A Large Ion Collider Experiment

ALICE

ALICE MEASUREMENTS OF FORWARD NEUTRONS IN ULTRAPERIPHERAL PB-PB COLLISIONS

Igor Pshenichnov for the ALICE collaboration

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Preface

- Many thanks for the invitation to present recent results of ALICE* on measurements of (very) forward neutrons emitted in ultraperipheral Pb–Pb collisions.
- The electromagnetic dissociation (EMD) of nuclei is mainly a soft-physics process of nuclear disintegration induced by low-energy photons.
- This topic supplements the studies of QCD, hadron structure, search for BSM particles with very forward detectors in pp collisions discussed at the LHC forward meetings.
- We would like to share with you:
  - our experience with ALICE ZDCs installed in the LHC tunnel far from the IP
  - dedicated methods to correct for the ZDC efficiency in multineutron events
  - validation of EMD models for their application in future projects like FCC-hh, HE-LHC, in particular, concerning the impact of EMD on collider operation

*) ALICE Collab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV.
arXiv:2209.04250 [nucl-ex]

Outline

- The motivation to conduct the measurements
- Introduction to EMD physics
- ALICE neutron (ZNC and ZNA) and proton (ZPC and ZPA) forward calorimeters to detect spectator nucleons from hadronic nucleus-nucleus collisions and nucleons from EMD of nuclei
- Two compact electromagnetic calorimeters, ZEM1 and ZEM2, to distinguish hadronic collisions and EMD of nuclei
- Corrections for the efficiency of these detectors
- Measured cross sections of the emission of 1, 2, 3, 4 and 5 neutrons in EMD of ^{208}Pb
- Measured 1n – 5n cross sections without proton emission and their relation to the production of ^{207,206,205,204,203}Pb as secondary nuclei in colliders
- Model predictions for proton emission in EMD and future work

Motivation of the ALICE measurements:

- Collect data for EMD of nuclei at the highest collision energy available in accelerator experiments.
- Several EMD models can be tested/validated with these data:
  - RELDIS: I. P., Phys. Part. Nucl. 42, 215 (2011)
  - Krakow model: M. Klusec-Gawenda et al., PRC 94 (2014) 054907
  - n_O^On, M. Broz et al., Comp. Phys. Com. p. 107181 (2020)
- Estimate the production of residual nuclei left after the emission of several neutrons and zero protons from ^{208}Pb in EMD:
  - ^{207}Pb, ^{206}Pb create heat load on LHC components: R. Bruce et al., Phys. Rev. ST 12 (2009) 071002; P.D. Hermes et al., NIM A 819 (2016) 73
  - Data can be extrapolated in collision energy for modelling HE-LHC or FCC-hh

Secondary ions in UPC at LHC: BFPP and EMD

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- Bound-free e^+e^- pair production (BFPP) (~270 b):
  $^{208}Pb^{82+} + {}^{208}Pb^{82+} \rightarrow ({}^{208}Pb+e^-_{1s,2s,2p(1/2)2p(2/3),3s})^{81+} + {}^{208}Pb^{82+} + e^+$

- Electromagnetic dissociation:
  $^{208}Pb^{82+} + {}^{208}Pb^{82+} \rightarrow {}^{208}Pb^{82+} + {}^{207}Pb^{82+} + n$ (~100 b)
  $\rightarrow {}^{208}Pb^{82+} + {}^{206}Pb^{82+} + 2n$ (~ 20 b)
  $\rightarrow {}^{208}Pb^{82+} + {}^{205}Pb^{82+} + 3n$ (~ 6 b)
  $\rightarrow$ several other channels, e.g., with proton emission

- Both BFPP and EMD change the momentum per unit charge, the magnetic rigidity: $p/Ze=Br$, where r is the bending radius in the magnetic field B of the LHC.
- $Br \rightarrow Br\,(1+d)$ as a result of UPC with $A_0 \rightarrow A$, $Z_0 \rightarrow Z$

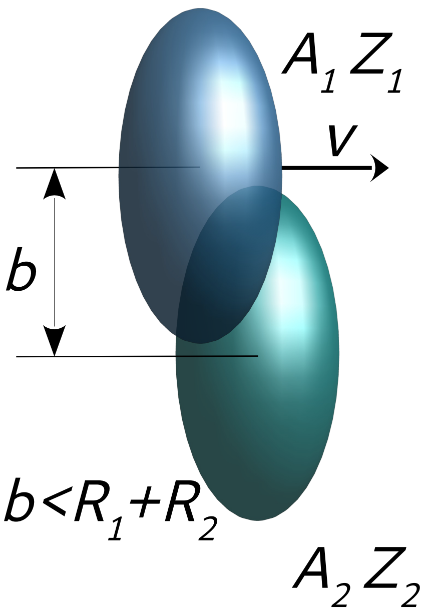
$$\delta = \frac{Z_0}{A_0}\frac{A}{Z} - 1$$

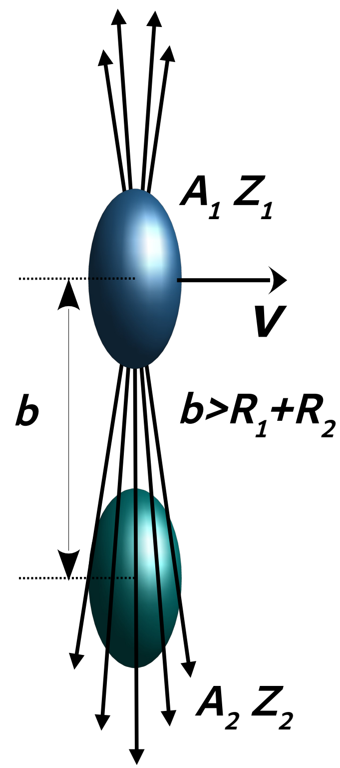
R. Bruce et al., Phys. Rev. ST Accel. Beams **12** (2009) 071002
C. Bahamonde Castro et al., TUPMW006, Proc. of IPAC2016, Busan, Korea
J.M. Jowett et al.,TUPMW028, Proc. of IPAC2016, Busan, Korea
P.D. Hermes et al., Nucl. Instr & Meth. A **819** (2016) 73

The production of secondary nuclei in EMD at the LHC should be addressed.

