Electromagnetic interactions of ultrarelativistic nuclei: a challenge for present and future heavy-ion colliders

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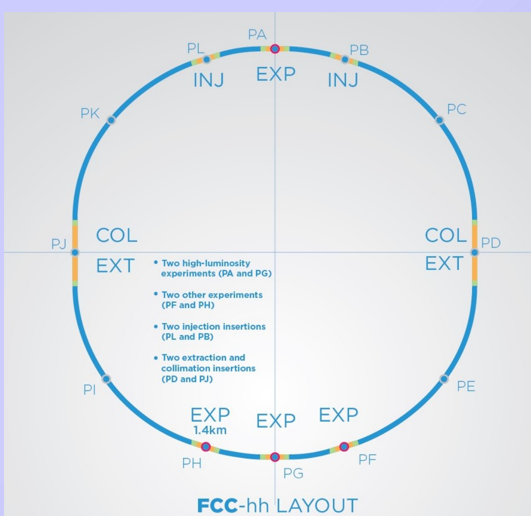

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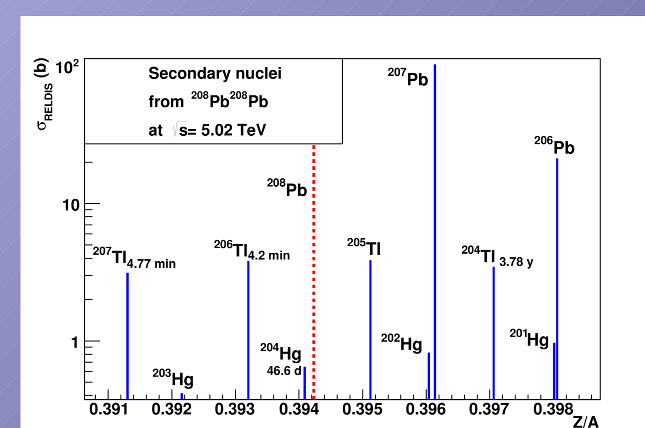

Introduction

- ***It was a good idea to build the LHC to discover Higgs boson in pp-collisions.***

- ***The LHC can also collide nuclei with a bit lower energy per nucleon-nucleon pair to search for the creation of quark-gluon plasma and other QCD phenomena:***

$$\sqrt{s_{NN}} = \sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \sqrt{s_{pp}}$$

$$\sqrt{s_{NN}} = 5.44\ \mathrm{TeV}\ \text{for}\ {}^{129}\mathrm{Xe}\text{-}{}^{129}\mathrm{Xe}\ \text{for}\ \sqrt{s_{pp}} = 13\ \mathrm{TeV}$$

- ***Electromagnetic interactions of ultrarelativistic nuclei in ultraperipheral collisions (UPC, talks at this session) can also be studied as a bonus.***

- ***However, UPC itself and their products affect the LHC operation. It is important to study them to calculate and measure the cross sections and yields of secondary nuclei to estimate their impact on the collider components.***

Outline of the talk:

I. The impact of ultraperipheral collisions of nuclei on the performance of colliders:

- *Decay of beam intensity due to the bound-free pair-production (BFPP) and electromagnetic dissociation (EMD) of beam nuclei;*
- *Example of ^{238}U—^{238}U UPC of at RHIC;*
- *Certain secondary nuclei (ions) from UPC can deposit heat locally and potentially cause a quenching of superconducting magnets of the LHC.*

II. Whether the measurements of such yields are possible?

III. Yields of secondary nuclei predicted by RELDIS model.

IV. Electromagnetic interactions of nuclei at the future hadron collider – FCC-hh: predictions and concerns:

- *Best ion species to collide at the FCC-hh ?*

V. Conclusions and suggestions for future work.

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Electromagnetic processes slightly changing beam ions are quite frequent in the LHC

- 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:

$$\begin{aligned} {}^{208}Pb^{82+} + {}^{208}Pb^{82+} &\rightarrow {}^{208}Pb^{82+} + {}^{207}Pb^{82+} + n \quad (\sim 100\ b) \\ &\rightarrow {}^{208}Pb^{82+} + {}^{206}Pb^{82+} + 2n \quad (\sim 20\ b) \\ &\rightarrow {}^{208}Pb^{82+} + {}^{205}Pb^{82+} + 3n \quad (\sim 6\ b) \\ &\rightarrow \text{several other channels, e.g., with proton emission} \end{aligned}$$

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

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

Hadronic cs vs EM cs at the LHC:

beams	E/A (TeV)	E/Z (TeV)	σ_{had} [a] (b)	σ_{EMD} [c] (b)	σ_{BFPP} (b)	σ_{tot} (b)	$\sigma_{had}/\sigma_{tot}$ (%)
$^{40}Ar^{18+}$	2.93	6.5	2.689	1.7	~0.016	4.4	61
$^{40}Ca^{20+}$	3.25	6.5	2.69	2.	0.034[d]	4.7	57
$^{63}Cu^{29+}$	2.99	6.5	3.65	5.8	~0.46	9.9	36
$^{78}Kr^{36+}$	3.00	6.5	4.19	12.4	~0.85	17.4	24
$^{84}Kr^{36+}$	2.79	6.5	4.38	13.4	~0.85	18.6	24
$^{115}In^{49+}$	2.77	6.5	5.34	40.4	~7.4	53.	10
$^{129}Xe^{54+}$	2.72	6.5	5.61[b]	50.6	~14.6	71.	8
$^{208}Pb^{82+}$	2.51	6.36	7.66[b]	211.4	271.8[d]	491.	1.6
$^{238}U^{92+}$	2.51	6.5	8.37	299.	602.2[d]	910.	0.9

[a] Modified abrasion-ablation (Glauber-like) model, C. Scheidenberger, et al., PRC **70** (2004) 014902

[b] Glauber MC 3.0 C. Loizides et al., **arXiv:1710.07098**

[c] RELDIS model, see I.P., Phys. Part. Nucl. **42** (2011) 215 for model description

[d] H. Meier et al., PRA **63** (2001) 032713, 1s-3s, 2p states, estimated as ~Z^7 for other collision species

^{238}U beam intensity decay at RHIC

PHYSICAL REVIEW C **89**, 014906 (2014)

Measurement of the total cross section of uranium-uranium collisions at $\sqrt{s_{NN}} = 192.8$ GeV

W. Fischer,* A. J. Baltz, M. Blaskiewicz, D. Gassner, K. A. Drees, Y. Luo, M. Minty, P. Thieberger, and M. Wilinski
Brookhaven National Laboratory, Upton, New York 11973, USA

I. A. Pshenichnov
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(Received 12 July 2013; published 23 January 2014)

TABLE I. Calculated total cross sections for Au + Au and U + U collisions in RHIC and Pb + Pb collisions in the LHC. The total cross section is given by the sum of BFPP, single EMD, and nuclear cross sections. The mutual EMD cross section is given for reference only.

Collider		RHIC	RHIC	LHC
Species		Au + Au	U + U	Pb + Pb
$\sqrt{s_{NN}}$	GeV	200	192.8	5520
BFPP	b	117	329	272
Single EMD	b	94.15	150.1	215
Mutual EMD	b	*3.79*	*7.59*	*6.2*
Nuclear	b	7.31	8.2	7.9
Total	b	218.46	487.3	494.9

$\sigma_{tot}^{meas} = 515 \pm 25$ b $\sigma_{tot}^{calc} = 487$ b

See R. Bruce et al., Phys. Rev. ST Accel. Beams **13** (2010) 091001 for measurements with Au beams

PHYSICAL REVIEW C **89**, 014906 (2014)

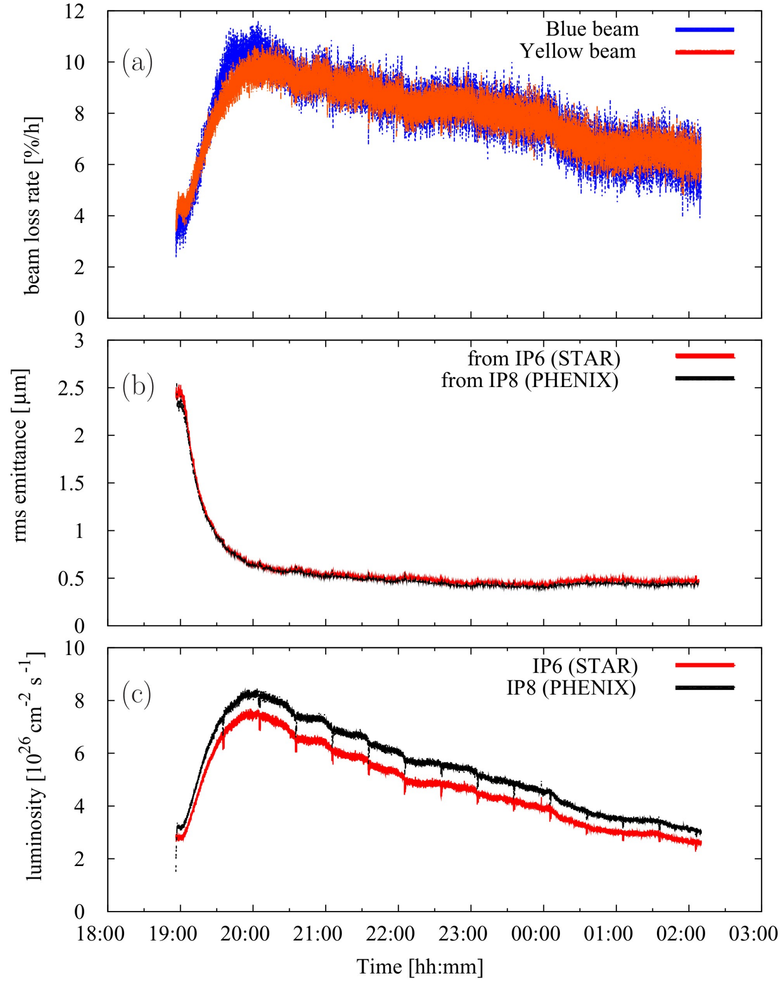
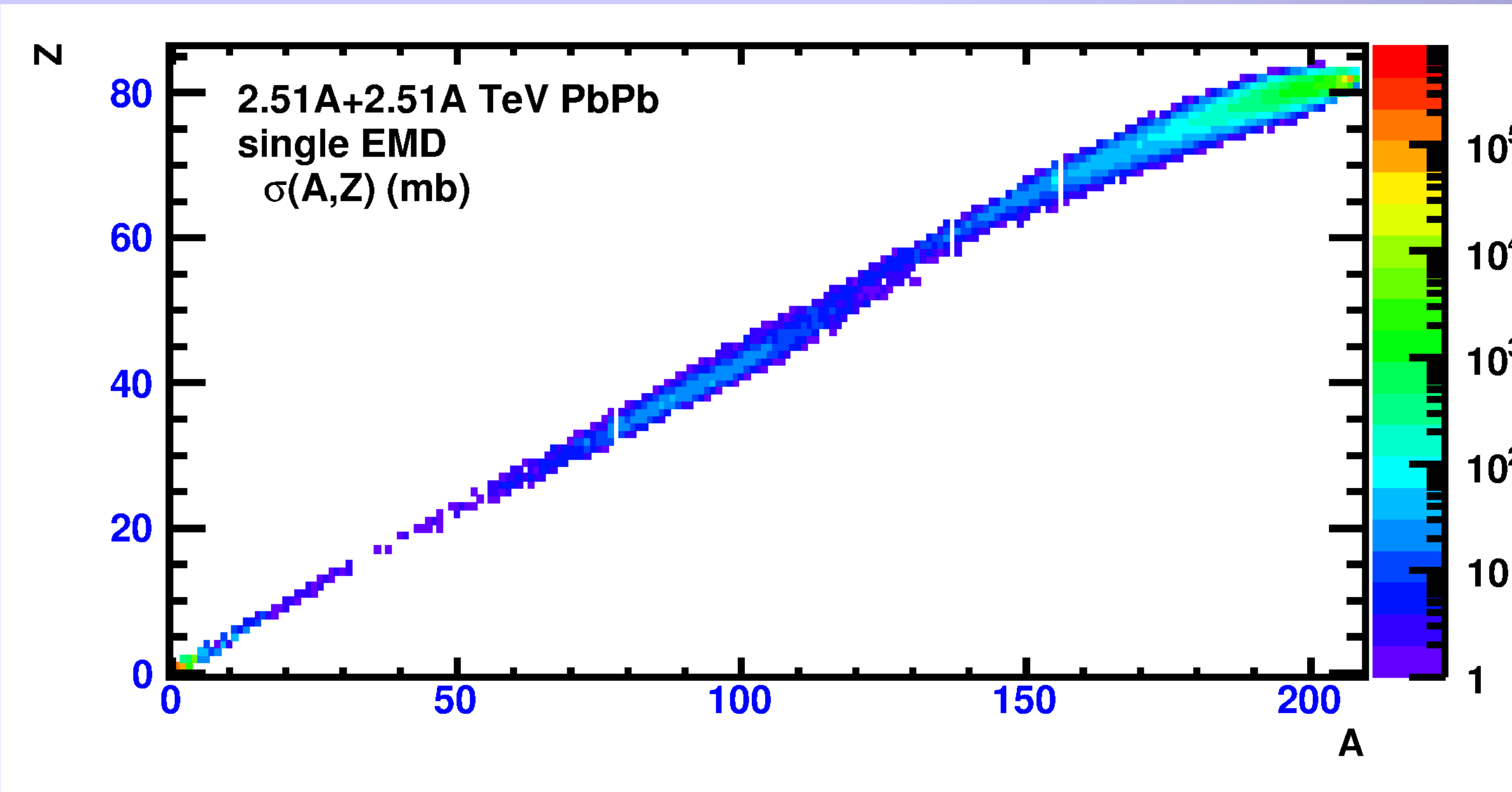


