Luminosity determination with ALICE at the LHC

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For the ALICE Collaboration

Outline

1. **Introduction**
   - Luminosity
   - van der Meer (vdM) scan
2. **vdM Analysis**
   - Overview
   - Process and corrections
   - Long-term stability and consistency
   - Run 2 results

Introduction

ALICE J/ψ and ψ(2S) in pp, arXiv:1702.00557 (2017)

	$\sqrt{s}$ = 13 TeV		$\sqrt{s}$ = 5.02 TeV	
Source	J/ψ (%)	ψ(2S) (%)	J/ψ (%)	ψ(2S) (%)
Branching ratio	0.6	11	0.6	11
Luminosity	3.4	3.4	2.1	2.1
Signal extraction	3 (3 – 8)	5 (5 – 9)	3 (1.5 – 10)	8
MC input	0.5 (0.5 – 1.5)	1 (0.5 – 4)	2 (0.5 – 2.5)	2.5
MCH efficiency	4	4	1	1
MTR efficiency	4 (1.5 – 4)	4 (1.5 – 4)	2 (1.5 – 2)	2
Matching	1	1	1	1

- **Luminosity**
  - For any cross-section measurement,

    $\sigma = N / L_{int}$

    a. σ : cross-section of a physics process

    b. N : yield of the physics process

    c. $L_{int} = \int L(t)\, dt$: integrated luminosity, where L is the instantaneous luminosity

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  - Two possible approaches to measure the luminosity during physics data-taking

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    a. $L = \frac{R_{ref}}{\sigma_{ref}}$: by using the cross-section of a known physical process (e.g., Z^0 boson)

    b. $L = \frac{R_{vis}}{\sigma_{vis}} = \frac{f_{rev}\, \mu_{vis}}{\sigma_{vis}}$: by using a visible cross-section (σ_{vis})

    b-1. f_{rev} : accelerator revolution frequency

    b-2. μ_{vis} : average # of "visible" interactions per bunch crossing

    b-3. σ_{vis} : "visible" cross-section measured experimentally

    b-4. The method used in ALICE

Introduction

- **Luminosity (continue)**
  - From an experimental point of view, ***L*** for a colliding bunch pair is:

$$L = \frac{R_{vis}}{\sigma_{vis}} = \frac{f_{rev}\,\mu_{vis}}{\sigma_{vis}} = f_{rev} N_1 N_2 \cdot \iint \rho_1(x, y)\, \rho_2(x, y)\, dxdy$$

a. N_1, N_2 : bunch intensity

b. ρ : particle density distribution in transverse plane

c. $\iint \rho_1 \rho_2 \, dxdy$: beam overlap integral

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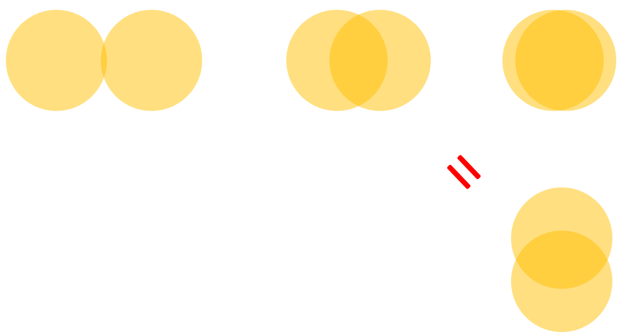

  - Assuming factorization stands, then L can be written as:

    $$L = \frac{f_{rev} N_1 N_2}{h_x h_y}$$

    a. $1/h_x : \int \rho_{1,x}(x)\, \rho_{2,x}(x)\, dx$, $h_{x\,(y)}$: effective beam overlap width in x (y) direction

    b. $N_1 N_2$: measured by using accelerator instrumentation

    c. $h_x h_y$:

    c-1. Can be derived from nominal machine parameters but large uncertainty (> 10%)

    c-2. Require dedicated session for direct & precise measurement: van der Meer (vdM) scan

Introduction

- **vdM scan**
  - Dedicated measurement of μ_{vis} vs. beam separation
    a. Estimate visible rate per bunch crossing
    b. Adjust separation distance of each bunch crossing:
       scan horizontal (*x*) or vertical (*y*) direction,
       while fixing the other direction in the head-on position
    c. "Tailored" running conditions are preferred:
       low μ_{vis}, low intensity, well-spaced bunches…
    d. 1-2 sessions per year

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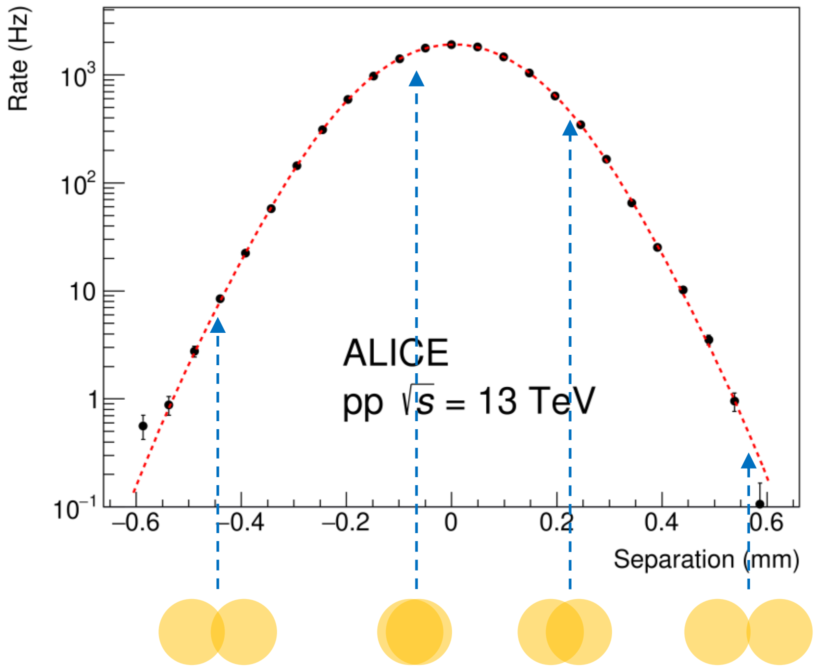

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$$L = \frac{f_{rev} N_1 N_2}{h_x h_y}$$

$h_{x\,(y)}$: the area under the curve normalized by its peak value, obtained during the horizontal (vertical) scan

