Drell-Yan process at moderate mass and transverse momentum

Werner Vogelsang
Univ. Tübingen

Berkeley, Sep. 16, 2019

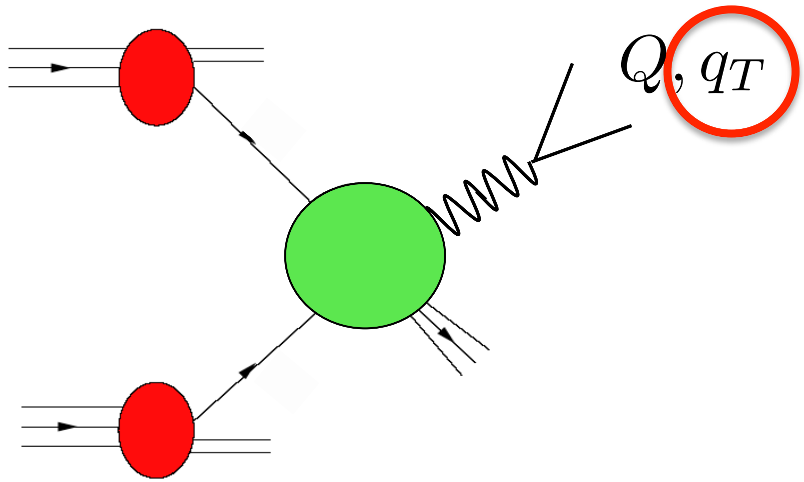
Outline:

- Motivation & Introduction
- Cross section in collinear factorization
- Further studies & thoughts
- Phenomenology

Will focus on "collinear pQCD perspective"
→ Drell-Yan extremely well explored

Collab. with A. Bacchetta, G. Bozzi, M. Lambertsen, F. Piacenza, J. Steiglechner

Motivation & Introduction



Lepton angular distribution (photon exchange):

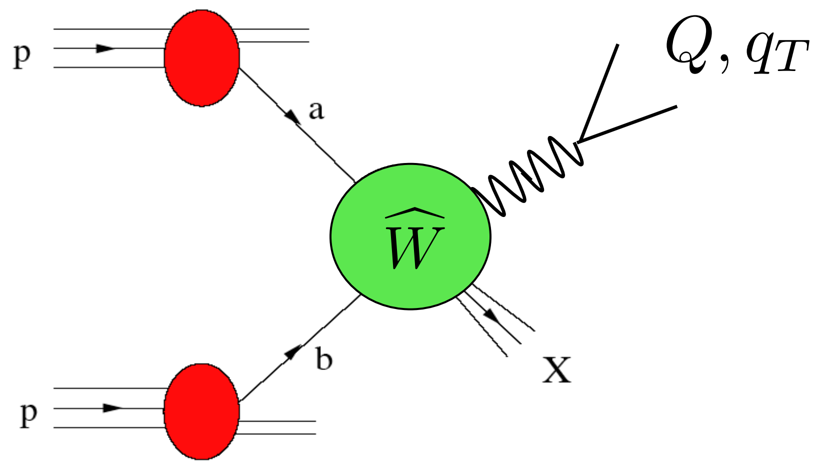
$$\frac{d\sigma}{d^4q\, d\Omega} = \frac{\alpha^2}{2\pi N_c Q^2 s^2}\Big(W_T\,(1+\cos^2\theta) + W_L\,(1-\cos^2\theta)$$

$$+W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta} \sin^2\theta \cos 2\phi\Big)$$

(e.g. Collins-Soper frame)

$$\frac{d\sigma}{d^4q} = \frac{4\alpha^2}{3N_c Q^2 s^2}\,(2W_T + W_L)$$

Collinear factorization:



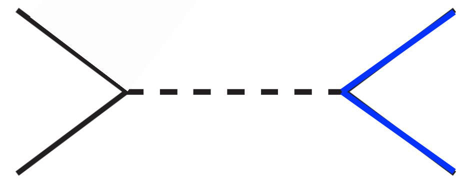
$$W_P = \sum_{a,b} \int dx_a dx_b \, f_a(x_a, \mu) \, f_b(x_b, \mu) \, \widehat{W}_{P,ab}(x_a P_a, x_b P_b, q, \alpha_s(\mu), \mu)$$

$$(P = T, L, \Delta, \Delta\Delta)$$

- $\widehat{W}_P$ partonic structure fcts.: perturbative

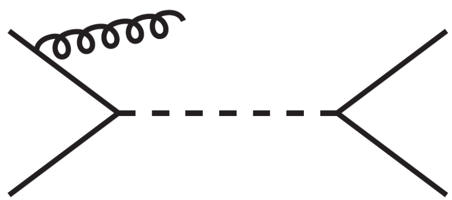
$$\widehat{W}_P = \frac{\alpha_s}{\pi} \widehat{W}_P^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \widehat{W}_P^{(2)} + \ldots \qquad \text{(fixed-order)}$$

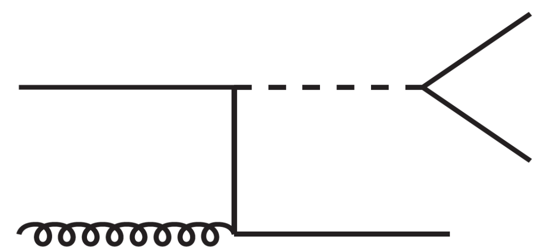
- zeroth order $q\bar{q} \to V \to \ell^+ \ell^-$:



$q_T = 0$

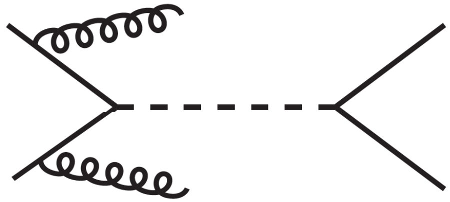
- $q_T \neq 0$: first non-trivial order (= LO) $\mathcal{O}(\alpha_s)$



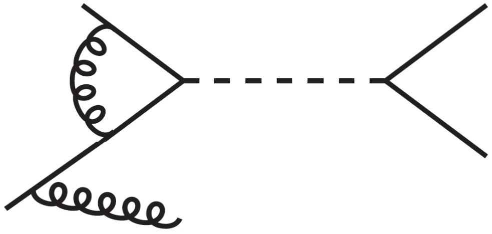


$W_L \neq 0 \quad W_\Delta \neq 0 \quad W_{\Delta\Delta} \neq 0$

NLO:

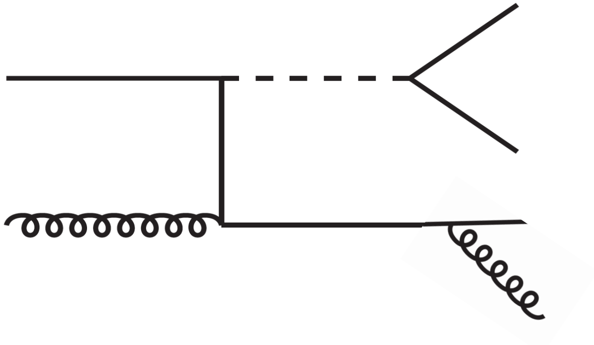


$+ \ldots$



$+ \ldots$

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



$+ \ldots$

first computed by Mirkes '92; Mirkes, Ohnemus '95

- a lot of work in recent 2 decades on $\mathcal{O}(\alpha_s^2)$ corrections for Drell-Yan process

  Hamberg, van Neerven, Matsuura; Harlander, Kilgore;
  Anastasiou, Dixon, Melnikov, Petriello; Melnikov, Petriello;
  Li, Petriello, Quackenbusch; Catani, Cieri, Ferrera, de Florian, Grazzini;
  Karlberg, Re, Zanderighi; …

