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

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Outline

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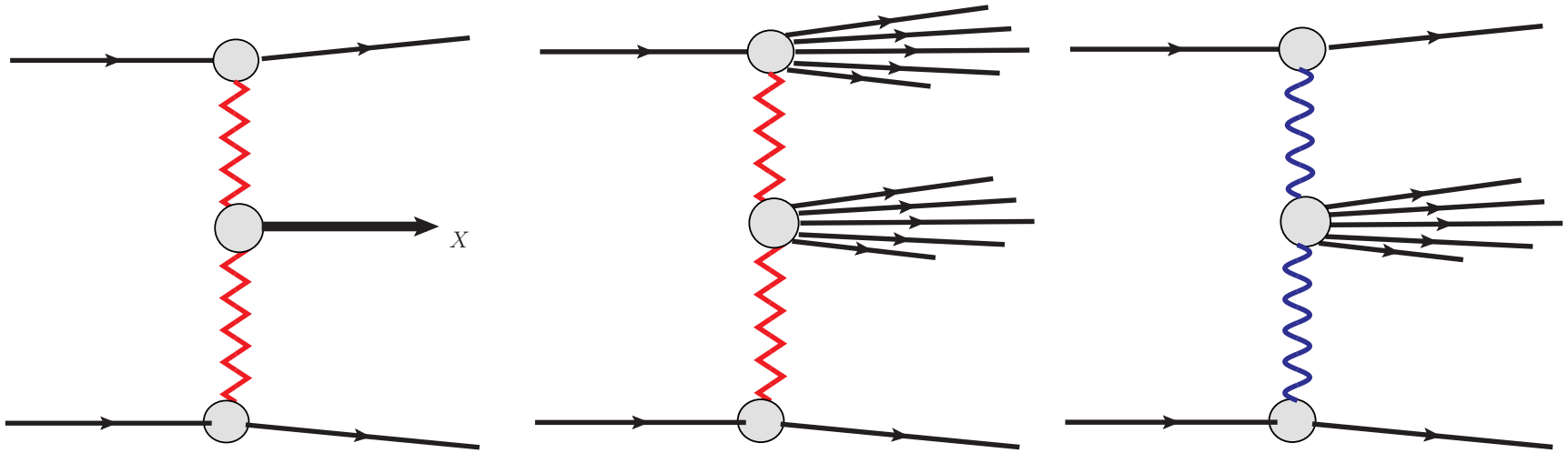
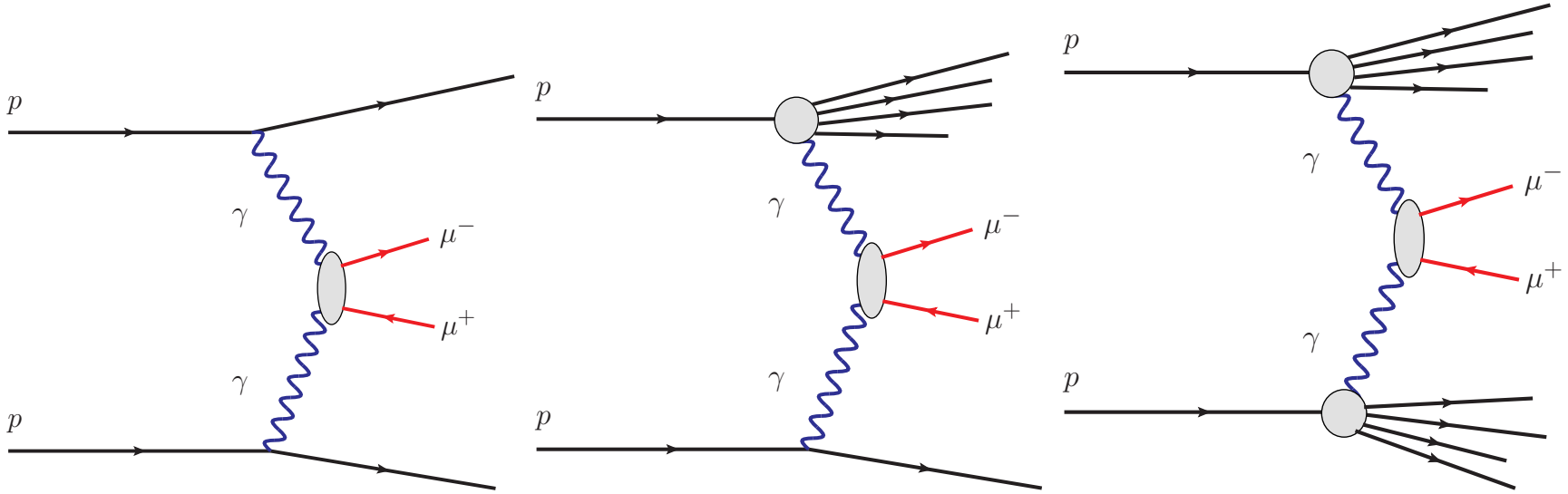


- we often have to deal with diffractive reactions which include excitation of incoming protons. Instead of fully inclusive final states: gap cross sections, gap vetos or even only vetos on additional tracks(!) from a production vertex.
- muons: continuum background in J/psi, Upsilon production; background in $pp \to ppW^+W^-$ which is measured via the $\mu^+\mu^-\nu\bar{\nu}$ channel.

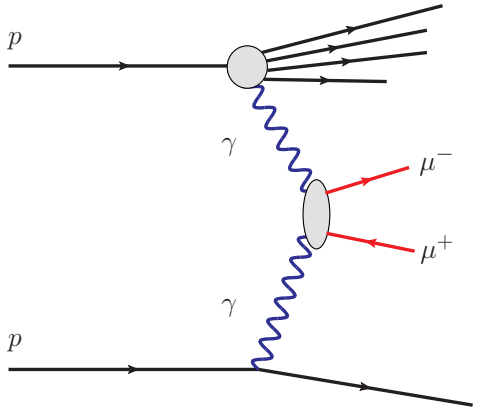
Introduction

- 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 $\gamma Z \to e^+ e^- Z$ 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, $\epsilon \sim m^2/s$, $\boldsymbol{p}^2/s$, $m|\boldsymbol{p}|/s \ll 1$, the "impact factor" form of the amplitude holds (Lipatov, Gribov & Frolov (1970), Cheng & Wu (1970)).



