ALICE

TWENTY-FIRST LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

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Luminosity determination by ALICE during LHC Run 3

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Introduction

- Luminosity is a fundamental parameter in collider physics:
  - **Instantaneous luminosity L_{inst} – how many collisions per second?**
  - Integrated luminosity L_{int} – how many collisions in a data sample?
- Cross-section of physical process:

$$\sigma_{inel} = N/L_{int}$$

Number of process events

Integrated luminosity

- Uncertainty on L_{int} a limiting factor in precision cross-sections:
  - Determining source of different systematic errors help to understand fraction of their influence cross section calculation.
- Luminosity measurements also important online:
  - LHC machine optimization , leveling and beam quality monitoring
  - Luminosity accounting

Luminosity calculation

Luminosity determination is based on detector-luminometer cross-section calculation:

$$\sigma_{vis} = \varepsilon \sigma_{inel}$$

Fraction of inelastic events which satisfy trigger conditions (ε)

Cross-section of inelastic process (σ_{inel})

Then indirect luminosity calculation can be expressed as: $L = R_{vis} / \sigma_{vis}$

Rate of events which satisfy trigger conditions (R_{vis})

Luminosity calculation

The luminosity of an accelerator is given by(*):

$$L = f_{rev} N_1 N_2 \int \rho_1^{lab}(\vec{r} - \Delta\vec{r}, t)\rho_2^{lab}(\vec{r}, t) d^3\vec{r}\, dt$$

- f_{rev}: Accelerator revolution frequency
- $N_1 N_2$: Bunch intensities
- Integral: Beam overlap integral with particle densities per bunch

Visible cross-section of the luminometer can be expressed as(*):

$$\sigma_{vis} = \int \frac{R(\Delta x, \Delta y)}{f_{rev} N_1 N_2} d\Delta x d\Delta y$$

- $R(\Delta x, \Delta y)$: Trigger rate at luminometer
- $d\Delta x d\Delta y$: Beam shift along XY plane, perpendicular to beam direction

(*) V. Balagura, “Notes on van der Meer Scan for Absolute Luminosity Measurement,” Nucl. Instrum. Meth. A654 (2011) 634–638, arXiv:1103.1129

Luminosity calculation

If factorization stands: $R(\Delta x, \Delta y) = R_x(\Delta x) R_y(\Delta y)$

Head-on rate(peak)

$$\sigma_{vis} = \frac{\int R_x(\Delta x, 0) d\Delta x * \int R_y(0, \Delta y) d\Delta y}{f_{rev} N_1 N_2 * R(0,0)} = \frac{R(0,0) h_x h_y}{f_{rev} N_1 N_2}$$

$$L = \frac{R(0,0)}{\sigma_{vis}} = \frac{f_{rev} N_1 N_2}{h_x h_y}$$

$$h_x = \frac{\int R_x(\Delta x, 0) d\Delta x}{R(0,0)}$$

$$h_y = \frac{\int R_y(0, \Delta y) d\Delta y}{R(0,0)}$$

Effective convolved beam widths along X/Y axes.
For direct and high precision measurements
Special Van-der-Meer scan is needed.
Integral under the curve, normalized by peak value *R(0,0)*

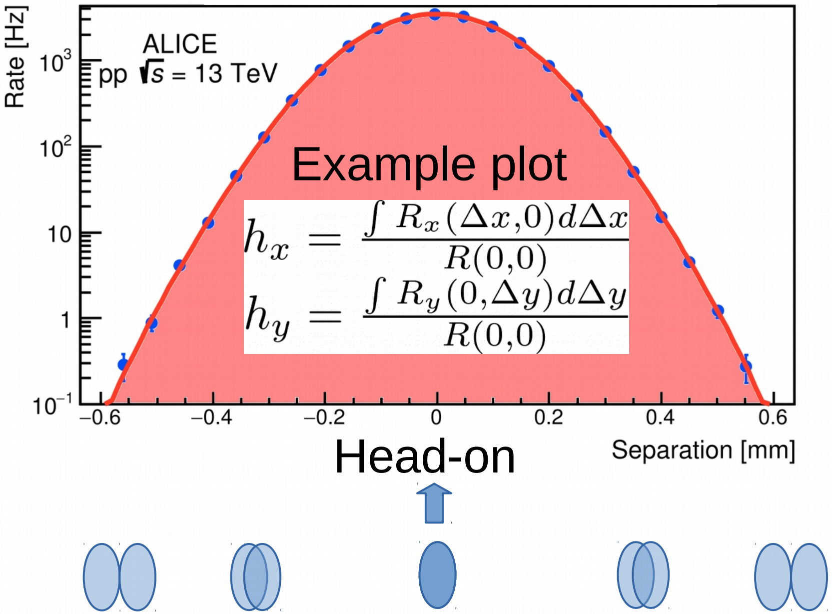
VdM session: rate scanning

$$\sigma_{vis} = \frac{\int R_x(\Delta x, 0) d\Delta x * \int R_y(0, \Delta y) d\Delta y}{f_{rev} N_1 N_2 * R(0,0)}$$

- Main stage is **luminometer rate scan** per beam step with constant length along X/Y axis when the opposite beam is at head-on position.

- dR/dx and dR/dy fitting is required.

- For h_x and h_y calculations - integral under dR/dx and dR/dy fitted curves will be taken and normalized by head-on rate R(0,0).



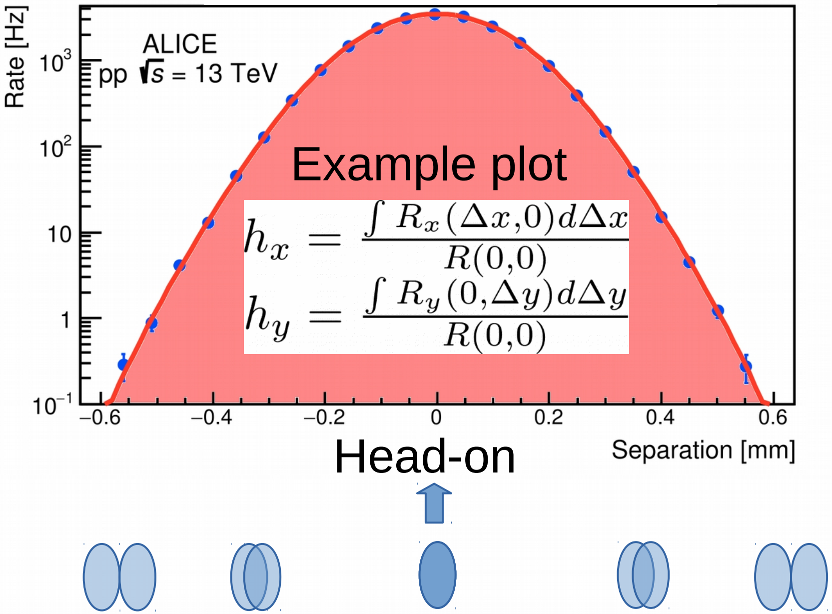
(*) VdM correction details at ALICE are given in backup slides

