Electromagnetic interaction of leptons and pions with heavy nuclei in ultra-peripheral ultra-relativistic collisions

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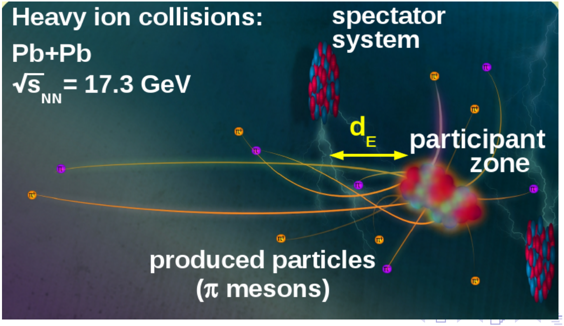
Heavy - Ion Collisions

Pb + Pb Collision - (Thanks to A. Szczurek)

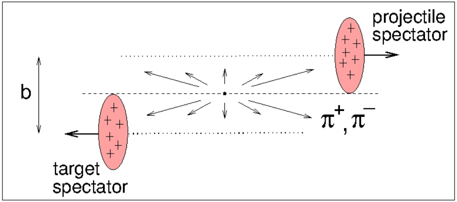
• Noncentral collisions unambiguously lead to azimuthal asymmetries and presence of spectators.

• Azimuthal correlations between particles and the reaction plane – one of the main subjects of heavy ion collisions provide information about collective effects.

• The presence of charged fast moving spectators generate strong electromagnetic fields. A. Rybicki and A. Szczurek, PRC**75** (2007) 054903;PRC**87** (2013) 054909.



Modeling a Peripheral Heavy - Ion Collisions



- The collision takes place at a given impact parameter b.
- The two charged spectator systems follow their initial path.
- The participating system evolves until pions are produced.
- Charged pion trajectories are modified by EM interaction.
- **The spectator systems undergo a complicated nuclear deexcitation/fragmentation process (not fully understood)**.
- The pion emission – single point in space. The emission time t_E is a free parameter. We assume that the initial (x_F, p_T) distribution of the emitted pion is that for underlying N+N collisions (rescaled).
- **The fragmentation of the spectator systems was neglected**, the influence of participant charge, strong Final State Interaction were not considered.

Modeling a Peripheral Heavy - Ion Collisions

Rapidity and Pseudo-Rapidity

Define *transverse momentum* p_T and *rapidity* y (natural units)

$$p_T \equiv \sqrt{p_x^2 + p_y^2}$$

$$y \equiv \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

kinematical variables used at hadron colliders

Transverse momentum p_T and a rapidity difference Δy are invariant under Lorentz boosts along z

For an "massless particle" ($E \gg M$)

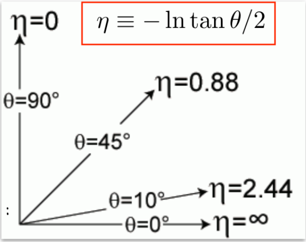
$$y \rightarrow \frac{1}{2} \ln \frac{1 + \cos\theta}{1 - \cos\theta} = -\ln\tan\theta/2 \equiv \eta$$

pseudo-rapidity

Define cone in η-φ space

$$\sqrt{(\eta - \eta_0)^2 + (\varphi - \varphi_0)^2} \leq \Delta R$$

Pseudo-rapidity



Thanks to G.H. Monchenault

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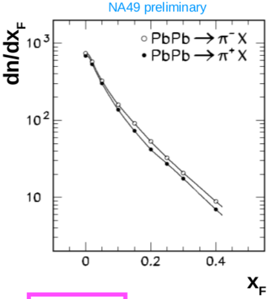
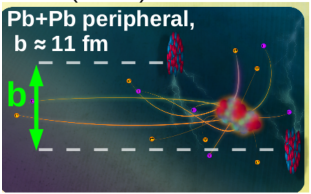
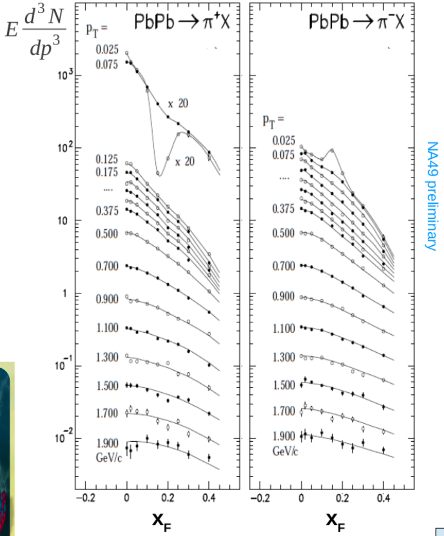
Modeling a Peripheral Heavy - Ion Collisions



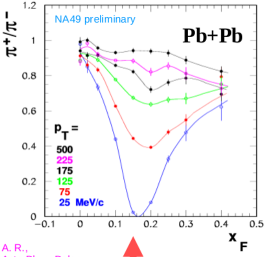
$$x_F = \frac{p_L}{p_L^{beam}}$$

(c.m.s.)

