Production of two and four pions in UPCS

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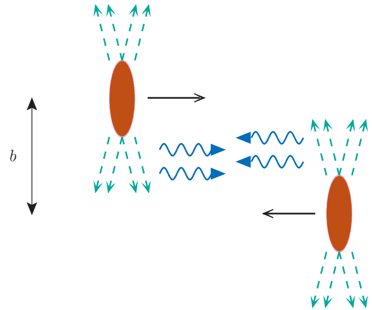
Photon-induced collisions at the LHC

CERN, Geneve, June 2-4, 2014

Contents

Photon-photon subprocesses, equivalent photon approximation



The strong electromagnetic field is a source of photons which induces single-photon or double-photon induced reactions.

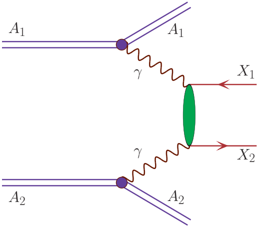
ultraperipheral collisions:

$b > R_1 + R_2 \cong 14$ fm

Cross section in EPA

$$\sigma\left(PbPb \longrightarrow PbPbX_1X_2; s_{NN}\right)$$

$$= \int \hat{\sigma}\left(\gamma\gamma \rightarrow X_1X_2; x_1x_2s_{NN}\right) \mathrm{d}n_{\gamma\gamma}\left(x_1, x_2, \mathbf{b}\right)$$



Impact parameter EPA

Cross section in the impact parameter EPA

Nuclear cross section -- EPA

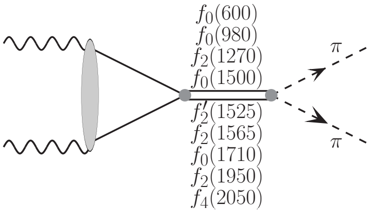
$$\sigma\left(PbPb \to PbPbX_1X_2; s_{NN}\right) =$$
$$= \int \hat{\sigma}\left(\gamma\gamma \to \pi\pi; W_{\gamma\gamma}\right) \partial\left(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A\right)$$
$$x \quad N\left(\omega_1, \mathbf{b}_1\right) N\left(\omega_2, \mathbf{b}_1\right) 2\pi b_m \, \mathrm{d}b_m \, \mathrm{d}\overline{b}_x \, \mathrm{d}\overline{b}_y \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \mathrm{d}Y$$

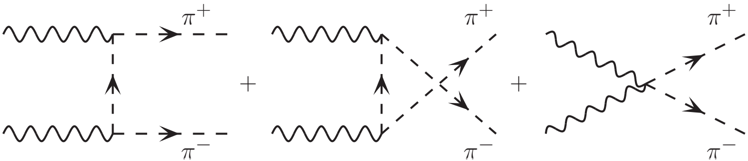
The details of derivation:

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''

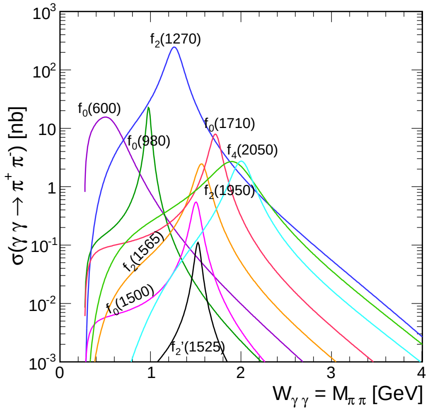
Elementary $\gamma\gamma \to \pi\pi$ cross section

Soft processes:





Resonance contributions

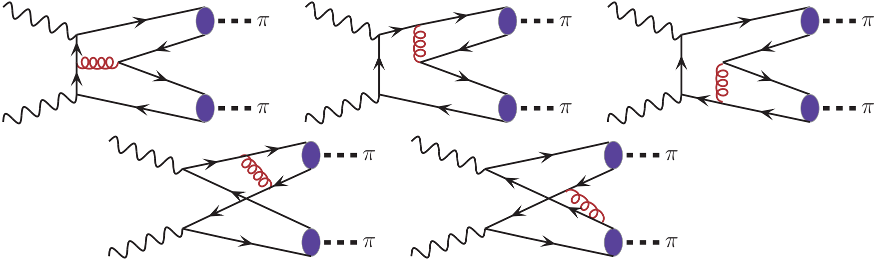


Many resonances (!)

