Exclusive and diffractive production of lepton pairs in $pp$ collision at high energy

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Plan of the talk

1. Exclusive production $l^+ l^-$
   - non-QED, $pp \rightarrow (\gamma P) \rightarrow pl^+ l^- p$
   - QED, $pp \rightarrow (\gamma \gamma) \rightarrow pl^+ l^- p$

2. Results

3. Inclusive diffractive production $l^+ l^-$
   - Single diffraction
   - Double diffraction

4. Results

5. Summary
Introduction

- Measuring absolutely normalized cross sections at the LHC is of great importance for high-energy physics community.
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The QED process $pp \rightarrow pl^+l^-p$ via $\gamma\gamma$- fusion is often discussed as a process which can be used for measuring the luminosity at the LHC.
Introduction

- Measuring absolutely normalized cross sections at the LHC is of great importance for high-energy physics community.
- The QED process $pp \rightarrow pl^+l^-p$ via $\gamma\gamma$-fusion is often discussed as a process which can be used for measuring the luminosity at the LHC.
- It is therefore important to estimate non-QED contributions to exclusive $l^+l^-$ production.
Amplitude for $\gamma p \to l^+ l^- p$
non-QED, \( pp \rightarrow (\gamma p) \rightarrow p l^+ l^- p \)

**Amplitude for \( \gamma p \rightarrow l^+ l^- p \)**
Amplitude for $\gamma p \rightarrow l^+ l^- p$

The amplitude for $\gamma p \rightarrow l^+ l^- p$ is given by:

$$\mathcal{F}(x, \kappa) = \frac{\partial G(x, \kappa)}{\partial \log \kappa^2}$$
Amplitude for $\gamma p \rightarrow l^+ l^- p$

- $\gamma \rightarrow \gamma^*$ Time-like Compton Scattering (TCS)
- exchange of off-diagonal QCD gluon ladder

W. Schafer, G. Sliepek, A. Szczurek
Amplitude for $\gamma p \rightarrow l^+ l^- p$

- $\gamma \rightarrow \gamma^*$ Time-like Compton Scattering (TCS)
- exchange of off-diagonal QCD gluon ladder
- W. Schafer, G. Slipek, A. Szczurek

- the imaginary part of the forward TCS amplitude

$$\mathcal{I}m M_f(\gamma p \rightarrow \gamma^*(q^2)p) = W^2 16\pi^2 a_{em} e_f^2 \left\{ \Theta(4m_f^2 - q^2) \int_{4m_f^2}^{\infty} dM^2 \frac{\mathcal{I}m a_f(W^2, M^2)}{M^2 - q^2} + \Theta(q^2 - 4m_f^2) \left( PV \int_{4m_f^2}^{\infty} dM^2 \frac{\mathcal{I}m a_f(W^2, M^2)}{M^2 - q^2} + \pi \Re a_f(W^2, q^2) \right) \right\}$$
Amplitude for $\gamma p \rightarrow l^+ l^- p$

- $\gamma \rightarrow \gamma^*$ Time-like Compton Scattering (TCS)
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W. Schafer, G. Slipek, A. Szczurek

- the imaginary part of the forward TCS amplitude

$$\Im m M_f(\gamma p \rightarrow \gamma^*(q^2)p) = W^2 16\pi^2 a_{em} e_r^2$$

$$\cdot \left\{ \Theta(4m_r^2 - q^2) \int_{4m_r^2}^{\infty} dM^2 \frac{\Im m a_f(W^2, M^2)}{M^2 - q^2} \right.$$ $$+ \Theta(q^2 - 4m_r^2) \left( PV \int_{4m_r^2}^{\infty} dM^2 \frac{\Im m a_f(W^2, M^2)}{M^2 - q^2} + \pi \Re e a_f(W^2, q^2) \right) \right\}$$

- spectral density $\Rightarrow a_f(W^2, M^2) = \int_{\frac{W^2}{2}}^{\infty} dM^2 \frac{dK^2}{d_r} A_f(M^2, k^2, W^2)$.
- $A_f(M^2, k^2, W^2) \Rightarrow$ a convolution of $F(x, \kappa^2)$ and some functions
- The Gluone exchange ladder is modelled by $F(x, \kappa^2)$
Amplitude for $pp \rightarrow pl^+ l^- p$ ($\gamma P$ exchange)

$$M_{\gamma P \rightarrow pl^+ l^-} = e F_1(q_1^2) \left( \bar{u}_1 \gamma^\mu u_a \left( \frac{-ig_{\mu\nu}}{t_1} \right) \sum \epsilon^\nu(j_1) M_{\gamma P \rightarrow pl^+ l^-}(W_2, M_{34}) \right)$$