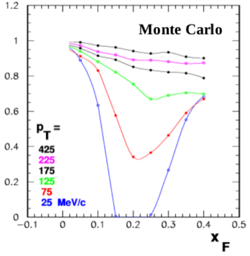


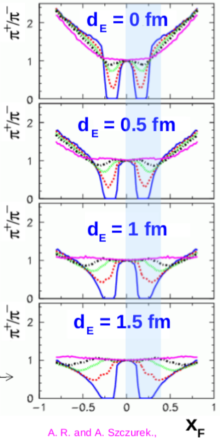


Modeling a Peripheral Heavy - Ion Collisions



A. R., Acta Phys. Polon. B42 (2011) 867





A. R. and A. Szczurek., Phys. Rev. C75 (2007) 054903

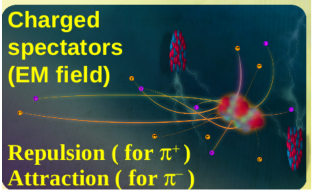
spectator velocity:

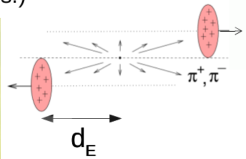
$x_F = 0.15 = m_\pi/m_N$

$$x_F = \frac{p_L}{p_L^{beam}}$$

(c.m.s.)

$d_E \approx 0.75$ fm !





K.Mazurek, A.Rybicki, N02 Seminar, IFJ PAN, 27.10.2017 14

Stochastic Approach

Dynamical effect

• path from equilibrium to scission slowed-down by the nuclear viscosity
• description of the time evolution of the collective variables like the evolution of Brownian particle that interacts stochastically with a "heat bath".
• excess of prescission particles
• all the parameters of the two dimensional fission fragment distribution and their dependence on various parameters of compound nucleus

Observables

• Pre- and post-scission particle multiplicity and energy spectra
• Mass, charge, angular distributions of the fragments
• Total Kinetic Energy distribution
• Isotopic distribution, $\langle N/Z \rangle$....

Limitations

• Wide domain in compound nucleus mass (from 50 to 250)
• Excitation energy $E^{\star}$ (from 30 to 250MeV)
• Angular momentum L (from 0 to 100 $\hbar$)

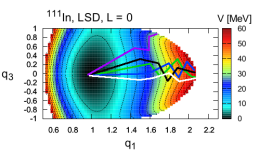
Stochastic Approach

Langevin Equations

are stochastic differential equations describing the time evolution of a subset of the degrees of freedom. These degrees of freedom typically are collective (macroscopic) variables changing only slowly in comparison to the other (microscopic) variables of the system. The fast (microscopic) variables are responsible for the stochastic nature of the Langevin equation.

$$\frac{dq_i}{dt} = \sum_j [M^{-1}(\vec{q})]_{ij} p_j$$

$$\frac{dp_i}{dt} = -\frac{1}{2}\sum_{j,k} \frac{d[M^{-1}(\vec{q})]_{jk}}{dq_i} p_j p_k - \frac{dF(\vec{q},K)}{dq_i} - \sum_{j,k} \gamma_{ij}(\vec{q})[M^{-1}(\vec{q})]_{jk} p_k + \sum_j g_{ij}(\vec{q})\Gamma_j(t)$$



Ingredients

Inertia ($[M^{-1}(\vec{q})]_{ij}$)
Friction ($\gamma_i(t)$) and fluctuation (g_{ik})
Macroscopic potential ($V(\vec{q},K) \rightarrow F(\vec{q},K) = V(\vec{q},K) - a(\vec{q})T^2$)

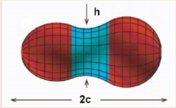
Coupling to the evaporation

Pre and post- scission emission of neutrons, protons, α and γ.

Model Ingredients

Collective coordinates (4D)

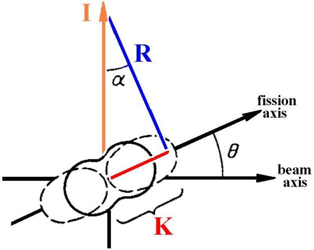
- Description of the nuclear shape by elongation, neck and asymmetry – 3 parameters.
- **K** – spin about the fission (symmetry) axis



Tilting coordinates - K

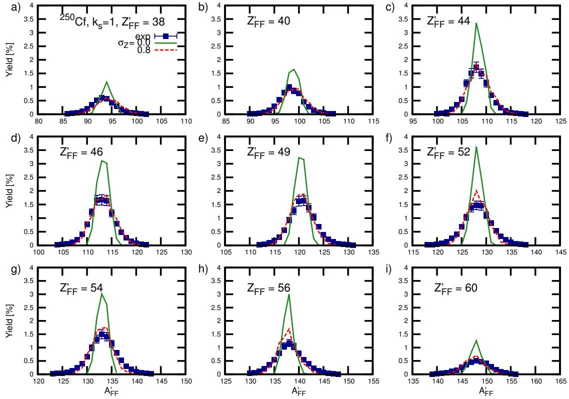
$$\delta \mathbf{K} = -\frac{\gamma_{\mathbf{K}}^2 \mathbf{I}^2}{2} \frac{\partial \mathbf{V}}{\partial \mathbf{K}} \delta \mathbf{t} + \gamma_{\mathbf{K}} \mathbf{I} \psi \sqrt{\mathbf{T} \delta \mathbf{t}}$$