FIG. 1. (Color online) U + U store (fill number 16858) with relative beam loss rates (a), normalized rms emittances calculated from luminosity and intensity (b), and luminosities at the STAR and PHENIX experiments (c). The reduction in the emittances and the corresponding increase in the luminosity are due to stochastic cooling during store.

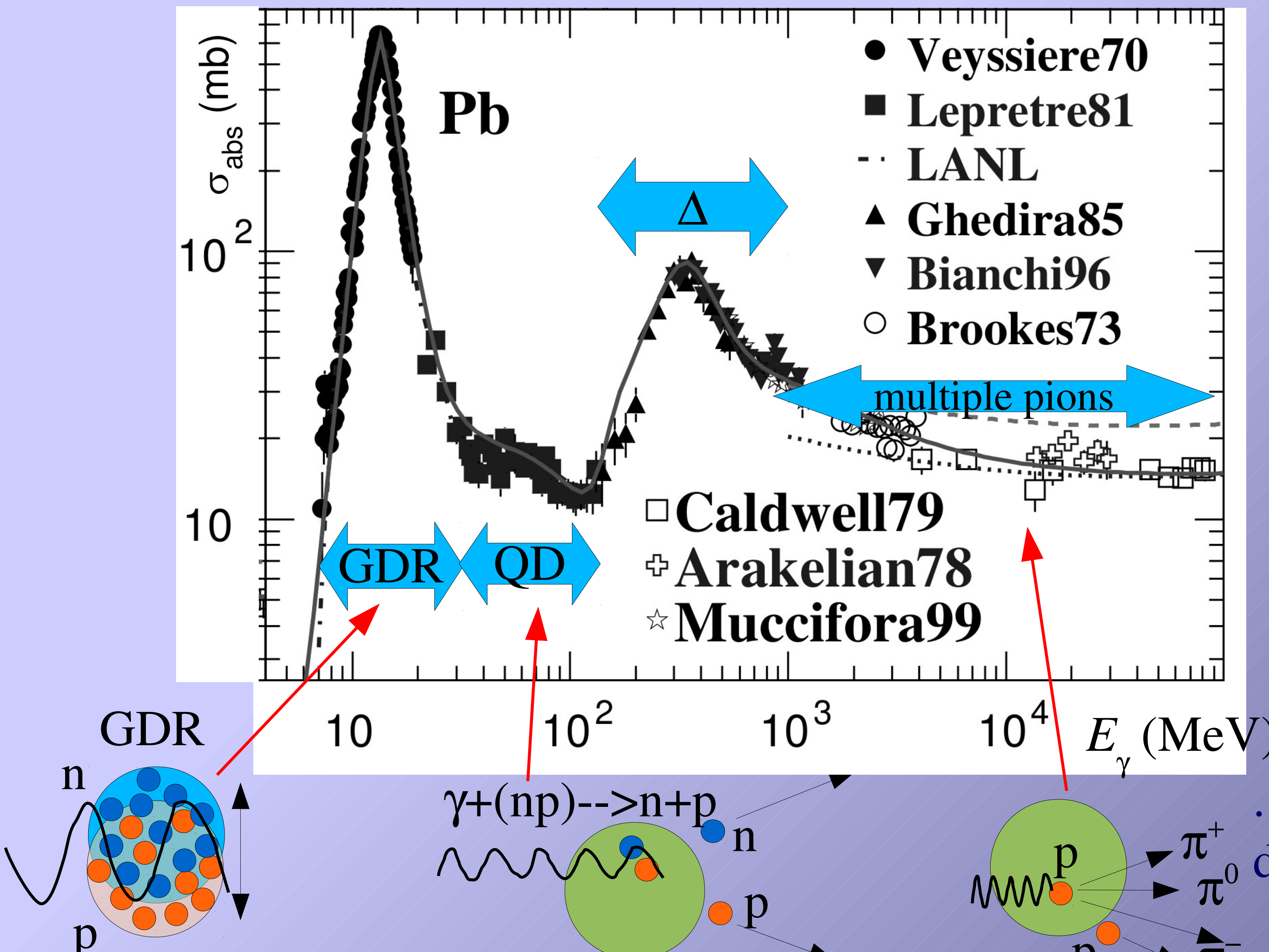
Various nuclei are produced in Pb-Pb UPC at the LHC according to RELDIS model...



Broad range, from n,H,He to $_{83}$Bi (see C. Scheidenberger et al., PRC **70** (2004) 014902)

Note: the inclusive cross section is plotted: e.g., multiplied by the neutron multiplicity

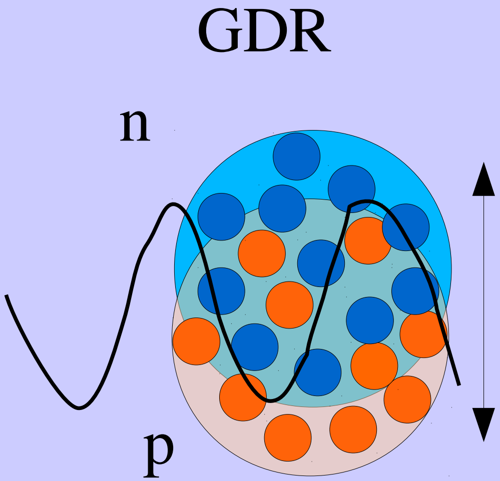
… due to various photonuclear absorption processes

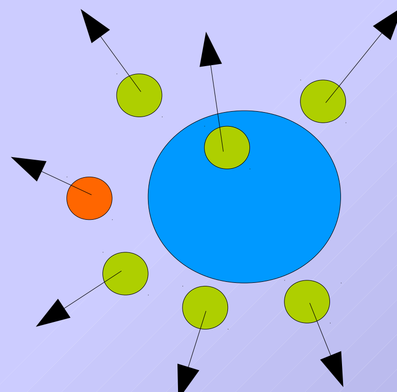


...and hadronic degrees of freedom

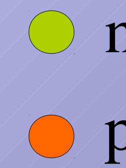
Nuclear ...

Decay of photoexcited nuclei: nucleon evaporation, fission or multifragmentation

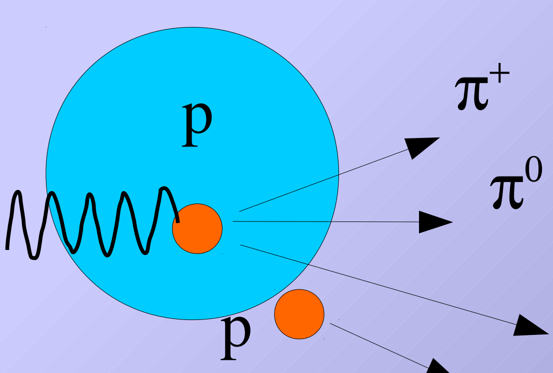


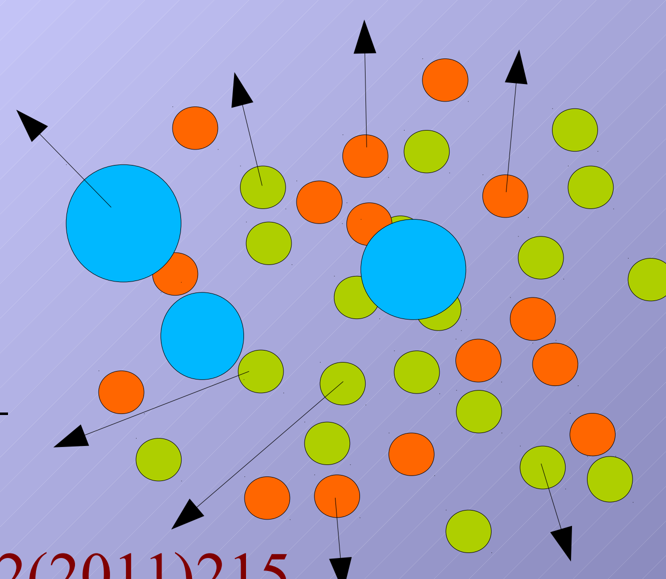


Mostly neutrons are evaporated from heavy nuclei at low excitations



Statistical multifragmentation model (SMM): J.P.Bondorf et al., Phys. Rept. 257(1995)133, includes evaporation and fission models