Ultraperipheral collisions (UPC)

- In UPC nuclei do not overlap in contrast to hadronic nucleus-nucleus collisions





Impact of Coulomb fields: equivalent photons

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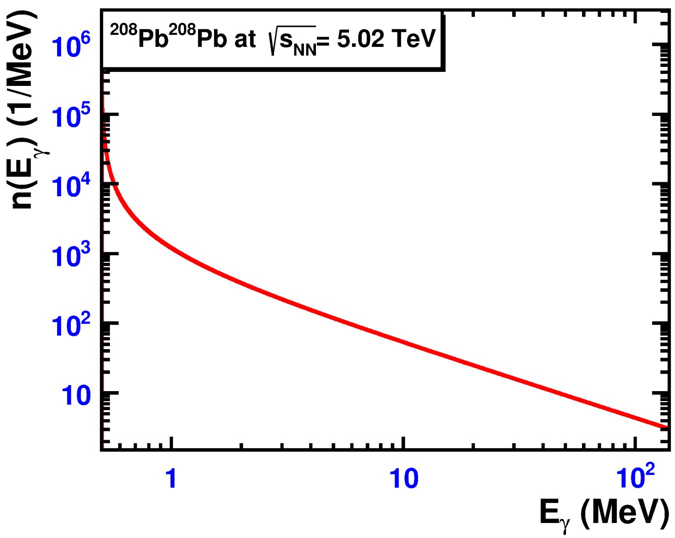
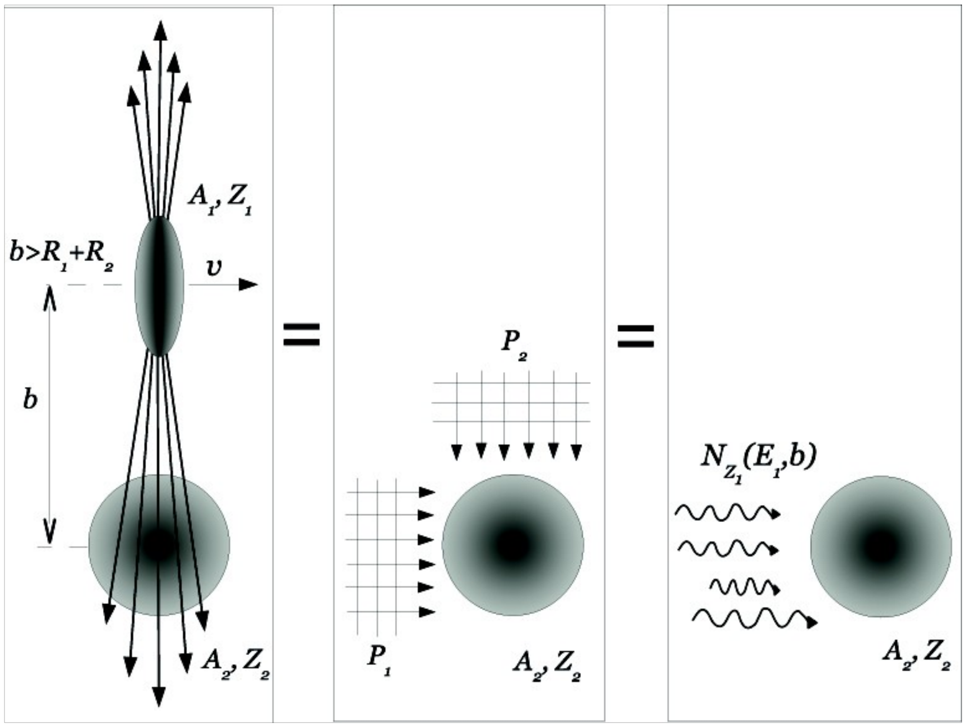
Following the Weizsäcker–Williams method the impact of the Coulomb field of the nucleus A_1 on A_2 can be represented as the absorption of one or more equivalent photons by the target nucleus A_2.