- especially: $\mathcal{O}(\alpha_s^2)$ Monte-Carlo codes

  FEWZ: Melnikov, Petriello; Melnikov, Petriello;
  Li, Petriello, Quackenbusch

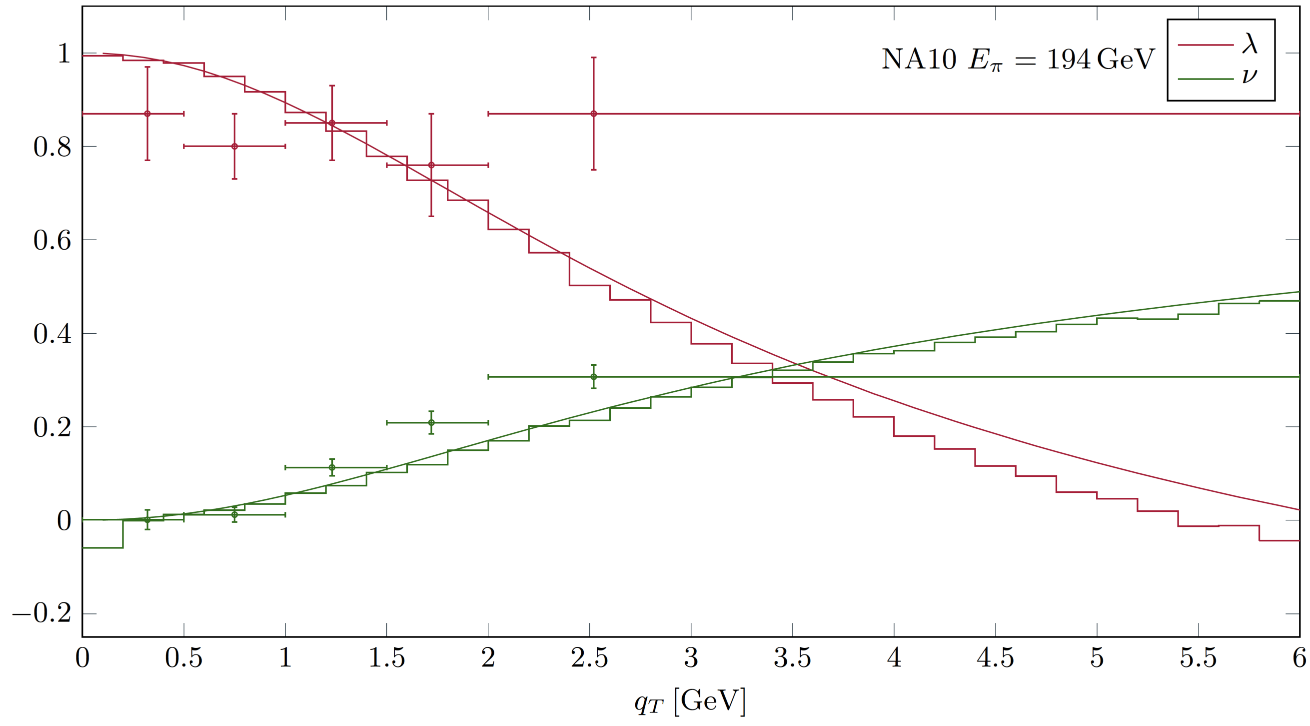
  DYNNLO: Catani, Cieri, Ferrera, de Florian, Grazzini

- most recently: $\mathcal{O}(\alpha_s^3)$

  Li, von Manteuffel, Schabinger, Zhu;
  Anastasiou, Duhr, Dulat, Herzog, Mistlberger;
  Gauld, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan

Lambertsen, WV '16

$\pi W,\ E_\pi = 194\,\mathrm{GeV}$ NA10



$$\nu = \frac{2W_{\Delta\Delta}}{W_T + W_L}$$

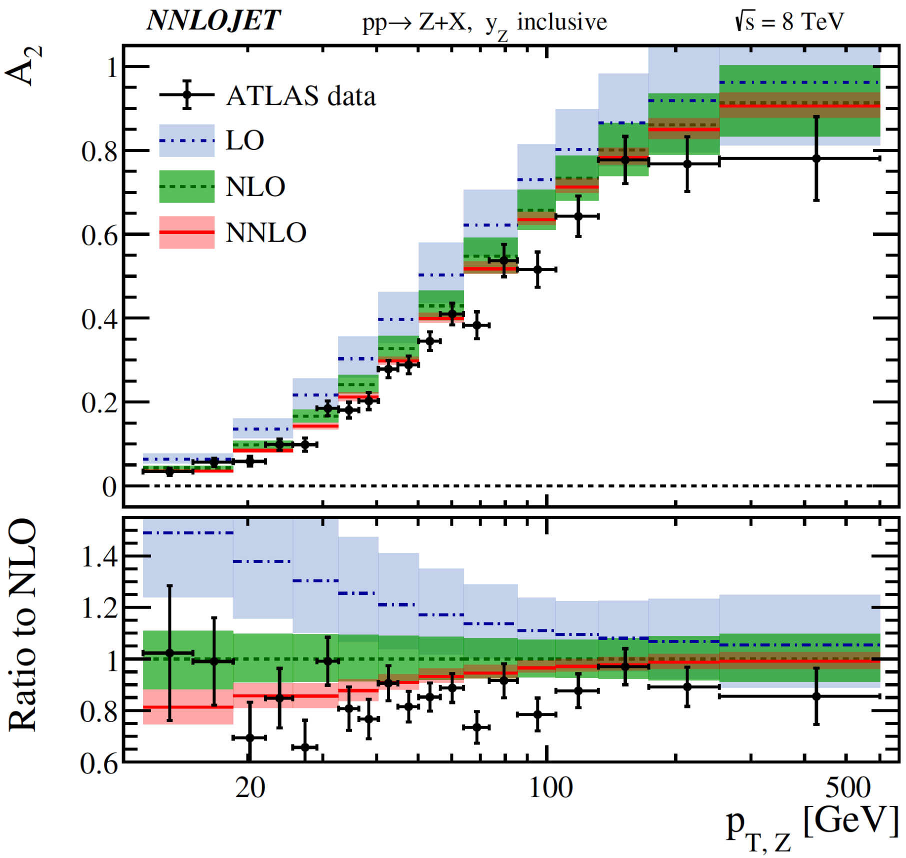
$$\lambda = \frac{W_T - W_L}{W_T + W_L}$$

lines: LO $\mathcal{O}(\alpha_s)$

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

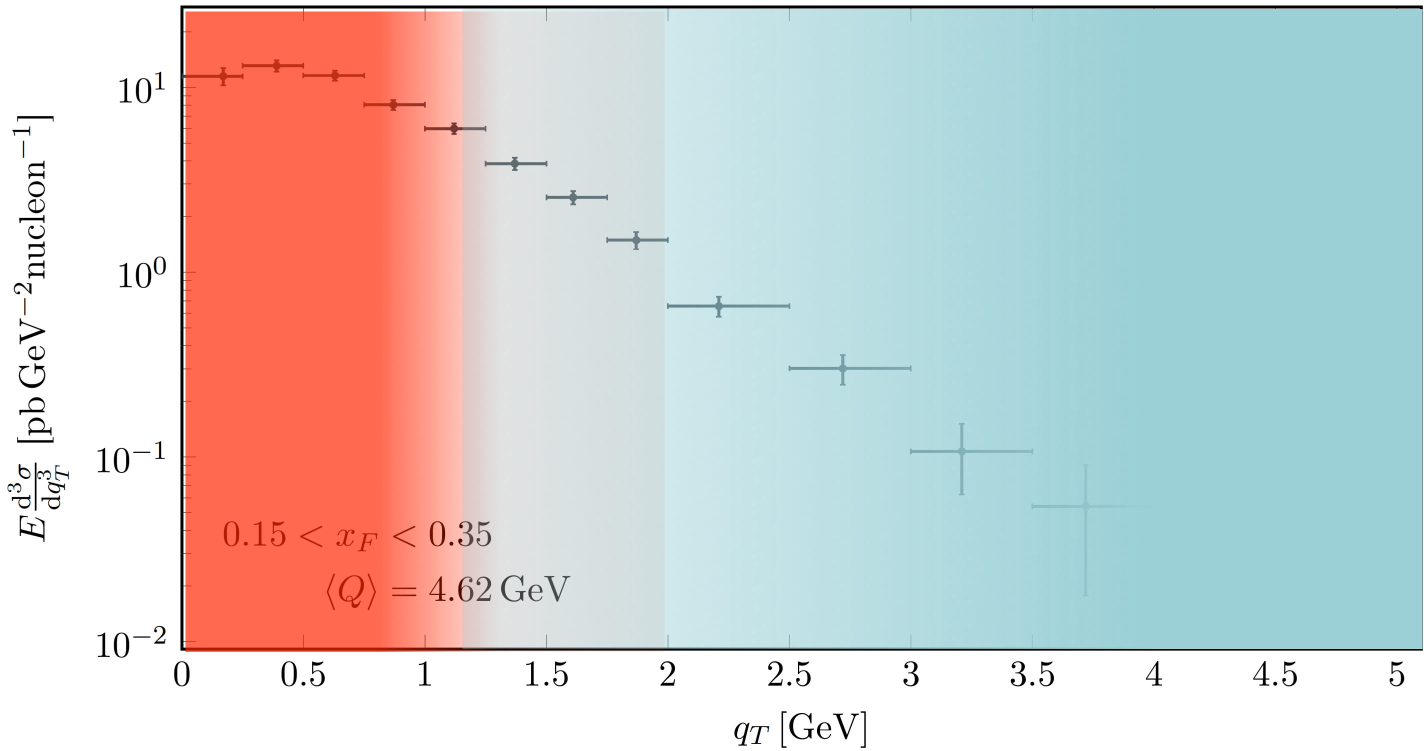
Gauld, Gehrmann-De Ridder, Gehrmann, Glover, Huss '17

