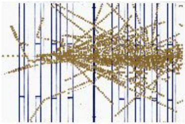
Performance of the ALICE Zero Degree Calorimeters and upgrade strategy

P. Cortese for the ALICE Collaboration

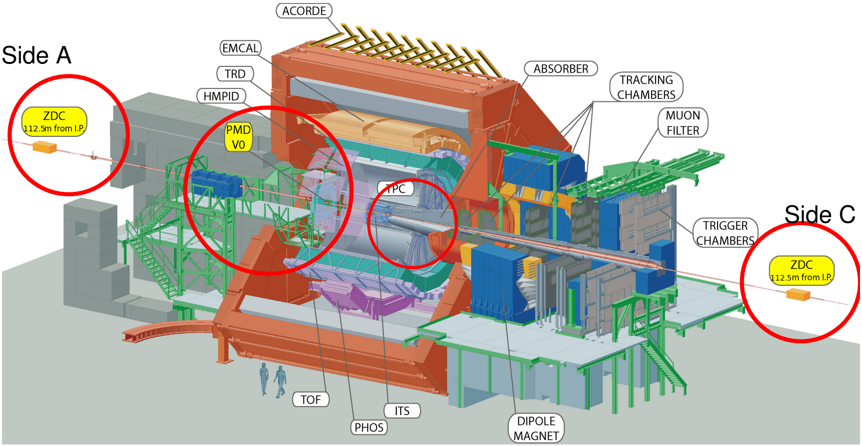
ALICE UNIVERSITÀ DEL PIEMONTE ORIENTALE INFN

CALOR 2018



18th International Conference on Calorimetry in Particle Physics
21-25 May 2015, Eugene, Oregon

ALICE: the dedicated heavy-ion experiment at LHC

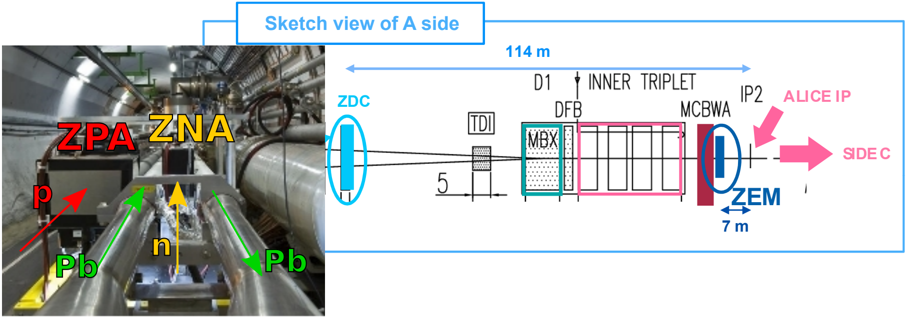


- Central barrel ($|\eta| < 1$) in a solenoidal field with excellent tracking and PID capabilities
Study of hadronic signals, photons and dielectrons
- Forward muon spectrometer ($2.5 < \eta < 4$): study quarkonia and heavy flavour decays
- Forward detectors ($|\eta| > 3$) to characterize the collision: timing, vertex, centrality, event plane. FMD,T0,V0 and ZDC ($|\eta| > 8.7$ at $\sim 112.5\,m$ from interaction point)

The ALICE Zero Degree Calorimeters: ZEM

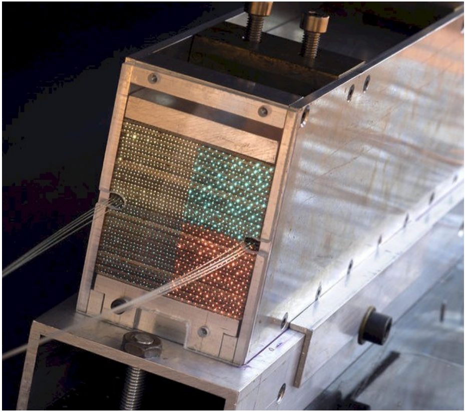
Placed at 0° w.r.t LHC axis, ~112.5 m from IP on both sides (A and C)
Based on the detection of Cherenkov light produced in quartz fibers

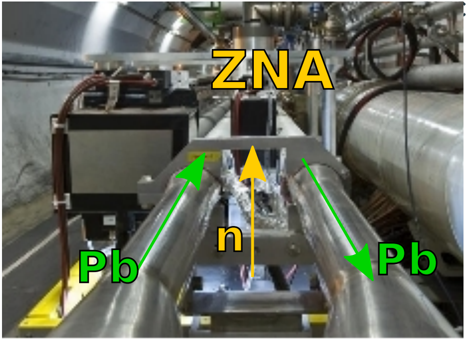
- 2 neutron calorimeters (ZNA and ZNC) placed between the beam pipes $|\eta| > 8.7$
- 2 proton calorimeters (ZPA and ZPC) close to the outgoing beam pipe
- 2 small electromagnetic calorimeters (ZEM1, ZEM2) placed at ~7.5 m from the IP, at ±8 cm from LHC axis, only mounted on A side covering $4.8 < \eta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



The neutron Zero Degree Calorimeter

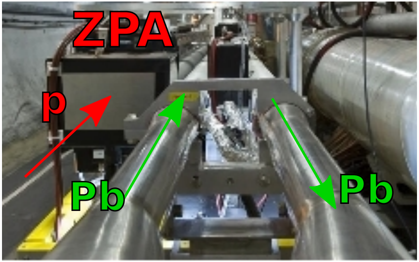
Severe space contraints due to the limited space available between the LHC beam pipes





