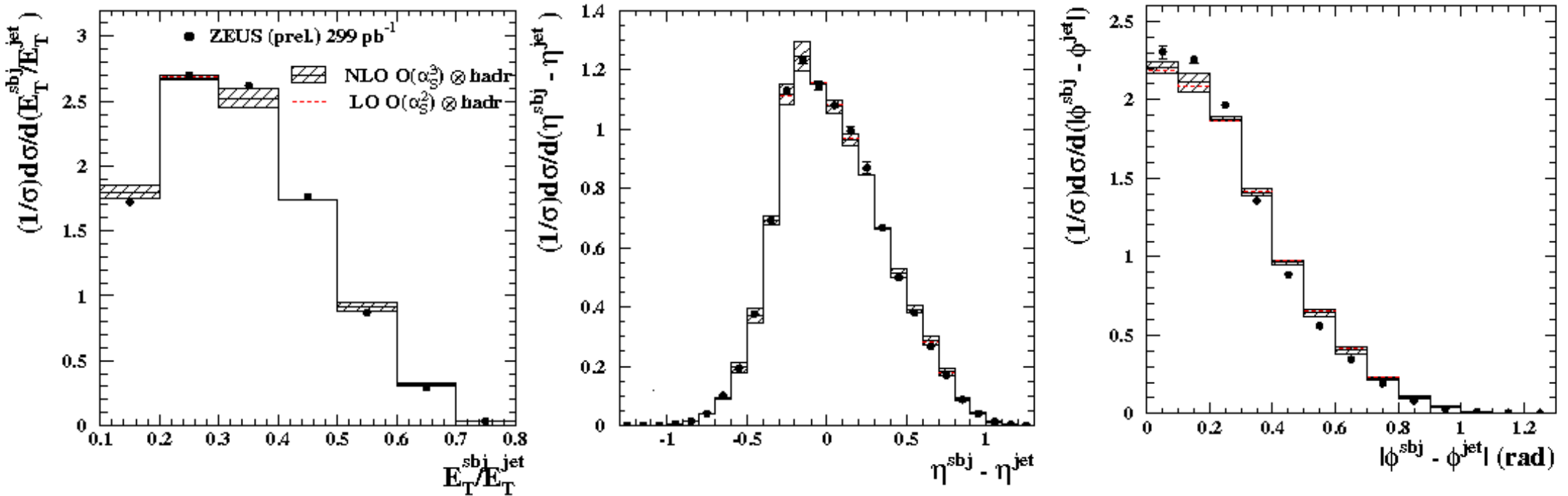
→ different behaviour in the distributions

→ 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  $Q^2 > 125 \text{ GeV}^2$  for jets with  $E_T^{jet} > 14 \text{ GeV}$  and  $-1 < \eta^{jet} < 2.5$  and **exactly THREE** subjects at  $y_{cut} = 0.01$   $\rightarrow \mathcal{L} = 299 \text{ pb}^{-1} \Rightarrow 80\,000 \text{ jets}$  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