$$A_2 = \frac{4W_{\Delta\Delta}}{2W_T + W_L}$$



- "dispel myth" that pQCD cannot describe data: overall reasonable description

Cross section in collinear factorization

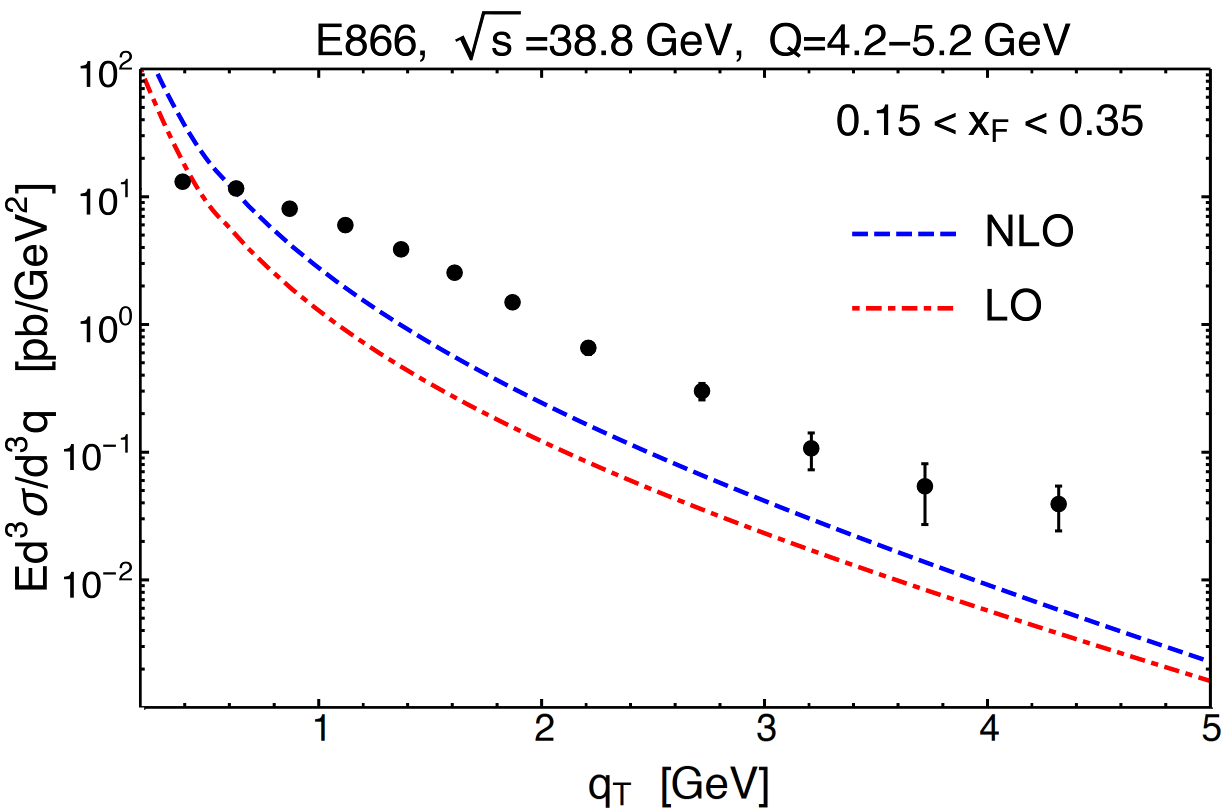


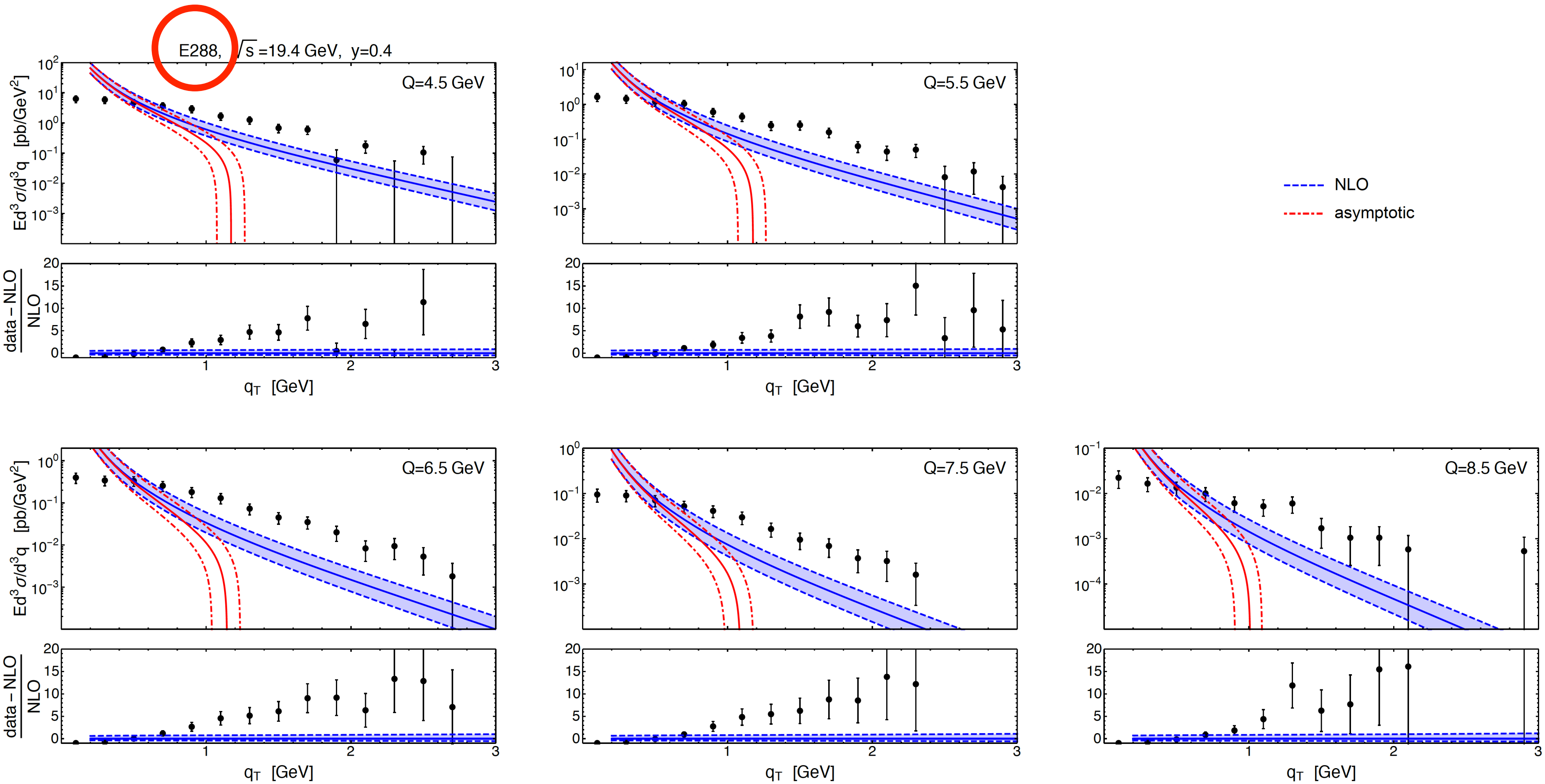
TMD regime collinear regime

- where and how does crossover take place?

