Lepton pair production and proton dissociation

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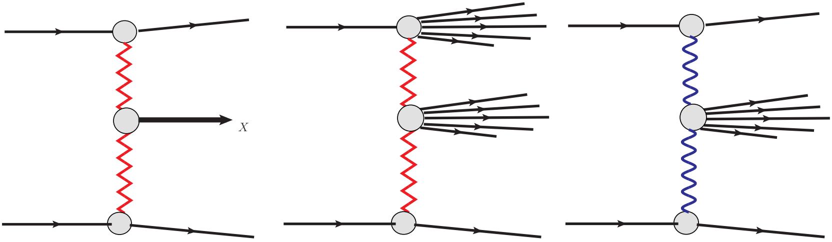
Outline

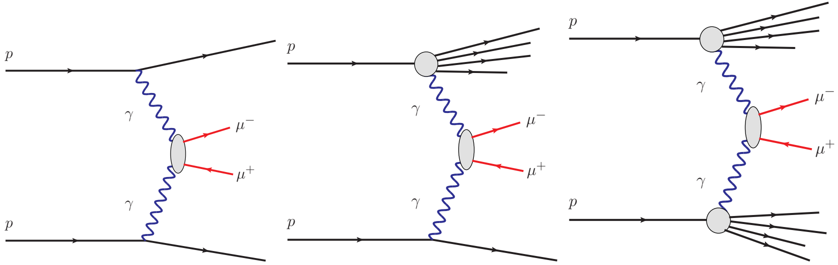
- Gustavo da Silveira, Laurent Forthomme, Krzysztof Piotrzkowski, W.S, Antoni Szczurek, JHEP 1502 (2015) 159.
- Marta Łuszczak, W.S., Antoni Szczurek, in preparation.



- large rapidity gaps: no exchange of charge or color. t-channel exchanges with the (running) spin $J(t) \geq 1$.
- C-parity constraint: $C_X = C_1 \times C_2$. even: Pomeron, odd: Odderon, photon.
- 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.
- This talk: $\gamma\gamma \to \mu^+\mu^-, \gamma\mathbb{P} \to \gamma^* \to \mu^+\mu^-$
- muons: continuum background in exclusive $J/\psi, \Upsilon$ production; background in $pp \to ppW^+W^-$ which is measured via the $\mu^+\mu^-\nu\bar{\nu}$ channel. Hunting for anomalous quartic gauge couplings in $\gamma\gamma \to W^+W^-$.

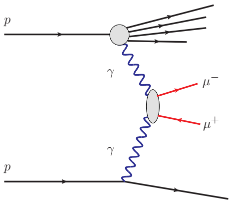
Introduction

- 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 (collinear).
- 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, $\epsilon \sim m^2/s$, $\mathbf{p}^2/s$, $m|\mathbf{p}|/s \ll 1$, 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

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

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

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

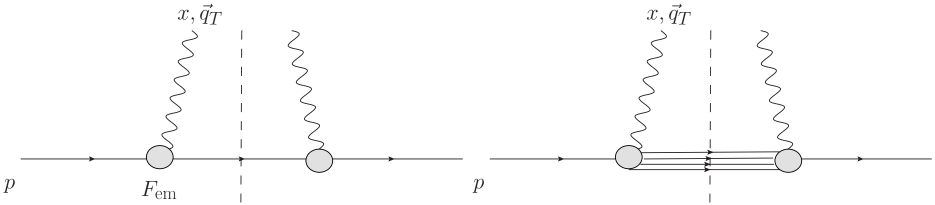
Using $q_i = x_i p_i + q_{i\perp}$ and gauge invariance $q_{i\alpha} \bar u_\lambda(p_-)\, T_{\alpha\beta} v_{\bar\lambda}(p_+) = 0$:

$$p_{1_\alpha} p_{2\beta} \bar u_\lambda(p_-)\, T_{\alpha\beta} v_{\bar\lambda}(p_+) = \frac{|\boldsymbol{q}_1||\boldsymbol{q}_2|}{x_1 x_2} e_{1_\alpha} e_{2\beta} \bar u_\lambda(p_-)\, T_{\alpha\beta} v_{\bar\lambda}(p_+)\,,$$

with $e_i = q_{\perp i}/|\boldsymbol{q}_i|, i = 1, 2$ ("off-shell" polarization vectors). Hence the off-shell cross section assumes the intuitively expected form

$$d\sigma^*(p_+, p_-; \boldsymbol{q}_1, \boldsymbol{q}_2) = \frac{1}{2 x_1 x_2 s} (4\pi\alpha_{\rm em})^2 \Big| e_{1_\alpha} e_{2\beta} \bar u_\lambda(p_-)\, T_{\alpha\beta} v_{\bar\lambda}(p_+) \Big|^2 d\Phi(M^2; p_+, p_-).\,,$$