Parameters (masses, widths, branching fractions) from PDG

pQCD mechanism

pQCD processes:



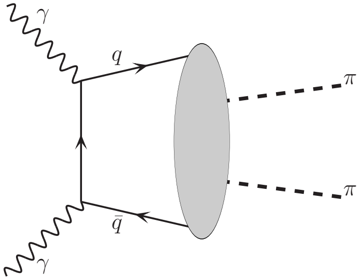
Brodsky-Lepage pQCD formalism

$$
\begin{aligned}
\mathcal{M}(\lambda_1, \lambda_2) &= \int_0^1 dx \int_0^1 dy\, \phi_\pi\left(x, \mu_x^2\right) T_H^{\lambda_1 \lambda_2}\left(x, y, \mu^2\right) \phi_\pi\left(y, \mu_y^2\right) \\
&\times F_{reg}^{pQCD}(t, u)
\end{aligned}
$$

T^{λ_1, λ_2} - hard matrix element (Brodsky-Lepage)

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

Hand-bag mechanism



Amplitude is parametrized (flavour symmetries)

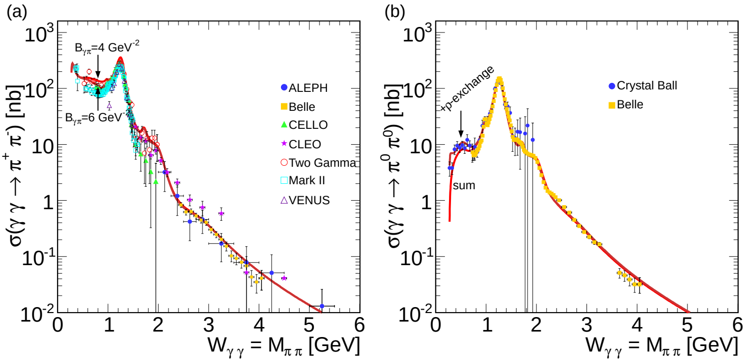
M. Diehl, P. Kroll and C. Vogt,

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

M. Diehl and P. Kroll,

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

$\gamma\gamma \longrightarrow \pi\pi$

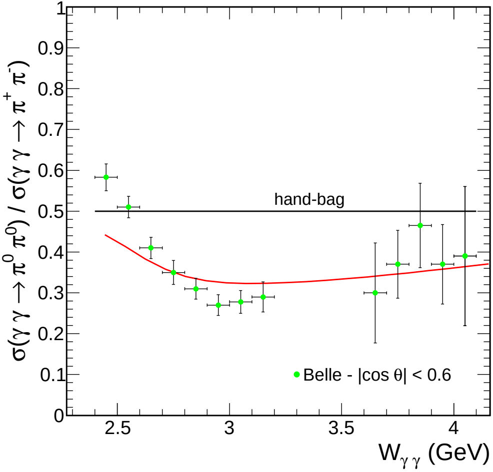


Good description of elementary $\gamma\gamma \to \pi\pi$ reactions (also $d\sigma/dz$)

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

Belle data

$\gamma\gamma \longrightarrow \pi\pi$



Neither Brodsky-Lapage nor hand-bag mechanism is sufficient.

