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Determination of luminosity and of the inelastic hadronic Pb-Pb cross section with ALICE at the LHC

Guillermo Contreras
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On behalf of the ALICE Collaboration

FORTE
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MINISTRY OF EDUCATION, YOUTH AND SPORTS

Introduction to luminosity determination with van der Meer scans

Luminosity

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The reference cross section is measured in special runs, called **van der Meer scans**

LHC luminosity*

Luminosity per bunch pair

$$\mathscr{L} = f_{\mathrm{LHC}}\, N_1\, N_2 \int f_1(x,y) f_2(x,y)\,\mathrm{d}x\mathrm{d}y$$

*presented for no crossing angle; formalism also valid for the general case

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Probability density distributions of the particles in each bunch in the transverse plane

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where the **effective widths** are defined as:

$$h_x = \frac{1}{\int f_{1x}(x) f_{2x}(x)\,\mathrm{d}x}, \qquad h_y = \frac{1}{\int f_{1y}(y) f_{2y}(y)\,\mathrm{d}y}$$

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These integrals are measured in van der Meer scans using the rate of a reference process defined by a set of detectors called **luminometers**

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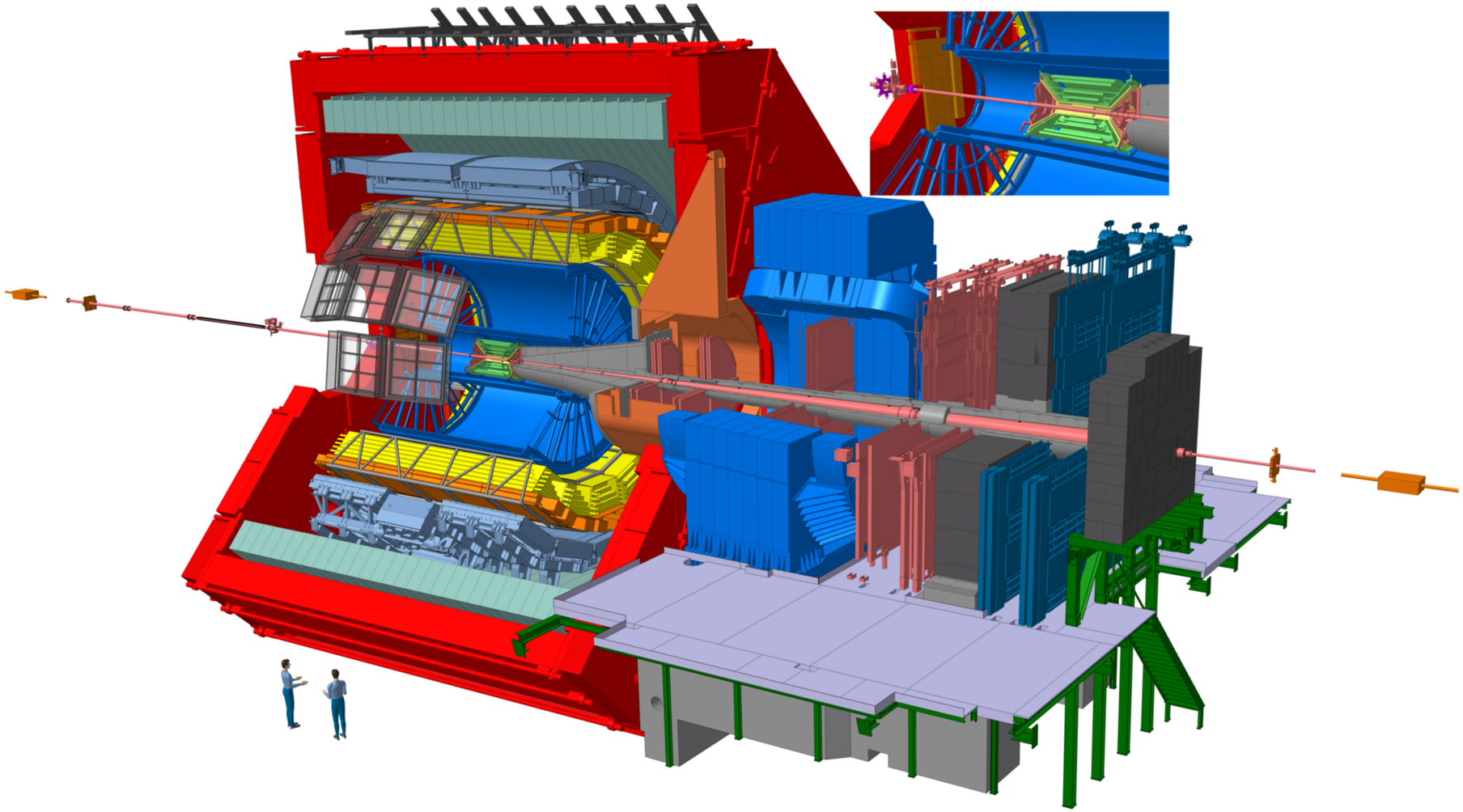
ALICE luminometers for the LHC Run 2

Three luminometers, each a two-arm system



A-side

C-side

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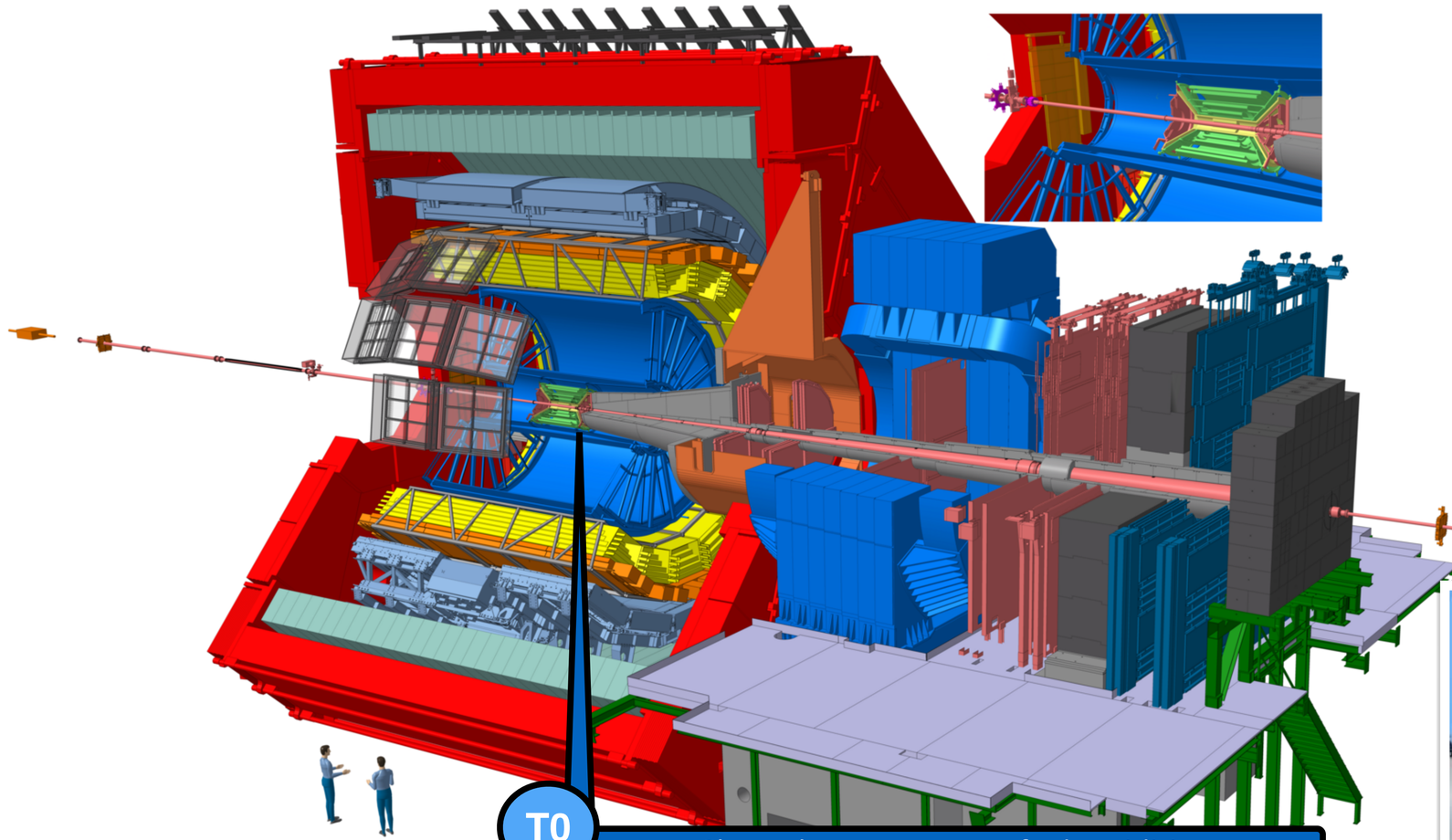

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T0

Fast Cherenkov counters at fwd rapidities
Reference process for pp, p-Pb and Pb-Pb: at least one hit in each side plus a vertex requirement from timing

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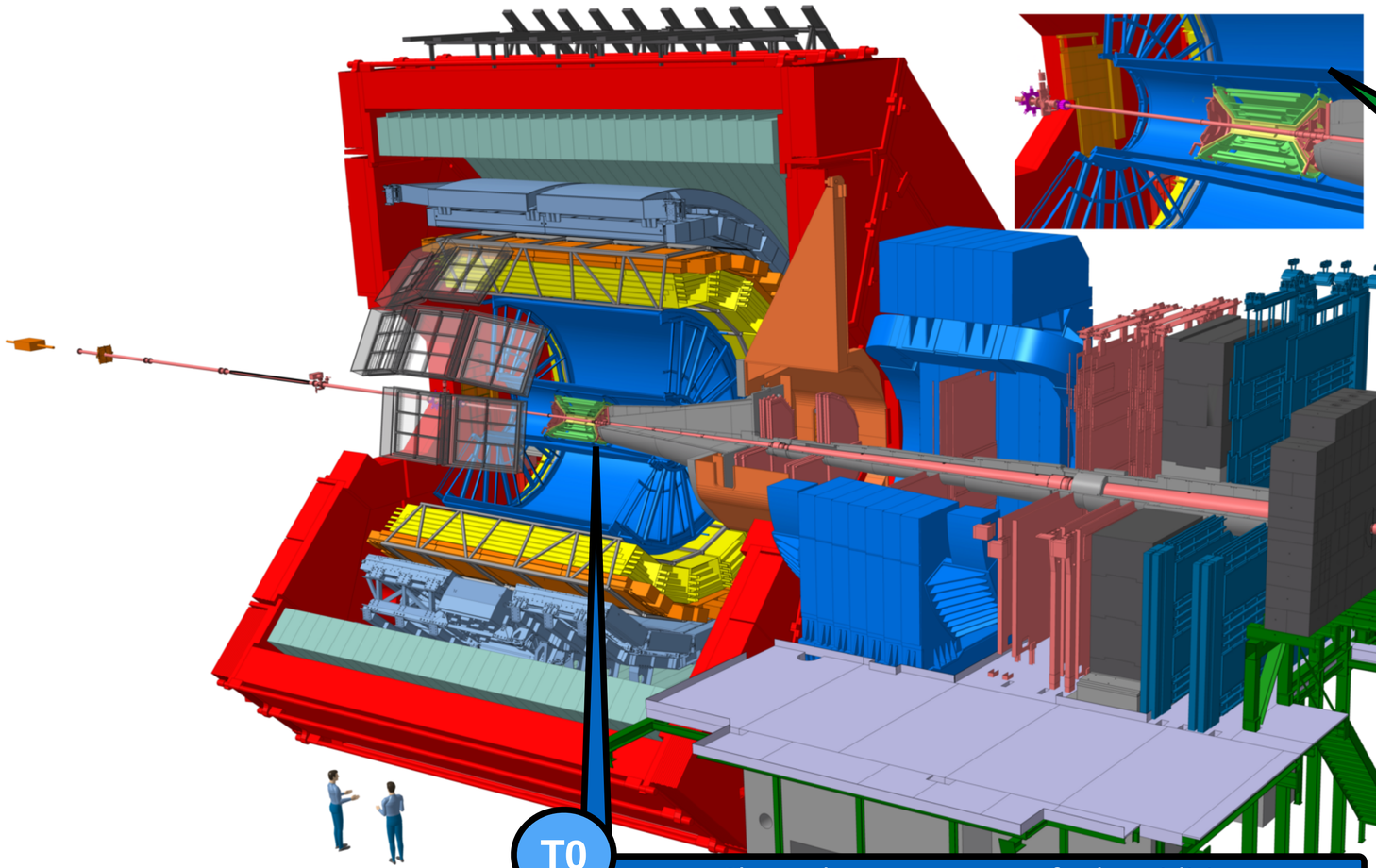