VdM session: corrections

- Several corrections are needed, some of them requires extra calibration stages within VdM scanning (*):

  - Δx,Δy step correction(separation) – **Long Scale Calibration** (LSC - second VdM scanning stage), Orbit Drift Correction, Beam-beam deflection.(*)
  - N1 and N2 bunch intensities – satellites and ghosts to be removed from intenseties.
  - Luminometer rate(R) corrections – background, pileup, beam decay.
  - Non-factorization effects – luminious region study + **offset calibration** (third stage in VdM scanning) (*)

$$\sigma_{vis} = \frac{\int R_x(\Delta x, 0) d\Delta x * \int R_y(0, \Delta y) d\Delta y}{f_{rev} N_1 N_2 * R(0,0)}$$



(*) VdM correction details at ALICE are given in backup slides

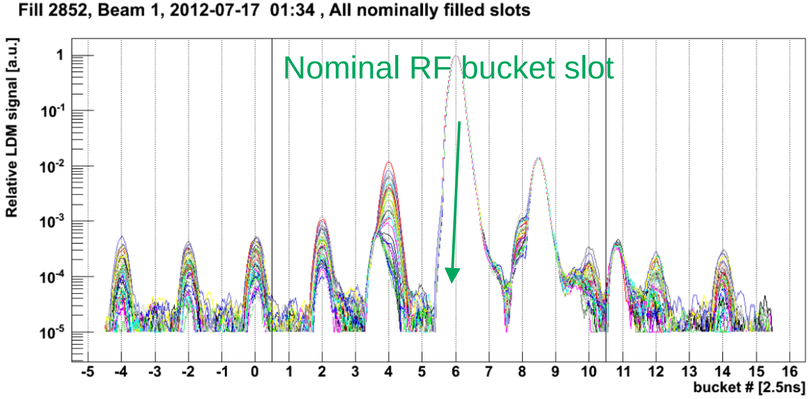
Large Hadron Collider

- 1 accelerator orbit:
  - 3564 bunch slots x 25 ns length
- 1 bunch slot:
  - 10 RF buckets x 2.5 ns

- Charges in RF bucket #6 are **nominal** for given BC, i.e. **nominal BC**

- Four beam-mask classes for bunch per beam:
  - **Empty** - nominally no charge in bunch
  - **BeamA** - BC slot with nominal charge in beam from A-side
  - **BeamC** - same as BeamA, but beam comes from C-side
  - **Beam-Beam** - both BeamA and BeamC mask in given BC. Collision should appear at interaction point - IP

CERN-ATS-Note-2013-034 TECH



Bunch slot = 25 ns = 10 RF buckets x 2.5 ns

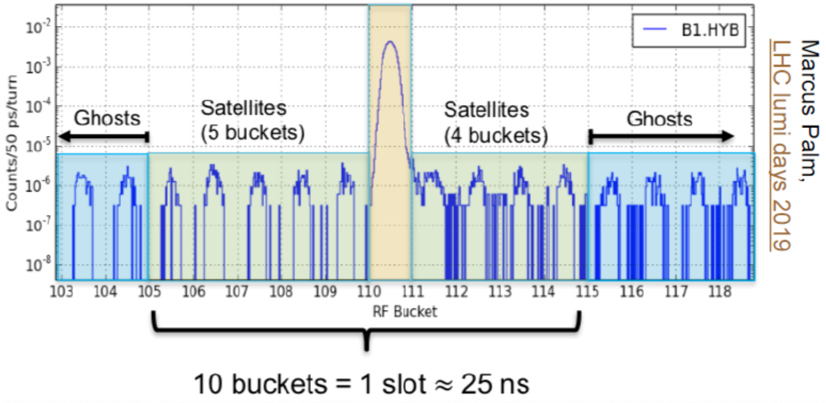
Large Hadron Collider

- Charges in other RF buckets within nominal BC slot are **satellites**

- Charges in bunch slots which are not nominal BC(Empty BC mask for given beam) in colliding schema are **ghosts**.

- **Bunch intensity:**

  Nbunch = Ntotal – Nsat – Nghost



- **Run 1-2 (2009-2018):**

System	Energy(TeV)	Collision rate	Luminometers
pp	0.9 , 2.76, 5.02, 13	< 100 kHz	T0 + V0
PbPb	2.76, 5.02	~ 1 kHz	V0 + ZDC
pPb, XeXe	...	...	..

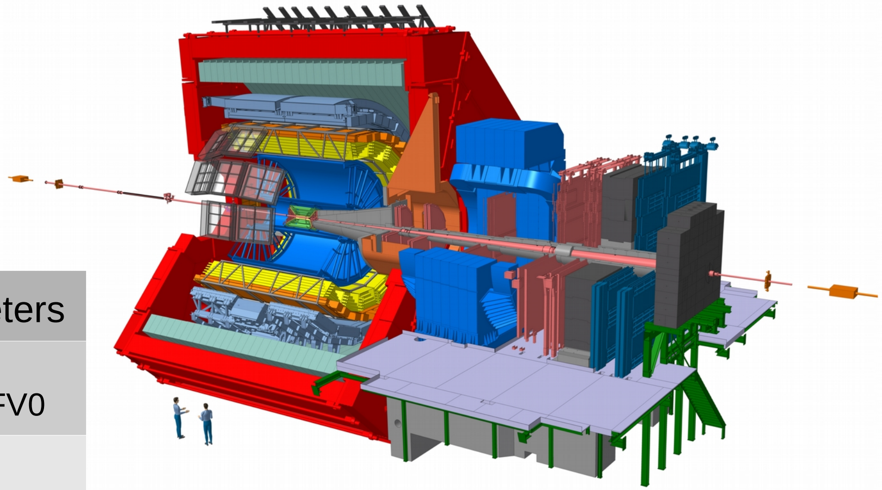
Long-Shutdown 2 ALICE Upgrade:

- ~ x50-x100 statistics increase
- New electronics
- New detectors (FIT)
- New software (Offline-Online O2 package)

- **Run 3 (2022 – 2025):**

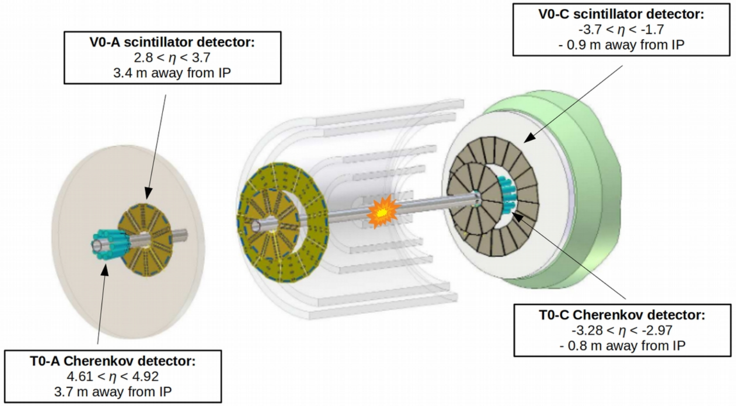
System	Energy(TeV)	Collision rate	Luminometers
pp	13.6	500-1000 kHz	FIT: FDD, FT0, FV0
PbPb	5.36	50 kHz	FIT + ZDC

- **Main goal is to study property of quark-gluon plasma matter:**
  - **deconfined strongly-interacting QCD matter with color degrees of freedom.**

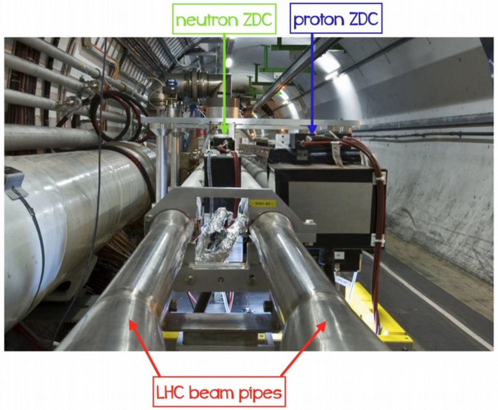


ALICE online luminometers in Run 2

- **T0:**
  - **Concept:** two circular arrays of Cherenkov radiators with PMTs (12 channels per side), located on opposite sides(T0-A and T0-C).
  - **Trigger** pp, p-Pb: coincidence of A and C sides (at least 1 hit in time range per side), and vertex trigger.



- **V0:**
  - **Concept:** two scintilattor arrays, located on opposite sides (V0-A and V0-C). 48 channels at C-side, and 32 at A-side.
  - **Trigger** pp, p-Pb: coincidence of A and C sides (at least 1 hit in time range per side).
  - **Trigger** Pb-Pb: multiplicity trigger (V0M).



- **ZDC:**
  - **Concept:** two sets of identical hadronic calorimeters at z = ± 114 m
  - **Trigger** Pb-Pb: At least one neutron.

Visible cross-sections in Run 2

ALICE

One VdM scan per year

	2016	2017	2018
σ_{T0} (mb)	29.838 ± 0.015	28.49 ± 0.02	28.159 ± 0.014
σ_{V0} (mb)	58.44 ± 0.03	58.10 ± 0.04	57.52 ± 0.03

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

ALICE-PUBLIC-2021-005, pp √s = 13 TeV

(*) $\sigma_{ZED} = 420.58 \pm 0.03$ (stat.) b

$\sigma_{V0M} = 3.933 \pm 0.003$ (stat.) b

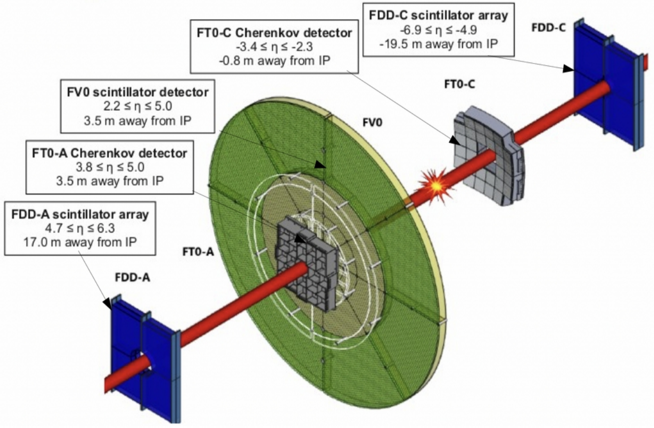
Source	Uncertainty (%)
	ZED | V0M
Statistical	0.008 | 0.08
$h_{x0}h_{y0}$ consistency (V0M vs ZED)	0.13
Length-scale calibration	1
Non-factorisation	1.1
Bunch-to-bunch consistency	0.1
Scan-to-scan consistency	1
Satellite collisions	1.2
Beam–gas and noise	0.3
Bunch intensity	0.8
Emittance variation	0.5
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

CERN-EP-2022-072, Pb-Pb √s = 5.02 TeV

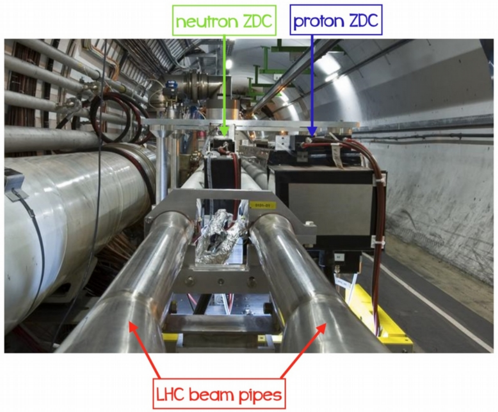
(*) Large due to electromagnetic dissociation of Pb
More details in presentation “Studies of electromagnetic dissociation of Pb-208 in ALICE experiment at the LHC” U.Dmitrieva

ALICE online luminometers in Run 3

- In total four luminometers in Run 3 at ALICE:
  - FIT system of forward detectors (FDD+FT0+FV0) and ZDC



