Recent progress in (some) exclusive and semi-exclusive processes in proton-proton collisions

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Only two topics out of many possible

- $pp \to ppJ/\psi$ and $pp \to pp\psi'$ (purely exclusive)
- $pp \to pp l^+ l^-$ (exclusive) and $pp \to l^+ l^-$ (semiexclusive)

**double photon fusion**

I will discuss our recent results and refer to other works
\( pp \rightarrow ppJ/\psi \)

The interference term vanishes for rapidity distributions in Born approximation

Imaginary part of the forward $\gamma p \rightarrow J/\psi p$ amplitude

$$\Im M_T(W, \Delta^2 = 0, Q^2 = 0) = W^2 \frac{c_v \sqrt{4\pi a_{em}}}{4\pi^2} 2 \int_0^1 \frac{dz}{z(1-z)} \int_0^\infty \pi dk^2 \psi_V(z, k^2)$$

$$\int_0^\infty \frac{\pi d\kappa^2}{\kappa^4} a_s(q^2) F(x_{\text{eff}}, \kappa^2) \left( A_0(z, k^2) W_0(k^2, \kappa^2) + A_1(z, k^2) W_1(k^2, \kappa^2) \right).$$

dependence on the meson wave function and UGDF

No wave functions in collinear calculations (Jones, Martin, Ryskin)

The full amplitude, at finite momentum transfer parametrized:

$$M(W, \Delta^2) = (i + \rho) \Im M(W, \Delta^2 = 0, Q^2 = 0) \exp(-B(W)\Delta^2/2).$$
$pp \rightarrow ppJ/\psi$

- $W = 40$ GeV
- $W = 60$ GeV
- $W = 80$ GeV
- $W = 100$ GeV
- $W = 120$ GeV
- $W = 140$ GeV

$\frac{d\sigma}{dt}$ vs $-t$ (GeV$^2$) for different $W$ values and Orear $\mu$ values.
In the Born approximation:

\[
M^{\vec{J}_1^* \vec{J}_2 \rightarrow \vec{J}'_1^* \vec{J}'_2} (s, s_1, s_2, t_1, t_2) = M_{\gamma P} + M_{\gamma \gamma}
\]

\[
= \langle p'_1, \vec{J}'_1 | J_\mu | p_1, \vec{J}_1 \rangle \epsilon^*_\mu (q_1, \vec{J}_V) \frac{\sqrt{4\pi \alpha_{em}}}{t_1} M^{\vec{J}_V^* \vec{J}_2 \rightarrow \vec{J}_V \vec{J}_2} (s_2, t_2, Q_1^2)
\]

\[
+ \langle p'_2, \vec{J}'_2 | J_\mu | p_2, \vec{J}_2 \rangle \epsilon^*_\mu (q_2, \vec{J}_V) \frac{\sqrt{4\pi \alpha_{em}}}{t_2} M^{\vec{J}_V^* \vec{J}_1 \rightarrow \vec{J}_V \vec{J}_1} (s_1, t_1, Q_2^2)
\]
Then, the amplitude of Eq. (3) for the emission of a photon of transverse polarization $\vec{n}_V$, and transverse momentum $\mathbf{q}_1 = -\mathbf{p}_1$ can be written as:

$$\langle p'_1, \vec{n}'_1|J_\mu|p_1, \vec{n}_1\rangle \epsilon^*_\mu(q_1, \vec{n}_V) = \left( e^{*(\vec{n}_V)} q_1 \right) \frac{2}{\sqrt{1 - z_1}} \chi^\dagger_{\vec{n}'_1} \left\{ F_1(Q^2) - \frac{i\kappa_p F_2(Q^2)}{2 m_p} (\sigma \cdot [\mathbf{q}_1, \mathbf{n}]) \right\} \chi_{\vec{n}_1}. \quad (4)$$

$F_1$ - Dirac em ff

$F_2$ - Pauli em ff (new)
$pp \rightarrow ppJ/\psi$

HERA data at $W \sim 100\text{--}200\text{ GeV}$
LHCb quasi-data at $W \sim 1\text{ TeV}$
$pp \rightarrow ppJ/\psi$
$pp \rightarrow ppJ/\psi$
$pp \rightarrow ppJ/\psi$

Survival factor depends on the phase space point!
$pp \rightarrow ppJ/\psi$

with absorption

similar for $\psi'$
$pp \rightarrow ppJ/\psi$

with absorption

similar for $\psi'$
$pp \rightarrow ppJ/\psi$

Ivanov-Nikolaev

Kutak-Stasto linear

Kutak-Stasto nonlinear

W = 7 TeV

Gauss WF much better than Coulomb WF
There is some model dependent indication of nonlinear effects

