Low mass Drell-Yan production with the CCFM-K eqvolution

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Plan

- Drell -Yan cross sections
- CCFM-K evolution
- Comparison with DY data

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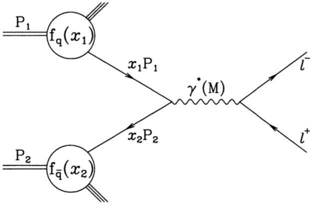
Inspiration:

A. Bacchetta, G. Bozzi, M, Lambertsen, F. Piacenza, J. Steiglechner, W. Vogelsang, *Difficulties in the description of Drell-Yan process at moderate invariant mass and high transverse momentum*, PRD 100 (2019) 014018

Drell-Yan process



- DY process cross section

$$\frac{d\sigma^{DY}}{dy_\gamma\, dM^2\, d^2q_T} = \frac{\alpha_{\rm em}^2}{24\pi^3 S^2 M^2}\left(-W^\mu_{\ \mu}\right),$$

- Hadronic tensor with k_T-factorization

$$W^{\mu\nu} = \frac{(2\pi)^4}{2N_c}\frac{S}{M^2}\sum_{q=1\ldots N_f} e_q^2 \int d^2k_{1T}\, d^2k_{2T}\, \delta^2(\vec{q}_T - \vec{k}_{1T} - \vec{k}_{2T})$$
$$\times \left[f_q(x_1, \vec{k}_{1T}, M)\, f_{\bar{q}}(x_2, \vec{k}_{2T}, M) + (1 \leftrightarrow 2)\right] \mathrm{Tr}\left[\not{k}_1\gamma^\mu \not{k}_2\gamma^\nu\right]$$

Treatment of matrix element

- On-shell: incoming quark momenta: $k_1 = x_1 P_1$ and $k_2 = x_2 P_2$

$$\mathrm{Tr}\,[\not{k}_1 \gamma^\mu \not{k}_2 \gamma_\mu] = -4S\, x_1 x_2$$

- Off-shell: incoming quark momenta: $k_1 = x_1 P_1 + k_{1T}$ and $k_2 = x_2 P_2 + k_{2T}$

$$\mathrm{Tr}\,[\not{k}_1 \gamma^\mu \not{k}_2 \gamma^\nu] \;\rightarrow\; \mathrm{Tr}\left[(x_1 \not{P}_1)\, \Gamma^\mu\, (x_2 \not{P}_2)\, \Gamma^\nu\right]$$

with gauge invariant Fadin-Sherman vertex (Nefedov, Saleev, PLB790(2019)551)

$$\Gamma^\mu = \gamma^\mu - \frac{2\not{k}_1}{x_2 S} P_1^\mu - \frac{2\not{k}_2}{x_1 S} P_2^\mu$$

which gives

$$\mathrm{Tr}\left[(x_1 \not{P}_1)\, \Gamma^\mu\, (x_2 \not{P}_2)\, \Gamma_\mu\right] = -4S\, x_1 x_2 \left(\frac{M^2 + \vec{k}_{1T}^2 + \vec{k}_{2T}^2}{M_T^2}\right)$$

- On-shell with $x_1 x_2 = M^2/S$

$$\frac{d\sigma^{DY}}{dy_\gamma\, dM^2\, dq_T^2} = \frac{\sigma_0}{M^2}\int_0^\infty \frac{bdb}{2} J_0(q_T b)\sum_q e_q^2 \Big[\tilde{f}_q(x_1,b,M)\,\tilde{f}_{\bar{q}}(x_2,b,M) + (1 \leftrightarrow 2)\Big]$$