Lepton pair production in the high energy limit



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

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

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

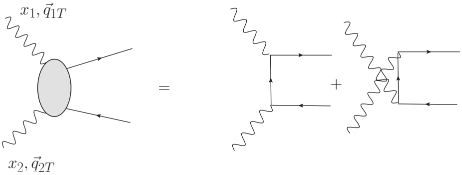
For the off-shell cross section a particularly simple form can be obtained in terms of the variables

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

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:

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

$$\underbrace{+ 4 z_+ z_- (z_+ - z_-) \Phi_0 (\boldsymbol{q}_1 \boldsymbol{\Phi}_1)}_{LT} \Big]$$

e.g. from Bartos, Gevorkyan, Kuraev & Nikolaev (2002) .

Input for our calculation

- elastic vertex: dipole formfactor

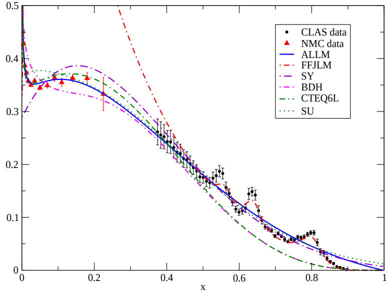
$$G_E(Q^2) = \frac{1}{(1+Q^2/\Lambda^2)^2}\,, G_M(Q^2) = \mu G_E(Q^2),\ \mu = 2.79, \Lambda^2 = 0.71\,\mathrm{GeV}^2\,.$$

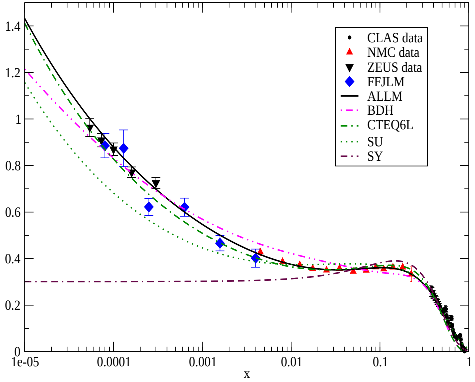
- inelastic vertex: different parametrizations of $F_2(x_{\rm Bj}, Q^2)$
  - "SU": A. Szczurek & V. Uleshchenko, (2000). Puts an emphasis on the low-to-intermediate Q^2-region and includes a smooth continuation to low-Q^2.
  - "ALLM": Abramowicz, Levin, Levy & Maor (1997), update by Abramowicz & Levy (2004). Regge theory inspired fit. Gives vary good description of available data, but extrapolates "hard Pomeron"'-like to very small x.
  - "BDH": Block, Durand & Ha (2014), available for $W > 20$ GeV. Also very good fit of data. Asymptotic behaviour "Froissart"-like.
  - "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:

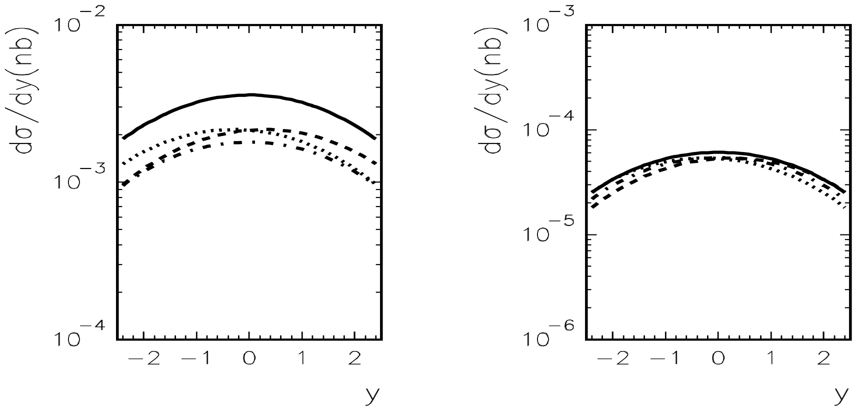
- $-2.5 < y < 2.5$ for the muon rapidities.
- two types of cuts on muon p_T: soft: $p_T > 3\,\mathrm{GeV}$ and hard: $p_T > 15\,\mathrm{GeV}$.
- mass M_X of the excited hadronic system: $m_p + m_\pi < M_X < 1\,\mathrm{TeV}$

