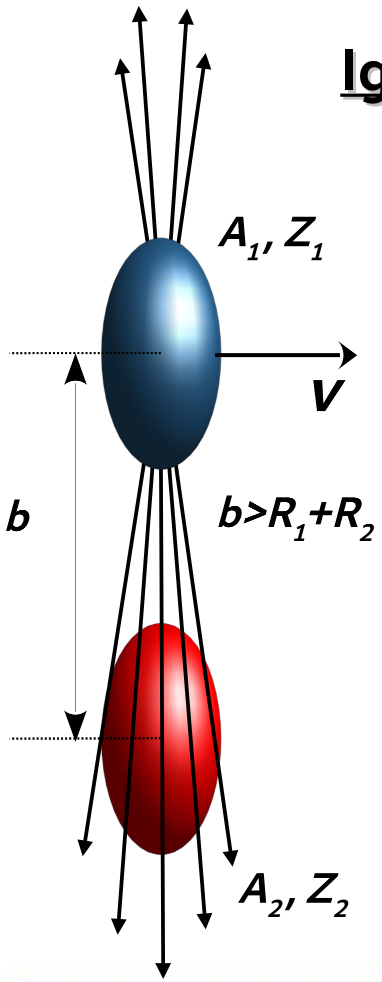
Electromagnetic dissociation of nuclei: from LHC to NICA



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Outline

- Physics of ultraperipheral collisions: Weizsäcker-Williams (WW) method of equivalent photons and REDLIS model

- Comparison of RELDIS results with data on EMD of ^{208}Pb at the CERN SPS and at the LHC

- EMD of ^{209}Bi and ^{124}Xe at NICA: what can we expect at lower energy?

- EMD as a source of well-collimated high energy neutrons: suitable for radiation biology studies at the highest neutron energy ?

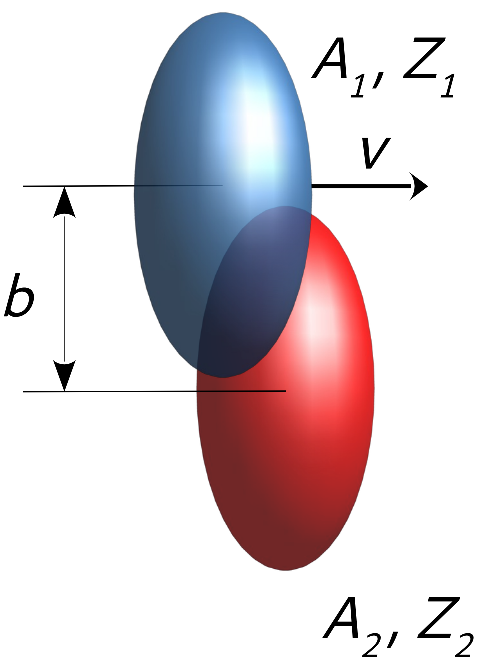
- Summary

Interactions of nuclei

hadronic

with overlap of nuclear densities

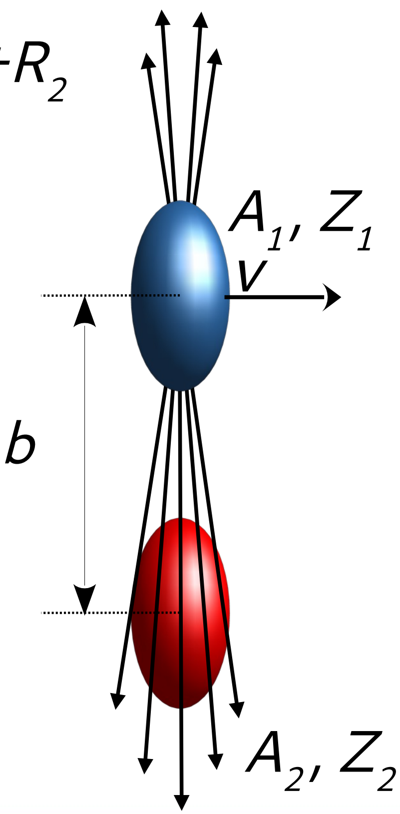
$b<R_1+R_2$



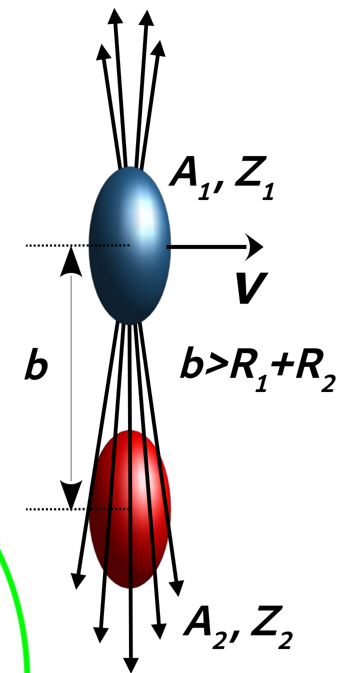
electromagnetic

without overlap of nuclear densities

$b>R_1+R_2$

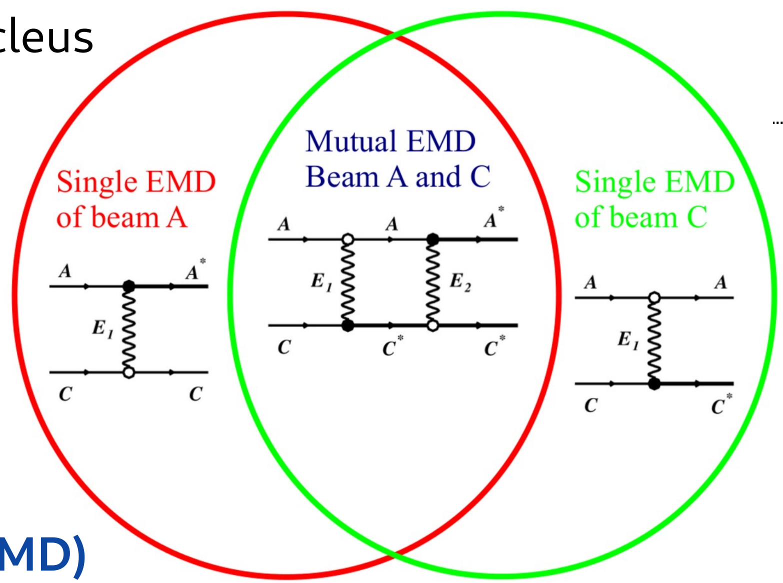


Ultraperipheral collisions and electromagnetic dissociation of nuclei



- In **ultraperipheral collisions (UPC)** nuclei interact electromagnetically, in particular, leading to their break-up – **electromagnetic dissociation (EMD)** of nuclei.

Venn diagram



- In most cases, EMD of a heavy nucleus results in the emission of a single or just few neutrons with the production of a single residual nucleus.

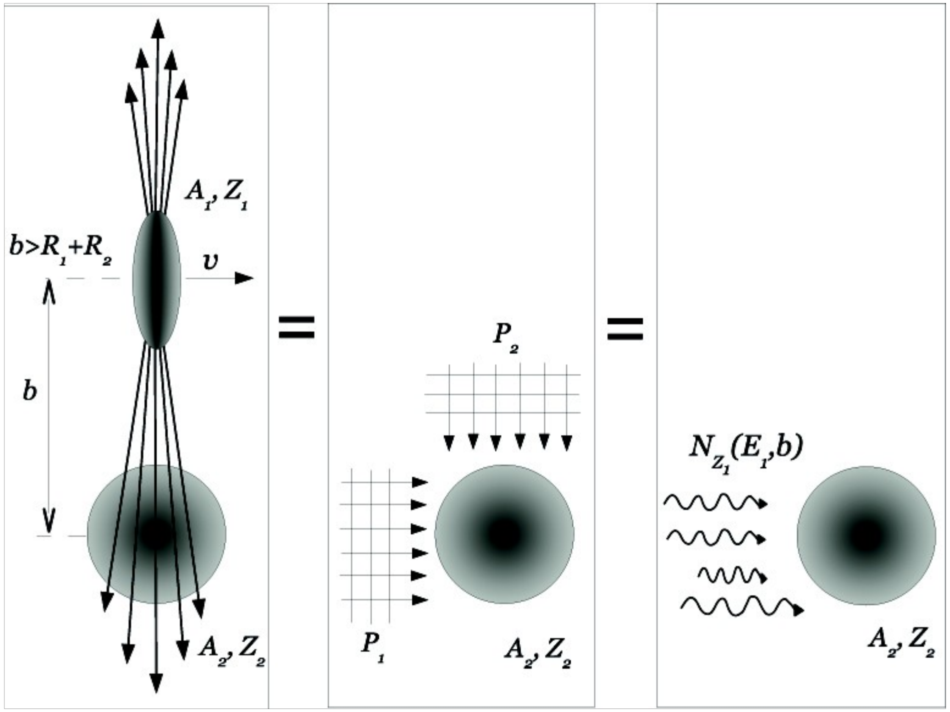
- In collider one can search for forward neutrons from EMD on one side **(single EMD)** or use detectors on both sides **(mutual EMD)**

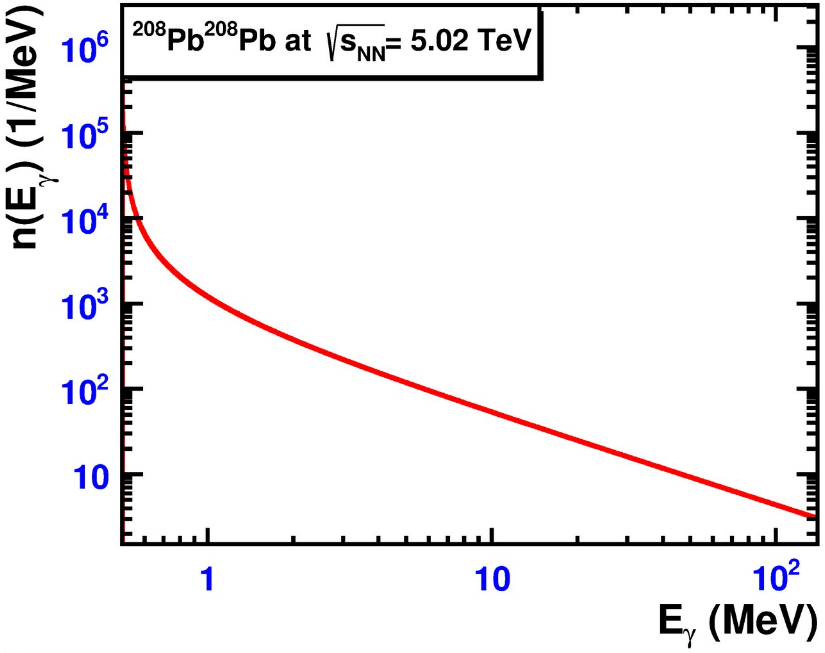
- The total single EMD cross section of EMD of ^{208}Pb (~ 210 b) at the LHC is much larger than the hadronic cross section (7.7 b). The mutual EMD is estimated as 3.9 b.

