Drell-Yan at low energy and high q_T

Fulvio Piacenza

in collaboration with A.Bacchetta, G.Bozzi

3DSPIN
MAPPING THE PROTON IN 3D

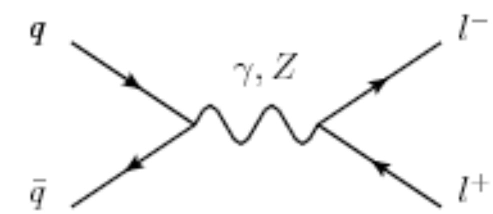
erc
European Research Council

INFN
Istituto Nazionale di Fisica Nucleare

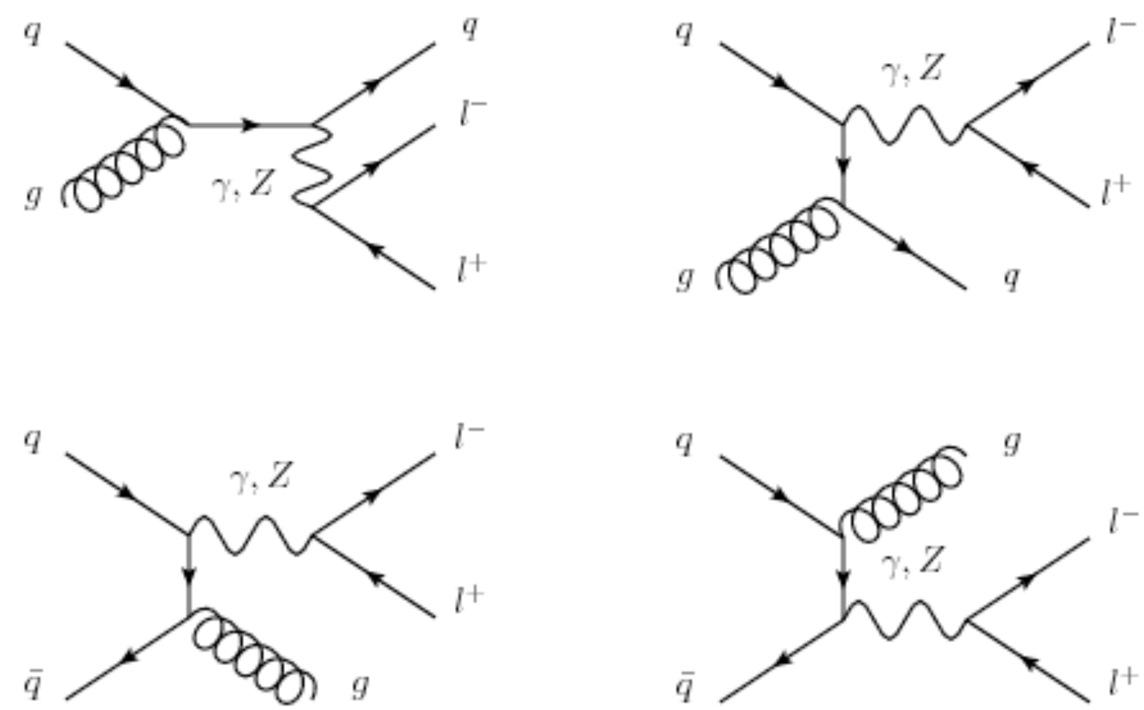
UNIVERSITÀ DI PAVIA

Transverse momentum of Drell-Yan pairs

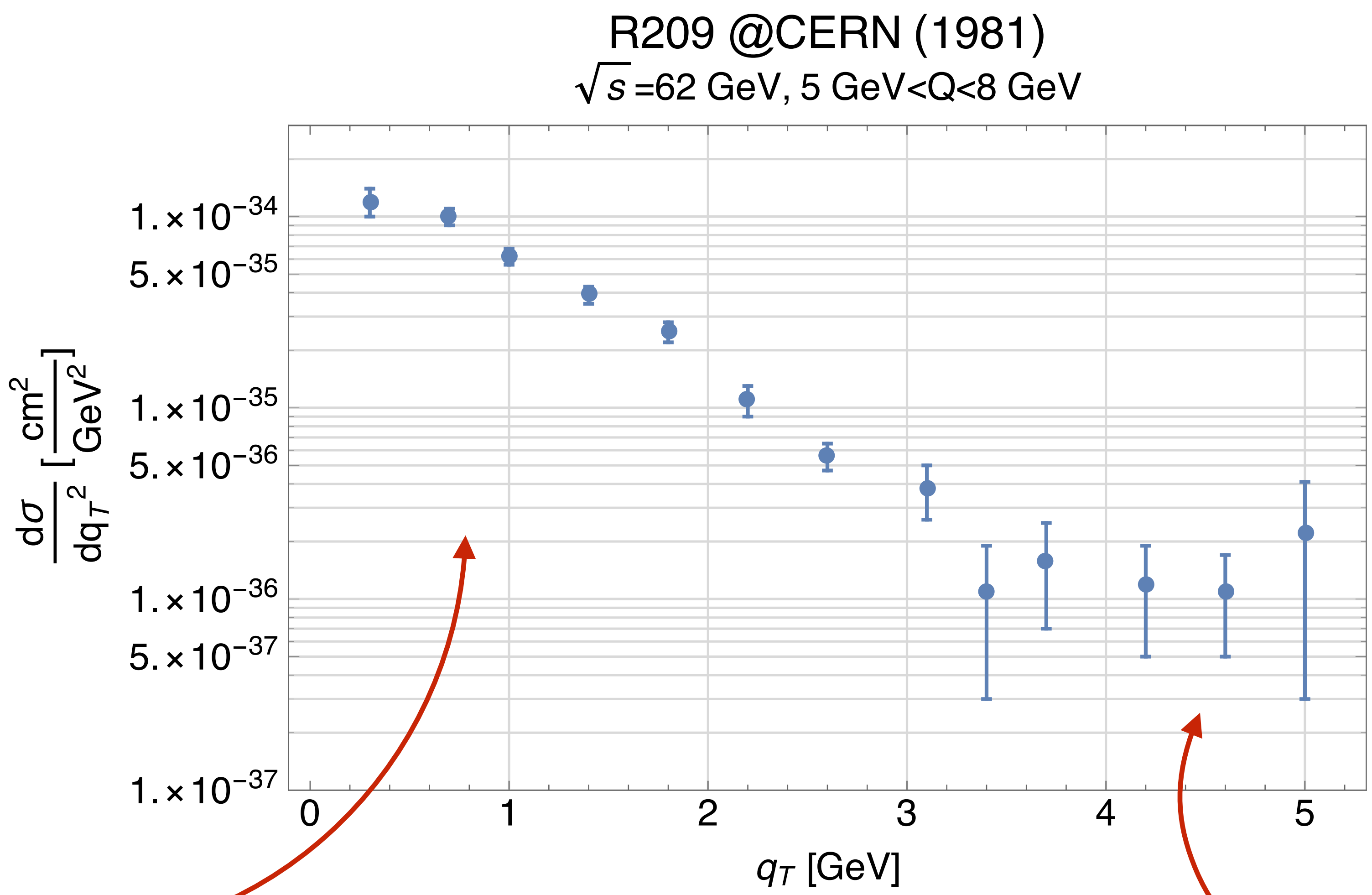
- No transverse momentum at $\mathcal{O}(\alpha_s^0)$



- 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

Fixed order collinear factorization

Matching resummation and collinear factorization

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

W+Y not reliable at large q_T !

(usually about Q/2)

