Neutron emission from electromagnetic dissociation of Pb nuclei at $\sqrt{s_{\rm NN}}$ = 2.76 TeV measured with the ALICE ZDC

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Outline

Measurement of neutron emission from electromagnetic dissociation of Pb nuclei with the ALICE Zero Degree Calorimeters at $\sqrt{s_{NN}} = 2.76$ TeV

Evaluate cross sections for:

- single EM dissociation
- mutual EM dissociation
- hadronic collisions

Comparison with Relativistic ELectromagnetic DISsociation model

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- describes EMD of ultra-relativistic nuclei including:
  - single and double virtual photon absorption by nuclei
  - intranuclear cascades of produced hadrons
  - statistical decay of excited residual nuclei
- good description of data at SPS energies

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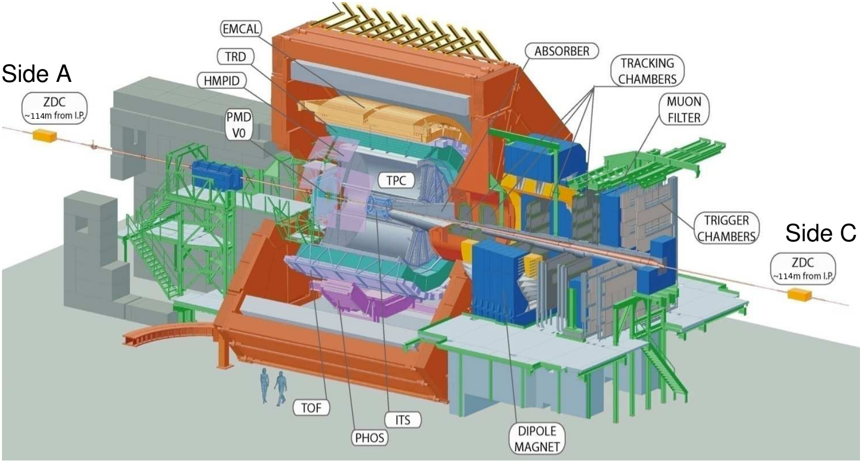
ALICE: the dedicated heavy-ion experiment at LHC

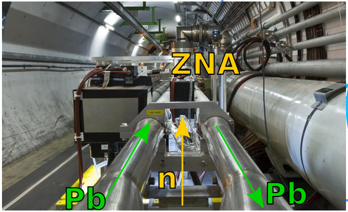


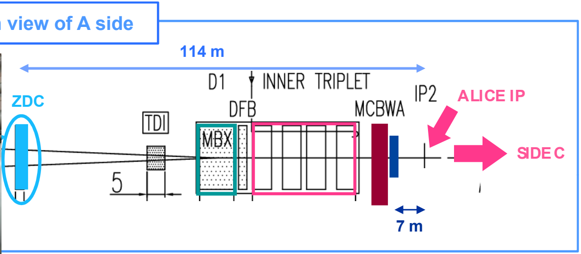
Central barrel ($|\eta|<1$) in a solenoidal field. Excellent tracking and PID capabilities
Forward muon spectrometer ($2.5<\eta<4$)
Forward detectors ($|\eta|>3$) to characterize the collision

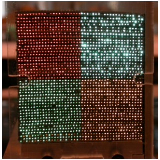
The ALICE Zero Degree Calorimeters

Placed at 0° w.r.t LHC axis, ~114 m far from IP on both sides (A and C)

- 2 neutron calorimeters (ZNA and ZNC) placed between the beam pipes $|\eta| > 8.7$
- 2 proton calorimeters (ZPA and ZPC) close to the outgoing beam pipe
- 2 small electromagnetic calorimeters (ZEM1, ZEM2) placed at ~7.5 m from the IP, at ±8 cm from LHC axis, only on A side covering $4.8 < \eta < 5.7$







- ZN are spaghetti calorimeters in W alloy
- Detection of Cherenkov light in quartz fibers
- Fast response and radiation hardness
- Dimensions: $7 \cdot 7 \cdot 100$ cm^3

