17th Lomonosov Conference on Elementary Particle Physics

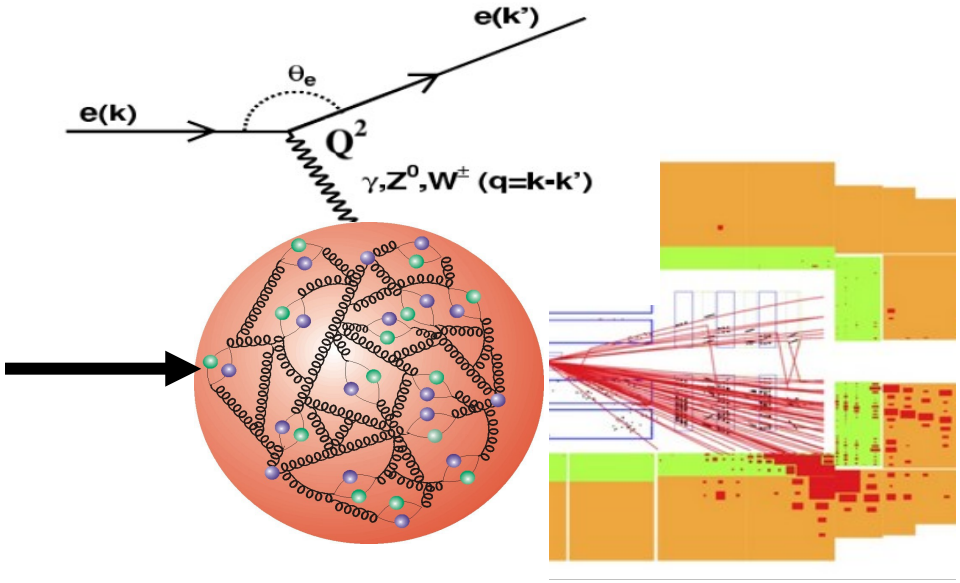
Hard QCD and heavy flavour production at HERA (on behalf of H1 and ZEUS)

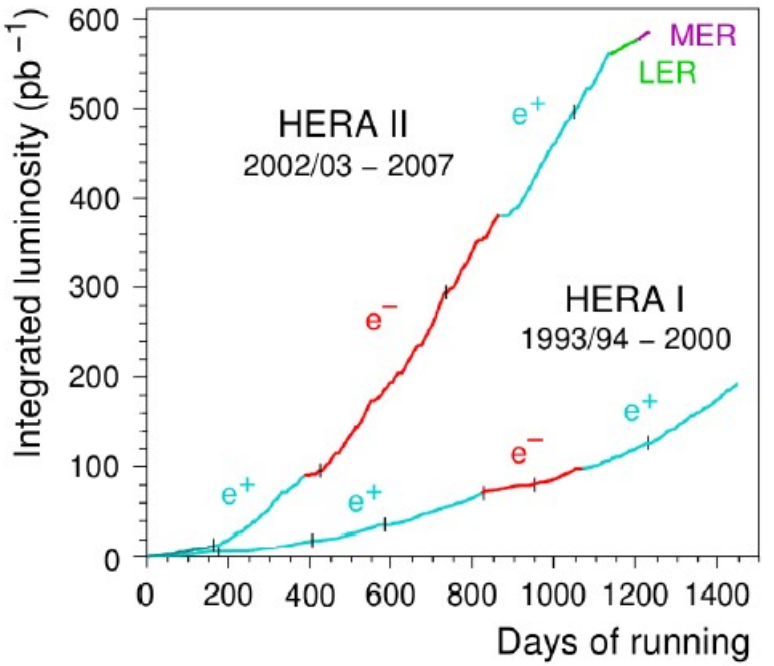
A. Rostovtsev

- Charm production
- Multijet production
- Running α_s and quark masses
- Isolated photon and jet photoproduction

Moscow, 26/08/2015

HERA is worlds only *e*±*p* collider : investigating quark-gluon structure of the matter





$$e(k) + p(P) \rightarrow e(k') + X \qquad s = (P+k)^2$$

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

Photoproduction $Q^2 \simeq 0\,GeV^2$

DIS $Q^2 > 1\,GeV^2$

$$y = \frac{qP}{kP} \cong \frac{W^2+Q^2}{s} \qquad W^2 = (P+q)^2$$

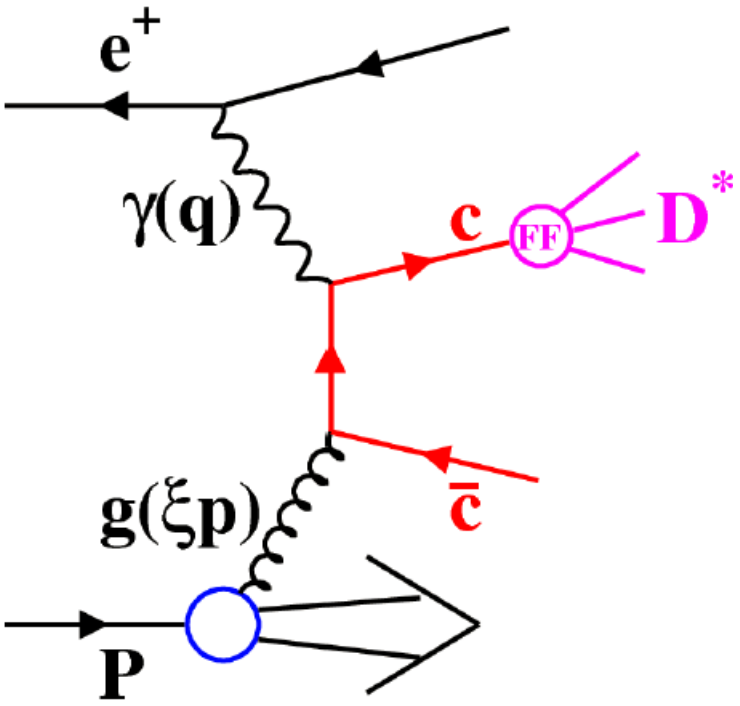
ZEUS ~ 0.5 fb^{-1}

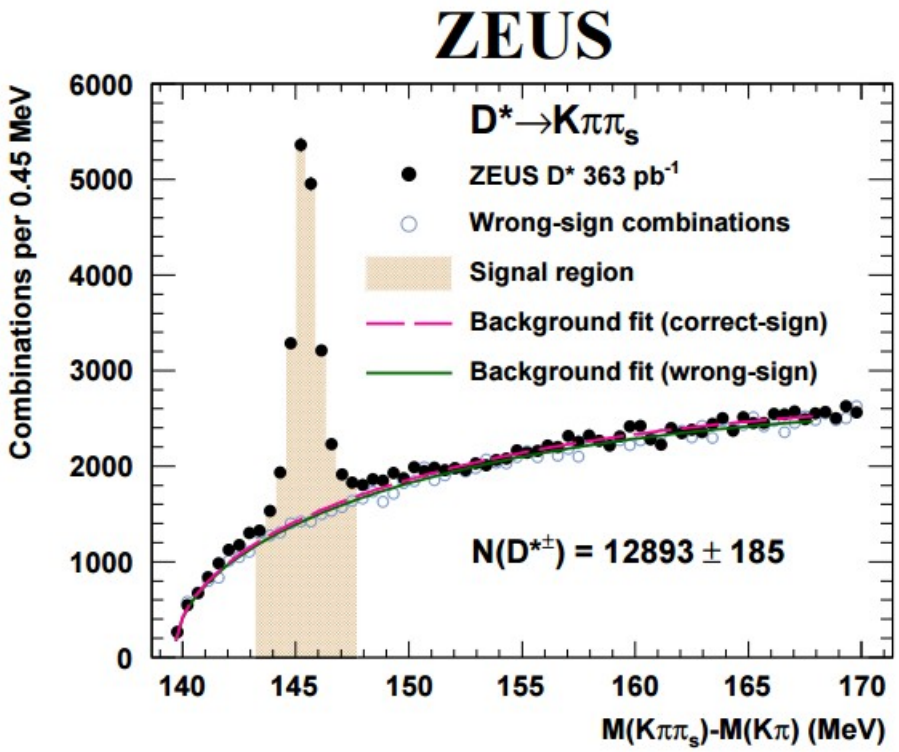
H1 ~ 0.5 fb^{-1}

Combination of Differential$D^{*\pm}$ Cross-SectionMeasurements in Deep-Inelastic *ep* Scattering at HERA

$$\sigma_{charm} \approx 1\mu b \Rightarrow 10^9 \, events \;\; for \; L = 1 \, fb^{-1}$$

submitted to JHEP
[arxiv:1503.06042]

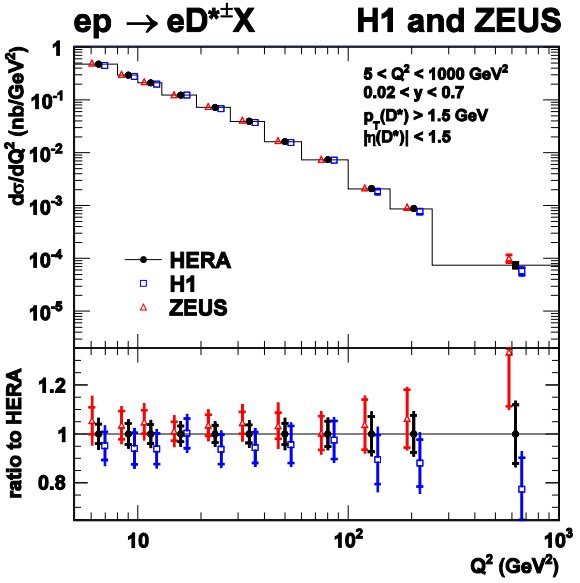


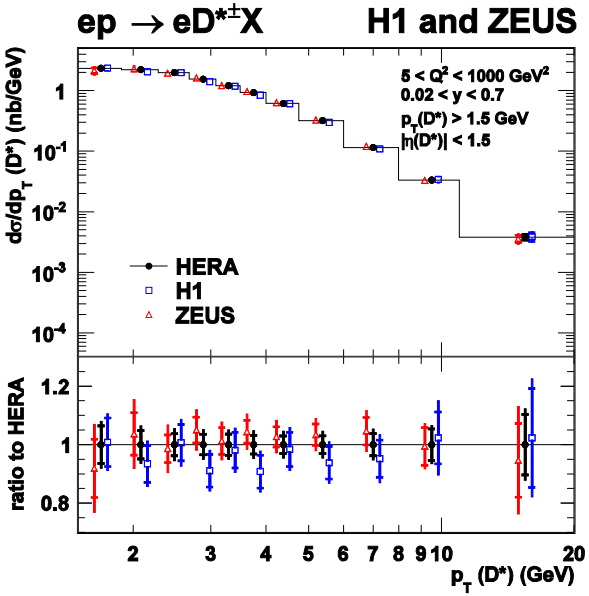


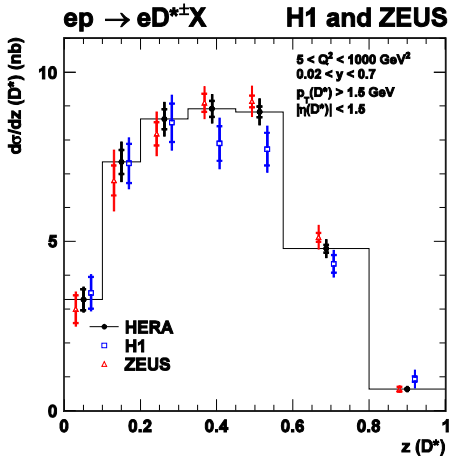
To measure: Q2, y, PT, η, $z(D*) = (E(D*) - pZ(D*))/(2Eey)$

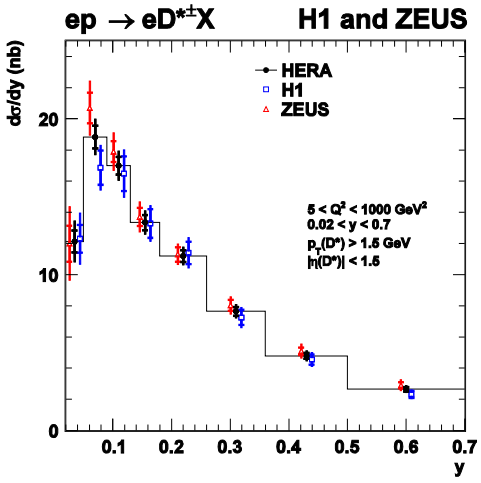
Data uncertainty ~ 5% Theory uncertainty ~ 10-15%