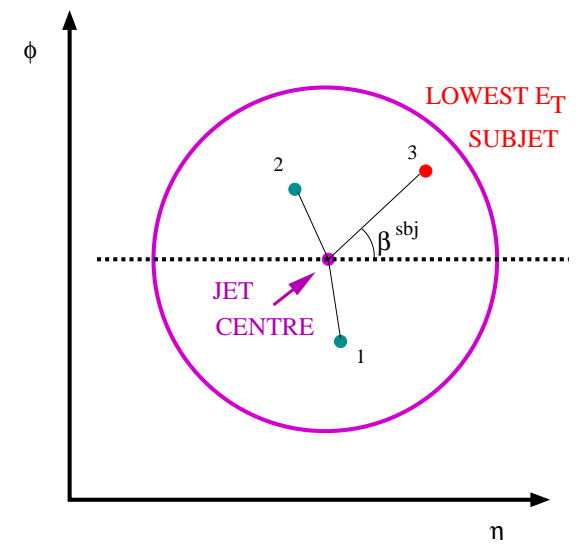
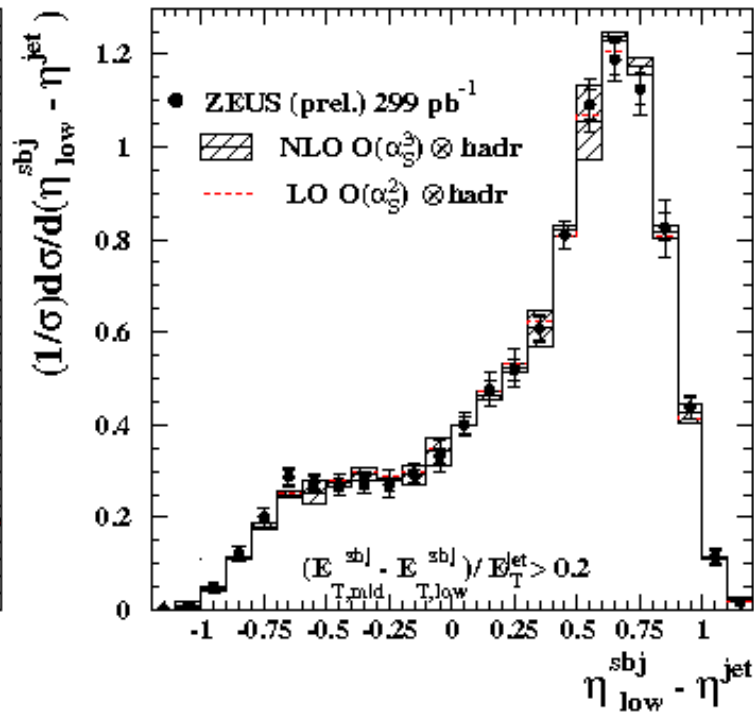
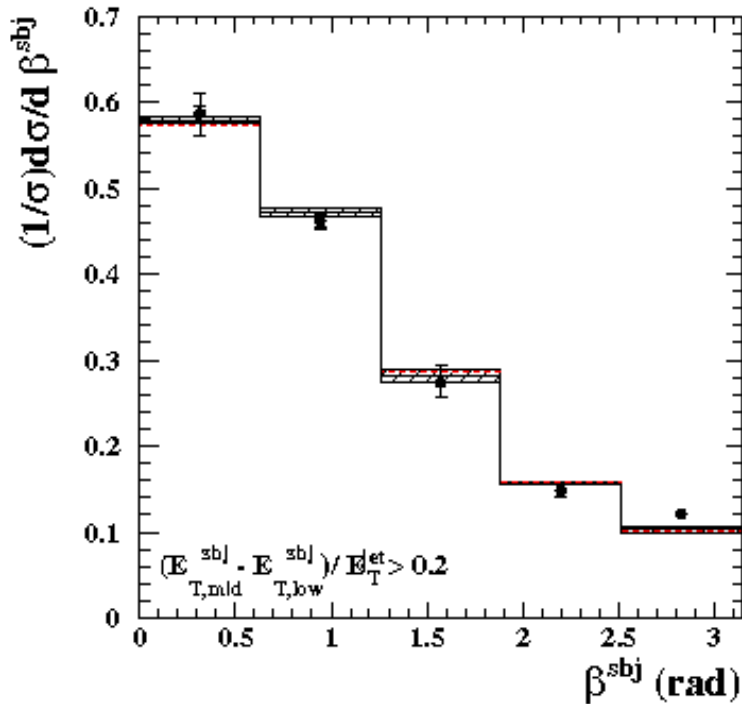


# Measurements of Three-Subject Distributions in NC DIS (II)

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

→ Additional cut to “separate” lowest- $E_T$  subjet:  $(E_{T,mid}^{sbj} - E_{T,low}^{sbj})/E_T^{jet} > 0.2$

