Central $\mu^+\mu^-$ production via photon-photon fusion in proton-proton collisions with proton dissociation

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Motivation/Introduction

Lepton pair production at high energies

Numerical results

Beyond the QED mechanism: continuum muons from $\gamma$-Pomeron fusion

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Central $\mu^+\mu^-$ production via photon-photon fusion in proton-proton collisions
we often have to deal with diffractive reactions which include excitation of incoming protons. Instead of fully inclusive final states: gap cross sections, gap vetos or even only vetos on additional tracks(!) from a production vertex.

- muons: continuum background in J/psi, Upsilon production; background in $pp \rightarrow ppW^+W^-$ which is measured via the $\mu^+\mu^-\nu\bar{\nu}$ channel.
The total cross section of pair production in $\gamma\gamma$ collisions (Landau and Lifshitz (1934)) and collisions of charged particles (Racah (1937)) is known for a long time. Pair production in the external field of a nucleus $\gamma Z \rightarrow e^+ e^- Z$ was solved exactly by Bethe & Heitler (1934).

Pair production in small angle scattering of charged particles via $\gamma\gamma$ fusion can be treated in terms of Weizsäcker-Williams-(Fermi) equivalent photons.

For practical reasons we are interested in pair production in a specific region of phase space (large $p_T$), have to deal with cuts e.g. on rapidity...
Lepton pair production in the high energy limit

In the high energy limit, 
\[ \epsilon \sim m^2/s, \, p^2/s, \, m|p|/s \ll 1, \] 
the "impact factor" form of the amplitude holds 
(Lipatov, Gribov & Frolov (1970), Cheng & Wu (1970)).

\[ \mathcal{M} = -is \frac{(8\pi \alpha_{em})^2}{q_1^2 q_2^2} N_1(q_1) B_{\lambda\bar{\lambda}}(p_+, p_-; q_1, q_2) N_2(q_2), \]

\[ N_1(q_1) = \frac{1}{s} p_{2\mu} V_{\mu}^{A\rightarrow X}(p_A, p_X), \quad N_2(q_2) = \frac{1}{s} p_{1\nu} V_{\nu}^{B\rightarrow Y}(p_B, p_Y) \]

\[ B_{\lambda\bar{\lambda}}(p_+, p_-; q_1, q_2) = \frac{1}{s} p_{1\alpha} p_{2\beta} \bar{u}_\lambda(p_-) T_{\alpha\beta} v_{\bar{\lambda}}(p_+). \]

\[ T_{\alpha\beta} = \gamma_{\alpha} \frac{\hat{q}_1 - \hat{p}_+ + m}{(q_1 - p_+)^2 - m^2} \gamma_{\beta} + \gamma_{\beta} \frac{\hat{q}_2 - \hat{p}_+ + m}{(q_2 - p_+)^2 - m^2} \gamma_{\alpha}, \quad \hat{q}_1 \equiv q_1 \mu \gamma \mu \text{ etc..} \]
**k_T-factorization form of the differential cross section**

\[
\frac{d\sigma(AB \rightarrow Xl^+l^- Y)}{dy_+ dy_- d^2p_+ d^2p_-} = \int \frac{d^2q_1}{\pi q_1^2} \frac{d^2q_2}{\pi q_2^2} \mathcal{F}_{\gamma^*/A}(x_1, q_1) \mathcal{F}_{\gamma^*/B}(x_2, q_2) \frac{d\sigma^*(p_+, p_-; q_1, q_2)}{dy_+ dy_- d^2p_+ d^2p_-},
\]

\[
x_1 = \frac{m_{\perp+}}{\sqrt{s}} e^{\gamma_+} + \frac{m_{\perp-}}{\sqrt{s}} e^{\gamma_-}, \quad x_2 = \frac{m_{\perp+}}{\sqrt{s}} e^{-\gamma_+} + \frac{m_{\perp-}}{\sqrt{s}} e^{-\gamma_-}, \quad m_{\perp\pm} = \sqrt{p_{\perp\pm}^2 + m_l^2}.
\]