- Off-shell with $x_1 x_2 = M_T^2/S$

$$\frac{d\sigma^{DY}}{dy_\gamma\, dM^2\, dq_T^2} = \frac{\sigma_0}{M^2}\int_0^\infty \frac{bdb}{2}\, J_0(q_T b)\sum_q e_q^2 \Big[\tilde{f}_q(x_1,b,M)\tilde{f}_{\bar{q}}(x_2,b,M) +$$
$$- \frac{1}{M^2}\left(\Delta_b \tilde{f}_q(x_1,b,M)\,\tilde{f}_{\bar{q}}(x_2,b,M) + f_q(x_1,b,M)\,\Delta_b \tilde{f}_{\bar{q}}(x_2,b,M)\right) + (1 \leftrightarrow 2)\Big]$$

with the radial part of the two dimensional laplacian

$$\Delta_b = \frac{\partial^2}{\partial b^2} + \frac{1}{b}\frac{\partial}{\partial b}$$

Transverse momentum dependent parton distributions

- Fourier transformed TMDs

$$\tilde{f}_q(x, \vec{b}, Q) = \int d^2k_T\, e^{i\vec{k}_T\cdot\vec{b}}\, f_q(x, \vec{k}_T, Q)$$

- Connection to collinear PDFs

$$\tilde{f}_q(x, \vec{b} = 0, Q) = q(x, Q^2)$$

- Catani-Ciafaloni-Fiorani-Marchesini-Kwieciński (CCFM-K) evolution equations for quark and gluon TMDs

  Kwieciński, Acta Phys. Polon. B34 (2003) 133

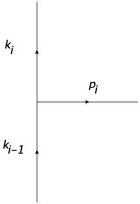
  Kwieciński, Gawron, Broniowski PRD 68 (2003) 054001

  Kwieciński, Gawron, PRD70 (2004) 014003

- CCFM branching scheme in single-loop approximation

Single-loop CCFM branching scheme

- Branching scheme with evolution variable $q_T = p_T/(1-z)$:



$$q_{Ti} > q_{T(i-1)}$$

- For $x \ll 1$: resummation of p_T orderd emissions (DGLAP)

$$p_{1\perp} < p_{2\perp} < \ldots < p_{n\perp}$$

- For $x \sim 1$: resummation of angularly ordered emissions (coherence)

$$\theta_1 < \theta_2 < \ldots < \theta_n$$

CCFM-K evolution equations

$$f_q(x,k_T,Q) = f_i^0(x,k_T) + \int_0^1 \frac{dz}{z} \int \frac{d^2\vec{q}}{\pi q^2} \frac{\alpha_s(q^2)}{2\pi} \theta(Q-q)\theta(q-Q_0)$$
$$\times \left\{ \theta(z-x) \left[P_{qq}(z) f_q\left(\frac{x}{z}, k'_T, q\right) + P_{qg}(z) f_g\left(\frac{x}{z}, k'_T, q\right) \right] \right.$$
$$\left. - zP_{qq}(z) f_i(x,k_T,q) \right\}$$

$$f_g(x,k_T,Q) = f_g^0(x,k_T) + \int_0^1 \frac{dz}{z} \int \frac{d^2\vec{q}}{\pi q^2} \frac{\alpha_s(q^2)}{2\pi} \theta(Q-q)\theta(q-Q_0)$$
$$\times \left\{ \theta(z-x) \left[P_{gq}(z) \sum_{q\bar{q}} f_q\left(\frac{x}{z}, k'_T, q\right) + P_{gg}(z) f_g\left(\frac{x}{z}, k'_T, q\right) \right] \right.$$
$$\left. - z\left[P_{gg}(z) + 2N_f P_{qg}(z)\right] f_g(x,k_T,q) \right\}$$

where

$$k'_\perp = |\vec{k}_\perp + (1-z)\vec{q}|$$

CCFM-K evolution equations in b-space

- Most economical formulation in b-space

$$\frac{\partial \tilde{f}_q(x,b,Q)}{\partial \ln Q^2} = \int_x^1 \frac{dz}{z} \left\{ P_{qq}(z,\alpha_s)\, J_0(Qb(1-z))\, \tilde{f}_q(x/z,b,Q) + \ldots \right\}$$

$$\frac{\partial \tilde{f}_G(x,b,Q)}{\partial \ln Q^2} = \int_x^1 \frac{dz}{z} \left\{ P_{Gq}(z,\alpha_s)\, J_0(Qb(1-z)) \sum_{q,\bar{q}} \tilde{f}_q(x/z,b,Q) + \ldots \right\}$$