$$+ e F_1(q_2^2) \left( \bar{u}_2 \gamma^\mu u_b \left( \frac{-ig_{\mu\nu}}{t_2} \right) \sum \epsilon^\nu(j_2) M_{\gamma P \rightarrow pl^+ l^-}(W_2, M_{34}) \right)$$

$$= e F_1(q_1^2) \left( \bar{u}_1 \gamma^\mu u_a \left( \frac{-ig_{\mu\nu}}{t_1} \right) \sum \epsilon^\nu(j_1) M_{\gamma P \rightarrow pl^+ l^-}(W_2, M_{34}) \right)$$

$$+ e F_1(q_2^2) \left( \bar{u}_2 \gamma^\mu u_b \left( \frac{-ig_{\mu\nu}}{t_2} \right) \sum \epsilon^\nu(j_2) M_{\gamma P \rightarrow pl^+ l^-}(W_2, M_{34}) \right)$$
Amplitude for $pp \rightarrow pl^+l^-p$ ($\gamma P$ exchange)

\[ M_{pp \rightarrow ppl^+l^-} = g_{\lambda_3 \lambda_4} \sum_{\lambda_1 \lambda_2} g_{\mu \nu} u_{a} \left( \frac{-ig_{\mu \nu}}{t_1} \right) \varepsilon^{\nu}(\lambda_1) M_{\gamma P \rightarrow \gamma^* P}(W_2, M_{34}) \]

\[ + g_{\alpha \beta} \sum_{\lambda_1} g_{\mu \nu} u_{b} \left( \frac{-ig_{\mu \nu}}{s_{34}} \right) \varepsilon^{\nu}(\lambda_2) M_{\gamma P \rightarrow \gamma^* P}(W_2, M_{34}) \]

\[ \Rightarrow \sigma \]

four-body phase-space numerically $\Rightarrow$ (long formula

QED, $pp \rightarrow (\gamma \gamma) \rightarrow p l^+ l^- p$

**Amplitude for $pp \rightarrow p l^+ l^- p$ ($\gamma \gamma$ fusion)**

\[ M_{pp\rightarrow pp l^+ l^-}^{\gamma \gamma} = \]
\[ \bar{u}(p_1, \lambda_1) \Gamma_1^{\mu_1} (q_1) u(p_a, \lambda_a) \left( \frac{-i g_{\mu_1 \nu_1}}{t_1} \right) \]
\[ \times \left[ V_{\lambda_3 \lambda_4}^{\nu_1 \nu_2}(q_1, q_2, p_3, p_4) \left( \frac{-i g_{\mu_2 \nu_2}}{t_2} \right) \bar{u}(p_2, \lambda_2) \Gamma_2^{\mu_2} (q_2) u(p_b, \lambda_b) \right] \]
Amplitude for $pp \rightarrow pl^+ l^- p$ ($\gamma\gamma$ fusion)

\[ M_{pp \rightarrow pp l^+ l^-} = \bar{u}(p_1, \lambda_1) \Gamma_{\lambda_1}^{\mu_1} (q_1) u(p_a, \lambda_a) \left( \frac{-ig_{\mu_1}v_1}{t_1} \right) \]

\[ V_{\lambda_3 \lambda_4}^{\nu_1 \nu_2} (q_1, q_2, p_3, p_4) \left( \frac{-ig_{\nu_2}v_2}{t_2} \right) \bar{u}(p_2, \lambda_2) \Gamma_{\lambda_2}^{\mu_2} (q_2) u(p_b, \lambda_b) \]

- the production amplitude of lepton pair

\[ V_{\lambda_3 \lambda_4}^{\nu_1 \nu_2} (q_1, q_2, p_3, p_4) = e^2 \bar{u}(p_3, \lambda_3) \left[ \gamma^{\nu_1} \frac{q_1 - p_3 - m}{(q_1 - p_3)^2 - m^2} \gamma^{\nu_2} - \gamma^{\nu_2} \frac{q_1 - p_4 + m}{(q_1 - p_4)^2 - m^2} \gamma^{\nu_1} \right] v(p_4, \lambda_4) \]
Amplitude for $pp \rightarrow pl^+l^-p$ ($\gamma\gamma$ fusion)

