

Peripheral, ultrarelativistic production of particles in heavy ion collisions

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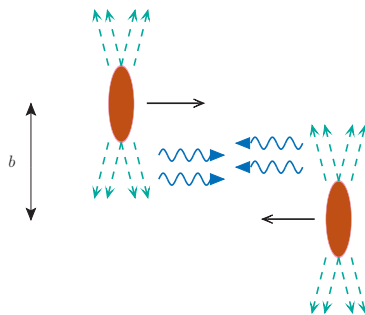
Kraków, January 7-10, 2014



Contents

- Introduction
- $AA \rightarrow AA\pi\pi$
- $AA \rightarrow AA\rho^0\rho^0$
- Electromagnetic dissociation of nuclei
- Conclusions

Equivalent photon approximation



The strong electromagnetic field is a source of photons which induce electromagnetic reactions.

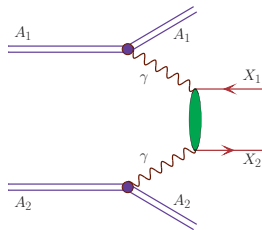
Peripheral collisions:

$$b > R_1 + R_2 \cong 14 \text{ fm}$$

Cross section in EPA

$$\sigma(PbPb \rightarrow PbPbX_1X_2; s_{NN})$$

$$= \int \hat{\sigma}(\gamma\gamma \rightarrow X_1X_2; x_1x_2s_{NN}) dn_{\gamma\gamma}(x_1, x_2, \mathbf{b})$$



Cross section in EPA

- $x_{1,2} = \frac{\omega_{1,2}}{\gamma M_A}$

$$dn_{\gamma\gamma}(x_1, x_2, \mathbf{b}) = \int \frac{1}{\pi} d^2\mathbf{b}_1 |\mathbf{E}(x_1, \mathbf{b}_1)|^2 \frac{1}{\pi} d^2\mathbf{b}_2 |\mathbf{E}(x_2, \mathbf{b}_2)|^2 \\ \times S_{abs}^2(\mathbf{b}) \delta^{(2)}(\mathbf{b} - \mathbf{b}_1 + \mathbf{b}_2) \frac{dx_1}{x_1} \frac{dx_2}{x_2}$$

- $\mathbf{E}(x, \mathbf{b}) = Z \sqrt{4\pi a_{em}} \int \frac{d^2\mathbf{q}}{(2\pi^2)} e^{-i\mathbf{b}\mathbf{q}} \frac{\mathbf{q}}{q^2 + x^2 M_A^2} F_{em}(q^2 + x^2 M_A^2)$

- $S_{abs}^2(\mathbf{b}) \cong \partial(\mathbf{b} - 2R_A)$

- $\frac{1}{\pi} \int d^2\mathbf{b} |\mathbf{E}(x, \mathbf{b})|^2 = \int d^2\mathbf{b} N(\omega, \mathbf{b})$

- $d\omega_1 d\omega_2 \rightarrow dW_{\gamma\gamma} dY_{X_1 X_2}$



Nuclear cross section -- EPA

$$\begin{aligned} \sigma (PbPb \rightarrow PbPbX_1X_2; s_{NN}) &= \\ &= \int \hat{\sigma} (\gamma\gamma \rightarrow \pi\pi; W_{\gamma\gamma}) \vartheta (|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A) \\ &\times N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_1) 2\pi b_m db_m d\bar{b}_x d\bar{b}_y \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY \end{aligned}$$

The details of derivation:

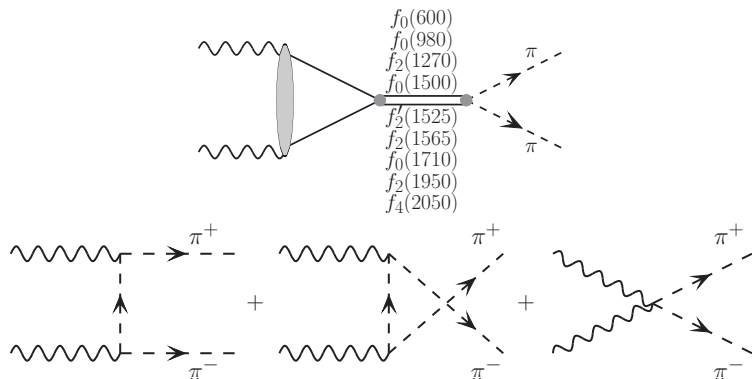
A. Szczurek, M. Kłusek-Gawenda; Phys. Rev. **C82** (2010) 014904,

“Exclusive muon-pair productions in ultrarelativistic heavy-ion collisions:
Realistic nucleus charge form factor and differential distributions”

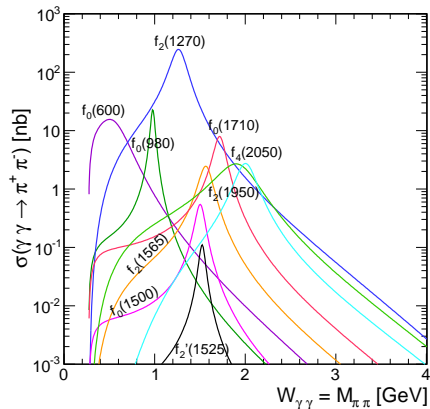


Elementary $\gamma\gamma \rightarrow \pi\pi$ cross section

Soft processes:



