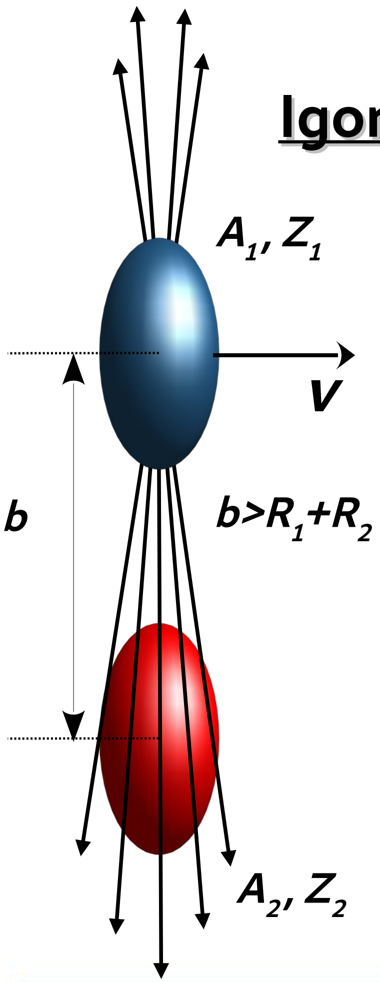
Electromagnetic dissociation of nuclei at NICA

... and also at the SPS and LHC



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Outline

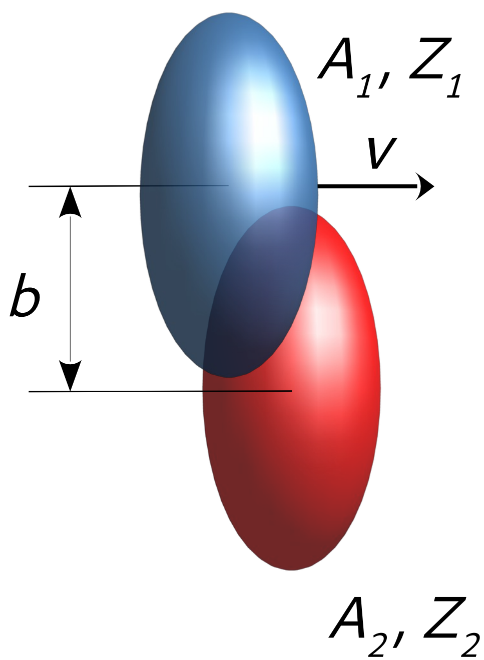
- Physics of ultraperipheral collisions: Weizsäcker-Williams (WW) method of equivalent photons
- Modeling of photonuclear reactions and electromagnetic dissociation (EMD) of nuclei with RELDIS
- Comparison of RELDIS results with data on EMD of ^{208}Pb and ^{115}In at the CERN SPS
- ALICE measurements of neutron emission in EMD of ^{208}Pb and comparison with RELDIS
- EMD of ^{209}Bi and ^{124}Xe at NICA: what can we expect at lower energy
- Summary

Interactions of nuclei

hadronic

with overlap of nuclear densities

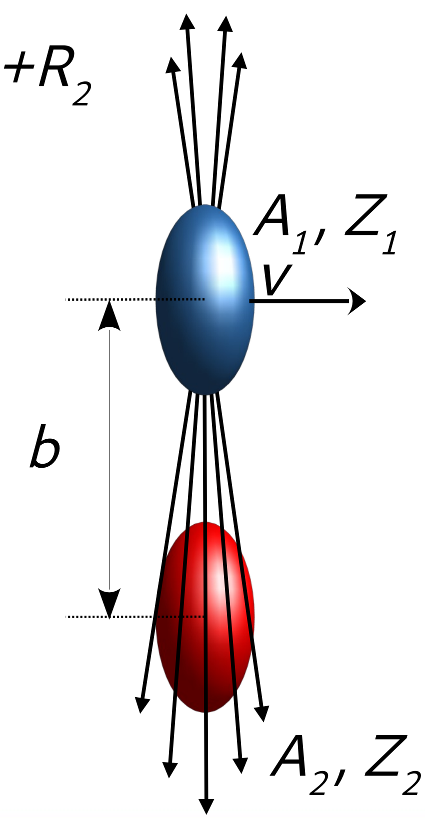
$b<R_1+R_2$



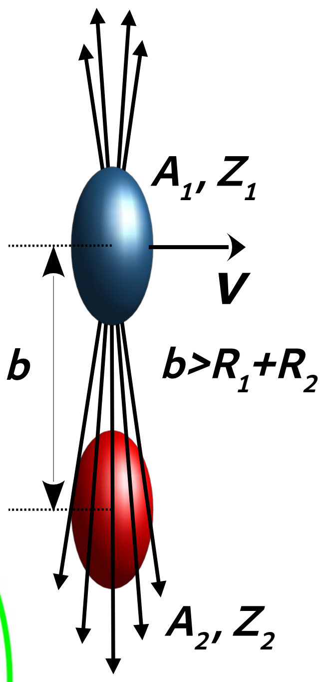
electromagnetic

without overlap of nuclear densities

$b>R_1+R_2$

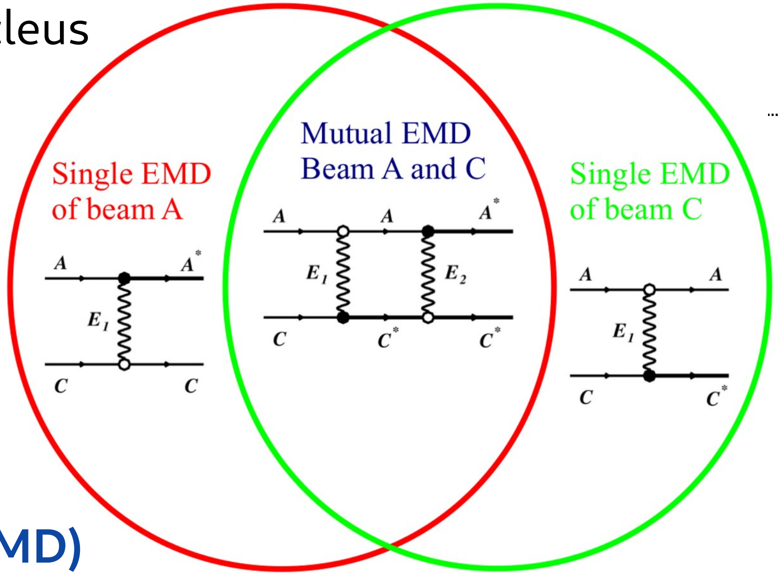


Ultraperipheral collisions and electromagnetic dissociation of nuclei



- 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.

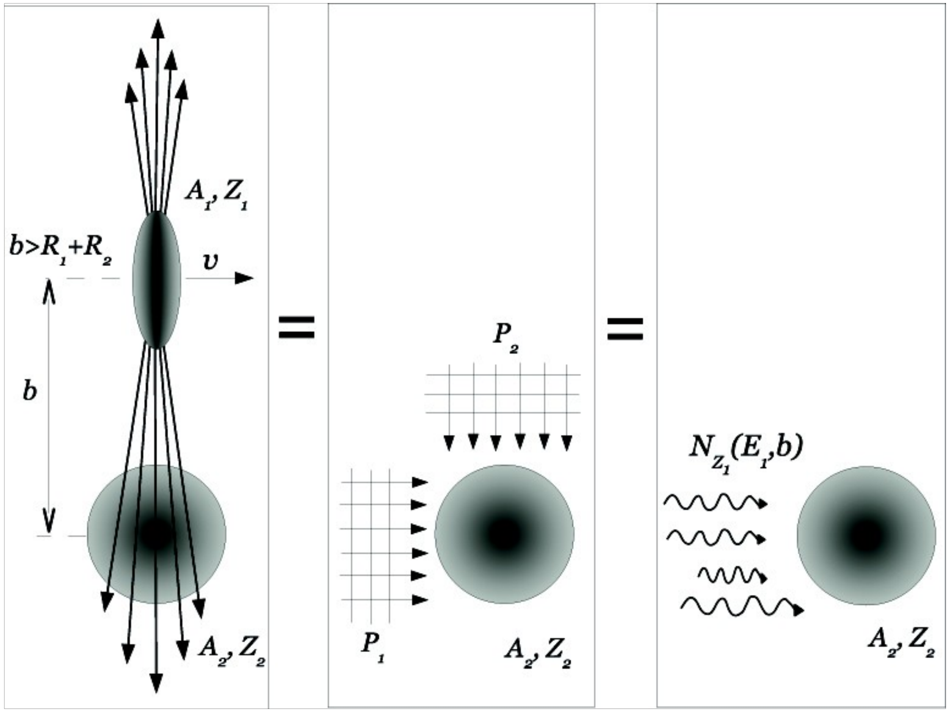
- In collider one can search for forward neutrons from EMD on one side **(single EMD)** or use detectors on both sides **(mutual EMD)**

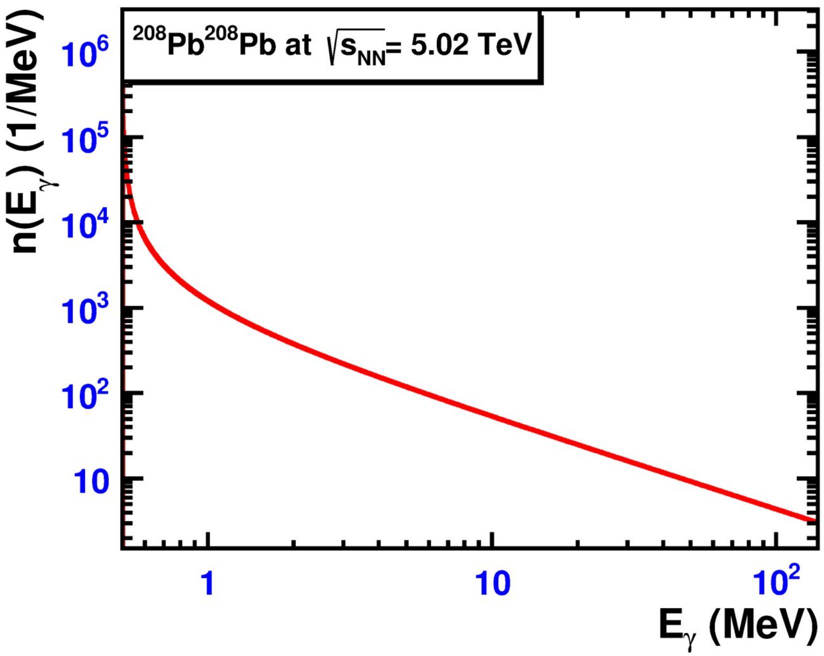
- The total single EMD cross section of EMD of ^{208}Pb (~ 210 b) at the LHC is much larger than the hadronic cross section (7.7 b). The mutual EMD is estimated as 3.9 b.

