Luminosity determination in ALICE at the LHC

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ALICE

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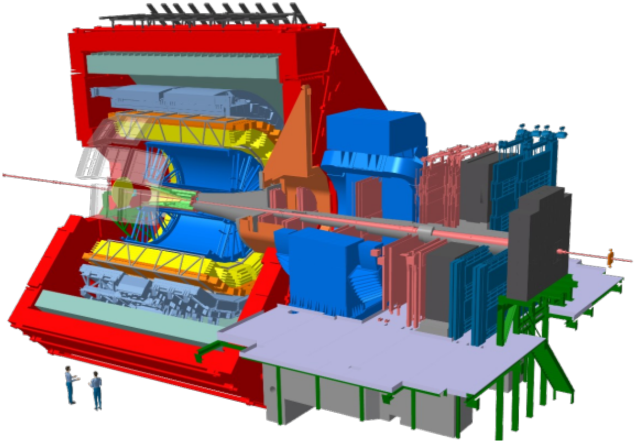
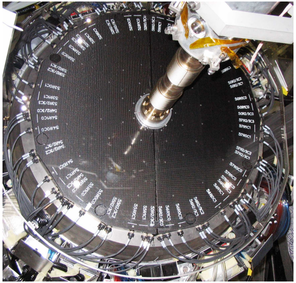
ALICE: the dedicated heavy-ion experiment at the LHC

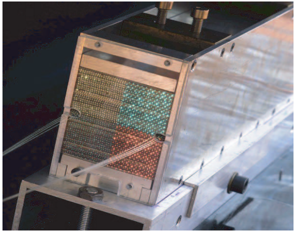
- Central barrel ($|\eta| < 1$) in a solenoidal field with excellent tracking and PID capabilities
- Forward muon spectrometer ($2.5 < \eta < 4$)
- Forward detectors ($|\eta| > 2.7$) to characterize the collision and measure luminosity
  - T0, V0 in the barrel on both sides of the interaction point
  - ZDC at ~ 112.5 m from interaction point



ALICE luminometers

- T0: $4.6 < \eta < 4.9$ (A side), $-3.3 < \eta < 3.0$ (C side)
  - two arrays of 12 Cherenkov counters
  - pp and p-A
    - trigger: $\boxed{\text{T0A and T0C}}$ - at least one hit per side with additional vertex requirement
- V0: $2.8 < \eta < 5.1$ (A side). $-3.7 < \eta < -1.7$ (C side)
  - array of 32 (48) scintillator counters on side A (C)
  - pp, p-A - trigger $\boxed{\text{V0A and V0C}}$ - at least one hit per side
  - A-A - trigger on $\boxed{\text{total amplitude}}$
- ZDC:
  - Cherenkov sampling calorimeters
    - neutron emission at beam rapidity: ZNA, ZNC ($\sim 100\%$ efficiency)
    - proton emission at beam rapidity: ZPA, ZPC
  - (p-A), A-A - trigger $\boxed{\text{ZED=ZNA or ZNC}}$ - at least one neutron
    - hadronic collisions: double side
    - mutual electromagnetic dissociation: double side
    - single side electromagnetic dissociation - dominant contribution in Pb-Pb





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Luminosity measurement with the van der Meer technique

The integrated luminosity can be related to the number of observed events through the “visible” cross section. Observed events can be used to estimate the integrated luminosity.

For any pair of colliding bunches the luminosity can be related to the beam parameters (ν_{rev} revolution frequency, N_1 and N_2 bunch intensities measured by LHC, f_1 and f_2 beam profiles).

$$n_{\mathrm{events}} = \boxed{\epsilon_{\mathrm{detection}}\sigma} \int \mathcal{L} \quad \Rightarrow \quad \int \mathcal{L} = \frac{n_{\mathrm{events}}}{\boxed{\sigma_{\mathrm{visible}}}} \qquad \mathcal{L} = \nu_{\mathrm{rev}} N_1 N_2 \int f_1(x,y) f_2(x,y) \mathrm{d}x\mathrm{d}y$$

