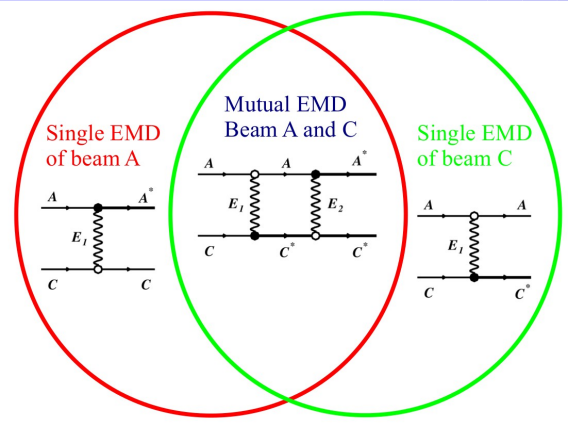
Excitation and decay of relativistic nuclei in ultraperipheral collisions studied with RELDIS and other models

Igor Pshenichnov[1)], Uliana Dmitrieva[1,2)]

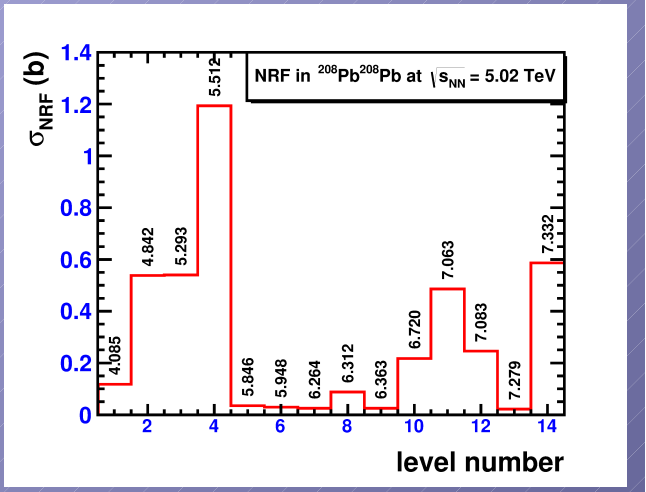
[1)] *Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia*

[2)] *Moscow Institute of Physics and Technology, Moscow Region, Russia*

Igor.Pshenichnov@cern.ch



EMMI workshop
"Challenges in photon induced interactions"
Cracow
6-8 September 2017



Outline of this talk

I. Basics of modeling of electromagnetic dissociation (EMD) of nuclei and other photon-induced processes

II. RELDIS, STARLIGHT and other models on the market

Open issues:

III. Neutronless EMD events

IV. Xe and other nuclei in the LHC

V. Nuclear resonance fluorescence: exciting physics below nucleon separation energy

VI. Conclusions

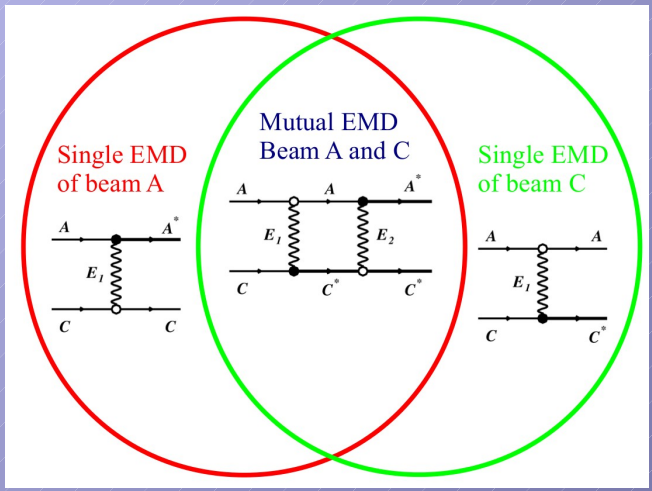
Spectrum of Weizsäcker-Williams photons

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 :

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

$\mathrm{x} = E_1 b / \gamma\beta$ 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)

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

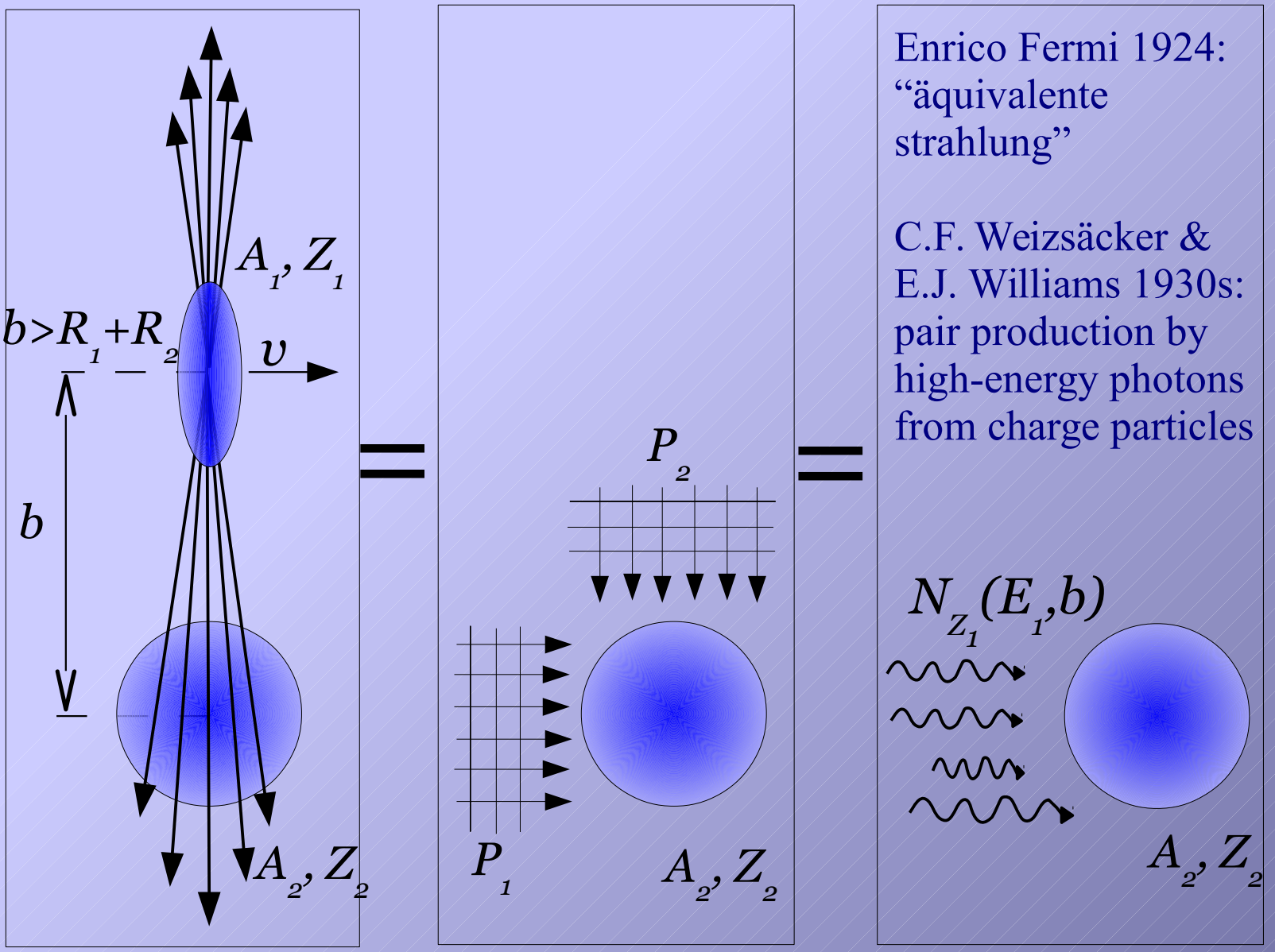
Assume that an ultrarelativitic nucleus $v,\ \gamma = 1/(1-v^2)^{1/2} \gg 1$ is left in its ground state after emission and only a small part of nucleus' kinetic energy is taken away. Together with the coherence condition this gives:

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

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

However, in this talk I will focus on the electromagnetic dissociation (EMD) of nuclei mostly induced by soft photons...

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

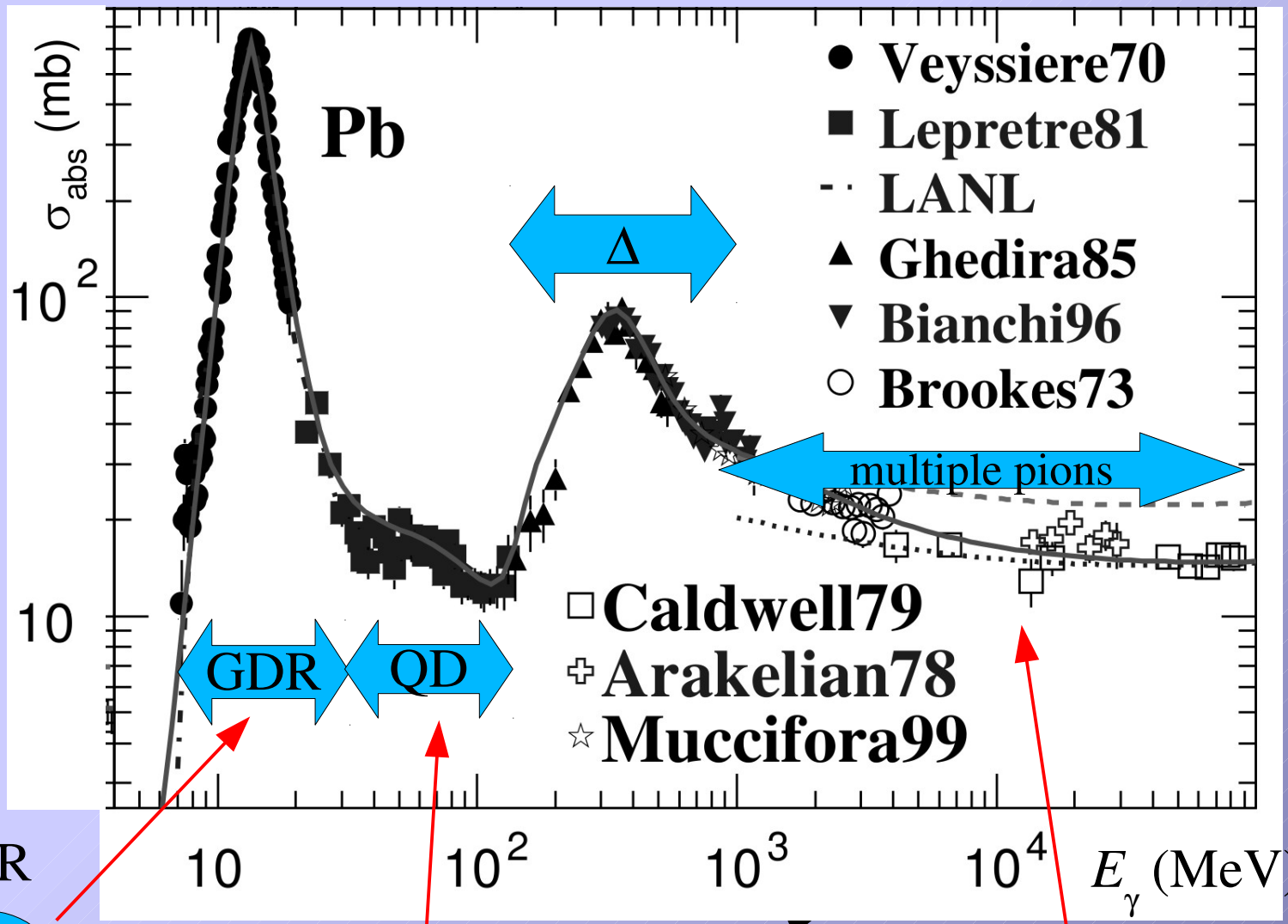


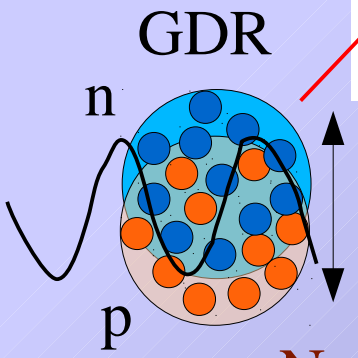
Enrico Fermi 1924: "äquivalente strahlung"

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

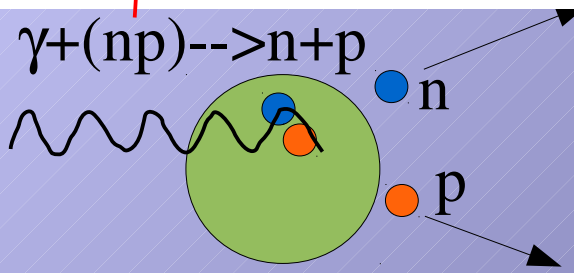
I.P., Phys. Part. Nuclei 42(2011)215

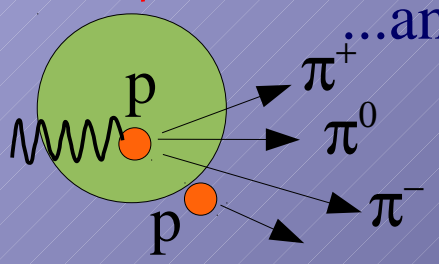
… but also absorb photons and become excited





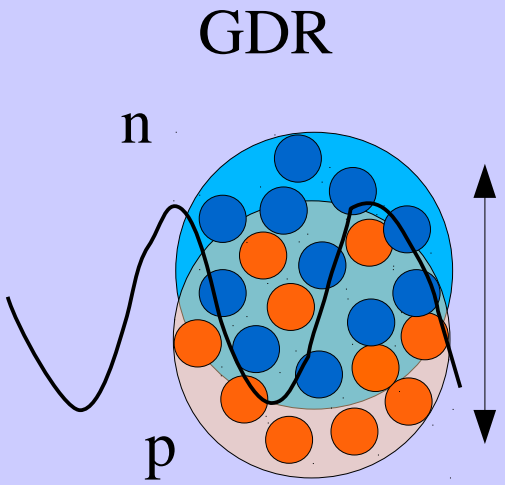
Nucleonic ...