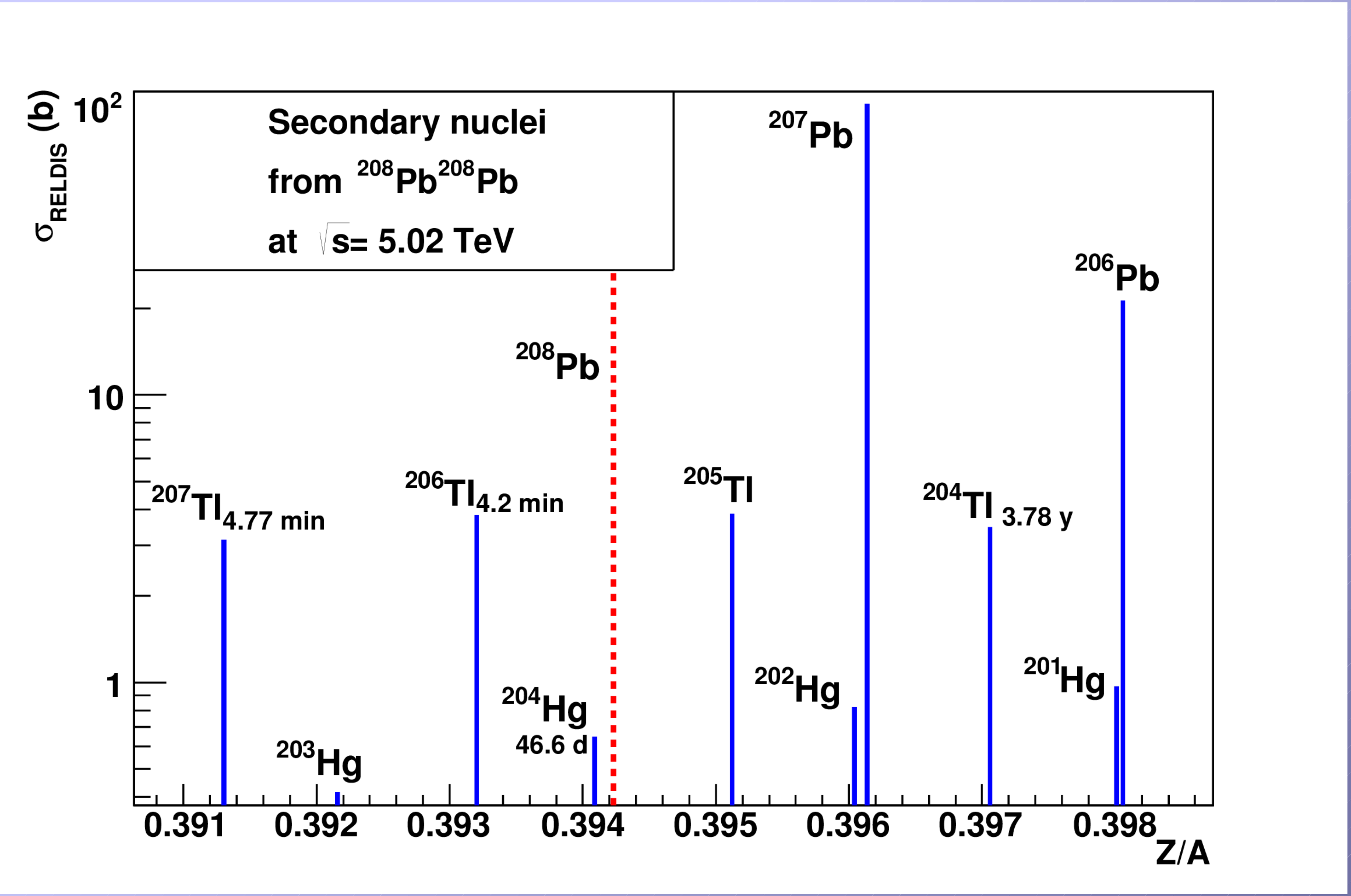




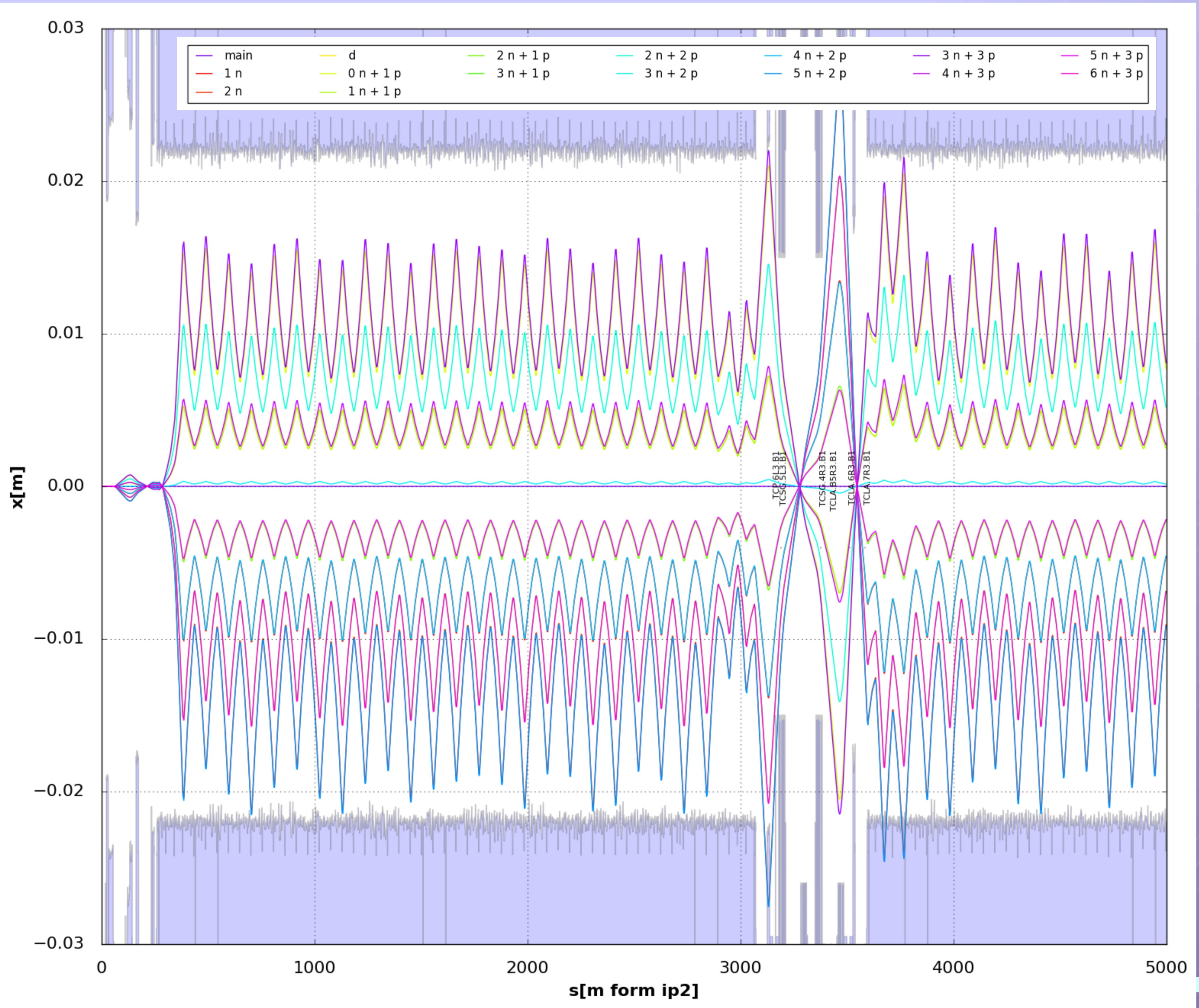
Multifragment breakup is typical for light nuclei, see I.P., I. Mishustin, J. Bondorf et al., PRC 57 (1998) 1920

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

Main concern: secondary nuclei close to ^{208}Pb: ^{206,207}Pb, ^{204,205,206,207}Tl, ^{202,204}Hg



Simulation of trajectories of specific secondary nuclei in the LHC



Distance from IP2 (ALICE)

Courtesy of Tom Mertens, John Jowett (CERN)

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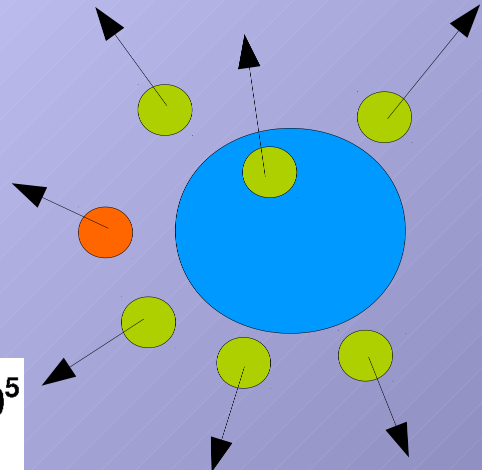
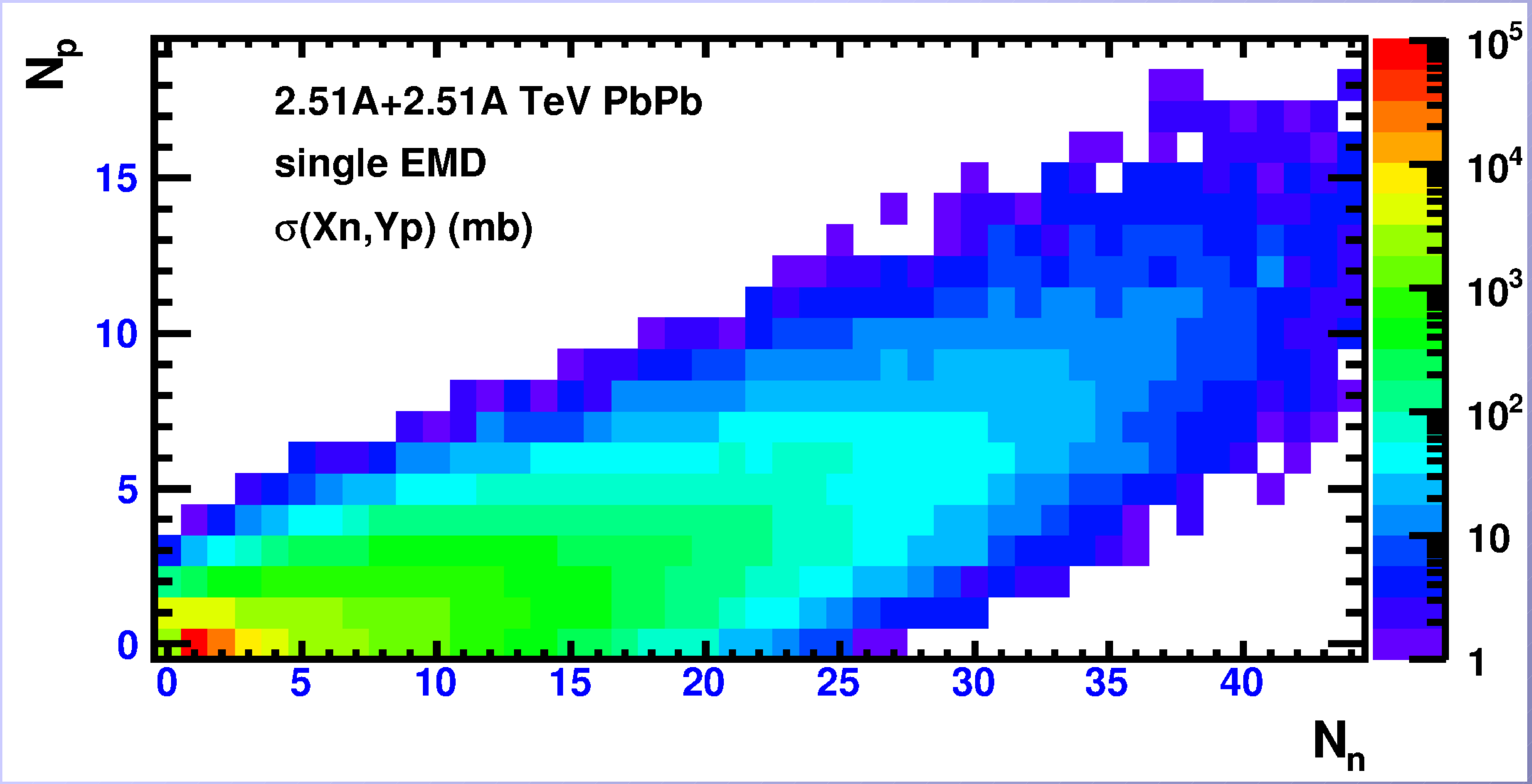
No chance to catch secondary nuclei, but counting nucleons for estimating the charge and size of these nuclei can be proposed



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



Zero degree calorimeters have been installed in several LHC experiments.