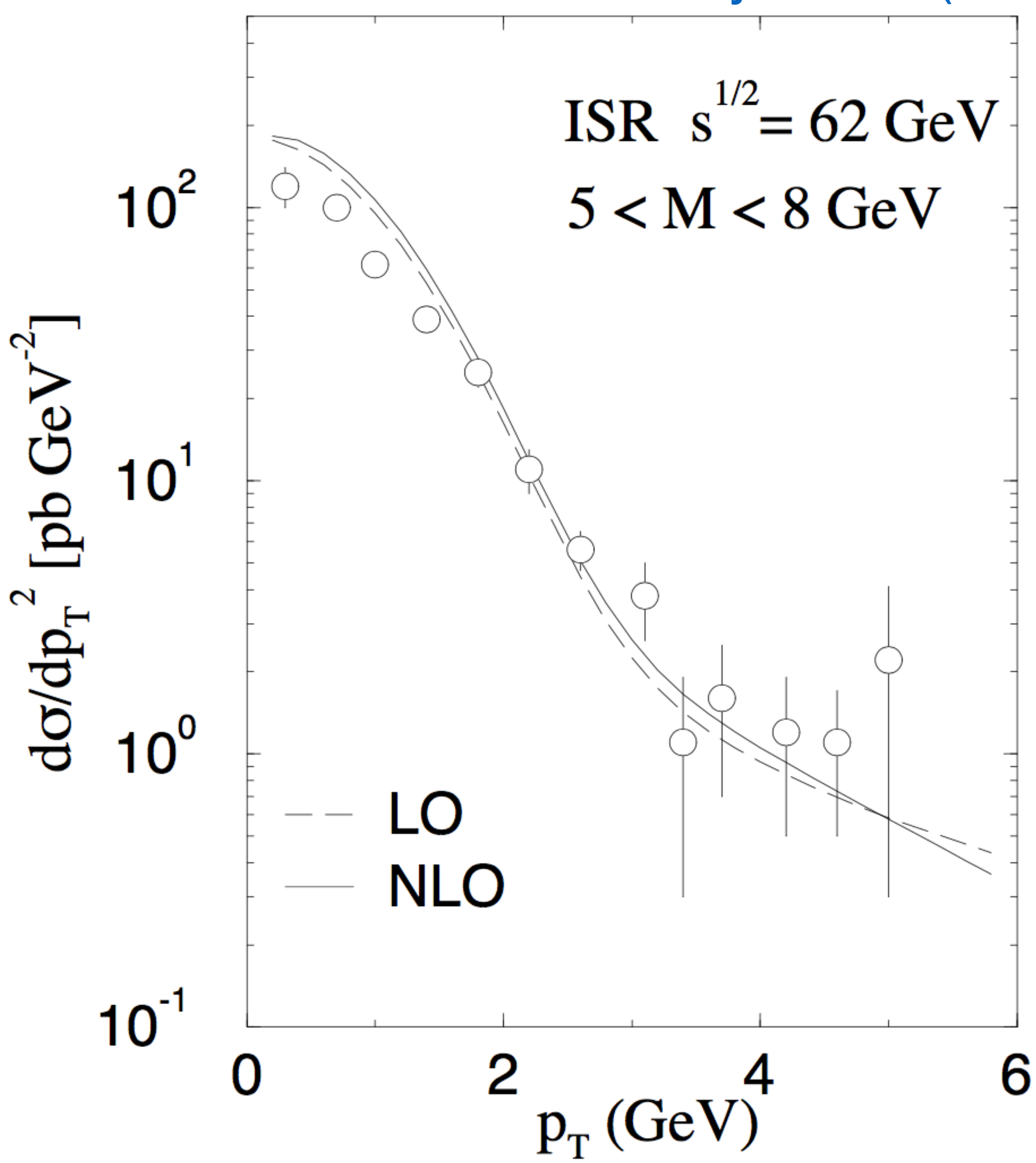
Arnold & Kauffman NP B349 381

Collins et al PRD94 034014

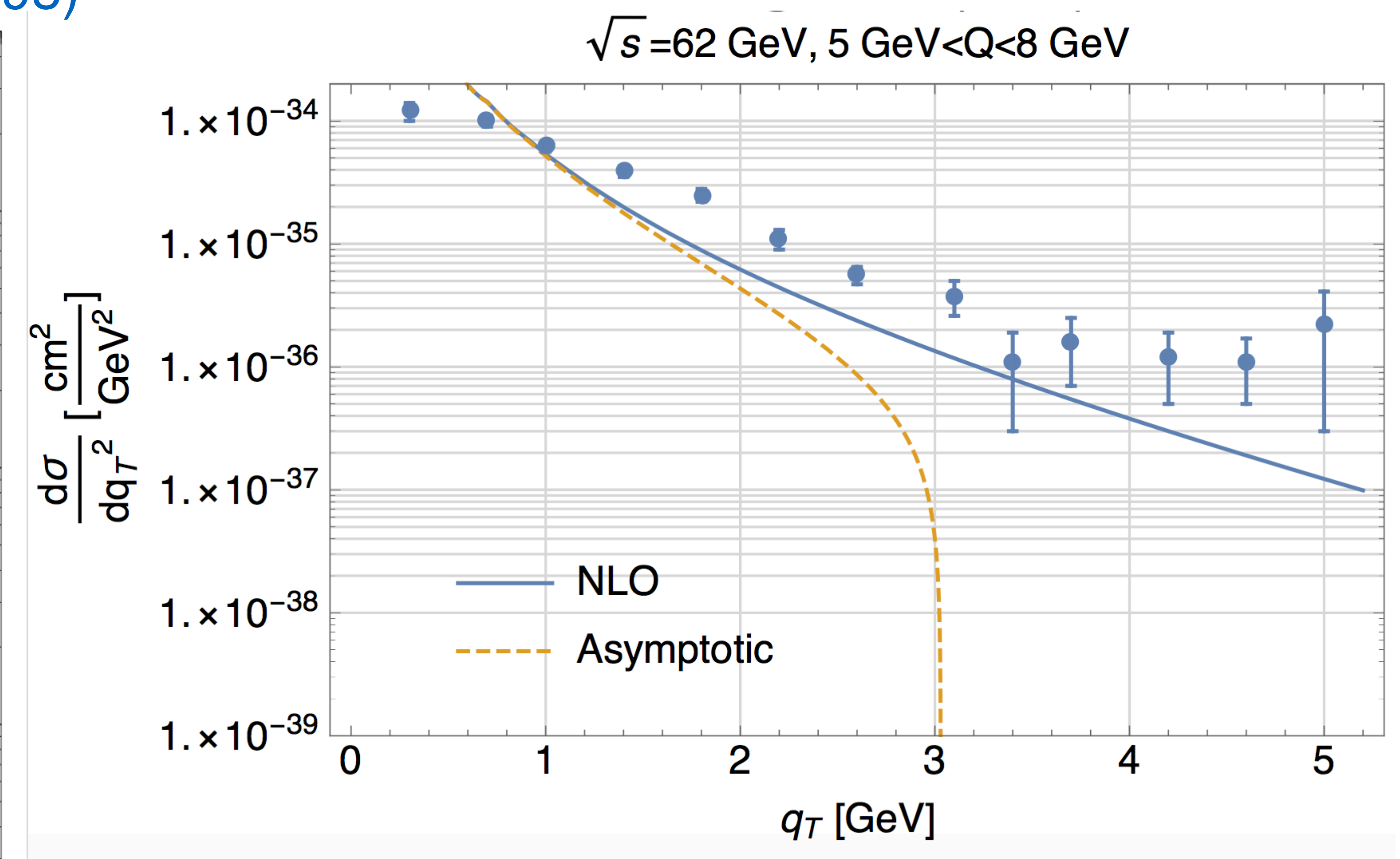
Matching resummation and collinear factorization

W + Y:

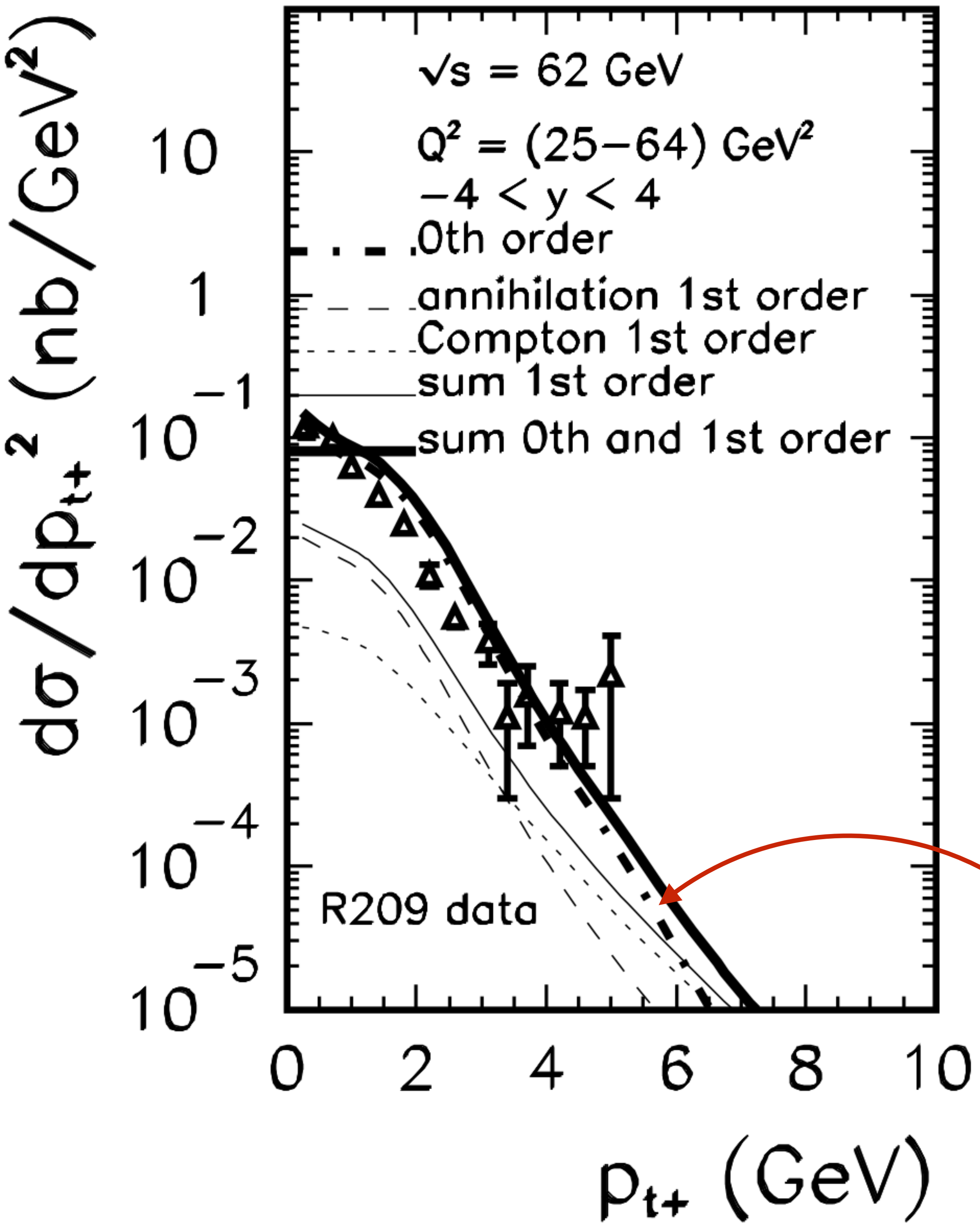
Gavin et al I.J.Mod.Phys. A10 (1995)



Pure NLO:



…"k_T-factorization" formalism?



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

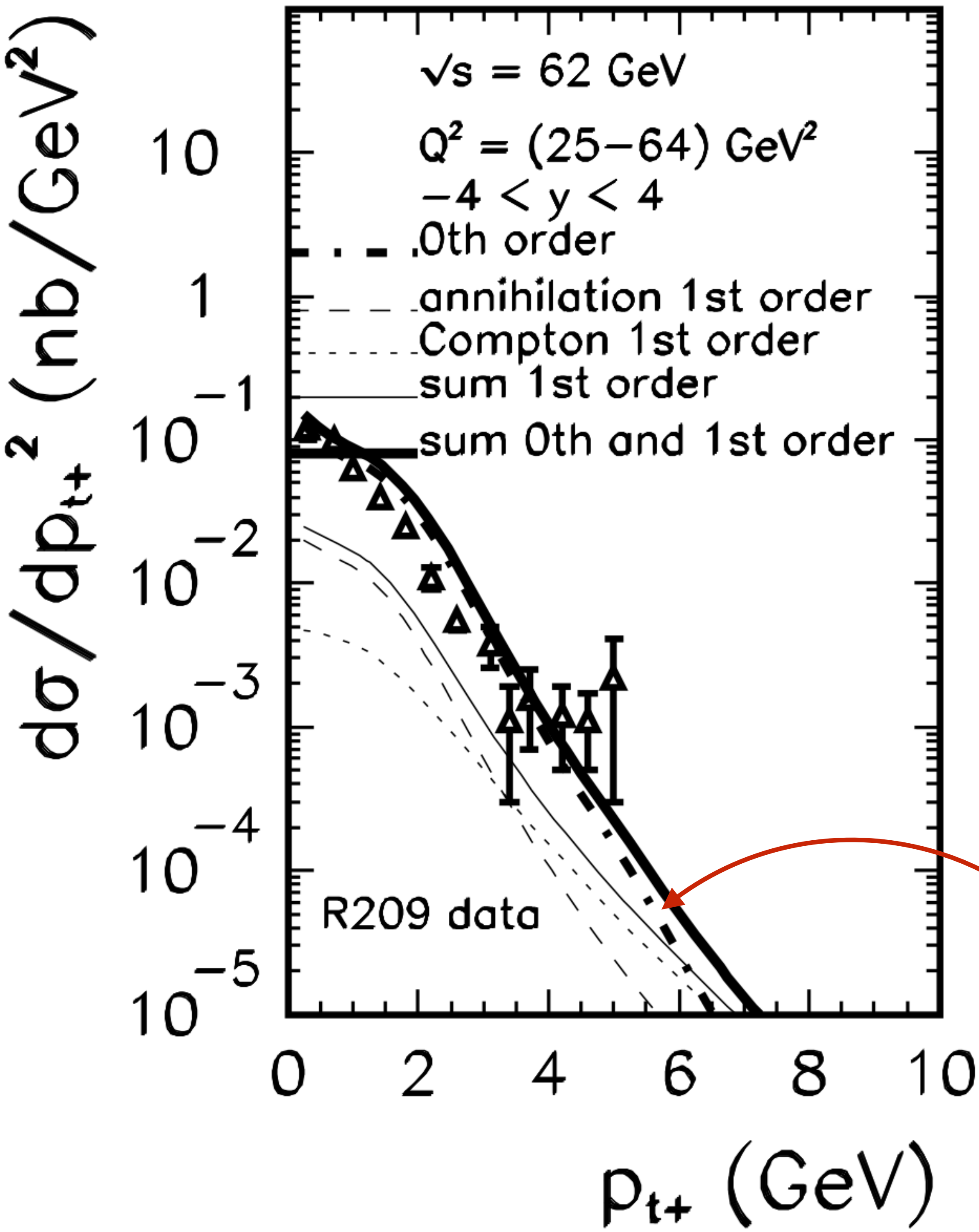
$$\times F^u_{a/A}\left(x_a, \mathbf{k}_{Ta}, \mu_F\right) F^u_{b/B}\left(x_b, \mathbf{k}_{Tb}, \mu_F\right) \frac{\hat{s}}{x_a x_b} d\hat{\sigma}^{ab \to l^+ l^-}$$

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

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

Szczurek, Slipek PRD 78, 114007

…”k_T-factorization” formalism?



