Electromagnetic excitations in high-energy proton-proton collisions

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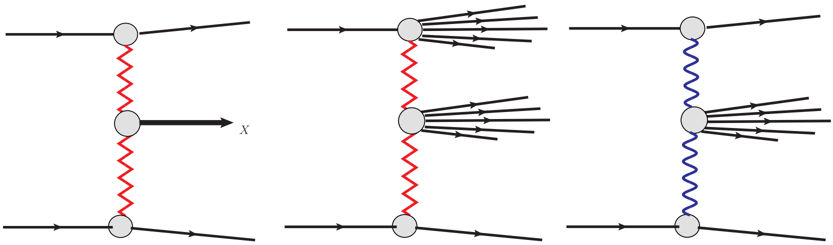
Outline

1. **Motivation/Introduction**
2. **Lepton pair production at high energies: k_T-factorization approach**
3. **Photons as DGLAP partons**
4. **Gap survival - simple estimates**
5. **A $\gamma - \mathbb{P}$-mechanism: timelike Compton scattering**

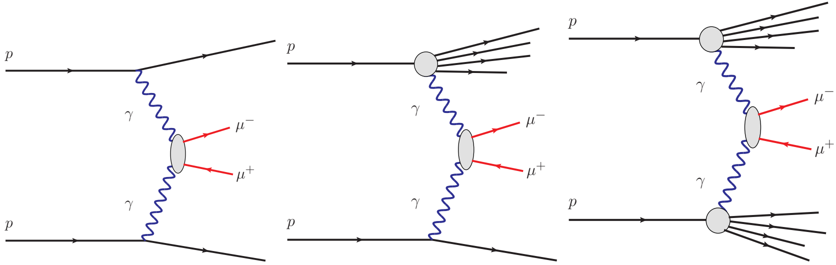
- Gustavo da Silveira, Laurent Forthomme, Krzysztof Piotrzkowski, W.S, Antoni Szczurek, JHEP 1502 (2015) 159.
- Marta Łuszczak, W.S., Antoni Szczurek, in preparation.



- 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...



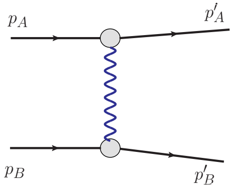
Photon exchanges at high energies

We want to describe ultrarelativistic collisions involving particles A, B with four-momenta p_A, p_B which fulfill the on-shell conditions $p_A^2 = m_A^2$, $p_B^2 = m_B^2$. It is useful to introduce the light-like, $p_i^2 = 0$ momenta:

$$p_1 = p_A - \frac{m_A^2}{\tilde{s}} p_B, \;\; p_2 = p_B - \frac{m_B^2}{\tilde{s}} p_A \,, \tilde{s} = s \cdot \frac{1}{2} \left\{ 1 + \sqrt{1 - \frac{4 m_A^2 m_B^2}{s^2}} \right\} \,, \; s \equiv 2(p_A \cdot p_B) \,,$$

Sudakov decomposition, Gribov decomposition of $g_{\mu\nu}$

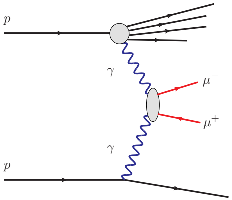
$$\begin{aligned} p &= \alpha\, p_1 + \beta\, p_2 + p_\perp \,. \\ g_{\mu\nu} &= g_{\mu\nu}^\perp + \frac{2}{s} (p_{1\mu} p_{2\nu} + p_{2\mu} p_{1\nu}) \,. \end{aligned}$$



$$A \propto j_\mu(p_A, p'_A) \frac{-g_{\mu\nu}}{q^2} j_\nu(p_B, p'_B) \to \frac{s}{\boldsymbol{q}^2} \cdot \left(\frac{1}{s} j_\mu(p_A, p'_A) p_{2\mu} \right) \left(\frac{1}{s} j_\nu(p_B, p'_B) p_{1\nu} \right)$$

