Jet Cross Sections in $D^{*\pm}$ Photoproduction with ZEUS

Takanori Kohno (University of Oxford)
for the ZEUS Collaboration

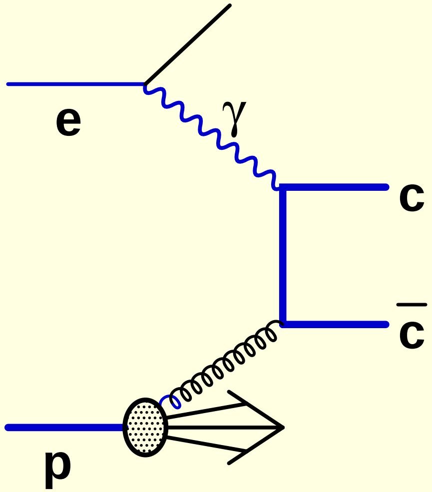
XIII International Workshop on Deep Inelastic Scattering
Madison, Wisconsin, USA
April 27 – May 1, 2005

Introduction

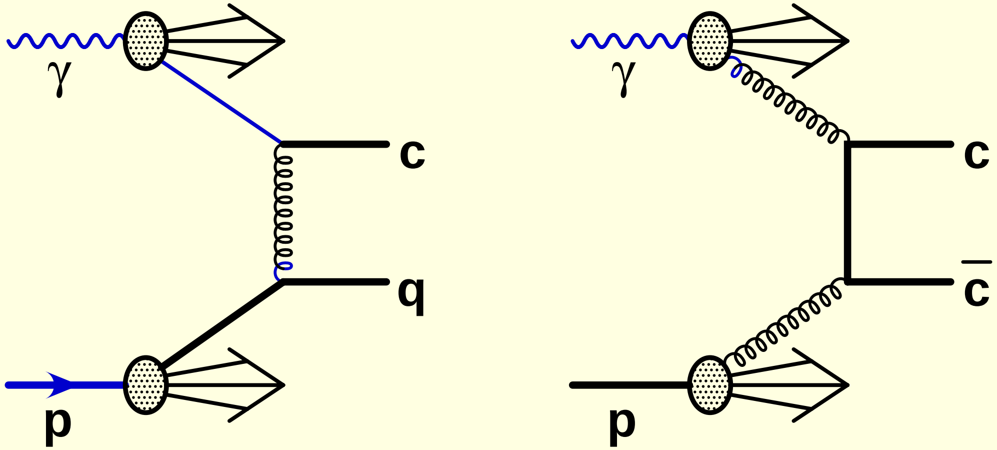
- Charm production in *ep* collisions
  - Hard scale is provided by charm mass (m_c). → pQCD applicable.
  - Study the parton dynamics of the hard scattering and gluon/charm PDFs.
  - Higher order radiation and hadronisation are also necessary for predictions.
- Inclusive jet cross section in D^* photoproduction
  - Reduce uncertainty from hadronisation effects.
  - Wide kinematic range of measurement in pseudo-rapidity.
  - $d\sigma/dE_T^{jet}$ and $d\sigma/d\eta^{jet}$ reflect the underlying parton dynamics.
- Dijet correlations ($d\sigma/dx_\gamma^{obs}$, $d\sigma/d(p_T^{jj})^2$, $d\sigma/d\Delta\varphi^{jj}$, $d\sigma/dM^{jj}$)
  - More stringent test of the QCD using new variables.
  - p_T of the dijet system (p_T^{jj}) and azimuthal difference of the two jets ($\Delta\varphi^{jj}$) are particularly sensitive to higher order effects.
  - The reconstruction of x_γ^{obs} allows to measure direct- and resolved-enriched samples separately.

(Results are compared to NLO QCD calculations and MC models.)

Charm Photoproduction at HERA



Direct photon process



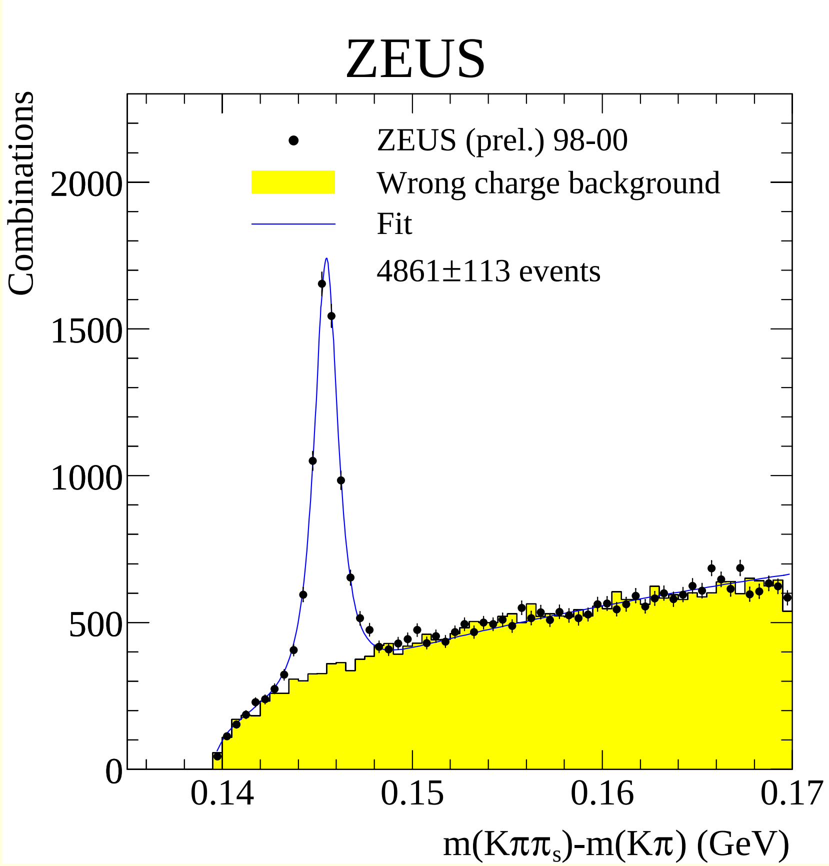
Resolved photon process

Kinematic variables
Q^2 : virtuality of the exchanged photon
W : photon-proton center of mass energy
y : inelasticity
η : pseudo-rapidity ($\eta=-\ln(\tan\theta/2)$)