Fits to the $F_2(x, Q^2)$ structure function, $Q^2 = 2.5\,\mathrm{GeV}^2$



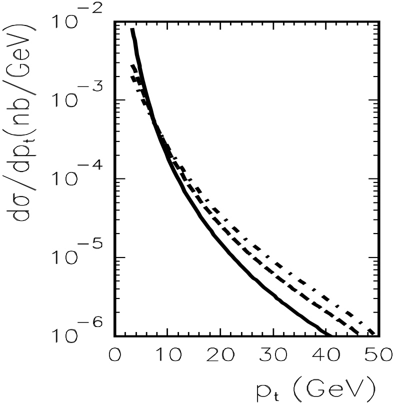


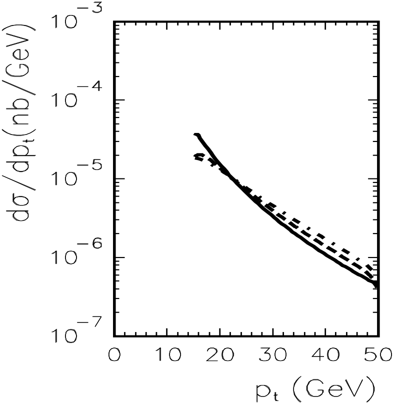
Rapidity distributions



- 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 → asymmetry of elastic-inelastic contribution.

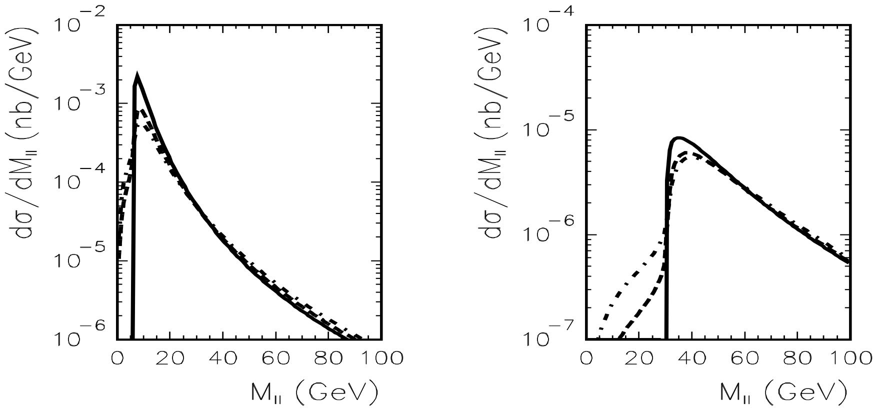
Transverse momentum distributions of muons





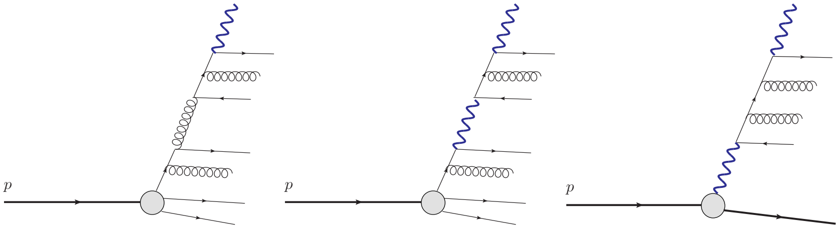
- left panel: $p_T > 3\,\mathrm{GeV}$, right panel: $p_T > 15\,\mathrm{GeV}$
- solid: elastic-elastic, dashed: inelastic - elastic, dash-dotted: inelastic - inelastic

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 $\boldsymbol{p}_{\mathrm{sum}}$.