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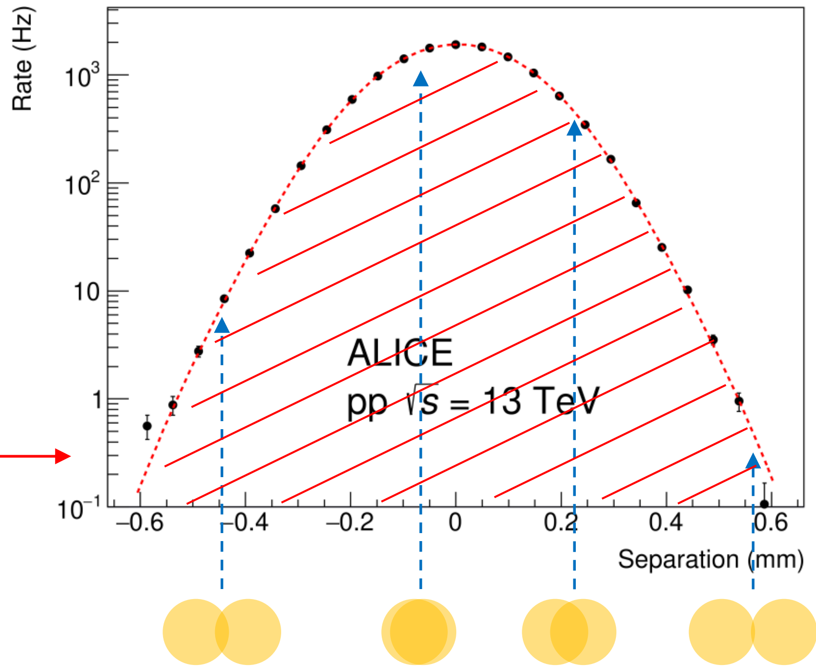
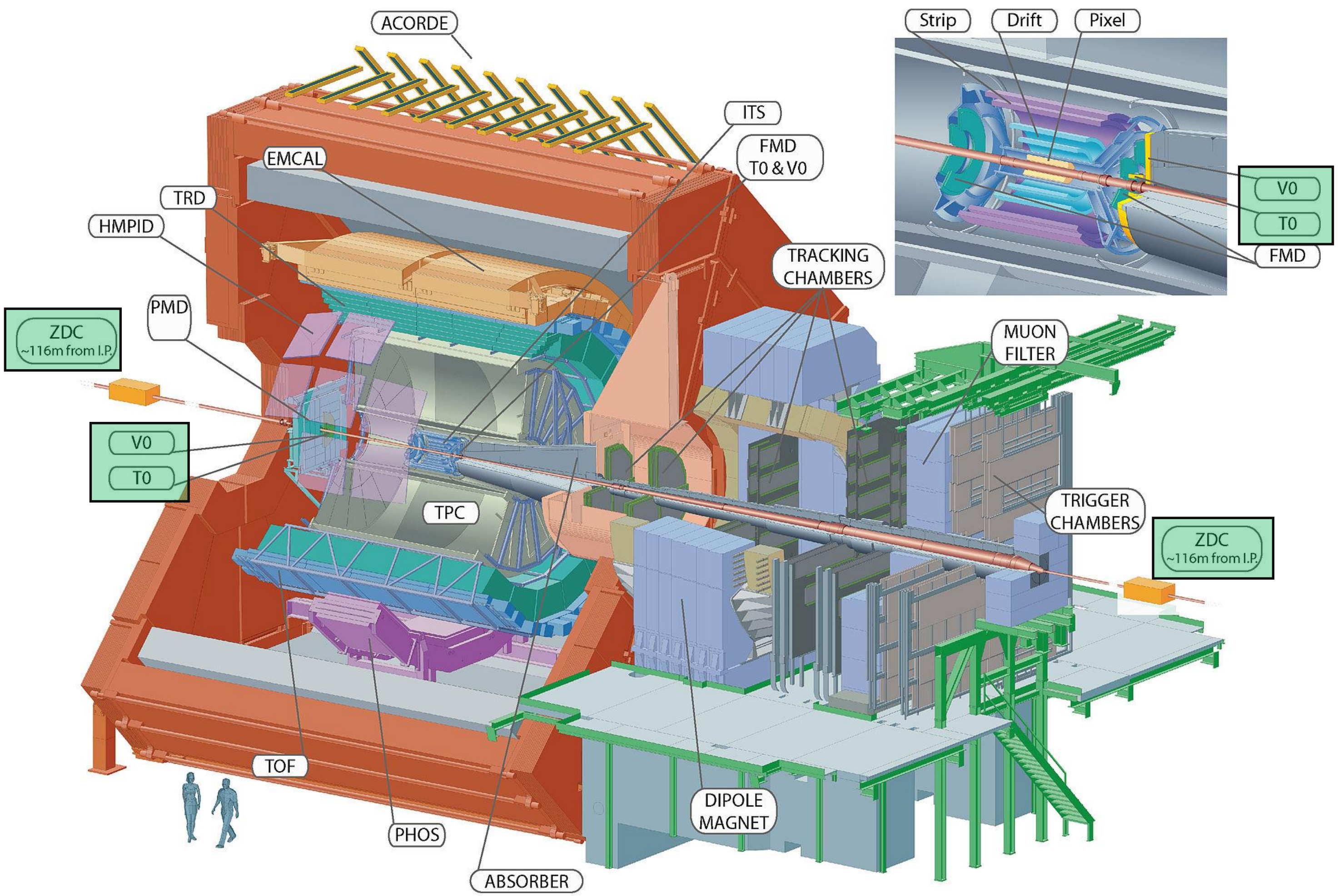


Introduction

- **vdM scan related apparatus in ALICE**



Introduction

- **vdM scan related apparatus in ALICE**
  - All detectors are built as a pair WRT the IP

    (* ATLAS (A-) side or CMS (C-) side)

    a. V0

    a-1. Two scintillator arrays

    a-2. $2.8 < \eta < 3.7$, $-3.7 < \eta < -1.7$

    b. T0

    b-1. Two Cherenkov detector arrays

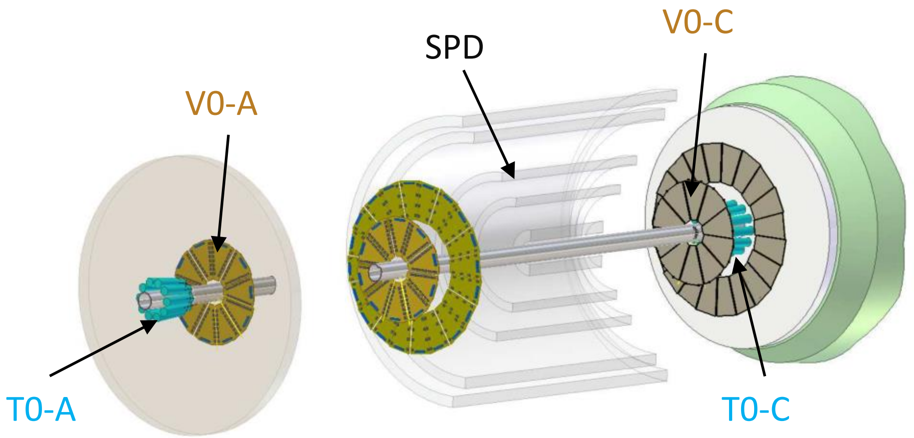
    b-2. $4.61 < \eta < 4.92$, $-3.28 < \eta < -2.97$