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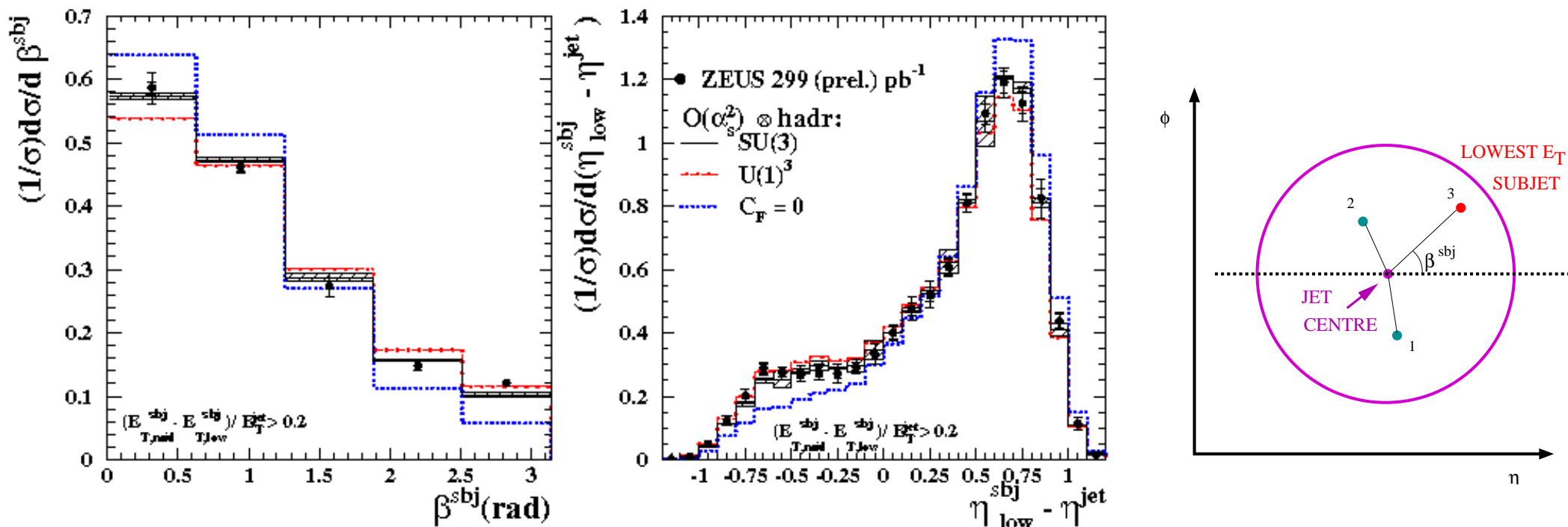


→ Good description of the measured distributions by NLO QCD

# Measurements of Three-Subject Distributions in NC DIS (III)

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

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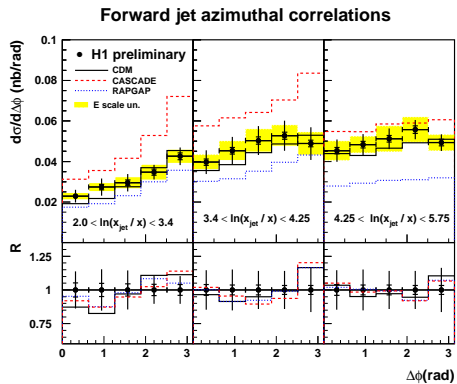
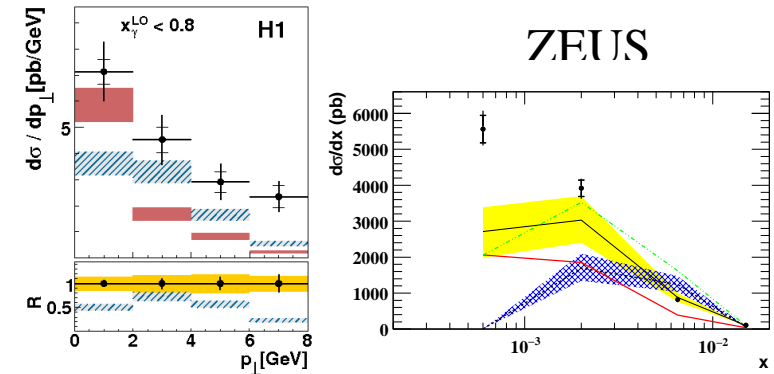


- The data disfavors the predictions based on  $C_F = 0$
- U(1)<sup>3</sup> vs SU(3): some differences are observed in the  $\beta^{sbj}$  distribution
- The predictions of SU(3) describe reasonably well the data

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

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

$\rightarrow$  **Challenge to theory**



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

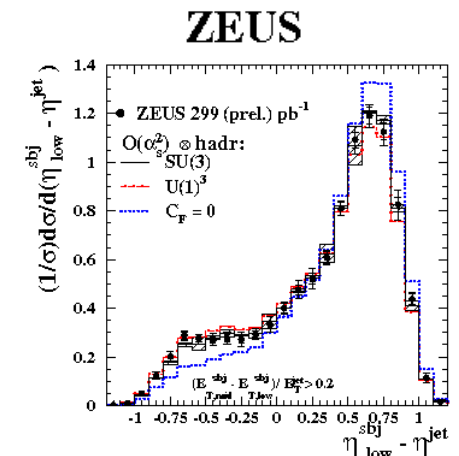
$\rightarrow$  **A stronger decorrelation in  $\Delta\phi$  as  $\ln(x_{jet}/x)$  increases is observed!**