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

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

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

$$T_{\alpha\beta} = \gamma_\alpha\frac{\hat{q}_1-\hat{p}_+ + m}{(q_1-p_+)^2-m^2}\gamma_\beta + \gamma_\beta\frac{\hat{q}_2-\hat{p}_+ + m}{(q_2-p_+)^2-m^2}\gamma_\alpha\,,\;\hat{q}_1 \equiv q_{1\mu}\gamma_\mu\,\text{etc..}$$

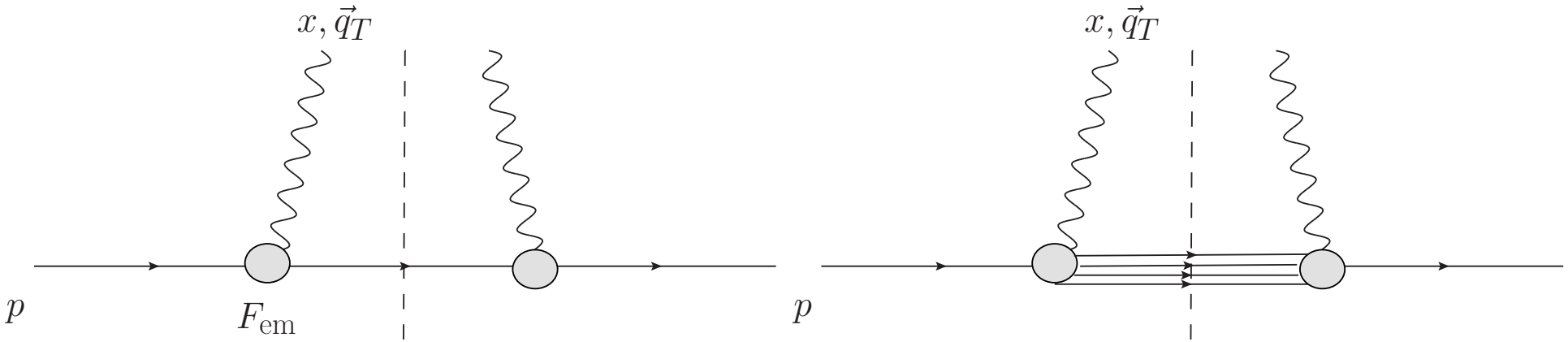
k_T-factorization form of the differential cross section

$$\frac{d\sigma(AB \to X l^+ l^- Y)}{dy_+ dy_- d^2\boldsymbol{p}_+ d^2\boldsymbol{p}_-} = \int \frac{d^2\boldsymbol{q}_1}{\pi \boldsymbol{q}_1^2} \frac{d^2\boldsymbol{q}_2}{\pi \boldsymbol{q}_2^2} \underbrace{\mathcal{F}_{\gamma^*/A}(x_1, \boldsymbol{q}_1)\, \mathcal{F}_{\gamma^*/B}(x_2, \boldsymbol{q}_2)}_{\text{unintegrated photon dist.}} \underbrace{\frac{d\sigma^*(p_+, p_-; \boldsymbol{q}_1, \boldsymbol{q}_2)}{dy_+ dy_- d^2\boldsymbol{p}_+ d^2\boldsymbol{p}_-}}_{\text{off-shell x-sec}},$$

$$x_1 = \frac{m_{\perp +}}{\sqrt{s}} e^{y_+} + \frac{m_{\perp -}}{\sqrt{s}} e^{y_-}\ ,\ x_2 = \frac{m_{\perp +}}{\sqrt{s}} e^{-y_+} + \frac{m_{\perp -}}{\sqrt{s}} e^{-y_-}\ ,\ m_{\perp \pm} = \sqrt{\boldsymbol{p}_\pm^2 + m_l^2}\,.$$

$$\frac{d\sigma^*(p_+, p_-; \boldsymbol{q}_1, \boldsymbol{q}_2)}{dy_1 dy_2 d^2\boldsymbol{p}_+ d^2\boldsymbol{p}_-} = \frac{\alpha_{\rm em}^2}{\boldsymbol{q}_1^2 \boldsymbol{q}_2^2} \sum_{\lambda, \bar{\lambda}} \left| B_{\lambda\bar{\lambda}}(p_+, p_-; q_1, q_2) \right|^2 \delta^{(2)}(\boldsymbol{q}_1 + \boldsymbol{q}_2 - \boldsymbol{p}_+ - \boldsymbol{p}_-).$$

Lepton pair production in the high energy limit



$$\mathcal{F}_{\gamma/A}(x, \boldsymbol{q}^2) = \frac{\alpha_{\rm em}}{\pi}(1-x)\left[\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + x^2 m_p^2}\right]^2 \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2}\left(1 - \frac{Q^2 - \boldsymbol{q}^2}{Q^2}\right).$$

$$\mathcal{F}^{(\rm inel)}_{\gamma/A}(x, \boldsymbol{q}^2) = \frac{\alpha_{\rm em}}{\pi}(1-x)\int_{M^2_{\rm thr}}^{\infty} \frac{dM_X^2 F_2(M_X^2, Q^2)}{M_X^2 + Q^2 - m_p^2}\left(1 - \frac{Q^2 - \boldsymbol{q}^2}{Q^2}\right)\left[\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + x(M_X^2 - m_p^2) + x^2 m_p^2}\right]^2.$$

$$Q^2 = \frac{1}{1-x}\left[\boldsymbol{q}_1^2 + x(M_X^2 - m_p^2) + x_1^2 m_p^2\right] \tag{1}$$

For the off-shell cross section a particularly simple form can be obtained in terms of the variables;

$$z_\pm = \frac{m_{\perp\pm}}{(x_1+x_2)\sqrt{s}}\, e^{y_\pm}\ ,\ \boldsymbol{p} = z_-\boldsymbol{p}_+ - z_+\boldsymbol{p}_-\ ,.$$