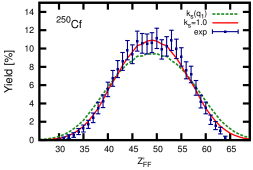
where ψ - random number, γ_K - friction parameter (coupling K with heat bath)– J.P.Leastone,S.G.McCalla,PRC79,044611



Isotopic Distributions: U + C→Cf (E_{lab}=6.2 AMeV)

The charge variance is necessary to reproduce the isotopic distribution.





A finite charge dispersion is necessary to reproduce the isotopic distribution.

$$Z_{FFi}^{UCD} = \frac{A_{FFi} Z_{fiss}}{A_{fiss}}$$

$$Z_{FFi}^{NUCD} = Z_{FFi}^{UCD} \pm 1; \pm 2...$$

K.M., C. Schmitt, P. Nadtochy PRC 91, 041603(R) (2015),

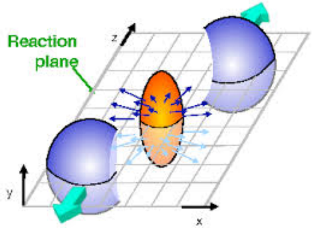
M. Caamano et al. PRC **88**, 024605 (2014)

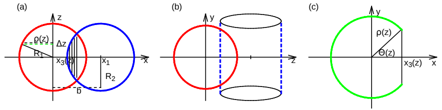
A.V. Karpov, G.D. Adeev Phys.At.Nucl. 65,1596 (2002);

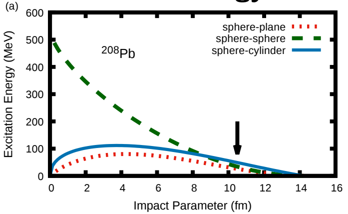
Eur.Phys.J. A 14,169 (2002)

Pb + Pb Collision - Geometrical Scenarios

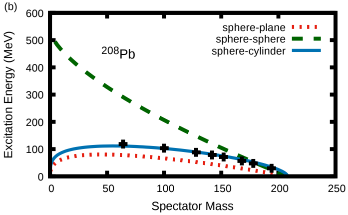
After collision - very deformed shapes of the spectator -
the deformation energy translated to excitation energy of the spectator







$$E_{def} = E_{surf}(def) - E_{surf}(0)$$

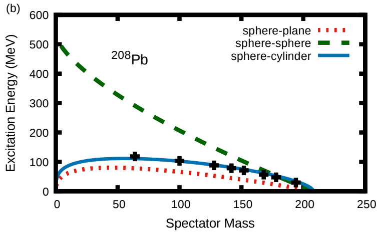


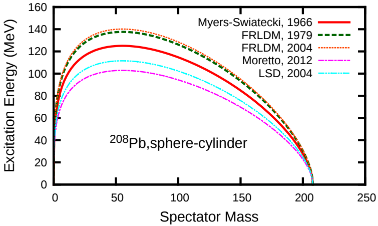
K. M., A. Szczurek, P.N. Nadtochy, APPB Proc. Suppl., 10 (2017) 113, arXiv:1708.03716

^{208}Pb + ^{208}Pb at 158 GeV/A SPS CERN

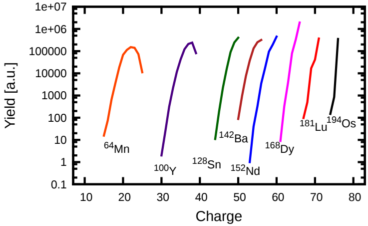
Pb + Pb Collision - Dynamic Evolution of Spectator

The excited Compound Nuclei (eight) have been evaluated in 4D Langevin code to estimate the evaporation and fission channels. We assume $\frac{Z_S}{A_S} = \frac{Z_{Pb}}{A_{Pb}}$