Photons as collinear DGLAP partons



photon distribution

$$\frac{d\gamma(x,Q^2)}{d\log Q^2} = \frac{\alpha_{\rm em}}{2\pi}\int_x^1 \frac{dy}{y}\Big\{\sum_f e_f^2 P_{\gamma\leftarrow q}(y)\Big[q_f\Big(\frac{x}{y},Q^2\Big)+\bar{q}_f\Big(\frac{x}{y},Q^2\Big)\Big]$$

$$+P_{\gamma\leftarrow\gamma}(y)\gamma\Big(\frac{x}{y},Q^2\Big)\Big\}.$$

$$\frac{dq_f(x,Q^2)}{d\log Q^2} = \frac{dq_f(x,Q^2)}{d\log Q^2}\Big|_{\rm QCD} + \frac{\alpha_{\rm em}}{2\pi}\int_x^1 \frac{dy}{y} P_{q\leftarrow\gamma}(y)\gamma\Big(\frac{x}{y},Q^2\Big)$$

Photons as collinear DGLAP partons

Due to the smallness of $\alpha_{\rm em}$ one would expect that the effect of photons on the quark and antiquark densities can be safely neglected, unless one is interested in high order perturbative corrections to the QCD splitting functions themselves. Then, at sufficiently large virtuality Q_0^2, the photon parton density can be calculated from the collinear splitting of quarks and antiquarks $q \to q\gamma, \bar{q} \to \bar{q}\gamma$ (Glück, Pisano, Reya '02).

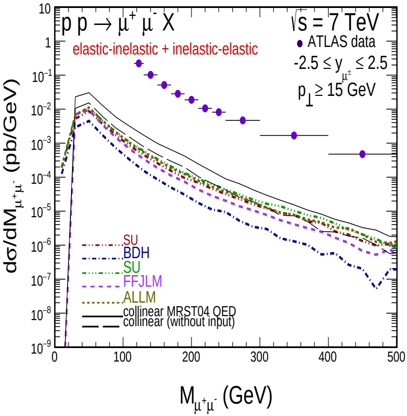
$$\gamma(z, Q^2) = \sum_f \frac{\alpha_{em} e_f^2}{\pi} \int_{Q_0^2}^{Q^2} \frac{d\mu^2}{\mu^2} \int_z^1 \frac{dx}{x} P_{\gamma \leftarrow q}\left(\frac{z}{x}\right) \left[q_f(x, \mu^2) + \bar{q}_f(x, \mu^2)\right] + \gamma(z, Q_0^2)\,.$$

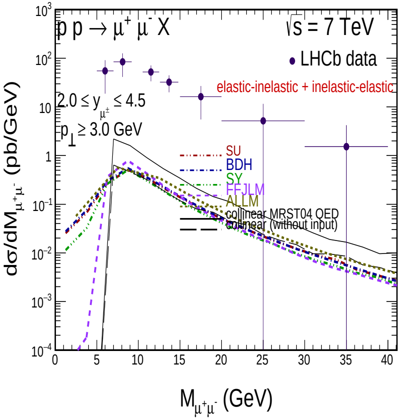
The "input" $\gamma(z, Q_0^2)$ will in general contain the elastic (coherent) contribution!

k_T-factorization

$$\begin{aligned} dn &= \frac{dz}{z} \frac{d^2\boldsymbol{q}}{\pi \boldsymbol{q}^2} \mathcal{F}_{\gamma^* \leftarrow A}(z, \boldsymbol{q}) \\ &= \frac{\alpha_{em}}{2\pi} \int_z^1 \frac{dx_{\rm Bj}}{x_{\rm Bj}} P_{\gamma \leftarrow q}\left(\frac{z}{x_{\rm Bj}}\right) \frac{F_2(x_{\rm Bj}, Q^2)}{x_{\rm Bj}} \left(1 - \frac{z}{x_{\rm Bj}}\right) \end{aligned}$$

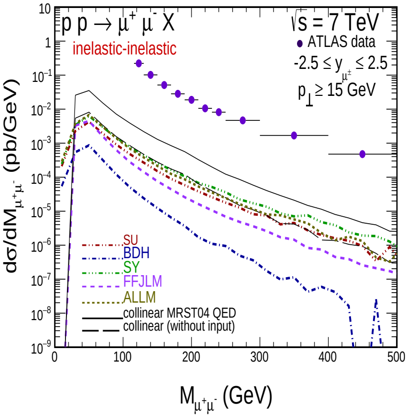
Comparison with Drell-Yan data – elastic-inelastic contributions