$\rightarrow$  **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 $^{-1}$**

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

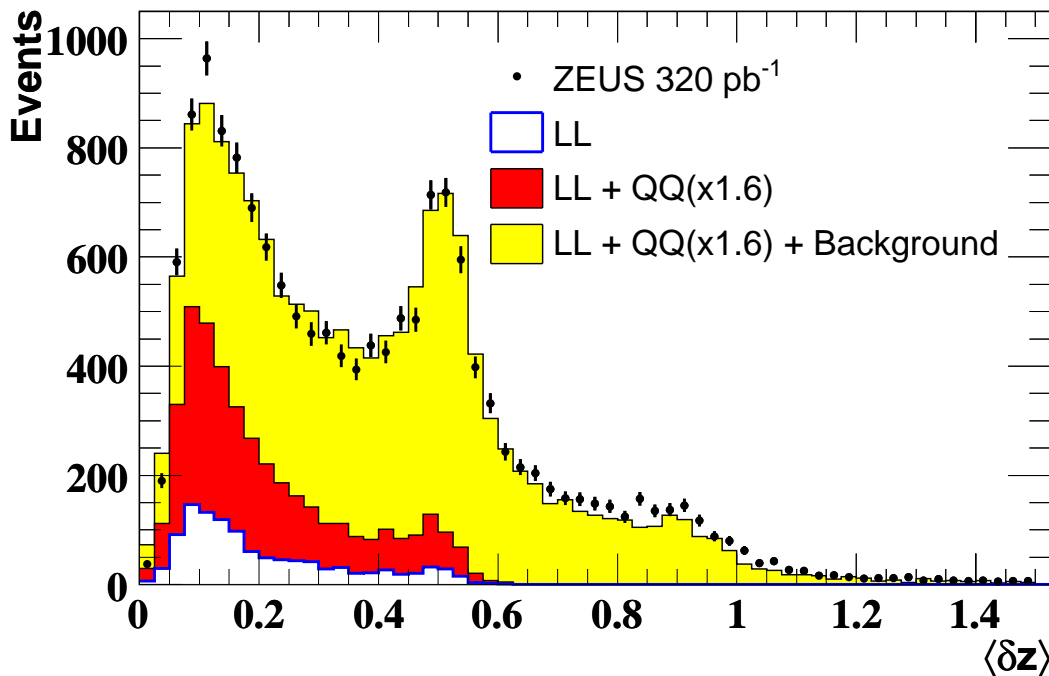
$\rightarrow$  **the subjet distributions are sensitive to the colour configurations and are found to be consistent with the predictions of SU(3)**