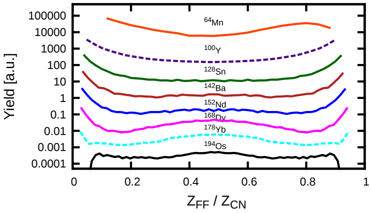




Evaporation Residue charge distribution



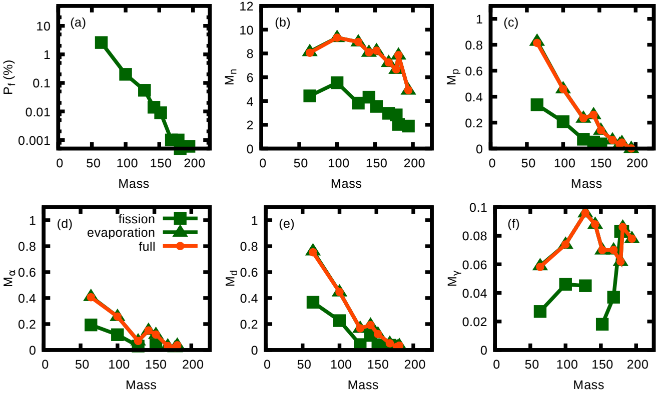
Fission Fragment charge distribution



K. M., A. Szczurek, P.N. Nadtochy, arXiv:1708.03716, PRC, 97 (2018) 024604

Pb + Pb Collision - Particle Multiplicities

At high energies the Zero Degree Calorimeters (ZDC) measure neutral particles (RHIC, LHC).



The fission probability and the multiplicities of emitted n, p, α, d and γ in fission and evaporation channels.

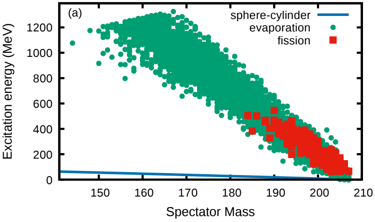
Larger impact parameter (more peripheral collision)

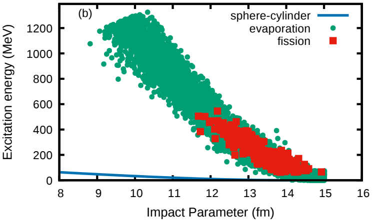
– lower fission probability.

Pb + Pb Collision – Alternative estimations

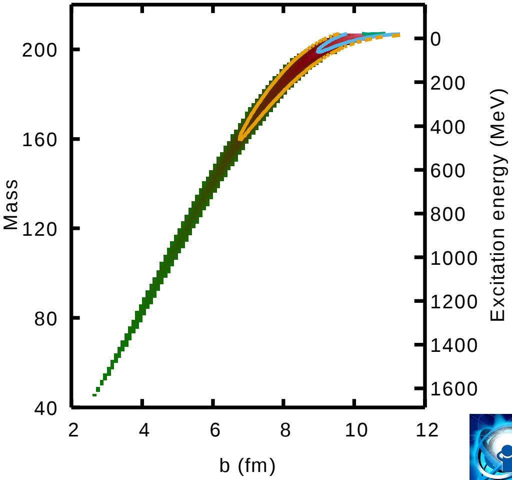
The spectator mass and excitation energy could be calculated by:

ABRABLA code





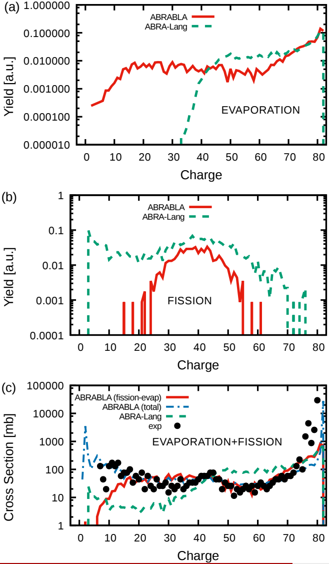
Glauber formula



K. M., A. Szczurek, P.N. Nadtochy, arXiv:1708.03716, submitted to PRC

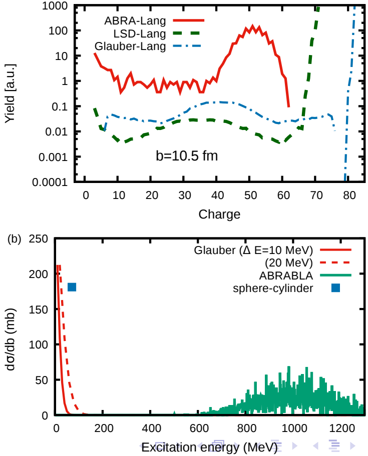
Pb + Pb Collision - Dynamic Evolution of Spectator

ABRA+Langevin



Impact parameter b=10.5 fm

following predictions of A. Rybicki and A. Szczurek, PR**C75** (2007) 054903;PR**C87** (2013) 054909.

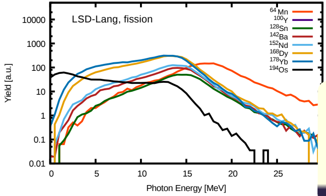


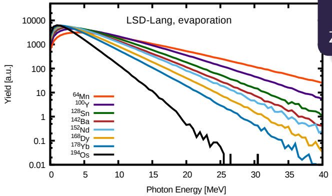
Pb + Pb Collision - Photon Emission

Statistical emission of particles and γ-rays with emission widths of A.S. Iljinov et al, Yad.Fiz.33(1981)997,