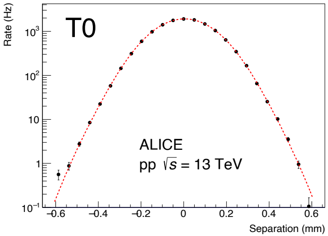
In ALICE the luminosity determination is based on the measurement of $\sigma_{\mathrm{visible}}$ for a set of detectors (luminometers)

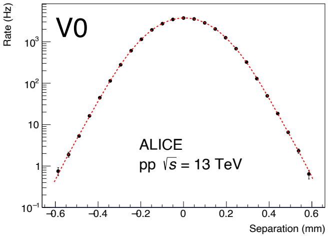
Usually the beam profiles can be factorized and therefore one can write:

$$f_1(x,y) = f_{1x}(x) f_{1y}(y), \quad f_2(x,y) = f_{2x}(x) f_{2y}(y)$$

$$\mathcal{L}_{\mathrm{head-on}} = \nu_{\mathrm{rev}} N_1 N_2 \int f_{1x}(x) f_{2x}(x) \mathrm{d}x \int f_{1y}(y) f_{2y}(y) \mathrm{d}y \qquad \Rightarrow \qquad \boxed{\mathcal{L}_{\mathrm{head-on}} = \frac{\nu_{\mathrm{rev}} N_1 N_2}{\Sigma_x \Sigma_y}}$$

Σ_x and Σ_y can be determined by displacing the beams in horizontal and vertical direction in van der Meer (vdM) scans from the integral of the scan curves divided by the peak rate

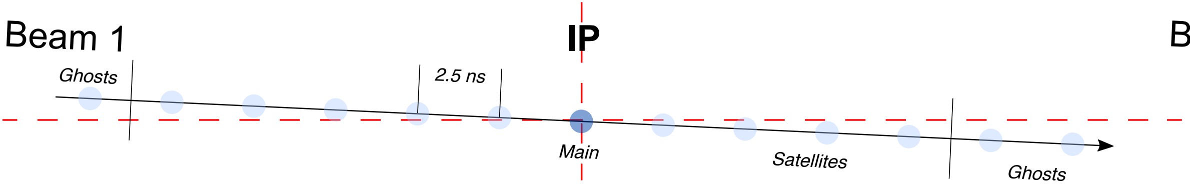




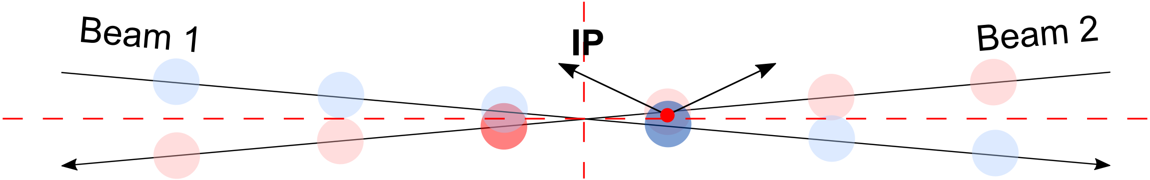
ALICE-PUBLIC-2021-005

- Rates for reference processes (triggers) are recorded separately for each colliding bunch pair
  - counts integrated over ~ 2 s time bins $\Rightarrow$ no dead time
  - vdM fits using full data sample
- Events with the same triggers are acquired to estimate the fraction of background in the trigger rate $\Rightarrow$ with dead time
  - ZDC trigger has large latency $\Rightarrow$ involves large dead time
- Statistically limited sample for background subtraction, especially in Pb-Pb

@zero separation	μ	events/step	fraction recorded
pp V0	~ 0.4	$1.2 \cdot 10^5$	2%
pp T0	~ 0.2	$6.3 \cdot 10^4$	2%
Pb-Pb V0	$\sim 5 \cdot 10^{-4}$	$1.6 \cdot 10^2$	20%
Pb-Pb ZED	$\sim 5 \cdot 10^{-2}$	$1.7 \cdot 10^4$	0.2%



1.25 ns afterwards..

