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Luminosity determination with ALICE at the LHC

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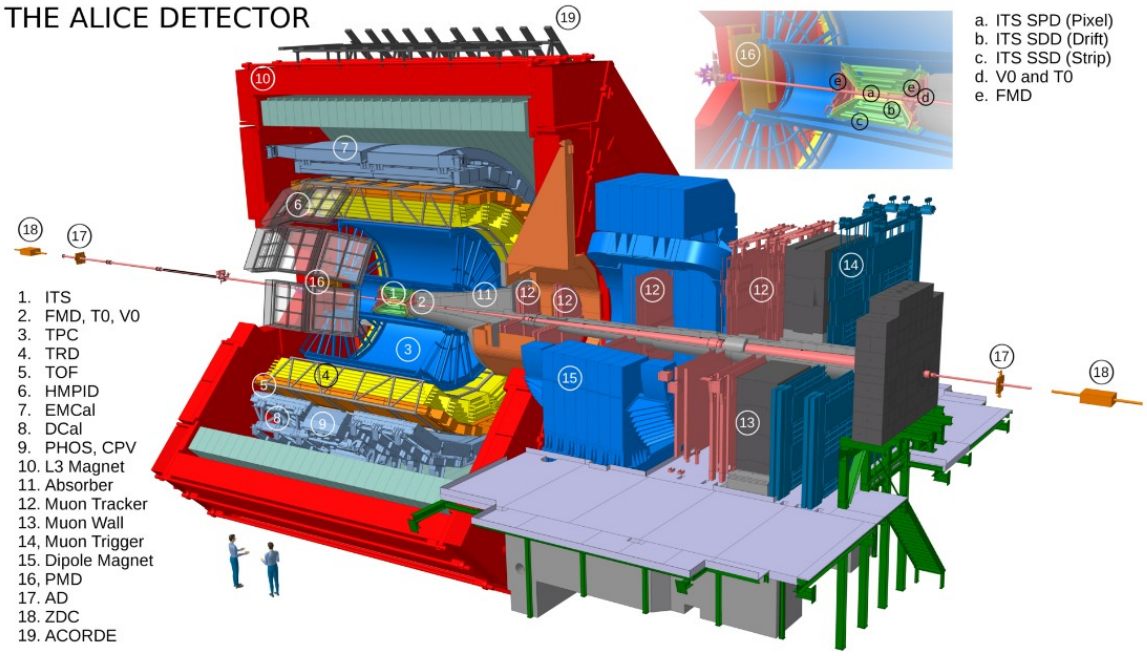
for the ALICE collaboration

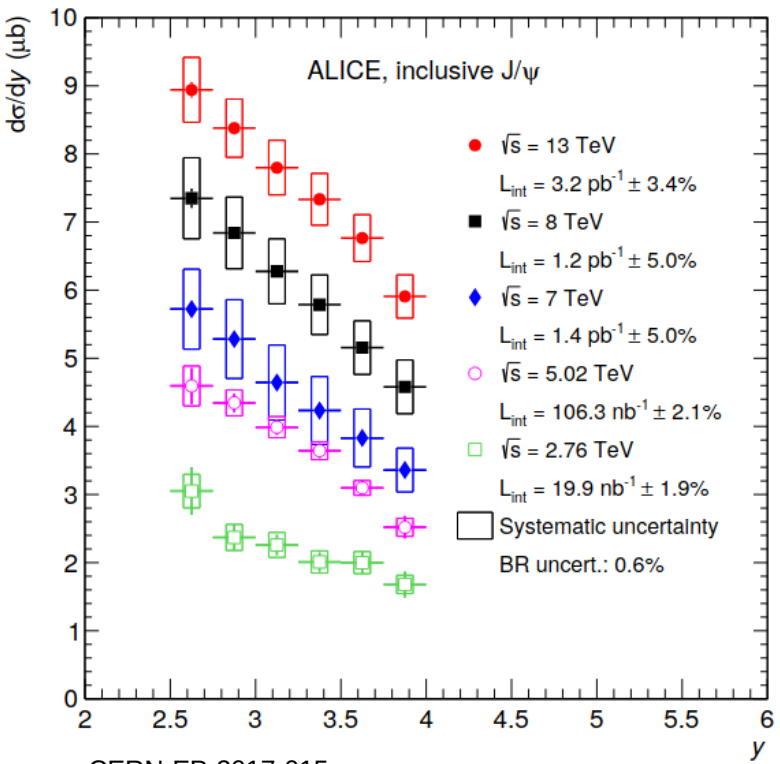
Introduction

Main purpose of the ALICE detector is to study properties of quark-gluon plasma. Specific state of matter when quarks and gluons are deconfined.
There are several types of collision – pp, p-Pb, Pb-Pb.
Cross section measurements are crucial to ALICE physics program, e.g. :

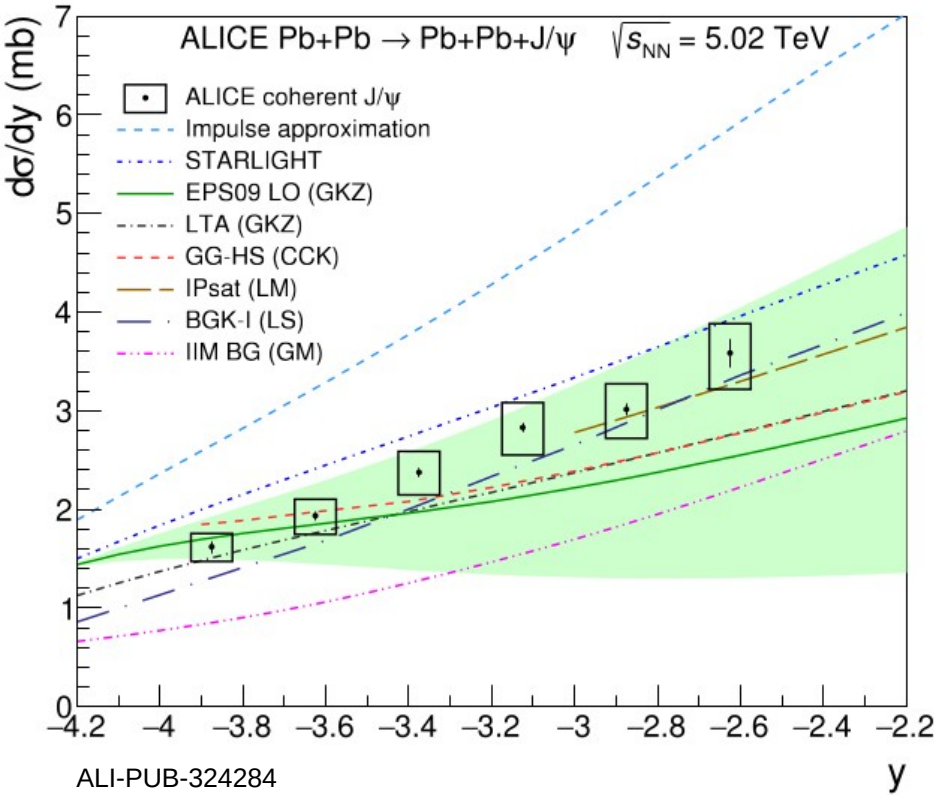
- J/psi production in pp and p-Pb
- UPC cross sections in Pb-Pb and p-Pb



Introduction



CERN-EP-2017-015, pp



ALI-PUB-324284

Luminosity

Indirect measurement of luminosity:

$$L = \frac{R_{vis}}{\sigma_{vis}} = \frac{f_{rev} * \mu_{vis}}{\sigma_{vis}}$$ - luminosity calculation by using visible cross section

$\sigma_{vis} = \epsilon \sigma_{inel}$ - visible cross section seen by a given detector with given trigger conditions, with fraction of inelastic events(ε) that satisfy the trigger condition.

