Lepton Pair Production Through Two Photon Process in Heavy Ion Collisions

Miniworkshop difrakce a UPC 2020

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Fundamental Interactions : Light & Matter

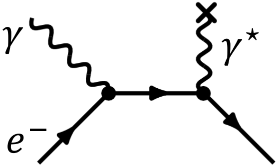
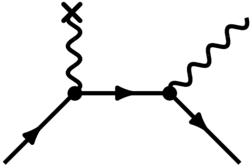
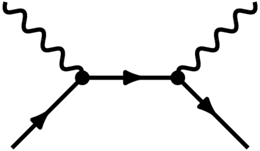


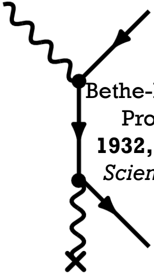
Photo Electric Effect
1887 *Hertz, Ann Phys (Leipzig) 31, 983*



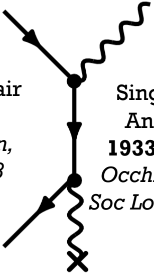
Bremsstrahlung
1895 *Röntgen, Ann Phys (Leipzig) 300, 1*



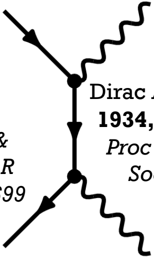
Compton Scattering
1906 *Thomson, Conduction of Electricity through Gases*



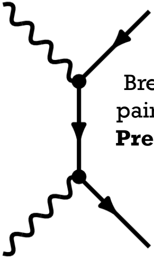
Bethe-Heitler Pair Production
1932, *Anderson, Science 76,238*



Single Photon Annihilation
1933, *Blackett & Occhialini, Proc R Soc Lond A 139, 699*



Dirac Annihilation
1934, *Klemperer, Proc Camb Phil Soc 30, 347*

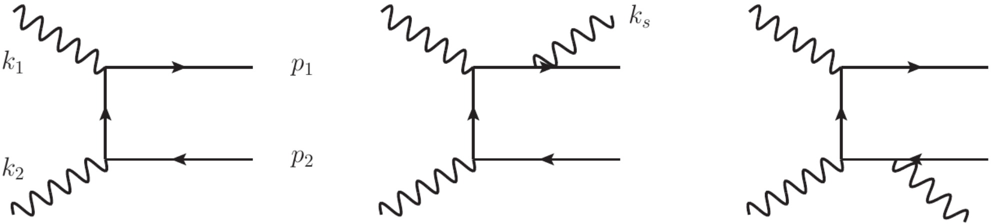


Breit-Wheeler pair production
Predicted 1934

The paper

- Investigates Electro-Magnetic production of lepton pairs with low p_{T}.
- Estimates the initial photons' transverse momentum distribution.
    - Via average transverse momentum squared.
    - Using models based on equivalent photon approximation (EPA).
        - Leading order QED.
        - Neglecting virtual masses.
    - Extending this calculation with new feature to describe data.
    - This talk concentrates on that.
- Discussion of p_{T}-broadening effect.
    - Potentially purely electromagnetic effect.
    - Can be used as a tag of EM interactions in QGP.
    - UPC ideal as a baseline measurement.
- If not stated otherwise, all figures and equations are from ref arXiv:2003.02947v2.

Leading order picture - initial conditions



- High mass dimuon with large $p_{i,\mathrm{T}}$ of each lepton (fixing t-channel singularity).
- Leptons are dominantly back-to-back in transverse plane.
- Dilepton $p_\mathrm{T} \ll p_{i,\mathrm{T}}$.
- Lepton $p_{i,\mathrm{T}}$ correspond to nucleus P_T.

$$P_T = \frac{1}{2}\left|\vec{p}_{1T} - \vec{p}_{2T}\right| \sim \left|p_{1T}\right| \sim \left|p_{2T}\right|$$

Leading order picture - differential cross section

$$\frac{d\sigma(AB[\gamma\gamma] \to \mu^+\mu^-)}{dy_1 dy_2 d^2p_{1T} d^2p_{2T}} = \sigma_0 \left[x_a f_A^\gamma(x_a) x_b f_B^\gamma(x_b)\right]_{b_\perp}$$

$$\times \delta^{(2)}(\vec{p}_{1T} + \vec{p}_{2T}) \ ,$$

- σ_0 - leading order CS,
- x_i - momentum fraction of nucleon carried by photon,
- $f_{A,B}^\gamma$ - photon distributions.
- For a specific impact parameter b_T!