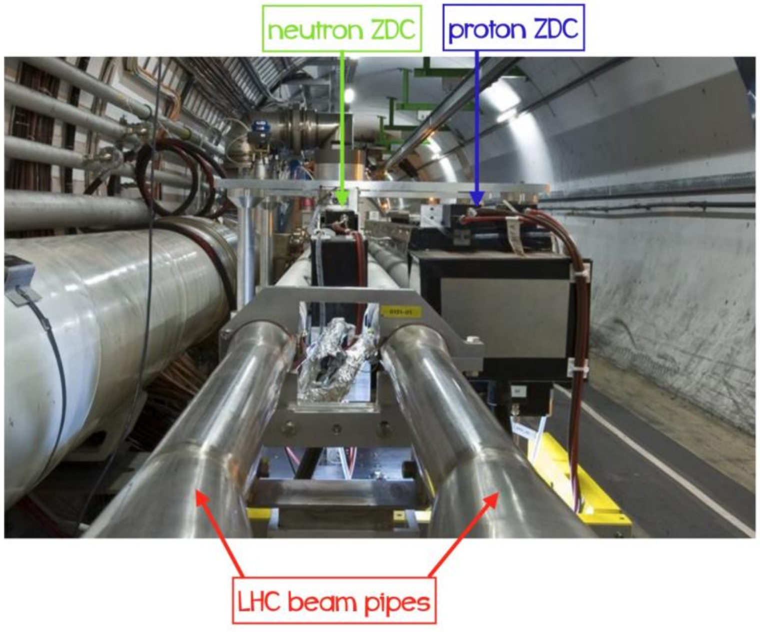
    c. ZN (Neutron ZDC)

    Two quartz-fiber spaghetti calorimeters at z = ± 114 m
  - Signal condition in vdM scan by collision system

    a. pp, p-Pb: coincidence of A- and C- side in T0, V0

    b. Pb-Pb: Amplitude trigger (V0), Single-neutron trigger (ZN)





vdM analysis

In ALICE

vdM analysis Overview

- **vdM analysis in ALICE**
  - Goal: determine visible cross-section (σ_{vis})

$$\sigma_{vis} = R(0,0)/L ,$$

$$L = f_{rev} N_1 N_2 / h_x h_y$$

1. **$N_1 N_2$**: beam intensities of colliding bunches
   (* Measured by using LHC instrumentation)
2. **Separation**
3. **R**: (visible) rate measured in ALICE
   (* $R(0,0)$: head-on (highest) rate)
4. **$h_x h_y$**: effective beam overlap width
   (* Area under the curve, divided by $R(0,0)$)
5. **Compute σ_{vis}**

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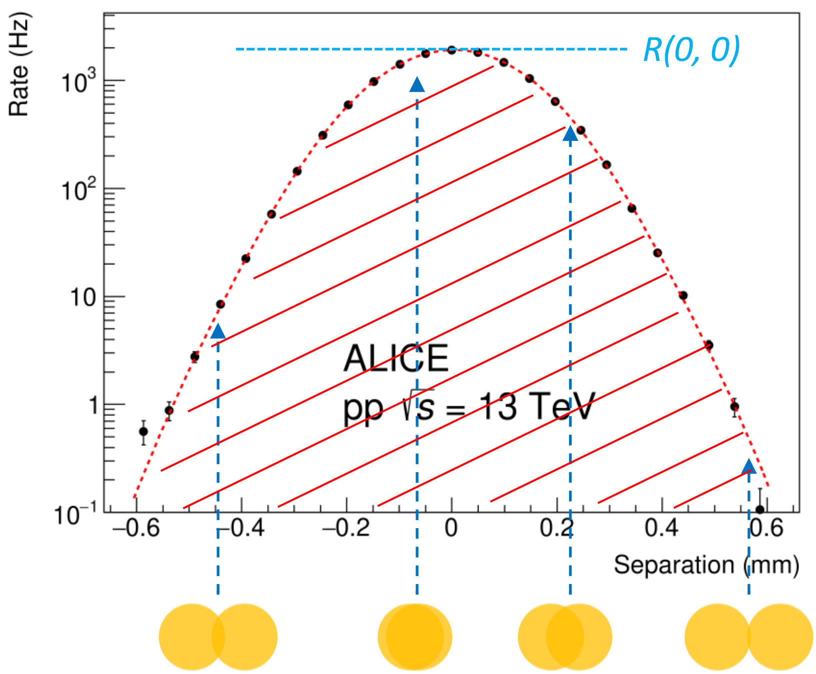

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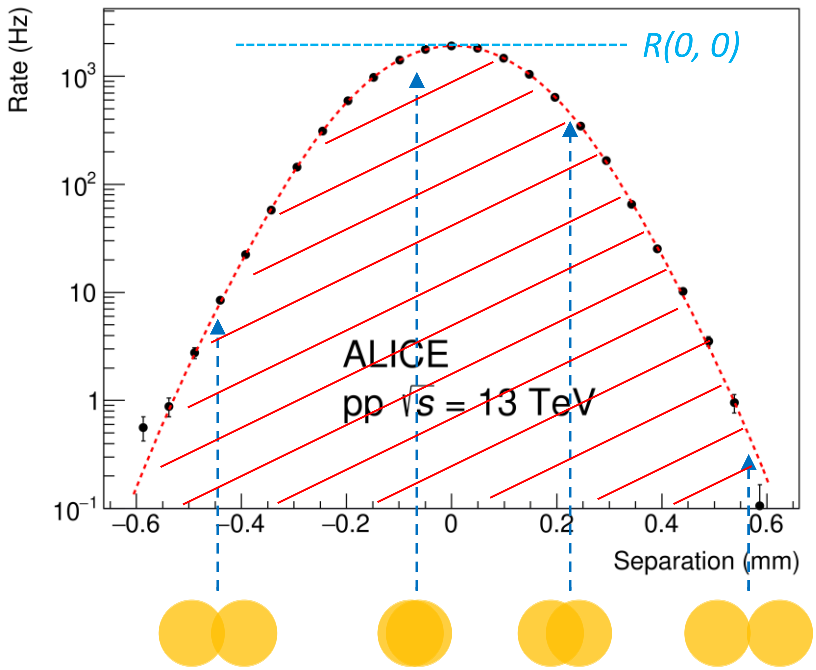