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

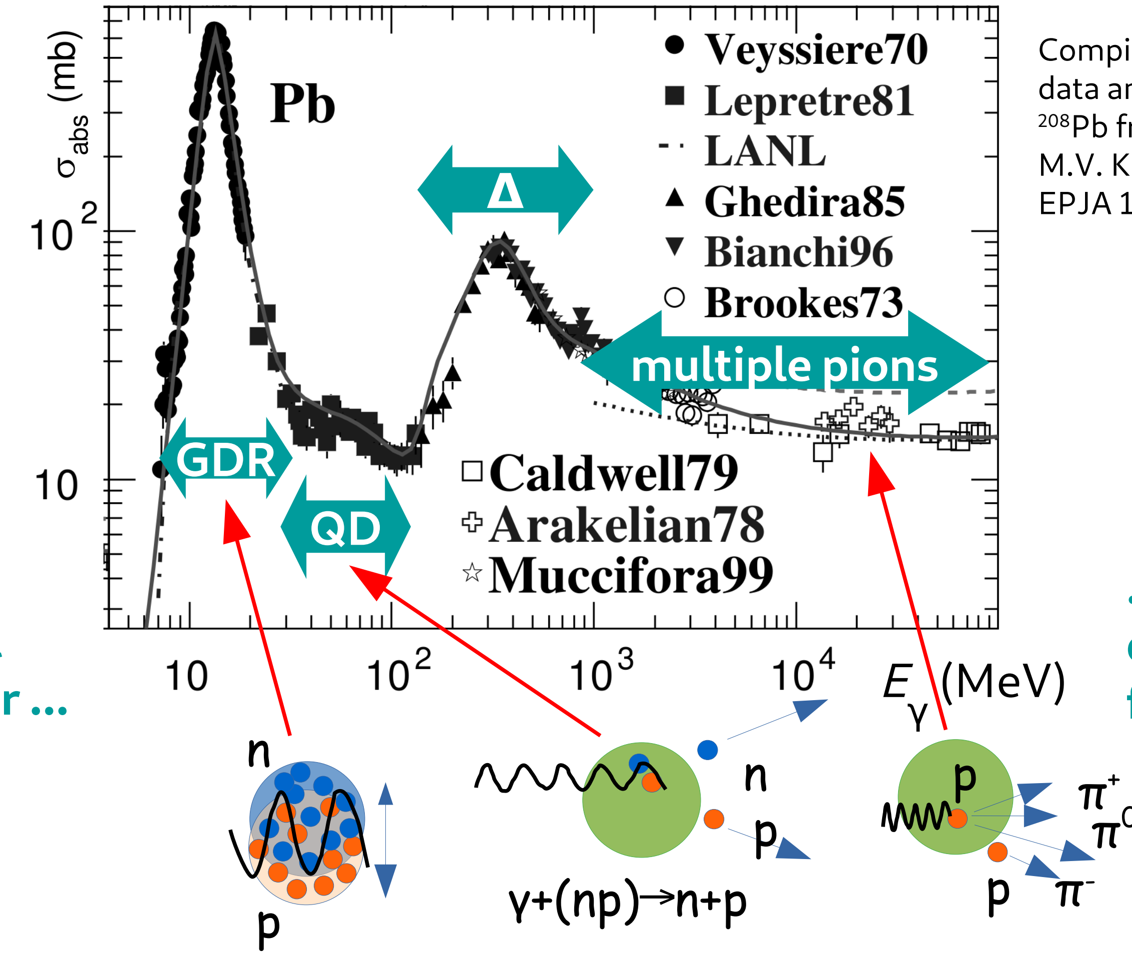


The spectrum of equivalent photons from a ultrarelativistic nucleus $(\gamma >> 1)$ with charge Z_1 is calculated as:

$$n(E_\gamma) = \frac{2\alpha Z_1^2}{\pi E_\gamma}\left(\mathrm{x}K_0(\mathrm{x})K_1(\mathrm{x}) - \frac{\mathrm{x}^2}{2}(K_1^2(\mathrm{x}) - K_0^2(\mathrm{x}))\right),$$

$$\mathrm{x} = \omega b/\gamma v = E_\gamma b/\gamma$$

Various processes of photon absorption by ^{208}Pb



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

Global nuclear …

… and hadronic degrees of freedom

A moderately exited residual nucleus is created after the emission of fast hadrons. It is likely to be de-excited by evaporating neutrons.

RELDIS: various residual nuclei are produced

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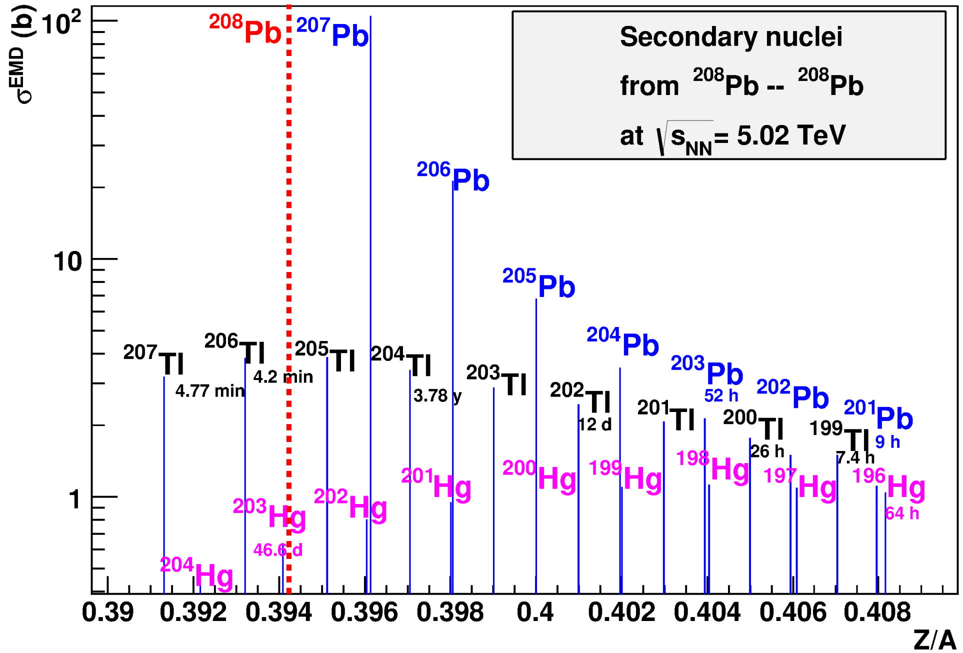
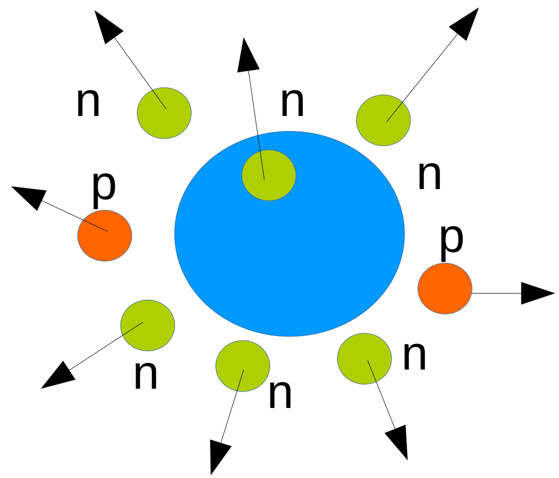


I.A. Pshenichnov et al.,
Bull. Russ. Acad. Sci.: Phys.
84 (2020) 1007



A kind of photospallation of ^{208}Pb ...

According to RELDIS in most of EMD events a single residual nucleus is produced along with free nucleons.