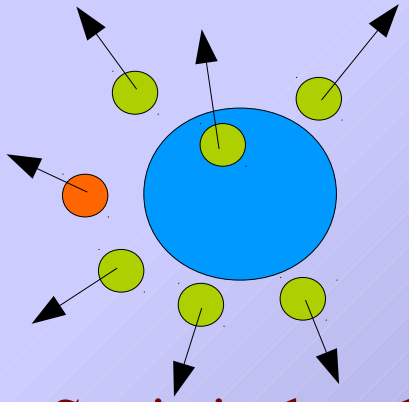




...and hadronic

Decay of photoexcited nuclei: nucleon evaporation, fission or multifragmentation

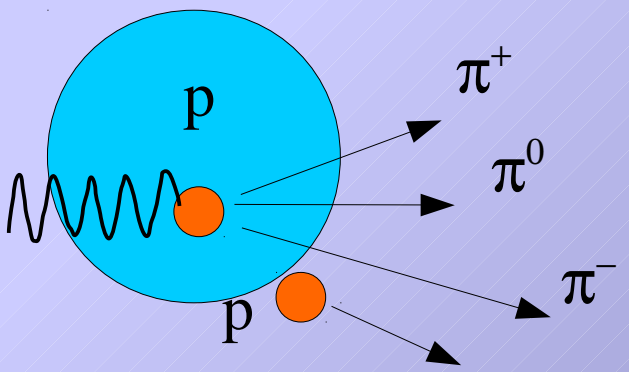


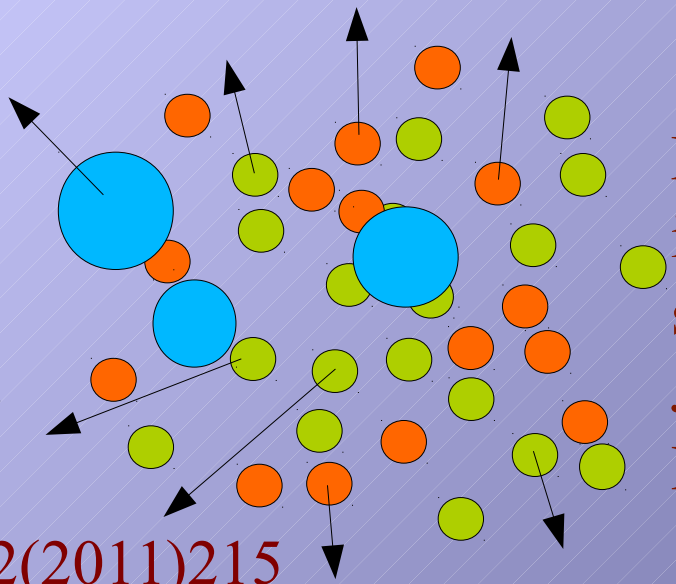


Mostly neutrons are evaporated from heavy nuclei at low excitations

n
p

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

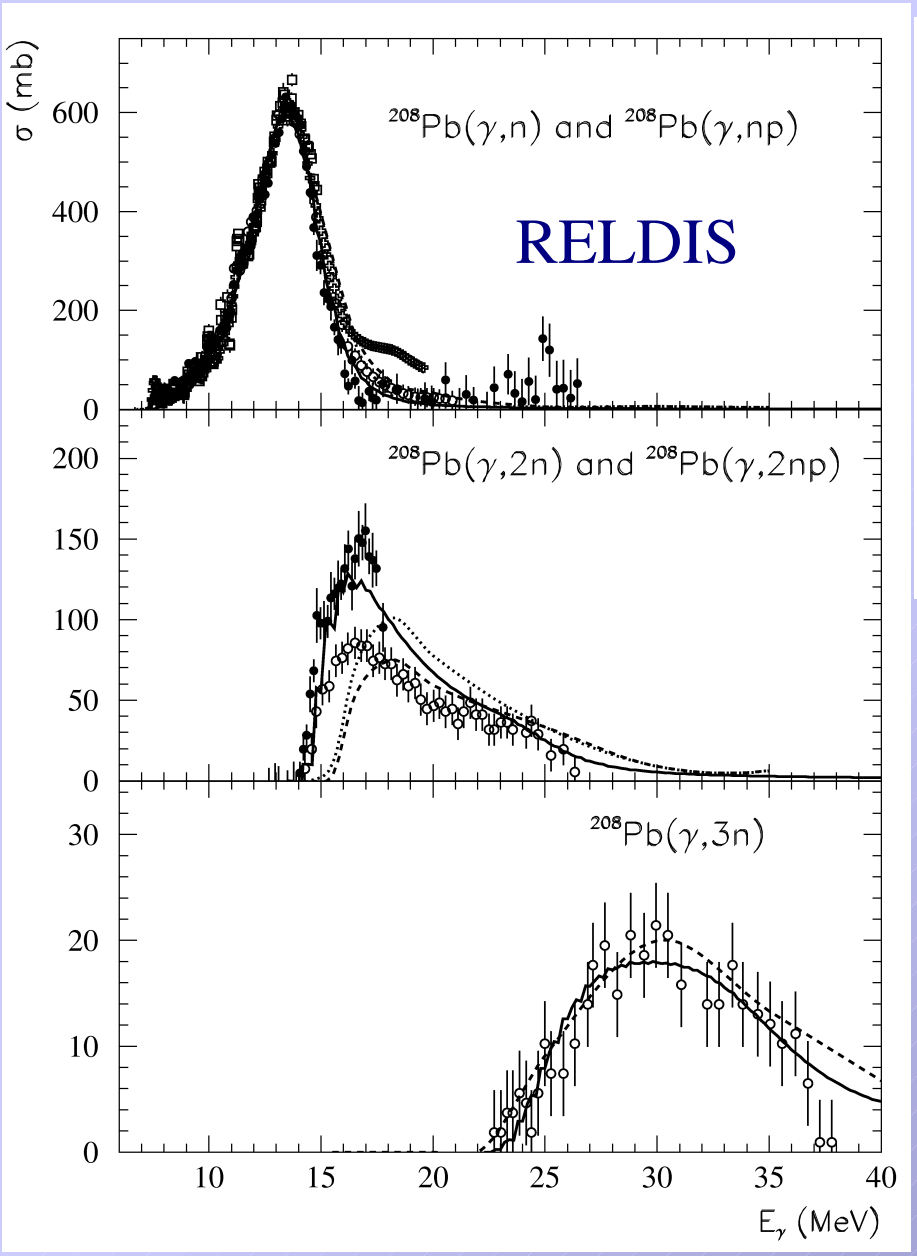
I.P., Phys. Part. Nuclei 42(2011)215

II. RELDIS, STARLIGHT and other models on the market

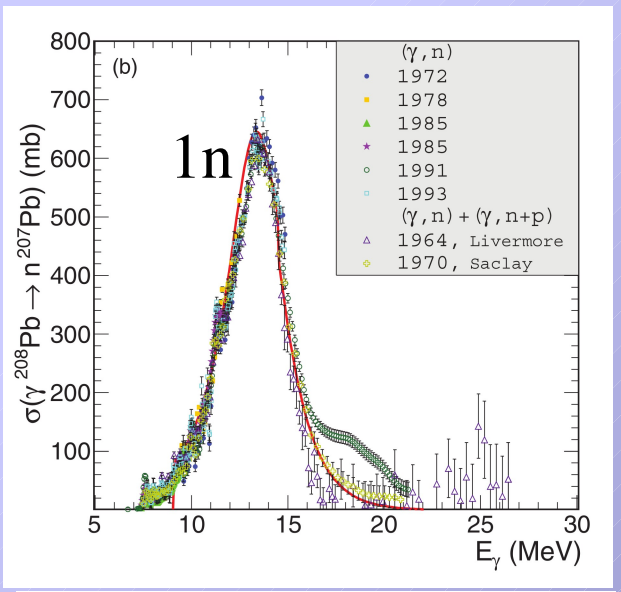
Several models (computer codes) successfully describe nuclear reactions, hadronic/partonic processes induced by WW photons

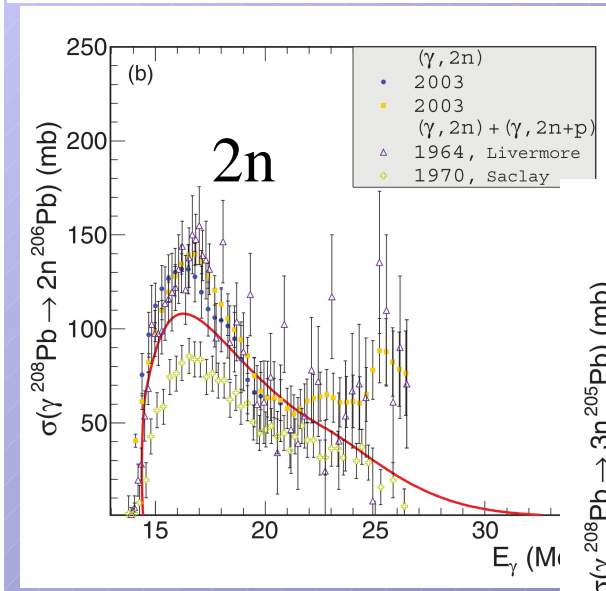
- RELDIS model: I.P., I. Mishustin, J. Bondorf et al., PRC 57 (1998) 1920 and other papers, see I.P., Phys. Part. Nuclei 42(2011)215 for a review
- STARLIGHT: S. Klein, J. Nystrand, Phys. Rev. C 60 (1999) 014903, and other papers, see S.R. Klein, J. Nystrand, J. Seger et al., CPC 212 (2017) 258 for a review, also Joakim's talk Friday morning
- EMD model of FLUKA: H. H. Braun, A. Fasso, A. Ferrari et al., Phys. Rev. ST Accel. Beams 17 (2014) 021006
- Simple EMD model of Geant4, see G4 Physics Reference Manual
- Cracow model: M. Kłusek-Gawenda, M. Ciemała, W. Schafer, A. Szczurek, PRC 89 (2014) 054907

Photoneutron cross sections measured in different laboratories may diverge. Evaluated nuclear data have to be used.



I.P. et al., PRC 64 (2001) 024903

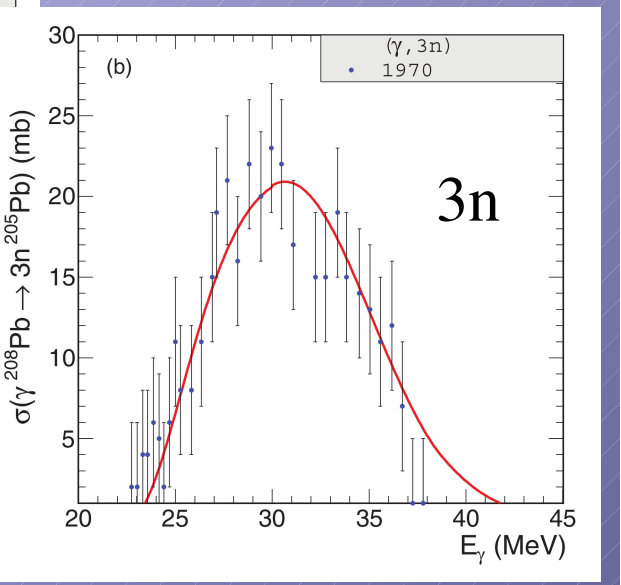




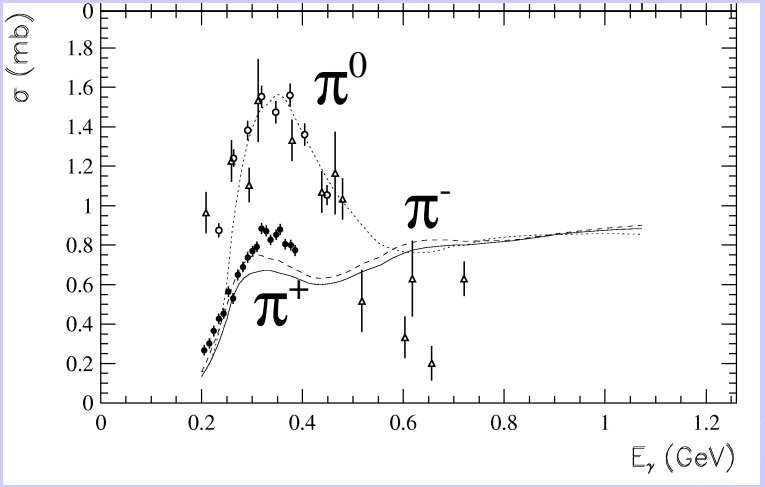
Cracow model

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

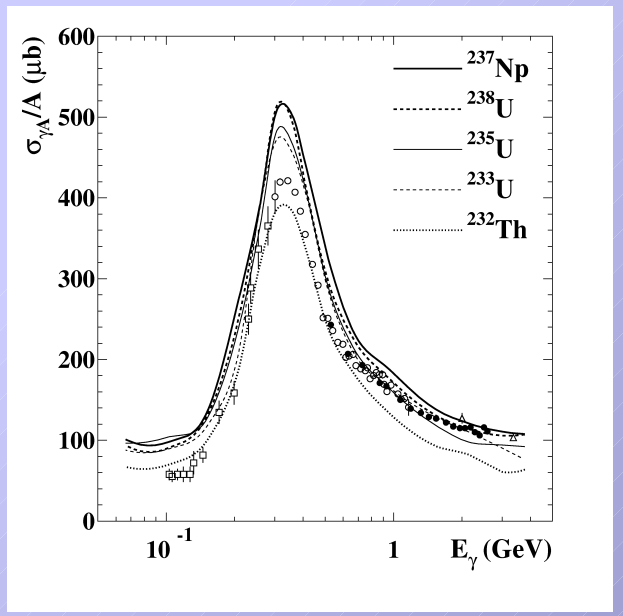
It is important to use reliable data and models to describe EMD of Au and Pb at RHIC and LHC