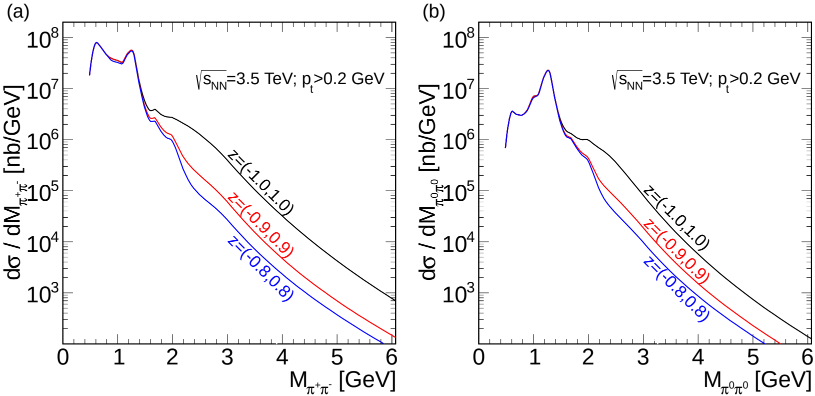
$AA \to AA\pi\pi$, total cross section

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

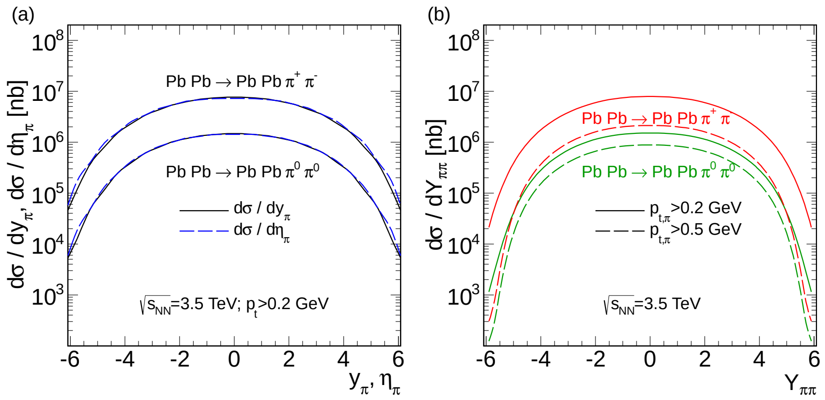
Relatively large cross sections

$AA \to AA\pi\pi$, differential distributions



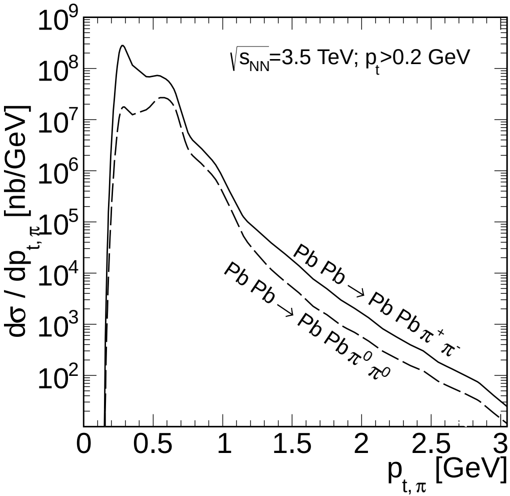
Large contribution of small-angle-scattering at larger invariant masses