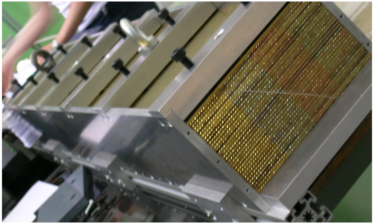
- W-alloy ($\rho = 17.6\, g/cm^3$)
- 44 grooved slabs, 1.6 mm thick, stacked to form a parallelepiped $7.2 \cdot 7.2 \cdot 100 cm^3$.
- 1936 quartz fibers ($\varnothing = 365\, \mu m$) embedded in the absorber with a pitch of 1.6 mm

The proton Zero Degree Calorimeter

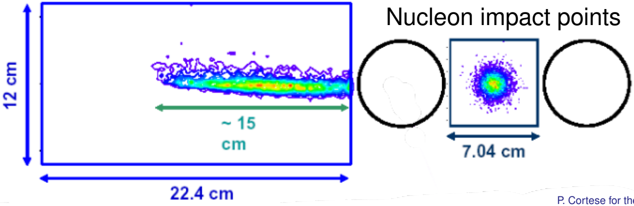


Protons and neutrons are separated by the LHC separator magnet D1

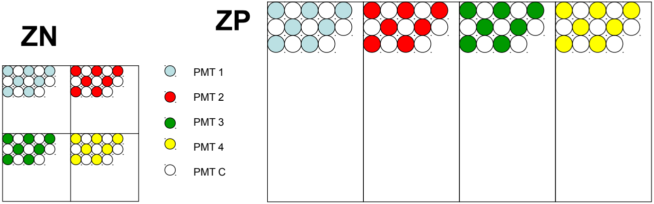
- Space constraints are less severe
- Use brass ($\rho = 9\,g/cm^3$)



- 30 grooved slabs, 4 mm thick, stacked to form a parallelepiped $22.4 \cdot 12 \cdot 150\,cm^3$
- 1680 quartz fibers ($\varnothing = 550\,\mu m$) embedded in the absorber with a pitch of 4 mm.



Detector structure and segmentation



The fibers are placed at 0° with respect to the beam axis and emerge on the rear face of the calorimeter, guiding the light to the PMTs.

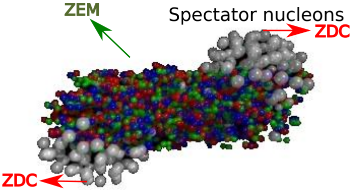
One out of two fibers is sent to a photomultiplier (PMTc), while the remaining fibers are grouped in bundles and connected to four different photomultipliers (PMT1 to PMT4), forming four independent towers.

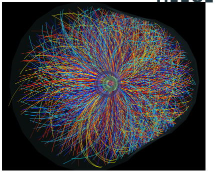
- Position-sensitive device (with limited resolution)
- Redundancy in case of PM failure
- Noise reduction using the coincidence of common PM with sum of towers

Physics processes involving ZDCs

Hadronic interaction

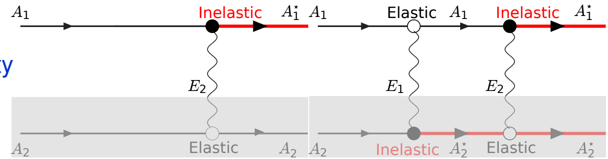
- impact parameter $< R_1 + R_2$
- spectator neutrons emitted from both nuclei
  $\Rightarrow$ signal in both ZN
- large signal at mid rapidity





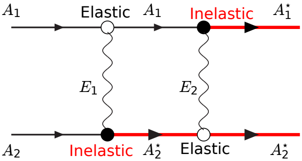
Single electromagnetic dissociaton: $b > 2r_{Pb} \Rightarrow$ EM interaction

- at least one neutron (1n) is emitted by a given Pb nucleus (whatever the fate of the other nucleus)
- small signal at mid rapidity

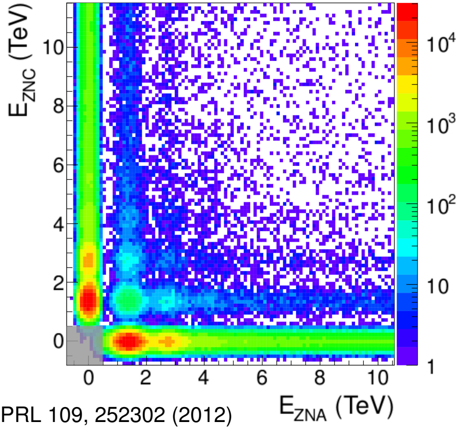


Mutual electromagnetic dissociation

- at least 1n is emitted by both Pb nuclei
- sub-process of single EMD
- small signal at mid rapidity



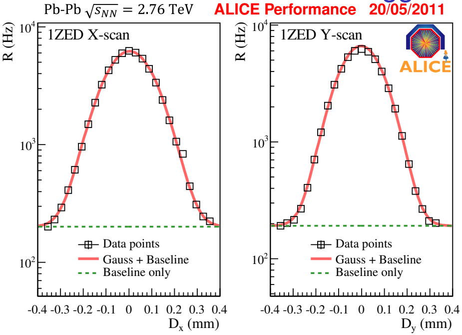
ZDC minimum bias trigger



PRL 109, 252302 (2012)