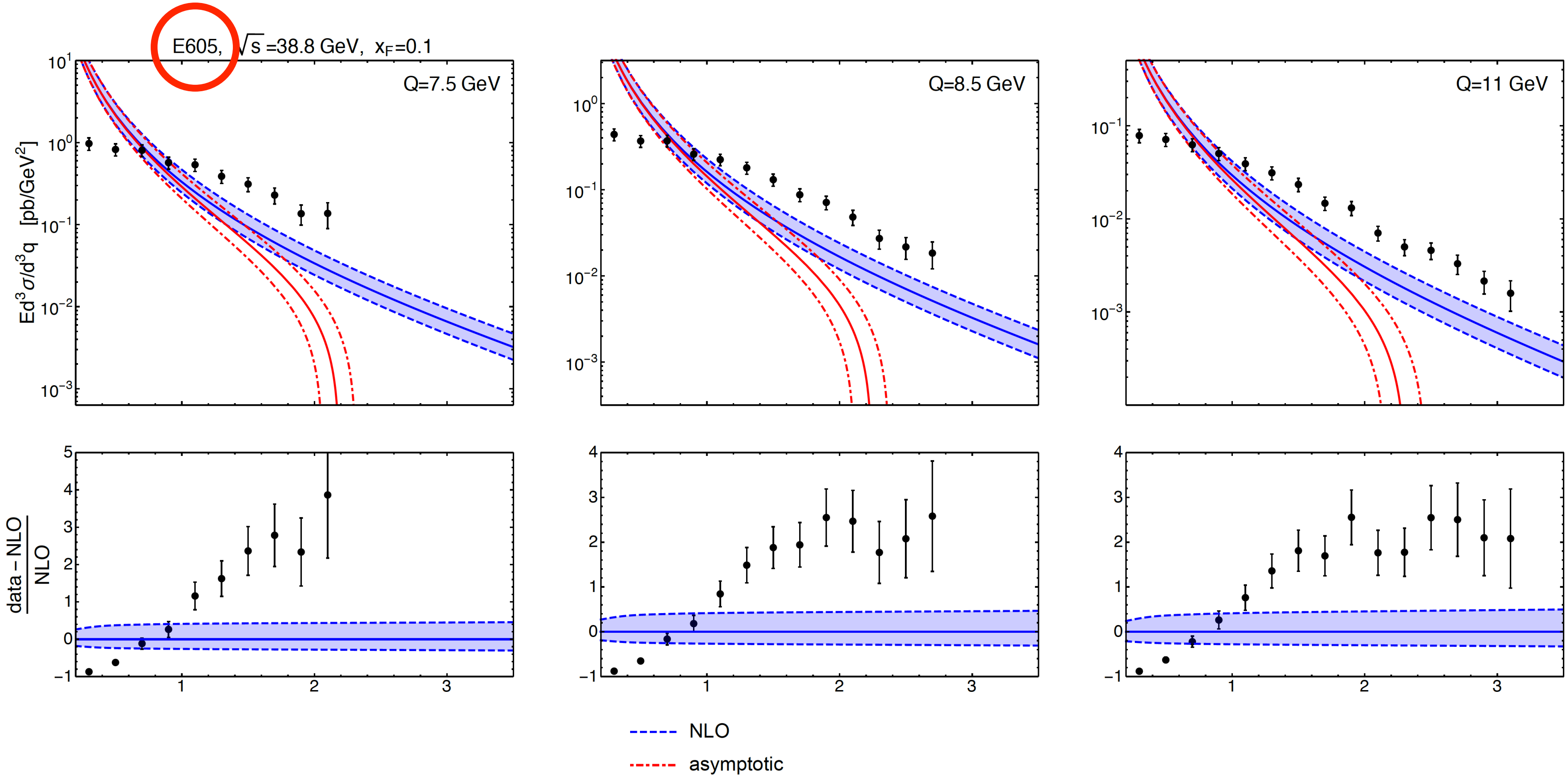
→ what is size and behavior of collinear-fact. cross section?

A. Bacchetta, G. Bozzi, M. Lambertsen, F. Piacenza, J. Steiglechner, WV

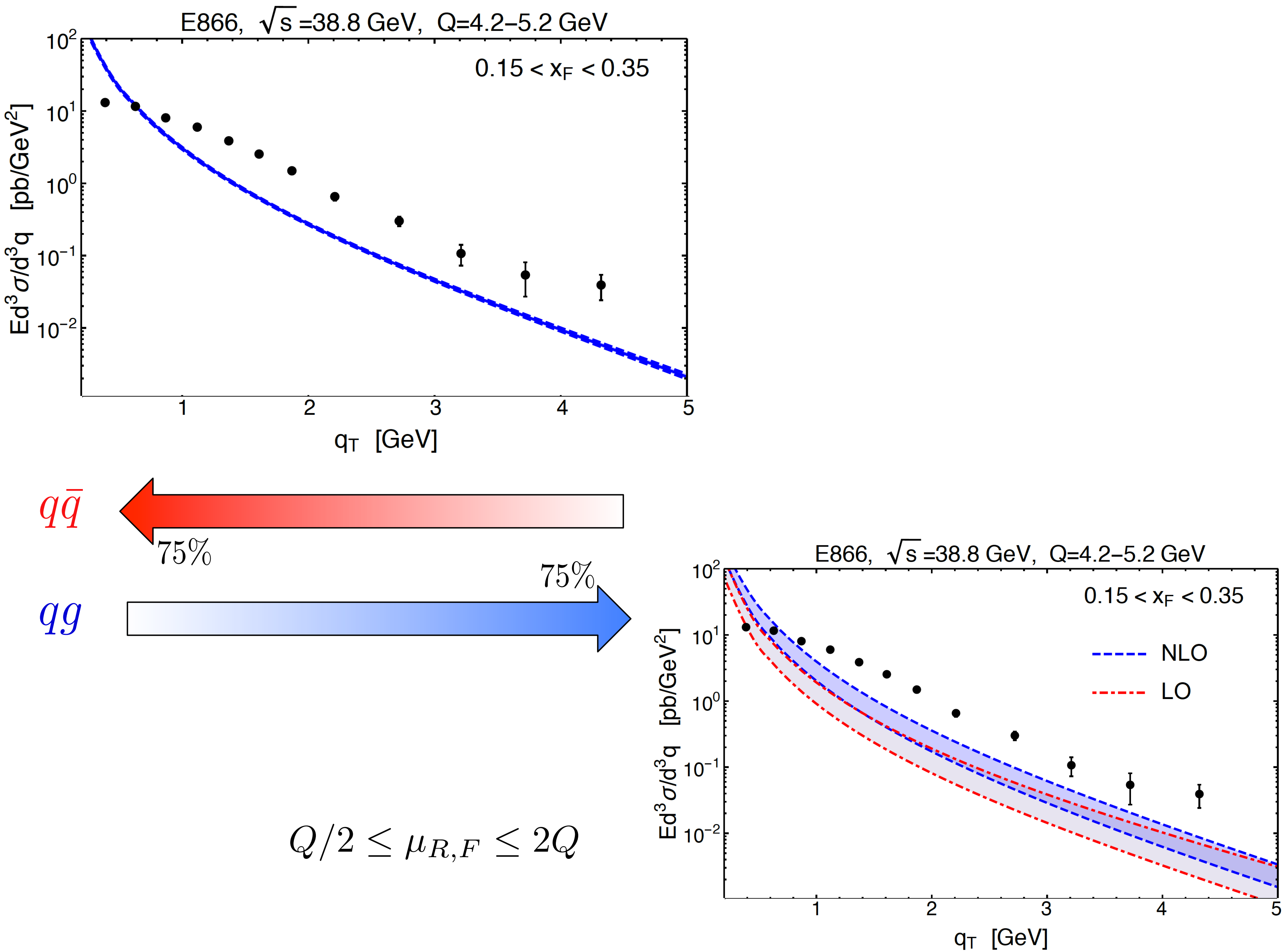




E288, $\sqrt{s}$ =19.4 GeV, y=0.4
Q=4.5 GeV
Q=5.5 GeV
Q=6.5 GeV
Q=7.5 GeV
Q=8.5 GeV
$Ed^3\sigma/d^3q$ [pb/GeV^2]
$\frac{\text{data - NLO}}{\text{NLO}}$
q_T [GeV]
NLO
asymptotic



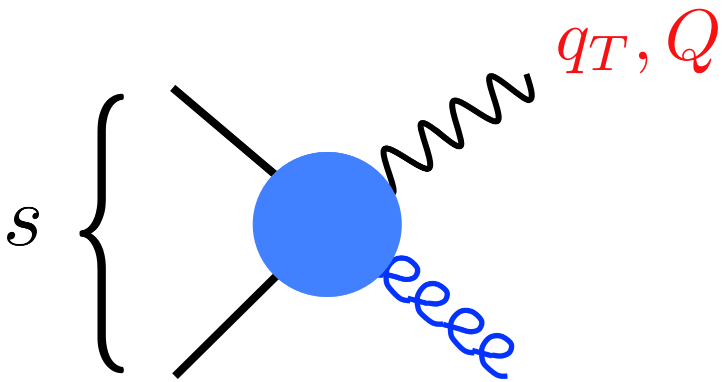
E605, $\sqrt{s}$ =38.8 GeV, x_F=0.1
Q=7.5 GeV
Q=8.5 GeV
Q=11 GeV
$Ed^3\sigma/d^3q$ [pb/GeV^2]
$\frac{\text{data} - \text{NLO}}{\text{NLO}}$
NLO
asymptotic



E866, $\sqrt{s}$ =38.8 GeV, Q=4.2–5.2 GeV
$0.15 < x_F < 0.35$
$Ed^3\sigma/d^3q$ [pb/GeV^2]
q_T [GeV]
$q\bar{q}$
75%
qg
75%
$Q/2 \leq \mu_{R,F} \leq 2Q$
E866, $\sqrt{s}$ =38.8 GeV, Q=4.2–5.2 GeV
$0.15 < x_F < 0.35$
NLO
LO
$Ed^3\sigma/d^3q$ [pb/GeV^2]
q_T [GeV]