$AA \to AA\pi\pi$, differential distributions

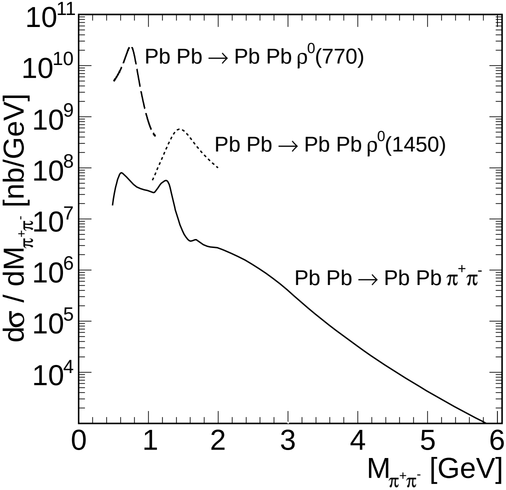


(pseudo)rapidity of pion and rapidity of the pion pair

$AA \to AA\pi\pi$, differential distributions

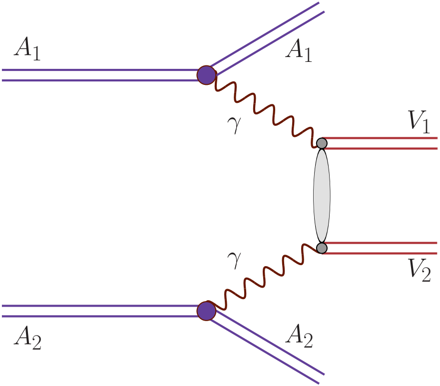


$AA \to AA\pi\pi$, differential distributions



Large contribution of ρ^0 and its excited states

$AA \to AA\rho^0\rho^0$



Klusek-Schäfer-Szczurek, Phys. Lett. **B674** (2009) 92.

Cross section for $AA \to AA\rho^0\rho^0$ comparable to that for $AA \to AA\pi^+\pi^-$

Single ρ^0 production

Glauber-VDM model

Klein-Nystrand

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

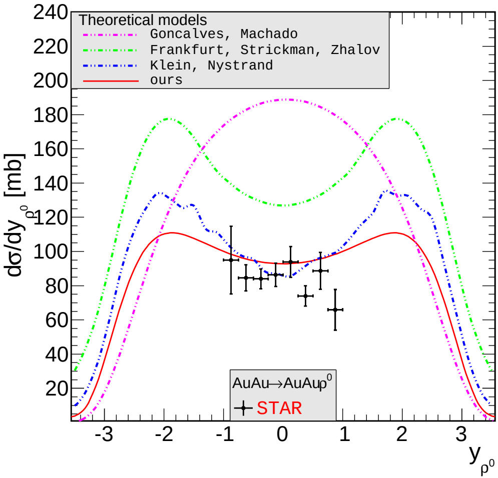
$$\frac{d\sigma(\gamma A \to \rho^0 A)}{dt}|_{t=0} = \frac{\alpha \sigma_{tot}(\rho^0 A; W)}{4 f_\rho^2}$$

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

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

The last cross section parametrized in the Regge parametrization.

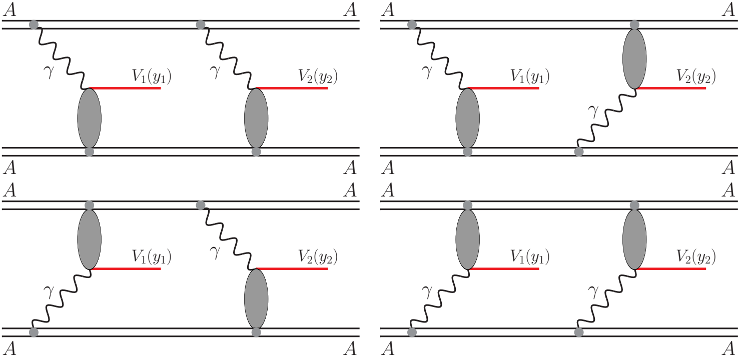
$AA \to AA\rho^0$



huge cross section (!)

$AA \to AA\rho^0\rho^0$

double-scattering mechanism



Klusek-Gawenda and Szczurek, arXiv:1309.2463, Phys. Rev. **C89** (2014) 024912.

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

$$\sigma_{AA\to AAV_1V_2}(\sqrt{s_{NN}}) = C \int P_{V_1}(b, \sqrt{s_{NN}}) P_{V_2}(b, \sqrt{s_{NN}}) d^2b \; , \qquad (1)$$

where the probability of single meson production is

$$P_V(b, \sqrt{s_{NN}}) = \frac{d\sigma_{AA\to AAV}(b; \sqrt{s_{NN}})}{2\pi b db} \; . \qquad (2)$$