A.J. Baltz et al., Phys. Rep. 458 (2008) 1

Weizsäcker–Williams method

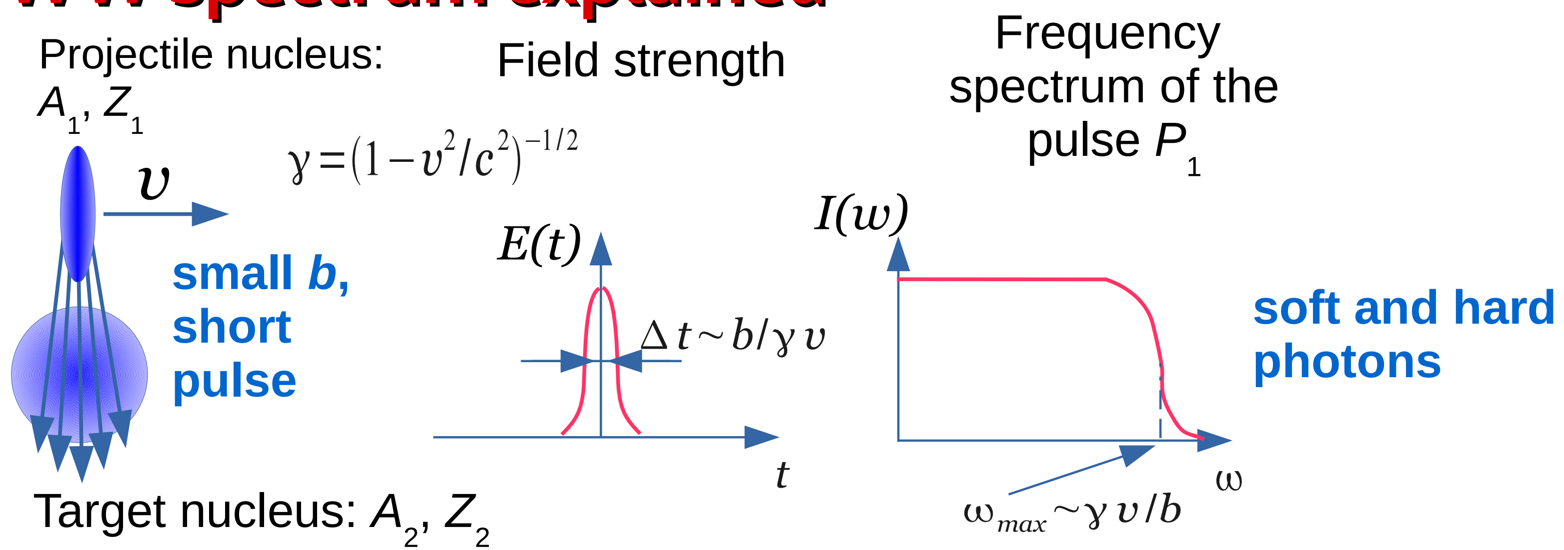
The impact of the Lorentz-contracted Coulomb field of the nucleus A_1 on A_2 can be represented by the absorption of one or more equivalent photons by the nucleus A_2.

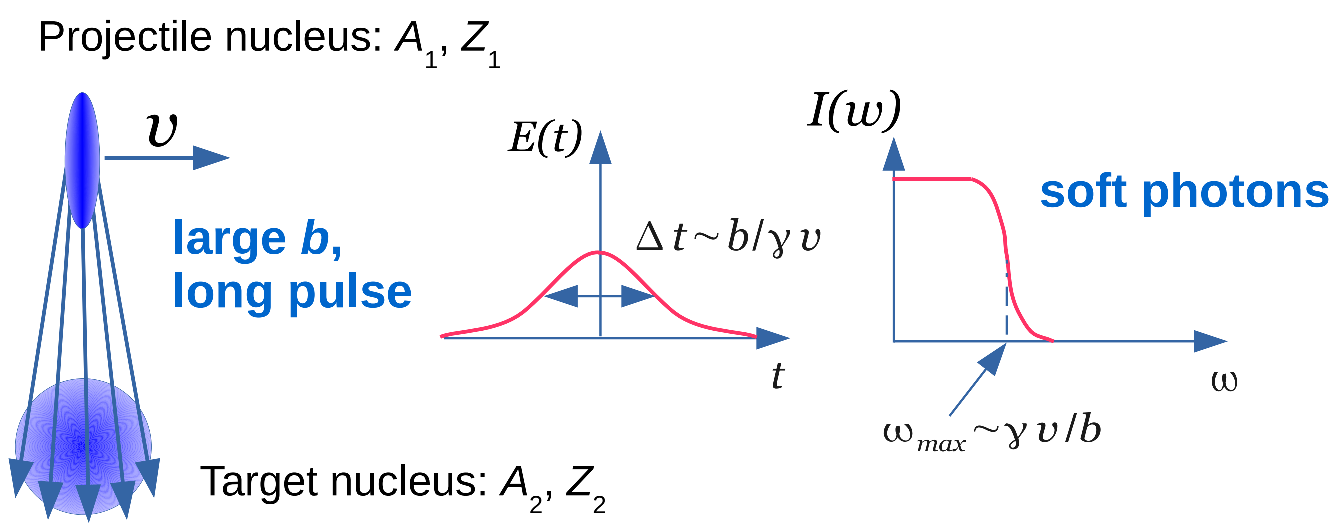




The modeling of UPC is then reduced to the simulation of photonuclear reactions on A_2 induced by (quasi)real WW photons with the characteristic WW spectrum.

The WW spectrum explained





I.P., Phys. Part. Nucl. 42 (2011) 215

Spectrum of Weizsäcker-Williams photons

Spectrum of equivalent photons from a nucleus (A_1, Z_1),
as seen by a nucleus (A_2, Z_2) in a collision with impact parameter b:

$$N_{Z_1}(E_1, b) = \frac{\alpha Z_1^2}{\pi^2} \frac{\mathrm{x}^2}{\beta^2 E_1 b^2} \left(K_1^2(\mathrm{x}) + \frac{1}{\gamma^2} K_0^2(\mathrm{x}) \right), \quad \mathrm{x} = E_1 b/\gamma\beta$$

α - fine structure constant

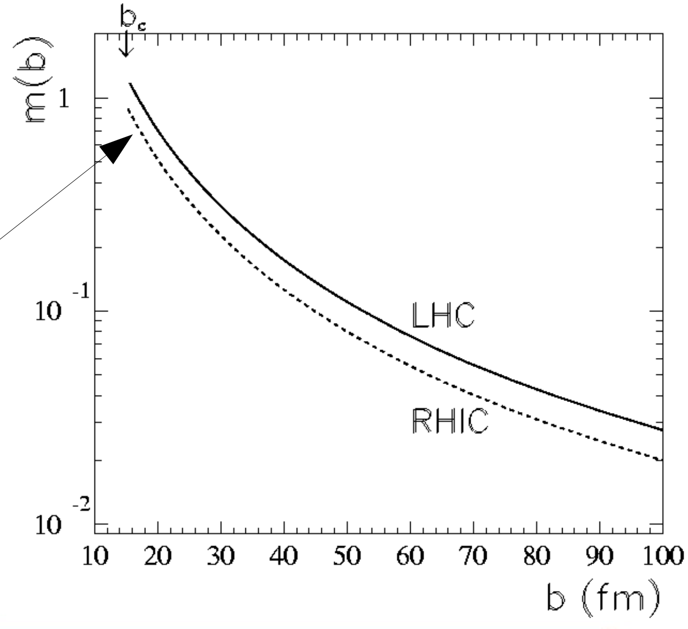
K_0, K_1 - modified Bessel functions

Average number of photons absorbed by the nucleus (A_2, Z_2) :

$$m_{A_2}(b) = \int_{E_{min}}^{E_{max}} dE_1 N_{Z_1}(E_1, b) \sigma_{A_2}(E_1),$$

$\sigma_{A_2}(E_1)$ - total photoabsorption cross sections for the nucleus (A_2, Z_2)

one photon is absorbed on average in close ($b \sim b_c = R_1 + R_2$) Pb–Pb or Au–Au in UPC at RHIC/LHC



Kinematics of photon emission

Photon is emitted coherently by all charges in the nucleus, they are all inside the radius *R*. The nucleus is left in its ground state. Therefore, the square of 4-momentum is restricted:

$$Q^2 \leq 1/R^2$$

Photons are almost real compared to photons emitted in (e,e') reactions.
The data from photonuclear experiments with real photons can be used safely.

Photon 4-momentum: $q^\mu = (E_\gamma, \vec{q}) = -Q^\mu$

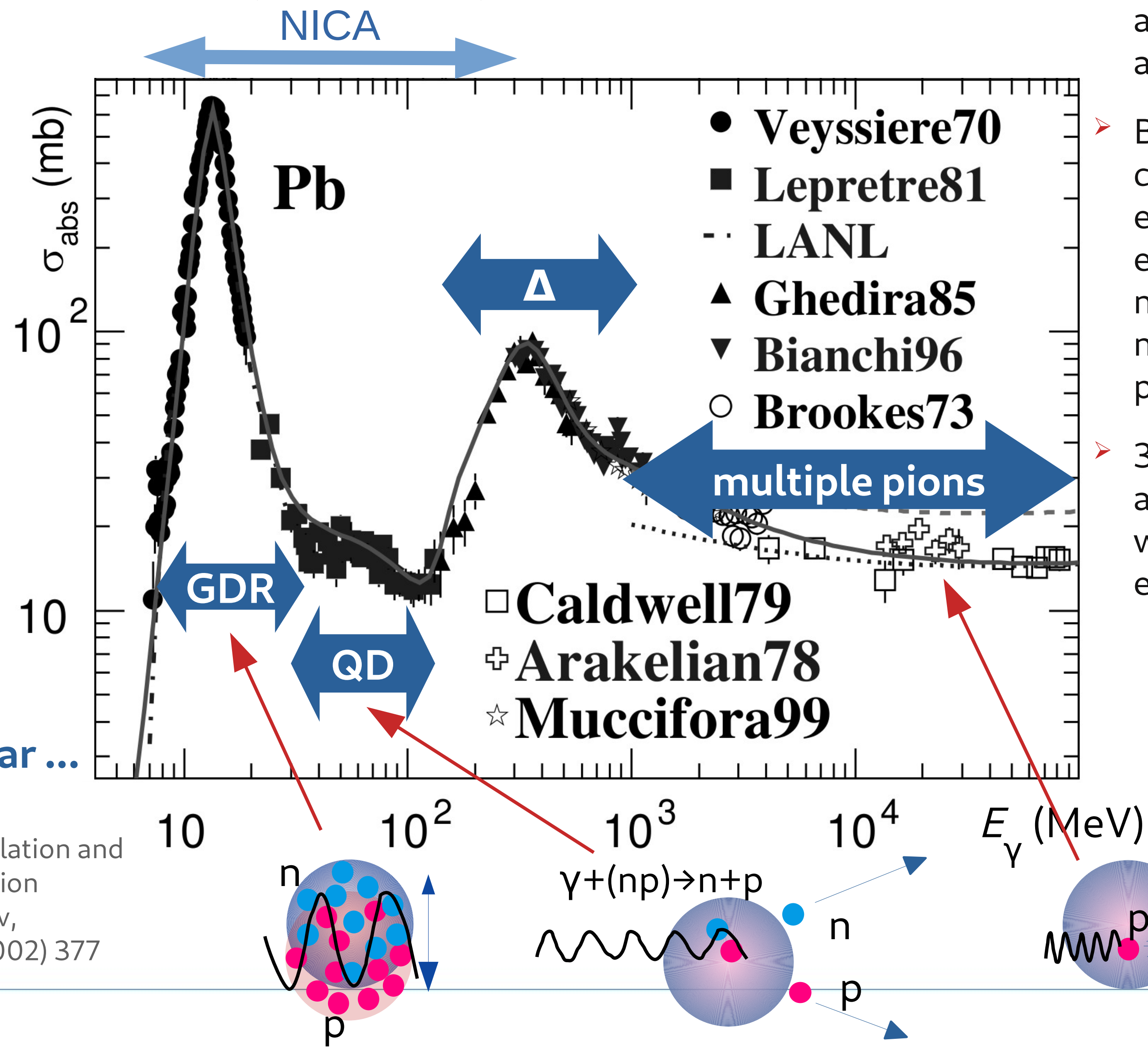
Assume that an ultrarelativitic nucleus $\gamma \gg 1$ is left in its ground state after the emission and only a small part of its kinetic energy is taken away. Together with the coherence condition this gives:

$$q_{||} \approx E_\gamma < \frac{\gamma}{R}, \quad q_\perp < \frac{1}{R}.$$

Note, for colliders: $\gamma = \gamma_{\text{eff}} = 2\gamma^2_{\text{beam}} - 1$