For a bunch crossing of a scan:
repeat for all bunches and scans

vdM Analysis Process and corrections

1. Intensity

– Measured with LHC (DCCT, FBCT) or ATLAS (BPTX) instrumentation

DCCT for total beam current (normalization) and FBCT/BPTX for relative bunch intensity

– Correction for satellite/ghost

a. One bunch slot = 10 buckets = 25 *ns*

Most of the ions in a bunch are well placed in a 2.5 *ns* wide central bucket of the RF system

b. Satellite: ions placed "outside the central bucket"

c. Ghost: ions placed in the slots "supposed to be empty"

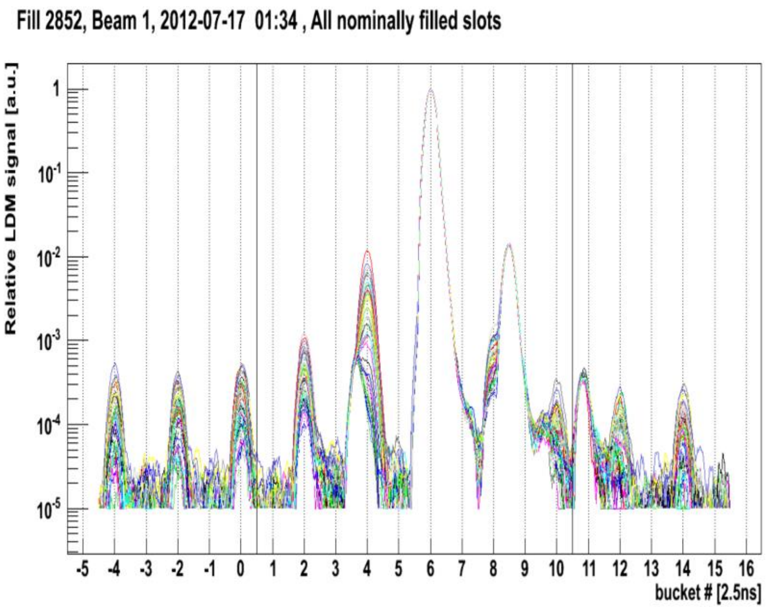
d. DCCT measures charge of all buckets:

contribution from satellite/ghost must be removed (i.e., $N_{bunch} = N_{tot} - N_{sat} - N_{ghost}$)

e. Large correction for Pb-Pb:

correction can reach few % level

CERN-ATS-Note-2013-034 TECH



f. However, either pp or Pb-Pb, the final effect on σ_{vis} uncertainty is a few per-mill (‰) level

vdM Analysis Process and corrections

2. Separation

- Start with the "nominal" separation

  The separation info provided by the LHC

- Corrections on nominal separation:

  a. LSC (length-scale calibration):

     measure the conversion factor

     between nominal and actual beam position

  b. Orbit drift correction (**ODC**):

     b-1. A bunch's orbit can vary from the reference beam orbit

     b-2. Time-dependent

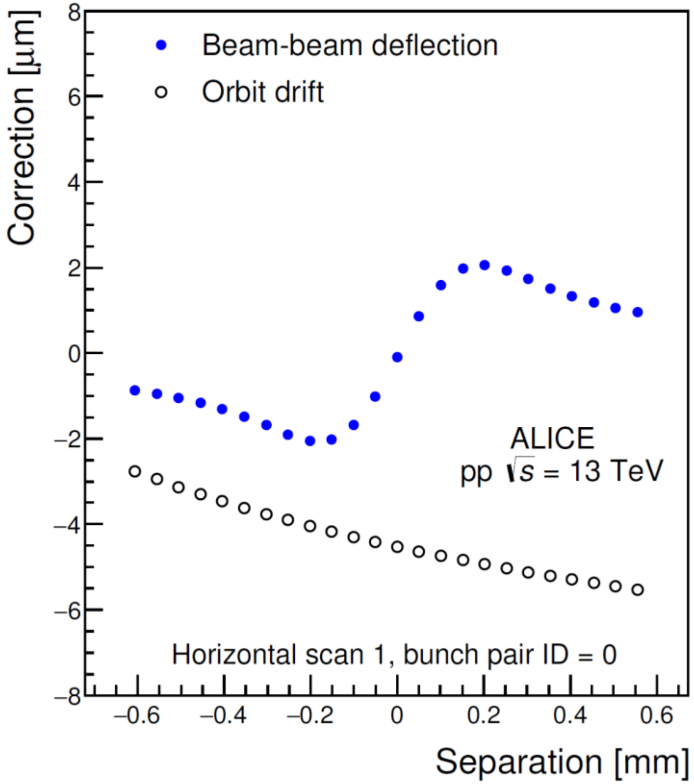
  c. Beam – Beam deflection (**BBD**):

     c-1. Each bunch (beam) is electrically charged

     c-2. Two beams exert a repulsive force upon each other:

     the repulsion affects the separation

ALICE-PUBLIC-2016-002



vdM Analysis Process and corrections

ALICE-PUBLIC-2021-005

3. Rate

- Measured with ALICE detectors (V0, T0, and ZN)
- Corrections on raw trigger rate:

  a. Backgrounds (**BB**):

  a-1. Beam-gas, Satellites, After-pulsing

  a-2. Use timing cut for the removal

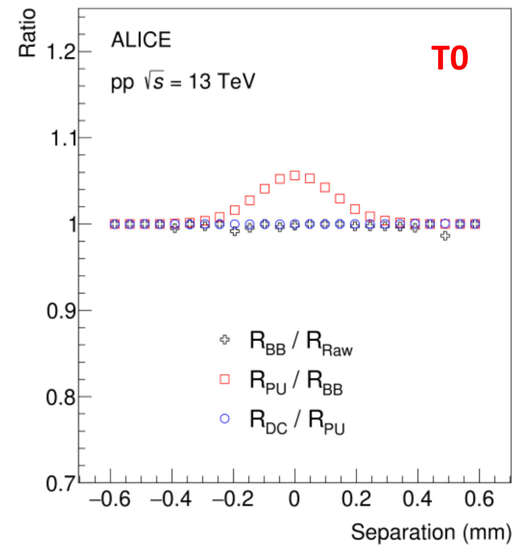
  b. Pile-up (**PU**):