R_{vis} – visible event rate

f_{rev} – accelerator revolution frequency

μ_{vis} – number of average visible interactions per colliding bunch pair

Luminosity

Luminosity measurement: $L = f_{\mathrm{rev}} N_1 N_2 * \iint \rho_1(\mathrm{x,y})\rho_2(\mathrm{x,y})\,\mathrm{dxdy}$

ρ_1 , ρ_2 – particle density for each bunch in transverse plane.
N_1 ,N_2 – bunch intensity.

$\iint \rho_1 \rho_2 \,\mathrm{dxdy}$ - beam overlap integral

If factorization stands: $\mathrm{L} = \dfrac{f_{\mathrm{rev}} N_1 N_2}{h_x h_y}$

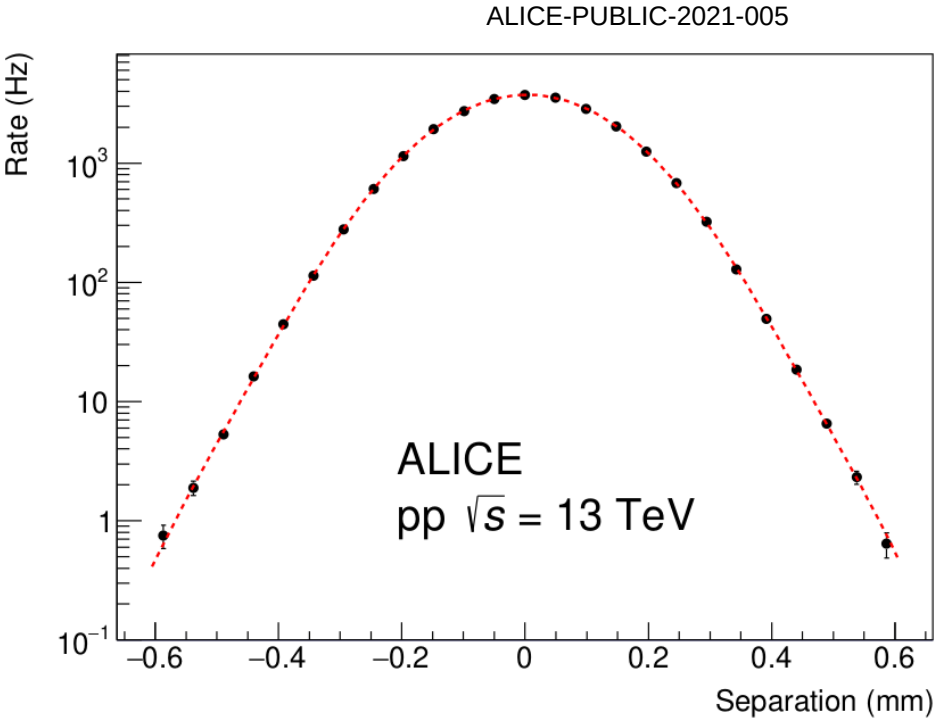
$1/h_x = \int \rho_1(x)\rho_2(x)\,\mathrm{dx}$ - effective width of beam overlap along X axis. Same for Y.

$h_x * h_y$ - one needs special session (van der Meer scan) for direct and high precision measurements.

van der Meer scan

vdM scan description:

- Special session for luminosity measurement.
- R_{vis} vs beam separation measurement.
- Estimation of visible rate per colliding bunch pair.
- Adjustment of separation distance for each colliding bunch pair. Scanning along given direction (X or Y) while the other direction is in head-on position.



vdM scan overview

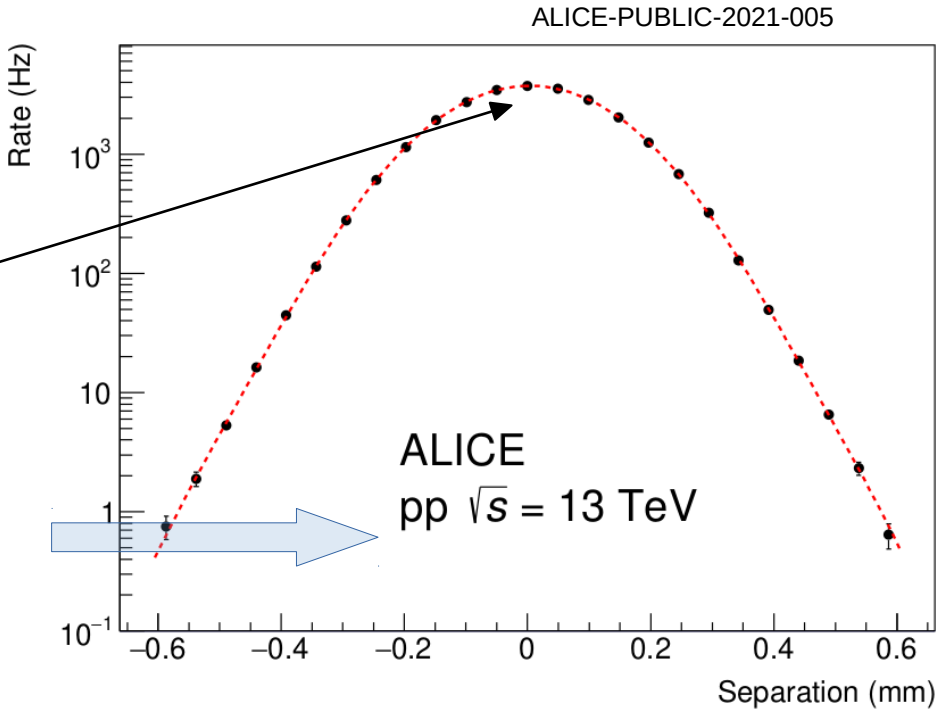
Main goal: calculation of visible cross section