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

Weizsäcker–Williams method

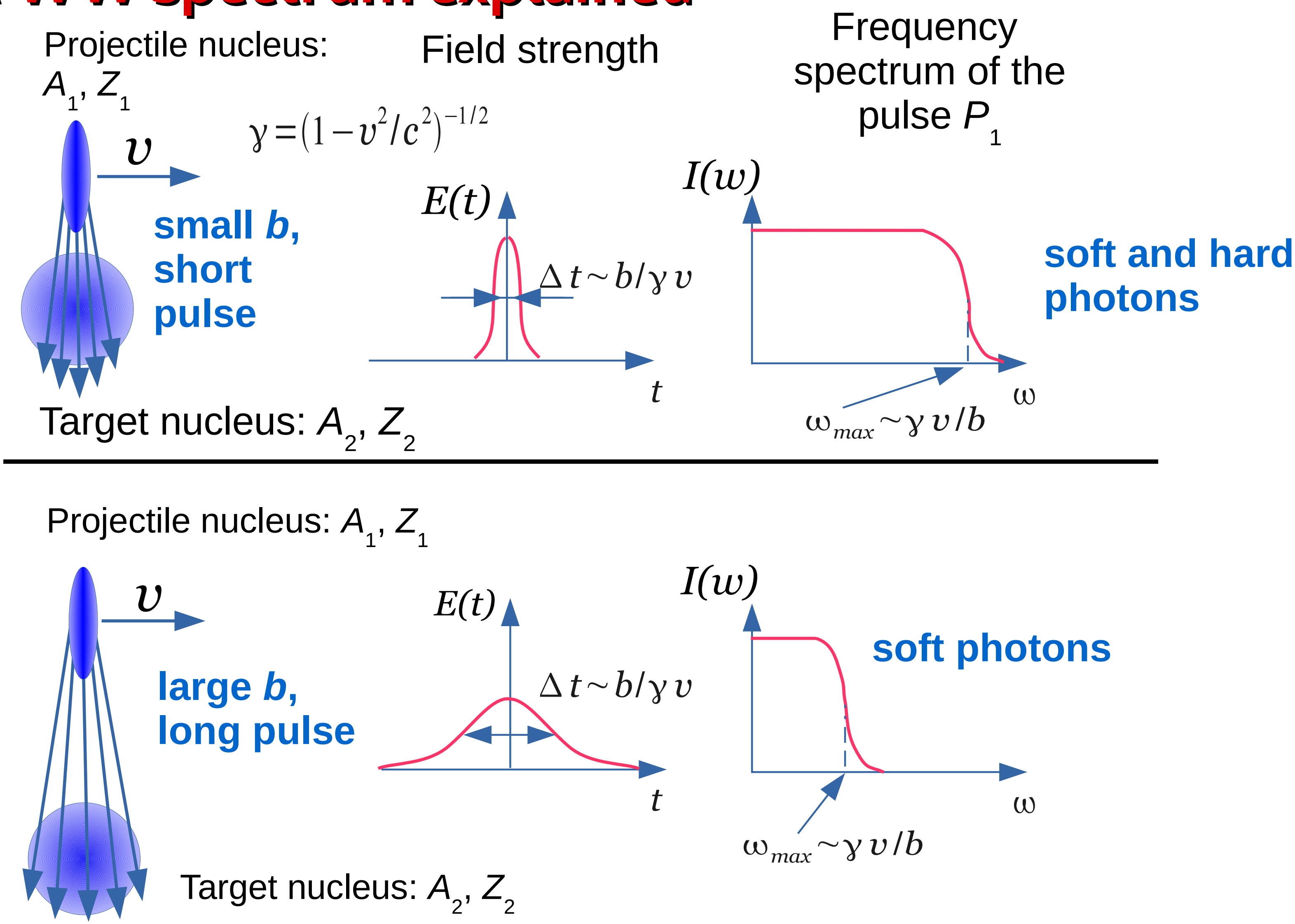
The impact of the Lorentz-contracted Coulomb field of the nucleus A_1 on A_2 can be represented by the absorption of one or more equivalent photons by the nucleus A_2.





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:

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

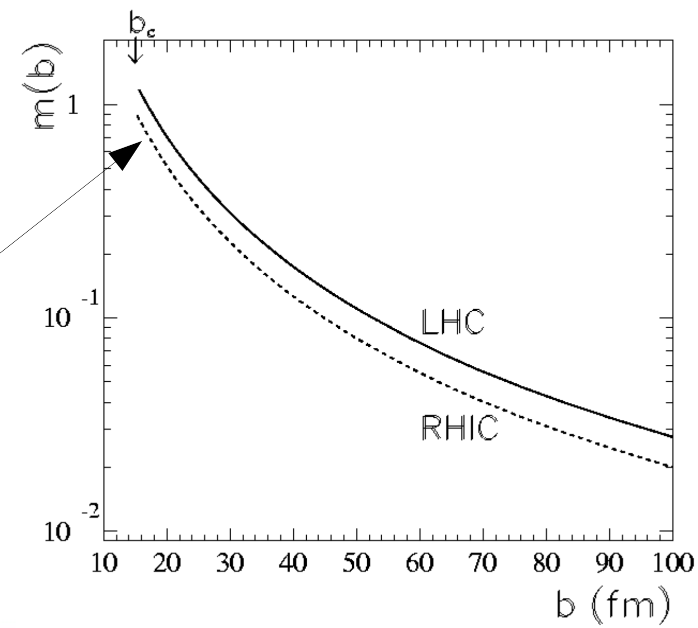
α - fine structure constant

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

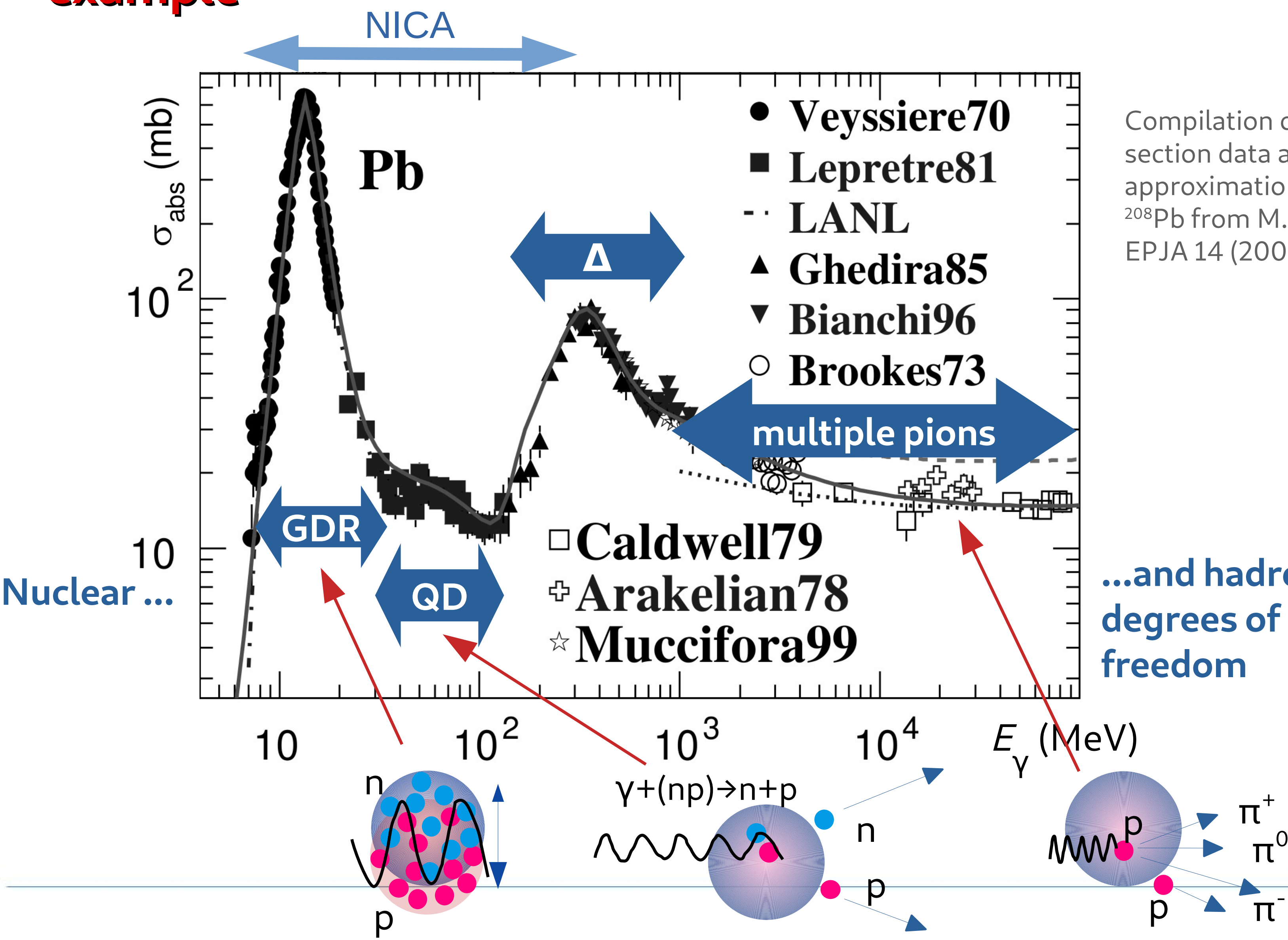
Assume that an ultrarelativitic nucleus $\gamma \gg 1$ is left in its ground state after the emission and only a small part of its kinetic energy is taken away. Together with the coherence condition this gives:

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

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

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

Various photoabsorption processes on nuclei: ^{208}Pb as an example



Compilation of cross section data and approximation for ^{208}Pb from M.V. Kossov, EPJA 14 (2002) 377