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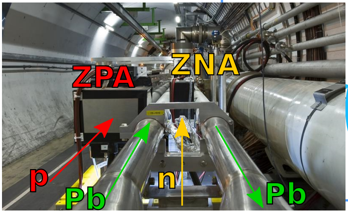

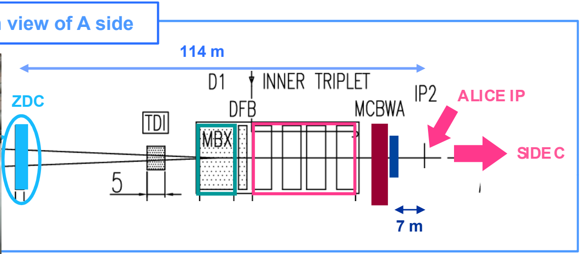

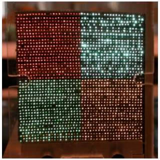

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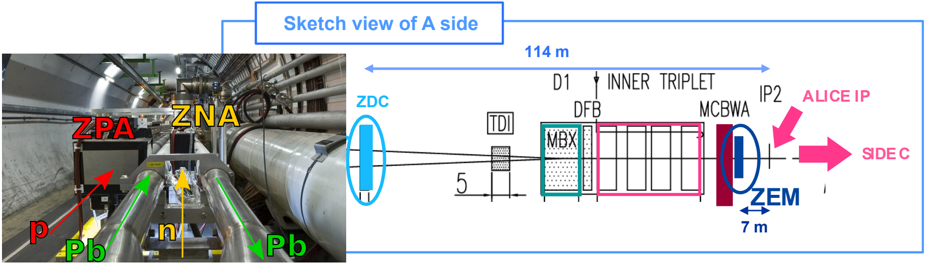

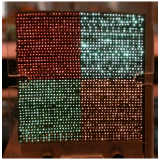

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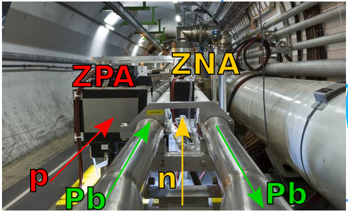
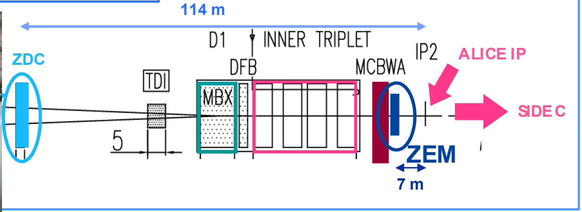
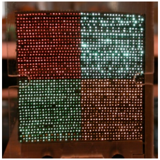


Sketch view of A side





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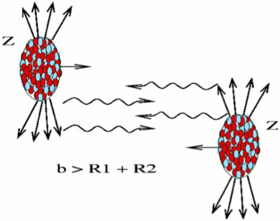
Electromagnetic processes

Two nuclei have impact parameter larger than the sum of the nuclear radii
⇒ interaction via long-range electromagnetic forces

Interaction can be described by the Weizsäcker and Williams equivalent photon method



Lorentz contracted electric field described by a photon flux

- proportional to Z^2
- increasing $\propto \gamma^2$ and hardening

Main processes:

- bound-free electron-positron pair production
- electromagnetic dissociation (EMD)
  - nucleus excitation followed by break-up
  - GDR excitation followed by neutron emission
    dominant channel for heavy nuclei

Cross sections for EM processes exceed hadronic for Pb-Pb at LHC
[R. Bruce et al., Phys.Rev. 12 071002 (2009)]

Limit to heavy ion beam lifetime

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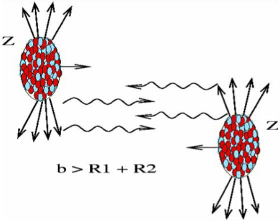