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

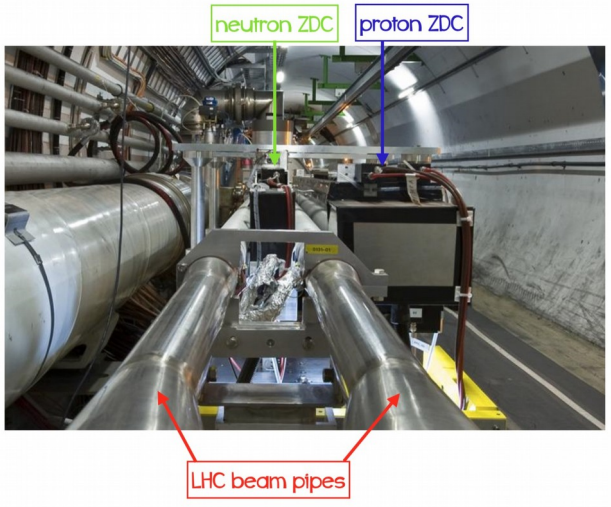
- *R(0,0)* – visible highest “head-on” rate

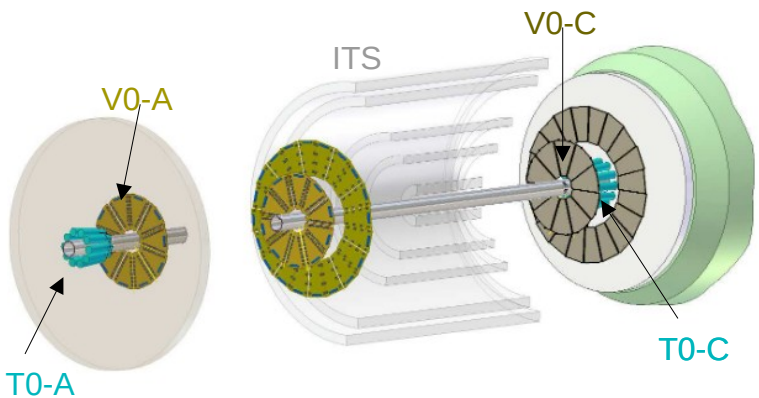
$$\mathrm{L} = \frac{f_{\mathrm{rev}} N_1 N_2}{h_x h_y}$$

- h_x , h_y - integral under the curve, normalized by peak value *R(0,0).*
- **Computation of σ_{vis}**



ALICE luminometers





T0:

- Two circular arrays of Cherenkov radiators with PMTs (12 per side), located on opposite sides(T0-A and T0-C), at z_a = 370 cm and z_c = - 70 cm.
- $4.61 < \eta < 4.92$, $-3.28 < \eta < -2.97$

V0:

- Two scintilattor arrays (32 per side), located on opposite sides (V0-A and V0-C), at z_a = 340 cm and z_c = - 90 cm.
- $2.8 < \eta < 3.7$, $-3.7 < \eta < -1.7$

ZDC:

- Two sets of identical hadronic calorimeters at z = ± 114 m

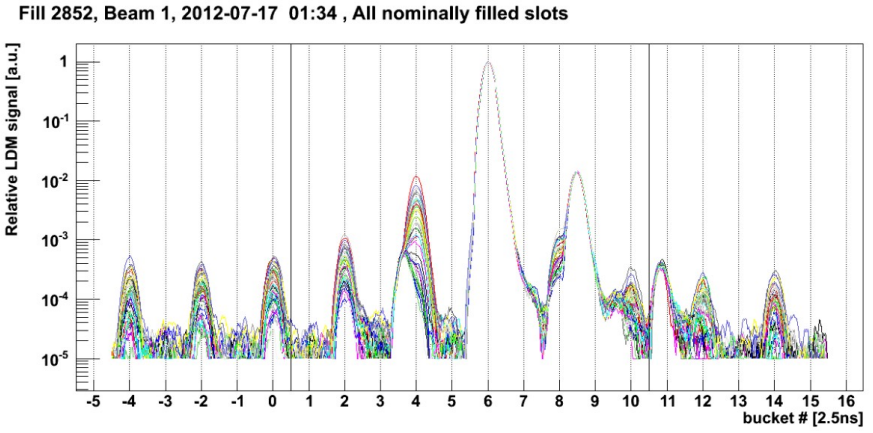
Trigger conditions:

- pp, p-Pb:
  T0: coincidence of A and C sides, and vertex cut.
  V0: coincidence of A and C sides
- Pb-Pb:
  V0: multiplicity trigger (V0M)
  ZDC: Single neutron trigger (ZN)

Intensity measurements

- Instruments:

1) LHC(DCCT) - DC current transformer, for total beam current (normalization).
2) LHC(BCT) - fast Beam Current Transformer, for relative bunch intensity
3) ATLAS(BPTX) - Beam Pick Up System, same purpose as BCT



CERN-ATS-Note-2013-034 TECH

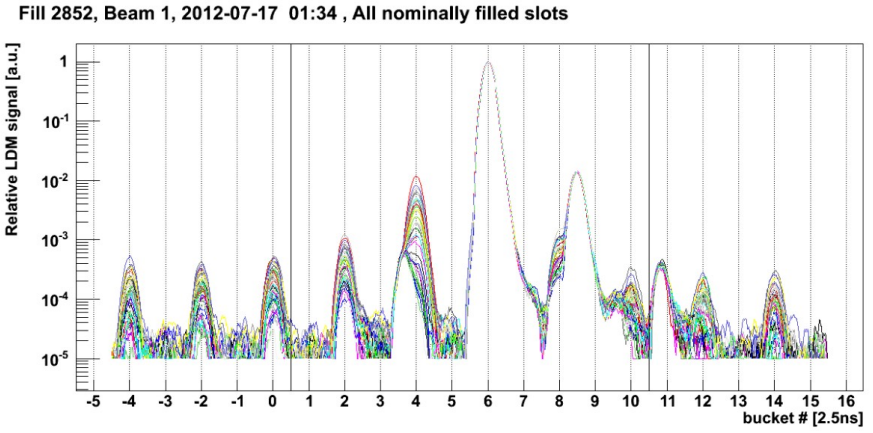
- Bunch spacing:

1) 2.5 ns between RF buckets.
2) 25 ns or 10 RF buckets between bunch slots.

Intensity measurements

- Ghost: nominal empty BCs which contain ions.

1) Ghost fraction is measured by LHC Longitudinal Density Monitor LDM (measures synchrotron radiation photons emitted by the beams).
2) Also LHCb provides information about ghost fraction, by measuring beam – gas event rate for nominal empty bunches.

