Neutron emission from the photon-induced reactions in UPC of heavy ions - impact of new ALICE data

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Introduction

- There is growing interest in ultraperipheral heavy ion collisions (LHC).
- The processes that fullfil these categories can be divided into:
  (a) photon-photon fusion (many examples: l^+l^-, M_1M_2, dijets or $\gamma\gamma$)
  (b) photoproduction (examples: production of vector mesons: ρ^0, ϕ, J/ψ)
- UPCs have usually simple final state in the measured midrapidity region.
- Very forward/backward region is not always of unterest.
- However, experimentally we have ZDC callorimeters. They can measure neutrons and also protons.
- Any extra photon exchange may lead to associated nucleus excitation. Excited nucleus may emit: neutrons, protons, alpha particles or photons. May even go to fission.
- The Lorentz boost causes that those are emitted very forward/backward.
- Emissions strongly depend on:
  (a) mechanism of photon-nucleus interactions
  (b) photon energy

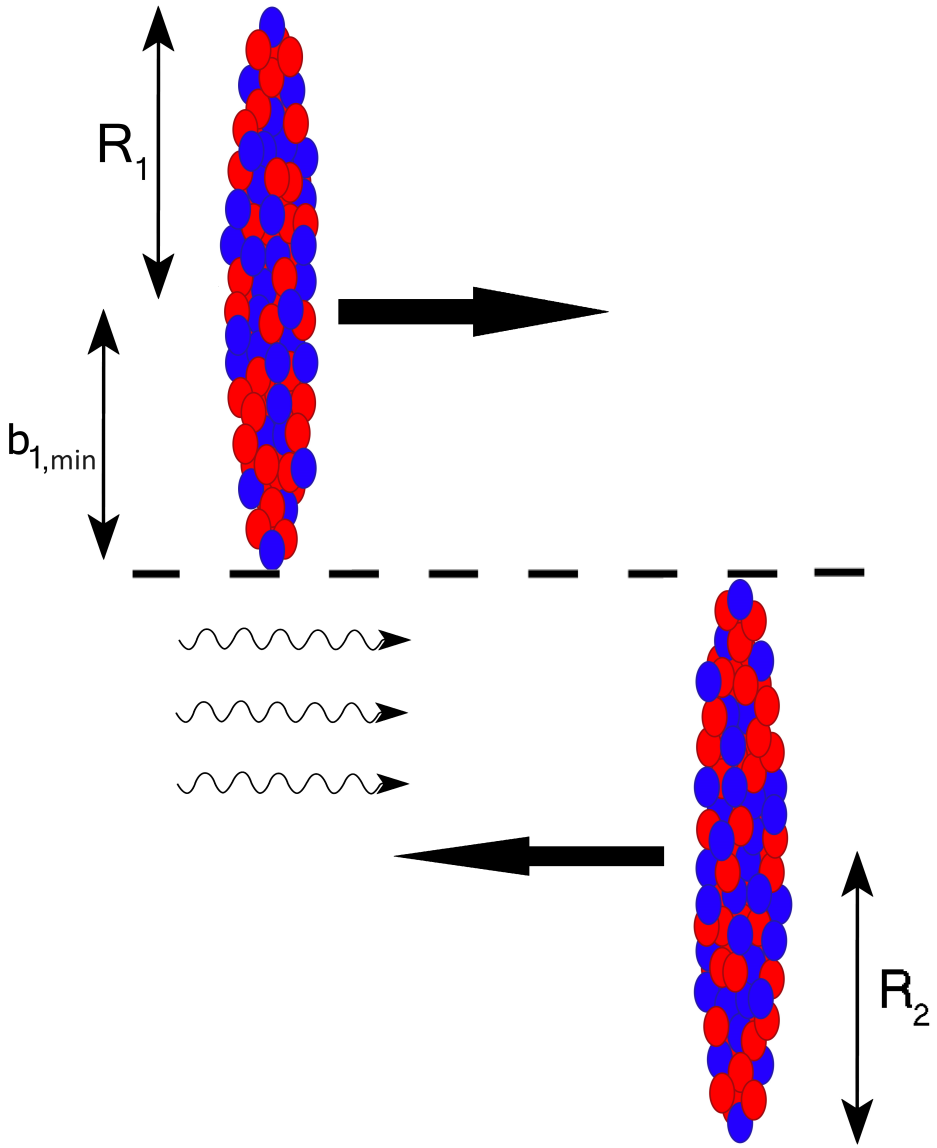
Introduction

- In general even Coulomb excitations alone (no midrapidity production) are possible. They lead to damping of the beams at the LHC.
- Neutron emission happens very frequently and it can be also easily measured.
- The ALICE collaboration measured cross section for a given number of neutrons ($n = 1, 2, 3,, 4, 5$) in ZDC.
- Recently the ALICE collaboration measured also protons.
- Also simultaneous measurement of neutrons and protons is possible.

Existing related approaches, programs

- RELDIS intranuclear cascade, not easily available
- DPMJET-III, dual parton model
- GEMINI++, Hauser-Feshbach formalism for nuclear cascade
- EMPIRE, traditional nuclear physics modelling, including equilibrium emission
- HIPSE, Heavy Ion Phase-Space Exploration, h+A, no photons!, preequilibrium model, for GANIL physics.
- STARlight (UPC), excitation in association with midrapidity emissions
  only 0n0n, 1n1n, Xn0n, XnXn categories
- BeAGLE (virtual photons), relevant for EIC
- GiBUU, BUU approach, can treat photons as projectiles
- Noon, parametrization of some fixed target data