Zero Degree Calorimeters (ZDC) have been used so far by ALICE, ATLAS and CMS:

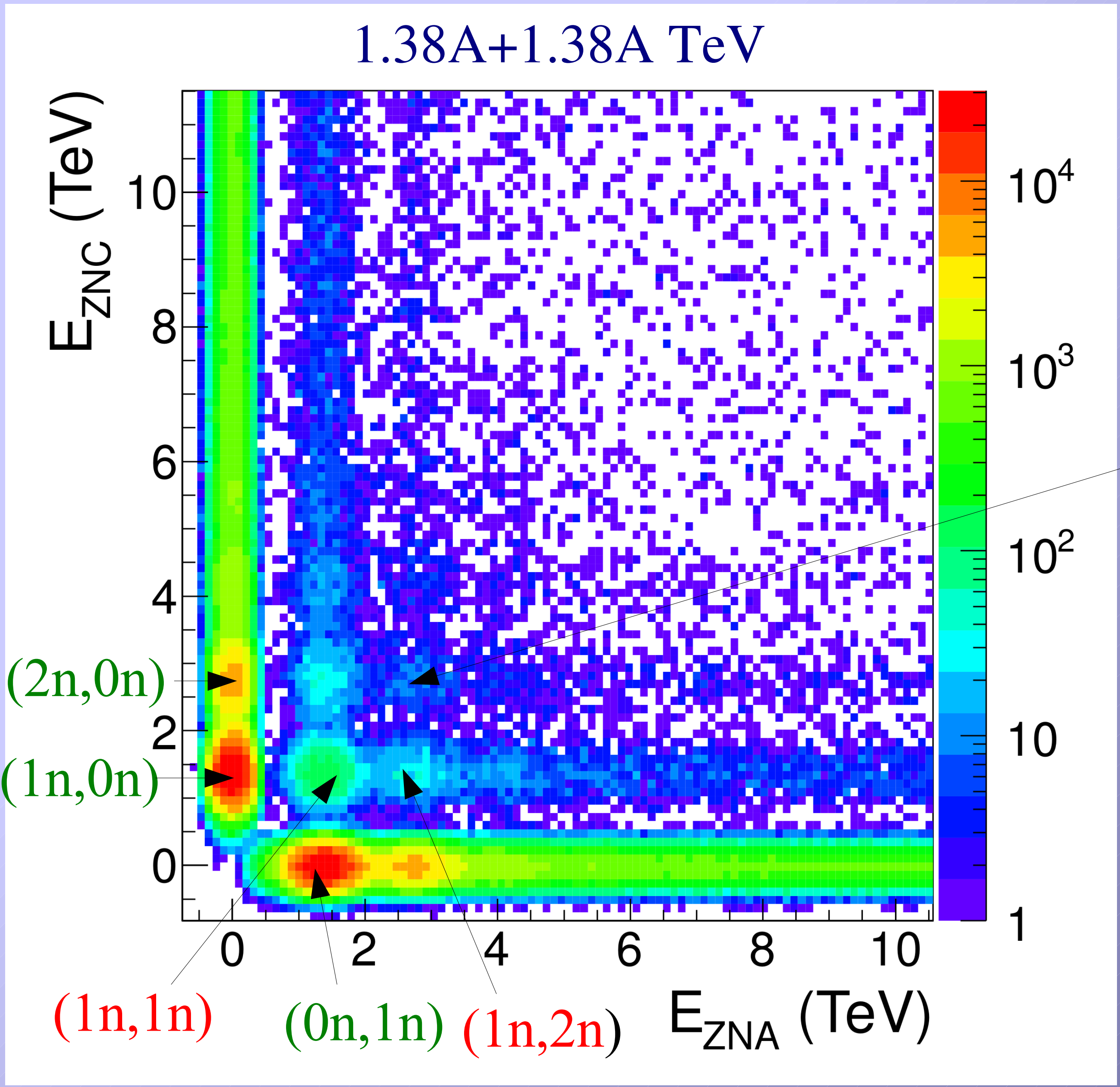
- to determine the collision centrality
  *ALICE Collaboration, Phys. Rev. C **88** (2013) 044909*
- to study EMD of lead nuclei in ultraperipheral collisions
  *ALICE Collaboration, Phys. Rev. Lett. **109** (2012) 252302*
- to trigger ultraperipheral events with particle production
  *V. Guzey et al., Eur. Phys. J. C **74** (2014) 2942.*
  *A.J. Baltz et al., Phys. Rev. C **80** (2009) 044902.*
- to monitor the collider luminosity
  *A.Morsch, I.P., LHC Experimental conditions, ALICE Int. note **2002-034***
  *ALICE Collaboration, J. Phys. G: Nucl. Part. Phys. **30** (2004) 1517*

ZDC can be also used to estimate the production of residual nuclei in EMD with a dedicated trigger for EM events. The cross sections to produce a single unexcited heavy residue (e.g., ^{207}Pb, ^{208}Pb) in hadronic interactions are relatively small (~ 100 mb).

Example: the emission of forward neutrons measured by ALICE Pb-Pb UPC

EMD of only one beam (dominant) labeled in green

Energy in ZDC at the side C



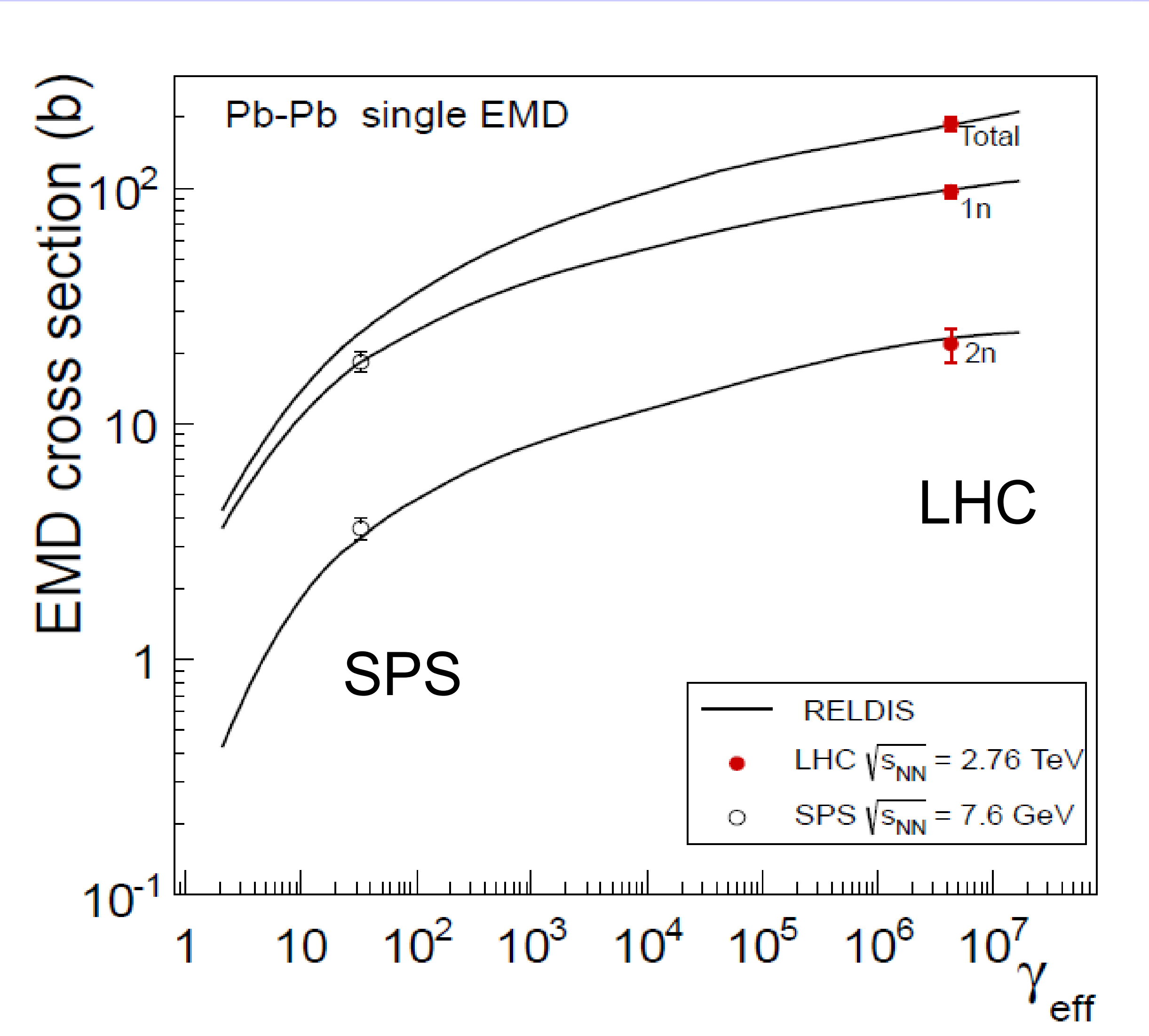
Mutual EMD in red

(2n,2n)

ALICE Collaboration, PRL **109** (2012)252302

Energy in ZDC at the side A

Dependence on the collision energy: SPS vs LHC vs RELDIS model



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

Data are well described by RELDIS within six orders of magnitude of γ_{eff}.

Smooth and monotonic energy dependence allows the extrapolation of results for the same nuclei to higher collision energy.

SPS: ALICE-LUMI experiment, PRC **71** (2005) 024905

LHC: ALICE Collaboration, PRL **109** (2012) 252302

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Does the registration of forward nucleons provide a reliable estimation of the residue in EMD: what about other particles (e.g., EM produced pions, multifragmentation)?

Exclusive EMD channel		Inclusive production of a given nuclide		Emission of a given number of neutrons	
Channel	σ (b)	Nuclide	σ (b)	Neutron multiplicity	σ (b)
^{207}Pb + 1n	101.6	^{207}Pb + X	103.3	1n + 0p	103.8
^{206}Pb + 2n	20.34	^{206}Pb + X	21.3	2n + 0p	22.06
^{205}Pb + 3n	5.99	^{205}Pb + X	6.77	3n + 0p	7.53
^{204}Pb + 4n	2.88	^{204}Pb + X	3.45	4n + 0p	4.30

Nucleons and a residue, no other particles

A given nucleus and anything else

This can be measured with ZDC

Are these cross sections similar?

Estimating the production of $_{82}Pb$ by counting emitted neutrons: RELDIS

Exclusive EMD channel		Inclusive production of a given nuclide		Emission of a given number of neutrons	
Channel	σ (b)	Nuclide	σ (b)	Neutron multiplicity	σ (b)
$^{207}Pb + 1n$	101.6	$^{207}Pb + X$	103.3	1n + 0p	103.8
$^{206}Pb + 2n$	20.34	$^{206}Pb + X$	21.3	2n + 0p	22.06
$^{205}Pb + 3n$	5.99	$^{205}Pb + X$	6.77	3n + 0p	7.53
$^{204}Pb + 4n$	2.88	$^{204}Pb + X$	3.45	4n + 0p	4.30

Mostly due to soft photons, no other particles or light fragments

Estimating the production of $_{81}$Tl by counting emitted nucleons: RELDIS

Exclusive EMD channel		Inclusive production of a given nuclide		Emission of certain numbers of n and p	
Channel	**σ (b)**	**Nuclide**	**σ (b)**	**Multiplicity**	**σ (b)**
^{206}Tl + 1n + 1p	2.57	^{206}Tl + X	3.82	1n + 1p	3.64
^{205}Tl + 2n + 1p	2.57	^{205}Tl + X	3.87	2n + 1p	3.51
^{204}Tl + 3n + 1p	2.27	^{204}Tl + X	3.46	3n + 1p	3.11
^{203}Tl + 4n + 1p	1.87	^{203}Tl + X	2.93	4n + 1p	2.75

