Drell-Yan at low energy and high transverse momentum

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3DSPIN MAPPING THE PROTON IN 3D

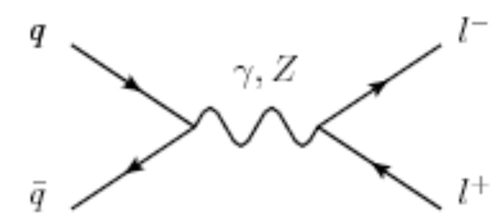
European Research Council

Istituto Nazionale di Fisica Nucleare

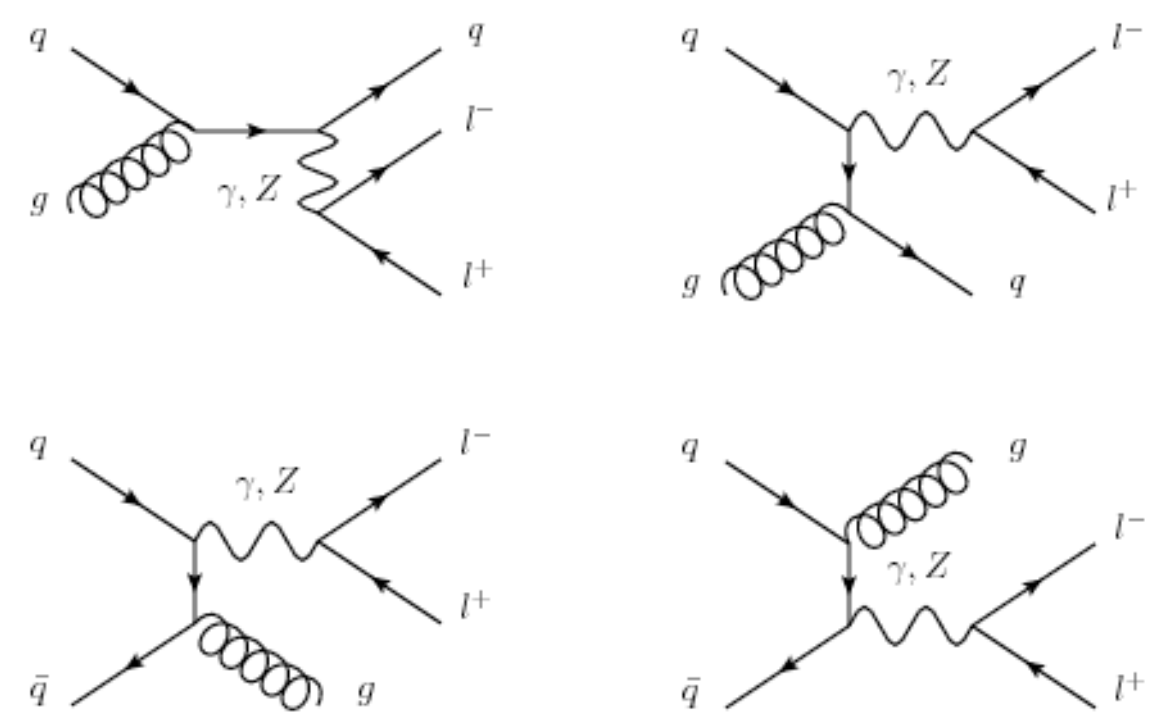
UNIVERSITÀ DI PAVIA

Transverse momentum of Drell-Yan pairs

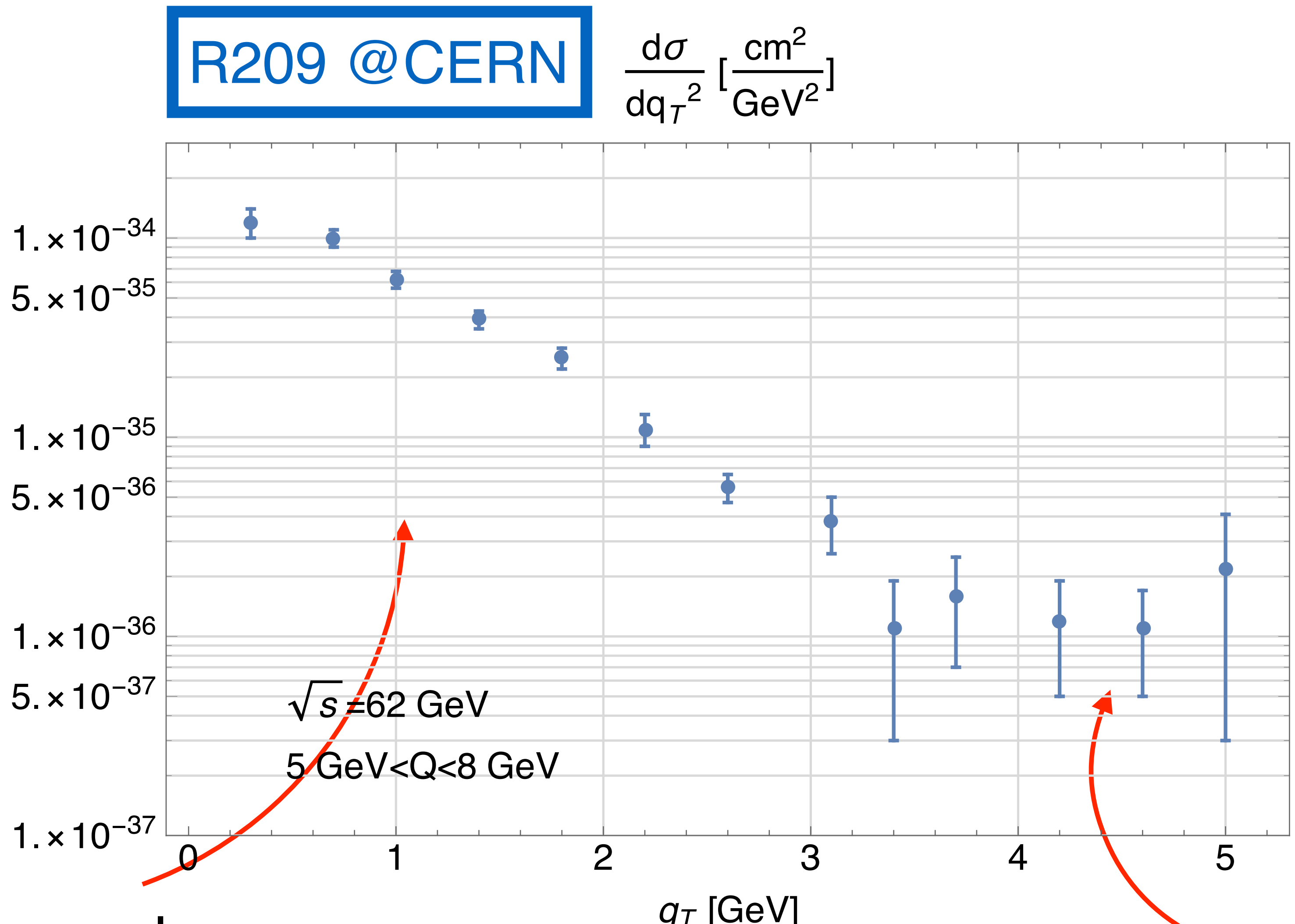
- No transverse momentum at $\mathcal{O}(\alpha_s^0)$



- LO = $\mathcal{O}(\alpha_s^1)$



Transverse momentum of Drell-Yan pairs

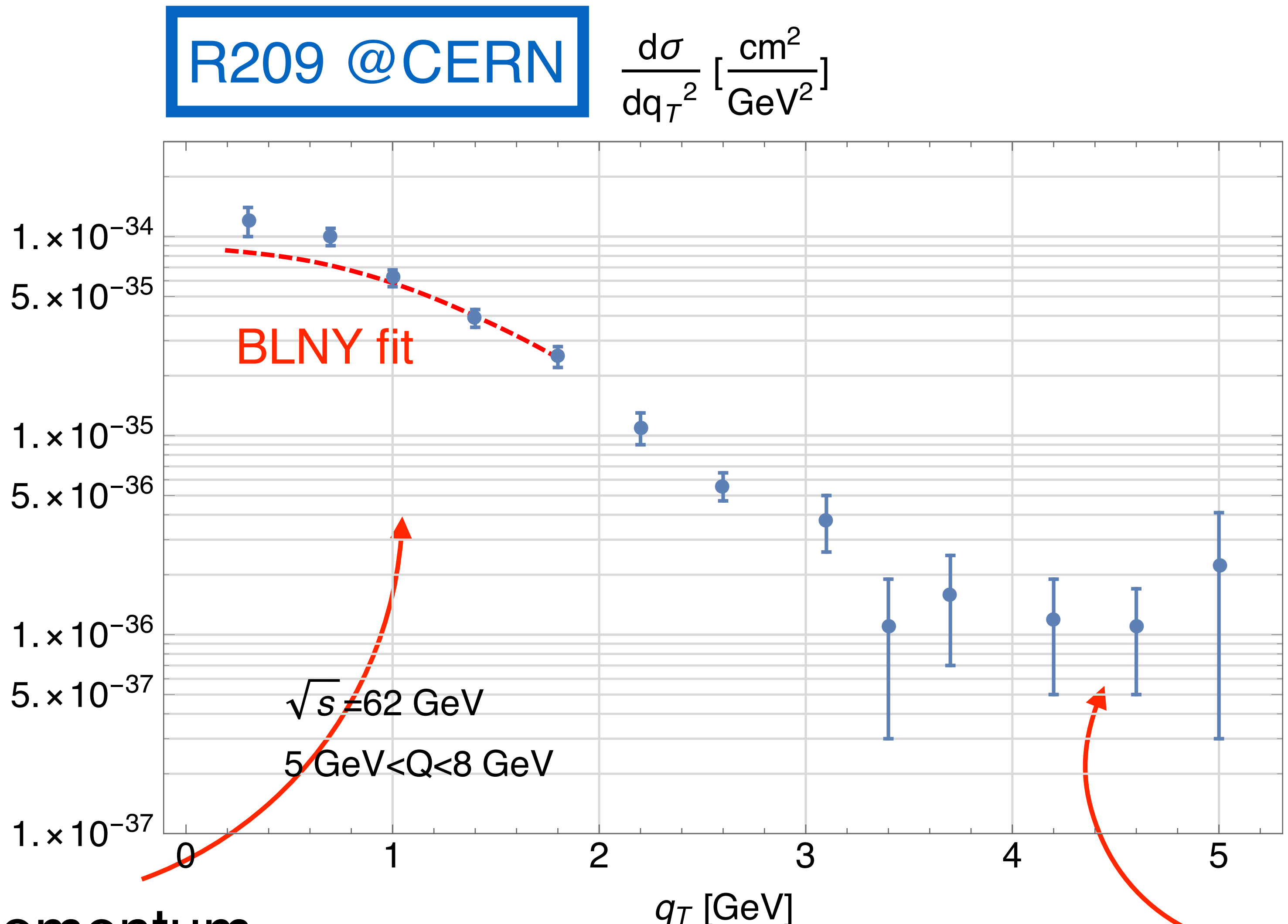


Transverse momentum resummation (q_T-logs) $\alpha_s^n \ln^m \frac{q_T^2}{Q^2}$

+ non perturbative effects

Fixed order collinear factorization

Transverse momentum of Drell-Yan pairs



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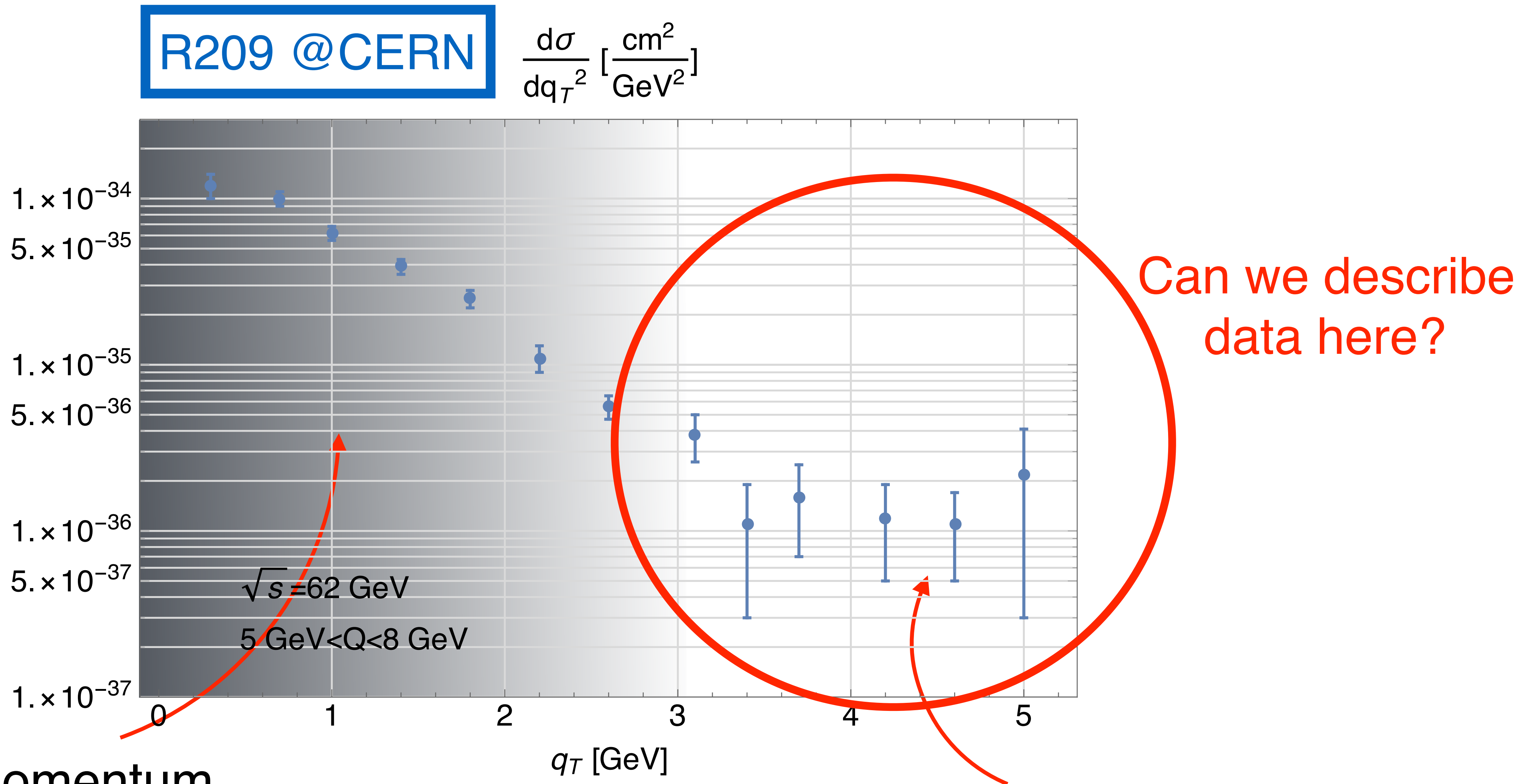