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

$$\frac{d\sigma_{AA\to AAV_1V_2}}{dy_1 dy_2} = C \int S^2_{el}(b) \left(\frac{dP_1^{\gamma\mathbf{P}}(b, y_1; \sqrt{s_{NN}})}{dy_1} + \frac{dP_1^{\mathbf{P}\gamma}(b, y_1; \sqrt{s_{NN}})}{dy_1} \right)$$

$$\times \left(\frac{dP_2^{\gamma\mathbf{P}}(b, y_2; \sqrt{s_{NN}})}{dy_2} + \frac{dP_2^{\mathbf{P}\gamma}(b, y_2; \sqrt{s_{NN}})}{dy_2} \right) d$$

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

$$S_{el}^2(b) = \exp\left(-\sigma_{NN}^{tot} T_{A_1A_2}(b)\right) \approx \partial\left(b - (R_1 + R_2)\right) \; . \tag{4}$$

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:

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

Smearing the ρ^0 masses

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

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

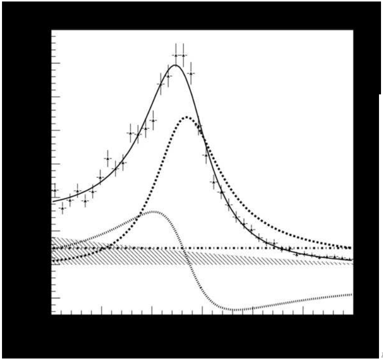
where m_1 and m_2 are running masses of ρ^0 mesons and $f_1(m_1)$ and $f_2(m_2)$ are respective distributions. The last term is the cross section for fixed masses m_1 and m_2. The spectral shapes are calculated as:

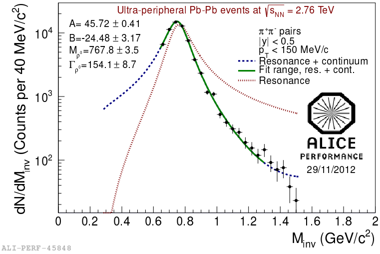
$$f(m) = |\mathcal{A}|^2 / \int |\mathcal{A}|^2 dm \, , \qquad (7)$$

where the amplitude is parametrized as:

$$\mathcal{A} = \mathcal{A}_{BW} \frac{\sqrt{m m_\rho \Gamma(m)}}{m^2 - m_\rho^2 + i m_\rho \Gamma(m)} + \mathcal{A}_{\pi\pi} \, . \qquad (8)$$

ρ^0 meson line shape

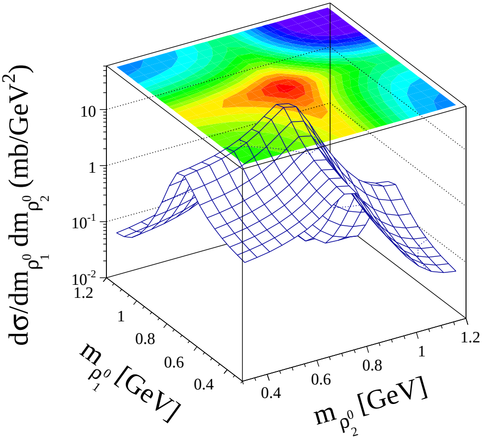




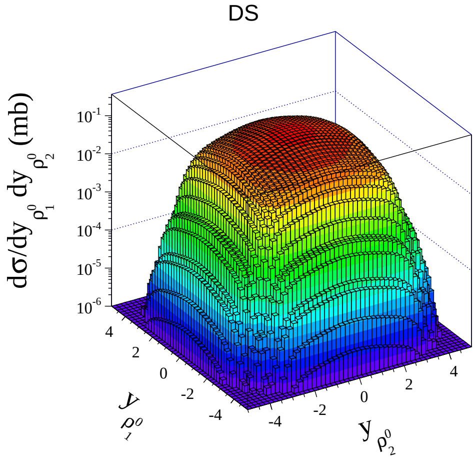
STAR (left) and ALICE (right) experimental distributions and parametrization

ALICE preliminary data from talk by Kyrie (2012-Nov-30)