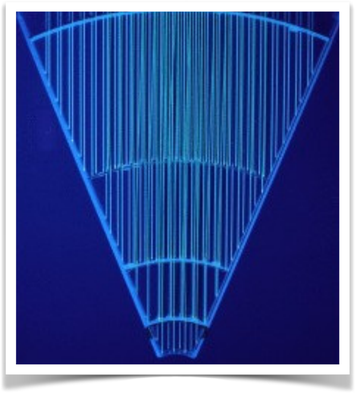

Fast scintillator hodoscopes at fwd rapidities
Reference process for pp and p-Pb:
at least one hit in each side
Reference process for Pb-Pb (V0M):
Total amplitude ≈ 0-50% centrality

V0

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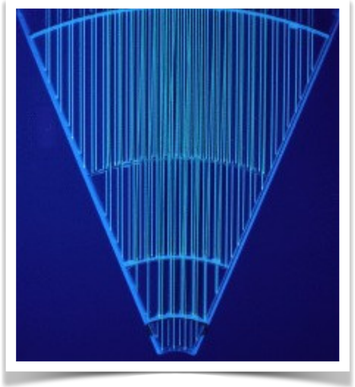

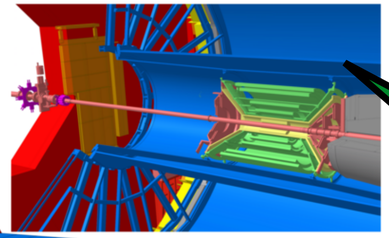

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Fast neutron calorimeters at beam rapidities
Reference process for Pb-Pb:
at least one hit on either side

ZN

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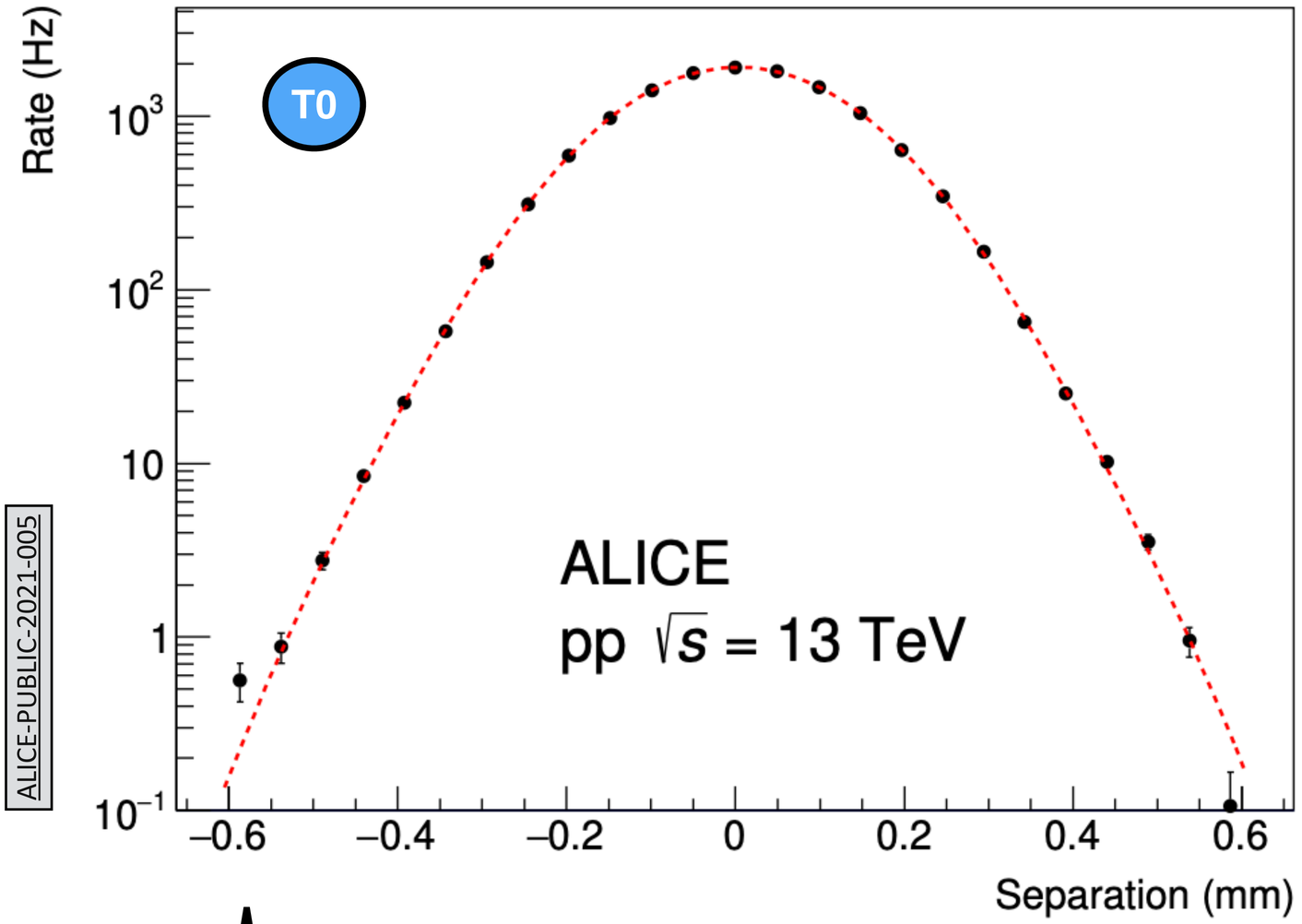
Fast Cherenkov counters at fwd rapidities
Reference process for pp, p-Pb and Pb-Pb: at least one hit in each side plus a vertex requirement from timing

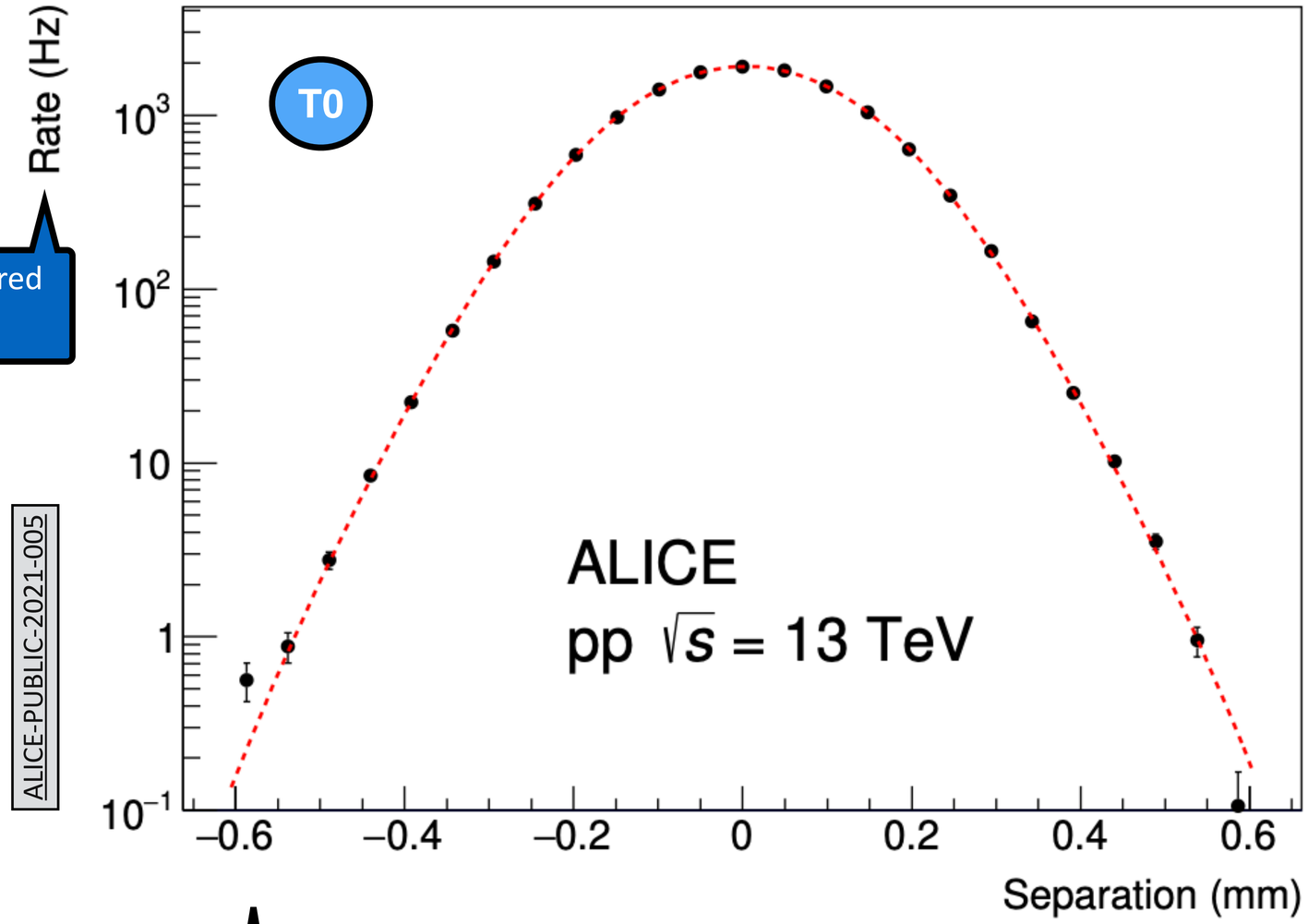
Determination of the effective widths



Beams moved in one direction, while keeping the other direction fixed

Determination of the effective widths

Rate of a reference process measured during 30 seconds at each step



Beams moved in one direction, while keeping the other direction fixed

Determination of the effective widths

The area under the curve gives the effective beam width for head-on collisions:

$$h_{x,0} = \frac{\int R_{\mathrm{ref}}(\Delta x, 0)\, \mathrm{d}\Delta x}{R_{\mathrm{ref}}(0,0)}$$