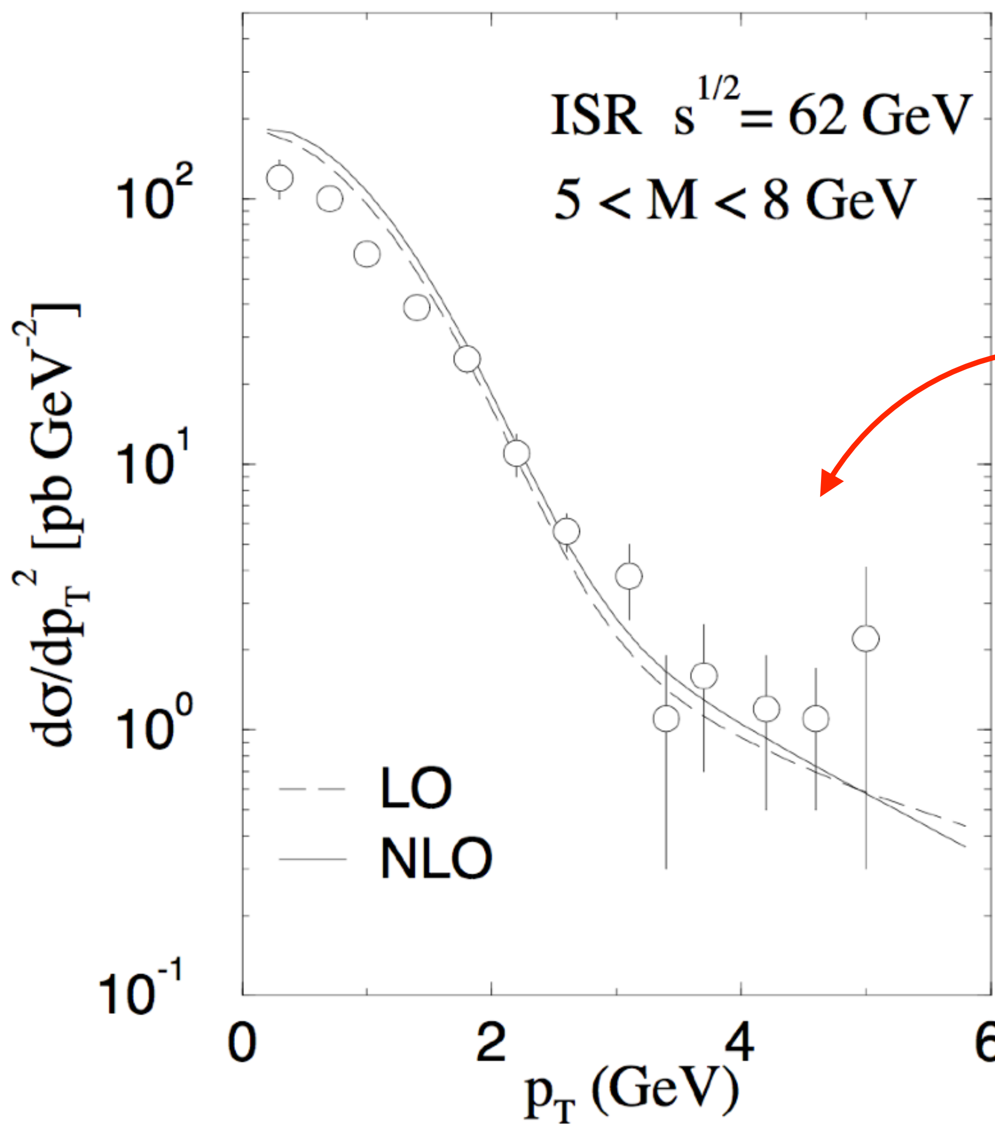
Transverse momentum resummation (q_T-logs) $\alpha_s^n \ln^m \frac{q_T^2}{Q^2}$

+ non perturbative effects

Fixed order collinear factorization

Matching resummation and fixed order

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



W + Y

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

Arnold & Kauffman's rule

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

When W < 0 switch to fixed order!

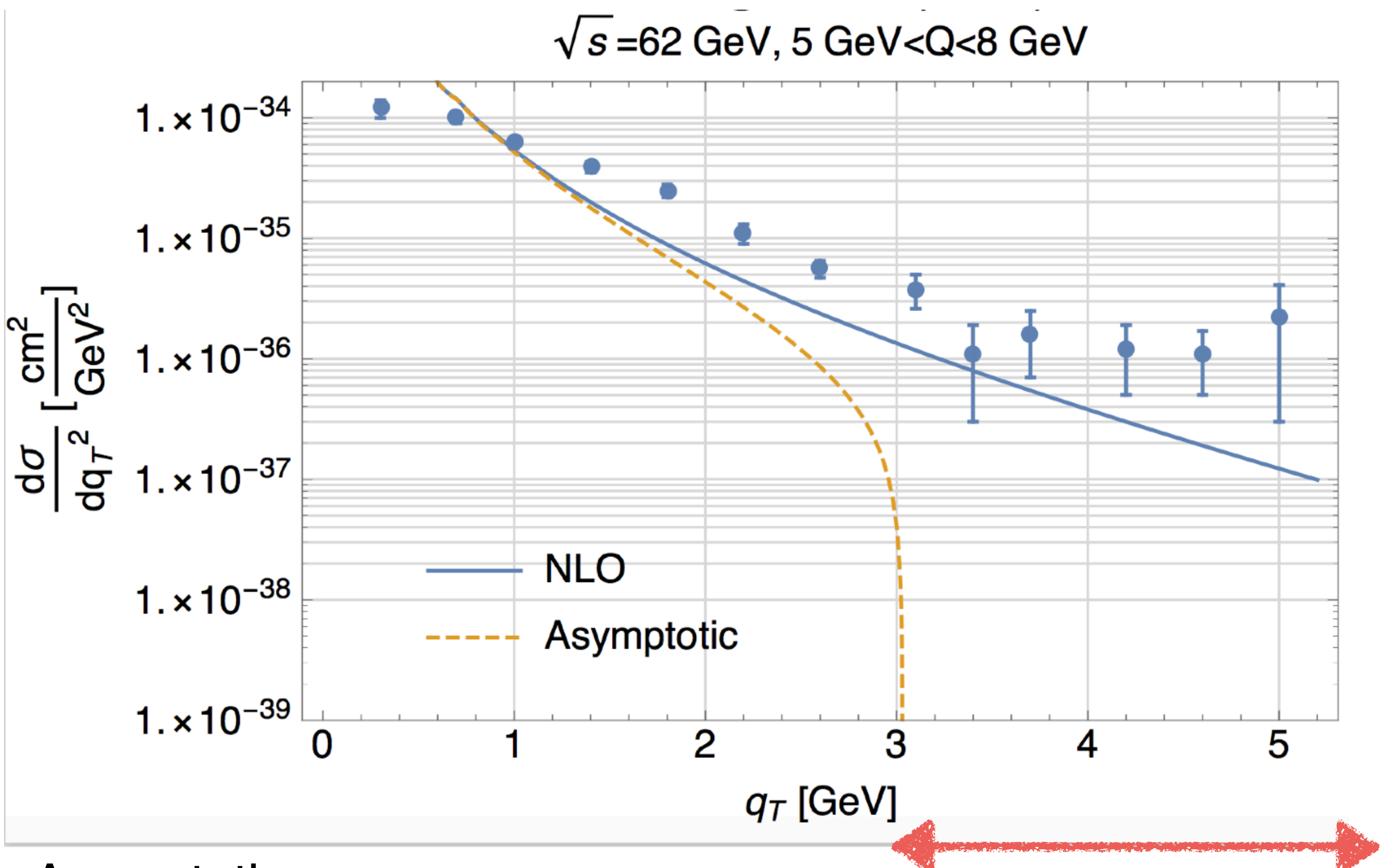
(usually happens at $q_T = Q/2$)

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

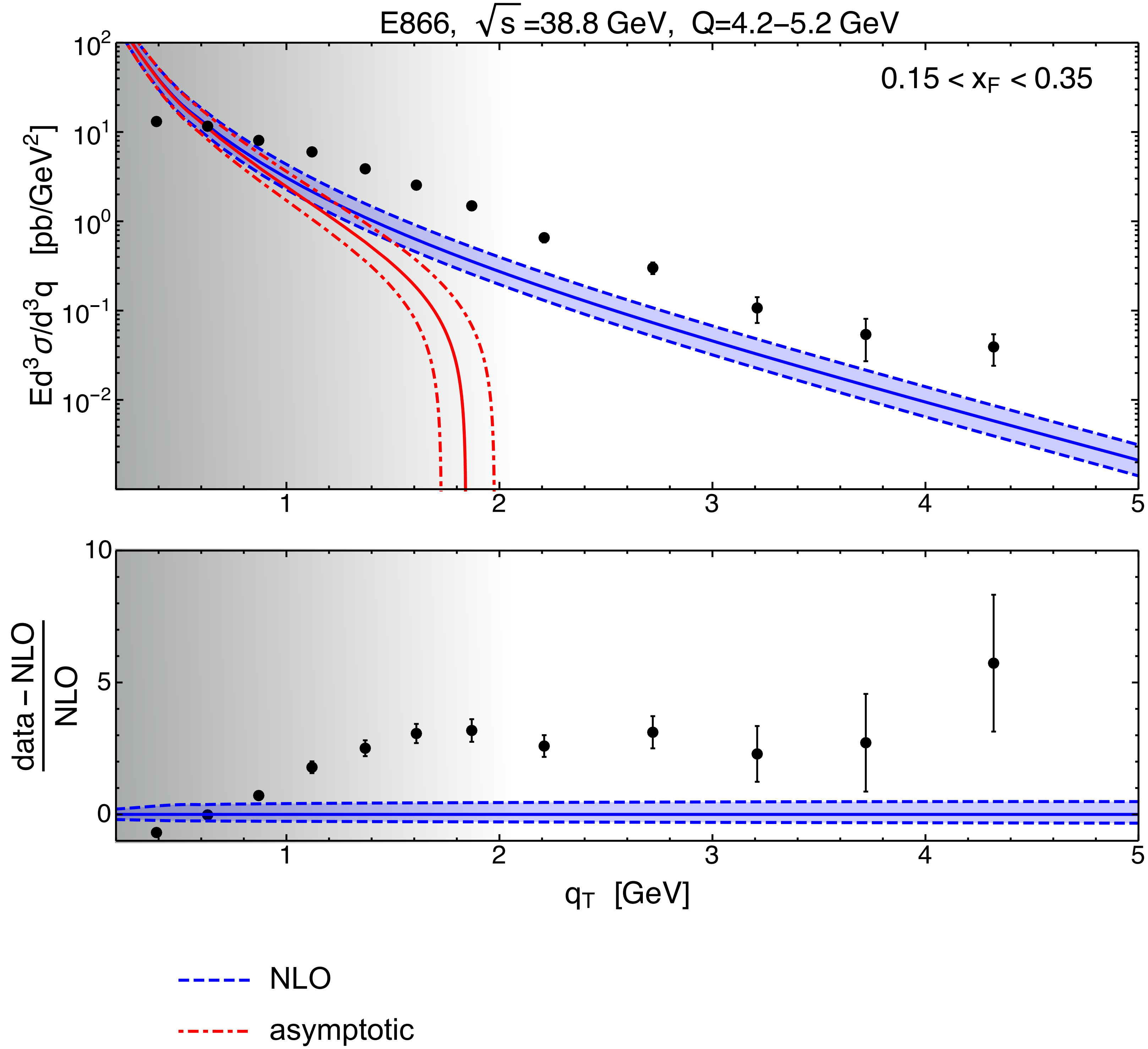
low energy DY data

Experiment	Reaction	Year	TMD fits	PDF fits
R209	p-p	1981	✔	✘
E288	p-Cu, p-Pt	1981	✔	✘
E605	p-Cu	1991	✔	✔
E866	p-p, p-d	2003	✘	✔

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

E866/NuSea

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



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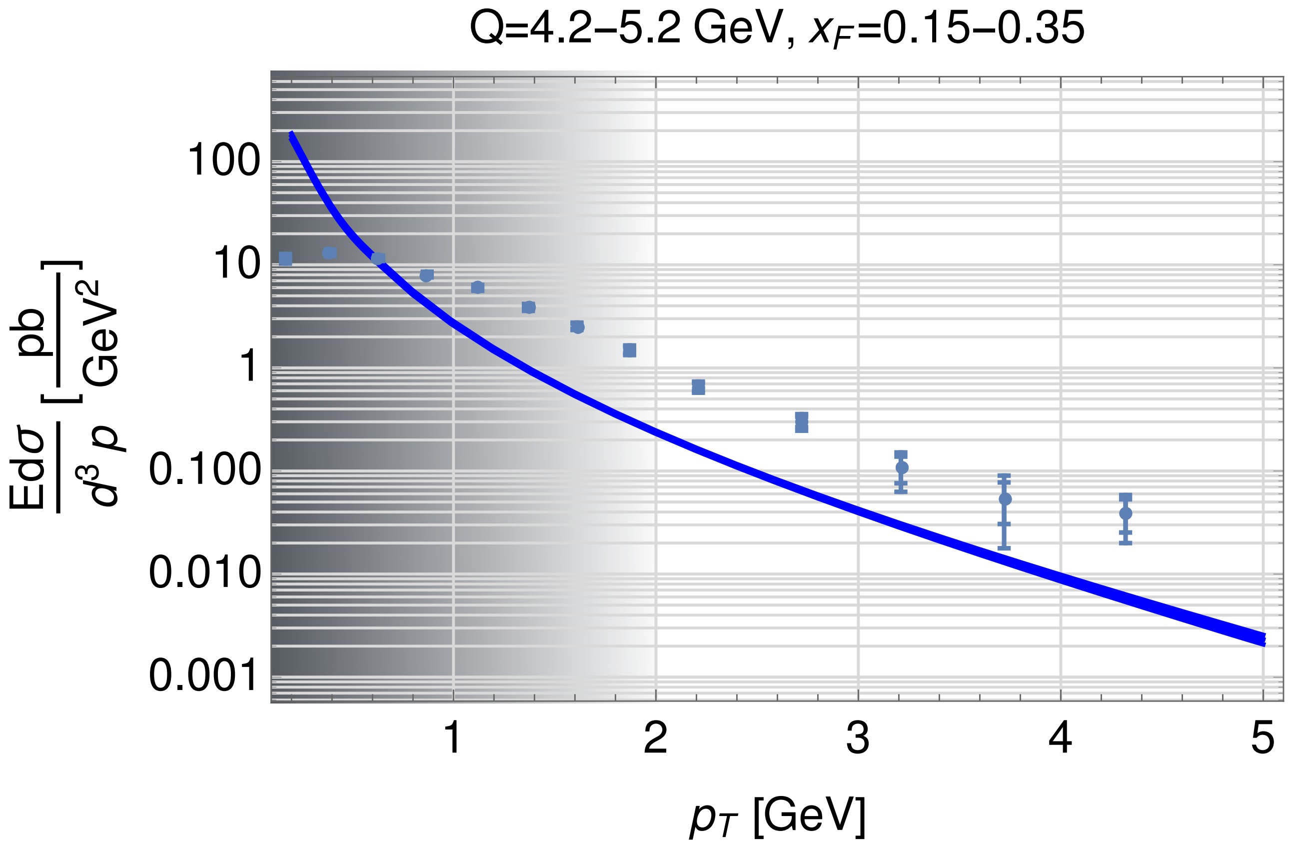
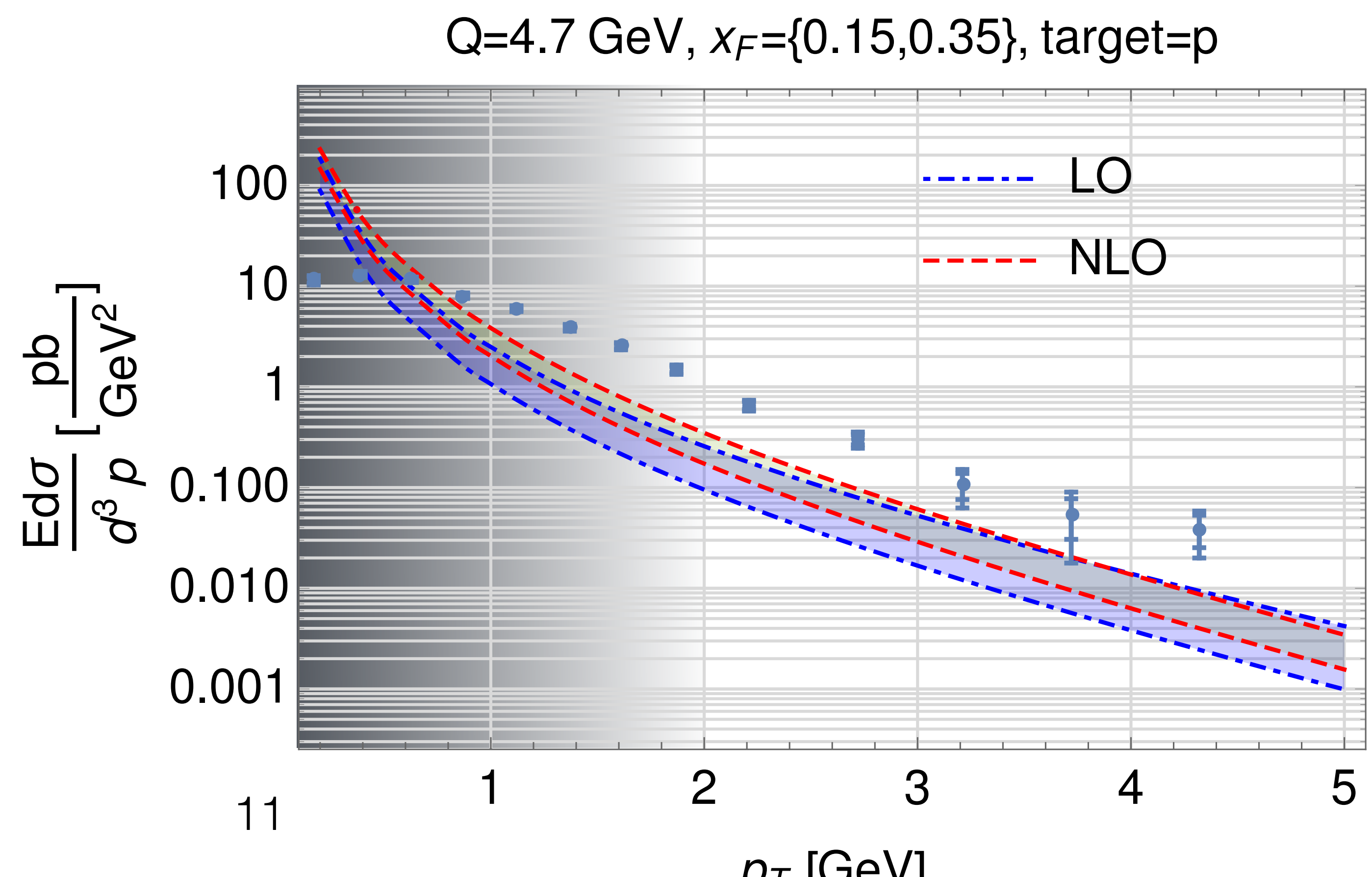