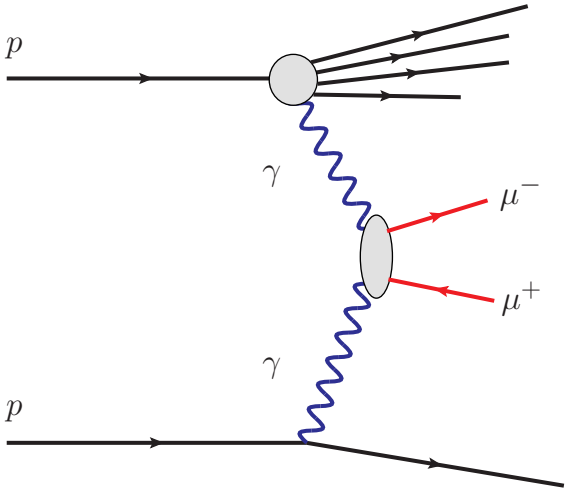
The familiar structures

$$\Phi_0 = \frac{1}{(\boldsymbol{p}+z_+\boldsymbol{q}_2)^2+\varepsilon^2} - \frac{1}{(\boldsymbol{p}-z_-\boldsymbol{q}_2)^2+\varepsilon^2}\ ,$$
$$\boldsymbol{\Phi}_1 = \frac{\boldsymbol{p}+z_+\boldsymbol{q}_2}{(\boldsymbol{p}+z_+\boldsymbol{q}_2)^2+\varepsilon^2} - \frac{\boldsymbol{p}-z_-\boldsymbol{q}_2}{(\boldsymbol{p}-z_-\boldsymbol{q}_2)^2+\varepsilon^2}\ ,$$

with $\varepsilon^2 = m_l^2 + z_+z_-\boldsymbol{q}_1^2$, enter the off-shell matrix element:

$$\sum_{\lambda,\bar\lambda}\left|B_{\lambda\bar\lambda}(p_+,p_-;q_1,q_2)\right|^2 = 2z_+z_-\boldsymbol{q}_1^2\Big[\underbrace{4z_+^2z_-^2\boldsymbol{q}_1^2\Phi_0^2}_{\mathrm{L}} + \Big(\underbrace{(z_+^2+z_-^2)\boldsymbol{\Phi}_1^2 + m_l^2\Phi_0^2}_{\mathrm{T}}\Big)$$
$$+\underbrace{4z_+z_-(z_+-z_-)\Phi_0(\boldsymbol{q}_1\boldsymbol{\Phi}_1)}_{LT}\Big]$$

Distribution in $\boldsymbol{p}_{\rm sum} = \boldsymbol{p}_+ + \boldsymbol{p}_-$ in "elastic-inelastic" events



- If $\boldsymbol{p}^2_{\rm sum} \gg \Lambda^2 \sim 0.71\,{\rm GeV}^2$, The decorrelation momentum $\boldsymbol{p}_{sum}$ is *exactly equal* to the transverse momentum carried by the "inelastic" photon.
- The "lepton dijet" decorrelation momentum distribution *directly probes* the unintegrated photon distribution.

$$\frac{d\sigma(AB \to Al^+l^-X)}{dy_1\,dy_2\,d^2\boldsymbol{p}_1\,d^2\boldsymbol{p}_2} = n(x_1)\,\frac{\alpha^2_{\rm em}\mathcal{F}(x_2,\boldsymbol{p}_1+\boldsymbol{p}_2)}{(\boldsymbol{p}_1+\boldsymbol{p}_2)^2}\,\frac{2z_+z_-(z_+^2+z_-^2)}{\boldsymbol{p}_1^2\boldsymbol{p}_2^2}\,. \tag{2}$$

Here

$$n(x_1) = \int \frac{d^2\boldsymbol{q}_1}{\pi\boldsymbol{q}_1^2}\,\mathcal{F}(x_1,\boldsymbol{q}_1)\,, \tag{3}$$

is the Weizsäcker-Williams flux of photons in the elastically scattered proton.

Input for our calculation

- elastic vertex: dipole formfactor

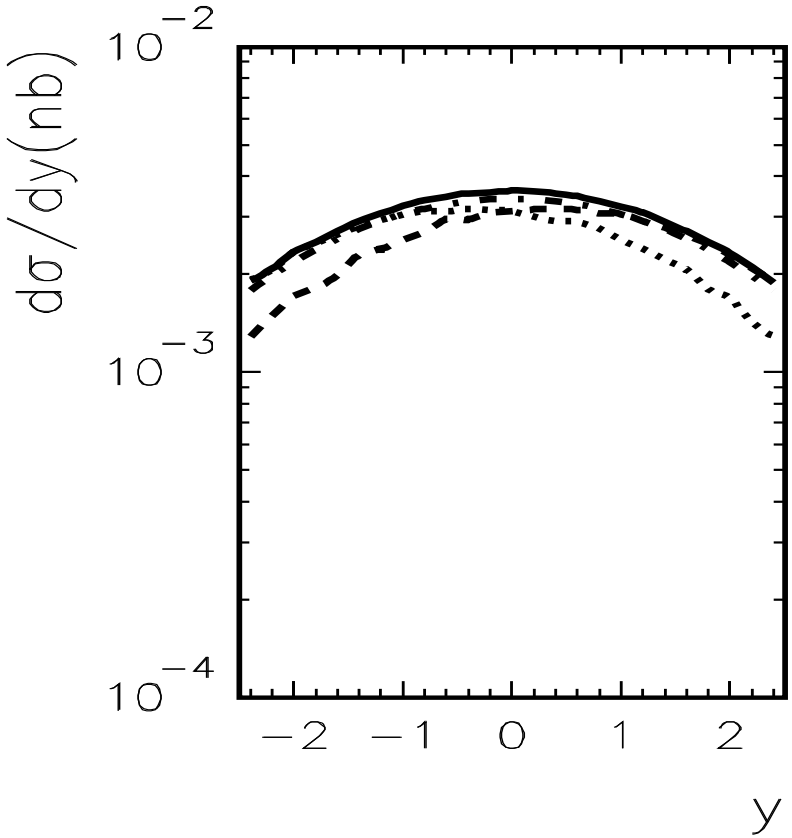
$$G_E(Q^2) = \frac{1}{(1+Q^2/\Lambda^2)^2}\,, G_M(Q^2) = \mu G_E(Q^2),\ \mu = 2.79, \Lambda^2 = 0.71\,\mathrm{GeV}^2\,.$$