Further studies and thoughts

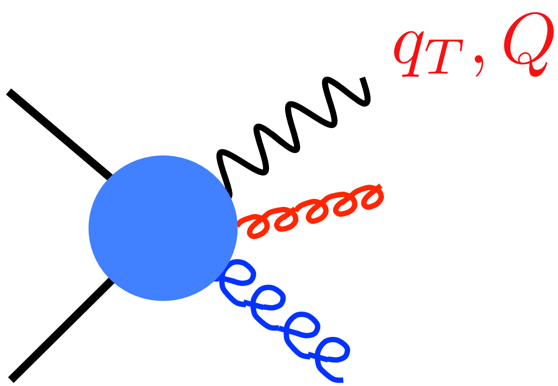
- LO :



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

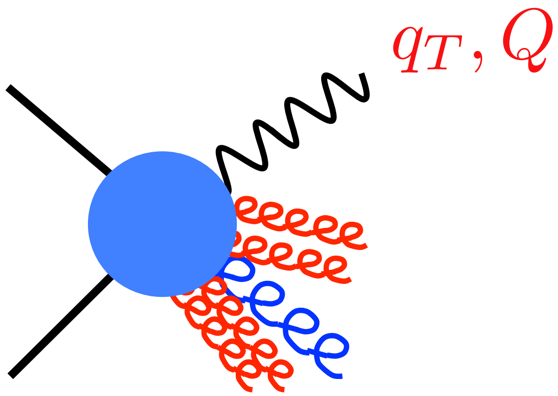
$$y_T \equiv \frac{q_T + \sqrt{q_T^2 + Q^2}}{\sqrt{s}} \leq 1$$

- NLO :



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

- $\mathrm{N^kLO}$:



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

- threshold logarithms

de Florian, Kulesza, WV; Kidonakis, Gonsalves; …

- threshold resummation:

$$\hat{\sigma}_{q\bar{q}\to\gamma^* g}(N) \equiv \int_0^1 dy_T^2 (y_T^2)^{N-1} \frac{d\hat{\sigma}_{q\bar{q}\to\gamma^* g}}{dp_T}$$

$$\hat{\sigma}^{(\mathrm{res})}_{q\bar{q}\to\gamma^* g}(N) = C_{q\bar{q}\to\gamma^* g}\, \Delta_N^q\, \Delta_N^{\bar{q}}\, J_N^g \Delta_N^{(\mathrm{int})}\, \hat{\sigma}^{\mathrm{LO}}_{q\bar{q}\to\gamma^* g}(N)$$

hard virtual corrections (comparison to NLO)

soft/coll. gluons

LO cross sec.

$$\ln \Delta_N^q = \int_0^1 dz\, \frac{z^{N-1}-1}{1-z} \int_{\mu_F^2}^{(1-z)^2 Q^2} \frac{dq^2}{q^2} A_q(\alpha_s(q^2))$$

$$\hat{\sigma}^{\rm LO}_{q\bar{q}\to\gamma^* g}(N) = C_F \frac{1-r}{1+r}\left[B\left(\frac{1}{2},N+1\right){}_2F_1\left(\frac{1}{2},N+1,N+\frac{3}{2},\left(\frac{1-r}{1+r}\right)^2\right)\right.$$
$$- \frac{2r^2}{(1+r)^2} B\left(\frac{1}{2},N+2\right){}_2F_1\left(\frac{1}{2},N+2,N+\frac{5}{2},\left(\frac{1-r}{1+r}\right)^2\right)$$
$$\left. + \left(\frac{1-r}{1+r}\right)^2 B\left(\frac{1}{2},N+3\right){}_2F_1\left(\frac{1}{2},N+3,N+\frac{7}{2},\left(\frac{1-r}{1+r}\right)^2\right)\right]$$

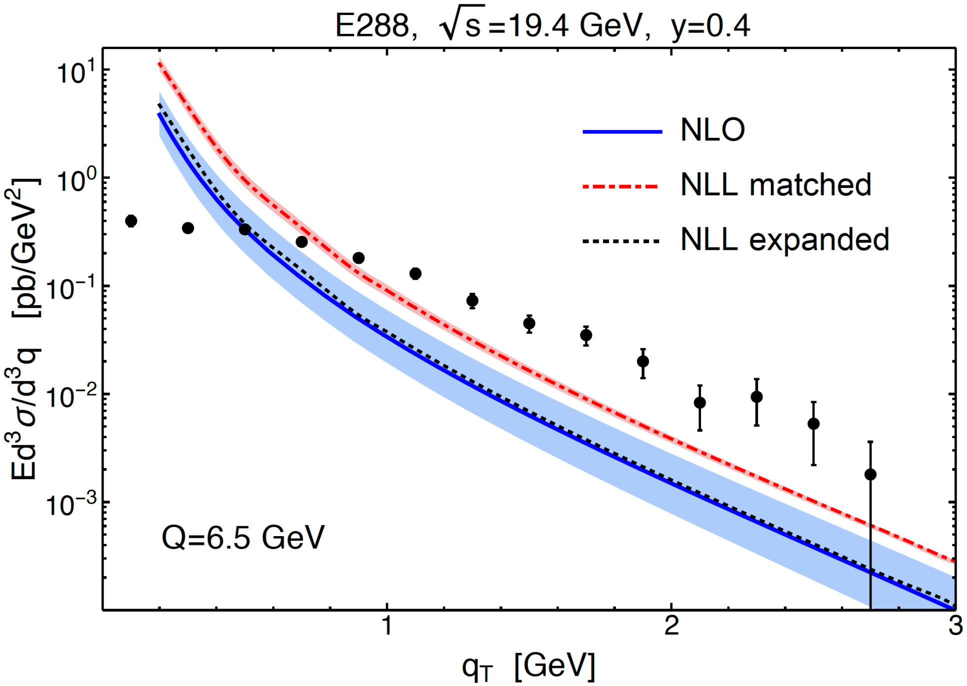
$$r \equiv \frac{q_T}{q_T^2+Q^2}$$

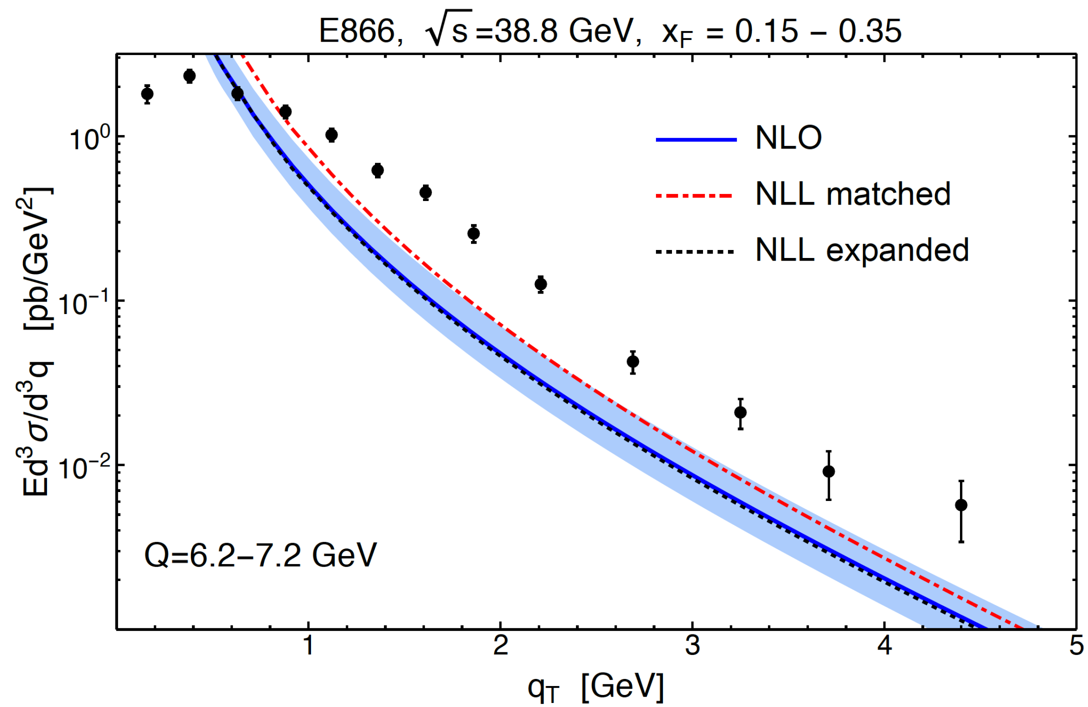
$$C^{(1)}_{q\bar{q}\to\gamma^* g} = \left(C_F\left(r^2+2r+2\right)-\frac{1}{2}C_A r(r+2)\right){\rm Li}_2(1-r)+\frac{1}{2}\left(r^2+2r+2\right)\left(C_A-2C_F\right){\rm Li}_2\left(\frac{1-r}{1+r}\right)$$
$$+ \pi b_0 \ln\left(\frac{\mu_R^2}{Q_0^2}\right)-\frac{3}{2}C_F\ln\left(\frac{\mu_F^2}{Q_0^2}\right)+\frac{1}{36}\left(C_A\left(9r^2-9r+67\right)+2\left(9C_F\left(r^3-8\right)-5N_f\right)\right)$$
$$+ \frac{1}{4}\left(r^2+2r+2\right)\left(C_A-2C_F\right)\ln^2(1+r)$$
$$- \frac{1}{8}(C_A-2C_F)\left(r^2(\ln(16)-3)+r(\ln(256)-2)+1+\ln(256)\right)\ln(1+r)$$
$$- \frac{1}{2}\left(r^2+2r+2\right)\left(C_A-2C_F\right)\ln(1-r)\ln(1+r)+\frac{1}{2}\ln r\left(-C_A r^3-C_F\left(r^4-2r^3-4r^2+3\right)\right)$$
$$+ \frac{1}{8}\ln(1-r)\left(C_A\left(4r^3+r^2(\ln(16)-3)+r(\ln(256)-2)+1+\ln(256)\right)\right.$$
$$\left. + 2C_F\left(2r^4-4r^3-r^2(5+\ln(16))+r(2-8\ln(2))+5-8\ln(2)\right)\right)$$
$$+ \pi^2\left(\frac{5C_F}{6}-\frac{C_A}{4}\right)-\frac{1}{2}C_A\ln^2(r)+C_A\ln(1-r)\ln(r)\,,$$