RELDIS model to describe photoabsorption and EMD

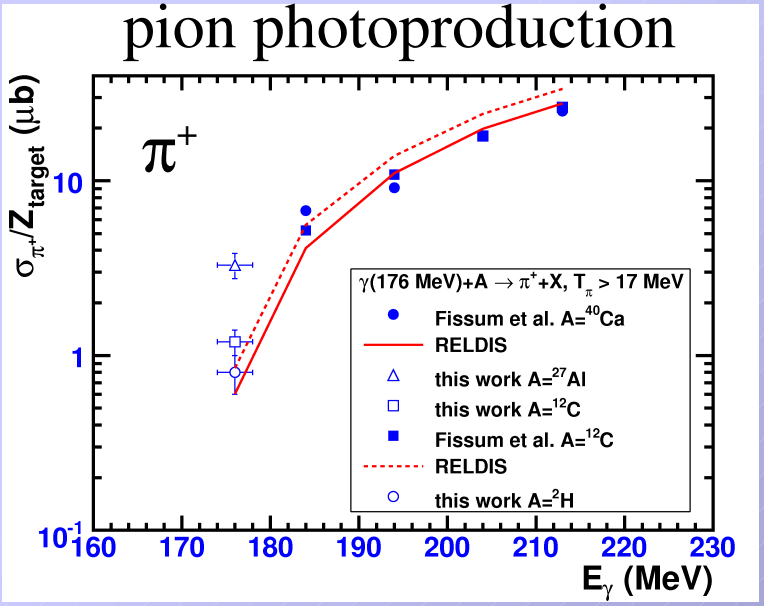


A.S. Iljinov, …, I.P. et al.,
Nucl. Phys. A 616(1997)575

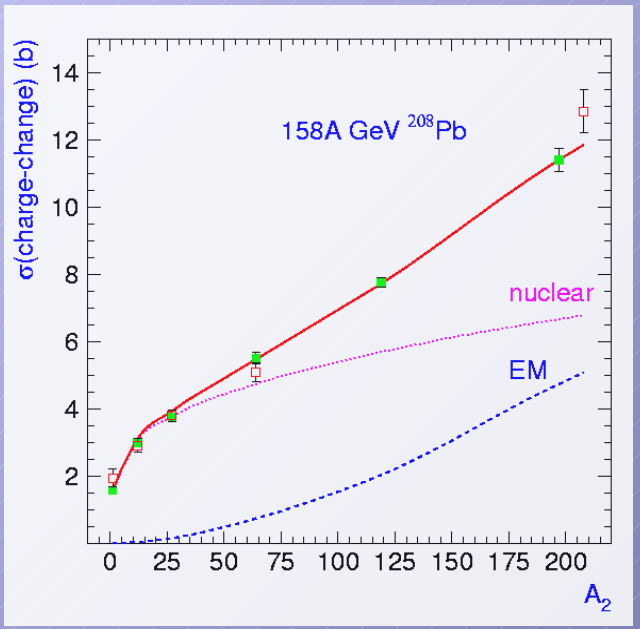


I.P. et al.,
Eur. J. Phys. A
24(2005)69
fission of
heavy nuclei by
photons

pion photoproduction



P.Golubev, …, I.P. et al.,
Nucl. Phys. A 806(2008)216

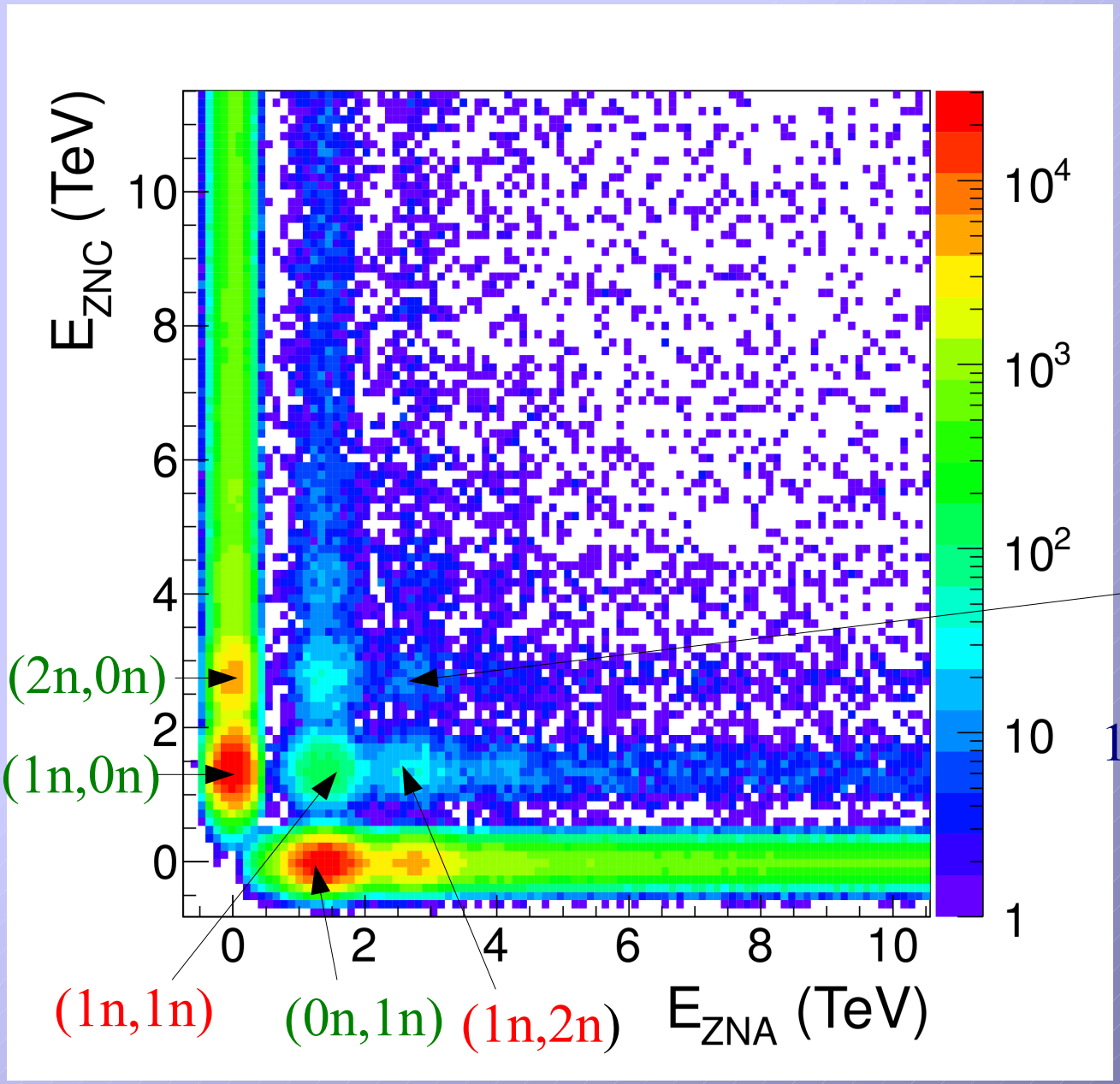


20+ papers since 1995

C. Scheidenberger,
I.P. et al.,
Phys. Rev. C
70(2004)014902

Electromagnetic
dissociation at
SIS (GSI),
AGS (BNL),
CERN SPS

Emission of forward neutrons as seen by ALICE in ultraperipheral Pb-Pb collisions



Event examples:

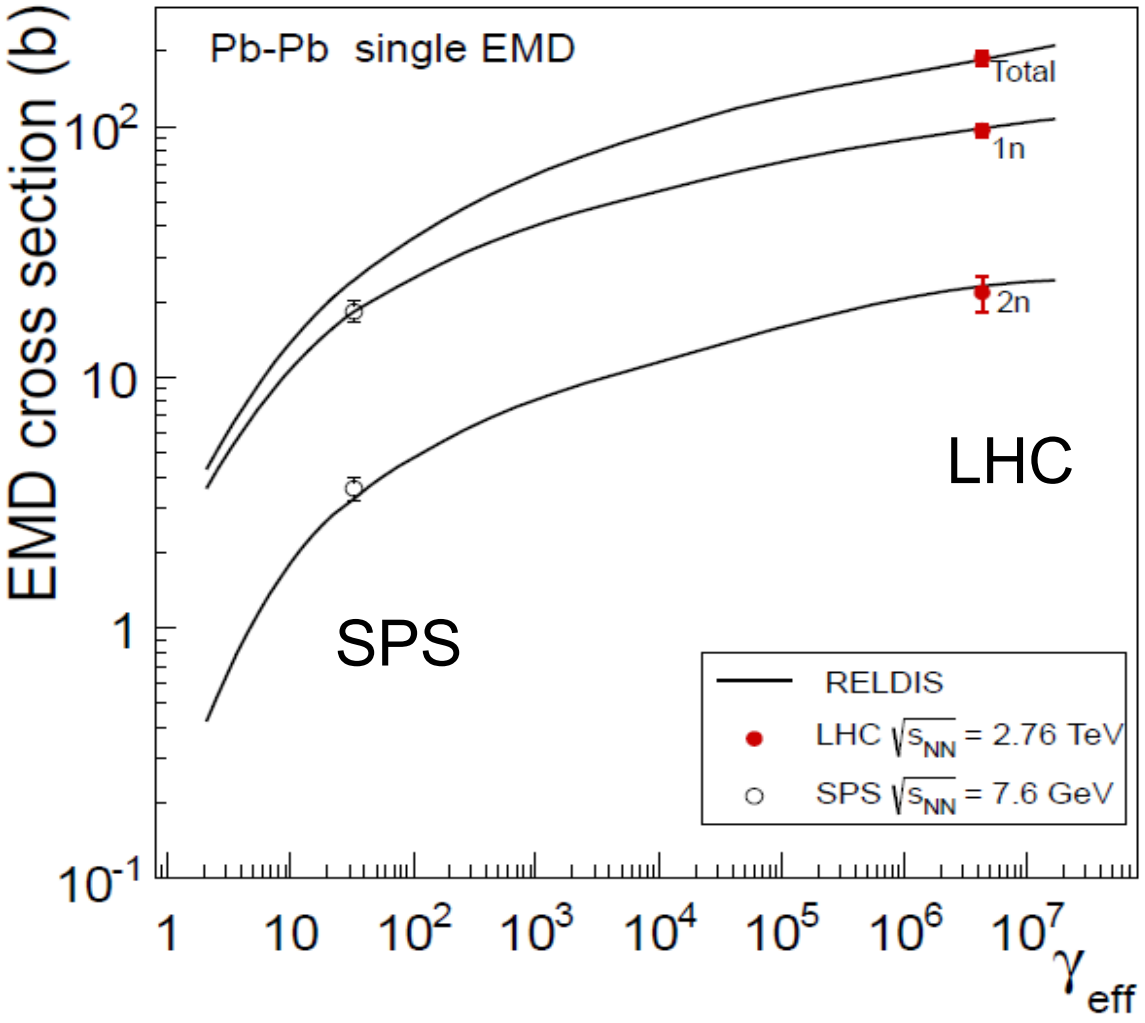
EMD of only one beam labeled in green

Mutual EMD in red

1.38A+1.38A TeV

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

Neutrons from PbPb UPC measured at the LHC vs RELDIS



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

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

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

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

Forward neutrons detected by Zero Degree Calorimeters (ZDC) have been used by ALICE, ATLAS and CMS:

- to determine the collision centrality
  ALICE Collaboration, Phys. Rev. C 88 (2013) 044909

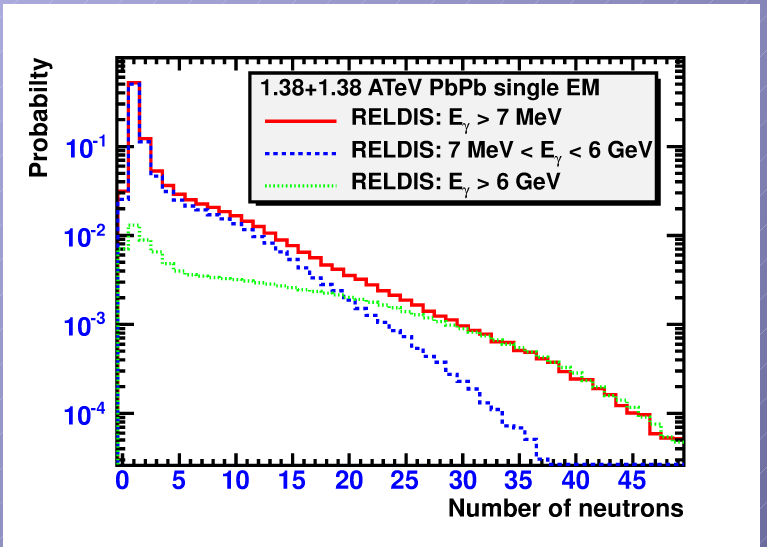
- to study EMD of lead nuclei in ultraperipheral collisions
  I.P., Phys. Part. Nucl. 42 (2011) 215–250 (RELDIS model)
  ALICE Collaboration, Phys. Rev. Lett. 109 (2012) 252302,
  see Chiara Oppedisano presentation

- 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 collider luminosity
  A.Morsch, I.P., LHC Experimental conditions, ALICE Int. note 2002-034

bibliography is incomplete ...

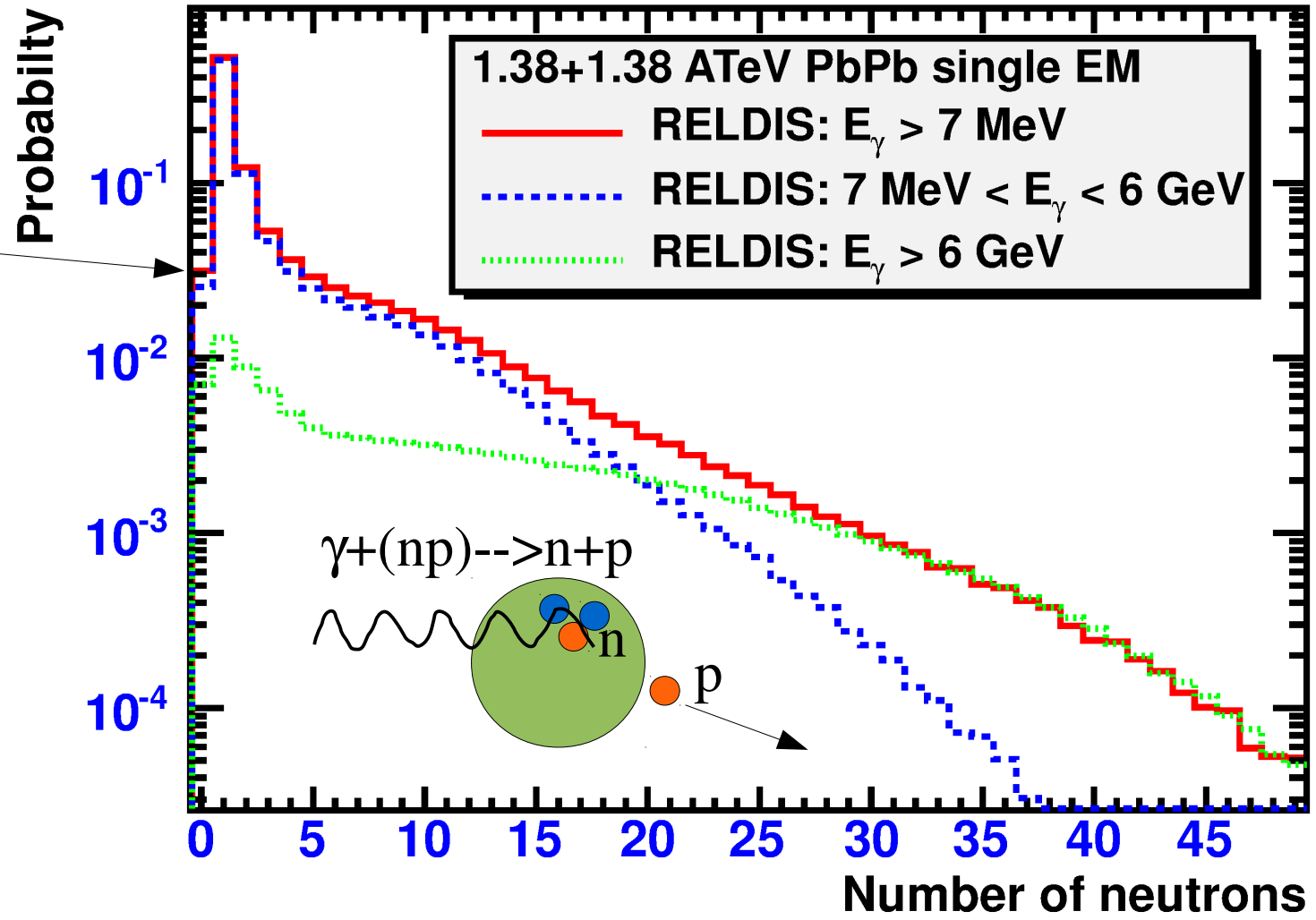
III. Neutronless EMD events



Neutron multiplicity distribution in UPC

RELDIS model: ~3% of EMD events contain no neutrons

Mostly due to photons of relatively low energy, GDR, QD absorption

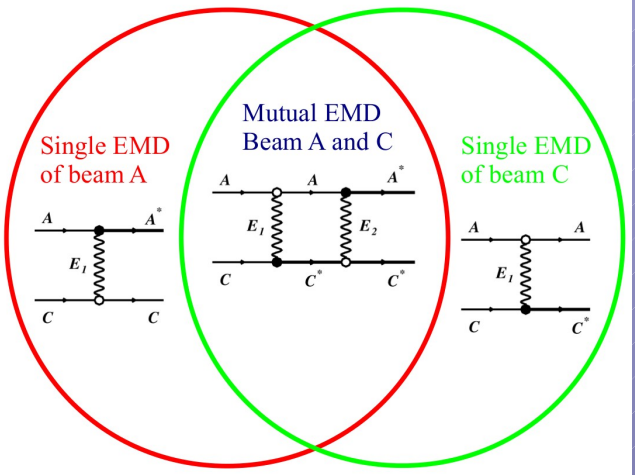


$$\sigma_{tot}(\gamma Pb) > \sigma(\gamma Pb \to kn), k = 1, 2, 3...$$

Neutronless UPC events

Collision energy sqrt(s_{NN}) (TeV)	Total single EMD cross section of **neutron emission** (at least one neutron in one ZDC) (b)		Total mutual EMD cross section of **neutron emission** (at least one neutron in both ZDCs) (b)	
	RELDIS model [f] (LO+NLO)	ALICE Measurements [g]	RELDIS model [f] (LO+NLO)	ALICE Measurements [g]
2.76	185.2±9.2	187.4±0.2 (stat) +13.2 -11.2 (syst)	5.5±0.6	5.7±0.1 (stat) ±0.4 (syst)
5.02	205.3±10.3		5.8±0.6	