General information



Some basic formulae for Coulomb excitations in UPC

single photon exchanges

$$\sigma_{A_1 A_2 \xrightarrow{1\gamma} X_1 X_2 + kn} = \int\int db d\omega \cdot 2\pi b \cdot e^{-m(b)} N(\omega, b) \sigma_{abs}(\omega) P_k(\omega)$$

$$m(b) = \int d\omega \cdot N(b, \omega) \sigma_{abs}(\omega)$$

multi photon exchanges

$$\sigma_{A_1 A_2 \xrightarrow{j\gamma} X_1 X_2 + kn} = \int d\omega_1 \ldots \int d\omega_j \int 2\pi b db \cdot \frac{e^{-m(b)}}{j!} \left(\prod_{i=1}^{j} N(\omega_i, b) \sigma_{abs}(\omega_i) \right) P_k(\Sigma_i^j(\omega_i))$$

Flux of photons

$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega b^2} \times \left| \int d\chi \, \chi^2 \frac{F\left(\frac{\chi^2 + u^2}{b^2}\right)}{\chi^2 + u^2} J_1(\chi) \right|^2 .$$

$$\chi = k_\perp b \qquad\qquad u = \frac{\omega b}{\gamma \beta}$$

$F(\mathbf{q}^2) = 1$ – point-like model

$F(\mathbf{q}^2) = \frac{4\pi}{|\mathbf{q}|} \int \rho(r) \cdot \sin(|\mathbf{q}| r) \cdot r dr$ – realistic model

Some details

- consider emitting (1) and absorbing (2) nucleus
  photon flux is associated with emitting nucleus, absorption cross section is associated with absorbing nucleus.
- distinguish $\vec{b}$, $\vec{b}_1$, $\vec{b}_2$
  In general are "independent", integrations: $d^2b\, d^2b_1$.
- from geometry:
  $b > 2R_A$ (UPC), $b_1 > R_A$ (UPC)
- equilibrium emission from Hauser-Feshbach theory:
- property of equilibrated nucleus:
  $E_{exc} < E_{\gamma/A_2}$
  spin: S $\approx$ 0 (may be too approximate for large E_{γ/A_2})

Flux of photons

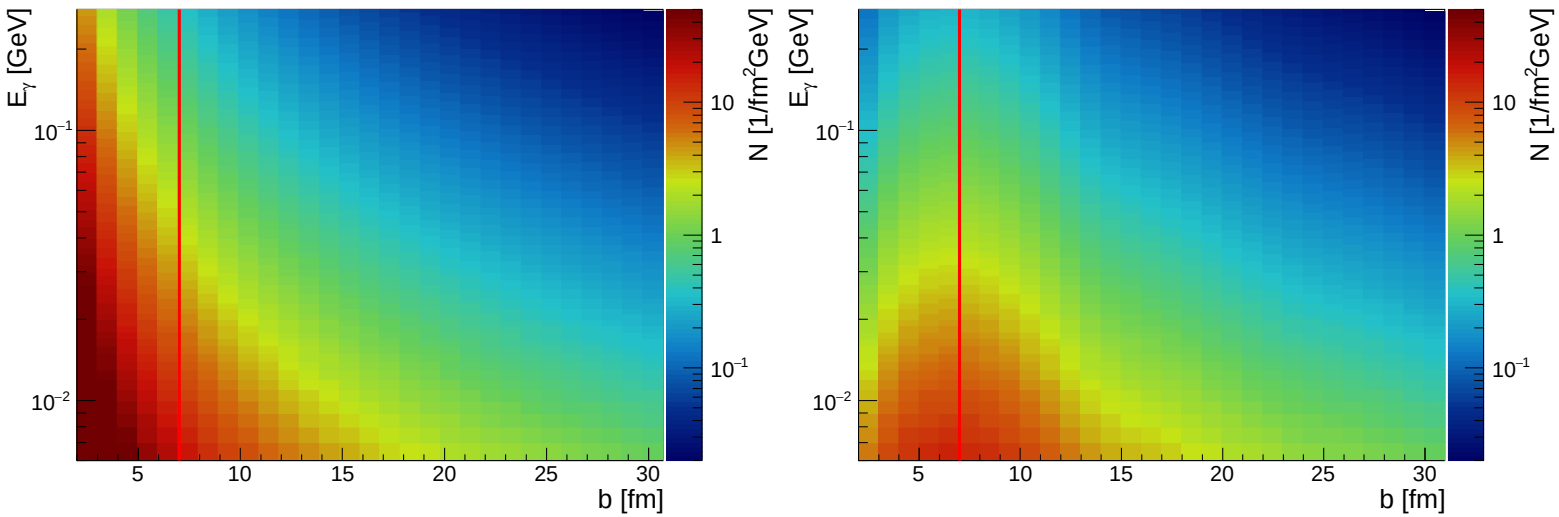
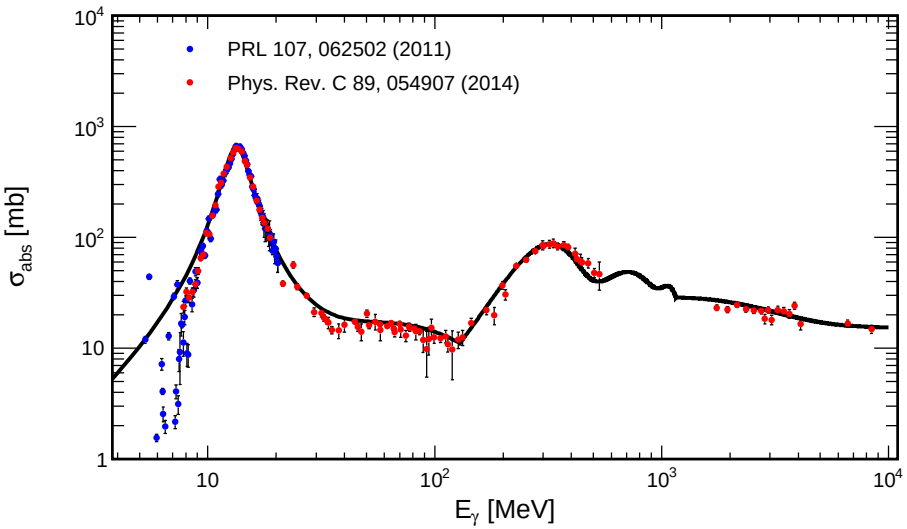


Figure: Point-like (left) versus realistic (right) photon flux.