Relativistic ELectromagnetic DISsociation: RELDIS model

- 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

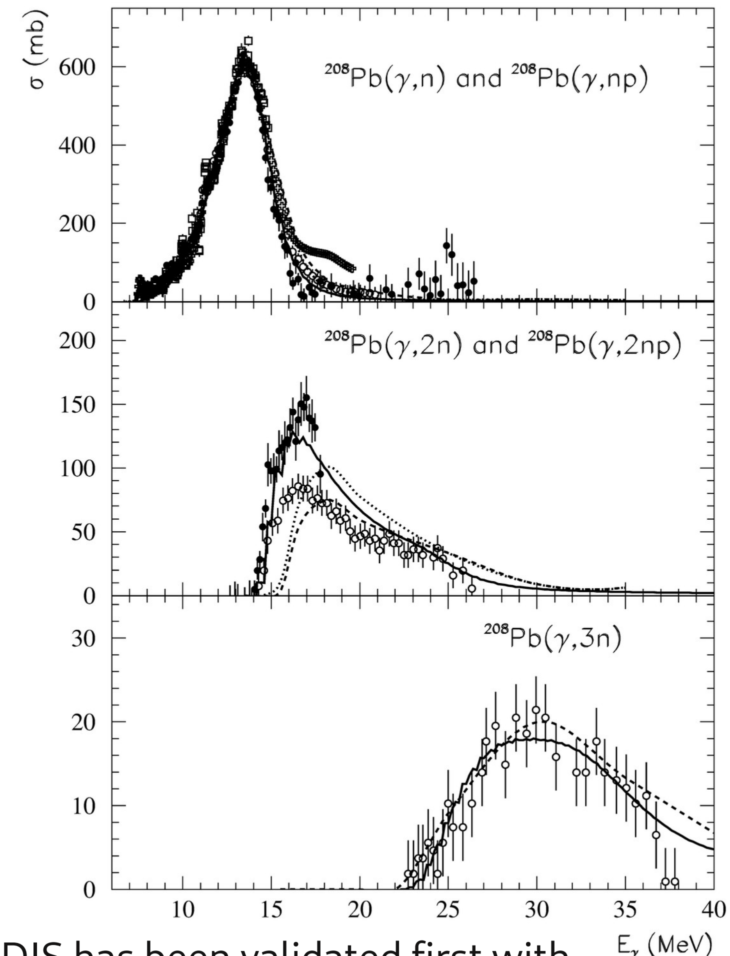
Jakob Bondorf
1933-2021

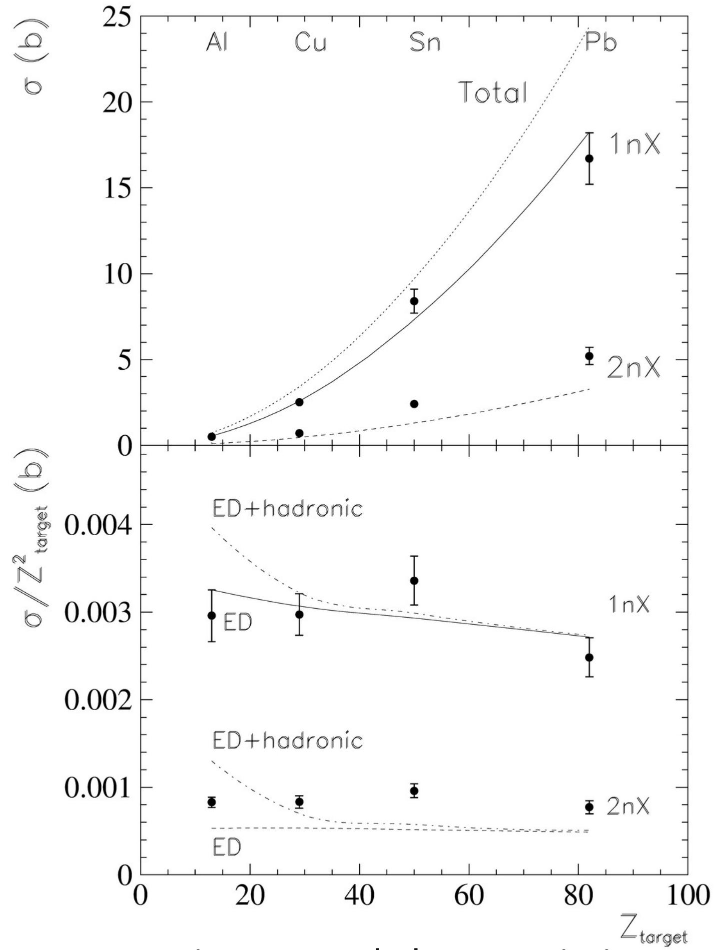
Alexander Botvina

Igor Mishustin

Igor Pshenichnov

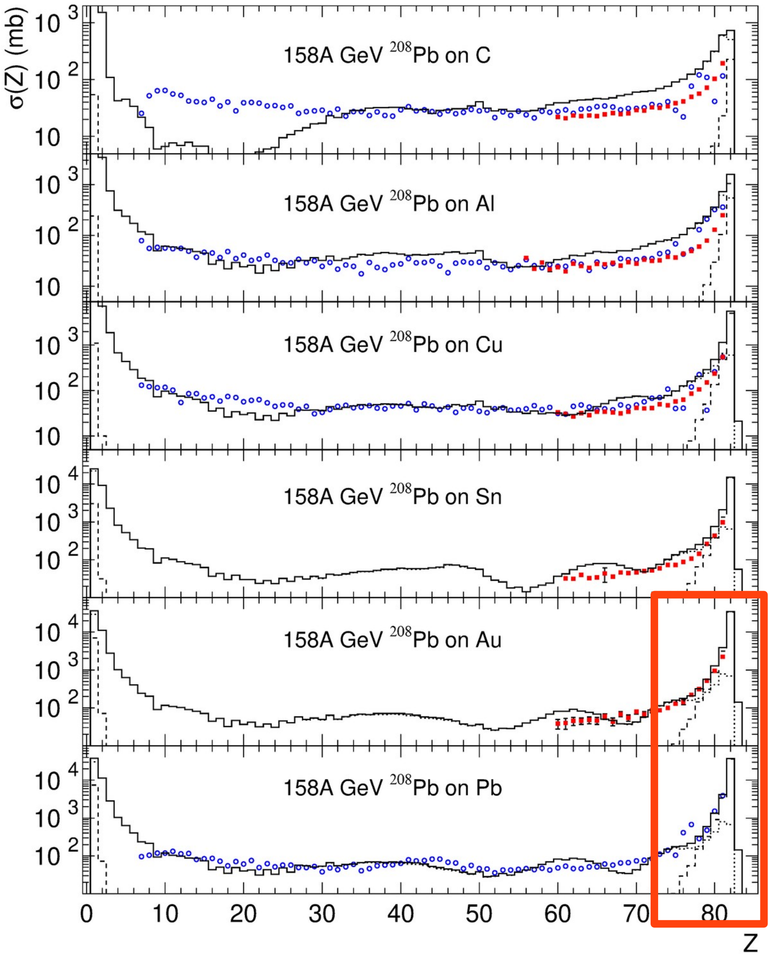
EMD of ^{208}Pb at the CERN SPS described by RELDIS



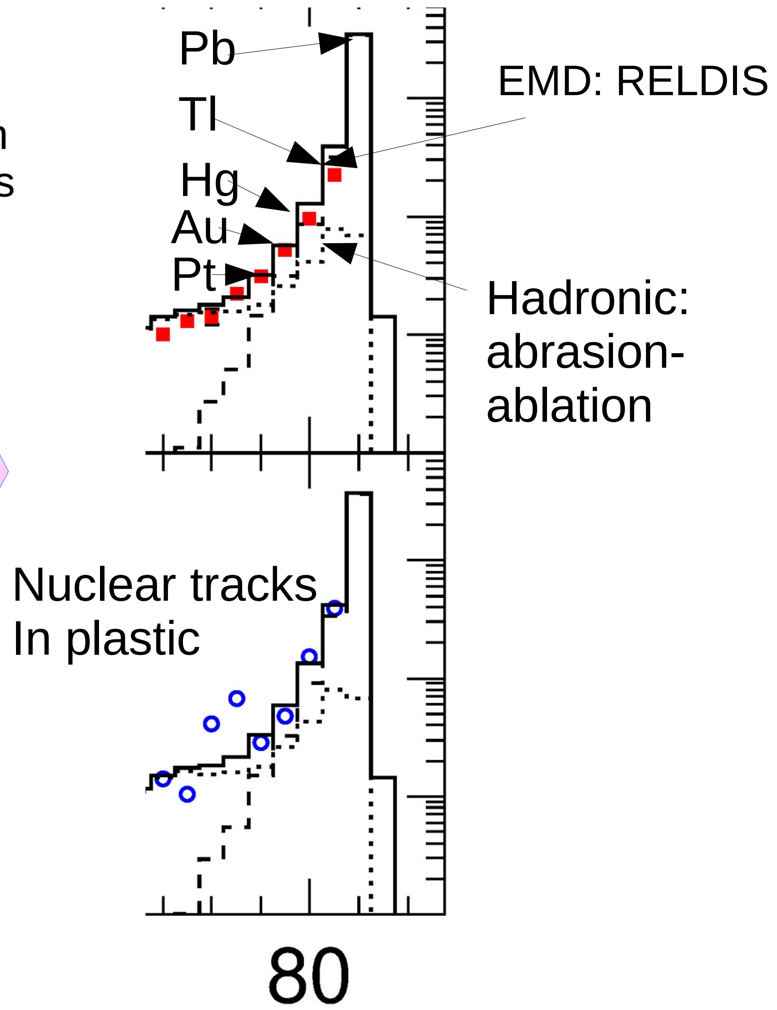


- RELDIS has been validated first with photonuclear data on 1n, 2n, 3n emission: I. Pshenichnov et al., PRC 64 (2001) 024903
- EMD cross sections reveal characteristic dependence on Z^2 of target nuclei: M.B. Golubeva et al., PRC 71 (2005) 024905