Collision energy sqrt(s_{NN}) (TeV)	Total single EMD cross section of **pure proton emission** (at least one proton in one ZDC **and without neutrons**) (b)		Total mutual EMD cross section of **pure proton emission** (at least one proton in both ZDCs **and without any neutrons**) (b)	
	RELDIS model [f] (LO+NLO)	ALICE Measurements [g]	RELDIS model [f] (LO+NLO)	ALICE Measurements [g]
5.02	6.1±0.6		0.36	

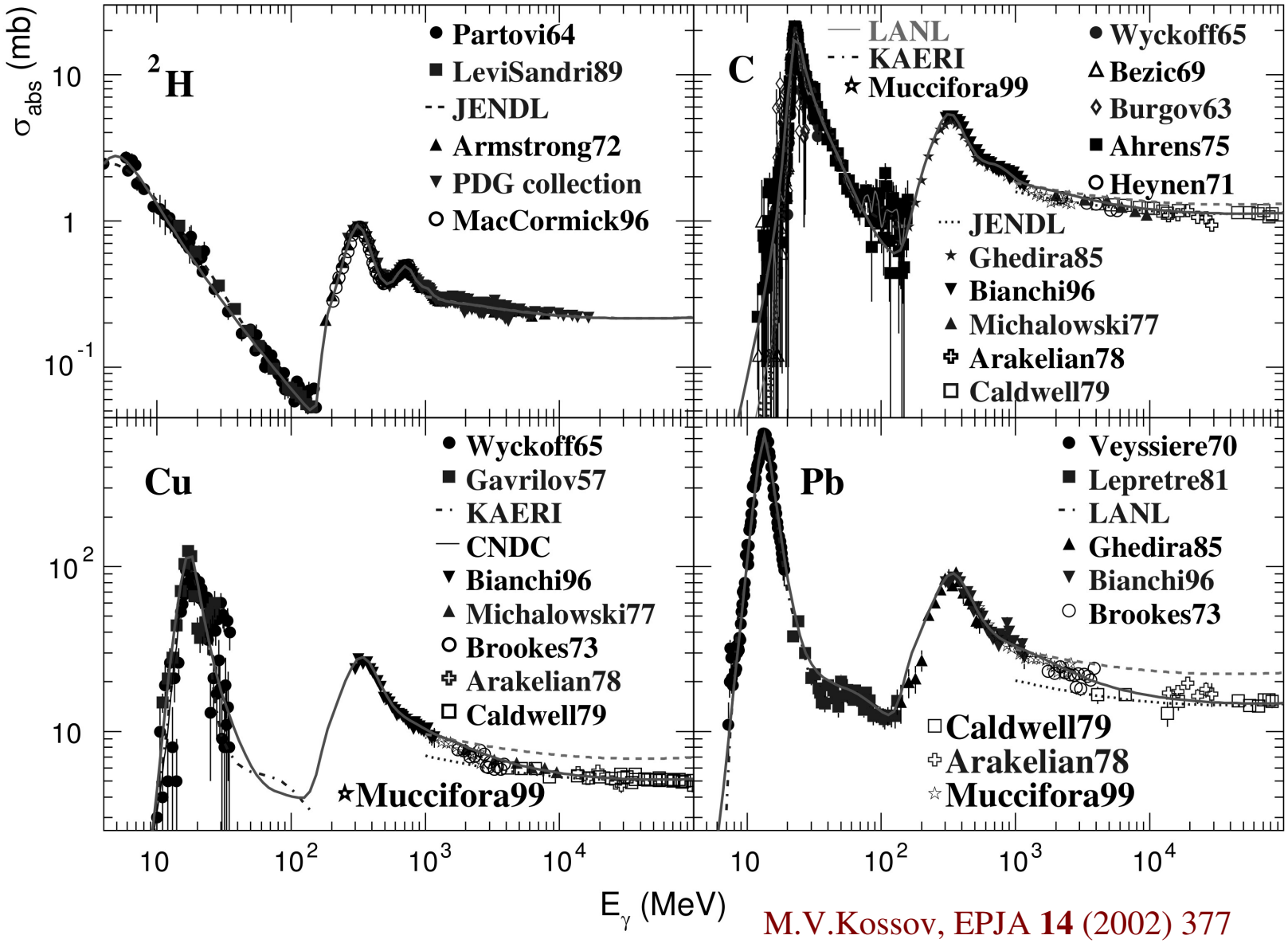


[f] I.A. Pshenichnov et al., PRC 64 (2001) 024903 http://link.aps.org/doi/10.1103/PhysRevC.64.024903; I.A. Pshenichnov, Phys. Part. Nuclei 42 (2011) 215 http://link.springer.com/10.1134/S1063779611020067

[g] ALICE Collaboration, Phys. Rev. Lett. 109 (2012) 252302 http://link.aps.org/doi/10.1103/PhysRevLett.109.252302

III. Xe and other nuclei in the LHC

Photoabsorption cross section is specific to target nucleus



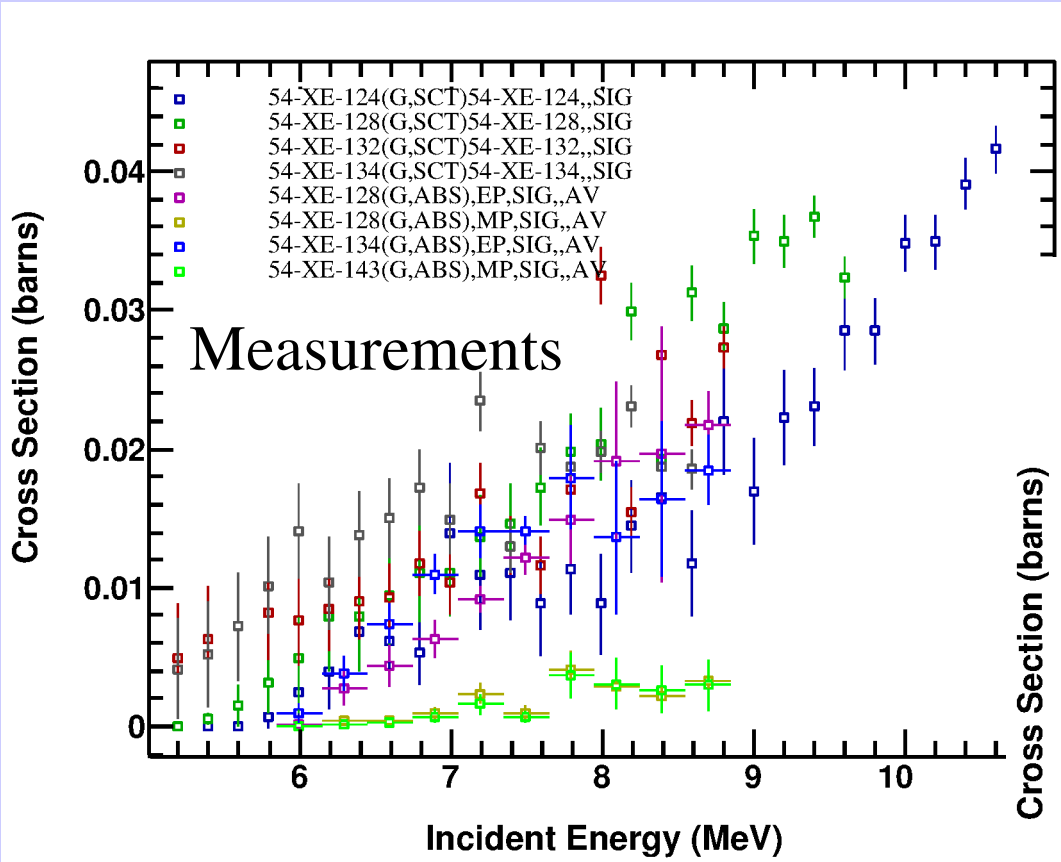
M.V.Kossov, EPJA **14** (2002) 377

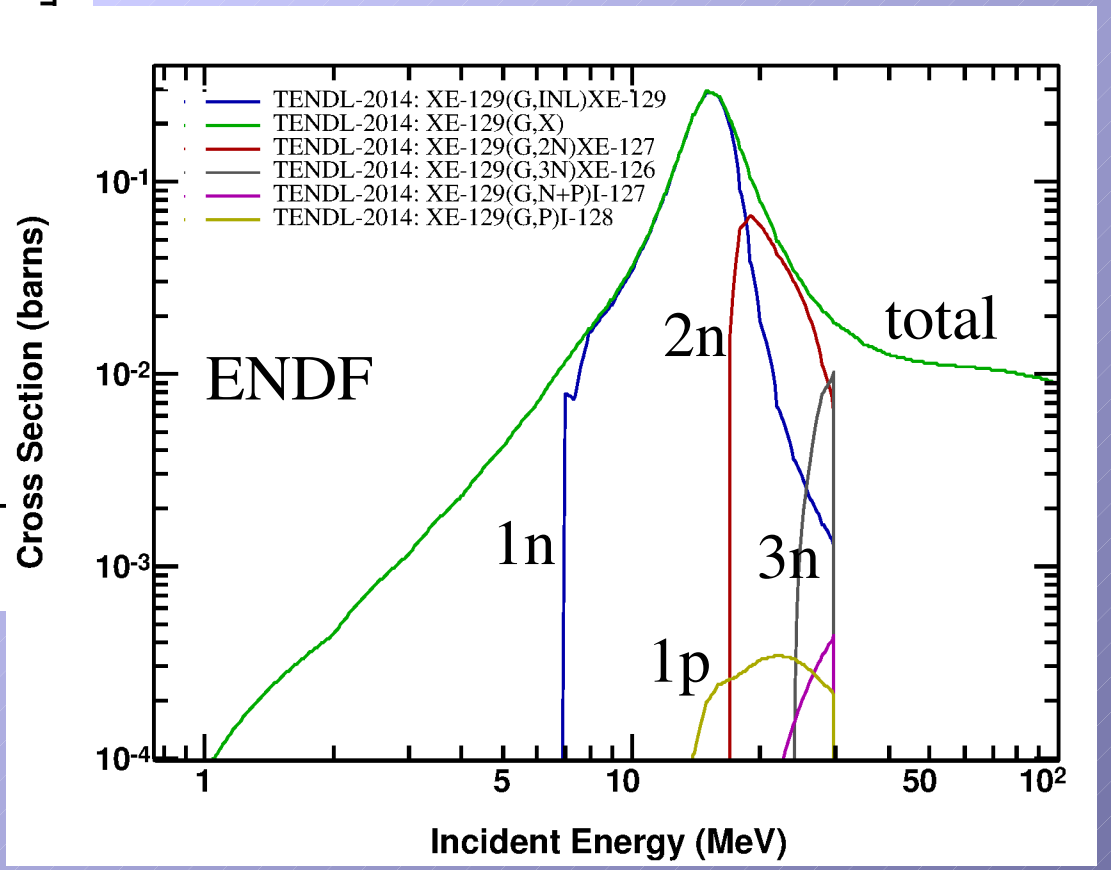
No accurate scaling with *A* or *Z*, each nucleus to be considered individually!

Injection of $^{129}Xe^{54+}$ ions to LEIR, SPS, NA is planned at CERN in 2017

- A possibility to collide ^{129}Xe in LHC has been considered as well...
- 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!