In photoproduction ($Q^2<1$ GeV^2), there are two types of subprocesses
- direct photon process (photon participates directly in the hard scattering)
- resolved photon process (partons in the photon participates in the hard scattering)

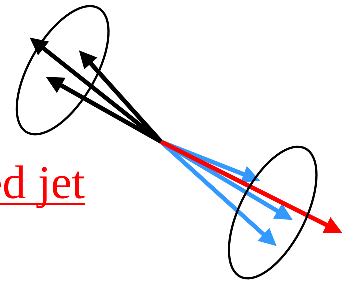
Kinematic region of the measurement

- Luminosity : 78.6 pb^{-1}
- <u>Kinematic range</u>
  - $Q^2 < 1$ GeV^2 (No scattered electron)
  - 130 < W < 280 GeV
- <u>D^* selection</u>
  - $D^{*+} \to D^0 \pi_s^+ \to (K^- \pi^+) \pi_s^+ + \text{c.c.}$
  - $p_T(\pi,K)>0.4$ GeV, $p_T(\pi_s)>0.12$ GeV
  - $|\eta(\text{track})|<1.75$
  - $p_T(D^*)>3$ GeV, $|\eta(D^*)|<1.5$
- <u>Jet reconstruction</u>
  - Inclusive k_T algorithm on energy flow objects
  - $E_T^{jet} > 6$ GeV, $-1.5 < \eta^{jet} < 2.4$
- <u>(Dijet sub-sample)</u>
  - $E_T^{jet1}>7$ GeV, $E_T^{jet2}>6$ GeV



Fit performed with modified Gaussian form.

$$f(\Delta M) = \frac{p_0}{\sqrt{2\pi}\,p_2} \cdot \exp\left(-0.5 \cdot x^{1+1/(1+0.5\cdot x)}\right), \; x = \left|\frac{\Delta M - p_1}{p_2}\right|$$



$$\Delta R(D^*, \text{jet}) = \sqrt{\left(\eta^{D^*} - \eta^{\text{jet}}\right)^2 + \left(\phi^{D^*} - \phi^{\text{jet}}\right)^2} < 0.6$$

NLO QCD Calculations

'Massive' scheme (FMNR)

- 3 active flavors. (charm produced dynamically)
- Proton PDF : CTEQ5M1, photon PDF : AFGHO
- $m_c = 1.5$ GeV, $\mu_F=\mu_R=m_T$ ($m_T^2=m_c^2+\langle p_{T,c}^2\rangle$)
- Use Peterson function with $\varepsilon=0.035$ for the fragmentation into a D^*.
- k_T jet algorithm over final state partons.
- Hadronisation correction by MC (HERWIG & PYTHIA).
- Estimation of theoretical uncertainty
  - $m_c=1.3$ GeV, $\mu_R=m_T/2$ (upper),
  - $m_c=1.7$ GeV, $\mu_R=2m_T$ (lower)