NICA ^{209}Bi–^{209}Bi: $E_\gamma < 340\,\text{MeV}$ LHC ^{208}Pb–^{208}Pb: $E_\gamma < 180\,\text{TeV}$

Photoabsoption in Relativistic ELectromagnetic DISsociation (RELDIS) model



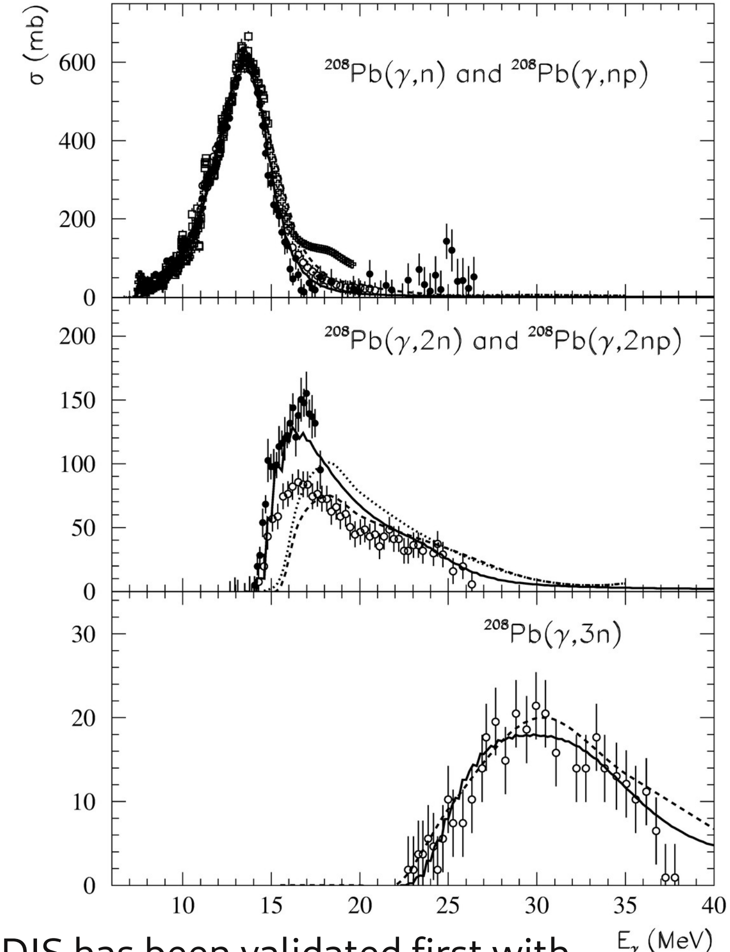
Nuclear ...

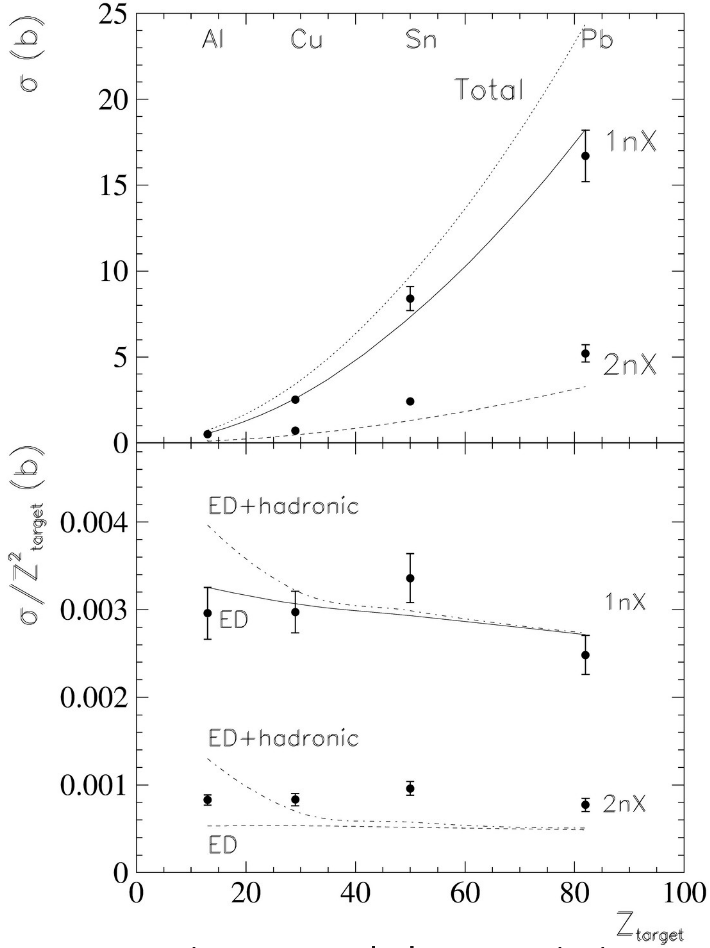
...and hadronic degrees of freedom

Data compilation and approximation M.V. Kossov, EPJA 14 (2002) 377

- Developed since 1995 at INR, NBI, ENEA, GSI and FIAS
- Based on intranuclear cascade, preeqilibrium emission, coalescence, evaporation-fission-multifragmentation model (SMM) of photonuclear reactions
- 30+ papers published, also in collaboration with several experimental groups

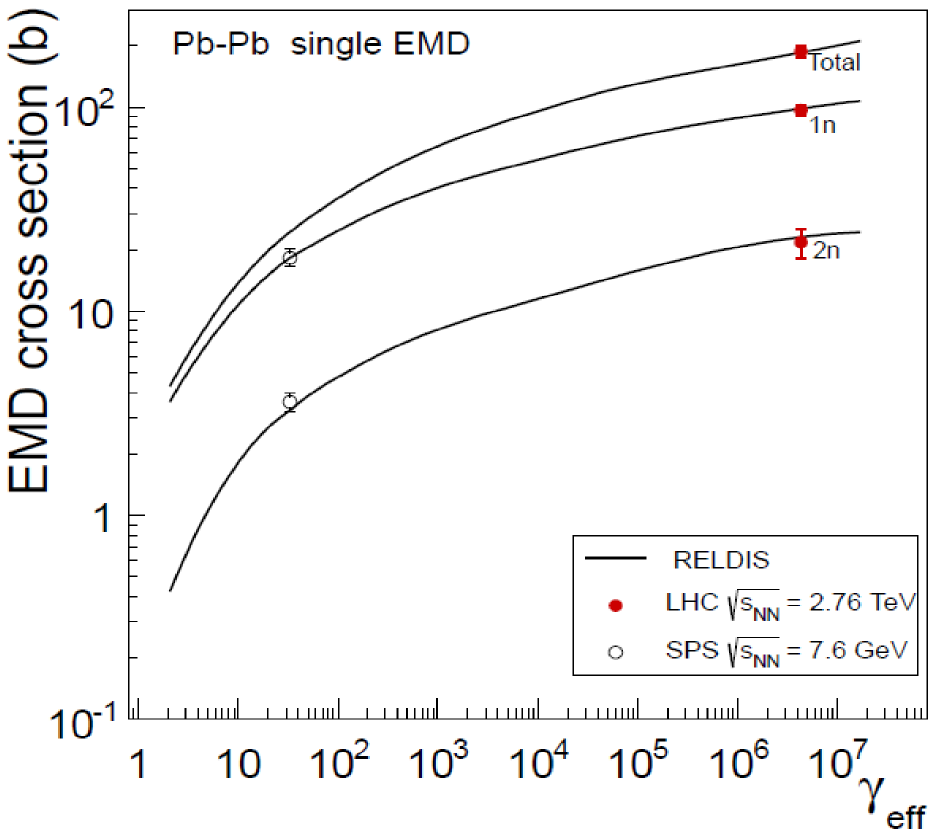
EMD of ^{208}Pb at the CERN SPS described by RELDIS





- RELDIS has been validated first with photonuclear data on 1n, 2n, 3n emission: I. Pshenichnov et al., PRC 64 (2001) 024903
- EMD cross sections reveal characteristic dependence on Z^2 of target nuclei: M.B. Golubeva et al., PRC 71 (2005) 024905

Dependence of EMD cross sections on the collision energy: SPS vs LHC vs RELDIS model



- Data are well described by RELDIS within six orders of magnitude of $\gamma_{\rm eff} = E_{\rm beam}/m_{\rm N}$

  for collider

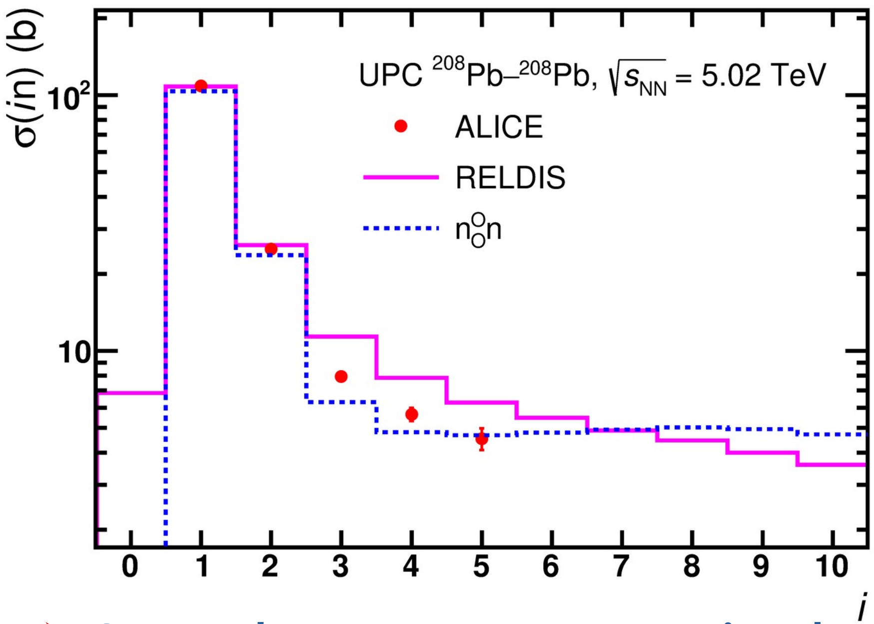
  $\gamma_{\rm eff} = 2\gamma_{\rm beam}^2 - 1$

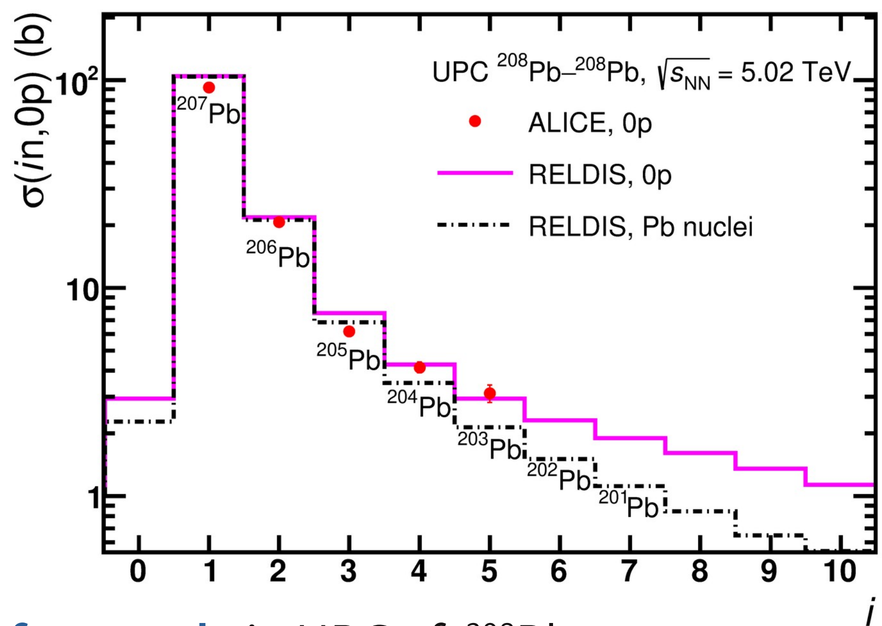
- Smooth and monotonic energy dependence allows safe extrapolation of results for collisions of the same nuclei (^{208}Pb) to higher or lower collision energy.