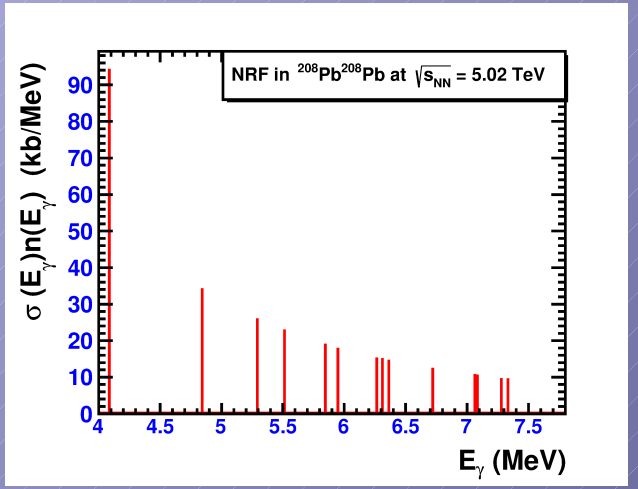
The case of ^{129}Xe





- 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

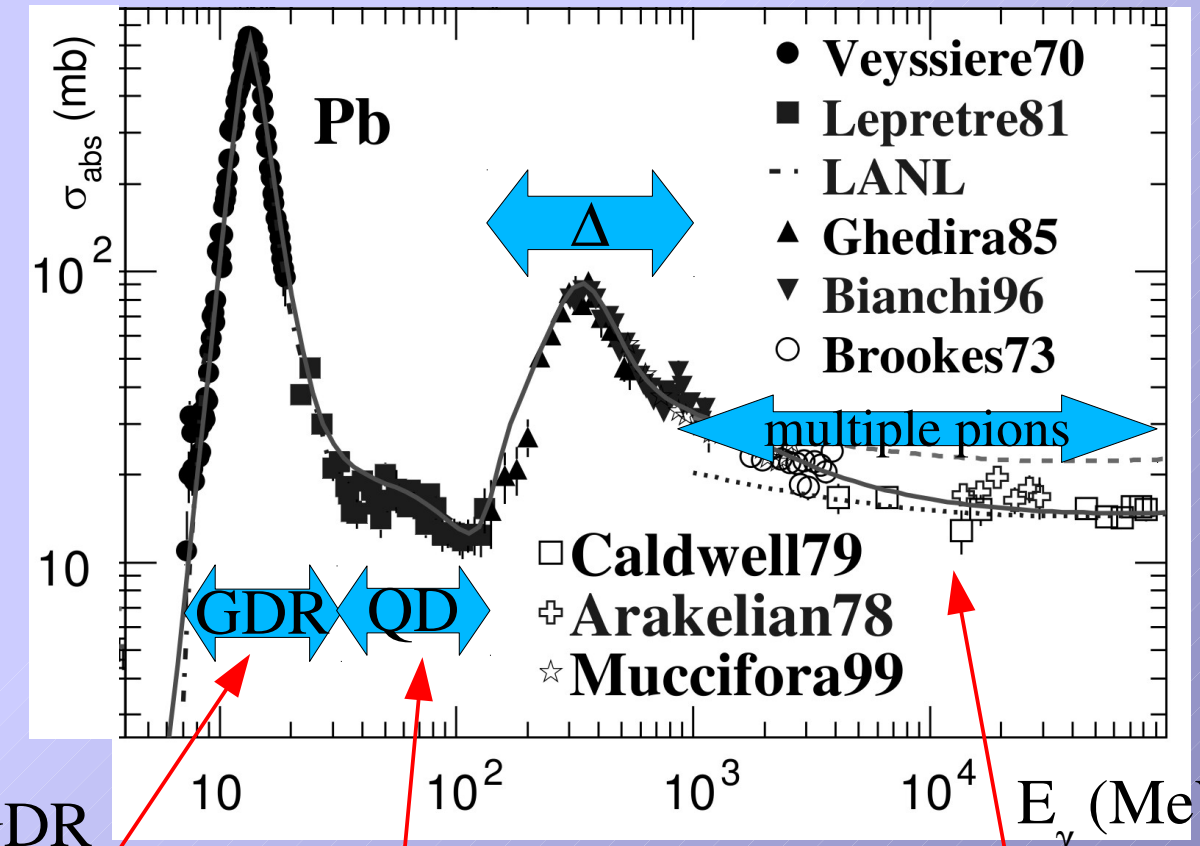
V. Nuclear resonance fluorescence: exciting physics below nucleon separation energy

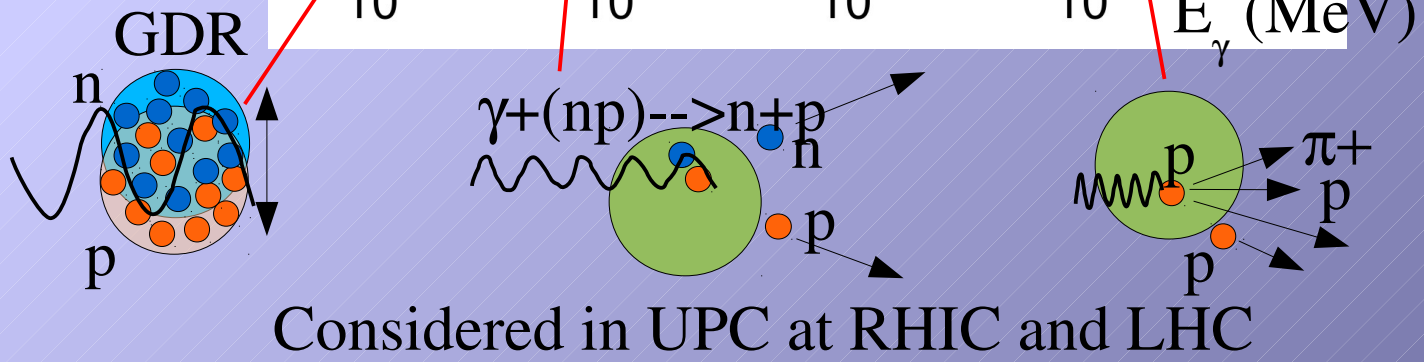


Nuclear excitations by virtual photons in UPC below nucleon emission threshold?

?

E_γ<7MeV

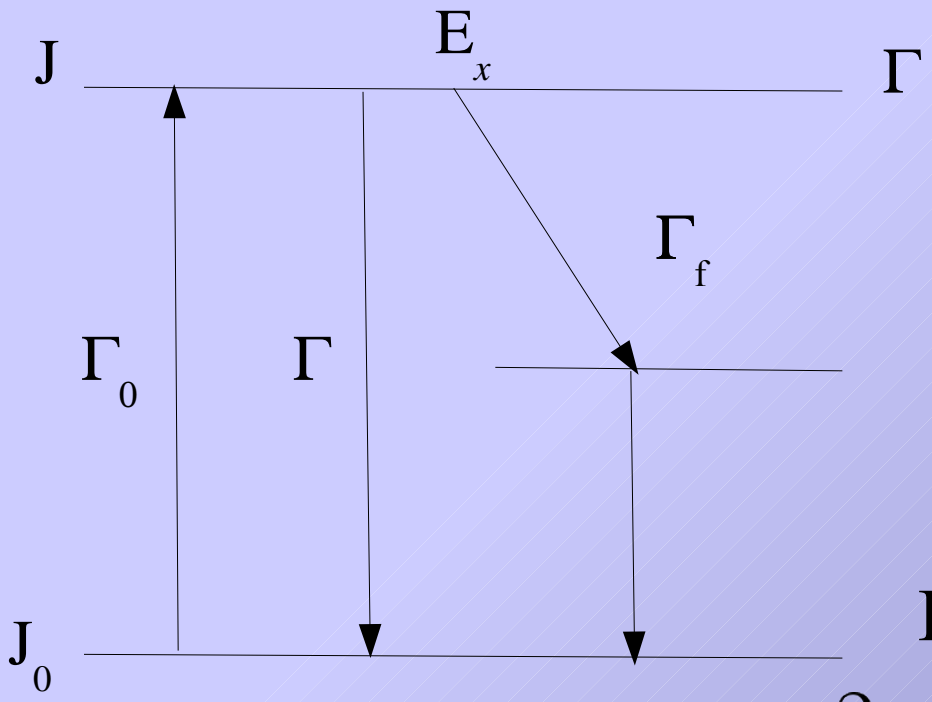


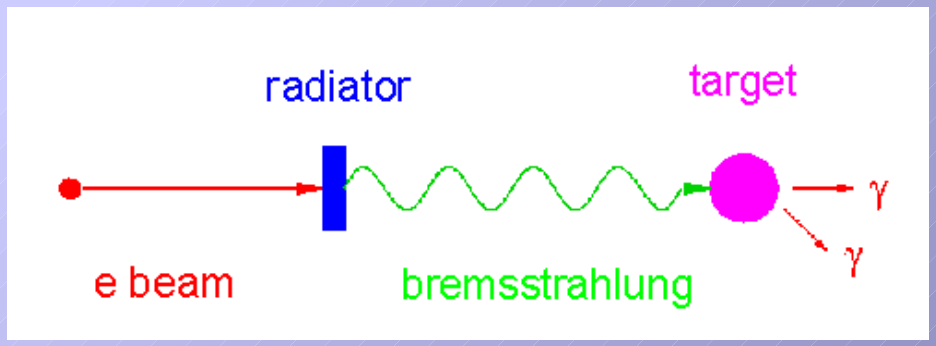


Considered in UPC at RHIC and LHC

Probing parton content of nucleon, nPDF

Excitation of discrete levels in ^{208}Pb via photon absorption: nuclear resonance fluorescence (NRF)





Pure NRF: decay back to the ground state

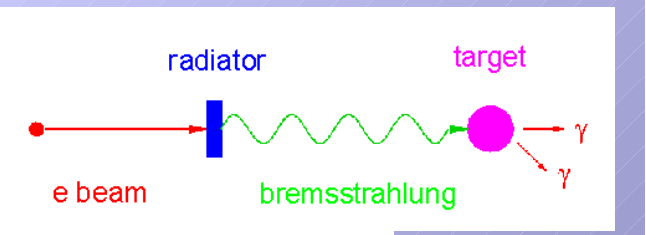
Breit-Wigner resonance shape

$$\sigma(E_\gamma) = \frac{\pi}{2}\left(\frac{\hbar c}{E_x}\right)^2 g \frac{\Gamma_0^2}{(E_\gamma - E_x)^2 + \Gamma^2/4}$$

$$g = (2J+1)/(2J_0+1)$$

$\Gamma_0 \approx \Gamma$ for most of low-lying levels in Pb

Nuclear resonance fluorescence (NRF) experiments on ^{208}Pb



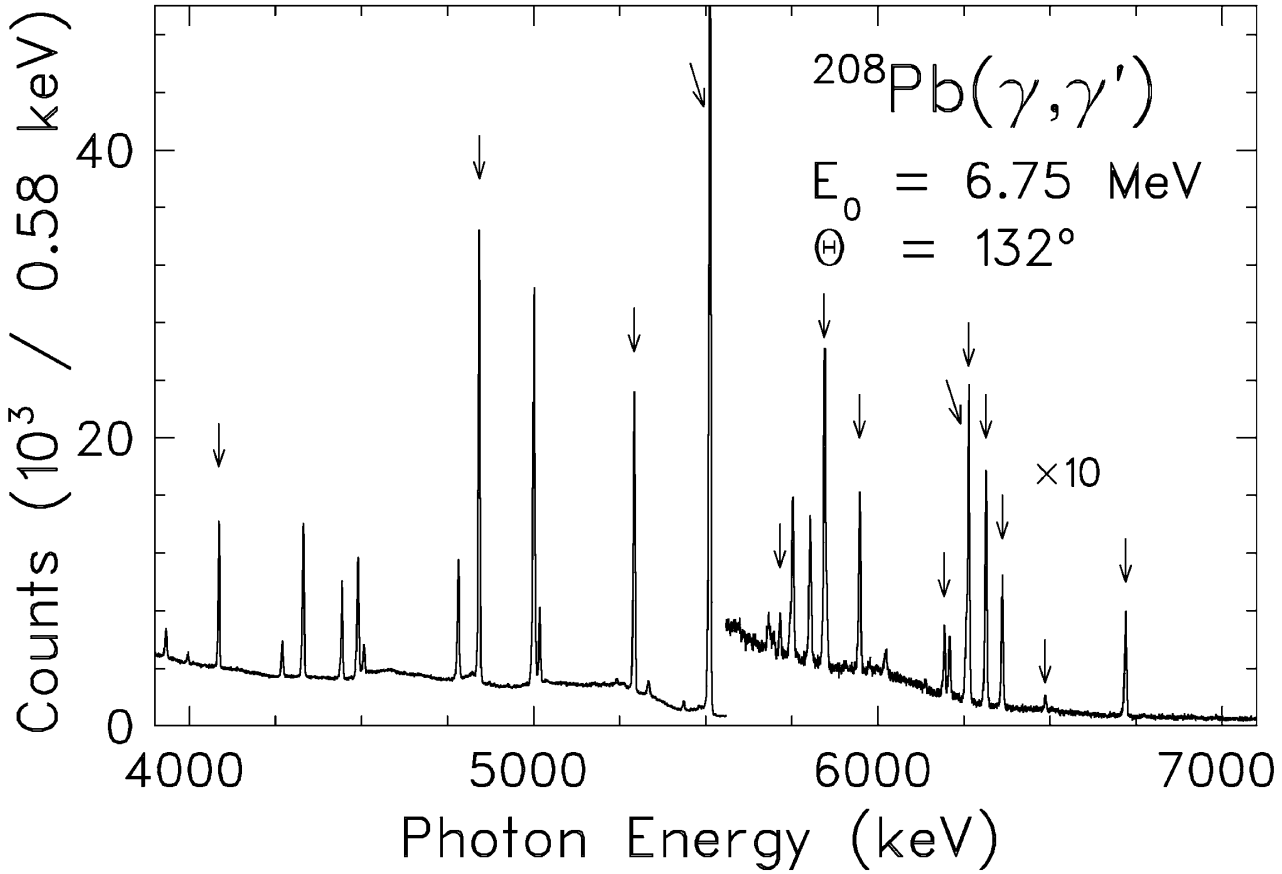
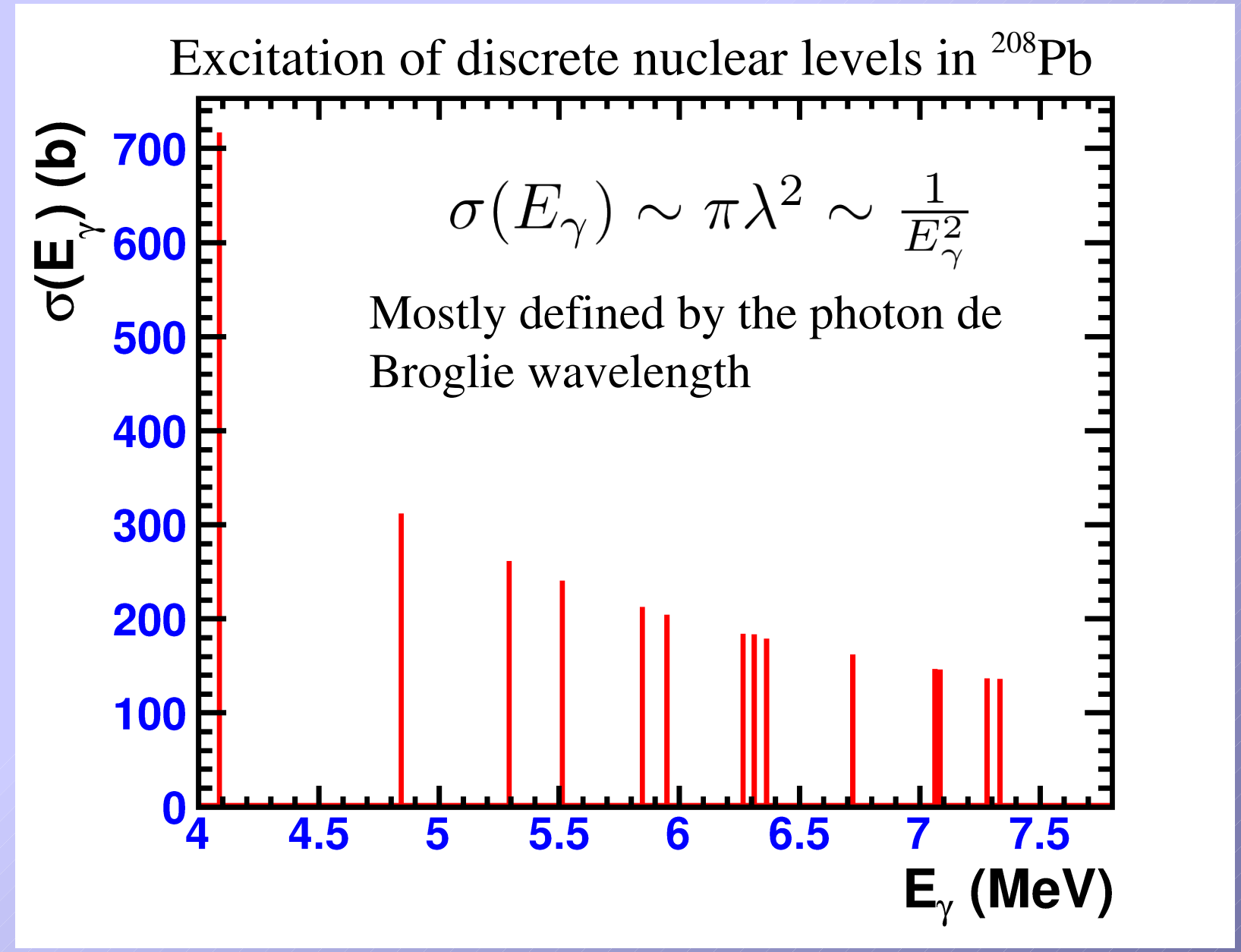


Fig. 2. Spectrum of the ^{208}Pb(γ, γ') reaction taken with the Euroball-Cluster detector at 132° at an endpoint energy of 6.75 MeV. Arrows mark transitions into the ground state of ^{208}Pb.