- For $b = 0$ DGLAP equations for collinear PDFs
- Factorized initial conditions with collinear PDFs

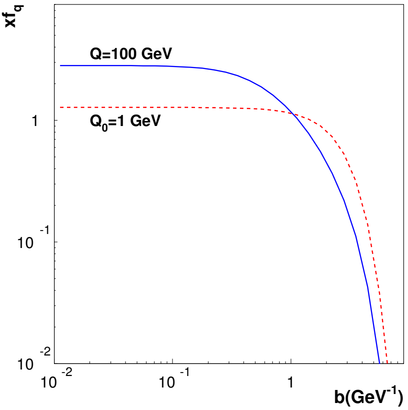
$$\tilde{f}_{q/G}(x,b,Q_0) = q/G(x,Q_0)\, F_{q/G}(b)\,, \qquad F_{q/G}(0) = 1$$

- In our analysis common Gaussian form factor

$$F(b) = \exp\{-b^2/b_0^2\}$$

CCFM-K evolution

- Solution as a function of b for $x = 10^{-2}$ and $Q = 100\ \mathrm{GeV}$



- Broadening in k_T-space due to evolution
  (Ruiz Arriola, Broniowski, PRD 70 (2004) 034012), PRD 97 (2018) 034031)

Relation to CSS

- CCFM-K equations contain CSS resummation of soft emissions $(z \to 1)$.
- The CCFM-K solution is given by LO CSS formulae for $\frac{1}{Q} \ll b \ll \frac{1}{Q_0}$

$$\tilde{f}_q(x,b,Q) = \exp\left\{ -\theta(Qb-1)\int_{1/b^2}^{Q^2} \frac{dq^2}{q^2}\frac{\alpha_s(q^2)}{2\pi}\left[A_q^{(1)}\ln(q^2b^2) + B_q^{(1)}\right]\right\} q(x,1/b)$$

$$\tilde{f}_g(x,b,Q) = \exp\left\{ -\theta(Qb-1)\int_{1/b^2}^{Q^2} \frac{dq^2}{q^2}\frac{\alpha_s(q^2)}{2\pi}\left[A_g^{(1)}\ln(q^2b^2) + B_g^{(1)}\right]\right\} g(x,1/b)$$

where

$$A_q^{(1)} = C_F\,, \qquad B_q^{(1)} = -\frac{3}{2}C_F$$

$$A_g^{(1)} = C_A\,, \qquad B_g^{(1)} = \frac{2}{3}T_R N_f - \frac{11}{6}C_A$$

(Catani, Webber, Marchesini, NPB 349 (1991) 635)

Comparison with data

- For the comparison with data we use the NLO CSS formulae with the form factor $W_{NP} = \exp(-S_{NP})$ from the BNLY fit

$$S_{NP} = \left[a_1 + a_2 \ln(Q/Q_1) + a_3 \ln(100\, x_1 x_2)\right] b^2$$

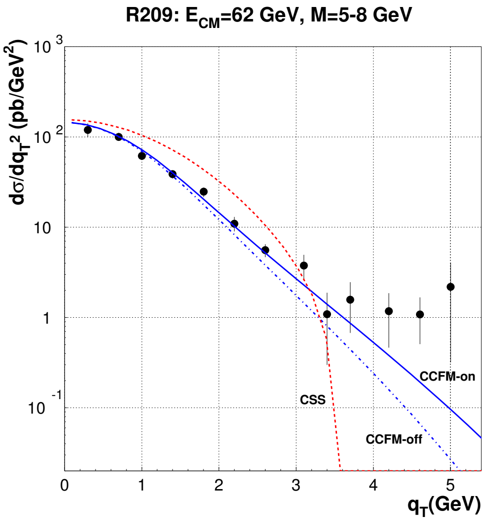
- while the CCFM-K form factor has only one parameter