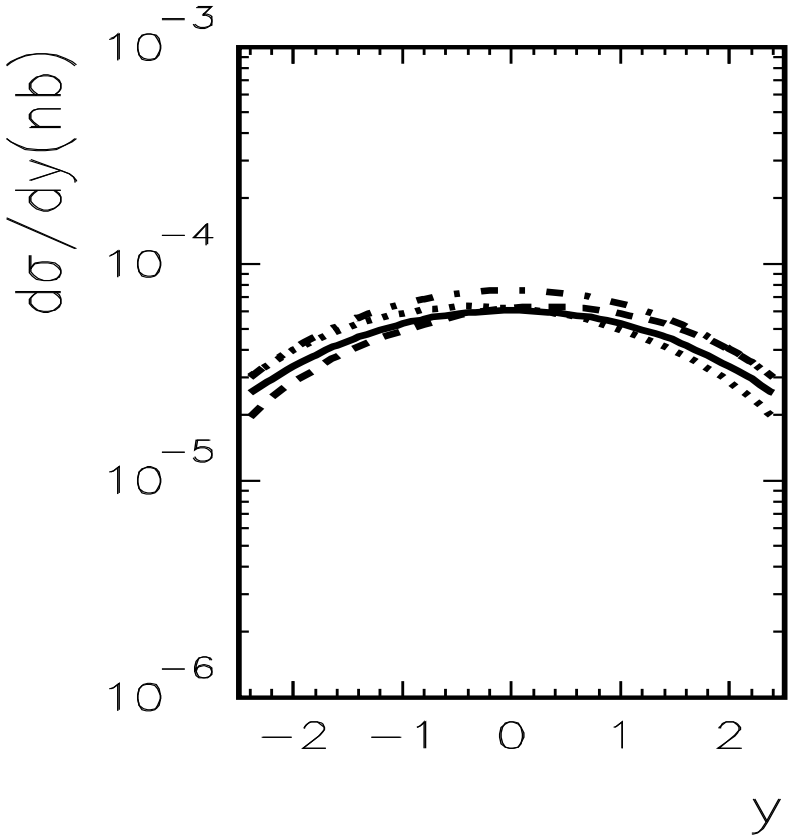
- inelastic vertex: different parametrizations of $F_2(x_{\mathrm{Bj}}, Q^2)$
  - "SU": A. Szczurek & V. Uleshchenko, (2000). Puts an emphasis on the low-to-intermediate Q^2-region and includes a smooth continuation to low-Q^2.
  - "MSTW": a modern parametrization of Partons, DGLAP evolution.
  - "SY": 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: $p_T > 3\,\mathrm{GeV}$ and hard: $p_T > 15\,\mathrm{GeV}$.
- mass M_X of the excited hadronic system: $m_p + m_\pi < M_X < 320\mathrm{GeV}$

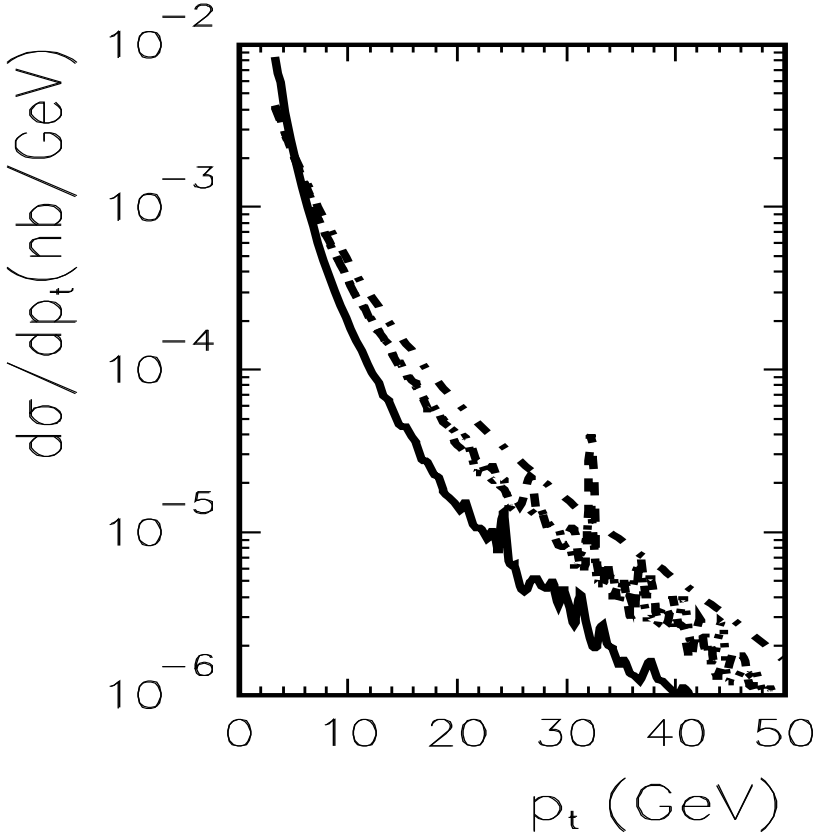
Rapidity distributions

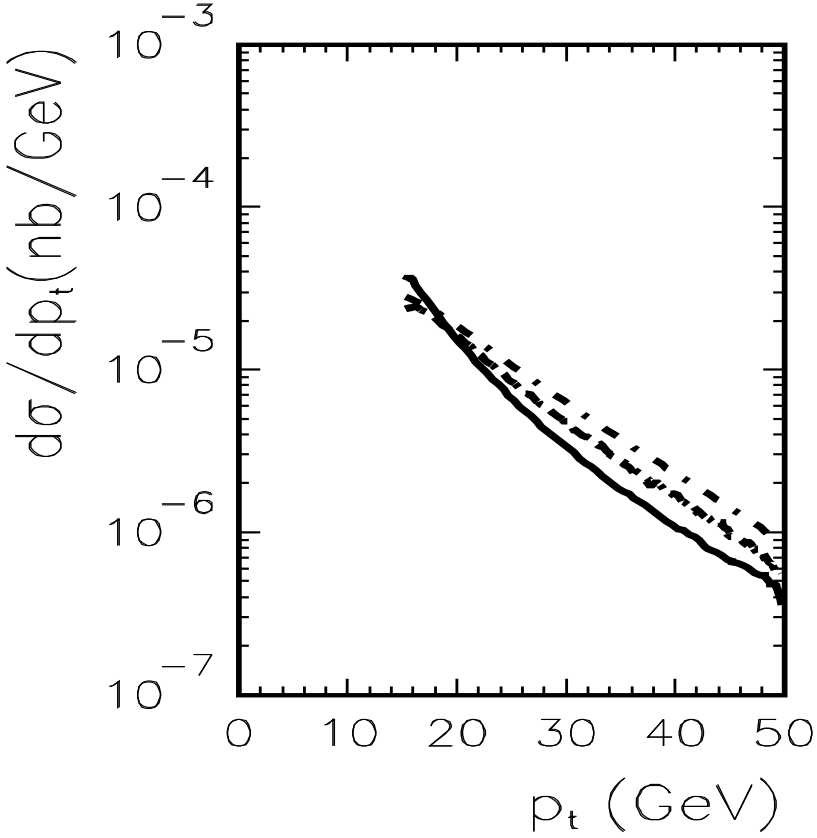




- left panel: $p_T > 3\,\mathrm{GeV}$, right panel: $p_T > 15\,\mathrm{GeV}$
- solid: elastic-elastic, dashed: inelastic - elastic, dash-dotted: inelastic - inelastic
- Photon from the inelastic vertex is harder $\rightarrow$ asymmetry of elastic-inelastic contribution.