Many very high (~100 b), but quite thin (< 0.1 keV) peaks



It was proposed to build a free-electron laser facility near the LHC to study such excitations ...

Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Instruments and Methods in Physics Research A 552 (2005) 440–448
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

CLIC–LHC-based FEL–nucleus collider: Feasibility and physics search potential

Omer Yavas[a,*], Roberto Corsini[b], Hans Braun[c], Saleh Sultansoy[c,d], Ekber Guliyev[c], Senay Yigit[a,e], Aynur Ozcan[d]

[a]*Department of Engineering of Physics, Faculty of Engineering, Ankara University, 06100 Tandogan, Ankara, Turkey*
[b]*CERN, CH-1211, Genève 23, Switzerland*
[c]*Institute of Physics Academy of Sciences, H. Cavid Ave. 33, Baku, Azerbaijan*
[d]*Department of Physics, Faculty of Arts and Science, Gazi University, 06500 Teknikokullar, Ankara, Turkey*
[e]*Turkish Atomic Energy Authority, 06530 Lodullu, Ankara, Turkey*

Received 29 March 2005; accepted 29 June 2005
Available online 20 July 2005

Quite expensive and challenging project

Hopefully, with WW photons we can performe such studies for free ...

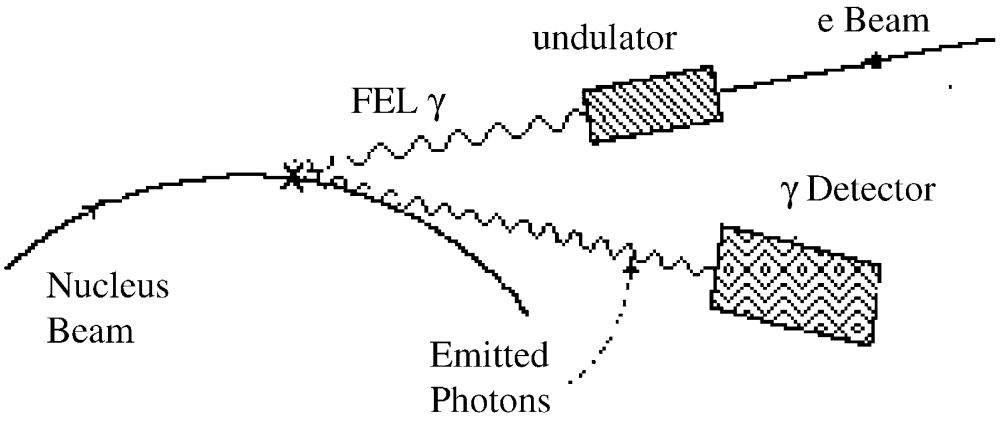


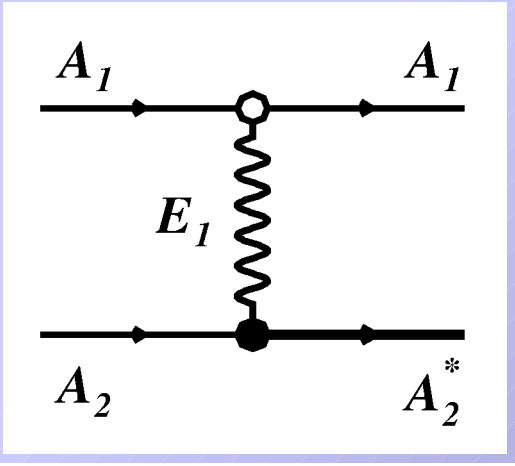
Fig. 1. Schematic view of the FEL–nucleus collider.

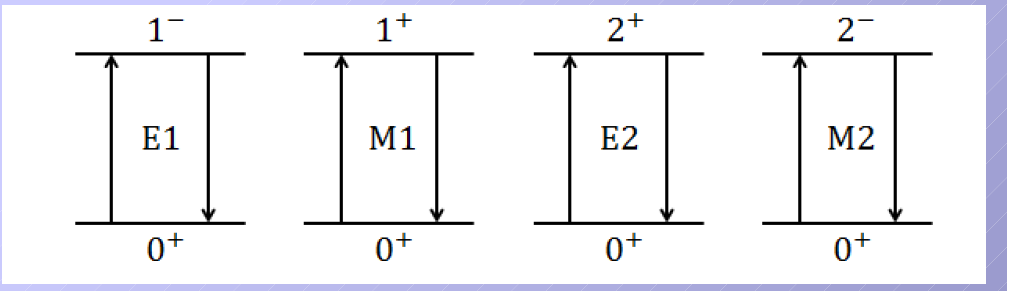
Estimating the rates of nuclear excitations by WW photons in UPC

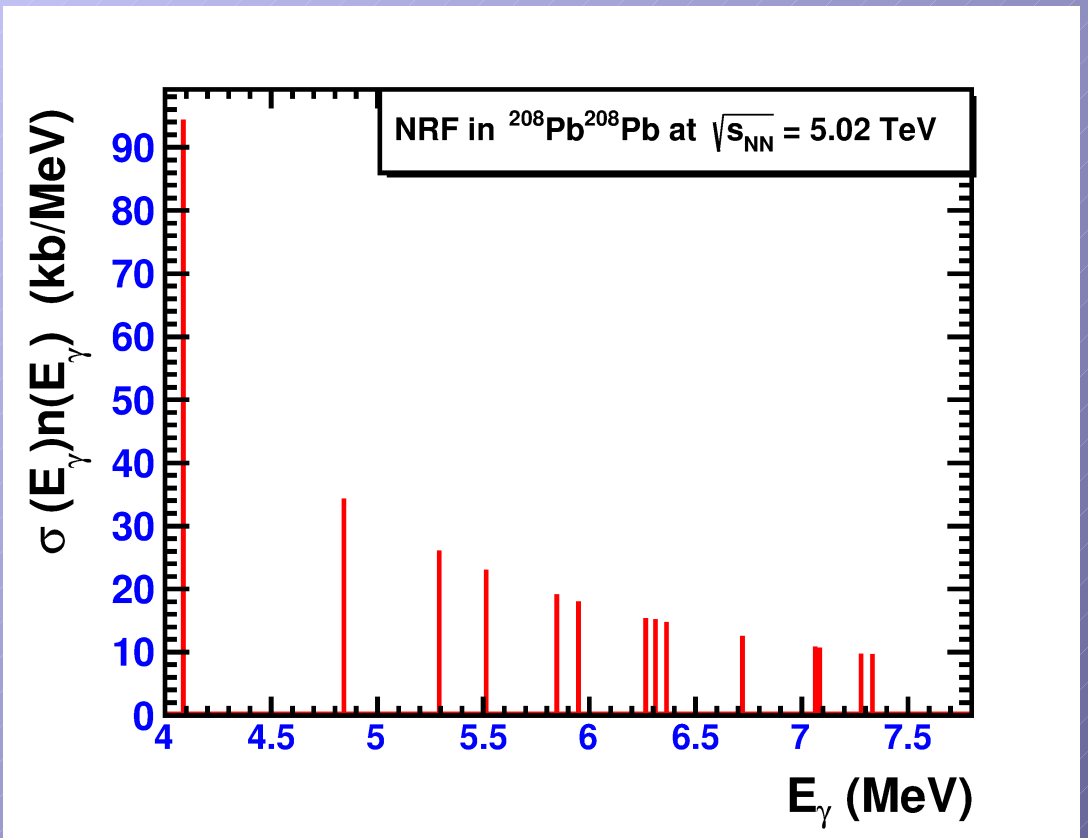
Transition to the nuclear ground state after photon emission is assumed.

Actual angular distributions of emitted photons are not important and assumed isotropic in the nuclear rest frame, because all photons are compressed into a narrow forward cone.

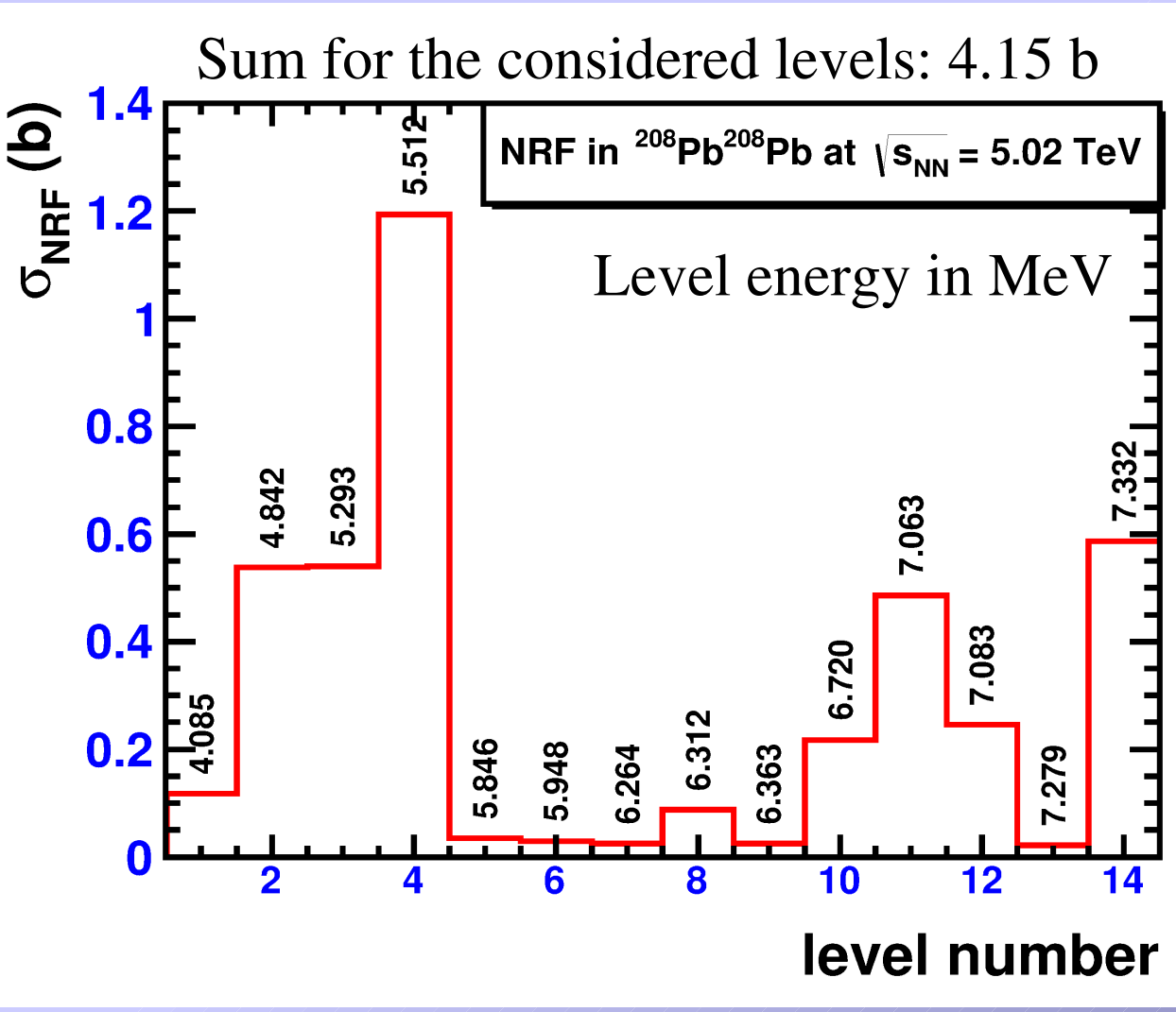
WW spectra have the same shape for all multipolarities E1, M1, E2 (valid for ultrarelativistic nuclei)







NRF cross section at the LHC



$$n_{WW}(E_\gamma) \sim \frac{1}{E_\gamma}$$

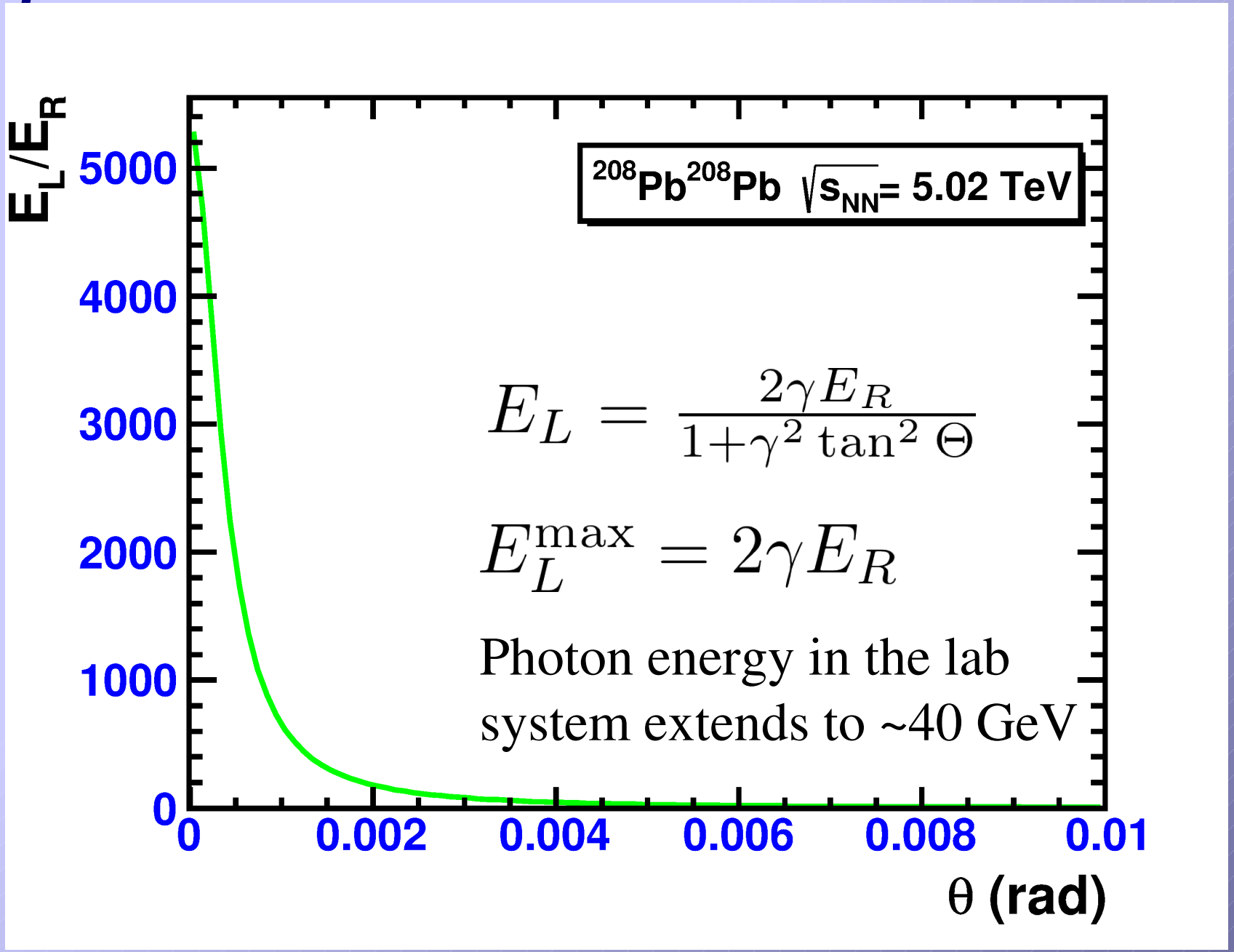
Contribution of low-lying levels is enhanced