Absorption cross section



Physics changes gradually with energy:
GDR, quasi deuteron, nucleon resonances, partonic reactions.

Probability of emission of a given number of neutrons

P_k is inclusive quantity !

k is number of neutrons, there can be any other particle in the accepted event.

It can be formally defined as:

$$P_k(E_\gamma) = \frac{\sigma(\gamma A \rightarrow knA'; E_\gamma)}{\sigma^{tot}_{\gamma A}(E_\gamma)} \tag{1}$$

can be calculated in a model.

The probabilities fullfil the condition:

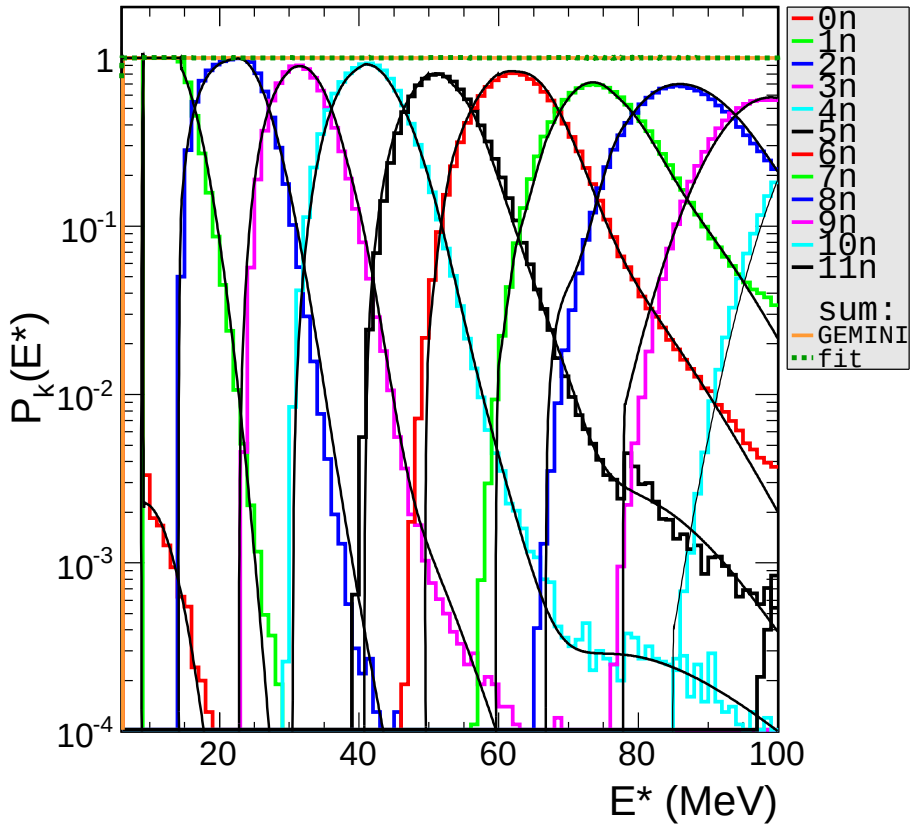
$$\Sigma_k P_k(E_\gamma) = 1, \tag{2}$$

for any energy.

Can be easily calculated in the Hauser-Feshbach approach.

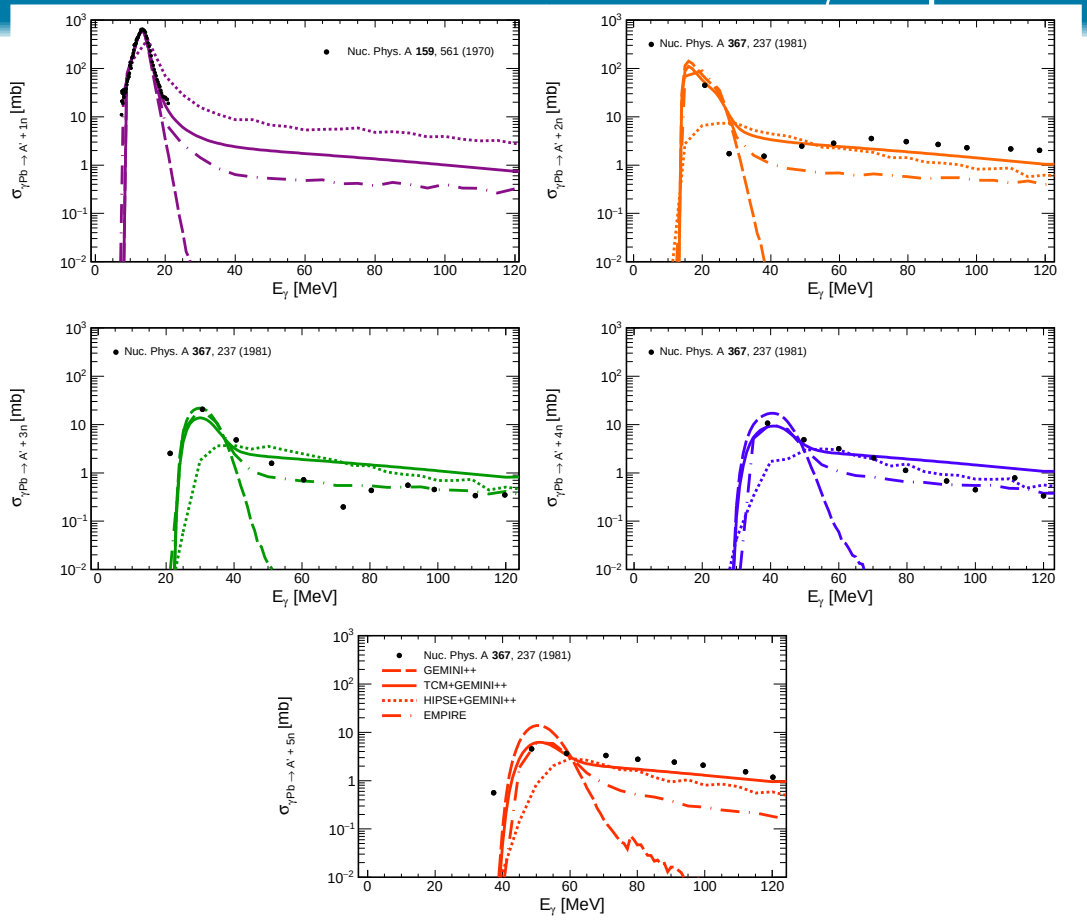
(see next slide from analyzing events from GEMINI++)