\[
\frac{d\sigma^*(p_+, p_-; q_1, q_2)}{dy_1 dy_2 d^2p_+ d^2p_-} = \frac{\alpha^2_{em}}{q_1^2 q_2^2} \sum_{\lambda, \bar{\lambda}} \left| B_{\lambda \bar{\lambda}}(p_+, p_-; q_1, q_2) \right|^2 \delta^{(2)}(q_1 + q_2 - p_+ - p_-).
\]
Lepton pair production in the high energy limit

\[ F_{\gamma/A}(x, q^2) = \frac{\alpha_{\text{em}}}{\pi} (1 - x) \left[ \frac{q^2}{q^2 + x^2 m_p^2} \right]^2 \left( \frac{4 m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4 m_p^2 + Q^2} \right) \left( 1 - \frac{Q^2 - q^2}{Q^2} \right). \]

\[ F_{\gamma/A}^{(\text{inel})}(x, q^2) = \frac{\alpha_{\text{em}}}{\pi} (1 - x) \int_{M_{thr}^2}^{\infty} \frac{dM_X^2 F_2(M_X^2, Q^2)}{M_X^2 + Q^2 - m_p^2} \left( 1 - \frac{Q^2 - q^2}{Q^2} \right) \left[ \frac{q^2}{q^2 + x(M_X^2 - m_p^2) + x^2 m_p^2} \right]^2. \]

\[ Q^2 = \frac{1}{1 - x} \left[ q_1^2 + x(M_X^2 - m_p^2) + x^2 m_p^2 \right] \]
For the off-shell cross section a particularly simple form can be obtained in terms of the variables:

\[ z_{\pm} = \frac{m_{\perp} \pm}{(x_1 + x_2)\sqrt{s}} e^{\gamma_{\pm}}, \quad p = z_- p_+ - z_+ p_-, \]

The familiar structures

\[
\Phi_0 = \frac{1}{(p + z_+ q_2)^2 + \varepsilon^2} - \frac{1}{(p - z_- q_2)^2 + \varepsilon^2},
\]
\[
\Phi_1 = \frac{p + z_+ q_2}{(p + z_+ q_2)^2 + \varepsilon^2} - \frac{p - z_- q_2}{(p - z_- q_2)^2 + \varepsilon^2},
\]

with \( \varepsilon^2 = m_i^2 + z_+ z_- q_1^2 \), enter the off-shell matrix element:

\[
\sum_{\lambda, \bar{\lambda}} \left| B_{\lambda \bar{\lambda}}(p_+, p_-; q_1, q_2) \right|^2 = 2z_+ z_- q_1^2 \left[ 4z_+^2 z_- q_1^2 \Phi_0^2_L + \left( z_+^2 + z_-^2 \right) \Phi_1^2_T + m_i^2 \Phi_0^2 \right] + 4z_+ z_- (z_+ - z_-) \Phi_0(q_1 \Phi_1)
\]
Beyond the QED mechanism: continuum muons from $\gamma$-Pomeron fusion

**Distribution in** $p_{\text{sum}} = p_+ + p_-$ **in “elastic-inelastic” events**

▶ If $p_{\text{sum}}^2 \gg \Lambda^2 \sim 0.71 \text{ GeV}^2$, The decorrelation momentum $p_{\text{sum}}$ is exactly equal to the transverse momentum carried by the “inelastic” photon.