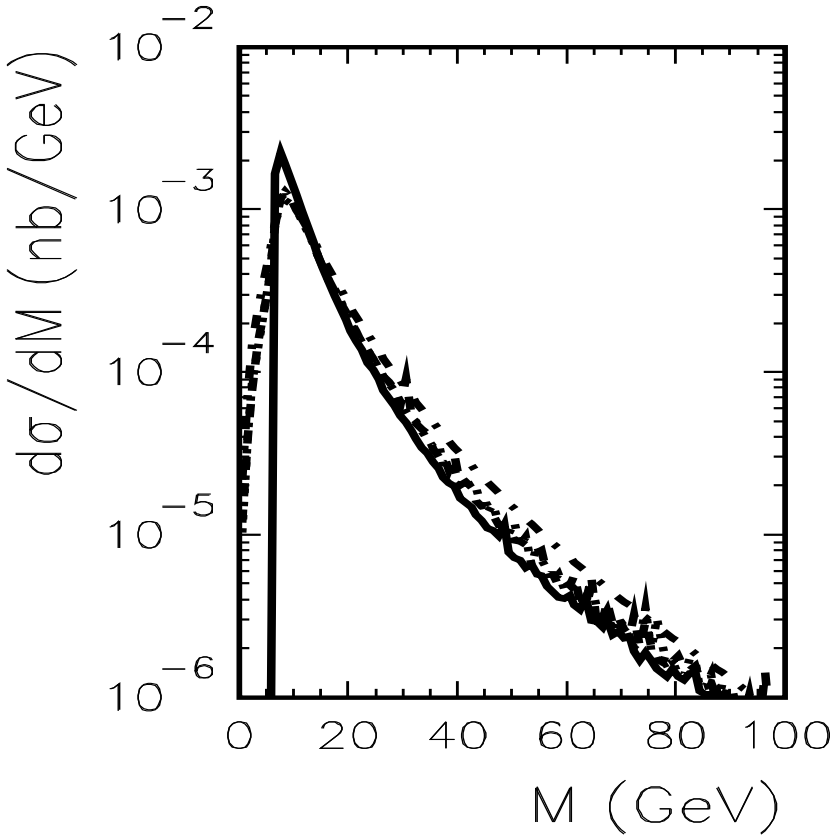
Transverse momentum distributions of muons

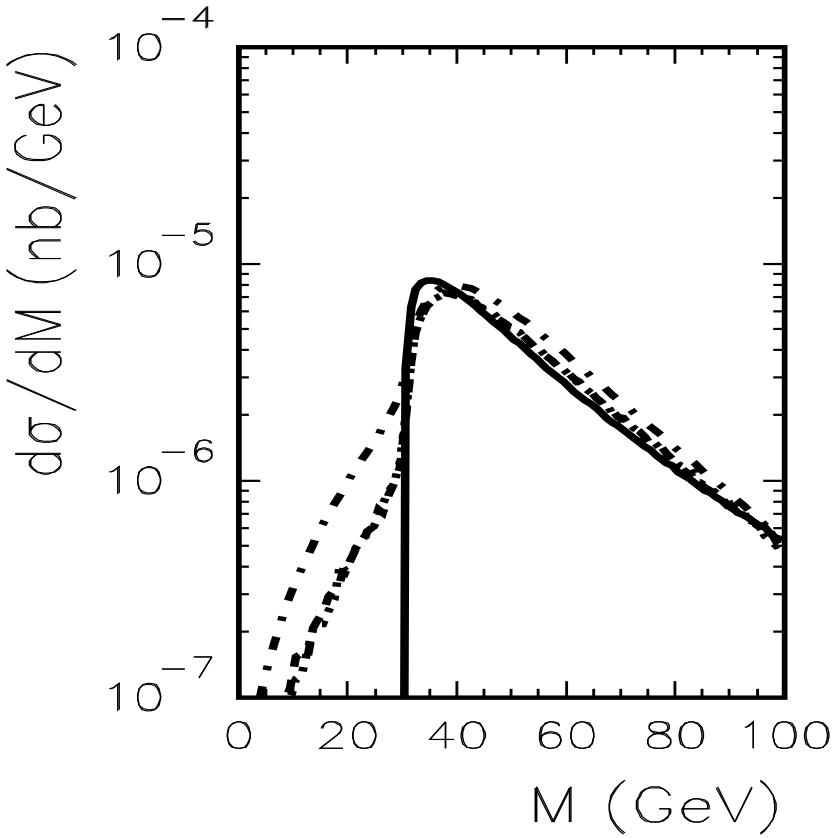




- left panel: $p_T > 3\,\mathrm{GeV}$, right panel: $p_T > 15\,\mathrm{GeV}$
- solid: elastic-elastic, dashed: inelastic - elastic, dash-dotted: inelastic - inelastic

