



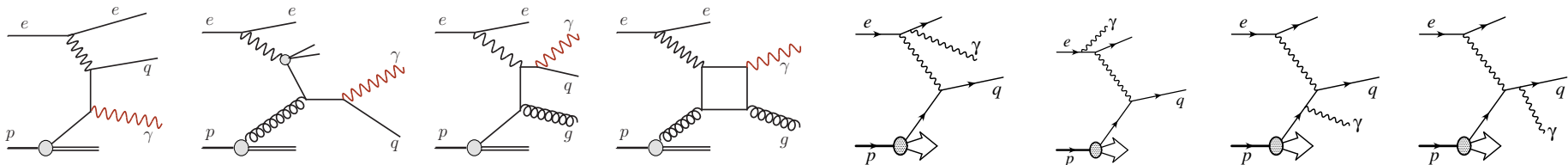
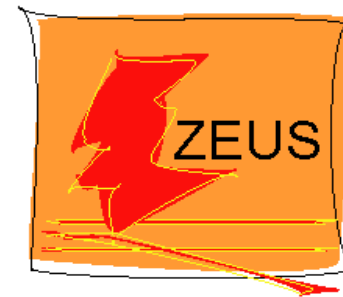
Isolated Photons at HERA

S. Levonian (DESY)

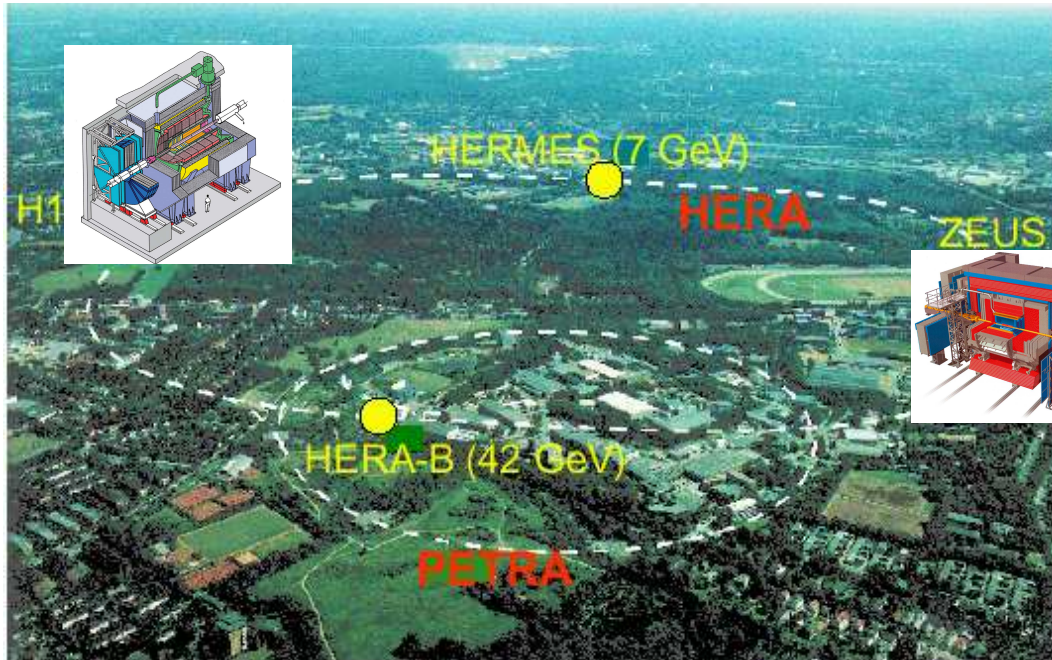
representing



and



HERA: The World's Only ep Collider

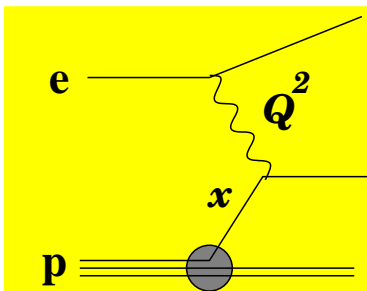
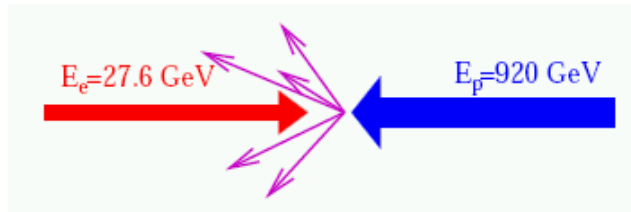
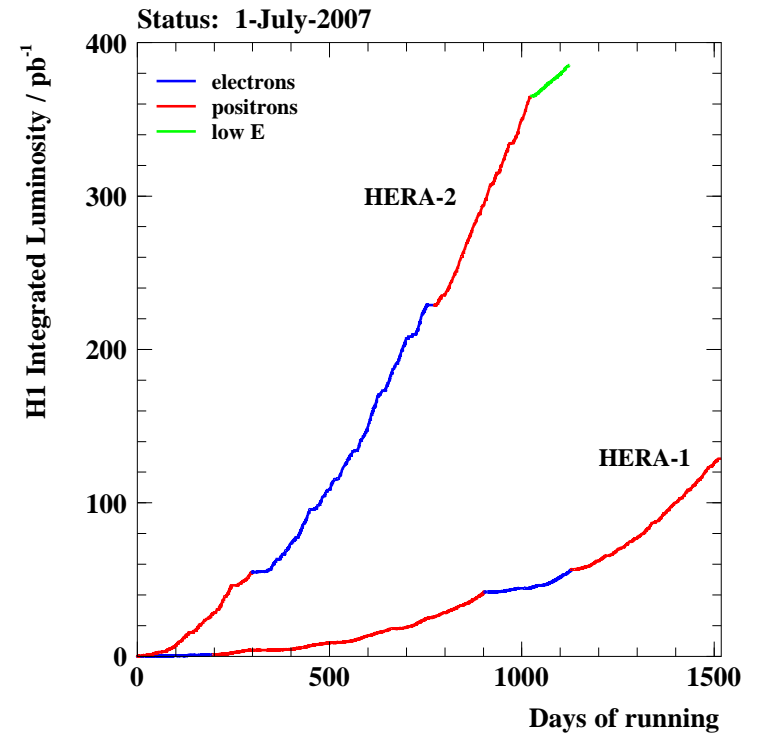