Leading order picture - b_{T}-dependent photon flux

- To calculate the CS, one has to introduce b_{T}-dependent photon distributions = flux.

$$[f_A^\gamma(x_a) f_B^\gamma(x_b)]_{b_\perp} = \int d^2 b_{1\perp} d^2 b_{2\perp} \delta^{(2)}(b_{1\perp} - b_{2\perp} - b_\perp) \times f_A^\gamma(x_a; b_{1\perp}) f_B^\gamma(x_b; b_{2\perp}) \ , \tag{6}$$

- $f_{A,B}^{\gamma}(x_{a,b}, b_{\mathrm{T}})$ - photon distribution at transverse position wrt colliding nucleus.
- Needed, because all impact-parameter picture is not enough to understand non-UPC two-photon processes and photo-production.
- Incoming photon also carry transverse momenta, which non-negligibly contributes to final state momenta $\rightarrow$ may help to understand hot medium effects such as $p_{\mathrm{T}} \ll p_{i,\mathrm{T}}$ broadening.

b_{T}-dependent photon flux

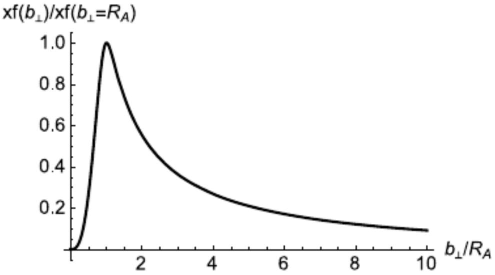
- Vidovic et all (doi:10.1103/PhysRevC.47.2308) describe b_{T}-dependent photon flux as:

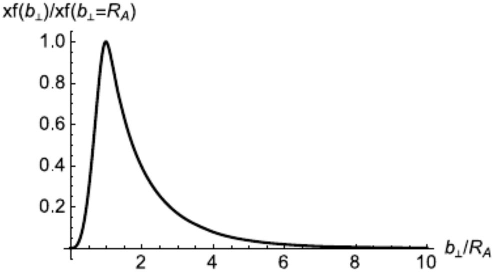
$$xf_A^{\gamma}(x; b_\perp) = 4Z^2\alpha \left| \int \frac{d^2k_T}{(2\pi)^2} e^{ik_T \cdot b_\perp} \frac{\vec{k}_T}{k^2} F_A(k^2) \right|^2$$

- $\vec{k}_{\mathrm{T}}$; k - photon momentum, energy.
- $F_A(k)$ - elastic charge form factor for the nucleus.
  - STARlight model uses convolution of hard sphere and Yukawa potential:

$$F_A(|\vec{k}|) = \frac{4\pi\rho^0}{|\vec{k}|^3\ A} \frac{1}{a^2\vec{k}^2 + 1} \times \left[\sin(|\vec{k}|R_A) - |\vec{k}|R_A \cos(|\vec{k}|R_A)\right]$$

Photon flux at LHC ($x = 10^{-3}$) and RHIC ($x = 10^{-2}$)





- Large b_{T} $\rightarrow$ classical electrodynamics
  - because $k \rightarrow 0$ and hence $F_A \rightarrow 1$ (point-like particles)
- Small b_{T}: flux b_{T}^{-3}
  - flux generated by the effective total charge of the nucleons inside b_{T} area.
- This actually ignores inter-dependence between the impact parameter and the photon's transverse momentum.

Connecting impact parameter and transverse momentum

- Already done with so-called QED approach.
  - Details not important. References in the paper.
- This paper strategy: Factorize the problem and study individual photon flux.
- The problem is, that b_{T} is Fourier conjugate variable associated with k_{T}.

$$xf_A^{\gamma}(x;b_\perp) = 4Z^2\alpha \left| \int \frac{d^2k_T}{(2\pi)^2} e^{ik_T\cdot b_\perp} \frac{\vec{k}_T}{k^2} F_A(k^2) \right|^2$$

- Combination of 2 fluxes is model dependent.
- Compute average transverse momentum squared by multiplying the integrand by the products of k_{T}.

$$\langle k_T^2 \rangle = \frac{4Z^2\alpha}{xf^{\gamma}(x;b_\perp)} \int \frac{d^2k_T}{(2\pi)^2} \frac{d^2k'_T}{(2\pi)^2} e^{i(k_T-k'_T)\cdot b_\perp} \times \frac{(k_T\cdot k'_T)^2}{k^2k'^2} F_A(k^2)F_A(k'^2) \, ,$$