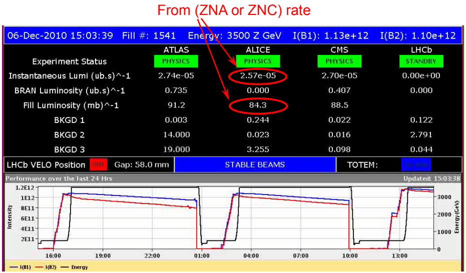
- Require a minimum energy deposition of $\sim$ 1 TeV ($\sim$ 500 GeV in RUN1) in ZNA or ZNC
  - $\sim 3\sigma$ below $1n$ energy deposition
- Electromagnetic dissociation dominates (mainly single neutron emission)
- Hadronic processes are also selected

Use of minimum bias ZDC trigger in ALICE (a.k.a. EMD or 1ZED)



The cross section for EMD trigger (1ZED) is measured in van der Meer (vdM) scans

ZDC rate is used for luminosity monitoring



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

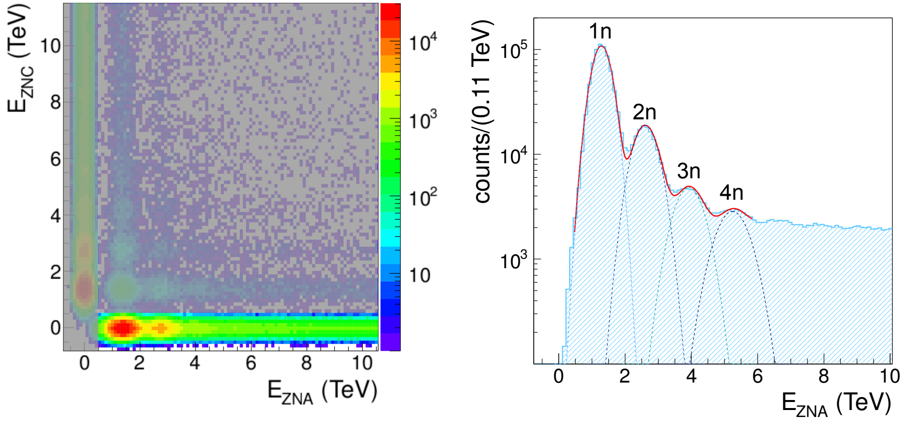
arXiv:1305.7044 [nucl-ex], Int. J. Mod. Phys. A 29 (2014) 1430044

Several cross section measurements in Pb-Pb data taking are related to ZDC vdM cross sections:

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

Isolate electromagnetic contribution

Require a signal over thresold in one calorimeter and not on the other side

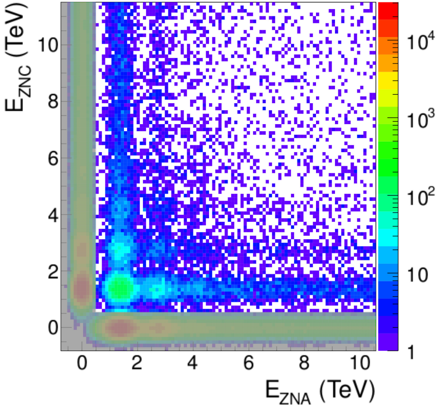


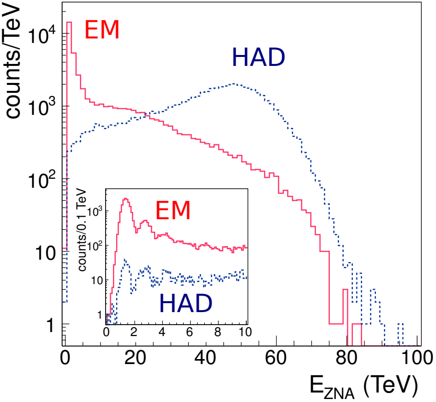
⇒ hadronic events, which always lead to disintegration of both colliding nuclei, are rejected

⇒ mutual EMD events are also removed from the spectrum

Identifying mutual EMD and hadronic contributions

Select events with activity in both neutron calorimeters





Separation of electromagnetic and hadronic contributions using ZEM calorimeters

Energy threshold for each ZEM $\sim$ 10 GeV

no signal in both ZEM calorimeters
$\Rightarrow$ mutual EMD

signal in at least one ZEM
$\Rightarrow$ hadronic events (HAD)

Comparison with models

Solid lines are the predictions by RELDIS (Relativistic ELectromagnetic DISsociation model) `Phys. Rev. C 64 (2001) 024903, Phys. Part. Nucl 42 (2011) 215.`

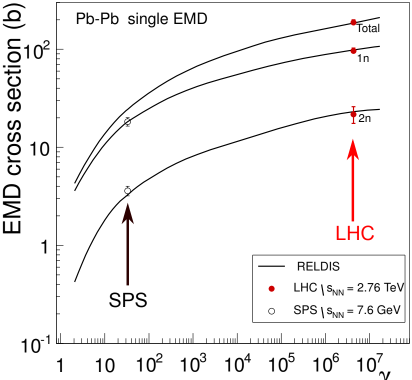
EMD cross sections as a function of the effective Lorentz factor $\gamma_{\rm eff} = 2\gamma^2 - 1$

i.e. γ of a nucleus in the rest frame of the other

$$\sigma_{singleEMD} = 187.4 \pm 0.2 stat.^{+13.2}_{-11.2} sys. b$$

prediction:

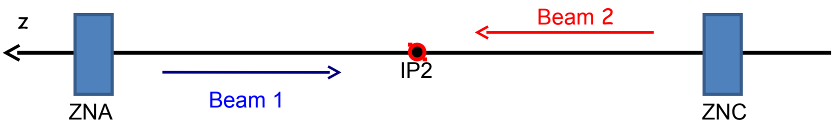
$$\sigma_{singleEMD} = 185.2 \pm 9.2\, b$$

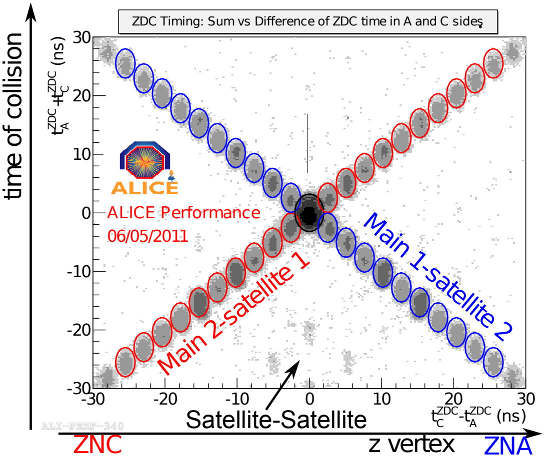


PRL 109, 252302 (2012)

Good description by the model despite large increase in $\gamma_{\rm eff}$

Event selection in Pb-Pb





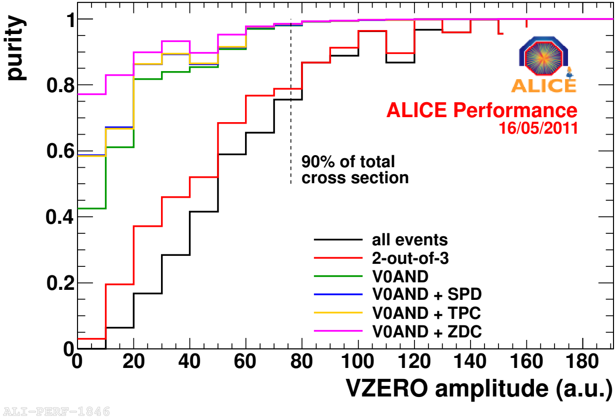
ZNs used to reject parasitic collisions of main bunches with satellite bunches positioned at one or more RF buckets from a main bunch.

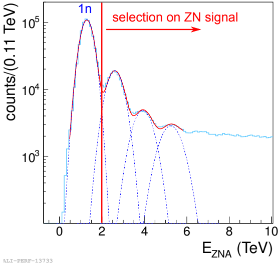
- Large cluster ⇒ collisions between ions in the nominal RF buckets of each beam
- Small clusters ⇒ collisions in which one of the ions is displaced by one or more RF buckets.
- Some satellite-satellite collisions are also visible

Reject EM interactions in Pb-Pb

ZNs used to increase the purity of the hadronic MB sample

$$purity = \frac{\frac{dN_{Had}}{dV_0}\frac{\sigma_{Had}}{N_{Had}}}{\frac{dN_{Had}}{dV_0}\frac{\sigma_{Had}}{N_{Had}} + \frac{dN_{SD}}{dV_0}\frac{\sigma_{SD}}{N_{SD}} + \frac{dN_{DD}}{dV_0}\frac{\sigma_{DD}}{N_{DD}} + \frac{dN_{QED}}{dV_0}\frac{\sigma_{QED}}{N_{QED}}}$$



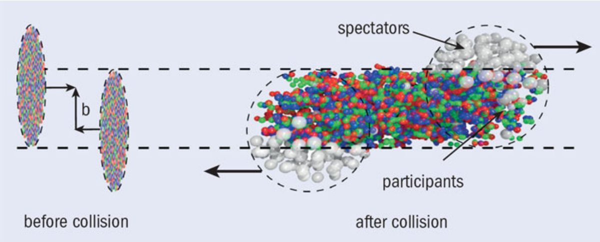


ZDC: 3σ cut above single neutron peak in ZNA and ZNC

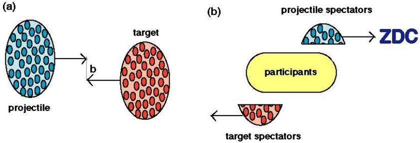
⇒ reduce the e.m. induced interactions.