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

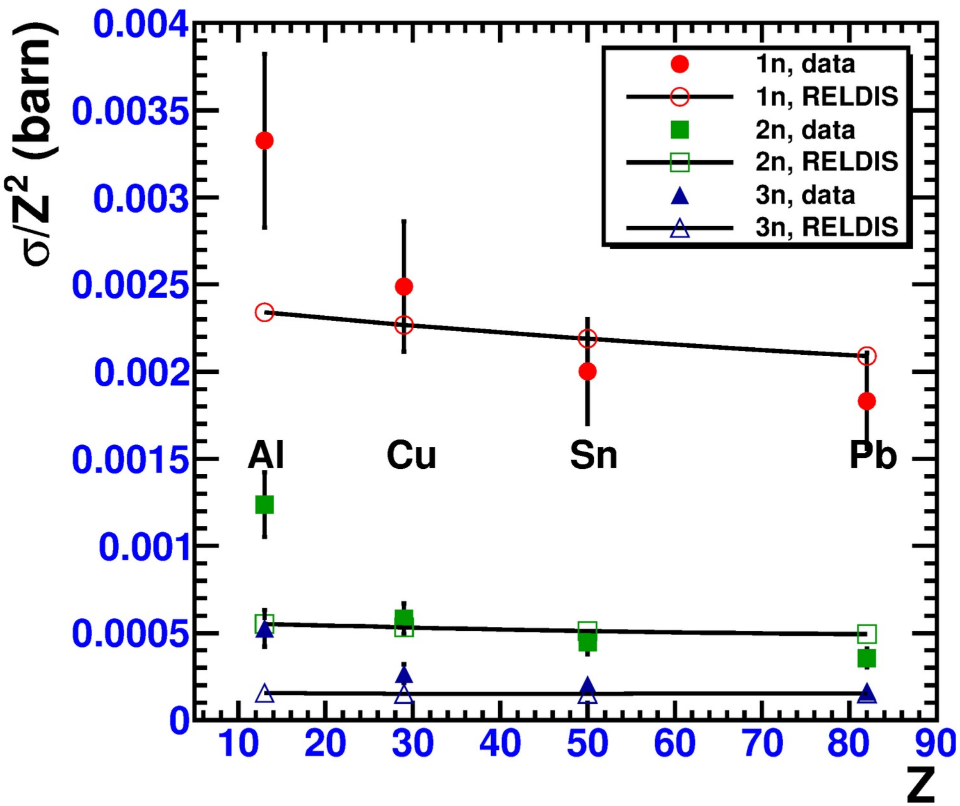


MUSIC
ionization
chambers



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

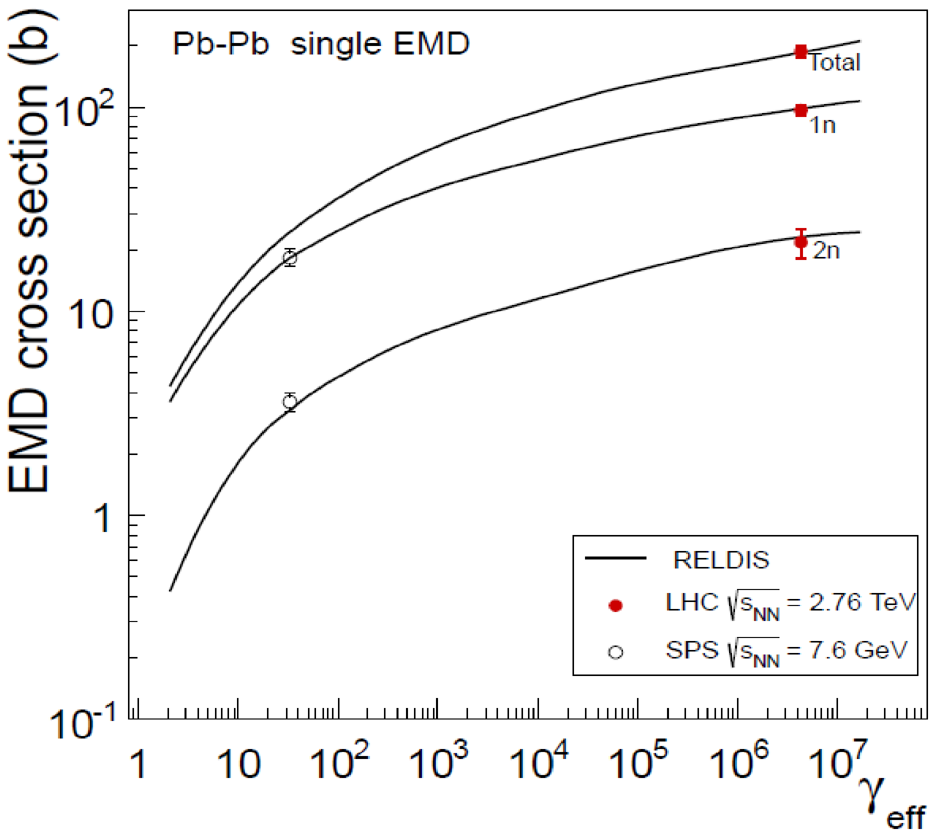
Emission of forward neutrons from ^{115}In at the CERN SPS



- 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

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



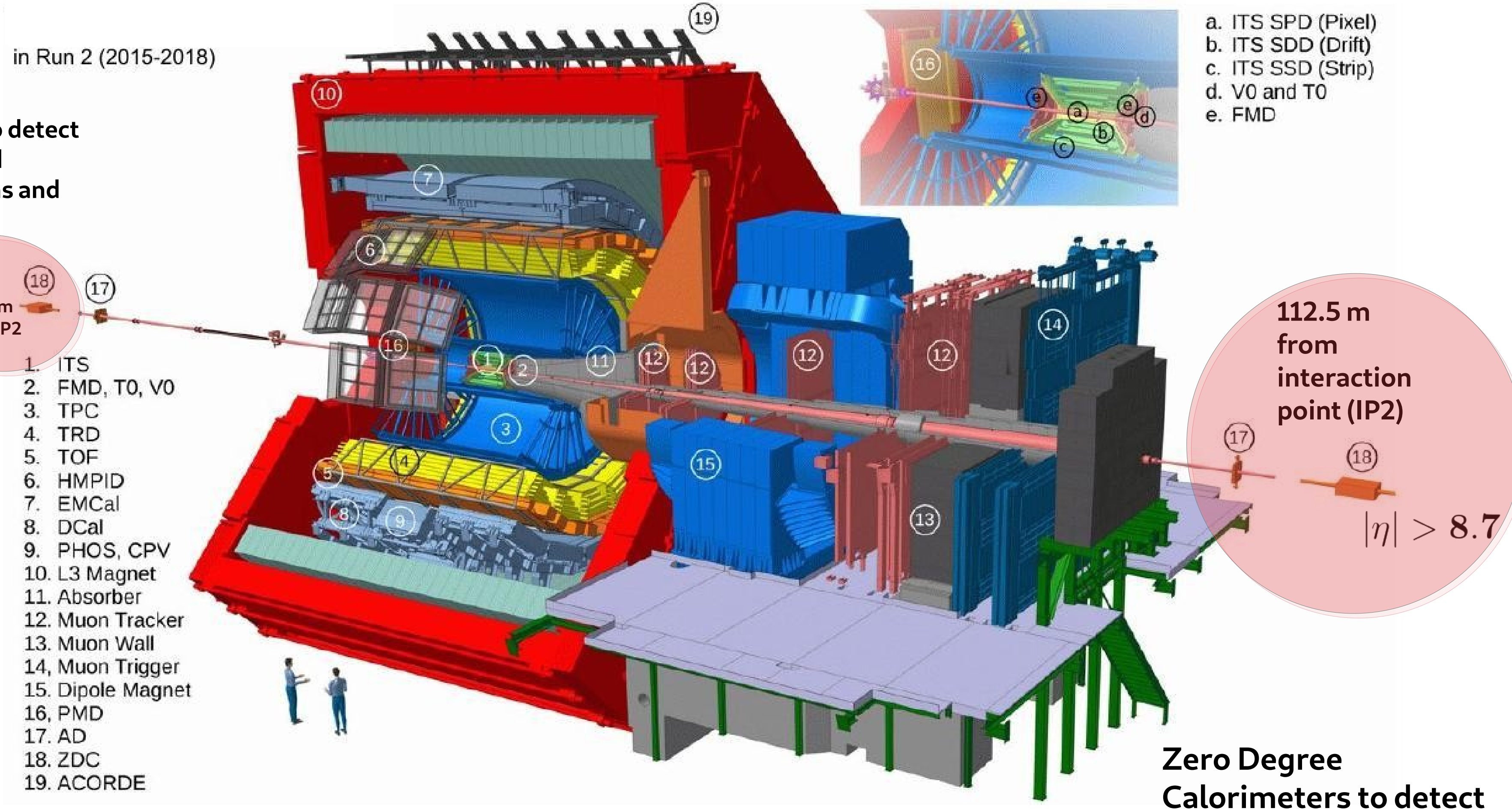
- Data are well described by RELDIS within six orders of magnitude of $\gamma_{\rm eff} = E_{\rm beam}/m_{\rm N}$ for collider $\gamma_{\rm eff} = 2\gamma_{\rm beam}^2 - 1$
- Smooth and monotonic energy dependence allows safe extrapolation of results for collisions of the same nuclei (^{208}Pb) to higher 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

The ALICE detector

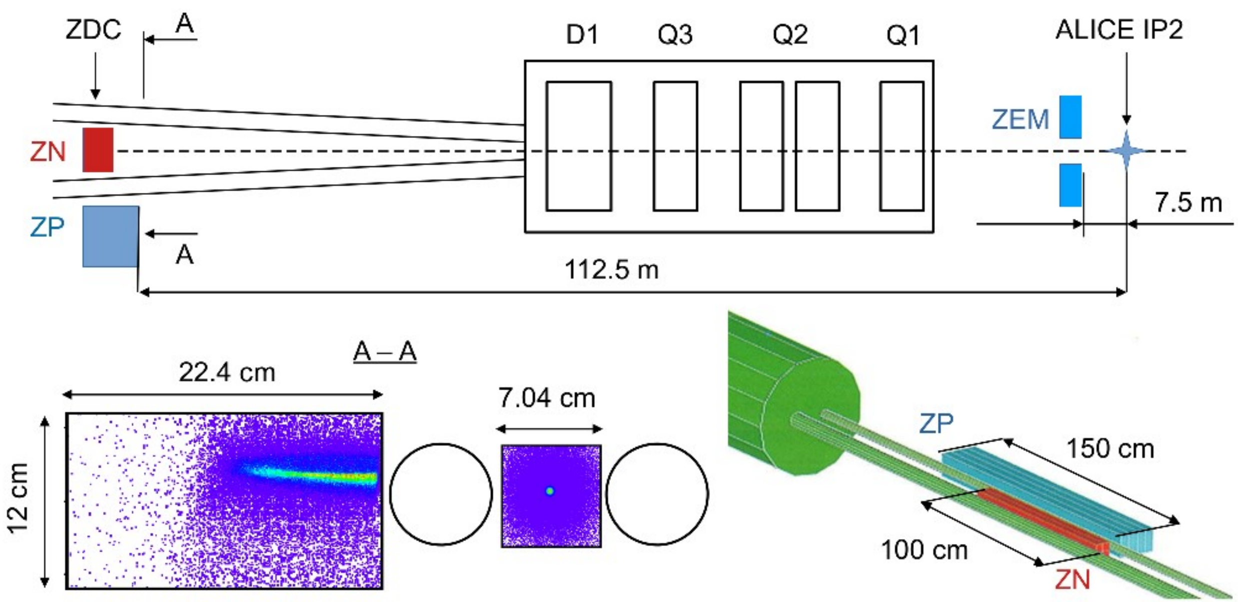
ZDCs to detect forward neutrons and protons



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)

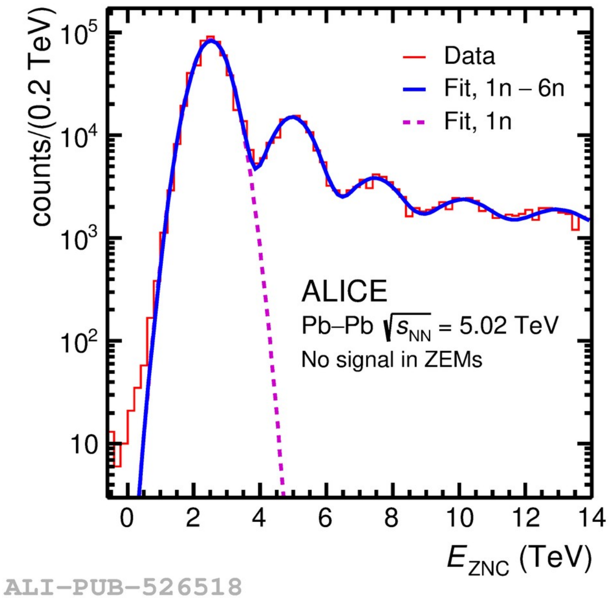
Measured distributions of the total energy of neutrons in ZDCs

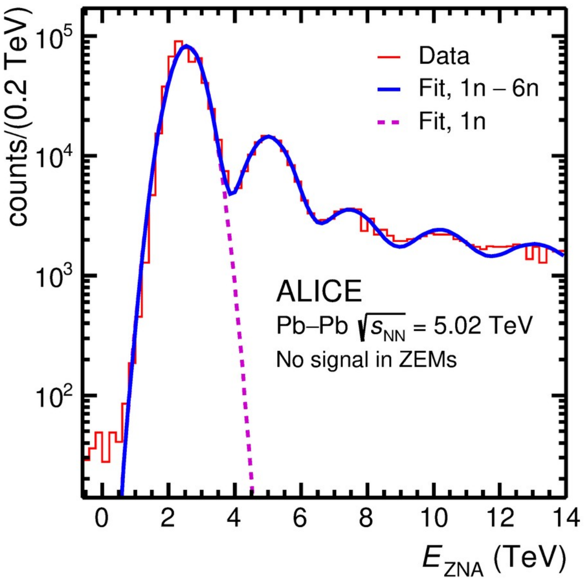
ZDC spectra are described by the **sum of Gaussians**:

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

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

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





ALICE, PRC 107 (2023) 064902

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

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

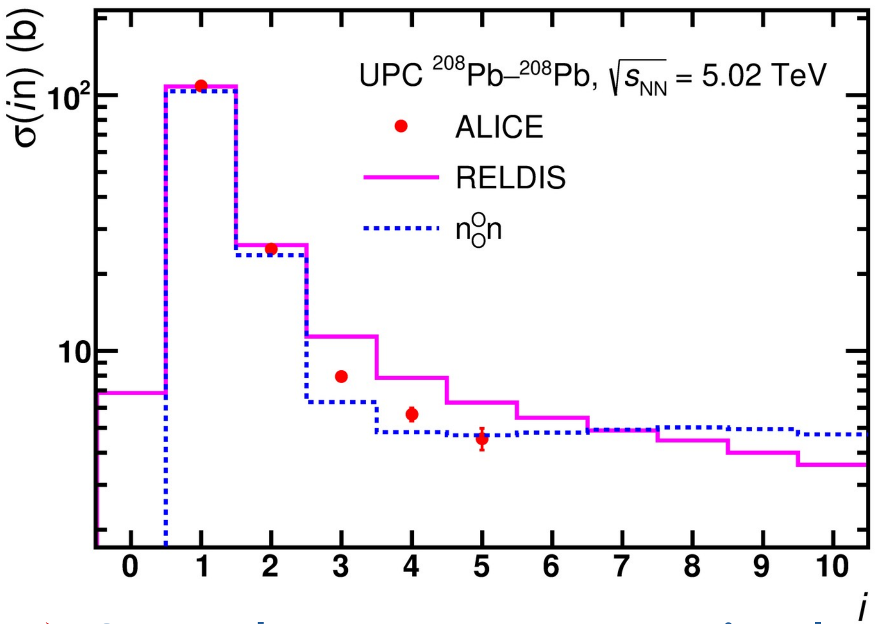
and without protons $\sigma(in, 0p) = \sigma_{\rm ZED} \frac{n_i}{N_{\rm tot}} \frac{f_{in} f_{0p}}{\varepsilon_i}$, where

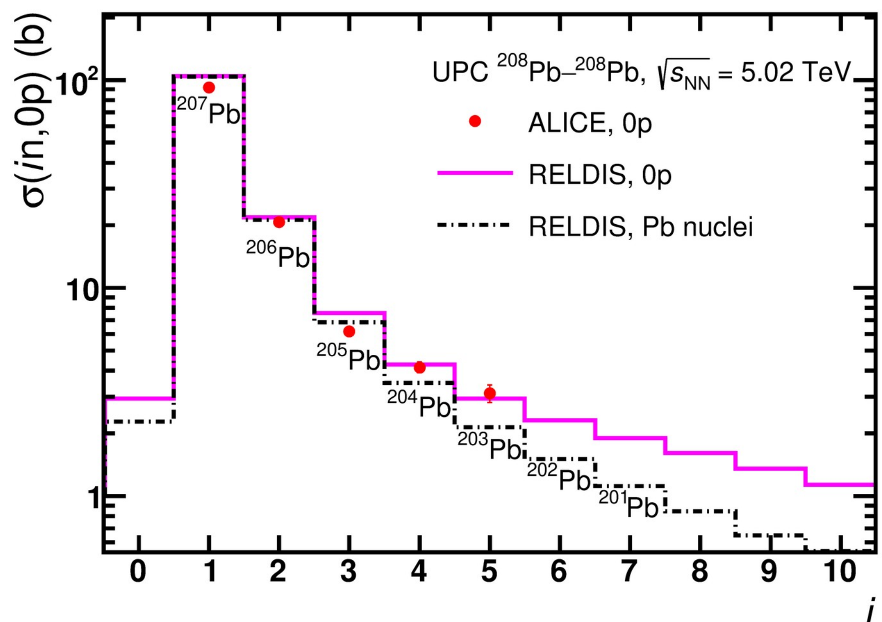
$N_{\rm tot}$ – the total number of events tagged by ZED-trigger,

$\sigma_{\rm ZED}$ *) – 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]

Neutron emission with and without protons at the LHC





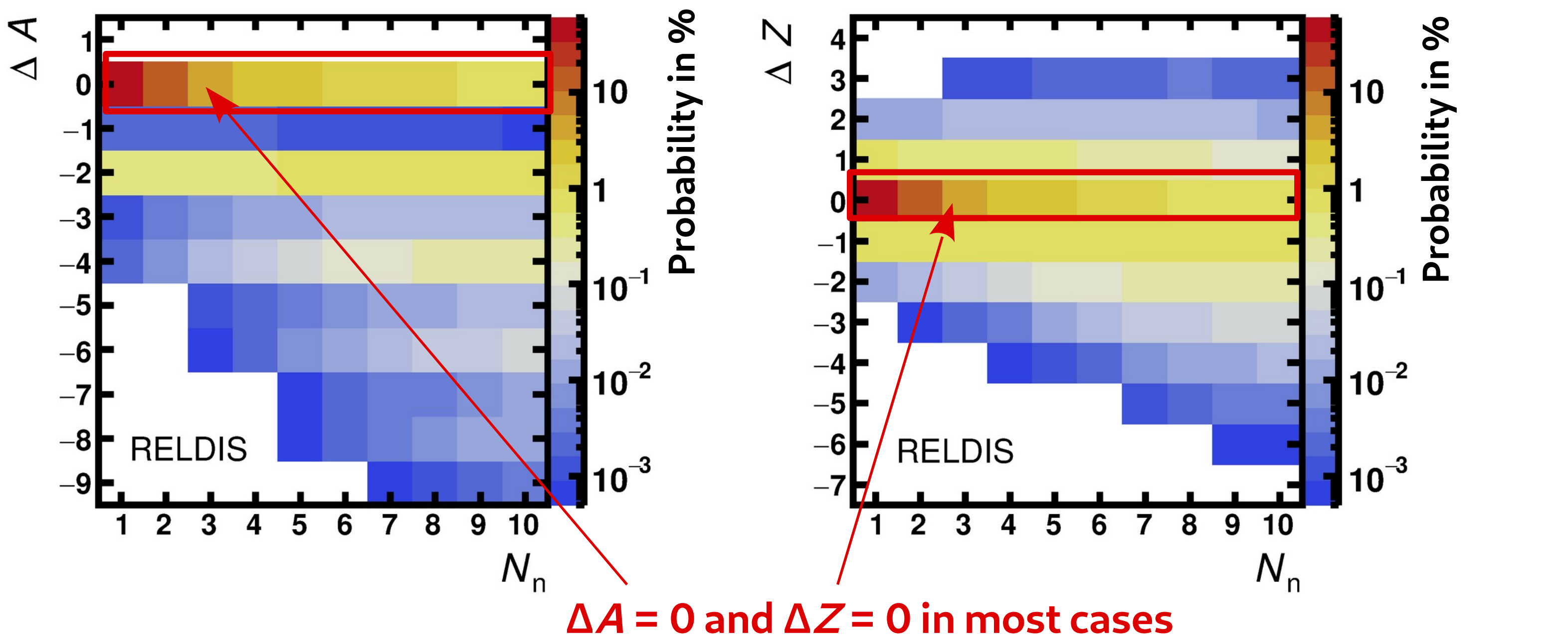
- **One and two neutrons are emitted most frequently** in UPC of ^{208}Pb
- 1n and 2n cross sections are well described by RELDIS and n_O^On models
- According to RELDIS, the cross sections to produce **^{207}Pb, ^{206}Pb, ^{205}Pb** are well approximated by **the 1n, 2n and 3n cross sections without 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^On, Comp. Phys. Comm. 253 (2020) 107181

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



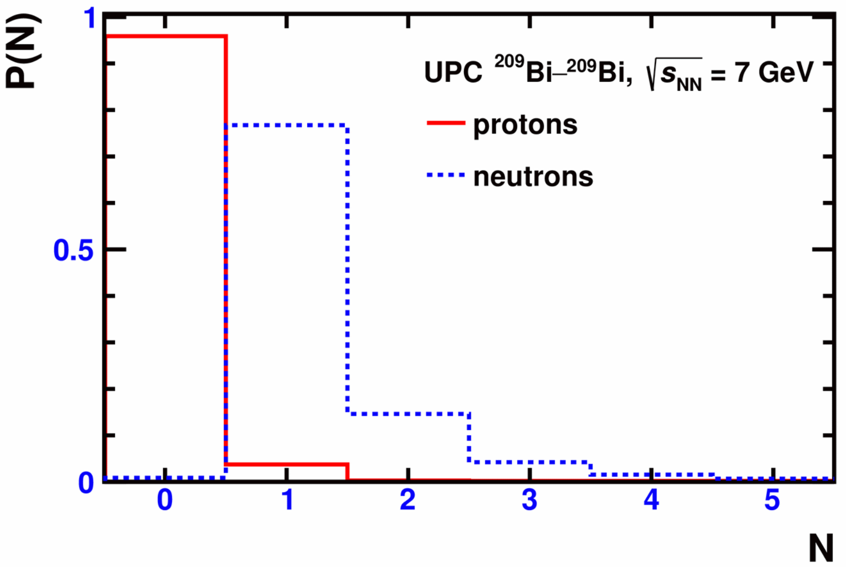
- Direct measurements of secondary nuclei at the LHC are impossible
- **The cross section of the production of a given nucleus can be well approximated by the cross section to emit the corresponding numbers of neutrons and protons**

