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

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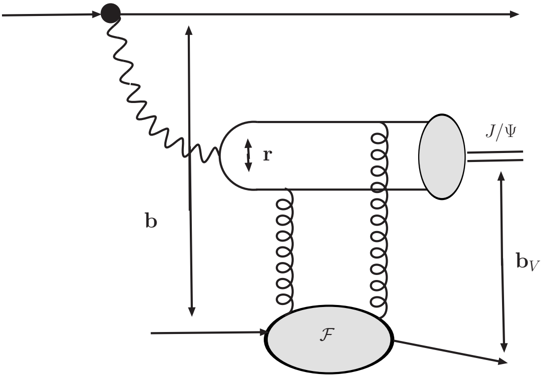
Contents

Only two topics out of many possible

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

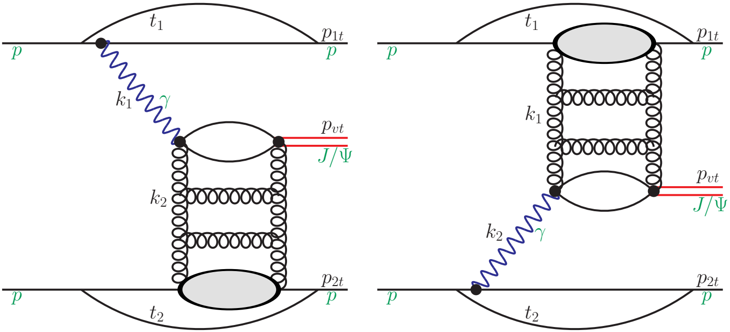
I will discuss our recent results and refer to other works

$pp \rightarrow ppJ/\psi$



A. Cisek, W. Schäfer and A. Szczurek, JHEP **1504** (2015) 159.

$pp \to ppJ/\psi$



The interference term vanishes for rapidity distributions in Born approximation

see W. Schäfer and A. Szczurek, Phys. Rev. **D76** (2007) 094014.

$pp \to ppJ/\psi$

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

$$\Im m\,\mathcal{M}_T(W, \Delta^2 = 0, Q^2 = 0) = W^2 \frac{c_V\sqrt{4\pi\alpha_{em}}}{4\pi^2}\, 2 \int_0^1 \frac{dz}{z(1-z)} \int_0^\infty \pi dk^2 \psi_V(z, k^2)$$
$$\int_0^\infty \frac{\pi d\kappa^2}{\kappa^4} \alpha_S(q^2) \mathcal{F}(x_{\rm eff}, \kappa^2) \Big(A_0(z, k^2)\; W_0(k^2, \kappa^2) + A_1(z, k^2)\; W_1(k^2, \kappa^2) \Big) .$$

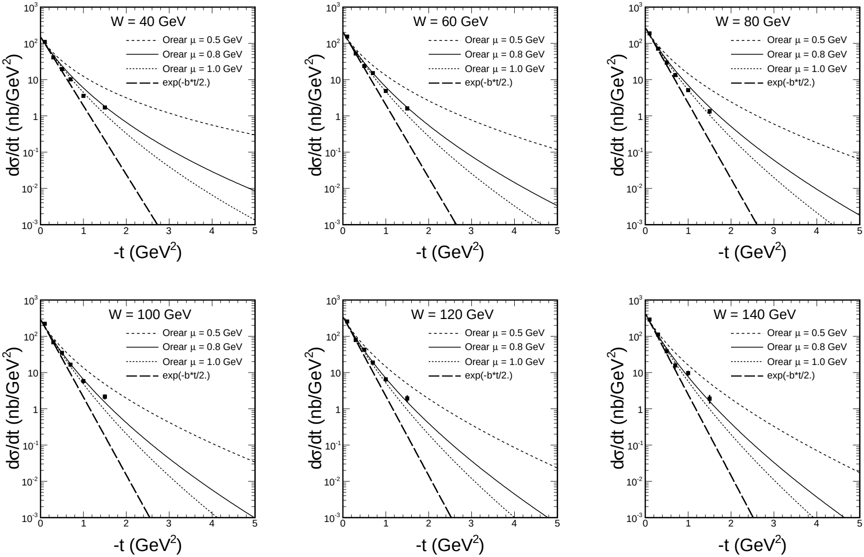
dependence on the meson wave function and UGDF