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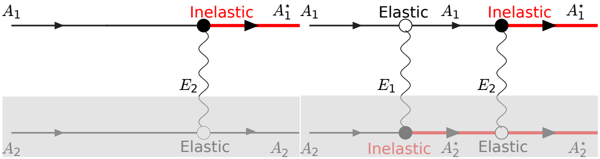
Limit to heavy ion beam lifetime

A matter of definitions…

Single electromagnetic dissociaton

- at least one neutron (1n) is emitted by a given Pb nucleus disregarding the fate of the other nucleus
- small signal in ZEM



Mutual electromagnetic dissociation

- at least 1n is emitted by both Pb nuclei
- subprocess of single EMD
- small signal in ZEM

Hadronic interaction

- impact parameter $< R_1 + R_2$
  $\Rightarrow$ strong interaction
- spectator neutrons emitted from both nuclei
  $\Rightarrow$ signal in both ZN
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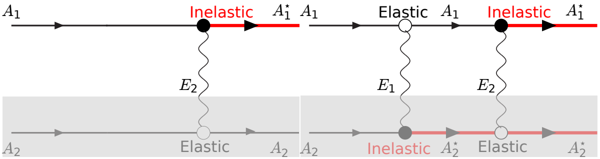

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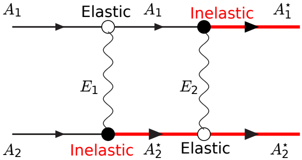

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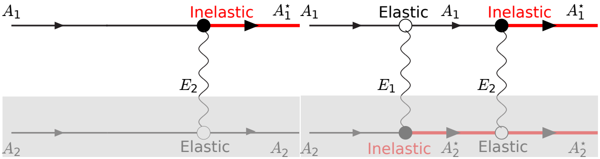

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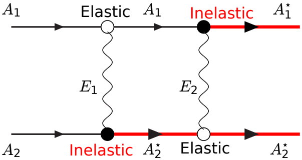

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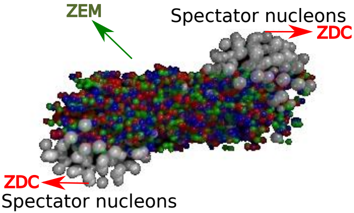
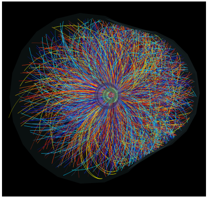
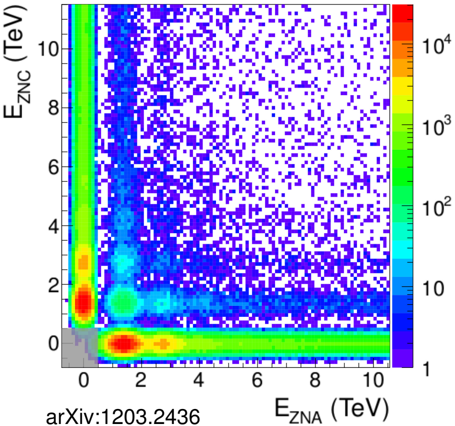




Dedicated data taking with ElectroMagnetic Dissociation trigger



arXiv:1203.2436

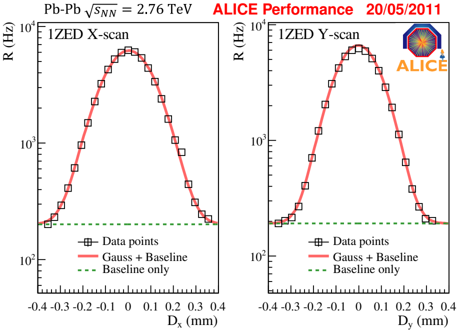
Require a minimum energy deposition of
$\sim$ 500 GeV in ZNA or ZNC
$\sim 3\sigma$ below $1n$ energy deposition

Collecting events where at least one neutron is detected:

- by one calorimeter or the other
- by both calorimeters

Selecting electromagnetic and hadronic processes

van der Meer scan



Beam separation (van der Meer) scan to measure the cross section for EMD trigger:

$$\sigma^{vdM}_{ZNA\,or\,ZNC} = 371.4 \pm 0.6\ (stat.)^{+24}_{-19}\ (syst.)\ b$$

Systematic errors of –5.2%+6.4% can be decomposed as follows:

- 4.3% uncertainty coming from the vdM scan analysis
  - calibration of the distance scale during the scan
- –3%+4.7% uncertainty coming from the measurement of the beam intensity
  - beam current transformers scale
  - non-colliding (ghost) charge fraction in the LHC beams

The cross section for any process measured in a data taking with the EMD trigger can be related to this cross section:

$$\sigma_{proc} = \sigma^{vdM}_{ZNA\,or\,ZNC} \cdot \frac{N_{proc}}{N_{ZNA\,or\,ZNC} \cdot \varepsilon_{proc}}$$

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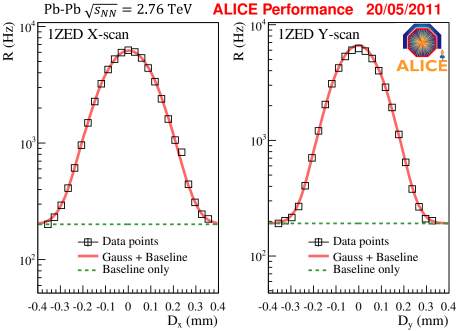

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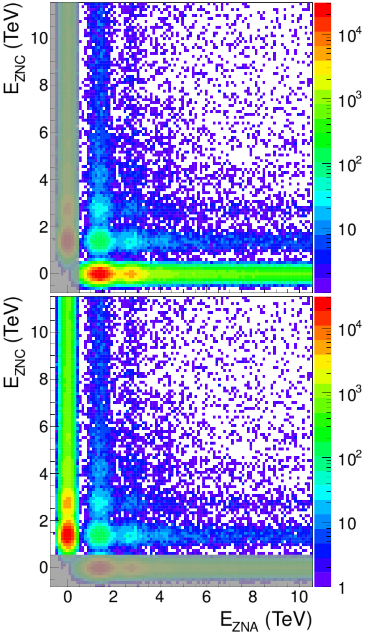
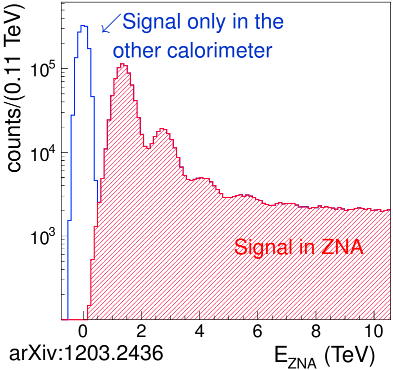
First event selection: single EMD + hadronic





arXiv:1203.2436

Select all processes involving neutron emission

- single EMD (mutual is a subset of single!)
- hadronic collisions

Two independent estimates of the number of events from single EMD + hadronic processes

Cross sections for Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

ALICE

Physical Process	Data (b)	RELDIS (b)
single EMD + hadronic	194.8±0.3 stat. $^{+13.6}_{-11.5}$ syst.	192.9±9.2
single EMD - mutual EMD	181.3±0.3 stat. $^{+12.8}_{-10.9}$ syst.	179.7±9.2
mutual EMD	6.3±0.1 stat. ±0.4 syst.	5.5±0.6
hadronic	7.7±0.1 stat. $^{+0.6}_{-0.5}$ syst.	7.7±0.4
single EMD	187.4±0.2 stat. $^{+13.2}_{-11.2}$ syst.	185.2±9.2

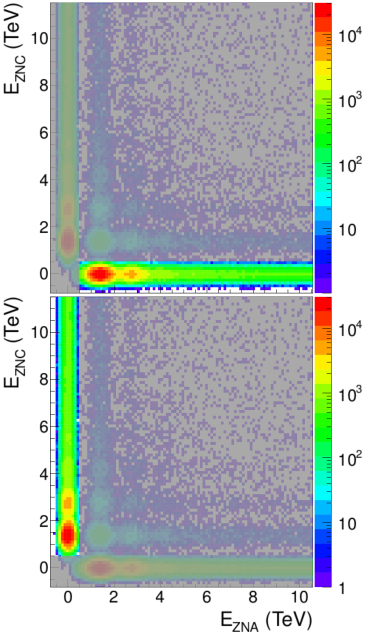
Systematic errors take into account:

- uncertainties of the cross sections measured during the vdM scan (dominant)
- difference between the response of ZNA and ZNC ($0.1 - 0.2\%$)
- subtraction of beam-gas background ($\sim 1\%$)

Single EMD cross section estimated from the average of:

- (single EMD + hadronic) − hadronic
- (single EMD − mutual EMD) + mutual EMD

Second event selection: single EMD - mutual EMD



- Require a signal over thresold in one calorimeter and not on the other side
  - ⇒ hadronic events, which always lead to disintegration of both colliding nuclei, are rejected
  - ⇒ mutual EMD events are also removed from the spectrum

Two independent estimates of the number of events from single EMD - mutual EMD

Study neutron multiplicities (1n, 2n, 3n. . . events) in EMD processes without the background from hadronic collisions

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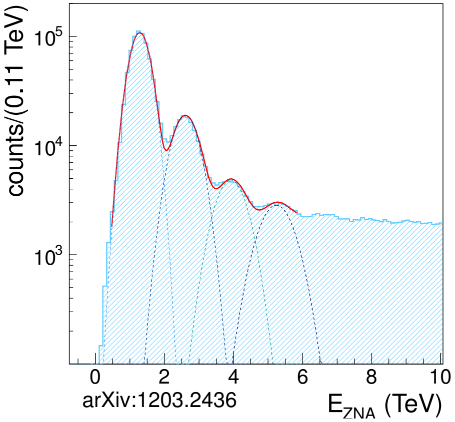
Fit to EMD spectra



ZNA energy spectrum requiring signal over threshold in ZNA but not in ZNC

Spectra fitted with the sum of 4 gaussians

- 1n peak (3 free parameters): normalization, μ_{1n} and σ_{1n}
- 2n, 3n, 4n peaks
  - free normalization,
  - $\mu_{i\mathrm{n}} = i \times \mu_{1\mathrm{n}}$
  - $\sigma_{i\mathrm{n}} = \sqrt{i \times (\sigma_{1\mathrm{n}}^2 - \sigma_{\mathrm{ped}}^2) + \sigma_{\mathrm{ped}}^2}$
  - σ_{ped} extracted from fit to 0n events

Neutron multiplicities

Neutron emission fractions for single EMD minus mutual EMD process

Ratio	Data(%)	RELDIS(%)
$1n/N_{tot}$	51.5±0.4 stat.±0.2 syst.	54.2±2.4
$2n/N_{tot}$	11.6±0.3 stat.±0.5 syst.	12.7±0.8
$3n/N_{tot}$	3.6±0.2 stat.±0.2 syst.	5.4±0.7
2n/1n	22.5±0.5 stat.±0.9 syst.	23.5±2.5

1n and 2n emission channels give the main contribution (63%)

⇒ EMD processes proceed predominantly via GDR excitation and subsequent decay

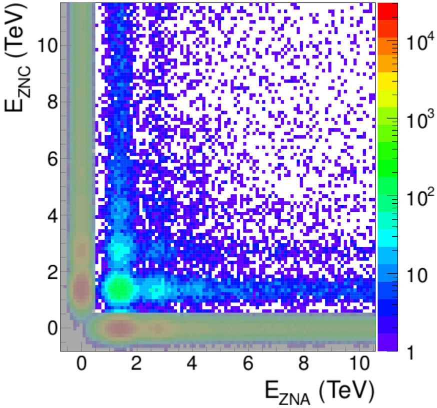
2n/1n in Pb-Pb

LHC $\sqrt{s} = 2.76$ TeV ⇒ $22.5 \pm 0.9\%$ in single EMD minus mutual
SPS $\sqrt{s} = 7.6$ GeV ⇒ $19.7 \pm 2.9\%$ in single EMD