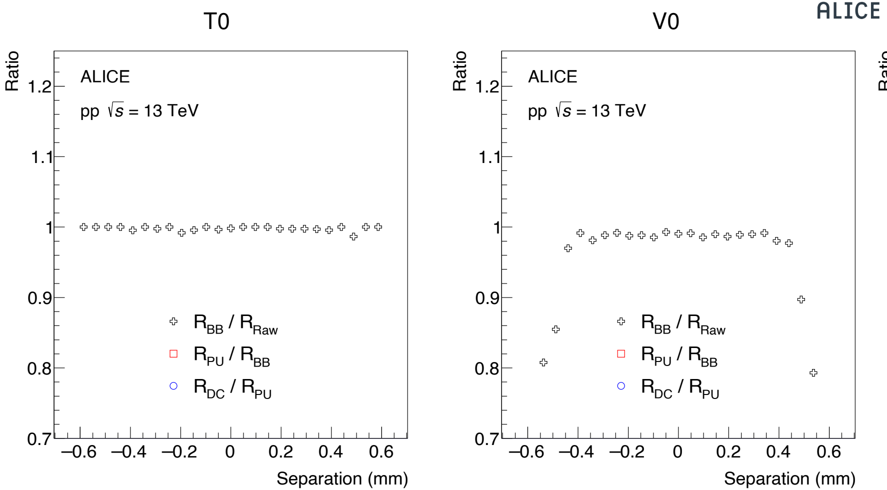


Collisions with satellite bunches have (one or both):

- displaced vertex
- incorrect time

Background subtraction and pile-up in pp

$$\boxed{n_{\text{events}}} = \epsilon_{\text{detection}} \sigma \int \mathcal{L}$$



R_{BB}/R_{Raw} Subtraction of background from beam-gas and satellites using timing information

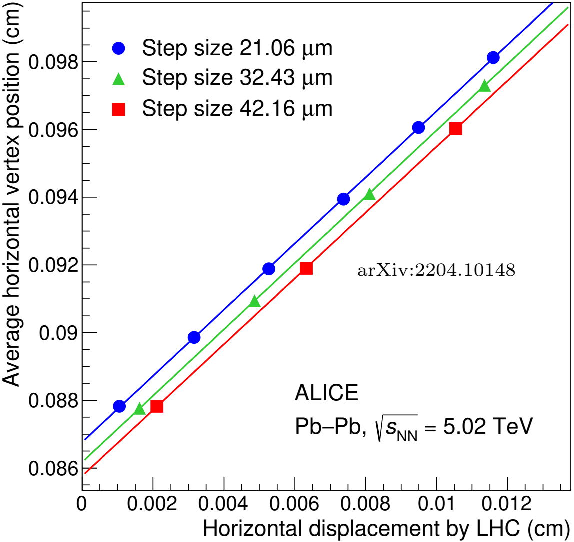
R_{PU}/R_{BB} Pile-up correction

R_{DC}/R_{PU} Correction for bunch intensity decay

$$\mathcal{L} = \nu_{\rm rev} N_1 N_2 \int f_1(x, y) f_2(x, y) \mathrm{d}x\mathrm{d}y$$

Beam positioning is affected by several systematics:

- beam drift during scan
  - take into account measurements by LHC Beam Position Monitors
- beam-beam deflection
  - correction based on deflection model
- scaling factor between expected position and actual beam position: “length scale”
  - calibration in dedicated scans in which beams are displaced in the same direction

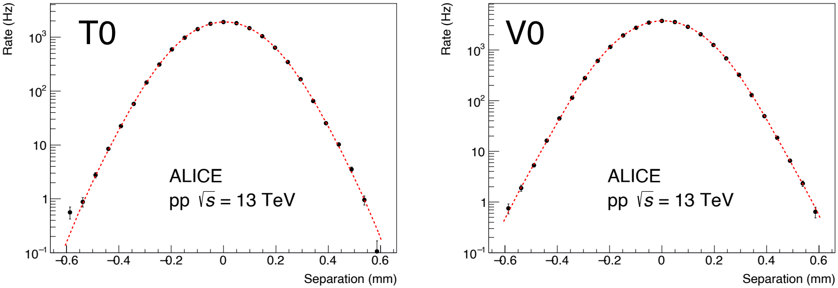


Length scale correction factor is common to all scans and is applied as a final correction on the cross sections

vdM χ^2 fits for pp 2016

$$\boxed{\Sigma_x} = \frac{\int \boxed{R_{\mathrm{vis}}(\Delta x, 0)}\, \mathrm{d}\Delta x}{R_{\mathrm{vis}}(0,0)}$$

$$\boxed{\Sigma_y} = \frac{\int \boxed{R_{\mathrm{vis}}(0, \Delta y)}\, \mathrm{d}\Delta y}{R_{\mathrm{vis}}(0,0)}$$