HERA-1 (1993-2000) $\simeq 120 \text{ pb}^{-1}$

HERA-2 (2003-2007) $\simeq 380 \text{ pb}^{-1}$

Final Data samples

H1+ZEUS: $2 \times 0.5 \text{ fb}^{-1}$



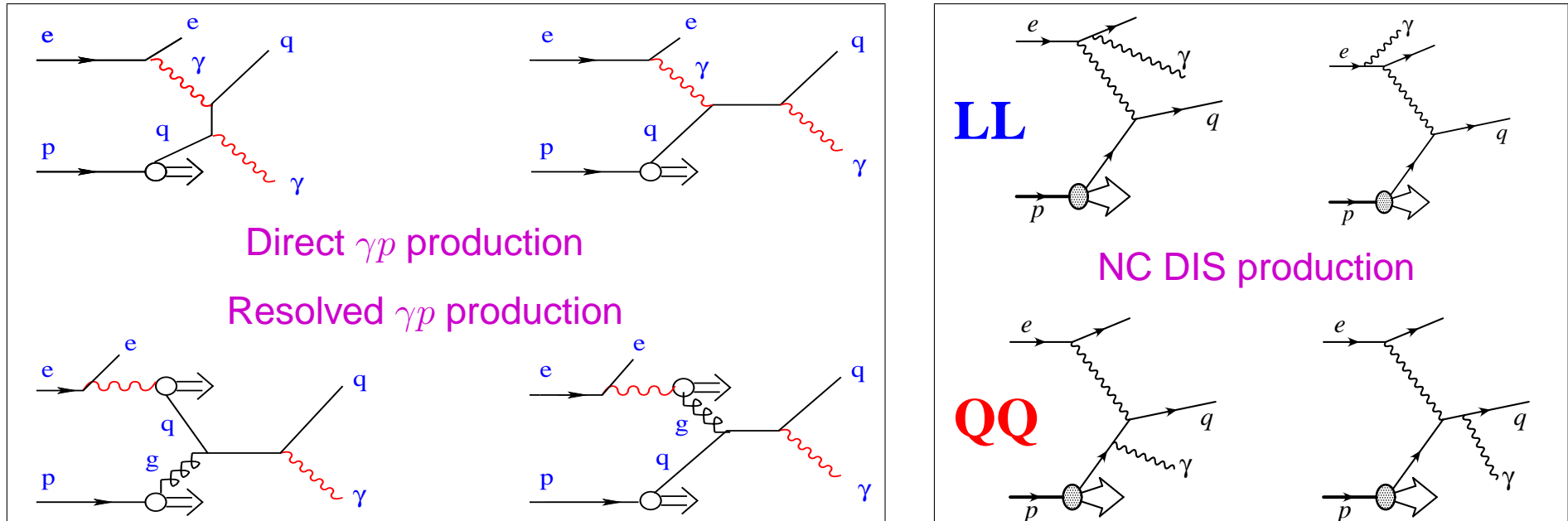
$$Q^2 > 1 \text{ GeV}^2$$

Deep Inelastic Scattering (DIS)



$$Q^2 \approx 0 \text{ GeV}^2$$

Photoproduction (PhP)

Prompt photons at HERA



Lowest-order diagrams for isolated photon production in ep scattering

- Free of hadronisation corrections for photon \Rightarrow direct link to parton level 
- DIS: Sensitivity to proton PDF (u -quarks radiate γ four times more often than d -quarks)
- PhP: Important SM background to possible New physics
- Low statistics as compared to jets (but somewhat smaller E-scale uncertainty)
- Difficult background from $\pi^0/\eta/\dots$ decays (dominant systematics, $\approx 5-10\%$) 

MC models and QCD calculations

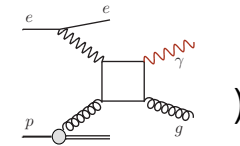
■ MC models

- ▷ PYTHIA: for QQ channels in DIS
- ▷ RAPGAP(H1), DGANGO(H1), DGANGO(ZEUS): for LL radiation in DIS
- ▷ PYTHIA, HERWIG: for photoproduction

■ QCD (Photoproduction)

- Fontannaz, Guillet, Heinrich (FGH) (2001,2004)

collinear factorisation, DGLAP evolution (includes also box diagram $\gamma g \rightarrow \gamma g$:



- Lipatov, Zotov (LZ) (2005, 2010)

k_t factorisation approach, using unintegrated parton densities (box diagram neglected so far)

■ QCD (D.I.S.)

- German-De Ridder, Kramer, Spiesberger (GKS) (2000)











- German-De Ridder, German, Poulsen (GGP) (2006)

collinear factorisation, DGLAP evolution ($\mathcal{O}(\alpha^3\alpha_s^0)$ for inclusive γ , $\mathcal{O}(\alpha^3\alpha_s)$ for $\gamma + jet$)

- Baranov,Lipatov, Zotov (BLZ) (2010)

k_t factorisation approach, using unintegrated parton densities (according to KMR prescription)