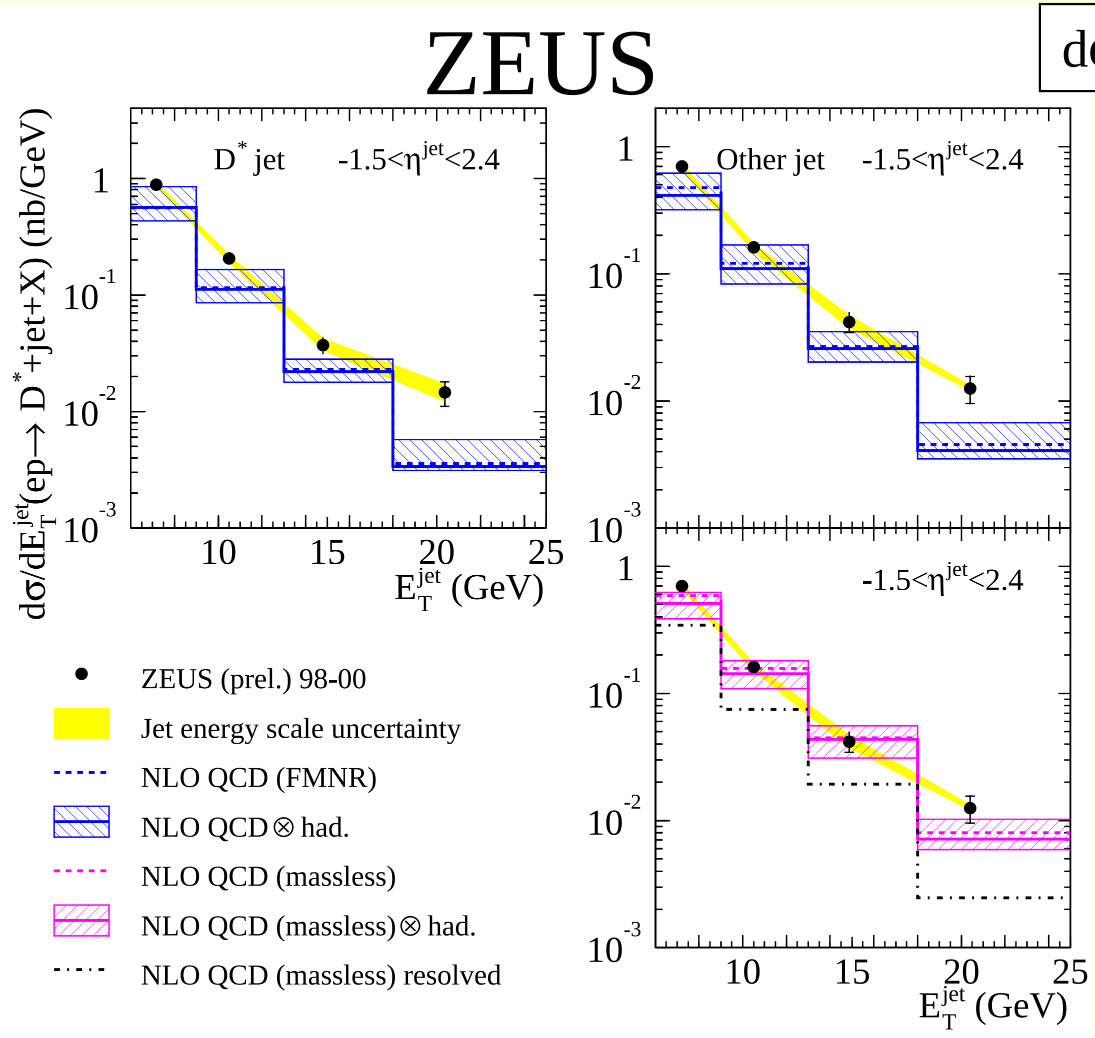
Beauty cross section

- $b \rightarrow D^*+X$
- Not added for inclusive cross sections.
- Used PYTHIA reweighted to massive NLO QCD predictions, for dijet cross sections.

'Massless' scheme (Heinrich & Kniehl)

- 4 massless flavors.
- Proton PDF: MRST03, photon PDF: AFG04
- $m_c=1.5$ GeV, $\mu_R=m'_T$ ($m'^2_T=m_c^2+(p_T^{D^*})^2$), $\mu_F=M_F=2m'_T$
- Estimation of theoretical uncertainty
  - $\mu_R=m'_T/2$, $\mu_F=M_F=4m'_T$ (upper),
  - $\mu_R=2m'_T$, $\mu_F=M_F=m'_T$ (lower)
- Only calculable for variables using D* and untagged jet.
- No beauty contribution shown in the plots, since calculation not available.

$d\sigma/dE_T^{jet}$ for D*-tagged/untagged jets

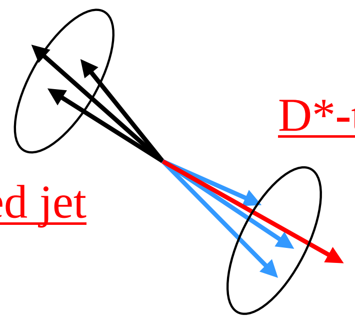


$d\sigma/dE_T^{jet}(ep \rightarrow D^*+jet+X)$ in bins of η^{jet}.

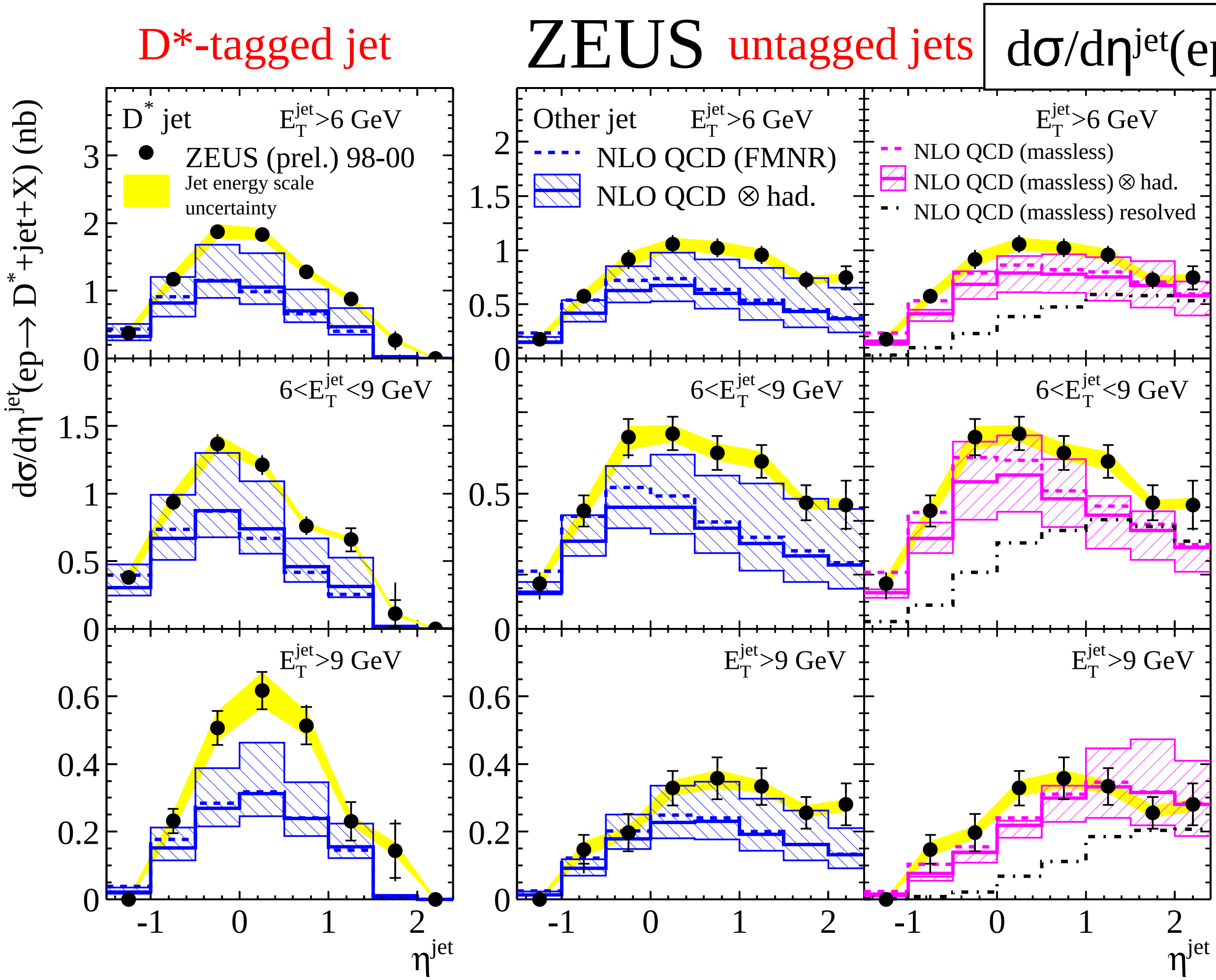
- $Q^2 < 1\ GeV^2$
- $130 < W < 280$ GeV
- $p_T(D^*) > 3$ GeV, $|\eta(D^*)| < 1.5$
- $E_T^{jet} > 6$ GeV, $-1.5 < \eta^{jet} < 2.4$