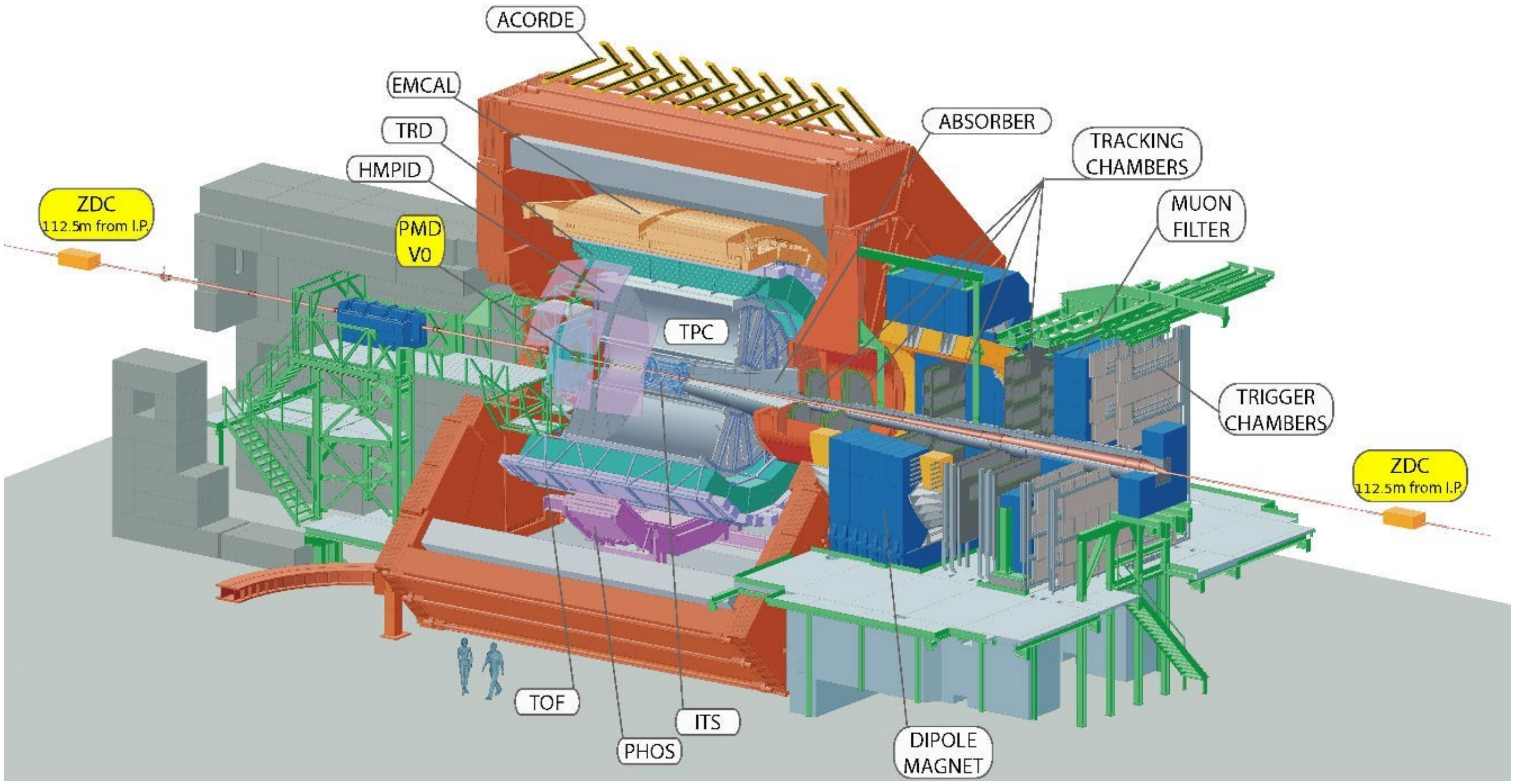
Fission events are extremely rare.

Therefore, the mass and charge of the residual nucleus can be evaluated by detecting neutrons and protons in EMD.

$$^{208}_{82}\mathrm{Pb} \rightarrow ^{208-X-Y}_{82-Y}\mathrm{A} + X\mathrm{n} + Y\mathrm{p}$$

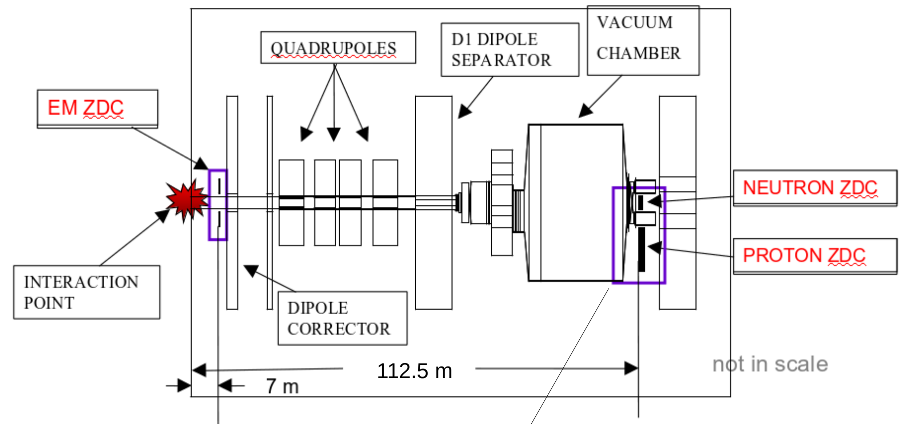
NZDC PZDC

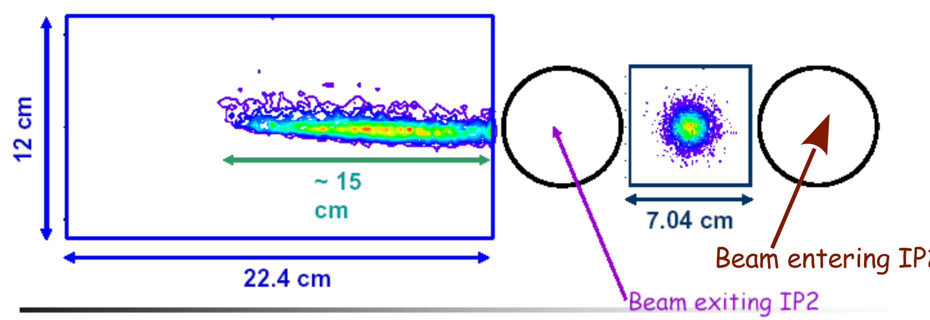
ALICE hadronic calorimeters to detect forward neutrons and protons



ALICE neutron and proton ZDCs

- ZDCs placed at both sides, 112.5 m from IP2
- Covering very forward angles $|\eta| > 8.7$
- 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





- R. Gemme, Studies of the ALICE ZDC detector performance, CERN-THESIS-2006-089
- G. Puddu et al., Nucl. Instrum. Meth. A 581 (2007) 397
- R. Gemme et al., Nucl. Phys. B Proc. Suppl. 197 (2009) 211
- C. Oppedisano et al., Nucl. Phys. B Proc. Suppl. 197 (2009) 206