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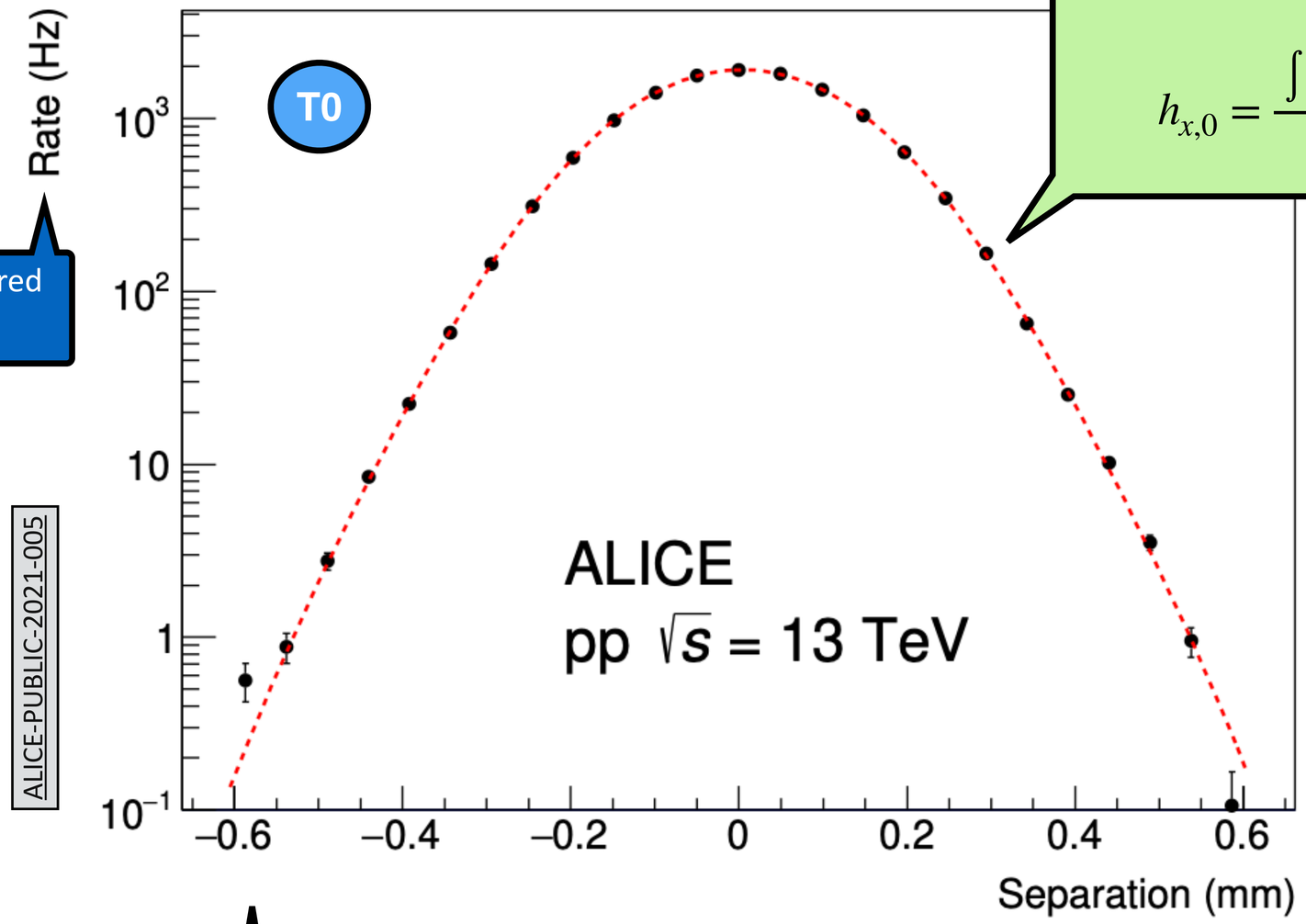

Beams moved in one direction, while keeping the other direction fixed

Corrections and uncertainties

Corrections for parasitic charges (ghost, satellites), and intensity decay

DCCT (LHC), measures the total beam intensity
fBCT (LHC) or BPTX (ATLAS) measure relative bunch intensities

$$\mathscr{L} = \frac{f_{\mathrm{LHC}} N_1 N_2}{h_x h_y}$$

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nominal separations from the LHC

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Rates for different luminometers

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Numerical or model based integral

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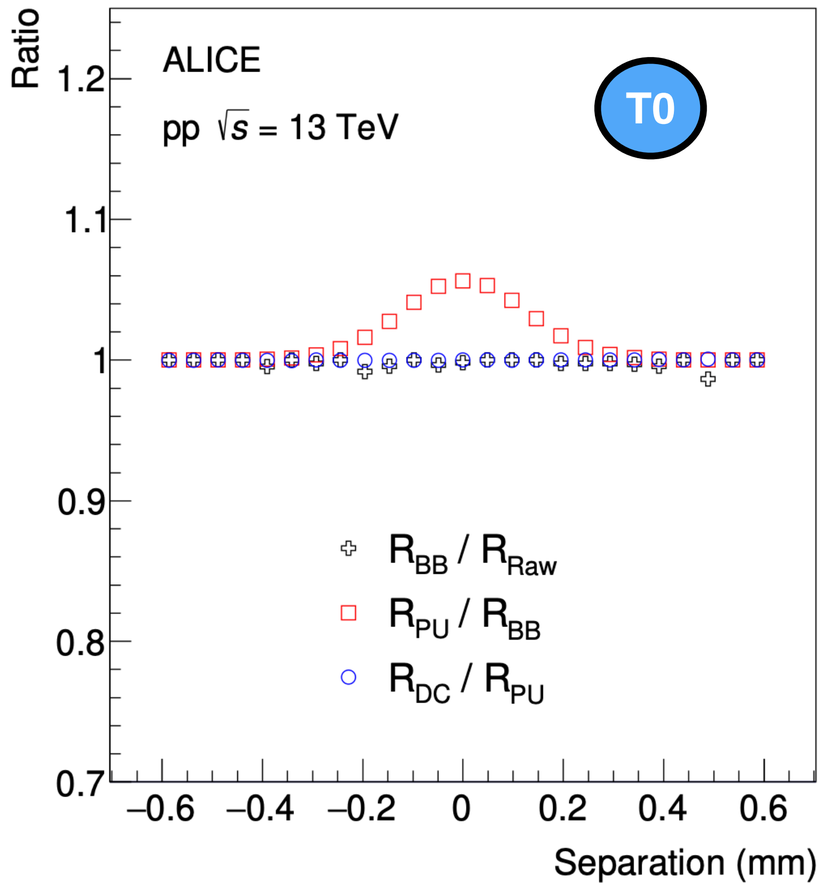
In addition: stability of the luminometers across the full data taking period

Luminosity determination for pp and Pb-Pb collisions with ALICE in LHC Run 2

Guillermo Contreras, CTU in Prague

Some examples from the pp analysis



Corrections to the rate
Large effect for pile-up for head-on collisions

ALICE-PUBLIC-2021-005

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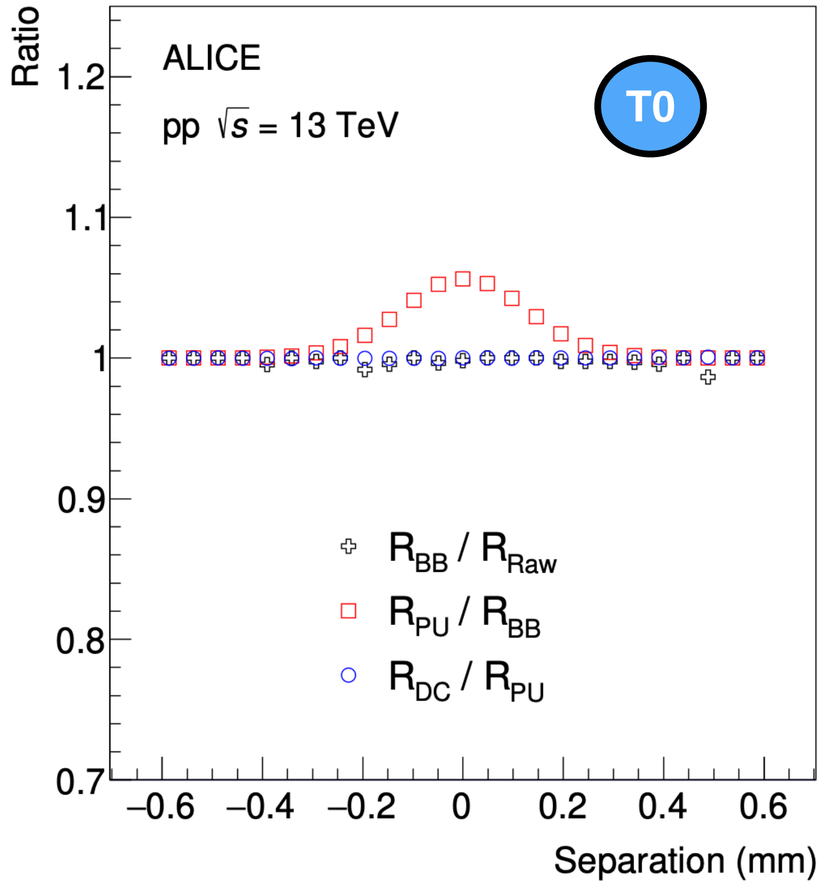

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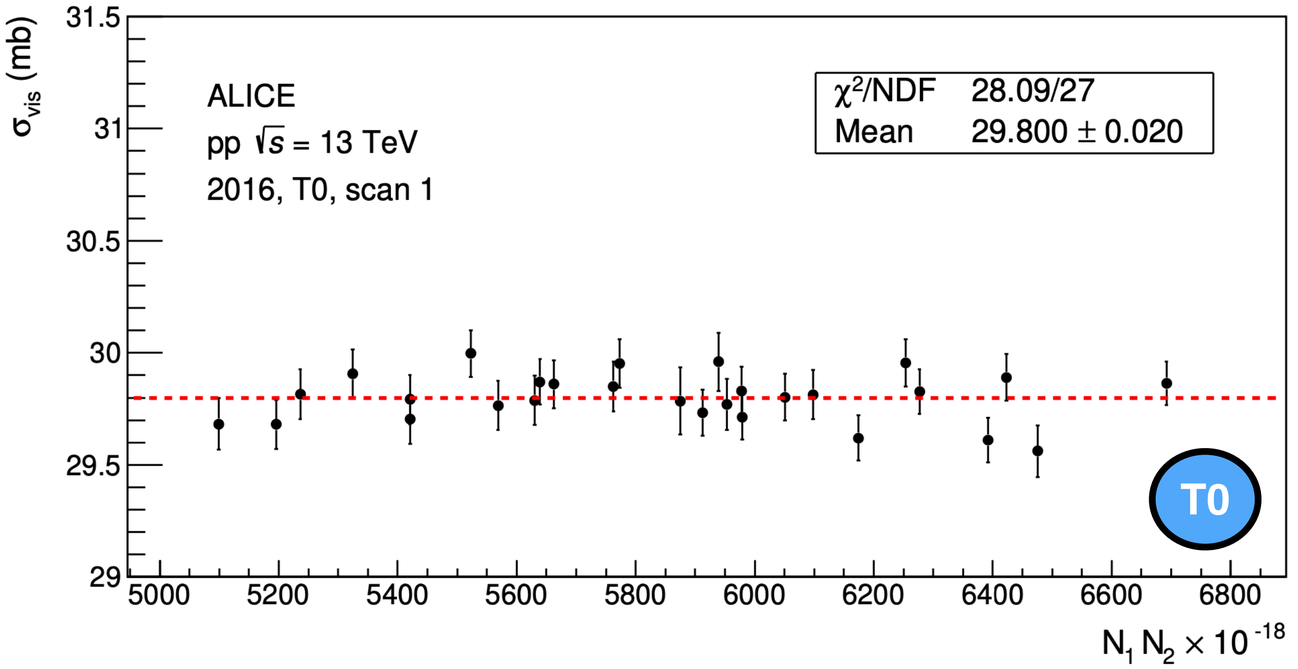
Cross section consistent across colliding bunch pairs