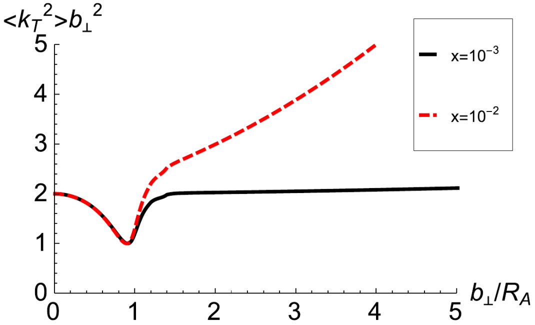
Average transverse momentum dependence on impact parameter

$$\langle k_T^2\rangle(x;b_\perp) = \frac{1}{b_\perp^2}\left[1+\left(1-\frac{c_2(x;b_\perp)}{c_1(x;b_\perp)}\right)^2\right]$$

where $c_2(x;b_\perp)$ is defined as

$$c_2(x;b_\perp) = \int dk_T^2 \frac{b_\perp^2 k_T^2 J_2(k_T b_\perp)}{k^2} F_A(k^2)$$

- Explicit dependence of average transverse momentum squared on b_{T}^2.
- Overall behaviour $< k_{\mathrm{T}}^2 > \propto 1/b_{\mathrm{T}}^2$.
- For RHIC case ($\mathrm{x} = 10^{-2}$), $x \cdot m_p \propto 1/b_{\mathrm{T}}$ for large b_{T}.

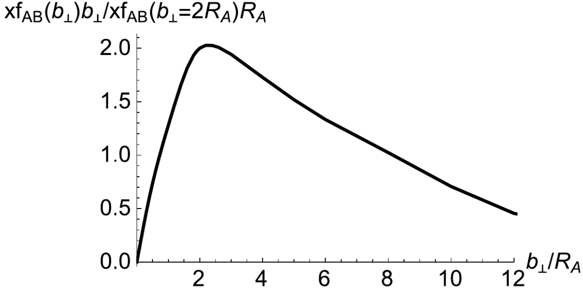


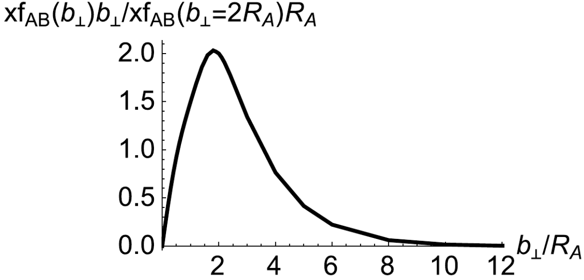
$$k^2 = k_T^2 + x^2 m_p^2$$

Combining two fluxes

$$x_a x_b f_{AB}(b_\perp) = \int d^2 b_{1\perp} d^2 b_{2\perp} \delta^{(2)}(b_\perp - b_{1\perp} - b_{2\perp})$$
$$\times x_a f_A(b_{1\perp}) x_b f_B(b_{2\perp}) \; , \qquad ($$

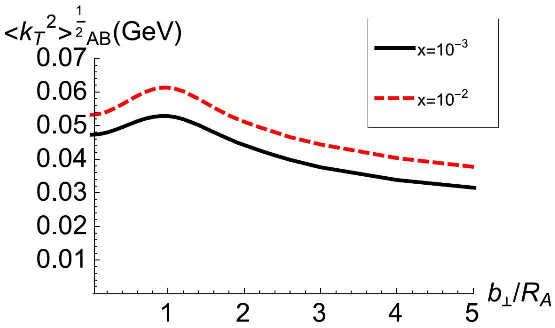
Photon-photon interaction rate





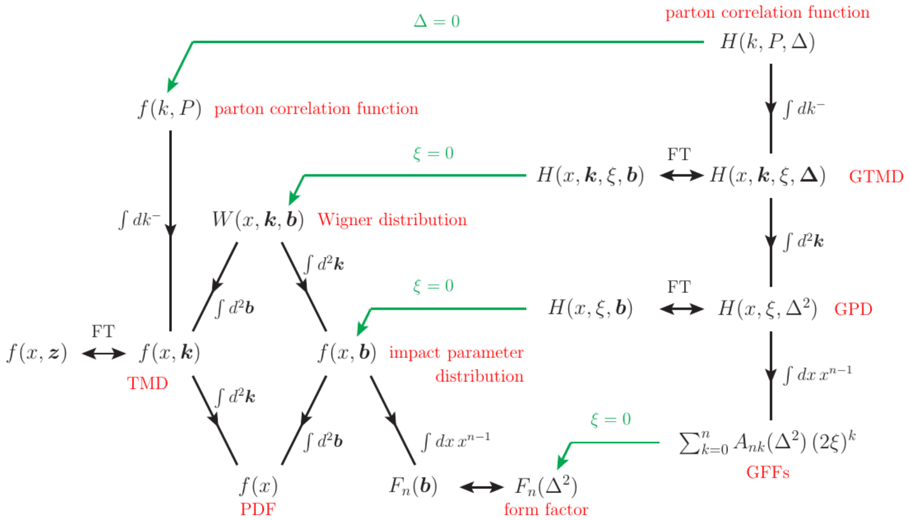
- LHC ($x = 10^{-3}$).
- Minimum bias sample.
- Peaks around $b_{\mathrm{T}} \sim R_A \rightarrow$ most of the dileptons produced in UPCs.
- RHIC ($x = 10^{-2}$).