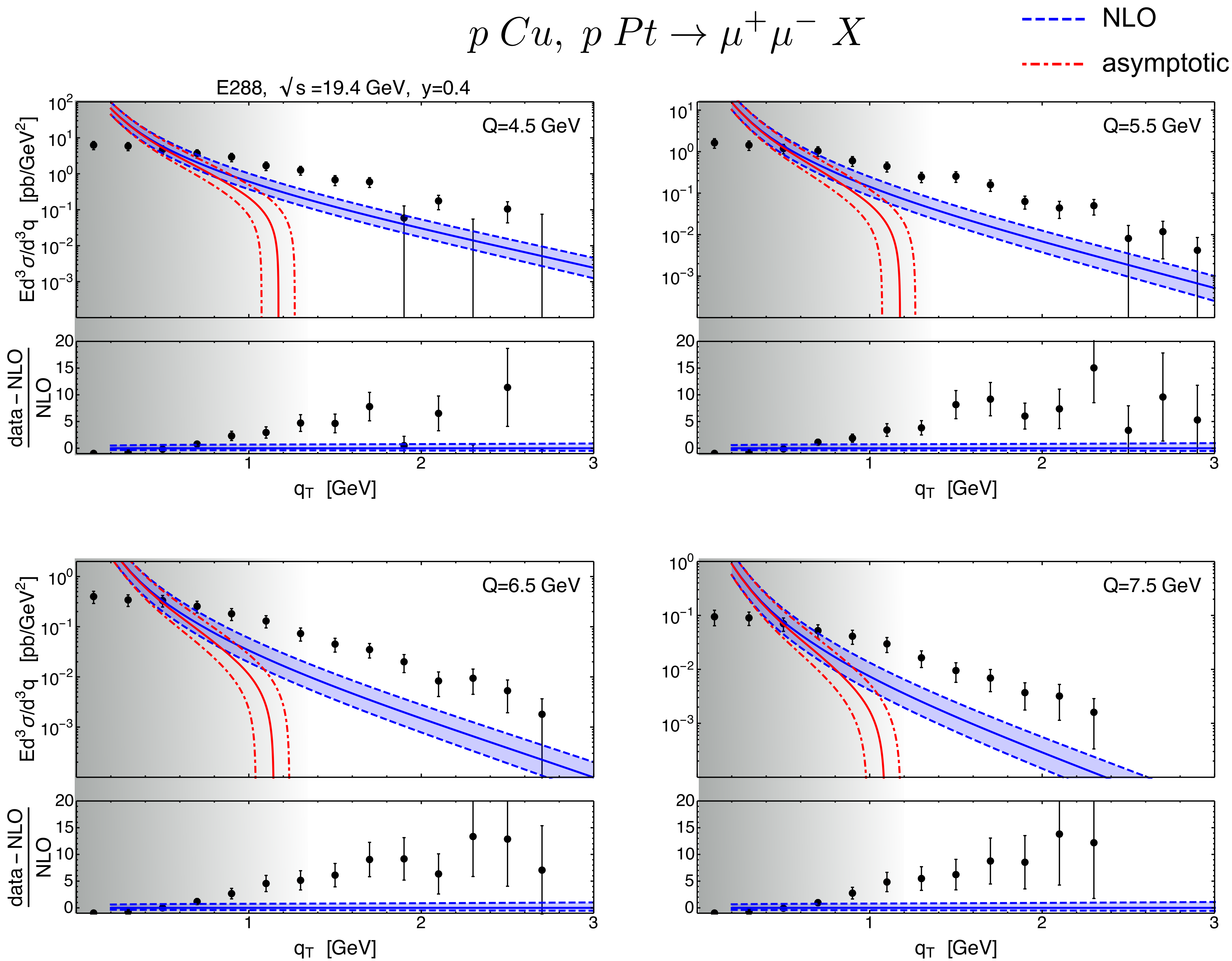
NLO $\mathcal{O}(\alpha_s^2)$
+PDF uncertainty

scale variations

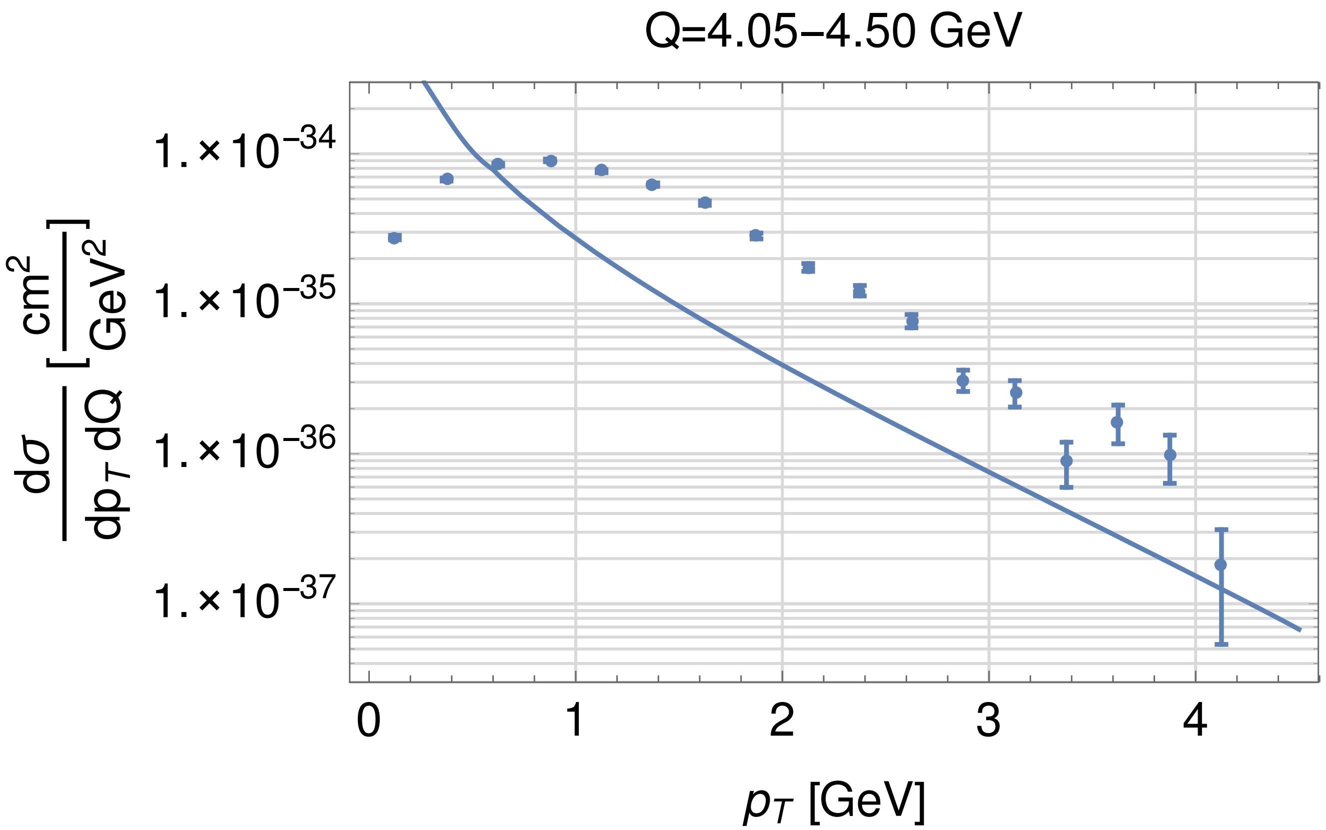


E288

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



pion-nucleus Drell-Yan

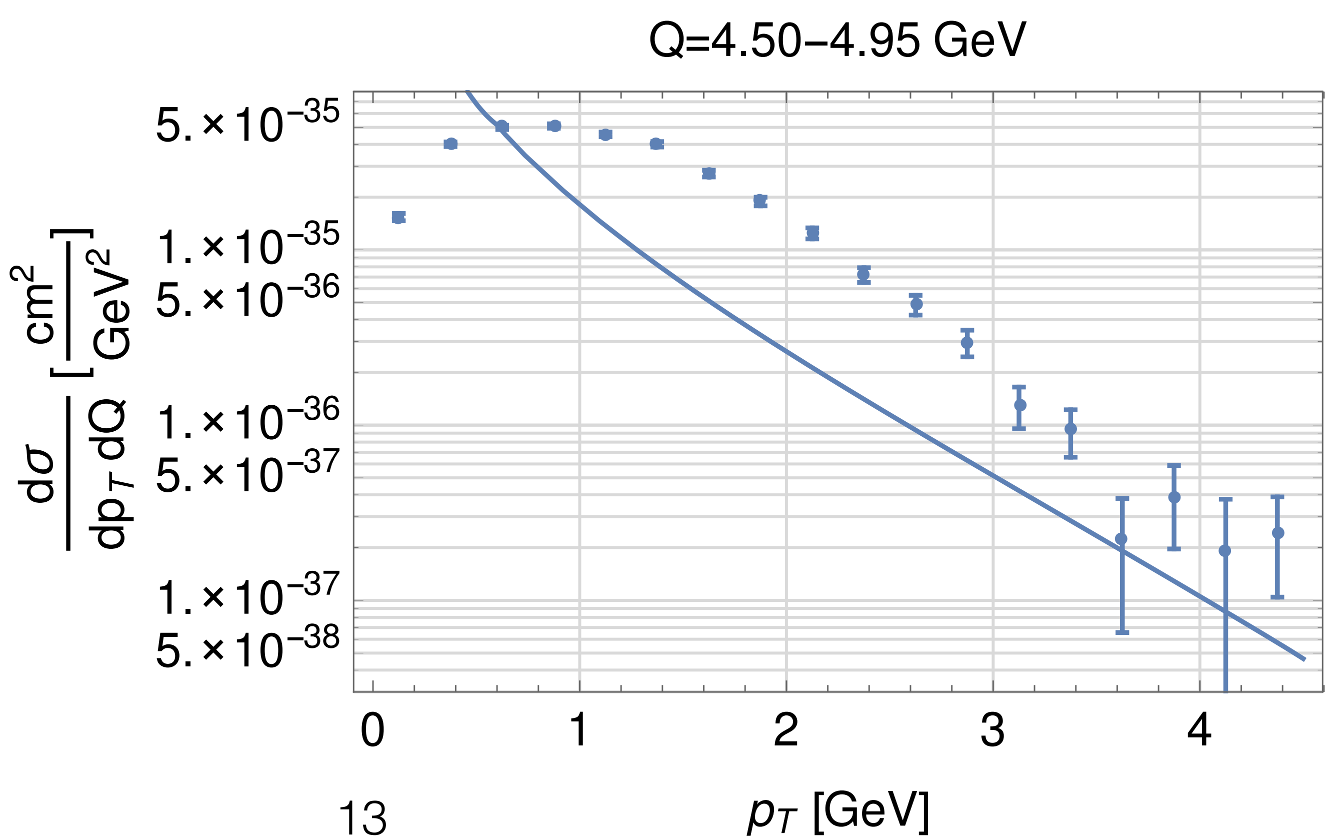


NLO $\mathcal{O}(\alpha_s^2)$

E615

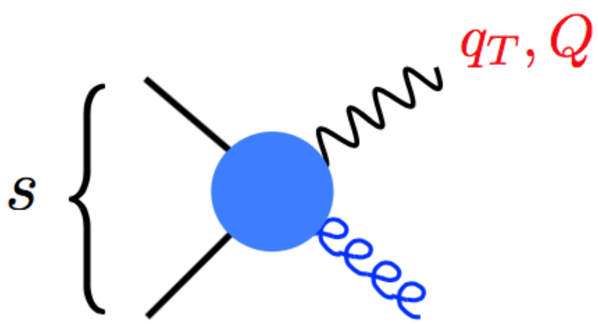
$$\pi W \to \mu^+ \mu^- X$$

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



threshold resummation

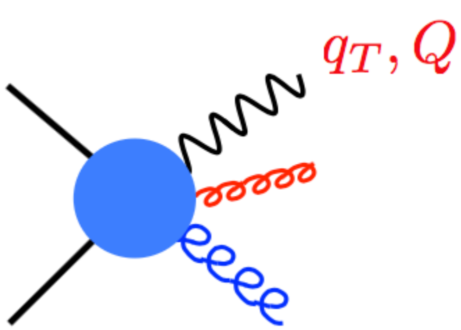
- LO :



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

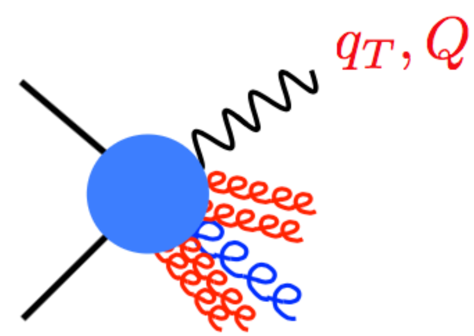
$$y_T \equiv \frac{q_T + \sqrt{q_T^2 + Q^2}}{\sqrt{s}} \leq 1$$

- 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^kLO :