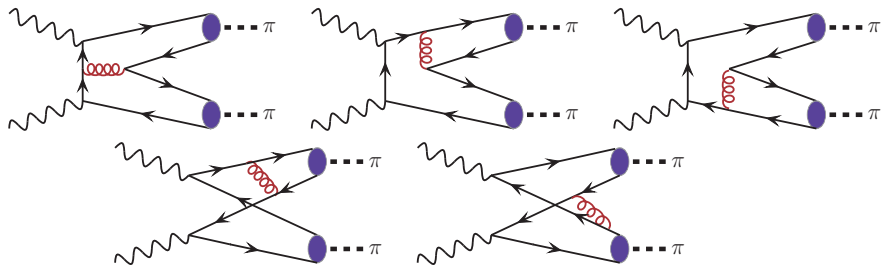
Resonance contributions



Many resonances (!)

pQCD mechanism

pQCD processes:



Brodsky-Lepage pQCD formalism

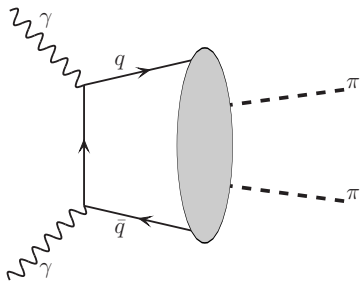
$$\mathcal{M}(\hat{n}_1, \hat{n}_2) = \int_0^1 dx \int_0^1 dy \phi_\pi(x, \mu_x^2) T_H^{\hat{n}_1 \hat{n}_2}(x, y, \mu^2) \phi_\pi(y, \mu_y^2) \\ \times F_{reg}^{pQCD}(t, u)$$

$T^{\hat{n}_1, \hat{n}_2}$ - hard matrix element (Brodsky-Lepage)

Distribution amplitudes describing *BABAR* data for
pion transition form factor.



Hand-bag mechanism



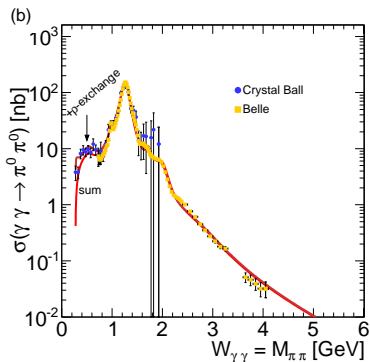
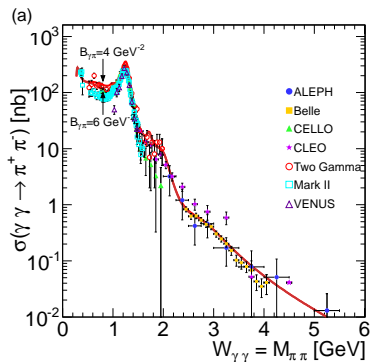
M. Diehl, P. Kroll and C. Vogt,

Phys. Lett. **B532** (2002) 99;

M. Diehl and P. Kroll,

Phys. Lett. **B683** (2010) 165.

$AA \rightarrow AA\pi\pi$



Good description of elementary $\gamma\gamma \rightarrow \pi\pi$ reactions (also $d\sigma/dz$)

Klusek, Szczurek, Phys. Rev. **C87** (2013) 054908

Belle data



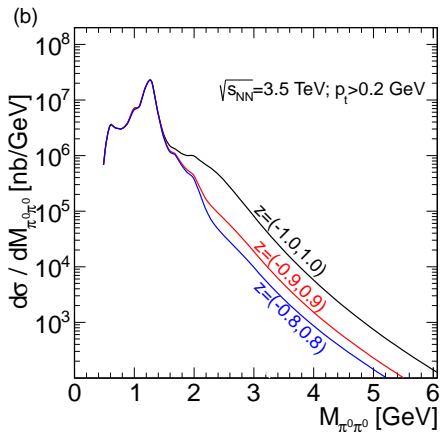
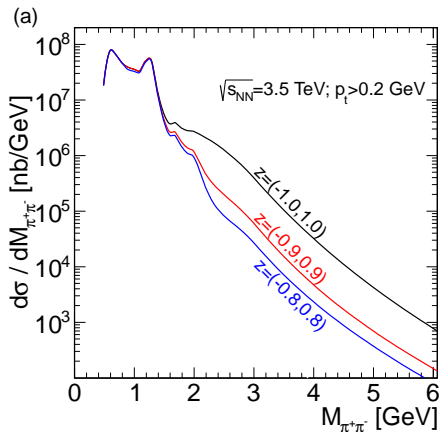
$AA \rightarrow AA\pi\pi$, total cross section

Table: Cross sections for different lower cuts on pion transverse momenta at $\sqrt{s_{NN}} = 3.5$ TeV.