Centrality estimation in Pb-Pb

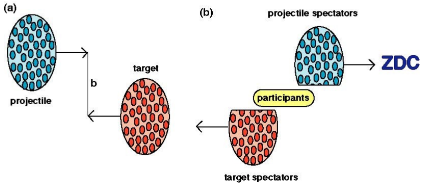
The volume of the interacting region depends on the impact parameter b and can be expressed via the number of participating nucleons N_{part}



central collisions

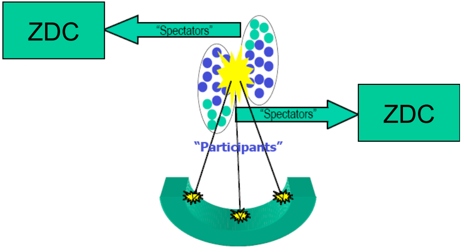


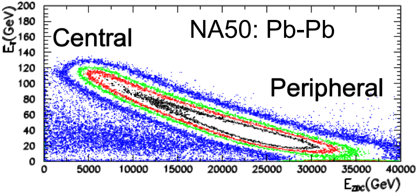
peripheral collisions



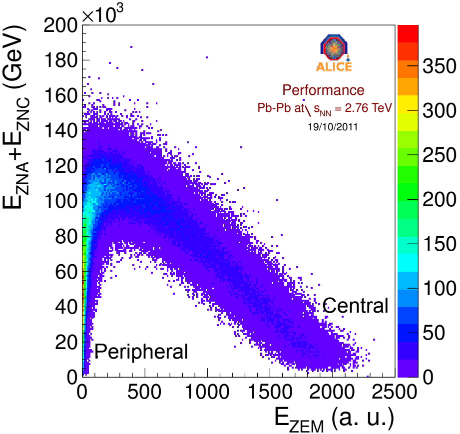
ZDCs in principle allow for a direct estimate of $N_{part} = A - N_{spec}$ through the detection of the energy carried away by the non-interacting nucleons (“spectators”), however. . .

Centrality estimation at colliders





ALICE Pb-Pb: E_{ZDC} vs. E_{ZEM}

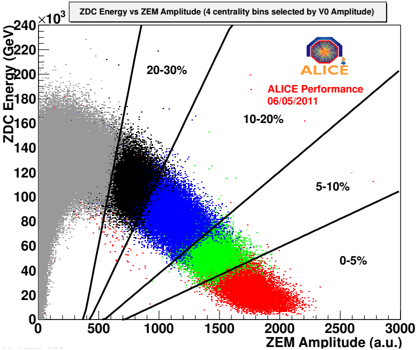


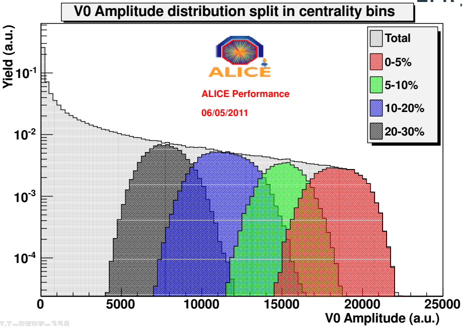
. . . unlike the fixed target experiment, at the colliders the monotonic correlation between impact parameter and ZDC response is partially destroyed.

In peripheral collisions many nucleons remain bound in nuclear fragments, that continue to travel in the beam pipe and are not detected by the ZDC.

Centrality estimation at colliders

Centrality classes defined by cuts on the two-dimensional distribution ZDC energy vs ZEM amplitude.





Distribution of V0 amplitude (Nch) for all triggered events and for centrality classes selected from the two-dimensional distribution ZDC energy vs ZEM amplitude.

Independent centrality estimate, complementary to the ones performed using particle multiplicity. Insensitive to vertex position.

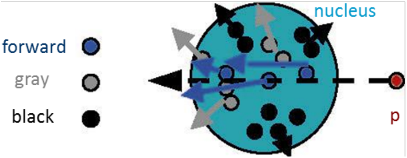
ZDC in p-Pb

In the Pb remnant side ZDC detects the so called “slow nucleons” emitted by the excited nucleus:

Black nucleons -> equilibrated particles, from evaporation, disintegration, or fragmentation of the remnants of the original nucleus

Gray nucleons -> prompt, pre-equilibrium particles, knocked out of the nucleus

	β	$p(MeV/c)$	$E_{kin}(MeV)$
Black	$0 \div 0.25$	$0 \div 250$	$0 \div 30$
Grey	$0.25 \div 0.70$	$250 \div 1000$	$30 \div 400$

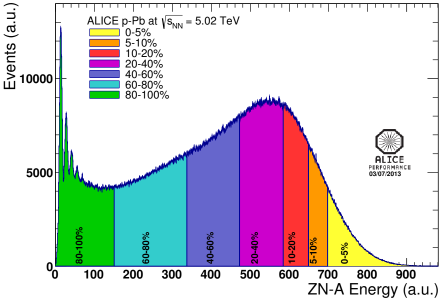


Experimental results modelled by Slow Nucleon Model (SNM): a parameterization of experimental results in hadron-nucleus interactions at lower energies

ZDC response in p-A is monothonic w.r.t. impact parameter

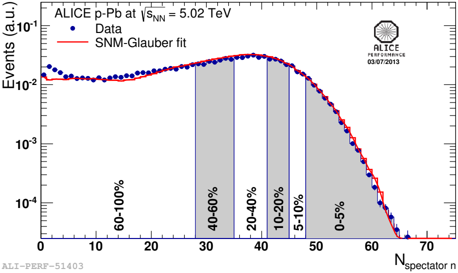
ZDC centrality estimation

ZDC energy distributions on the Pb remnant side and classification in centrality bins.