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

The full amplitude, at finite momentum transfer parametrized:

$$\mathcal{M}(W, \Delta^2) = (i + \rho)\, \Im m \mathcal{M}(W, \Delta^2 = 0, Q^2 = 0)\; \exp(-B(W)\Delta^2/2) \quad (2)$$

$pp \to ppJ/\psi$


W = 40 GeV
W = 60 GeV
W = 80 GeV
W = 100 GeV
W = 120 GeV
W = 140 GeV
Orear μ = 0.5 GeV
Orear μ = 0.8 GeV
Orear μ = 1.0 GeV
exp(-b*t/2.)
dσ/dt (nb/GeV²)
-t (GeV²)

$pp \to ppJ/\psi$

In the Born approximation:

$$\mathcal{M}^{\lambda_1\lambda_2\to\lambda'_1\lambda'_2\lambda_V}_{h_1h_2\to h_1h_2V}(s,s_1,s_2,t_1,t_2) = \mathcal{M}_{\gamma\mathbf{P}} + \mathcal{M}_{\mathbf{P}\gamma}$$

$$= \langle p'_1,\lambda'_1|J_\mu|p_1,\lambda_1\rangle\epsilon^*_\mu(q_1,\lambda_V)\frac{\sqrt{4\pi\alpha_{em}}}{t_1}\mathcal{M}^{\lambda_{\gamma^*}\lambda_2\to\lambda_V\lambda_2}_{\gamma^*h_2\to Vh_2}(s_2,t_2,Q_1^2)$$

$$+\langle p'_2,\lambda'_2|J_\mu|p_2,\lambda_2\rangle\epsilon^*_\mu(q_2,\lambda_V)\frac{\sqrt{4\pi\alpha_{em}}}{t_2}\mathcal{M}^{\lambda_{\gamma^*}\lambda_1\to\lambda_V\lambda_1}_{\gamma^*h_1\to Vh_1}(s_1,t_1,Q_2^2)\,. \qquad (3)$$

$pp \to ppJ/\psi$

Then, the amplitude of Eq. (3) for the emission of a photon of transverse polarization λ_V, and transverse momentum $\boldsymbol{q}_1 = -\boldsymbol{p}_1$ can be written as:

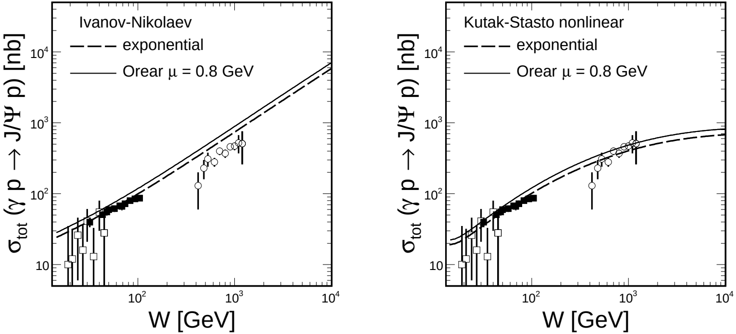
$$\langle p_1', \lambda_1' | J_\mu | p_1, \lambda_1 \rangle \epsilon_\mu^*(q_1, \lambda_V)$$

$$= \frac{(\boldsymbol{e}^{*(\lambda_V)} \boldsymbol{q}_1)}{\sqrt{1 - z_1}} \frac{2}{z_1} \chi^\dagger_{\lambda'} \Big\{ F_1(Q_1^2) - \frac{i\kappa_p F_2(Q_1^2)}{2m_p} (\sigma_1 \cdot [\boldsymbol{q}_1, \boldsymbol{n}]) \Big\} \chi_\lambda \,. \qquad (4)$$

F_1 - Dirac em ff

F_2 - Pauli em ff (new)