- $d\sigma/dE_T^{jet}$ of tagged/untagged jets compared to massive and massless NLO QCD preditions.
- Both theories gives similar predictions and describe the measured slope well, although the normalisation is at the upper bound of the uncertainty.

Untagged jet originates either from the other charm quark than the D* or gluon or light quarks.



Inclusive jet cross section ($d\sigma/d\eta^{jet}$)



$d\sigma/d\eta^{jet}(ep \rightarrow D^*+jet+X)$ in bins of E_T^{jet}.

- $Q^2 < 1$ GeV^2
- $130 < W < 280$ GeV
- $p_T(D^*) > 3$ GeV, $|\eta(D^*)| < 1.5$
- $E_T^{jet} > 6$ GeV, $-1.5 < \eta^{jet} < 2.4$

$E_T^{jet} > 6$ GeV (top)
$6 < E_T^{jet} < 9$ (middle)
$E_T^{jet} > 9$ GeV (bottom)

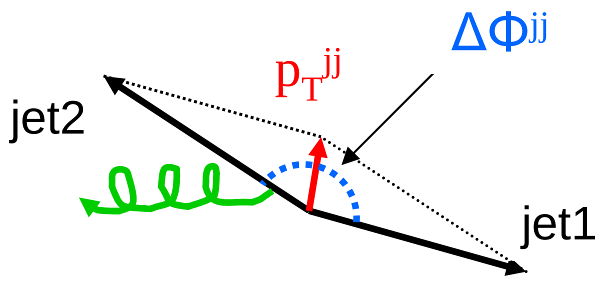
- Shapes of $d\sigma/d\eta^{jet}$ agree with the NLO QCD predictions with hadronization corrections for high and low E_T^{jet} regions.
- No significant excess in the forward region seen in jet cross sections.
- Untagged jet distribution extends up to $\eta^{jet}=2.4$.

Dijet cross sections in D* photoproduction

In <u>inclusive cross sections</u> ($d\sigma/dE_T^{jet}$, $d\sigma/d\eta^{jet}$) , a general agreement was observed between the measurement and both NLO QCD predictions.

⇩

Dijet sample enables more detailed comparison.



M^{jj}: invariant mass of the 2-jet system

$$x_\gamma^{obs} = \frac{E_T^{jet1} e^{-\eta^{jet1}} + E_T^{jet2} e^{-\eta^{jet2}}}{2yE_e}$$

fractional momentum of the photon participating in the jet production.

$$M^{jj} = \sqrt{2E_T^{jet1} E_T^{jet2} \left[\cosh\left(\eta^{jet1} - \eta^{jet2}\right) - \cos\left(\phi^{jet1} - \phi^{jet2}\right)\right]}$$

$$\Delta\phi^{jj} = \left|\phi^{jet1} - \phi^{jet2}\right|$$

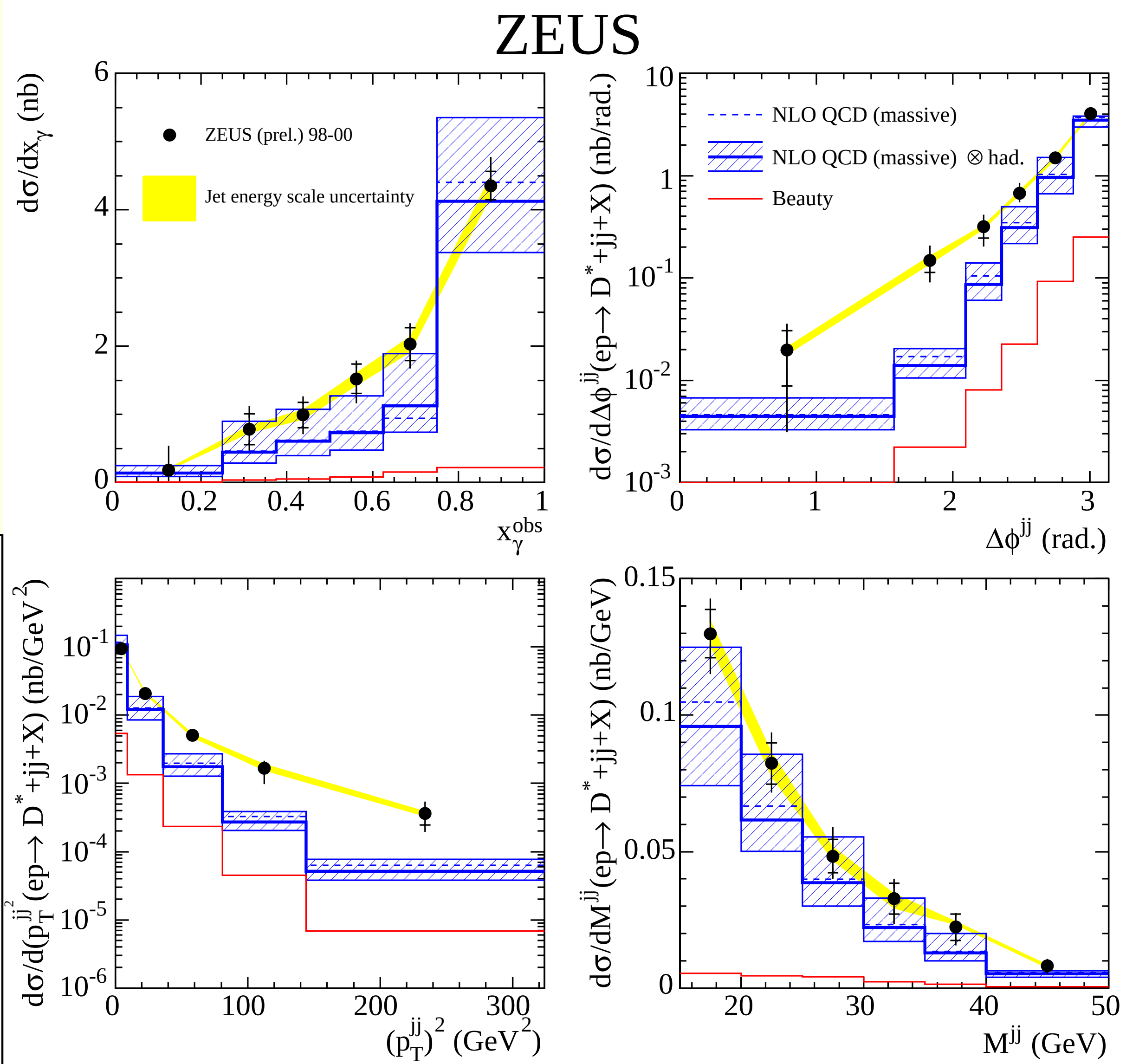
$$\left(p_T^{jj}\right)^2 = \left(p_x^{jet1} + p_x^{jet2}\right)^2 + \left(p_y^{jet1} + p_y^{jet2}\right)^2$$