SPS: M.B. Golubeva et al., (ALICE-LUMI experiment), PRC 71 (2005) 024905

LHC: B. Abelev et al., ALICE Collaboration, PRL 109 (2012) 252302

Neutron emission with and without protons at the LHC





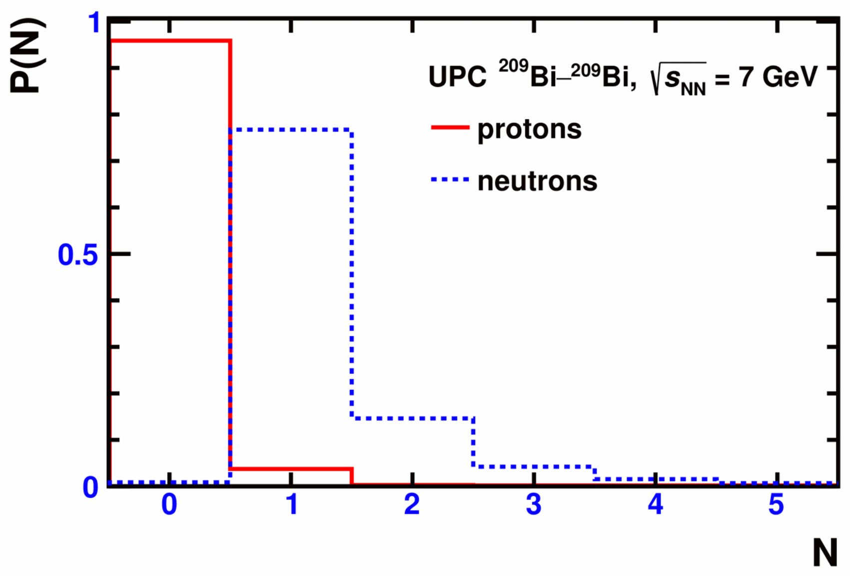
- **One and two neutrons are emitted most frequently** in UPC of ^{208}Pb
- 1n and 2n cross sections are well described by RELDIS and $n^{O}_{O}n$ models
- According to RELDIS, the cross sections to produce **^{207}Pb, ^{206}Pb, ^{205}Pb** are well approximated by **the 1n, 2n and 3n cross sections without proton emission**

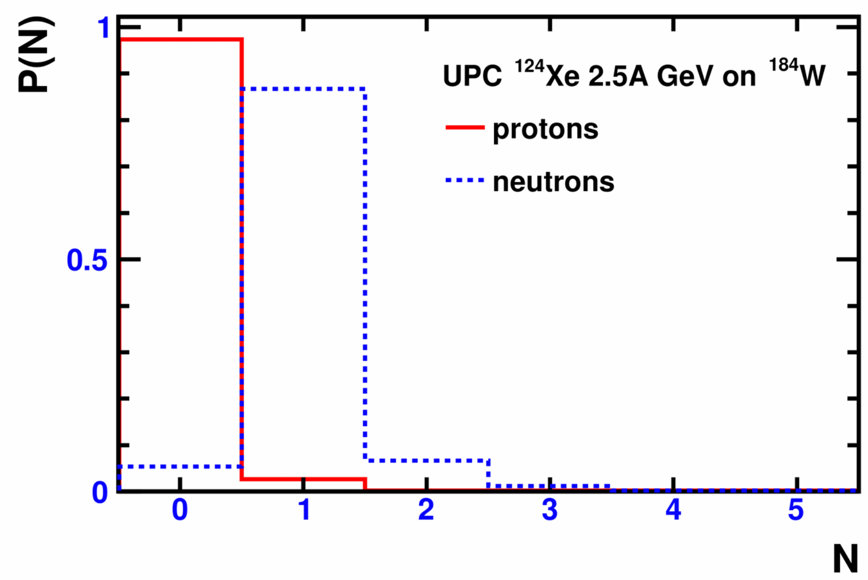
ALICE, Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV, PRC 107 (2023) 064902
M.Broz et al., A generator of forward neutrons for ultra-peripheral collisions: $n^{O}_{O}n$, Comp. Phys. Comm. 253 (2020) 107181

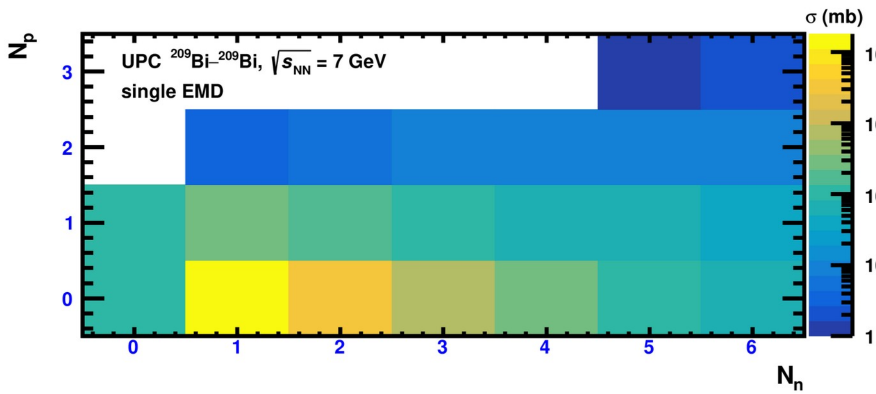
EMD in MPD experiment in collider and fixed target modes

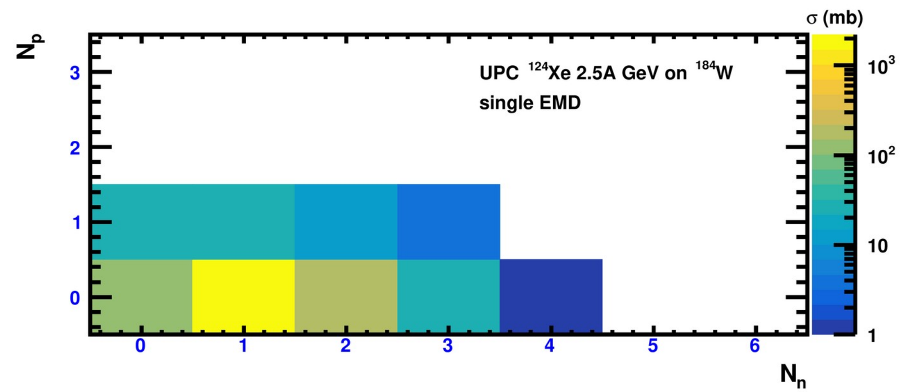
Parameter (units)	colliding nuclei	
	^{209}Bi–^{209}Bi $\sqrt{s_{NN}} = 7$ GeV	2.5A GeV ^{124}Xe–^{184}W
γ_{eff}	26.7	3.66
E_{min} (MeV)	8.	11.5
E_{max} (MeV)	**339.**	**52.**
total single dissociation σ_{sEMD} (b)	**23.8**	**2.58**
total mutual dissociation σ_{mEMD} (b)	2.1	
$\langle E^{\star}_{RN} \rangle$ (MeV)	15.7	16.4
$\langle N_n \rangle$	1.3823	1.0384
$\langle N_p \rangle$	0.0463	0.0269
$\langle N_{\pi^+} \rangle$	0.0007	0.
$\langle N_{\pi^-} \rangle$	0.0013	0.
$\langle N_{\pi^o} \rangle$	0.0016	0.
$\langle N_d \rangle$	0.0206	0.0025
$\langle N_t \rangle$	0.0004	0.
$\langle N_{^3He} \rangle$	0.00006	0.
$\langle N_{^4He} \rangle$	0.0002	0.0017
σ_{fiss} (b)	0.003	0.

Multiplicity distributions and σ(in,kp) in collider and fixed target modes in the MPD experiment







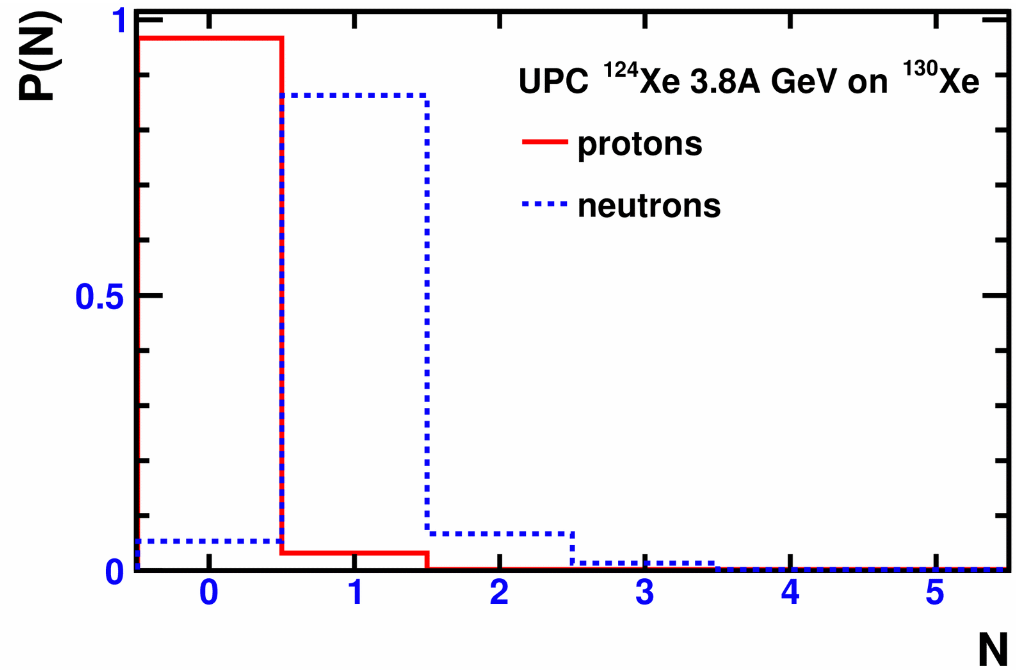


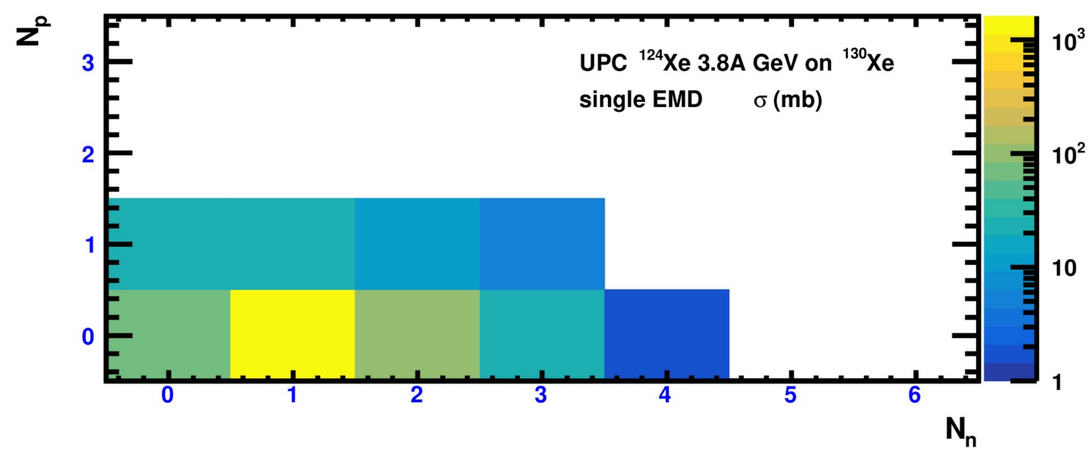
Emission of EMD neutrons and protons in the MPD experiment

