Drell-Yan at low energy and high transverse momentum

Fulvio Piacenza

in collaboration with A.Bacchetta, G.Bozzi, W.Vogelsang, M.Lambertsen

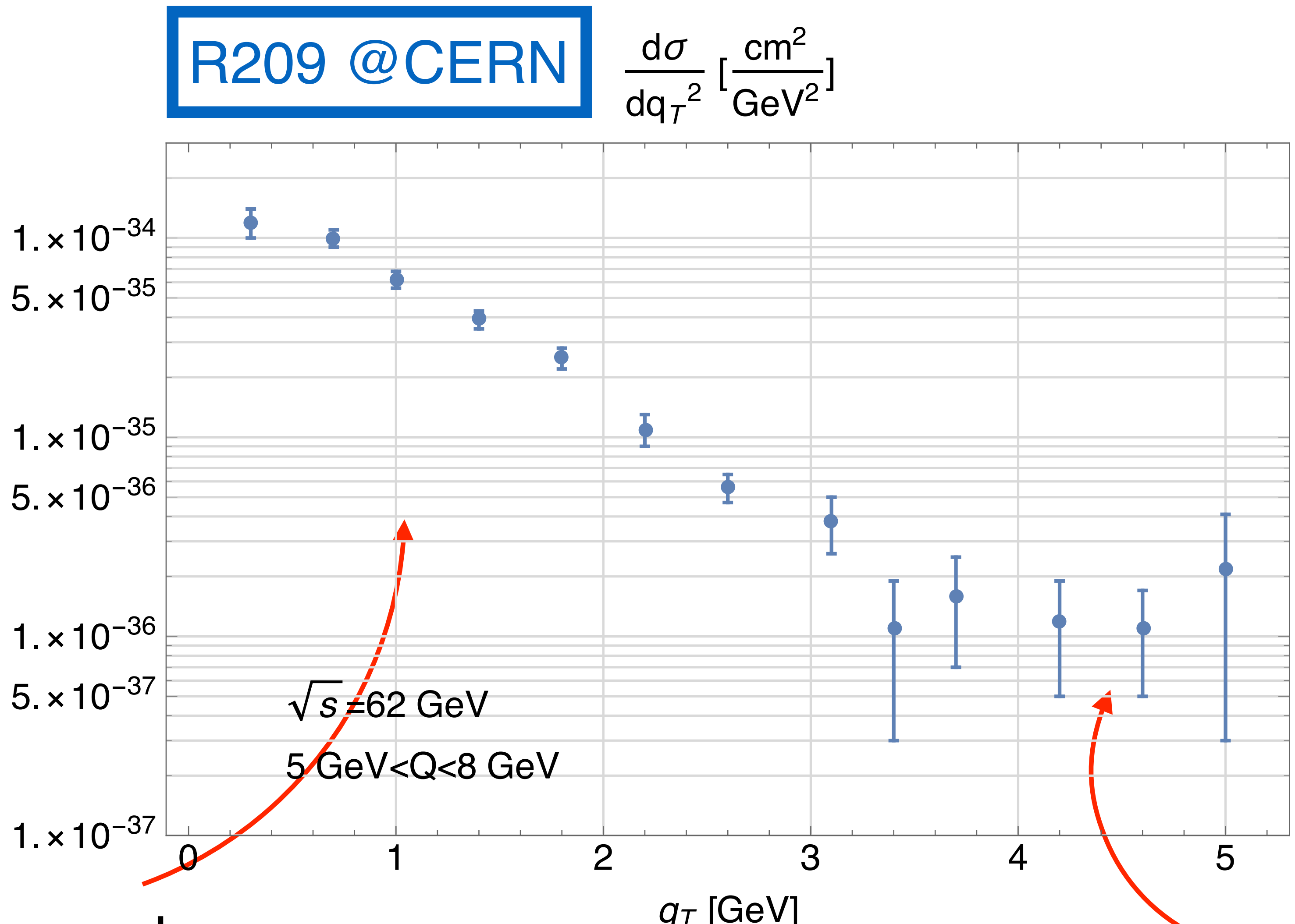
3DSPIN MAPPING THE PROTON IN 3D

European Research Council

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

Transverse momentum of Drell-Yan pairs

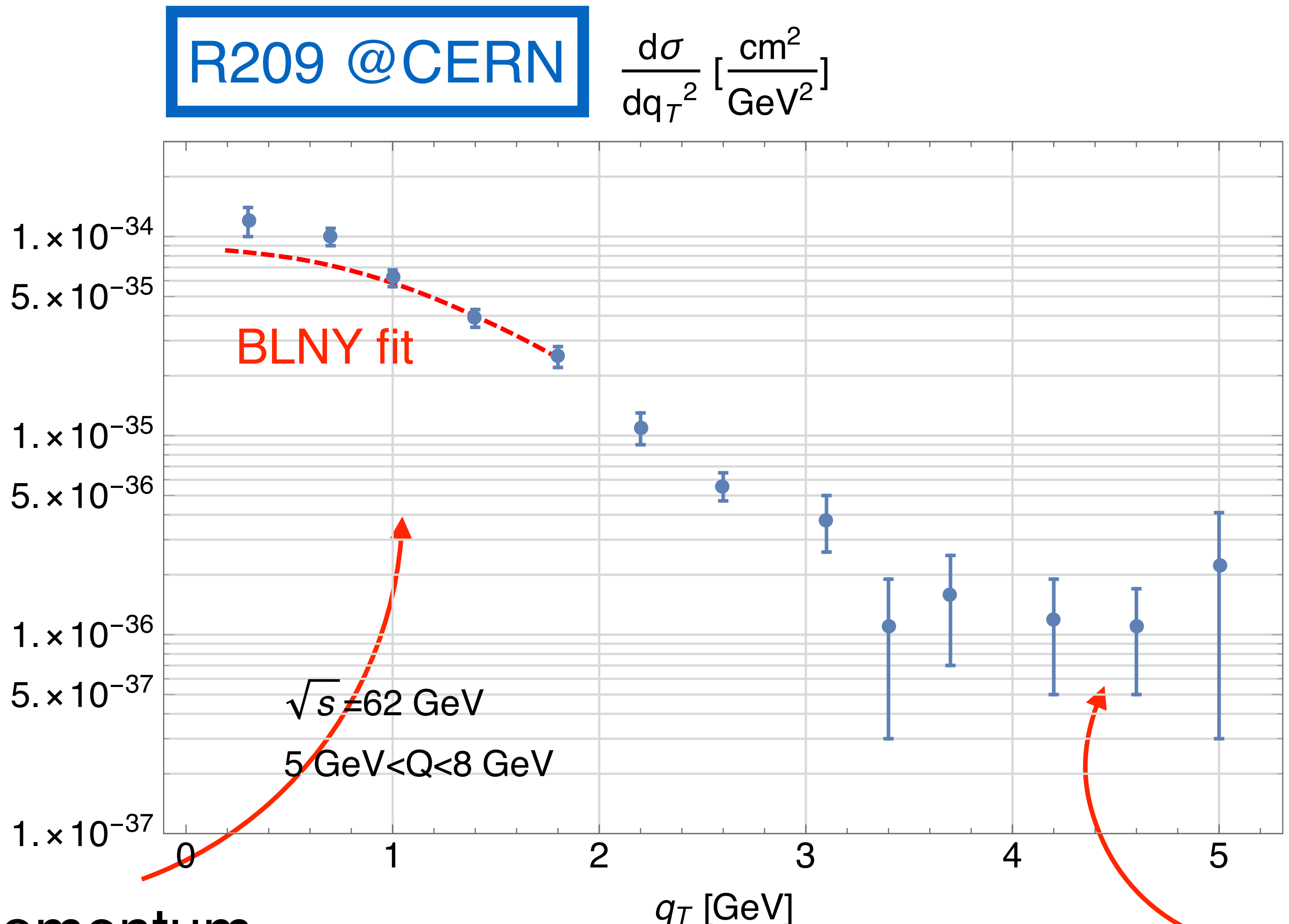


Transverse momentum resummation (q_T-logs) $\alpha_s^n \ln^m \frac{q_T^2}{Q^2}$

\+ non perturbative effects

Fixed order collinear factorization

Transverse momentum of Drell-Yan pairs

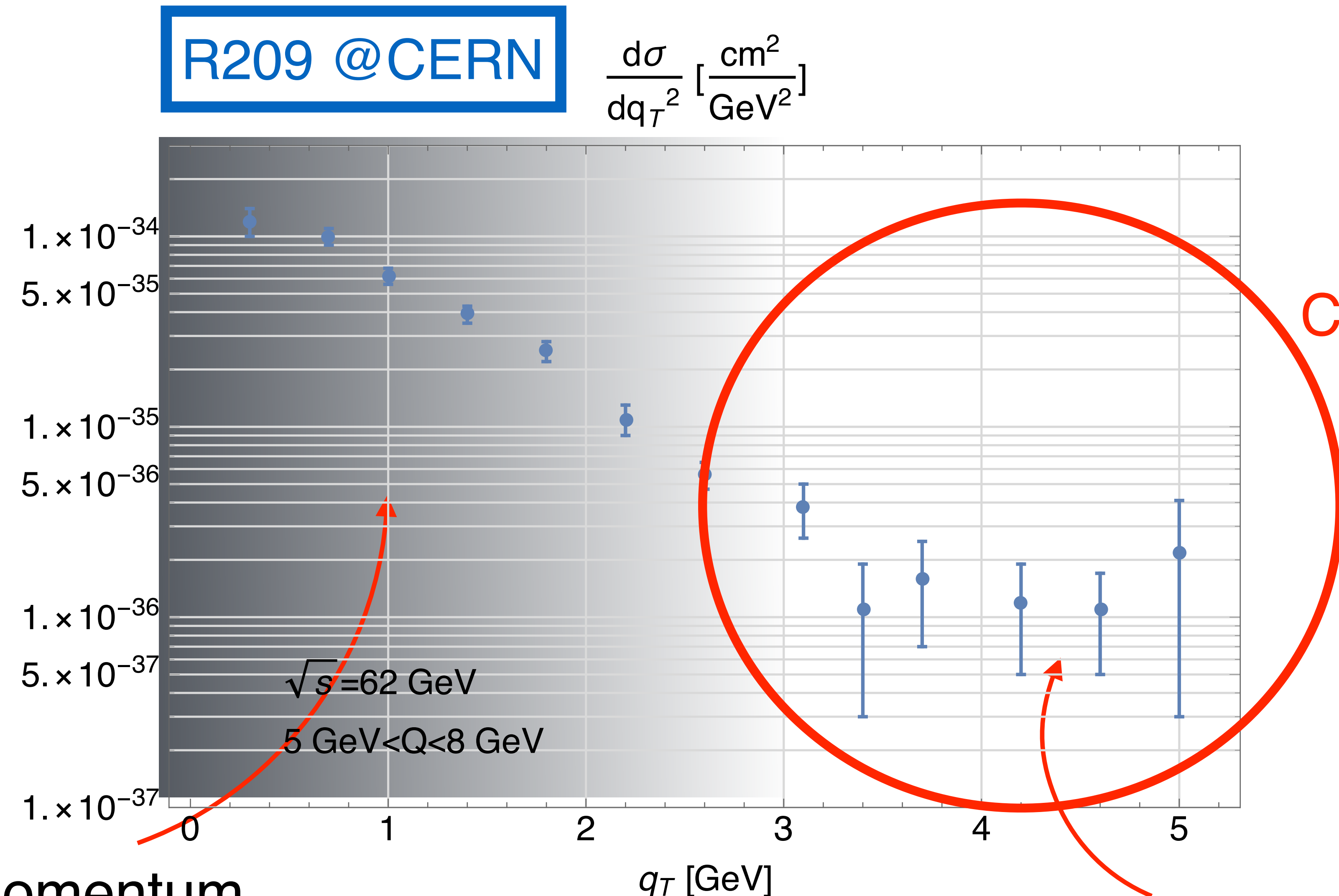


Transverse momentum resummation (q_T-logs) $\alpha_s^n \ln^m \frac{q_T^2}{Q^2}$

+ non perturbative effects

Fixed order collinear factorization

Transverse momentum of Drell-Yan pairs



Can we describe data here?

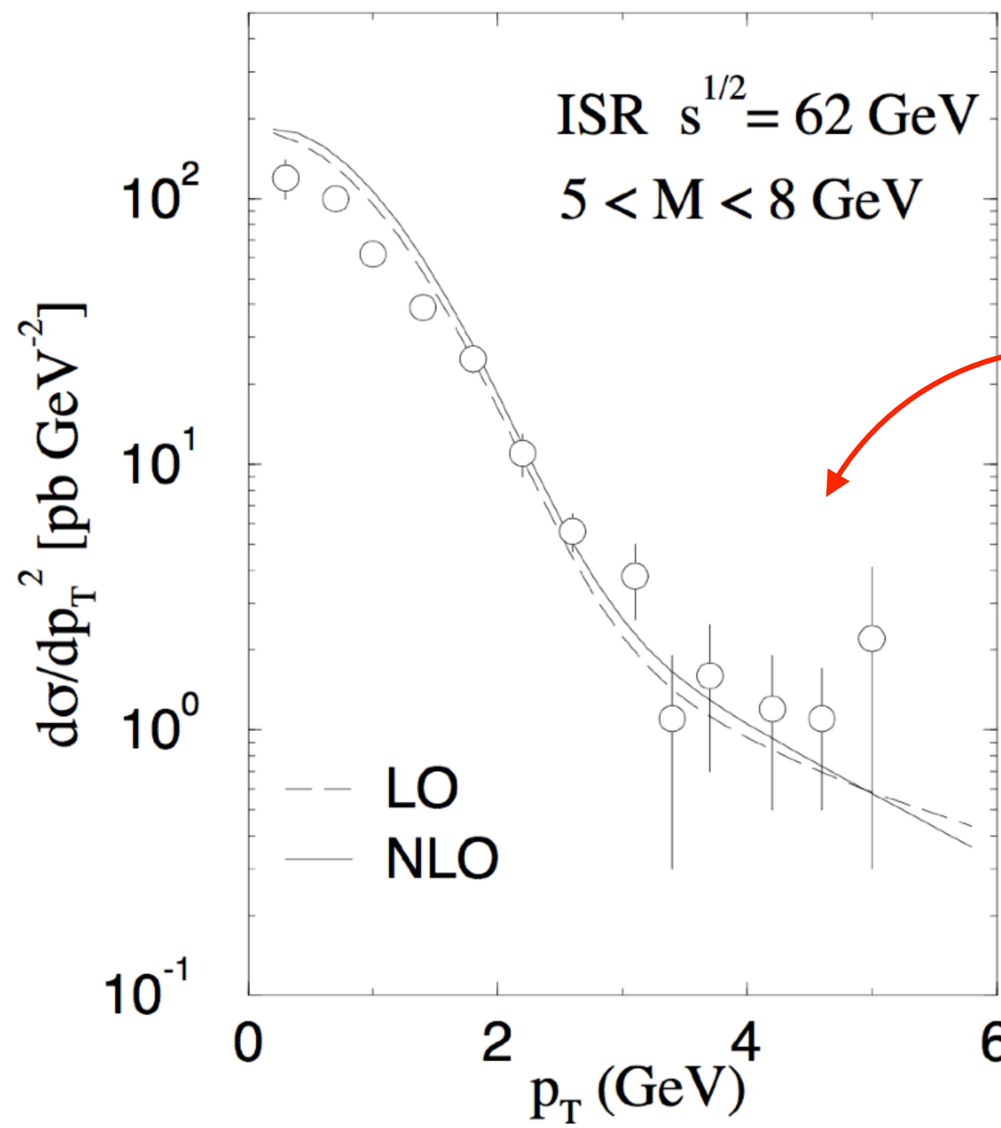
Transverse momentum resummation (q_T-logs) $\alpha_s^n \ln^m \frac{q_T^2}{Q^2}$

+ non perturbative effects

Fixed order collinear factorization

Matching resummation and fixed order

$$\frac{d\sigma}{dq_T^2}(matched) = \underbrace{\frac{d\sigma}{dq_T^2}(resum)_{NLL}}_{W} - \underbrace{\frac{d\sigma}{dq_T^2}(expanded)\Big|_{\mathcal{O}(\alpha_s)} + \frac{d\sigma}{dq_T^2}(LO)}_{Y}$$



W + Y

Gavin et al
I.J.Mod.Phys. A10 (1995)

Arnold & Kauffman's rule

$$\frac{d\sigma}{dq_T^2}(matched) = \underbrace{\frac{d\sigma}{dq_T^2}(resum)_{NLL}}_{\text{W}} - \underbrace{\frac{d\sigma}{dq_T^2}(expanded)\Big|_{\mathcal{O}(\alpha_s)} + \frac{d\sigma}{dq_T^2}(LO)}_{\text{Y}}$$

When W < 0 switch to fixed order!