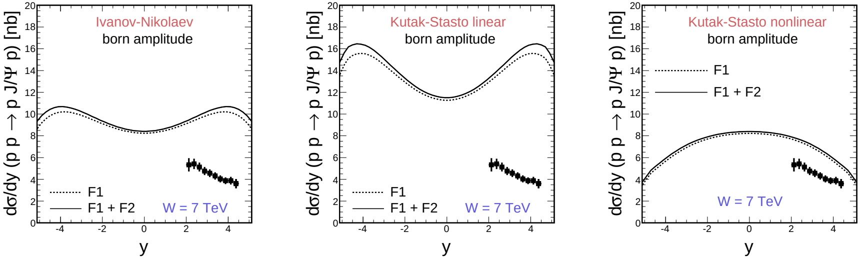
$pp \longrightarrow ppJ/\psi$



HERA data at W ~ 100-200 GeV

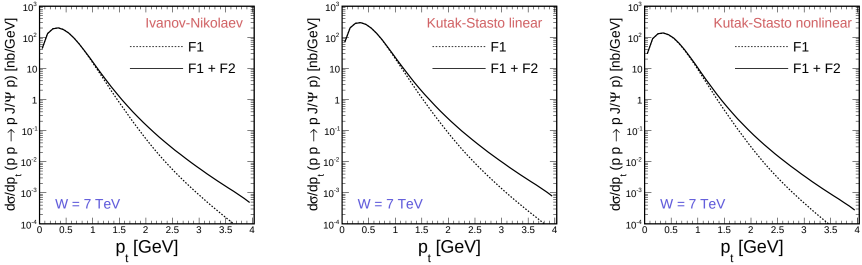
LHCb quasi-data at W ~ 1 TeV

$pp \to ppJ/\psi$

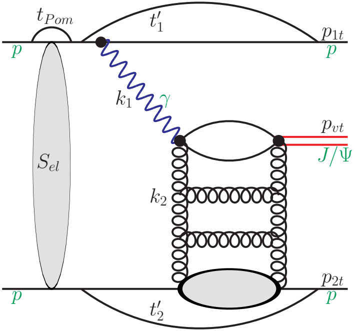


Ivanov-Nikolaev
born amplitude
F1
F1 + F2
W = 7 TeV
Kutak-Stasto linear
born amplitude
F1
F1 + F2
W = 7 TeV
Kutak-Stasto nonlinear
born amplitude
F1
F1 + F2
W = 7 TeV
dσ/dy (p p → p J/Ψ p) [nb]
y

$pp \to ppJ/\psi$


Ivanov-Nikolaev
F1
F1 + F2
W = 7 TeV
Kutak-Stasto linear
F1
F1 + F2
W = 7 TeV
Kutak-Stasto nonlinear
F1
F1 + F2
W = 7 TeV
dσ/dp_t (p p → p J/Ψ p) [nb/GeV]
p_t [GeV]

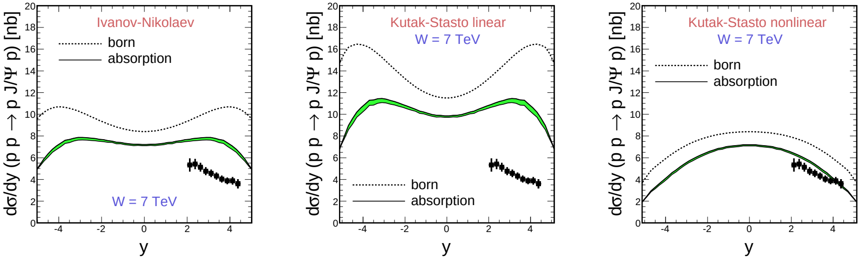
$pp \to ppJ/\psi$



Survival factor depends on the phase space point !