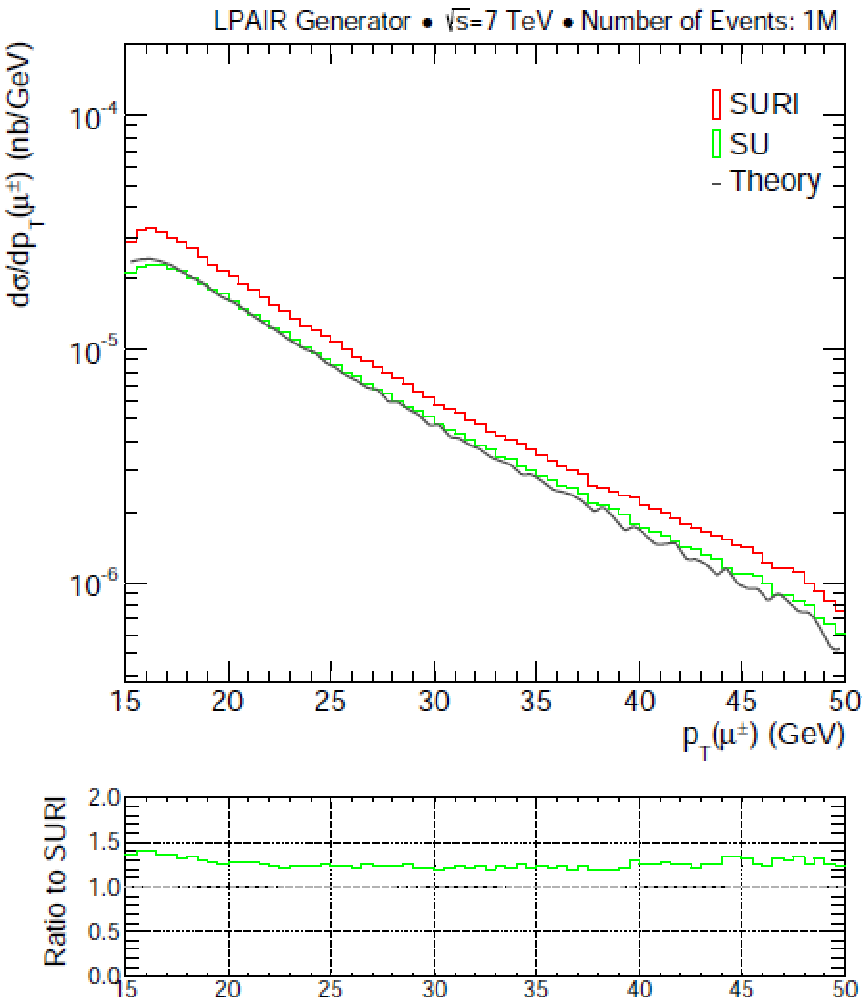
Invariant mass distributions

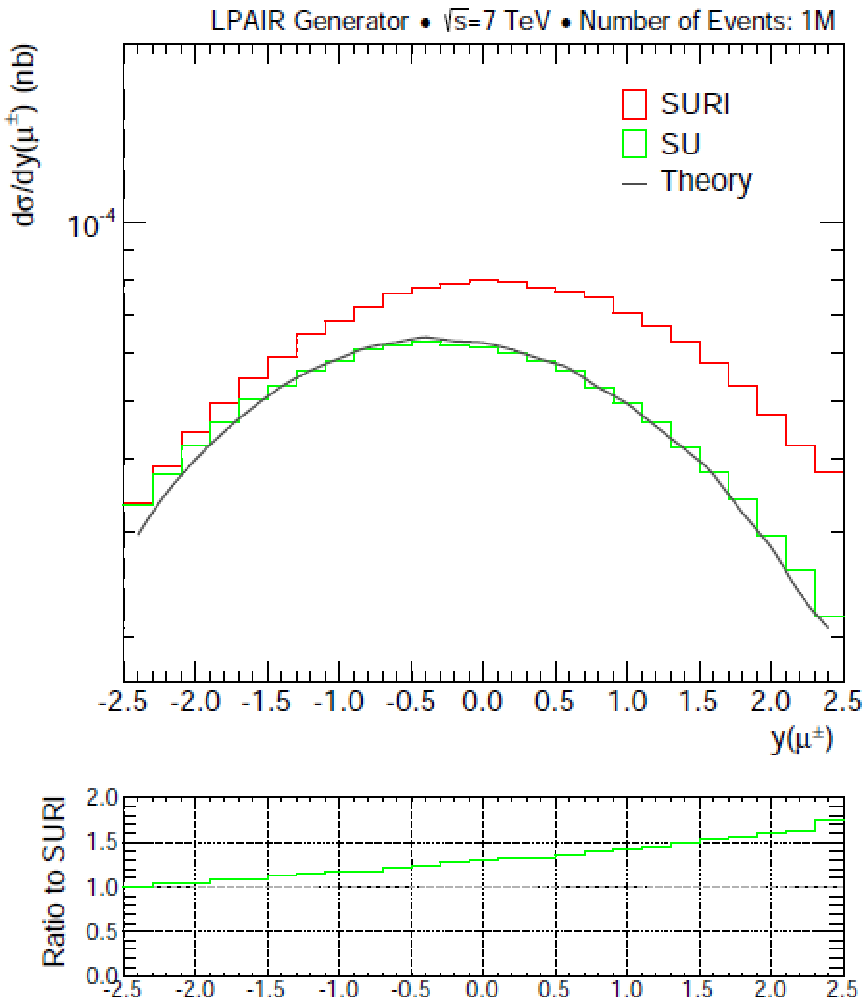




- left panel: $p_T > 3\,\mathrm{GeV}$, right panel: $p_T > 15\,\mathrm{GeV}$
- solid: elastic-elastic, dashed: inelastic - elastic, dash-dotted: inelastic - inelastic
- low-mass tail for the inelastic contribution comes from pairs with large $\boldsymbol{p}_{\mathrm{sum}}$.