Probability of f neutrons



M. Kłusek-Gawenda, M. Ciemała, W. Schäfer and A. Szczurek,
"Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions",
Phys. Rev. **C89** (2014) 054907.

Nucleus de-excitation channels from γA processes



those are from "low" energy reactions, Lepretre et al.

Long tails at high photon energies for a given k

Two-component model

In our previous approach (Klusek-Gawenda et al.), we implicitly assumed

$$P(E_{exc}; E_\gamma) \propto \delta\left(E_{exc} - E_\gamma\right) \ , \tag{3}$$

where δ is the Dirac delta function. Above $P(E_{exc}; E_\gamma)$ can be interpreted as a probability of populating equilibrated compound nucleus with a given excitation energy E_{exc} in a process initiated by the photon with energy E_γ. It must be constructed to fulfill the following probabilistic relation:

$$\int_0^{E_\gamma} P(E_{exc}; E_\gamma)\, dE_{exc} = 1 \ . \tag{4}$$

Two-component model

In order to better understand the situation, we consider a simple model in which different excitation energies $E_{exc} < E_\gamma$ (for the equillibrated nucleus) can be populated. We started with the somewhat academic step-like function:

$$P(E_{exc}; E_\gamma) = \mathrm{const}(E_{exc}) = 1/E_\gamma \tag{5}$$

for $E_{exc} < E_\gamma$, i.e. uniform population in excitation energy.
Another option is to take the simple sinus-like function:

$$P(E_{exc}; E_\gamma) = \frac{\pi}{2E_\gamma} \sin\left(\pi E_{exc}/E_\gamma\right) \tag{6}$$

for $E_{exc} < E_\gamma$.

Two-component model

In general, the bigger number of neutrons, the larger the fraction of energy carried by neutrons.

$$P(E_{exc}; E_\gamma) = c_1(E_\gamma)\delta\left(E_{exc} - E_\gamma\right) + c_2(E_\gamma)/E_\gamma \ . \tag{7}$$

The probabilistic interpretation requires:

$$c_1(E_\gamma) + c_2(E_\gamma) = 1 \ . \tag{8}$$

In general, c_1 and c_2 may (should) depend on photon energy E_γ. As a trial function for further analysis, we propose

$$c_1(E_\gamma) = \exp\left(-E_\gamma/E_0\right) \ , \tag{9}$$

$$c_2(E_\gamma) = 1 - \exp\left(-E_\gamma/E_0\right) \ . \tag{10}$$

The parameter E_0 can be adjusted to the ALICE data. We suggest $E_0 \approx 50$ MeV to start with.

Two-component model

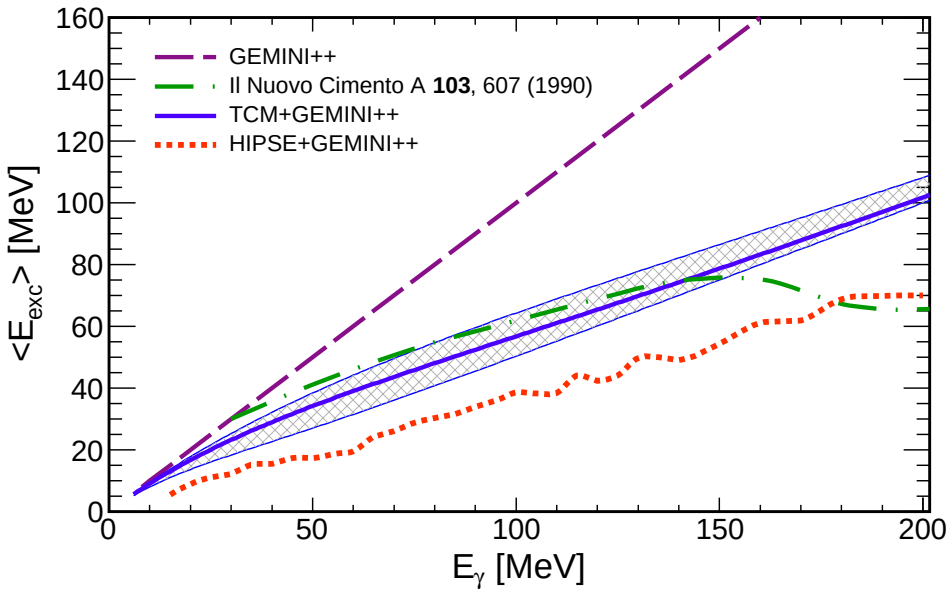
The full TCM formula for the probability of emitting a specified number of neutrons for a given photon energy is calculated by:

$$P_k(E_\gamma) = \sum_{E_{exc}}^{E_\gamma} (1 - \exp(-E_\gamma/E_0)) \frac{1}{E_\gamma} \frac{N_k(E_{exc})}{N_{ev}} \Delta E_{exc} + \exp(-E_\gamma/E_0) \frac{N_k(E_\gamma)}{N_{ev}}. \quad (11)$$

Here, the $N_k(E)$ is a number of events with k emitted neutrons for a given E_γ or an excitation energy, and N_{ev} is a total number of events for a given energy. Both numbers are obtained from GEMINI++ event generator. The ΔE_{exc} is a chosen interval of excitation energy in a discrete sum in (11). This is purely technical parameter to simplify the calculations.