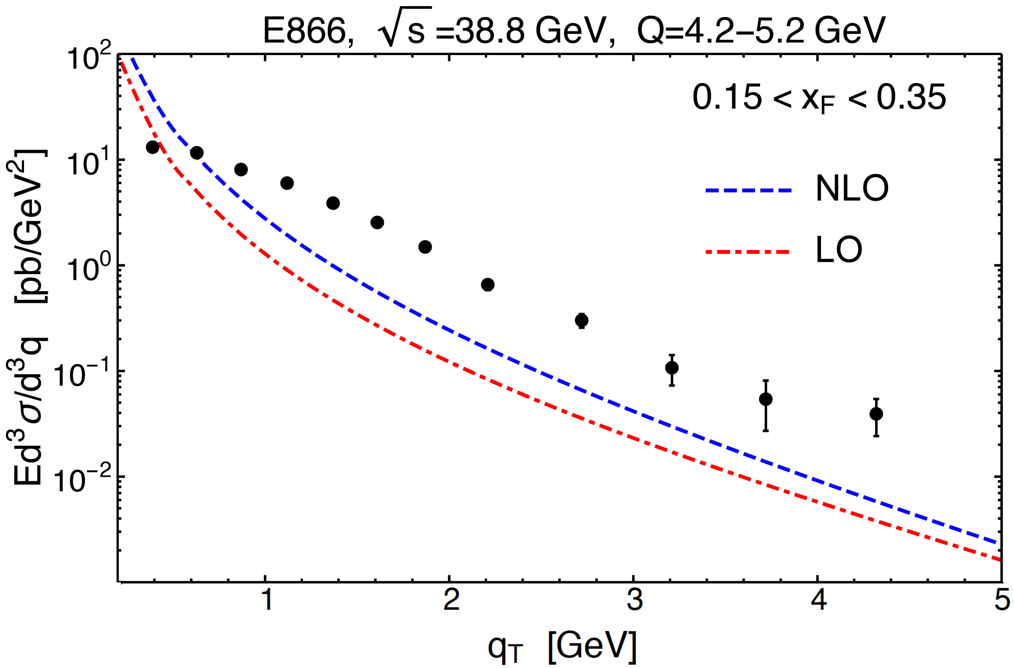
“matched” cross section”

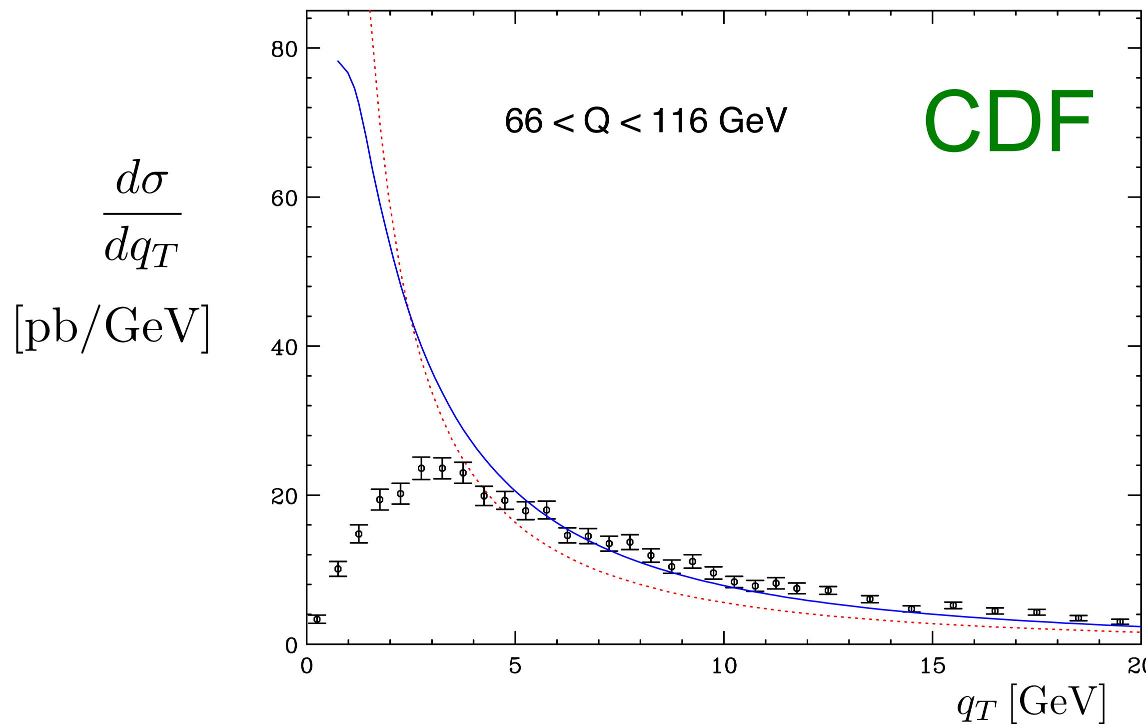
$$\frac{d\sigma^{(\mathrm{match})}}{dQ^2 dq_T^2} = \sum_{a,b} \int_{C_{MP}-i\infty}^{C_{MP}+i\infty} \frac{dN}{2\pi i} \left(y_T^2\right)^{-N} f_{a/h_1}(N+1,\mu_F^2)\, f_{b/h_2}(N+1,\mu_F^2)$$

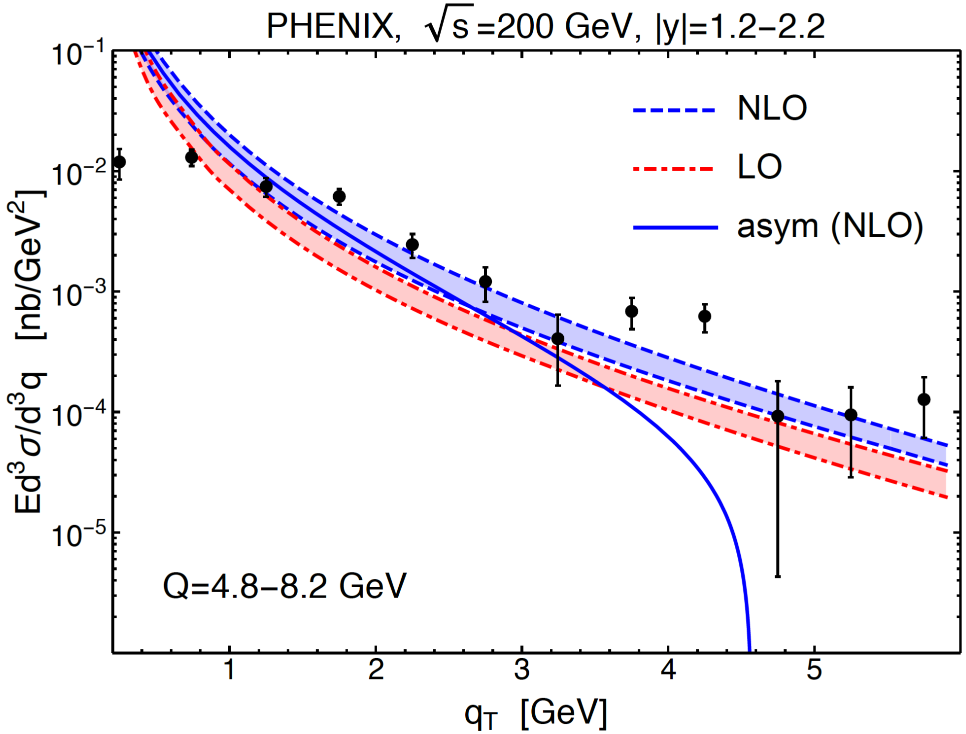
$$\times \left[\tilde{\omega}_{ab}^{(\mathrm{res})}(N) - \tilde{\omega}_{ab}^{(\mathrm{res})}(N)\Big|_{\mathcal{O}(\alpha_s^2)} \right] + \frac{d\sigma^{(\mathrm{NLO})}}{dQ^2 dq_T^2}$$