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

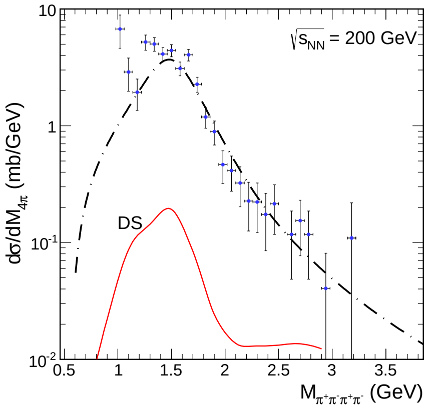


$AA \to AA\rho^0\rho^0$, RHIC



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

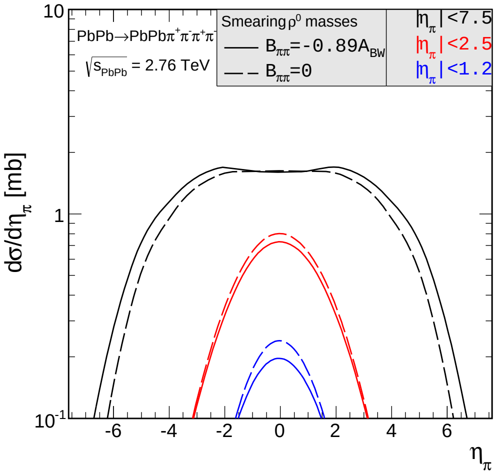
$AA \to AA\rho^0\rho^0$, RHIC



Still another mechanism at RHIC dominates

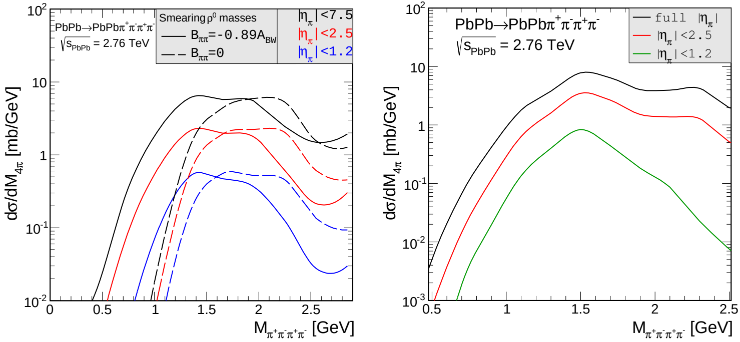
How to identify double scattering?

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



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

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

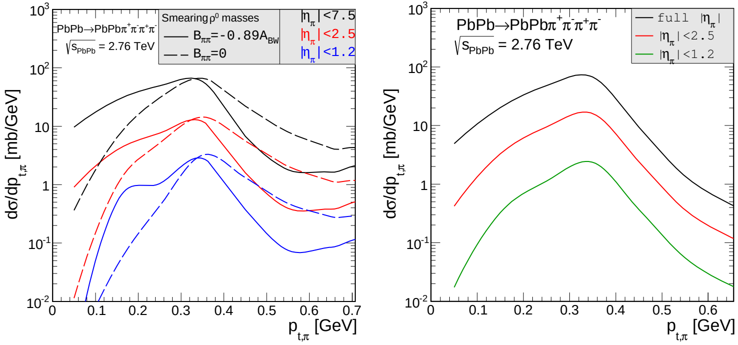


STAR line shape (left) and ALICE line shape (right)

Could be verified experimentally but other contributions possible:

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

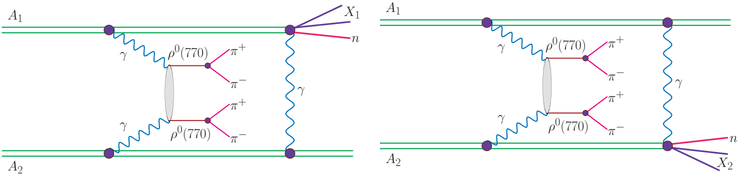
$AA \to AA\rho^0\rho^0$, LHC



STAR line shape (left) and ALICE line shape (right)

Can be verified experimentally.