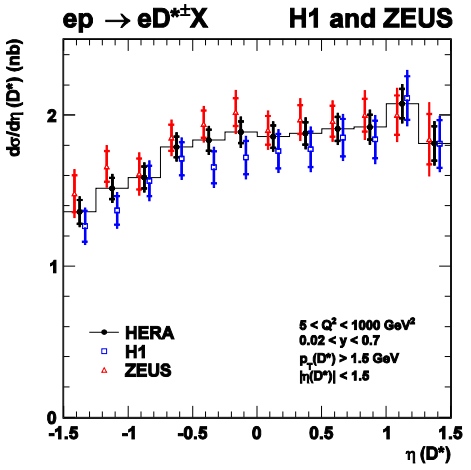
Differential $D*$-production cross section as a function of Q^2, P_T, z, y, η











NLO QCD predictions: HVQDIS

Massive scheme → only light flavours in pdf: u,d,s,g; NLO = o(α_s^2)

HVQDIS setup for ep →cc X→D*X (uncertainties):

- $\mu_r = \mu_f = \sqrt{Q^2 + 4m_c^2}$ vary independently by factor 0.5 and 2
- $m_c^{pole} = 1.50 \pm 0.15$ GeV
- $\alpha_s^{nf=3}(m_Z) = 0.105 \pm 0.002$ (corresponds to $\alpha_s^{nf=5}(m_Z) = 0.116 \pm 0.002$)
- HERAPDF1.0 FFNS
- Fragmentation:
  - Longitudinal: Karvelishvili FF with $\alpha_K(D^*)$

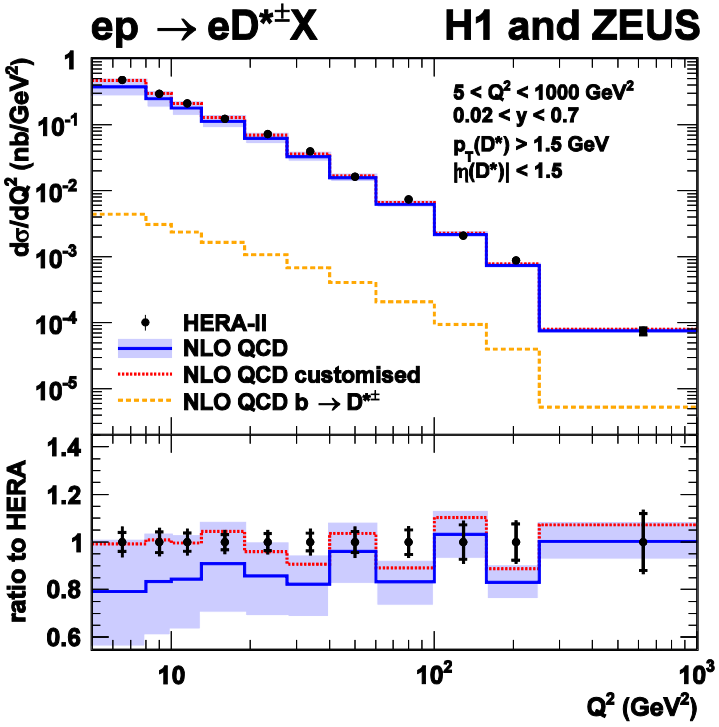
$\hat{s}$ range	$\alpha_K(D^*)$
$\hat{s} \leq \hat{s}_1$	6.1 ± 0.9
$\hat{s}_1 < \hat{s} \leq \hat{s}_2$	3.3 ± 0.4
$\hat{s} > \hat{s}_2$	2.67 ± 0.31

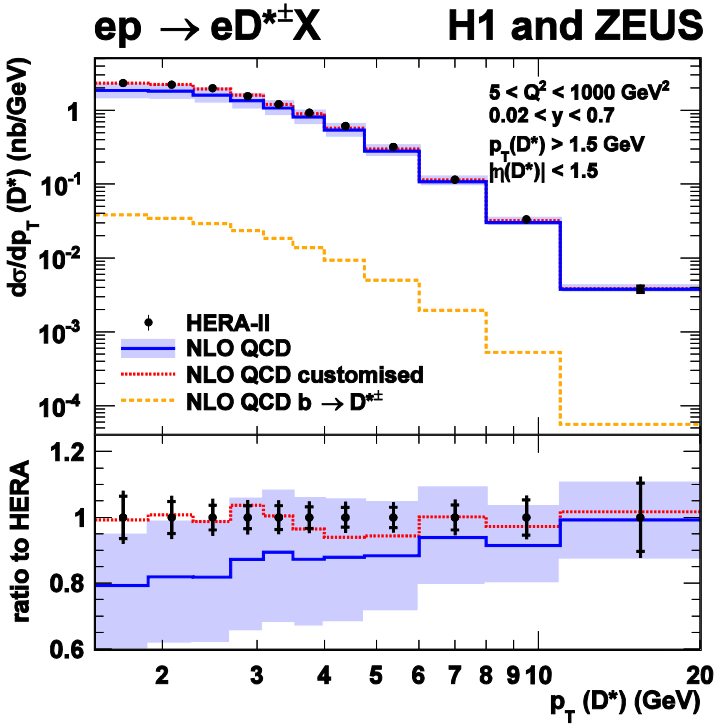
$\hat{s}_1 = 70 \pm 40$ GeV^2
$\hat{s}_2 = 324$ GeV^2

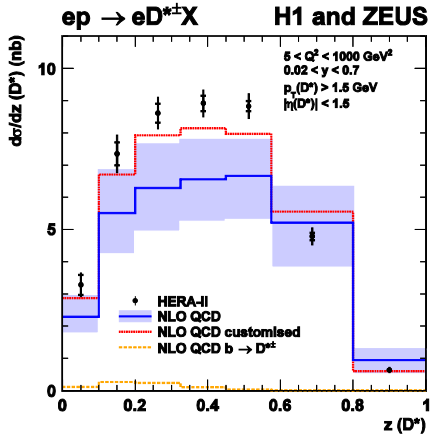
  - Transverse: $f(k_T) = k_T \exp(-\frac{2k_T}{\langle k_T \rangle})$; $\langle k_T \rangle = 0.35 \pm 0.15$ GeV
  - $f(c \to D^*) = 0.2287 \pm 0.0056$

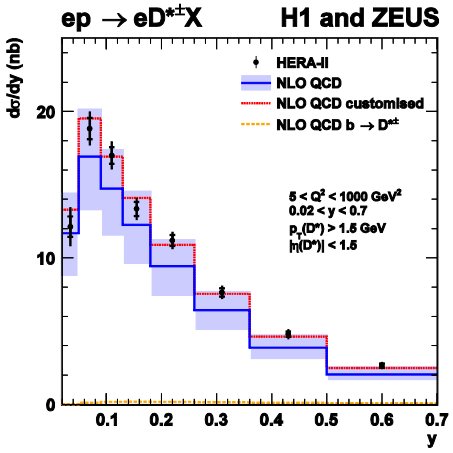
Use HVQDIS also to predict small additional component: ep → bb X → D* X

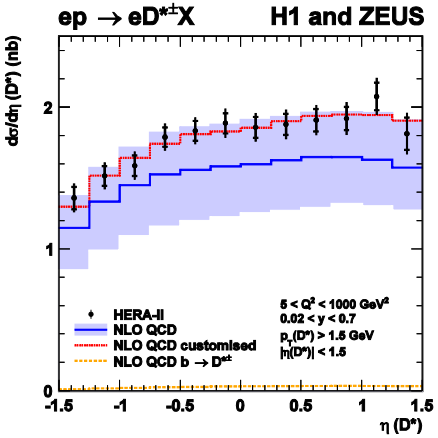
Data vs NLO predictions as a function of Q^2, P_T, z, y, η











Customised NLO QCD predictions: HVQDIS

Try to find parameters such that calculation describes normalisation & shapes of all differential cross sections presented in the following

- $\mu_r = \sqrt{Q^2 + 4m_c^2}$ → $0.5\sqrt{Q^2 + 4m_c^2}$ → Increase cross section
- $m_c^{pole} = 1.50\ \text{GeV}$ → $1.40\ \text{GeV}$ → Increase cross section
- Fragmentation:
  - Longitudinal: Karvelishvili FF with $\alpha_K(D^*)$

$\hat{s}$ range	$\alpha_K(D^*)$
$\hat{s} \leq \hat{s}_1$	6.1 ± 0.9
$\hat{s}_1 < \hat{s} \leq \hat{s}_2$	3.3 ± 0.4
$\hat{s} > \hat{s}_2$	2.67 ± 0.31

- $\hat{s}_1 = 70\ \text{GeV}^2$ → $30\ \text{GeV}^2$ → Soften fragmentation

Leave all other parameters at their default values

This is no prediction → but may give hints in which direction to develop theory

L. Gladilin @ QFTHEP 2015

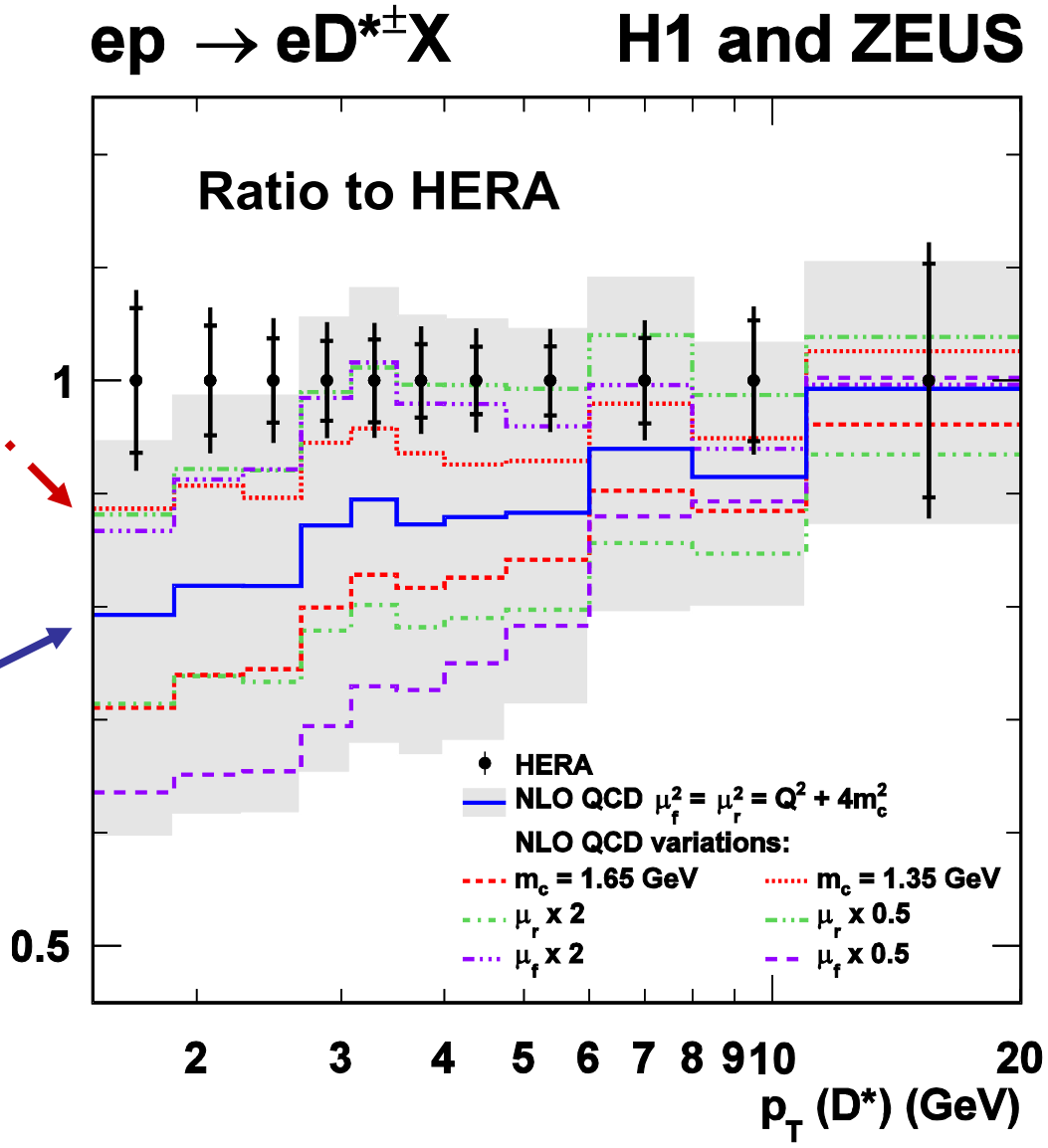
Getting into the details of phenomenological description