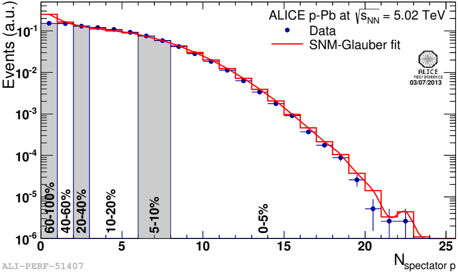


ALI-PERF-51392

ZN/ZP Glauber fit with slow nucleon model



ALI-PERF-51403

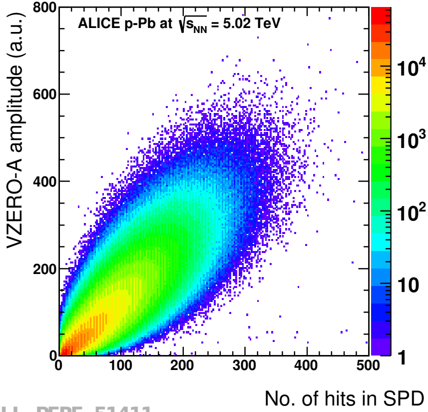


ALI-PERF-51407

Other centrality estimators: p-Pb vs. Pb-Pb

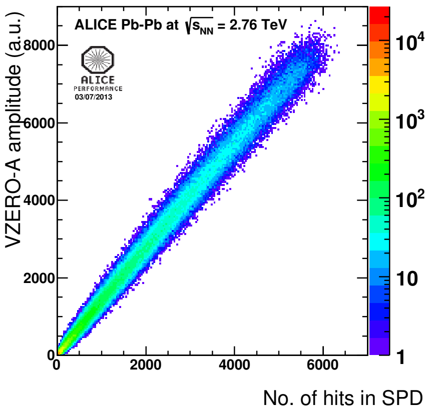
Correlation between $V0$ amplitude ($2.8 < \eta < 5$)
with hits in Silicon Pixel Detector SPD ($-2 < \eta < 2$)

$p-Pb$



ALI−PERF−51411

$Pb-Pb$

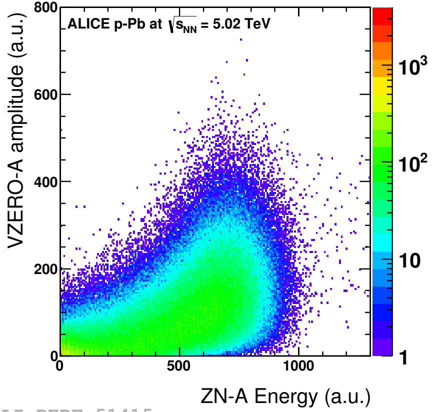


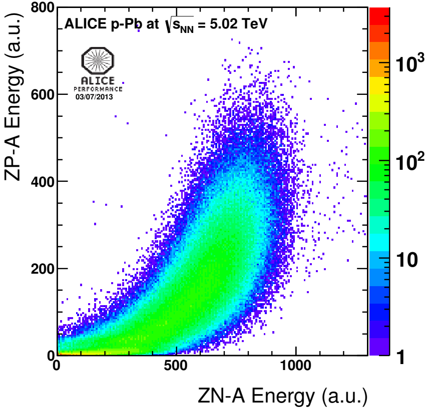
ZN vs. V0 in p-Pb

V0 vs. ZNA

$2.8 < \eta < 5$ vs. $\eta > 8.8$

ZPA vs. ZNA



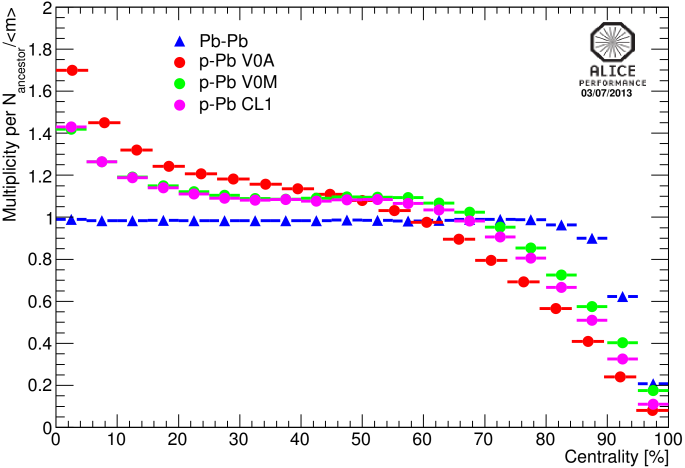


ALI-PERF-51415

stronger correlation between ZPA and ZNA w.r.t. V0.