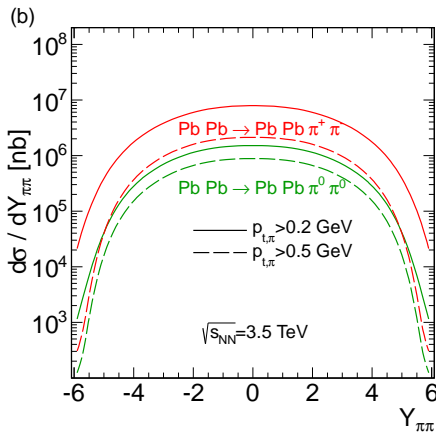
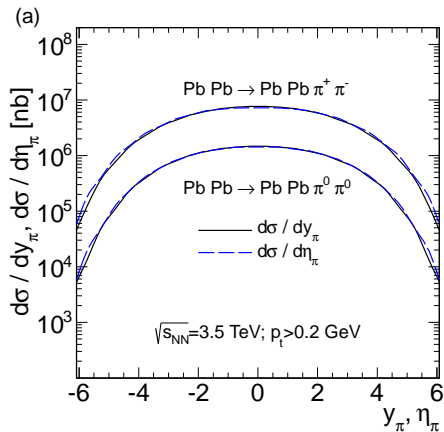
$p_{t,min}$ (GeV)	$\pi^+ \pi^-$ (mb)	$\pi^0 \pi^0$ (mb)
0.2	46.7	8.7
0.5	12.1	5.1
1.0	0.08	0.05



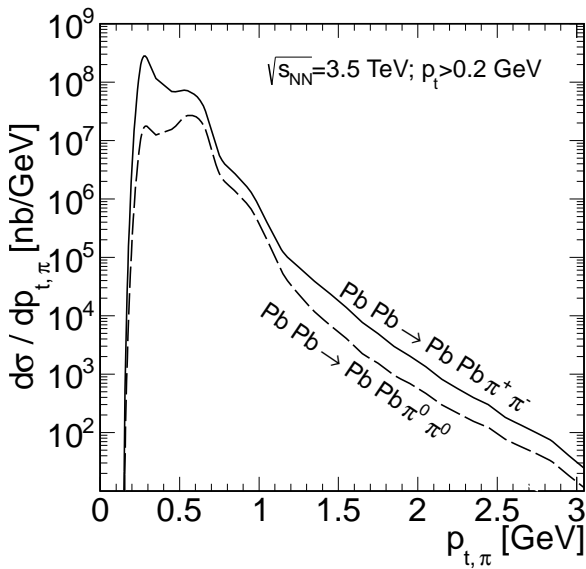
AA \rightarrow AA $\pi\pi$, differential distributions



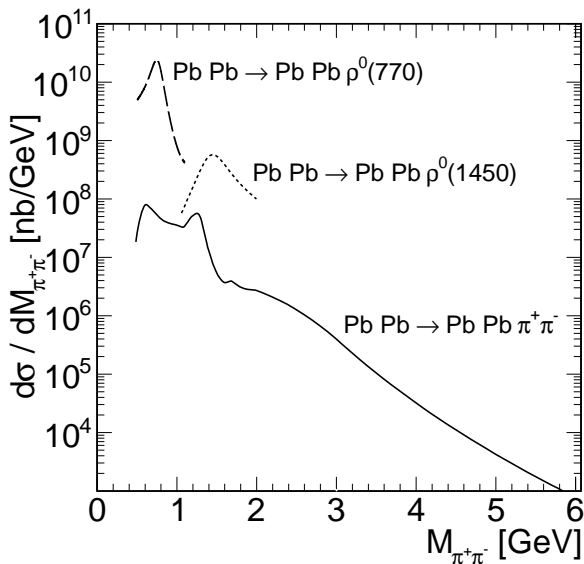
AA \rightarrow AA $\pi\pi$, differential distributions



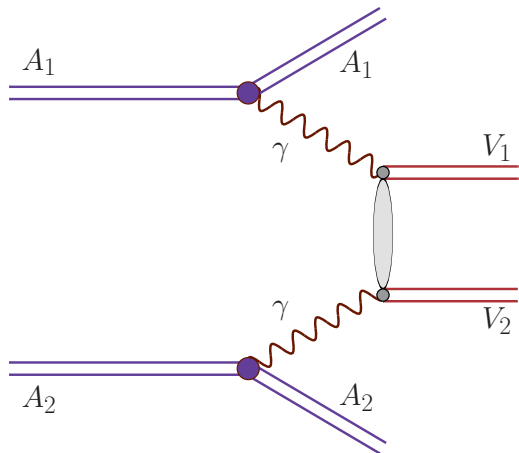
AA \rightarrow AA $\pi\pi$, differential distributions



$AA \rightarrow AA\pi\pi$, differential distributions



$$AA \rightarrow AA\rho^0\rho^0$$



Single ρ^0 production

Glauber-VDM model

Klein-Nystrand

$$\sigma(\gamma A \rightarrow \rho^0 A; W) = \frac{d\sigma(\gamma A \rightarrow \rho^0 A)}{dt} \Big|_{t=0} \int_{-\infty}^{t_{max}} dt |F(t)|^2$$

$$\frac{d\sigma(\gamma A \rightarrow \rho^0 A)}{dt} \Big|_{t=0} = \frac{\alpha \sigma_{tot}(\rho^0 A; W)}{4t_\rho^2}$$