$$F(b) = \exp(-b^2/b_0^2)\,, \qquad\qquad b_0 = 2.7\ \mathrm{GeV}^{-1}$$

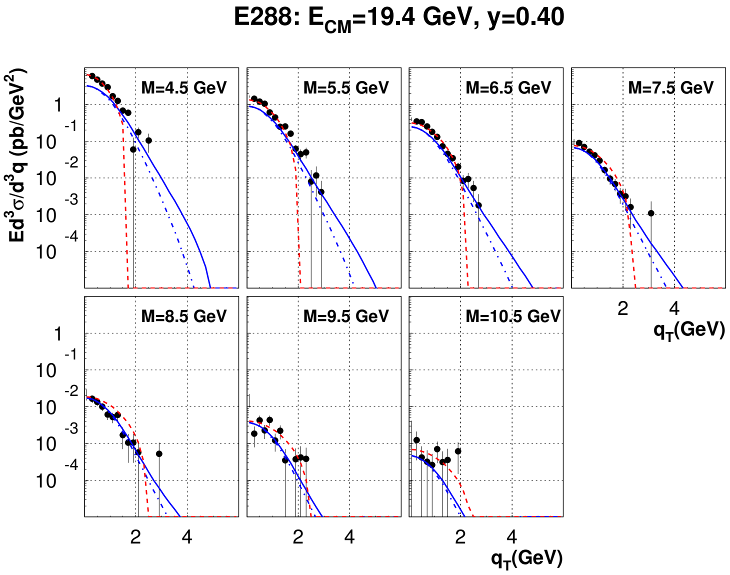
- LO MSTW08 PDFs are used in the CCFM-K initial conditions