- the production amplitude of lepton pair
  \[
  V_{\lambda_3, \lambda_4}^{\nu_1, \nu_2}(q_1, q_2, p_3, p_4) = e^2 \bar{u}(p_3, \lambda_3) \left[ y^{\nu_1} \frac{\hat{q}_1 - \hat{p}_3 - m}{(q_1 - p_3)^2 - m^2} y^{\nu_2} - y^{\nu_2} \frac{\hat{q}_1 - \hat{p}_4 + m}{(q_1 - p_4)^2 - m^2} y^{\nu_1} \right] v(p_4, \lambda_4)
  \]
- $\Gamma_{\lambda_1}^{\mu_1}(q_1) = \gamma^{\mu_1} F_1(q_1) + \frac{i\kappa_p}{2M_p} \sigma^{\mu_1 \nu_1} q_{\nu_1} F_2(q_1)$
- $\Gamma_{\lambda_2}^{\mu_2}(q_2) = \gamma^{\mu_2} F_1(q_2) + \frac{i\kappa_p}{2M_p} \sigma^{\mu_2 \nu_2} q_{\nu_2} F_2(q_2)$
Dependence on dilepton invariant mass and $p_{t,\text{sum}}$

- $M_{ll}$ invariant mass of outgoing leptons

- $\vec{p}_{t,\text{sum}} = \vec{p}_{1t} + \vec{p}_{2t}$
Azimuthal angle and rapidity distributions

\[ \sqrt{s} = 14\,000 \text{ GeV} \]

**p p → p l^+ l^- p**

- \( \gamma\gamma \)
- \( \gamma P \)
Transverse momentum correlations of outgoing protons

\[\xi_1 = \log_{10}\left[\frac{p_{1t}}{1\text{GeV}}\right] \quad \xi_2 = \log_{10}\left[\frac{p_{1t}}{1\text{GeV}}\right]\]

- expect ⇒ difficult to measure
Transverse momentum correlations of outgoing leptons

![Graph showing transverse momentum correlations](image-url)
Rapidity correlations of leptons
more complicated processes $\Rightarrow$ inclusive diffractive processes. They are discussed in terms of Pomeron exchanges.
Introduction

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- Pomeron has a well defined partonic structure
**Introduction**

- Pomeron has a well defined partonic structure
- the hard process take place in
  - pomeron-proton or proton-pomeron → **single diffraction**

Pomeron has a well defined partonic structure

the hard process take place in

- pomeron-proton or proton-pomeron → single diffraction

- pomeron-pomeron → double diffraction
Single diffraction

\[ \frac{d\sigma_{SD}}{dy_1 dy_2 dp_{t}^2} = K \frac{|M|^2}{16\pi^2 s^2} \left( x_1 q_f^D(x_1, \mu^2) x_2 \bar{q}_f(x_2, \mu^2) \right) + \left( x_1 \bar{q}_f^D(x_1, \mu^2) x_2 q_f(x_2, \mu^2) \right). \]

- \( |M|^2 \) - matrix element (text book formula)

\[ |M(q\bar{q} \rightarrow l^+ l^-)|^2 = 32\pi^2 a_{em}^2 \frac{(m_l^2-q^2)^2+(m_l^2-u^2)^2+2m_l^2 s}{s^2}. \]
Single diffraction

\[ \frac{d\sigma_{SD}}{dy_1 dy_2 dp_f^2} = K \frac{|M|^2}{16\pi s^2} (x_1 q_f^D (x_1, \mu^2) x_2 \bar{q}_f (x_2, \mu^2)) + (x_1 \bar{q}_f^D (x_1, \mu^2) x_2 q_f (x_2, \mu^2)). \]

- \(|M|^2\) - matrix element (textbook formula)
\[
|M(q\bar{q} \rightarrow l^+ l^-)|^2 = 32\pi^2 a_{em}^2 \frac{(m_t^2-t)^2+(m_t^2-0)^2+2m_t^2s}{s^2}.
\]

- \(x_1 = \frac{m_t}{\sqrt{s}} (\exp(y_1) + \exp(y_2))\),

- \(x_2 = \frac{m_t}{\sqrt{s}} (\exp(-y_1) + \exp(-y_2))\), \text{ where } m_t = \sqrt{p_t^2 + m_t^2}.\]
Single diffraction

\[ \frac{d \sigma_{SD}}{dy_1 dy_2 dp_T^2} = K \frac{|M|^2}{16 \pi^2 s^2} \left( x_1 q_f^D(x_1, \mu^2) x_2 \bar{q}_f(x_2, \mu^2) \right) 
+ \left( x_1 \bar{q}_f^D(x_1, \mu^2) x_2 q_f(x_2, \mu^2) \right). \]