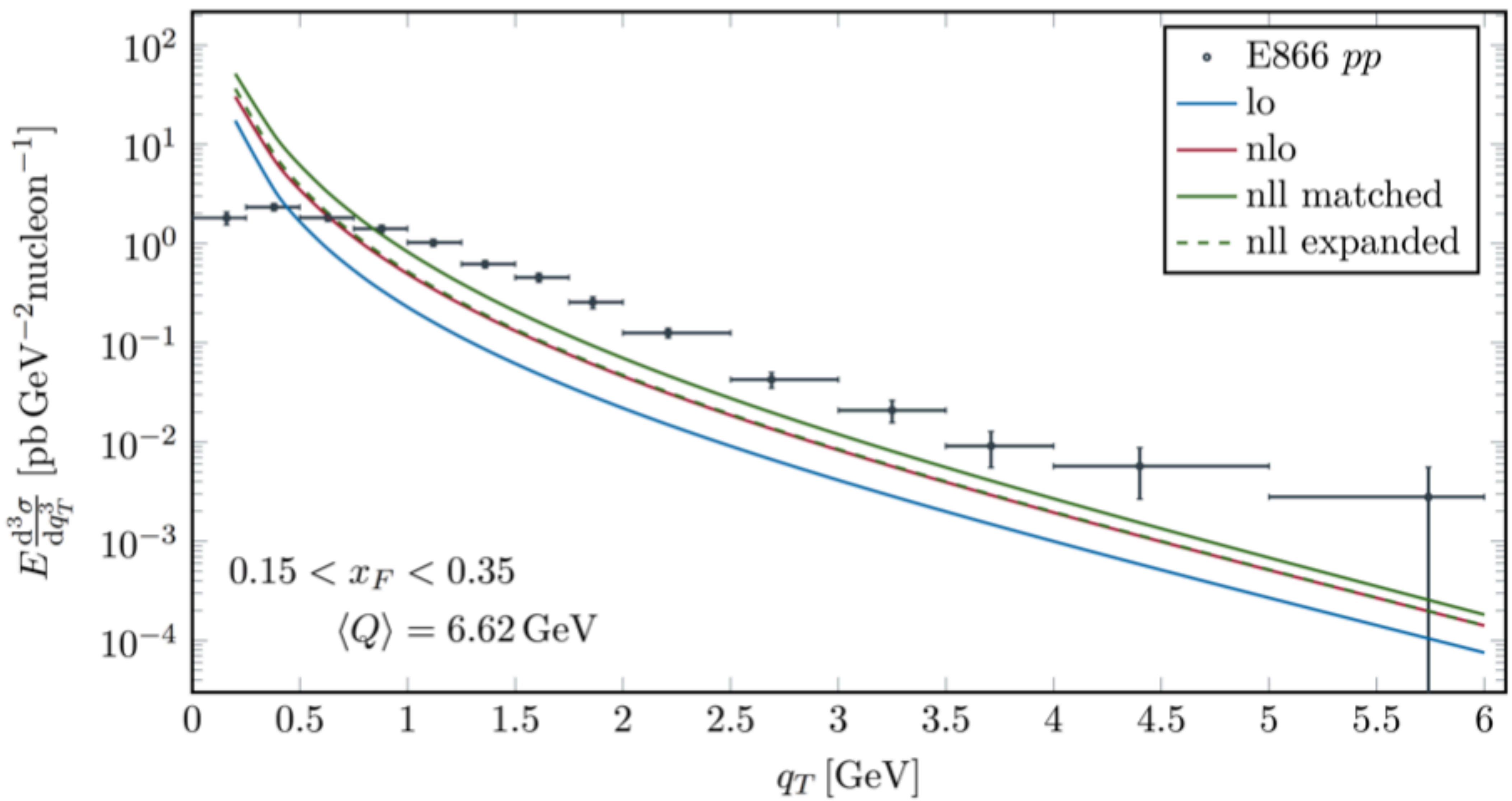


$$\frac{d\hat{\sigma}^{\mathrm{N}^k\mathrm{LO}}}{dq_T} \propto \alpha_s^k \log^{2k}(1 - y_T^2) + \ldots$$

- threshold logarithms

W. Vogelsang @Transversity 2017

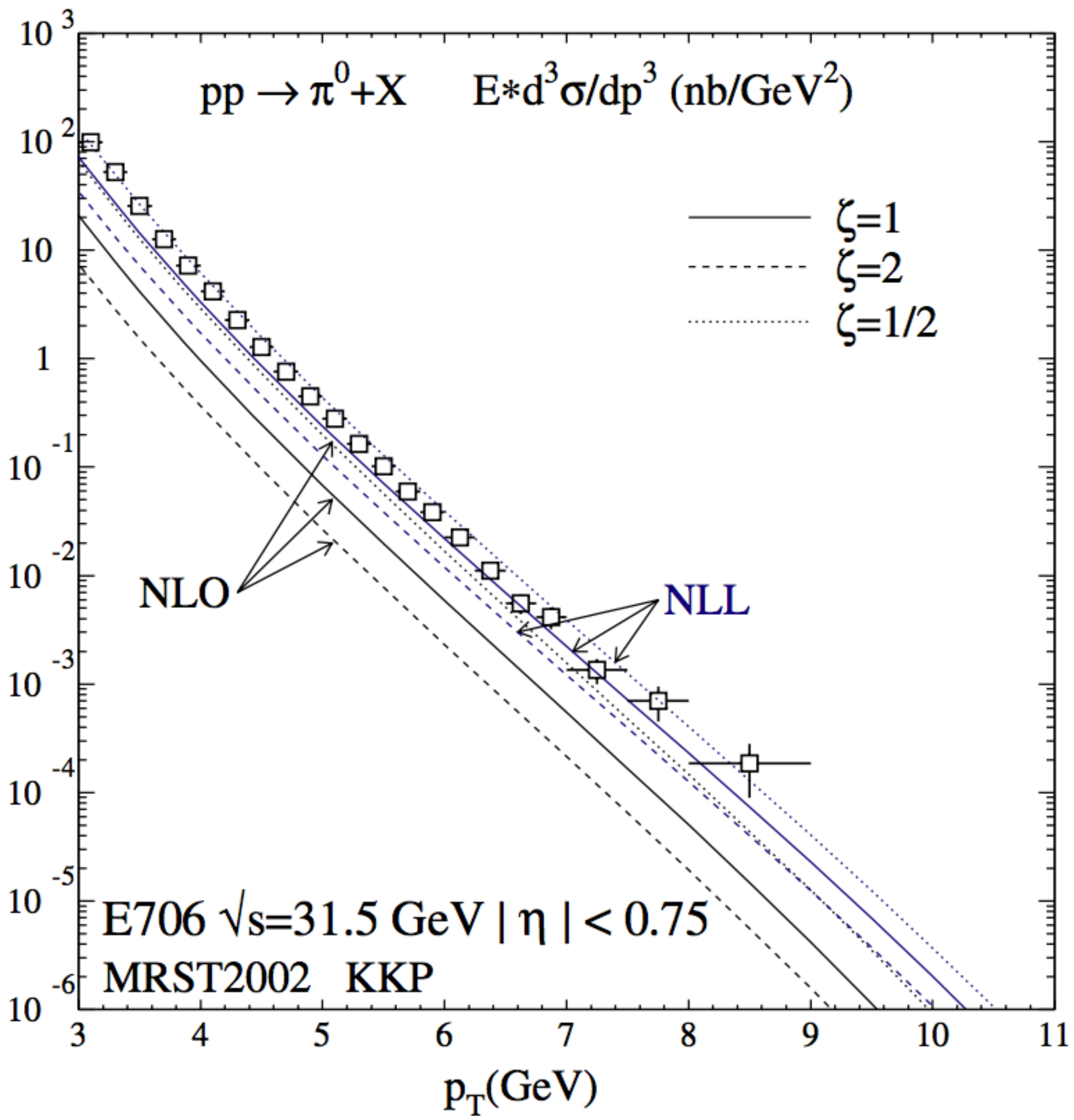
threshold resummation

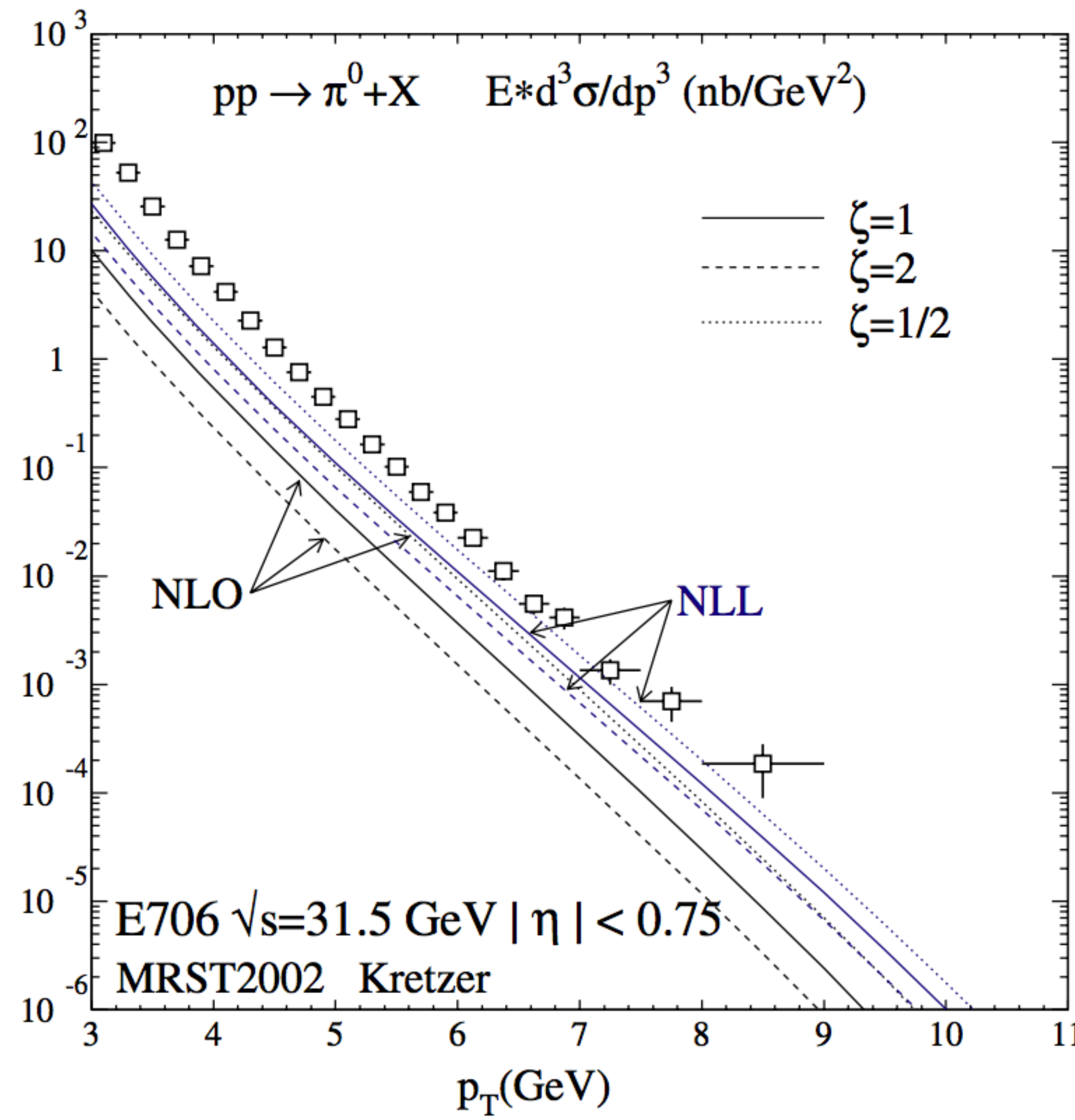


W. Vogelsang @Transversity 2017

known similar cases

pion production

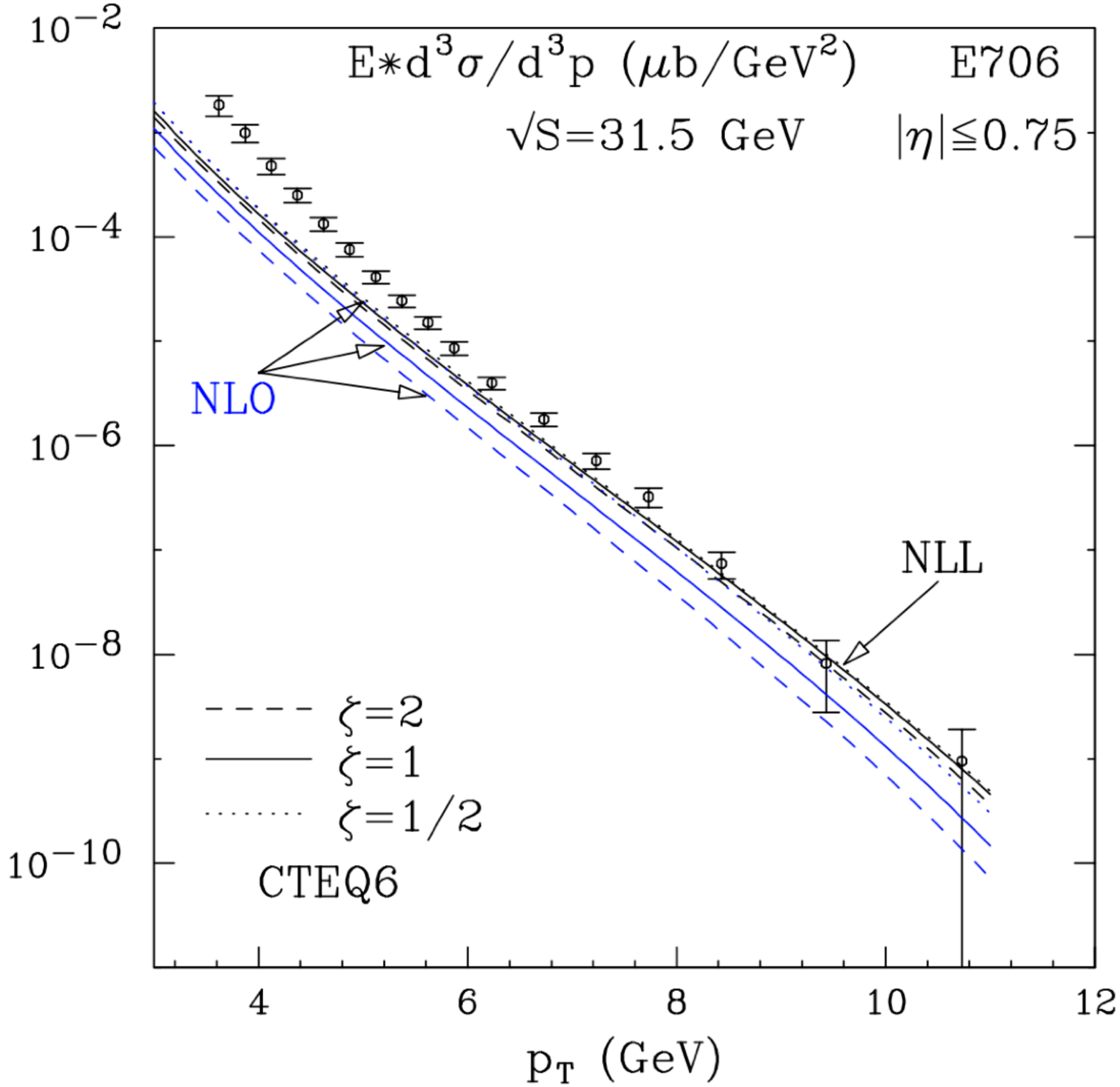




de Florian Vogelsang PRD71 114004 (2005)

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)
…

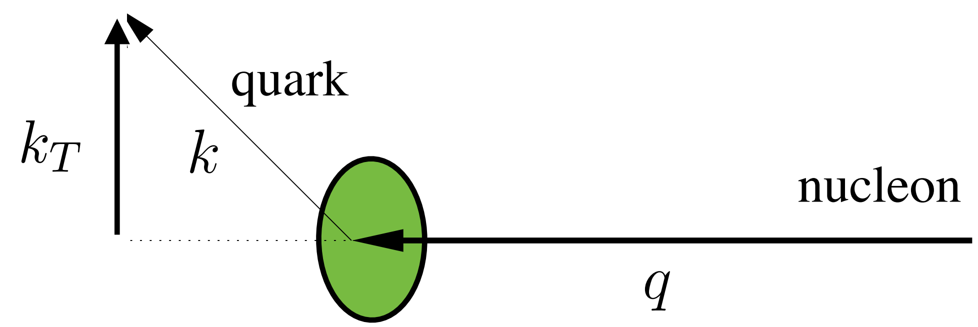
- give the incoming partons a small k_T

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

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

intrinsic k_T smearing

non-perturbative k_T



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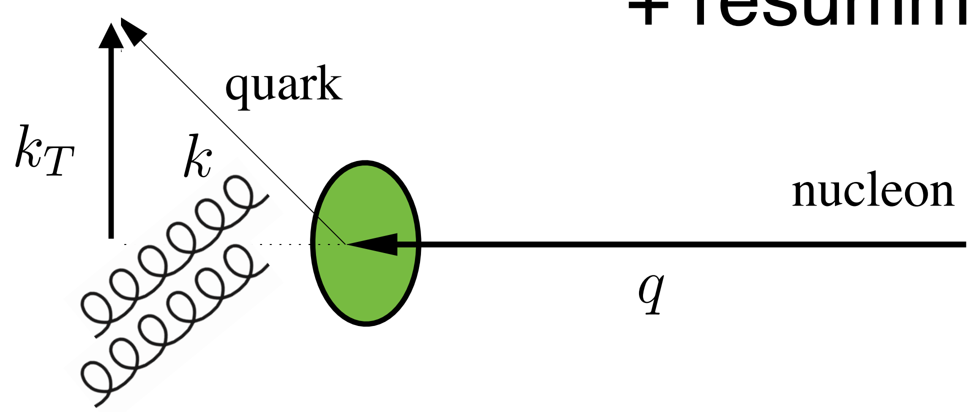
intrinsic k_T smearing

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

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

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parton momentum:

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

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:

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

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

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:

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

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

make sure

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

not too small

Fixed Order must be valid!