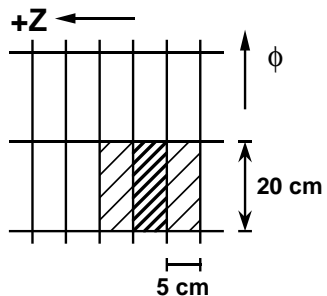
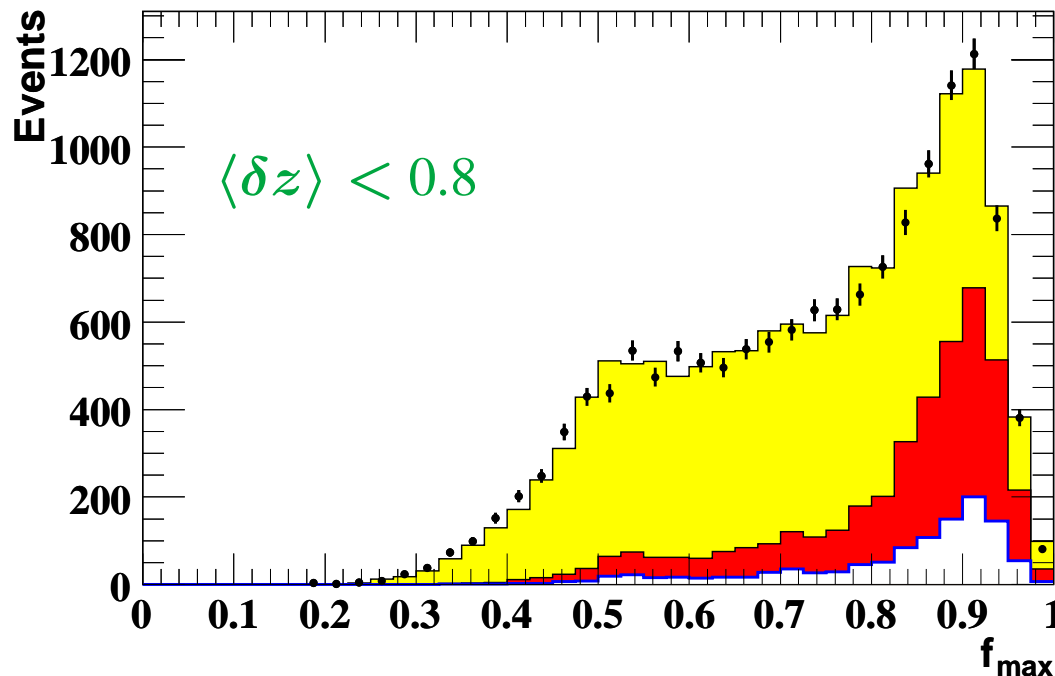
**Backup**

# Extraction of the isolated-photon signal

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

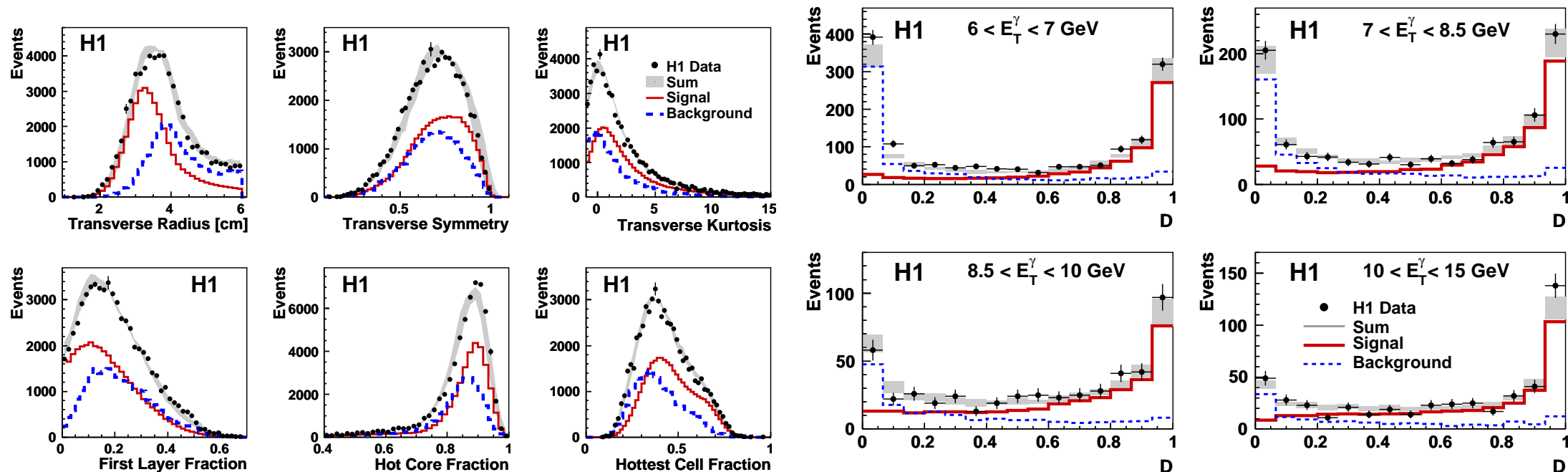
$$\langle \delta z \rangle = \sum_i E_i |Z_i - Z_{cluster}| / (w_{cell} \sum_i E_i) \quad (\text{in units of 5 cm})$$
 → Peaks due to  $\gamma$ 's and  $\pi^0$ 's clearly visible