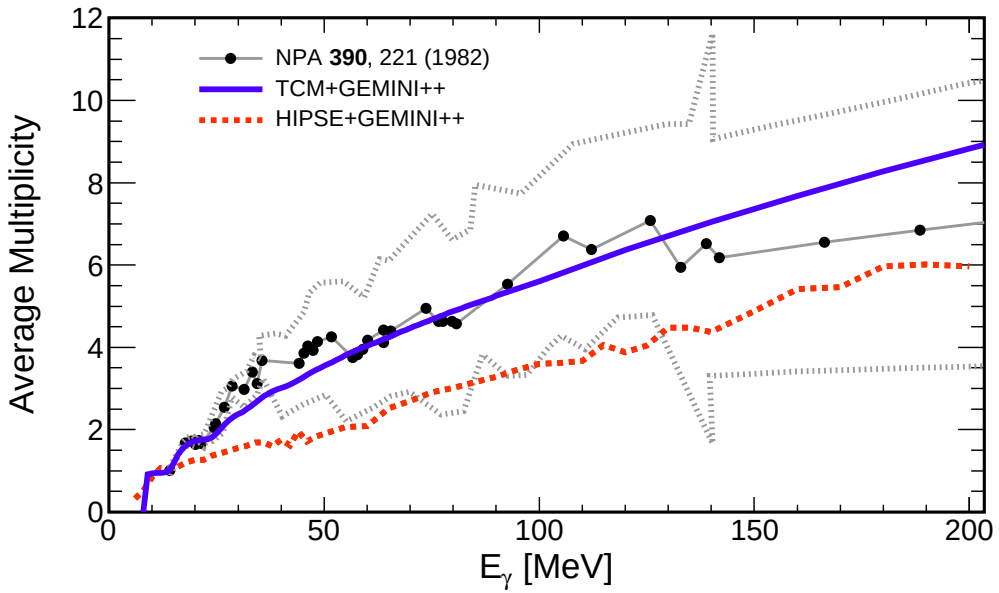
The neutron emission probability fulfill the following condition:

Some model results



TCM gives main observed deviations from pure statistical model

Some model results



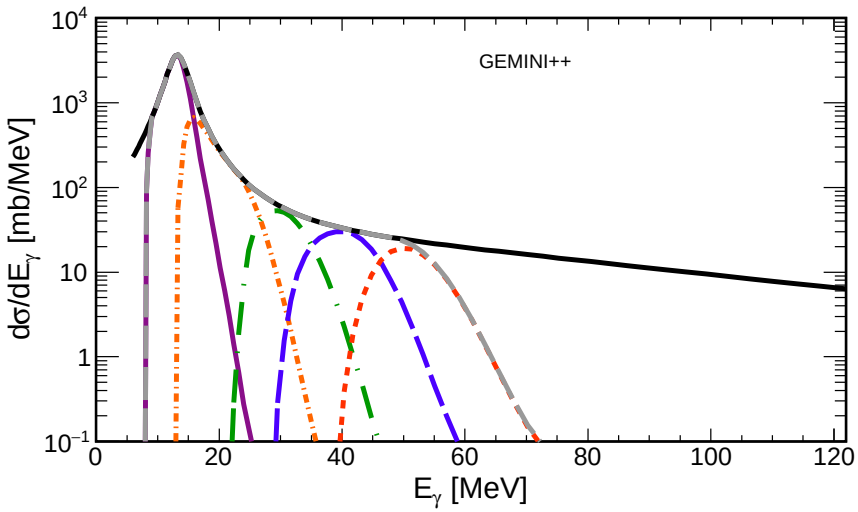
TCM reproduces $< n > (E_\gamma)$ from $\gamma + A$ reaction