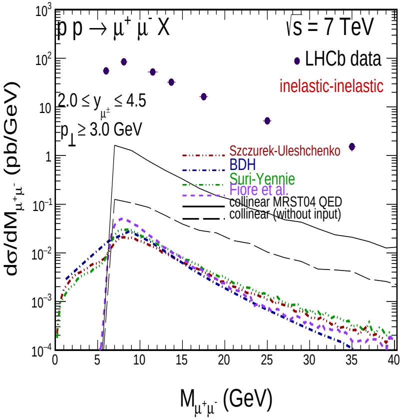




- inclusive Drell-Yan data

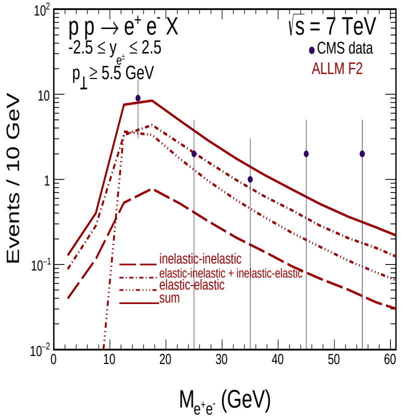
Comparison with Drell-Yan data – inelastic -inelastic contributions

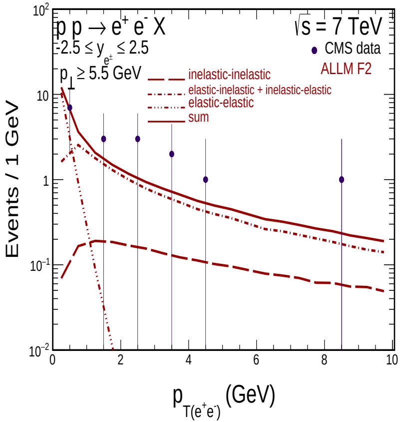




- inclusive Drell-Yan data

Comparison with CMS data

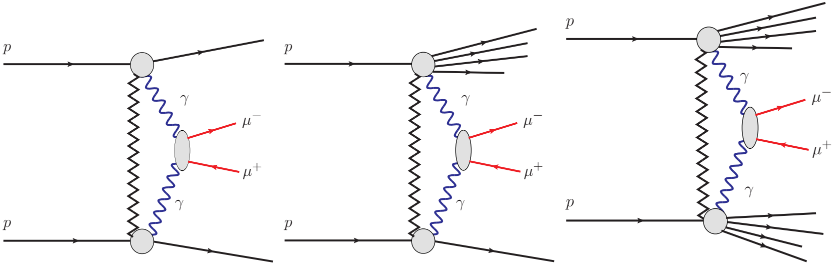




- data from CMS collab. JHEP 11 (2012) 080.
- caveat: data not acceptance corrected, we apply global efficiencies given in the paper:
- $\epsilon(\mathrm{el}-\mathrm{el}) \sim 0.048\,,\ \epsilon(\mathrm{in}-\mathrm{el}) \sim 0.034\,,\ \epsilon(\mathrm{in}-\mathrm{in}) \sim 0.012\,.$

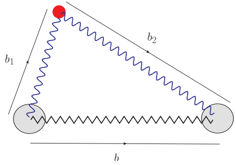
Absorptive corrections - what can we expect?

Like for any process with rapidity gaps, we have to account for the *gap survival probability*.



Absorptive corrections-what can we expect?

Accounting for the *gap survival probability* is easiest done in impact parameter space.



Weizsäcker–Williams approximation

$$\sigma\left(pp \to \mu^+\mu^- pp; s\right) = \int \hat{\sigma}\left(\gamma\gamma \to \mu^+\mu^-; x_1 x_2 s\right)\, dn_{\rm abs}\left(x_1, x_2, \mathbf{b}\right).$$

effective Weizsäcker–Williams photon flux:

$$dn_{\rm abs}(x_1, x_2, \boldsymbol{b}) = \frac{dx_1}{x_1}\frac{dx_2}{x_2}\int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2\, \delta^{(2)}(\boldsymbol{b} - \boldsymbol{b}_1 + \boldsymbol{b}_2) S^2_{\rm abs}(\boldsymbol{b})\, \frac{1}{\pi^2}|\boldsymbol{E}(x_1, \boldsymbol{b}_1)|^2\, \frac{1}{\pi^2}|\boldsymbol{E}(x_2, \boldsymbol{b}_2)|^2$$

e.m. fields:

$$\boldsymbol{E}\left(x, \boldsymbol{b}\right) = \sqrt{4\pi\alpha_{em}}\int \frac{d^2\boldsymbol{q}}{(2\pi)^2} e^{-i\boldsymbol{q}\boldsymbol{b}}\, \frac{\boldsymbol{q}}{\boldsymbol{q}^2 + x^2 m_p^2} F_{em}\left(\boldsymbol{q}^2 + x^2 m_p^2\right).$$