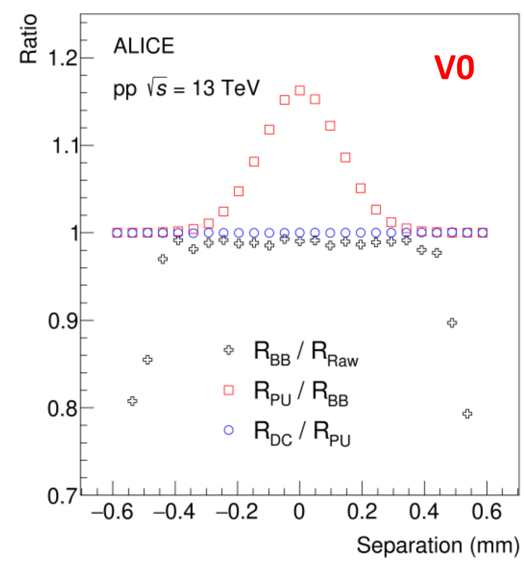
  b-1. Effect of multiple collisions per bunch crossing

  b-2. Corrections based on the Poisson distribution of coincidences

  c. Intensity decay (**DC**)

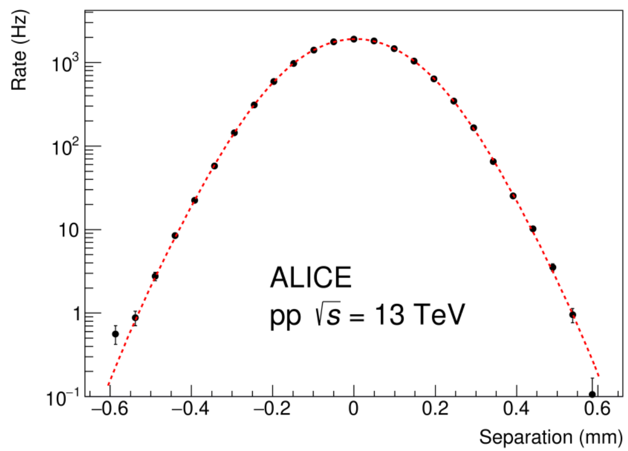
- Note that explanations here are written WRT pp, but equivalent procedures exist in Pb-Pb





vdM Analysis Process and corrections

ALICE-PUBLIC-2021-005



4. Effective beam width ($h_x h_y$)

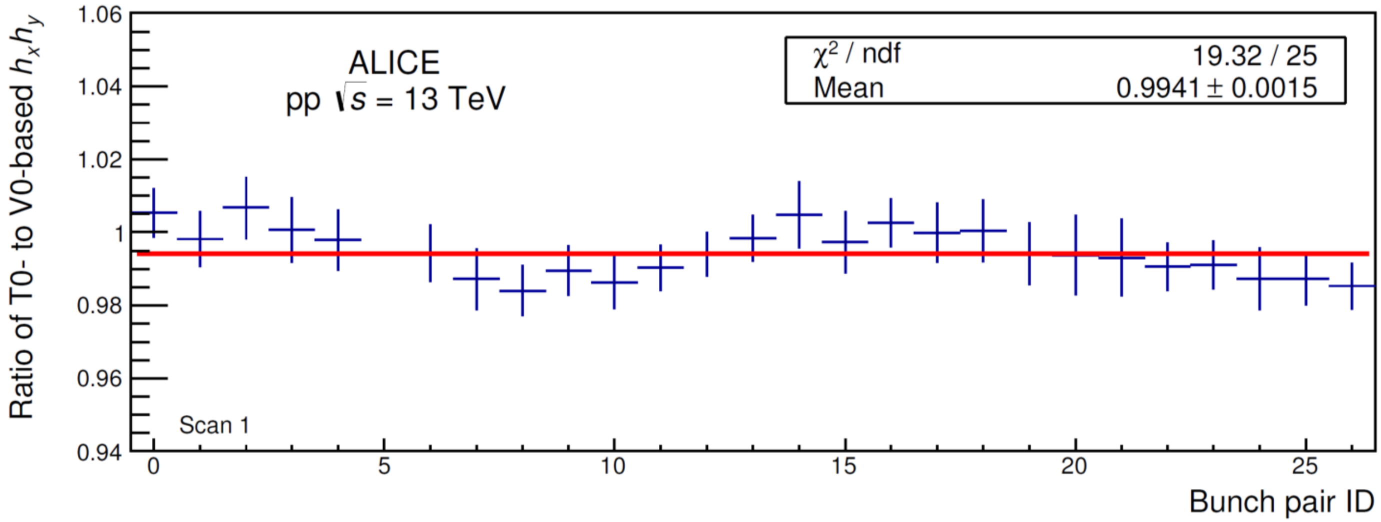
– Bunch by Bunch $h_x h_y$:

a. Estimated by fitting the measured rate vs. separation

b. Standard fit function in pp: Gaussian x partial pol6

$$A(x) = N \cdot exp(-\frac{(x-\mu)^2}{2\sigma}) \cdot (1 + p_2(x - \mu)^2 + p_4(x - \mu)^4 + p_6(x - \mu)^6)$$

c. Final crosscheck by using the ratio of $h_x h_y$ from different detectors



ALICE-PUBLIC-2016-002

vdM Analysis Process and corrections

4. Effective beam width ($h_x h_y$) (continue)

– Non-factorization

a. Let's take a few steps back:

$L = f_{rev} N_1 N_2 / h_x h_y = f_{rev} N_1 N_2 \cdot \iint \rho_1(x, y)\, \rho_2(x, y)\, dxdy$,

only if **factorization stands**

b. If factorization is broken,

b-1. The motion in x direction also affects the y

b-2. 3D convolution on two colliding bunches' overlapped region (aka luminous region)

c. Specific data taken for study:

with offset in *x* (*y*)