Average transverse momentum - both photons contributing



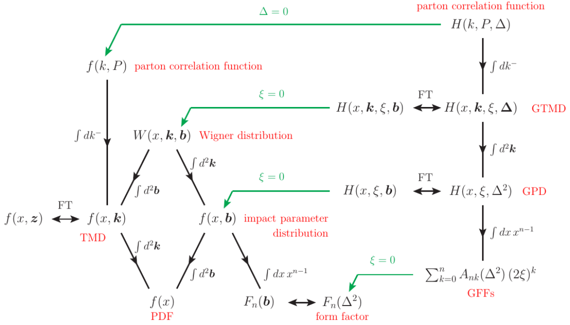
- $< k_\mathrm{T}^2 >$ does not change dramatically with impact parameter.
- Nearly constant from central to peripheral collisions.
- Different result wrt. QED approach.
- Maybe because of different treatment of impact parameter dependences in EPA
- Next step: Generalize the EPA.
  - Introducing photon Wigner distribution.
  - It is called GEPA.

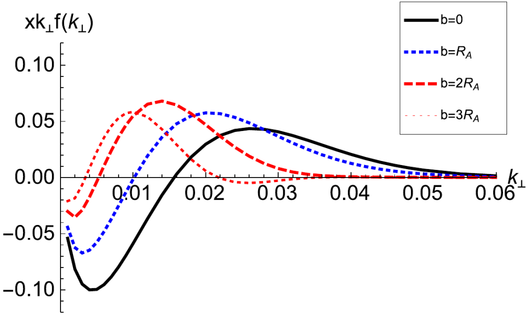
Different structure functions



arXiv:1512.01328v2

Introducing GEPA

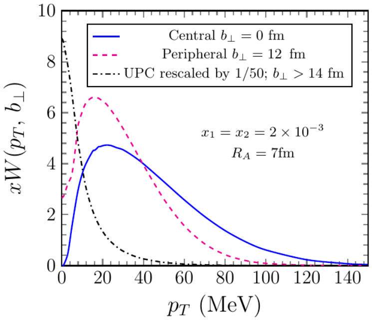


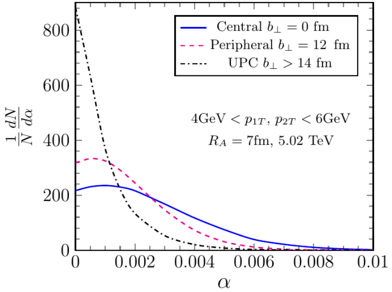


- GTMD/Wigner photon distribution.
- Parametrization: usual photon flux + linearly-polarized photon flux.
- Resulting formulas have no clear probabilistic interpretation.

- Oscillating function of k_{T} on different b_{T}.
- Distribution function is not positive definite.
- !In the two photon process, it is OK!
- Results matches QED approach.

GEPA results - Numerical calculation and ATLAS result



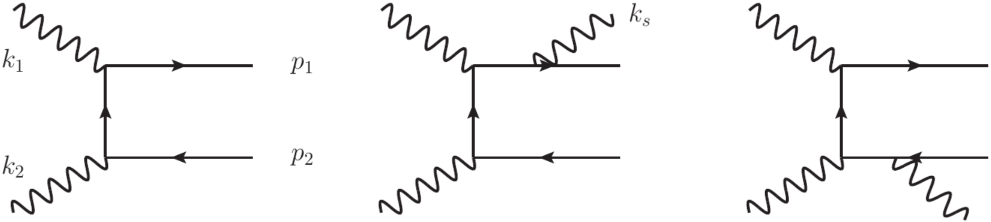


- Dip at low-p_{T} for more central collisions.
- $xW(x, 0, 0)$ should vanish.
- Gaussian and Wood-Saxon FF similar results.

- Dip is less visible due to smearing effects.
- GEPA agrees with ATLAS.
- p_{T}-broadening:
  - Peripheral described by photon distribution.
  - NOT sufficient for central data (multiple scattering).

BACK UP

Leading order picture - kinematics



- Outgoing leptons momenta (rapidity, transverse momentum, nucleus momenta, *s*)

$$p_1 = \frac{P_T}{\sqrt{s}} \left(e^{y_1} + e^{y_2}\right) P_A \ ,$$

$$p_2 = \frac{P_T}{\sqrt{s}} \left(e^{-y_1} + e^{-y_2}\right) P_B \ ,$$