$pp \longrightarrow ppJ/\psi$

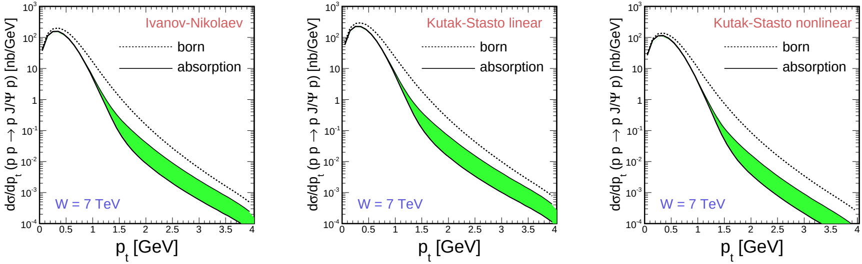
with absorption



similar for ψ'

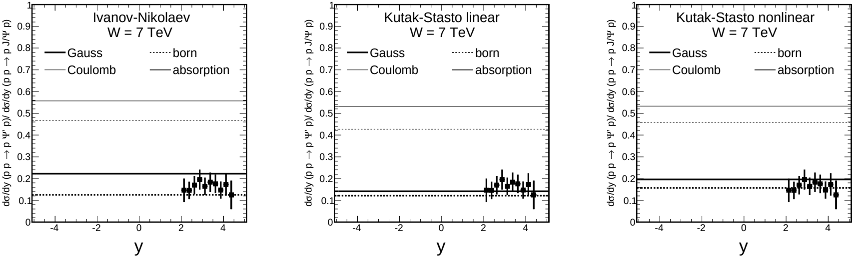
$pp \longrightarrow ppJ/\psi$

with absorption



similar for ψ'

$pp \to ppJ/\psi$



Gauss WF much better than Coulomb WF

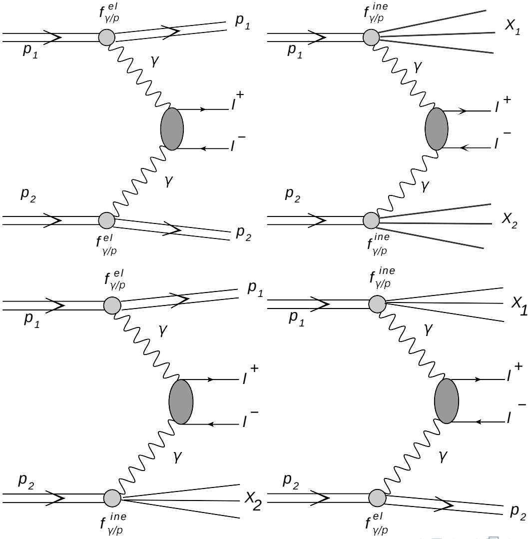
$pp \to ppJ/\psi$

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 ϕ_{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.

$pp \to l^+ l^-$



$f^{el}_{\gamma/p}$
p_1
p_1
γ
l^+
l^-
γ
p_2
$f^{el}_{\gamma/p}$
p_2
$f^{ine}_{\gamma/p}$
X_1
p_1
γ
l^+
l^-
γ
p_2
X_2
$f^{ine}_{\gamma/p}$
$f^{el}_{\gamma/p}$
p_1
p_1
γ
l^+
l^-
γ
p_2
X_2
$f^{ine}_{\gamma/p}$
$f^{ine}_{\gamma/p}$
X_1
p_1
γ
l^+
l^-
γ
p_2
p_2
$f^{el}_{\gamma/p}$

$pp \to l^+l^-$

Two different approach:

- collinear - factorization:

(M. Łuszczak, A. Szczurek and Ch. Royon, JHEP 1502 (2015) 098, arXiv:1409.1803)

- 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

MRST parton distributions

The factorization of the QED-induced collinear divergences leads to QED-corrected evolution equations for the parton distributions of the proton.

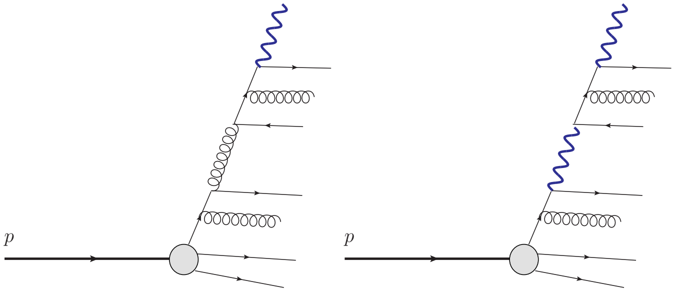
$$\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{qq}(y)\; q_i(\frac{x}{y},\mu^2) + P_{qg}(y)\; g(\frac{x}{y},\mu^2)\right\}$$

$$+ \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{\tilde{P}_{qq}(y)\; e_i^2 q_i(\frac{x}{y},\mu^2) + P_{q\gamma}(y)\; e_i^2 \gamma(\frac{x}{y},\mu^2)\right\}$$