intrinsic k_T smearing

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

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

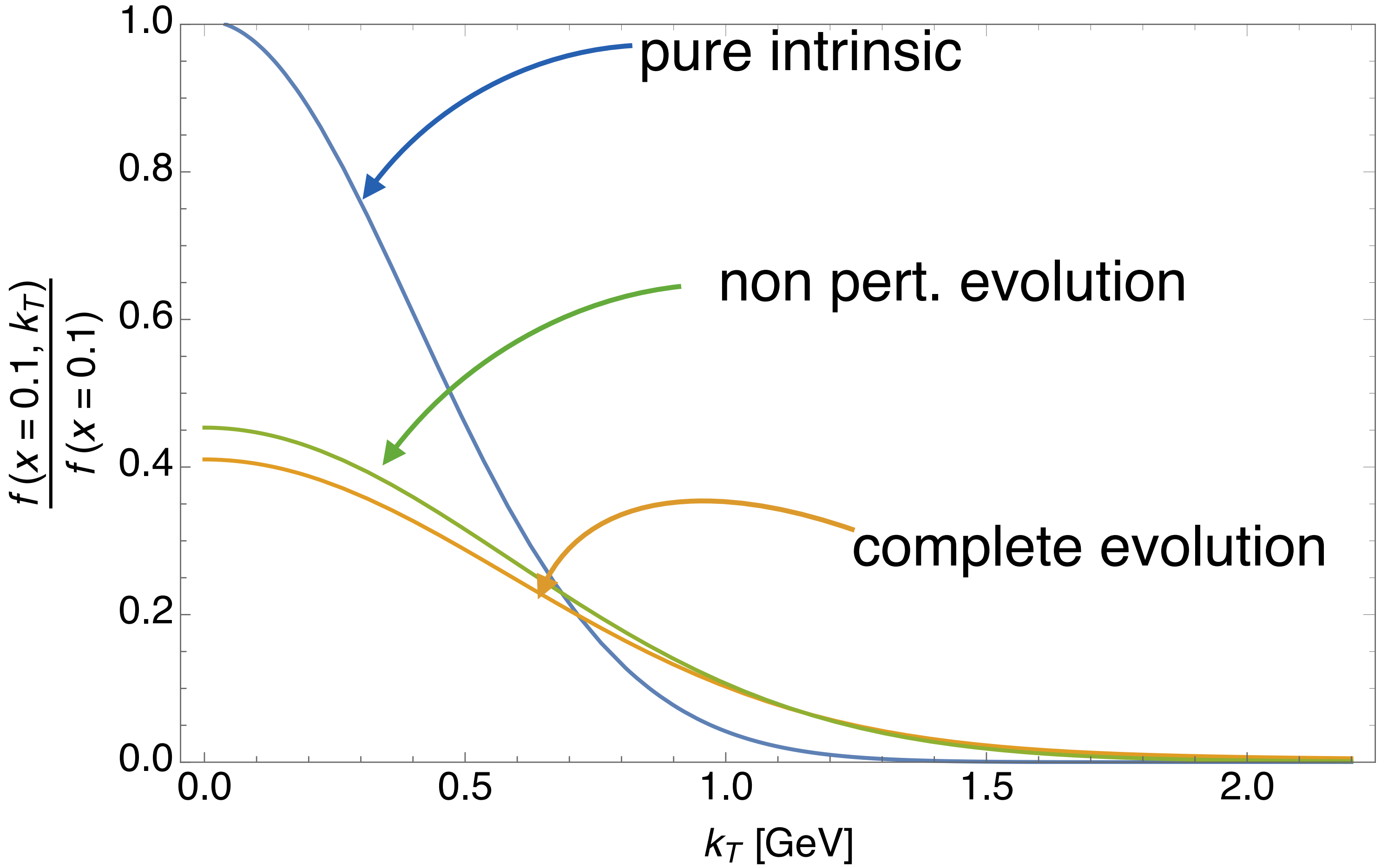
$$\int_0^{k^2_{T max}} \pi dk_T^2$$

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:



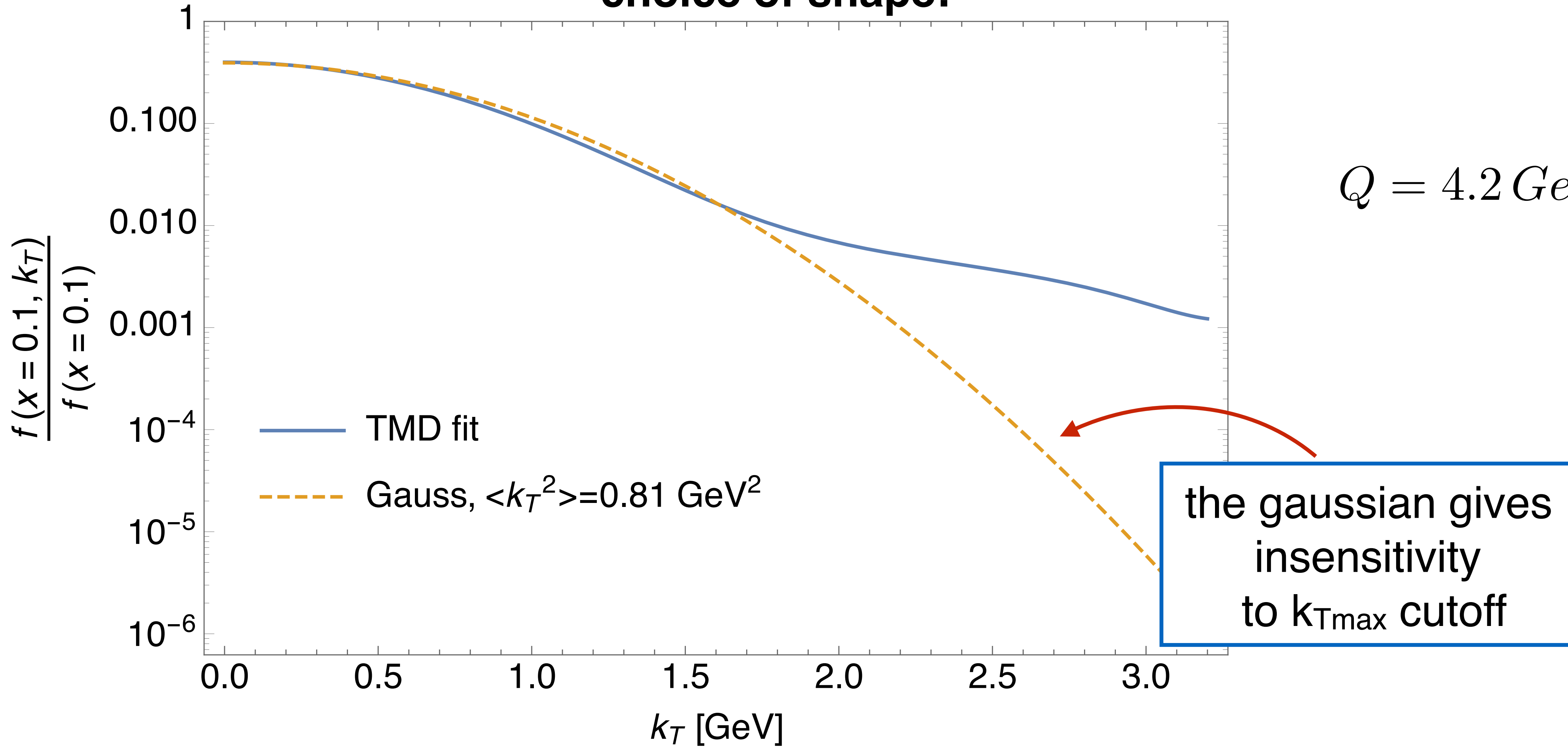
$Q = 4.2\, GeV$

Bacchetta et al JHEP 1706 081

intrinsic k_T smearing

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

choice of shape:



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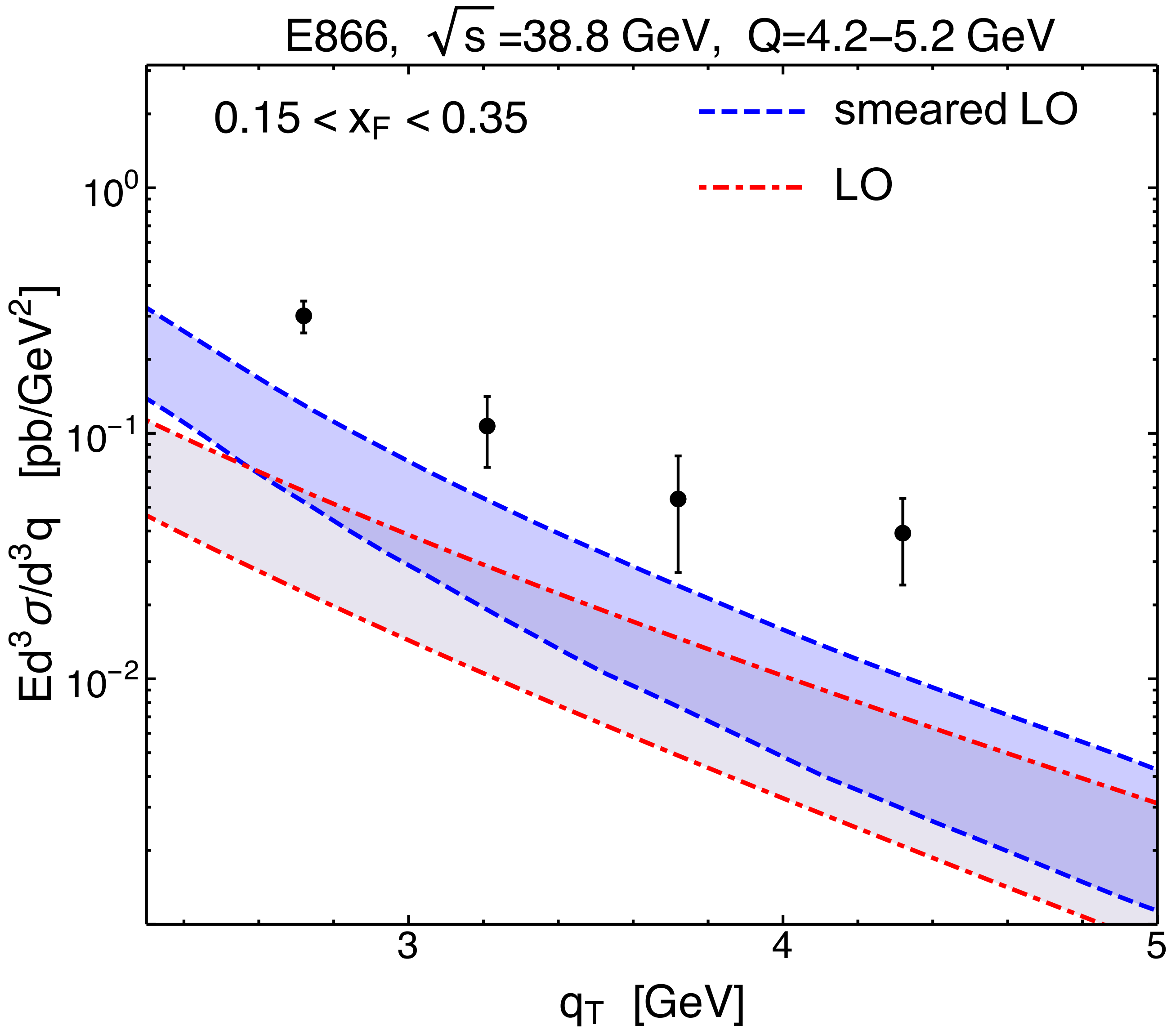
intrinsic k_T smearing



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

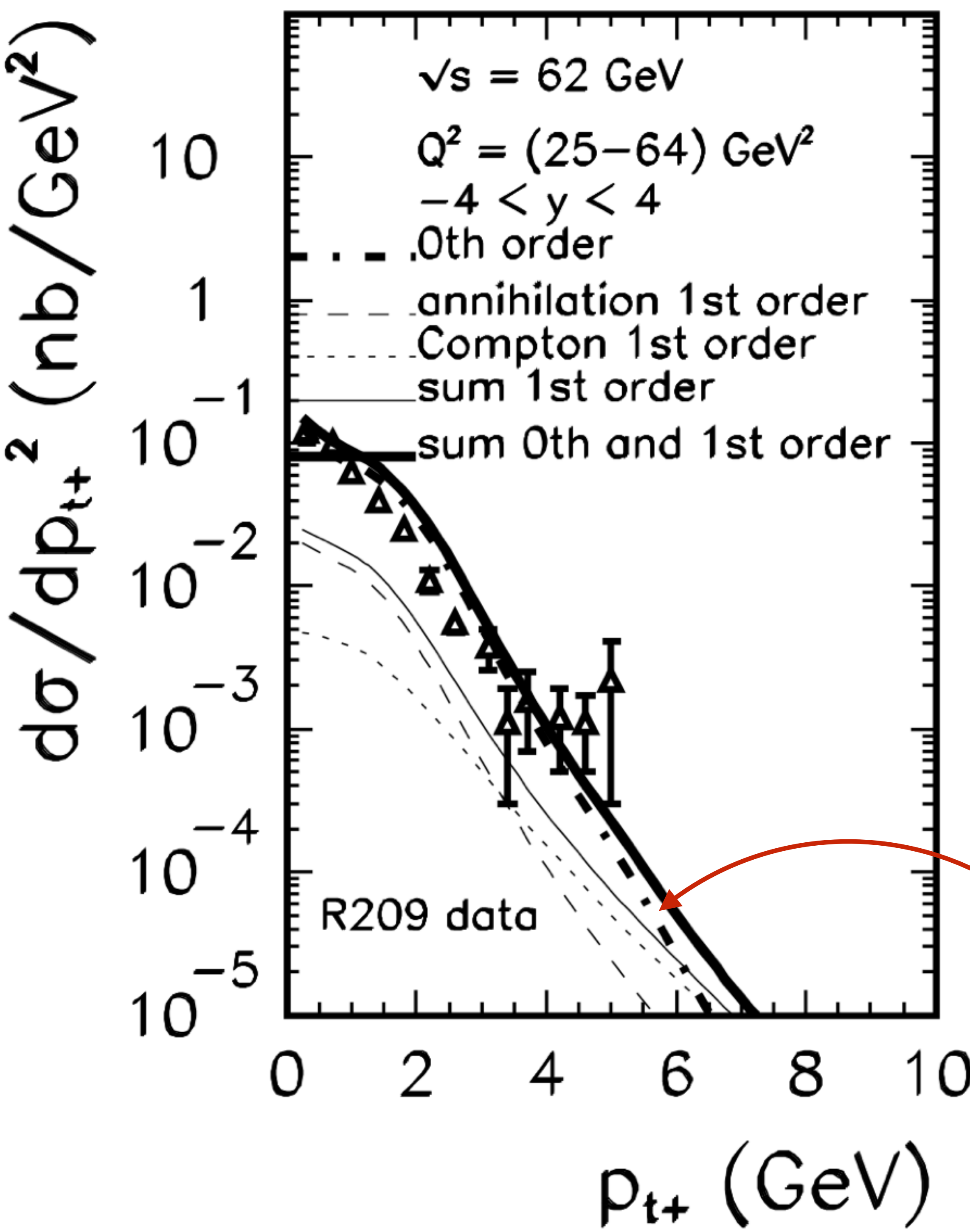
$$\left\langle k_T^2 \right\rangle = 0.81\, GeV^2$$ same for any x and flavor

…and for gluons!!

Summary

- fixed-order pQCD largely underestimates low-energy DY data at high q_T
- nor threshold resummation nor intrinsic-k_T model seem to help
- more high q_T data needed (Compass ?)

…"k_T-factorization" formalism?