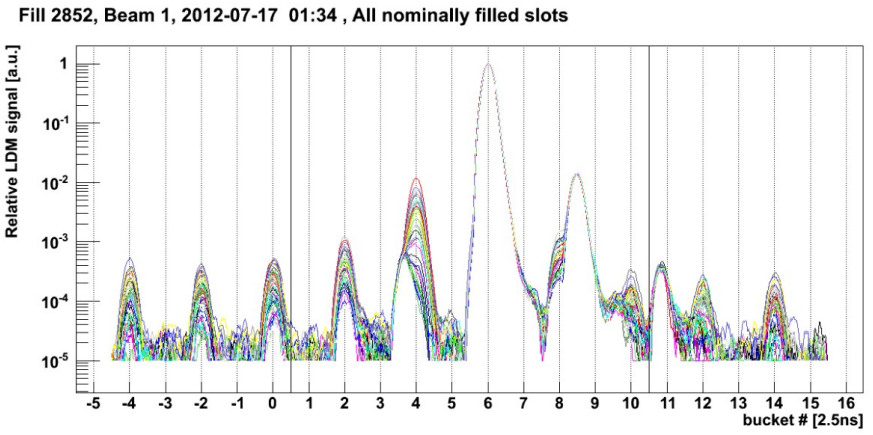


CERN-ATS-Note-2013-034 TECH

Intensity measurements

- Satellite: some ions could be located in RF bucket between two closest bunches. Events caused by satellite-bunch or sat.-sat. collisions should be excluded.

1) LHC LDM is used for measuring satellite fraction, for all scans it was negligible (< 0.05%).



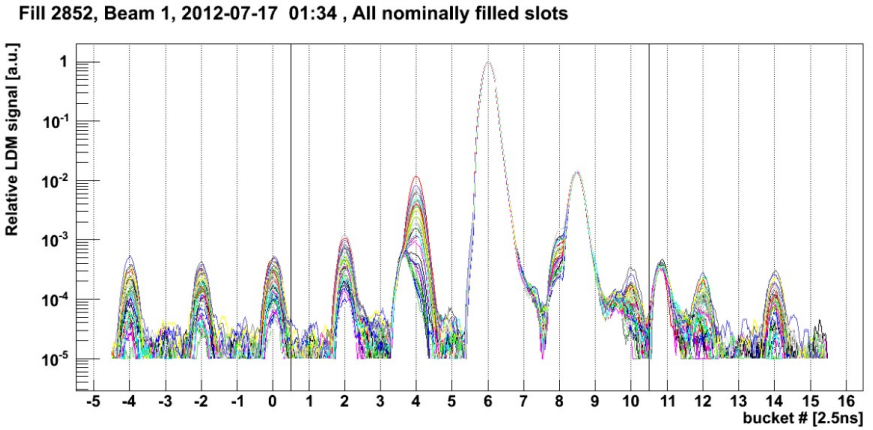
CERN-ATS-Note-2013-034 TECH

Intensity measurements

- Total bunch intensity:

  $N_{bunch} = N_{tot} - N_{sat} - N_{ghos}$

1) Large correction for Pb-Pb - correction can reach few % level.
2) In pp or Pb-Pb, the final effect on σ_{vis} uncertainty is negligible.



CERN-ATS-Note-2013-034 TECH

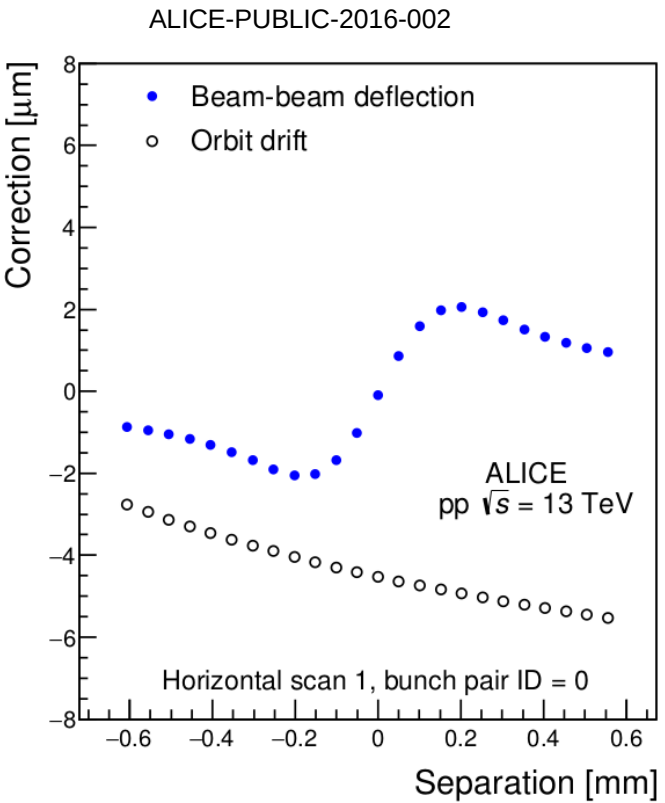
Separation

- Starting from nominal beam separation, provided by LHC
- Corrections needed:

1)ODC (Orbit drift correction), bunch orbits can vary from nominal.

2)BBD (Beam – Beam deflection), during separation, two bunches exert repulsive electrical forces on each other. Affects the beam separation.

3)LSC (length-scale calibration), for measuring the conversion factor between nominal and actual beam position.



Separation(LSC)

- LSC (length-scale calibration)

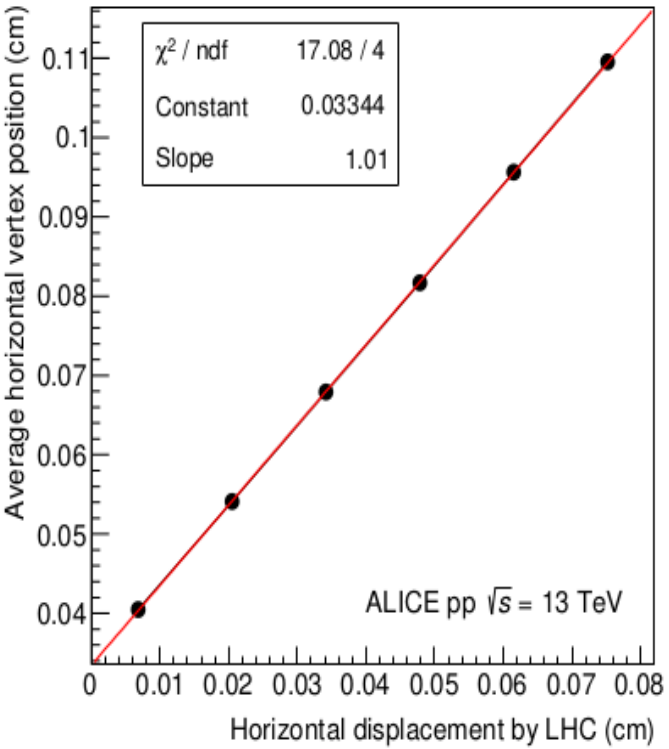
1)Two beams are moved simultaneously in the same direction in steps of equal size.

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.