Open problems:

- The present experiments are not exclusive.
- So far proton dissociation "extracted" in a model dependent way assuming some functional form in $p_t$.
- We have some knowledge about diffractive dissociation (HERA).
- Compare to HERA there is also photon dissociation (never discussed, probably bigger).
- Interference effects due to the two diagrams were predicted. It would be nice to see modulation in $\phi_{pp}$ due to interference effects between the two diagrams.
- CMS+TOTEM and ATLAS+ALFA could measure purely exclusive reaction and study dependences on many more variables.
\( pp \rightarrow l^+ l^- \)
Two different approaches:
- Collinear factorization:
- $k_T$ factorization
  (G. Gil da Silveira, L. Forthomme, K. Piotrzkowski, W. Schafer, A. Szczurek, JHEP 1502 (2015) 159,
  M. Luszczak, W. Schafer and A. Szczurek, arXiv:1510.00294)

In collinear factorization approach one needs photons as parton in proton:
- MRST
- NNPDF
The factorization of the QED-induced collinear divergences leads to QED-corrected evolution equations for the parton distributions of the proton.

\[
\frac{\partial q_i(x, \mu^2)}{\partial \log \mu^2} = \frac{a_s}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{qq}(y) \frac{x}{y} q_i\left(\frac{x}{y}, \mu^2\right) + P_{qg}(y) g\left(\frac{x}{y}, \mu^2\right) \right\} \\
+ \frac{a}{2\pi} \int_x^1 \frac{dy}{y} \left\{ \tilde{P}_{qq}(y) e_i^2 \frac{x}{y} q_i\left(\frac{x}{y}, \mu^2\right) + P_{q\gamma}(y) e_i^2 \gamma\left(\frac{x}{y}, \mu^2\right) \right\}
\]

\[
\frac{\partial g(x, \mu^2)}{\partial \log \mu^2} = \frac{a_s}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{gq}(y) \sum_j q_j\left(\frac{x}{y}, \mu^2\right) + P_{gg}(y) g\left(\frac{x}{y}, \mu^2\right) \right\}
\]

\[
\frac{\partial \gamma(x, \mu^2)}{\partial \log \mu^2} = \frac{a}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{\gamma q}(y) \sum_j e_j^2 q_j\left(\frac{x}{y}, \mu^2\right) + P_{\gamma\gamma}(y) \gamma\left(\frac{x}{y}, \mu^2\right) \right\},
\]
Diagramatic representation of the DGLAP with photons
**Collinear photon distribution in nucleon**

**Initial input is crucial**

MRST(QED) input overestimated (see discussion in our paper)
The elastic photon fluxes are calculated using the Drees-Zeppenfeld parametrization, where a simple parametrization of nucleon electromagnetic form factors was used.
$\mathcal{F}_{\gamma^* \rightarrow A}(z, q) = \frac{a_{\text{em}}}{\pi} (1 - z) \left( \frac{q^2}{q^2 + z(M_X^2 - m_A^2) + z^2 m_A^2} \right)^2 \cdot \frac{p_B^\mu p_B^\nu}{s^2} W_{\mu\nu}(M_X^2, Q^2)$

The hadronic tensor is expressed in terms of the electromagnetic currents as:

$W_{\mu\nu}(M_X^2, Q^2) = \sum_X (2\pi)^3 \delta^{(4)}(p_X - p_A - q) \langle p| J_\mu |X \rangle \langle X | J_\nu^\dagger | p \rangle \ d\Phi_X , \quad (6)$
$$W_{\mu\nu}(M_X^2, Q^2) = -\delta_{\mu\nu}^{\perp}(p_A, q) W_T(M_X^2, Q^2) + e^{(0)}_\mu e^{(0)}_\nu W_L(M_X^2, Q^2). \quad (7)$$

The virtual photoabsorption cross sections are defined as

$$\sigma_T(\gamma^* p) = \frac{4\pi a_{em}}{4\sqrt{X}} \left( -\frac{\delta_{\mu\nu}^{\perp}}{2} \right) 2\pi W^{\mu\nu}(M_X^2, Q^2)$$

$$\sigma_L(\gamma^* p) = \frac{4\pi a_{em}}{4\sqrt{X}} e^0_\mu e^0_\nu 2\pi W^{\mu\nu}(M_X^2, Q^2). \quad (8)$$