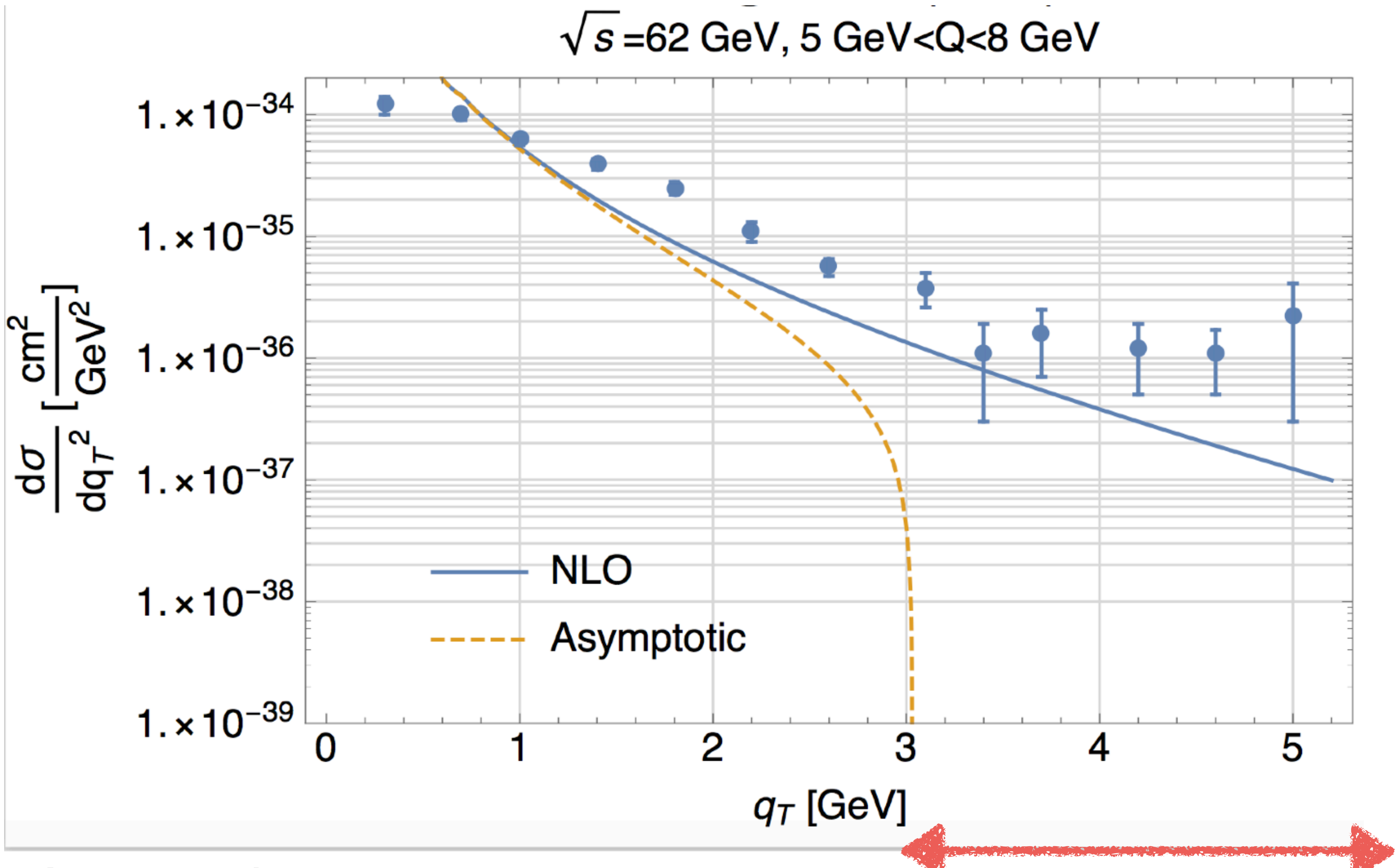
(usually happens at $q_T = Q/2$)

Arnold & Kauffman NP B349 381

Collins et al PRD94 034014

Transverse momentum of Drell-Yan pairs

NLO collinear factorization: $\mathcal{O}(\alpha_s^2)$



Asymptotic =
expansion of resummed result
at fixed order

here collinear factorization
should be reliable

low energy DY data

Experiment	Reaction	Year	TMD fits	PDF fits
R209	p-p	1981	✔	✘
E288	p-Cu(Pt)	1981	✔	✘
E605	p-Cu	1991	✔	✔

$$20\,GeV \lesssim \sqrt{s} \lesssim 60\,GeV$$

low energy DY data

Experiment	Reaction	Year	TMD fits	PDF fits
R209	p-p	1981	✔	✘
E288	p-Cu(Pt)	1981	✔	✘
E605	p-Cu	1991	✔	✔
E866	p-p(d)	2003	✘	✔
E615	π-W	1989	✘	✔

$$20\,GeV \lesssim \sqrt{s} \lesssim 60\,GeV$$

low energy DY data

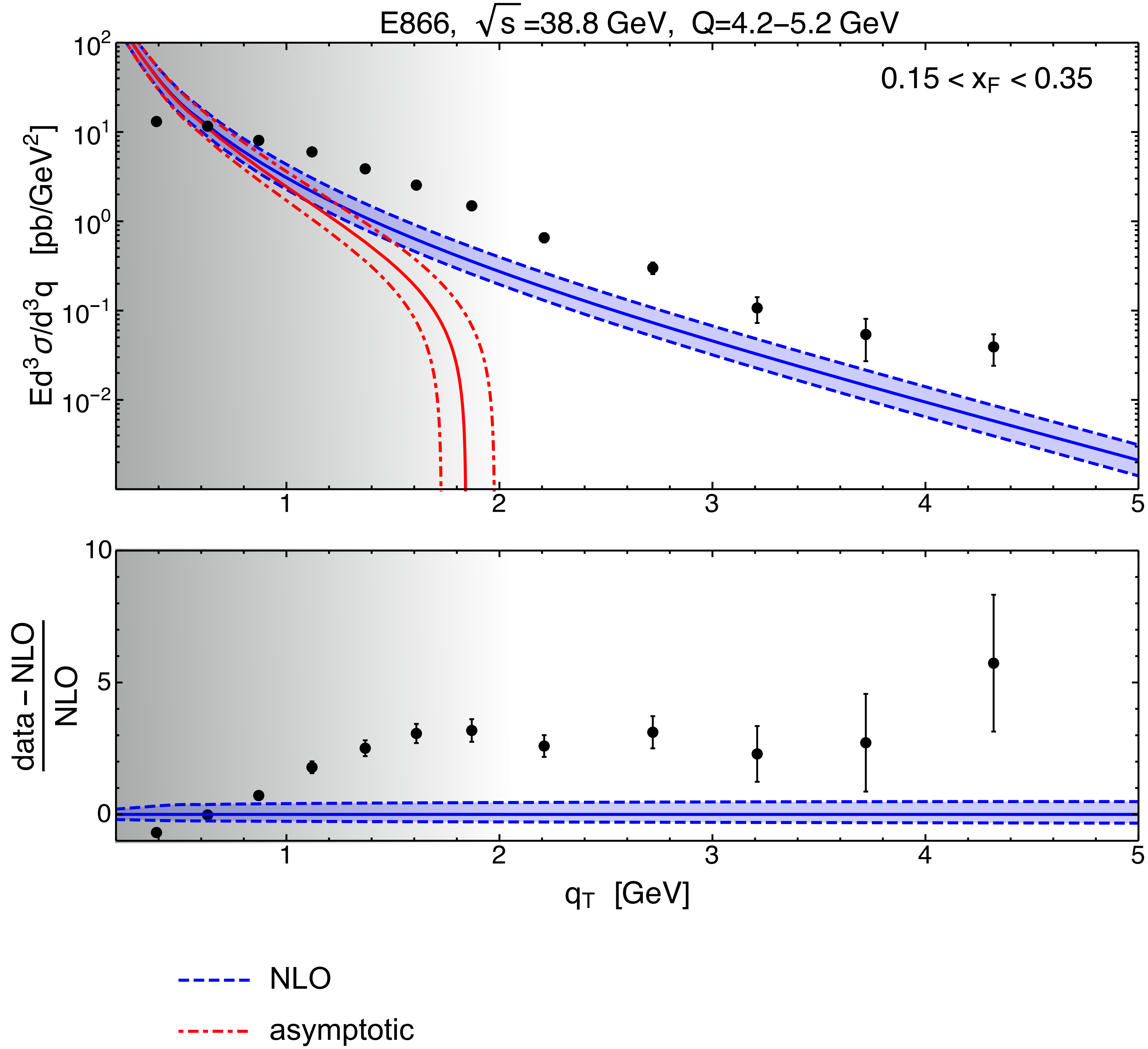
Experiment	Reaction	Year	TMD fits	PDF fits
R209	p-p	1981	✔	✘
E288	p-Cu(Pt)	1981	✔	✘
E605	p-Cu	1991	✔	✔
E866	p-p(d)	2003	✘	✔
E615	π-W	1989	✘	✔
E772	p-d	1994		
E537	pbar-W	1988		