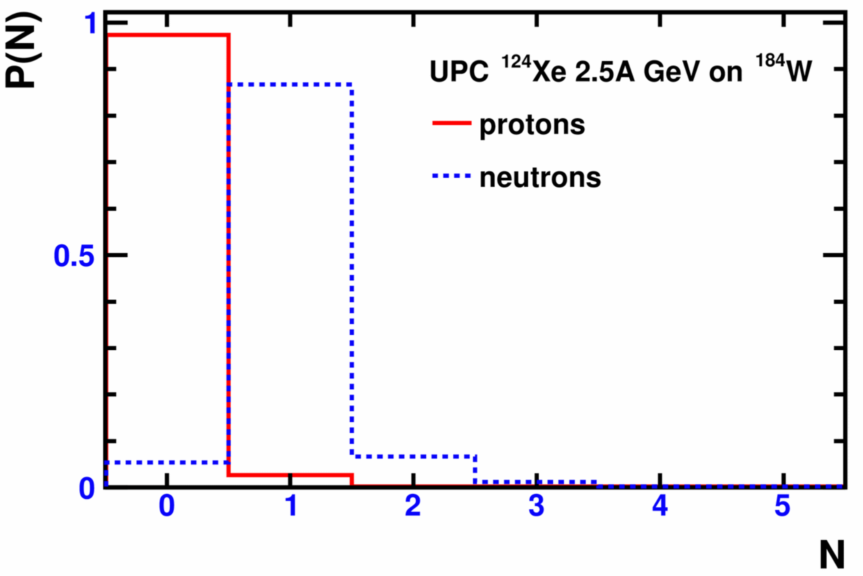
ALICE, Phys. Rev. C 107 (2023) 064902

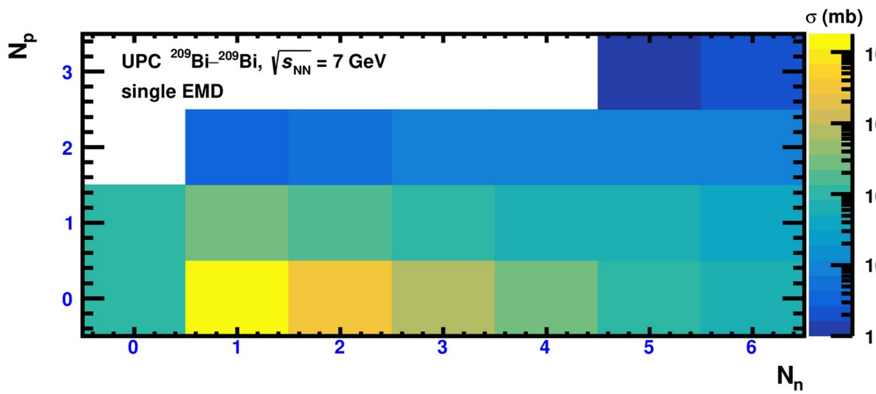
EMD in MPD experiment in collider and fixed target modes

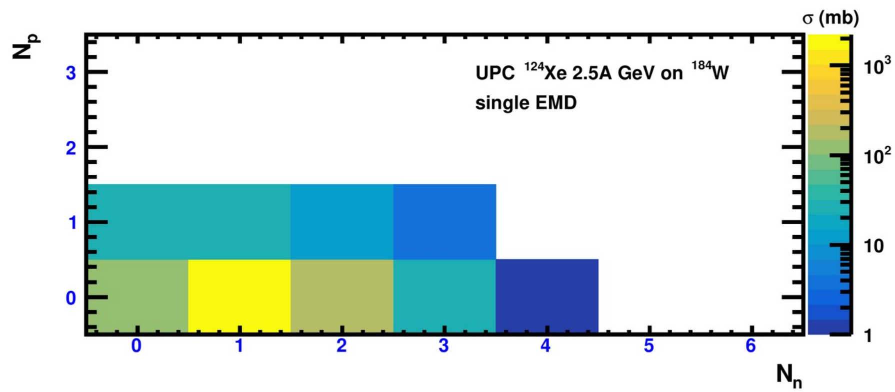
Parameter (units)	colliding nuclei	
	^{209}Bi–^{209}Bi $\sqrt{s_{NN}} = 7$ GeV	2.5A GeV ^{124}Xe–^{184}W
γ_{eff}	26.7	3.66
E_{min} (MeV)	8.	11.5
E_{max} (MeV)	**339.**	**52.**
total single dissociation σ_{sEMD} (b)	**23.8**	**2.58**
total mutual dissociation σ_{mEMD} (b)	2.1	
$\langle E^{\star}_{RN} \rangle$ (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 mode at NICA





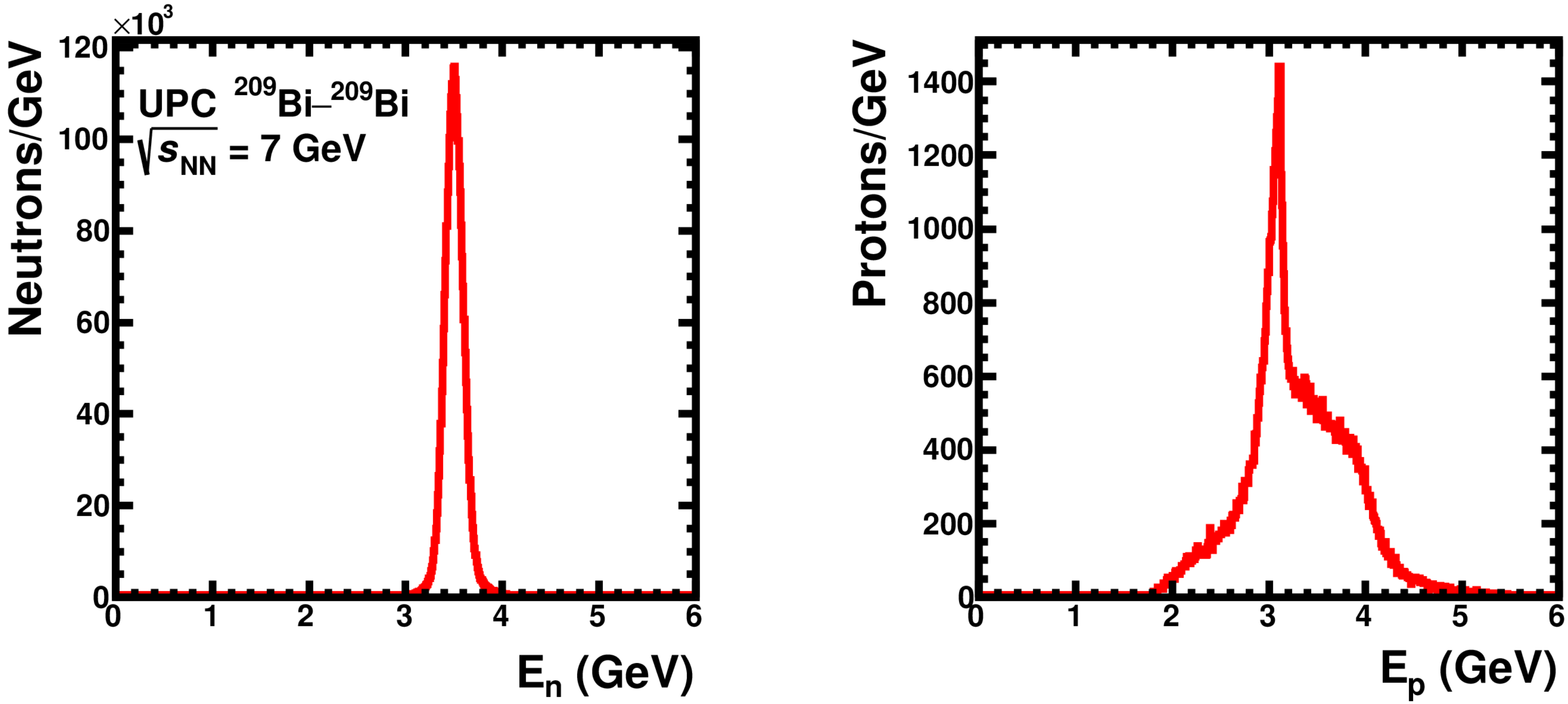




Cross sections of emission of given numbers of neutrons and protons calculated with RELDIS

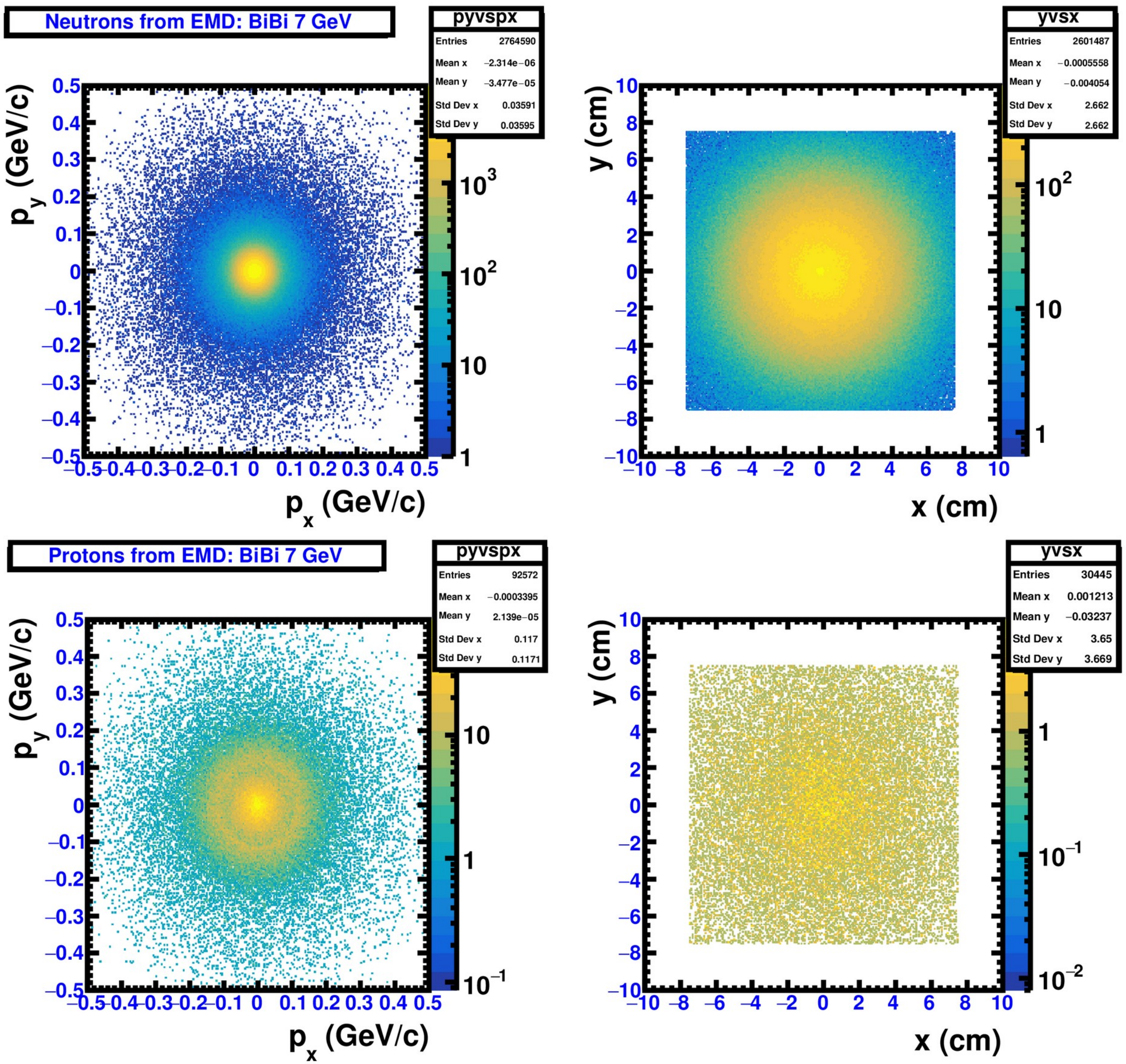
Neutron and proton multiplicity (in,kp)	single EMD cross section (b)	
	^{208}Pb–^{208}Pb $\sqrt{s_{NN}} = 7$ GeV	2.5A GeV ^{124}Xe–^{184}W
(0n,0p)	0.09	0.12
(1n,0p)	18.14	2.21
(2n,0p)	3.32	0.16
(3n,0p)	0.90	0.03
(4n,0p)	0.28	0.
(5n,0p)	0.12	0.
(6n,0p)	0.06	0.
total (Xn,0p)	**22.9**	**2.51**
(0n,1p)	0.12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