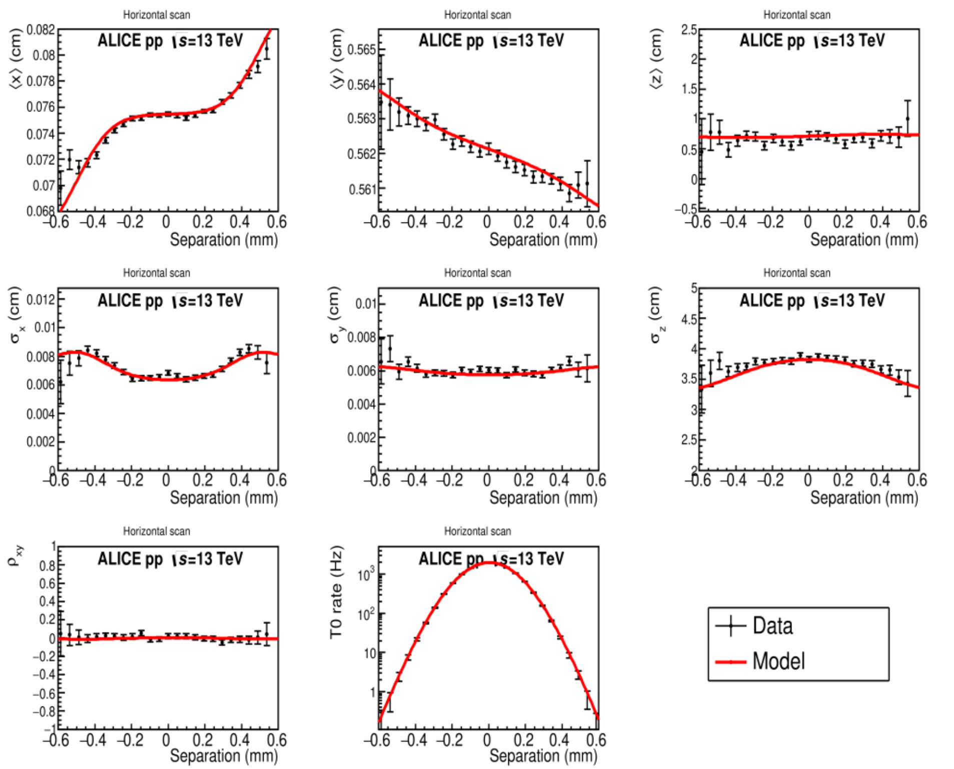
d. Compute correction factors:

measure luminous region by 3D vertexing based on barrel detectors

e. Overall uncertainty on σ_{vis} :

< 0.5% for pp and < 1.1% for Pb-Pb

ALICE-PUBLIC-2021-005



vdM Analysis   Process and corrections

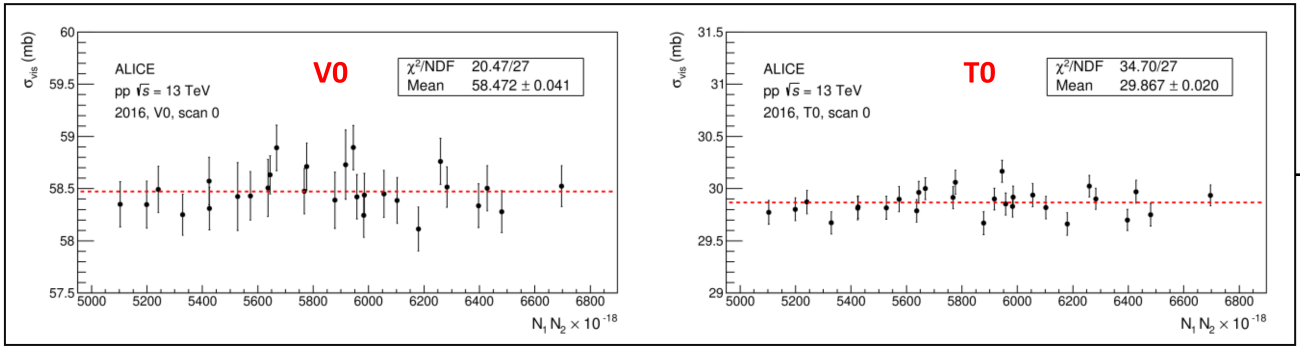
5. Compute σ_{vis}

– Extracting final σ_{vis}

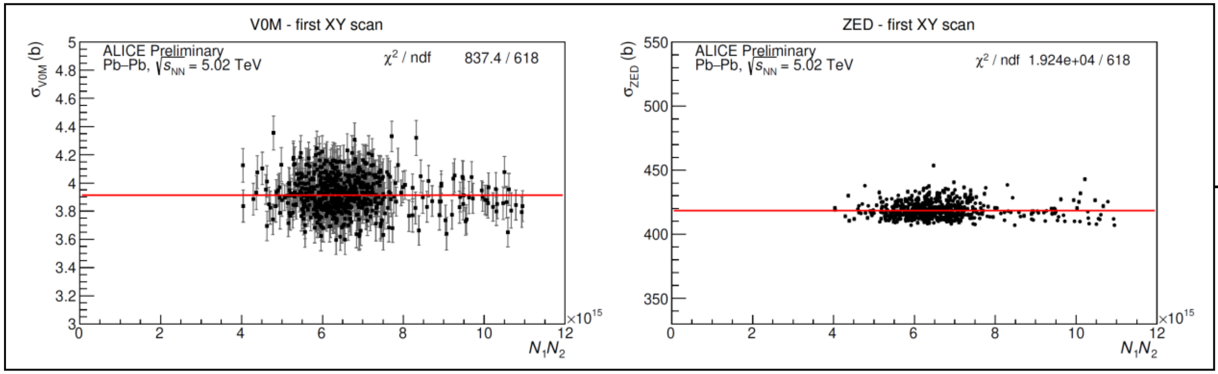
a. σ_{vis} is computed for each bunch crossing

b. Get average σ_{vis} of a given scan (either 0 or 1) by constant fit

c. Final σ_{vis} is the average of the two scans



pp √s = 13 TeV
ALICE-PUBLIC-2021-005

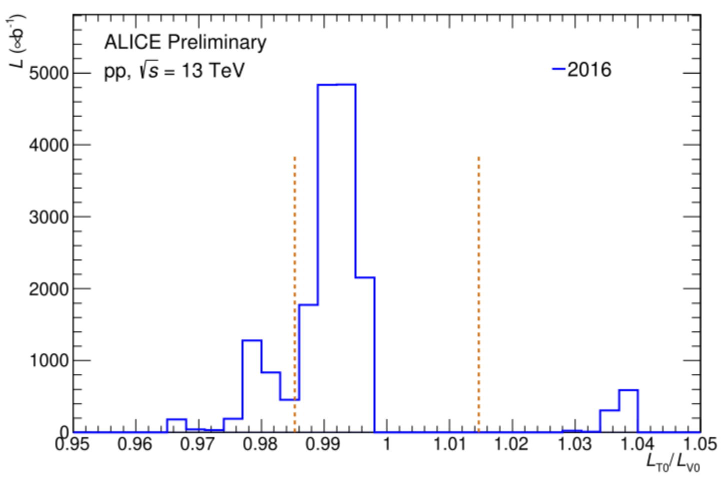


Pb-Pb √s = 5.02 TeV
ALICE-PUBLIC-2021-001

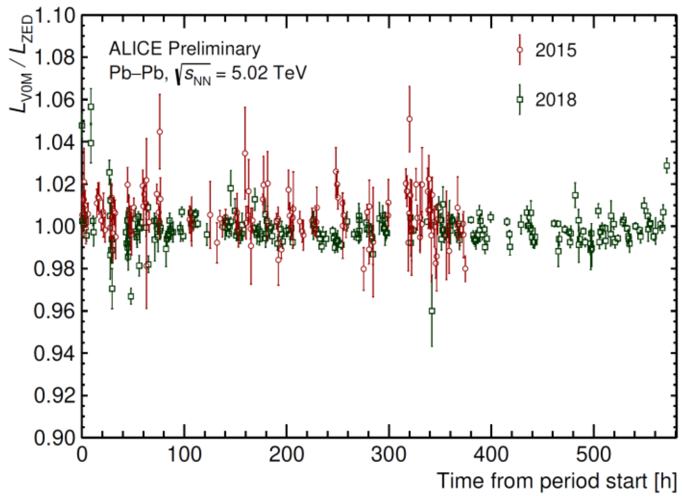
vdM Analysis Long-term stability and consistency