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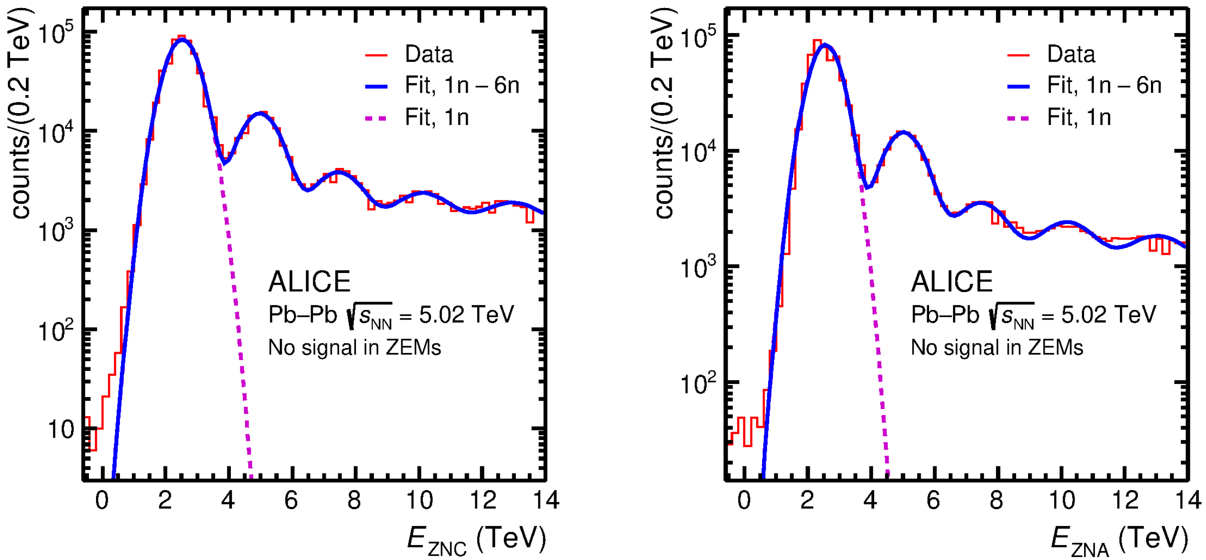
Samples of calibrated ZDC spectra for EMD events

Pedestals were placed at zero energy.

The average distance between neighbor peaks was set to the beam energy per nucleon



Calibrated spectra were fitted by the sum of six Gaussians to ensure good fit quality for 1n, 2n, … 5n peaks

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

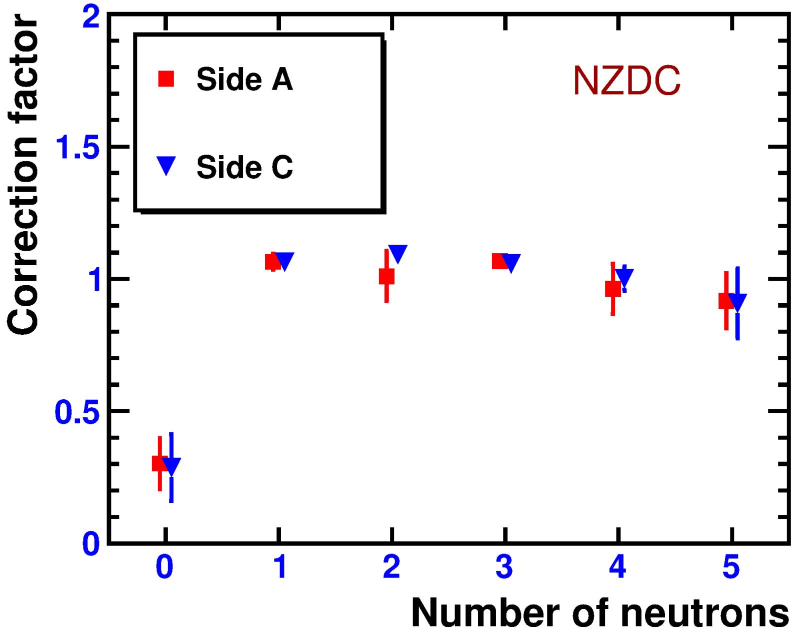
ALICE Collab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. arXiv:2209.04250 [nucl-ex]

Three methods to calculate ZDC efficiency

- One neutron may be lost in 2n or 3n events, leading to the registration of 1n and 2n events, respectively. Similarly for other topologies – event migration.
- **S-method:** obtaining ZDC energy spectra from MC production, fit them in the same way as data in order to extract the numbers of detected nucleons and divide the numbers by the initial numbers of nucleons in each topology given by RELDIS.
- **H-method:** MC modeling of nucleons which hit the ZDC surface separately in events of each multiplicity (for each topology)
- **P-method:** analytical model* based on RELDIS model predictions and on a single parameter p, defined as the probability for a nucleon to hit ZDC. Used to validate results of MC modeling.
- All methods account for the redistribution of true high multiplicity events in favor of detected low multiplicity events due to nucleon loss

*) See details in U. Dmitrieva, I. Pshenichnov, NIM **A 906** (2018) 114, and in backup slides

Calculated correction factors for neutron and proton ZDCs



Neutron multiplicity in	Correction 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 f_{0p}	
	ZPC	ZPA
0p	0.848 ± 0.015	0.852 ± 0.018

- Calculated as the average between H-method and S-method
- Good agreement between the results for C and A sides

Tables: ALICE Collab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. arXiv:2209.04250 [nucl-ex]

Efficiency of ZEM veto to select EMD events

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Neutron multiplicity in	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

- Estimated from the comparison of single-side and all events with and without ZEM veto.
- More than 99% of 1n–5n EMD events survive after ZEM veto
- The higher neutron multiplicity, the lower ZEM veto efficiency in selecting EMD events and slightly more EMD events are suppressed.

ALICE Collab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. arXiv:2209.04250 [nucl-ex]

Determination of neutron emission cross sections

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- Neutron emission with any number of protons (Yp)

$$\sigma(in) = \sigma_{\mathrm{ZED}} \frac{n_i}{N_{\mathrm{tot}}} \frac{f_{in}}{\varepsilon_i}$$

- Neutron emission without protons (0p)

$$\sigma(in, 0\mathrm{p}) = \sigma_{\mathrm{ZED}} \frac{n_i}{N_{\mathrm{tot}}} \frac{f_{in} f_{0\mathrm{p}}}{\varepsilon_i}$$

With σ_{ZED} as the cross section from vdM scan*

n_i as the numbers of events in each neutron peak

N_{tot} as the total number of EMD events

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

ALICE Collab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. arXiv:2209.04250 [nucl-ex]

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Relative systematic uncertainties