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

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

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

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

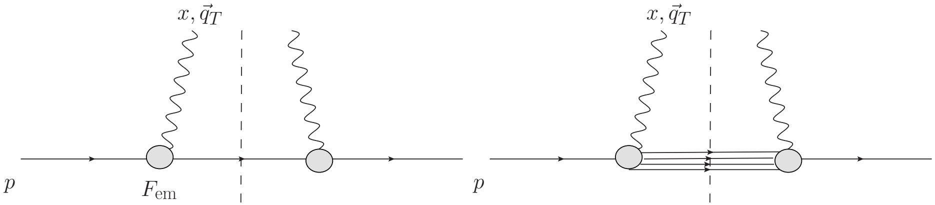
Using $q_i = x_i p_i + q_{i\perp}$ and gauge invariance $q_{i\alpha} \bar u_\lambda(p_-)\, T_{\alpha\beta} v_{\bar\lambda}(p_+) = 0$:

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

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



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

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

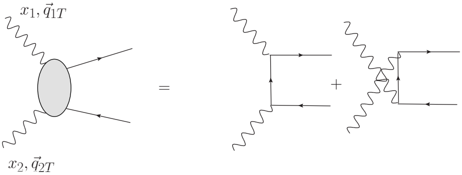
$$Q^2 = \frac{1}{1-x}\left[\boldsymbol{q}^2 + x(M_X^2 - m_p^2) + x^2 m_p^2\right]$$

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

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

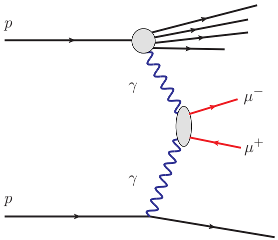


with $\varepsilon^2 = m_l^2 + z_+ z_- \boldsymbol{q}_1^2$, enter the off-shell matrix element:

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

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

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



- If $\boldsymbol{p}_{\rm sum}^2 \gg \Lambda^2 \sim 0.71\,\mathrm{GeV}^2$, 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.

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

Here

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

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

Constructing the unintegrated photon flux

Unintegrated photon flux

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

Hadronic tensor

$$\begin{aligned} W_{\mu\nu}(M_X^2, Q^2) &= \overline{\sum_X} (2\pi)^3 \, \delta^{(4)}(p_X - p_A - q) \, \langle p | J_\mu | X \rangle \langle X | J_\nu^\dagger | p \rangle \, d\Phi_X \,, \\ &= -\delta^\perp_{\mu\nu}(p_A, q) \, W_T(M_X^2, Q^2) + e_\mu^{(0)} e_\nu^{(0)} \, W_L(M_X^2, Q^2) \end{aligned}$$

$$e_\mu^{(0)} = \sqrt{\frac{Q^2}{X}} \left(p_{A\mu} - \frac{(p_A \cdot q)}{q^2} q_\mu \right) , \; X = (p_A \cdot q)^2 + m_A^2 Q^2 \, , \; e^{(0)} \cdot e^{(0)} = +1 \,,$$

$$\delta^\perp_{\mu\nu}(p_A, q) = g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} - e_\mu^{(0)} e_\nu^{(0)}$$

Constructing the unintegrated photon flux

Virtual photoabsorption cross sections

$$\sigma_T(\gamma^* p) = \frac{4\pi\alpha_{em}}{4\sqrt{X}} \Big(- \frac{\delta^\perp_{\mu\nu}}{2} \Big) 2\pi W^{\mu\nu}(M_X^2, Q^2)$$

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

Structure functions

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

$$F_T(x_{\rm Bj}, Q^2) = 2x_{\rm Bj} F_1(x_{\rm Bj}, Q^2) \, ,$$

$$F_2(x_{\rm Bj}, Q^2) = \frac{F_T(x_{\rm Bj}, Q^2) + F_L(x_{\rm Bj}, Q^2)}{1 + \frac{4x_{\rm Bj}^2 m_A^2}{Q^2}}$$

Then, our structure functions $W_{T,L}$ are expressed through the more conventional $F_{T,L}$ a

$$W_{T,L}(M_X^2, Q^2) = \frac{1}{x_{\rm Bj}} F_{T,L}(x_{\rm Bj}, Q^2)\,.$$

Performing the contraction

$$\frac{p_B^\mu p_B^\nu}{s^2} W_{\mu\nu}(M_X^2, Q^2) = \left(1 - \frac{z}{x_{\rm Bj}} + \frac{z^2}{4x_{\rm Bj}^2}\right) \frac{F_2(x_{\rm Bj}, Q^2)}{Q^2 + M_X^2 - m_p^2} + \frac{z^2}{4x_{\rm Bj}^2} \frac{2x_{\rm Bj} F_1(x_{\rm Bj}, Q^2)}{Q^2 + M_X^2 - m_p^2}\,.$$