ALICE-PUBLIC-2021-005

Summary of pp collisions at 13 TeV from 2016 to 2018

Uncertainty	2016	2017	2018	Correlated?
	T0 | V0	T0 | V0	T0 | V0	
Statistical	0.05% | 0.05%	0.07% | 0.07%	0.05% | 0.05%	No
Bunch intensity				
Beam current normalisation	0.5%	0.5%	0.4%	Yes
Relative bunch populations	0.1%	0.3%	0.1%	No
Ghost and satellite charge	< 0.1%	< 0.1%	< 0.1%	No
Non-factorisation	0.5%	0.2%	0.4%	Yes
Length-scale calibration	0.2%	0.3%	0.3%	No
Beam-beam effects	0.3%	0.3%	0.3%	Yes
Orbit drift	0.1%	0.1%	0.2%	No
Magnetic non-linearities	0.1%	0.2%	0.2%	Yes
Beam centring	< 0.1%	< 0.1%	0.1%	No
Luminosity decay	0.5%	0.5%	0.3%	No
Background subtraction	0.1% | 0.6%	0.1% | 0.8%	0.1% | 0.7%	Yes
Pile-up	0.1% | < 0.1%	0.5%	0.2% | < 0.1%	Yes
Fit model	0.2%	0.6%	0.4%	Yes
$h_x h_y$ consistency (T0 vs V0)	0.1%	0.4%	0.4%	No
Bunch-by-bunch consistency	< 0.1% | < 0.1%	0.1% | 0.1%	0.1% | 0.1%	No
Scan-to-scan consistency	0.2% | 0.1%	0.1% | 0.1%	0.5% | 0.5%	No
Stability and consistency	1.5%	2.3%	1.6%	No
Total correlated	0.8% | 1.0%	1.0% | 1.2%	0.8% | 1.0%	Yes
Total uncorrelated	1.6% | 1.6%	2.4% | 2.4%	1.8% | 1.8%	No
Total	1.8% | 1.9%	2.6% | 2.7%	1.9% | 2.1%	Partially

Main contribution to uncertainty

Uncertainty from combined sample slightly better than 2%

ALICE-PUBLIC-2021-005

Some examples from the Pb-Pb analysis

New fit model to deal with low rates in some steps

Time bin

orbits

triggers

Poissonian log-likelihood

$$\ln \mathcal{L} = \sum_i [t_i \ln P_i + (n_i - t_i) \ln(1 - P_i)]$$

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$$P_i = 1 - e^{-\mu_i}$$

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mean number of triggers per bunch pair

$$\mu_i = \frac{R_{\mathrm{ref}}(\Delta x_i, \Delta y_i)}{f_{\mathrm{LHC}}} + p_{s,i} + \tilde{p}_1 N_{1,i} + \tilde{p}_2 N_{2,i} + p0$$

Satellites (from another log-likelihood fit)

beam-gas

det. noise

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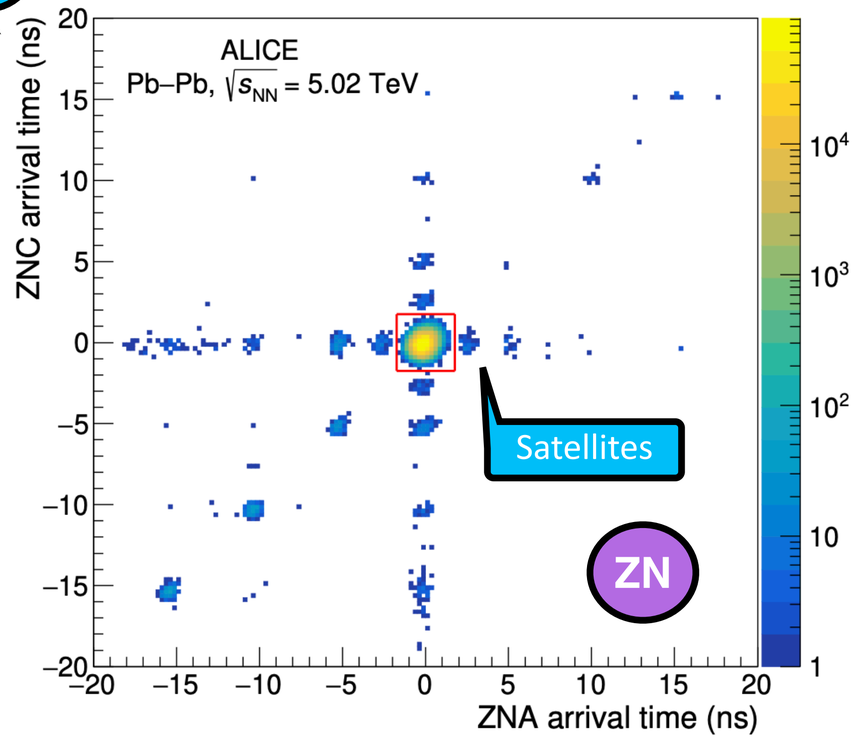

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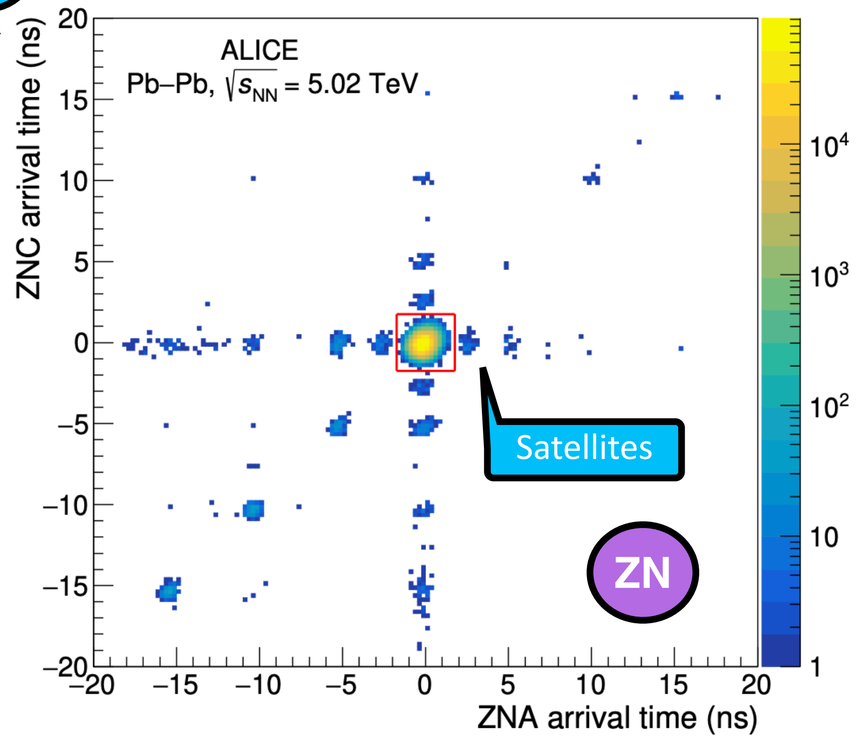
$$R_{\mathrm{ref}}(\Delta x_i, \Delta y_i) = f_{\mathrm{LHC}} N_{1,i} N_{2,i} \frac{\sigma_{\mathrm{ref}}}{h_{x0} h_{y0}} f(\Delta x_i) g(\Delta y_i)$$

Gaussian core with flexible tails



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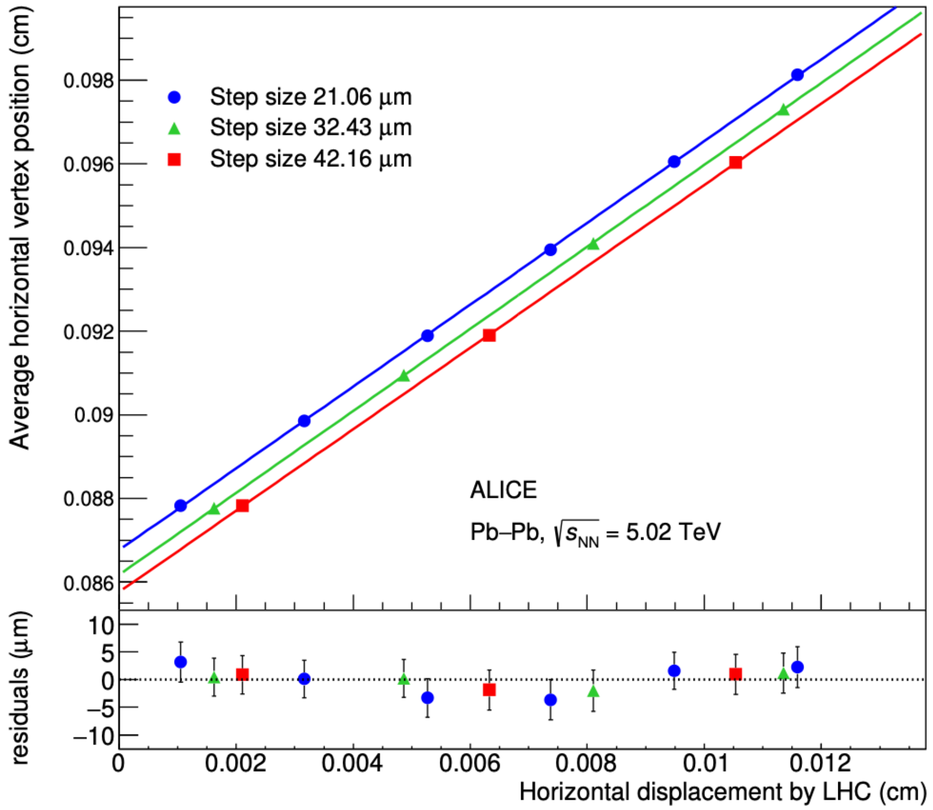
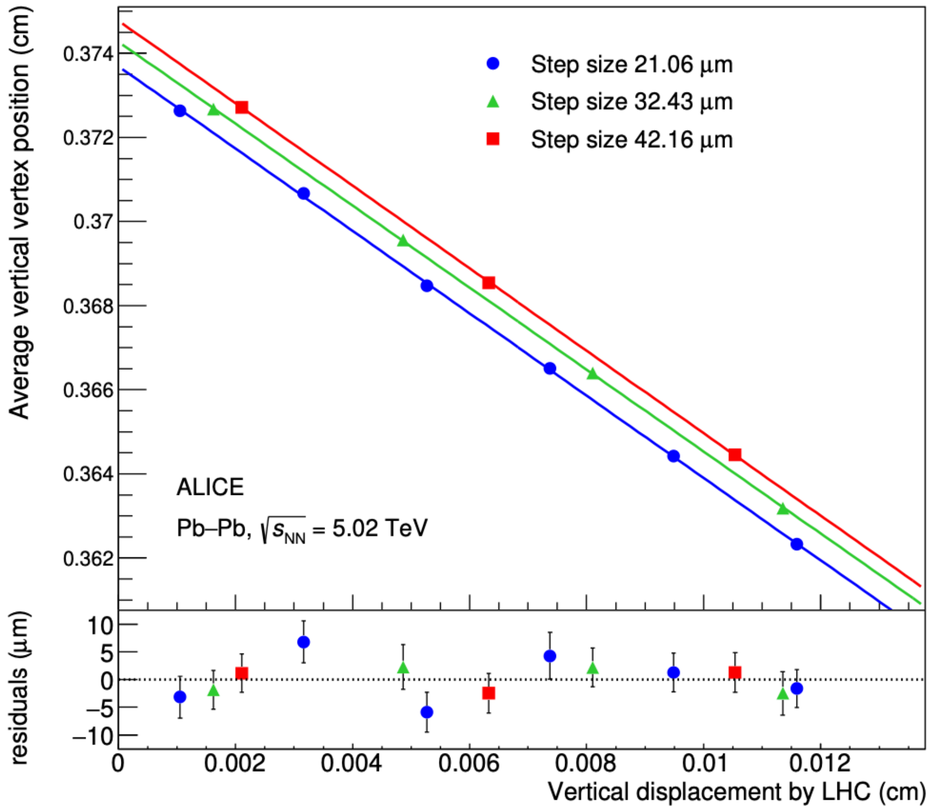
Some examples from the Pb-Pb analysis