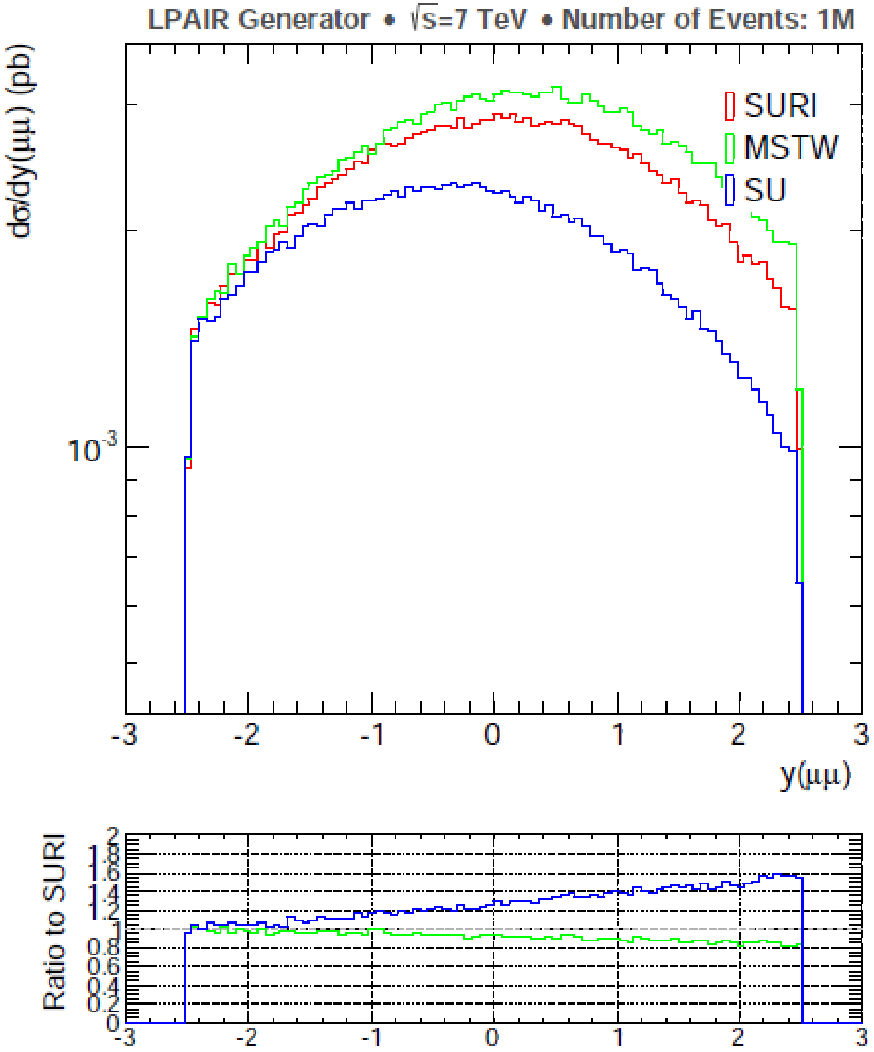
Comparison "k_T-factorization" vs. LPAIR