Final result

$$\frac{p_B^\mu p_B^\nu}{s^2} W_{\mu\nu}(M_X^2, Q^2) = Q^2 \cdot f_T\left(\frac{z}{x_{\rm Bj}}\right) x_{\rm Bj} F_2(x_{\rm Bj}, Q^2)\,,$$

$$f_T(y) = 1 - y + y^2/2 = \frac{1}{2}\left[1 + (1-y)^2\right]$$

Constructing the unintegrated photon flux: elastic contribution

Elastic structure functions

$$W_T^{\rm el}(M_X^2, Q^2) = \delta(M_X^2 - m_p^2)\, Q^2 G_M^2(Q^2)\,,\; W_L^{\rm el}(M_X^2, Q^2) = \delta(M_X^2 - m_p^2) 4 m_p^2 G_E^2(Q^2)\,.$$

The contribution to the photon flux is then again obtained by contracting

performing the contraction

$$\frac{p_B^\mu p_B^\nu}{s^2} W_{\mu\nu}^{\rm el}(M_X^2, Q^2) = \delta(M_X^2 - m_p^2)\Big[\Big(1 - \frac{z}{2}\Big)^2 \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2} + \frac{z^2}{4} G_M^2(Q^2)\Big]$$

Salient features of the $k_\perp$-factorization approach

- Due to the high-energy kinematics, the structure of the cross section very much simplifies. In the general case we would have to account for density matrices of photons in the colliding protons, as well as separately cross sections and interferences for all possible combinations of T and L photon polarizations.
- Only the proton structure function $F_2(M_X^2, Q^2)$ appears, which has been measured in a broad kinematic range. We do not need the much less known longitudinal structure function $F_L(M_X^2, Q^2)$.
- The colliding photons carry transverse momenta in the cms of the proton-proton collision. The dilepton pair carries a transverse momentum $\boldsymbol{p}_{\rm pair} = \boldsymbol{q}_1 + \boldsymbol{q}_2$, we get distributions in $\boldsymbol{p}_{\rm pair}$, azimuthal decorrelation of dileptons etc., already at the leading order.
  This goes beyond the conventional Weizsäcker-Williams approximation,in which the colliding photons are collinear to incoming protons.

Input for our calculation

- elastic vertex: dipole formfactor

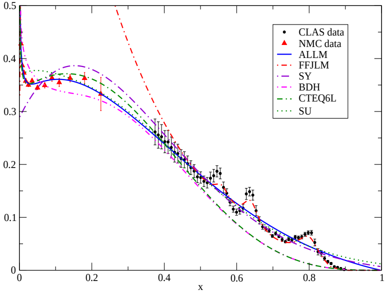
$$G_E(Q^2) = \frac{1}{(1+Q^2/\Lambda^2)^2}\,, G_M(Q^2) = \mu G_E(Q^2),\ \mu = 2.79, \Lambda^2 = 0.71\,\mathrm{GeV}^2\,.$$

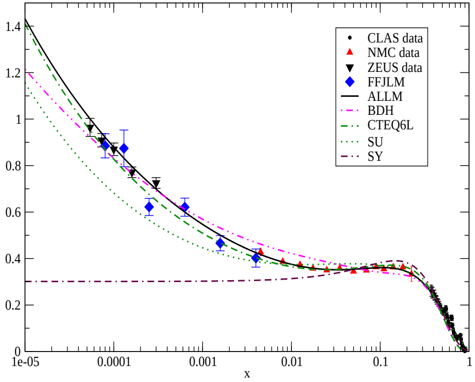
- inelastic vertex: different parametrizations of $F_2(x_{\rm Bj}, Q^2)$
  - "SU": A. Szczurek & V. Uleshchenko, (2000). Puts an emphasis on the low-to-intermediate Q^2-region and includes a smooth continuation to low-Q^2.
  - "ALLM": Abramowicz, Levin, Levy & Maor (1997), update by Abramowicz & Levy (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:

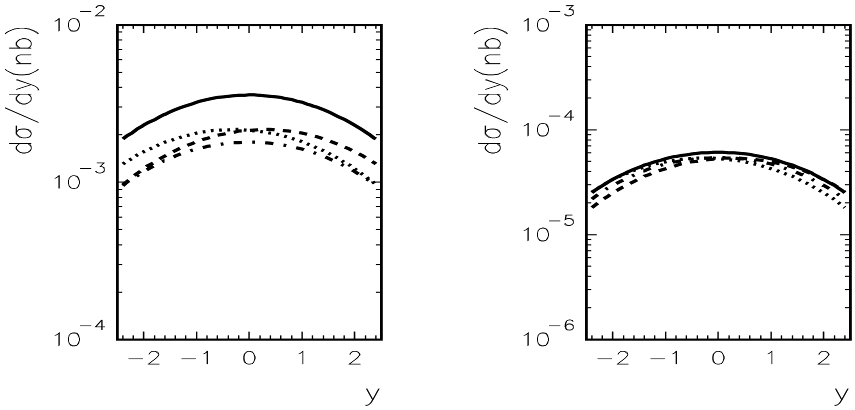
- $-2.5 < y < 2.5$ for the muon rapidities.
- two types of cuts on muon p_T: soft: $p_T > 3\,\mathrm{GeV}$ and hard: $p_T > 15\,\mathrm{GeV}$.
- mass M_X of the excited hadronic system: $m_p + m_\pi < M_X < 1\,\mathrm{TeV}$

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



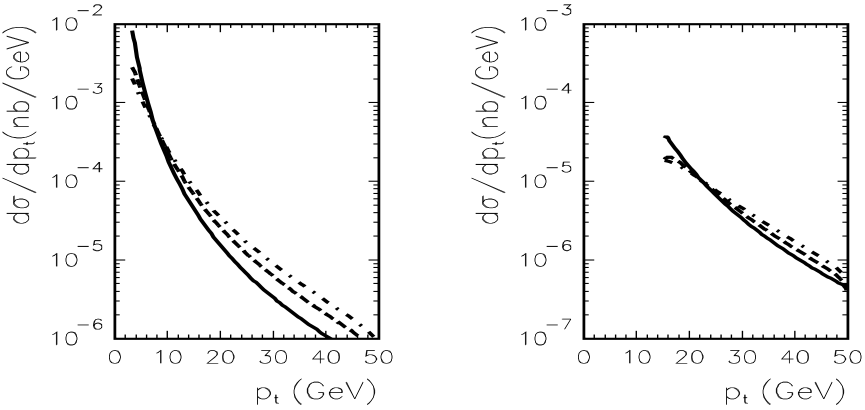


Rapidity distributions



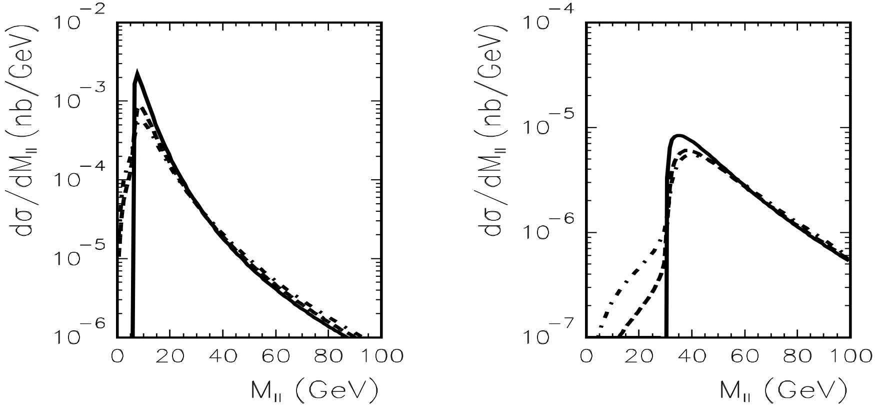
- left panel: $p_T > 3\,\mathrm{GeV}$, right panel: $p_T > 15\,\mathrm{GeV}$
- solid: elastic-elastic, dashed: inelastic - elastic, dash-dotted: inelastic - inelastic
- Photon from the inelastic vertex is harder → asymmetry of elastic-inelastic contribution.

Transverse momentum distributions of muons



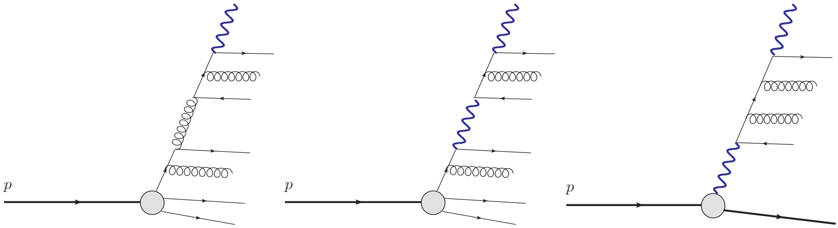
- left panel: $p_T > 3\,\mathrm{GeV}$, right panel: $p_T > 15\,\mathrm{GeV}$
- solid: elastic-elastic, dashed: inelastic - elastic, dash-dotted: inelastic - inelastic

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).