Three length-scale calibrations (move both beams in one direction in steps)

Separation according to ALICE





Separation according to LHC

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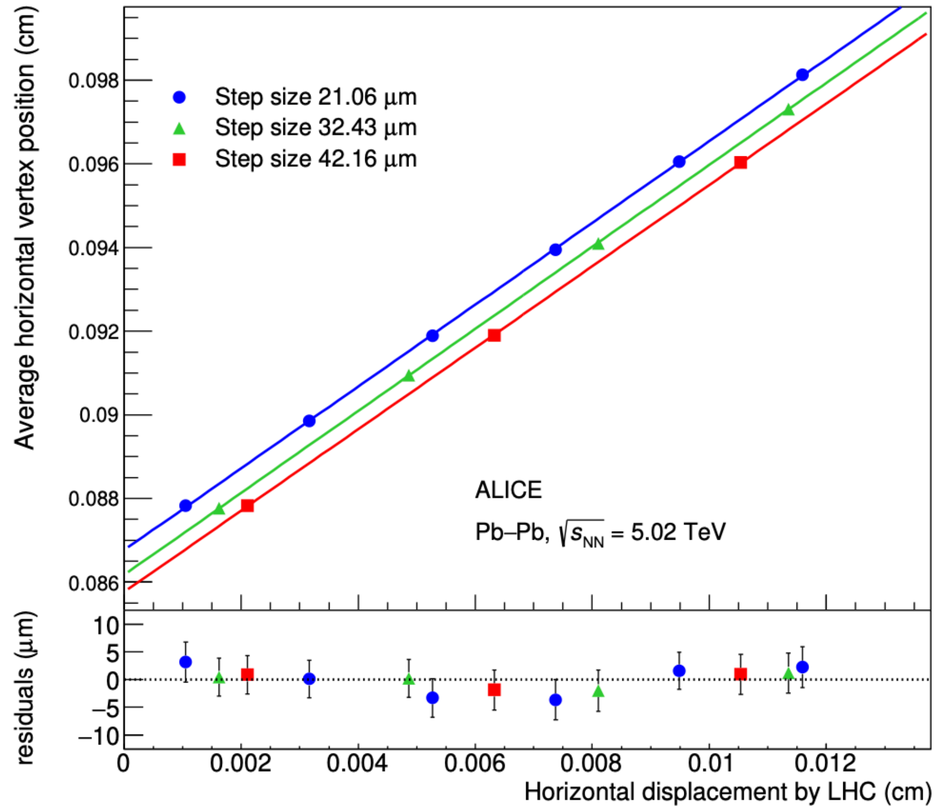
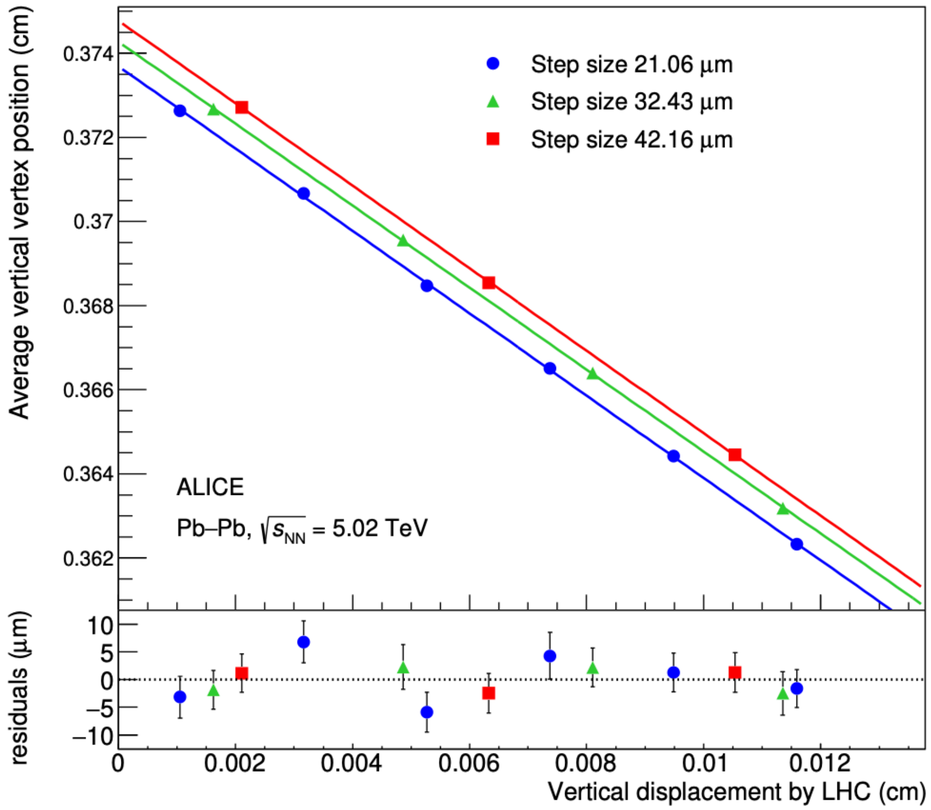




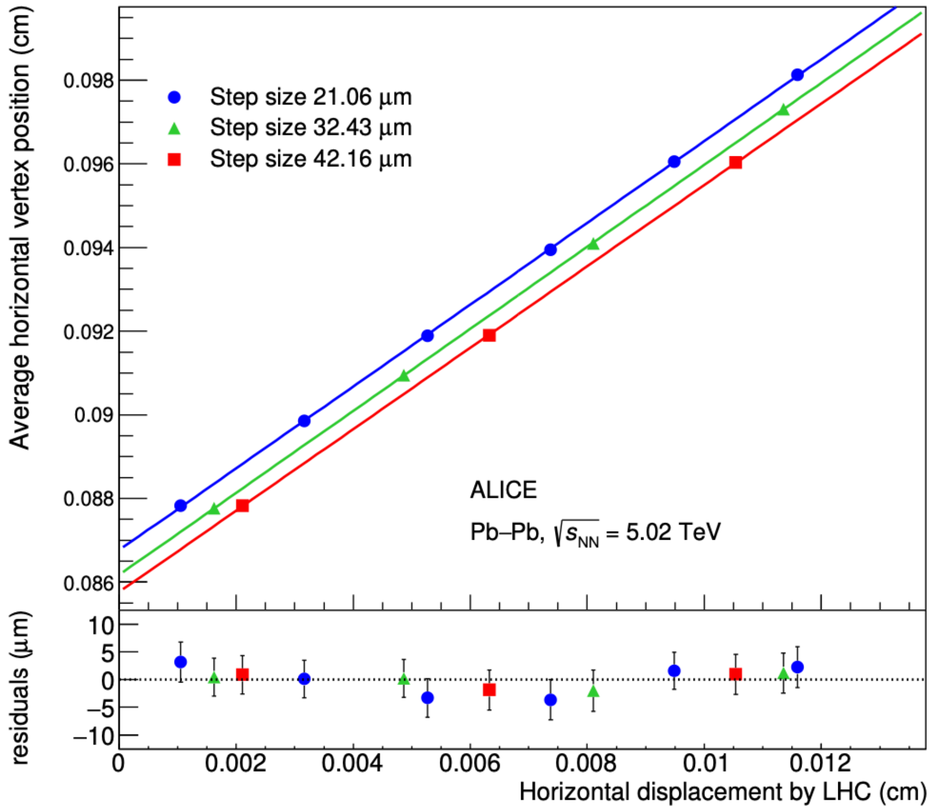
Separation according to LHC

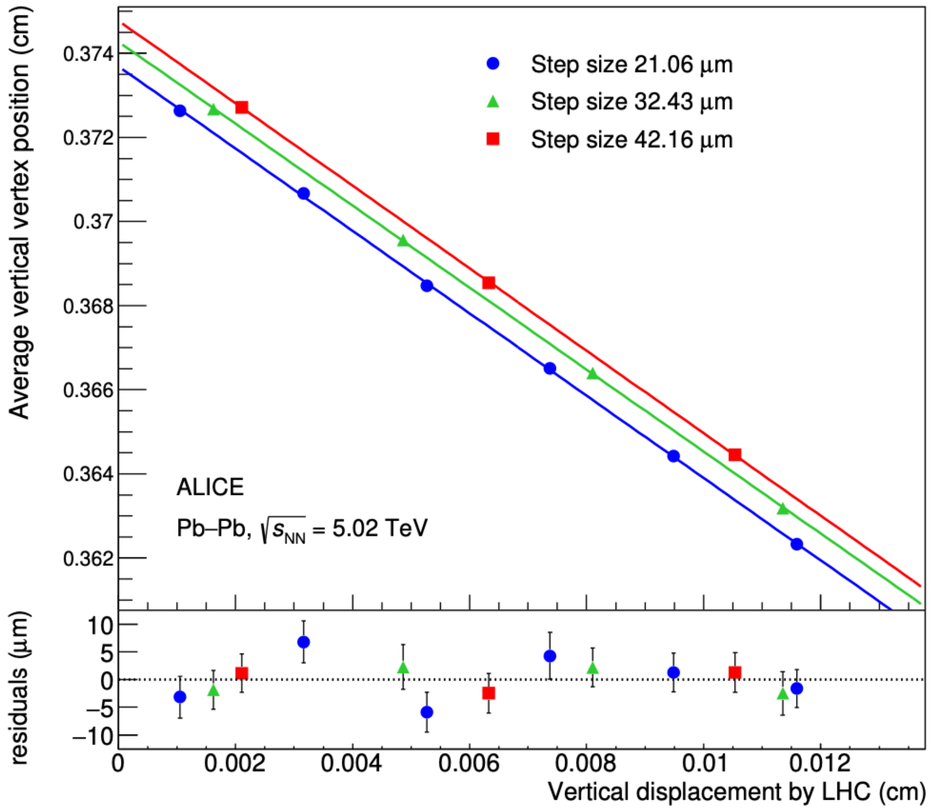
Use the slope to correct from nominal to real displacement: 3.6±1.0% effect for this analysis