ALICE-PUBLIC-2021-005



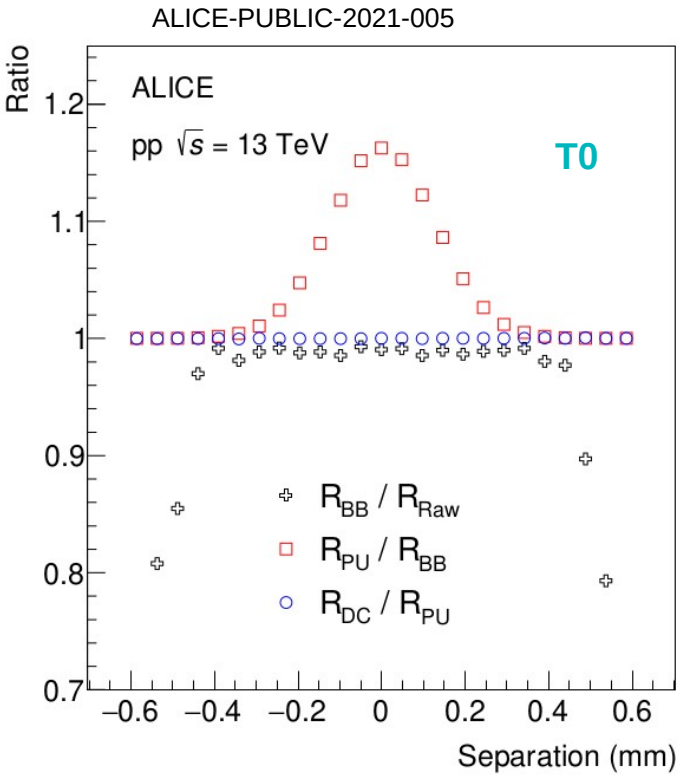
Rate

- 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.

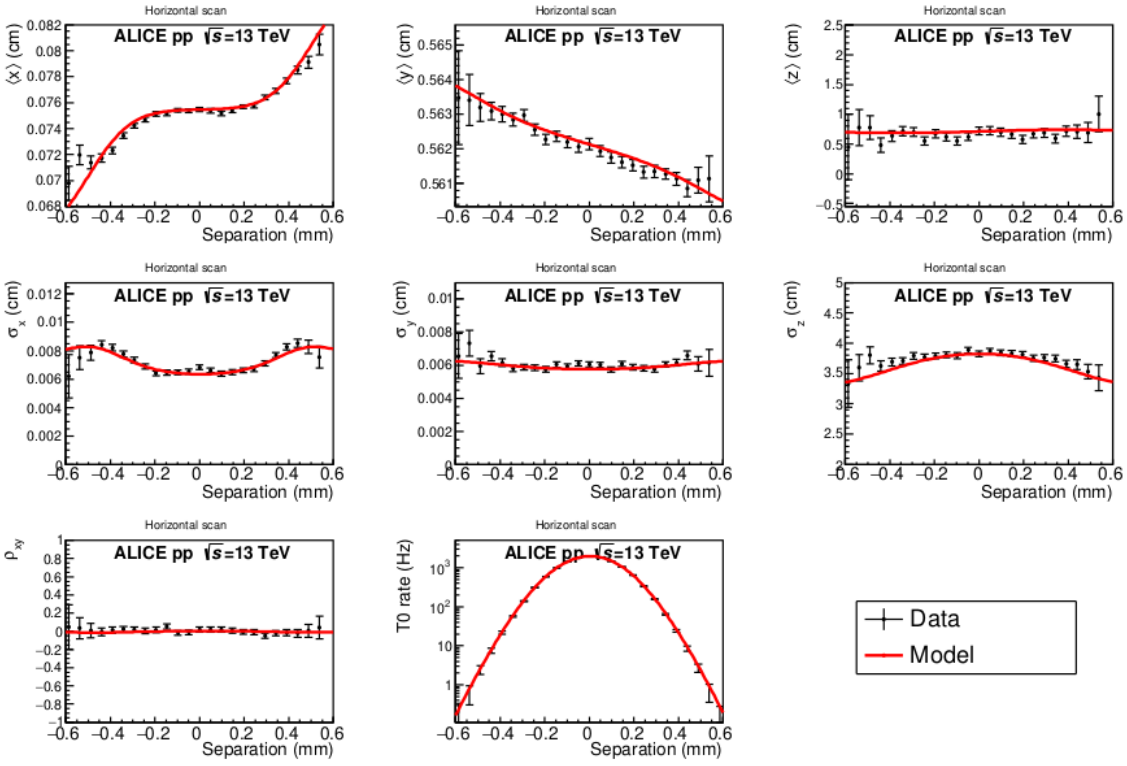
  3)DC (Intensity decay): to account for the bunch intensity (and, hence, the luminosity) decay with time.



Non-factorization effects

- **Assuming that factorization stands:** $L = \frac{f_{rev} N_1 N_2}{h_x h_y} = f_{rev} N_1 N_2 * \iint \rho_1(x,y)\rho_2(x,y)\,dxdy$

- 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.

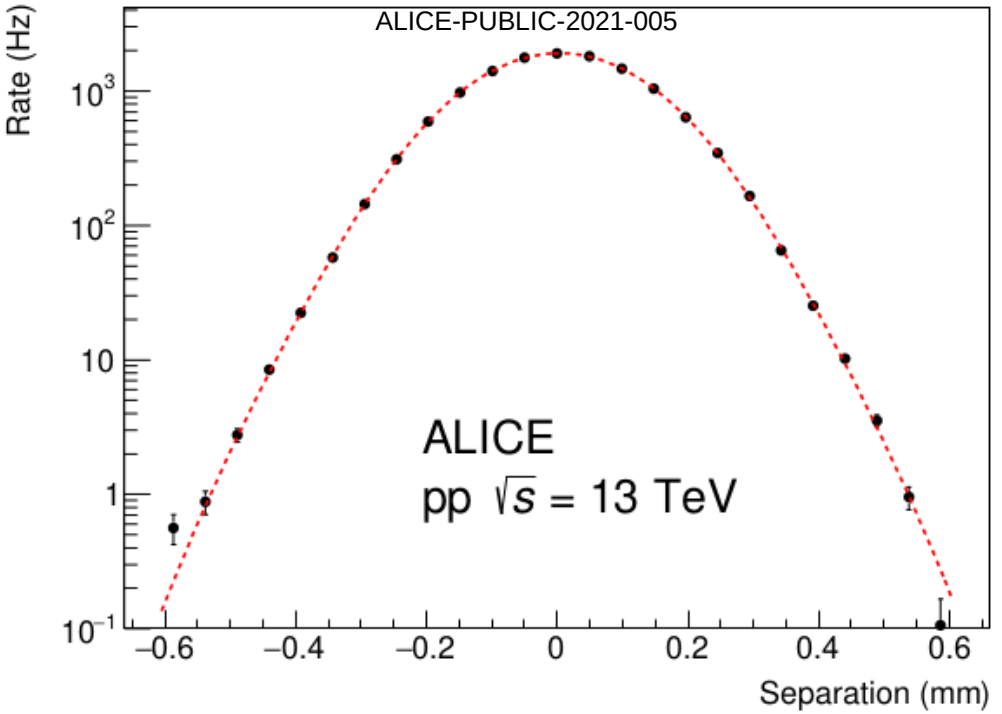


ALICE-PUBLIC-2021-005

Effective beam width

- Bunch by bunch measurement of h_x , h_y
- For each direction(X/Y) and detector(T0, V0), one needs to fit Rate vs separation curve.
- Fit functions