...photons from splitting af quarks & antiquarks:

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

gives the photon distribution:

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

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

a comparison with to the fluxes from k_T factorization

k_T-factorziation

$$dn = \frac{dz}{z}\frac{d^2\boldsymbol{q}}{\pi\boldsymbol{q}^2}\mathcal{F}_{\gamma^*\leftarrow A}(z,\boldsymbol{q})\,.$$

$$\frac{zdn(z,Q^2)}{dzd\log(Q^2)} = \frac{\alpha_{em}}{\pi}\int_{x_{\rm min}}^{x_{\rm max}}\frac{dx_{\rm Bj}}{x_{\rm Bj}}\left(1-\frac{z}{x_{\rm Bj}}-\frac{z^2m_p^2}{Q^2}\right)\left(1-\frac{z}{x_{\rm Bj}}+\frac{z^2}{4x_{\rm Bj}^2}\right)F_2(x_{\rm Bj},Q^2)$$

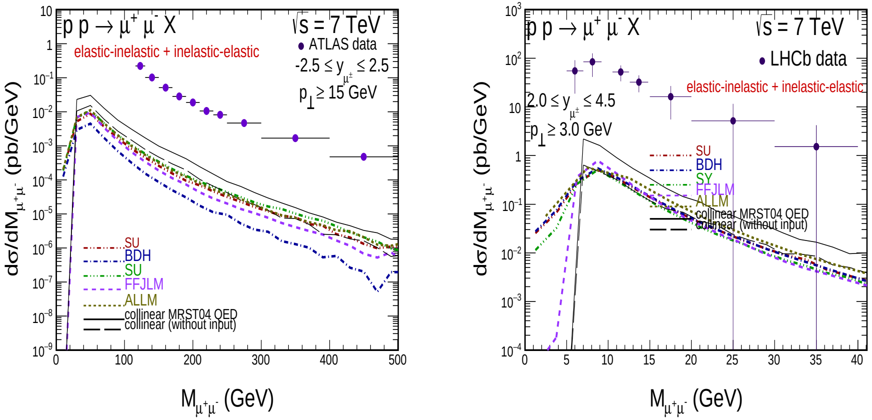
$$. = \frac{\alpha_{em}}{2\pi}\int_z^1\frac{dx_{\rm Bj}}{x_{\rm Bj}}P_{\gamma\leftarrow q}\left(\frac{z}{x_{\rm Bj}}\right)\frac{F_2(x_{\rm Bj},Q^2)}{x_{\rm Bj}}\left(1-\frac{z}{x_{\rm Bj}}\right)$$

DGLAP photons:

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

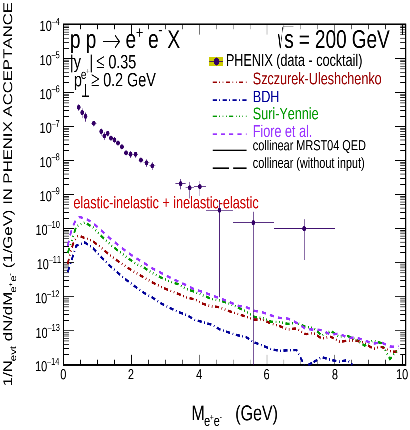
n.b.: the k_T factorization piece is only the inelastic one!