ghost data

$$20\,GeV \lesssim \sqrt{s} \lesssim 60\,GeV$$

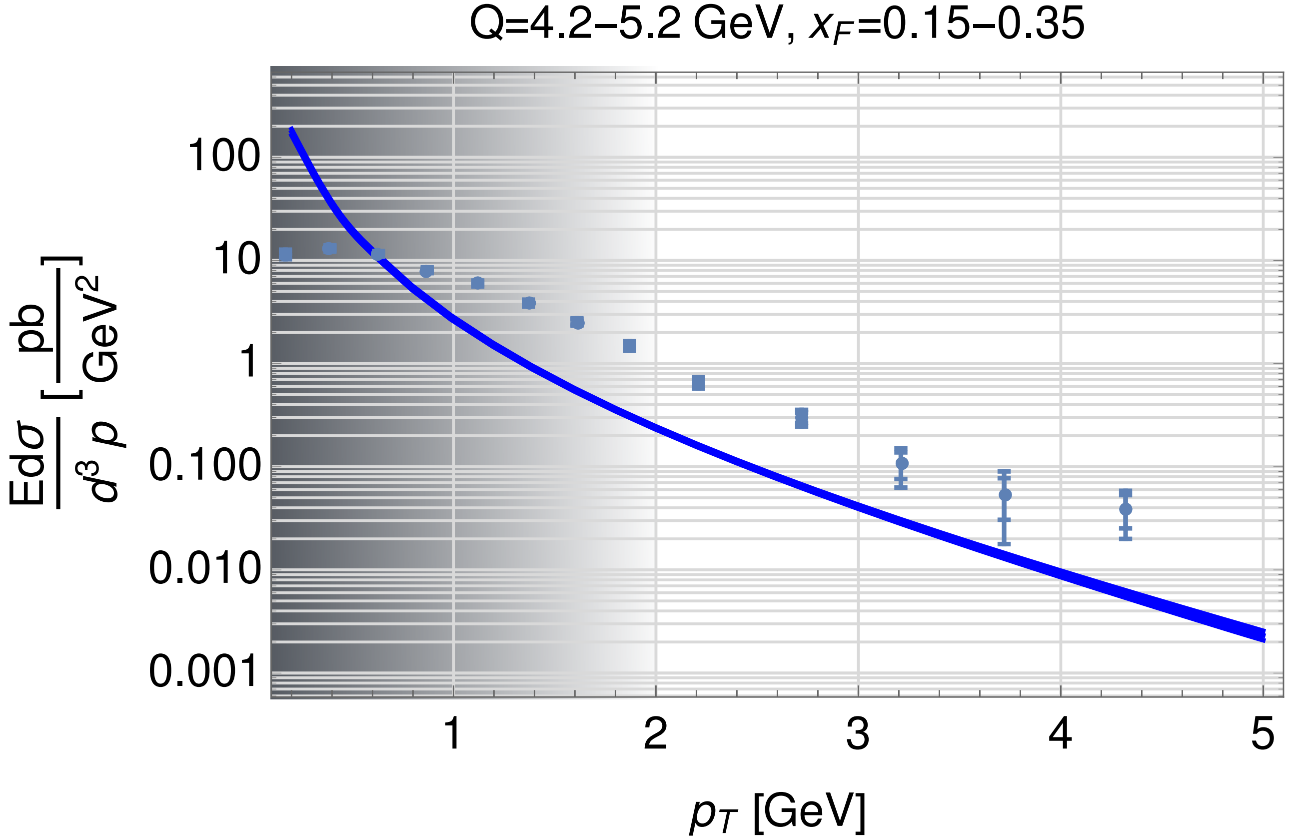
E866/NuSea

$$p\,p \to \mu^+\mu^- X \qquad \sqrt{s} = 38.8\,GeV$$



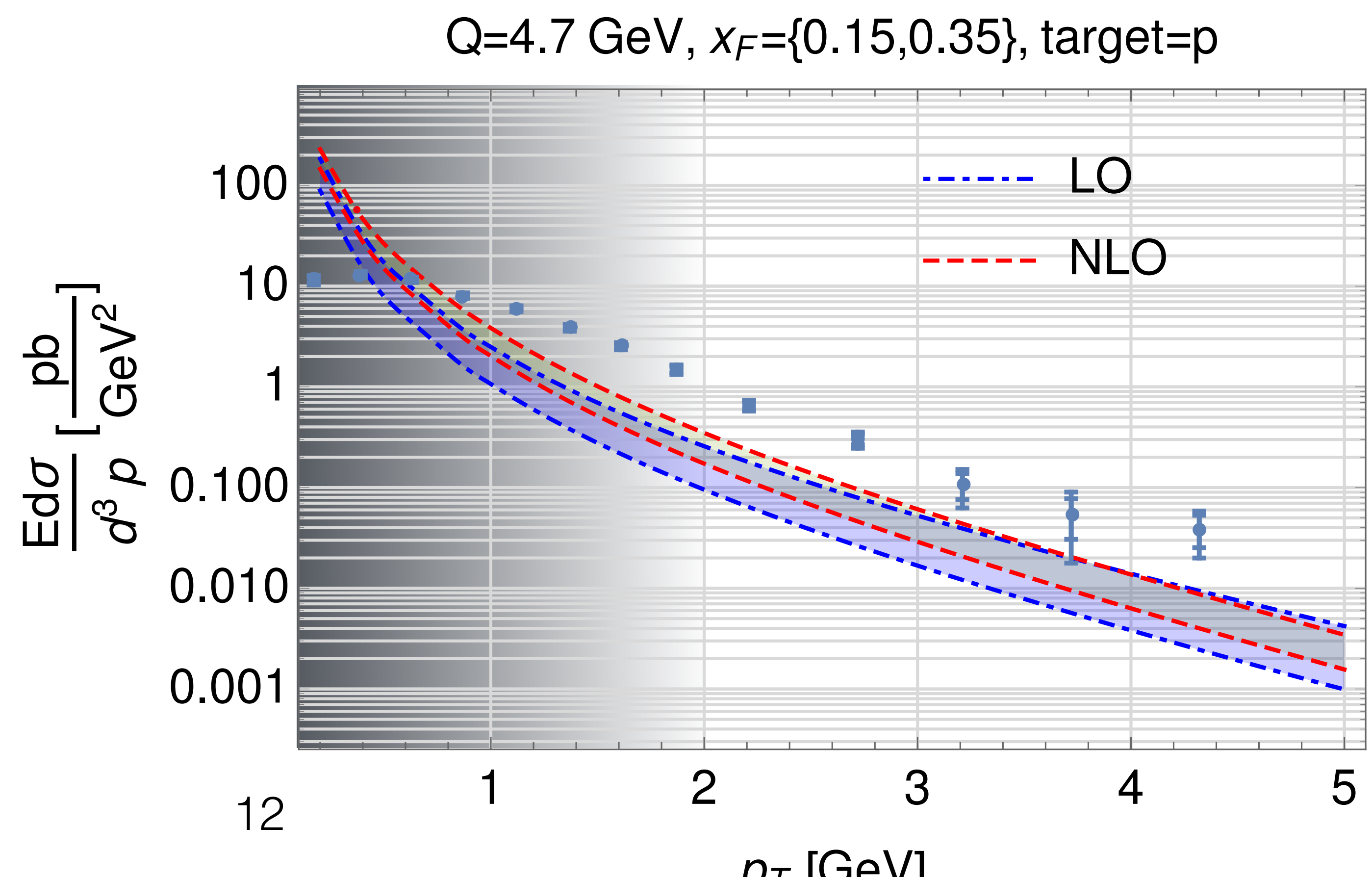
E866/NuSea

$$p\,p \to \mu^+\mu^- X \qquad \sqrt{s} = 38.8\,GeV$$



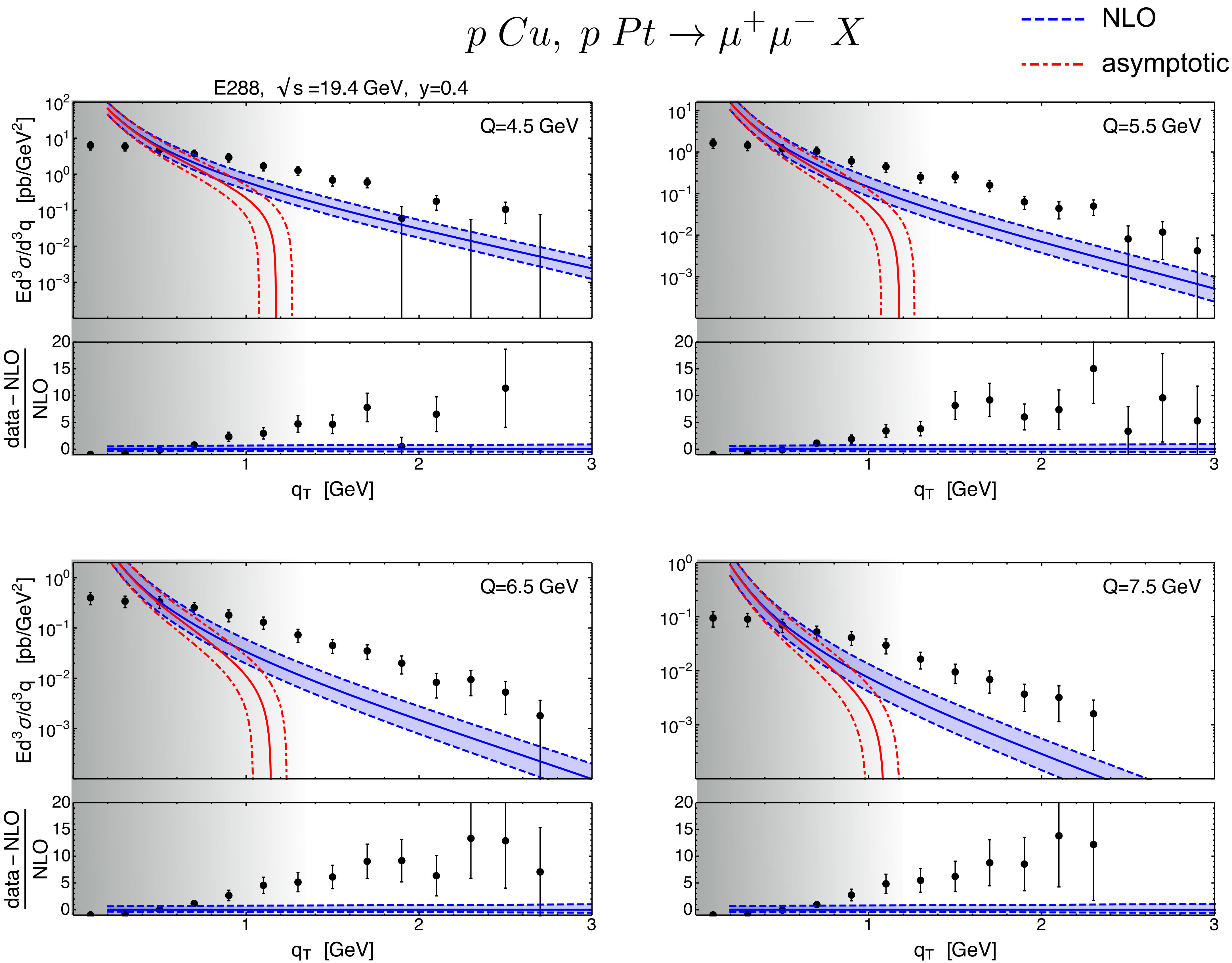
NLO $\mathcal{O}(\alpha_s^2)$
+PDF uncertainty

scale variations

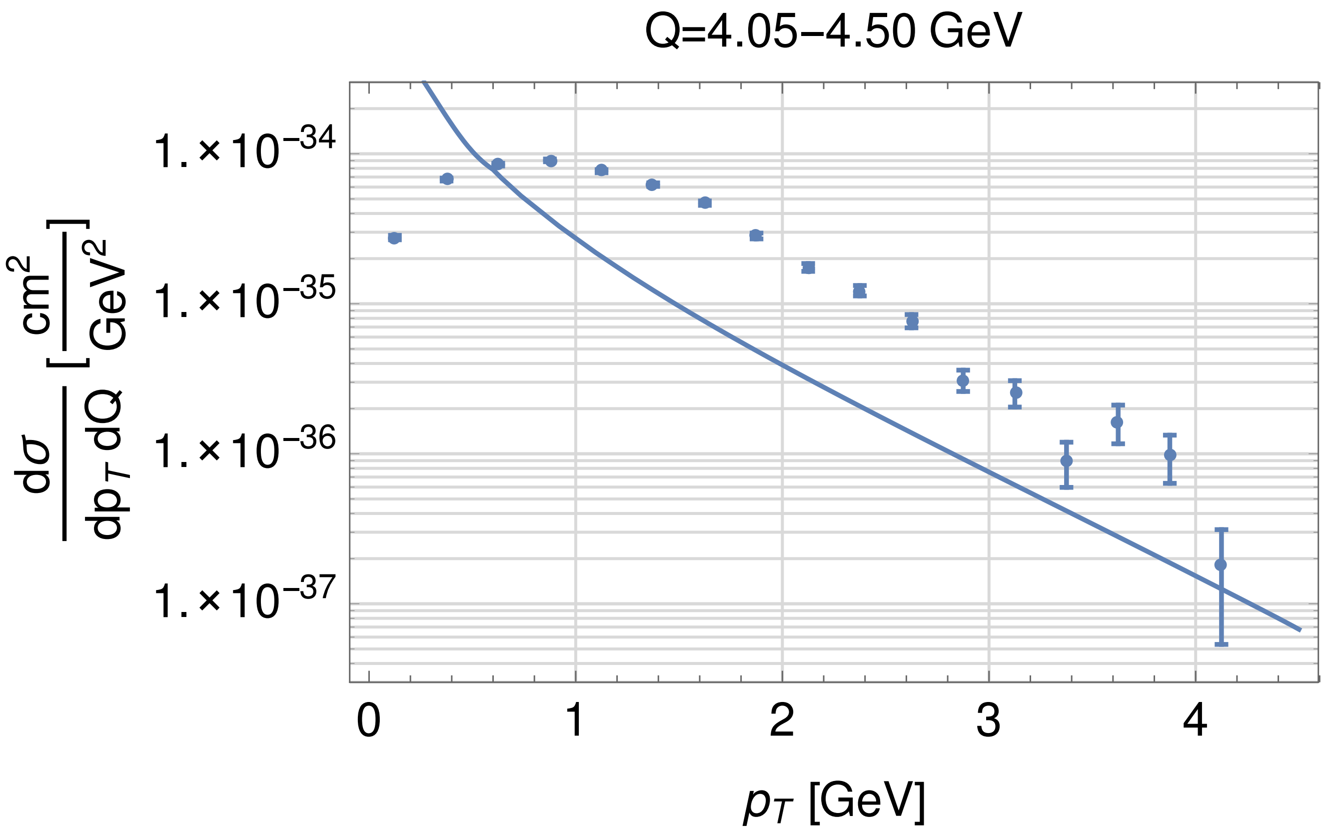


E288

$$p\,Cu,\ p\,Pt \to \mu^+\mu^-\ X$$



pion-nucleus Drell-Yan

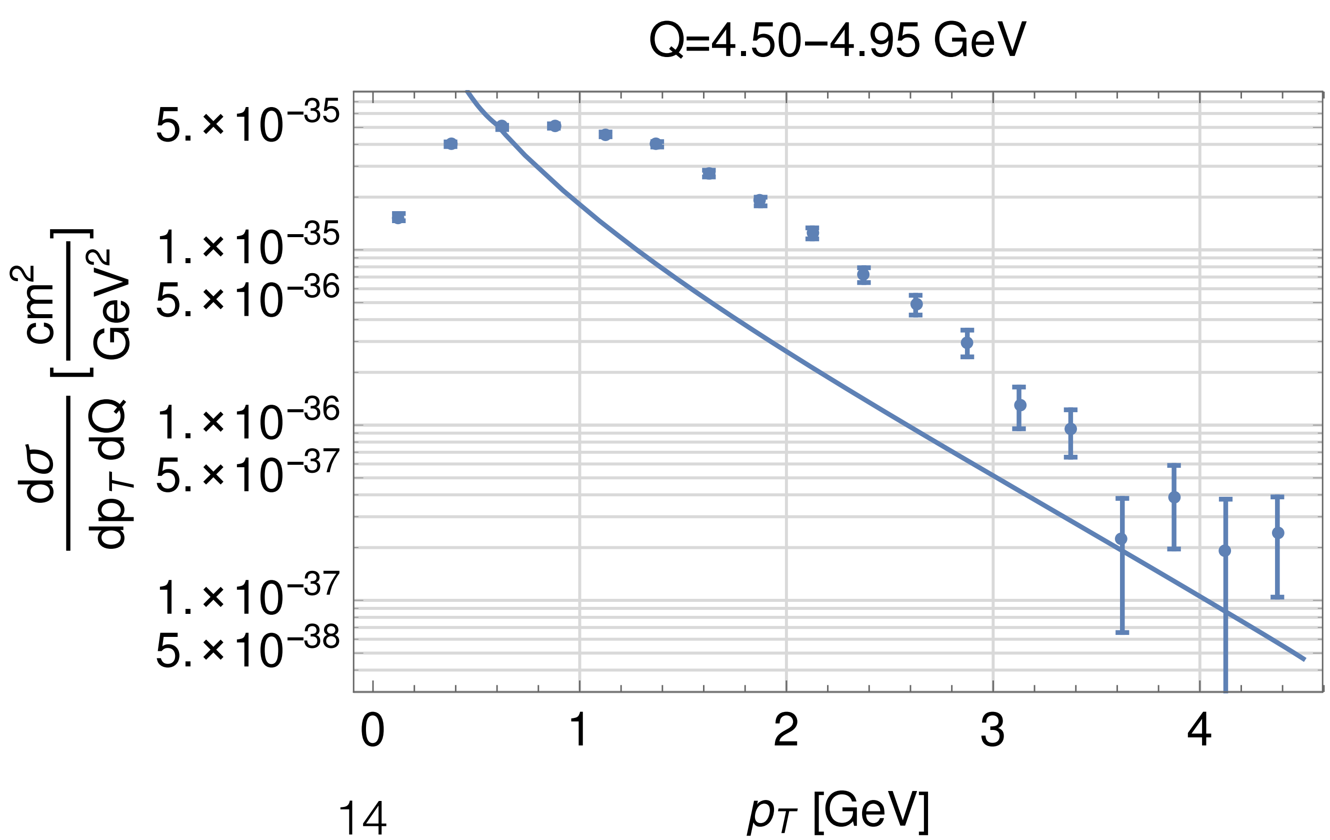


NLO $\mathcal{O}(\alpha_s^2)$

E615

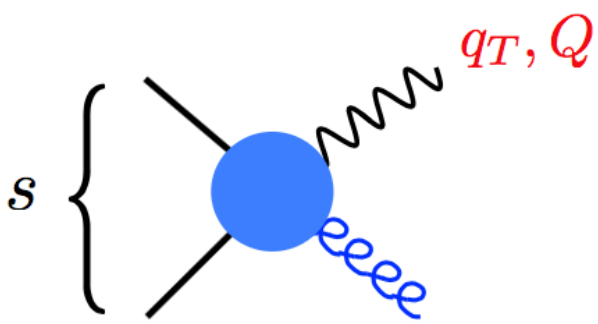
$$\pi W \to \mu^+\mu^- X$$

$$\sqrt{s} = 21.8\ GeV$$



threshold resummation

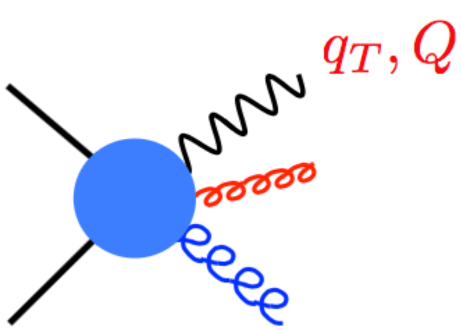
- LO :



$$\sqrt{s} \geq q_T + \sqrt{Q^2 + q_T^2}$$

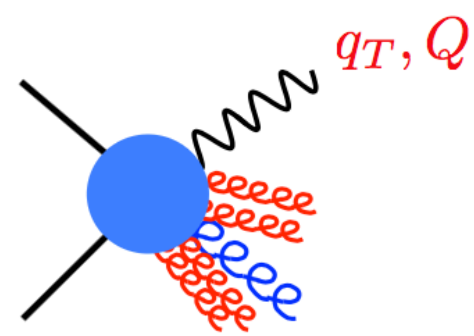
$$y_T \equiv \frac{q_T + \sqrt{q_T^2 + Q^2}}{\sqrt{s}} \leq 1$$

- NLO :



$$\frac{d\hat{\sigma}^{\mathrm{NLO}}}{dq_T} \propto \alpha_s \left[\mathcal{A} \log^2(1 - y_T^2) + \mathcal{B} \log(1 - y_T^2) + \mathcal{C} \right]$$

- N^{k}LO :

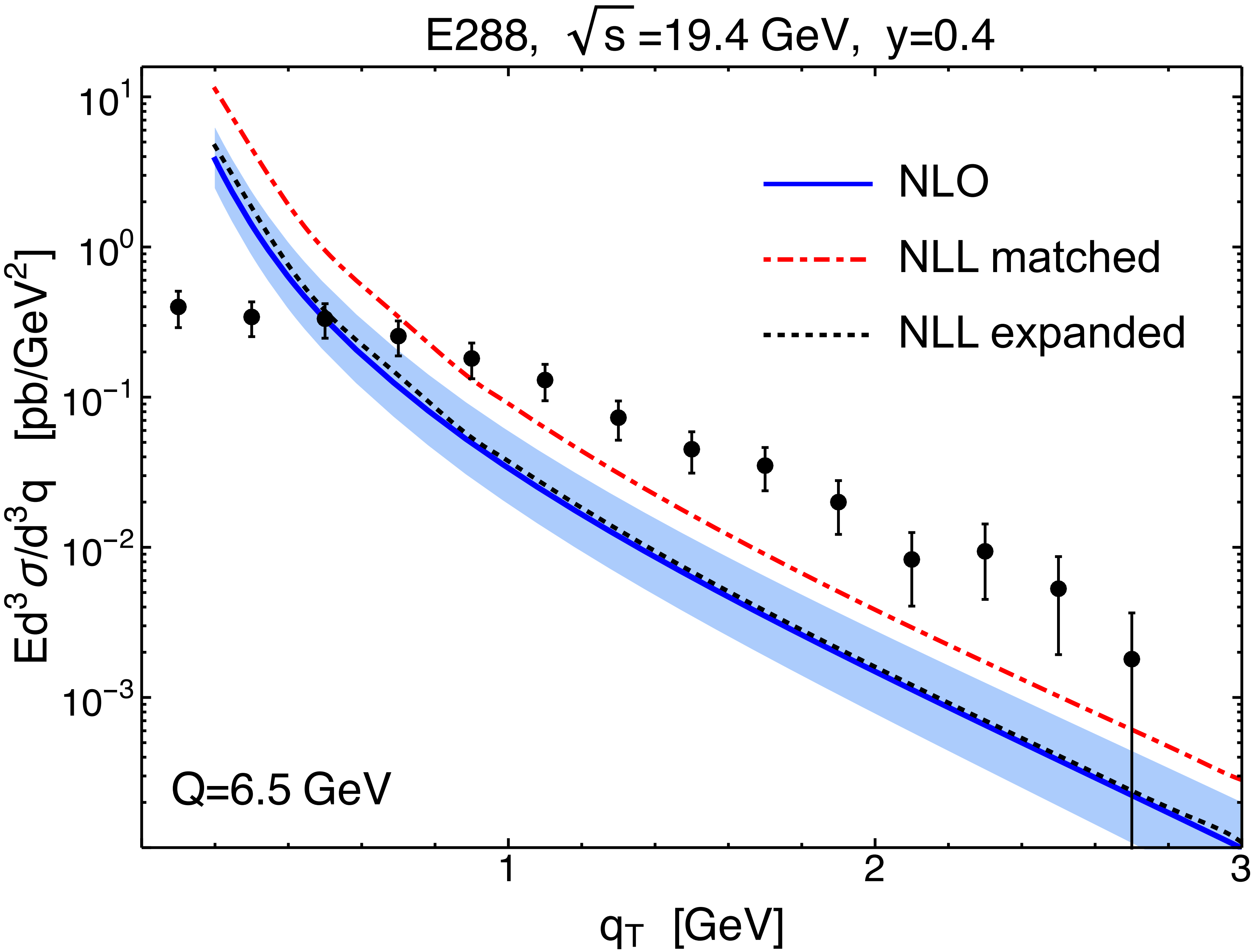


$$\frac{d\hat{\sigma}^{\mathrm{N}^k\mathrm{LO}}}{dq_T} \propto \alpha_s^k \log^{2k}(1 - y_T^2) + \ldots$$