Szczurek, Slipek PRD 78, 114007

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

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

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

low energy data in TMD fits

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

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

low energy data in TMD fits

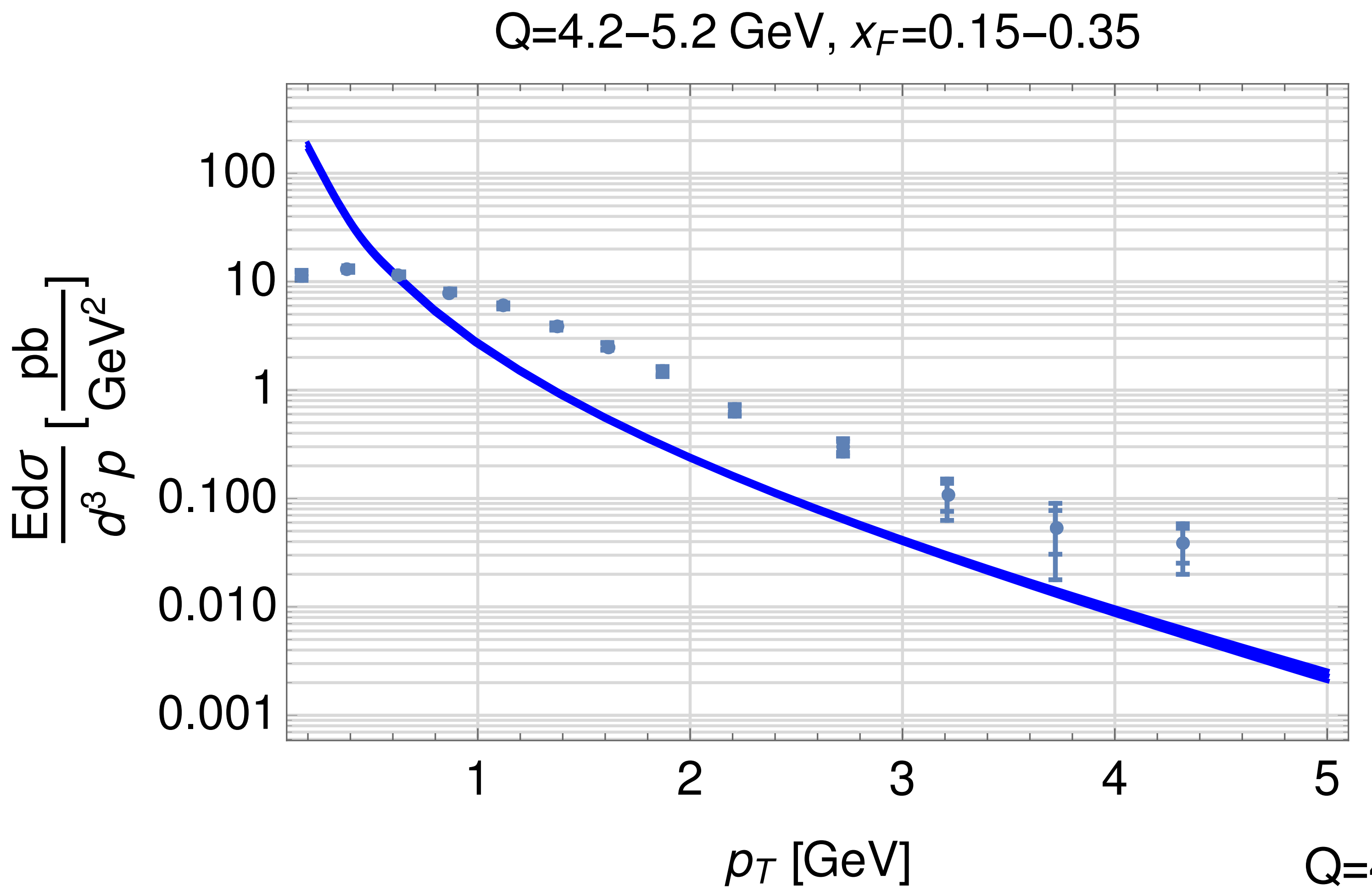
Experiment	Reaction	Year	TMD fits	PDF fits	high-qT tail
R209	p-p	1981	✔	✘	✔
E288	p-Cu, p-Pt	1981	✔	✘	✘
E605	p-Cu	1991	✔	✔	✘
E866	p-p, p-d	2003	✘	✔	✔

Widest kinematic range:

$$-0.05 \leq x_F \leq 0.8$$

$$4.2\,GeV \leq Q \leq 16.85\,GeV$$

Main part of DY data in PDF fits!