Neutron and proton multiplicity (in,kp)	single EMD cross section (b)	
	^{208}Pb–^{208}Pb $\sqrt{s_{NN}} = 7$ GeV	2.5A GeV ^{124}Xe–^{184}W
(0n,0p)	0.09	0.12
(1n,0p)	18.14	2.21
(2n,0p)	3.32	0.16
(3n,0p)	0.90	0.03
(4n,0p)	0.28	0.
(5n,0p)	0.12	0.
(6n,0p)	0.06	0.
total (Xn,0p)	**22.9**	**2.51**
(0n,1p)	0.12	0.02
(1n,1p)	0.25	0.03
(2n,1p)	0.18	0.01
(3n,1p)	0.12	0.
(4n,1p)	0.08	0.
(5n,1p)	0.05	0.
(6n,1p)	0.03	0.
total (Xn,1p)	**0.84**	**0.07**
total EMD	**23.8**	**2.58**

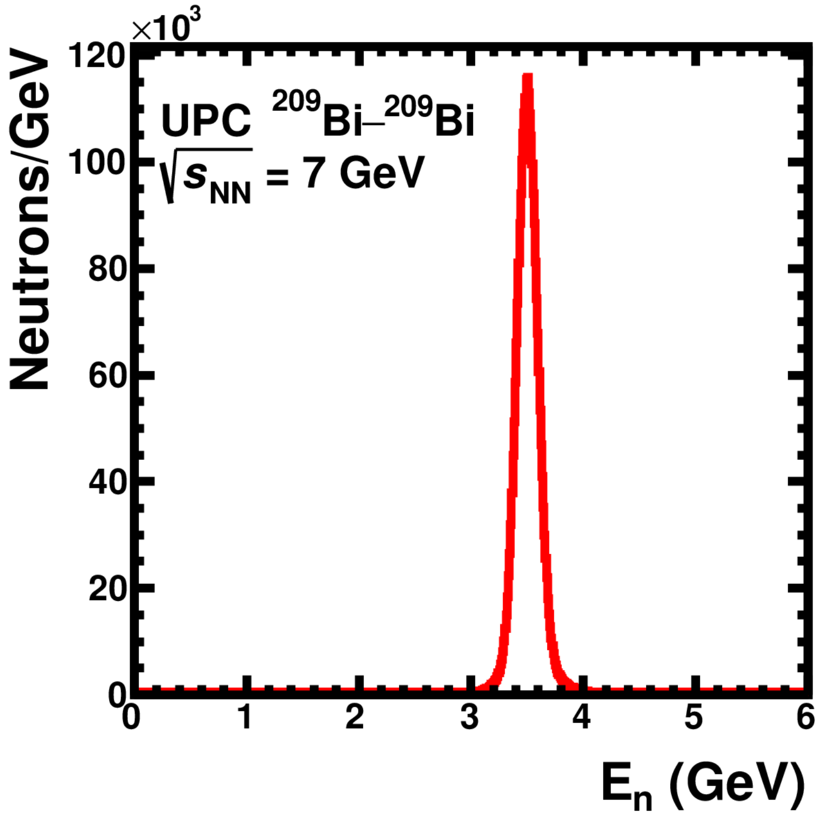
Emission of EMD neutrons and protons in the BM@N experiment

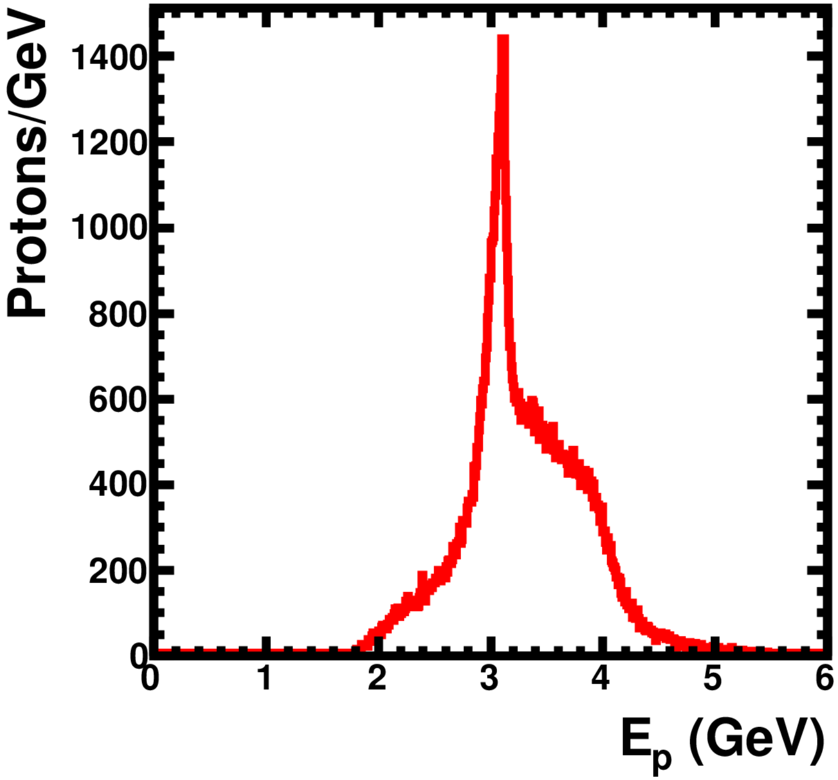
Neutron and proton multiplicity (in,kp)	single EMD cross section (b) 3.8A GeV ^{124}Xe–^{130}Xe (CsI)
(0n,0p)	0.08
(1n,0p)	1.61
(2n,0p)	0.12
(3n,0p)	0.02
(4n,0p)	0.
total (Xn,0p)	**1.83**
(0n,1p)	0.020
(1n,1p)	0.023
(2n,1p)	0.013
(3n,1p)	0.004
(4n,1p)	0.
total (Xn,1p)	**0.06**
total EMD	**1.89**





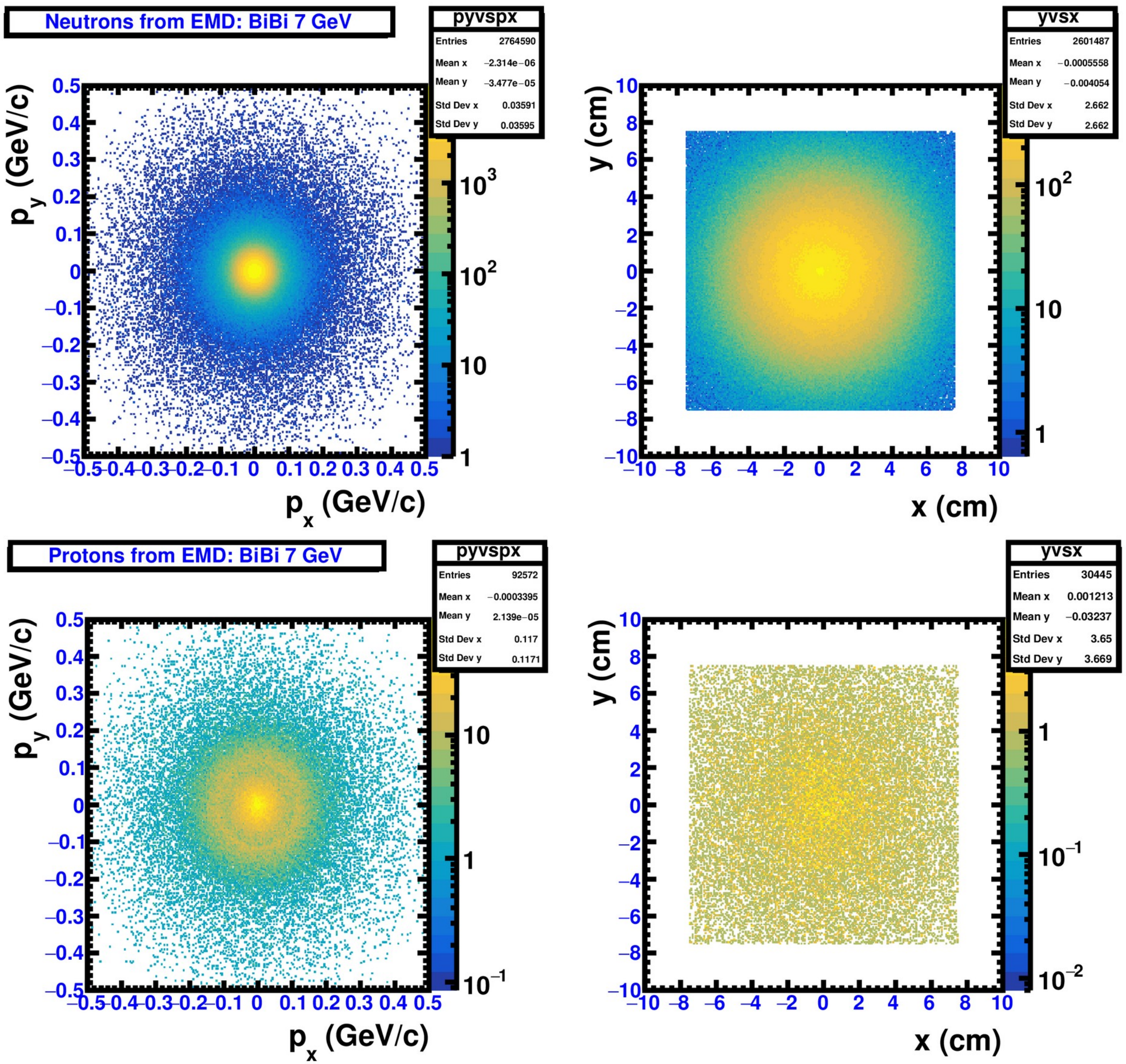
Energy distributions of neutrons and protons from EMD