It is customary to introduce dimensionless structure function

$$F_i(x_{Bj}, Q^2), i = T, L$$

as

$$\sigma_{T,L}(\gamma^* p) = \frac{4\pi^2 a_{em}}{Q^2} \frac{1}{\sqrt{1 + \frac{4x_{Bj}^2 m_A^2}{Q^2}}} F_{T,L}(x_{Bj}, Q^2), \quad (9)$$

In the literature one often finds structure functions

$$F_1(x_{Bj}, Q^2), F_2(x_{Bj}, Q^2),$$

which are related to $F_{T,L}$ through
The unintegrated fluxes enter the cross section for dilepton production as

\[
\frac{d\sigma^{(i,j)}}{dy_1 dy_2 d^2p_1 d^2p_2} = \int \frac{d^2q_1}{\pi q_1^2} \frac{d^2q_2}{\pi q_2^2} \mathcal{F}^{(i)}_{\gamma^*/A}(x_1, q_1) \mathcal{F}^{(j)}_{\gamma^*/B}(x_2, q_2) \frac{d\sigma^*(p_1, p_2; q_1, q_2)}{dy_1 dy_2 d^2p_1 d^2p_2}
\]

(11)

where \(i,j=el,\bar{e}e\)

\[
x_1 = \sqrt{\frac{p_1^2 + m_i^2}{s}} e^{y_1} + \sqrt{\frac{p_2^2 + m_i^2}{s}} e^{y_2},
\]

\[
x_2 = \sqrt{\frac{p_1^2 + m_i^2}{s}} e^{-y_1} + \sqrt{\frac{p_2^2 + m_i^2}{s}} e^{-y_2}.
\]

(12)
$pp \rightarrow l^+ l^-$
$pp \rightarrow l^+ l^-$
$pp \rightarrow l^+ l^-$
$pp \rightarrow l^+ l^-$

![Graph showing the comparison of various models with experimental data. The graph plots the differential cross section for $pp \rightarrow l^+ l^-$ against $x$ (where $x$ is the momentum fraction). The models compared include CLAS data, NMC data, ALLM, FFJLM, SY, BDH, CTEQ6L, and SU. The data points and curves represent the different models, with the legend indicating the specific models and datasets.](image-url)
$pp \to l^+l^-$

$k_t$-factorization, including photon transverse momenta

**Graphical Content**

- Multiple plots showing differential distributions in $M_{l^+l^-}$ (GeV) for $pp \to \mu^+\mu^- X$ at $\sqrt{s} = 7$ TeV, illustrating LHCb data, ATLAS data, and theoretical predictions.

- Additional plots for $pp \to e^+e^- X$ at $\sqrt{s} = 63$ GeV and 200 GeV, demonstrating ISR data and theoretical models like SU, BDH, SY, FFJLM, ALLM, with emphasis on inelastic-inelastic processes.

**Legend Details**

- Theoretical models include SU, BDH, SY, FFJLM, ALLM, with specific emphasis on inelastic-inelastic contributions.

**Additional Notations**

- Inelastic-inelastic distributions for various experimental and theoretical scenarios, with emphasis on transverse momentum and rapidity intervals.
$pp \to l^+ l^-$

$k_t$-factorization, including photon transverse momenta

![Graphs and plots showing $pp \to \mu^+ \mu^-$ and $pp \to e^+ e^-$ for different CMS, ATLAS, and PHENIX data sets at various energies and kinematic cuts.](image-url)
$pp \rightarrow l^+ l^-, SU, FFJLM, SY, ALLM$
$pp \rightarrow \ell^+ \ell^-, \text{ISR, PHENIX, ATLAS, LHCb}$
\[ pp \rightarrow l^+ l^- \]

isolated electrons
**$pp \rightarrow l^+ l^-$**

![Graphs showing event distributions for $pp \rightarrow e^+ e^- X$ at $\sqrt{s} = 7$ TeV.](image)

The graphs illustrate the event rates as a function of $p_{T(e^e)}$ for different $p_T$ and $y$ ranges. The plots are labeled with CMS data and theoretical predictions from ALLM F2 and SY F2 models.

**isolated electrons**
$pp \rightarrow l^+ l^-$

isolated electrons
Two different approaches for $\gamma\gamma$ processes discussed

Strong dependence on the structure function input in the $k_t$-factorization approach

Semi-exclusive contributions (with dissociation) large

(lesson for $pp \rightarrow ppJ/\psi$)

Photon-photon contribution rather small compared to Drell-Yan contribution

Reasonable description of the CMS data with isolated electrons

(recently also ATLAS)

So far only collinear approach applied to

$pp \rightarrow (\gamma\gamma) \rightarrow W^+W^-XY$ processes

(important in searches for Beyond Standard Model effects)