▶ The “lepton dijet” decorrelation momentum distribution directly probes the unintegrated photon distribution.

$$\frac{d\sigma(AB \rightarrow AL^+l^-X)}{dy_1 dy_2 d^2p_1 d^2p_2} = n(x_1) \frac{\alpha_{\text{em}}^2 F(x_2, p_1 + p_2)}{(p_1 + p_2)^2} \frac{2z_+z_- (z_+^2 + z_-^2)}{p_1^2 p_2^2}. \quad (2)$$

Here

$$n(x_1) = \int \frac{d^2q_1}{\pi q_1^2} F(x_1, q_1), \quad (3)$$

is the Weizsäcker-Williams flux of photons in the elastically scattered proton.
Input for our calculation

- **elastic vertex**: dipole formfactor

  \[ G_E(Q^2) = \frac{1}{(1 + Q^2/\Lambda^2)^2}, \quad G_M(Q^2) = \mu G_E(Q^2), \quad \mu = 2.79, \quad \Lambda^2 = 0.71 \text{ GeV}^2. \]

- **inelastic vertex**: different parametrizations of \(F_2(x_{Bj}, Q^2)\)
  
  - “SU”: A. Szczurek & V. Uleshchenko, (2000). Puts an emphasis on the low-to-intermediate \(Q^2\)-region and includes a smooth continuation to low-\(Q^2\).
  
  - “MSTW”: a modern parametrization of Partons, DGLAP evolution.
  
  - “SY”: Suri & Yennie (1972) a standard option in the LPAIR event generator. Provides a description of old SLAC data.
  
  - “FFJLM”: Fiore, Flachi, Jenkovszky, Lengyel, Magas (2002). A parametrization which describes very well photoabsorption in the resonance region from low to large \(Q^2\). Excellent description of JLAB data.

We use the following cuts:

- \(-2.5 < y < 2.5\) for the muon rapidities.

- two types of cuts on muon \(p_T\): **soft**: \(p_T > 3\) GeV and **hard**: \(p_T > 15\) GeV.

- mass \(M_X\) of the excited hadronic system: \(m_p + m_\pi < M_X < 320\) GeV.
Rapidity distributions

- left panel: $p_T > 3 \text{ GeV}$, right panel: $p_T > 15 \text{ GeV}$
- solid: elastic-elastic, dashed: inelastic - elastic, dash-dotted: inelastic - inelastic
- Photon from the inelastic vertex is harder $\rightarrow$ asymmetry of elastic-inelastic contribution.
Transverse momentum distributions of muons

- left panel: $p_T > 3\, \text{GeV}$, right panel: $p_T > 15\, \text{GeV}$
- solid: elastic-elastic, dashed: inelastic - elastic, dash-dotted: inelastic - inelastic
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**Invariant mass distributions**

- left panel: $p_T > 3\,\text{GeV}$, right panel: $p_T > 15\,\text{GeV}$
- solid: elastic-elastic, dashed: inelastic - elastic, dash-dotted: inelastic - inelastic
- low-mass tail for the inelastic contribution comes from pairs with large $p_{\text{sum}}$. 

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Comparison "$k_T$-factorization" vs. LPAIR

- left panel: $p_T > 3\text{ GeV}$, right panel: $p_T > 15\text{ GeV}$
Options for $F_2$ in LPAIR

- left panel: $p_T > 3 \text{ GeV}$, right panel: $p_T > 15 \text{ GeV}$
shares many properties with vector meson production, but the \textit{timelike} nature of the photon leads to a complicated phase & interferences & flavour dependence.

- dileptons are of \textit{odd} C-parity.
Dileptons from $\gamma - \text{IP}-\text{fusion}$

- G. Kubasiak & A. Szczurek, Phys. Rev. D84 (2011)
- caveat: calculation does not include absorptive effects. (compare A. Cisek’s talk on VM’s).
production of dilepton pairs with large transverse momenta has a large contribution from proton dissociation events (at the "Born" level).

there can be substantial differences depending on the input for $F_2$. "Standard input" in e.g. (some versions of (?)) LPAIR is outdated.

"non-QED" processes can be non-negligible.

What is missing?

absorptive corrections will diminish the proton dissociation contribution, especially at large $M_X$.

- large (esp. longitudinal) momentum transfer implies a more central collision, where absorption effects are stronger.

- a "universal" input which works for all $M_X^2, Q^2$.

- inclusion of other processes into the event generation: $\gamma P$-fusion ...