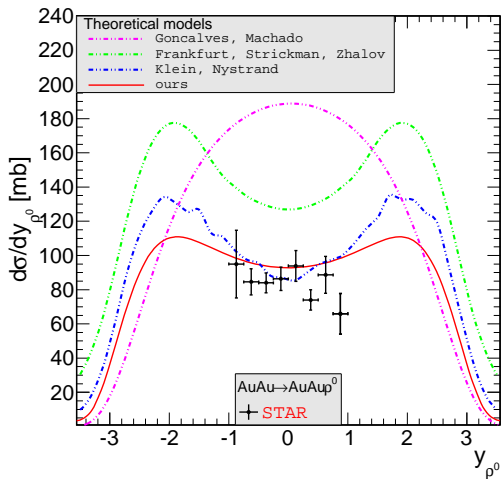
$$\sigma_{tot}(\rho^0 A \rightarrow \rho^0 A; W) = \int d^2r (1 - \exp(-\sigma_{tot}(\rho^0 p; W) T_A(\vec{r})))$$

$$\sigma_{tot}^2(\rho^0 p; W) = 16\pi \frac{d\sigma(\rho^0 p \rightarrow \rho^0 p; W)}{dt} \Big|_{t=0} .$$

The last cross section parametrized in the [Regge parametrization](#).



$AA \rightarrow AA\rho^0$

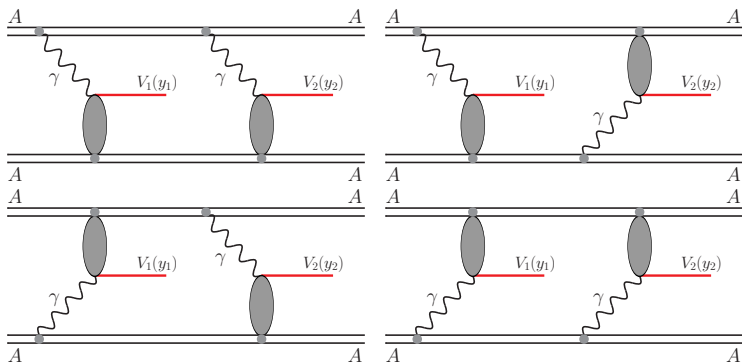


huge cross section (!)



$$AA \rightarrow AA\rho^0\rho^0$$

double-scattering mechanism



Klusek-Gawenda and Szczurek, arXiv:1309.2463.

$AA \rightarrow AA\rho^0\rho^0$, double scattering

$$\sigma_{AA \rightarrow AA V_1 V_2}(\sqrt{s_{NN}}) = C \int P_{V_1}(b, \sqrt{s_{NN}}) P_{V_2}(b, \sqrt{s_{NN}}) d^2 b, \quad (1)$$

where the probability of single meson production is

$$P_V(b, \sqrt{s_{NN}}) = \frac{d\sigma_{AA \rightarrow AA V}(b; \sqrt{s_{NN}})}{2\pi b db}. \quad (2)$$

The simple formula (1) can be generalized to calculate two-dimensional distributions in rapidities of both vector mesons

$$\frac{d\sigma_{AA \rightarrow AA V_1 V_2}}{dy_1 dy_2} = C \int S_{el}^2(b) \left(\frac{dP_1^{yP}(b, y_1; \sqrt{s_{NN}})}{dy_1} + \frac{dP_1^{Py}(b, y_1; \sqrt{s_{NN}})}{dy_1} \right) \times \left(\frac{dP_2^{yP}(b, y_2; \sqrt{s_{NN}})}{dy_2} + \frac{dP_2^{Py}(b, y_2; \sqrt{s_{NN}})}{dy_2} \right)$$

$AA \rightarrow AA\rho^0\rho^0$, double scattering

$$S_{el}^2(b) = \exp\left(-\sigma_{NN}^{tot} T_{A_1 A_2}(b)\right) \approx \vartheta(b - (R_1 + R_2)) . \quad (4)$$

It may be interpreted as a survival probability for nuclei not to undergo break up of nuclei.

dP_1 and dP_2 are probability densities to produce one vector meson V_1 at rapidity y_1 and second vector meson V_2 at rapidity y_2 , respectively, for fixed impact parameter b . Then the more differential probability can be written as:

$$\frac{dP_V(b, \sqrt{s_{NN}})}{dy} = \frac{d\sigma_{AA \rightarrow AA V}(b; \sqrt{s_{NN}})}{2\pi b db dy} . \quad (5)$$



Smearing the ρ^0 masses

In a more refined approximation (b) one has to include in addition a smearing of the ρ^0 mass. Then the cross section can be written as

$$\frac{d\sigma_{AA \rightarrow AA\rho_0^*\rho_0^*}}{dm_1 dm_2 dy_1 dy_2} = f(m_1)f(m_2) \frac{d\sigma_{AA \rightarrow AA\rho_0^*\rho_0^*}}{dy_1 dy_2}(y_1 y_2; m_1, m_2), \quad (6)$$

where m_1 and m_2 are running masses of ρ^0 mesons and $f_1(m_1)$ and $f_2(m_2)$ are respective distributions. The last term is the cross section for fixed masses m_1 and m_2 . The spectral shapes are calculated as:

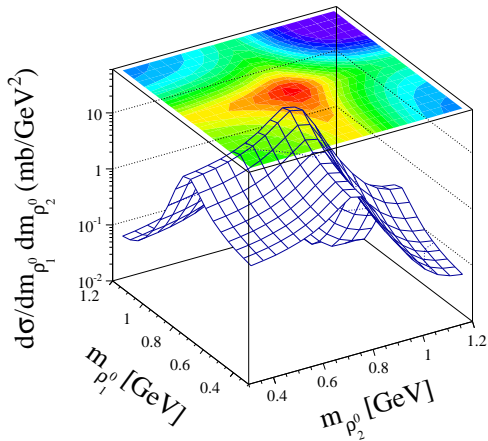
$$f(m) = |\mathcal{A}|^2 / \int |\mathcal{A}|^2 dm, \quad (7)$$

where the amplitude is parametrized as:

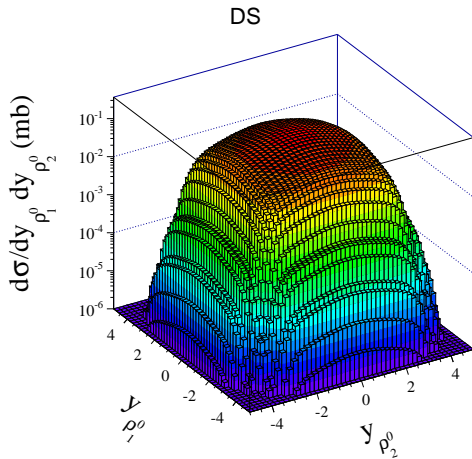
$$\mathcal{A} = \mathcal{A}_{BW} \frac{\sqrt{mm_\rho \Gamma(m)}}{m^2 - m_\rho^2 + im_\rho \Gamma(m)} + \mathcal{A}_{\pi\pi}.$$



$AA \rightarrow AA\rho^0\rho^0$, mass smearing



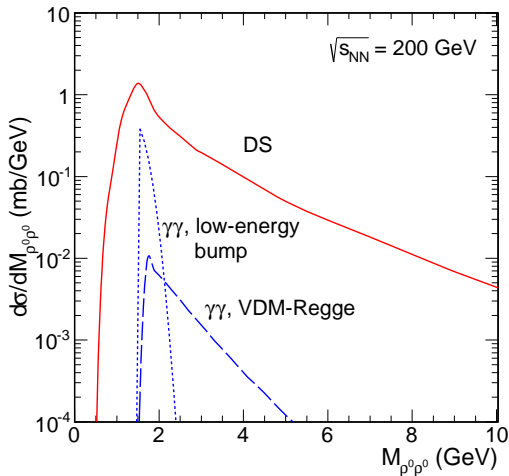
$AA \rightarrow AA\rho^0\rho^0$, RHIC



rather flat distribution compared to $\gamma\gamma$ contribution



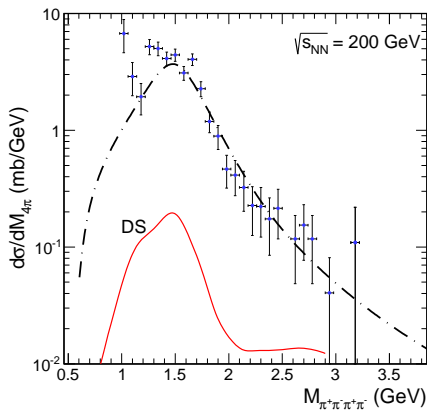
$AA \rightarrow AA\rho^0\rho^0$, RHIC



double scattering contribution much bigger than photon-photon



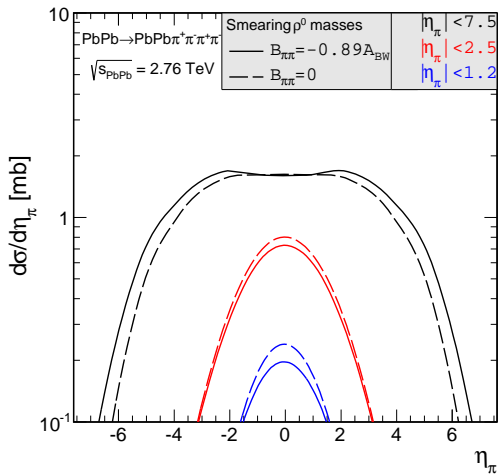
$AA \rightarrow AA\rho^0\rho^0$, RHIC



Other mechanism at RHIC!

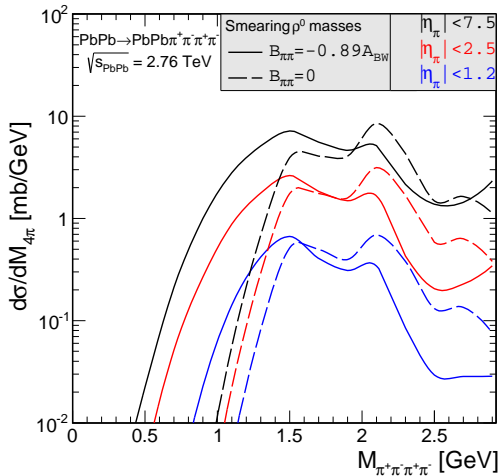
How to identify double scattering?

$AA \rightarrow AA\rho^0\rho^0$, LHC



Similar cross section as for $\pi^+\pi^-$ production.