Because of thin peaks the average of n_{ww} can be used within each peak

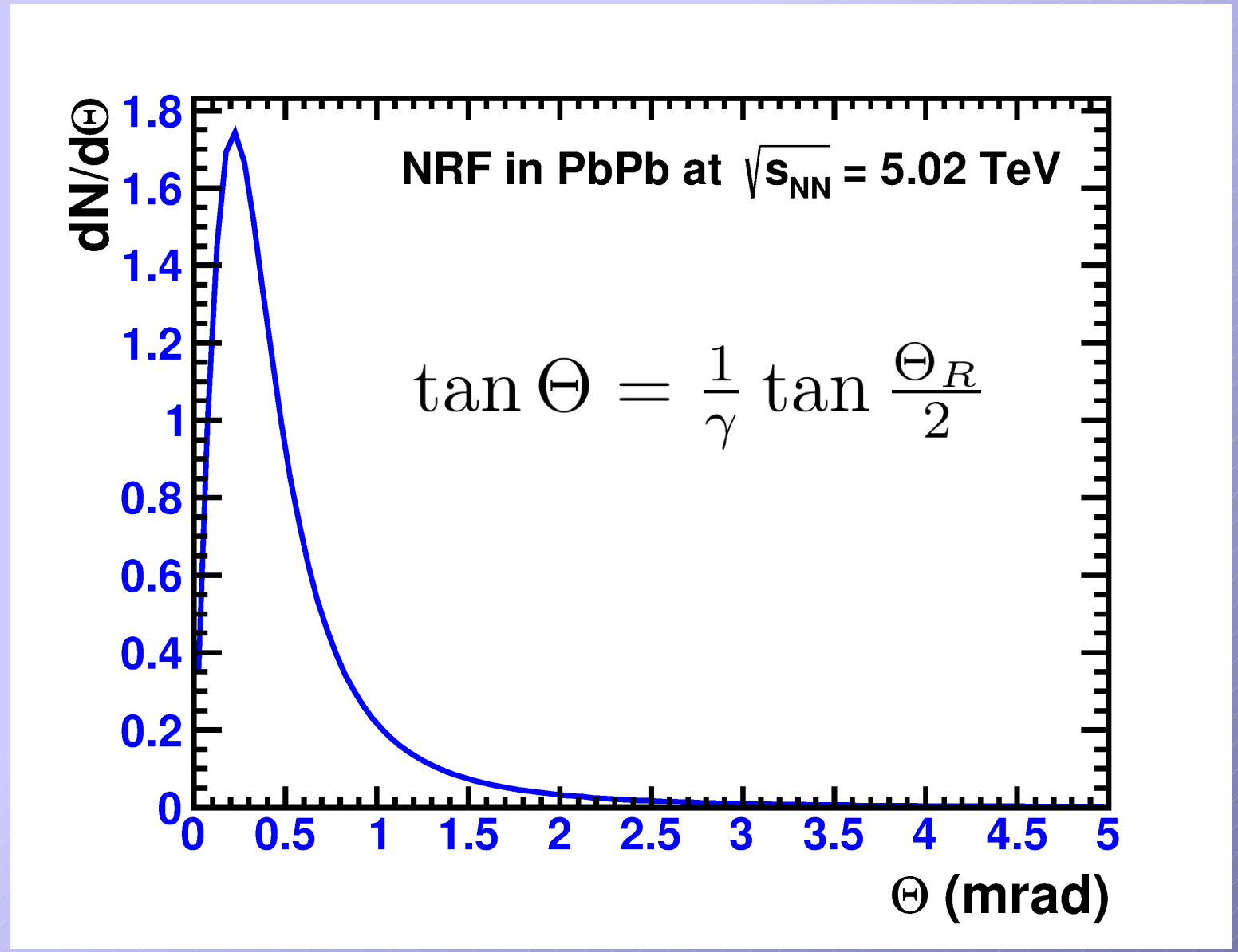
$$I(E_x) = \int \mathrm{d}E_\gamma \sigma(E_\gamma) = \pi^2 \left(\frac{\hbar c}{E_x}\right)^2 g \frac{\Gamma_0^2}{\Gamma} = \frac{\pi}{2}\Gamma_0 \sigma_{\max}(E_x)$$

$$\sigma_{\mathrm{NRF}}(E_x) = \int \mathrm{d}E_\gamma \sigma(E_\gamma) n_{\mathrm{WW}}(E_\gamma) = n_{\mathrm{WW}}(E_x) I(E_x)$$

Lorentz boost of photon energy – relativistic Doppler effect

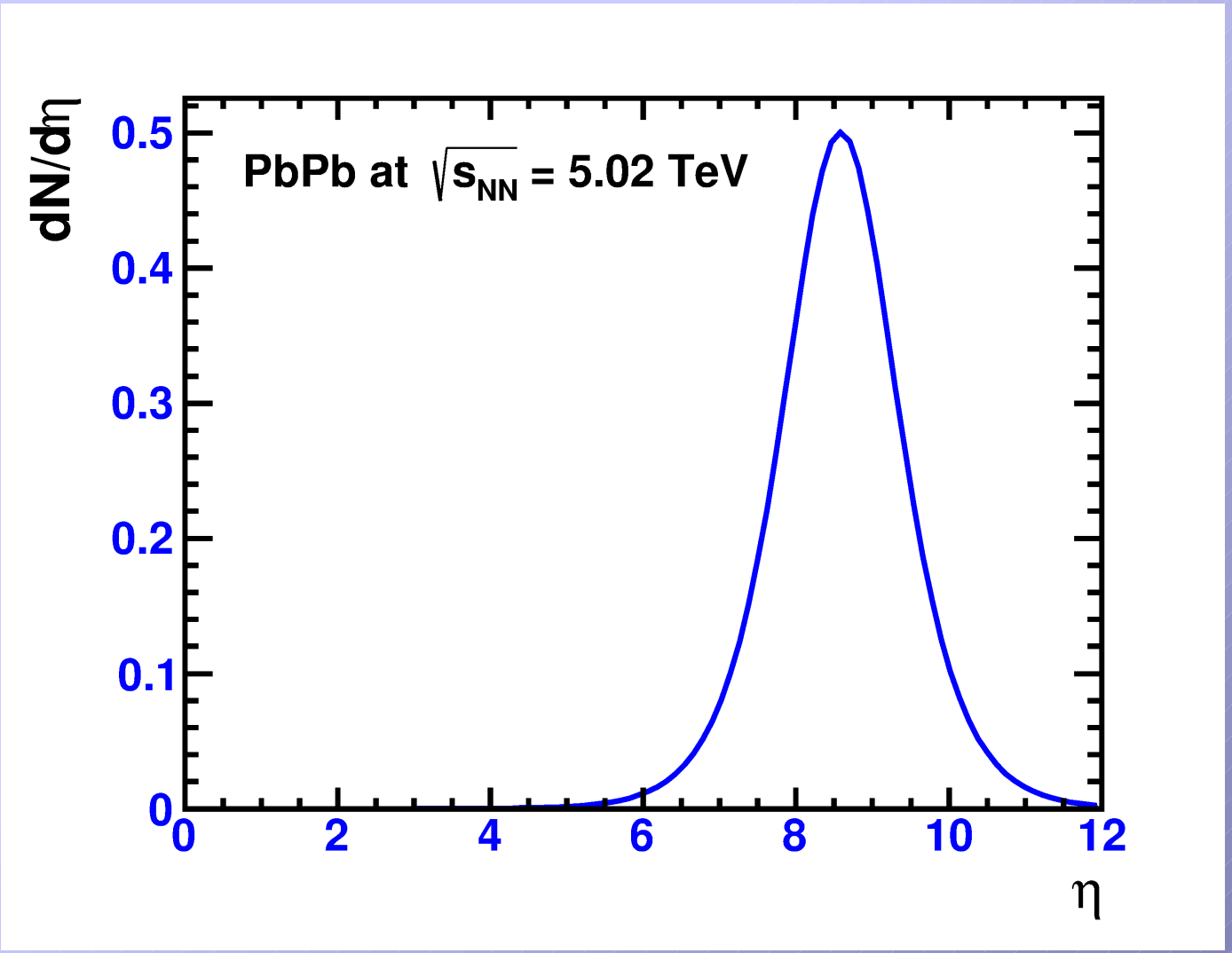


“Projector effect”



Gamma radiation is compressed into a forward cone

Photon pseudorapidity distribution



$$\frac{\mathrm{d}N}{\mathrm{d}\eta} = \frac{2\gamma \tanh\eta \left(\sinh^2\eta + 1\right)}{\left(\sinh^2\eta + \gamma^2\right)^2}$$

Photons from nuclear collisions at the LHC did not receive much attention so far ...

Photons as a trigger for γγ fusion in UPC:
Y.V. Kharlov, V.L. Korotkikh, Eur. Phys. J A 21 (2004) 437

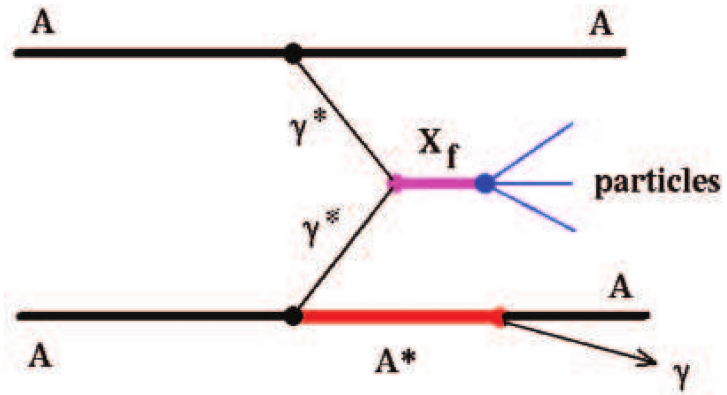


Fig. 1. Diagram of the process $A_1 + A_2 \to A_1^*(\lambda^P, E_0) + A_2 + X_f,\ A_1^* \to A_1 + \gamma$.

… and from nuclei excited by e^+, e^-
V.L. Korotkikh, K.A. Chikin,
Eur. Phys. J. A 14 (2002) 199

To the best of our knowledge ...