E288, √s =19.4 GeV, y=0.4
NLO
NLL matched
NLL expanded
Q=6.5 GeV
Ed³σ/d³q [pb/GeV²]
q_T [GeV]

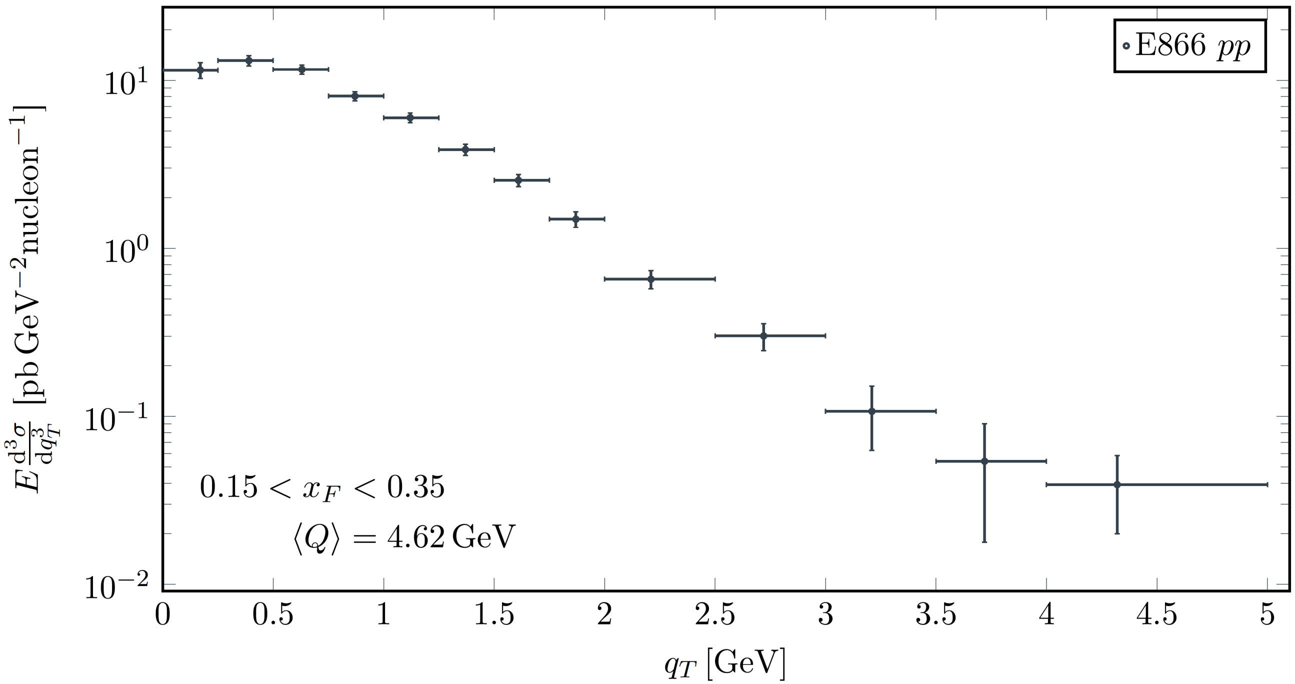

E866, √s =38.8 GeV, x_F = 0.15 − 0.35
NLO
NLL matched
NLL expanded
Q=6.2−7.2 GeV
Ed³σ/d³q [pb/GeV²]
q_T [GeV]


E866, √s =38.8 GeV, Q=4.2–5.2 GeV
0.15 < x_F < 0.35
NLO
LO
Ed^3σ/d^3q [pb/GeV^2]
q_T [GeV]


66 < Q < 116 GeV
CDF
dσ/dq_T [pb/GeV]
q_T [GeV]

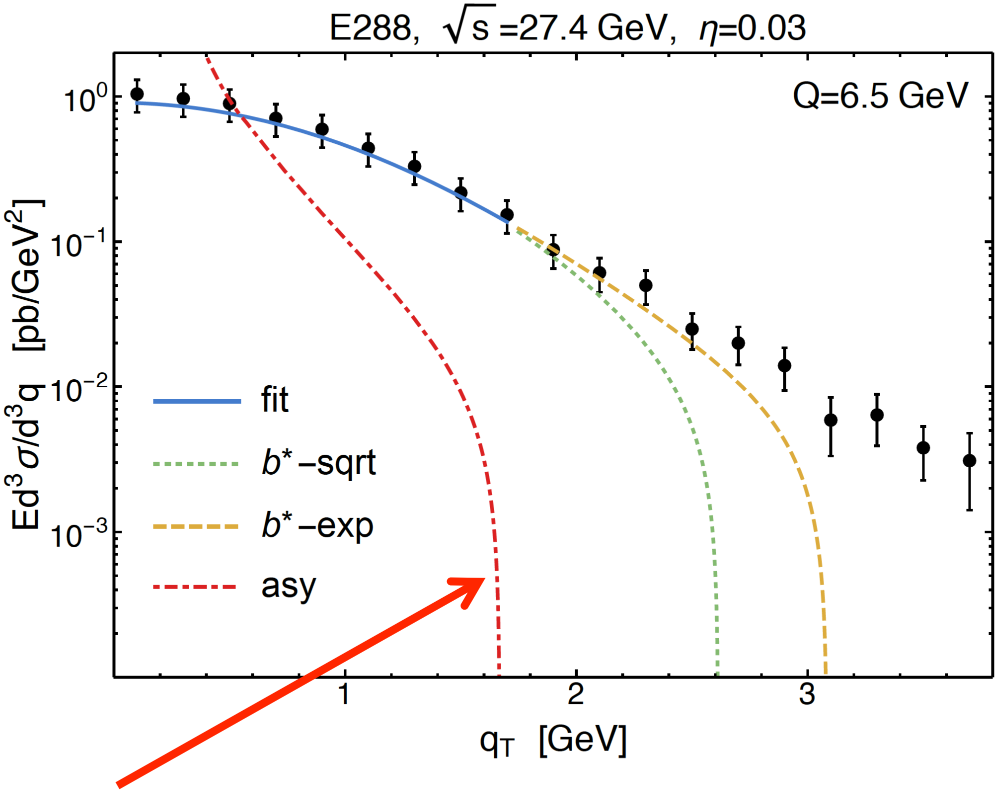


PHENIX, $\sqrt{s}$=200 GeV, |y|=1.2–2.2
NLO
LO
asym (NLO)
Q=4.8–8.2 GeV
$Ed^3\sigma/d^3q$ [nb/GeV^2]
q_T [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
2
3
4
5



- is it all just TMD physics?
- TMD fits typically stop at q_T~1.5 GeV   Sun,Yuan; Bertone,Scimemi,Vladimirov
- do we understand TMD physics properly?
  Power corrections q_T/Q?

→ high-q_T / matching will make difference for extraction of TMDs



$\mathcal{O}(\alpha_s)$ asymptotic piece

Bacchetta,Delcarro,Pisano,Radici,Signori;
Bacchetta,Echevarria,Mulders,Radici,Signori

$$b^*_{\rm sqrt} = \frac{b}{\sqrt{1 + b^2/b^2_{\rm max}}}$$

$$b^*_{\rm exp} = b_{\rm max}\left[1 - \exp(-b^4/b^4_{\rm max})\right]$$

- also b→0 behavior of Sudakov exponent becomes relevant:

$$\tilde{\sigma}(b) \sim \exp\left[-2 \int_0^{Q^2} \frac{dk_\perp^2}{k_\perp^2} A_q(\alpha_s(k_\perp)) \left(J_0(bk_\perp) - 1 \right) \ln\left(\frac{\bar{N} k_\perp}{Q} \right) \right]$$

$$\frac{d\sigma(q_T)}{dq_T} \sim \int \frac{d^2 b}{(2\pi)^2} \, \mathrm{e}^{i\vec{b}\cdot\vec{q}_T} \, \tilde{\sigma}(b)$$