Softer spectrum prefers lower mass of charm quark

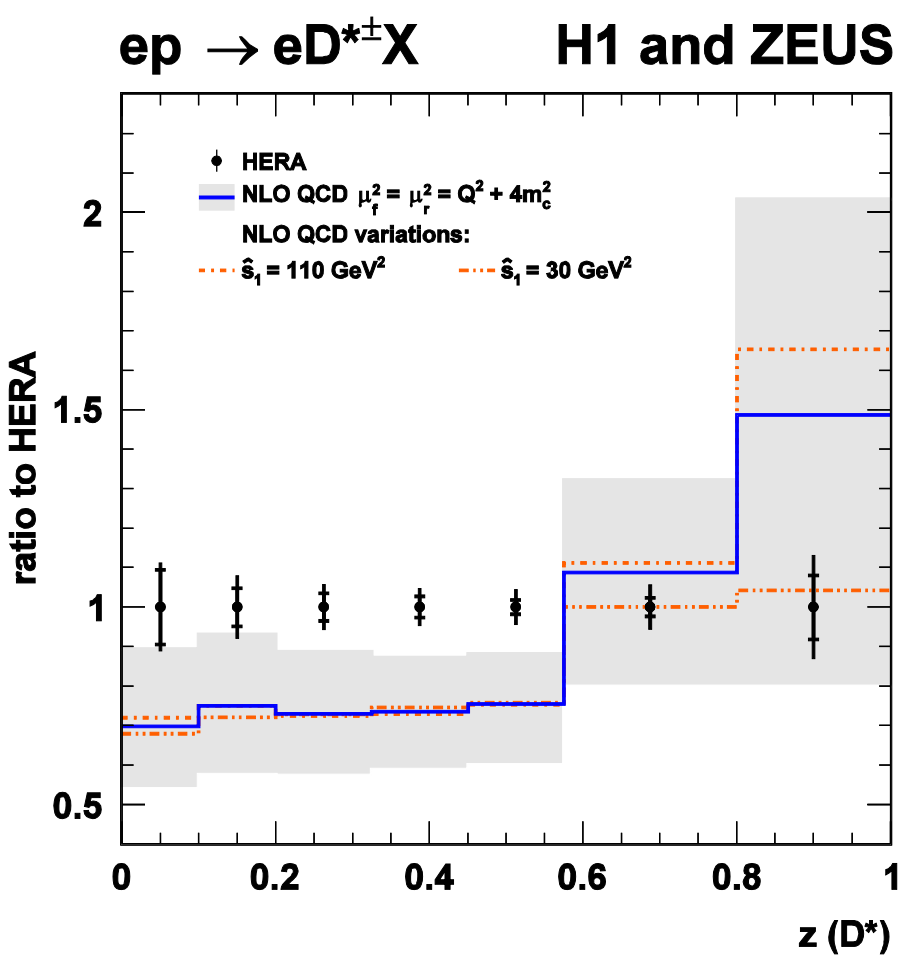
..lower μ_r

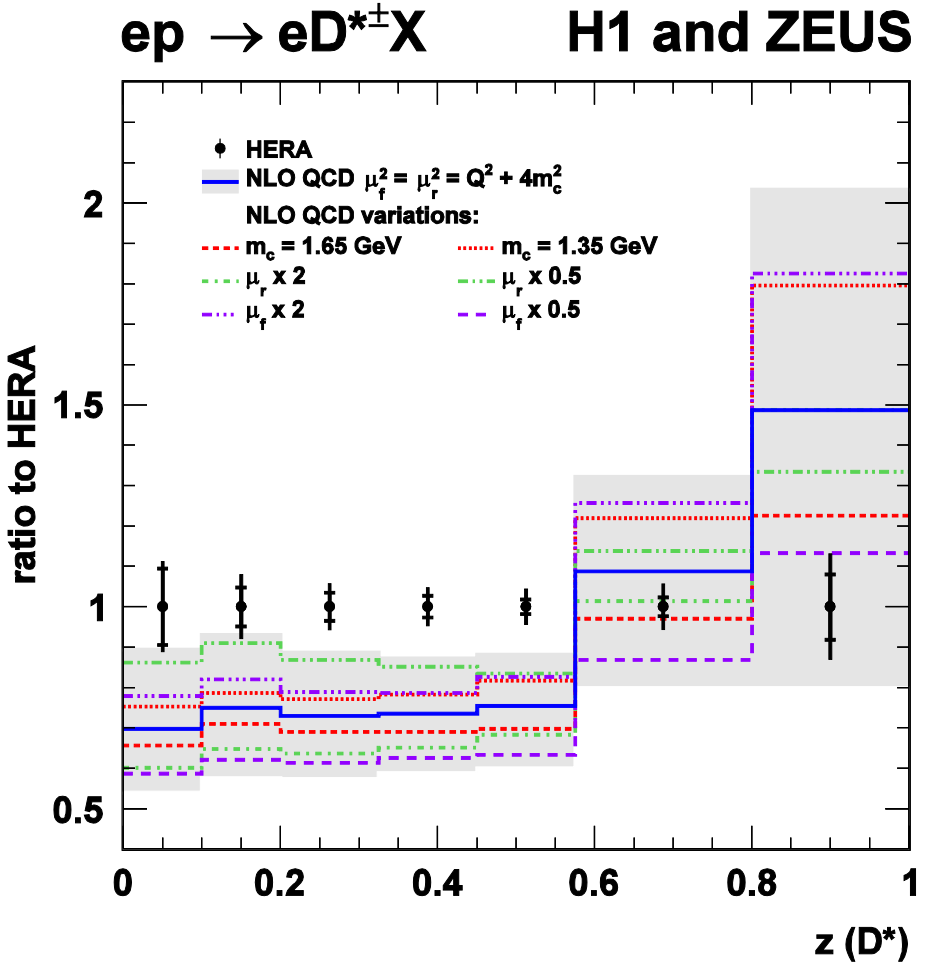
and larger μ_f

Correlated with low-Q2 deficit



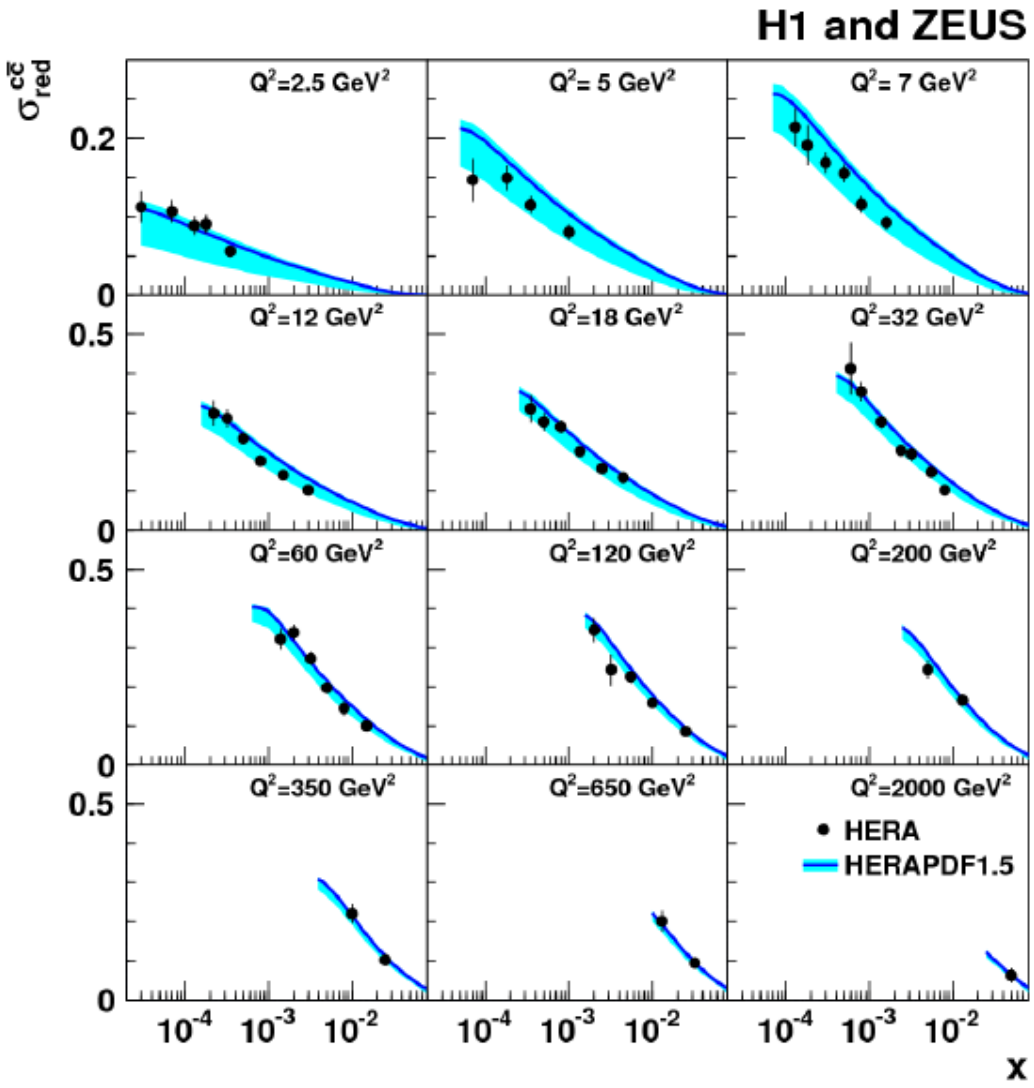
…still not fully satisfactory description of the $z(D*)$





NLO predicts too many D taking large fraction of photon momentum. Next orders calculations may help as they come close to a concept of "resolved" photon.*

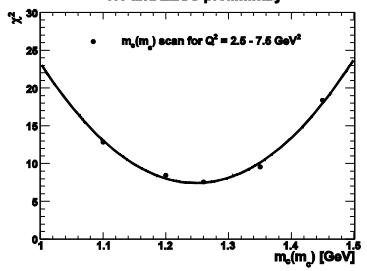
HERA data on charm production are sensitive to the m_c value

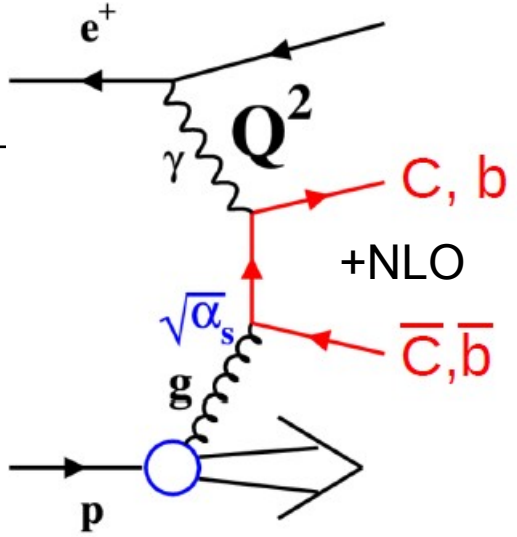


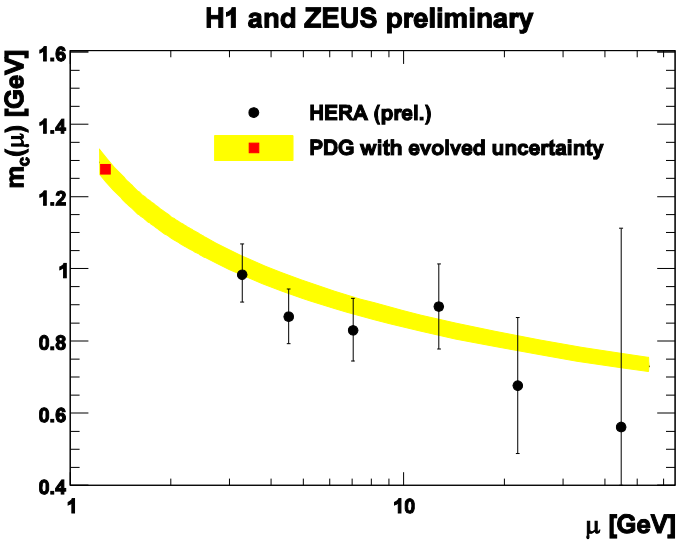
Blue band corresponds to 1.35 < m_c < 1.6 GeV