Szczurek, Slipek PRD 78, 114007

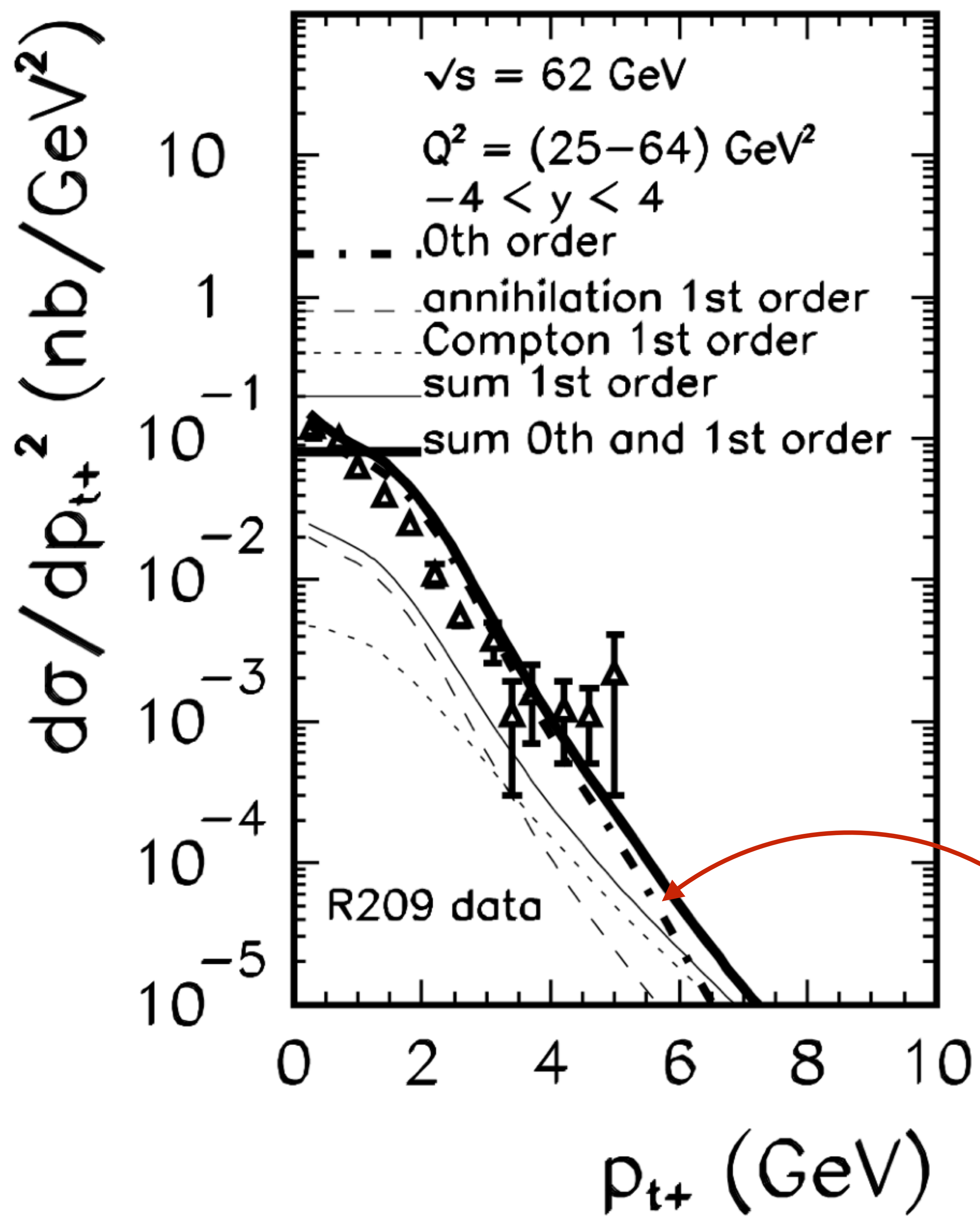
$$d\sigma = \sum_{ab} \int dx_a\, d^2\mathbf{k}_{Ta}\, dx_b\, d^2\mathbf{k}_{Tb}$$

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

"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

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

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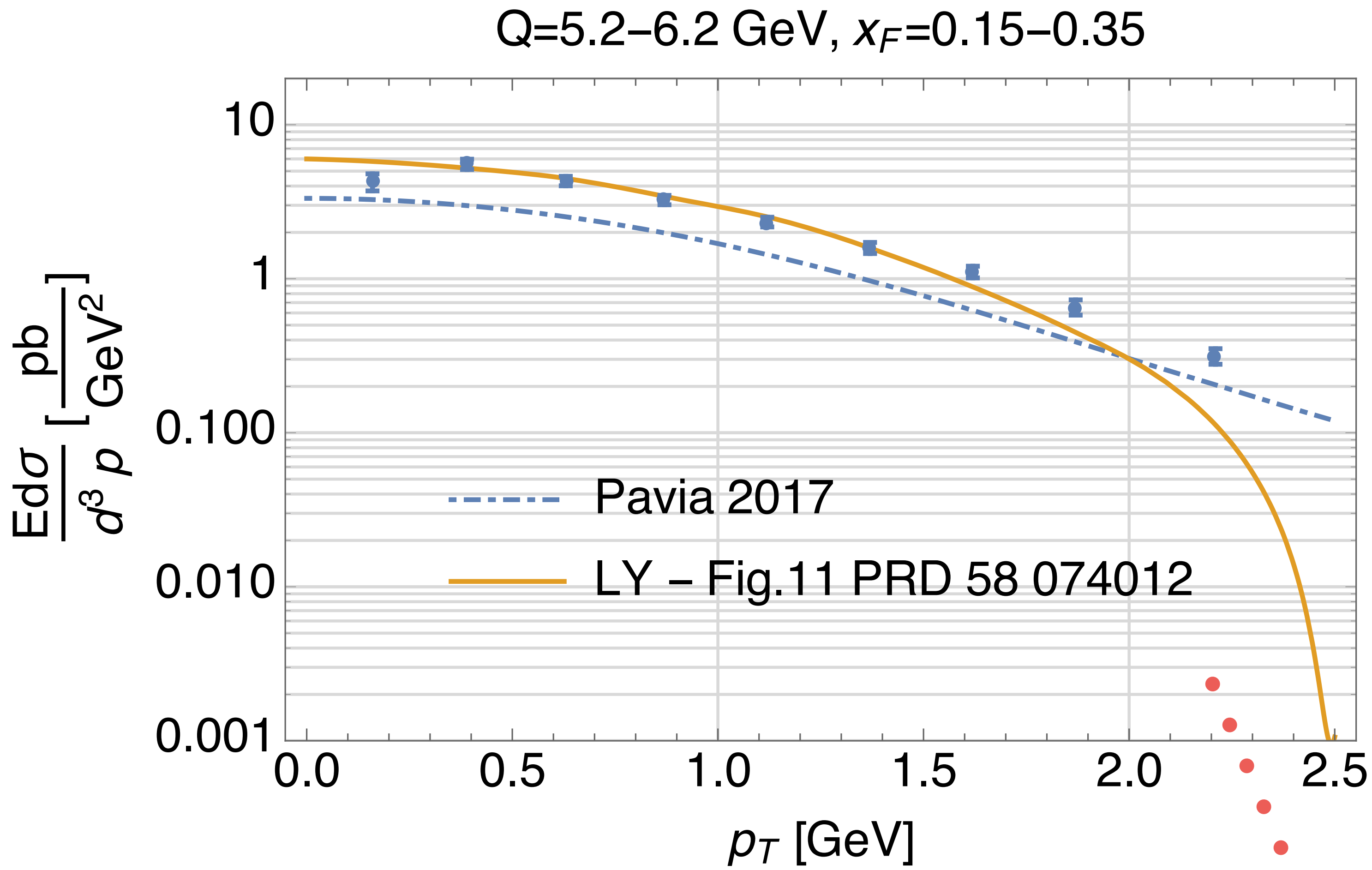
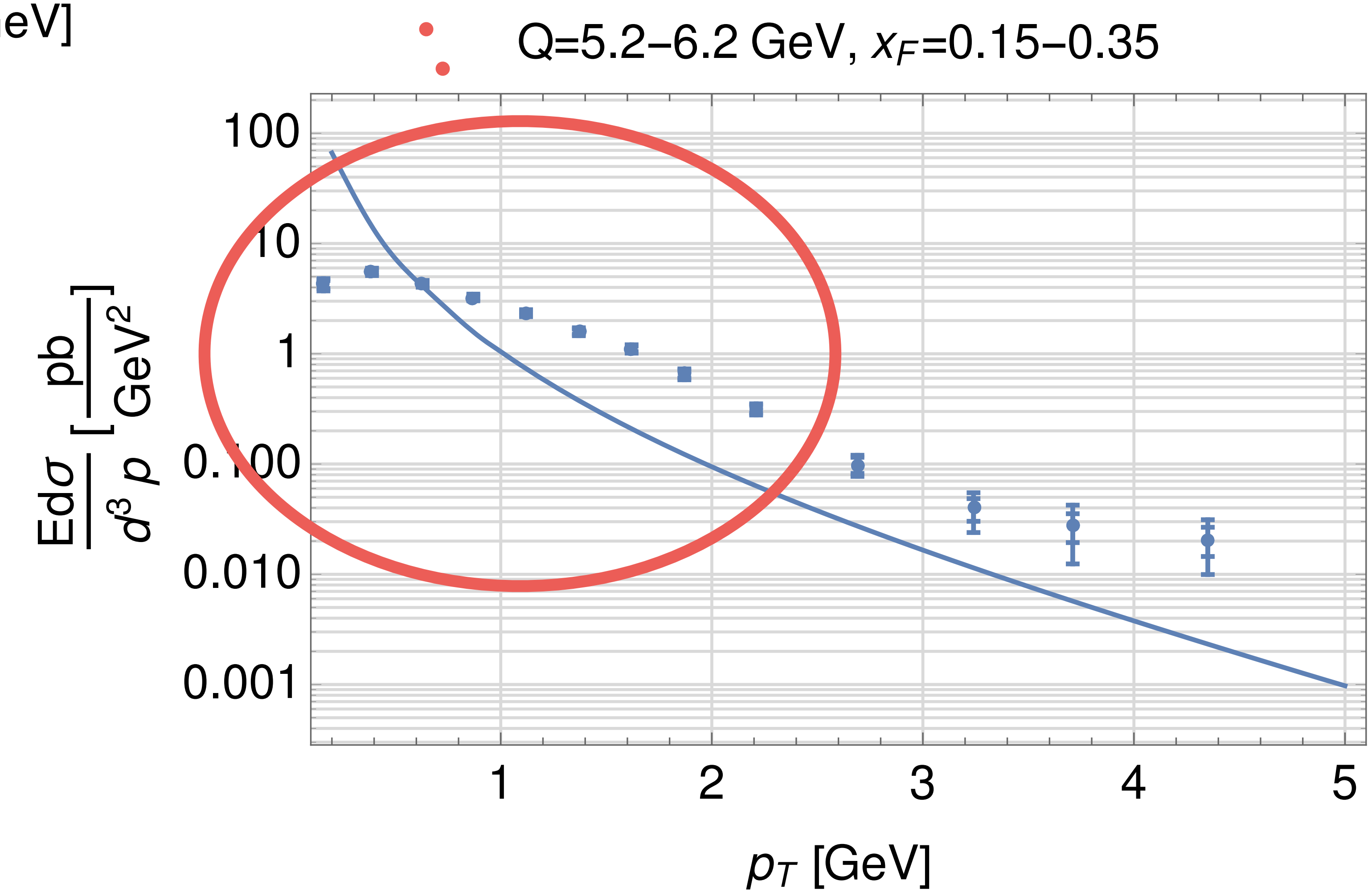
apparently difficult to find a formal proof
Avsar, Collins arXiv:1209.1675

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

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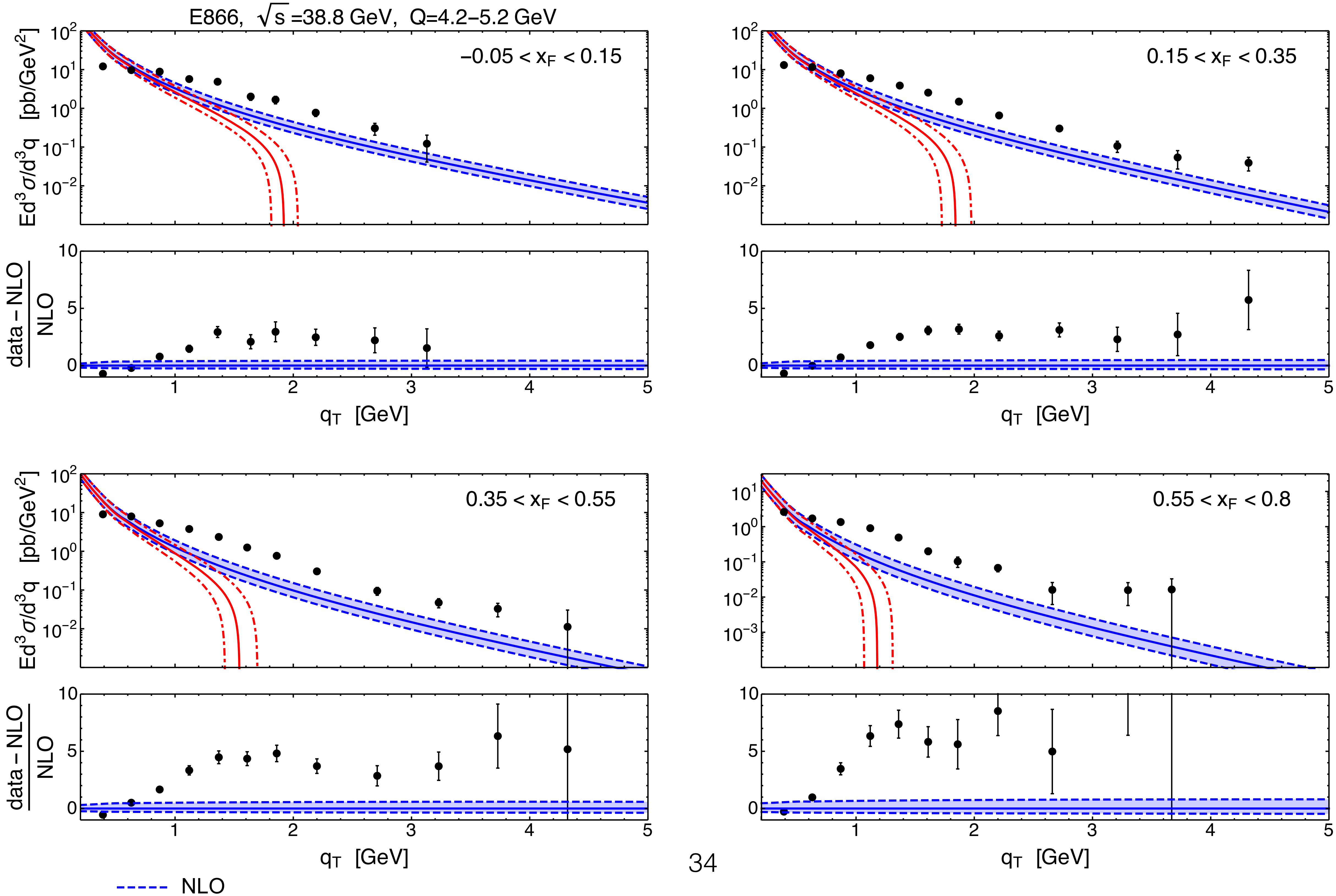

