Low Mass Lepton Pair Production at Large Transverse Momentum

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✓ Why low mass Drell-Yan
✓ QCD factorization for low mass Drell-Yan
✓ Sensitivity of low mass Drell-Yan on gluon distribution
✓ Summary

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based on work with J. -W. Qiu, and W. Vogelsang

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Why low mass Drell-Yan

- Gluon distribution of a proton or an nucleus is essential for discovering new physics at any hadron and heavy ion colliders, as well as EIC.

- Low mass Drell-Yan at high transverse momentum is a good probe of gluon distribution, and is complementary to prompt photon production due to the cleaner lepton signal, but, relatively lower rate.

\[
\frac{d\sigma_{AB\rightarrow\ell^+\ell^-}(Q)X}{dQ^2
dQ_T^2
dy} = \left( \frac{\alpha_{em}}{3\pi Q^2} \right) \sqrt{1 - \frac{4m_\ell^2}{Q^2}} \left( 1 + \frac{2m_\ell^2}{Q^2} \right) \frac{d\sigma_{AB\rightarrow\gamma^*(Q)X}}{dQ_T^2
dy}
\]
Gluon distribution of a proton

gluon at $Q = 3.16 \text{ GeV}$

Ratio to CTEQ6

$X$
Gluon distribution of a nucleus
Latest gluon distribution of a large nucleus

\[ \text{EPS08 (fit DIS-DY-RHIC data)} \]


\[ g(x, Q_0) \sim x^{-d} \]

\[ R_G(x \to 0) \sim x^{-d_A} / x^{-d_p} \to 0 \]

\[ 0 < d_A < d_p \]
Low mass lepton pair production

- Process:
  \[ Q_T \sim Q \]

- QCD Factorization:
  \[
  \frac{d\sigma_{AB \rightarrow \ell^+\ell^-}(Q)X}{dQ^2\,dQ_T^2\,dy} = \left( \frac{\alpha_{em}}{3\pi Q^2} \right) \sqrt{1 - \frac{4m_{\ell}^2}{Q^2}} \left( 1 + \frac{2m_{\ell}^2}{Q^2} \right) \frac{d\sigma_{AB \rightarrow \gamma^*(Q)X}}{dQ_T^2\,dy}
  \]

  \[
  \frac{d\sigma_{AB \rightarrow \gamma^*(Q)X}}{dQ_T^2\,dy} = \sum_{a,b} \int dx_1 f_a^A(x_1, \mu) \int dx_2 f_b^B(x_2, \mu) \frac{d\hat{\sigma}_{ab \rightarrow \gamma^*(Q)X}}{dQ_T^2\,dy}(x_1, x_2, Q, Q_T, y; \mu)
  \]

  Dominated by Compton subprocess

  Power series of \( \alpha_s \)
Low mass lepton pair at high $Q_T$

**If** $Q_T \gg Q \gg \Lambda_{QCD}$:

Perturbative hard part has large logarithm: $\ln \left( \frac{Q^2}{Q_T^2} \right)$

Resummation of the large logarithms = re-organization of the perturbative hard part:

$$\frac{d\hat{\sigma}^{\text{Pert}}_{ab\to\gamma^*(Q)X}}{dQ_T^2 dy} = \frac{d\hat{\sigma}^{\text{Dir}}_{ab\to\gamma^*(Q)X}}{dQ_T^2 dy} + \frac{d\hat{\sigma}^{\text{Asym}}_{ab\to\gamma^*(Q)X}}{dQ_T^2 dy}$$

- **All logarithms**
- **Short-distance + power**

**If** $Q_T \gg Q \gtrsim \Lambda_{QCD}$:

$Q_T$ is the perturbative scale, but, $Q$ is not!

QCD factorization is still valid, except the fragmentation function now involves non-perturbative physics
Non-perturbative fragmentation function

- **Factorization:**
  \[ D_{f \rightarrow \ell^+\ell^-}(Q)(z, \mu_0^2; Q^2) = \left( \frac{\alpha_{em}}{3\pi Q^2} \right) \sqrt{1 - \frac{4m_\ell^2}{Q^2}} \left( 1 + \frac{2m_\ell^2}{Q^2} \right) D_{f \rightarrow \gamma^*}(z, \mu_0^2; Q^2) \]

- **Fragmentation function:**
  \[ \mu_F^2 \frac{d}{d\mu_F^2} D_{c \rightarrow \gamma^*}(z, \mu_F^2; Q^2) = \left( \frac{\alpha_{em}}{2\pi} \right) \gamma_{c \rightarrow \gamma^*}(z, \mu_F^2, \alpha_s; Q^2) \]
  \[ + \left( \frac{\alpha_s}{2\pi} \right) \sum_d \int_z^1 \frac{dz'}{z'} P_{c \rightarrow d}(\frac{z}{z'}, \alpha_s) D_{d \rightarrow \gamma^*}(z', \mu_F^2; Q^2) \]

- **Input fragmentation function:**
  \[ D_{f \rightarrow \gamma^*}(z, \mu_0^2; Q^2) \equiv D_{f \rightarrow \gamma^*}^{\text{QED}}(z, \mu_0^2; Q^2) + D_{f \rightarrow \gamma^*}^{\text{NonPert}}(z, \mu_0^2; Q^2) \]
Model the input fragmentation function