- threshold logarithms

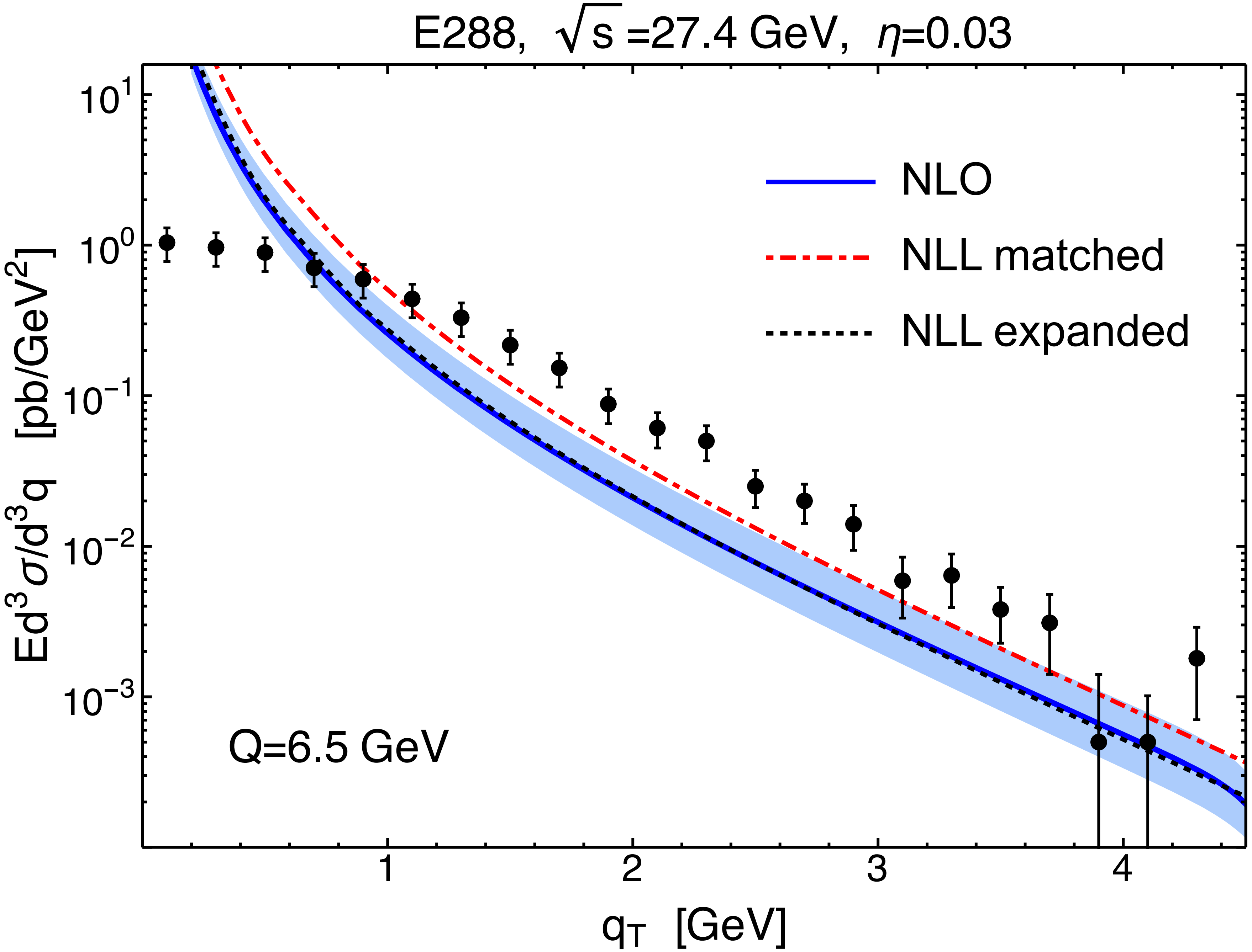
W. Vogelsang

threshold resummation



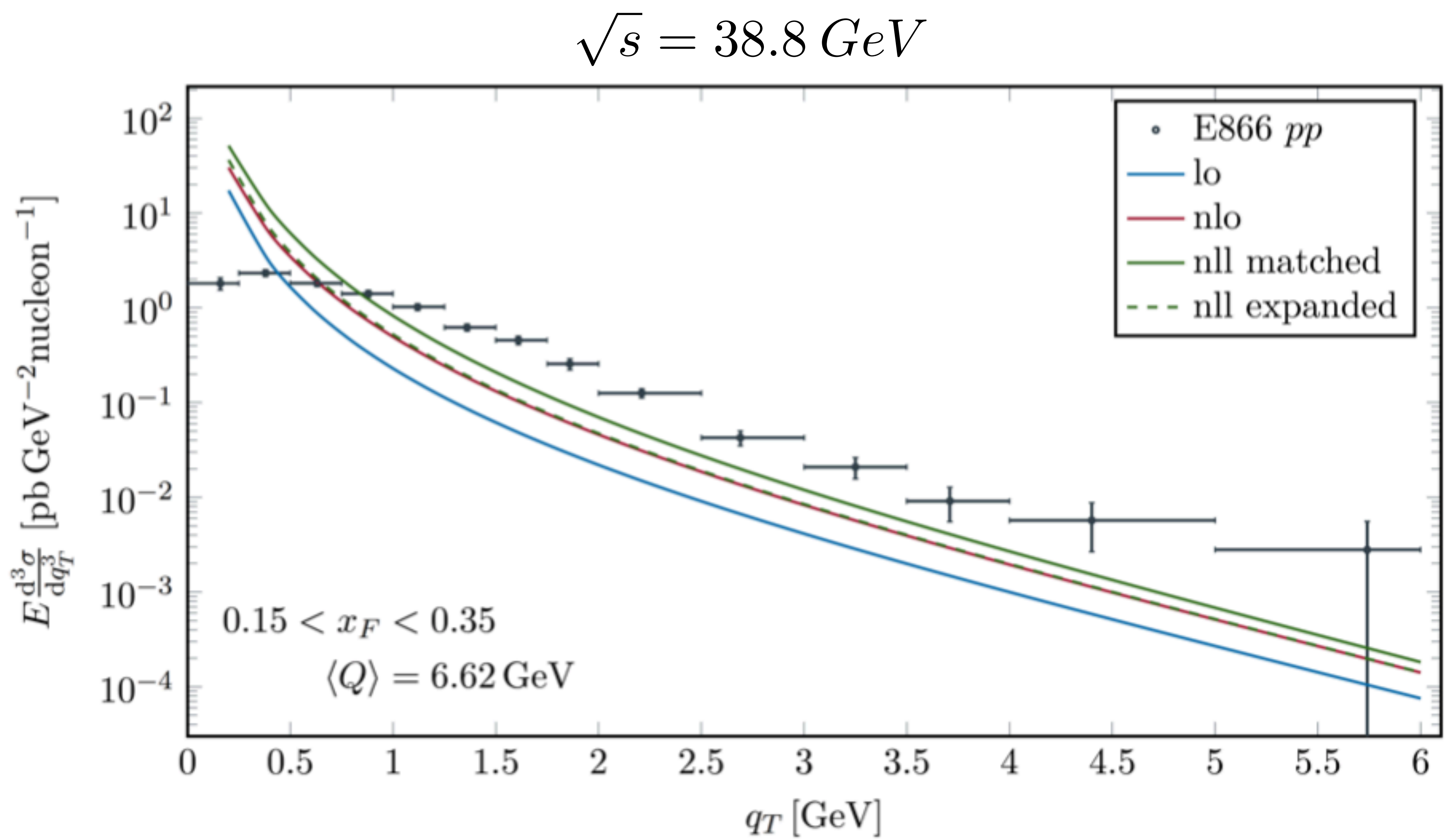
Vogelsang, Lambertsen, Steiglechner

threshold resummation



Vogelsang, Lambertsen, Steiglechner

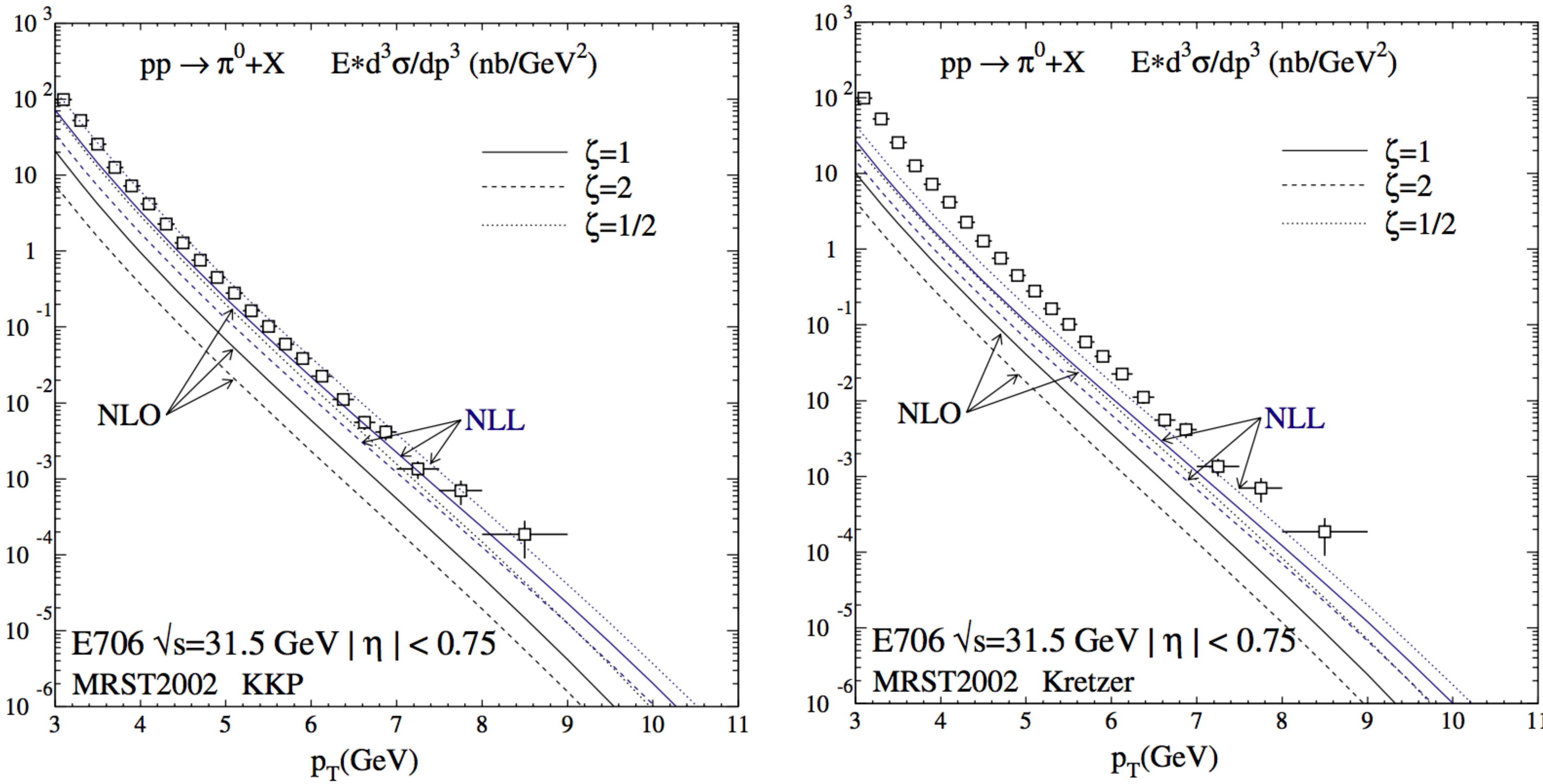
threshold resummation



Vogelsang, Lambertsen, Steiglechner

known similar cases

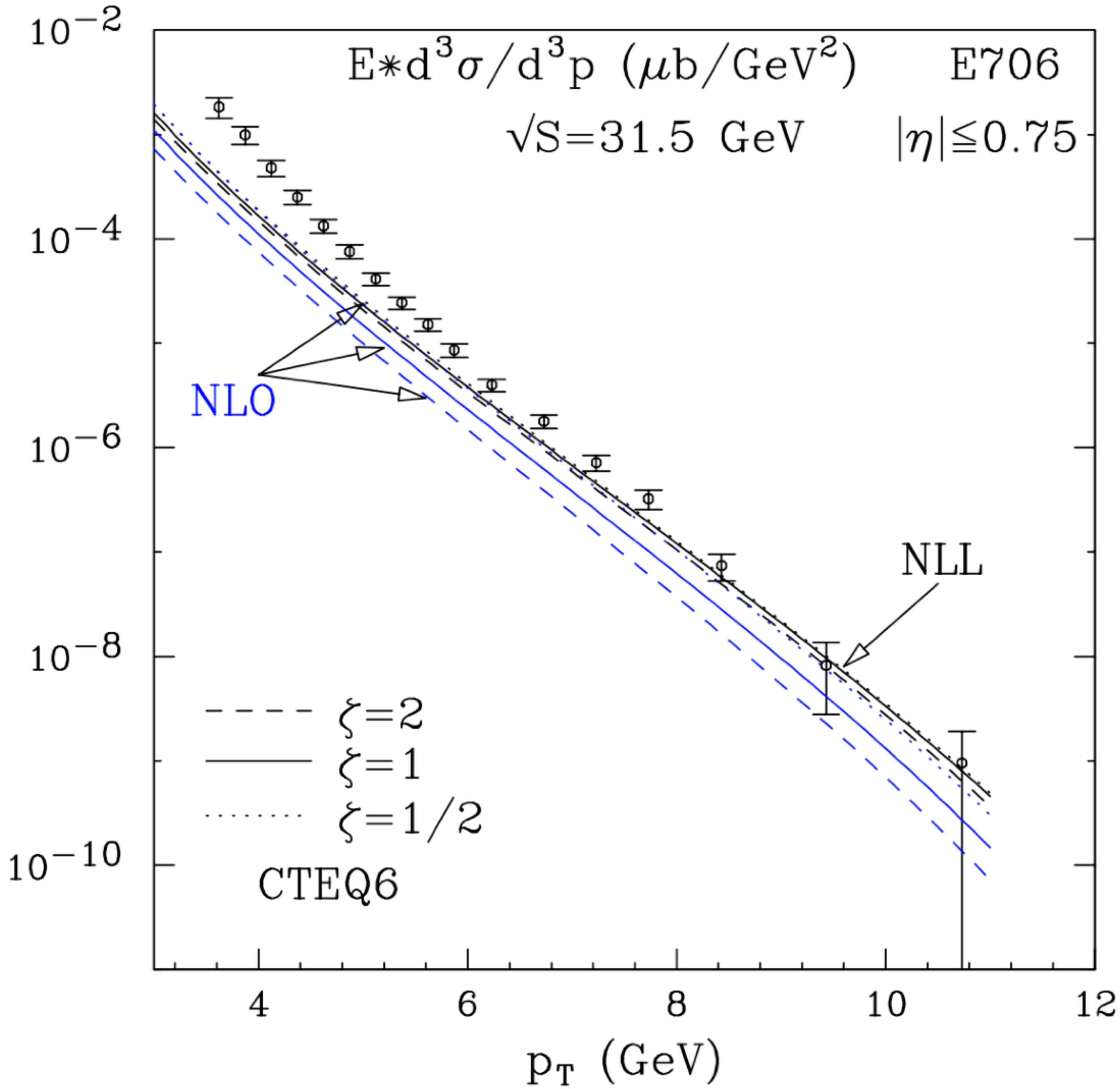
pion production



de Florian Vogelsang PRD71 114004 (2005)

known similar cases

prompt photon



de Florian Vogelsang PRD72 014014 (2005)

intrinsic k_T smearing

- take collinear factorization formula

$$d\sigma = \sum_{ab} \int dx_a \, dx_b f_{a/A}(x_a) \, f_{b/B}(x_b) \, d\hat{\sigma}^{ab \to l^+ l^-}$$

- give the incoming partons a small k_T

$$d\sigma = \sum_{ab} \int dx_a \, d^2\mathbf{k}_{Ta} \, dx_b \, d^2\mathbf{k}_{Tb}$$

$$\times f_{a/A}(x, \mathbf{k}_{Ta}) \, f_{b/B}(x, \mathbf{k}_{Tb}) \, \frac{\hat{s}}{x_a x_b s} d\sigma^{ab \to l^+ l^-}$$

intrinsic k_T smearing

intrinsic k_T has a long history…
(for prompt photon and pion production)

Owens RMP59, 465 (1987)
Sivers PRD41, 83 (1990)
D'Alesio Murgia PRD70, 074009 (2004)
…