HERA data and publications on Isolated Photons

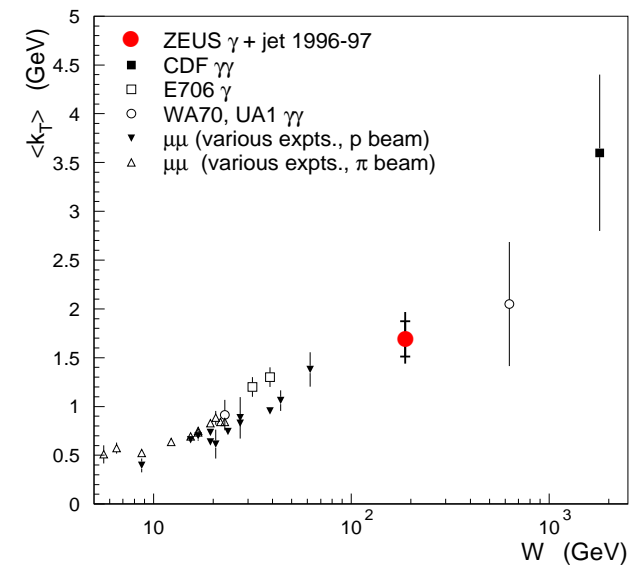
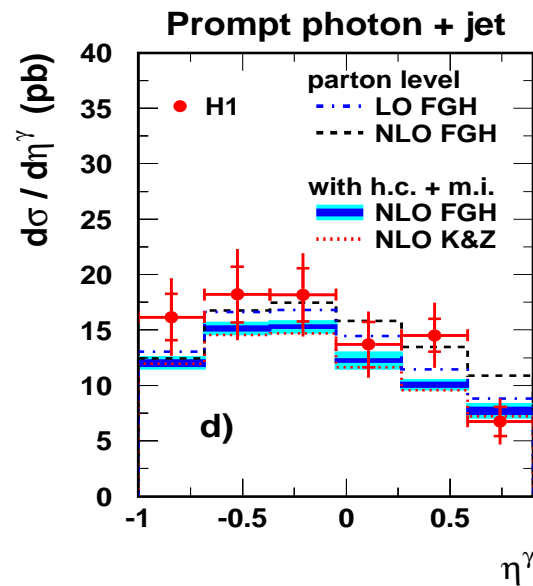
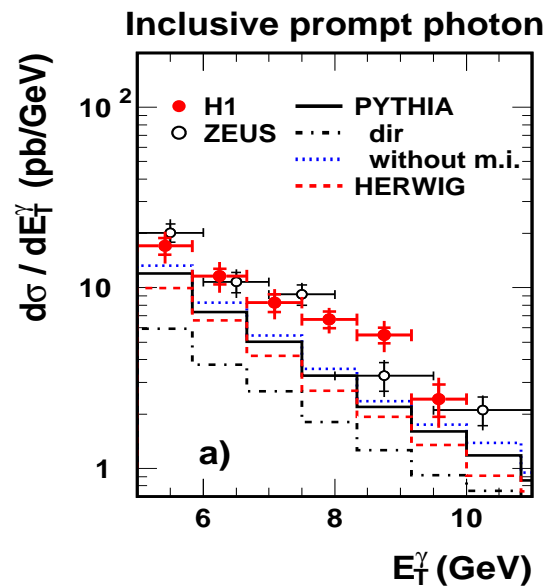
Publication	\mathcal{L}/pb^{-1}	Photoproduction	D.I.S.
1997 <i>PL B413</i>	(6)	 γ +jet	
2000 <i>PL B472</i>	■ (38)	 incl. γ	
2001 <i>PL B511</i>	■ (38)	 $\langle k_t \rangle$	
2004 <i>PL B595</i>	■ (121)	 incl. γ ; γ +jet	
2005 <i>EPJ C38</i>	■ (105)	 incl. γ ; γ +jet	
2007 <i>EPJ C49</i>	■ (77)	 γ +jet	
2008 <i>EPJ C54</i>	(227)	 incl. γ ; γ +jet	
2010 <i>EPJ C66</i>	(340)	 incl. γ ; γ +jet	
2010 <i>PL B687</i>	(320)	 incl. γ	
2012 => <i>PLB</i>	(326)	 γ +jet	

HERA-1

HERA-2

Messages from HERA-1 results

- ★ **LO MC**: shapes are well described, but overall cross sections fall below data by $\sim 50\%$
- ★ **NLO/LO** corrections are substantial, but still NLO rate is low by 25 – 30%
(note however limited experimental precision) \Rightarrow **Need for HO corrections?**
- ★ Intrinsic transverse momentum of the partons in the proton may explain $\gamma + jet$ data
 $\langle k_T \rangle = 1.7 \text{ GeV}$ is required (inferred from tuned Pythia) \Rightarrow **Non-collinear approximation?**



\Rightarrow **HERA-2: (3-4) fold statistics, improved systematics**

Isolated Photon Event selection



PhP sample ($\mathcal{L} = 340 \text{ pb}^{-1}$)

- **Inclusive phase space**

- ▷ $6 < E_T^\gamma < 15 \text{ GeV}$
- ▷ $-1.0 < \eta^\gamma < 2.43$
- ▷ $z = E_T^\gamma / E_T^{\gamma \text{ jet}} > 0.9$
- ▷ $Q^2 < 1 \text{ GeV}^2, \quad 0.1 < y < 0.7$

- **Photon + jet phase space**

- ▷ $p_T^{\text{jet}} > 4.5 \text{ GeV}$ (inclusive k_T algorithm)
- ▷ $-1.3 < \eta^{\text{jet}} < 2.3$



DIS sample ($\mathcal{L} = 326 \text{ pb}^{-1}$)

- **Inclusive phase space**

- ▷ $4 < E_T^\gamma < 15 \text{ GeV}$
- ▷ $-0.7 < \eta^\gamma < 0.9$
- ▷ $z = E_T^\gamma / E_T^{\gamma \text{ jet}} > 0.9$
- ▷ $10 < Q^2 < 350 \text{ GeV}^2, W_X > 5 \text{ GeV}$

- **Photon + jet phase space**

- ▷ $p_T^{\text{jet}} > 2.5 \text{ GeV}$ (inclusive k_T algorithm)
- ▷ $-1.5 < \eta^{\text{jet}} < 1.8$

Isolated Photon Event selection



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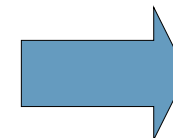
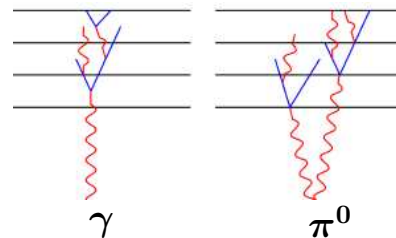
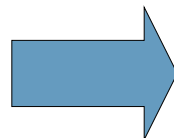
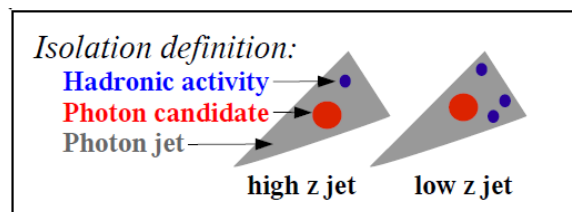
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- Photon + jet phase space**