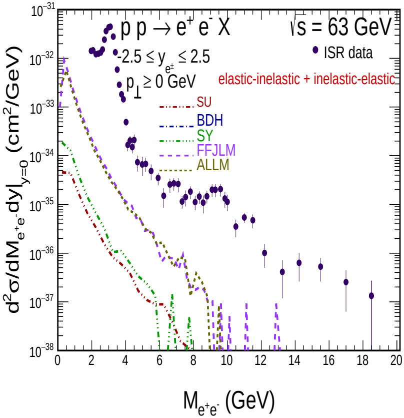
Comparison with Drell-Yan data



- inclusive Drell-Yan data

Comparison with Drell-Yan data





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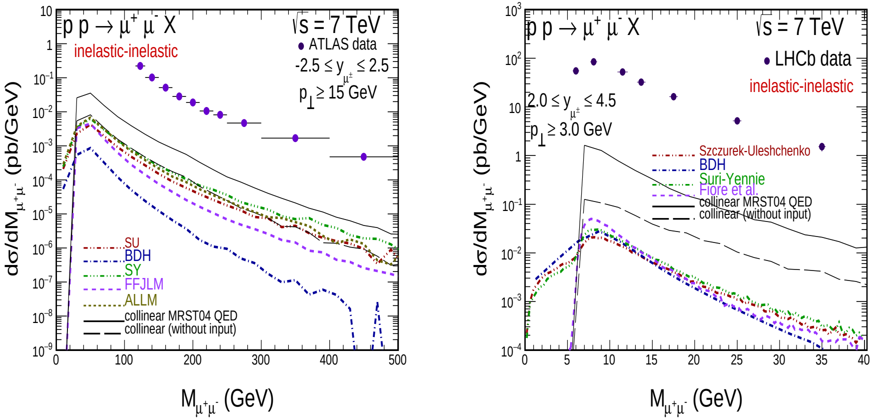
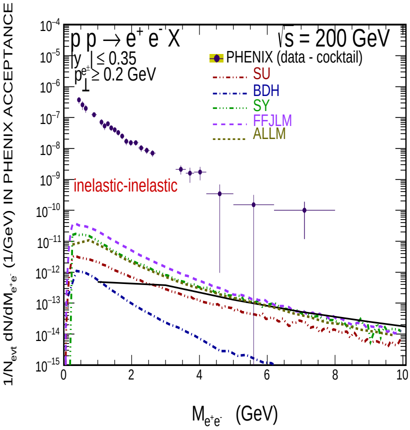
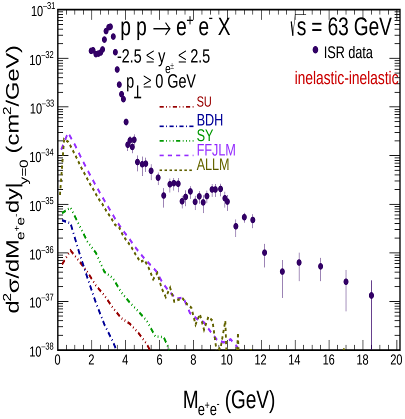
Comparison with Drell-Yan data



- inclusive Drell-Yan data

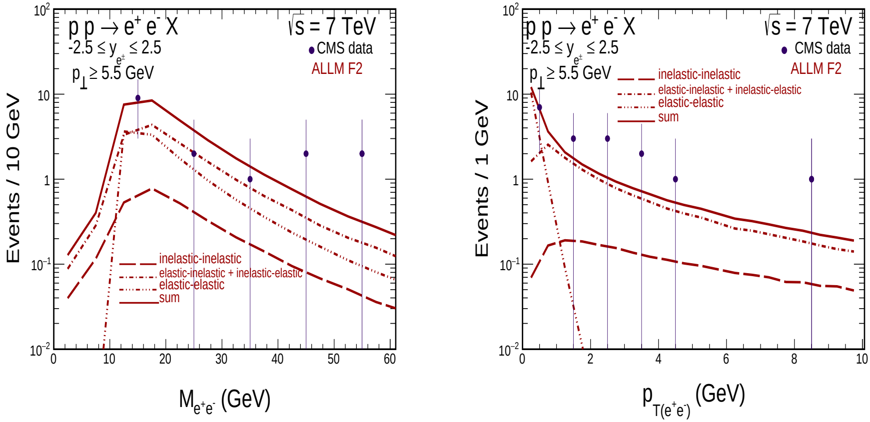
Comparison with Drell-Yan data





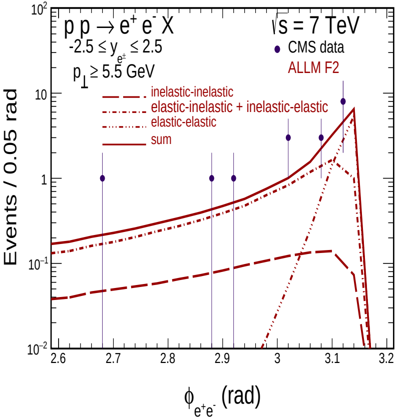
- inclusive Drell-Yan data

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:
- $\epsilon(\mathrm{el} - \mathrm{el}) \sim 0.048\,,\ \epsilon(\mathrm{in} - \mathrm{el}) \sim 0.034\,,\ \epsilon(\mathrm{in} - \mathrm{in}) \sim 0.012\,.$