$\Delta\varphi^{jj}=\pi$ and $(p_T^{jj})^2=0$ for LO 2→2 process. Deviation from these values is due to higher order radiation effects which is implemented as,

- parton shower (PS) algorithm in LO+PS MC like HERWIG and PYTHIA.
- 2→3 real correction in NLO QCD calculations.
- $O(\alpha_S^2)$ is the "Leading Order" for $\Delta\varphi^{jj}\neq\pi$ and $(p_T^{jj})^2\neq 0$.

Dijet Cross Sections

• Good description of $d\sigma/dx_\gamma^{obs}$ and $d\sigma/dM^{jj}$ by massive NLO QCD.
• However, a significant excess is observed at large p_T^{jj} and low $\Delta\varphi^{jj}$. These are the regions where higher order effects are expected to become larger.



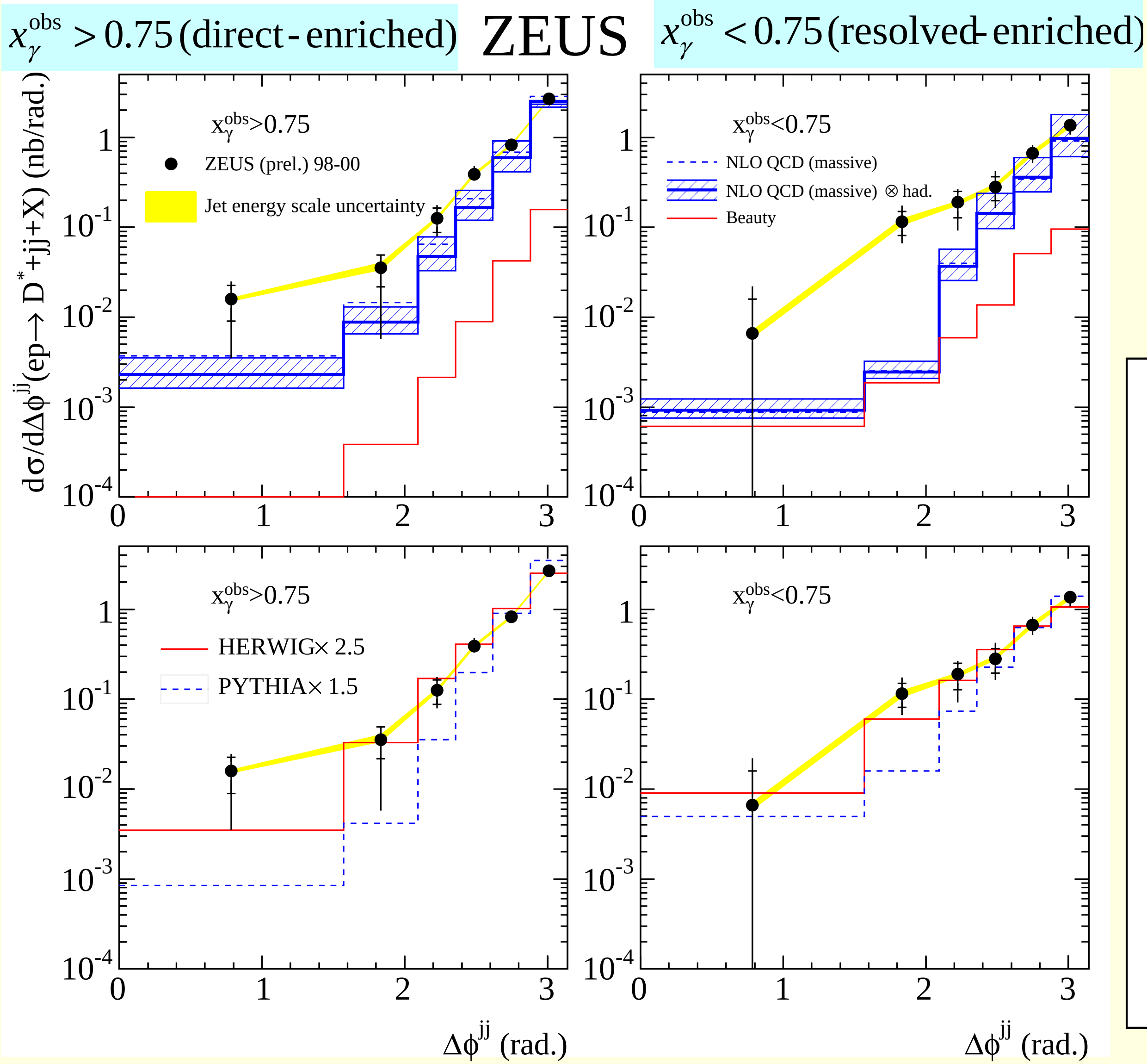
Estimation of beauty ($b \rightarrow D^* + X$)