Multiplicity bias

In p-A multiplicity fluctuations at a given impact parameter *b* cause a bias in centrality estimation for barrel detectors



Phys. Rev. C 91 (2015) 064905

Black/gray neutron doesn't seem to be correlated with multiplicity fluctuations

For the moment there is no indication of bias in the ZN centrality estimator

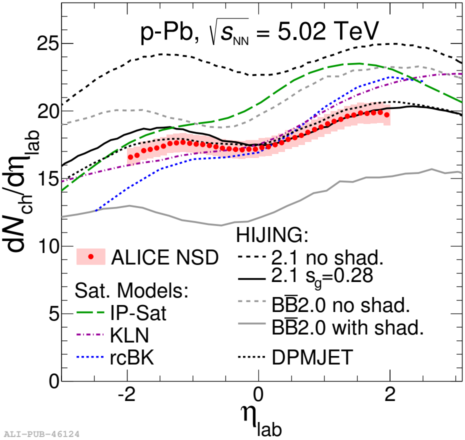
Longitudinal asymmetry

$p - A \Rightarrow$ asymmetric collision

- unequal number of participant nucleons
- longitudinal asymmetry
- rapidity shift

$Pb - Pb \Rightarrow$ symmetric collision

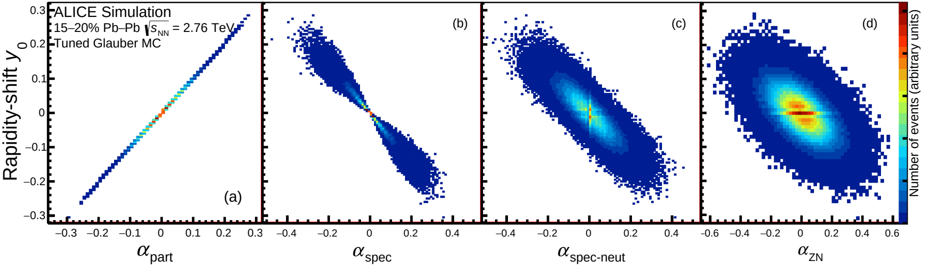
- fluctuations in the number of participants
  - A in one colliding nucleus, B in the other nucleus
- rapidity shift?



ALICE Collaboration, PRL 110 (2013) 032301

Longitudinal asymmetry in simulation

Pb-Pb Glauber Monte-Carlo



longitudinal asymmetry of participants

$$\alpha_{part} = \frac{A-B}{A+B}$$

rapidity shift

$$y_0 \simeq \frac{1}{2} \ln \frac{A}{B}$$

longitudinal asymmetry of spectators

- taking into account multiple interactions

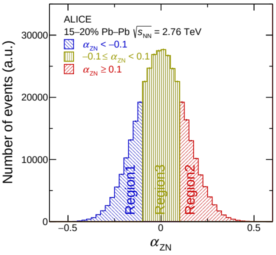
longitudinal asymmetry of spectators reaching ZN calorimeters

- loss of spectator fragments into the beamline

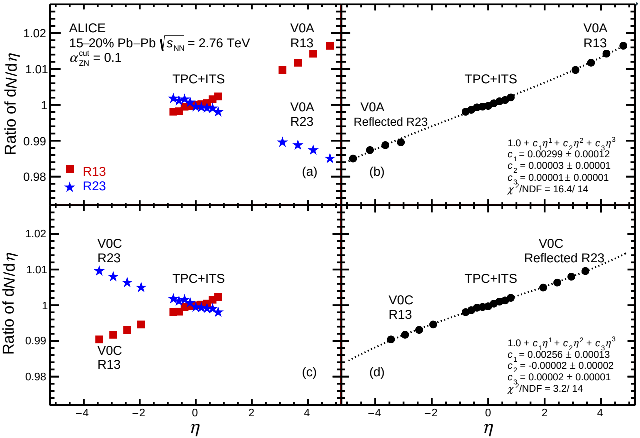
measured spectator longitudinal asymmetry

- take into account energy resolution

Measuring rapidity shift



$$\frac{(dN/dy)_{asym}}{(dN/dy)_{sym}} = \sum c_i y^i$$



- Pesudorapidity distributions are affected by longitudinal asymmetry
  - results in a rapidity shift
- Study influence on other signals

The LHC heavy-ion program

- The LHC heavy-ion program will extend to RUN 3-4 (Pb-Pb, p-Pb, Ar-Ar)
- Upgrades of the injection chain will allow to reduce bunch spacing to 50 ns in Pb-Pb
  - interaction rate from 8 kHz[1] to ≥ 50 kHz
  - delivered luminosity $> 10\times$ w.r.t. Run 1-2
- A major upgrade of the ALICE detector during LS2 (2019-2020) will allow to exploit delivered luminosity and to improve the physics performance

[1] ALICE can acquire full MB data at ~ 1 kHz

Opportunities and challenges

- Higher luminosity
  - Better significance for rare signals
- Central barrel upgrades
  - Access to low p_T heavy-quark probes
- Forward upgrades
  - Detection of signals from thermalization

- High rate
  - Heavy data
- Low p_T
  - Low signal over background

ALICE strategy

- Run triggerless
  - Online filtering
- Online data reduction

ALICE upgrade strategy

Time Projection Chamber
- GEM readout chambers
- faster FEE and continuous readout

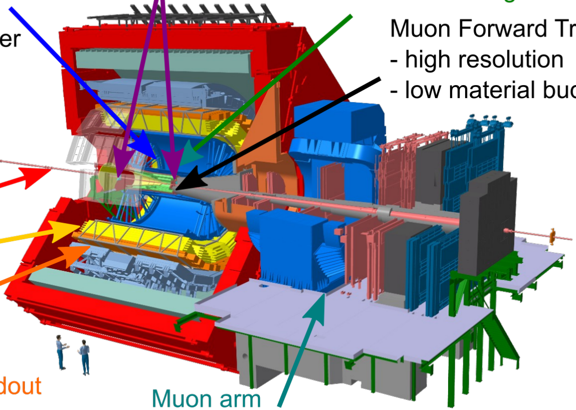
New MB trigger
detector: FIT

New inner tracking system
- high resolution
- low material budget

DAQ and High Level Trigger
- new architecture

Computing
- fast online reconstruction
- data reduction @ 50 kHz

Muon Forward Tracker
- high resolution
- low material budget



New beryllium pipe with
smaller radius

TRD
- Faster readout

TOF, ZDC
- continuous readout

New Central Trigger Processor

Muon arm
- continuous readout

Strategy for ZDC upgrade

- Improvement of the readout performance:
  read out the detector at 100 kHz hadronic rate without dead time