Nucl.Phys.A543(1992)517

LSD+Langevin

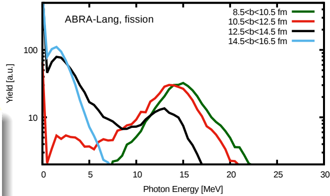


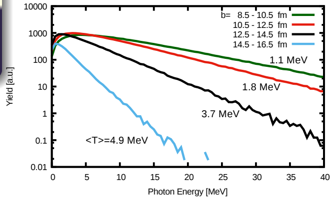


duction is possible. A rapid rupture of the neck during the fission process together with strong Coulomb forces involved (causing a displacement of neutrons against protons) may create giant resonances formed upon the fission fragments. One of possible decay channels of giant resonances is the light particle emis-

T.Srokowski, A.Szczurek, A.Budzanowski, Z.Phys.A 333(1989)83

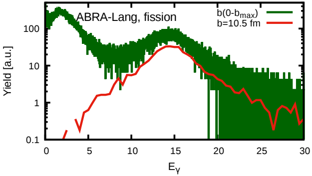
ABRA+Langevin

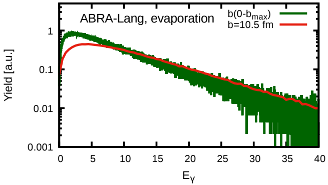


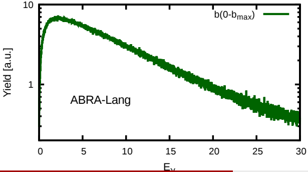


Pb + Pb Collision - Time

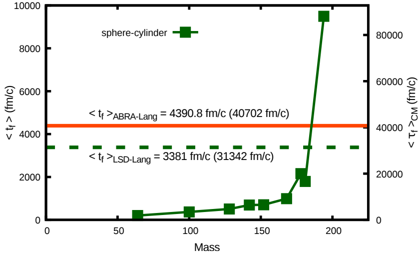
Photon energy spectra

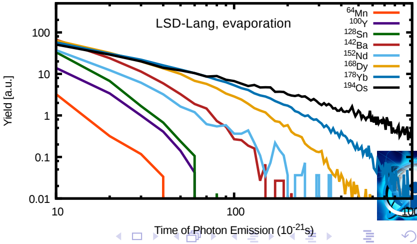






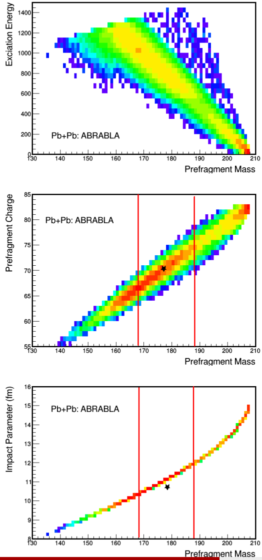
Fission/Photon emission time



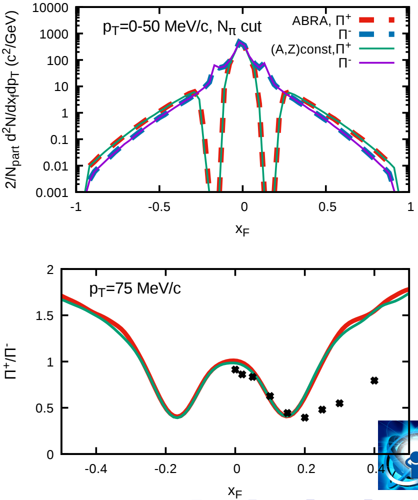


Pb + Pb Collision - Fluctuation

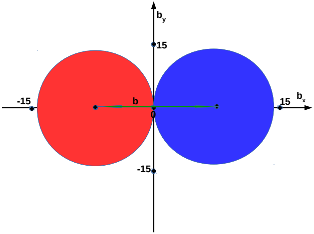
Mass/charge of the spectator

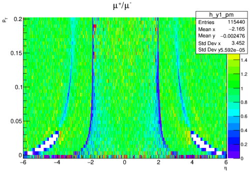


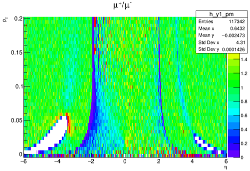
A/Z/B fluctuation in pion ratio

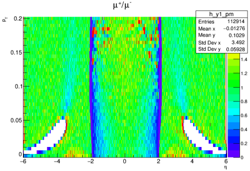


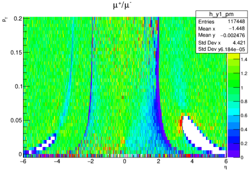
Pb + Pb Collision - Muon - spectator interaction