$$\tilde{f}_{q/G}(x, b, Q_0) = q/G(x, Q_0)\, F(b)$$

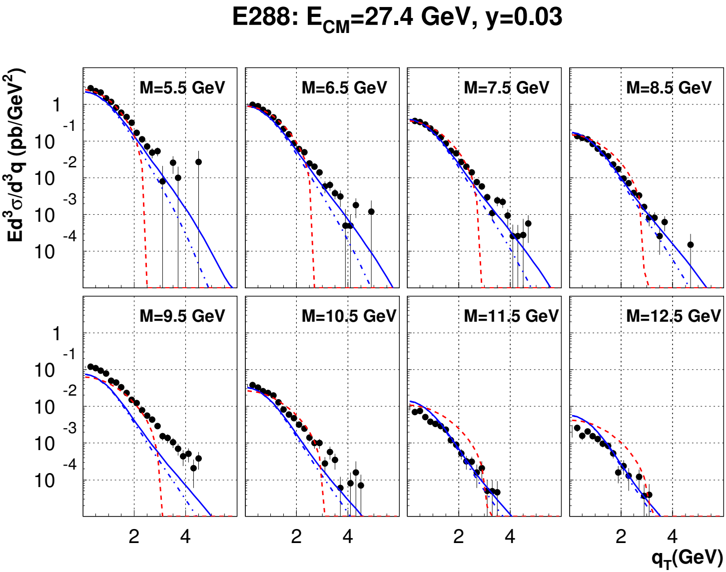
Comparison with R209 data

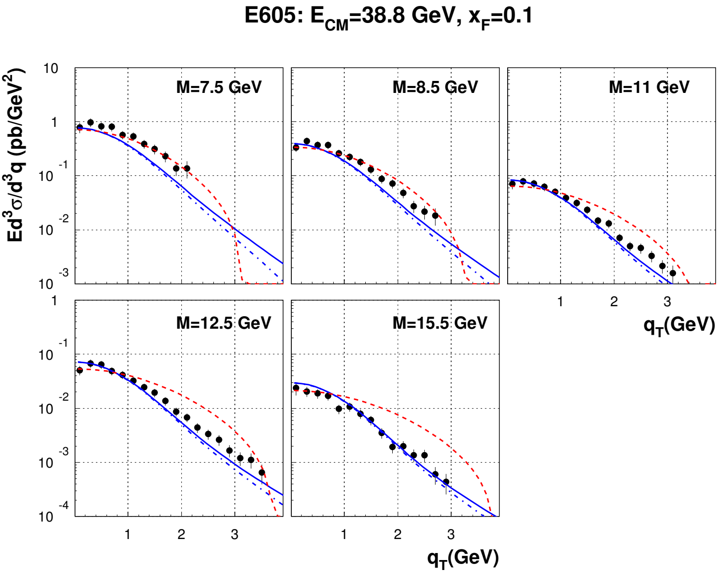


- CCFM-K evolution accounts for high-q_T tail

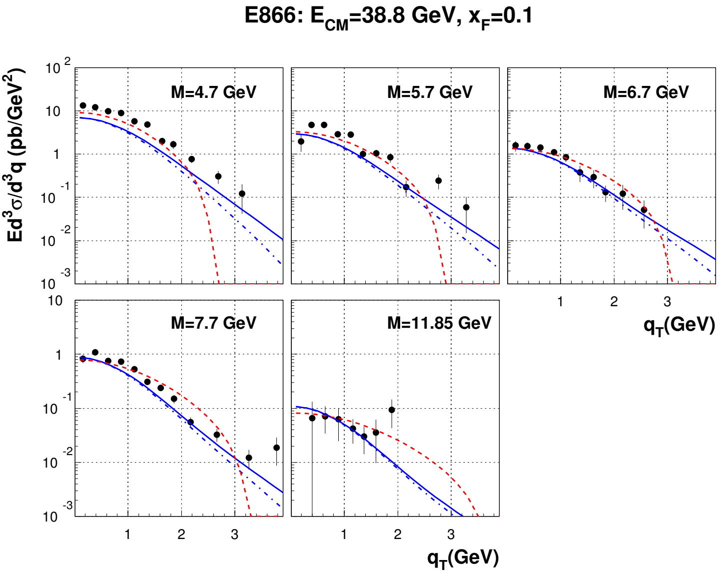

E288: E_{CM}=19.4 GeV, y=0.40
$Ed^3\sigma/d^3q$ (pb/GeV^2)
M=4.5 GeV
M=5.5 GeV
M=6.5 GeV
M=7.5 GeV
M=8.5 GeV
M=9.5 GeV
M=10.5 GeV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2
4
q_T(GeV)

Comparison with E288 data

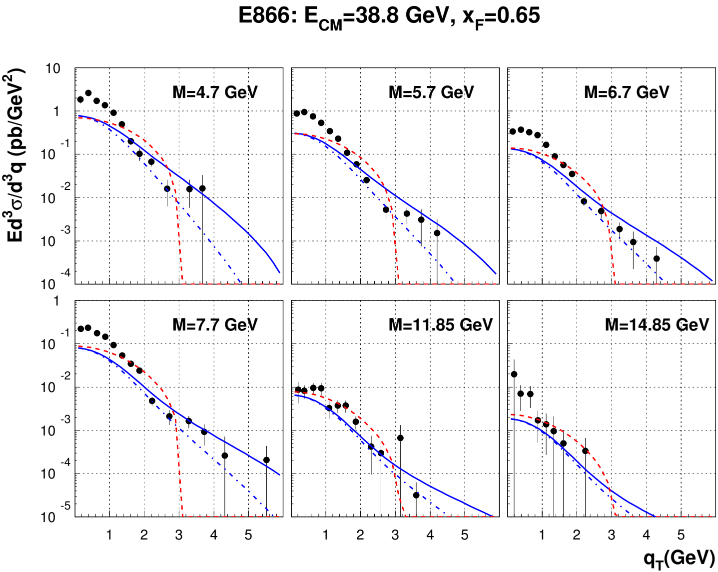



E605: E_{CM}=38.8 GeV, x_F=0.1
$Ed^3\sigma/d^3q$ (pb/GeV^2)
M=7.5 GeV
M=8.5 GeV
M=11 GeV
M=12.5 GeV
M=15.5 GeV
q_T(GeV)
q_T(GeV)