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

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

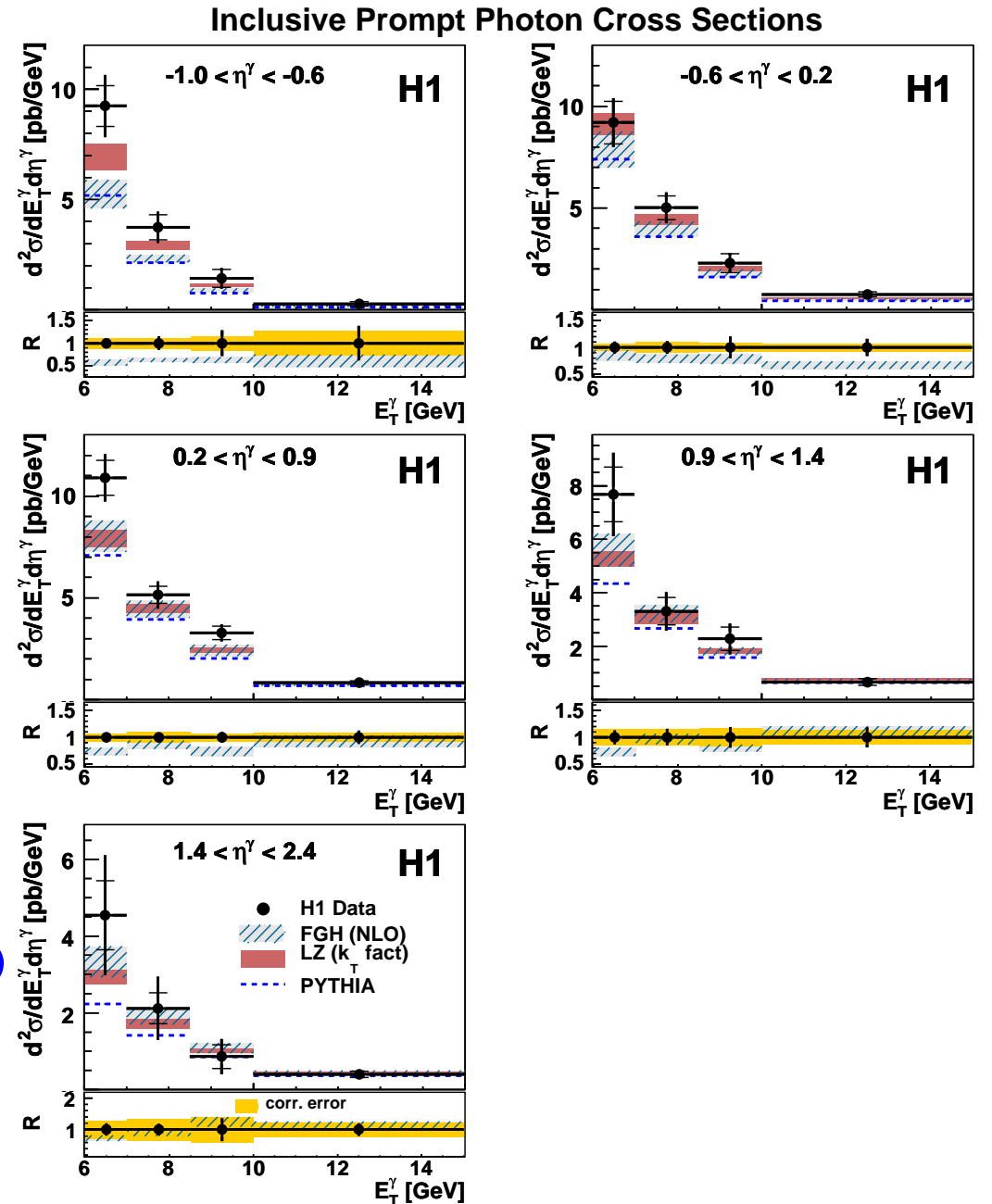
# Extraction of the prompt-photon signal

- **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  $\rightarrow$  isolation condition: the jet containing the  $\gamma$  should fulfill  $E_T^\gamma / E_T^{\gamma\text{-jet}} > 0.9$   $\implies$  Isolated- $\gamma$  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**