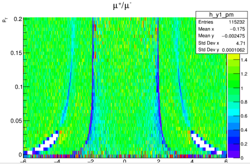






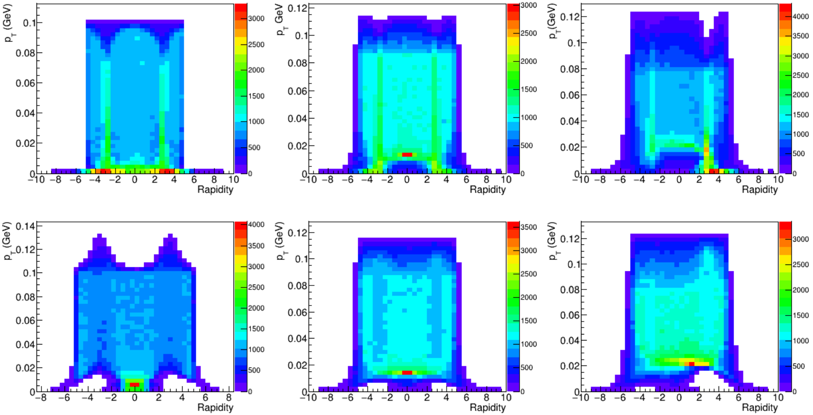






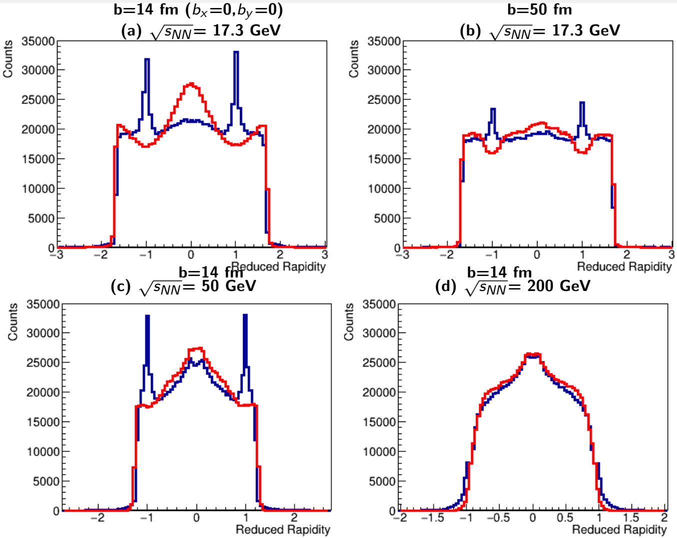
Pb + Pb Collision - electron and positron - spectator interaction

(a) (b_x=0, b_y=0) (b) (b_x=0, b_y=15 fm) (c) (b_x=15 fm, b_y=0)



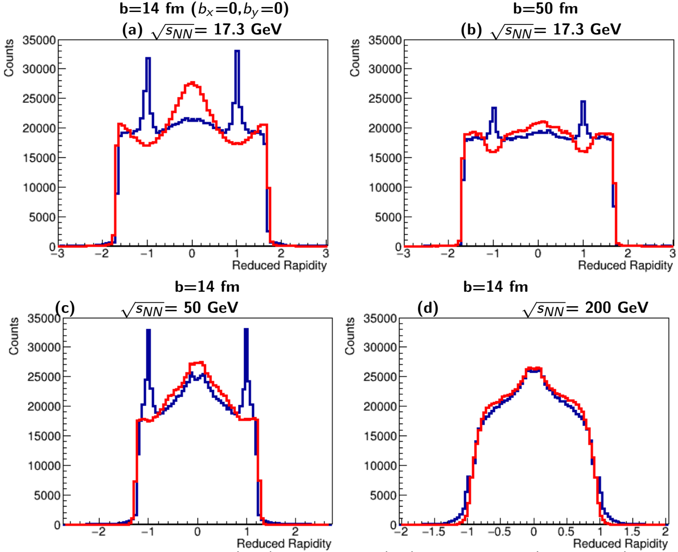
K. M., M. Kłusek-Gawenda, J. Józefiak, and A. Szczurek, arXiv:2107.13239v1, submitted to PRC

Pb + Pb Collision - electron and positron - spectator interaction



Reduced rapidity distributions for final electrons (blue) and positrons (red) for fixed b and (b_x=0,b_y=0) plane of emission points at three collision energies: $\sqrt{s_{NN}}$=17.3, 50 and 200 GeV.

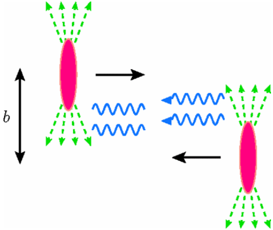
Pb + Pb Collision - electron and positron - spectator interaction

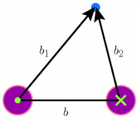


Reduced rapidity distributions for final electrons (blue) and positrons (red) for fixed b and (b_x=0,b_y=0) plane of emission points at three collision energies: $\sqrt{s_{NN}}$=17.3, 50 and 200 GeV.

Electron and positron production - EPA model

The equivalent photon approximation (EPA) is standard semiclassical alternative to the Feynman rules for calculating the cross section of EM interaction.Due to coherent action of all the protons in the nucleus , the EM field surrounding the ions is very strong. Produce the 'equivalent' or 'quassireal' photons.