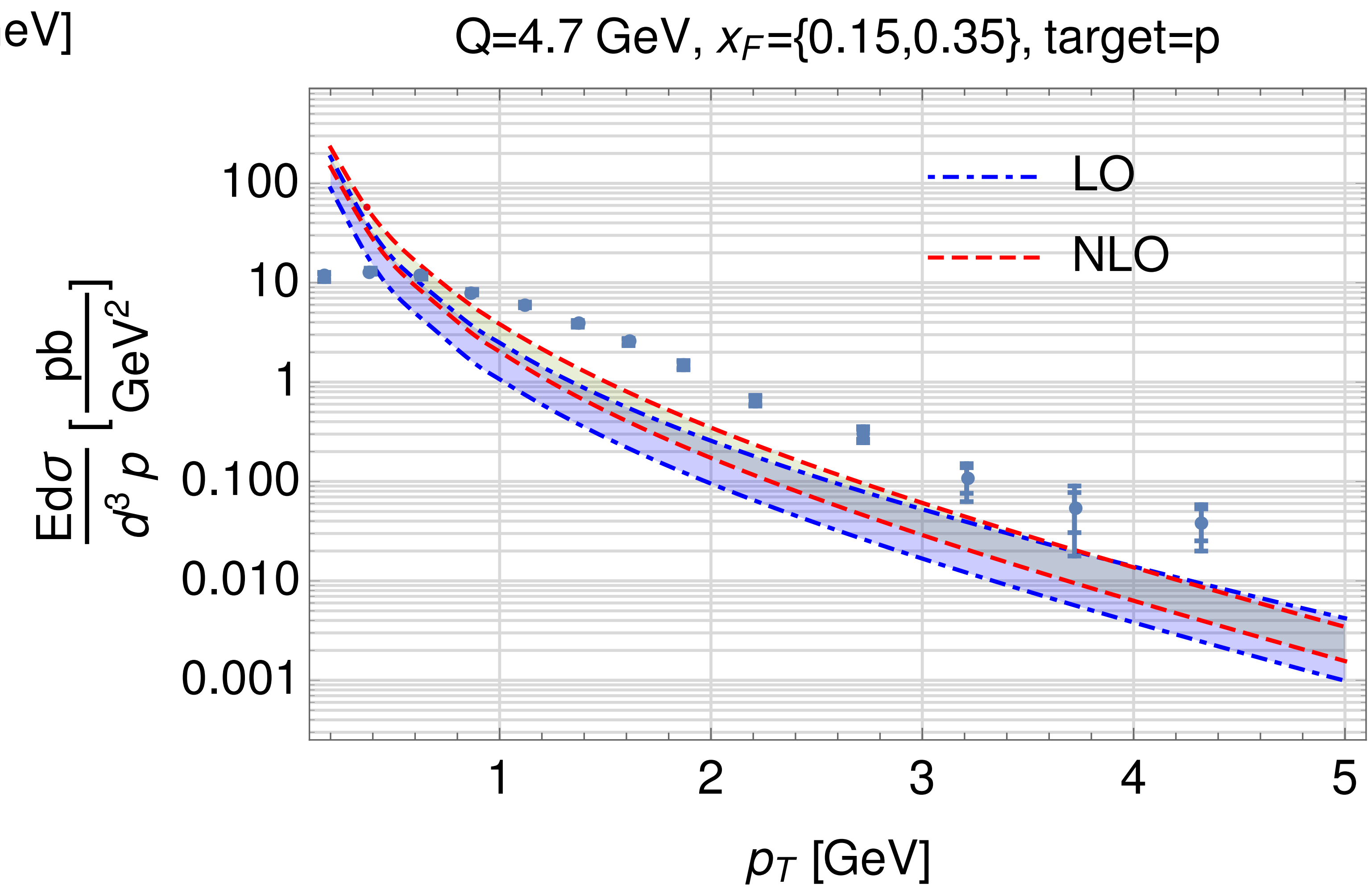


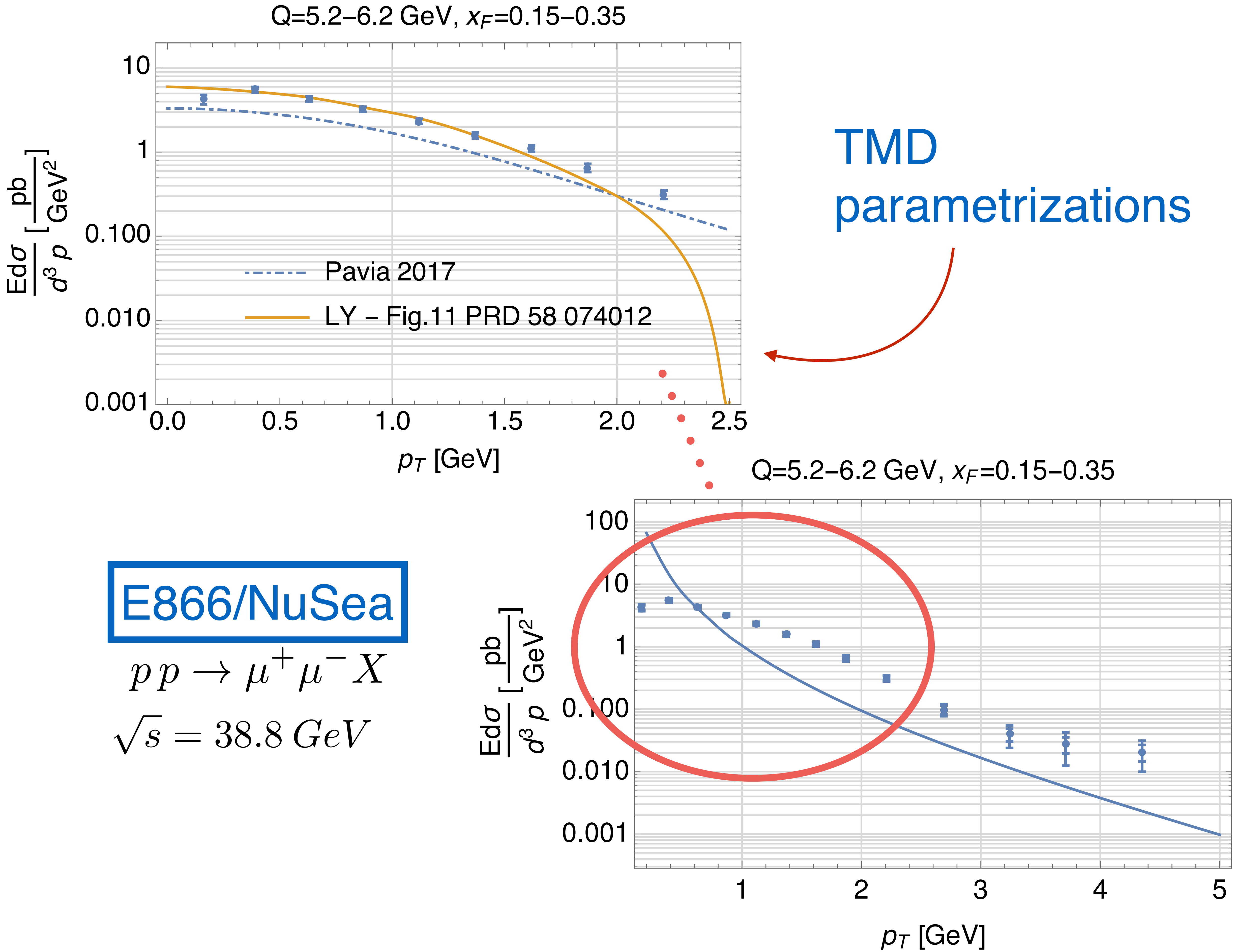
NLO $\mathcal{O}(\alpha_s^2)$
+PDF uncertainty

E866/NuSea

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

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





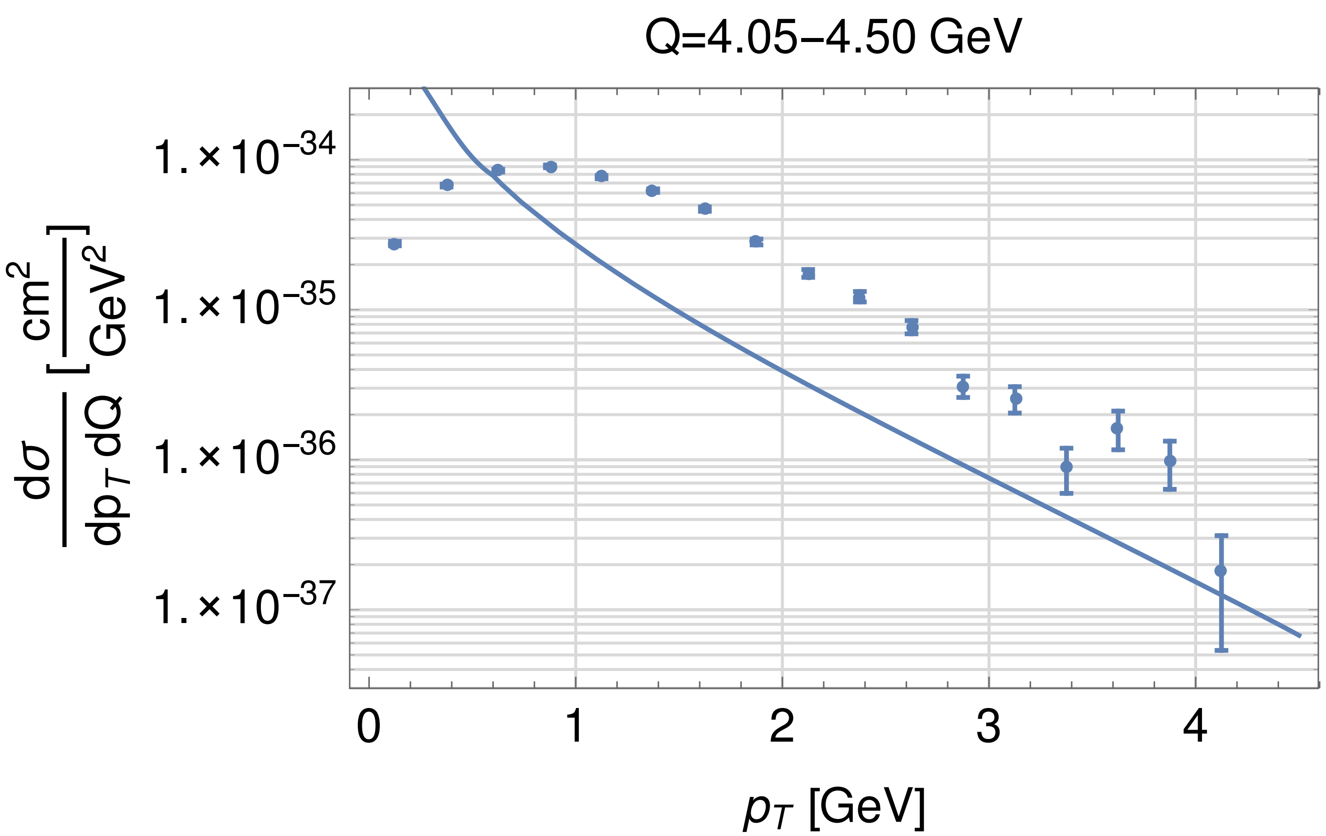
TMD parametrizations

E866/NuSea

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

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

pion-nucleus Drell-Yan

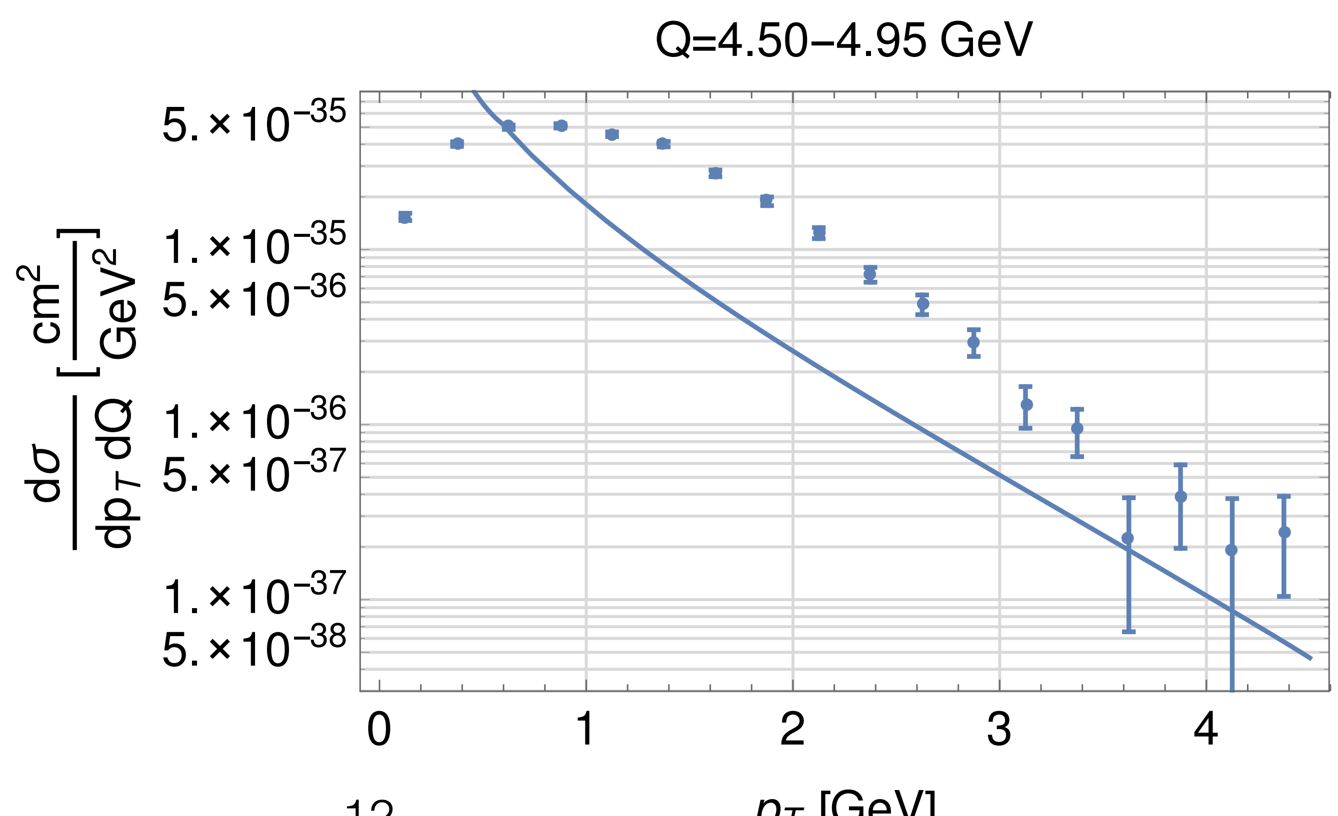


NLO $\mathcal{O}(\alpha_s^2)$

E615

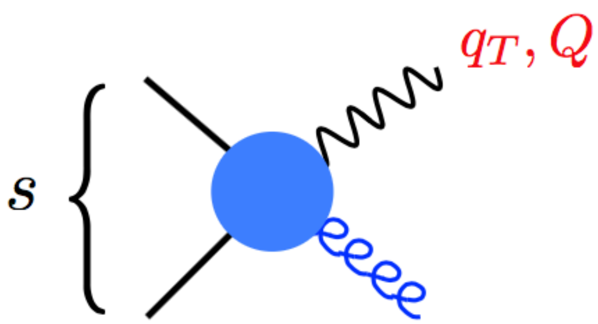
$$\pi W \to \mu^+ \mu^- X$$

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



threshold resummation

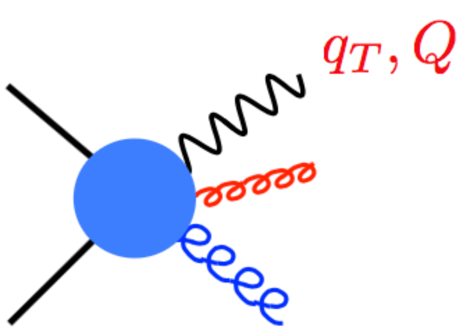
- LO :