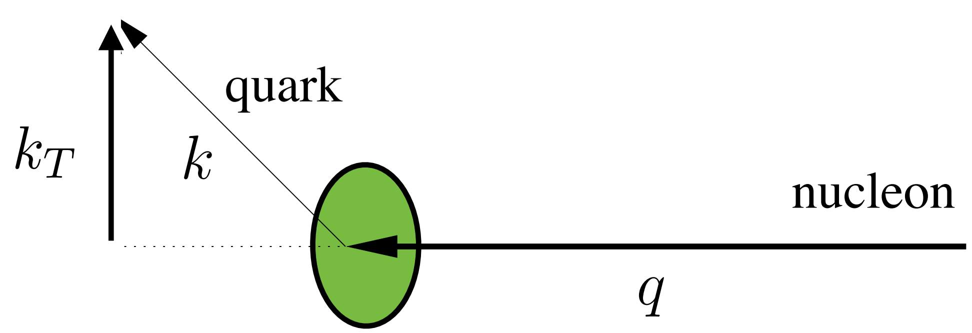
- give the incoming partons a small k_T

$$d\sigma = \sum_{ab} \int dx_a \, d^2\mathbf{k}_{Ta} \, dx_b \, d^2\mathbf{k}_{Tb}$$

$$\times f_{a/A}\left(x, \mathbf{k}_{Ta}\right) f_{b/B}\left(x, \mathbf{k}_{Tb}\right) \frac{\hat{s}}{x_a x_b s} d\sigma^{ab\to l^+ l^-}$$

intrinsic k_T smearing

non-perturbative k_T



- give the incoming partons a small k_T

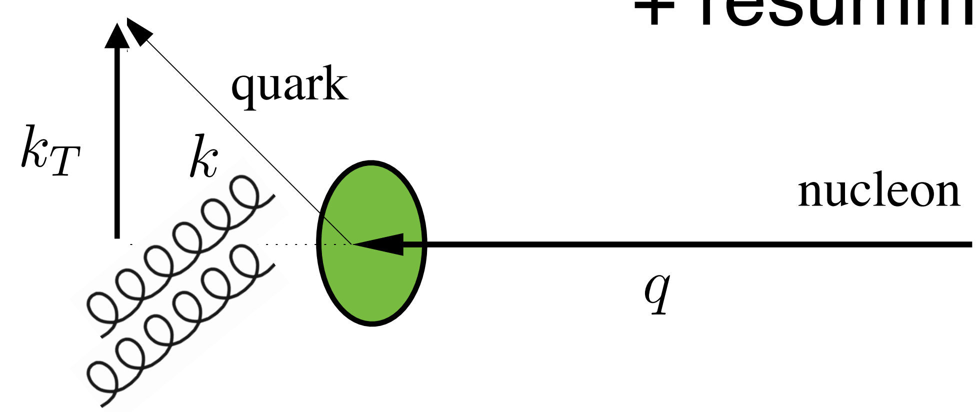
$$d\sigma = \sum_{ab} \int dx_a \, d^2\mathbf{k}_{Ta} \, dx_b \, d^2\mathbf{k}_{Tb}$$

$$\times f_{a/A}\left(x, \mathbf{k}_{Ta}\right) f_{b/B}\left(x, \mathbf{k}_{Tb}\right) \frac{\hat{s}}{x_a x_b s} d\sigma^{ab \to l^+ l^-}$$

intrinsic k_T smearing

non-perturbative k_T

+ resummed gluons



this means double-counting !

- give the incoming partons a small k_T

$$d\sigma = \sum_{ab} \int dx_a \, d^2\mathbf{k}_{Ta} \, dx_b \, d^2\mathbf{k}_{Tb}$$

$$\times f_{a/A}\left(x, \mathbf{k}_{Ta}\right) f_{b/B}\left(x, \mathbf{k}_{Tb}\right) \frac{\hat{s}}{x_a x_b s} d\sigma^{ab \to l^+ l^-}$$

intrinsic k_T smearing

$$d\sigma = \sum_{ab} \int dx_a \, d^2\mathbf{k}_{Ta} \, dx_b \, d^2\mathbf{k}_{Tb}$$

$$\times f_{a/A}\left(x, \mathbf{k}_{Ta}\right) f_{b/B}\left(x, \mathbf{k}_{Tb}\right) \frac{\hat{s}}{x_a x_b s} d\sigma^{ab \to l^+ l^-}$$

parton momentum:

$$p_a^\mu \doteq \left(p_a^0, \mathbf{p}_a^T, p_a^3\right) = \left(x_a P_A + \frac{k_{Ta}^2}{4 x_a P_A}, \mathbf{k}_{Ta}, x_a P_A - \frac{k_{Ta}^2}{4 x_a P_A}\right)$$

this enforces: $p_a^\mu p_{a\mu} = 0$ $\quad x_a = p_a^+ / P_A^+$

intrinsic k_T smearing

$$d\sigma = \sum_{ab} \int dx_a \, d^2\mathbf{k}_{Ta} \, dx_b \, d^2\mathbf{k}_{Tb}$$

$$\times f_{a/A}\left(x, \mathbf{k}_{Ta}\right) f_{b/B}\left(x, \mathbf{k}_{Tb}\right) \frac{\hat{s}}{x_a x_b s} d\sigma^{ab\to l^+ l^-}$$

parton momentum:

$$p_a^\mu \doteq \left(p_a^0, \mathbf{p}_a^T, p_a^3\right) = \left(x_a P_A + \frac{k_{Ta}^2}{4x_a P_A}, \mathbf{k}_{Ta}, x_a P_A - \frac{k_{Ta}^2}{4x_a P_A}\right)$$

this enforces: $p_a^\mu p_{a\mu} = 0$ $\quad x_a = p_a^+ / P_A^+$

must make sure

- quark energy < proton energy
- quark direction = proton direction

$$k_{Ta} < \sqrt{x_a\left(1 - x_a\right)}\sqrt{s}$$

$$k_{Ta} < x_a \sqrt{s}$$

better to stay far from the bounds!

intrinsic k_T smearing

$$d\sigma = \sum_{ab} \int dx_a\, d^2\mathbf{k}_{Ta}\, dx_b\, d^2\mathbf{k}_{Tb}$$

$$\times f_{a/A}\left(x, \mathbf{k}_{Ta}\right) f_{b/B}\left(x, \mathbf{k}_{Tb}\right) \frac{\hat{s}}{x_a x_b s} d\sigma^{ab\to l^+l^-}$$

parton momentum:

$$p_a^\mu \doteqdot \left(p_a^0, \mathbf{p}_a^T, p_a^3\right) = \left(x_a P_A + \frac{k_{Ta}^2}{4x_a P_A}, \mathbf{k}_{Ta}, x_a P_A - \frac{k_{Ta}^2}{4x_a P_A}\right)$$

$$\hat{t} = \left(q_\gamma - p_a\right)^2 = Q^2 - 2q_\gamma^- p_a^+ {\color{red} - 2q_\gamma^+ p_a^- + 2\mathbf{q}_T \cdot \mathbf{p}_{Ta}}$$

make sure

$\hat{t},\ \hat{u}$

not too small

Fixed Order must be valid!

intrinsic k_T smearing

$$d\sigma = \sum_{ab} \int dx_a \, d^2\mathbf{k}_{Ta} \, dx_b \, d^2\mathbf{k}_{Tb}$$

$$\times f_{a/A}\left(x, \mathbf{k}_{Ta}\right) f_{b/B}\left(x, \mathbf{k}_{Tb}\right) \frac{\hat{s}}{x_a x_b s} d\sigma^{ab \to l^+ l^-}$$

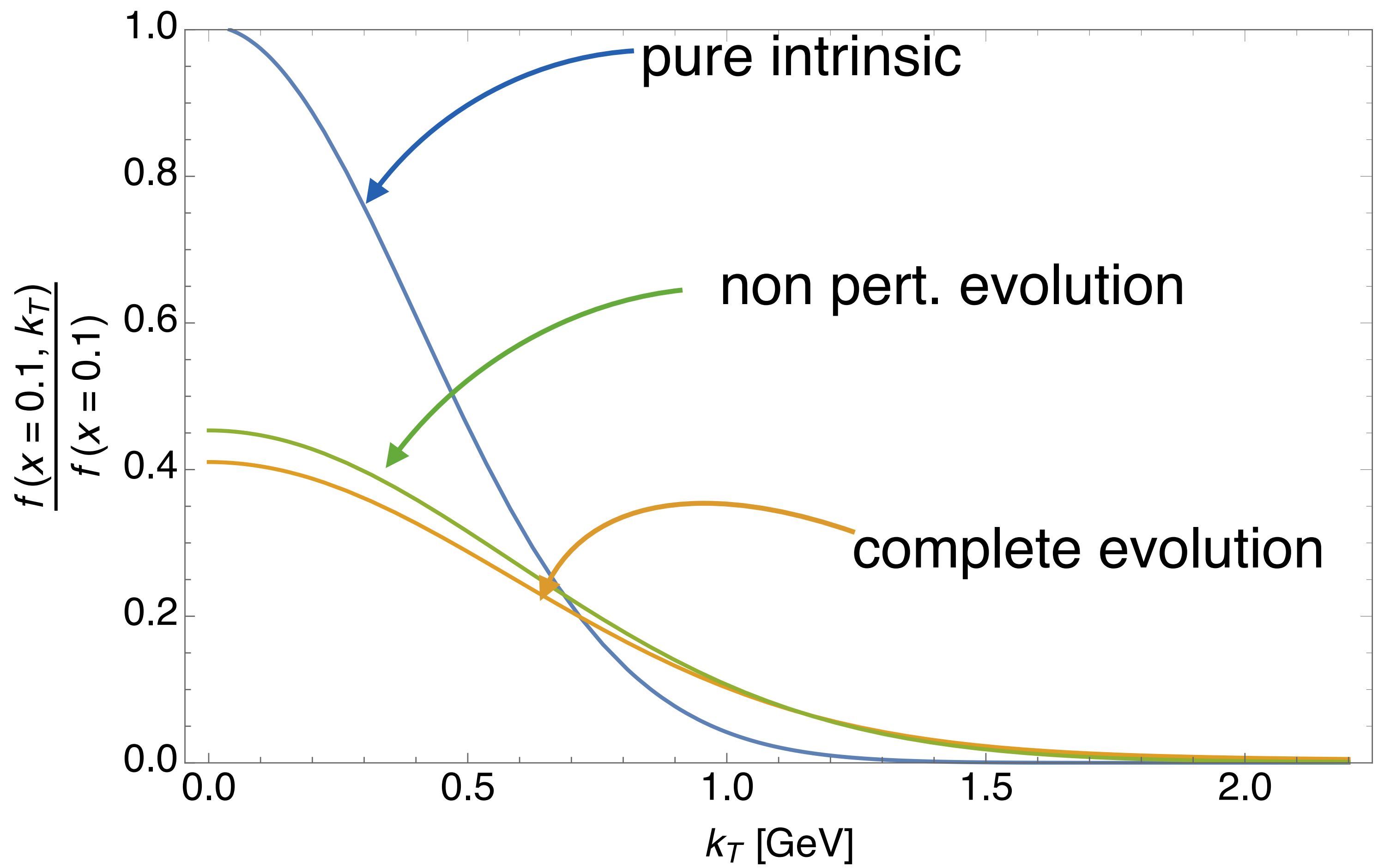
$$\int_0^{k^2_{Tmax}} \pi dk_T^2$$

check independence from cutoff!

intrinsic k_T smearing

$$\frac{f_{a/A}\left(x_a, \mathbf{k}_{Ta}\right)}{f_{a/A}\left(x_a\right)}$$

Q evolution from TMD extraction:

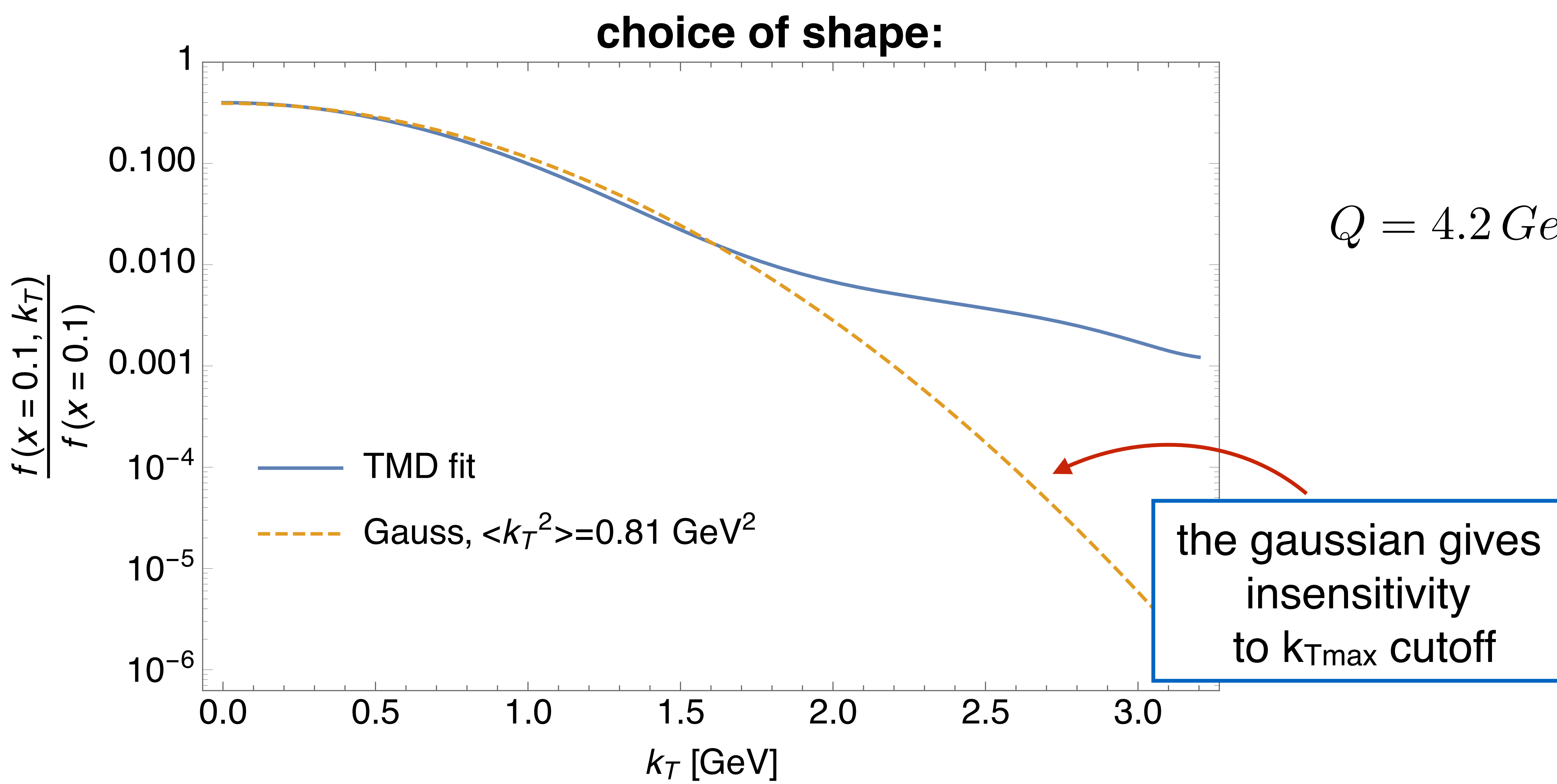


$Q = 4.2\,GeV$

Bacchetta et al JHEP 1706 081

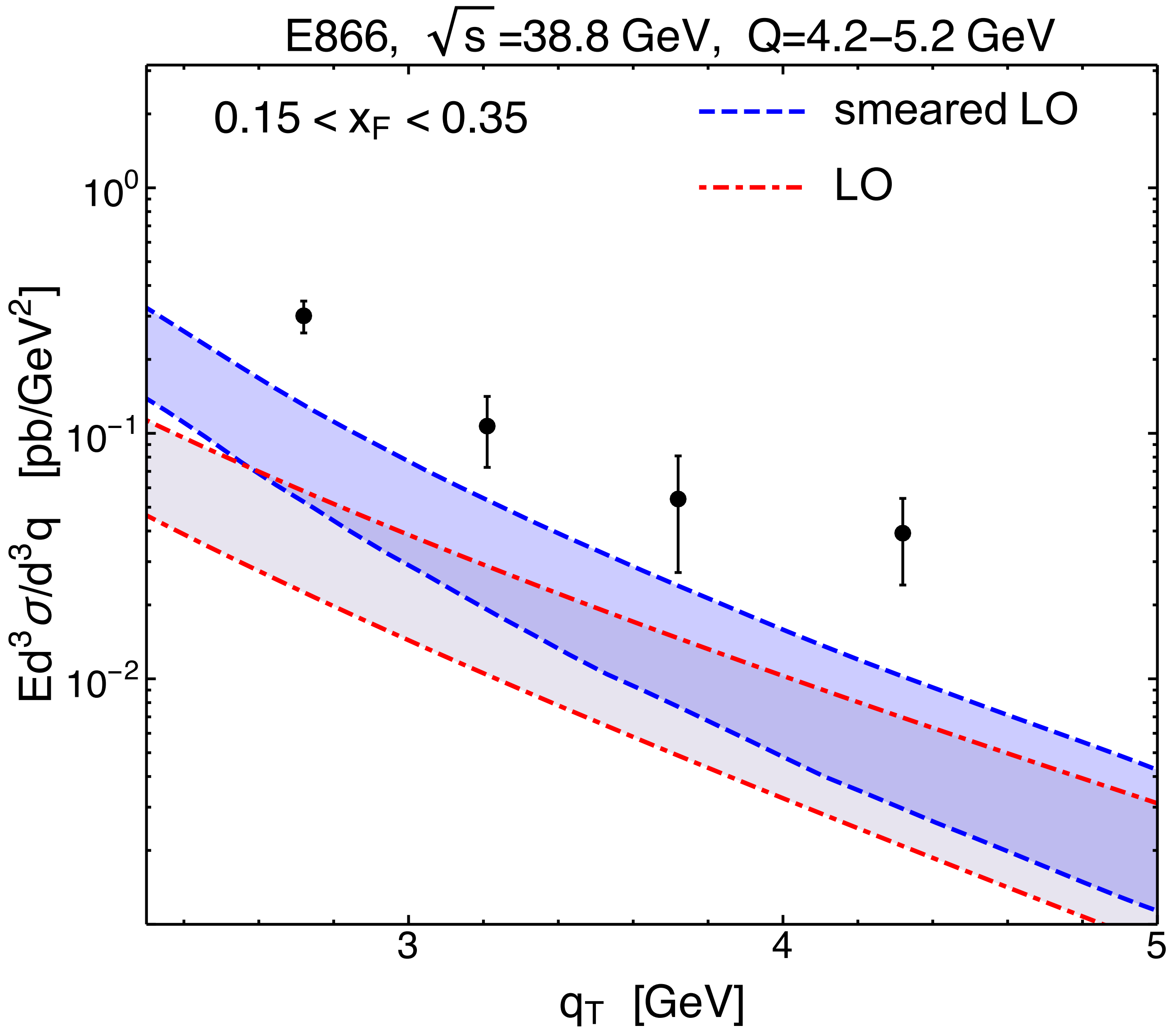
intrinsic k_T smearing

$$\frac{f_{a/A}\left(x_a, \mathbf{k}_{Ta}\right)}{f_{a/A}\left(x_a\right)}$$



$Q = 4.2\, GeV$

intrinsic k_T smearing



$$f_q\left(x,\mathbf{k}_T\right)=f\left(x\right)\frac{1}{\pi<k_T^2>}e^{-\frac{k_T^2}{<k_T^2>}}$$