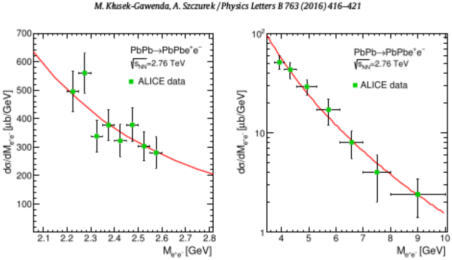


Fig. 2. Invariant mass distributions of dielectrons in UPC of heavy ions calculated within our approach [10] together with the recent ALICE data [22].

M. Kłusek-Gawenda, PRC82,014904

Electron and positron production - EPA model

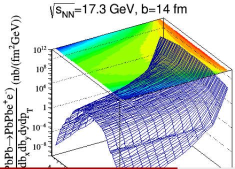
Double scattering production of positron-electron pairs using the b-space equivalent photon approximation (EPA) model (G. Baur, L. Filho, Nuclear Physics A 518(4), 786 (1990); M. Kłusek-Gawenda,Phys. Lett. B 790, 339 (2019)). The total cross section for the considered process ($AA \rightarrow AAe^{+}e^{-}$) can be written as:

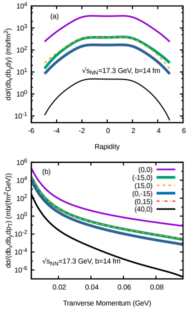
$$\sigma_{\mathbf{A_1A_2\rightarrow A_1A_2e^+e^-}}(\sqrt{\mathbf{s_{A_1A_2}}}) =$$

$$= \int \frac{\mathbf{d}\sigma_{\gamma\gamma\rightarrow \mathbf{e^+e^-}}(\mathbf{W}_{\gamma\gamma})}{\mathbf{d}\cos\theta}\mathbf{N}(\omega_1, \mathbf{b_1})\mathbf{N}(\omega_2, \mathbf{b_2})\mathbf{S^2_{abs}(b)}$$

$$\times \quad 2\pi \mathbf{bdbd\overline{b}_xd\overline{b}_y}\frac{\mathbf{W}_{\gamma\gamma}}{2}\mathbf{dW}_{\gamma\gamma}\mathbf{dY_{e^+e^-}}\ \mathbf{d}\cos\theta, \qquad (1)$$

where $\mathbf{N(\omega_i, b_i)}$ are photon fluxes, $\mathbf{W}_{\gamma\gamma} = \mathbf{M_{e^+e^-}}$ is invariant mass and $\mathbf{Y_{e^+e^-}} = (\mathbf{y_{e^+}} + \mathbf{y_{e^-}})/2$ is rapidity of the outgoing system and θ is the scattering angle in the $\gamma\gamma \rightarrow \mathbf{e^+e^-}$ center-of mass system. The gap survival factor $\mathbf{S^2_{abs}}$ assures that only ultra-peripheral reactions are considered.



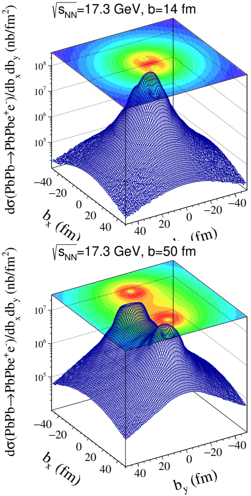


The differential cross section for various emission points of electrons/positrons produced in the ^{208}Pb+^{208}Pb reaction at 158 GeV/nucleon energy ($\sqrt{s_{NN}} =$ 17.3 GeV) at impact parameter 14±0.05 fm. The cross section for selected points (b_x, b_y): (0, 0), (±15 fm, 0), (0, ±15 fm) and (40 fm, 0) are integrated over p_T (a) and rapidity (b), respectively.The map of differential cross section in rapidity of electron or positron and lepton transverse momentum for $(b_x, b_y) = (0, 0)$ which will be called CM point for brevity.

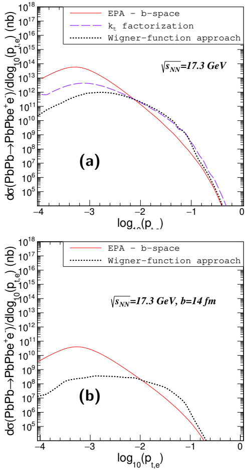
Electron and positron production - EPA model

(a)

(b)

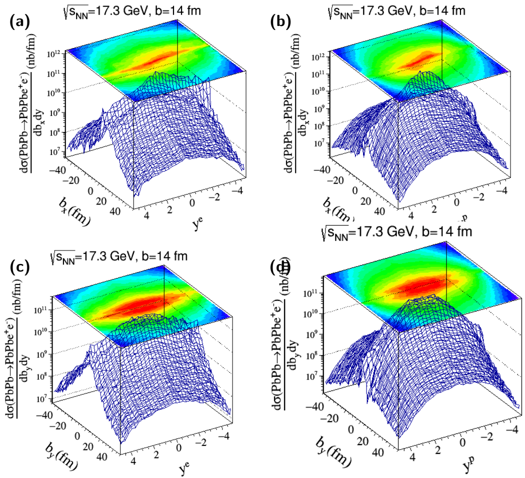


Two-dimensional cross section as a function of b_x and b_y for two values of impact parameter: (a) b=14±0.05 fm and (b) b=50±0.05 fm.