- **K** - factor ⇒ effectively higher order Drell-Yan contributions
  \[ K = 1 + \frac{\alpha_s}{2 \pi} \frac{4}{3} \left( 1 + \frac{4}{3} \pi^2 \right). \]

V. Barger and R. Phillips "Collider Physics"
Single diffraction

\[
\frac{d\sigma_{SD}}{dy_1 dy_2 dp_t^2} = K \frac{|M|^2}{16\pi^2 s^2} \left( x_1 q_f^D(x_1, \mu^2) x_2 \bar{q}_f(x_2, \mu^2) \right) + \left( x_1 \bar{q}_f^D(x_1, \mu^2) x_2 q_f(x_2, \mu^2) \right).
\]

- \( K \) - factor \( \Rightarrow \) effectively higher order Drell-Yan contributions

\[ K = 1 + \frac{\alpha_s}{2\pi} \left( 1 + \frac{4}{3} \pi^2 \right). \]

**V. Barger and R. Phillips** "Collider Physics"

- diffractive quark distribution
  \[ q_f^D(x, \mu^2) = \int dx_P d\beta \delta(x - x_P\beta) q_f/P(\beta, \mu^2) f_P(x_P) = \int_x^1 \frac{dx_P}{x_P} f_P(x_P) q_f/P(\frac{x}{x_P}, \mu^2) \]
  \[ q_f/P(\frac{x}{x_P}, \mu^2) \rightarrow \text{the parton distribution in the Pomeron} \]
  \[ f_P(x_P) \rightarrow \text{the flux of Pomeron} \]

- \( f_P(x_P) \) and \( q_f/P(\frac{x}{x_P}, \mu^2) \)
Single diffraction

\[
\frac{d\sigma_{SD}}{dy_1 dy_2 dp_T^2} = K \frac{|M|^2}{16 \pi^2 s^2} \left( x_1 q_f^D(x_1, \mu^2) x_2 \bar{q}_f(x_2, \mu^2) \right) + \left( x_1 \bar{q}_f^D(x_1, \mu^2) x_2 q_f(x_2, \mu^2) \right).
\]

- **K - factor**: effectively higher order Drell-Yan contributions
  \[ K = 1 + \frac{\alpha_s}{2\pi} \frac{4}{3} \left( 1 + \frac{4}{3} \pi^2 \right). \]

V. Barger and R. Phillips* Collider Physics*

- diffractive quark distribution
  \[
  q_f^D(x, \mu^2) = \int dx_P d\beta \delta(x - x_P, \beta) q_f/P(\beta, \mu^2) f_P(x_P) = \int_x^1 \frac{dx_P}{x_P} f_P(x_P) q_f/P\left(\frac{x}{x_P}, \mu^2\right).
  \]

- \( q_f/P\left(\frac{x}{x_P}, \mu^2\right) \rightarrow \) the parton distribution in the Pomeron
  \( f_P(x_P) \rightarrow \) the flux of Pomeron

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q_f/P\left(\frac{x}{x_P}, \mu^2\right) \rightarrow \text{the parton distribution in the Pomeron}
\]

\[
f_P(x_P) \rightarrow \text{the flux of Pomeron}
\]

- \( f_P(x_P) \) and \( q_f/P\left(\frac{x}{x_P}, \mu^2\right) \)

\[
\]
Double diffraction

\[
\frac{d\sigma_{DD}}{dy_1 dy_2 dp_T^2} = K \frac{|M|^2}{16\pi^2 s^2} \left( x_1 q_f^D(x_1, \mu^2) x_2 \bar{q}_f^D(x_2, \mu^2) \right)
\]

\[+ \left( x_1 \bar{q}_f^D(x_1, \mu^2) x_2 q_f^D(x_2, \mu^2) \right). \]
Dependence on dilepton invariant mass and $p_t$

![Graph showing dependence on dilepton invariant mass and $p_t$](image)

$\sqrt{s} = 1960$ GeV
Dependence on dilepton rapidity

\[ \frac{d\sigma}{dy_{\text{sum}}} \] (nb)

\( y_{\text{sum}} \)

\( \sqrt{s} = 1960 \text{ GeV} \)
Rapidity correlations of leptons

Drell-Yan

double diff

single diff

single diff
EXCLUSIVE Vs DIFFRACTIVE

\[ \sqrt{s} = 14\,000\,\text{GeV} \]
I have presented results for exclusive and diffractive production of lepton pairs.
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Both of them were calculated and compared for the first time.
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Future:

- to include absorptive corrections (the ‘elastic rescattering’)
- to include Pauli form factor
Thank You for attention!