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

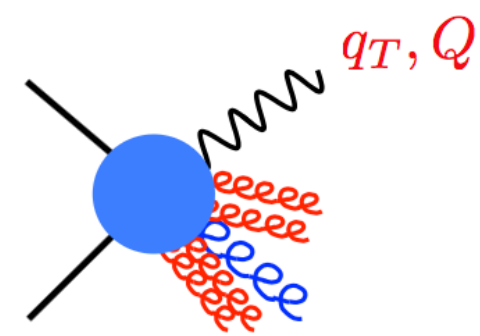
$$y_T \equiv \frac{q_T + \sqrt{q_T^2 + Q^2}}{\sqrt{s}} \leq 1$$

- NLO :



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

- $\mathrm{N^kLO}$:

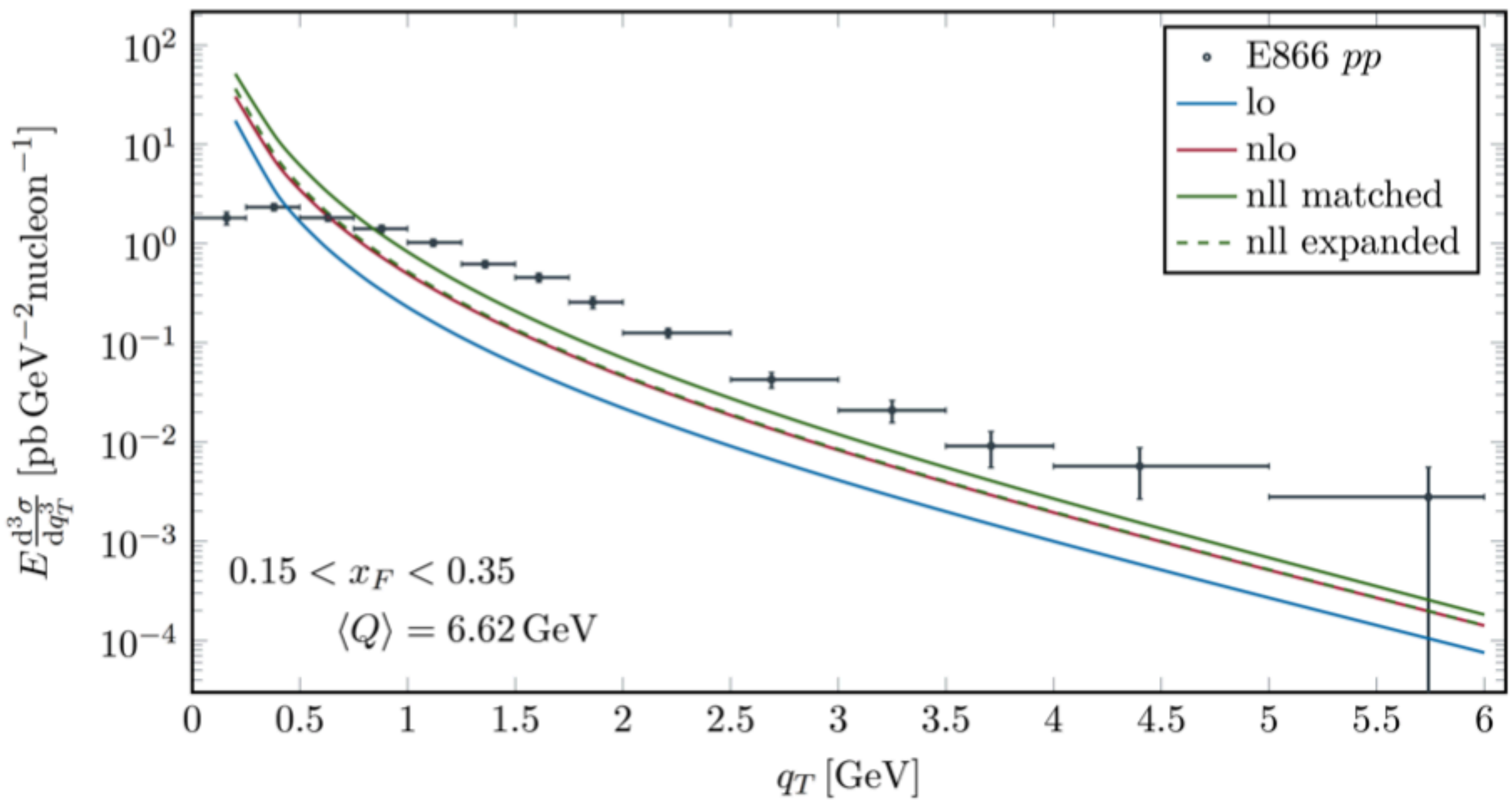


$$\frac{d\hat{\sigma}^{\rm N^kLO}}{dq_T} \propto \alpha_s^k \log^{2k}(1-y_T^2) + \ldots$$