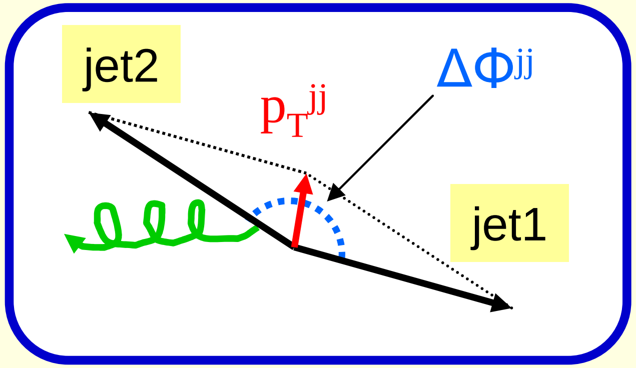
• Use PYTHIA to estimate the beauty contribution.
• p_T distributions of the two stable B hadrons in PYTHIA were reweighted to the massive NLO QCD distributions.
• Massive NLO QCD calculation was done with m_b=4.75 GeV, $\mu_{F,R}=m_b^2+\langle p_{T,b}^2 \rangle$
• Use Peterson function with ε =0.0035 for the fragmenation into B hadrons.

$x_\gamma^{obs} > 0.75$ (direct-enriched sample)

$x_\gamma^{obs} < 0.75$ (resolved-enriched sample)