E866/NuSea

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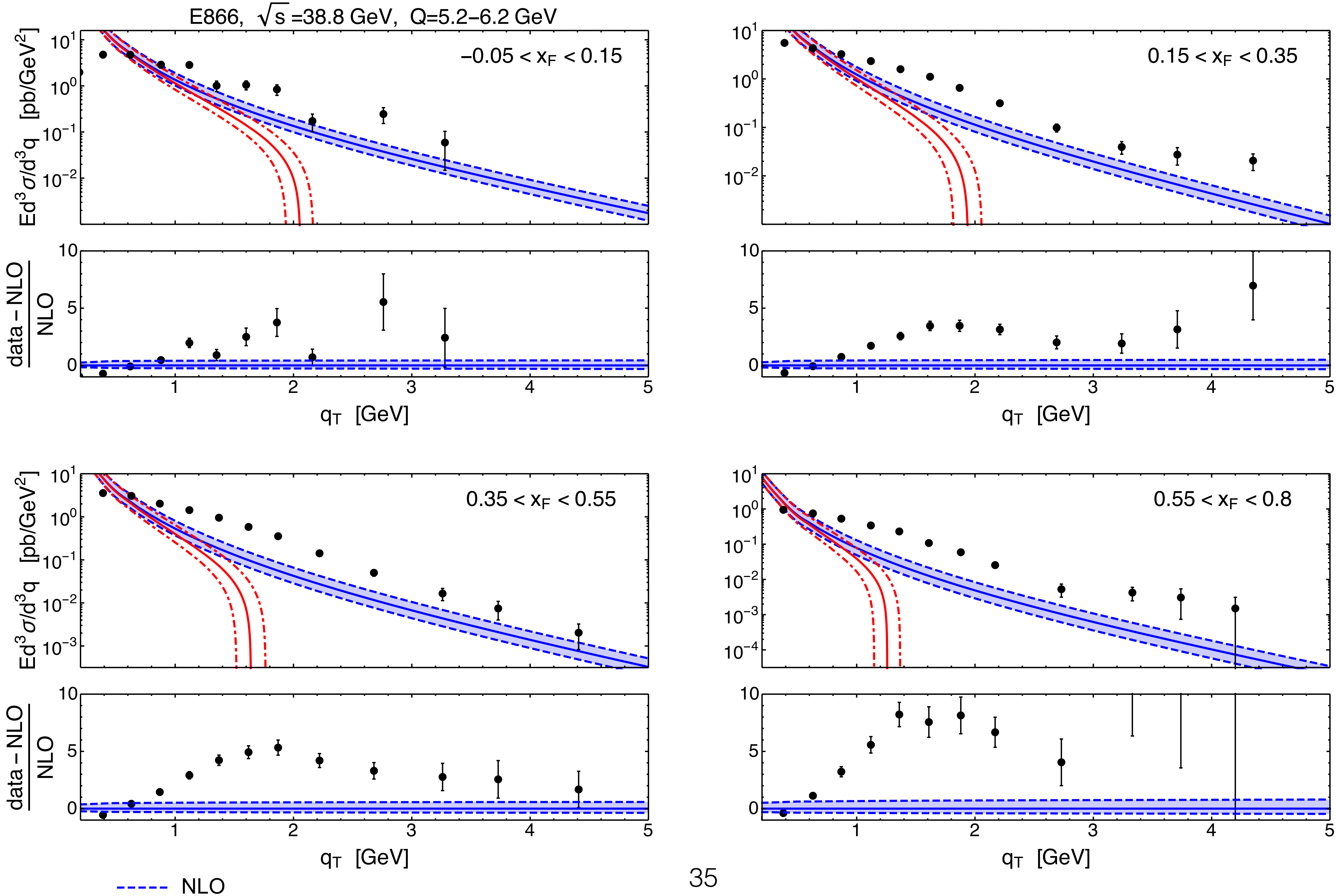
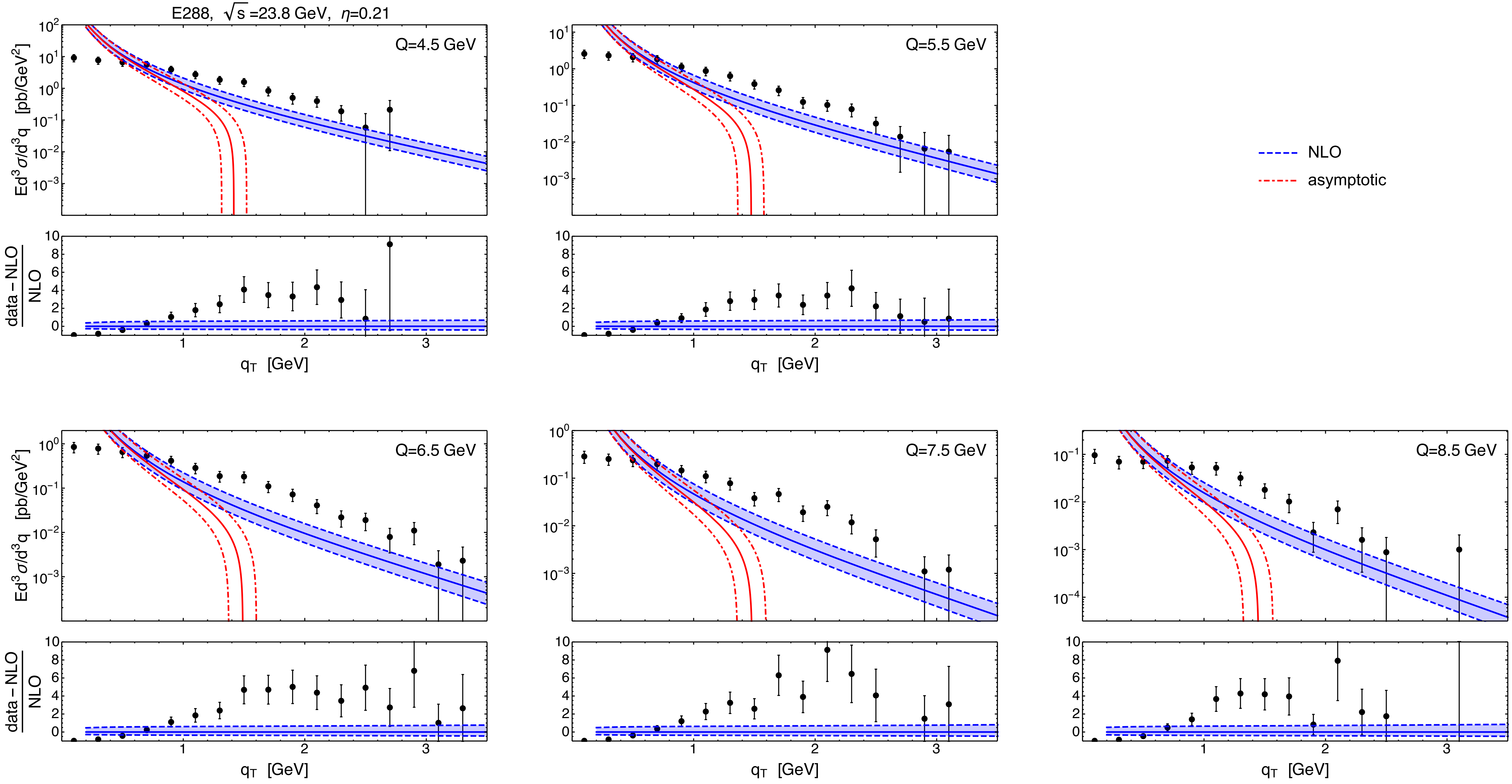