- **FT0**(T0 successor):
  - **Concept**: two arrays of Cherenkov radiators with MCP-PMTs, 96 channels at A-side and 112 at C-side
  - **Trigger** pp: coincidence of A and C side with hardware cut on the signal arrival time difference (like OTVX in Run 2), based on OR-A and OR-C signals
  - **Trigger** PbPb: 2 amplitude triggers-> multiplicity trigger with amplitude range (Semi-central,Central)

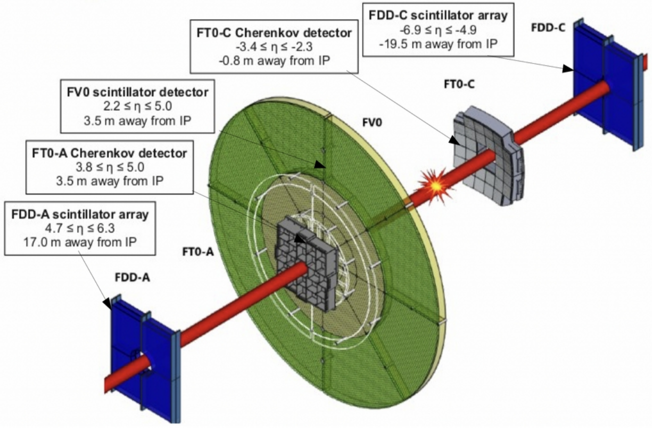


- **FDD**(AD* successor):
  - **Concept**: two scintillator arrays, two layers per array, 4 channels per layer. In total 16 channels at both sides(A and C)
  - **Trigger**: same conditions as FT0's

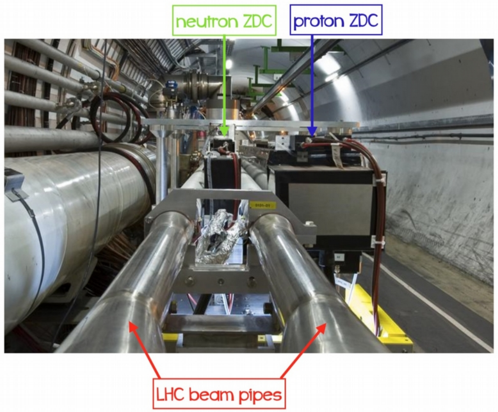
(*) AD detector was a forward detector in Run 2 for diffraction physics. Haven't been considered as luminometer.

ALICE online luminometers in Run 3

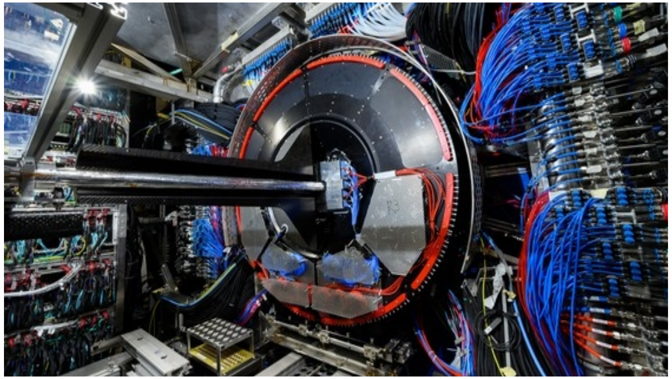
- **FV0**(V0 successor):
  - **Concept**: one array of scintillators at A-side, divided by sectors and rings, 48 channels in total.
  - **Trigger** pp(under discussion): Amplitude ring triggers-> ring multiplicity trigger
  - **Trigger** PbPb: Amplitude trigger -> multiplicity trigger with amplitude range (like V0 multiplicity trigger)
  - Time trigger based on hardware arrival time, FV0-OR signal



- **ZDC**(upgraded after Run 2, new FEE electronics):
  - **Concept**: two sets of identical hadronic calorimeters at z = -+ 114m
  - **Trigger** PbPb: At least one neutron.



System of forward detectors - FIT



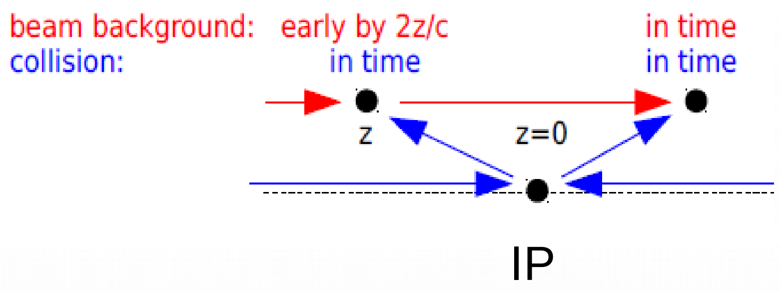
FIT - **F**ast **I**nteracting **T**rigger

Main purpose of FIT:

- **Luminosity monitoring**.
- **Background monitoring**.
- Production of fast and clean trigger signals(**Minimum-bias** and based on **centrality**).
- Precise **collision time** calculation for Time-Of-Flight based particle ID.
- **Multiplicity** measurements – reaction plane calculation and event centrality.
- **Diffraction** physics.