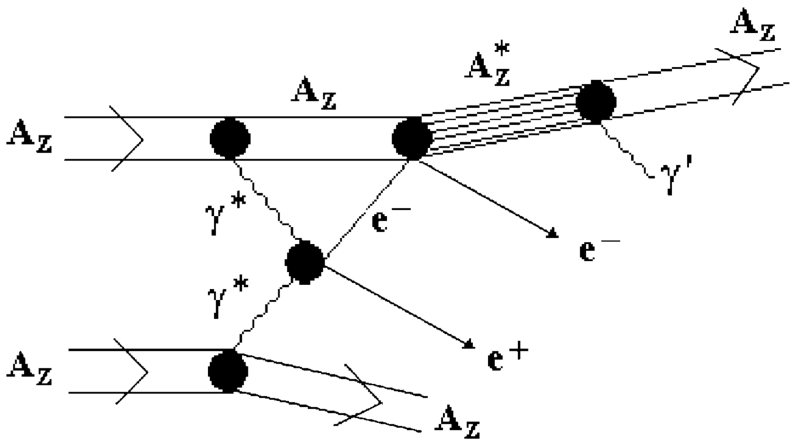
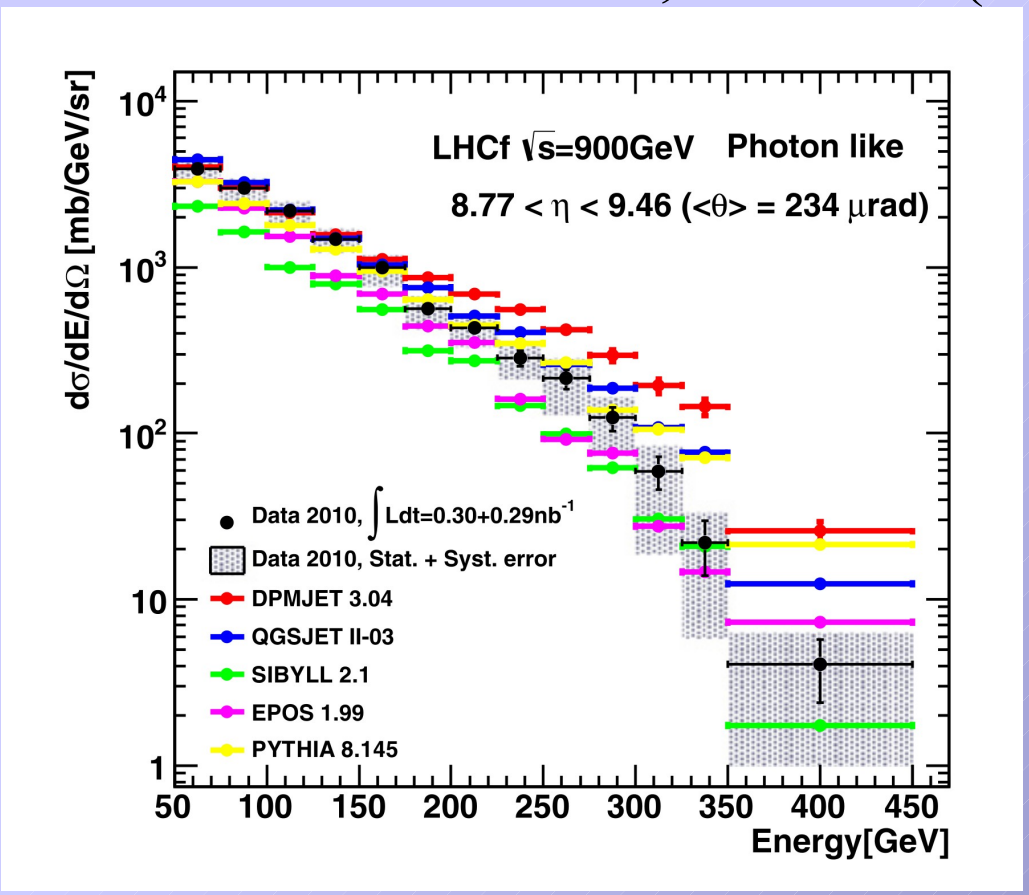
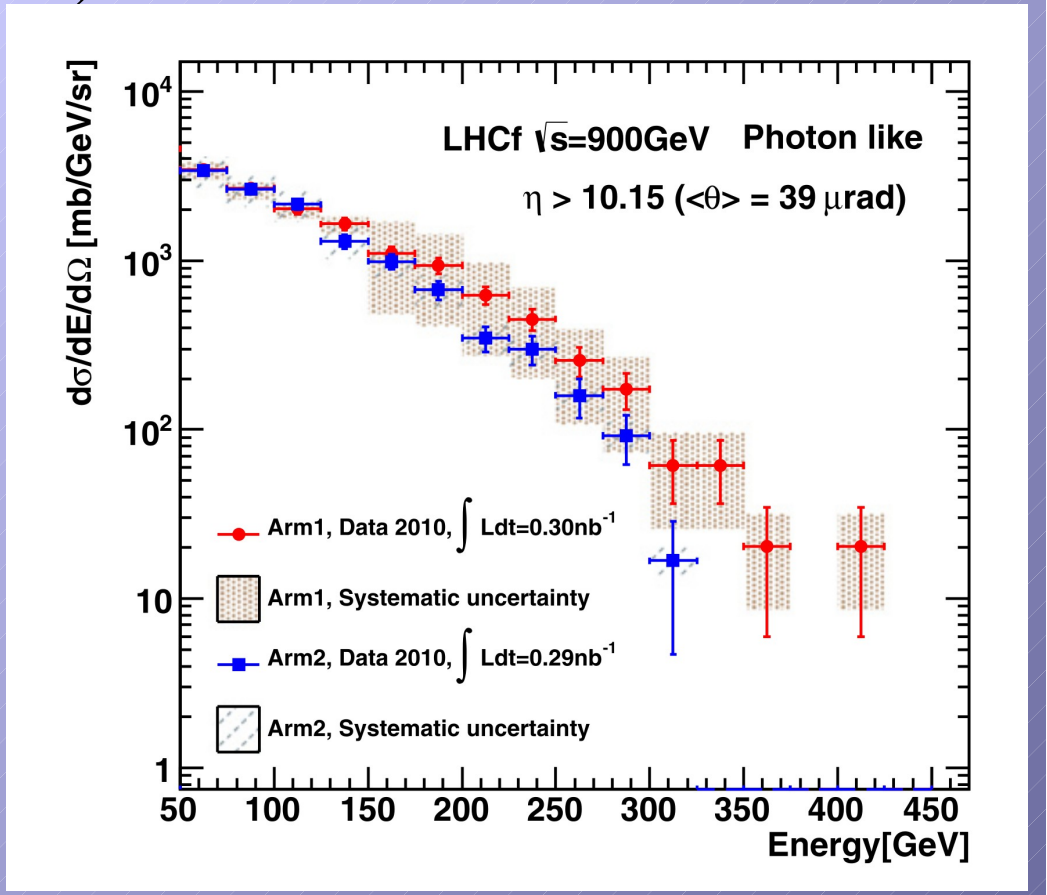


Fig. 1. Diagram of the two-stage process of nuclear excitation by an electron (positron) produced by the virtual-photon interaction in an AA collision at the LHC.

Electromagnetic calorimeters are relatively compact and have better energy resolution

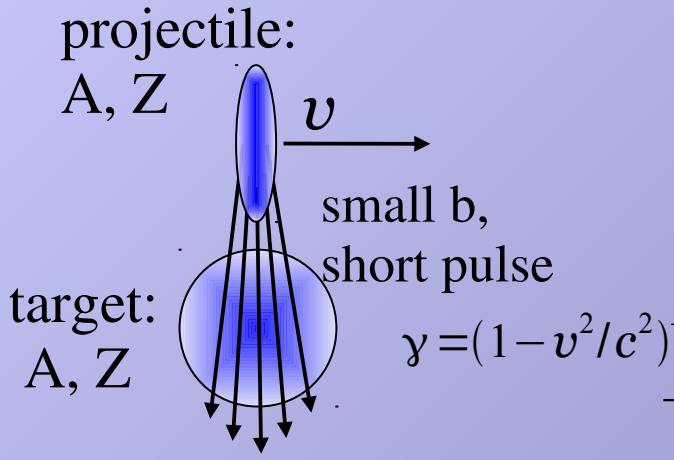
- Can be placed in front of hadronic calorimeters (ZDCs) or elsewhere.
- LHCf detects photons starting from 50 GeV:
  O. Adriani *et al.*, PLB **715** (2012) 298

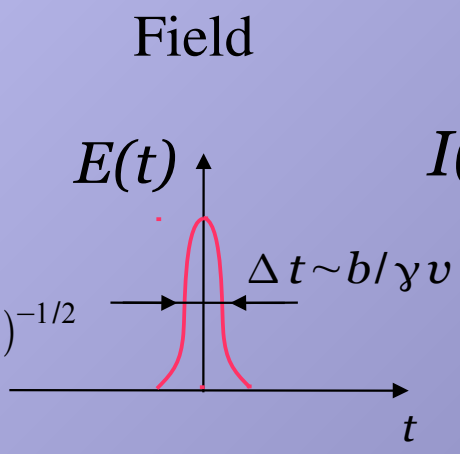


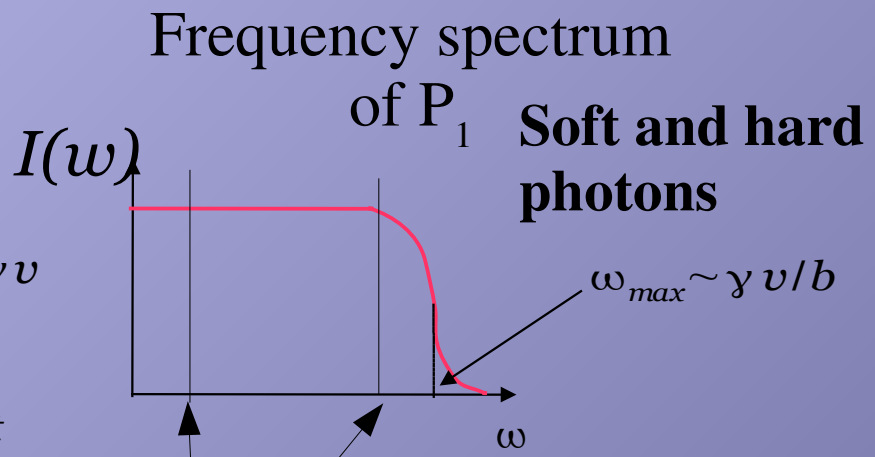


Hopefully, the thresholds can be lowered to 10 GeV to detect NRF photons.

Ultraperipheral interactions accompanied by nuclear excitation: a trigger?

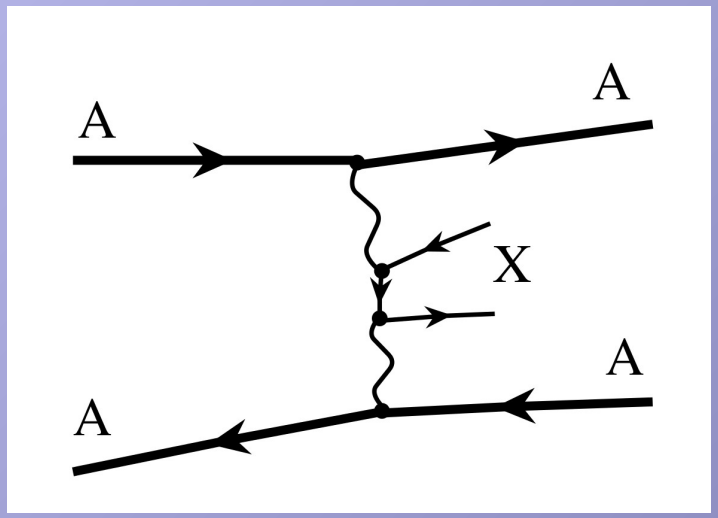




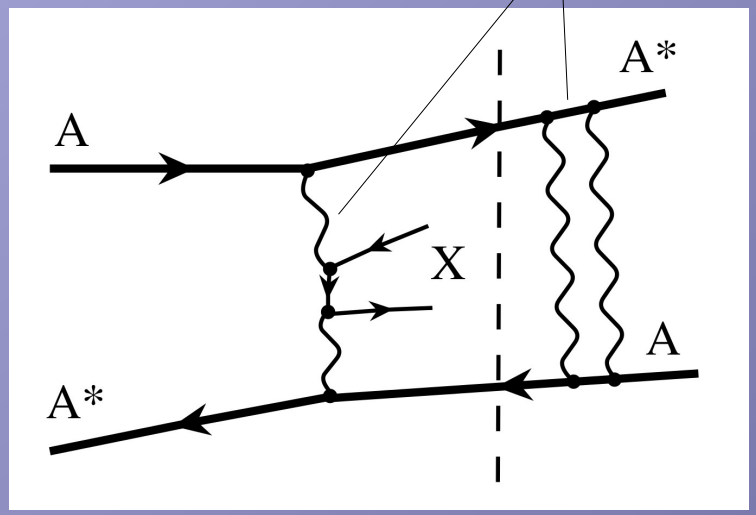


Soft and hard photons

w/o nuclear excitation



with nuclear excitation – served as a trigger



Events accompanied by neutron emission are considered.

What about additional events with photon emission used as a trigger?

A.J. Baltz et al., Phys. Rev. C 80 (2009) 044902.

VI. Conclusions

- Models are quite successful in simulating photon-induced dissociation of nuclei in UPC.

- However, further theoretical studies are needed to study:
  - Neuronless EMD events
  - EMD of Xe or other nuclei in the LHC

- Photons of few tens GeV energy are emitted at the LHC in forward direction as discrete levels in Pb nuclei are excited. Such photons can be detected by LHCf.

- Such photons can be potentially used to trigger UPC events or employed to monitor collider luminosity with relatively simple forward EM calorimeters.

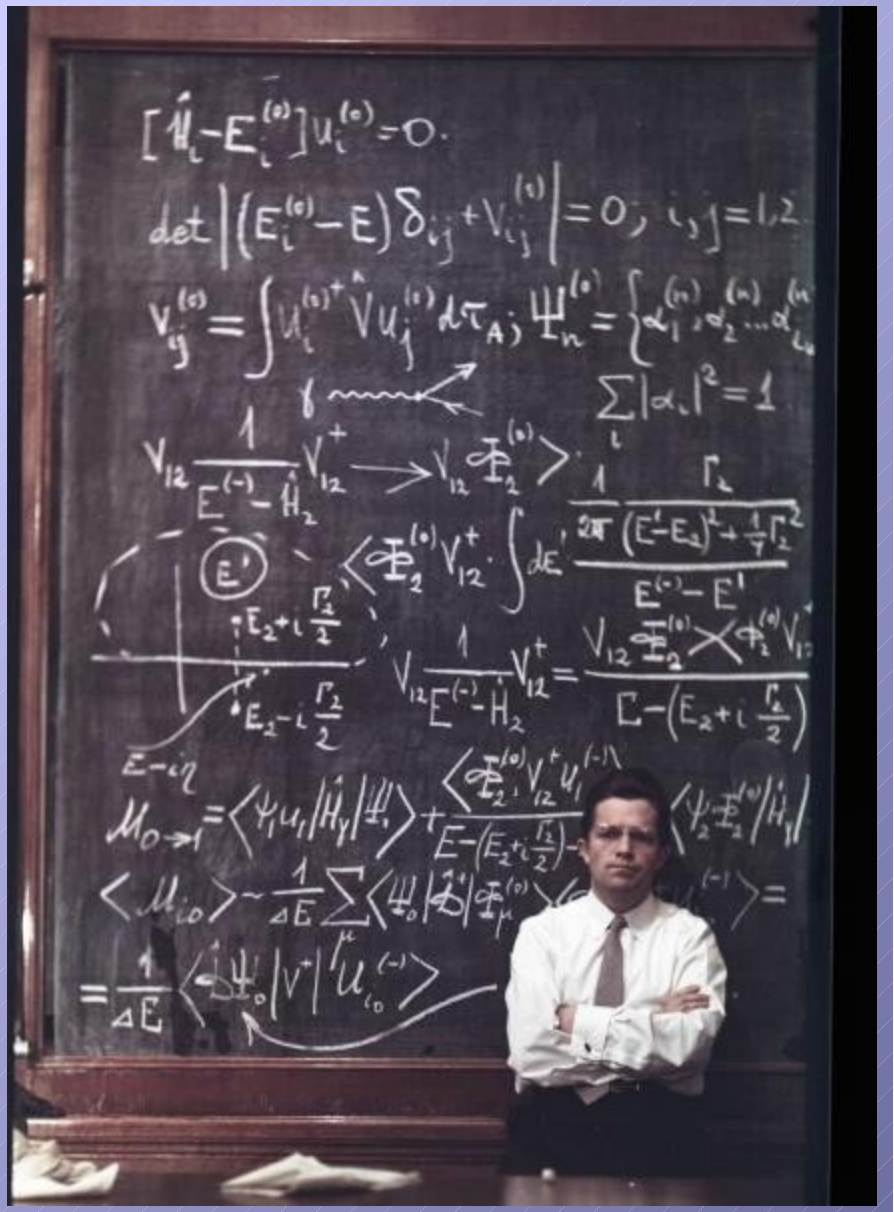
- All this tights the link between nuclear structure/nuclear reaction physics and high energy physics (see next slide).

"It is a great pity that a wall between nuclear and high-energy physics has been build..." V.V. Balashov

- This I've heard from Prof. Vsevolod Balashov in 80's when I was a student of Moscow State University.

- Prof. Balashov stated his career with Lev Landay and passed famous Landau exam. Apparently, because of that he felt the unity of physics, which we are missing nowadays.

- In this talk I tried to pierce the wall:
  (1) to demonstrate how nuclear structure effects reveal themselves in ultraperipheral collisions of high-energy nuclei;
  (2) to show that in certain cases nuclear reaction data are important also for high energy physics.



"Duel" by V. Tarasevich, Word Press Photo Prize, 1963

Thank you for your attention!

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

http://destinopoland.com