Energy distributions of neutrons and protons from EMD



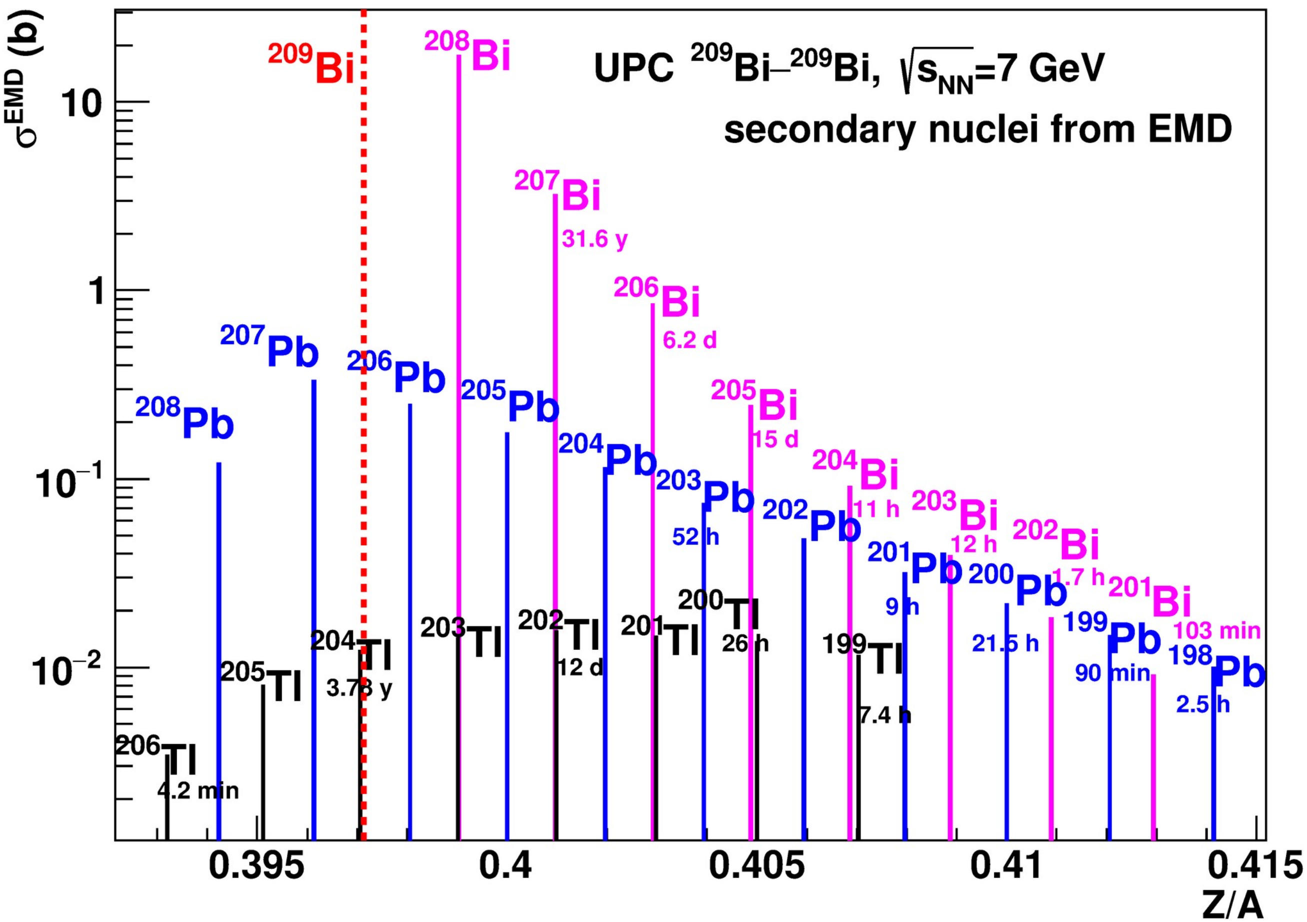
- Energy distribution of protons from EMD is much wider compared to the distribution of much more abundant neutrons.
- Neutrons are produced mostly by sequential evaporation from excited ^{209}Bi while protons are produced by more energetic photons along with other particles.

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 and the MPD trigger system in collider mode: $^{209}Bi+^{209}Bi$

- EMD events generated with RELIDIS were uploaded to ncx101 /eos/nica/mpd/sim/RELDIS along with scripts for their convertation to MCini format (thanks to Alexander Svetlichnyi)

- The impact of EMD on MPD trigger system has been studied by Viktor Ryabov (Cross-PWG Meeting 05.03.24): https://indico.jinr.ru/event/4450/#3-electromagnetic-processes-an

- Because of EMD, ^{209}Bi ions are lost from the beam three times more frequently than due to hadronic interactions

- 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)

- 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 at NICA and the MPD trigger system in fixed target mode: $^{124}Xe+^{184}W$

- EMD events generated with RELIDIS were uploaded to ncx101 /eos/nica/mpd/sim/RELDIS along with scripts for their convertation to MCini format (thanks to Alexander Svetlichnyi)
- The impact of EMD on MPD trigger system has been studied by Viktor Ryabov (Cross-PWG Meeting 19.03.24): https://indico.jinr.ru/event/4506/#4-electromagnetic-processes-an
- EMD and hadronic interactions cause comparable loses of ^{124}Xe ions
- EMD processes will contaminate very peripheral events (>90% of centrality)
- FHCAL trigger is most affected by EMD
- The analysis of very peripheral hadronic events may require extra efforts to reject the contamination of EMD events

Summary

- The measured cross sections of neutron emission in EMD of ^{208}Pb measured by ALICE at the LHC were described by RELDIS model
- Good description of data on neutron emission and charge-changing cross sections of ^{208}Pb and ^{115}In nuclei at the CERN SPS was demonstrated as well
- This gives us confidence in predicting the characteristics of EMD of ^{209}Bi at lower energy available at NICA
- In contrast to ALICE, 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

THANK YOU FOR YOUR ATTENTION!

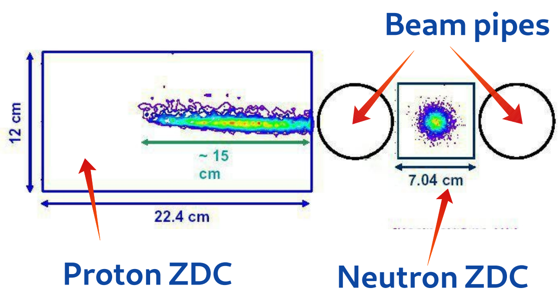
- We will be happy to provide you event files generated with RELDIS for further studies
- Please contact
  - Igor Pshenichnov (pshenich@inr.ru),
  - Alexander Svetlichnyi (aleksandr.svetlichnyy@phystech.edu)
  - Savva Savenkov (savenkov.sd@phystech.edu)

Backup slides:

more on ALICE measurements of EMD of ^{208}Pb

ALICE Collaboration, Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV.
https://doi.org/10.1103/PhysRevC.107.064902

ALICE ZDC



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

- 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 were obtained by Monte-Carlo modeling of the transport of nucleons from EMD in the ALICE setup

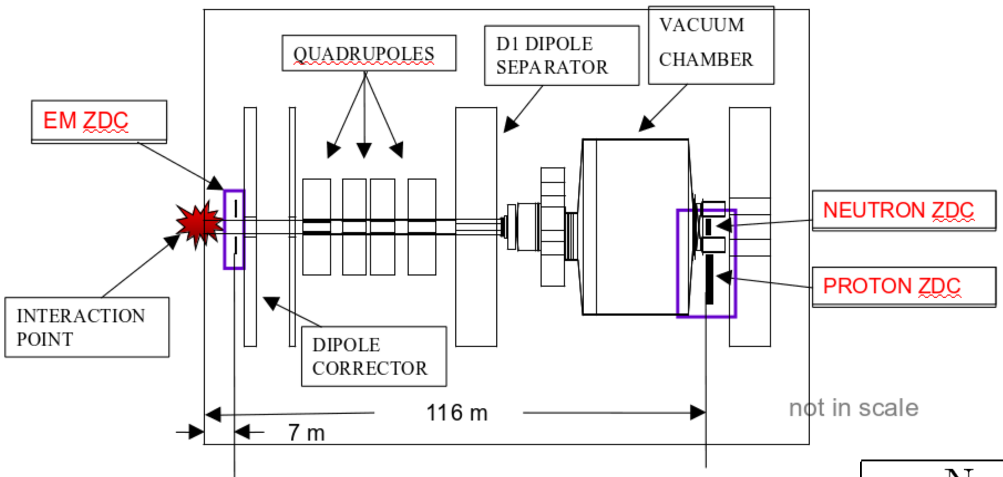
Neutron multiplicity in	Correction factor* f_{in}	
	ZNC	ZNA
0n	0.286 ± 0.126	0.302 ± 0.097
1n	1.064 ± 0.031	1.064 ± 0.030
2n	1.092 ± 0.024	1.010 ± 0.095
3n	1.057 ± 0.032	1.066 ± 0.018
4n	1.001 ± 0.046	0.962 ± 0.094
5n	0.907 ± 0.132	0.917 ± 0.104

Proton multiplicity	Correction factor* f_{0p}	
	ZPC	ZPA
0p	0.848 ± 0.015	0.852 ± 0.018

*) correction factor = 1/efficiency

Selecting electromagnetic events in ALICE

M. Gallio, Joint LHC Machine-Experiment Workshop, 25 January 2007



ZDCs are supplemented by two ZEM calorimeters at 7 m only on the side A: $4.8 < \eta < 5.7$

- **ZEMs are sensitive to > 92 % of hadronic events**
- **No signals in ZEMs in > 99 % of EMD events**

Neutron multiplicity in	efficiency of ZEM veto ε_i (%)	
	Side C	Side A
1n	99.875 ± 0.005	99.902 ± 0.005
2n	99.766 ± 0.014	99.819 ± 0.013
3n	99.457 ± 0.039	99.349 ± 0.042
4n	99.479 ± 0.043	99.321 ± 0.049
5n	99.368 ± 0.050	99.025 ± 0.064
total 1n–5n	99.802 ± 0.005	99.806 ± 0.005
total Xn	96.722 ± 0.017	96.117 ± 0.019

Corrections for ZDC efficiency to detect multinucleon events

- The numbers of initial/true events N_i and detected events n_i of a given multiplicity i are connected by means of a triangular transformation matrix P:

$$\begin{pmatrix} n_0 \\ n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \end{pmatrix} = \begin{pmatrix} p_{00} & p_{01} & p_{02} & p_{03} & p_{04} & p_{05} \\ 0 & p_{11} & p_{12} & p_{13} & p_{14} & p_{15} \\ 0 & 0 & p_{22} & p_{23} & p_{24} & p_{25} \\ 0 & 0 & 0 & p_{33} & p_{34} & p_{35} \\ 0 & 0 & 0 & 0 & p_{44} & p_{45} \\ 0 & 0 & 0 & 0 & 0 & p_{55} \end{pmatrix} \begin{pmatrix} N_0 \\ N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_5 \end{pmatrix} = P \begin{pmatrix} N_0 \\ N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_5 \end{pmatrix}$$