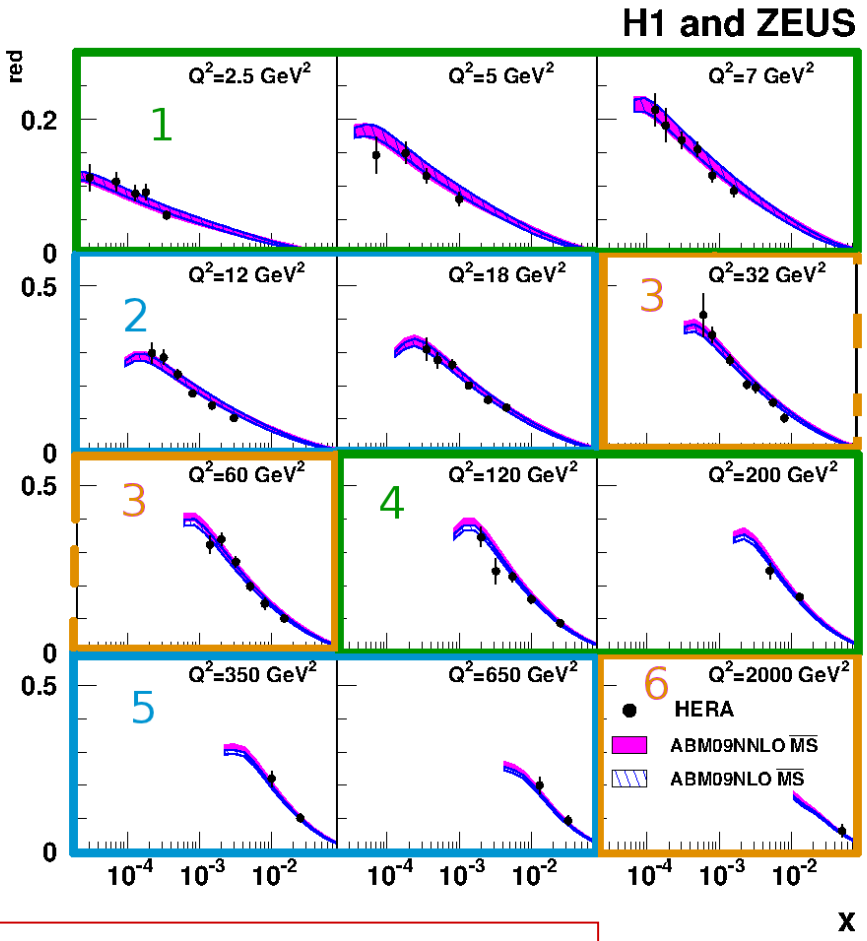
Running charm mass. H1+ZEUS

$$\mu_r = \sqrt{Q^2 + 4m_c^2}$$







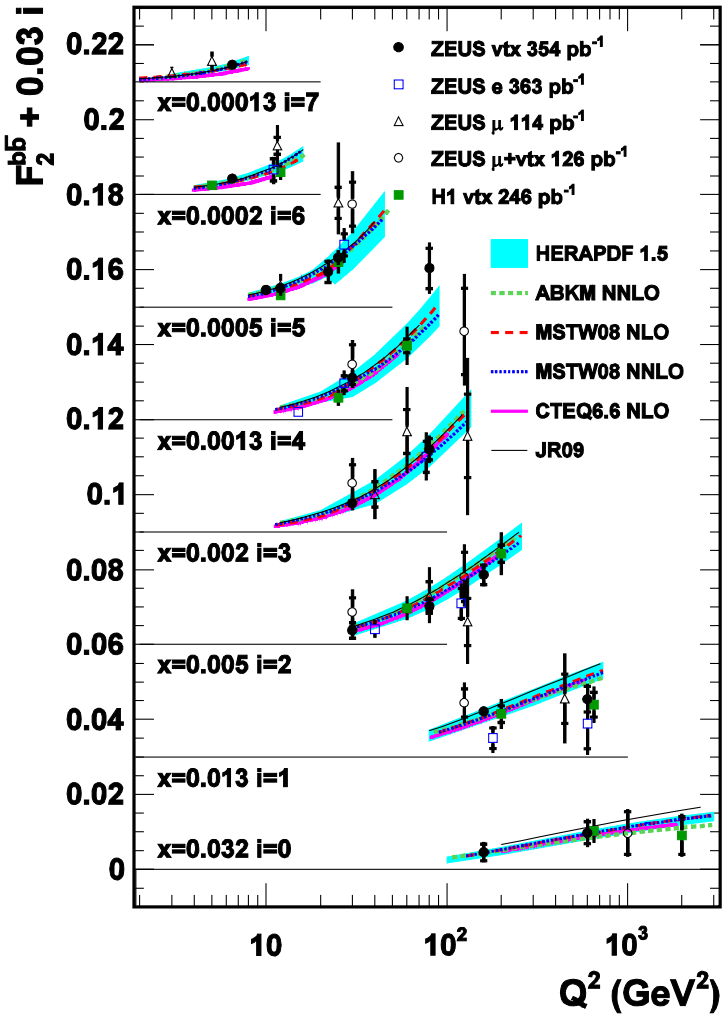


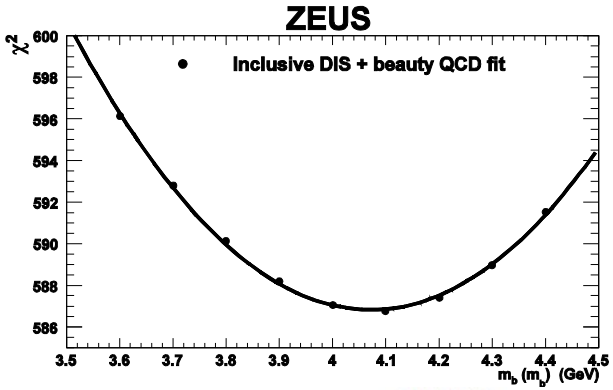
Running $m_c(\mu_r)$ is observed

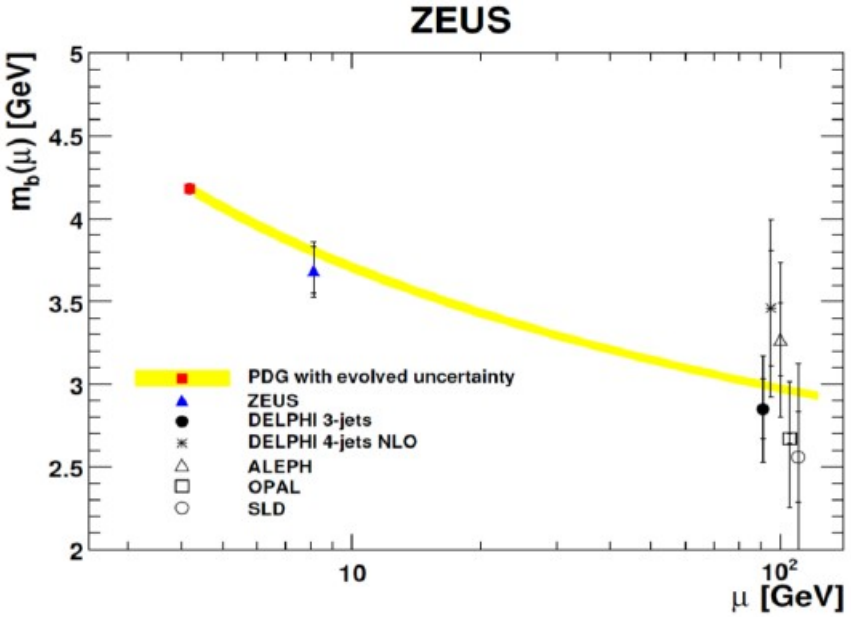
$$m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{param} \pm 0.02_{\alpha_s}\ GeV$$

Running b-quark mass. ZEUS

JHEP09(2014)127



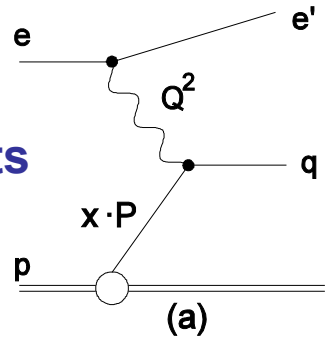


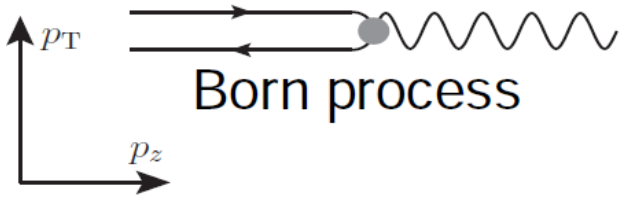


$$m_b(m_b) = 4.07 \pm 0.14\,(fit)\,^{+0.01}_{-0.07}(mod.)\,^{+0.05}_{-0.00}(param.)\,^{+0.08}_{-0.05}(theo.)\,GeV$$

Multijet production at HERA

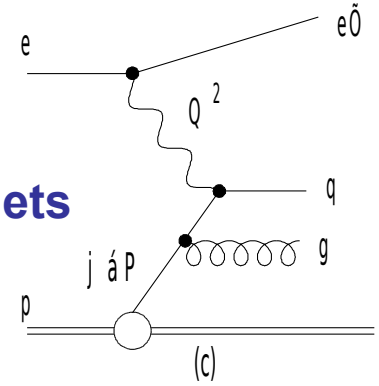
0 jets

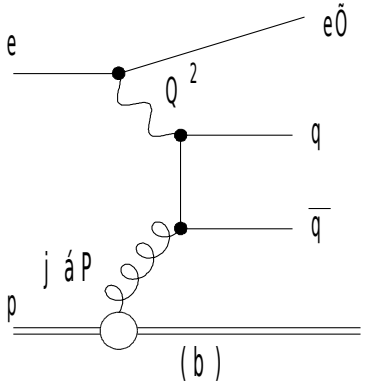


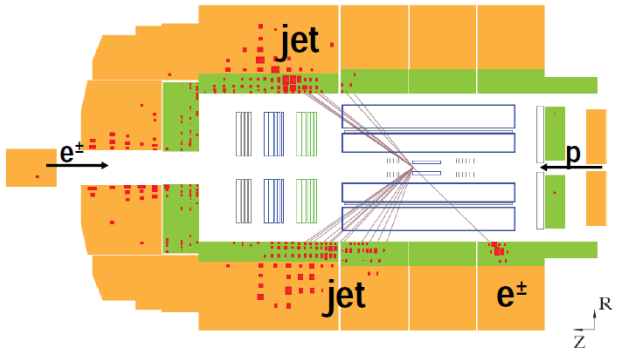


- No high-Pt jets in Breit frame

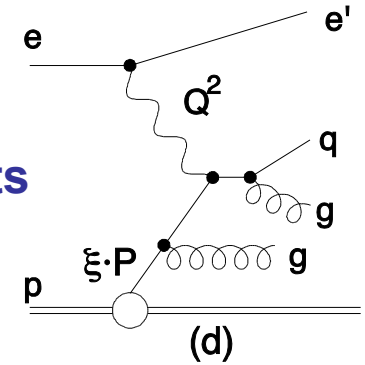
2 jets







3 jets



Variables:

$\xi = x(1 + M_{12}^2/Q^2)$ - parton momentum fraction

$\langle P_T \rangle_2 = \frac{1}{2}(P_T^{jet1} + P_T^{jet2})$ - average jet Pt

Multijet production and α_s extraction

$150 < Q^2 < 15\,000$ GeV^2 **$0.2 < y < 0.7$**

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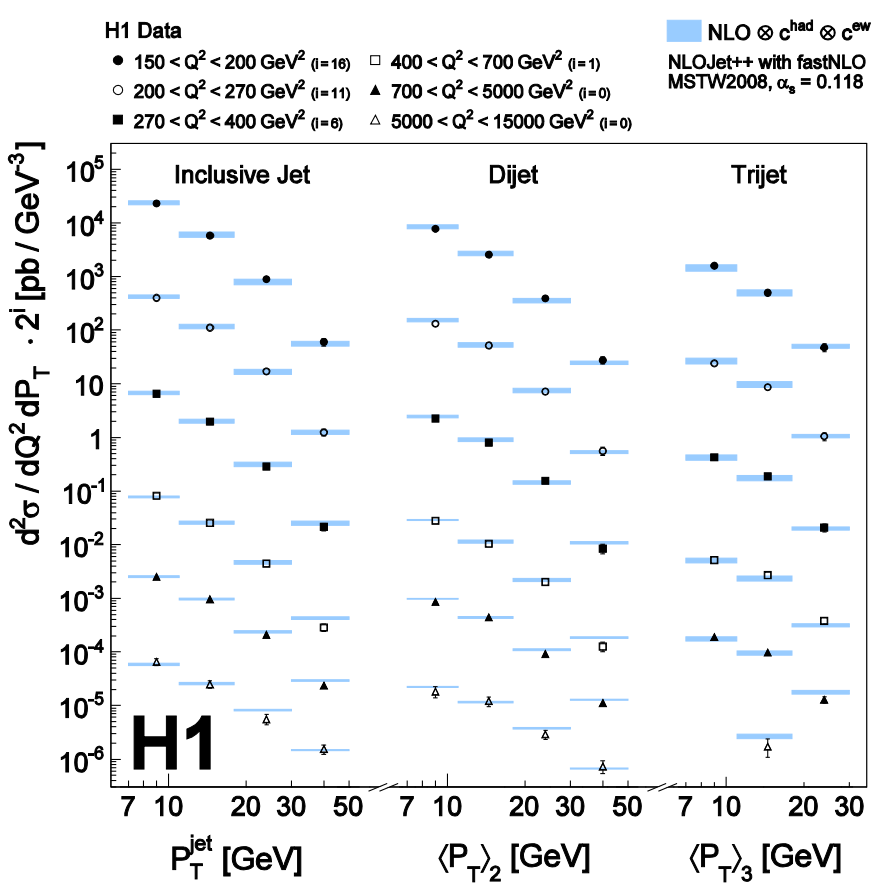
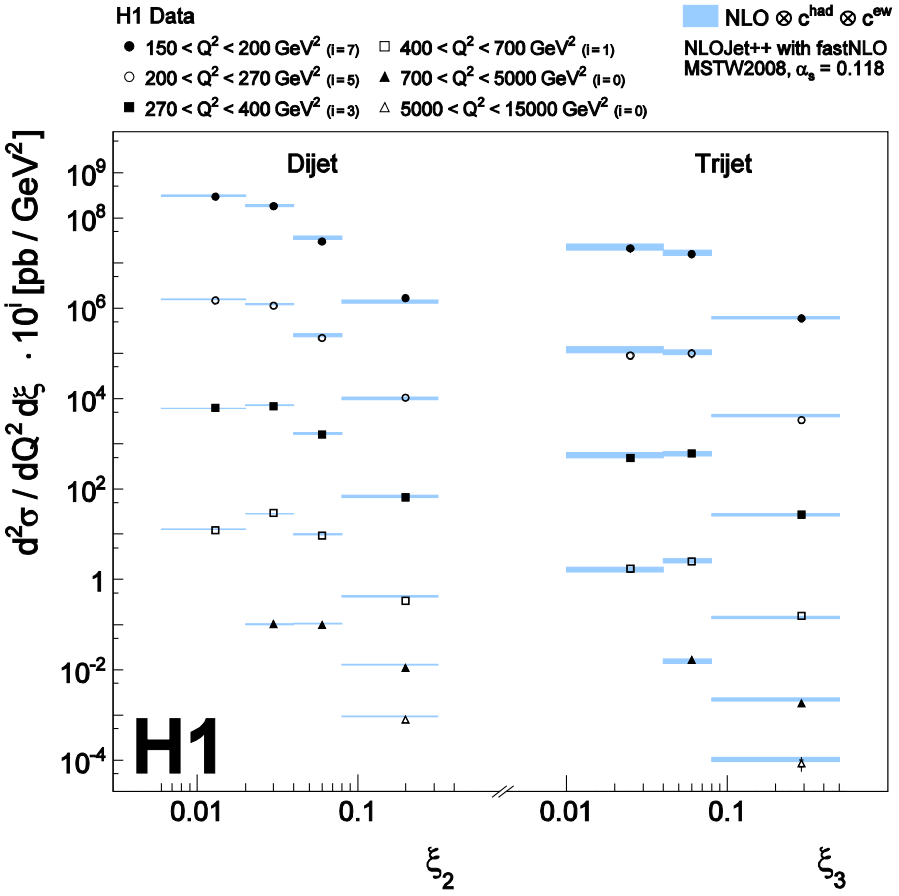
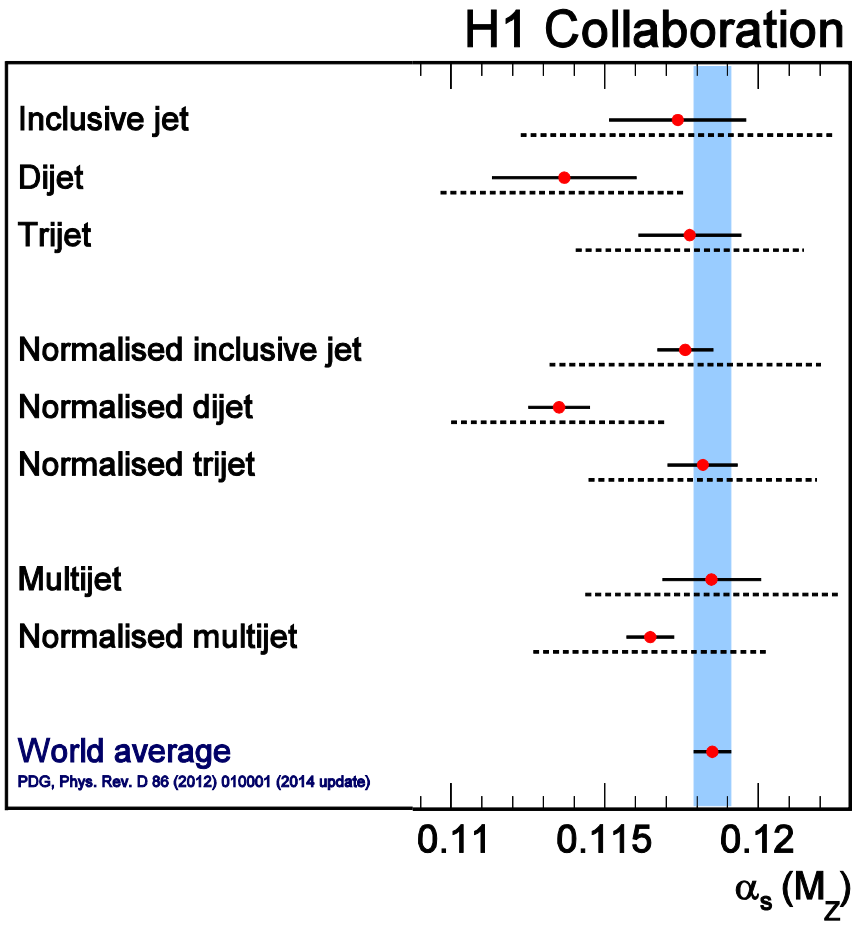
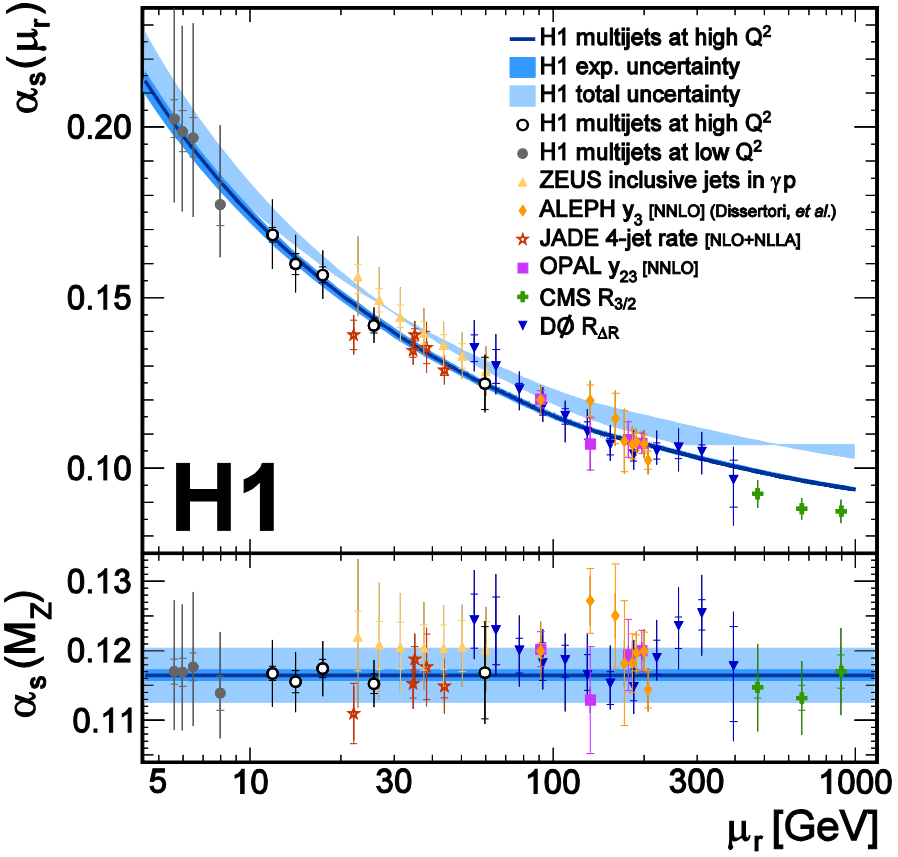




$$-1 < \eta_{lab}^{jet} < 2.5 \quad 5(7) < P_T^{jet} < 50GeV \quad M_{12} > 16GeV$$