- **Validity throughout the runs**
  - The luminosity of a physics run = Luminosity trigger counts of the run / σ_{vis}
  - The stability and consistency of ALICE detectors (V0, T0, and ZN)
    a. Evaluation by the ratio of "T0-based / V0-based luminosity" (or V0/ZN, in Pb-Pb)
    b. Estimate the uncertainty by using RMS (WRT unity) over the runs
  - The largest uncertainty source in pp (2016 - 2018)

pp √s = 13 TeV, ALICE-PUBLIC-2021-005



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



vdM Analysis Run 2 results

- **Table of systematic errors**
  - Presenting only recent results (pp/Pb-Pb 2015-2018): check backup for others
  - Source of the largest error is different for each system: stability for pp and non-factorization for Pb-Pb
  - In pp, one must consider the correlation across the years:

    the overall uncertainty of the luminosity for the analyses use data from all 3 years ~ 1.6%

pp $\sqrt{s}$ = 13 TeV (2016, 2017, and 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

ALICE-PUBLIC-2021-005

Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV (2015 + 2018)

Source	Uncertainty (%)
	V0M | ZED
Statistical	0.09 | 0.04
Bunch intensity	0.8
$h_x h_y$ consistency (V0M vs ZED)	0.13
Length-scale calibration	1
Non-factorisation	1.1
Bunch-to-bunch consistency	0.1 | 0.4
Scan-to-scan consistency	1
Background subtraction	0.5 | 0.8
Magnetic non-linearities	0.2
Orbit drift	0.15
Beam–beam deflection and distortion	0.1
Fitting scheme	0.4
Total on visible cross section	2.1 | 2.2
Stability and consistency	0.7
Total on luminosity	2.2 | 2.3

ALICE-PUBLIC-2021-001

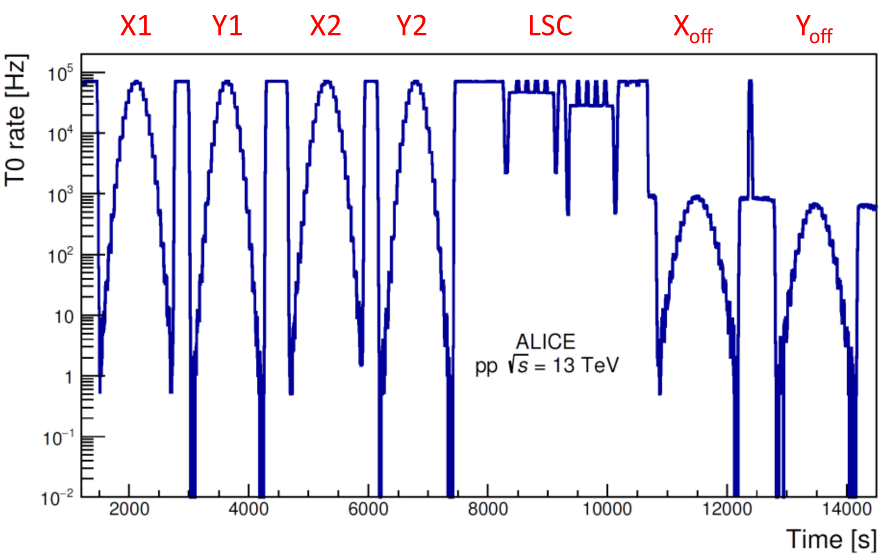
Summary

- **Luminosity determination in ALICE**
  - Luminosity
    a. Baseline of the normalization
    b. A source of non-negligible uncertainty for precision measurements
  - vdM scan
    a. Simple principle, but complicated calibrations and corrections
    b. Require dedicated data taking
    c. Rely on LHC instrumentation for beam control info and beam intensity, ALICE detectors (V0, T0, and ZN) for rate measurements
  - 2015-2018 results for pp and Pb-Pb
    a. Source of the largest error: stability and consistency for pp and non-factorization for Pb-Pb
    b. Total luminosity uncertainty for the analyses using 2015-2018 data: ~1.6% for pp and ~1.1% for Pb-Pb

Backup Scans in a vdM session

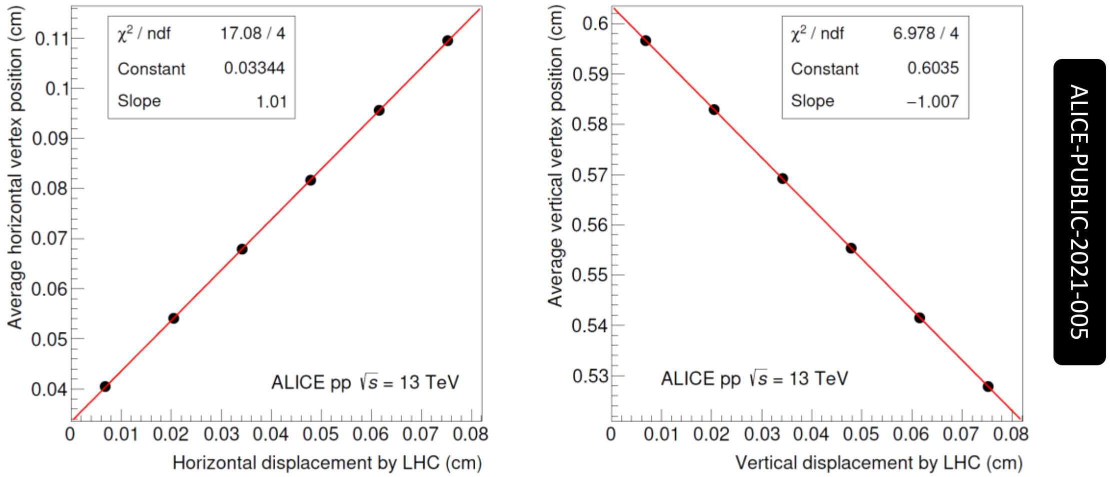
- **Type of scans in a vdM session**
  - Standard, symmetric scans (X1 - Y2)
    a. Range: [-6 σ_{beam} , +6 σ_{beam}]
    b. Step width: 0.5 σ_{beam} per step, total 25 steps
    c. Elapsed time: 30 *s / step*
  - Length-scale calibration (LSC)
    a. Step width: ~ σ_{beam} per step, total 5 steps
    b. Beams kept at ~ Σ
  - Offset scan
    a. Typical offset ~ 4 σ_{beam}
    b. Input to non-factorization fits