Source	Relative uncertainty (%)									
	1n		2n		3n		4n		5n	
	Yp	0p	Yp	0p	Yp	0p	Yp	0p	Yp	0p
Fitting procedure	0.55	0.55	0.32	0.29	0.83	0.72	0.73	0.67	1.14	1.01
ZDC+ZEM efficiency	2.03	2.45	4.68	4.88	1.78	2.25	5.35	5.52	9.26	9.36
σ_{ZED} determination from vdM scan	2.2									
Total	3.04	3.34	5.18	5.36	2.95	3.23	5.83	5.98	9.59	9.67

ALICE Collab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. arXiv:2209.04250 [nucl-ex]

Resulting cross sections

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

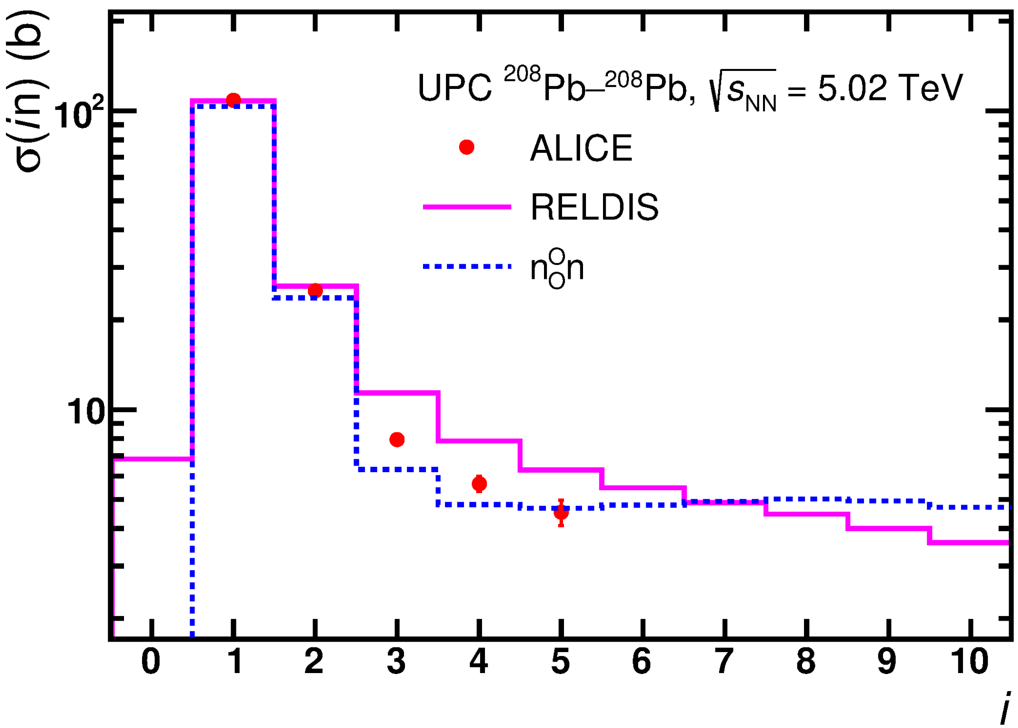
ZN	ZP	$\sigma(in, 0p)$ (b)		$\sigma(in, 0p)$ (b)	$\sigma^{\mathrm{RELDIS}}(in, 0p)$ (b)
		Side C	Side A		
1n	0p	$92.6 \pm 0.1 \pm 3.8$	$90.9 \pm 0.1 \pm 3.9$	$91.8 \pm 0.1 \pm 3.3$	104.1 ± 5.2
2n		$21.4 \pm 0.1 \pm 0.8$	$20.0 \pm 0.1 \pm 2.0$	$20.7 \pm 0.1 \pm 1.1$	21.9 ± 1.1
3n		$6.14 \pm 0.07 \pm 0.27$	$6.21 \pm 0.04 \pm 0.23$	$6.17 \pm 0.04 \pm 0.20$	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 Collab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. arXiv:2209.04250 [nucl-ex]

Neutron emission accompanied by any number of protons (including 0p)

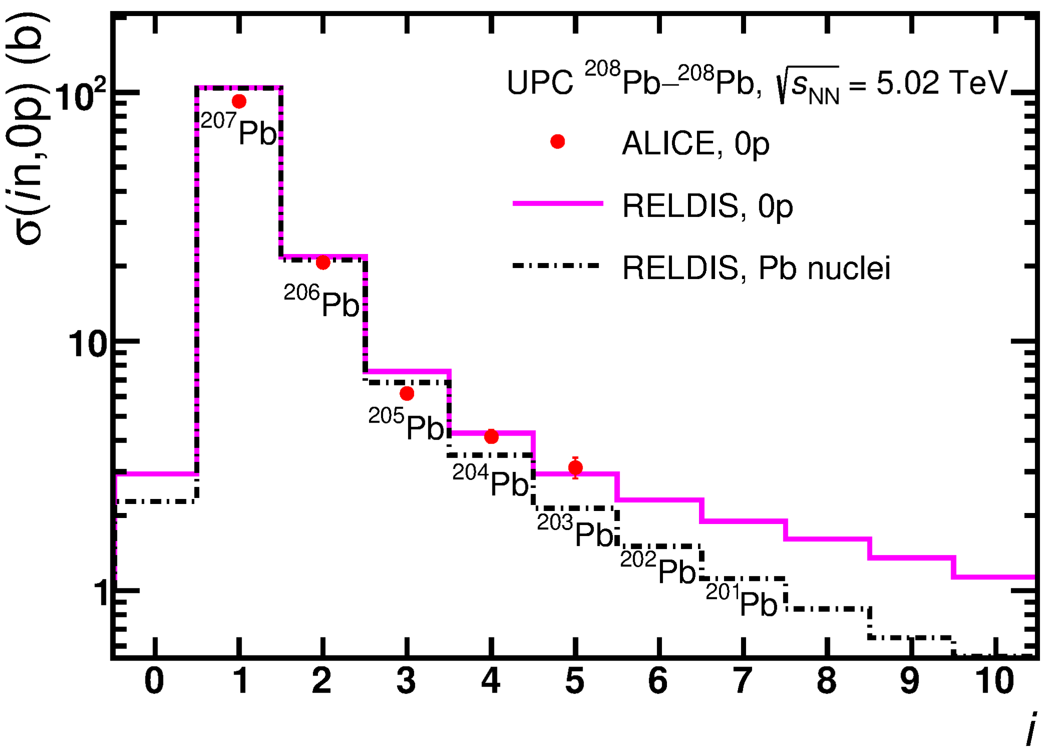
- 1n and 2n cross sections agree well with RELDIS and $\mathrm{n}_{\mathrm{O}}^{\mathrm{O}}\mathrm{n}$.
- Data are in between the results of these two models for 3n, 4n and 5n cross sections.