- threshold logarithms

W. Vogelsang @Transversity 2017

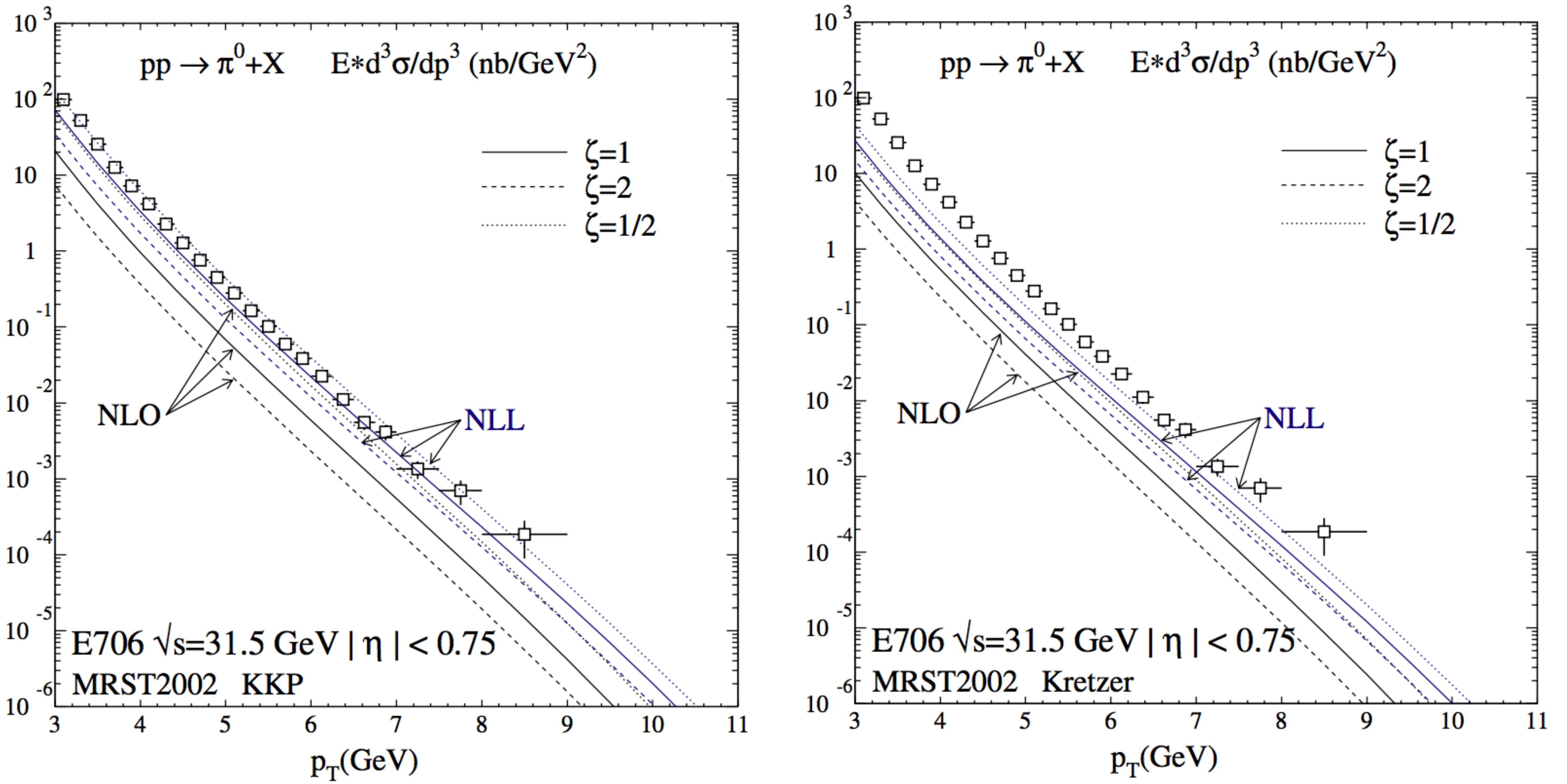
threshold resummation



W. Vogelsang @Transversity 2017

known similar cases

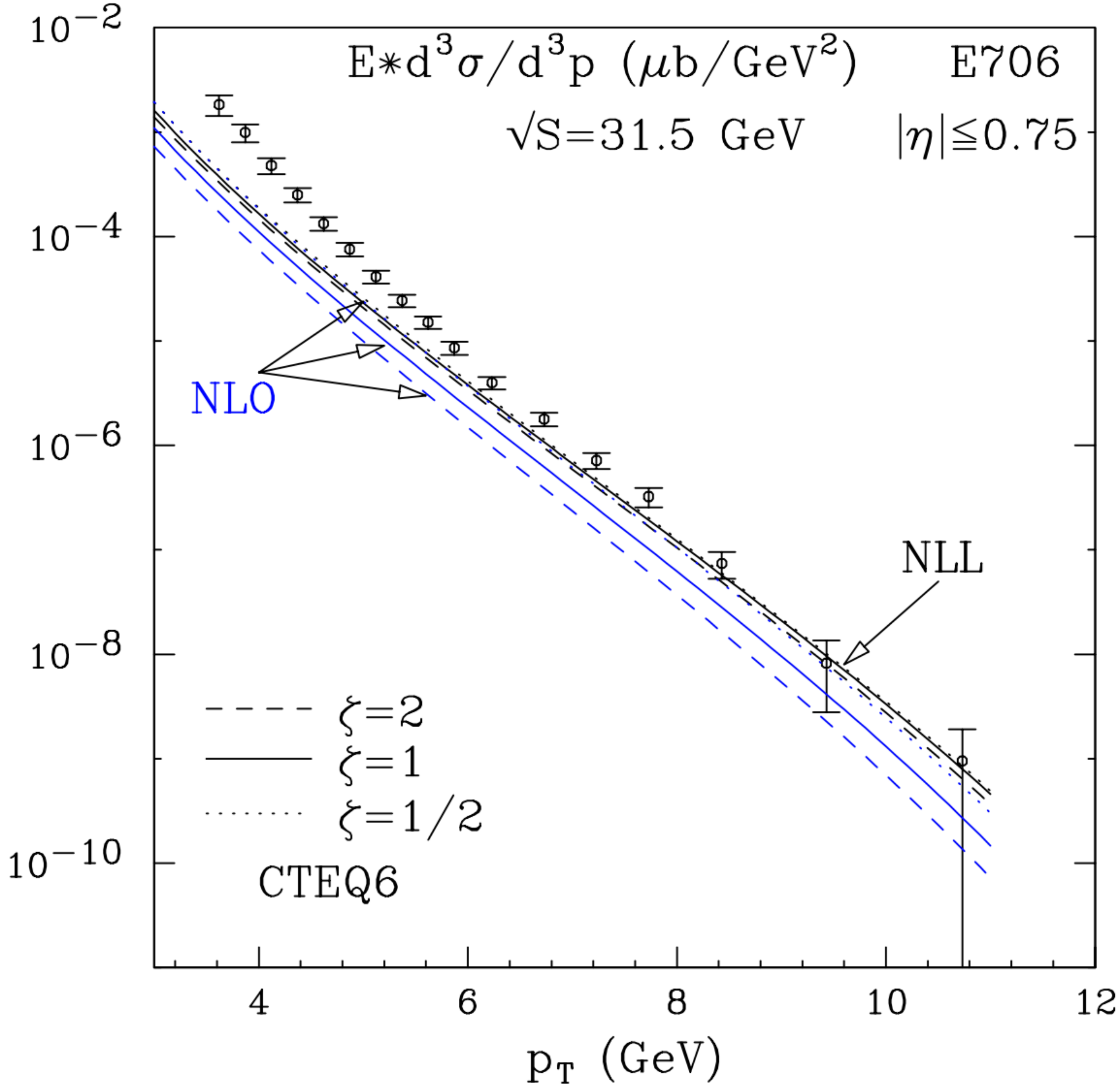
pion production



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

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

- give the incoming partons a small k_T

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

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

intrinsic k_T smearing

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)
…

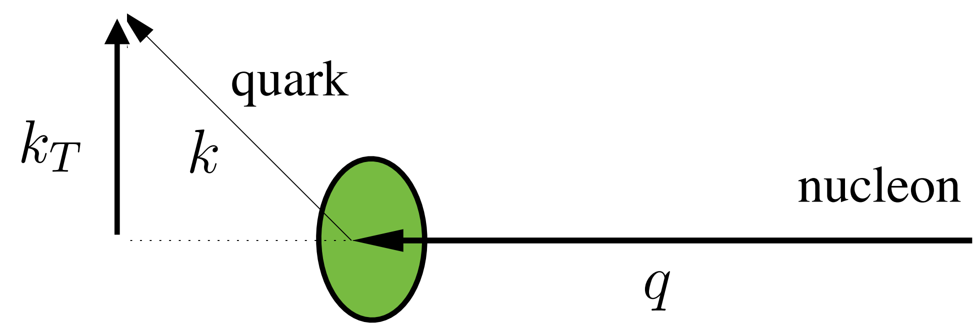
- give the incoming partons a small k_T

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

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

intrinsic k_T smearing

non-perturbative k_T



- give the incoming partons a small k_T

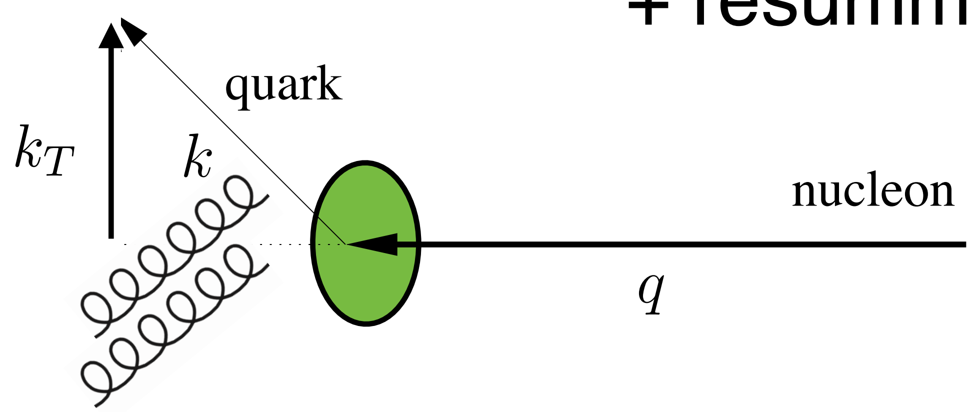
$$d\sigma = \sum_{ab} \int dx_a\, d^2\mathbf{k}_{Ta}\, dx_b\, d^2\mathbf{k}_{Tb}$$

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

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:

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

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:

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

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

make sure

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

not too small

Fixed Order must be valid!

intrinsic k_T smearing

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

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

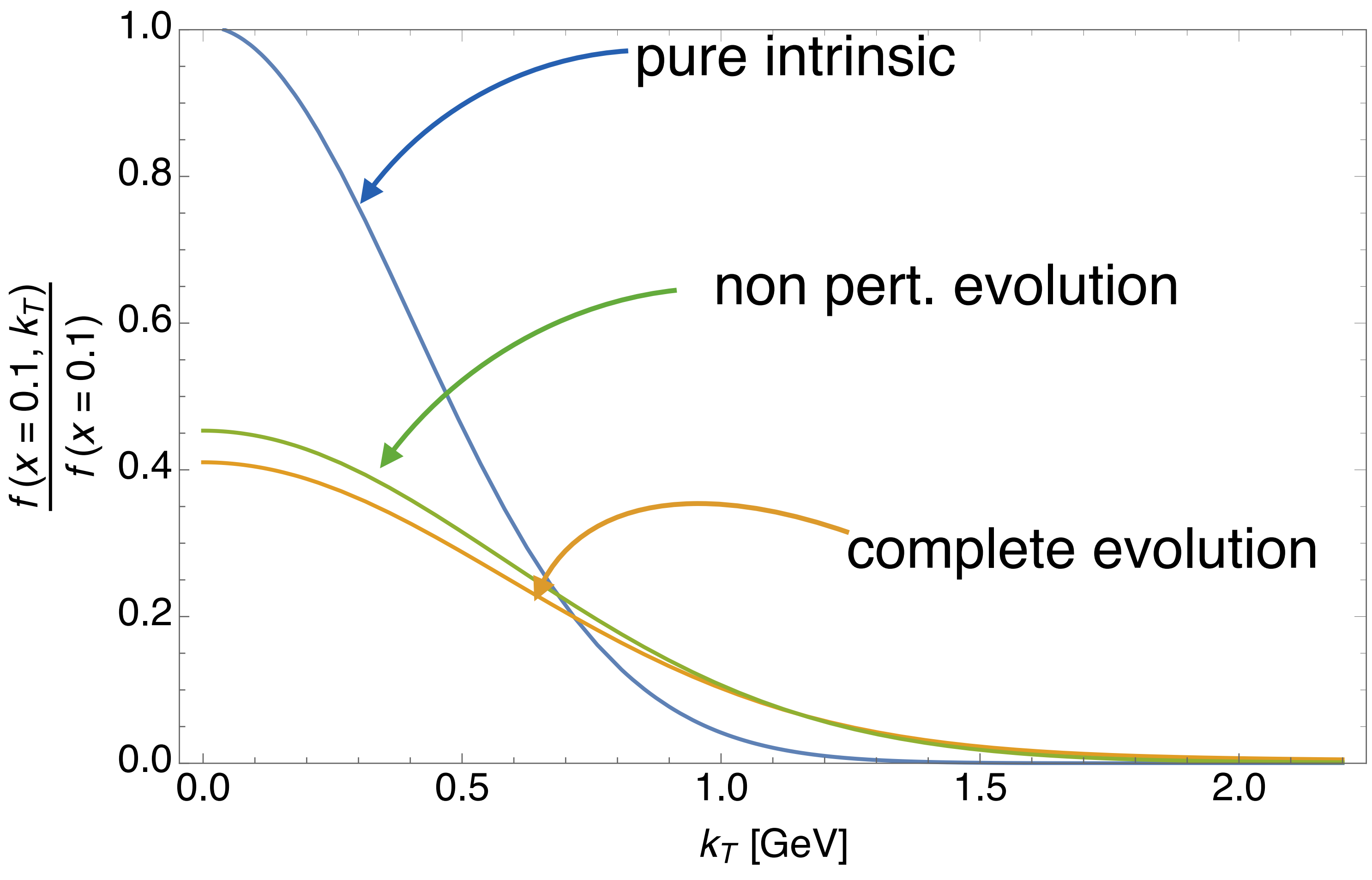
$$\int_0^{k^2_{Tmax}} \pi dk_T^2$$

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:



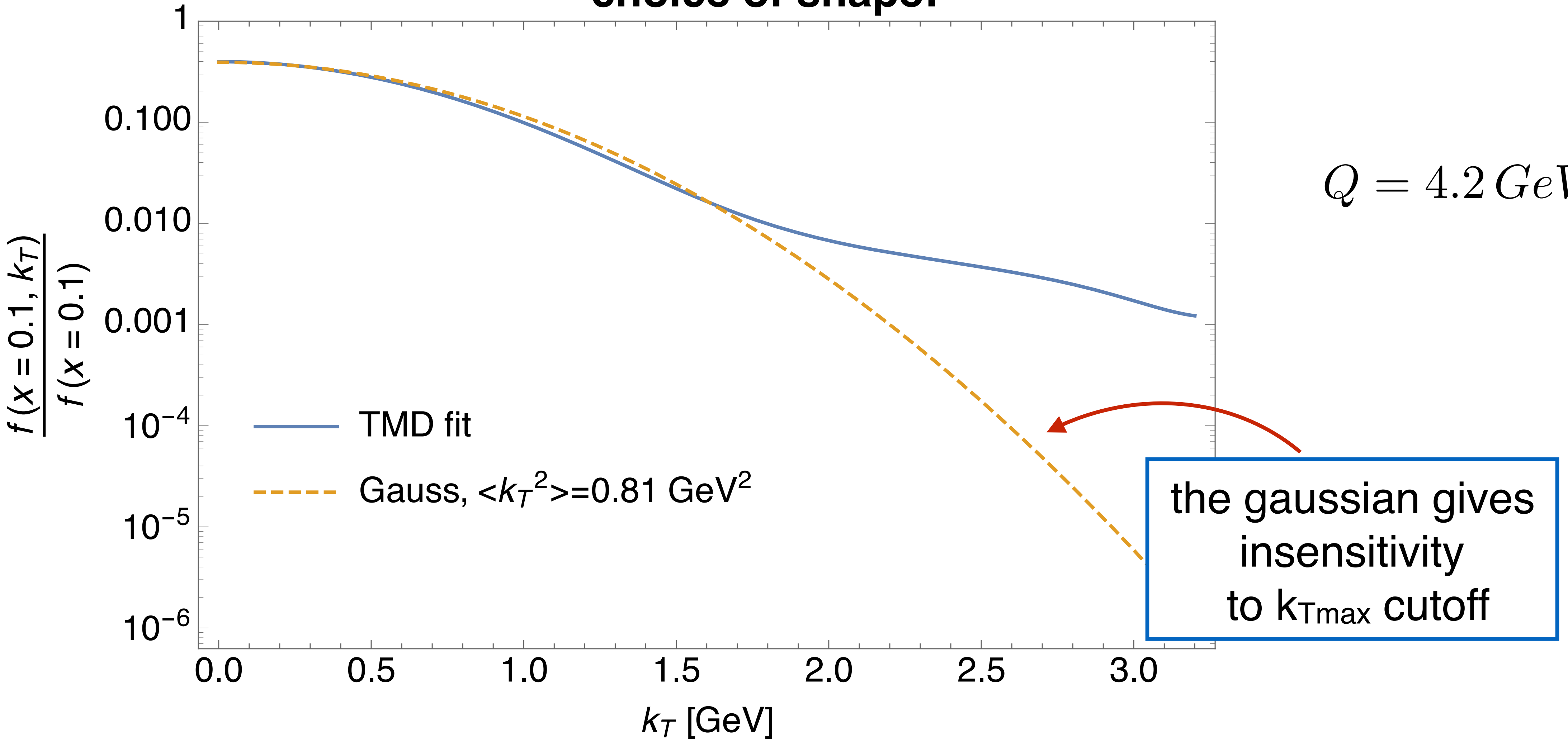
$Q = 4.2\, GeV$

Bacchetta et al JHEP 1706 081

intrinsic k_T smearing

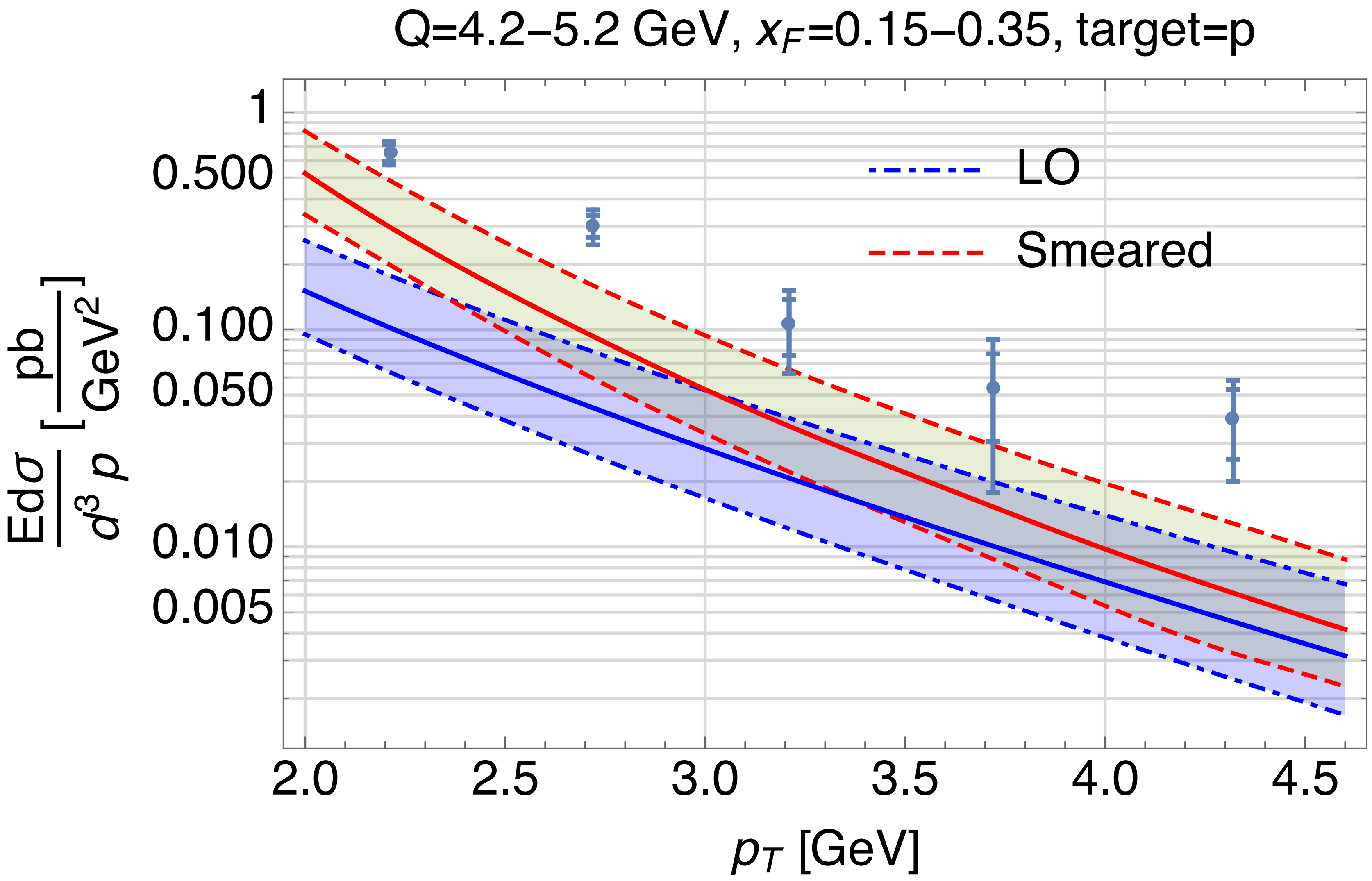
$$\frac{f_{a/A}(x_a, \mathbf{k}_{Ta})}{f_{a/A}(x_a)}$$

choice of shape:



$Q = 4.2\, GeV$

intrinsic k_T smearing



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

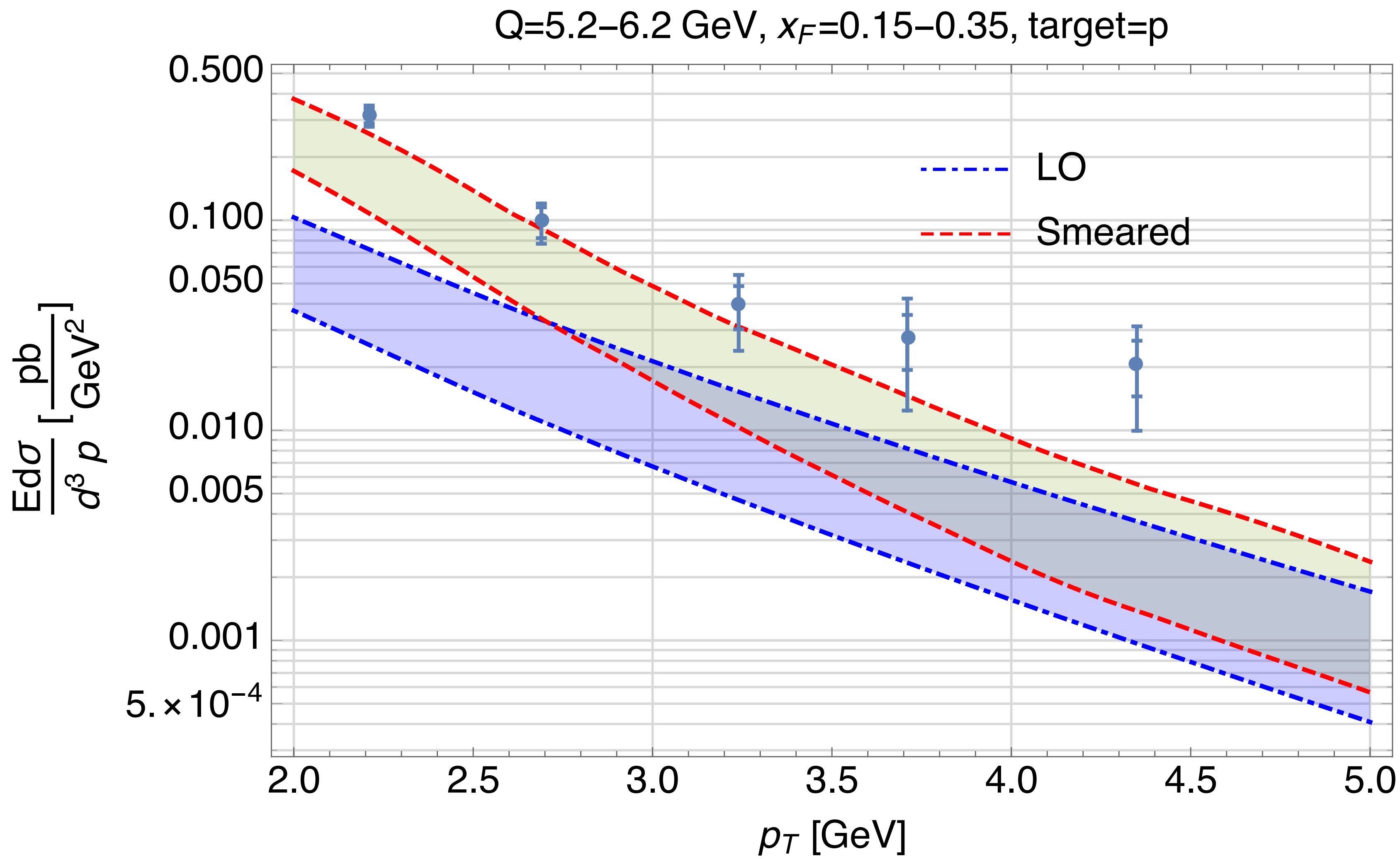
$$\left\langle k_T^2 \right\rangle = 0.81\, GeV^2$$

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 neither intrinsic-k_T models seem to help
- more high q_T data needed (E906, Compass ?)
- important to see effects of E866 data in TMD fits