FIT properties

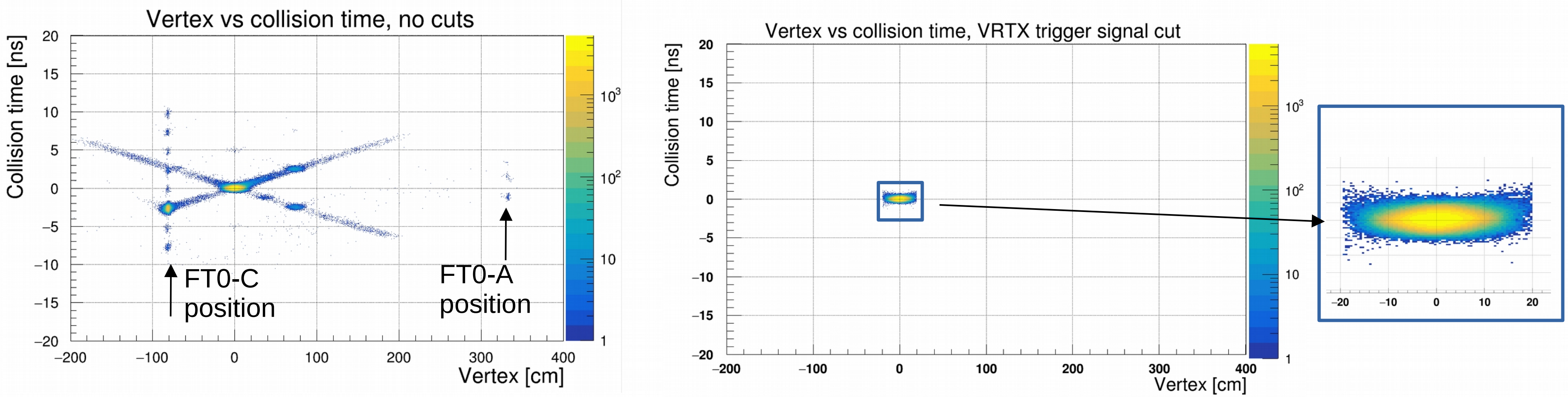
- FT0 is currently taken as main luminometer:
  - Not sensitive to particles coming from backward direction (amplitudes will be suppressed ~1/16 due to radiator's back coverage).
  - Is not triggered by satellites.
  - For luminosity Beam-Beam colliding bunches are taken for monitoring.
- For background monitoring:
  - FT0 uses non-colliding bunches (non Beam-Beam bunch mask)
  - FDD and FV0 uses early arrival time



Detector	z [mm]	η_{min}	η_{max}
FDD-A	16960	4.8	6.3
FT0-A	3346	3.5	4.9
FV0	3208	2.2	5.1
FT0-C	-843	-3.3	-2.1
FDD-C	-19566	-7.0	-4.9

z - distance parallel to beam direction between the nominal interaction point and the middle of sensitive detector elemenet. Based on the latest detector position measurements as of 7.02.2022

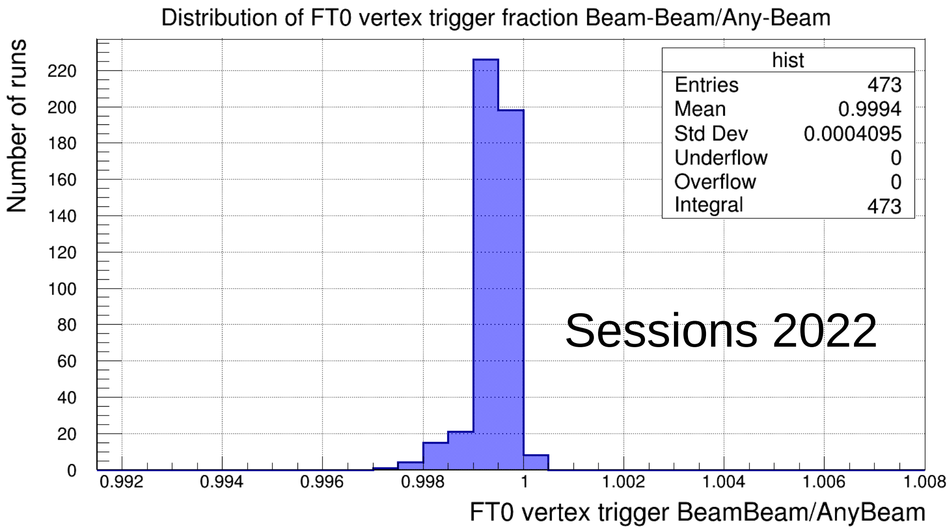
FT0 vertex trigger signal

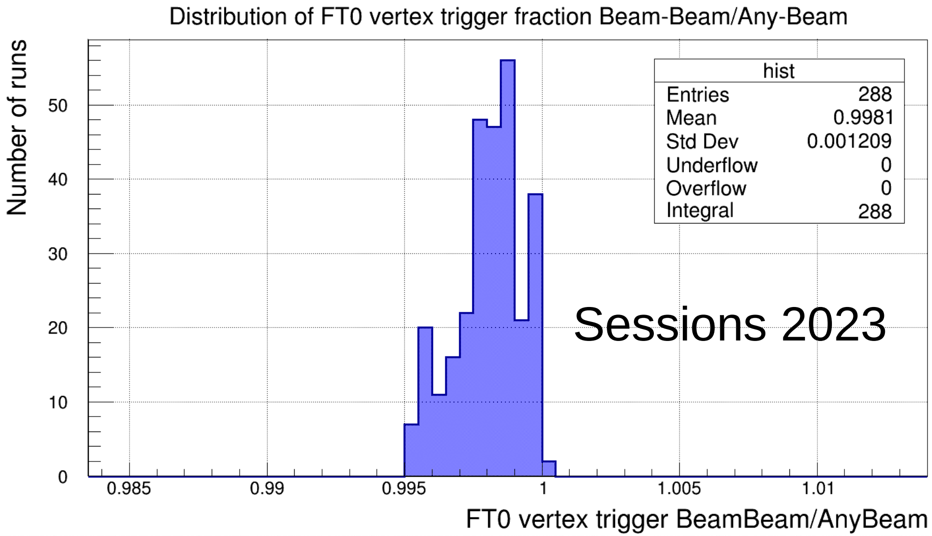


- Time-based FT0 vertex(VRTX signal) trigger logic concept:
  - Time trigger signal - OR-A and OR-C, production is based on averaged time taken from channels which satisfy hardware time cut(*) : -+2 ns
  - Hardware vertex position measurement is difference of OR-A and OR-C times. VRTX signal will be produced if HW vertex position within range(*) -+20cm
- **Such VRTX trigger signal concept allows to remove satellite events online/offline.**