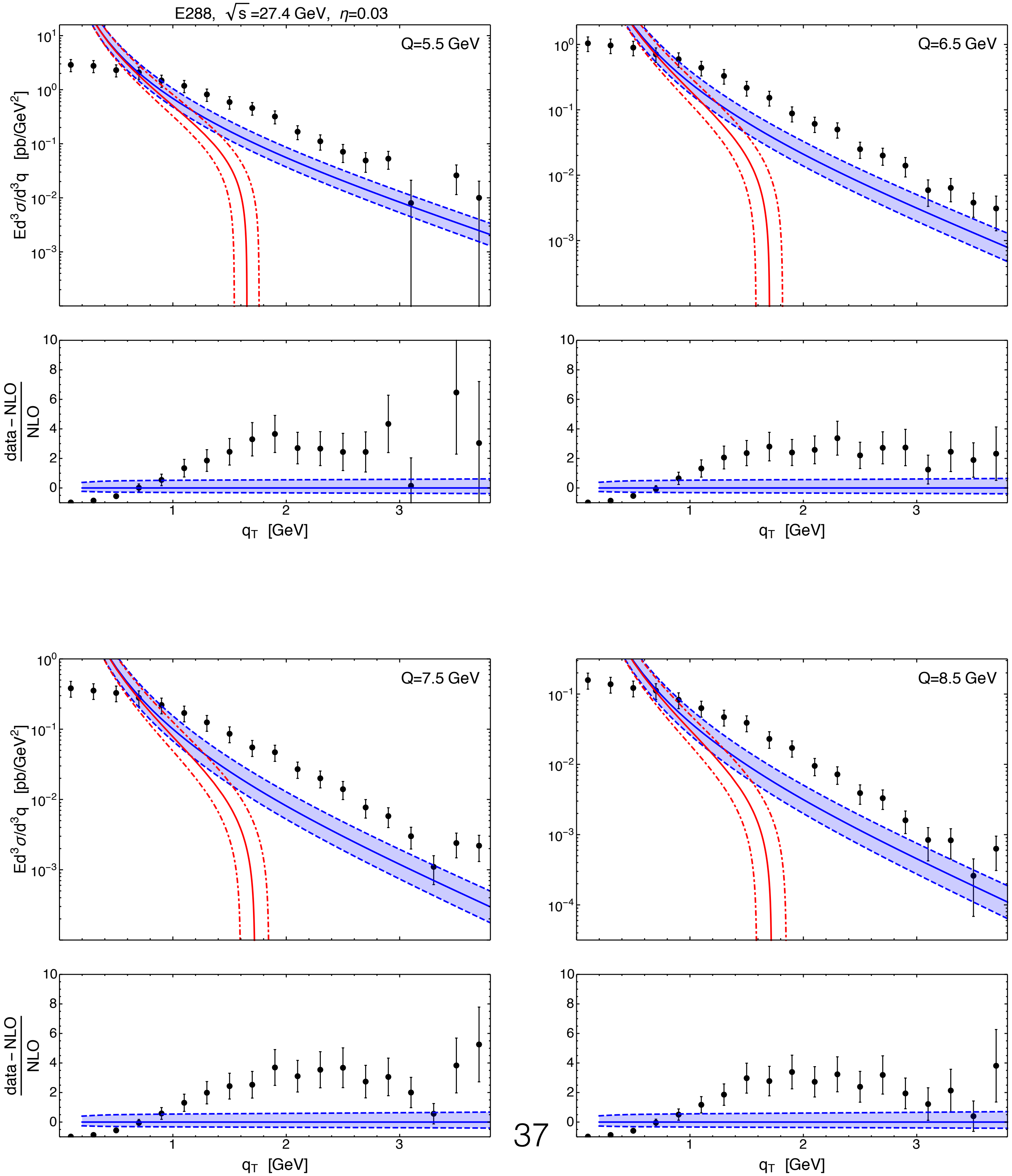
E288

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



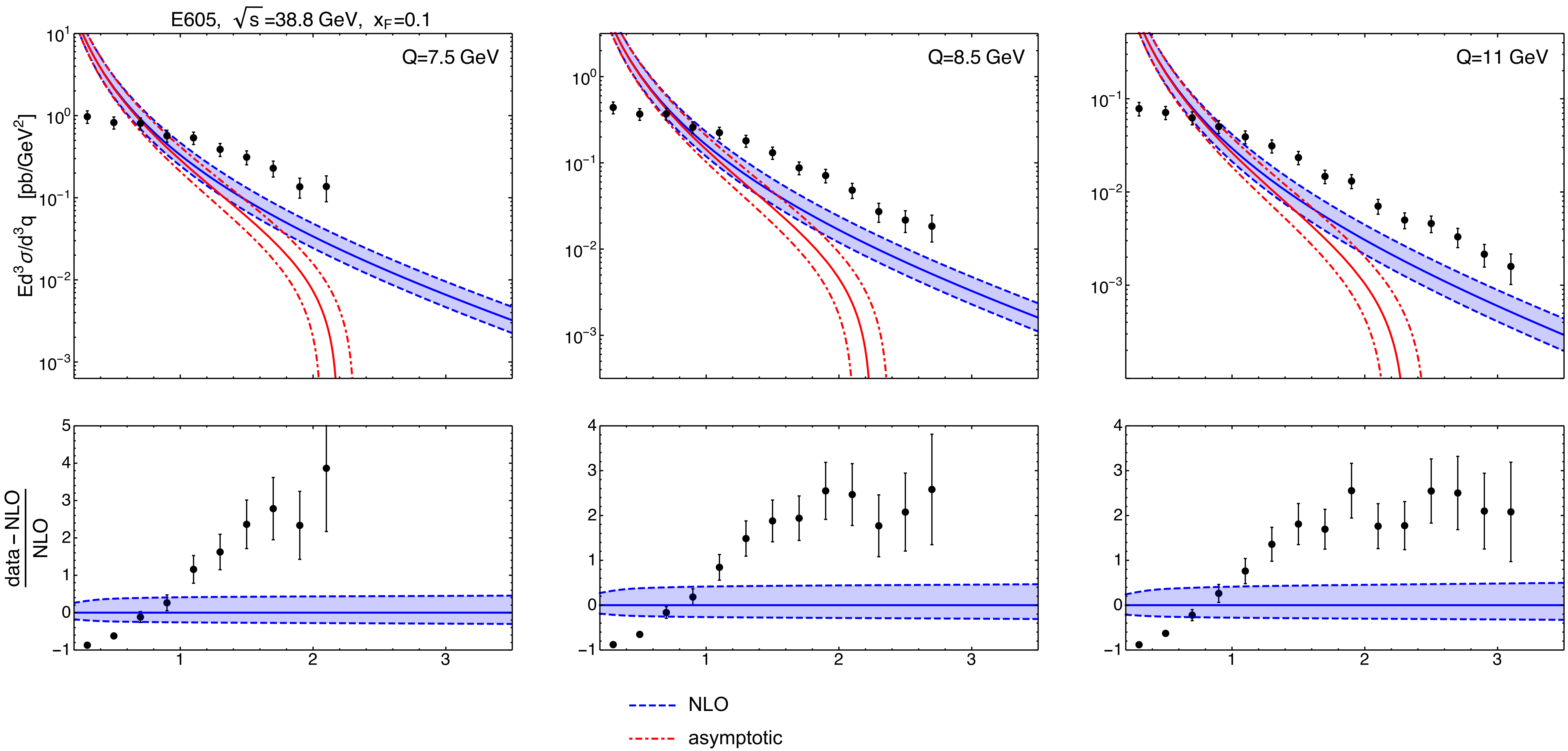
E288

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

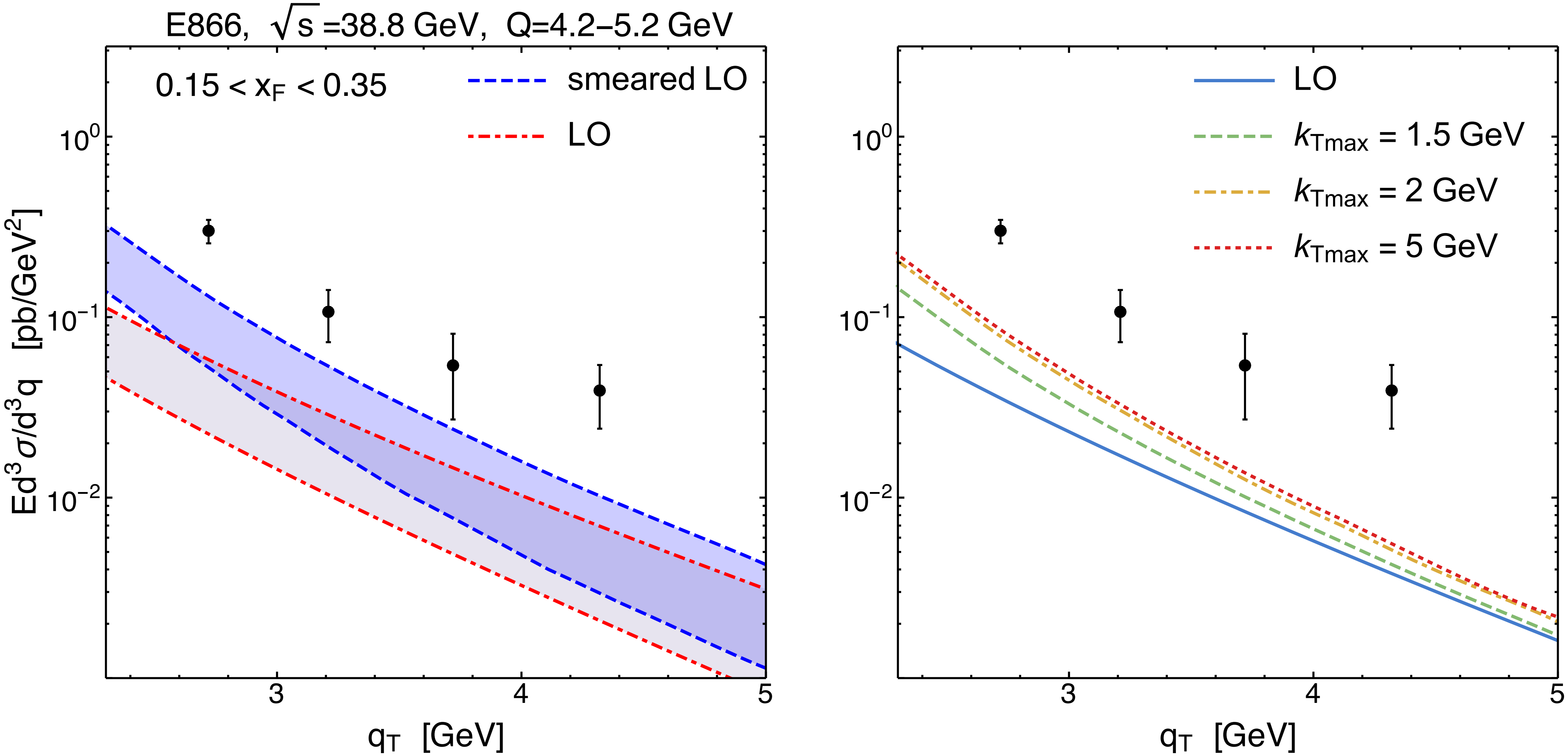


E605

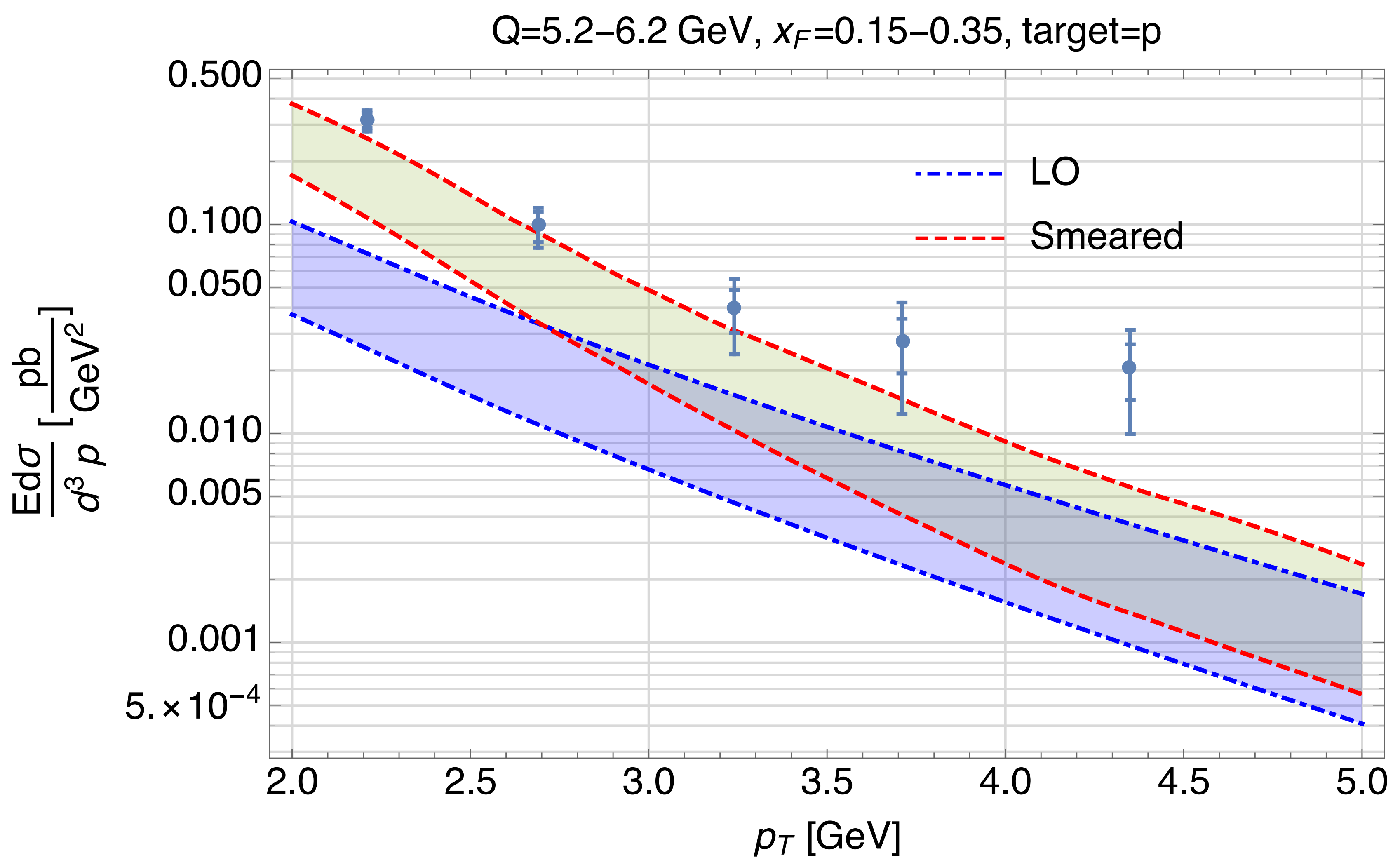
$$p\,Cu \to \mu^+\mu^-\;X$$



intrinsic k_T smearing



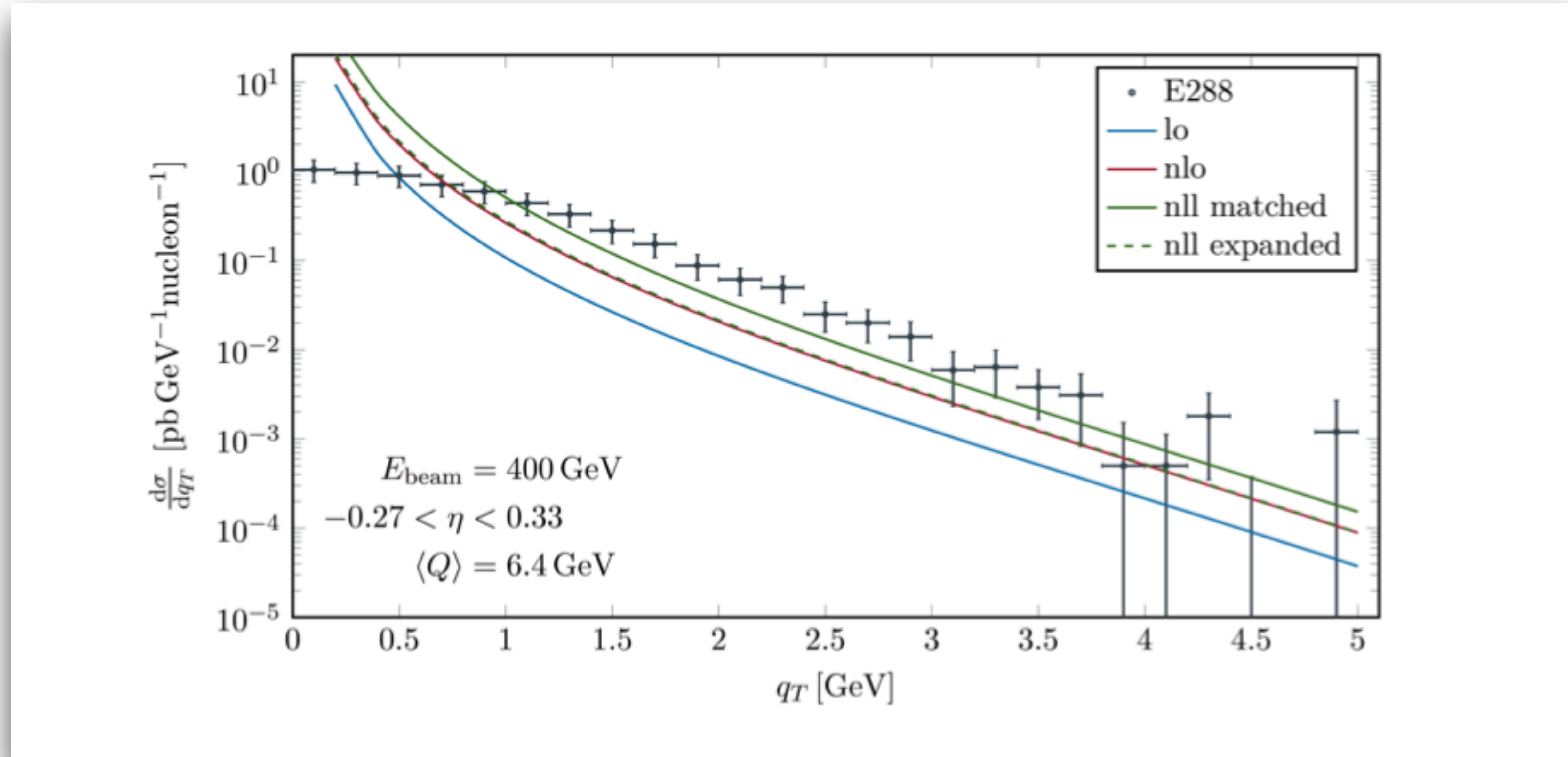
intrinsic k_T smearing



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

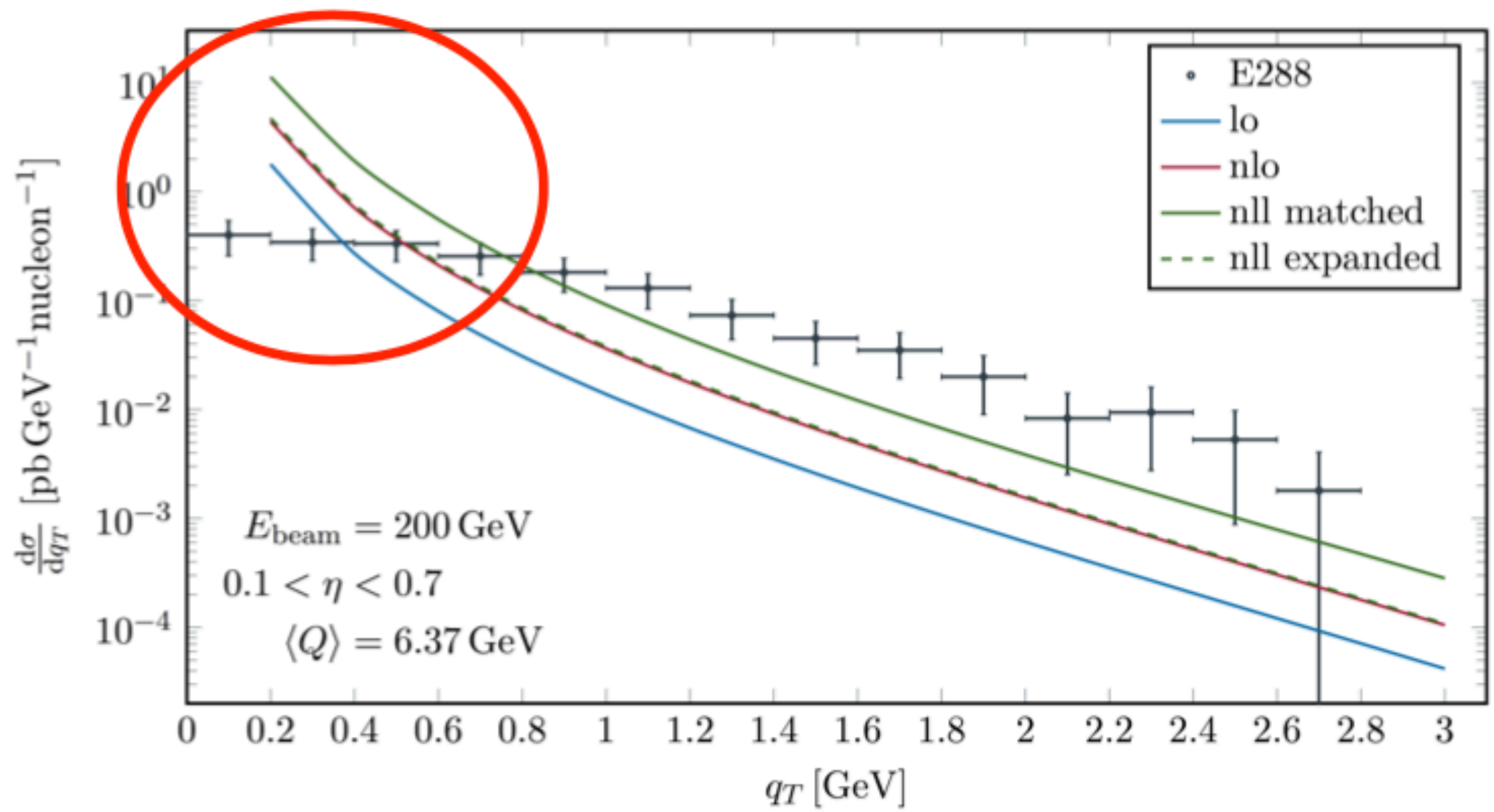
$$\left\langle k_T^2 \right\rangle = 1\, GeV^2$$

threshold resummation



W. Vogelsang @Transversity 2017

threshold resummation



Lambertsen, Steiglechner, WV

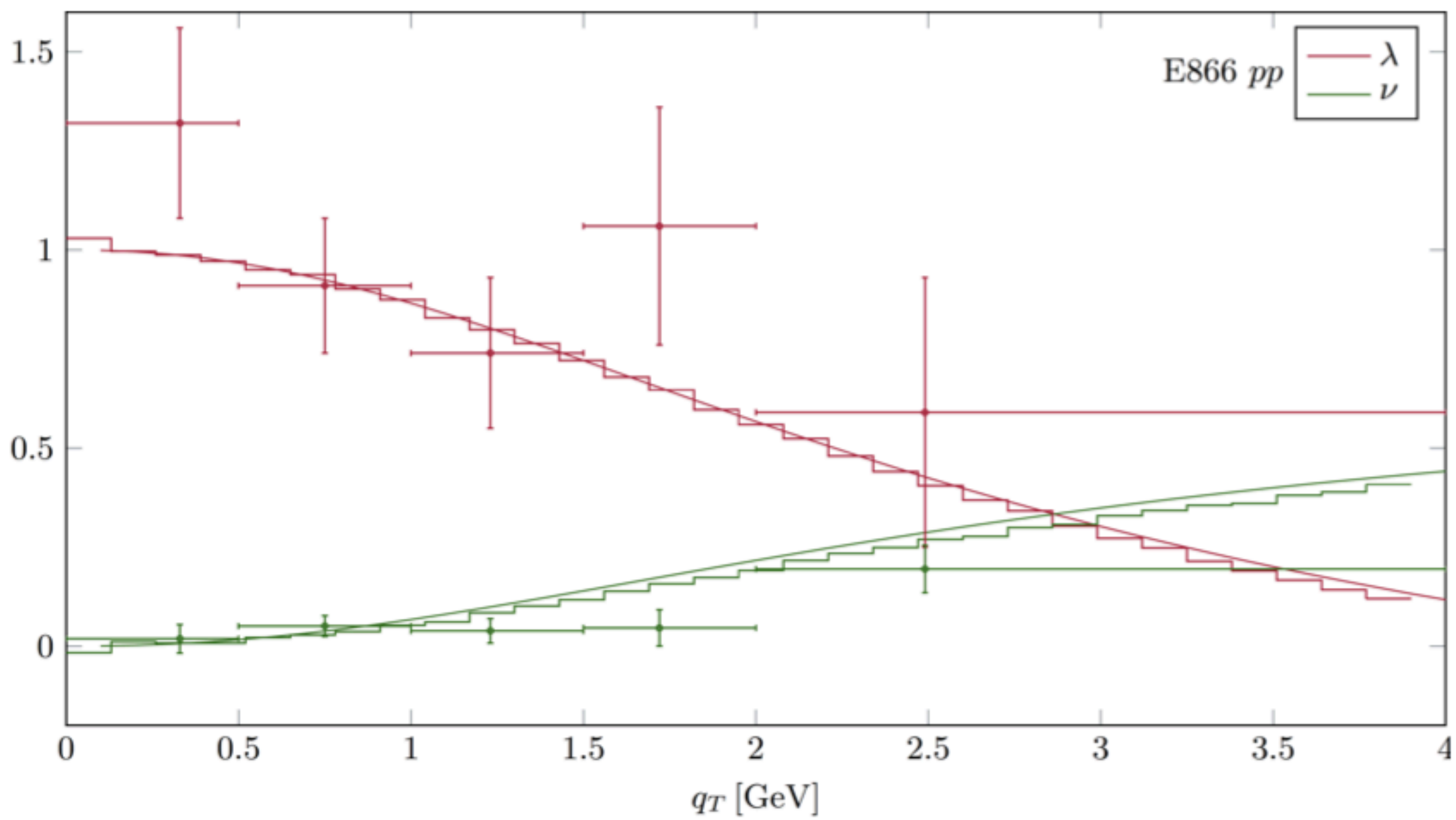
W. Vogelsang @Transversity 2017

angular coefficients

Lambertsen, WV '16

$pp,\ E = 800\ \mathrm{GeV}$

E866



W. Vogelsang @Transversity 2017

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