dσ/dΔφ^{jj}

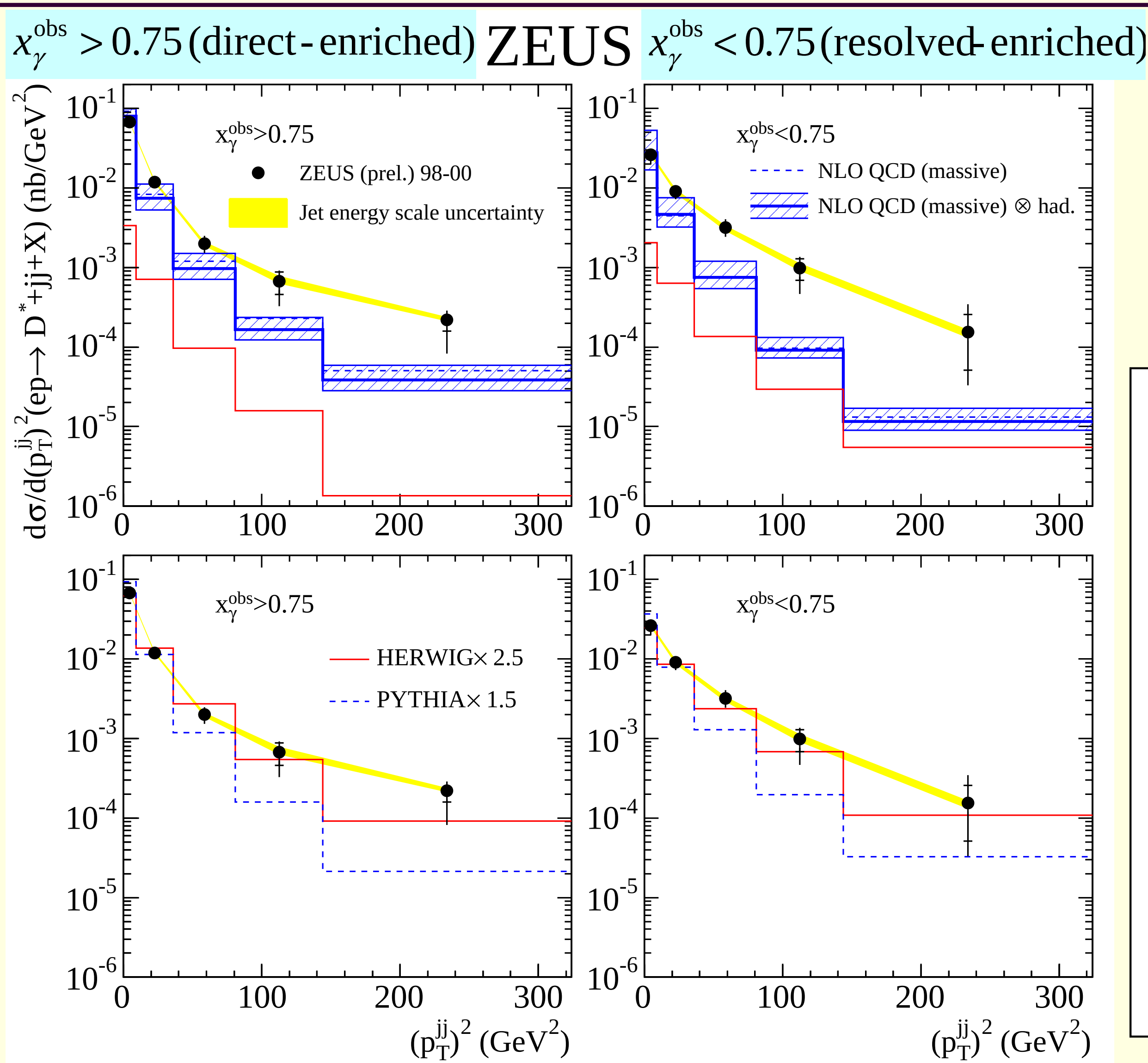


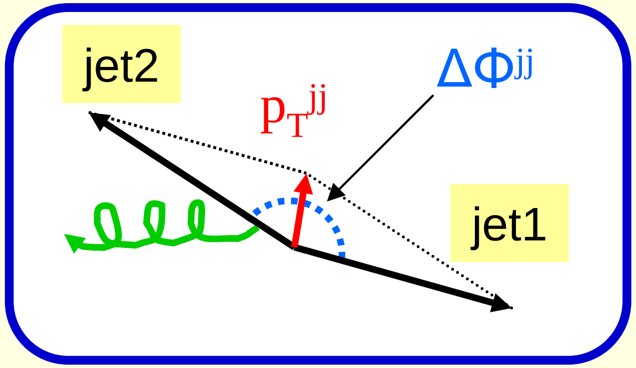


- Discrepancy between massive NLO QCD and data increases at low Δφ^{jj}.
- Disagreement is more pronounced in resolved-enriched sample (Additional radiation is expected from the photon remnant in the resolved process.).
- HERWIG6.301 (LO+PS) gives an excellent description of the shape for both direct and resolved. PYTHIA6.156 is slightly worse.

O(α_S^2) correction to 2→2 process is not sufficient.
Even higher order correction or parton shower algorithm is needed.

$d\sigma/d(p_T^{jj})^2$

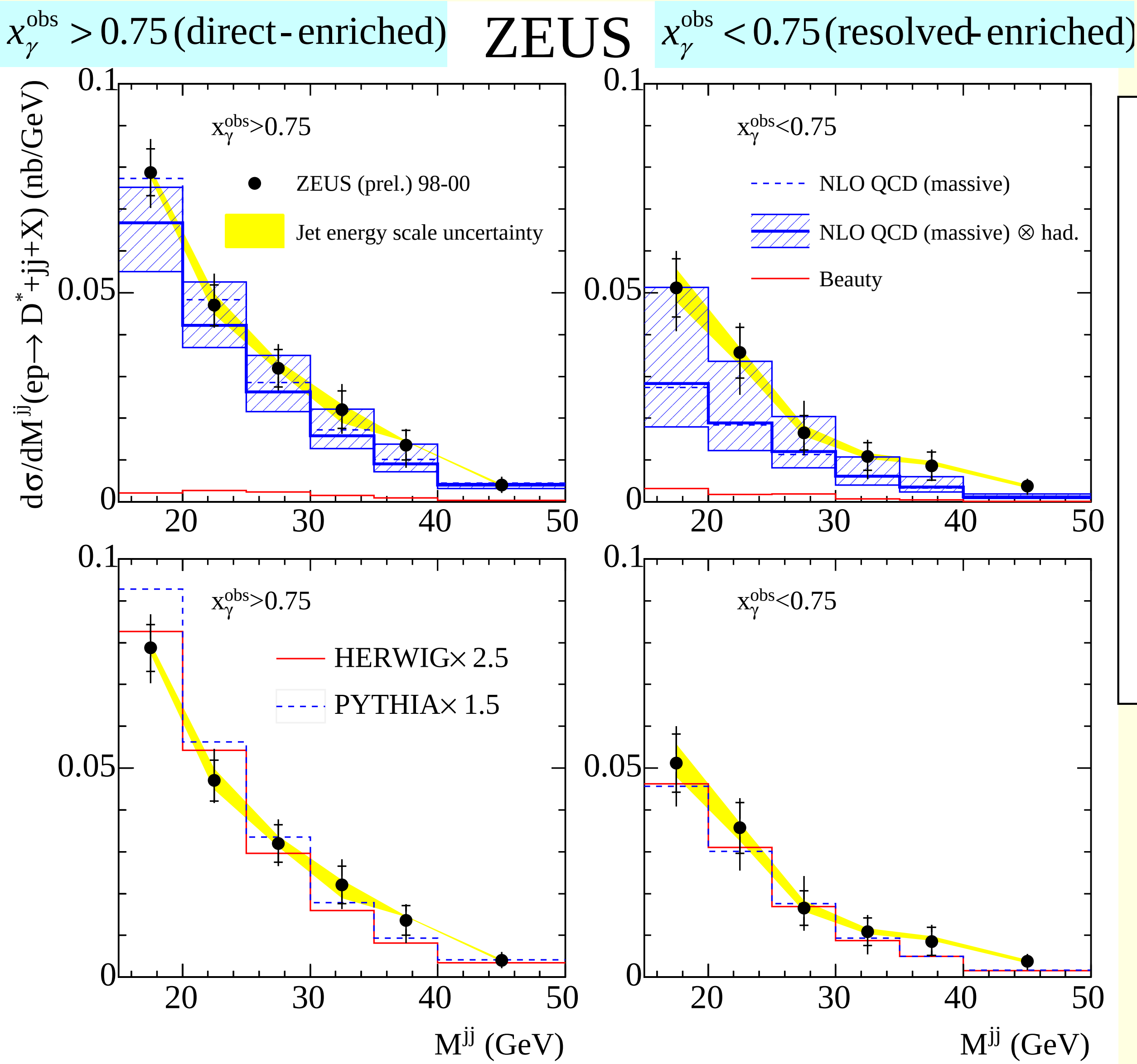




- Discrepancy between massive NLO QCD and data increases at large $(p_T^{jj})^2$.
- Disagreement is more pronounced in resolved-enriched sample (Additional radiation is expected from the photon remnant in the resolved process.).
- HERWIG (LO+PS) gives an excellent description of the shape for both direct and resolved. PYTHIA is slightly worse.