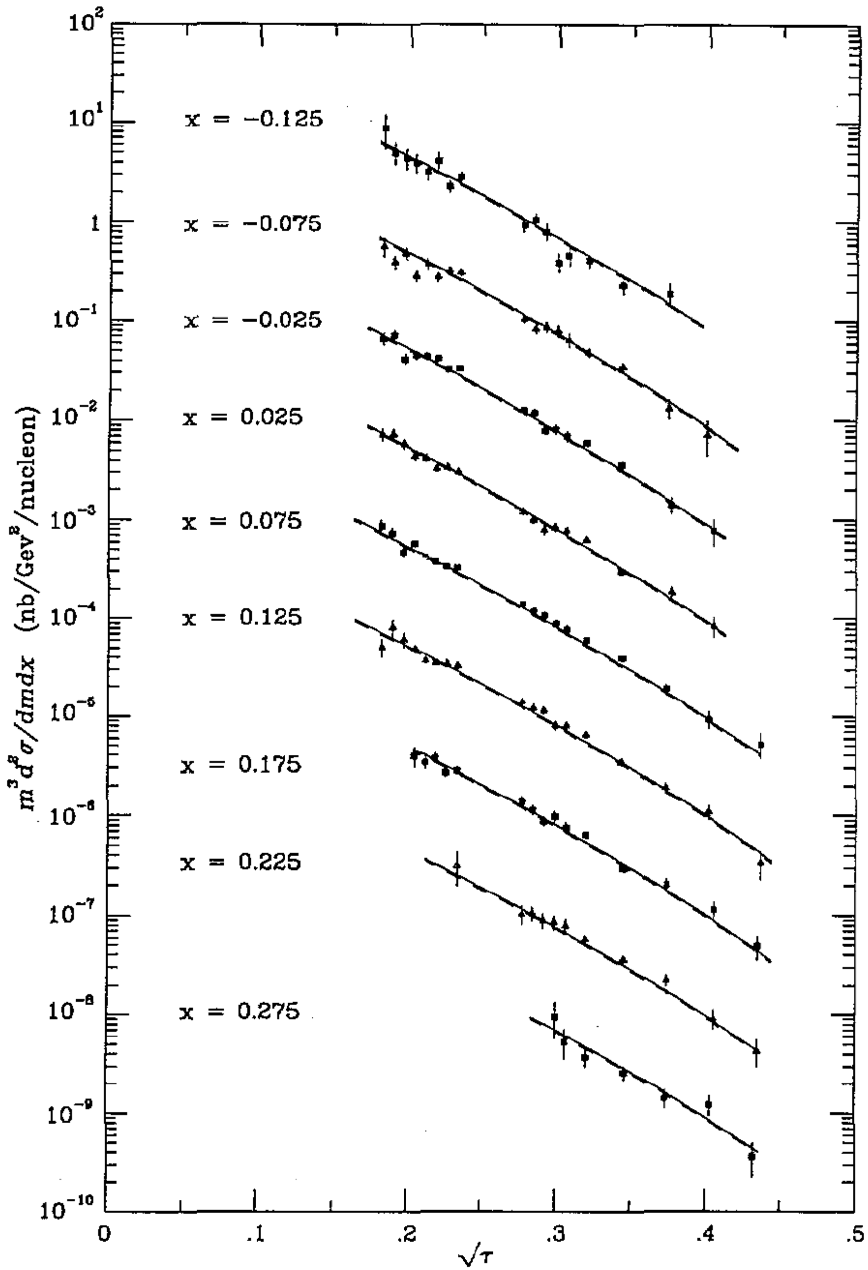
qT-integrated cross section probes b→0

Collins, Gamberg, Prokudin, Rogers, Sato, Wang

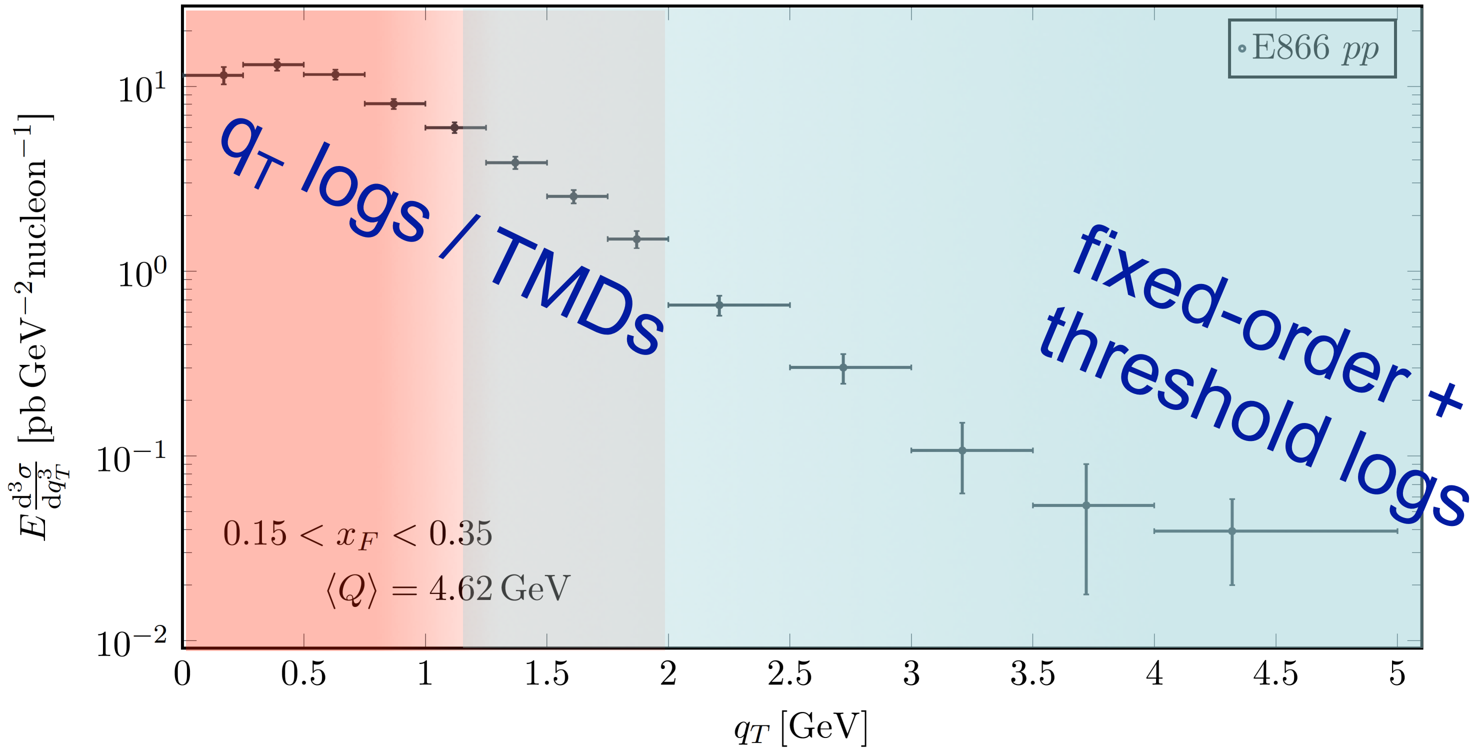
Stirling/Whalley

E605 (800 GeV pC)

(NLO scaled by 1.071)



$$x = \frac{2p_L}{\sqrt{S}}$$



- ultimately, may need joint resummation of both types of logs

- framework exists:

Laenen, Sterman, WV '00
Lustermans, Waalewihn, Zeune '16
Muselli, Forte, Ridolfi '17

- e.g. inclusive Drell-Yan:

$$\hat{\sigma}^{(\mathrm{res})} \propto \exp\left[2\int_0^{Q^2}\frac{dk_\perp^2}{k_\perp^2}\,A_q(\alpha_s(k_\perp))\left[J_0(bk_\perp)\,K_0\left(\frac{2Nk_\perp}{Q}\right)+\ln\left(\frac{\bar{N}k_\perp}{Q}\right)\right]\right]$$

- "jointly resummed" cross section:

Laenen,Sterman,WV
Kulesza,Sterman,WV

$N \gg bQ$: threshold logs (e.g. b=0)

$bQ \gg N$: q_T logs

- leads to "threshold-resummed" TMDs:

$$\tilde{f}_q(N,b,Q) \sim \exp\left\{-\frac{1}{2}\int_{Q^2/\eta^2}^{Q^2}\frac{dk_T^2}{k_T^2}\left[A_q(\alpha_s(k_T))\log\frac{Q^2}{k_T^2}+B_q(\alpha_s(k_T))\right]\right\}$$

$$\times\exp\left\{-\frac{1}{2}\left[g_1^{\mathrm{NP}}+g_2^{\mathrm{NP}}\log\frac{Q}{Q_0}\right]\left(b^2-\frac{4N^2}{Q^2}\right)\right\}$$

$$\times\exp\left\{\int_{\mu_F^2}^{Q^2/\eta^2}\frac{dk_T^2}{k_T^2}\,\mathcal{P}_{qq}^N(\alpha_s(k_T))\right\}\tilde{f}_q^N(\mu_F)$$

$$\eta^2 \sim (bQ)^2+N^2$$

Conclusions:

- presently not a really sound understanding of Drell-Yan cross section at moderate Q, q_T
- need better methods of connecting TMD and collinear regimes