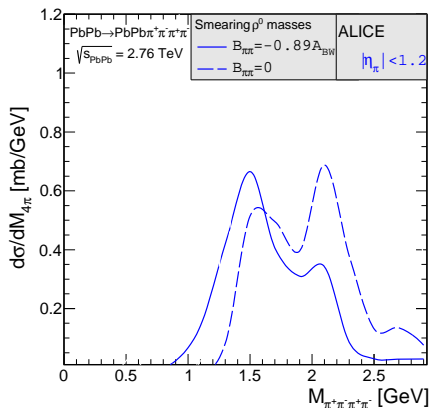
$AA \rightarrow AA\rho^0\rho^0$, LHC



Standard Breit-Wigner versus skewed distribution



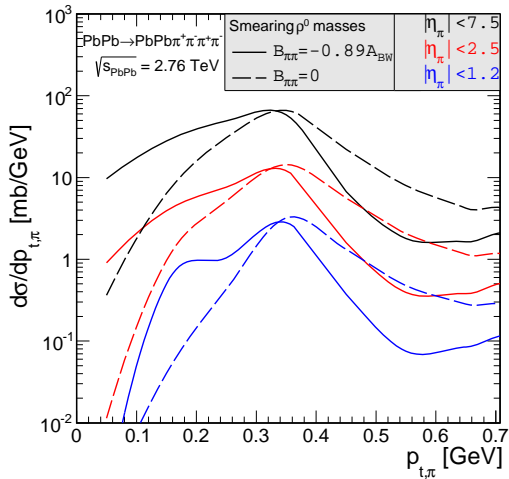
AA \rightarrow AA $\rho^0\rho^0$, LHC



Could be verified experimentally but other contributions possible:

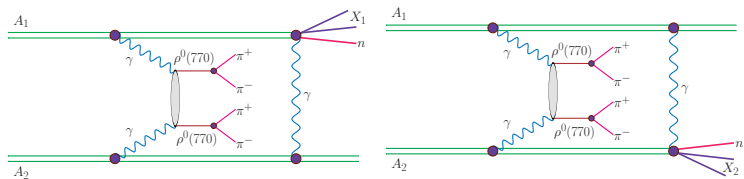
$\rho^0(1450)$ and $\rho^0(1700)$ – decay into 4 π .

AA \rightarrow AA $\rho^0\rho^0$, LHC



Can be verified experimentally.

Electromagnetic dissociation



Neutrons can be measured by Zero Degree Calorimeters

They are a "good trigger" for the exclusive reactions

Kłusek-Ciemala-Schäfer-Szczurek, arXiv:1311.1938.



Neutron emission

Cross section for production of "something" with a given number of neutrons in each ZDC

is an interesting (measureable) quantity,

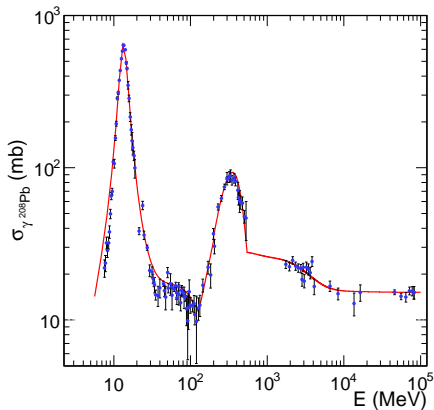
$$\sigma_{AA \rightarrow AAX}(n_1, n_2)$$

$X = 0$ (Coulomb excitation), ρ^0 , $\mu^+ \mu^-$, etc

For each exclusive process one can calculate (topological cross section) with given number of neutrons emitted from first and second nucleus.



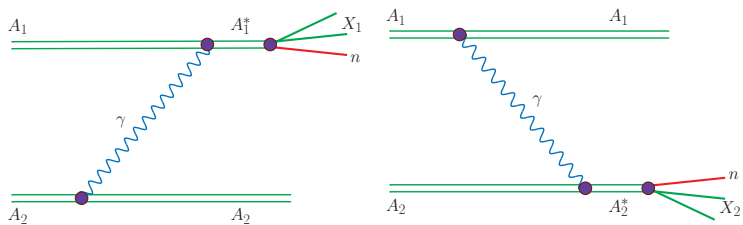
photon- ^{208}Pb cross section



quite a span of energies (!) Different regions -- different physics



Electromagnetic dissociation



Huge damping of heavy-ion fluxes at LHC !



Electromagnetic dissociation - a bit of formalism

In the single photon-exchange approximation the cross section for dissociation of **second** and **first** nucleus:

$$\begin{aligned}\sigma^{(1)} &= \int d^2b \int d\omega_1 \frac{d^3n(b, \omega_1)}{d\omega_1 d^2b} S(b) \sigma_{\gamma A_2 \rightarrow A_2^*}(\omega_1) . \\ \sigma^{(2)} &= \int d^2b \int d\omega_2 \frac{d^3n(b, \omega_2)}{d\omega_2 d^2b} S(b) \sigma_{\gamma A_1 \rightarrow A_1^*}(\omega_2) ,\end{aligned}\tag{9}$$

Of course: $\sigma^{(1)} = \sigma^{(2)}$.

Above $S(b)$ can be interpreted as a **survival probability** of the nuclei not to desintegrate.