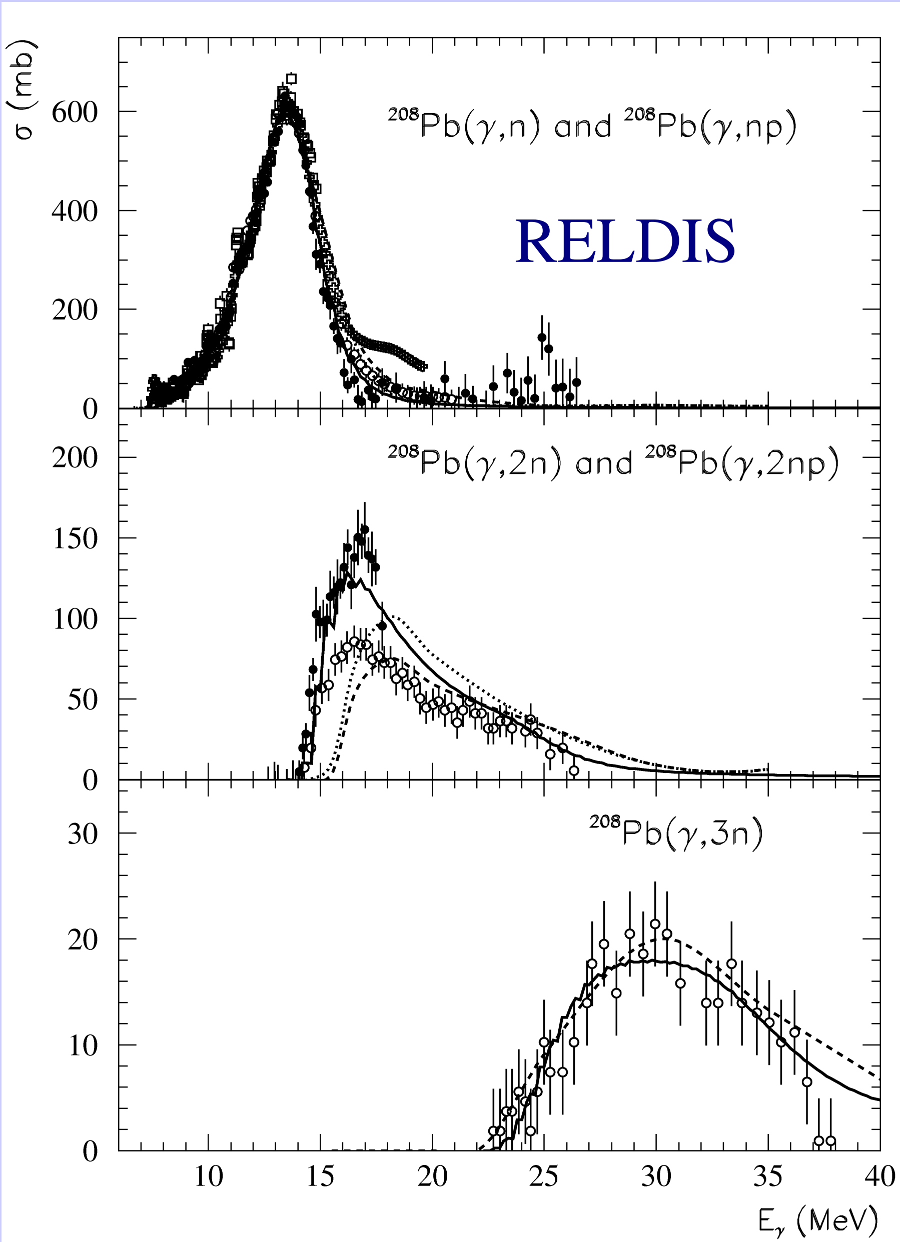
A good estimation of the upper limit for the production of Tl nuclei. However, apart of ^{206}Tl + n + p, the channel ^{206}Tl + d is also possible with a smaller rate.

Estimating the production of $_{80}$Hg by counting emitted nucleons: RELDIS

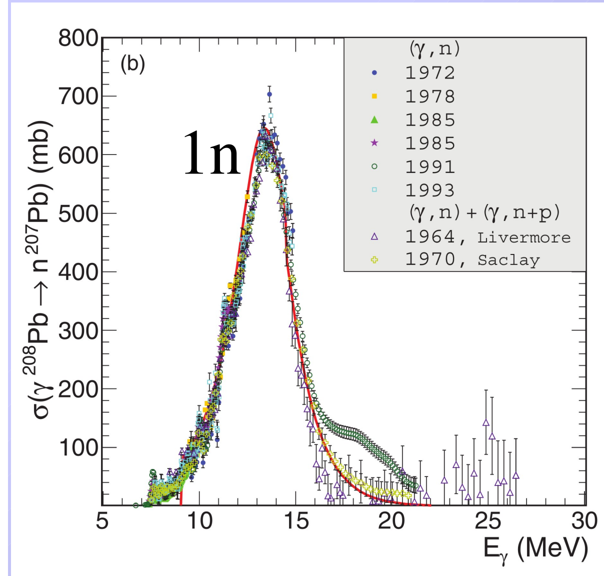
Exclusive EMD channel		Inclusive production of a given nuclide		Emission of certain numbers of n and p	
Channel	**σ (b)**	**Nuclide**	**σ (b)**	**Multiplicity**	**σ (b)**
^{205}Hg + 1n + 2p	0.122	^{205}Hg + X	0.245	1n + 2p	0.274
^{204}Hg + 2n + 2p	0.202	^{204}Hg + X	0.415	2n + 2p	0.404
^{203}Hg + 3n + 2p	0.305	^{203}Hg + X	0.647	3n + 2p	0.566
^{202}Hg + 4n +2p	0.382	^{202}Hg + X	0.824	4n + 2p	0.693

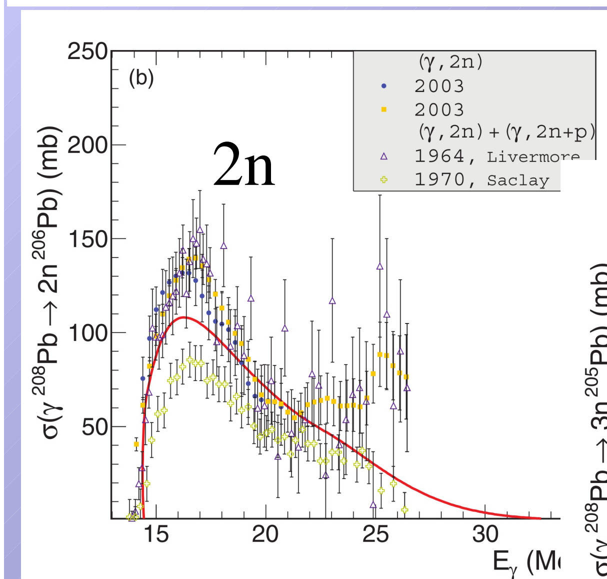
Few charged pions are also produced in addition to protons and neutrons.
Some nucleons are bound in light fragments.

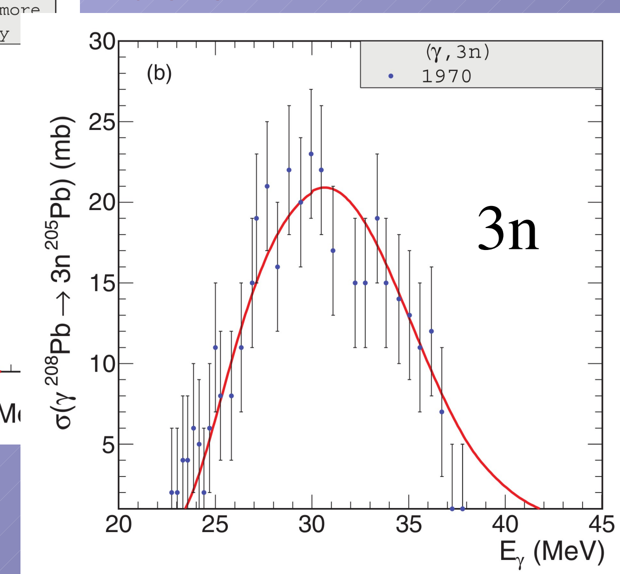
Nuclear data have to be used to validate models, but cross sections measured at different laboratories may diverge.



I.P. et al., PRC 64 (2001) 024903,
Phys. Part. Nuclei 42(2011)215







Cracow model

M.Klusec-Gawenda et al., PRC 94 (2014) 054907

It is important to use reliable data and models to describe the EMD of various nuclei

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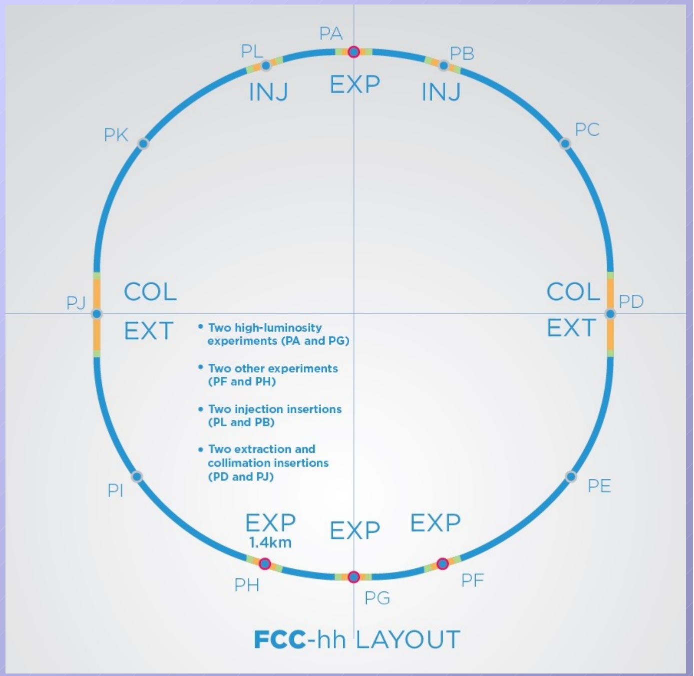
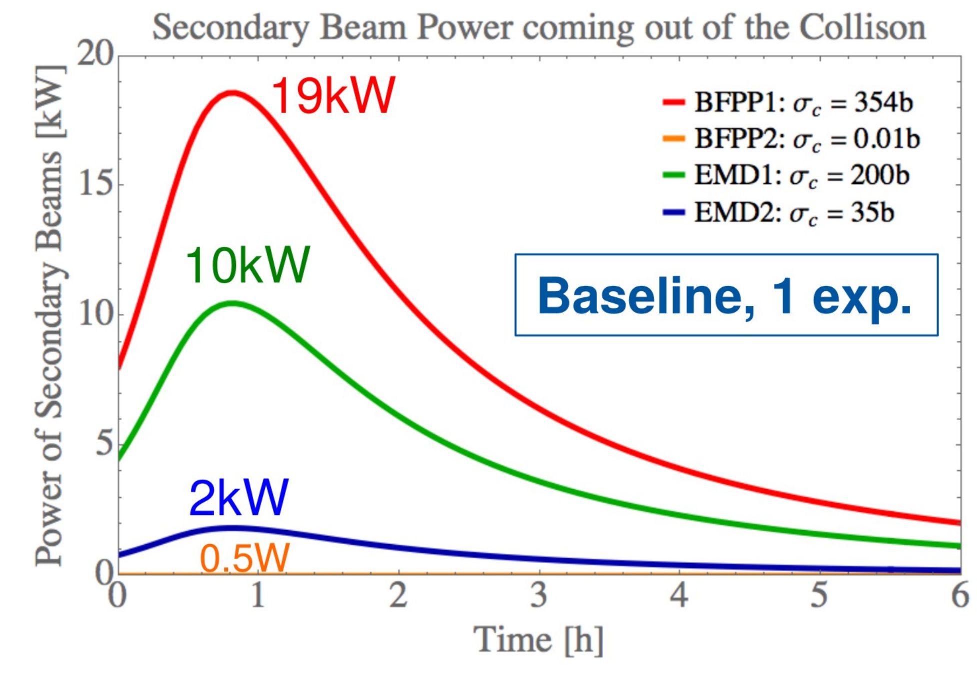
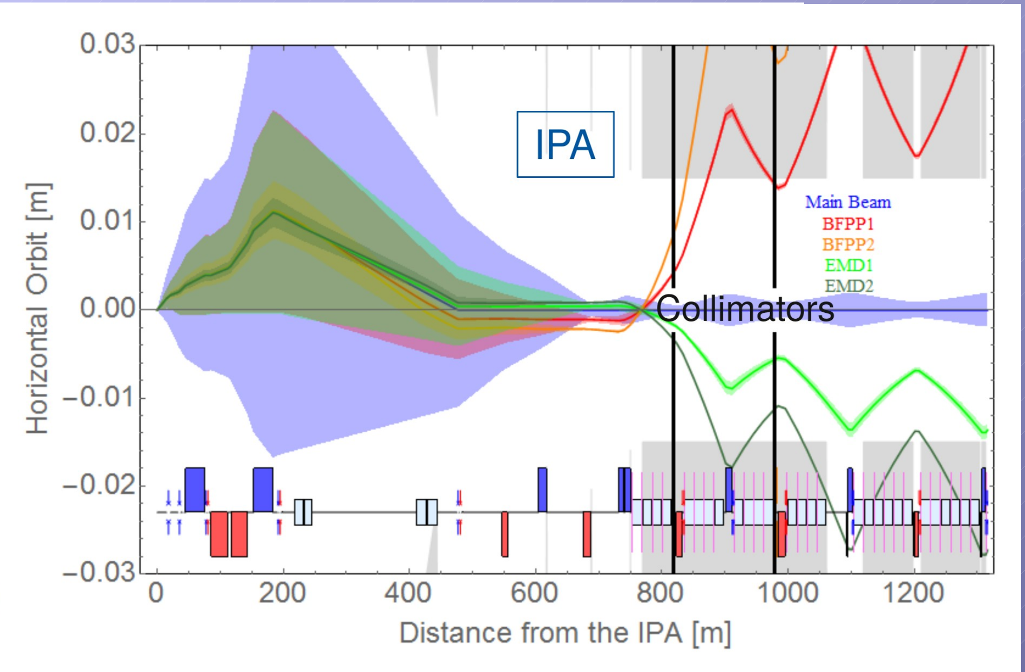
Ions in the future hadron collider FCC-hh