Electromagnetic dissociation



Neutrons can be measured by Zero Degree Calorimeters

They are a "good trigger" for the exclusive reactions

Kłusek-Ciemała-Schäfer-Szczurek,arXiV:1311.1938,

Phys. Rev. **C89** (2014) 094019.

Neutron emission

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

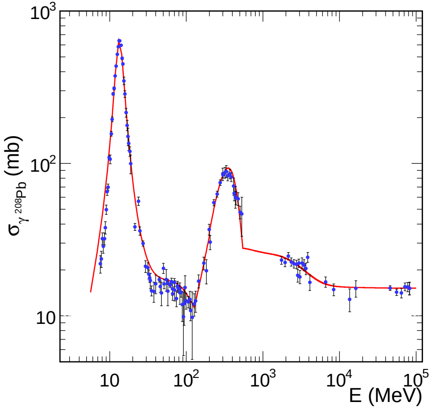
is an interesting (measureable) quantity,

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

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

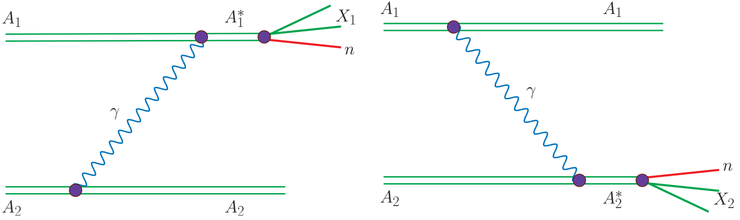
For each exclusive process one can calculate (topological cross section) with a given number of neutrons emitted from first and second nucleus.

photon-^{208}Pb cross section



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

Electromagnetic dissociation



Huge damping of heavy-ion fluxes at the LHC !

Electromagnetic dissociation - a bit of formalism

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

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

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

$$S(b) \approx \partial\left(|\mathbf{b}| - \mathbf{R_1} - \mathbf{R_2}\right) \ . \tag{10}$$

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

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

Notice Z^2 enhancement compared to protons.

Electromagnetic dissociation - a bit of formalism

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

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

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

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

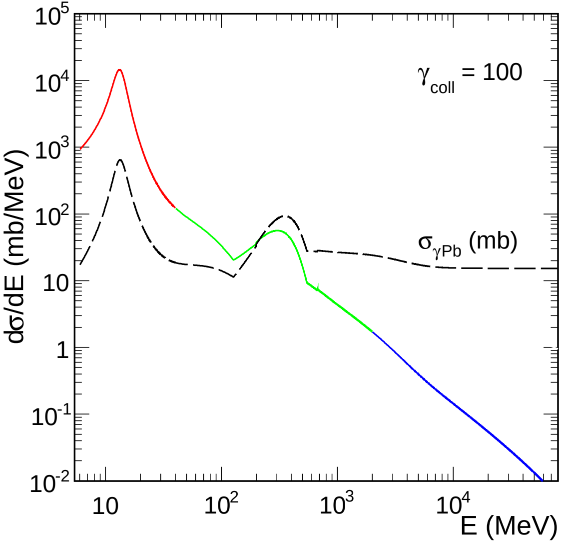
$$\frac{d\sigma^{(2)}}{d^2b d\omega_2} = \frac{d^3 n(b,\omega_1)}{d\omega_2 d^2 b} \sigma_{\gamma A_1 \to A_1^*}(\omega_2) \ ,$$