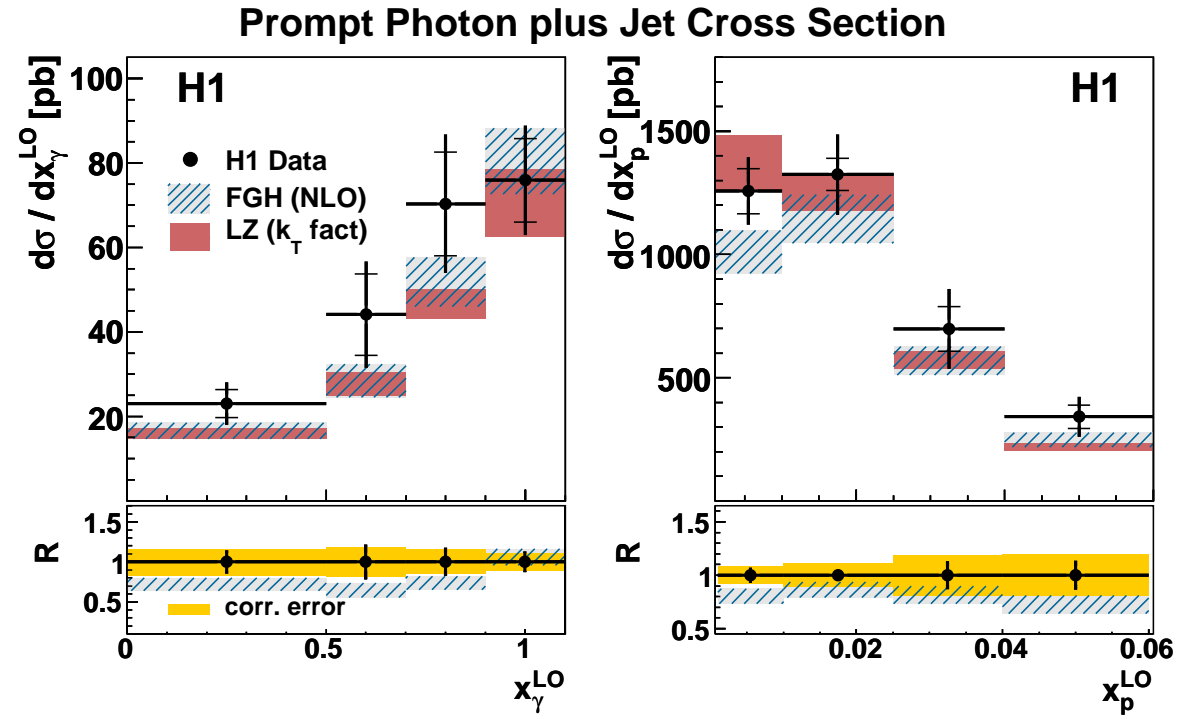
# Inclusive prompt-photons (II)

- Measurement of inclusive prompt photon production in the kinematic region defined by  $Q^2 < 1 \text{ GeV}^2$  and  $0.1 < y < 0.7$  for photons with  $E_T^\gamma / E_T^{\gamma\text{-jet}} > 0.9$ ,  $6 < E_T^\gamma < 15 \text{ GeV}$  and  $-1 < \eta^\gamma < 2.4$  using  $\mathcal{L} = 340 \text{ pb}^{-1}$
- Comparison to calculations:
  - LZ provides a reasonable description of the data except for the lowest  $E_T^\gamma$  bin in the central region ( $0.2 < \eta^\gamma < 0.9$ )
  - 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  $Q^2 < 1 \text{ GeV}^2$  and  $0.1 < y < 0.7$  for photons with  $E_T^\gamma / E_T^{\gamma\text{-jet}} > 0.9$ ,  $6 < E_T^\gamma < 15 \text{ GeV}$  and  $-1 < \eta^\gamma < 2.4$  and for jets with  $E_T^{\text{jet}} > 4.5 \text{ GeV}$  and  $-1.3 < \eta^{\text{jet}} < 2.3$  using  $\mathcal{L} = 340 \text{ pb}^{-1}$



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

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

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

- LZ and FGH describe the data within errors



# Measurements of Three-Subject Distributions in NC DIS

- Measurements of the normalised cross sections in NC DIS for  $Q^2 > 125 \text{ GeV}^2$ :
  - Jets with  $E_T^{jet} > 14 \text{ GeV}$  and  $-1 < \eta^{jet} < 2.5$
  - Selected sample of jets: jets with **exactly THREE** subjects at  $y_{cut} = 0.01$
  - $\mathcal{L} = 299 \text{ pb}^{-1} \Rightarrow 80\,000 \text{ jets}$