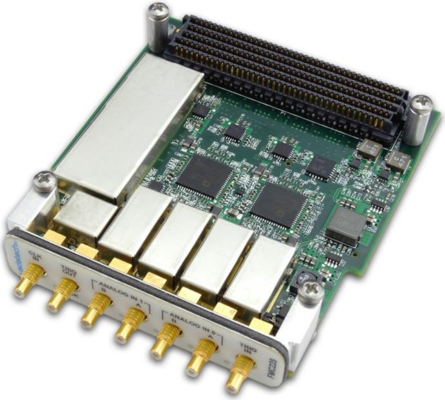
For ZDC this is accompanied by $\sim$ 5 MHz EMD rate

- cannot be achieved using the current QDCs because of the fixed dead time due to the charge conversion of $\approx 10\,\mu$s per event
  - possible using digitizers

This proposal was tested during the Pb-Pb 2016 data taking with a parallel acquisition system
Main features of investigated digitizer are:

- ✔ sampling frequency 1 Gsample/s
- ✔ 1 Vpp dynamics
  - ✔ Adjustable offset
- !! 10 bit resolution, 12 bit would be better
- ✔ 8 channels
- ✘ 80 MB/s readout bandwidth

Test of a FMC digitizer

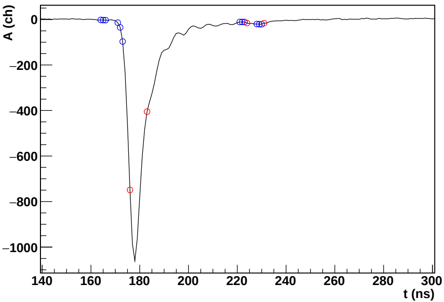


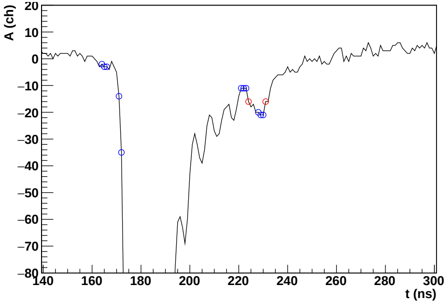
FPGA Mezzanine Card

- ✔ 1 Gsample/s
- ✔ 1 Vpp dynamics
  - !! Not ajustable offset
  - !! Not full DC coupling (balun + capacitors)
- ✔ 12 bit resolution
- ✔ 4 channels
- ✔ continuous waveform readout to FPGA through 8 JESD204B serial lines

Triggering in extreme events

- Bunch spacing in Pb-Pb will be reduced to 50 ns in LHC
- Worst case is an event with maximum neutron multiplicity followed by an event with single-neutron emission





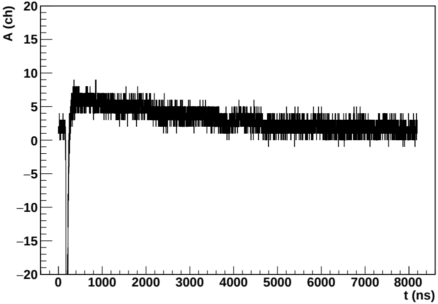
○ samples that satisfy trigger requirement: digital differential discriminator

$$(y_i - y_{i+shift}) > th \&\& \ (y_{i+1} - y_{i+shift+1}) > th \&\& \ (y_{i+2} - y_{i+shift+2}) > th$$

○ samples for which derivative turns positive: rough estimation of the signal time

- Discriminator principle is working
  - Will benefit from a reduction in ringing
- A few similar algorithms were developed
  - Will be tested during the Pb-Pb data taking in November 2018

Issues with present digitizer



- Digitizer has not full DC coupling
  - baseline is not immediately restored
  - $\sim 0.5\%$ effect but can become important at high rates
- Full DC digitizers are not very common on the market
  - identified a new board and preparing to test in the lab.

- VITA 57 standard is not VME. . .
  - Match between FMC and carrier board is not straightforward
    - FPGA performance
    - pin usage
    - configuration
  - Varying degree of vendor lock-in
- Clocking issues
  - Ideally board clock should be synchronized with machine clock
  - most digitizers have not enough flexibility
  - need to replace on-board VCXO

Conclusions

- ZDCs are widely employed in ALICE
  - trigger
  - event selection
  - geometry of the collision
    - centrality
    - longitudinal asymmetry
    - event plane

- EMD cross sections are well described by theoretical models
  - luminosity monitoring

- Need to preserve ZDC performances in Pb-Pb operation in RUN3
  - challenging due to the reduced bunch spacing and higher rates
  - fast digitizers seem to be a viable solution