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

$$\frac{\partial \gamma(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{\gamma q}(y)\; \sum_j e_j^2\; q_j(\frac{x}{y},\mu^2) + P_{\gamma\gamma}(y)\; \gamma(\frac{x}{y},\mu^2)\right\},$$

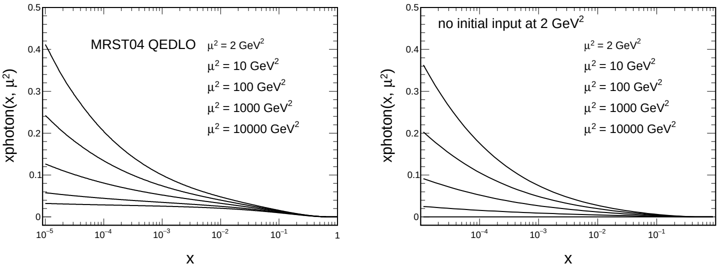
$pp \to l^+ l^-$



Diagramatic representation of the DGLAP with photons

$pp \to l^+ l^-$

Collinear photon distribution in nucleon



initial input is crucial

MRST(QED) input overestimated (see discussion in our paper)

$pp \to l^+ l^-$

$$\frac{d\sigma^{\gamma_{in}\gamma_{in}}}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} x_1\gamma_{in}(x_1, \mu^2)\; x_2\gamma_{in}(x_2, \mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}$$

$$\frac{d\sigma^{\gamma_{in}\gamma_{el}}}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} x_1\gamma_{in}(x_1, \mu^2)\; x_2\gamma_{el}(x_2, \mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}$$

$$\frac{d\sigma^{\gamma_{el}\gamma_{in}}}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} x_1\gamma_{el}(x_1, \mu^2)\; x_2\gamma_{in}(x_2, \mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}$$

$$\frac{d\sigma^{\gamma_{el}\gamma_{el}}}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} x_1\gamma_{el}(x_1, \mu^2)\; x_2\gamma_{el}(x_2, \mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}$$

The elastic photon fluxes are calculated using the Drees-Zeppenfeld parametrization, where a simple parametrization of nucleon electromagnetic form factors was used

$pp \rightarrow l^+ l^-$

$$\mathcal{F}_{\gamma^* \leftarrow A}(z, \boldsymbol{q}) = \frac{\alpha_{\rm em}}{\pi} (1 - z) \left(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_A^2) + z^2 m_A^2} \right)^2 \cdot \frac{p_B^\mu p_B^\nu}{s^2} W_{\mu\nu}(M_X^2, Q^2$$

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

$$W_{\mu\nu}(M_X^2, Q^2) = \overline{\sum_X} (2\pi)^3 \, \delta^{(4)}(p_X - p_A - q) \, \langle p|J_\mu|X\rangle\langle X|J_\nu^\dagger|p\rangle \, d\Phi_X \,, \quad (6)$$

$$W_{\mu\nu}(M_X^2, Q^2) = -\delta^{\perp}_{\mu\nu}(p_A, q)\, W_T(M_X^2, Q^2) + e_\mu^{(0)} e_\nu^{(0)}\, W_L(M_X^2, Q^2)\,. \quad (7)$$

The virtual photoabsorption cross sections are defined as

$$\begin{aligned} \sigma_T(\gamma^* p) &= \frac{4\pi\alpha_{em}}{4\sqrt{X}} \left(-\frac{\delta^{\perp}_{\mu\nu}}{2}\right) 2\pi W^{\mu\nu}(M_X^2, Q^2) \\ \sigma_L(\gamma^* p) &= \frac{4\pi\alpha_{em}}{4\sqrt{X}}\, e_\mu^0 e_\nu^0\, 2\pi W^{\mu\nu}(M_X^2, Q^2)\,. \end{aligned} \quad (8)$$