Some examples from the Pb-Pb analysis

Three length-scale calibrations (move both beams in one direction in steps)

Separation according to ALICE





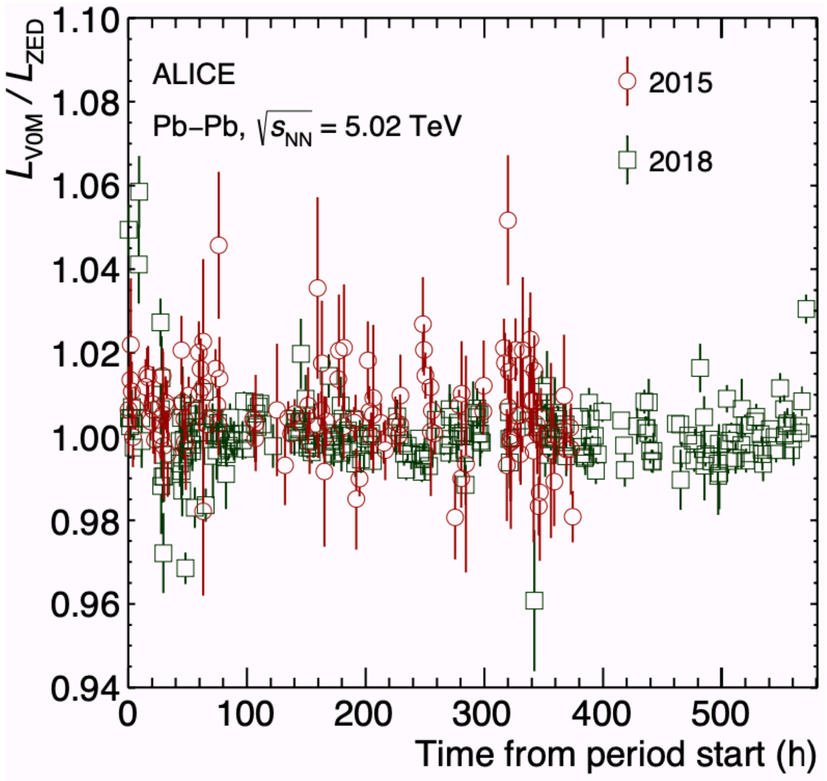
Separation according to LHC

Use the slope to correct from nominal to real displacement: 3.6±1.0% effect for this analysis

Uncertainties from size of data sample (0.5%), event selection (0.7%), comparison across LSC runs (0.4%), deviations from linear trends in the fits (0.3%)

JINST 19 (2024) 02, P02039

Results for Pb-Pb collisions at 5.02 TeV



Main contributions to uncertainty

Source	Uncertainty (%) ZED | V0M
Statistical	0.008 | 0.08
$h_{x0}h_{y0}$ consistency (V0M vs ZED)	0.13
Length-scale calibration	1
Non-factorisation	1.1
Bunch-to-bunch consistency	0.1
Scan-to-scan consistency	1
Satellite collisions	1.2
Beam–gas and noise	0.3
Bunch intensity	0.8
Emittance variation	0.5
Magnetic non-linearities	0.2
Orbit drift	0.15
Beam–beam deflection and distortion	0.1
Fitting scheme	0.4
Total of visible cross section	2.4
Stability and consistency	0.7
Total of luminosity	2.5 | 2.5

Uncertainty slightly above 2%

JINST 19 (2024) 02, P02039

Total inelastic hadronic cross section in Pb-Pb collisions at 5.02 TeV

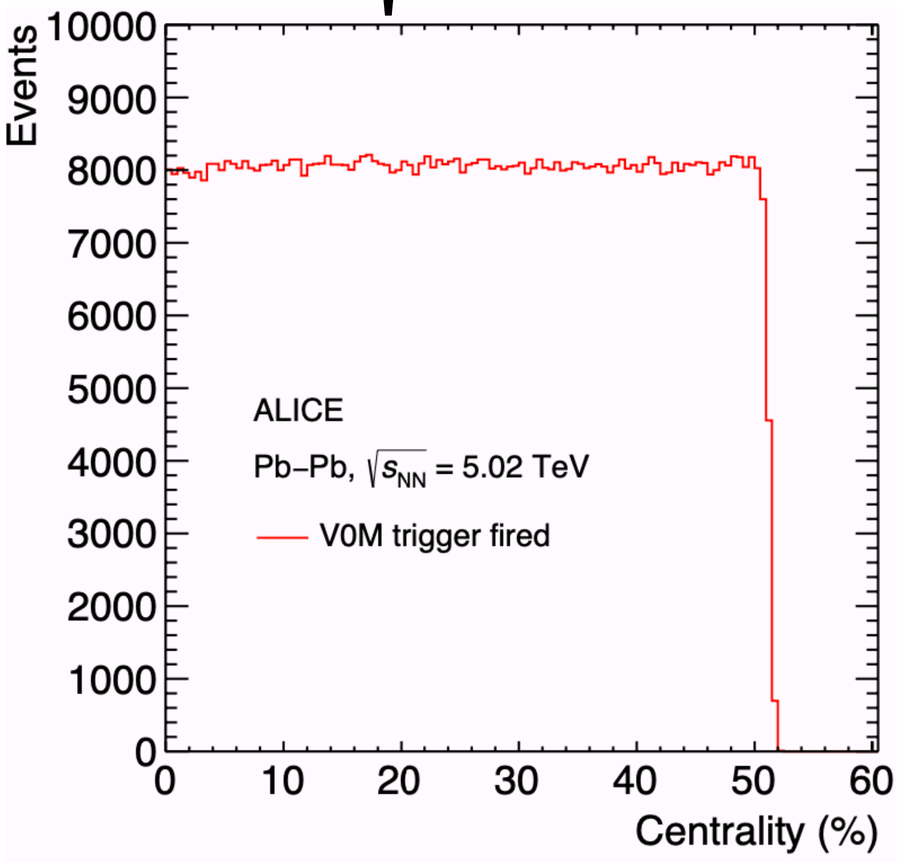
Total inelastic hadronic Pb-Pb cross section

From the vdM scans

$$\sigma_{\mathrm{had}} = \frac{\sigma_{\mathrm{V0M}}}{\epsilon_{\mathrm{had}}}$$

Total inelastic hadronic Pb-Pb cross section

Efficiency from the integral of the centrality distribution of V0M triggers



From the vdM scans

$$\sigma_{had} = \frac{\sigma_{V0M}}{\epsilon_{had}}$$

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Total inelastic hadronic Pb-Pb cross section

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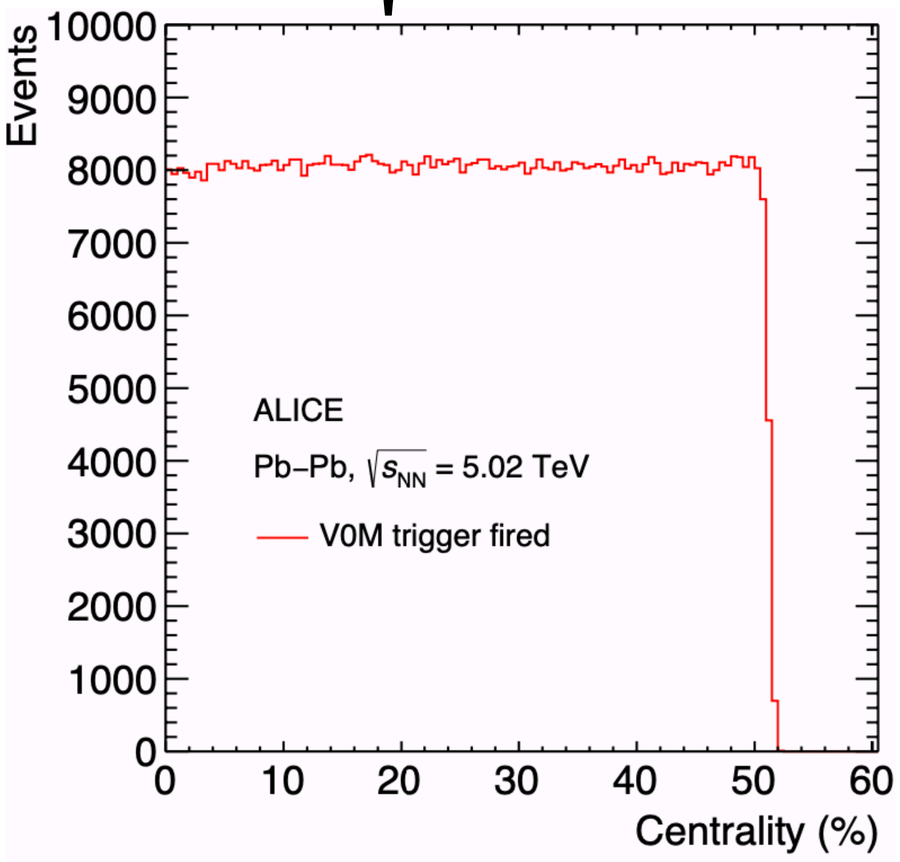

From the vdM scans

$$\sigma_{had} = \frac{\sigma_{V0M}}{\epsilon_{had}}$$

Uncertainties in centrality [1] definition from:
Variations in the anchor point by ±1%
Comparison of Glauber and Trento fits
[1] https://journals.aps.org/prc/abstract/10.1103/PhysRevC.88.044909

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Total inelastic hadronic Pb-Pb cross section