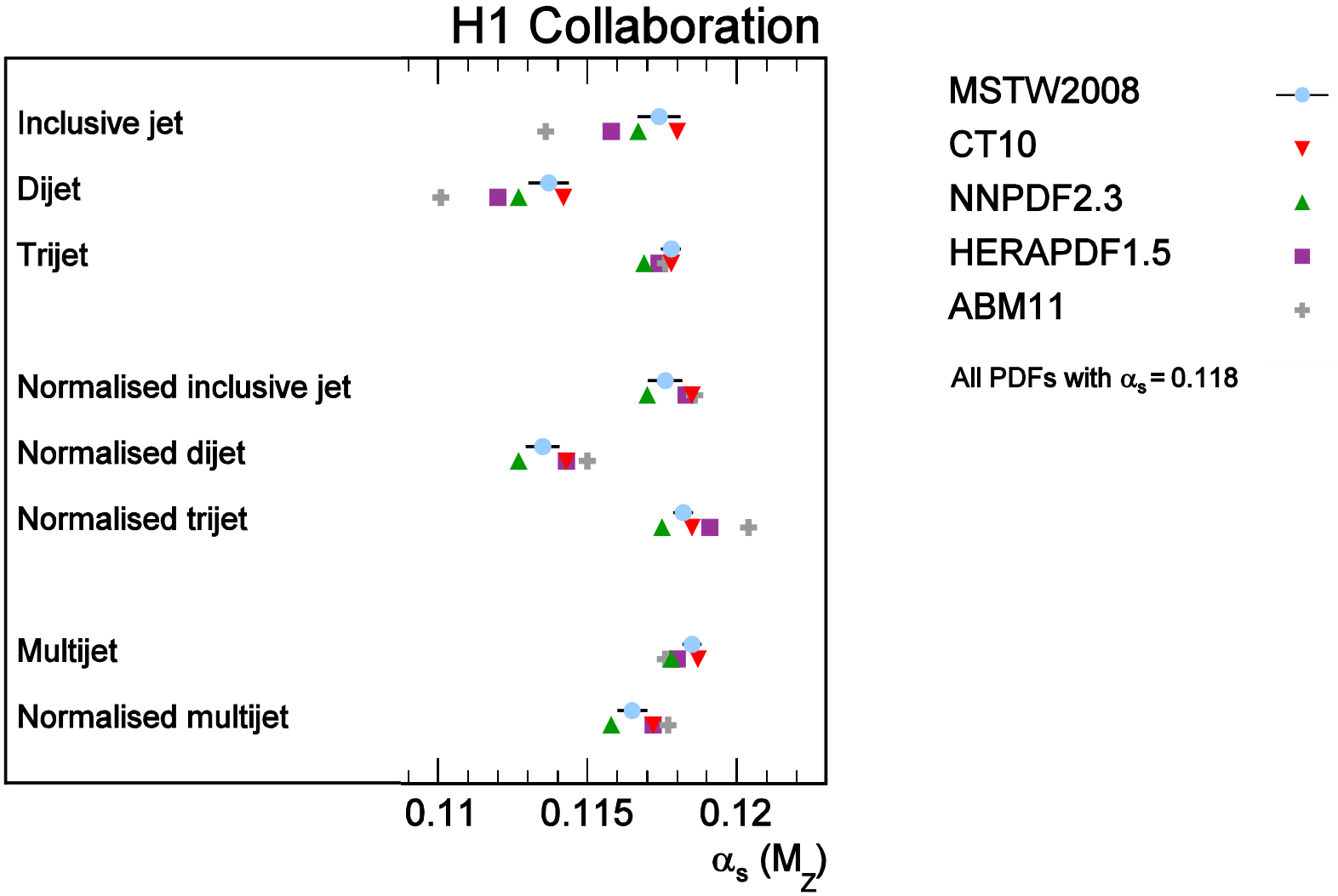
Multijet production and α_s extraction





$$\alpha_s(M_Z)|_{k_T} = 0.1165\ (8)_{\mathrm{exp}}\ (5)_{\mathrm{PDF}}\ (7)_{\mathrm{PDFset}}\ (3)_{\mathrm{PDF}(\alpha_s)}\ (8)_{\mathrm{had}}\ (36)_{\mu_r}$$
$$= 0.1165\ (8)_{\mathrm{exp}}\ (38)_{\mathrm{pdf,theo}}\ .$$

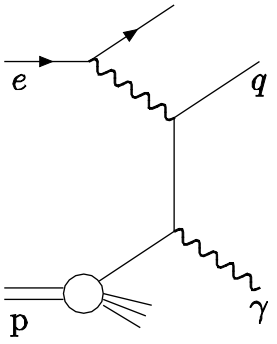
Deficit of dijets leads to lower value of α_s

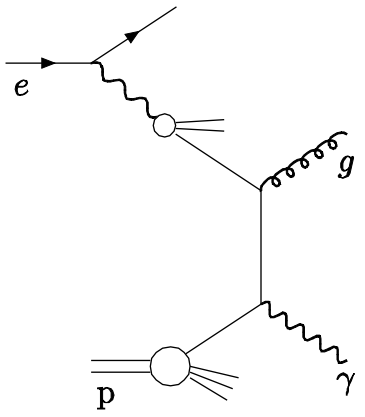


…attributed to missing higher order contributions in the calculations

Photoproduction of Isolated Photons, Inclusively and with a Jet, at HERA

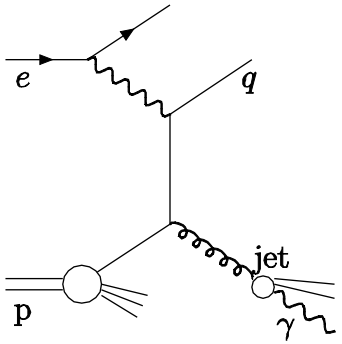
LO:

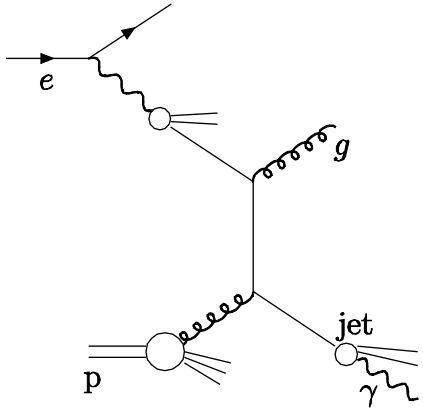




Direct (high x_γ) **Resolved (low x_γ)**

HO:





$$Q^2 < 1GeV^2$$

$$0.2 < y < 0.7$$

$$6 < E_T^\gamma < 15GeV$$

$$-0.7 < \eta^\gamma < 0.9$$

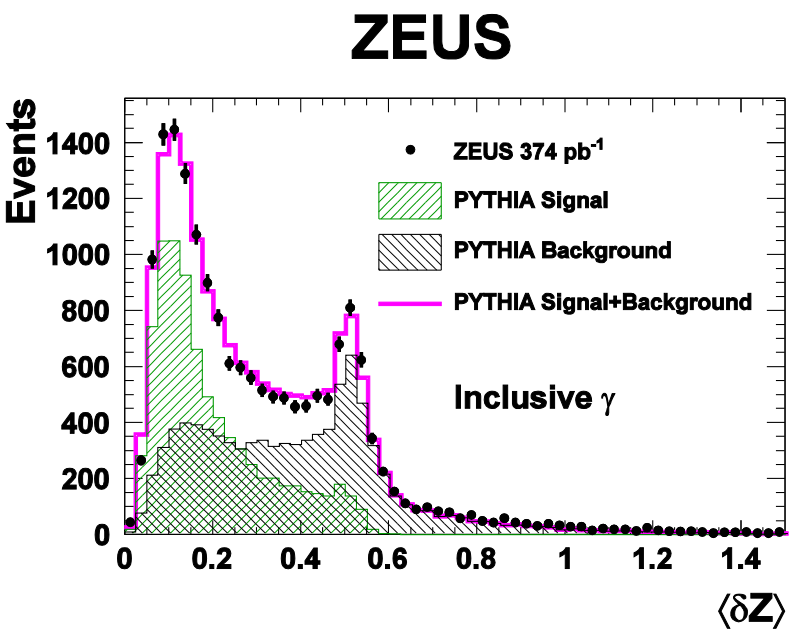
$$4 < E_T^{jet} < 35GeV$$

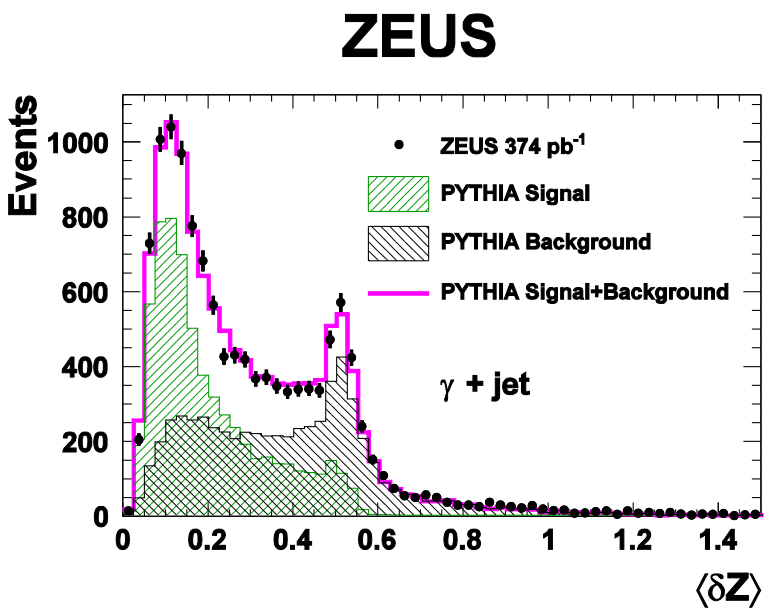
$$-1.5 < \eta^{jet} < 1.8$$

$$x_\gamma^{\mathrm{meas}} = \frac{E^\gamma - p_Z^\gamma + E^{\mathrm{jet}} - p_Z^{\mathrm{jet}}}{E^{\mathrm{all}} - p_Z^{\mathrm{all}}}$$

- **fraction of the incoming photon energy**

Extruction of Isolated Photon signal



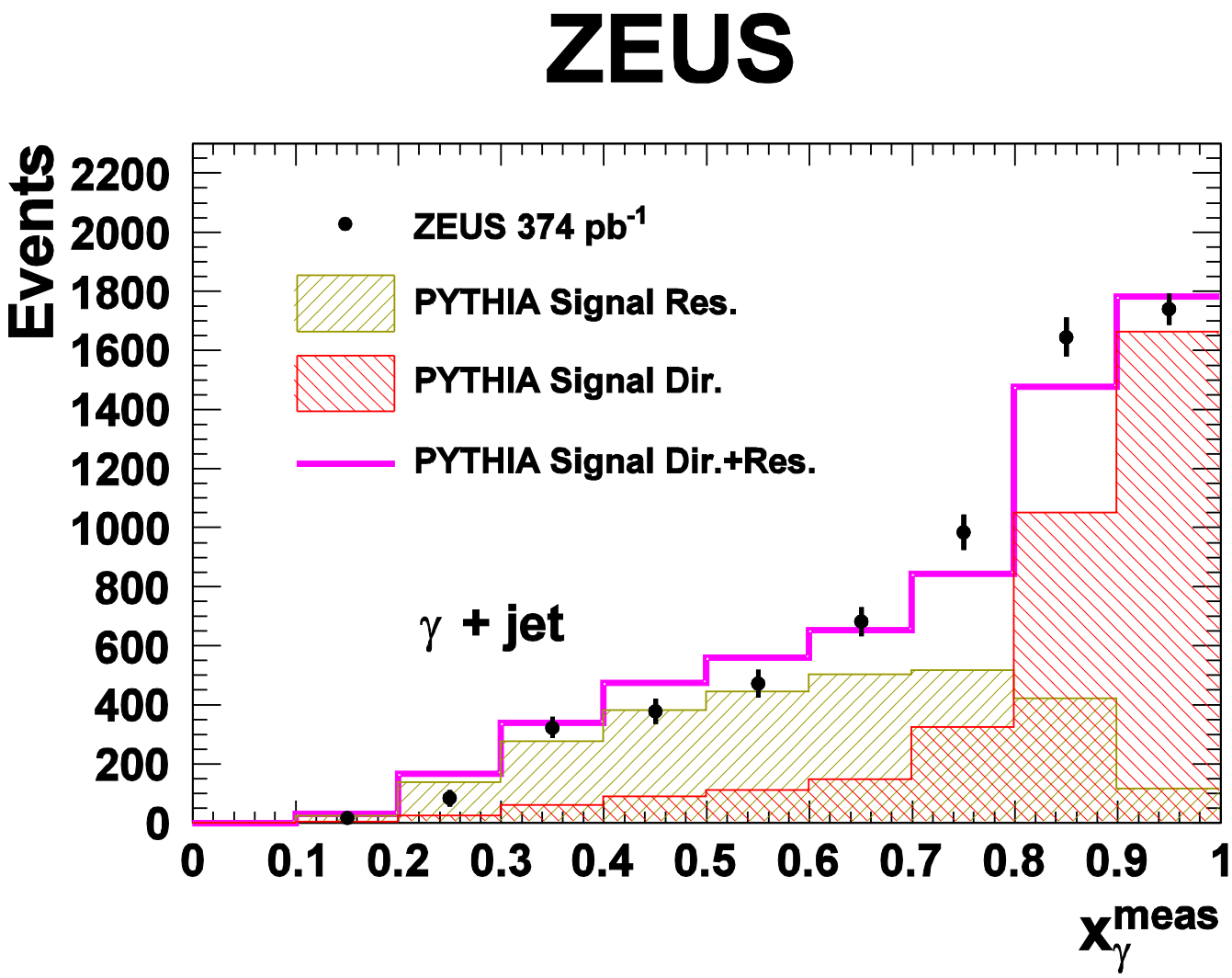


$$\langle \delta Z \rangle = \sum_i \left| Z_i - Z_{cluster} \right| / (w_{cell} \sum_i E_i)$$