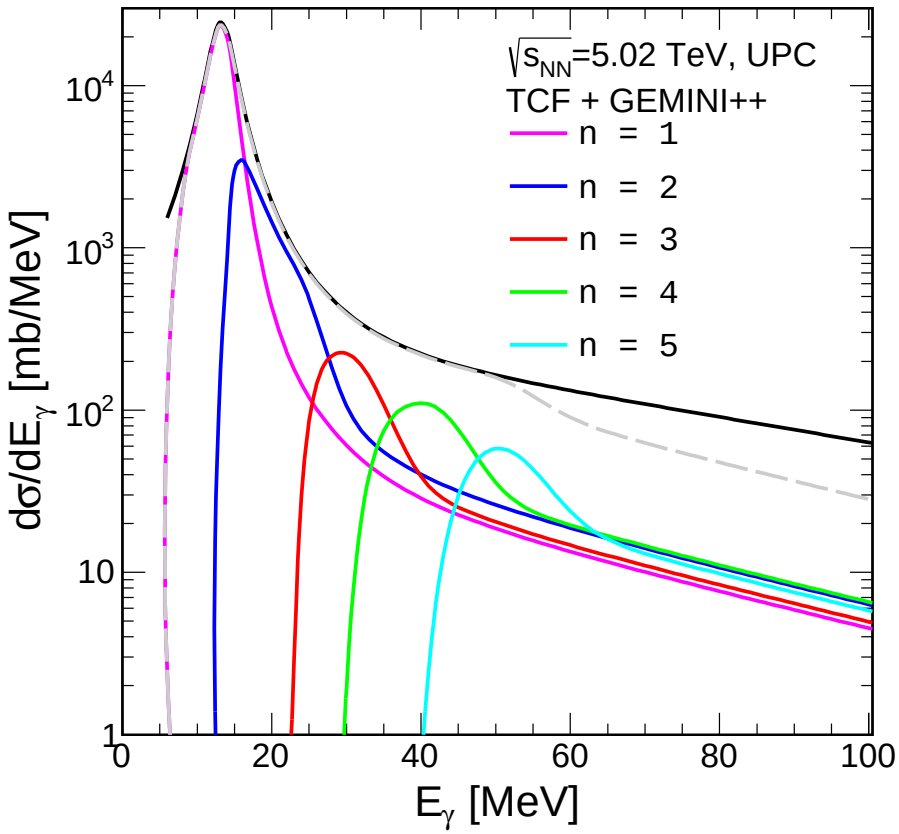
Neutron emission in UPC

Cross section σ_{tot} [b] for generating a given number of neutrons in UPC for $\sqrt{s_{NN}} = 5.02$ TeV, for different values of E_0 parameter of the step-like TCM confronted with pure GEM-
INI++ and TCM with sin-like function predictions. In bold we show results for $E_0 = 50$ MeV.

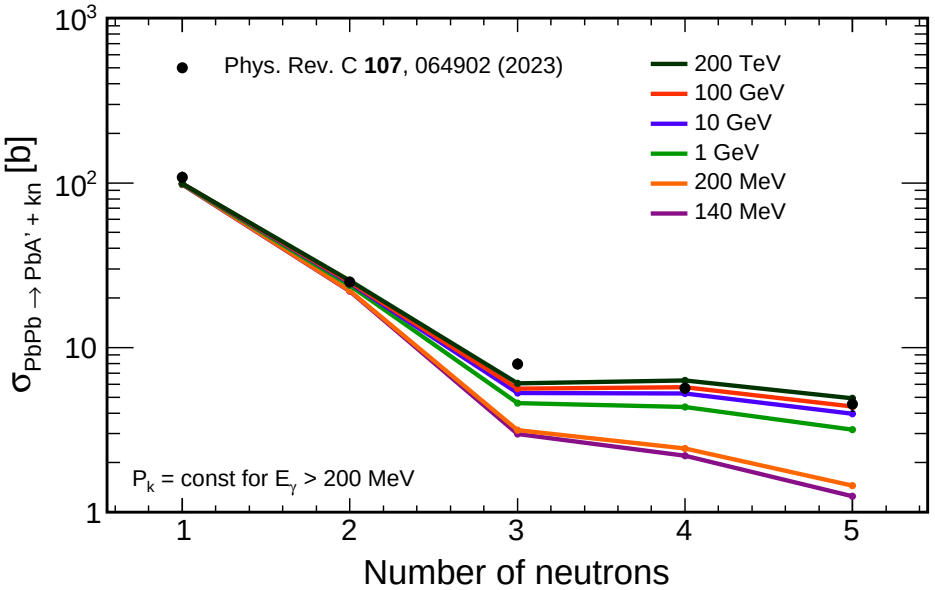
	σ [b]						
	ALICE	RELDIS	GEMINI++	TCM			
	experiment			sin-like	step-like		
knE$_0$ [MeV]				50	30	40	**50**
1	108.4±3.90	104.1± 5.2	93.71	83.37	99.39	99.06	**98.75**
2	25.0±1.30	21.9± 1.1	25.06	21.16	23.51	24.77	**25.55**
3	7.95±0.25	7.59± 0.38	3.05	4.05	5.91	6.02	**6.07**
4	5.65±0.33	4.29± 0.22	2.32	4.19	6.22	6.30	**6.32**
5	4.54±0.44	2.95 ± 0.15	1.51	3.42	4.84	4.90	**4.91**

Model results and comparison





Dependence on photon upper energy limit in the integration



Both low, intermediate and high energies play important role for a given k

Cross section for $\gamma + A \rightarrow kn + A'$

The multiplicity dependent cross section

$$\sum_{k=0}^{N_{max}} \sigma_{\gamma+A\rightarrow kn+A'}(E_\gamma) \approx \sigma^{tot}_{\gamma+A}(E_\gamma). \tag{13}$$

Somewhat formally one can write each term in k, corresponding to the emissions of k neutrons, as:

$$\sigma_{\gamma+A\rightarrow kn+A'}(E_\gamma) = \sigma^{tot}_{\gamma+A}(E_\gamma) P_k(E_\gamma). \tag{14}$$

Alternatively one can therefore parametrize $P_k(E_\gamma)$ function to include tails at large E_γ.