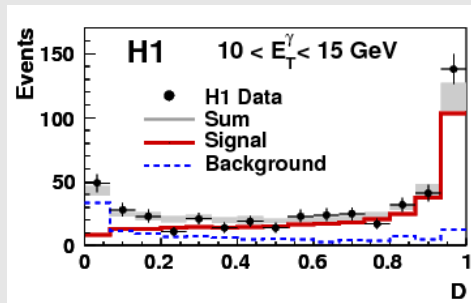
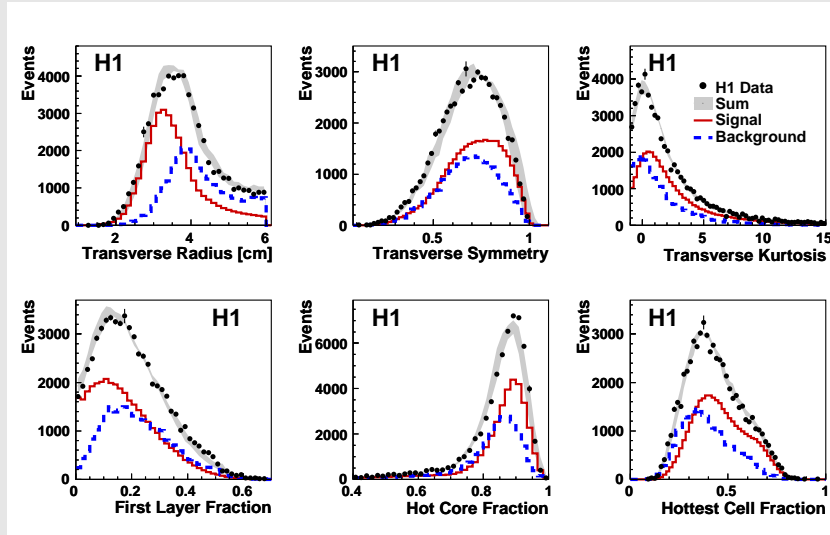
- ▷ $p_T^{\text{jet}} > 2.5 \text{ GeV}$ (inclusive k_T algorithm)
- ▷ $-1.5 < \eta^{\text{jet}} < 1.8$



shower shape
analysis

Signal extraction

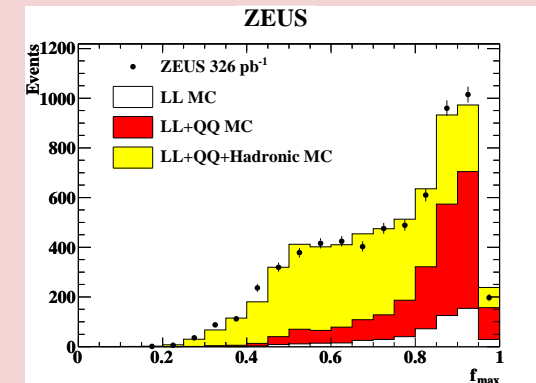
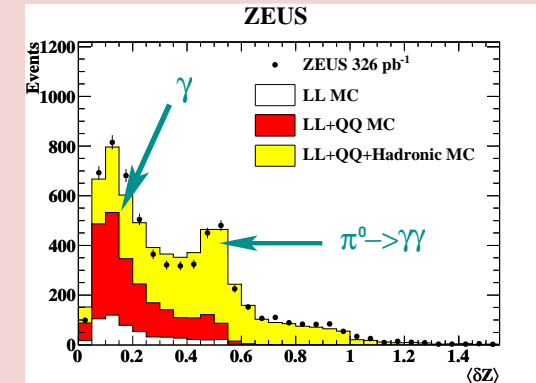
H1 (photoproduction)



Discriminant distribution
in one $(E_T^\gamma, \eta^\gamma)$ bin

- Use combined discriminant $D = P_\gamma / (P_\gamma + P_{bgr})$ based on *em* shower shape parameters, then unfold to extract signal
- Signal purity is in average $\sim 60\%$

ZEUS (NC DIS)



- Use lateral e.m. cluster width $\langle \delta z \rangle$, and energy fraction in most energetic cell, f_{max}
- Remaining bgr is subtracted statistically
- Signal purity is **30%** (γ) and **40%** ($\gamma + jet$)

Prompt Photons in PhP: Cross sections

• Inclusive cross sections

FGH: underestimate cross section by $\sim 20\%$,
problems at low η^γ

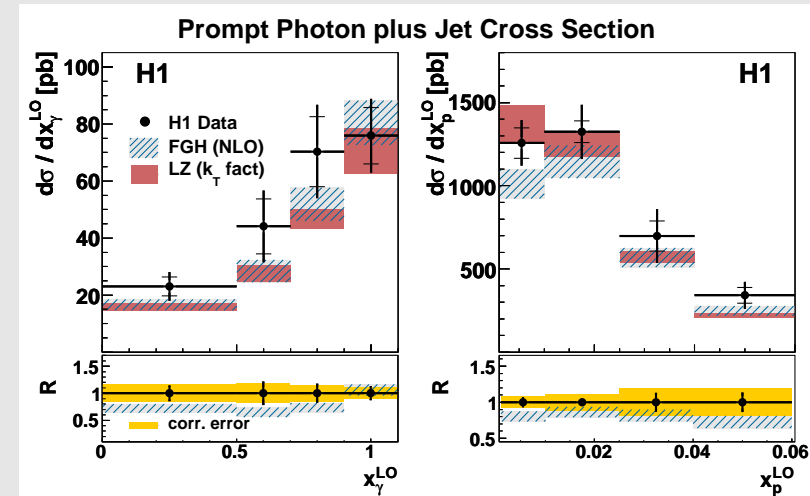
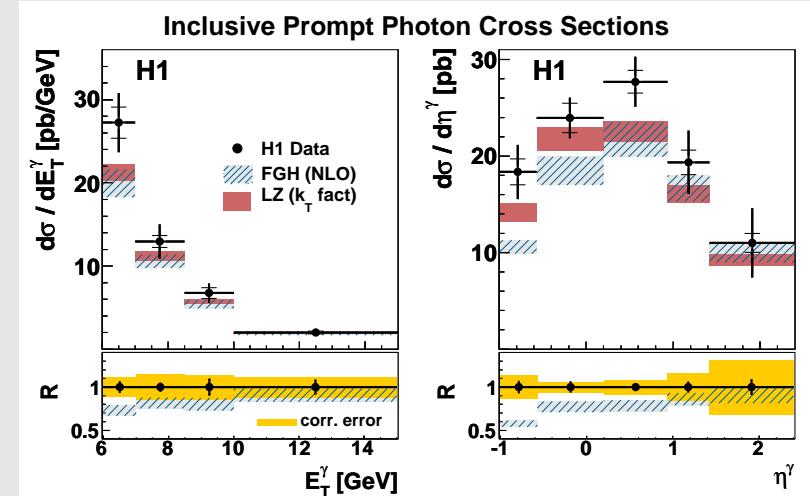
LZ: comes closer to the data