It is customary to introduce dimensionless structure function $F_i(x_{\mathrm{Bj}}, Q^2)$, $i = T, L$ as

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

In the literature one often finds structure functions $F_1(x_{\mathrm{Bj}}, Q^2)$, $F_2(x_{\mathrm{Bj}}, Q^2)$, which are related to $F_{T,L}$ through

The unintegrated fluxes enter the cross section for dilepton production as

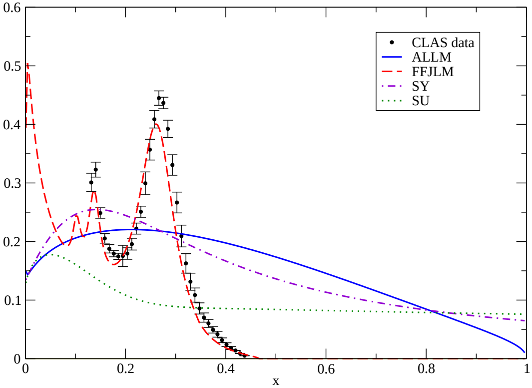
$$\frac{d\sigma^{(i,j)}}{dy_1 dy_2 d^2\mathbf{p}_1 d^2\mathbf{p}_2} = \int \frac{d^2\mathbf{q}_1}{\pi \mathbf{q}_1^2} \frac{d^2\mathbf{q}_2}{\pi \mathbf{q}_2^2} \mathcal{F}^{(i)}_{\gamma^*/A}(x_1, \mathbf{q}_1)\, \mathcal{F}^{(j)}_{\gamma^*/B}(x_2, \mathbf{q}_2) \frac{d\sigma^*(p_1, p_2; \mathbf{q}_1, \mathbf{q}_2)}{dy_1 dy_2 d^2\mathbf{p}_1 d^2\mathbf{p}_2} \tag{11}$$

where i,j=el,ine

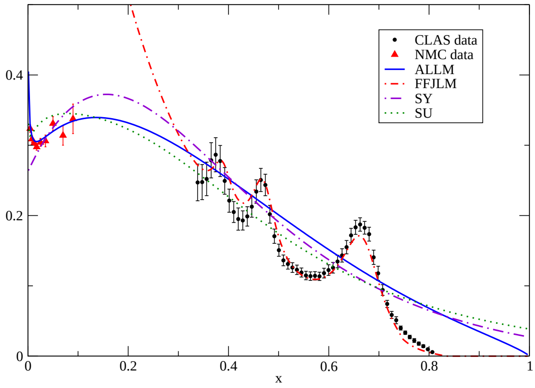
$$x_1 = \sqrt{\frac{\mathbf{p}_1^2 + m_l^2}{s}} e^{y_1} + \sqrt{\frac{\mathbf{p}_2^2 + m_l^2}{s}} e^{y_2} \,,$$

$$x_2 = \sqrt{\frac{\mathbf{p}_1^2 + m_l^2}{s}} e^{-y_1} + \sqrt{\frac{\mathbf{p}_2^2 + m_l^2}{s}} e^{-y_2} \,. \tag{12}$$