Photon energy distribution

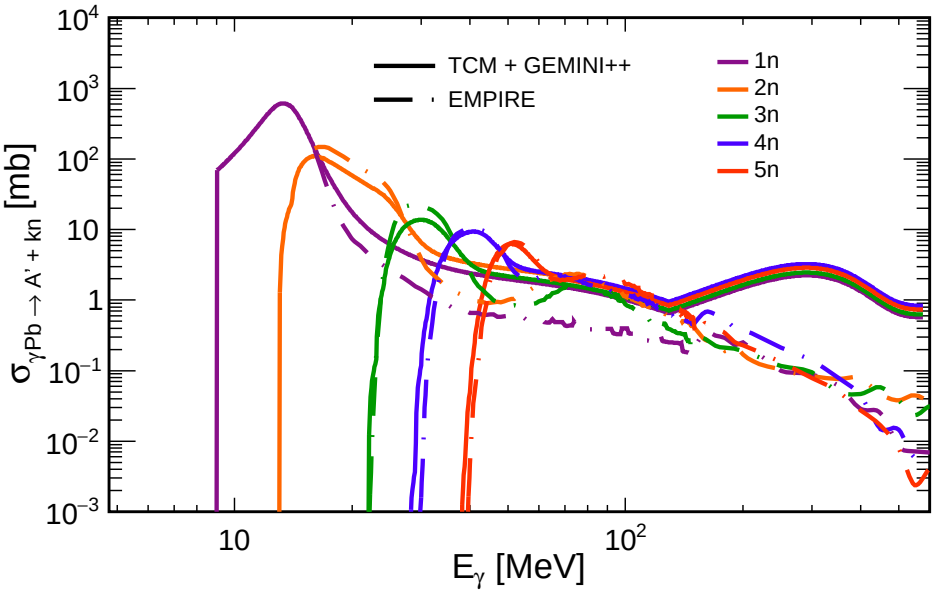
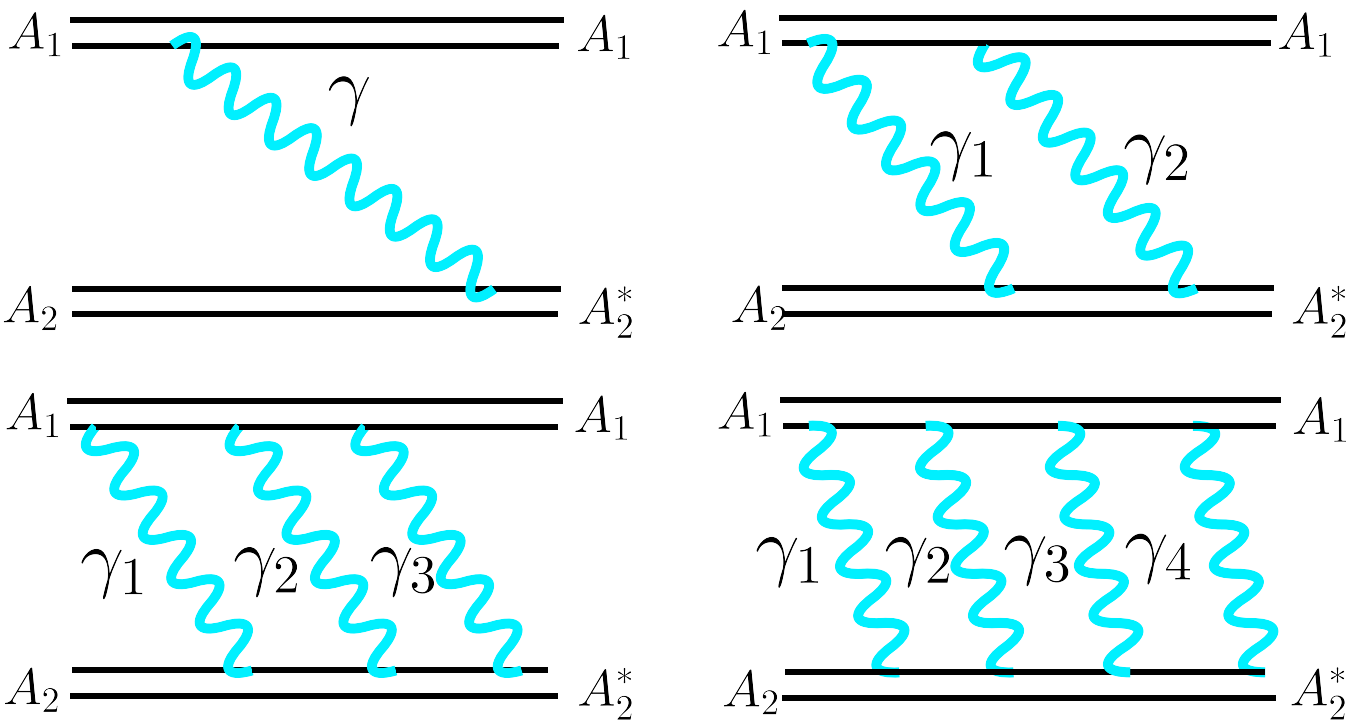


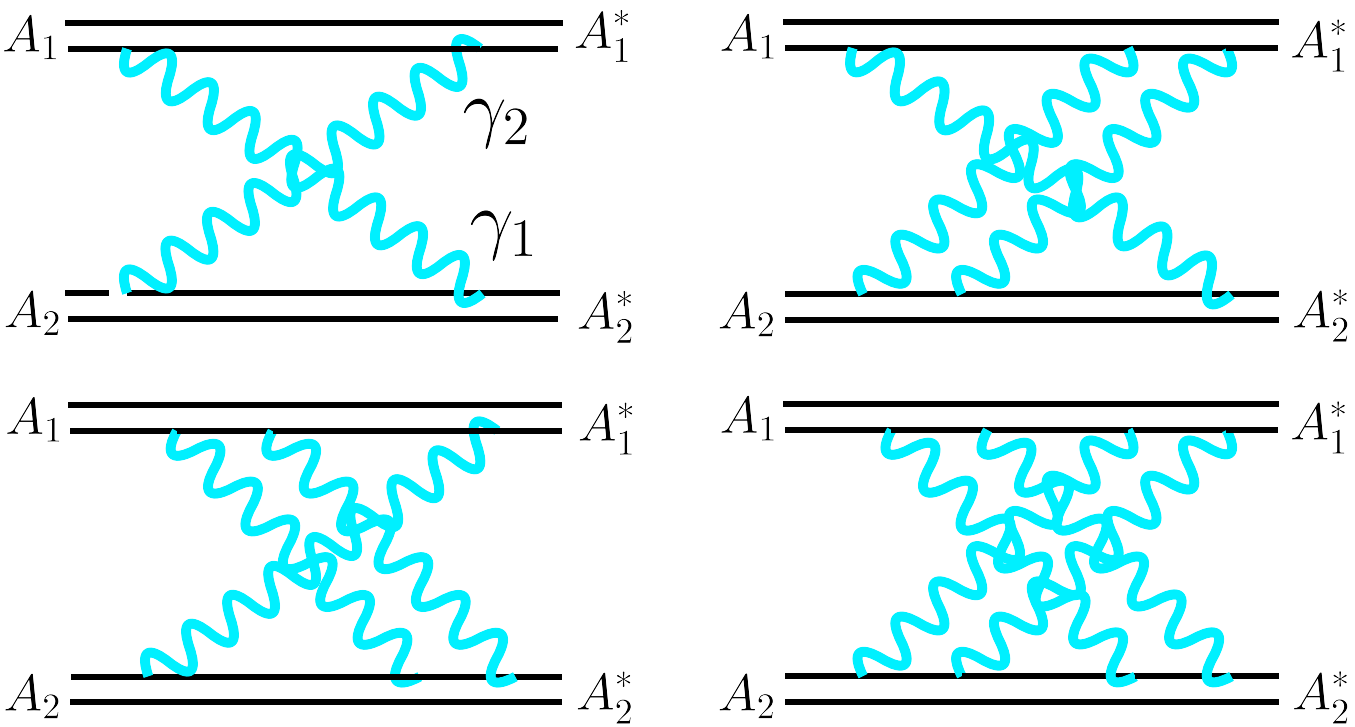
Figure: Photon energy dependence for a given k in our approach.