Electromagnetic dissociation

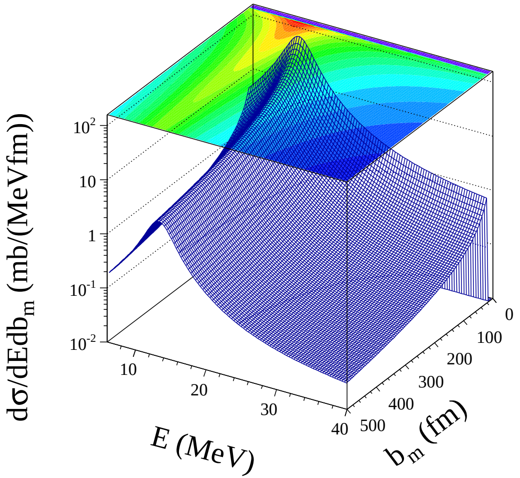
Cross section in barns

	(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

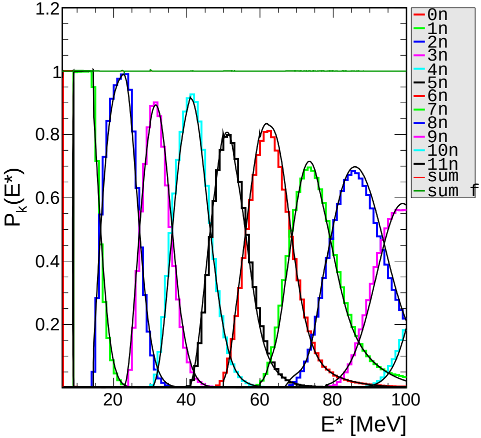
Electromagnetic excitation



Electromagnetic excitation



Neutron production from excited nucleus

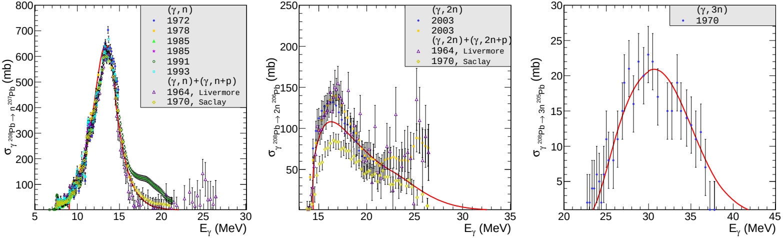


Hauser-Feshbach theory

The approach assumes equilibrated excited nucleus (!)

Cross section for single neutron photoproduction

$\gamma + A \rightarrow kn$



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

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

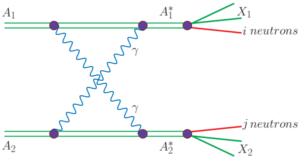
$E_2^* = \omega_1$?

first nucleus excited, second nucleus in the ground state

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

$E_1^* = \omega_2$?

Mutual excitation



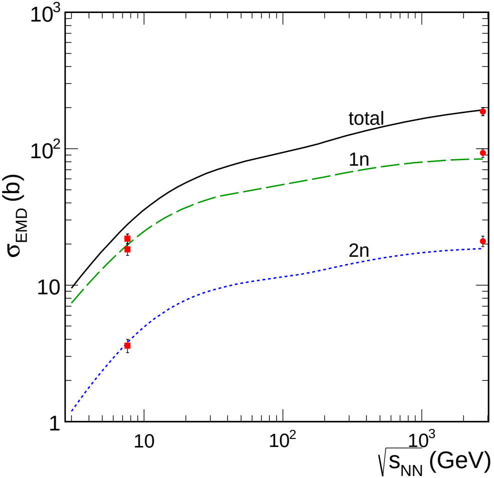
Second-order effects lead to mutual excitations. Then first nucleus emits i neutrons and second nucleus j neutrons

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

$$\left(\int_{E_{min}}^{E_{max}} d\omega_1 \frac{dN}{d\omega_1 d^2b} \sigma_{\gamma A_2 \to A_2^*}(\omega_1) P^i_{A_2}(E_2^*)\right)\left(\int_{E_{min}}^{E_{max}} d\omega_2 \frac{dN}{d\omega_2 d^2b} \sigma_{\gamma A_1 \to A_1^*}(\omega_2) P^j_{A_1}(E_1^*)\right)$$

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}Pb + ^{208}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

- $\gamma\gamma \to \pi^+\pi^-$ 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 beetween charged pions of opposite sign.
- New tool for controlling the "exclusive" processes (electromagnetc excitation and neutron emission).

List of our publications on the subjects discussed here

$AA \to AAX_1X_2$ and similar reactions

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