FCC-hh Physics YR 3, 635–692, arXiv:1605.01389
M. Schaumann, Phys. Rev. ST Accel. Beams 18 (2015) 9, 091002, arXiv:1503.09107

Similar UPC rates and somehow larger EM cross sections, but the energy of secondary nuclei as large as 8 times higher!







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

Which nuclei to collide at the FCC-hh?

beams	E/A (TeV)	E/Z (TeV)	σ_{had} [a] (b)	σ_{EMD} [c] (b)	σ_{BFPP} (b)	σ_{tot} (b)	$\sigma_{had}/\sigma_{tot}$ (%)
$^{40}Ar^{18+}$	22.5	50.	2.764	2.2	~0.02	5.	55
$^{40}Ca^{20+}$	25.	50.	2.767	2.7	0.042 [d]	5.5	50
$^{63}Cu^{29+}$	23.	50.	3.74	7.8	~0.6	12.4	31
$^{78}Kr^{36+}$	23.	50.	4.29	16.6	~1.	22.	20
$^{84}Kr^{36+}$	21.4	50.	4.5	18.	~1.	23.5	19
$^{115}In^{49+}$	21.3	50.	5.47	53.8	~9.4	68.7	8
$^{129}Xe^{54+}$	20.9	50.	5.89	67.9	~18.5	92.3	6
$^{208}Pb^{82+}$	19.7	50.	7.9 [b]	284.2	344. [d]	636.	1.2
$^{238}U^{92+}$	19.3	50.	8.53	402.	761. [d]	1171.	0.7

[a] Modified abrasion-ablation (Glauber-like) model, C. Scheidenberger, et al., PRC **70** (2004) 014902

[b] Glauber MC 3.0 C. Loizides et al., **arXiv:1710.07098**

[c] RELDIS model, see I.P., Phys. Part. Nucl. **42** (2011) 215 for model description

[d] H. Meier et al., PRA **63** (2001) 032713, $\sigma_{BFPP}=A\ln\gamma_c+B$, estimated as ~$Z^7$ for other collision species

LHC vs FCC-hh: a comparison

- The total cross sections σ_{tot} for Pb-Pb and U-U collisions are very large, 490 b and 910 b, respectively, which leads to a noticeable luminosity decay at the LHC.

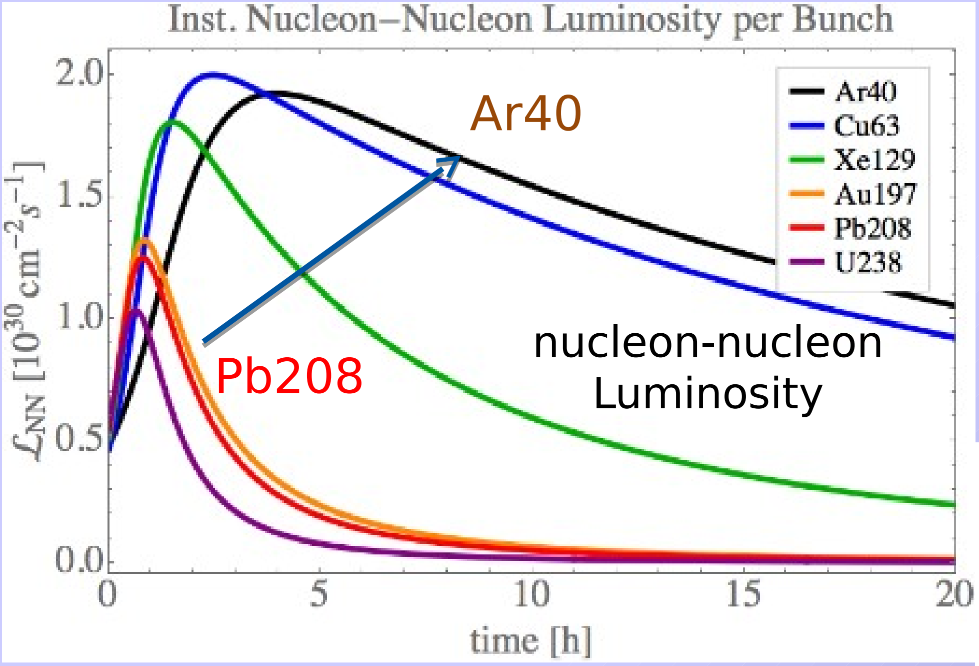
- Even larger σ_{tot}=636 b for Pb-Pb and σ_{tot}=1171 b for U-U are expected at the FCC-hh.

- The fractions of hadronic events (~1%) for Pb-Pb and U-U at the FCC-hh remain comparable to that at the LHC. A similar trigger scheme is possible.

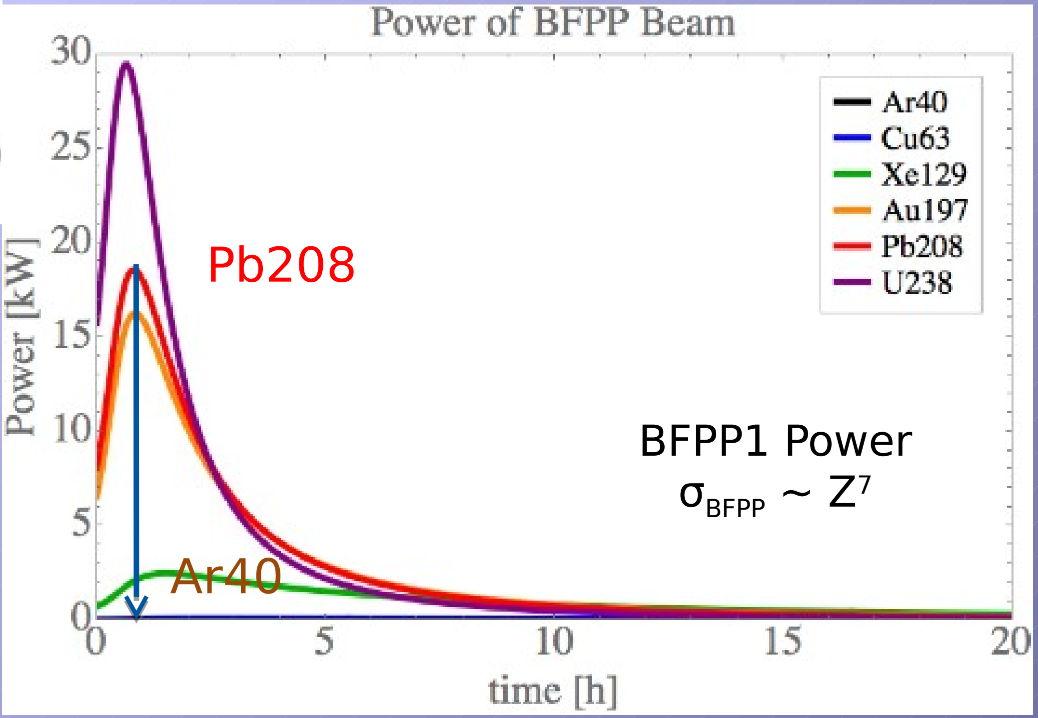
- In collisions of medium-weight nuclei (Kr, In, Xe) beam ions can be used more effectively: typically 1 out of 4 ions or 1 out of 10 ions produce hadronic evens we are going to study.

- However, secondary nuclei produced electromagnetically is an issue.

Advantages of lighter nuclei at the FCC-hh



◇ Increased luminosity lifetime, more particles available for hadronic interactions.



◇ Reduced secondary beam power emerging from collision point.

J.M.Jowett et al., FCC week, Amsterdam, 10.04.18
https://indico.cern.ch/event/656491/contributions/2939104/

Which ions are the best for FCC-hh?

- Monoisotopic (ideally, an element represented by a single natural stable isotope)

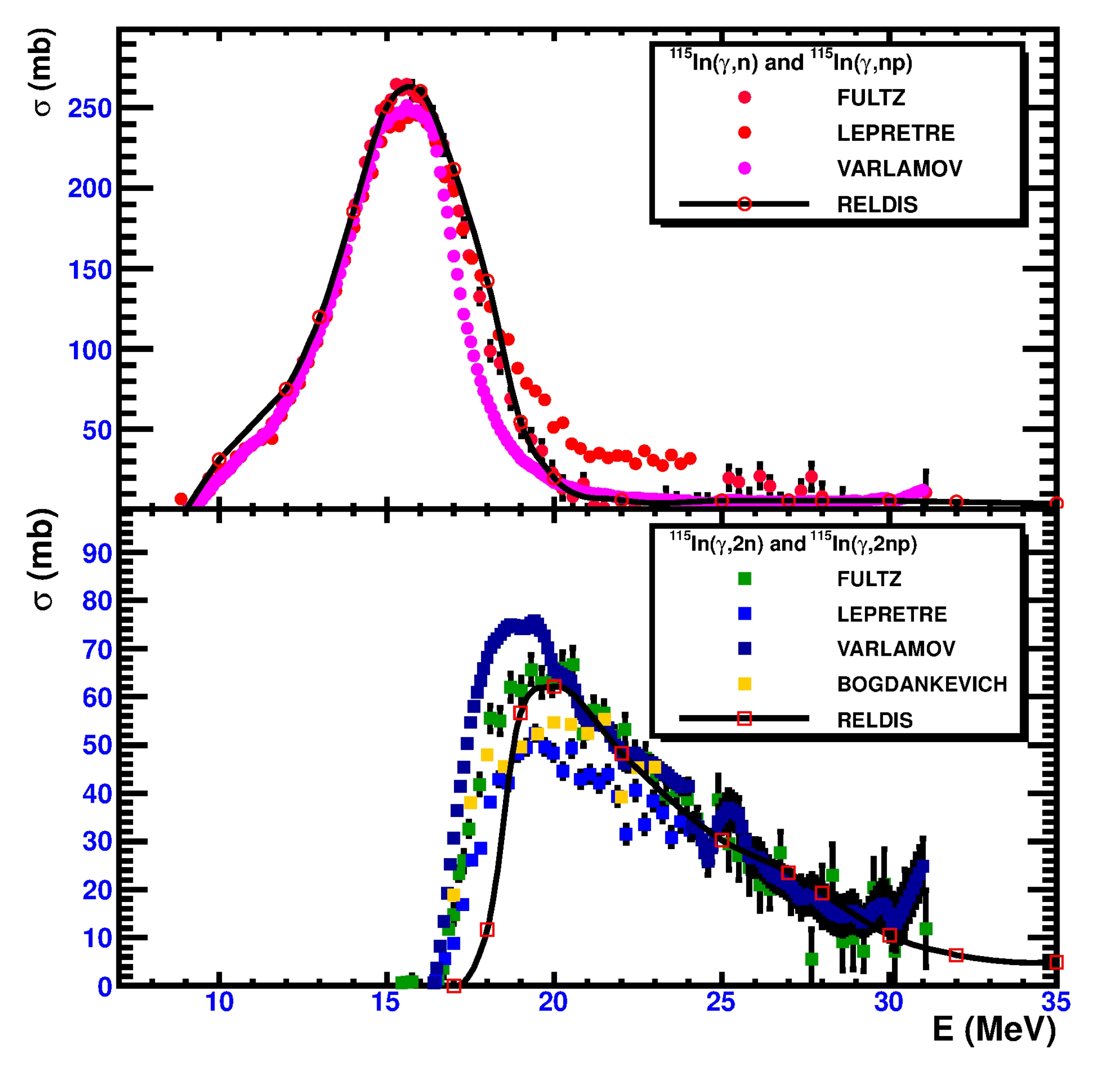
- Reasonable cost of the amount to feed ECR ion source. For example, 10 g of pure ^{208}Pb costs some € 9700, and about 1.3 g is consumed in two run weeks, see Cian O'Luanaigh, *Heavy metal: Refilling the lead source for the LHC,* CERN Accelerating science, 4 Feb 2013, http://cds.cern.ch/record/1997797