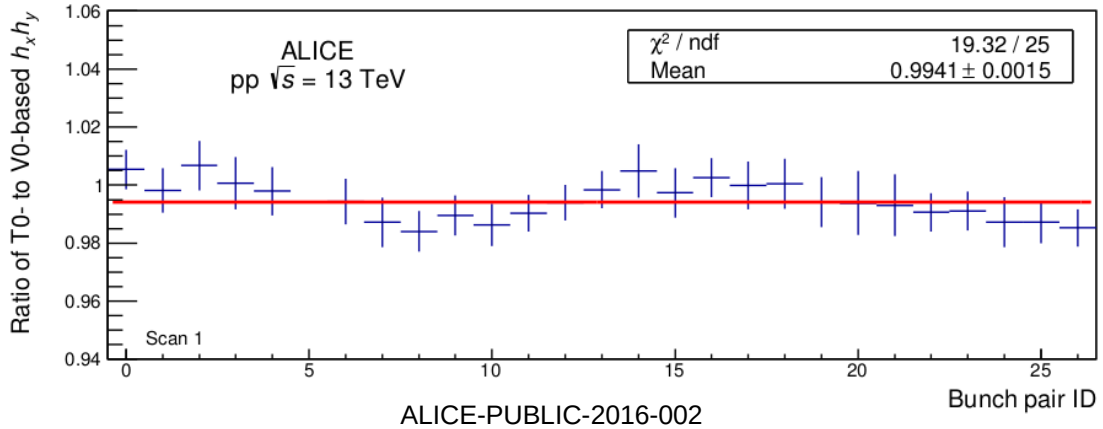
On average $\chi^2/ndf \sim 1$, and typically ≤2

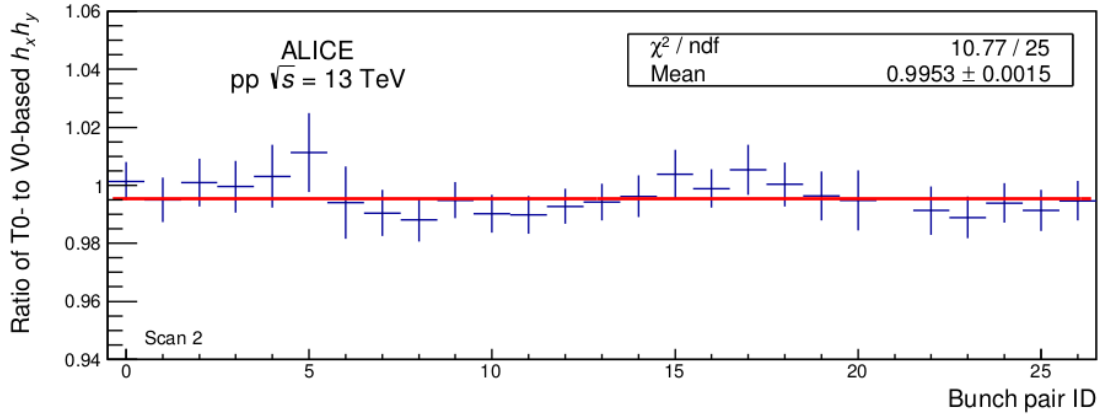


$$R(\Delta x,0)=R(\mu,0)\exp\left(-(\Delta x-\mu)^2/2\sigma^2\right)\left[1+p^2(\Delta x-\mu)^2+p^4(\Delta x-\mu)^4+p^6(\Delta x-\mu)^6\right]$$

Stability of effective beam width

- Crosscheck by using T0/V0 ratio of effective beam width.
- For each bunch crossing.



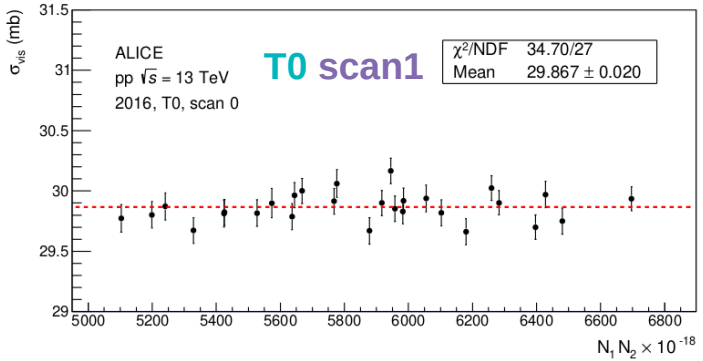


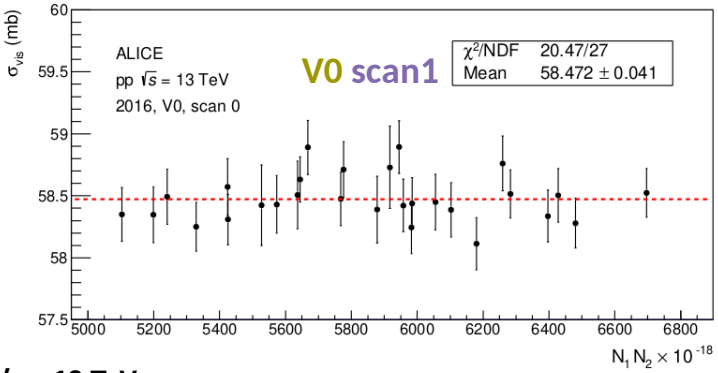
Calculation of visible cross section

- σ_{vis} – one needs to calculate for each colliding bunch pair.
- After that zero-order-polynomial fit should be applied for each scan and detector.
- Weighted mean value of scans is the σ_{vis} for given detector