• $\gamma + jet$ cross sections

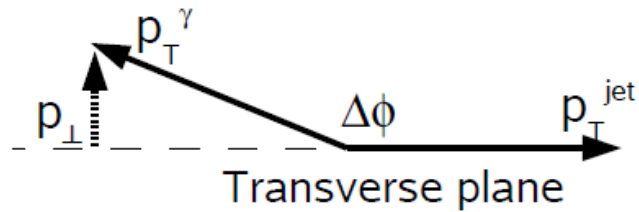
both calculations provide fair description,

k_T -fact. (LZ) improves agreement at low x_p^{LO}

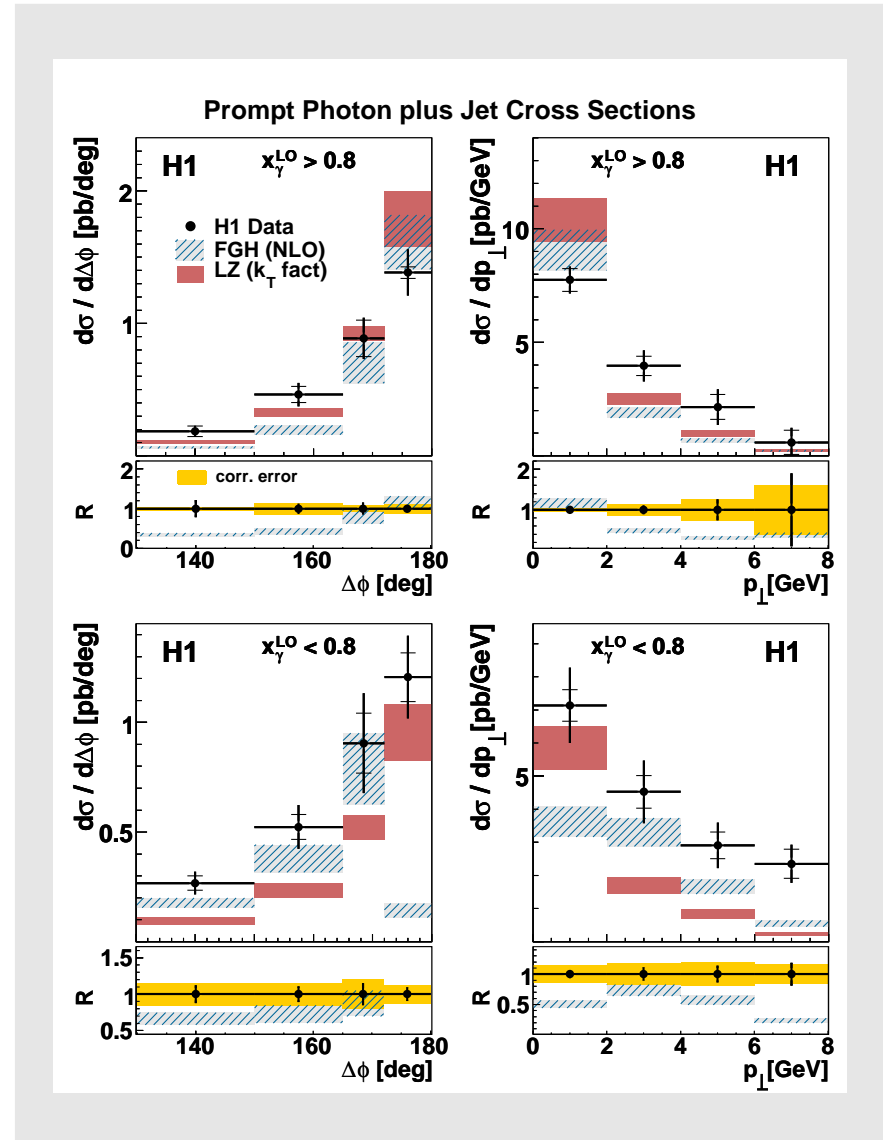
$$x_\gamma^{LO} = E_T^\gamma \frac{e^{-\eta^{jet}} + e^{-\eta^\gamma}}{2yE_e}; \quad x_p^{LO} = E_T^\gamma \frac{e^{\eta^{jet}} + e^{\eta^\gamma}}{2E_p}$$



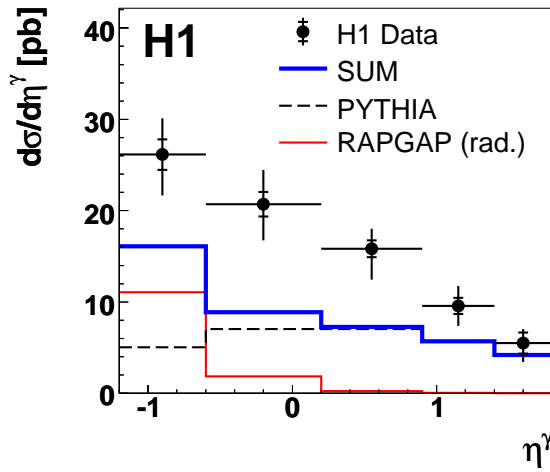
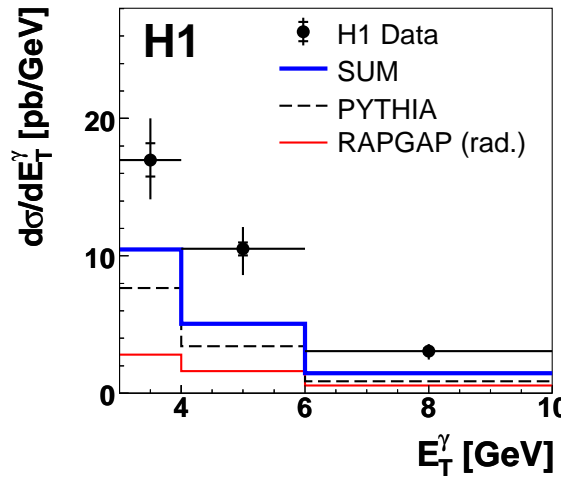
Prompt Photons in PhP: γ -jet correlations



- Study photon-jet correlations in direct (resolved) enhanced phase space
- Direct process is more back-to-back
- Sensitive to soft gluon emission in the highest $\Delta\Phi$ bin
- LZ missing diagrams are expected to contribute in tails of resolved cross sections