- **energy weighted em-cluster size**

- *major background source – π^0 decays ($\langle \delta Z \rangle \approx 0.5$)*
- *statistical isolated photons counting (fit results)*

MC description of photoproduction of Isolated Photon + jet

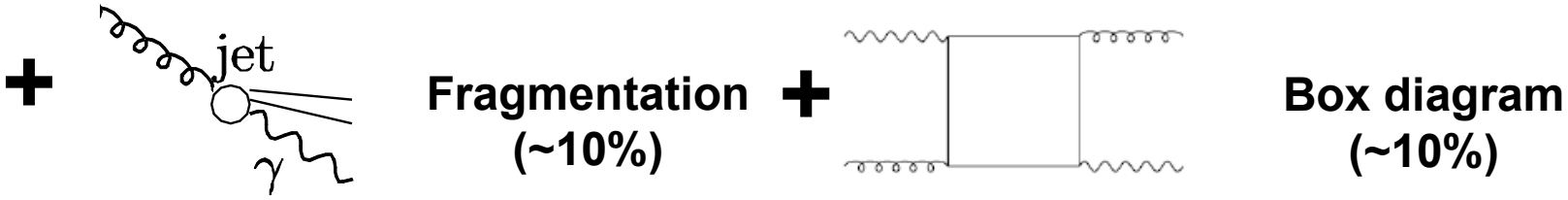


reasonable phenomenological description
(used to correct for detector effects)

Theoretical predictions for photoproduction of Isolated Photons

1. M. Fontannaz, J.Ph. Guillet and G. Heinrich (FGH)

Explicit calculation LO and NLO diagrams

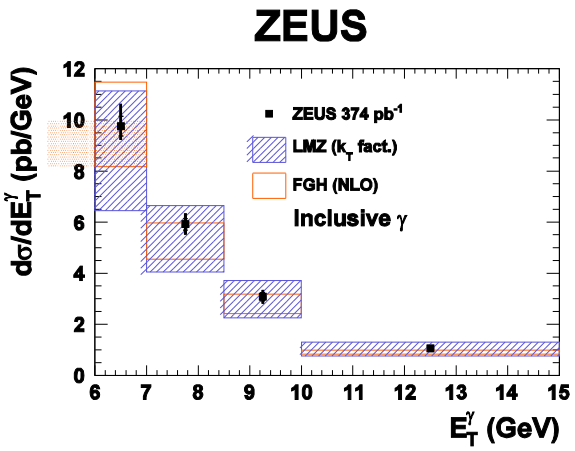


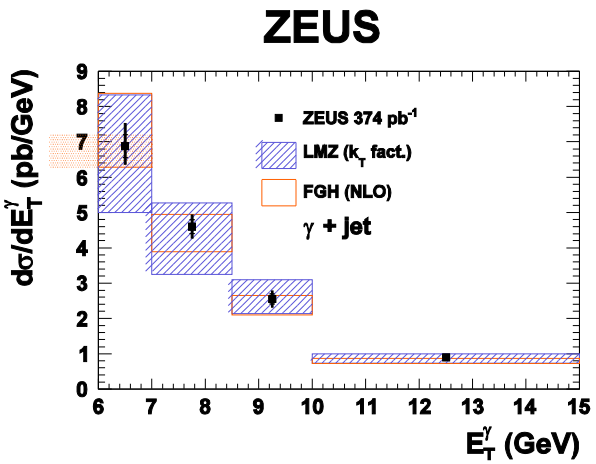
2. A.V. Lipatov, M.A. Malyshev and N.P. Zotov (LMZ)

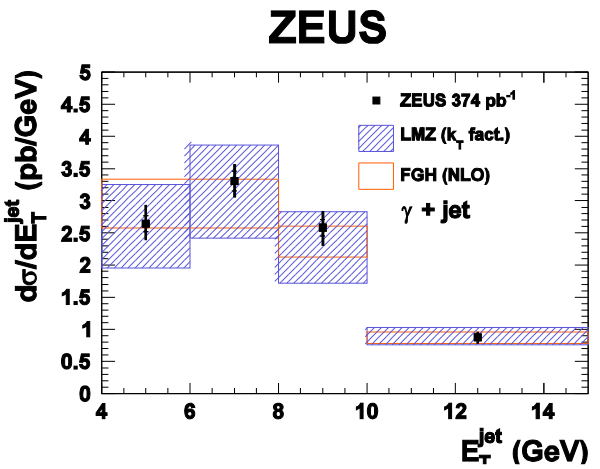
- *makes use of unintegrated parton densities in the proton, using the KMR formalism*

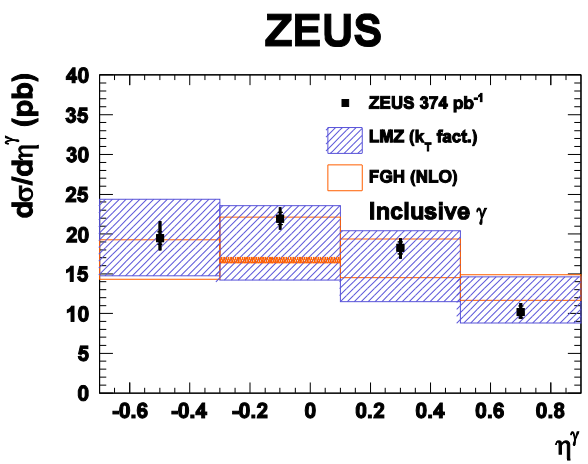
- *fragmentation terms are not included*