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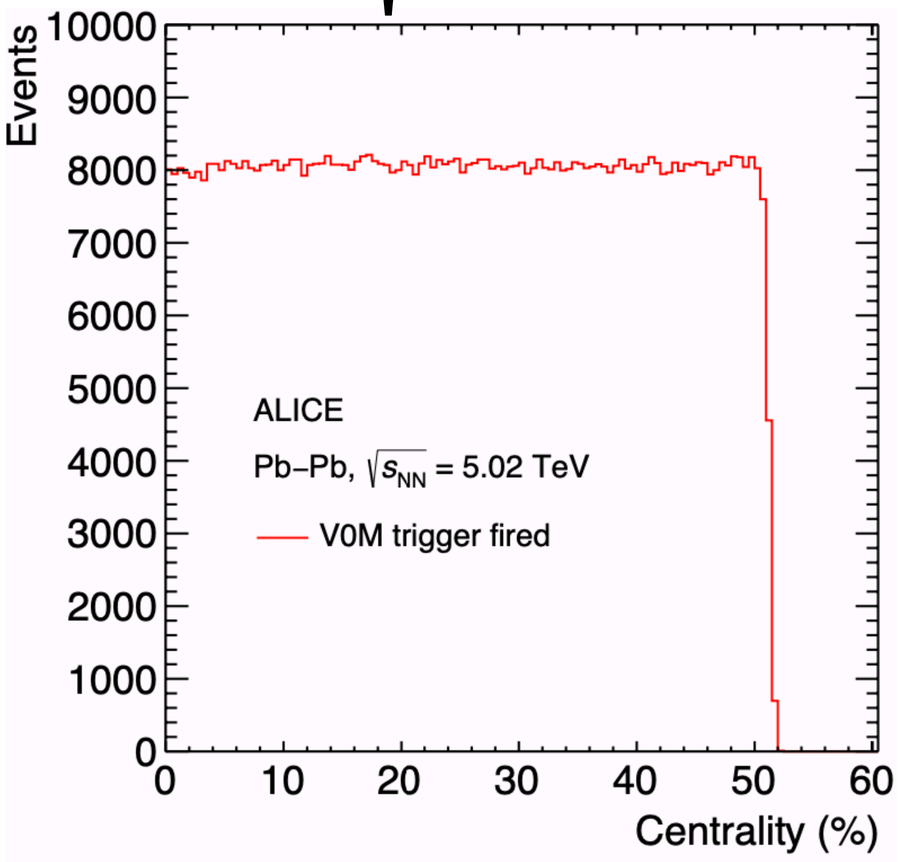


From the vdM scans

$$\sigma_{had} = \frac{\sigma_{V0M}}{\epsilon_{had}} = 7.67 \pm 0.25 \text{ b}$$

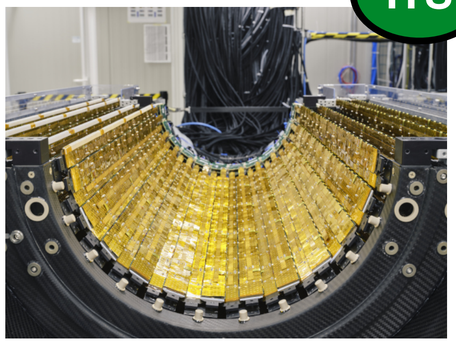
Uncertainties in centrality [1] definition from:
Variations in the anchor point by ±1%
Comparison of Glauber and Trento fits
[1] https://journals.aps.org/prc/abstract/10.1103/PhysRevC.88.044909

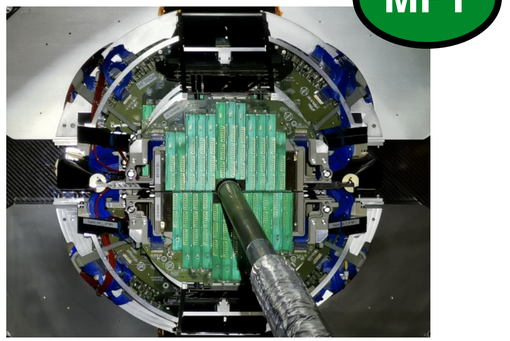
JINST 19 (2024) 02, P02039

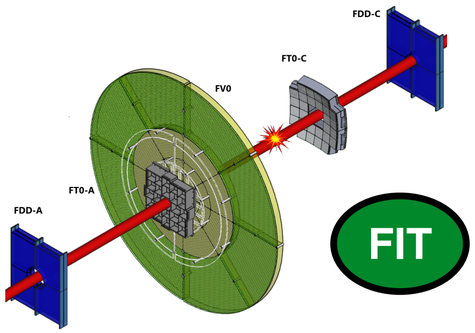
Luminosity determination with ALICE in LHC Run 3

ALICE upgrades for Run 3

New detectors:
Inner tracking sytem (ITS)
Muon forward tracker (MFT)
Fast interaction trigger (FIT)







JINST 19 (2024) 05, P05062

ALICE upgrades for Run 3

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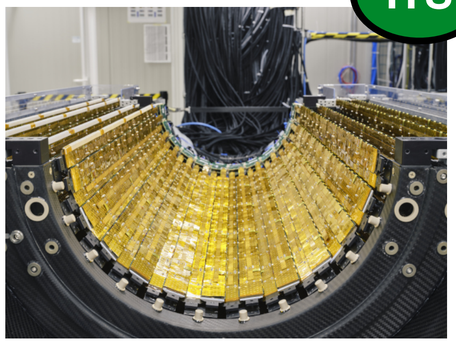
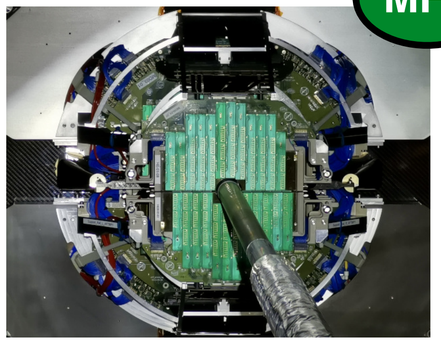
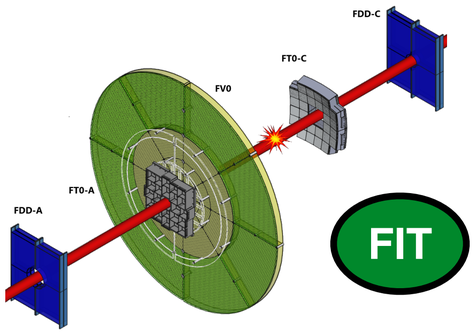
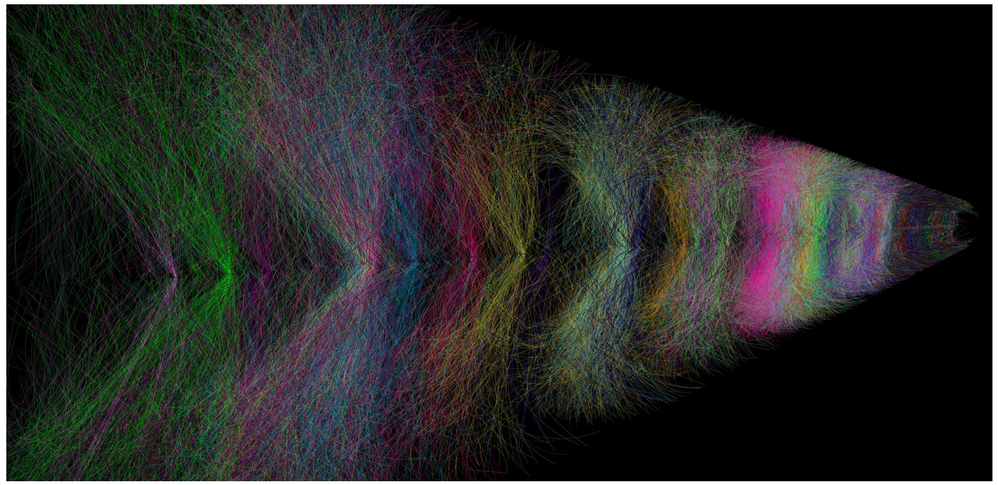






Improved detectors and systems:
GEMs for TPC
New electronics for several systems
Continuous data taking



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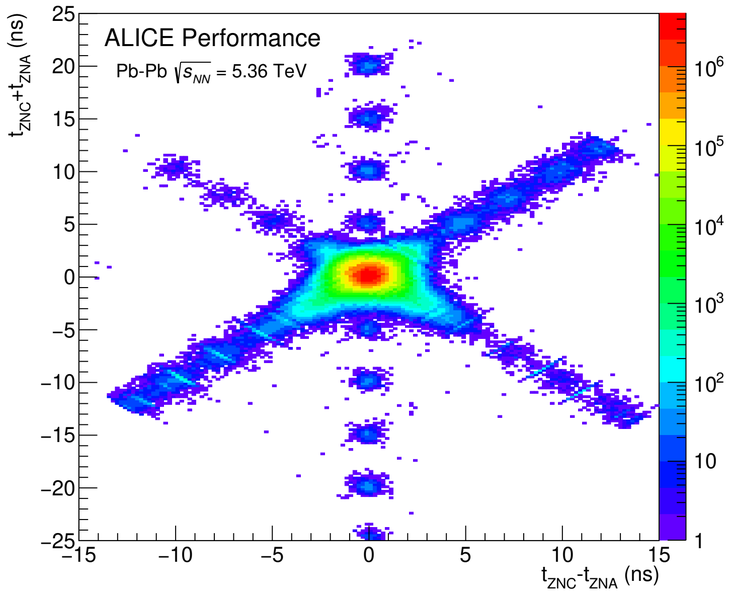
Luminometers for Run 3



Same detector, improved electronics

ZN

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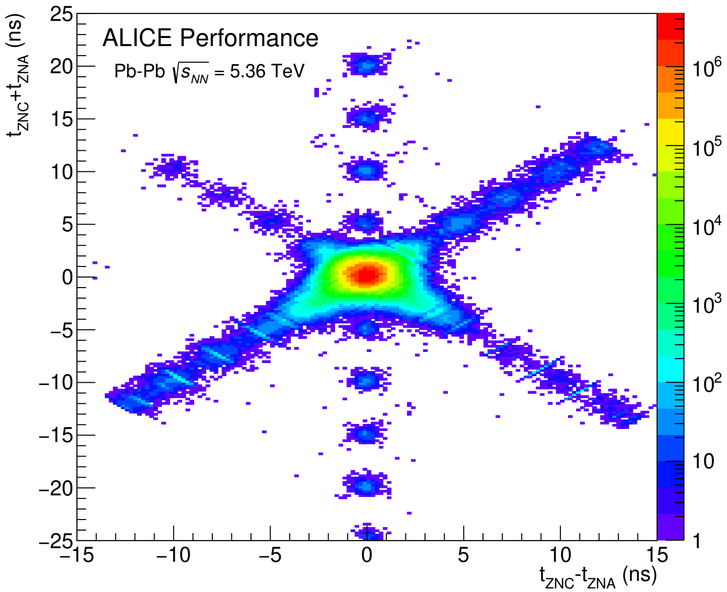
Luminometers for Run 3



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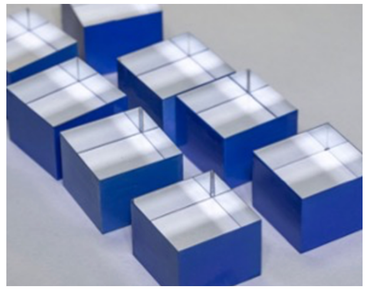
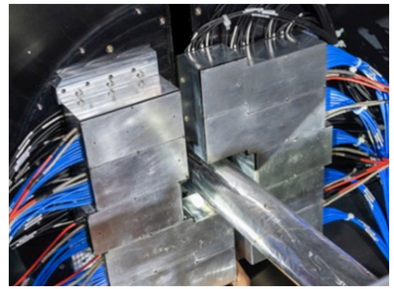
ZN

New detector (quartz Cherenkov radiators, MCP-PMT)
More channels, larger rapidity coverage