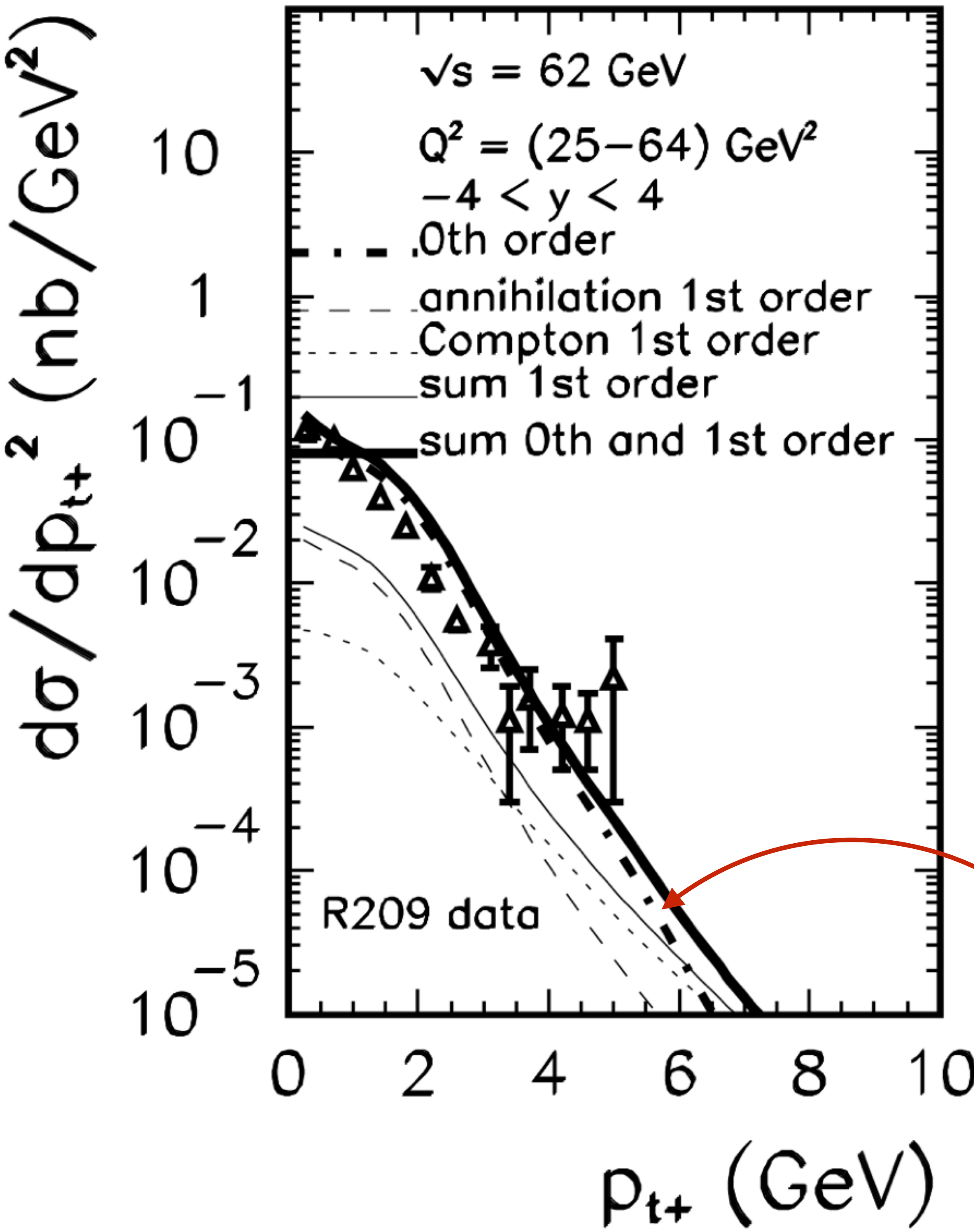
$$\left\langle k_T^2\right\rangle=0.81\,GeV^2$$

same for any x and flavor
…and for gluons!!

Summary

- fixed-order pQCD largely underestimates low-energy DY data at high q_T
- only partial improvement from threshold resummation, and only for some kinematics
- intrinsic-k_T model does not seem to help
- more low Q and high q_T data needed

…"k_T-factorization" formalism?



Szczurek, Slipek PRD 78, 114007

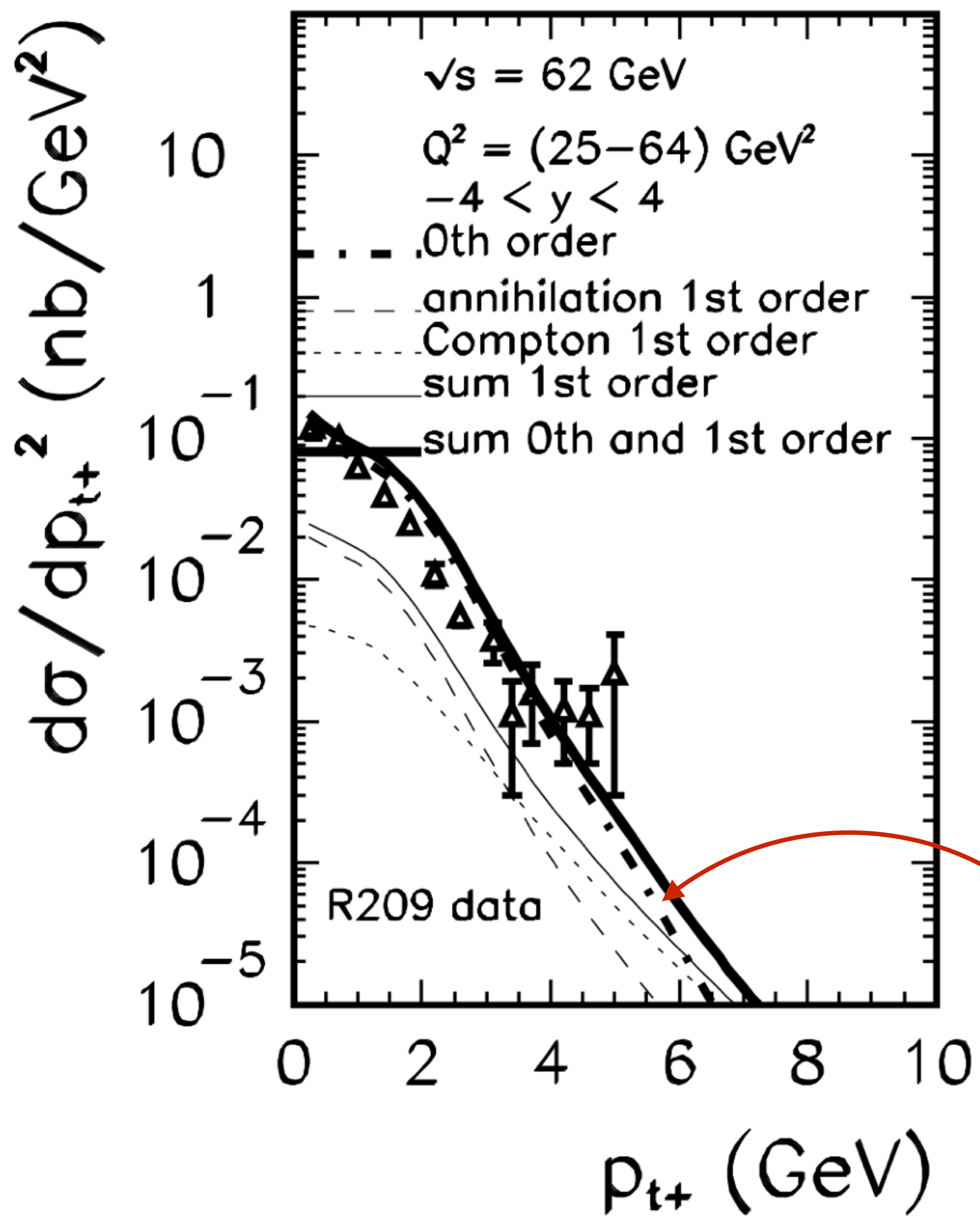
$$d\sigma = \sum_{ab} \int dx_a \, d^2\mathbf{k}_{Ta} \, dx_b \, d^2\mathbf{k}_{Tb}$$

$$\times F^u_{a/A}(x_a, \mathbf{k}_{Ta}, \mu_F) \, F^u_{b/B}(x_b, \mathbf{k}_{Tb}, \mu_F) \, \frac{\hat{s}}{x_a x_b} d\hat{\sigma}^{ab \to l^+ l^-}$$

"unintegrated parton distributions"
(from extension of CCFM equations)

almost all of the cross-section given by soft gluons + intrinsic k_T

…"k_T-factorization" formalism?



Szczurek, Slipek PRD 78, 114007

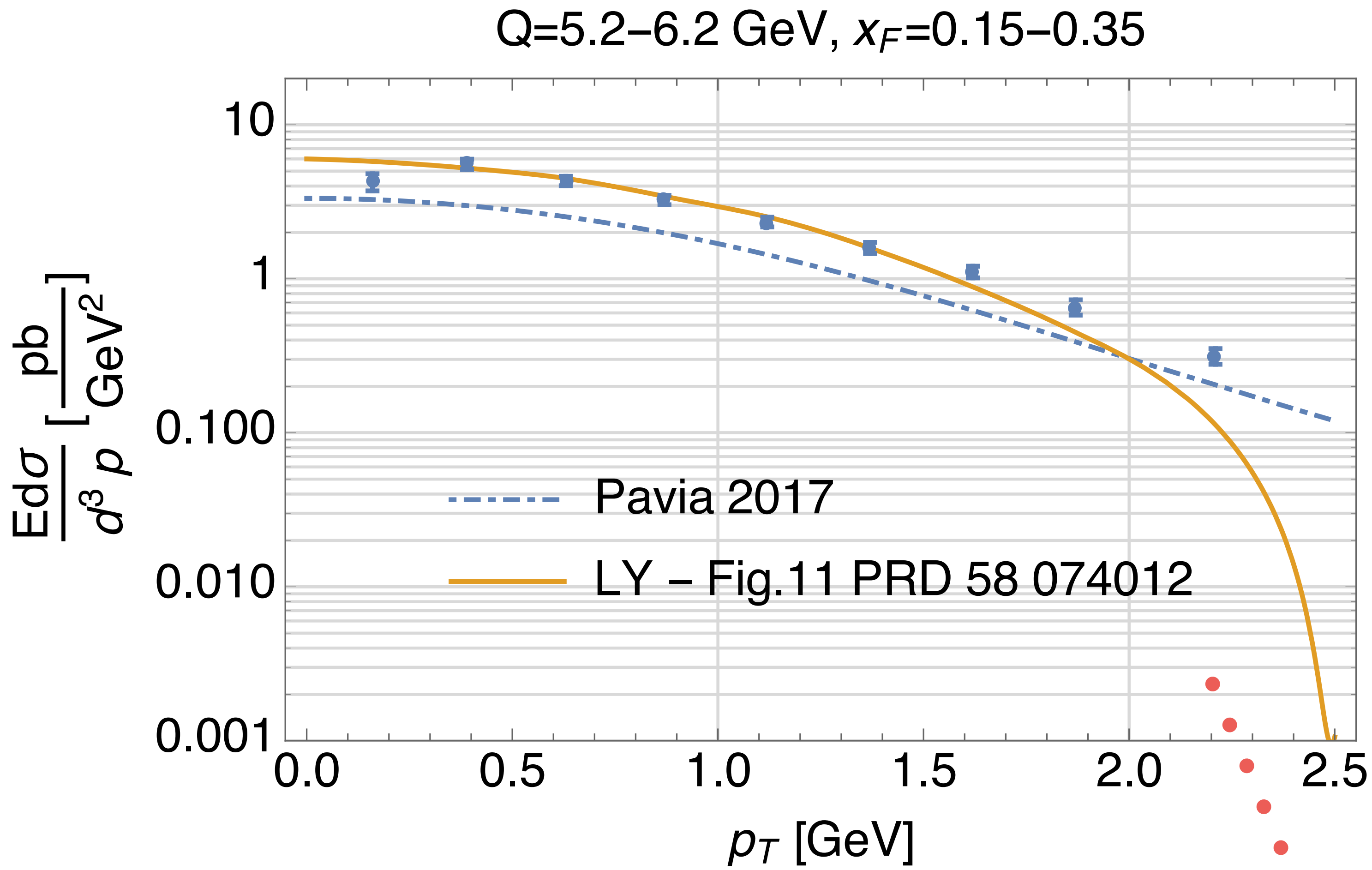
$$d\sigma = \sum_{ab} \int dx_a \, d^2\mathbf{k}_{Ta} \, dx_b \, d^2\mathbf{k}_{Tb}$$

$$\times F^u_{a/A}(x_a, \mathbf{k}_{Ta}, \mu_F) \, F^u_{b/B}(x_b, \mathbf{k}_{Tb}, \mu_F) \, \frac{\hat{s}}{x_a x_b} d\hat{\sigma}^{ab \to l^+ l^-}$$