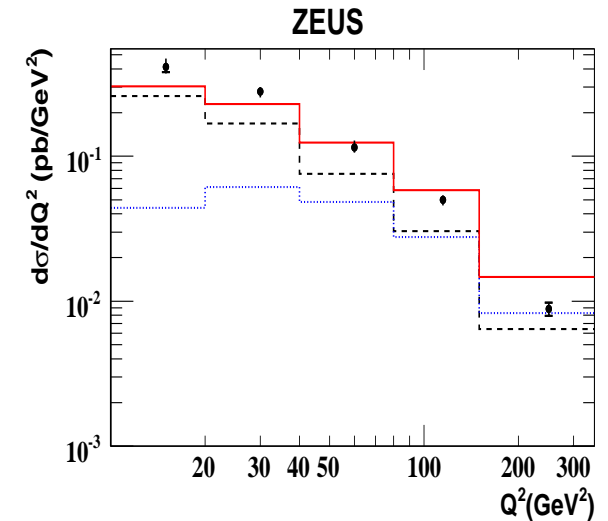
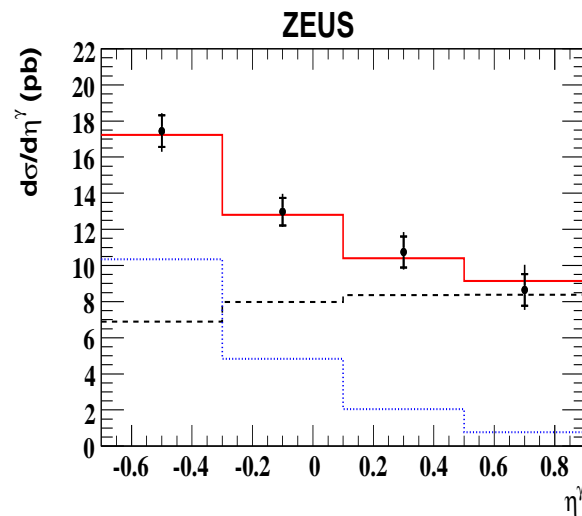
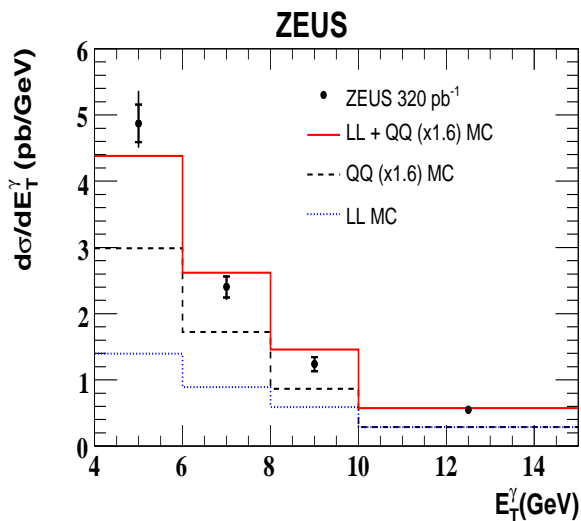
Prompt Photons in DIS: Inclusive cross sections



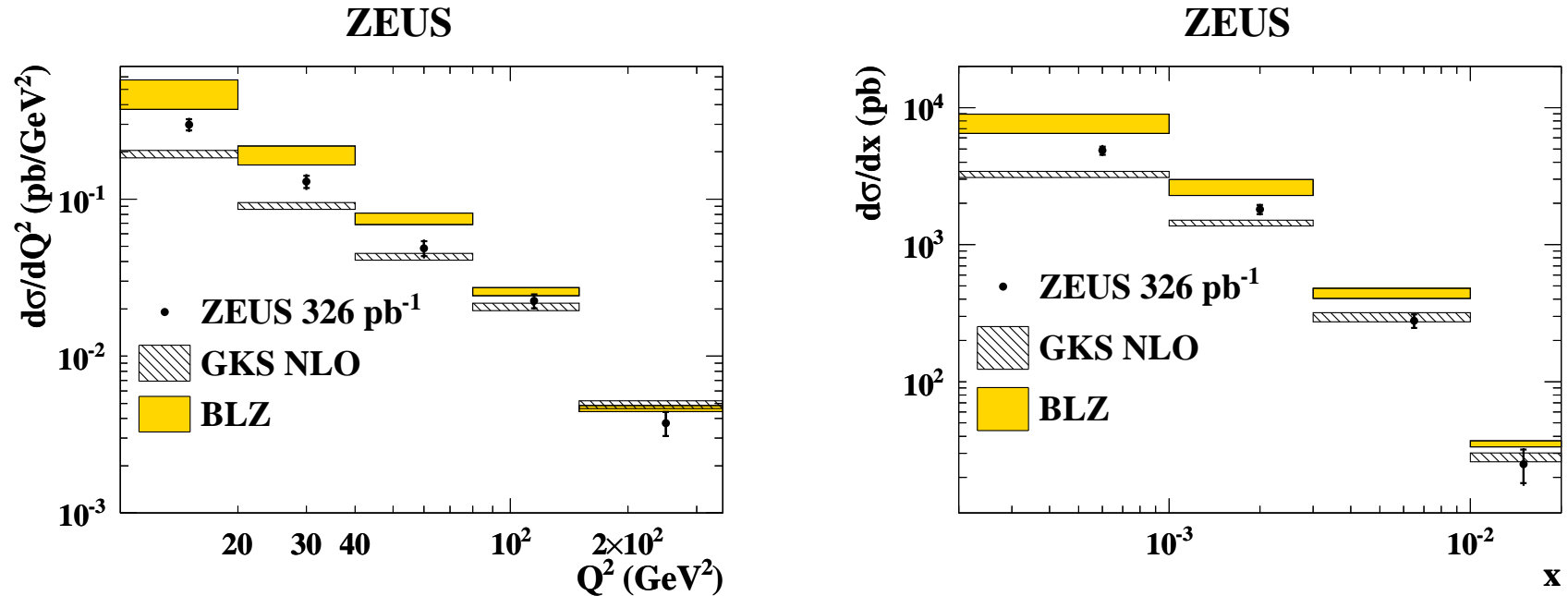
Both measurements are consistent

LO MC needs significant scaling:
 $QQ(PYTHIA) \times 1.6$

Same for $\mathcal{O}(\alpha^3\alpha_s^0)$ QCD calculations (not shown)