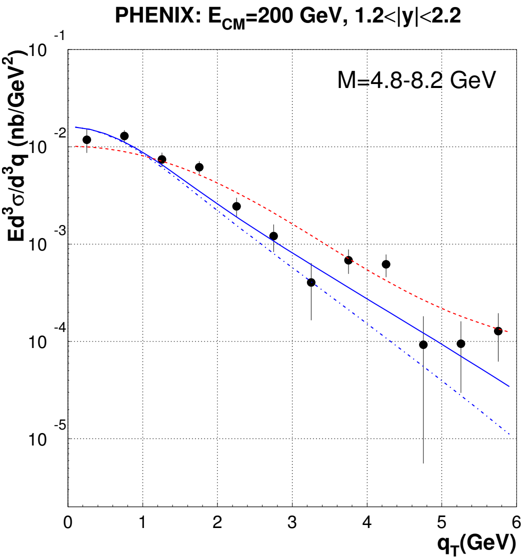
Comparison with E866 data



Comparison with E866 data



Comparison with PHENIX data



Conclusions

- CCFM-K evolution accounts for high-q_T of DY process spectra
- For large x_F neither CCFM-K nor CSS describe low-q_T spectra.

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- For large x_F neither CCFM-K nor CSS describe low-q_T spectra.

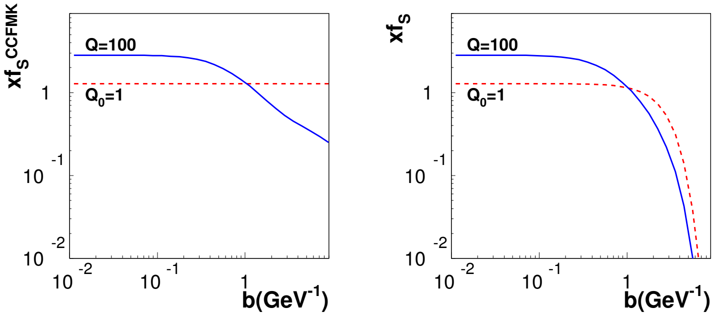
- CCFM-K analysis with refined form of $F(b)$ should be done.
- Z_0 production should also be analysed.

Thank you for your attention

Backup

CCFM-K evolution in detail

$$f_{q/g}(x, b, Q) = f_{q/g}^{\mathrm{CCFMK}}(x, b, Q)\, F(b)$$



- In the CSS approach

$$S(b,Q) = -\int_{c^2/b^2}^{Q^2} \frac{dq^2}{q^2}\left[A_q(\alpha_s(q^2))\ln\left(\frac{Q^2}{q^2}\right) + B_q(\alpha_s(q^2))\right]$$

where

$$A_q(\alpha_s) = \sum_{n=1}^{\infty}\left(\frac{\alpha_s}{2\pi}\right)^n A_q^{(n)}\,, \qquad B_q(\alpha_s) = \sum_{n=1}^{\infty}\left(\frac{\alpha_s}{2\pi}\right)^n B_q^{(n)}$$

- The NLL CSS approach is defined by

$$A_q^{(1)} = C_F\,, \qquad A_q^{(2)} = C_F K\,, \qquad B_q^{(1)} = -\frac{3}{2}C_F$$

while CCFM-K gives only $A_q^{(1)}$ and $B_q^{(1)}$.

- The NLO splitting functions in the CCFM-K equations would give $A_q^{(2)}$.