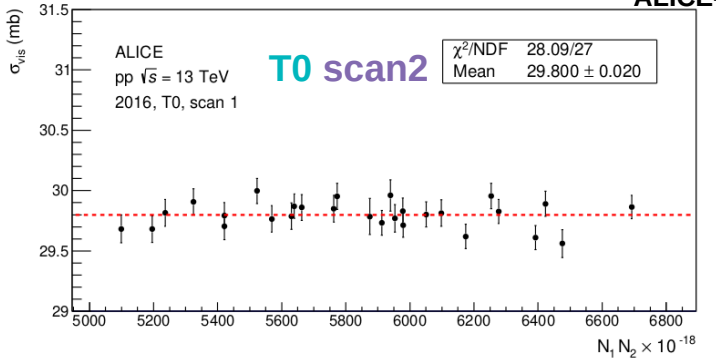
ALICE-PUBLIC-2021-005, pp √s = 13 TeV

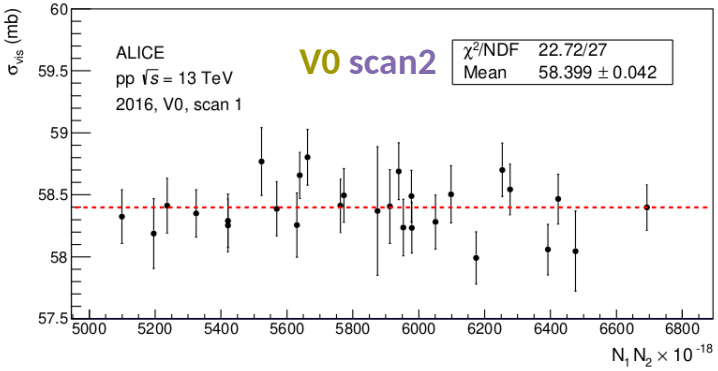
	2016	2017	2018
σ_{T0} (mb)	29.838 ± 0.015	28.49 ± 0.02	28.159 ± 0.014
σ_{V0} (mb)	58.44 ± 0.03	58.10 ± 0.04	57.52 ± 0.03





ALICE-PUBLIC-2021-005, pp √s = 13 TeV





Calculation of visible cross section

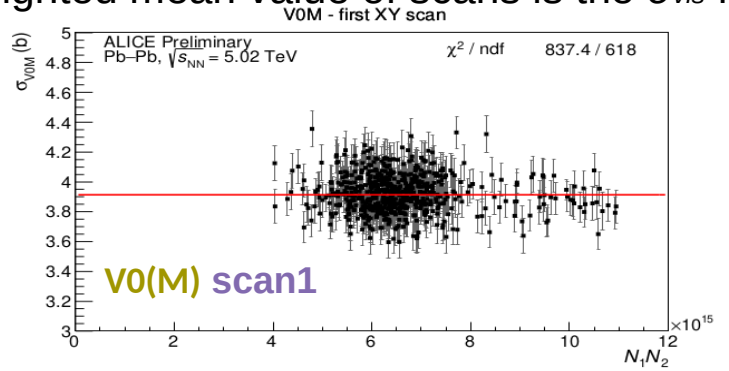
- σ_{vis} – one needs to calculate for each colliding bunch pair.
- After that zero-order-polynomial fit should be applied for each scan and detector.
- Weighted mean value of scans is the σ_{vis} for given detector

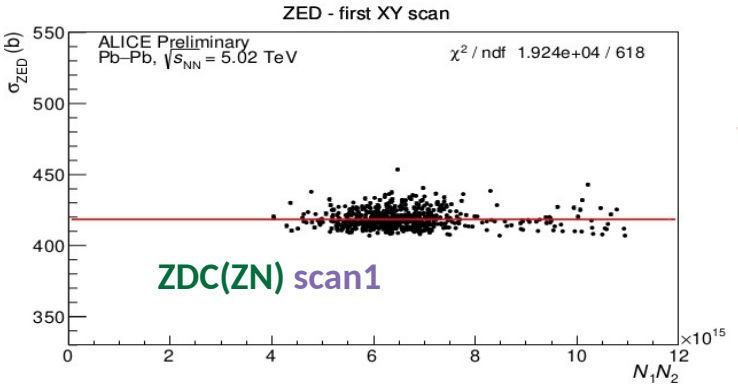
ALICE-PUBLIC-2021-001, Pb-Pb √s = 5.02 TeV

$\sigma_{ZED} = 420.5\ \text{b} \pm 0.2\ \text{b (stat.)}$

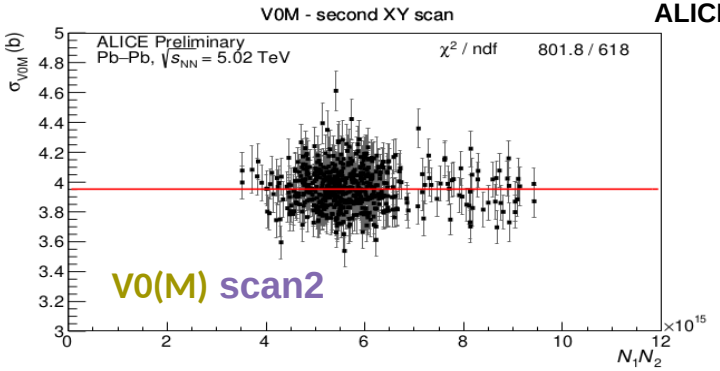
$\sigma_{V0M} = 3.933\ \text{b} \pm 0.004\ \text{b (stat.)}$

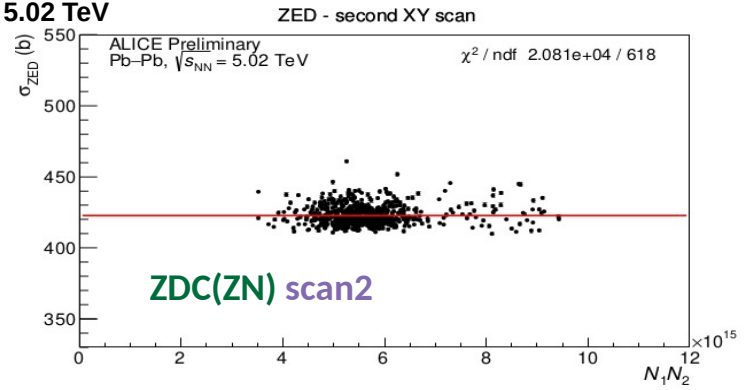
Large due to electromagnetic dissociation of Pb





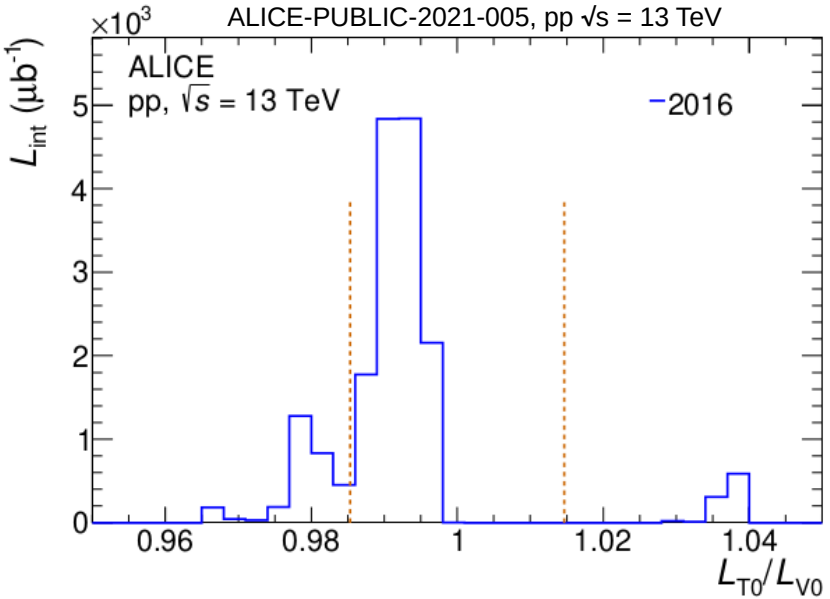
ALICE-PUBLIC-2021-001, Pb-Pb √s = 5.02 TeV