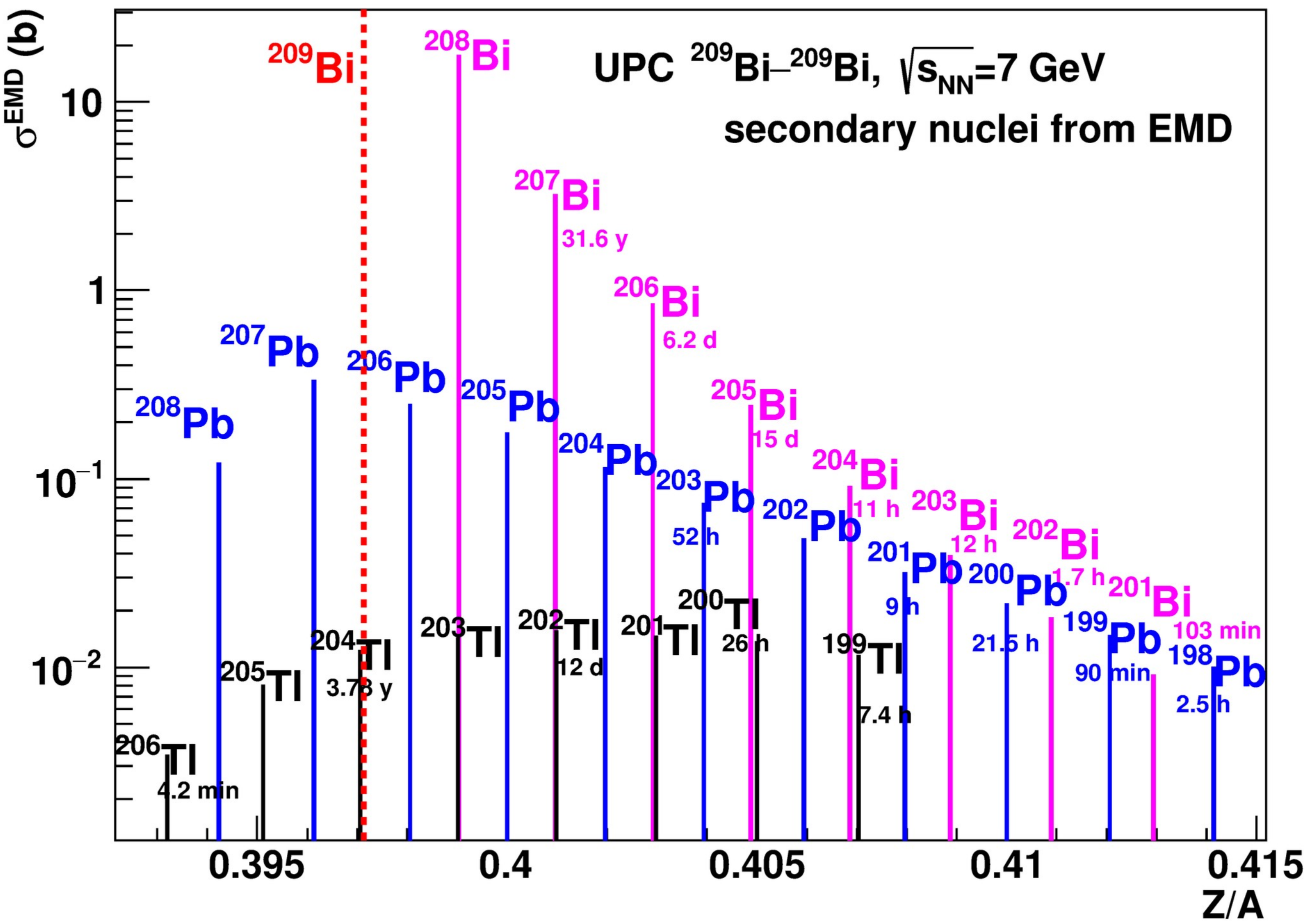
- Energy distribution of protons from EMD is much wider compared to the distribution of much more abundant neutrons.
- Neutrons are produced mostly by sequential evaporation from excited ^{209}Bi while protons are produced by more energetic photons along with other particles.

p_t-distributions of neutrons and protons from EMD



- Pt-distributions of EMD neutrons and protons (left column)
- Estimation of distributions of neutrons and protons in the central (beam) hole of FHCal (right column).
- About 94% of neutrons, but only ~33% of protons pass through the hole
- Magnetic field, beam crossing angle and other detectors were neglected in this simple estimation

Secondary nuclei from EMD of ^{209}Bi in collider mode



- Most of secondary nuclei leave MPD through the beam hole of FHCal
- These nuclei possibly impact NICA components after propagating far from the interaction point. This requires further studies.

EMD at NICA/MPD in collider (^{209}Bi+^{209}Bi) and fixed target (^{124}Xe+^{184}W) modes

- In collider, ^{209}Bi ions are lost from the beam due to EMD three times more frequently than due to hadronic interactions
- In fixed target mode EMD and hadronic interactions cause comparable loses of ^{124}Xe ions
- EMD processes (pile-up single EMD and mutual EMD) will contaminate only very peripheral events (events with ~ 1 neutron per side and minimum activity at midrapidity)
- In both modes the analysis of very peripheral hadronic events may require extra efforts to reject the contamination of EMD events (e.g., by rejecting events with empty central detector)

EMD and projectile fragmentation as sources of high-energy neutrons

- Vladimir Yurevich, Production of neutrons in thick targets by high-energy protons and nuclei, Phys. Part. Nucl., 41 (2010) 778:

  "Although production of neutrons as a result of fragmentation of nuclei that are heavier than deuterons is still not applied for production of neutron beams of very high energies, this possibility seems essentially promising for research with neutrons at energies higher than 1 GeV."

In poster session on Wednesday, July 3rd:

- #17 id:184 **Measurement of forward neutron yields with a High-Granularty Neutron Time-of-Flight Detector prototype from electromagnetic dissociation and nuclear interaction in Xe+CsI@3.8 AGeV collisions at the BM@N experiment,** to be presented by Aleksandr Zubankov
  - A narrow spot of forward EMD neutrons has been seen for the first time at the BM@N experiment at Nuclotron with a prototype of HGND.
  - The measured yields of EMD neutrons were compared to those from spectator fragmentation.

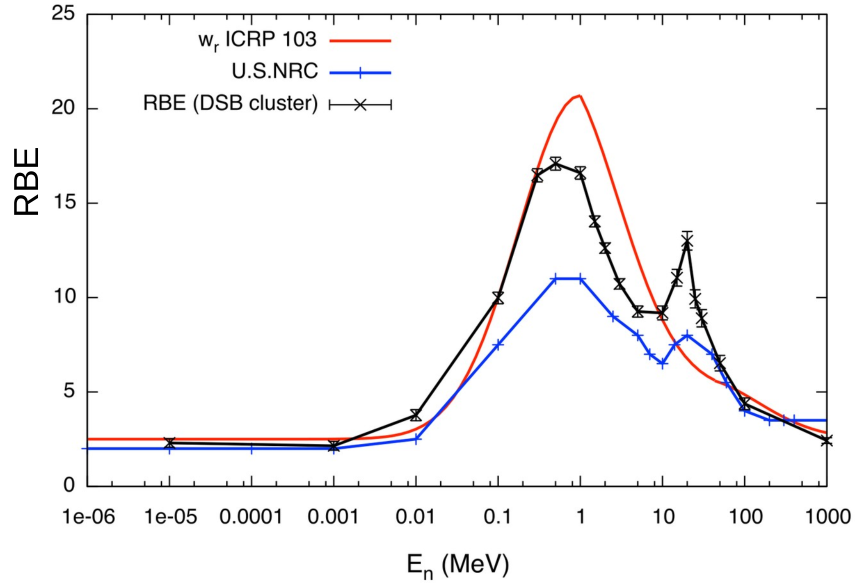
Radiobilogocal properties of high-energy neutrons (> 1 GeV) remain unexplored ...

- Calculations: G. Baiocco et al., The orgin of neutron biological effectiveness as a function of energy, Sci. Reports 6 (2016) 34033

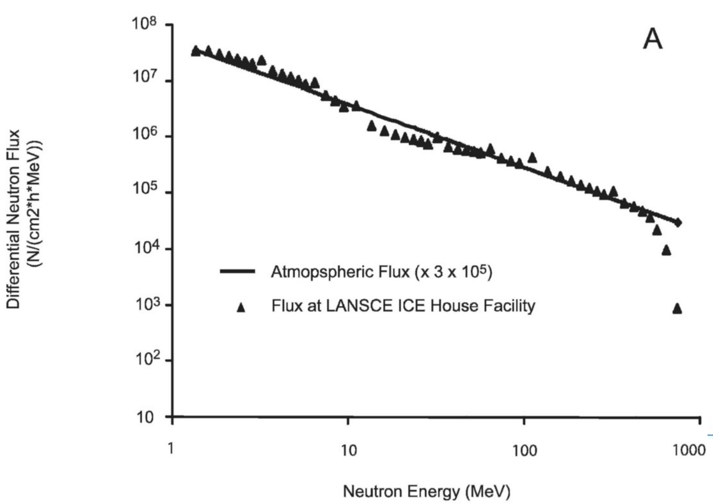
  RBE is the ratio of the dose of a reference radiation (250 keV photons) to the absorbed dose of the neutron radiation with the same biological effect.

- W. Kuhne et al.,Biological effects of HE neutrons measured in vivo using a vertebrate model, Radiat. Res. 172 (2009) 473

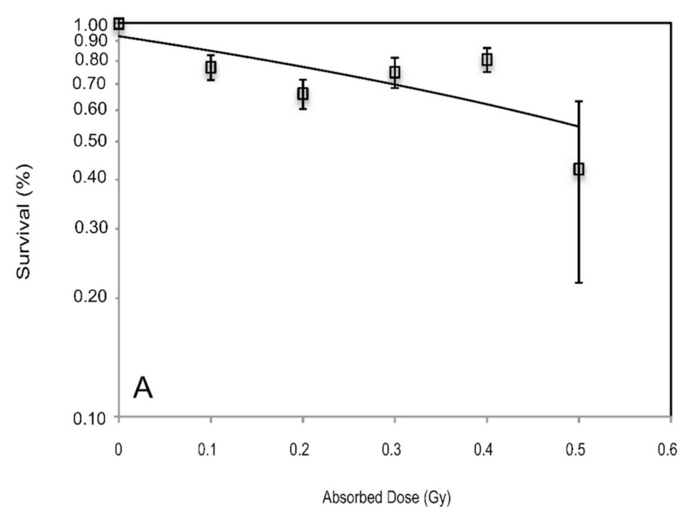
  Measured RBE: 24.9 – 48.1



Very wide neutron energy spectrum: 1 – 1000 MeV



Large measurement uncertainties



Summary

- The cross sections of neutron emission in EMD of ^{208}Pb measured at the SPS and LHC were described well by RELDIS model
- This gives us confidence in predicting the characteristics of EMD of ^{209}Bi at NICA
- The MPD detector is not optimized for EMD studies because of poor acceptance of EMD neutrons and protons
- "An inverse problem" has to be solved at NICA to subtract the contamination of EMD events from very peripheral hadronic events
- However, further modeling may be necessary to understand a possible impact of secondary nuclei (^{208}Bi, ^{207}Bi, ^{206}Bi , ^{205}Bi, … ^{208}Pb, ^{207}Pb, ^{206}Pb, ^{205}Pb …) on NICA components including those located quite far from the interaction point
- EMD and spectator neutrons can be potentially used as a source of well-collimated monoenergetic neutrons at the BM@N setup to measure for the first time biological effectiveness of high energy (>1 GeV) neutrons
- **We have a chance to measure RBE of neutrons of the highest energy available on our planet!**