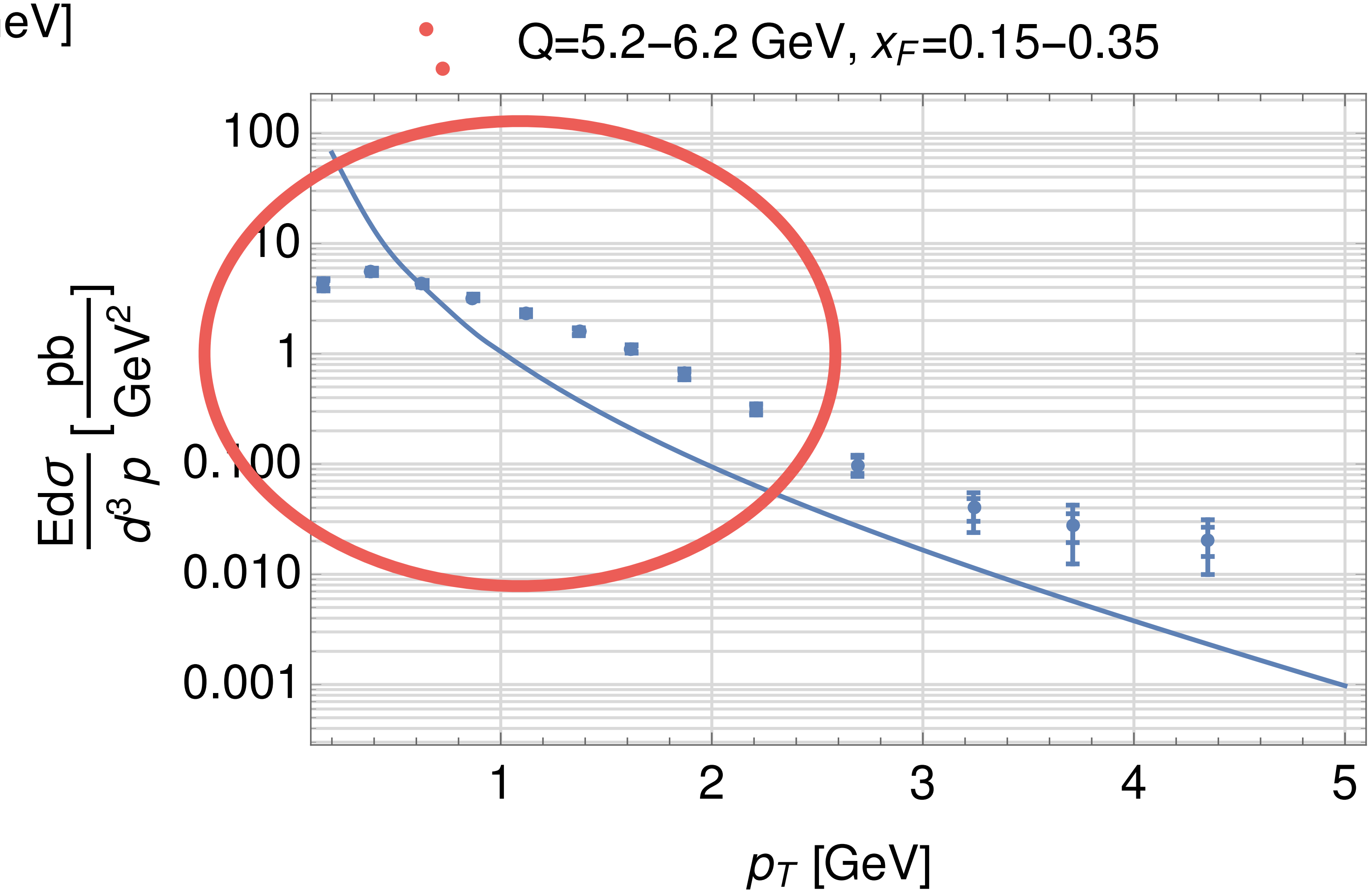
apparently difficult to find a formal proof
Avsar, Collins arXiv:1209.1675

not clear why it should differ from "traditional" formalism at this kinematics (not small-x)