Slight increase increase of the 2n to 1n ratio with collision energy

According to RELDIS is due to hardening of photon spectra

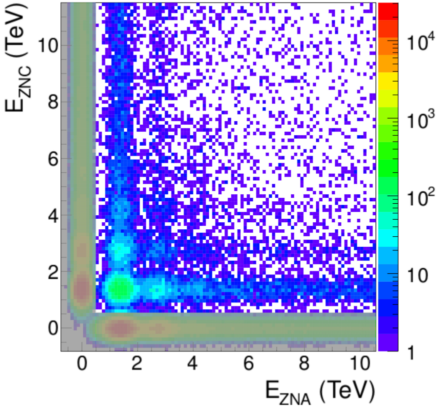
Mutual EMD + hadronic

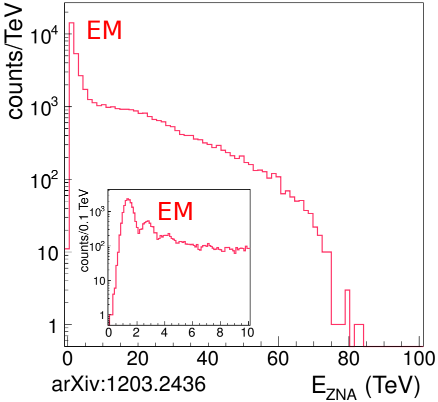


Separation of electromagnetic and hadronic contributions using ZEM calorimeters

Energy threshold for each ZEM $\sim$ 10 GeV

Mutual EMD + hadronic





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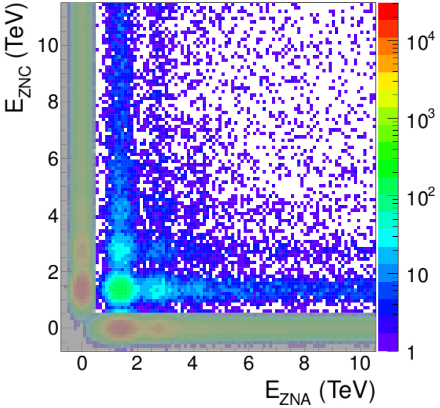
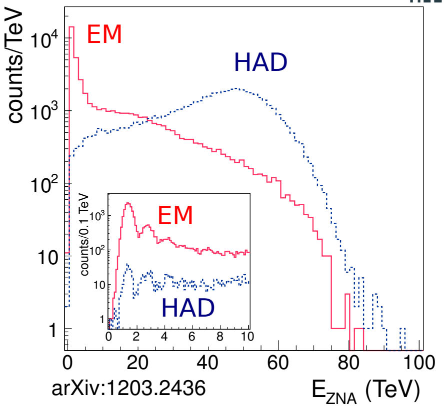
  - $\Rightarrow$ mutual EMD
- signal in at least one ZEM
  - $\Rightarrow$ hadronic events

Mutual EMD + hadronic





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Removing cross contamination

The ZEM trigger efficiencies are estimated with Monte-Carlo:

- ε_{mutual} =96.0% $\pm$ 0.1%(stat.) $\pm$ 0.6%(syst.) for mutual EMD event selection
- $\varepsilon_{hadronic}$ =92.4% $\pm$ 0.3%(stat.) $\pm$ 1.0%(syst.) for hadronic event selection

There is therefore a small cross contamination due to mis-identification:

$$\begin{cases} N_{mutual,observed} & = \varepsilon_{mutual} \cdot N_{mutual} + (1 - \varepsilon_{hadronic}) \cdot N_{hadronic} \\ N_{hadronic,observed} & = (1 - \varepsilon_{mutual}) \cdot N_{mutual} + \varepsilon_{hadronic} \cdot N_{hadronic} \end{cases}$$

By solving this system $\Rightarrow$ extract the true number of mutual EMD and hadronic events

Finally correct for trigger probability:

- for mutual EMD: 95.7% $\pm$ 0.07%(stat.) $\pm$ 0.5%(syst.)
- for hadronic events: 97.0% $\pm$ 0.2%(stat.) $\pm$ 3%(syst.)