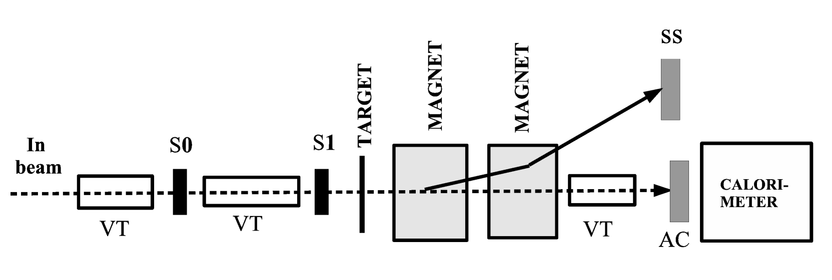
- Acceptable chemical properties, environment friendly. Nobel gases are good, but metals are also welcome.

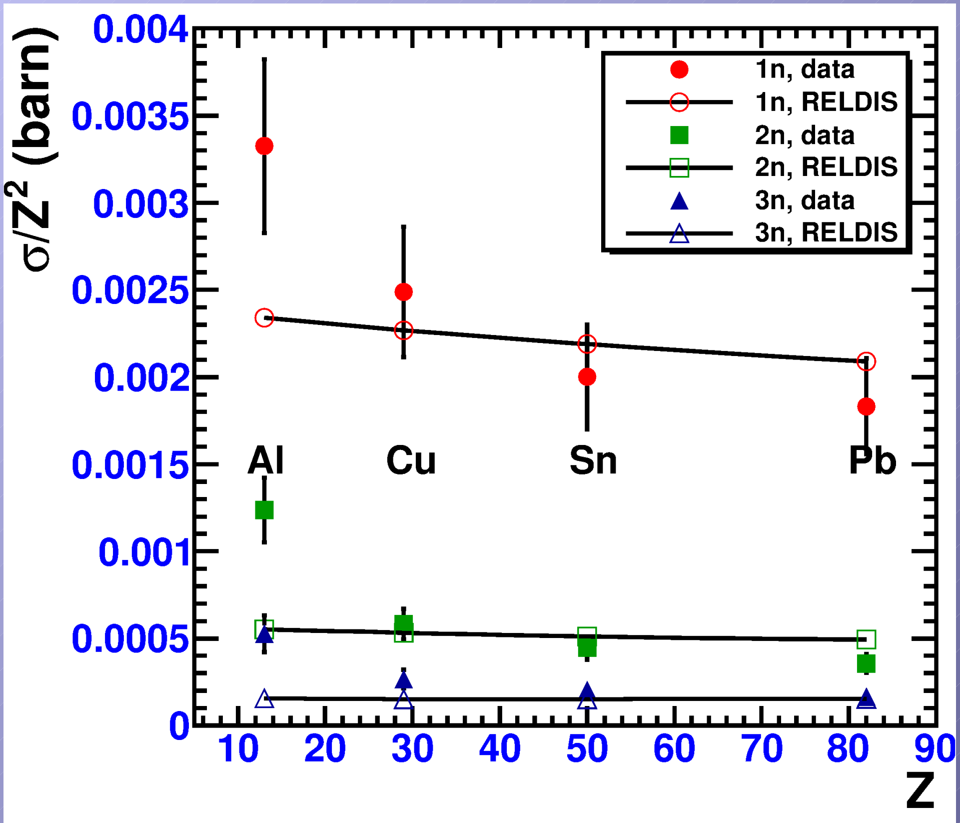
- ^{115}In may be a good choice due to previous experience at the CERN SPS. EMD cross sections has been measured for these beam nuclei and compared to RELDIS.

EMD of ^{115}In has been studied at the CERN SPS and thus validated for future use

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







Conclusions and future work

- BFPP and EMD are very frequent in the LHC and will be even more frequent in the FCC-hh once it will be constructed.

- BFPP is an atomic physics process which generally follows Z^7 trend and it is presently well understood.

- EMD is a more sophisticated process which entirely connected with the nuclear structure of beam nuclei. It also does affect the performance of the LHC and FCC-hh.

- It is important to have reliable calculations and measurements for EMD of nuclei other than Au and Pb:
  - to upgrade the collimator system of the LHC
  - to design the collimator system of the FCC-hh and chose proper species to collide.

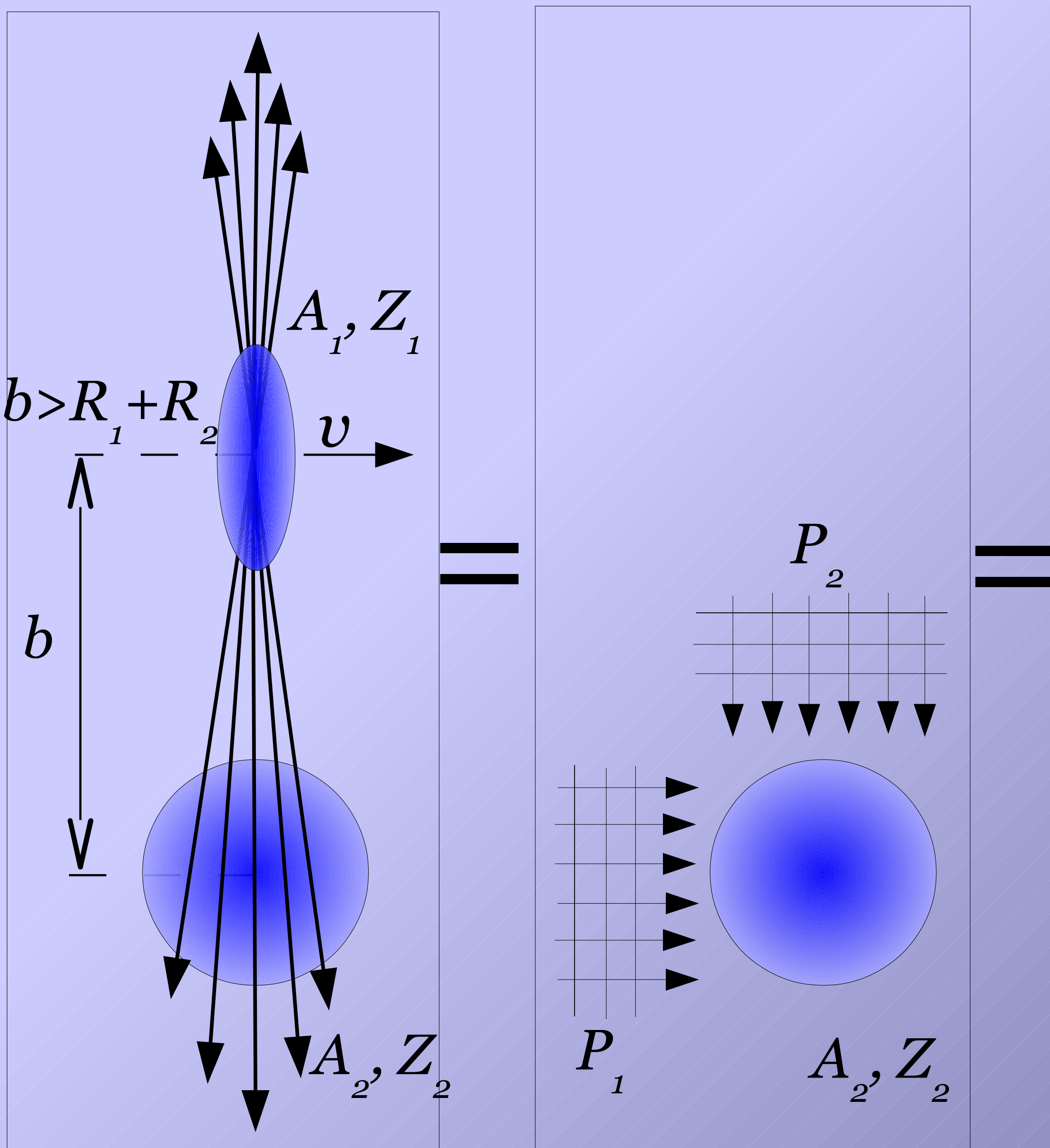
Thank you for your attention!

Many thanks to the workshop organizers for inviting me to give this talk!

Image credits: http://viator.com

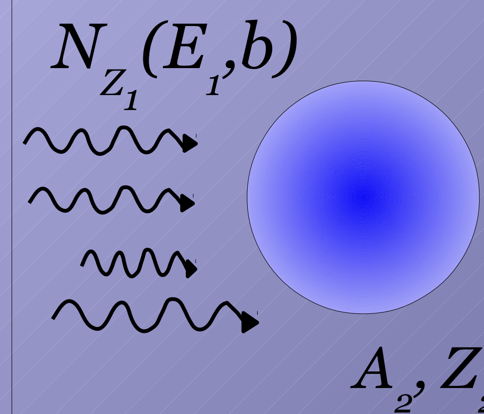
Back-up slides

Heavy ultrarelativistic nuclei are not only the emitters of WW photons ...



Enrico Fermi 1924:
“äquivalente strahlung”

C.F. Weizsäcker & E.J. Williams 1930s: pair production by high-energy photons from charge particles



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

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 can be used.

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

Assume that an ultrarelativitic nucleus $v,\ \gamma = 1/(1-v^2)^{1/2} \gg 1$ is left in its ground state after emission and only a small part of nucleus' kinetic energy is taken away. Together with the coherence condition this gives:

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

RHIC: $E_\gamma < 300\,\mathrm{GeV}$ LHC: $E_\gamma < 200\,\mathrm{TeV}$

Eelectromagnetic dissociation (EMD) of nuclei mostly induced by soft photons...