Electromagnetic dissociation - a bit of formalism

$$S(b) \approx \partial (|\mathbf{b}| - \mathbf{R}_1 - \mathbf{R}_2) . \quad (10)$$

$\frac{d^3 n(b, \omega)}{d\omega d^3 b}$ is a flux of equivalent photons.

In some approximation:

$$\frac{dN}{d\omega_{1/2} d^2 b} = \frac{Z^2 a_{em} X^2}{\pi^2 \omega_{1/2} b^2} K_1^2(X) \quad (11)$$

Notice Z^2 enhancement compared to protons.



Electromagnetic dissociation - a bit of formalism

The total cross section for dissociation of either A_1 or A_2 can be written as:

$$\sigma_{diss} = \sigma^{(1)} + \sigma^{(2)} . \quad (12)$$

A differential distribution (integrand of total cross section) may be interesting

$$\frac{d\sigma^{(1)}}{d^2bd\omega_1} = \frac{d^3n(b, \omega_1)}{d\omega_1 d^2b} \sigma_{\gamma A_2 \rightarrow A_2^*}(\omega_1) ,$$
$$\frac{d\sigma^{(2)}}{d^2bd\omega_2} = \frac{d^3n(b, \omega_1)}{d\omega_2 d^2b} \sigma_{\gamma A_1 \rightarrow A_1^*}(\omega_2) ,$$



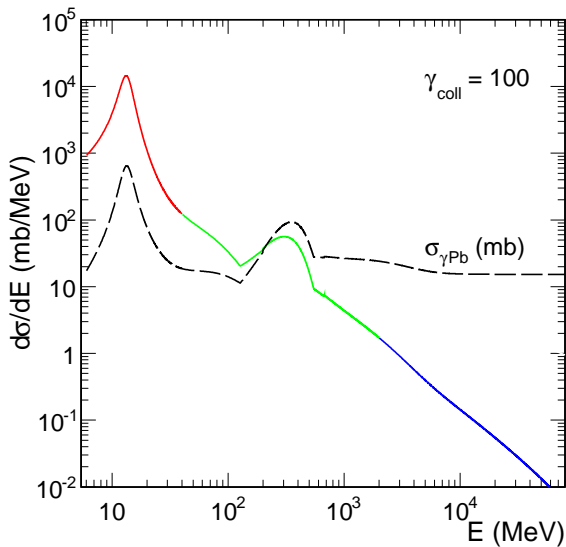
Electromagnetic dissociation

Cross section in barns

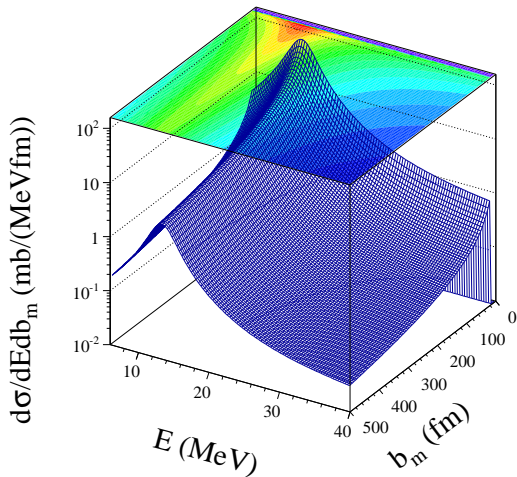
	(6-40) MeV	(40-2000) MeV	(2-80) GeV
$\gamma_{coll} = 100$			
Our results	80.16	25.6	5.6
$\gamma_{coll} = 3100$			
Our results	133.8	54.6	18.7



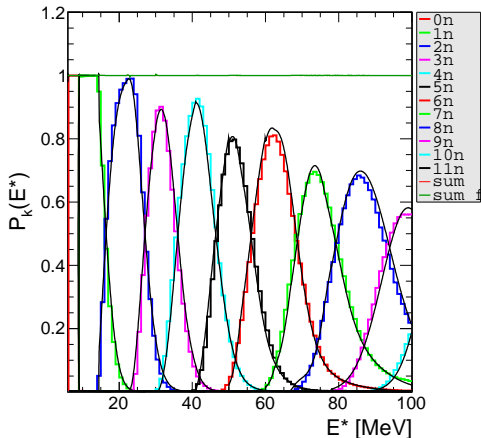
Electromagnetic excitation



Electromagnetic excitation



Neutron production from excited nucleus

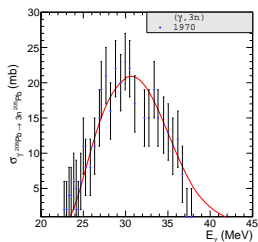
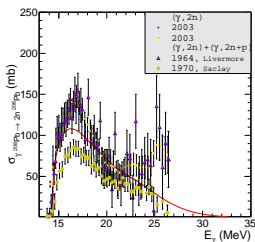
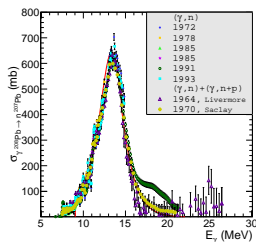


Hauser-Feshbach theory (M. Ciemata)

The approach assumes **equilibrated** excited nucleus (!)



Cross section for single neutron photoproduction



Surprisingly good agreement!

Model assumes equilibrium.