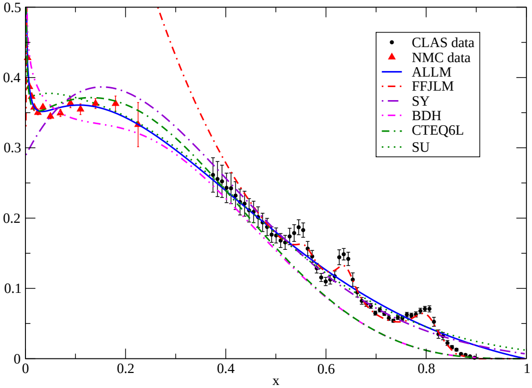
$pp \to l^+ l^-$



$pp \rightarrow l^+ l^-$

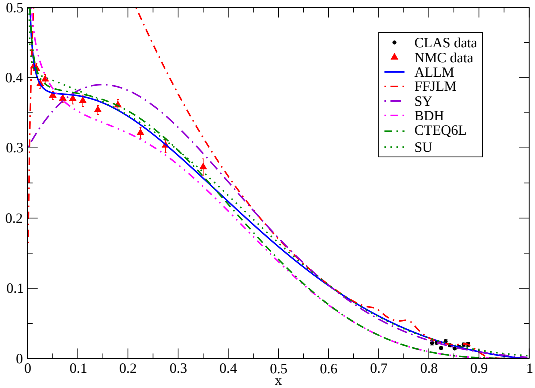


$pp \to l^+ l^-$



CLAS data
NMC data
ALLM
FFJLM
SY
BDH
CTEQ6L
SU
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
x

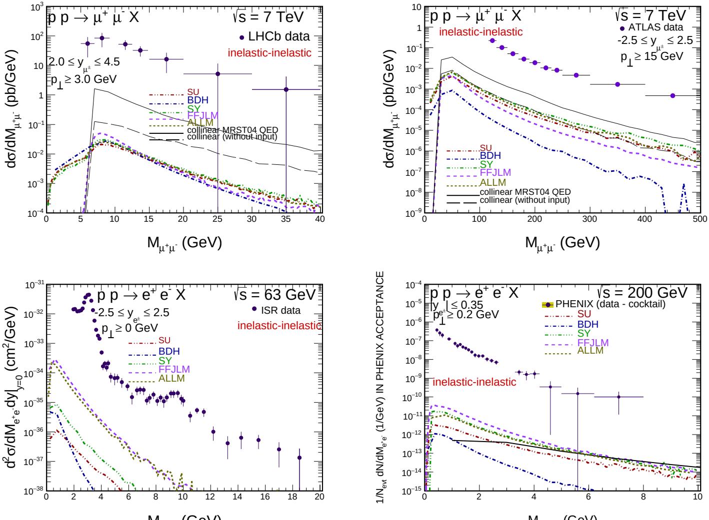
$pp \to l^+ l^-$



0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x
CLAS data
NMC data
ALLM
FFJLM
SY
BDH
CTEQ6L
SU