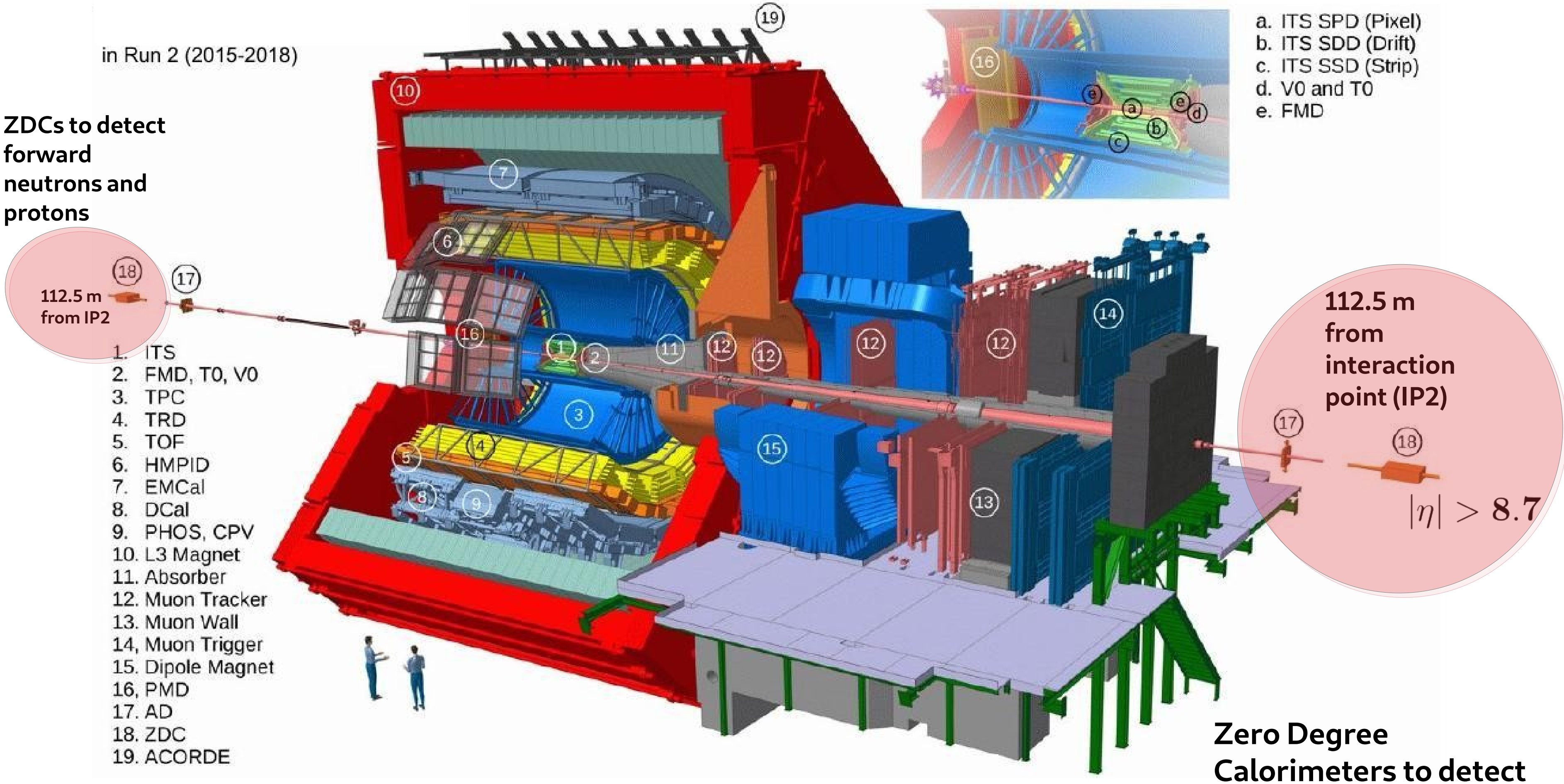
Thank you for your attention!

- We will be happy to provide event files generated with RELDIS to study:
  - the impact of secondary nuclei from EMD on collider operation;
  - the possibility to use neutrons from EMD as a neutron beam to study, e.g., biological impact of high-energy neutrons.
- We are also ready to run calculations of RBE for high-energy neutrons, see L. Burigo, I.P.,I. Mishustin, M. Bleicher, Microdosimetry of radiation field from a therapeutic ^{12}C beam in water: A study with Geant4 toolkit, Nucl. Inst. Meth. B 310 (2013) 37.
- Please contact:
  - Igor Pshenichnov (pshenich@inr.ru),
  - Alexander Svetlichnyi (aleksandr.svetlichnyy@phystech.edu)
  - Savva Savenkov (savenkov.sd@phystech.edu)

Back-up slides

The ALICE detector

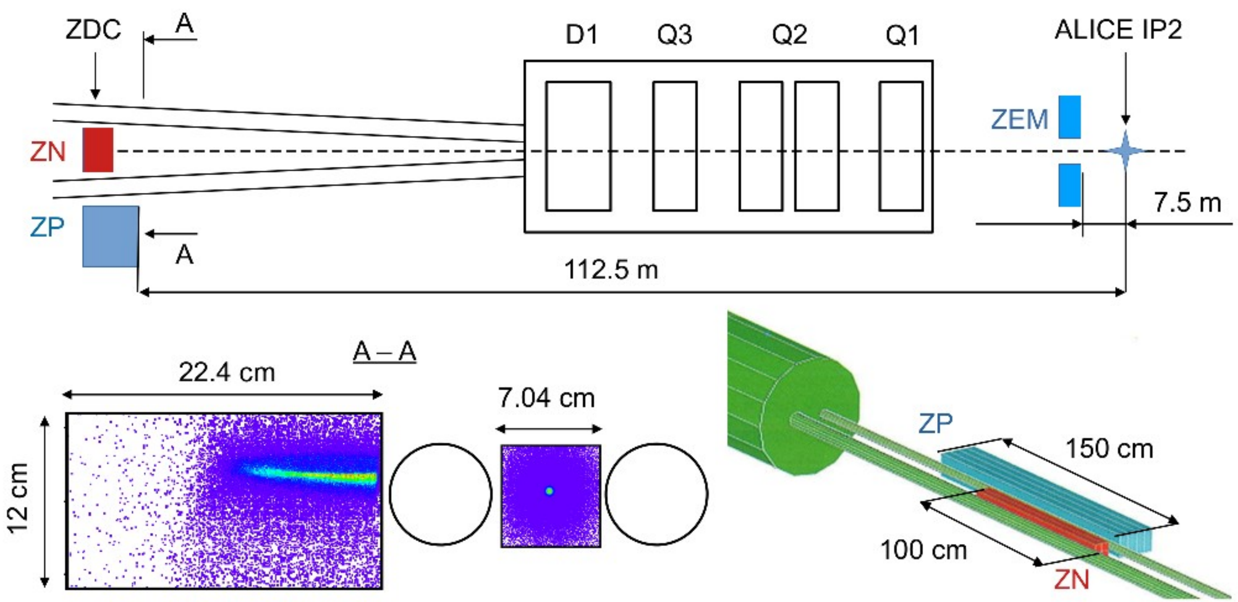
ZDCs to detect forward neutrons and protons



Zero Degree Calorimeters to detect forward neutrons and protons

ALICE ZDC

are placed far from the IP2 and they are **partially shadowed** by collimators and other collider components



- ZDCs are supplemented by **two ZEM calorimeters** at 7 m only on the side A:

$$4.8 < \eta < 5.7$$

- Imposing **ZEM veto** provides opportunity **to select EMD events**
- ZEMs are sensitive to > 92 % of hadronic events
- No signals in ZEMs in > 99 % of EMD events with 5 or less neutrons

- **Nucleon losses lead to the redistribution of true high multiplicity events in favor of detected low multiplicity events**
- Visible cross sections should be corrected for the efficiency of nucleon registration
- Correction factors (= 1/efficiency) were obtained by Monte-Carlo modeling of the transport of nucleons from EMD in the ALICE setup (more details in the back-up slides)

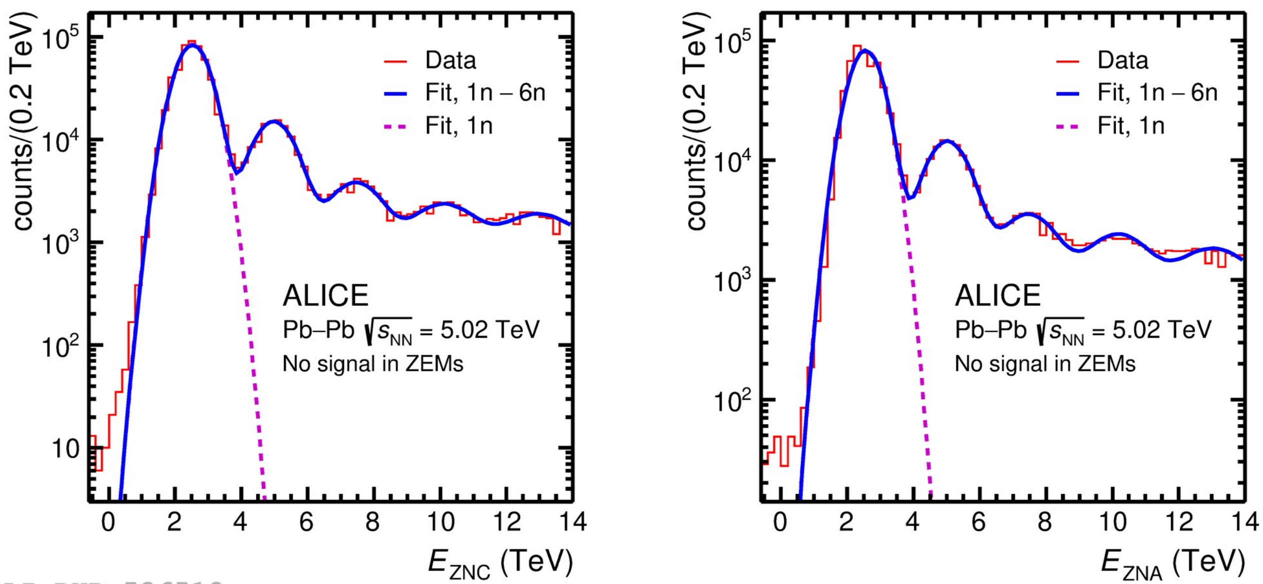
Measured distributions of the total energy of neutrons in ZDCs

ZDC spectra are described by the **sum of Gaussians**:

$$F(E) = \sum_{i=1}^{6} f_i(E) =$$

$$= \sum_{i=1}^{6} \frac{n_i}{\sqrt{2\pi}\sigma_i} e^{-\frac{(E-\mu_i)^2}{2\sigma_i^2}}$$

with n_i – number of events of corresponding neutron multiplicity *i*



ALI-PUB-526518

ALICE, PRC 107 (2023) 064902

The cross section of neutron emission can be calculated for each channel:

for EMD with $\sigma(in) = \sigma_{\rm ZED} \frac{n_i}{N_{\rm tot}} \frac{f_{in}}{\varepsilon_i}$

and without protons $\sigma(in, 0p) = \sigma_{\rm ZED} \frac{n_i}{N_{\rm tot}} \frac{f_{in} f_{0p}}{\varepsilon_i}$, where