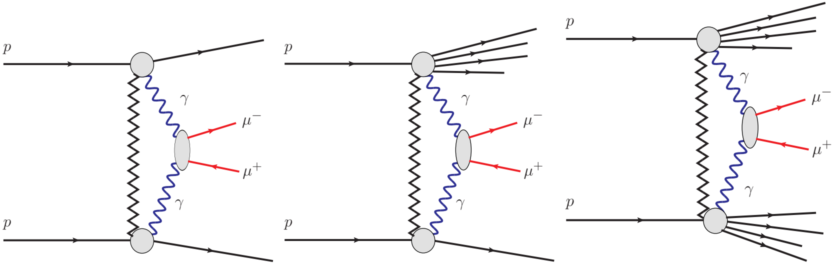
Comparison with CMS data



- data from CMS collab. JHEP 11 (2012) 080.
- caveat: data not acceptance corrected, we apply global efficiencies given in the paper.

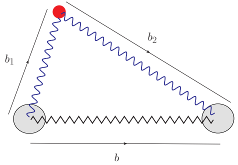
Absorptive corrections - what can we expect?

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

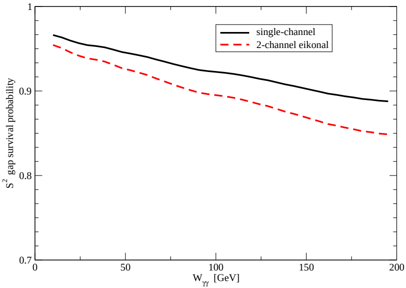
effective luminosity, gap survival prob. as function of $W_{\gamma\gamma}$

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

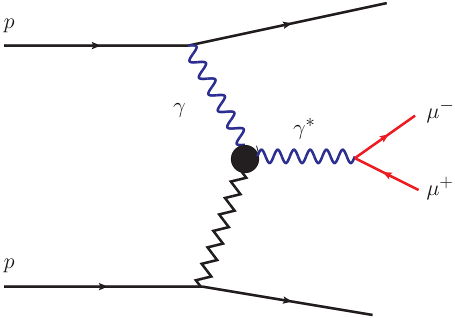
- simple elastic rescattering:

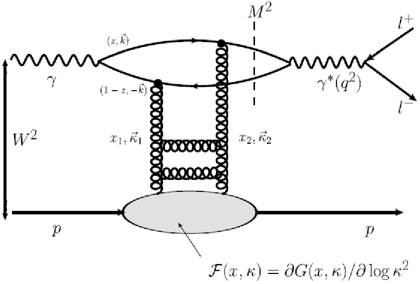
$$S^2_{\rm abs}(\boldsymbol{b}) = \left(1 - \frac{\sigma^{\rm pp}_{\rm tot}}{4\pi B_{\rm el}} \exp[-\boldsymbol{b}^2/(2B_{\rm el})]\right)^2$$

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



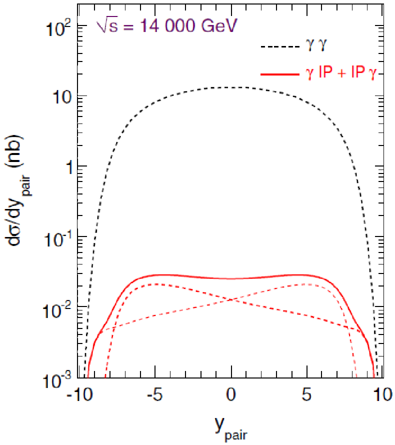
Timelike Compton scattering

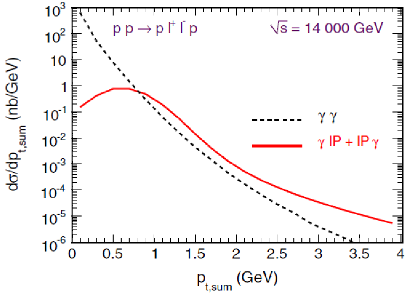




- shares many properties with vector meson production, but the *timelike* nature of the photon leads to a complicated phase & interferences & flavour dependence. W.S., G. Ślipek & A. Szczurek, Phys. Lett. B688 (2009).
- dileptons are of *odd* C-parity.

Dileptons from γ – **I**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.
- 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 ...