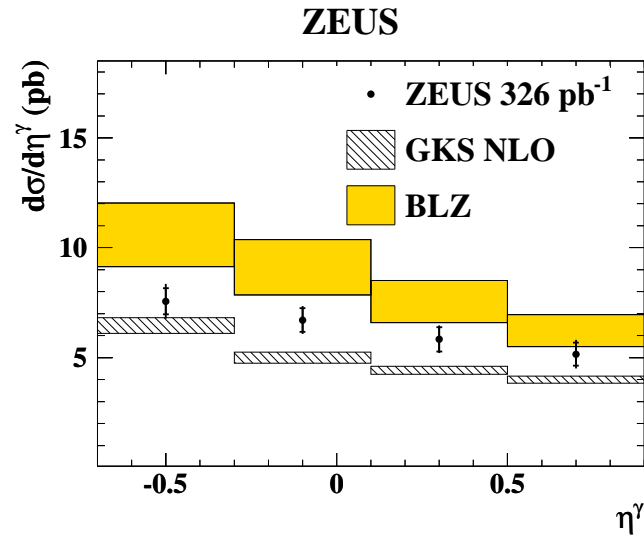
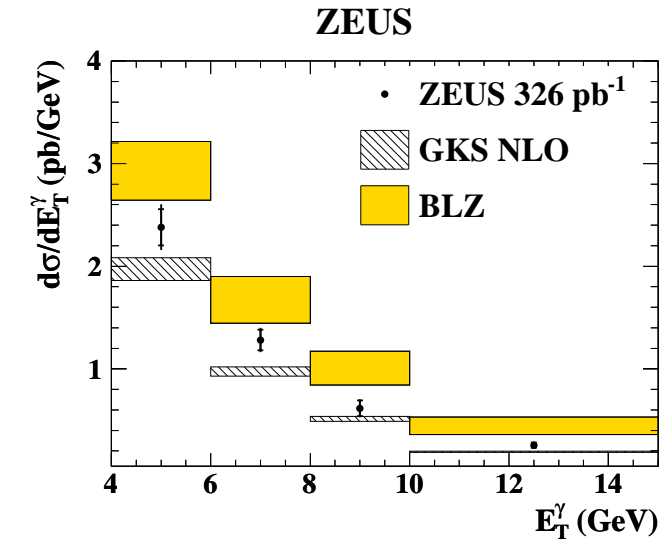


Prompt Photons in DIS: $\gamma + jet$



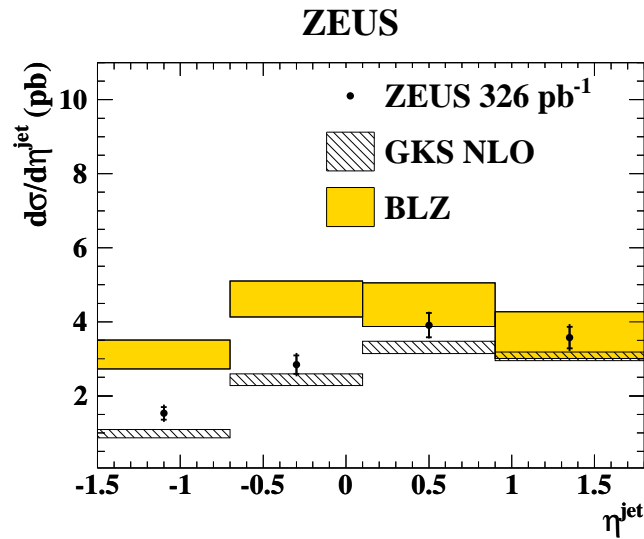
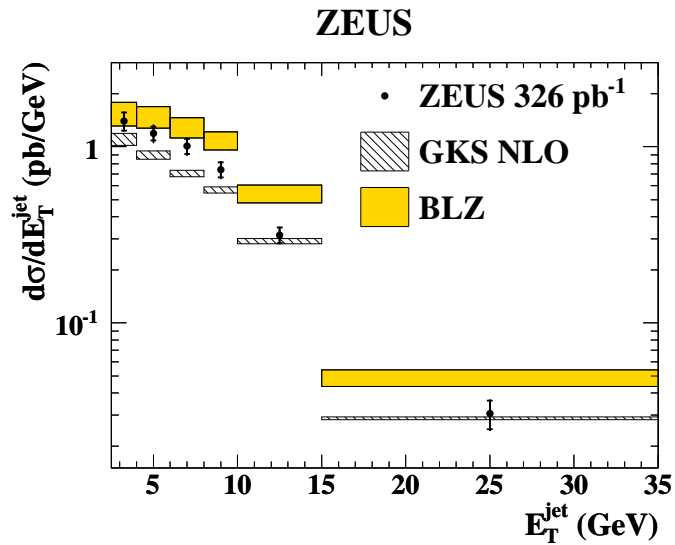
- Significantly improved precision as compared to HERA-1 data
- NLO calculations improves LO ones by 35%
- Problems are mainly observed at low Q^2 and low x :
GKS NLO still underestimate cross sections by $\sim 20\%$
while BLZ (k_T -factorisation) predicts too high rate

Prompt Photons in DIS: $\gamma + jet$



Photon

Shapes are fairly well described



Jet

GKS NLO describes shapes
 BLZ comes too high at backward η^{jet}

Summary

- HERA collider experiments completed measurements of high E_t isolated photons both in photoproduction and DIS regimes, using full HERA-2 data samples.