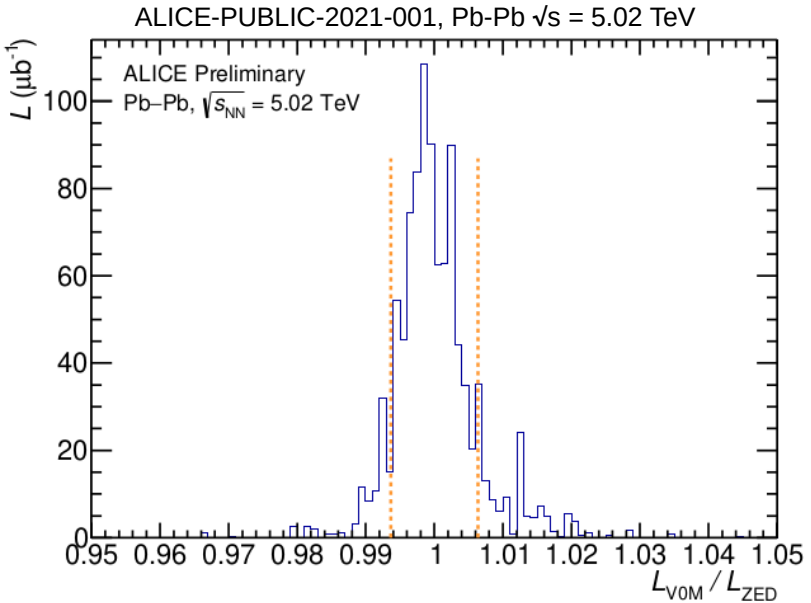




Stability

- Assess the consistency and stability over time of the vdM-based calibration of the luminometers.
- For such analysis T0/V0(or V0/ZN for Pb-Pb) trigger counter ratio normalized by visible cross section of each detector, was calculated by using data collected in given pp (Pb-Pb) session.
- Estimation of uncertainty over all runs by using RMS. Largest uncertainty is in p-p(2016,2017, and 2018).





Systematic errors

- In p-p sessions(2016-2017-2018), the obtained luminosity uncertainty ranges from 1.8% to 2.7% depending on the year and luminometer.
- For all p-p 2016-2018 samples, total uncertainty is 1.6 %.(obtained by taking into account the lumi uncertainty correlations across 2016-2018 years).
- For Pb-Pb total uncertainty – 2.2% for V0(Multiplicity trigger) and 2.3% for ZDC .

ALICE-PUBLIC-2021-005, pp √s = 13 TeV

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-2021-001, Pb-Pb √s = 5.02 TeV

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

Summary

- **Luminosity:**

1) Short overview.
2) Two pairs of detectors are used as luminometers: T0 and V0(time based triggers) for p-p, V0(multiplicity trigger) and ZDC for Pb-Pb

- **van der Meer scan:**

1) Simple method, but complicated corrections are needed.
2) One should run special session.
3) Based on LHC instrumentation for beam control info and beam intensity, ALICE detectors (V0, T0, and ZN) for rate measurements.

- **p-p and Pb-Pb results for 2016-2018:**

1) Stability and consistency(~2.3%) is the largest, for p-p runs.
2) For Pb-Pb non-factorization is largest error ~1.1%
3) Total luminosity uncertainty for the analyses using 2016-2018 data:

~1.6% for pp and ~2.2% for Pb-Pb

BACKUP

- **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).

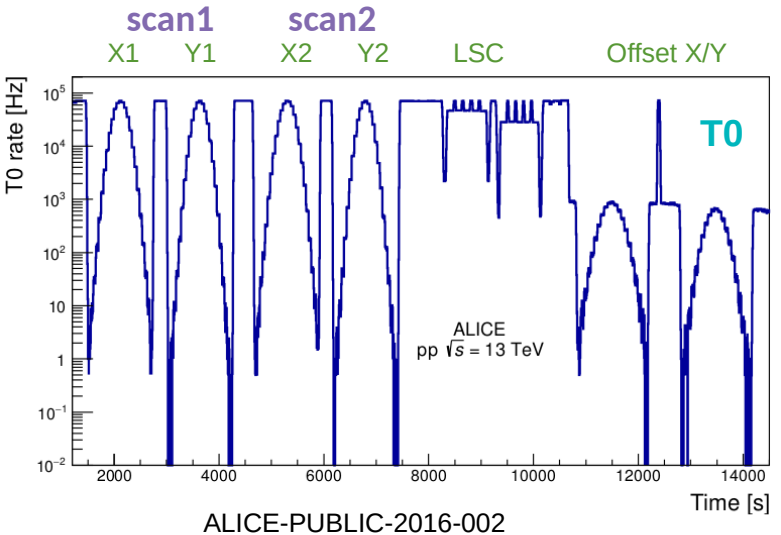
Step width: ~σ_{beam}

Total number of steps: 5

Offset scan(X/Y directions).

Typical offset: ~4σ_{beam}

Required for non-factorization analysis



BACKUP

Run 2 : pp √s = 5 TeV(2015 and 2017)

pp √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 √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 : pp √s = 13 TeV(2015)

pp √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 : 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
Bunch-by-bunch consistency	2%	1%	No
Scan-to-scan consistency	0.5%	1.5%	No
Length-scale calibration	1.5%	1.5%	Yes
Bunch size vs trigger	1.4%	1.4%	No
Background subtraction (V0 only)	0.5%	0.5%	Yes
Method dependence	0.4%	0.3%	No
Beam centering	0.3%	0.2%	No
Bunch intensity	0.5%	0.5%	No
Ghost charge	0.1%	0.2%	No
Satellite charge	<0.1%	0.1%	No
Orbit drift	0.4%	0.1%	No
Dynamic β^*	<0.1%	0.1%	Partially
Beam-beam deflection	0.2%	0.3%	Partially
Total on visible cross section	**3.0%**	**2.8%**	
V0- vs T0-based integrated luminosity	1%	1%	No
Total on integrated luminosity	**3.2%**	**3.0%**	

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)	