(*) Configurable via FEE parameters, given values are currently nominal

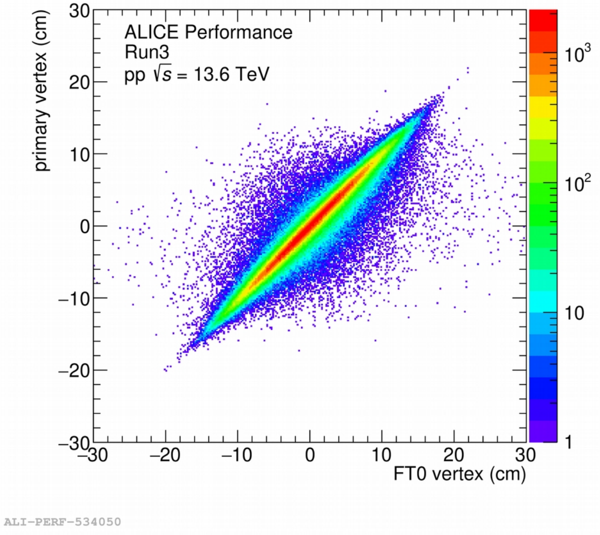
FT0 vertex trigger signal

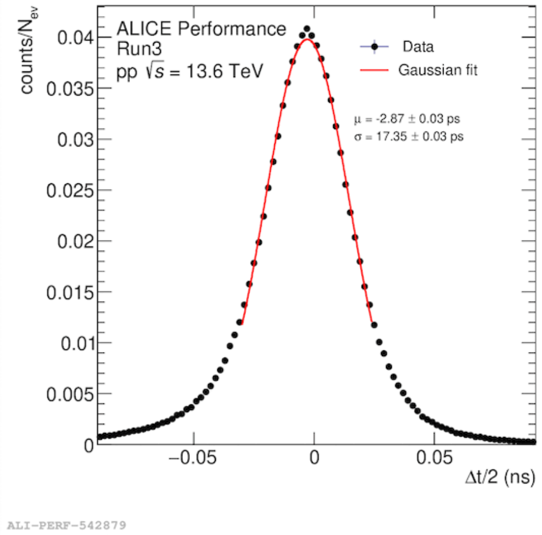




- FT0 detector FEE architecture and it’s concept allows to see events with exact BC identification.
- With such features FT0 can identify **BC**s with 100% efficiency, and can remove events from ghosts **BC**s(with non Beam-Beam mask).
- Sessions taken during 2022-2023 show less than 0.6% of vertex trigger fraction out of Beam-Beam collision BCs => **perfect ghost BC event rejection.**

FT0 vertex reconstruction

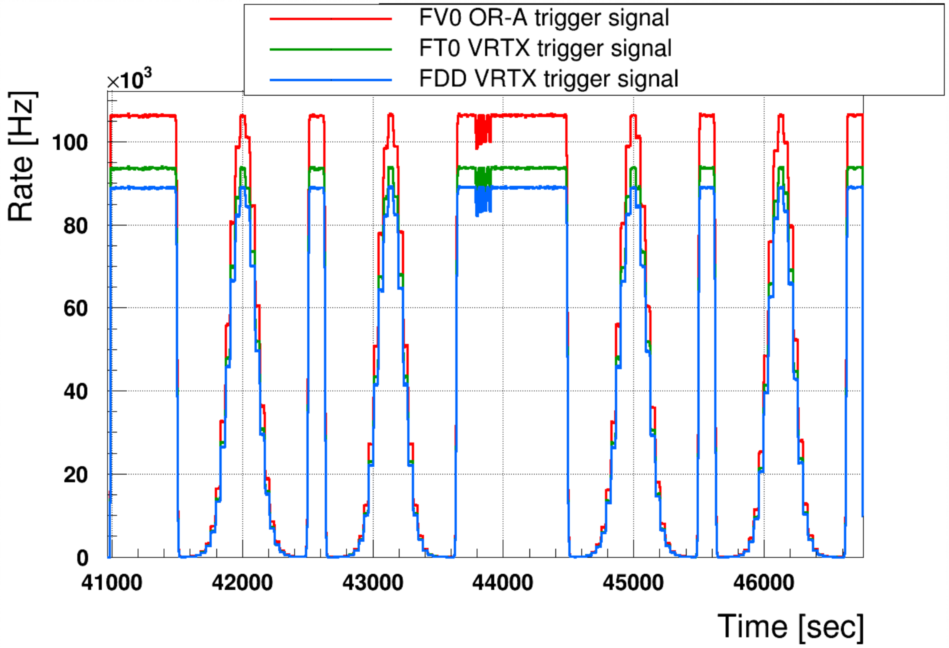




- After reconstruction FT0 shows perfect correlation with primary vertex reconstructed by tracking detectors.
- Hardware Vertex trigger for range -+ 20 cm, is good signal for registering collision and monitoring luminosity.
- FT0 has best time resolution among all FIT detectors ~ 17 ps

VdM status in Run 3

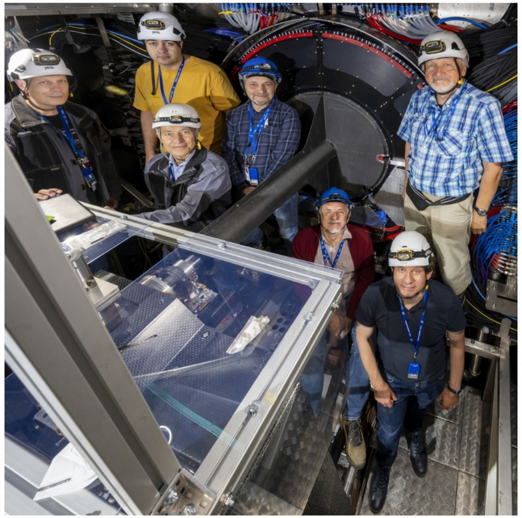
- VdM scan data taking in Run 3 was done in November 2022
- VdM scan data was collected by using ALICE detectors – FIT and ITS.
- Also was collected information about beam property during that session by using independent LHC tools.



Summary

- Measured visible cross-section and its uncertainties during VdM scans in Run 2 for pp and PbPb collision systems.
- Main ALICE luminometer for pp sessions:
    - In Run 2 - T0 and V0.
    - In Run 3 - FT0:
        - Background suppression from backward direction.
        - Satellite rejection.
        - Ghost bunch rejection.
- VdM scan analysis for Run 3 is currently ongoing.
- FT0 shows good performance:
    - Good correlation between FT0 reconstructed and primary vertex.
    - Precise collision time for TOF-based particle identification.

Thank you for your attention!