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By solving this system $\Rightarrow$ extract the true number of mutual EMD and hadronic events

Finally correct for trigger probability:

- for mutual EMD: $95.7\% \pm 0.07\%(\text{stat.}) \pm 0.5\%(\text{syst.})$
- for hadronic events: $97.0\% \pm 0.2\%(\text{stat.}) \pm 3\%(\text{syst.})$

Cross sections for Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

Physical Process	Data (b)	RELDIS (b)
single EMD + hadronic	194.8 ± 0.3 stat. $^{+13.6}_{-11.5}$ syst.	192.9 ± 9.2
single EMD - mutual EMD	181.3 ± 0.3 stat. $^{+12.8}_{-10.9}$ syst.	179.7 ± 9.2
mutual EMD	6.3 ± 0.1 stat. ± 0.4 syst.	5.5 ± 0.6
hadronic	7.7 ± 0.1 stat. $^{+0.6}_{-0.5}$ syst.	7.7 ± 0.4
single EMD	187.4 ± 0.2 stat. $^{+13.2}_{-11.2}$ syst.	185.2 ± 9.2

Systematic errors take into account:

- uncertainties of the cross sections measured during the vdM scan (dominant)
- difference between the response of ZNA and ZNC ($0.1 - 0.2\%$)
- subtraction of beam-gas background ($\sim 1\%$)

Single EMD cross section estimated from the average of:

- (single EMD + hadronic) − hadronic
- (single EMD − mutual EMD) + mutual EMD

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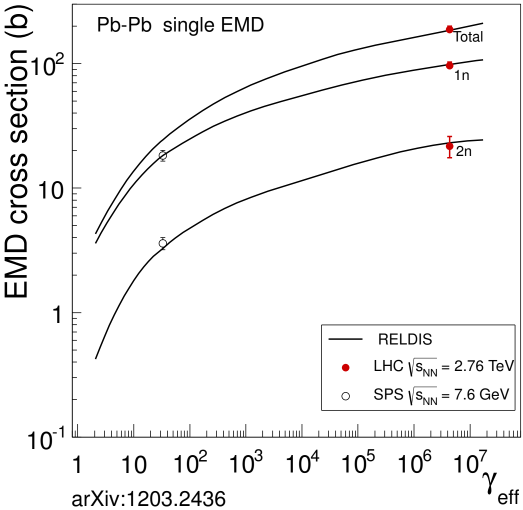
Energy dependence of EMD cross sections

Total single EMD cross sections and partial EMD cross sections as a function of the effective Lorentz factor $\gamma_{\rm eff} = 2\gamma^2 - 1$
i.e. γ of a nucleus in the rest frame of the other

Solid lines are the RELDIS predictions



arXiv:1203.2436

Good description by the model despite of six orders-of-magnitude span of $\gamma_{\rm eff}$

Conclusions

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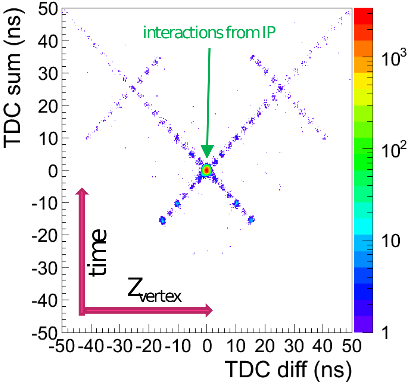
- The ZDCs provide an independent monitor of the beam luminosity measuring the rate of neutron emission by EMD processes

$$\mathscr{L} = Rate_{EMD}/\sigma_{EMD}$$

Thanks for your attention

ALICE

Backup. Event selection for mutual EMD and hadronic collisions



- Events corresponding to interaction between main bunch with satellite bunches can be identified using the ZN timing information
- not all satellite events are synchronized with the ADC gate ZEM signal is not correctly integrated in some cases
- select only events from IP rejecting events from satellite bunch interactions:
  - 3.8% events from mutual EMD sample and
  - 2.6% events from the hadronic sample are removed