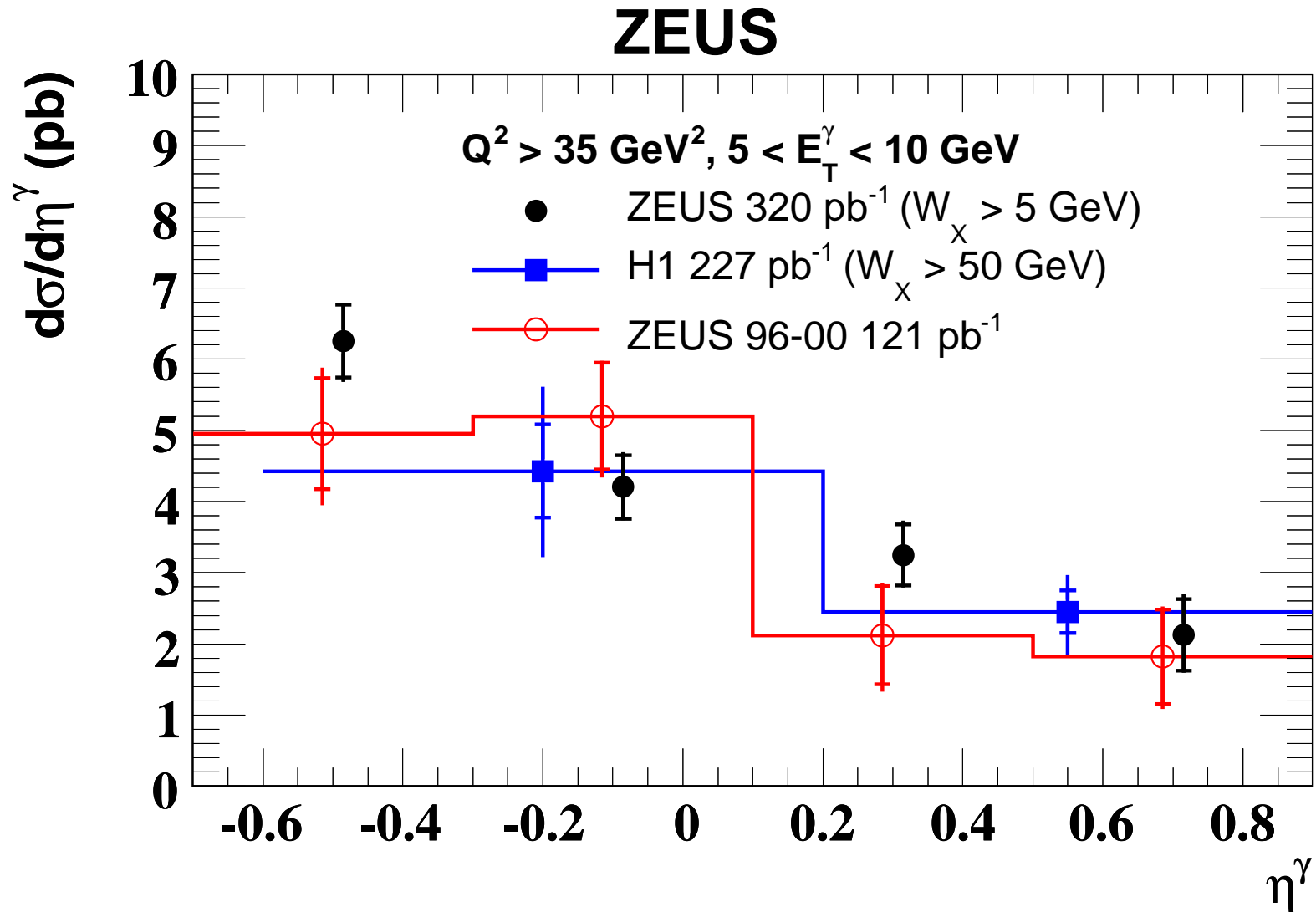
Compared to previous publications based on HERA-1 data experimental precision is improved by factor of two (from 25 – 30% to 10 – 15%)

- Prompt photons production still remains a challenge for theory: NLO QCD calculations in collinear approximation underestimate cross sections. k_T -factorisation approach in several aspects comes closer to the data, yet it fails to describe them in all details.

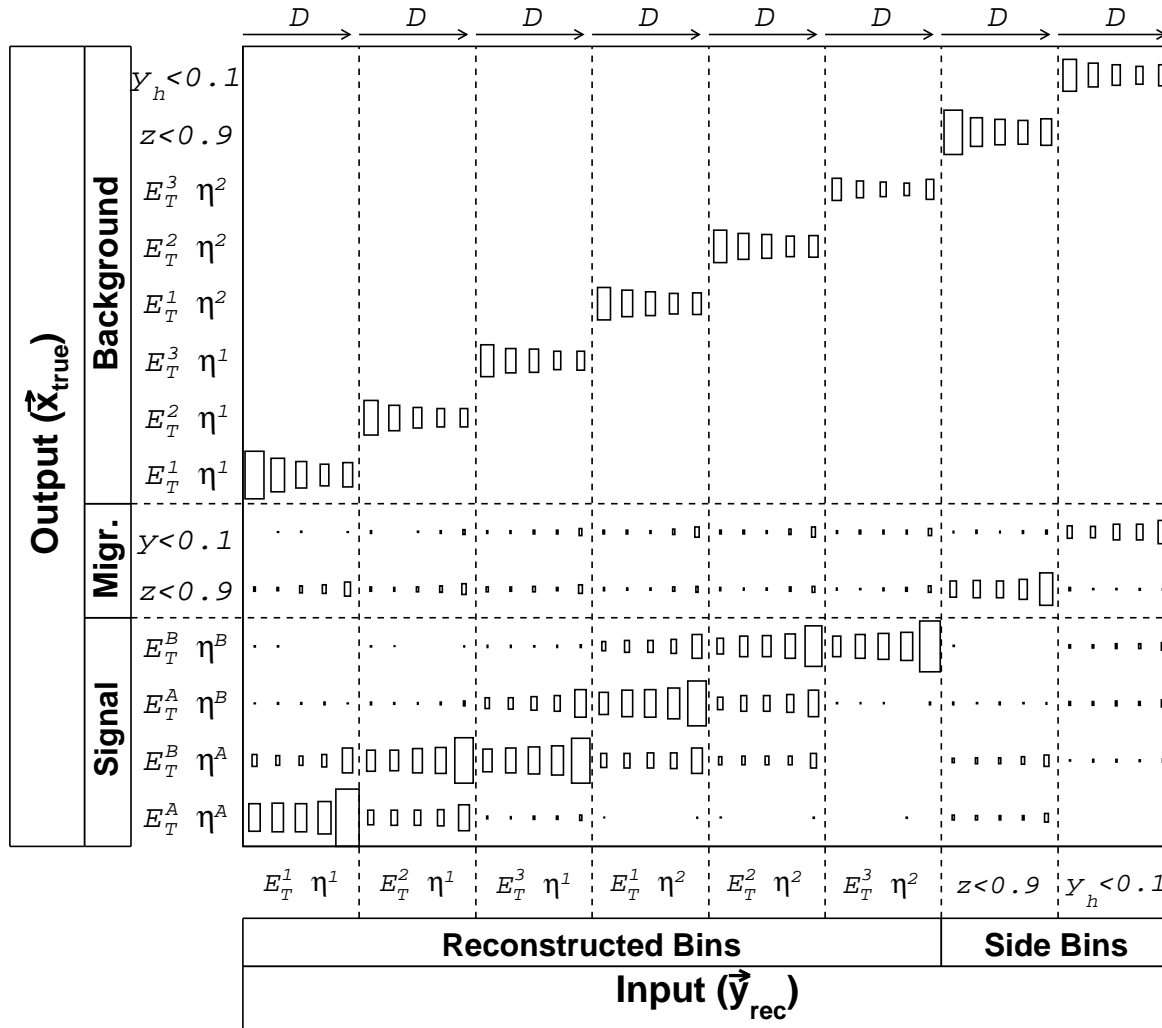
- Recently published H1 and ZEUS results can be used to gain deeper insight into underlying QCD dynamics of this reaction.

Backup Slides

Prompt photons: H1 vs ZEUS in a common phase space



Prompt photons: Unfolding Matrix



$$A \vec{x}_{\text{true}} = \vec{y}_{\text{rec}}$$

(A is computed using PYTHIA simulation for sig + bgr in extended phase space)