FT0





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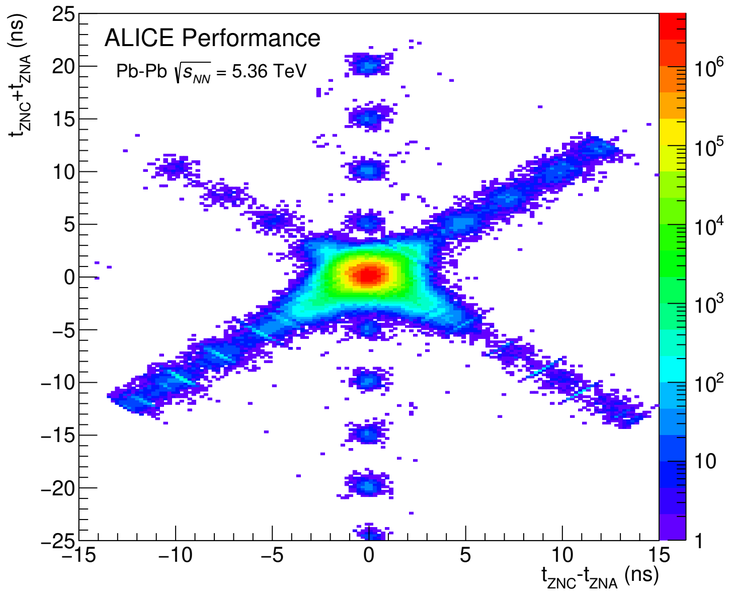
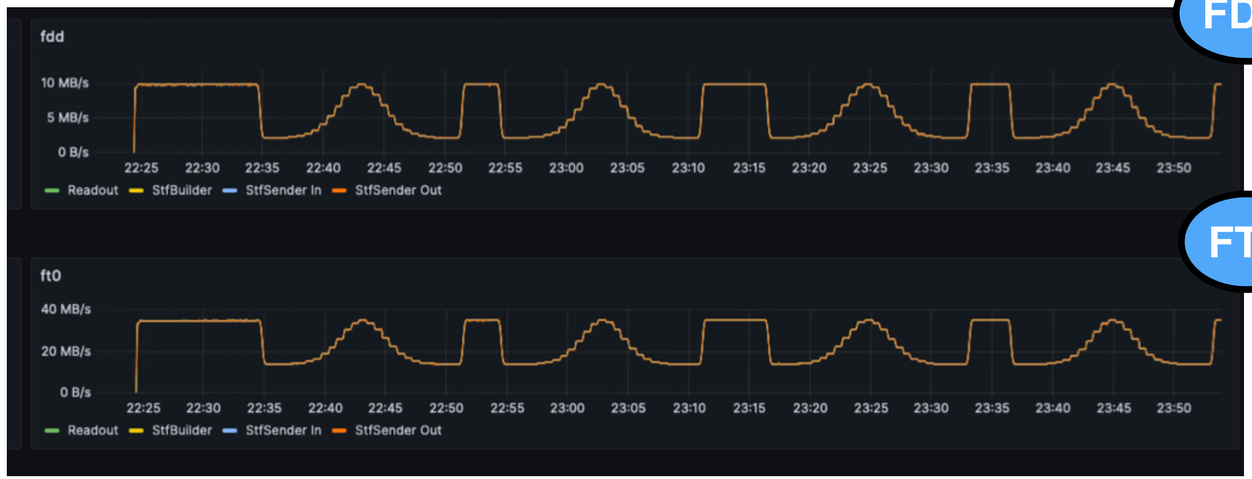


ALI-PERF-565487

Same detector, improved electronics

ZN

pp van der Meer scan, September 2023



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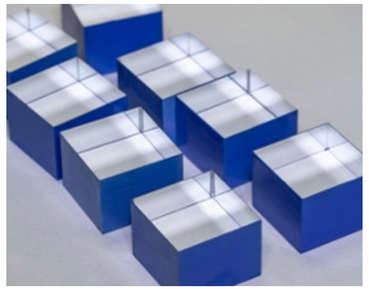

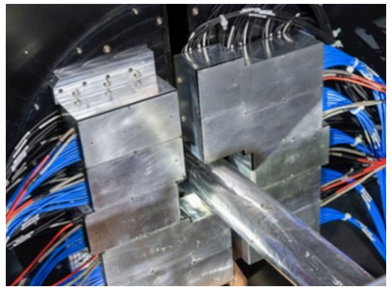

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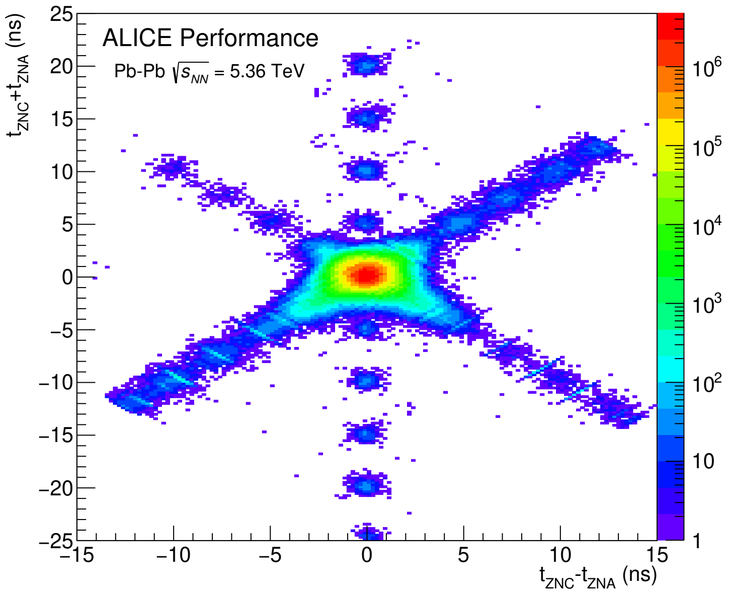

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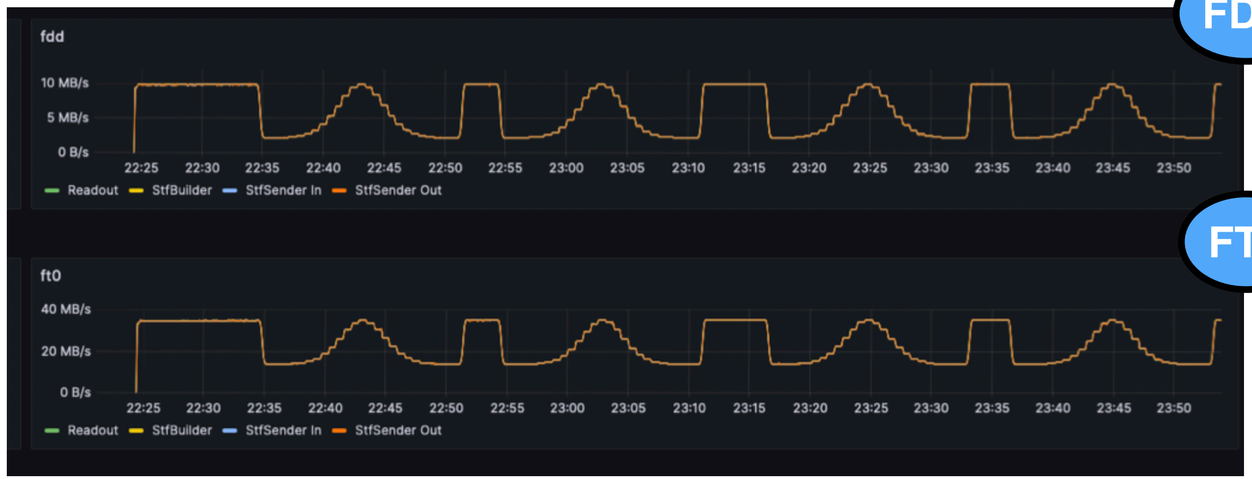

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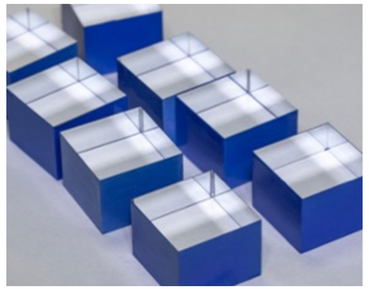

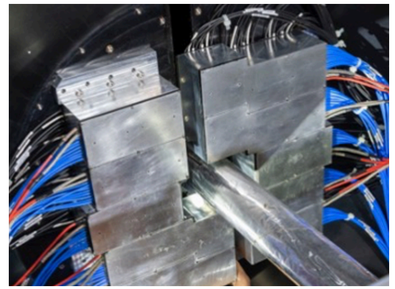

Other new detectors being evaluated as luminometers

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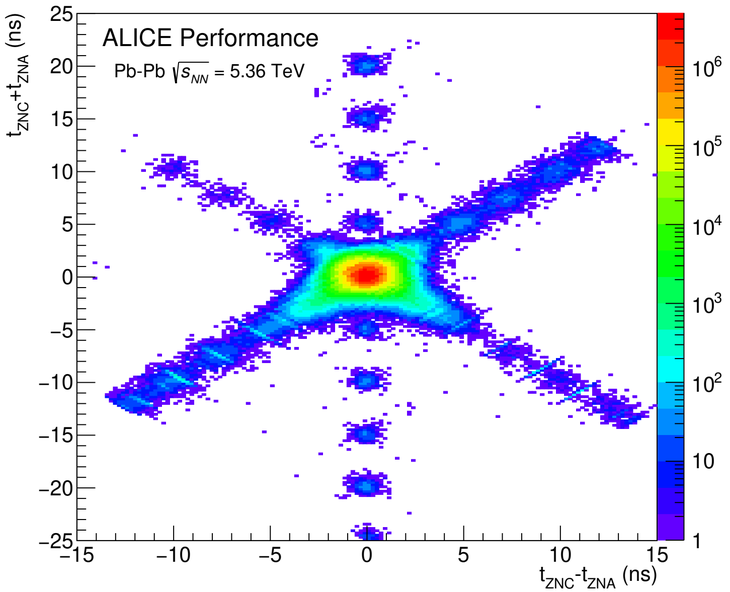
Luminometers for Run 3



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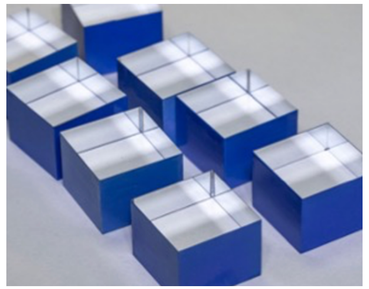

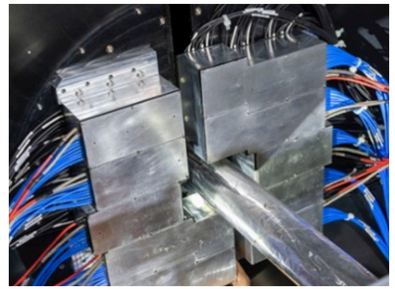

Other new detectors being evaluated as luminometers

Furthermore, ALICE now operates in continuous readout mode → New possibilities to define reference processes

JINST 19 (2024) 05, P05062

Summary

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ALICE uses van der Meer scans to determine the luminosity

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The analysis of Run 3 scans is underway → stay tuned!