this is for single photon exchange

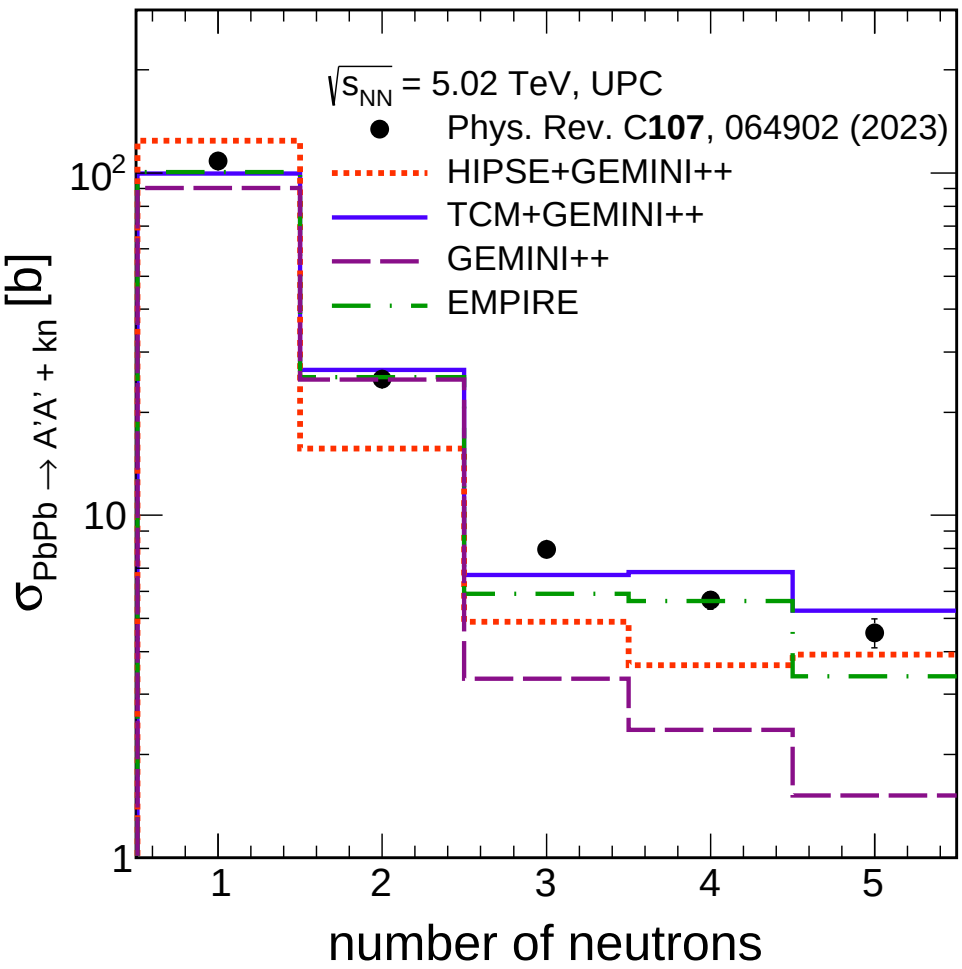
Multipole photon exchanges



Mutual excitation



Final results



Charged particles

	$\sqrt{S_{NN}}$ = 5.02 TeV					
Model	σ[b]					
	1p1n	1p2n	1p3n	1pXn	1dXn	1αXn
GEMINI++	0	0	0	19.56	6.91	30.66
TCM+GEMINI++	0.66	0.92	0.72	16.72	11.42	15.47
HIPSE+GEMINI++	9.86	0.82	0.93	28.48	64.02	42.38
EMPIRE	2.43	2.81	0.23	7.06	2.65	0.28
ALICE experiment	1.05	1.35	1.58	40.4	-	-

Table: Total cross section for charged particle emission.

Short summary

In order to understand neutron and proton emissions by the nucleus excited in UPC one has to understand well:

- Photon induced intranuclear cascade in a broad range of photon energy.
- Preequilibrium emissions is also very important.
- The latter lead to initial conditions for equilibrium emission (GEMINI++ in our case).
- Multipole photon exchanges give extra contributions of the order of 10 % for $n = 3, 4, 5$.