$N_{\rm tot}$ – the total number of events tagged by ZED-trigger,

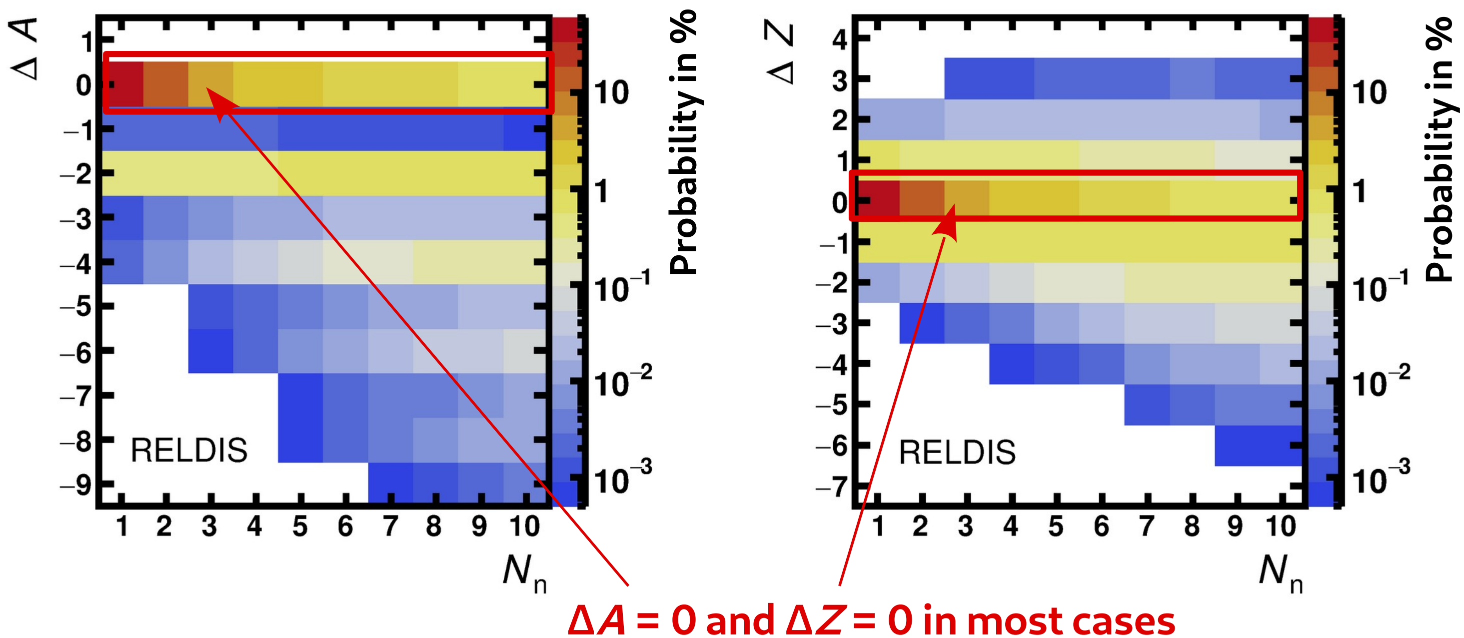
$\sigma_{\rm ZED}$ *) – visible cross section of ZED-trigger

*) ALICE Collaboration, ALICE luminosity determination for Pb−Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV, arXiv:2204.10148 [nucl-ex]

EMD: mostly a single residual nucleus + nucleons

$\Delta A = A_{res} + N_n + N_p - 208$ $\Delta Z = Z_{res} + N_p - 82$

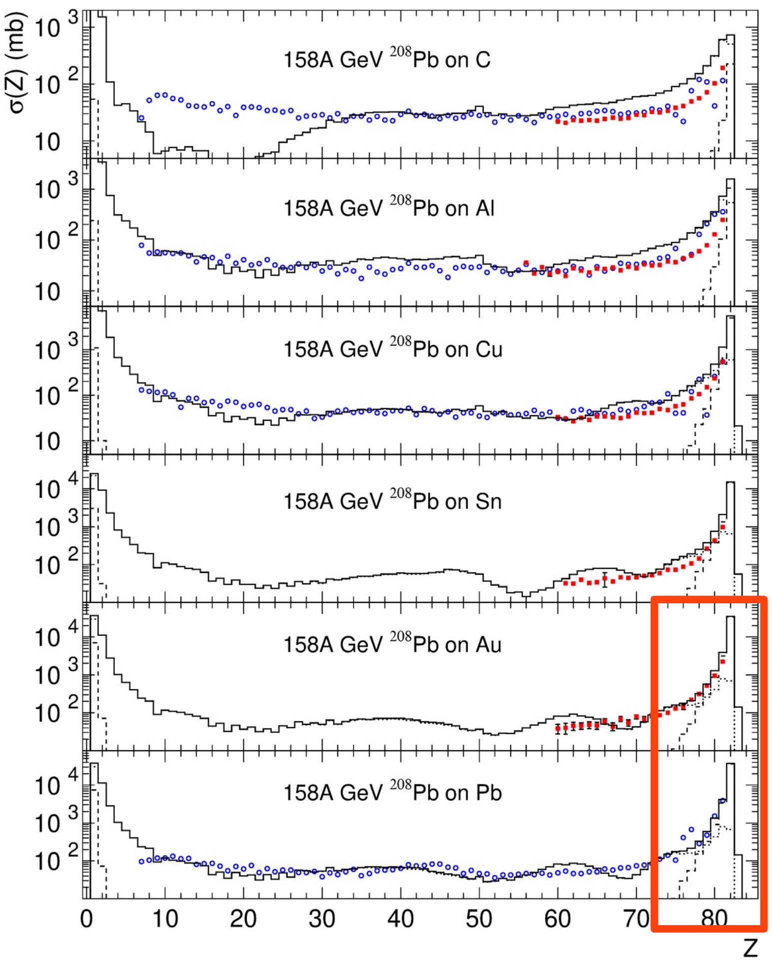
Z_{res} and A_{res} – the charge and mass of the heaviest residual nucleus
N_n and N_p – the numbers of emitted neutrons and protons



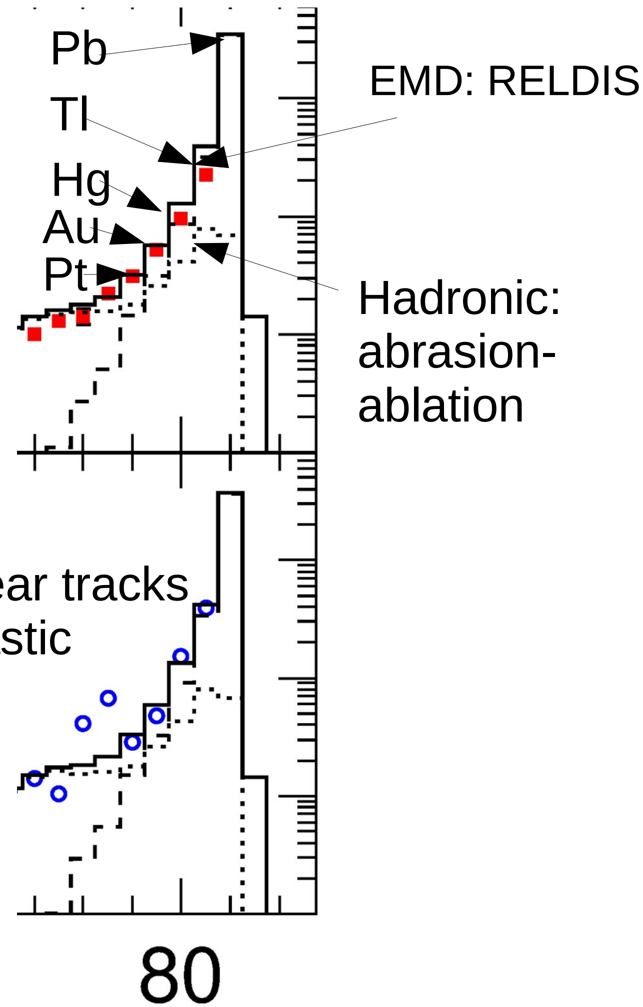
- Direct measurements of secondary nuclei at the LHC are impossible
- **The cross section of the production of a given nucleus can be well approximated by the cross section to emit the corresponding numbers of neutrons and protons**

ALICE, Phys. Rev. C 107 (2023) 064902

Charge-changing cross sections of ^{208}Pb at SPS

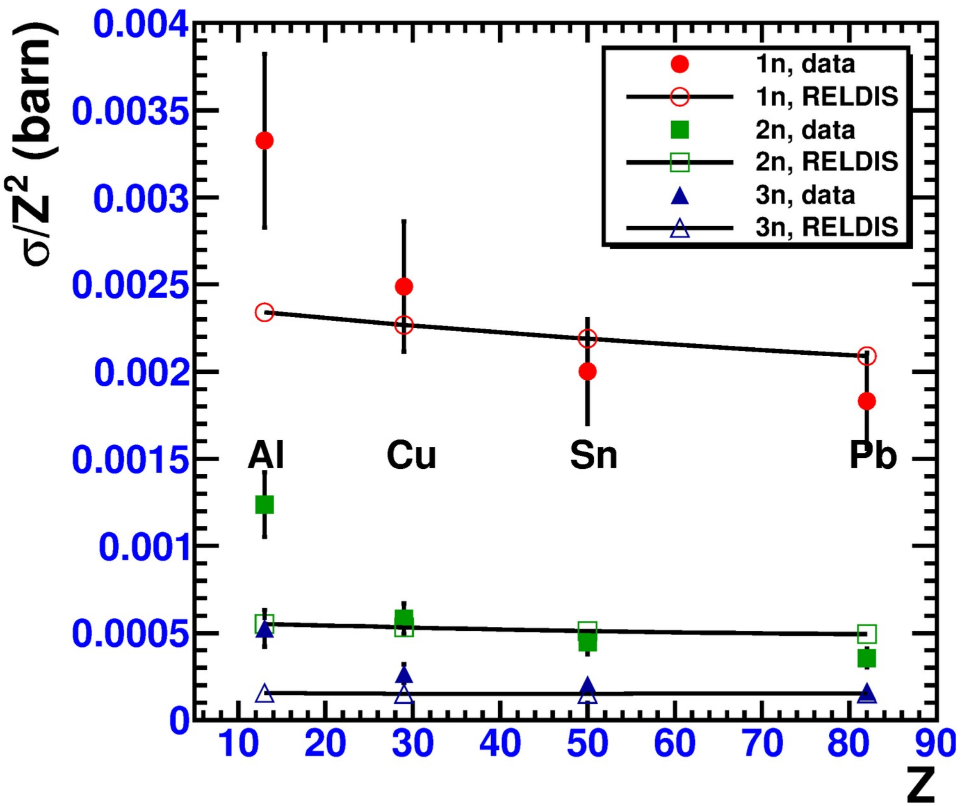


MUSIC ionization chambers



C. Scheidenberger et al., PRC 70 (2004) 014902

Emission of forward neutrons from ^{115}In at the CERN SPS



- Data on 1n, 2n, 3n emission were corrected for multiple EMD, hadronic events and neutron absorption to extract the EMD cross sections
- The dependence on target Z^2 demonstrates the electromagnetic nature of the neutron emission
- The data are well described by RELDIS (with the exception of Al target with large hadronic contribution)

E.V. Karpechev et al., Emission of forward neutrons by 158A GeV ^{115}In in collisions with Al, Cu, Sn and Pb, NPA 921 (2014) 60