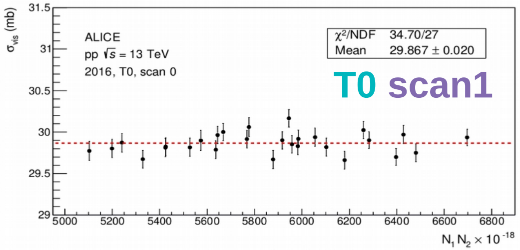
FIT youtube videos:

Russian: https://youtu.be/phN0AohEDKI
English: https://youtu.be/PjsBIbKsuO0
Spanish: https://youtu.be/qR_lG7K3pfs
Polish: https://youtu.be/31s8jix2omo

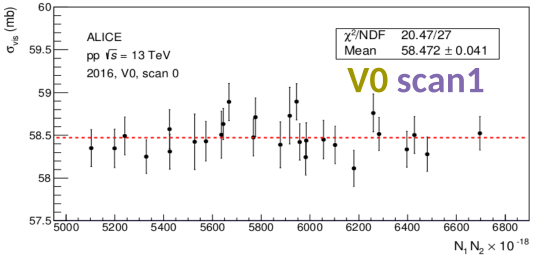
Backup

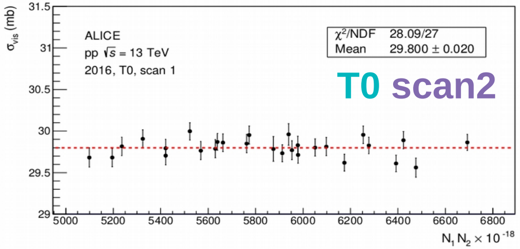
VdM in Run 2

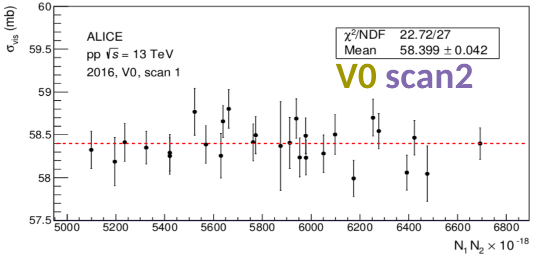
ALICE-PUBLIC-2021-005, pp √s = 13 TeV



Visible cross-section per BC

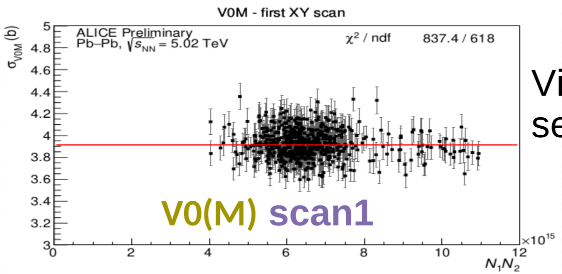




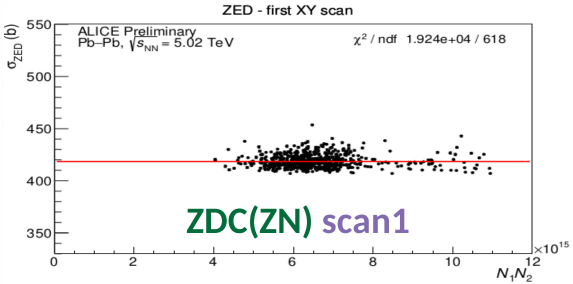


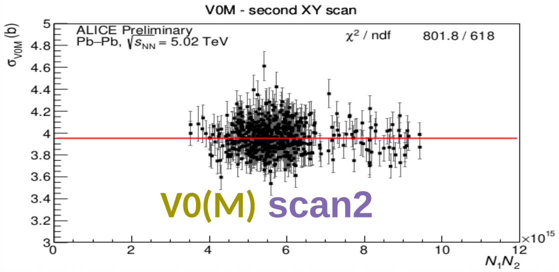
VdM in Run 2

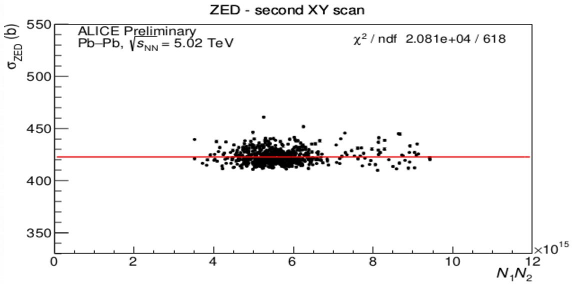
ALICE-PUBLIC-2021-001, Pb-Pb √s = 5.02 TeV



Visible cross-section per BC





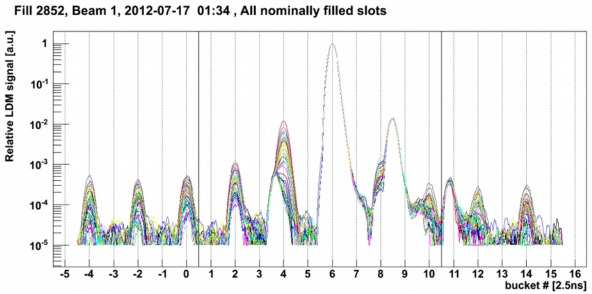


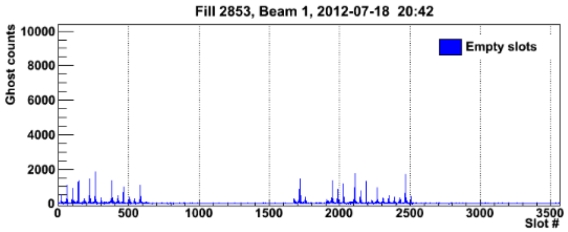
Bunch intensities

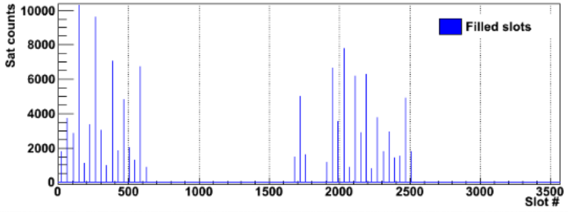
LHC instruments

CERN-ATS-Note-2013-034 TECH

- Total bunch intensity:
  - LHC(DCCT) - DC current transformer, for total beam current (normalization).
  - LHC(BCT) - fast Beam Current Transformer, for relative bunch intensity
  - ATLAS(BPTX) - Beam Pick Up System, same purpose as BCT
- Ghost intensity:
  - Ghost fraction is measured by LHC Longitudinal Density Monitor LDM (measures synchrotron radiation photons emitted by the beams).
  - Also LHCb provides information about ghost fraction, by measuring beam – gas event rate for nominal empty bunches.
- Satellite intensity:
  - LHC LDM is used for measuring satellite fraction, for all scans it was negligible (< 0.05%).