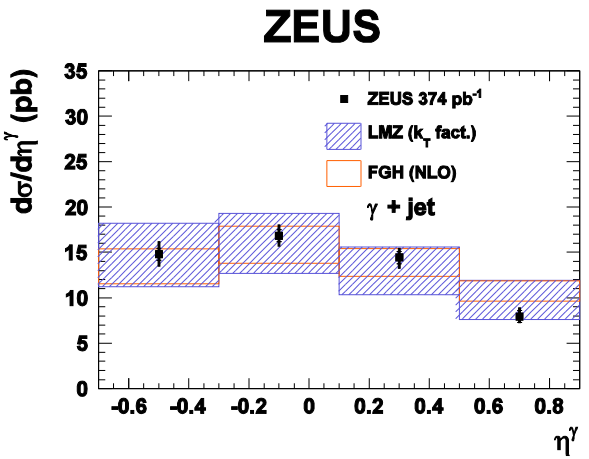
Isolated Photon cross sections

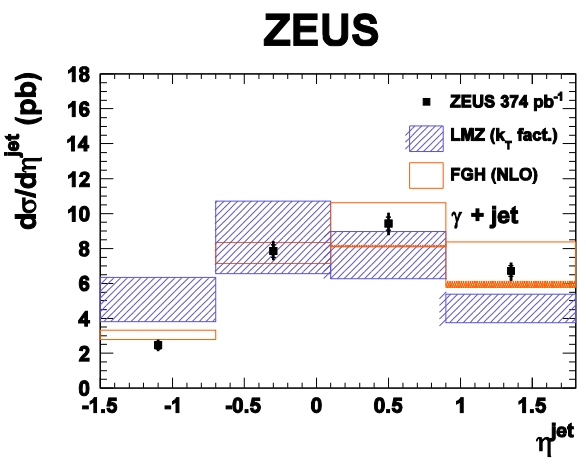






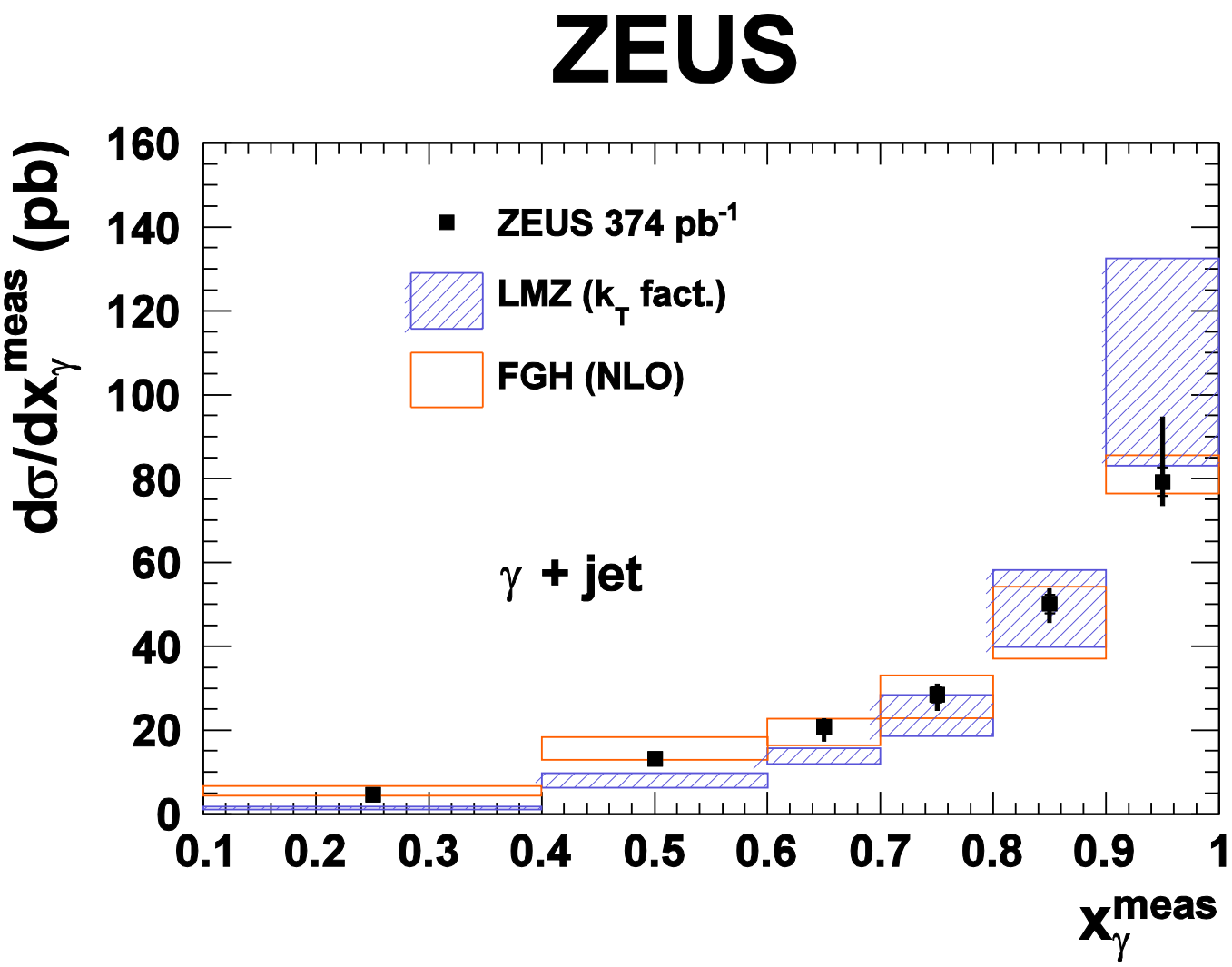






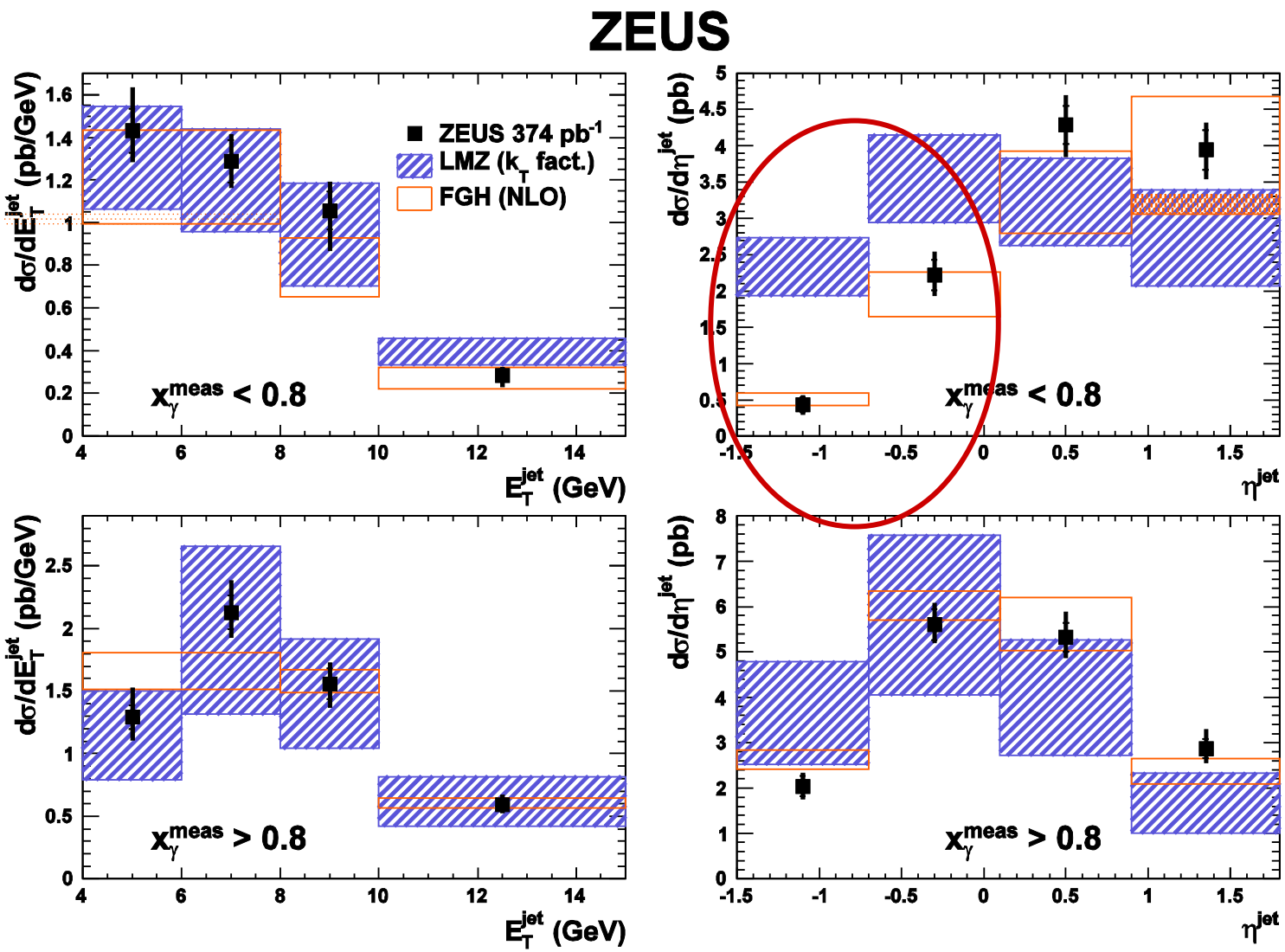
Overall reasonable agreement between data and both models

Further Isolated Photon cross sections



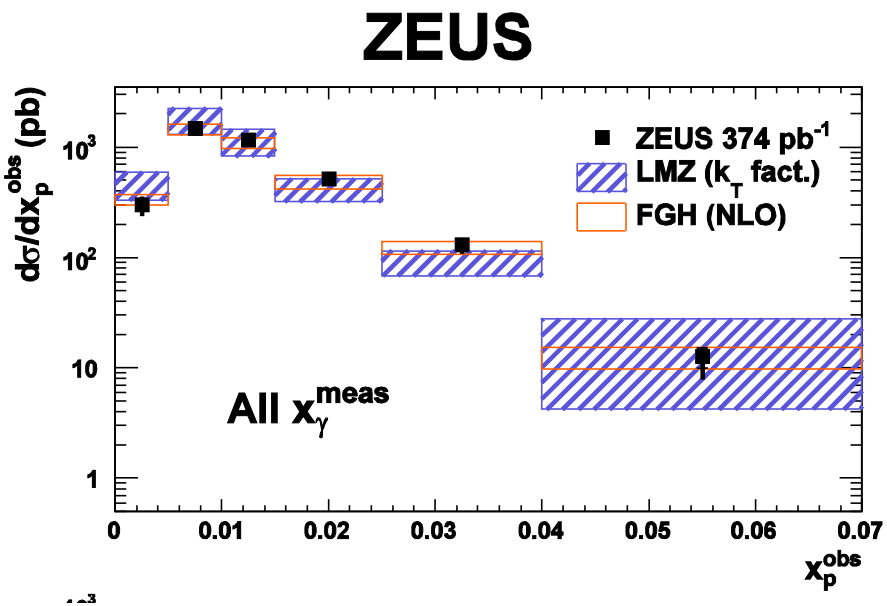
LMZ seems to be to much "direct"

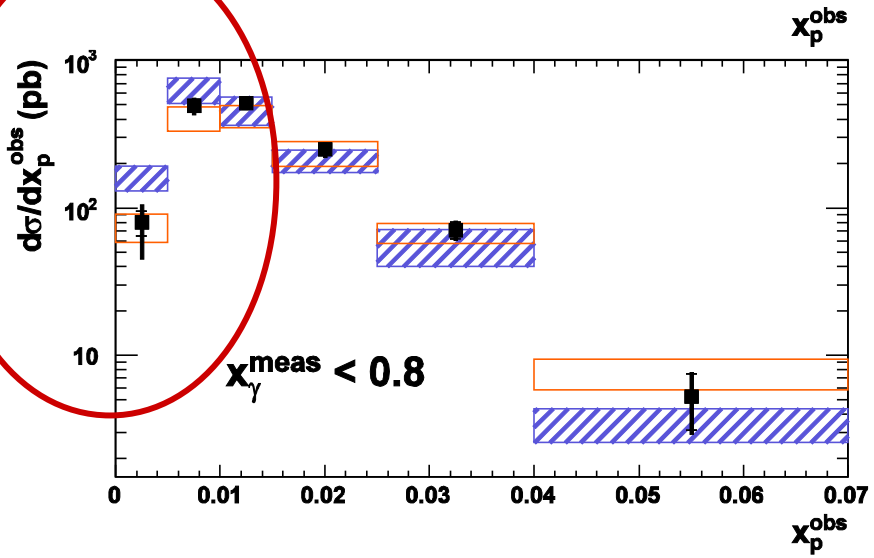
Further Isolated Photon cross sections

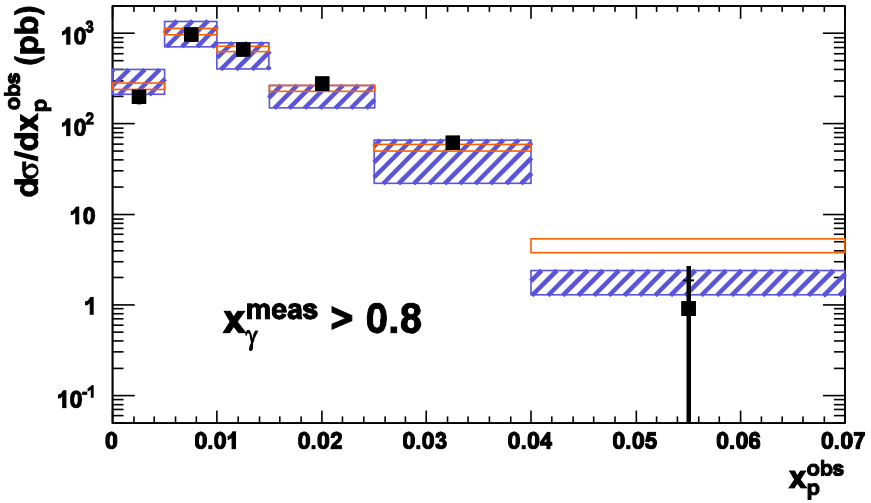


Too many LMZ jets shooting on proton side (mainly in resolved photon events)

Further Isolated Photon cross sections

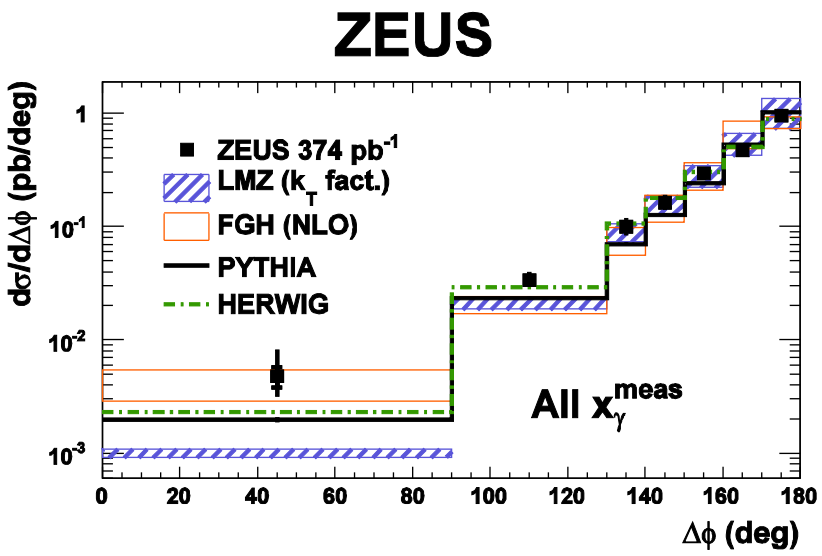


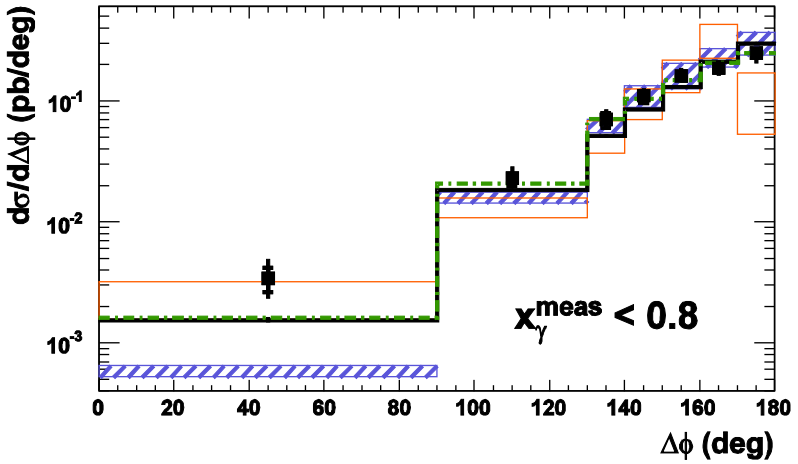


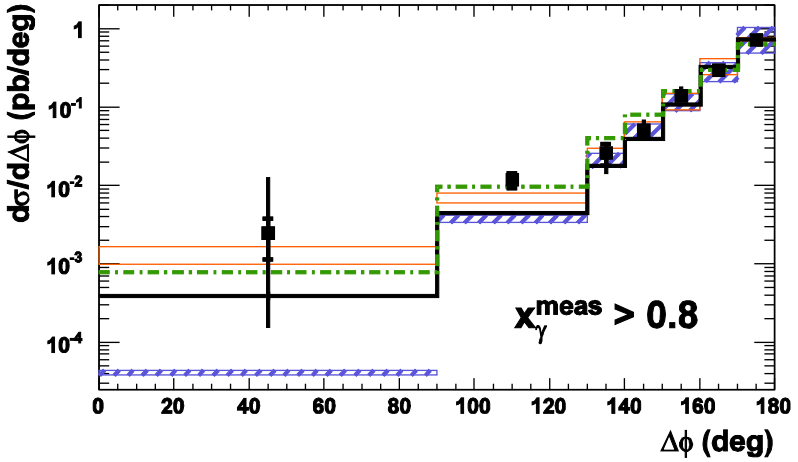


Too many low momentum partons in pronon contribute (mainly in resolved photon events) to the photon+jet photoproduction in LMZ model.

Further Isolated Photon cross sections







Too few same-side photon-jet pairs (both in resolved and direct photon events) predicted by the LMZ model.

Hadronic jet fragmentation contribution is important?

SUMMARY

H1 and ZEUS provide new results

Combination of H1 and ZEUS measurements:
→ HIGHER PRECISION

Sensitivity to the detailed QCD dynamics

Demand for the higher order QCD calculations

More final H1+ZEUS results to come