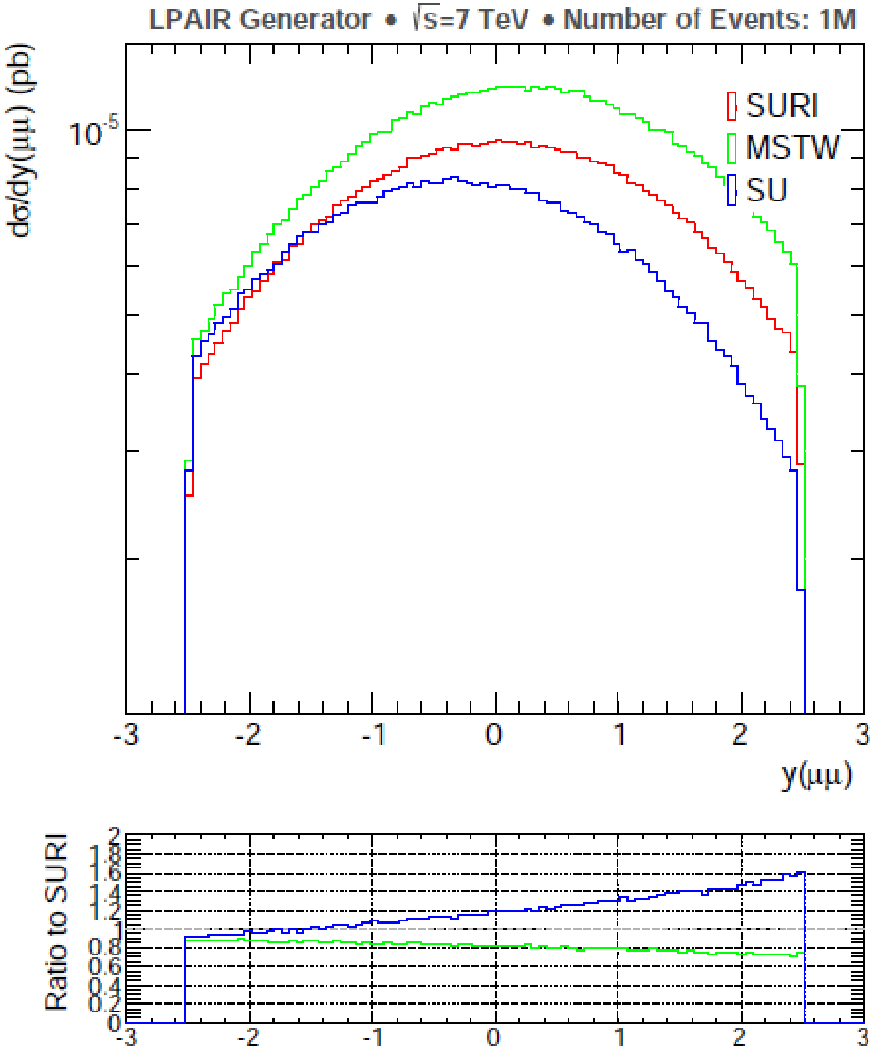




- left panel: $p_T > 3\,\mathrm{GeV}$, right panel: $p_T > 15\,\mathrm{GeV}$

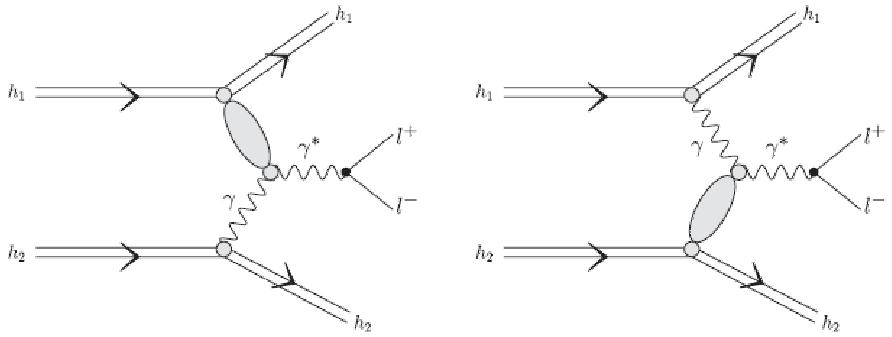
Options for F_2 in LPAIR

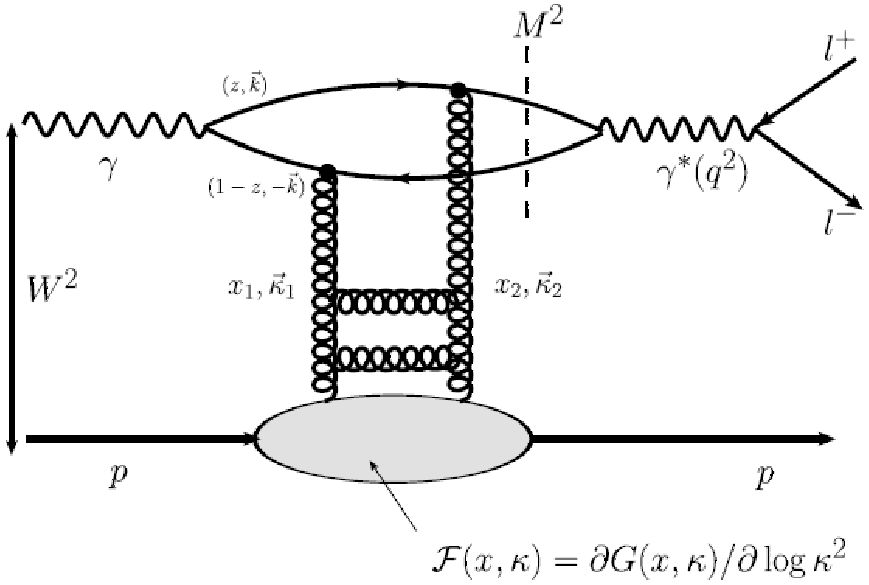




- left panel: $p_T > 3\,\mathrm{GeV}$, right panel: $p_T > 15\,\mathrm{GeV}$

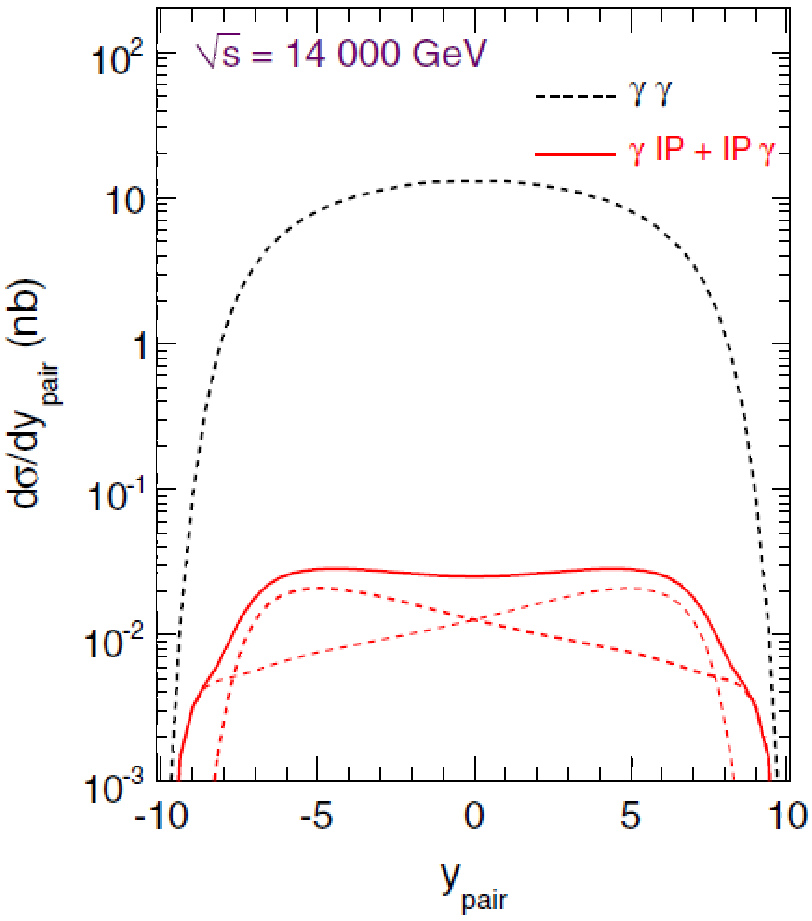
Timelike Compton scattering

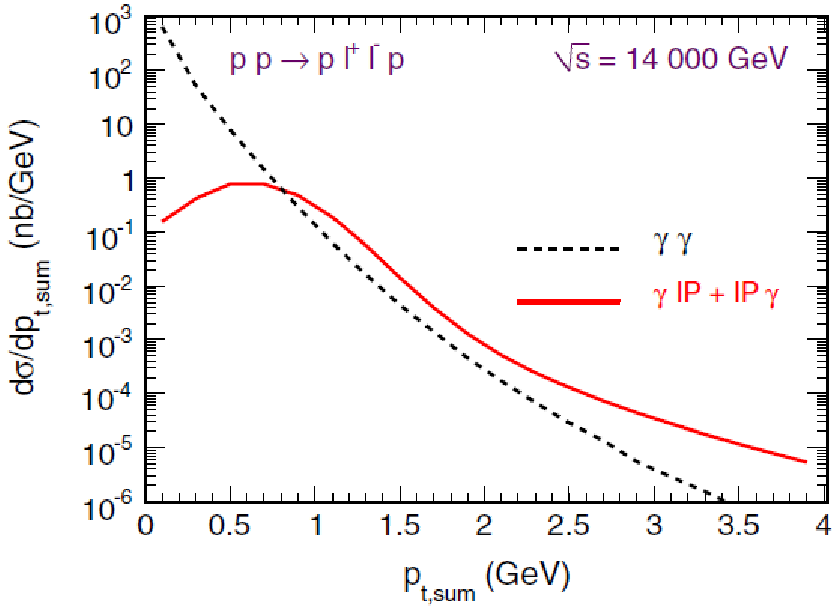




- shares many properties with vector meson production, but the *timelike* nature of the photon leads to a complicated phase & interferences & flavour dependence.
- dileptons are of *odd* C-parity.

Dileptons from $\gamma - \mathbb{P}$-fusion





- G. Kubasiak & A. Szczurek, Phys. Rev. **D84** (2011)
- caveat: calculation does not include absorptive effects. (compare A. Cisek's talk on VM's).

Summary & Outlook

- 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 ar 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: $\gamma\mathbb{P}$-fusion ...