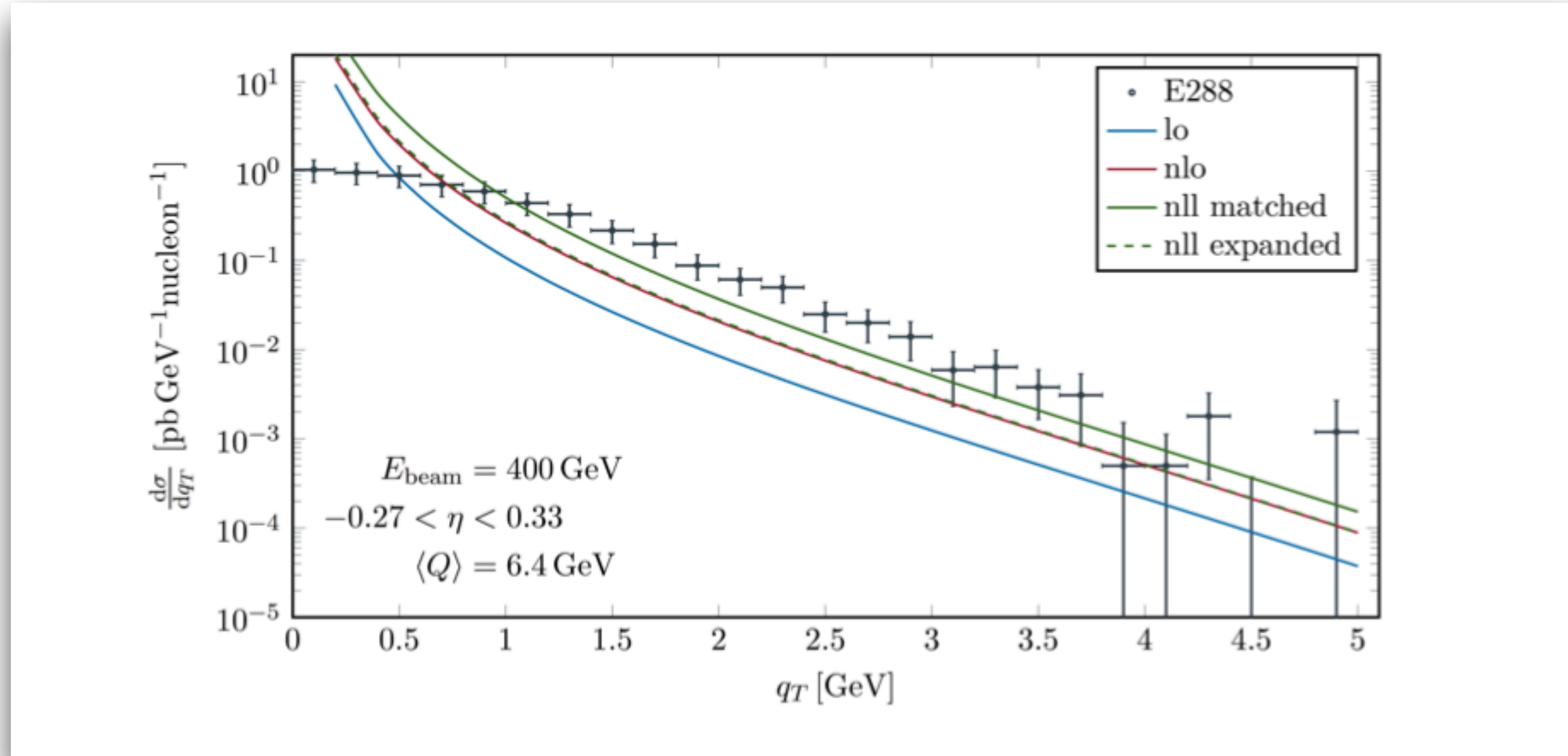
intrinsic k_T smearing



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

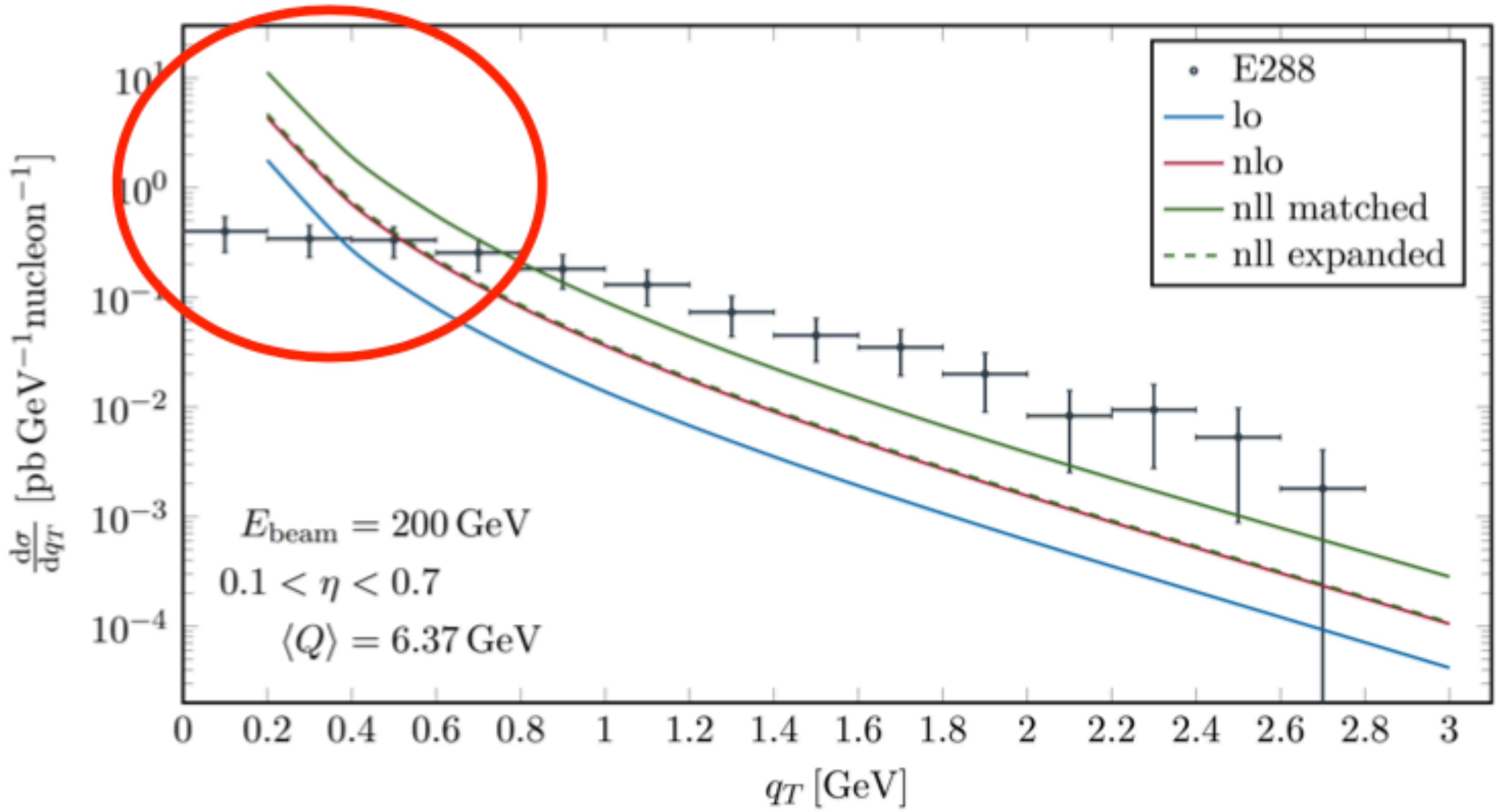
$$\left\langle k_T^2 \right\rangle = 1\, GeV^2$$

threshold resummation



W. Vogelsang @Transversity 2017

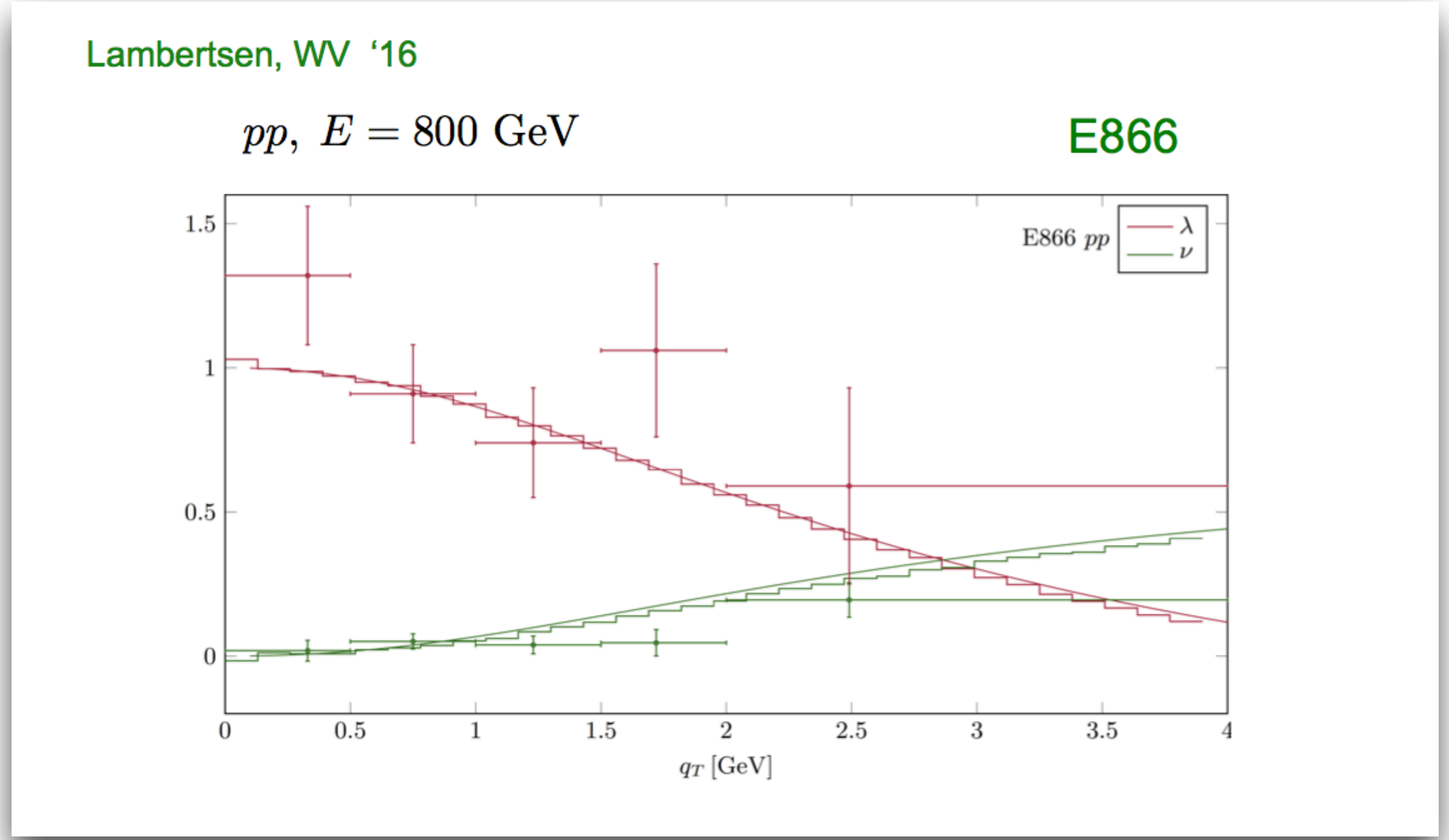
threshold resummation



Lambertsen, Steiglechner, WV

W. Vogelsang @Transversity 2017

angular coefficients



W. Vogelsang @Transversity 2017

angular coefficients