ALICE Collab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. arXiv:2209.04250 [nucl-ex]

Neutron emission without protons

- Measured 1n, 2n and 3n cross sections agree with RELDIS
- According to RELDIS, the cross sections to produce ^{207}Pb, ^{206}Pb, ^{205}Pb are well approximated by 1n, 2n and 3n cross sections (next slide).

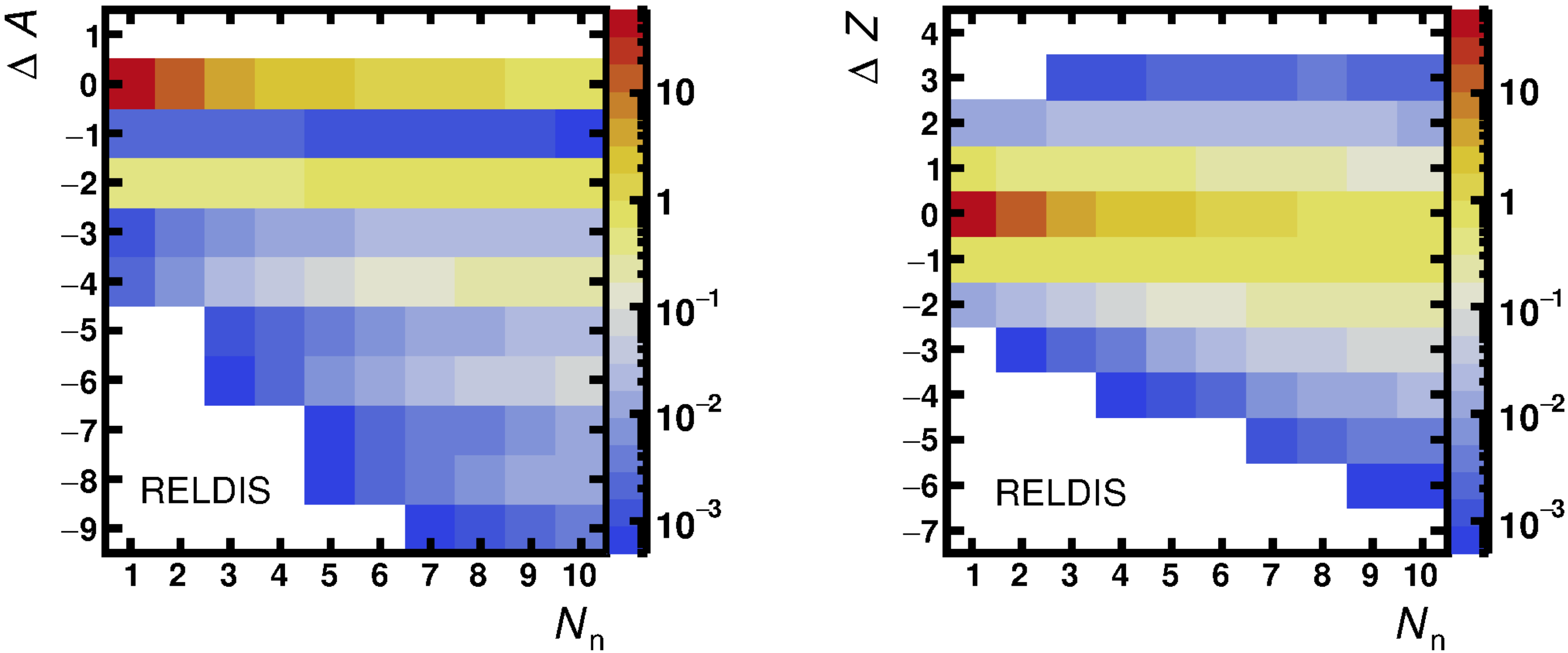


ALICE Colab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. arXiv:2209.04250 [nucl-ex]

RELDIS: emitted nucleons and a single residue

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

Probability in %

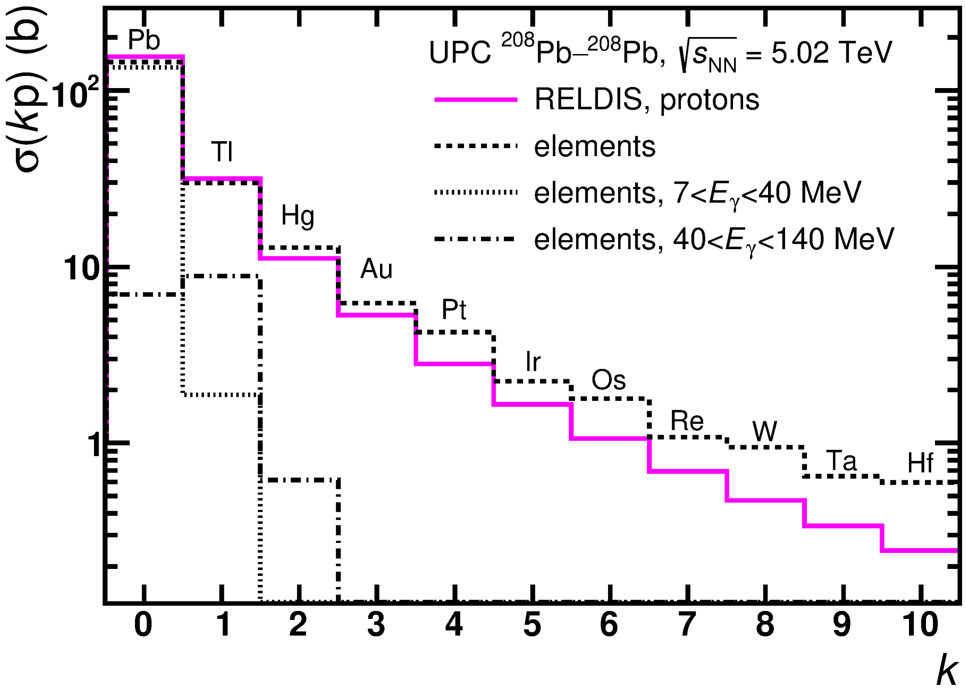


ΔA=0 and ΔZ=0 in most of events. Therefore, the properties of residual nuclei can be estimated by detecting forward neutrons and protons.