Gap survival for elastic $\gamma\gamma$ processes

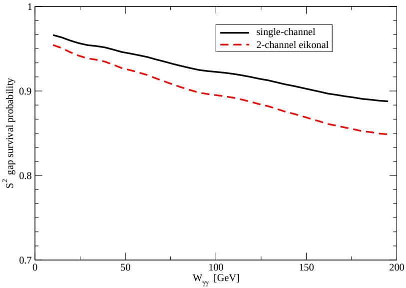
effective luminosity, gap survival prob. as function of $W_{\gamma\gamma}$

$$\mathcal{L}_{\rm abs}(W^2_{\gamma\gamma}) = \int d^2\boldsymbol{b}\,\delta(x_1 x_2 s - W^2_{\gamma\gamma})\,dn_{\rm abs}(x_1, x_2, \boldsymbol{b})\,.\;\langle S^2(W^2_{\gamma\gamma})\rangle = \frac{\mathcal{L}_{\rm abs}(W^2_{\gamma\gamma})}{\mathcal{L}_0(W^2_{\gamma\gamma})}$$

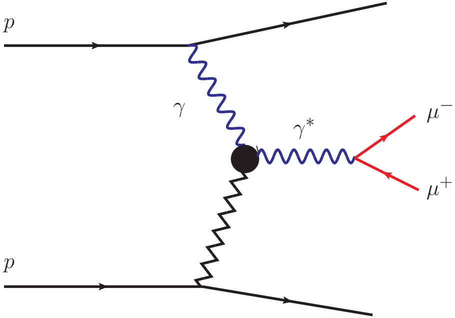
- simple elastic rescattering:

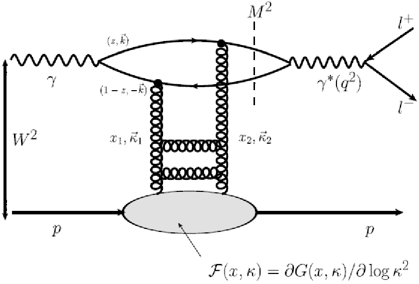
$$S^2_{\rm abs}(\boldsymbol{b}) = \left(1 - \frac{\sigma^{\rm pp}_{\rm tot}}{4\pi B_{\rm el}}\exp[-\boldsymbol{b}^2/(2B_{\rm el})]\right)^2$$

- ...one of the popular multichannel eikonal models (e.g. KMR).



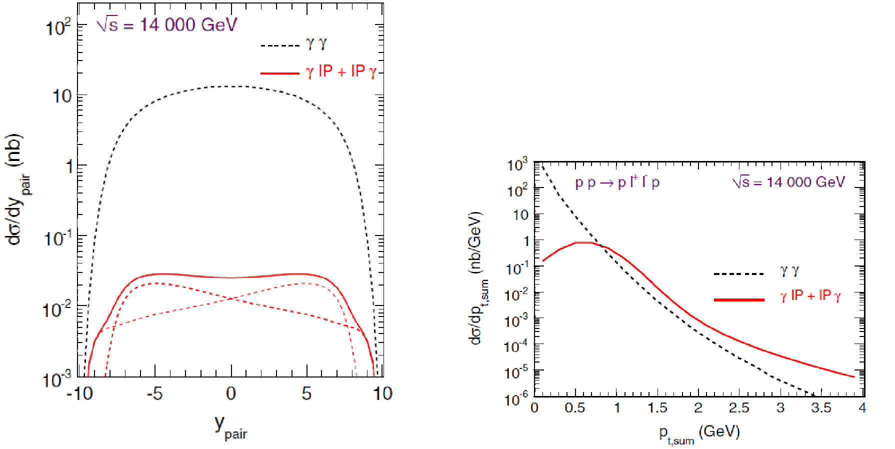
Timelike Compton scattering





- shares many properties with vector meson production, but the *timelike* nature of the photon leads to a complicated phase & interferences & flavour dependence.
  W.S., G. Ślipek & A. Szczurek, Phys. Lett. B688 (2009).
- 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.

Summary

- production of dilepton pairs with large transverse momenta has a large contribution from proton dissociation events (at the "Born" level).
- reasonable agreement with CMS data on exclusive dileptons.
- there can be substantial differences depending on the input for F_2. "Standard input" in e.g. (some versions of (?)) LPAIR is outdated. ALLM gives a good description of F_2 wherever it is measured, and if the resonance region is "averaged over".

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