Does it mean the nucleus goes to equilibrium after photon absorption and before neutron emission?



Electromagnetic dissociation with forward/backward neutrons

first nucleus in ground state, second nucleus excited

$$\sigma_{0*}^{(i)} = 2\pi \int dbbS(b) \int_{E_{min}}^{E_{max}} d\omega_1 \frac{dN}{d\omega_1 d^2b} \sigma_{\gamma A_2 \rightarrow A_2^*}(\omega_1) P_{A_2}^j(E_2^*),$$

$$E_2^* = \omega_1?$$

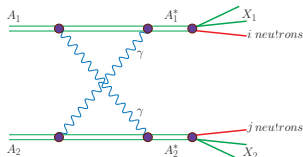
first nucleus excited, second nucleus in the ground state

$$\sigma_{*0}^{(j)} = 2\pi \int dbbS(b) \int_{E_{min}}^{E_{max}} d\omega_2 \frac{dN}{d\omega_2 d^2b} \sigma_{\gamma A_1 \rightarrow A_1^*}(\omega_2) P_{A_1}^j(E_1^*),$$

$$E_1^* = \omega_2?$$



Mutual excitation



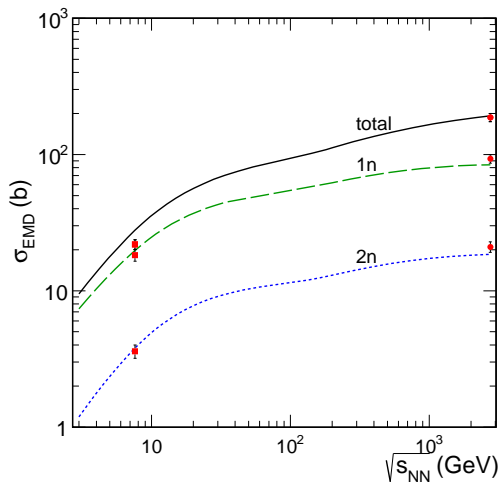
Second-order effects lead to mutual excitations. Then first nucleus emits i neutrons and second nucleus j neutrons

$$\sigma_{**}^{(i,j)} = 2\pi \int db b S(b)$$

$$\left(\int_{E_{min}}^{E_{max}} d\omega_1 \frac{dN}{d\omega_1 d^2 b} \sigma_{\gamma A_2 \rightarrow A_2^*}(\omega_1) P_{A_2}^i(E_2^*) \right) \left(\int_{E_{min}}^{E_{max}} d\omega_2 \frac{dN}{d\omega_2 d^2 b} \sigma_{\gamma A_1 \rightarrow A_1^*}(\omega_2) P_{A_1}^j(E_1^*) \right)$$

Both excitations independent (no correlations).

Comparison with experimental data



Mutual excitations, results

Table: Cross section in barns for mutual excitation with a given number of neutrons in $^{208}\text{Pb} + ^{208}\text{Pb}$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Mutual excitations (b)					
	0 neutrons	1 neutron	2 neutrons	3 neutrons	$\exp(-\bar{n})$
0 neutrons	0.00917	0.12093	0.02675	0.00414	without
	0.00883	0.09317	0.02483	0.00402	with
1 neutron	0.12093	1.59450	0.35275	0.05448	without
	0.09317	1.00124	0.26286	0.04238	with
2 neutrons	0.02675	0.35275	0.07803	0.01205	without
	0.02483	0.26286	0.06989	0.01130	with
3 neutrons	0.00413	0.05448	0.01205	0.00186	without
	0.00402	0.04238	0.01130	0.00183	with
sum	0.16098	2.12266	0.46958	0.07252	without
	0.19285	1.39965	0.36888	0.05953	with
		2.82574			without
		2.02091			with



Conclusions

- $\gamma\gamma \rightarrow \pi^+\pi^-$ mechanism evaluated carefully for a first time.
- $\gamma\gamma$ production of pionic pairs in exclusive nuclear collisions gives a **background to $\rho^0(770)$ and its higher excitations.**
- Large **double scattering** contribution to exclusive $\rho^0\rho^0$ production in nuclear peripheral collisions.
Open question: **how to identify different components?**
- Produced ρ^0 's have very small transverse momenta.
Therefore charged pions are emitted back-to-back.
One could impose a **cut on relative azimuthal angle between charged pions of opposite sign.**
- New tool for controlling the "exclusive" processes (**electromagnetic excitation and neutron emission**).



List of our publications on the subjects discussed here

AA \rightarrow AA X_1X_2 and similar reactions

- M. Kłusek, W. Schäfer and A. Szczurek, "Exclusive production of $\rho^0\rho^0$ pairs in $\gamma\gamma$ collisions at RHIC", Phys. Lett. **B674** (2009) 92.
- M. Kłusek-Gawenda and A. Szczurek, "Exclusive muon-pair production in ultrarelativistic heavy-ion collisions - realistic nucleus charge form factor and differential distributions", Phys. Rev. **C82** (2010) 014904.
- M. Kłusek-Gawenda, A. Szczurek, M. Machado and V. Serbo, "Double - photon exclusive processes with heavy quark - heavy antiquark pairs in high-energy Pb-Pb collisions at LHC", Phys. Rev. **C83** (2011) 024903.
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