ALICE Colab., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. arXiv:2209.04250 [nucl-ex]

Measurements of forward protons from EMD by ALICE: work in progress

- RELDIS predictions (stay tuned for new ALICE data):
  - 1p, 2p, 3p cross sections approximate well the cross sections to produce Tl, Hg, Au
  - these elements are produced mostly by energetic photons



U. Dmitrieva, "Production of various elements in ultraperipheral ^{208}Pb--^{208}Pb collisions at the LHC", talk given at the XXVI International Scientific Conference of Young Scientists and Specialists (AYSS-2022)

Conclusions

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- The cross sections of emission of given numbers of neutrons in UPC of ^{208}Pb nuclei at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV were measured with ALICE neutron zero degree calorimeters.
- The cross sections for the exclusive emission of 1, 2, 3, 4 and 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, respectively.
- 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).
- The predictions from the available models describe the measured cross sections.
- These measurements are important for the extraction of the contributions of high- and low-energy photons from coherent vector meson photoproduction measurements accompanied by neutron emission.

Backup slides

P-method: simple combinatorial model

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The numbers of detected events n_i and those calculated by RELDIS N_i for a given multiplicity *i* are connected by means of a triangular transformation matrix P:

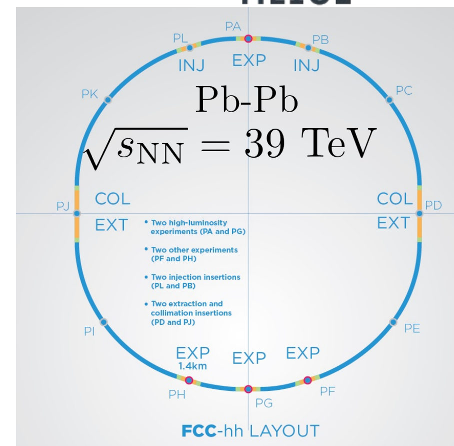
$$\begin{pmatrix} n_0 \\ n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \end{pmatrix} = \begin{pmatrix} p_{00} & p_{01} & p_{02} & p_{03} & p_{04} & p_{05} \\ 0 & p_{11} & p_{12} & p_{13} & p_{14} & p_{15} \\ 0 & 0 & p_{22} & p_{23} & p_{24} & p_{25} \\ 0 & 0 & 0 & p_{33} & p_{34} & p_{35} \\ 0 & 0 & 0 & 0 & p_{44}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

with $p_{nk} = \binom{n}{k} p^k (1-p)^{n-k}$, where p – probability to detect a nucleon.

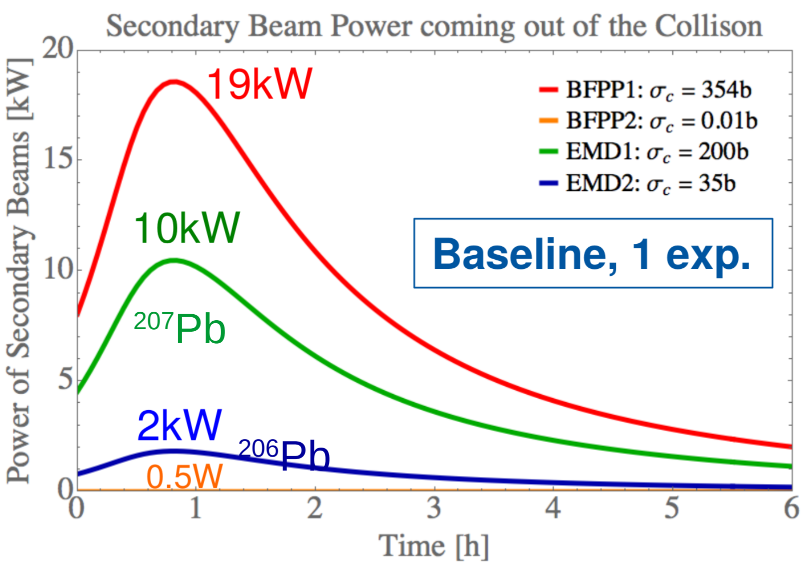
U. Dmitrieva, I. Pshenichnov, NIM **A 906** (2018) 114 *https://doi.org/10.1016/j.nima.2018.07.072*

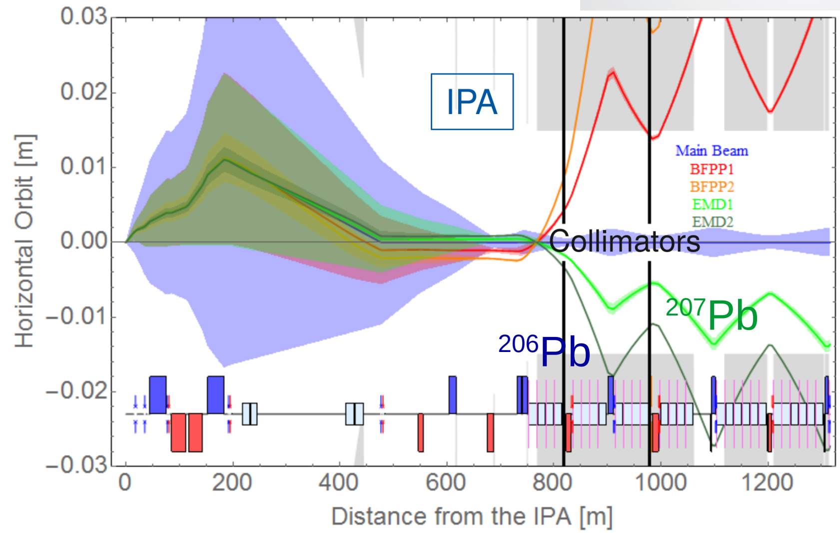
Ions in the future hadron collider FCC-hh

Somehow larger EMD cross sections, but the energy of secondary nuclei is as high as 8 times compared to the LHC! Powerful beams of secondary nuclei are predicted ...



FCC-hh Physics YR 3, 635–692,
CERN-TH-2016-107, arXiv:1605.01389
M. Schaumann, Phys. Rev. ST Accel. Beams 18 (2015) 9, 091002





M. Schaumann at al., FCC week Berlin, 30.05.2017
https://indico.cern.ch/event/556692/contributions/2484258/

Note localized impact of ^{206}Pb and ^{207}Pb on FCC-hh components