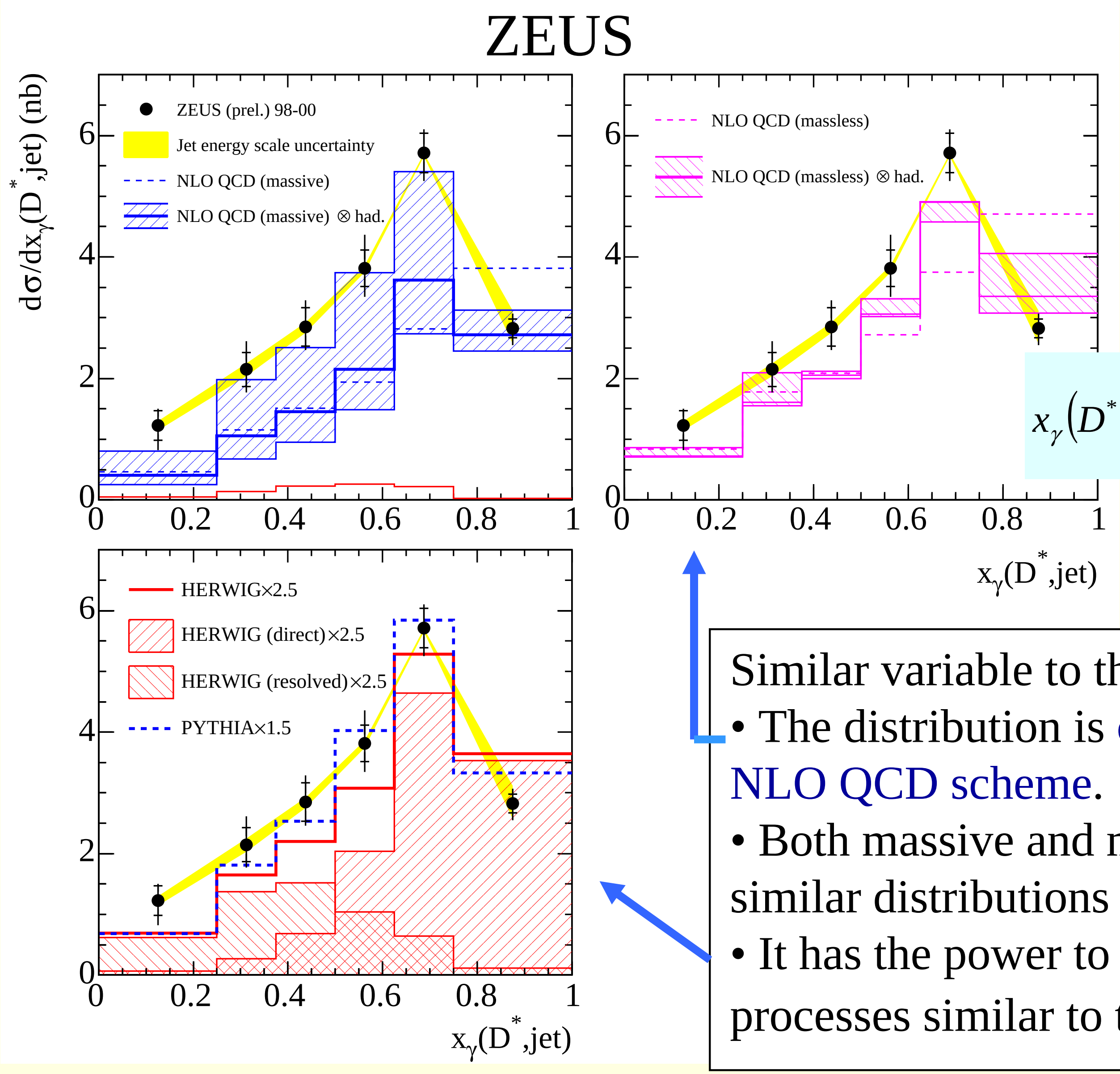
$O(\alpha_S^2)$ correction to 2→2 process is not sufficient.
Even higher order correction or parton shower algorithm is needed.

dσ/dM^{jj}



- dσ/dM^{jj} is described well by the upper bound of the massive NLO QCD predictions, both for direct- and resolved-enriched samples.
- LO+PS MC models reproduce the shape as well, although the normalisation is off by a factor of ~2.

$d\sigma/dx_\gamma(D^*,\text{jet})$



$$x_\gamma\left(D^*,\text{jet}\right)=\frac{p_T^{D^*}e^{-\eta^{D^*}}+E_T^{(\text{untagged jet})}e^{-\eta^{(\text{untagged jet})}}}{2yE_e}$$

Similar variable to the traditional x_γ^{obs}.

- The distribution is calculable by the massless NLO QCD scheme.
- Both massive and massless calculations show similar distributions and describe the data.
- It has the power to separate direct and resolved processes similar to the traditional x_γ^{obs}.

Summary & Conclusion

- **Summary**
- Inclusive jet cross sections in D* photoproduction is described well by both massive and massless NLO QCD predictions with hadronisation correction.
- Dijet correlation cross sections show that massive NLO QCD prediction underestimates the measurement at low $\Delta\varphi^{jj}$ and large $(p_T^{jj})^2$, in particular, in the resolved-enriched sample.
- HERWIG (LO+PS MC) describes the shape of $d\sigma/d(p_T^{jj})^2$ and $d\sigma/d\Delta\varphi^{jj}$ very well, although the normalisation is underestimated by a factor of 2.5.
- **Conclusion**
- Jet cross sections in D* photoproducion are, in general, described reasonably well by the NLO QCD predictions.
- For dijet correlation variables, $O(\alpha_S^2)$ calculation is not sufficient. Even higher order calculations or parton shower algorithm has to be incorporated into the NLO QCD framework. MC@NLO might be a solution.