ALICE-PUBLIC-2016-002



Backup Separation – LSC correction

- **Length scale calibration (LSC)**
  - LHC operators control the beam separation by using the B-fields:
    to check if the applied adjustment is properly converted to the desired length scale
  - Specific LSC scan is performed during a vdM session:
    a. The beams are moved simultaneously in one direction
    b. The position after the move is measured by using ALICE trackers, to compare w/ LHC broadcasted separation
  - The calibration factor is estimated as the slope of the measured position vs. intended beam-spot position
  - The effect of the correction on σ_{vis} is < 2%, but the uncertainty is much less than that



Backup Run 2 results: pp $\sqrt{s}$ = 5 TeV (2015, 2017)

pp $\sqrt{s}$ = 5 TeV (2015), ALICE-PUBLIC-2016-005

Source	Uncertainty
Non-factorisation	1%
Orbit drift	< 0.1%
Beam-beam deflection	0.4%
Dynamic β^*	0.2%
Background subtraction	0.3% (T0), 1.1% (V0)
Pileup	0.7%
Length-scale calibration	1%
Fit model	0.7%
$h_x h_y$ consistency (T0 vs V0)	0.2%
Luminosity decay	0.7%
Bunch-by-bunch consistency	< 0.1%
Scan-to-scan consistency	0.5%
Beam centreing	0.1%
Bunch intensity	0.4%
Total on visible cross section	2.05% (T0), 2.31% (V0)
Stability and consistency	0.4%
Total on luminosity	2.09% (T0), 2.34% (V0)

pp $\sqrt{s}$ = 5 TeV (2017), ALICE-PUBLIC-2018-014

Source	Uncertainty
Non-factorisation	0.1%
Orbit drift	0.1%
Beam-beam deflection	0.5%
Dynamic β^*	0.2%
Background subtraction	0.2% (T0), 1.1% (V0)
Pileup	0.5%
Length-scale calibration	0.2%
Fit model	0.5%
$h_x h_y$ consistency (T0 vs V0)	< 0.1%
Luminosity decay	0.9%
Bunch-by-bunch consistency	< 0.1%
Scan-to-scan consistency	0.5% (T0), 0.4% (V0)
Beam centreing	0.2%
Bunch intensity	0.4%
Total on visible cross section	1.5% (T0), 1.8% (V0)
Stability and consistency	1.1%
Total on luminosity	1.8% (T0), 2.1% (V0)

Backup Run 2 results: pp $\sqrt{s}$ = 13 TeV (2015)

pp $\sqrt{s}$ = 13 TeV (2015), ALICE-PUBLIC-2016-002

Source	Uncertainty
Non-factorisation	0.9%
Orbit drift	0.8%
Beam-beam deflection	0.8%
Dynamic β^*	0.3%
Background subtraction	0.1% (T0), 0.7% (V0)
Pileup	0.7%
Length-scale calibration	0.5%
Fit model	0.6%
$h_x h_y$ consistency (T0 vs V0)	0.6%
Luminosity decay	0.4%
Bunch-by-bunch consistency	$<0.1\%$
Scan-to-scan consistency	$<0.1\%$
Beam centreing	$<0.1\%$
Bunch intensity	0.6%
Total on visible cross section	2.05% (T0), 2.16% (V0)
Stability and consistency	0.6% (isolated bunches) 2.7% (whole 2015)
Total on luminosity	2.2% (isolated bunches) 3.4% (whole 2015)

Backup Run 2 results: p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV (2013) and 8.16 TeV (2016)

p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV (2013), CERN-PH-EP-2014-087

Uncertainty	p–Pp	Pb–p	Correlated between p–Pb and Pb–p
Transverse correlations	2.6%	2.3%	No
Bunch-by-bunch consistency	1.6%	-	No
Scan-to-scan consistency	0.5%	1.5%	No
Length-scale calibration	1.5%	1.5%	Yes
Background subtraction (V0 only)	0.5%	0.5%	Yes
Method dependence	0.3%	0.3%	No
Beam centering	0.3%	0.2%	No
Bunch size vs trigger	0.2%	0.2%	No
Bunch intensity	0.5%	0.5%	No
Orbit drift	0.4%	0.1%	No
Beam-beam deflection	0.2%	0.3%	Partially
Ghost charge	0.1%	0.2%	No
Satellite charge	<0.1%	0.1%	No
Dynamic β^*	<0.1%	0.1%	Partially
Total on visible cross section	3.5%	3.2%	
V0- vs T0-based integrated luminosity	1%	1%	No
Total on integrated luminosity	3.7%	3.4%	

p-Pb $\sqrt{s_{NN}}$ = 8.16 TeV (2016), ALICE-PUBLIC-2018-002

Uncertainty	p–Pp	Pb–p	Correlated
Transverse correlations	0.6%	0.9%	No
Scan-to-scan consistency	0.6%	0.1%	No
Length-scale calibration	0.5%	0.8%	No
Background subtraction	0.5% (< 0.1%) V0 (T0)	0.6% (0.3%) V0 (T0)	Yes
Intensity decay	0.6%	0.7%	No
Method dependence	0.4% (0.5%) V0 (T0)	0.9% (0.6%) V0 (T0)	No
Beam centring	0.1%	0.1%	No
Bunch size vs trigger	0.2%	0.4%	No
Absolute DCCT calibration	0.3%	0.3%	No
Orbit drift	0.7%	0.3%	No
Beam-beam deflection	< 0.1%	0.4%	Partially
Ghost charge	< 0.1%	< 0.1%	No
Satellite charge	< 0.1%	< 0.1%	No
Dynamic β^*	< 0.1%	< 0.1%	Partially
Total on visible cross section	1.5% (1.5%) V0 (T0)	1.9% (1.7%) V0 (T0)	
V0 vs T0 integrated luminosity	1.1%	0.6%	No
Total on integrated luminosity	**1.9% (1.8%) V0 (T0)**	**2.0% (1.8%) V0 (T0)**	
Correlated part	0.5% (< 0.1%) V0 (T0)	0.7% (0.5%) V0 (T0)	
Uncorrelated part	1.8% (1.8%) V0 (T0)	1.9% (1.7%) V0 (T0)	