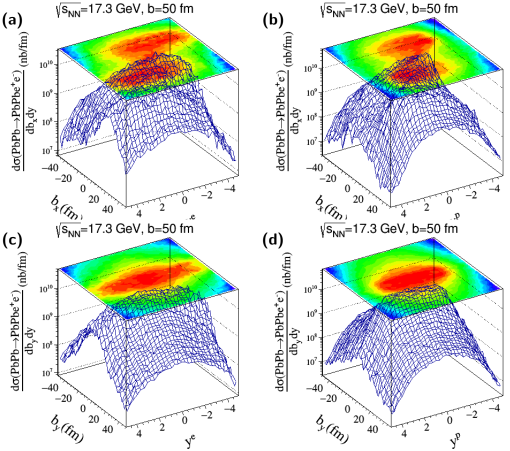
Differential cross section for PbPb→PbPbe^+e^- as a function of $\log_{10}(p_{t,e})$. The left panel shows impact parameter integrated cross section while the right panel is for a narrow range of impact parameter $b \in (13.95, 14.05)$ fm.The b-space EPA with its counterpart for the Wigner-function approach

Pb + Pb Collision - electron and positron - spectator interaction



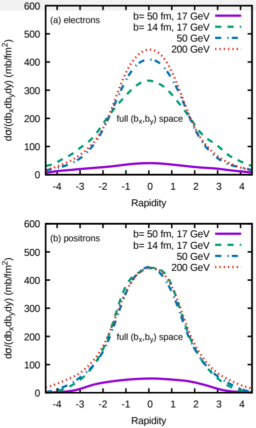
Distribution of electrons ((a), (c)) and positrons ((b), (d)) for $\sqrt{s_{NN}}$= 17.3 GeV at b=14 fm integrated over (b_x, b_y)=(-50 fm, 50 fm), p_T^{ini}=(0, 0.1 GeV)

Pb + Pb Collision - electron and positron - spectator interaction

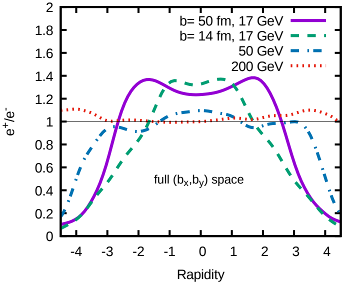


Distribution of electrons ((a), (c)) and positrons ((b), (d)) for $\sqrt{s_{NN}}$= 17.3 GeV at b=50 fm integrated over (b_x, b_y)=(-100 fm, 100 fm), p_T^{ini}=(0, 0.1 GeV).

Pb + Pb Collision - electron and positron - spectator interaction



Rapidity distribution of electrons for $\sqrt{s_{NN}}$= 17.3 GeV (b=14 fm, 50 fm) and 50 GeV and 200 GeV with b=14±0.05 fm (only) integrated over (b_x, b_y)=(-50 fm, 50 fm), p_T^{ini}=(0, 0.1 GeV).



The ratio of rapidity distributions of positrons and electrons for $\sqrt{s_{NN}}$= 17.3 GeV and fixed b=14 fm and 50 fm and $\sqrt{s_{NN}}$ = 50 GeV and 200 GeV with fixed b=14 fm integrated over (b_x, b_y)=(-50 fm, 50 fm) and transverse momenta in the interval p_T^{ini}=(0, 0.1 GeV).

Summary

- The moddeling of the heavy-ion collisions suffered of the lack of knowledge about time evolution of the spectators and deexcitation channels.
- Our calculation estimated the excitation energy of the spectators.
- The dynamic evolution of various spectators produced in peripheral collisions Pb+Pb at 158 GeV/nucleon energies has been investigated.
- The photon energy spectra and emission time are estimated.
- Spectator-induced EM effects in charged pion production give insight to space-time properties of the system of hot and dense matter created in heavy ion collisions.
- They suggest a picture of the longitudinal evolution of the system at the initial stage at CERN SPS energies largely governed by the energy-momentum conservation.
- The cross section of electrons/positrons produced via photon-photon fusion in heavy ion UPC can be rather reliably calculated and turned out to be large, especially for low transverse momentum electrons/positrons.
- The impact parameter equivalent photon approximation is well suitable for investigating the electromagnetic effects.
- On the experimental side only rather large transverse momentum electrons/positrons could be measured so far at RHIC and the LHC, typically larger than 0.5 GeV.
- However, the integration over full (b_x, b_y) plane washes out this effect to large extent.
- We have found that only at small transverse momenta of electrons/positrons one can observe sizeable EM effects.

The NA61/SHINE collaboration prepared a proposal to the CERN SPS [?] for new, high statistics measurements of Pb+Pb collisions to be performed after 2020. This includes using the