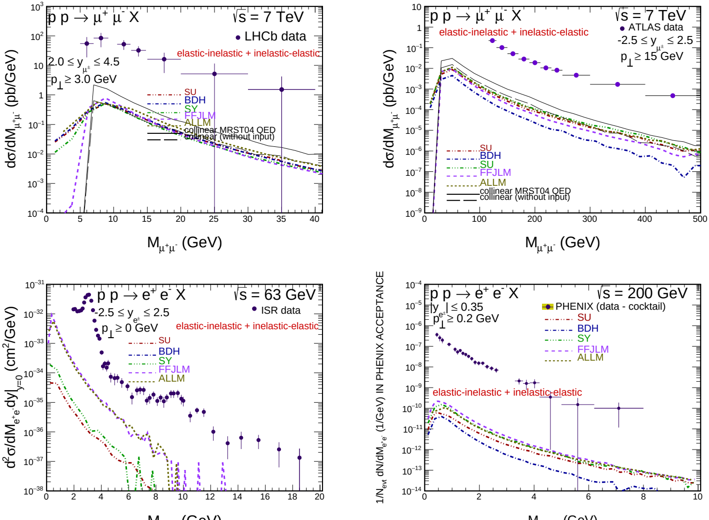
$pp \to l^+ l^-$

k_t-factorization, including photon transverse momenta

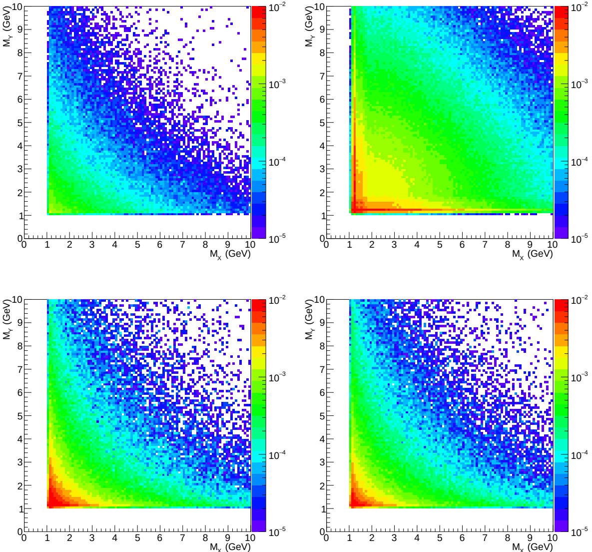


$pp \to l^+ l^-$

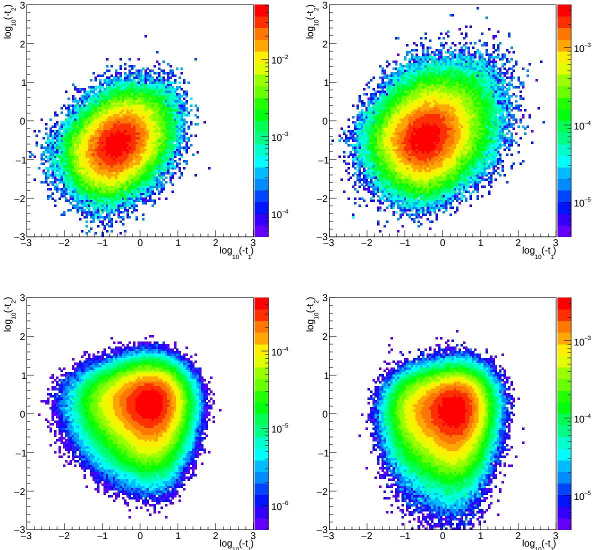
k_t-factorization, including photon transverse momenta



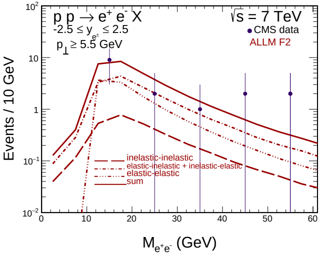
$pp \rightarrow l^+ l^-$,SU,FFJLM,SY,ALLM

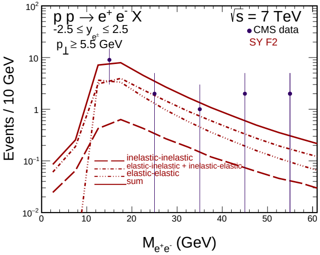


$pp \to l^+ l^-$, ISR, PHENIX, ATLAS, LHCb



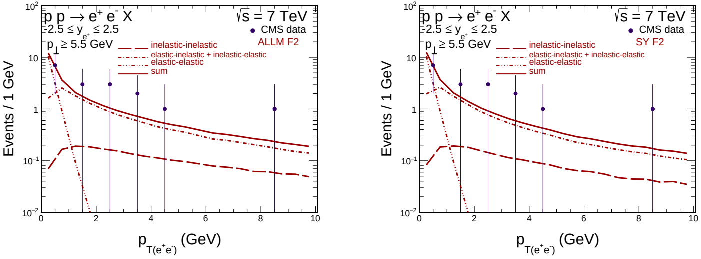
$pp \to l^+ l^-$





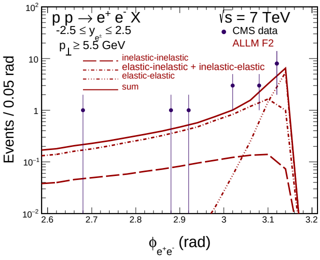
isolated electrons

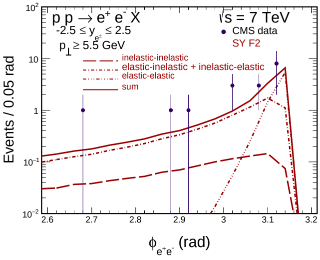
$pp \to l^+ l^-$



isolated electrons

$pp \to l^+ l^-$





isolated electrons

$pp \to l^+l^-$

- 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 $pp \to ppJ/\psi$)
- 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 $pp \to (\gamma\gamma) \to W^+W^-XY$ processes (important in searches for Beyond Standard Model effects)