almost all of the cross-section given by soft gluons + intrinsic k_T



TMD parametrizations



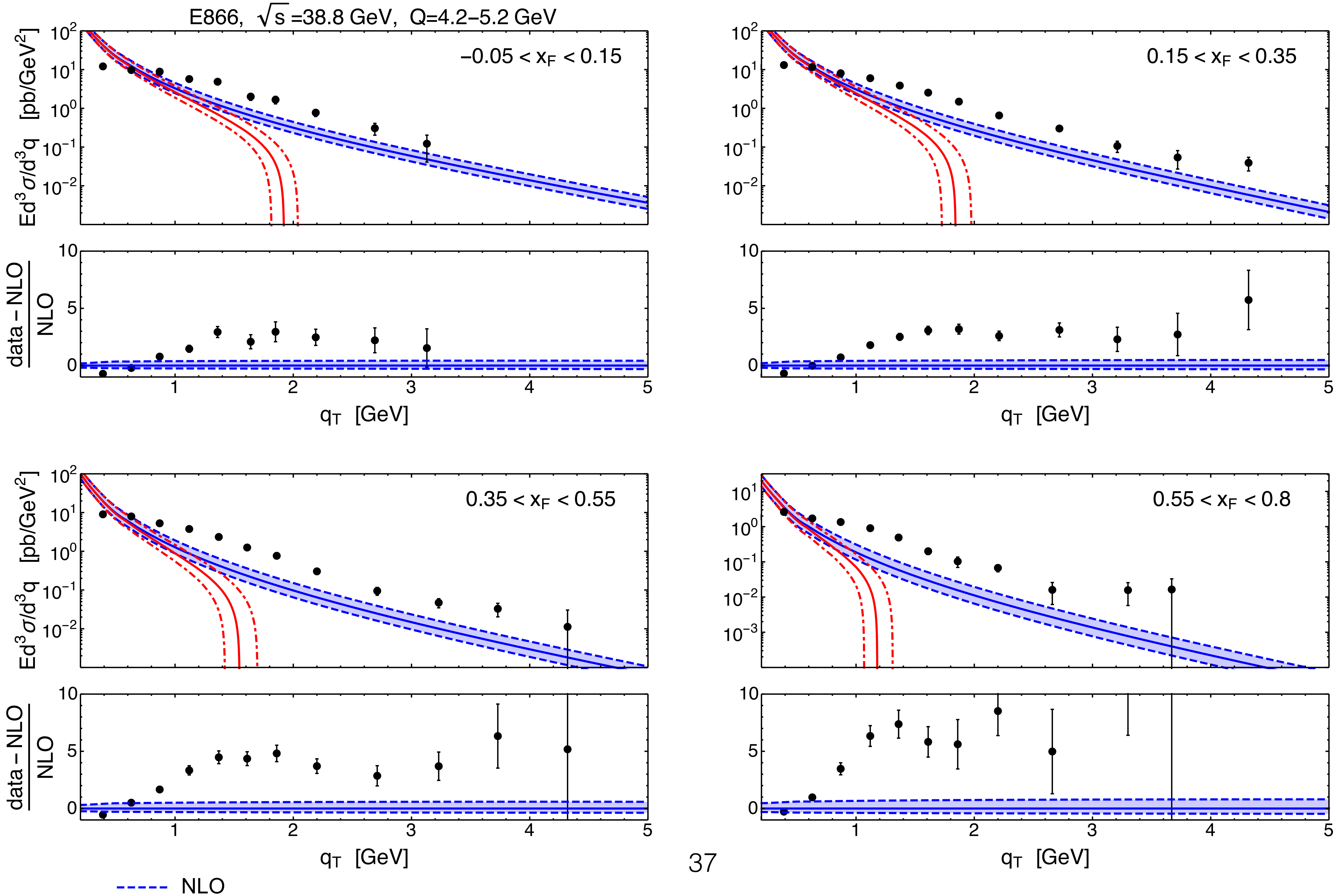
E866/NuSea

$$p\,p \rightarrow \mu^+\mu^- X$$

$$\sqrt{s} = 38.8\,GeV$$

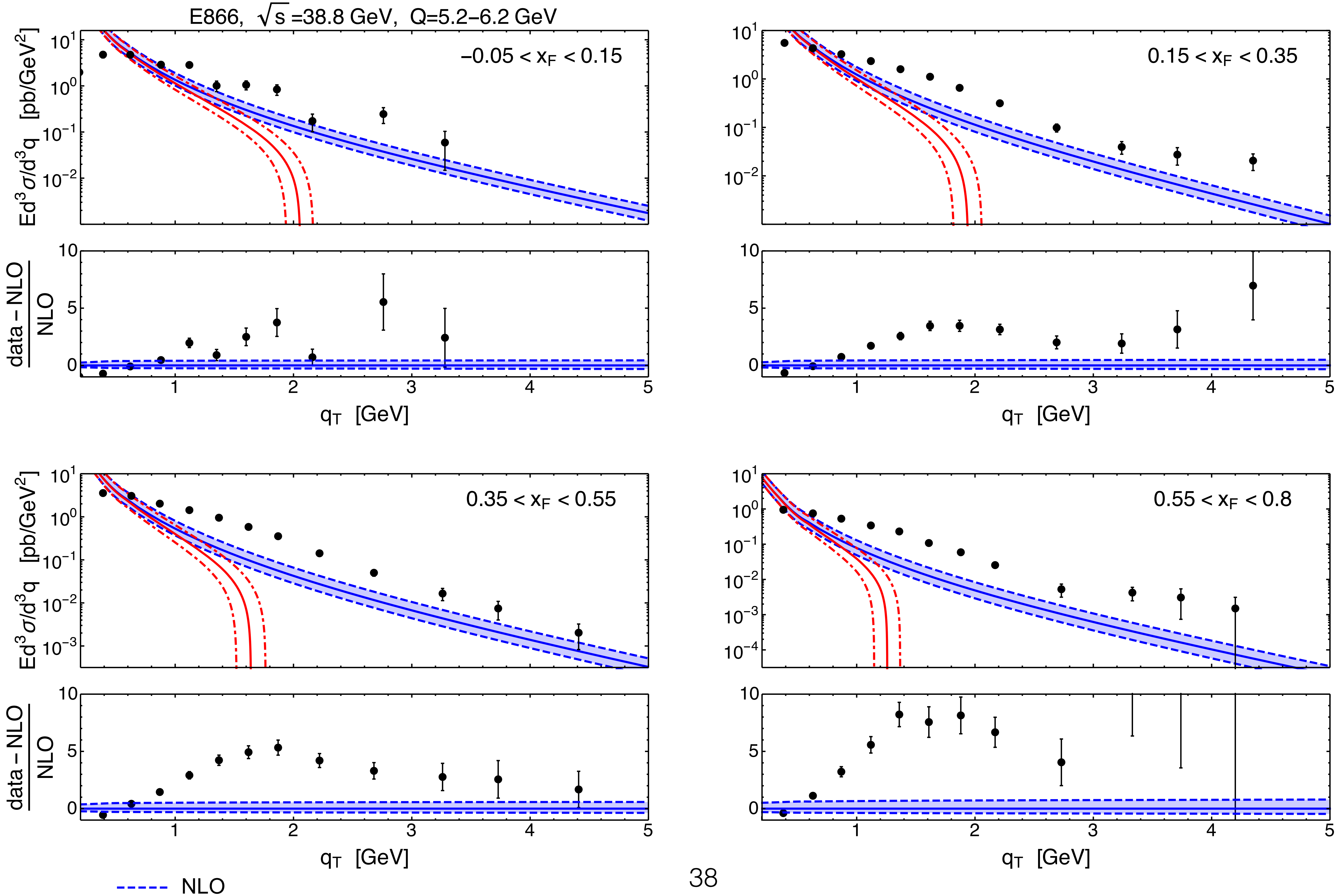
E866/NuSea

$$p\,p \to \mu^+\mu^- X \qquad \sqrt{s} = 38.8\,GeV$$



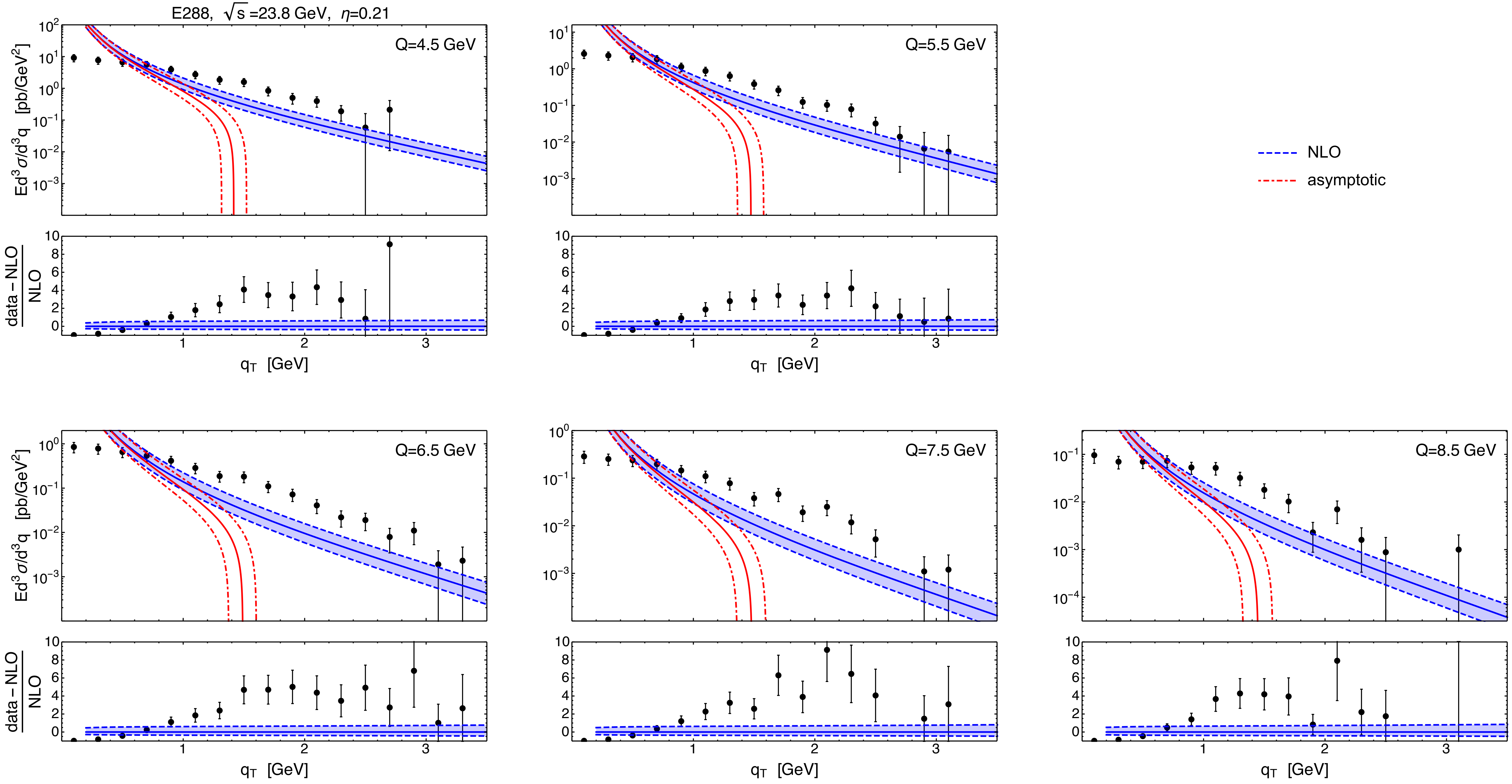
E866/NuSea

$$p\,p \to \mu^+\mu^- X \qquad \sqrt{s} = 38.8\,GeV$$



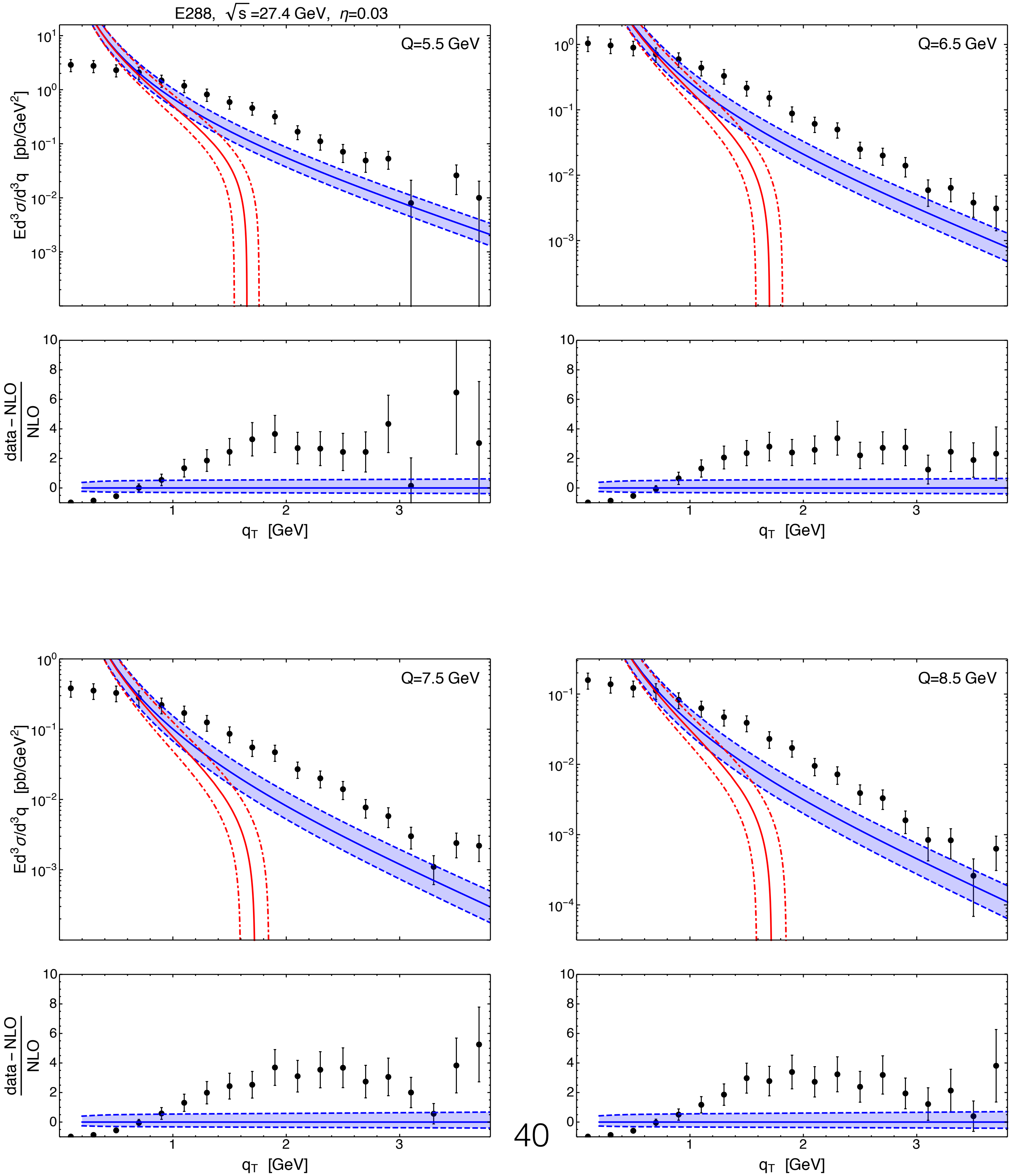
E288

$$p\,Cu,\ p\,Pt \to \mu^+\mu^-\ X$$



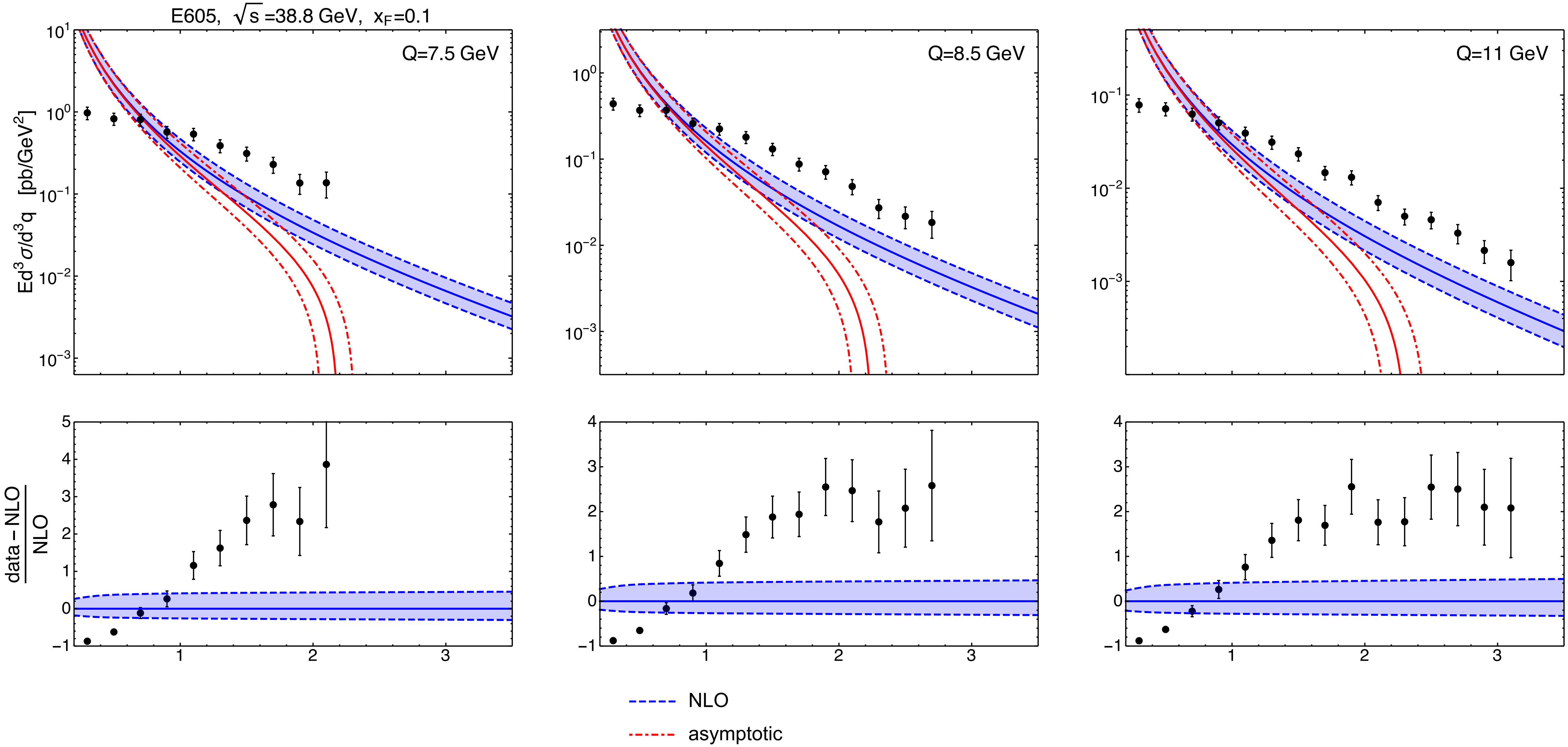
E288

$$p\,Cu,\ p\,Pt \to \mu^+\mu^-\ X$$

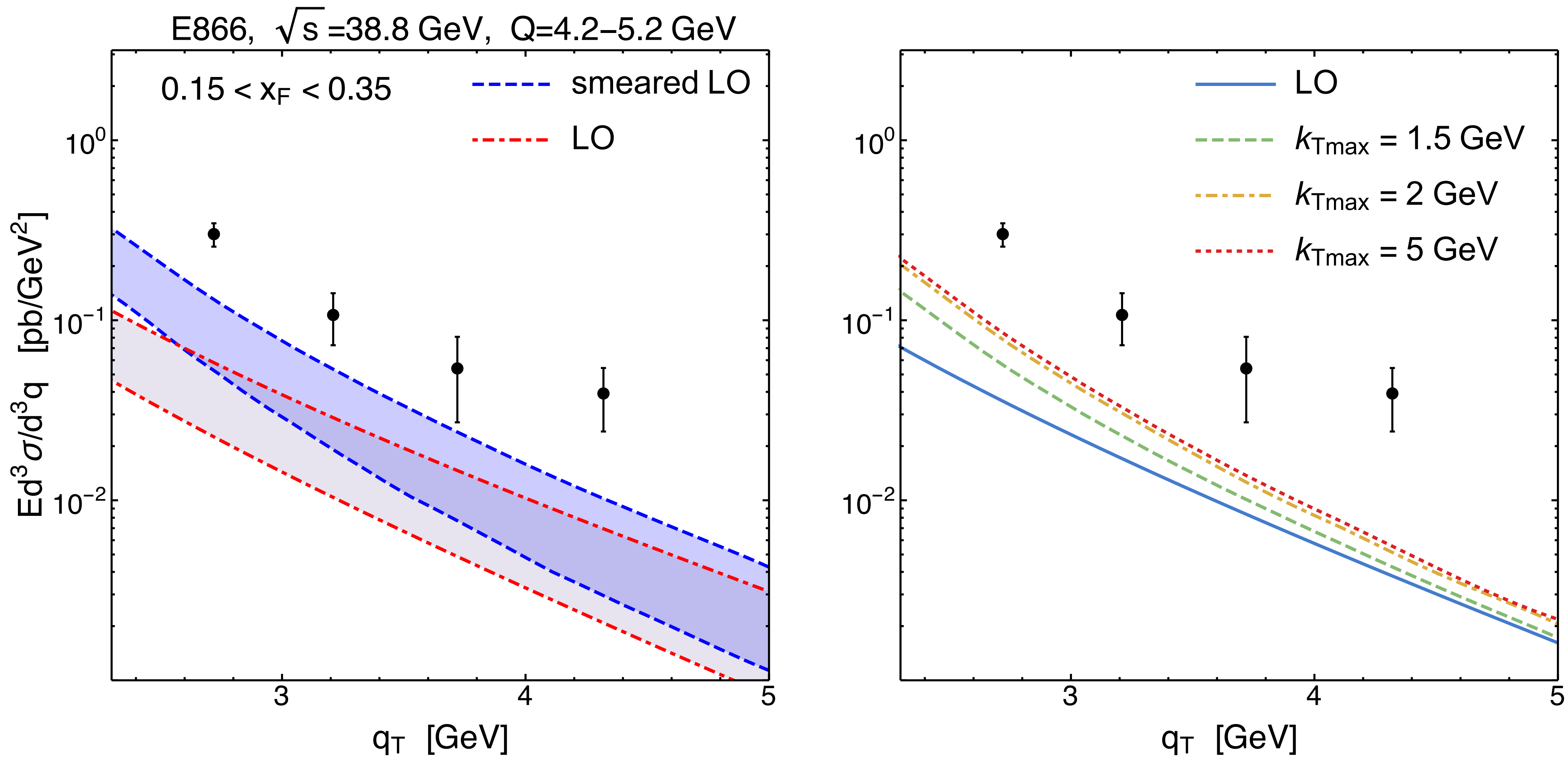


E605

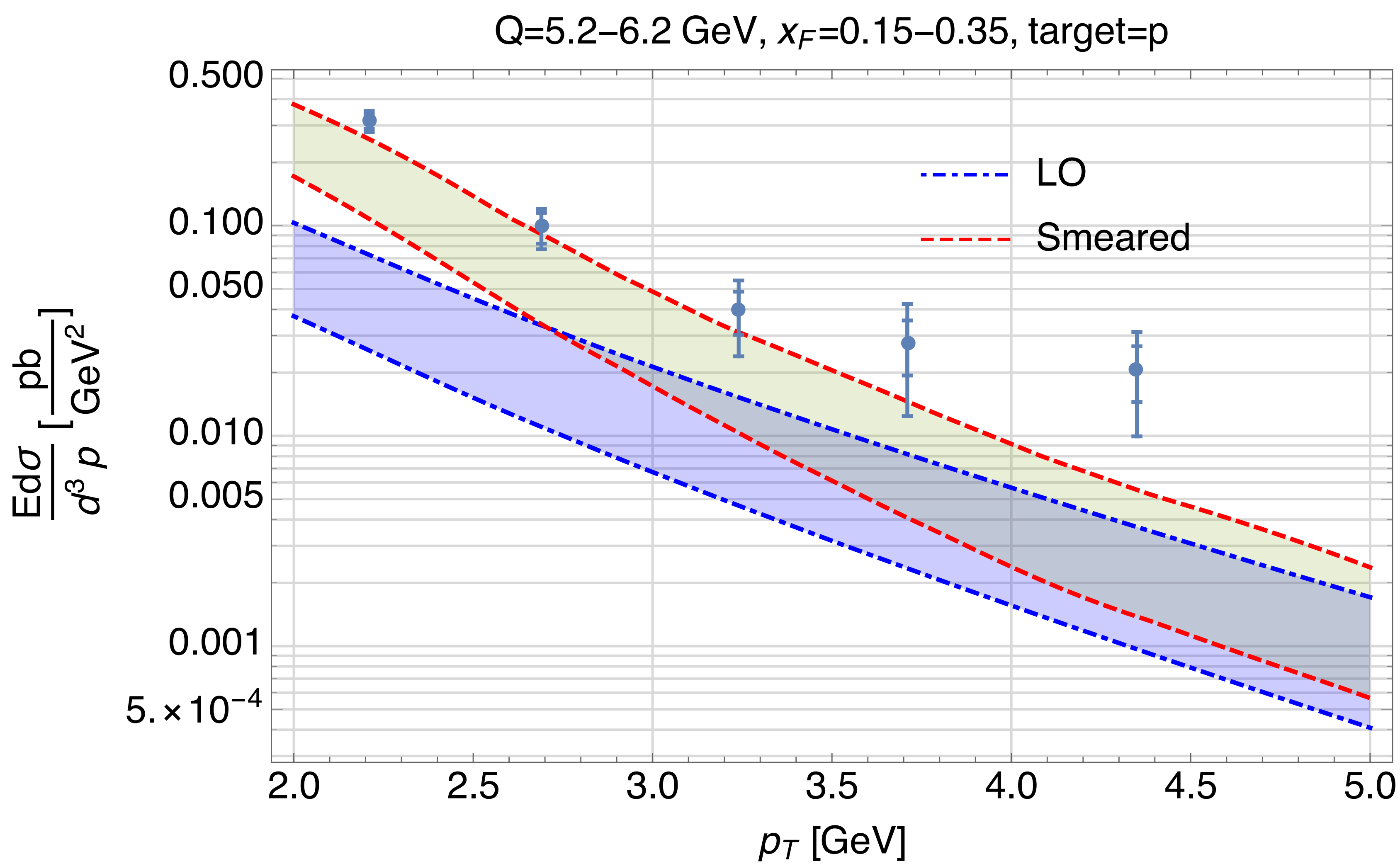
$$p\,Cu \to \mu^+\mu^-\;X$$



intrinsic k_T smearing



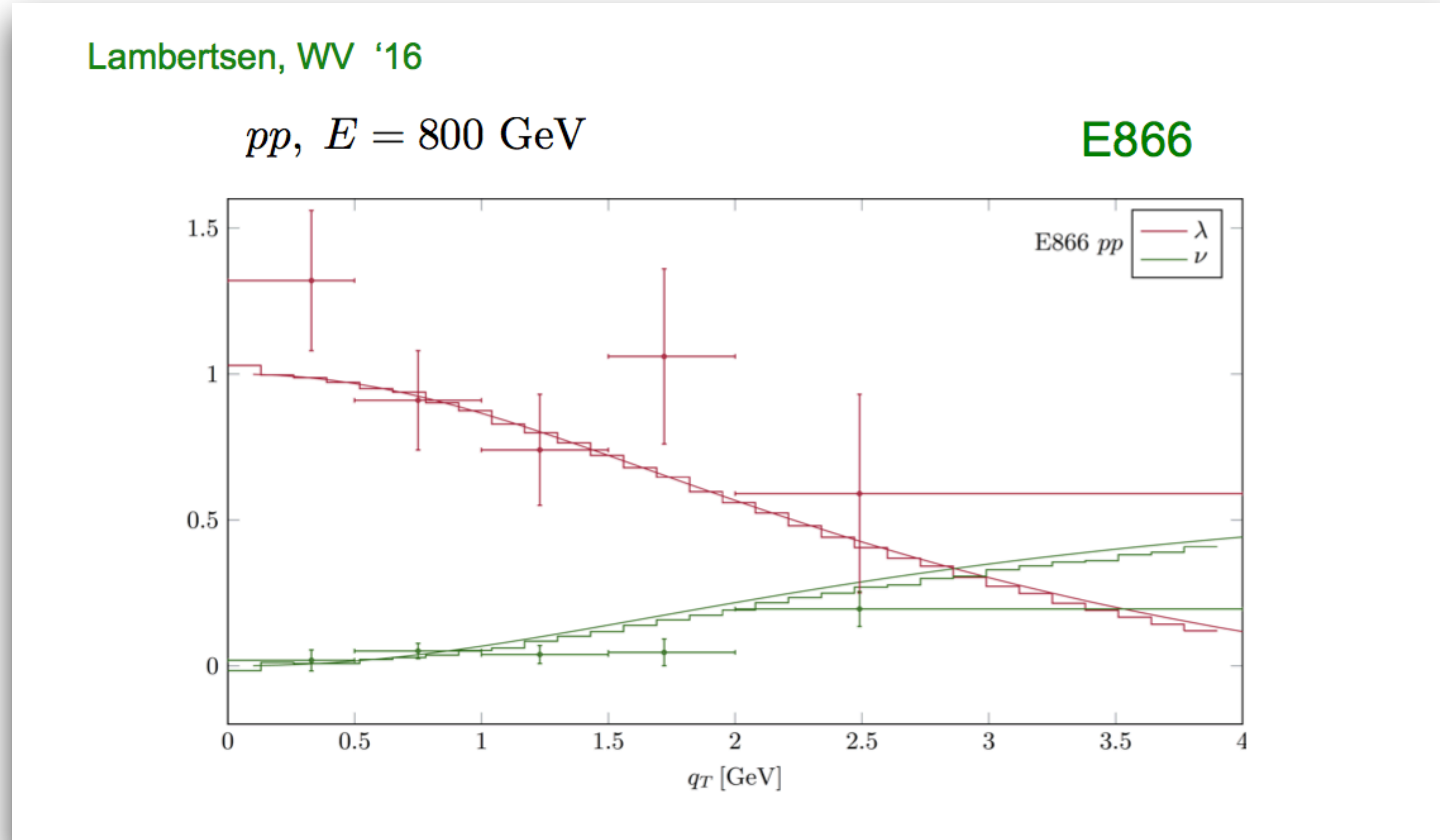
intrinsic k_T smearing



$$f_q\left(x, \mathbf{k}_T\right) = f\left(x\right)\frac{1}{\pi < k_T^2 >}e^{-\frac{k_T^2}{< k_T^2 >}}$$

$$\left\langle k_T^2 \right\rangle = 1\, GeV^2$$

angular coefficients



W. Vogelsang @Transversity 2017

angular coefficients