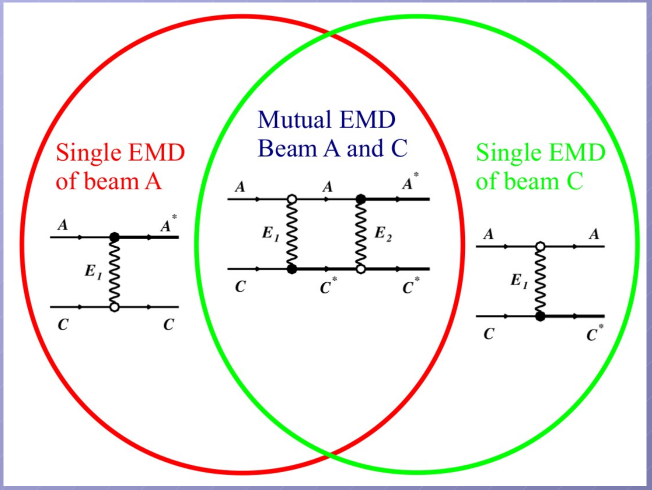
Spectrum of Weizsäcker-Williams photons

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

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

$\mathsf{x} = E_1 b / \gamma\beta$ α - fine structure constant

K_0, K_1 - modified Bessel functions

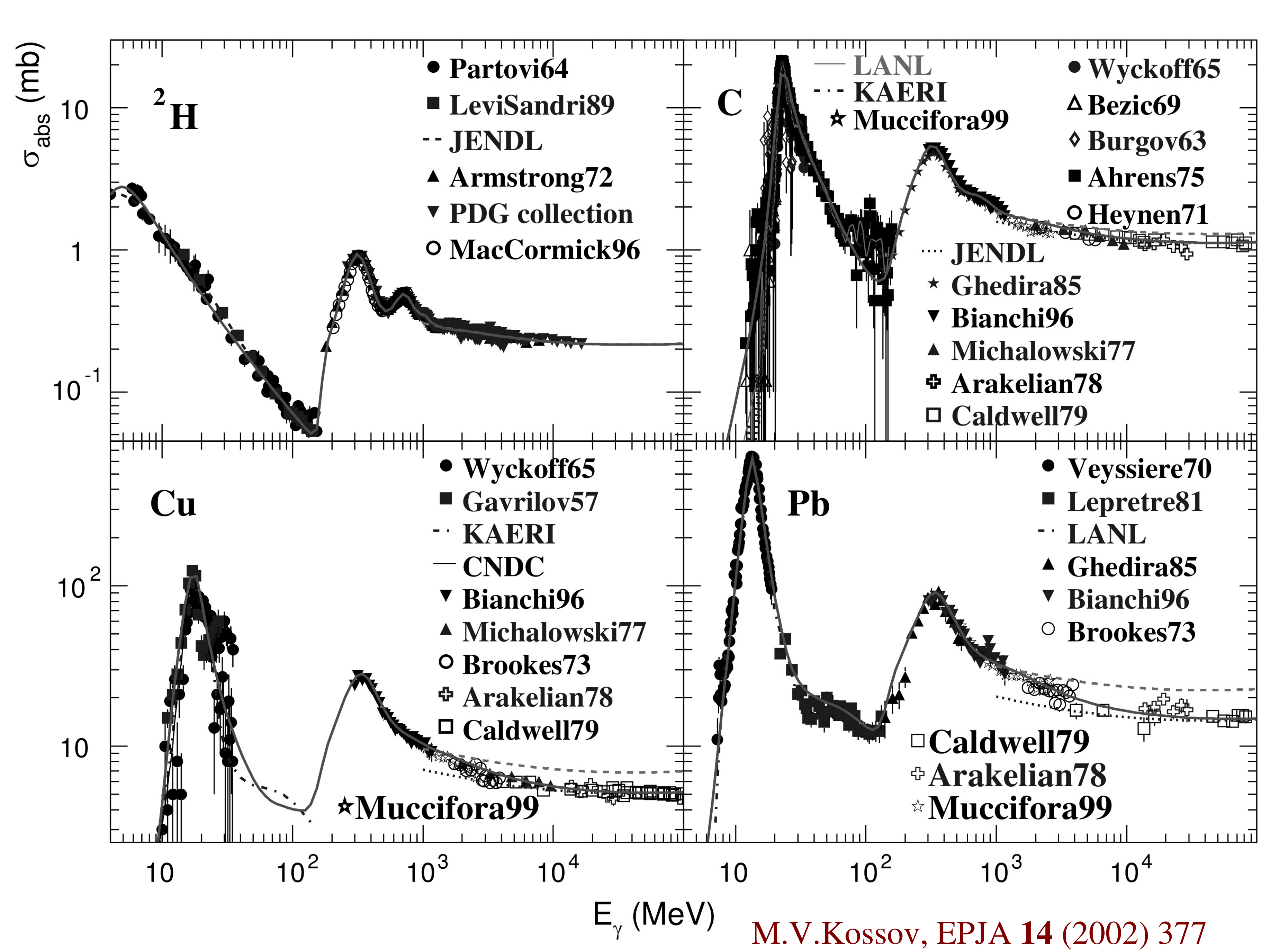


Average number of photons absorbed by (A_2, Z_2) :

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

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

Photoabsorption cross section is specific to target nucleus



M.V.Kossov, EPJA **14** (2002) 377

No precise scaling with *A* or *Z*, each nucleus to be considered individually!

Injection of $^{129}Xe^{54+}$ ions to the LHC has been performed in October, 2017

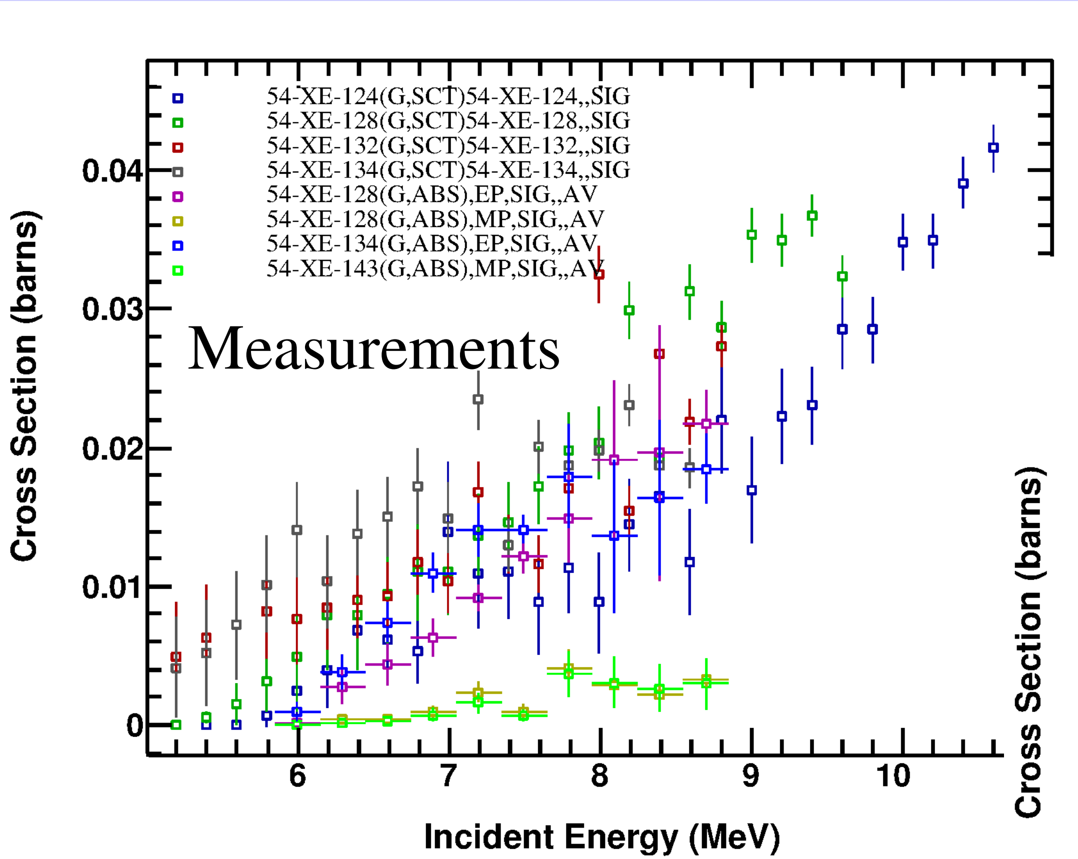
- An option to collide ^{40}Ar in LHC has been discussed few years ago...

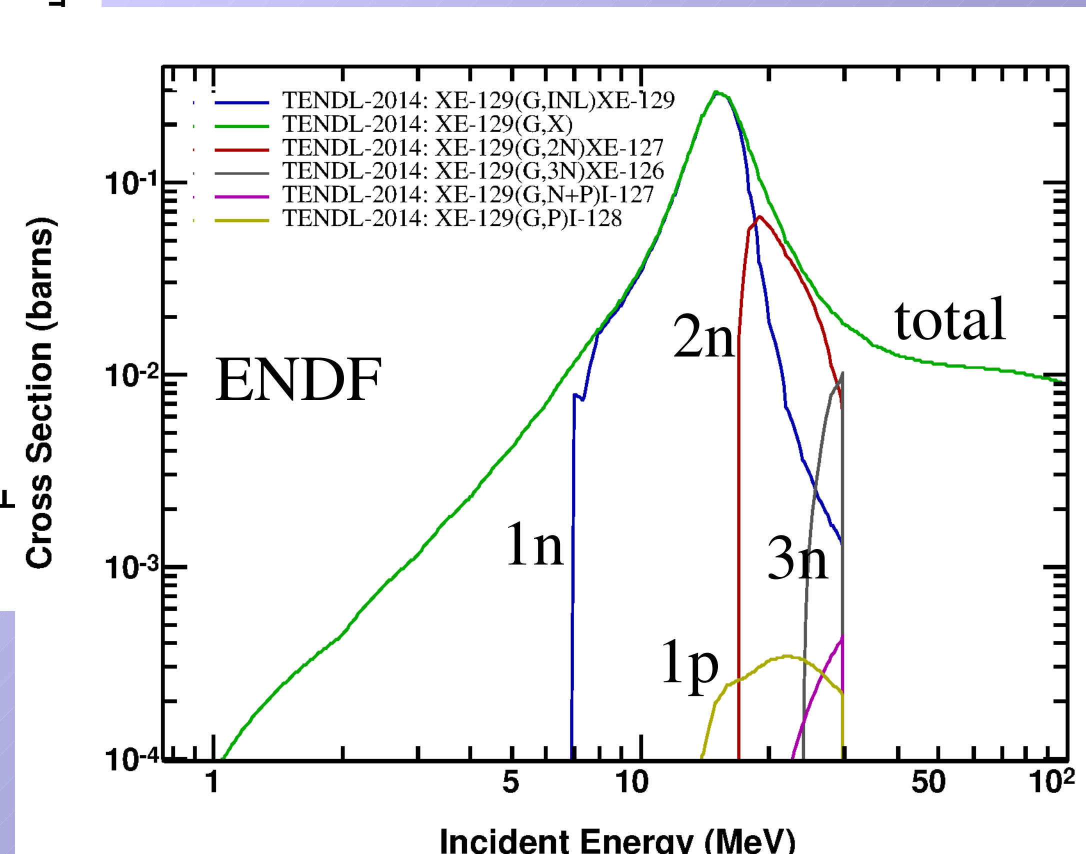
- We need accurate photonuclear cross section data specifically for these nuclei in order to model their ultraperipheral collisions, e.g., for the purpose of luminosity monitoring.

- We have to be confident in data for nuclear radii, nuclear density distribution functions we use in Glauber model and other codes for these new ion species.

- A lot of work for experts in nuclear structure and nuclear reactions!

The case of ^{129}Xe





- No measurements of photon-induced neutron emission for this isotope
- Only rather scarce evaluated nuclear data (TENDL-2014 ENDF library)
- Evaluated data = model-guided inter-/extrapolation of real measurements made by top experts in the field