Separation(LSC)

ALICE-PUBLIC-2021-005

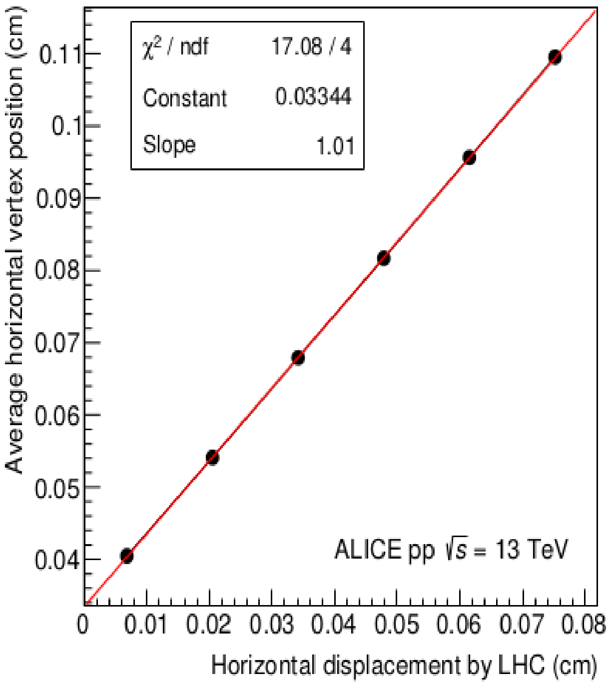
- LSC (length-scale calibration)

1)Two beams are moved simultaneously in the same direction in steps of equal size.

2)The changes in the primary interaction vertex position provide a measurement of the actual beam displacement, which is used to extract a correction factor to the nominal displacement scale.

3)ALICE Inner Tracker System (ITS) is used for vertex measurement.

4)Length-scale correction factor is the slope parameter of a linear fit.



Rate correction

- Measurements from ALICE detectors: T0, V0, ZDC
- Corrections needed for raw trigger rate:

1)BB (Background): Satellites, beam-gas, after-pulses. Timing cuts should be applied.

2)PU (Pile-up): multiple events in each colliding bunch pair. Corrections based on the Poisson distribution of coincidences.

3)DC (Intensity decay): to account for the bunch intensity (and, hence, the luminosity) decay with time.

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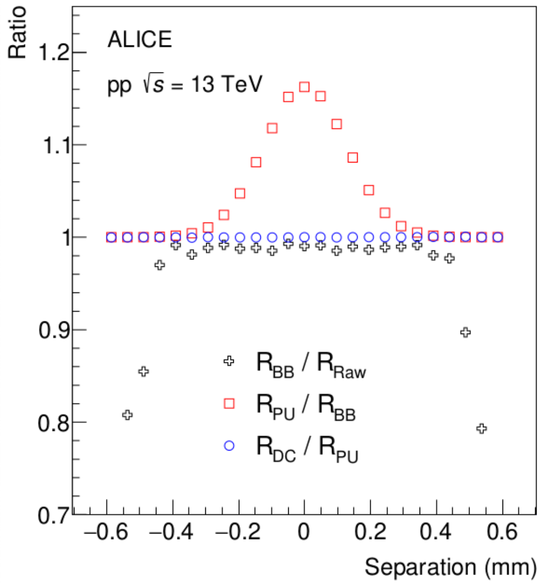
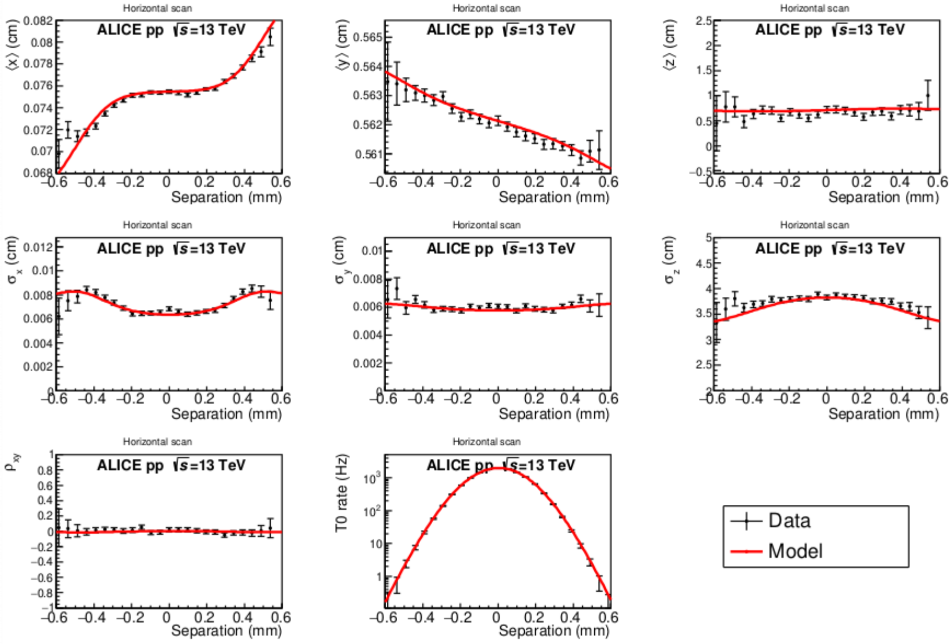


T0

Non-factorization effects

- **Assuming that factorization stands:** $R(\Delta x, \Delta y) = R_x(\Delta x) R_y(\Delta y)$

- Non-factorization effects can be studied and quantified by measuring the luminous region parameters, via the distribution of interaction vertices, as a function of the beam separation.
- Non-zero separation (offset) in the non-scanned direction should be performed, to provide additional input for non-factorization studies.
- Barrel detectors are used for measurement of luminous region by 3D vertexing.



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Run 2 VdM session

- **Total types of scan in vdM session:**

X1,Y1,X2,Y2 – standard scans in X/Y direction.

Range: from -6σ_{beam} to -6σ_{beam}

Step size: 0.5σ_{beam}

Eotal number of steps: 25

Length-scale calibration(LSC).

Step width: ~σ_{beam}

Total number of steps: 5

Offset scan(X/Y directions).

Typical offset: ~4σ_{beam}

Required for non-factorization analysis