- **QED part:**
  \[
  D_{q\to\gamma^*}^{\text{QED}(0)}(z, \mu_0^2; Q^2) = e^2_q \left( \frac{\alpha_{\text{em}}}{2\pi} \right) \left[ \left( \frac{1 + (1 - z)^2}{z} \right) \ln \left( \frac{z\mu_0^2}{Q^2} \right) - z \left( 1 - \frac{Q^2}{z\mu_0^2} \right) \right],
  \]
  \[
  D_{\bar{q}\to\gamma^*}^{\text{QED}(0)}(z, \mu_0^2; Q^2) = D_{q\to\gamma^*}^{\text{QED}(0)}(z, \mu_0^2; Q^2),
  \]
  \[
  D_{g\to\gamma^*}^{\text{QED}(0)}(z, \mu_0^2; Q^2) = 0
  \]

- **Non-perturbative part (need to be fixed by the data)**

  **Assumption:**
  \[
  \frac{D_{f\to\gamma}^{\text{NonPert}}(z, \mu_0^2; Q^2)}{D_{f\to\pi}(z, \mu_0^2)} \propto e^2_f \frac{4\pi \alpha_{\text{em}}}{f^2_V} = \frac{4\pi \alpha_{\text{em}}}{f^2_V}
  \]

  \[
  D_{q\to\gamma^*}^{\text{NonPert}}(z, \mu_0^2; Q^2) \propto D_{q\to\pi}(z, \mu_0^2) \frac{4\pi \alpha_{\text{em}}}{f^2_V} |F(Q^2)|^2 \left( 1 - \frac{Q^2}{m_V^2} \right)^3
  \]

  **Model:**
  \[
  D_{q\to\gamma^*}^{\text{NonPert}}(z, \mu_0^2; Q^2) \equiv \kappa D_{q\to\pi}(z, \mu_0^2) \frac{4\pi \alpha_{\text{em}}}{f^2_V} \left( 1 - \frac{Q^2}{m_V^2} \right)^3
  \]

  \[
  D_{f\to\pi} \approx D_{f\to\pi}, \quad f^2_\rho/4\pi = 2.2, \quad m_V = m_\rho
  \]

  **One fitting constant:** \( \kappa \)
Invariant cross section

**Definition:**
\[
\frac{d\sigma_{AB\rightarrow \ell^+\ell^- (Q)X}}{d^3Q} \equiv \int_{Q_{\min}^2}^{Q_{max}^2} dQ^2 \frac{1}{\pi} \frac{d\sigma_{AB\rightarrow \ell^+\ell^- (Q)X}}{dQ^2 dQ_T^2 dy}
\]

**Role of non-perturbative fragmentation function:**

- **QED Input FF:**
  \[
  \kappa = 0 \quad \text{at} \quad \mu_0 = 1 \text{ GeV}
  \]

- **QED + NonPert Input:**
  \[
  \kappa = 1 \quad \text{at} \quad \mu_0 = 1 \text{ GeV}
  \]

Hadronic component of fragmentation is very important at low \(Q_T\)

Data from PHENIX: arXiv:0804.4168
Isospin effect in nuclear collisions

- **Definition:**

\[
R_{dAu}^{iso} = \frac{\frac{1}{2A} d^2 \sigma_{dAu} / dQ_T dy}{d^2 \sigma_{pp} / dQ_T dy}
\]

\[
f_i^p(x, Q^2) \to F_i(x, Q^2) = \left[ Z \cdot f_i^p + (A - Z) \cdot f_i^n \right] / A \quad i = q, \bar{q}, g
\]

- **Strong isospin effect:**

\[
\sigma_{qg} \propto \frac{4}{9} f_u^n + \frac{1}{9} f_d^n = \frac{4}{9} f_d^p + \frac{1}{9} f_u^p
\]

\[
f_u^p > f_d^p
\]

\[\sigma^{nn} < \sigma^{np} = \sigma^{pn} < \sigma^{pp}\]

\[
R_{AB}^{iso} < 1
\]
Nuclear parton distributions

Nuclear PDFs:
\[ f_i^A(x, Q^2) \equiv R_i^A(x, Q^2) f_i^p(x, Q^2) \]

Sample nuclear gluon distribution:

- Solid: EKS98
- Dotted: EPS08
- Dashed: FS2003

All nPDFs fit existing data!
Sensitivity on gluon distribution

- **Nuclear modification factor:**

\[ R_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{dAu}}{dQ_T dy} \text{min.bias} = \frac{1}{2A} \frac{d^2 \sigma_{dAu}}{dQ_T dy} \]

- **Prediction for RHIC kinematics:**

The band is given by \( \kappa=1 \) (top lines) and \( \kappa=0 \) (bottom lines)
Remove isospin effect - “pure” shadowing effect:

- Isospin effect for nuclear modification factor $R$ is very important
- $Q_T$ dependence is very sensitive to the shape of gluon distribution
Comparison to AuAu data

- **Enhancement at low $Q_T$:**

  ![Graph 1: AuAu 0-20%](image)
  ![Graph 2: AuAu 20-40%](image)
  ![Graph 3: AuAu MB](image)

- **Effects other than shadowing:**
  - parton multiple scattering
  - thermal radiation
Low mass lepton pair production at large transverse momentum is perturbatively calculable. Its factorization is equally good as that for prompt photon production.

Low mass lepton pair production is complementary to prompt photon production in getting information on gluon distribution. Cleaner lepton signals, no complication on isolation cut but, relatively lower rate.