- In a simple probabilistic model with p defined as a probability to detect a nucleon: $p_{nk} = \binom{n}{k} p^k (1-p)^{n-k}$,
- In more detailed calculations files of events were generated with RELDIS and then nucleons were transported to ZDC by Monte Carlo transport with ALIRoot
- Correction factors were calculated from the numbers of detected events obtained with ALIRoot modeling

U. Dmitrieva, I. Pshenichnov, NIM **A 906** (2018) 114
https://doi.org/10.1016/j.nima.2018.07.072

Neutron emission cross sections measured by ALICE

ZN	$\sigma(in)$ (b)		$\sigma(in)$ (b)	$\sigma^{\mathrm{RELDIS}}(in)$ (b)	$\sigma^{\mathrm{nOn}}(in)$ (b)
	Side C	Side A			
1n	$109.7 \pm 0.1 \pm 4.0$	$107.2 \pm 0.1 \pm 4.0$	$108.4 \pm 0.1 \pm 3.7$	108.0 ± 5.4	103.7 ± 2.1
2n	$25.8 \pm 0.1 \pm 0.8$	$24.1 \pm 0.1 \pm 2.3$	$25.0 \pm 0.1 \pm 1.3$	25.9 ± 1.3	23.6 ± 0.5
3n	$7.97 \pm 0.07 \pm 0.32$	$7.94 \pm 0.04 \pm 0.24$	$7.95 \pm 0.04 \pm 0.23$	11.4 ± 0.6	6.3 ± 0.1
4n	$5.73 \pm 0.04 \pm 0.30$	$5.56 \pm 0.04 \pm 0.56$	$5.65 \pm 0.03 \pm 0.33$	7.8 ± 0.4	4.8 ± 0.1
5n	$4.61 \pm 0.04 \pm 0.68$	$4.47 \pm 0.04 \pm 0.52$	$4.54 \pm 0.03 \pm 0.44$	6.3 ± 0.3	4.7 ± 0.1
1n–5n			$151.5 \pm 0.2 \pm 4.6$	159.8 ± 5.6	143.1 ± 2.2

ZN	ZP	$\sigma(in, 0p)$ (b)		$\sigma(in, 0p)$ (b)	$\sigma^{\mathrm{RELDIS}}(in, 0p)$ (b)
		Side C	Side A		
1n	0p	$92.6 \pm 0.1 \pm 3.8$	$90.9 \pm 0.1 \pm 3.9$	$91.8 \pm 0.1 \pm 3.3$	104.1 ± 5.2
2n		$21.4 \pm 0.1 \pm 0.8$	$20.0 \pm 0.1 \pm 2.0$	$20.7 \pm 0.1 \pm 1.1$	21.9 ± 1.1
3n		$6.14 \pm 0.07 \pm 0.27$	$6.21 \pm 0.04 \pm 0.23$	$6.17 \pm 0.04 \pm 0.20$	7.59 ± 0.38
4n		$4.21 \pm 0.04 \pm 0.23$	$4.08 \pm 0.04 \pm 0.42$	$4.15 \pm 0.03 \pm 0.25$	4.29 ± 0.22
5n		$3.16 \pm 0.04 \pm 0.47$	$3.08 \pm 0.03 \pm 0.36$	$3.12 \pm 0.03 \pm 0.30$	2.95 ± 0.15
1n–5n				$126.0 \pm 0.2 \pm 4.0$	140.8 ± 5.3

Good agreement between C and A sides for both kinds of cross sections

ALICE Collaboration, Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV.
https://doi.org/10.1103/PhysRevC.107.064902

Motivation to measure proton emission in EMD

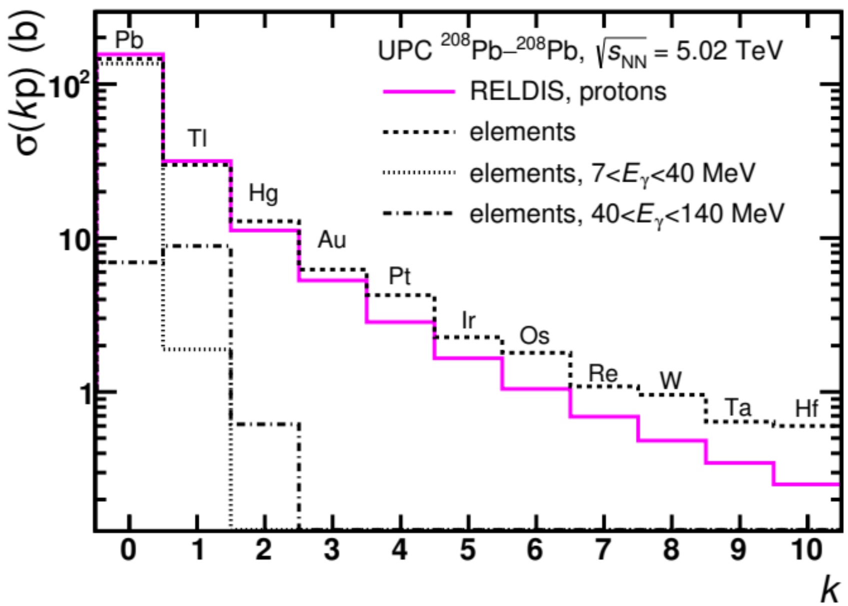
- **Recent ALICE results**: "Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV", Phys. Rev. C 107 (2023) 064902, https://doi.org/10.1103/PhysRevC.107.064902
- Different EMD models can be tested/validated with these data, in particular, RELDIS [1)] and nOOn [2)]
- **EMD with protons has not been studied yet**
- Together with the bound-free e+e- pair production[3)],EMD results in the production of secondary ions with their charge-to-mass ratio different from those of beam ions

EMD cross sections can:

  - be used **for evaluating the impact of secondary nuclei** on the LHC components
  - provide **input** for the design of the **Future Circular Collider** [4)] (FCC-hh)

1) I. Pshenichnov, Phys. Part. Nucl. **42** (2011) 215
2) M. Broz et al., Comp. Phys. Com. **253** 107181 (2020)
3) M. Schaumann et al., Phys. Rev. Accel. Beams **23** (2020) 121003
4) M. Schaumann, Phys. Rev. ST Accel. Beams **18** (2015) 091002

RELDIS: proton emission accompanied by any number of neutrons

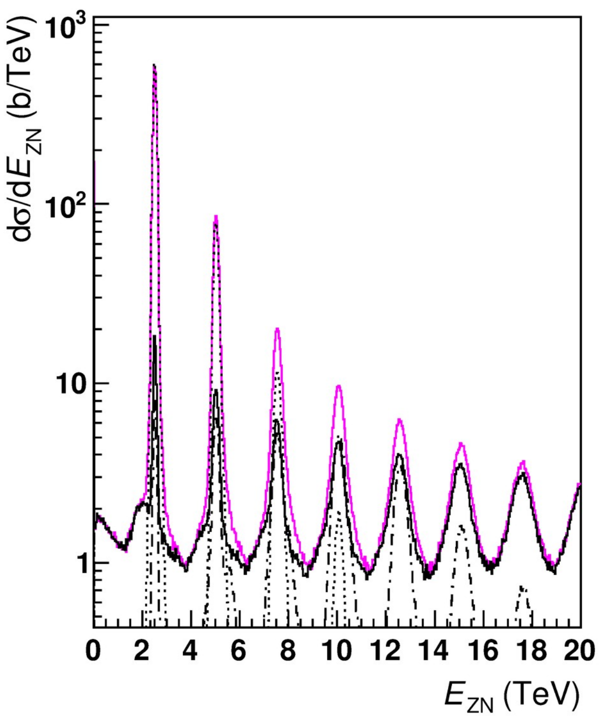


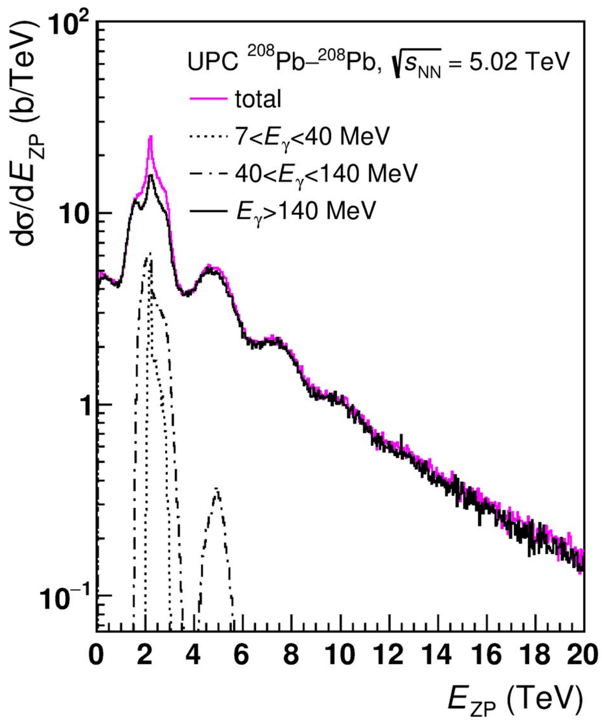
- Cross sections of emission of a given number of protons predicted by RELDIS are compared to the cross sections of the production of corresponding secondary nuclei at the LHC
- A single heavy residue nucleus is produced in EMD due to low excitation energies of a ^{208}Pb nucleus

- It is possible to estimate the cross sections of production of corresponding elements by measuring the cross sections of the emission of a certain number of protons
- Contributions of photons of different energies are shown as explained in the legend *)

*) U.Dmitrieva, I.Pshenichnov, PEPAN Letters, **20** (2023) 5

Distributions of the total energy of neutrons and protons from EMD calculated with RELDIS





without accounting for the energy resolution and efficiency of ZDCs

Proton peaks are much wider in comparison to neutron peaks, that makes difficult to measure the EMD cross sections other than 1p, 2p and 3p

Contributions of photons of different energies are shown as explained in the legend *)

*) U.Dmitrieva, I.Pshenichnov, PEPAN Letters, **20 (**2023) 5

Summary of ALICE results and future plans

- The cross sections of emission of given numbers of neutrons in UPC of ^{208}Pb nuclei at $\sqrt{s_{NN}}$ = 5.02 TeV were measured with ALICE neutron ZDCs
- The cross sections for the emission of 1 – 5 forward neutrons in UPC, not accompanied by protons were measured for the first time. They mostly correspond to the production of ^{207,206,205,204,203}Pb
- The measured 1n and 2n cross sections are described by available EMD models, but there is a room for improvement of the models in describing 3n and 4n emission
- The obtained cross sections can be used for evaluating the impact of secondary nuclei on the LHC components, in particular, on superconducting magnets, and also provide useful input for the design of the Future Circular Collider (FCC-hh)
- Next step: to measure cross sections of proton emission with ALICE proton ZDCs