ALICE-PUBLIC-2021-005

- Fit to corrected event rates (e.g. X scan)
- Fitting function takes into account:
  - possible mismatch between LHC operator setting and actual head-on position: μ_x
  - non Gaussian symmetric tails

$$R(\Delta x, 0) = R(0,0) e^{-\frac{1}{2}\left(\frac{x-\mu_x}{\sigma_x}\right)^2} \left[1 + p_2 \left(\Delta x - \mu_x\right)^2 + p_4 \left(\Delta x - \mu_x\right)^4 + p_6 \left(\Delta x - \mu_x\right)^6\right]$$

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

Likelihood fit for Pb-Pb 2018

Low statistics would introduce a bias in a χ^2 based fit $\Rightarrow$ likelihood fit

For any colliding bunch pair, the fit likelihood is obtained by summing over the scan steps i and considering:

t_i: triggered events n_i: sampled orbits P_i: trigger probability

The trigger probability accounts for Poissonian pile-up

$$\ln \mathcal{L} = \sum_i \left[t_i \ln P_i + (n_i - t_i) \ln (1 - P_i) \right] \qquad P_i = 1 - e^{-\mu_i}$$

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$$\mu_i = \frac{\mu_{\mathrm{vis}}(\Delta x_i, \Delta y_i)}{\nu_{\mathrm{rev}}} + p_{\mathrm{sat},i} + p_{\mathrm{beam1}} N_1 + p_{\mathrm{beam2}} N_2 + p_0$$

$$\mu_i = \frac{\mu_{\mathrm{vis}}(\Delta x_i, \Delta y_i)}{\nu_{\mathrm{rev}}} + p_{\mathrm{sat},i} + p_{\mathrm{beam1}} N_1 + p_{\mathrm{beam2}} N_2 + p_0$$

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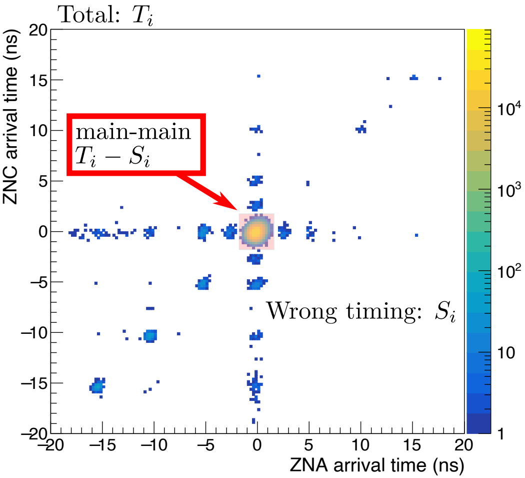
Satellite subtraction and Pb-Pb fits

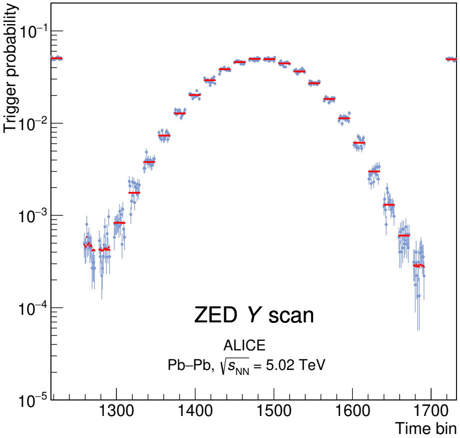
$$\ln \mathcal{L}_i = \boxed{S_i \ln\left(\frac{p_{\mathrm{sat},i}}{P_i}\right) + (T_i - S_i)\ln\left(\frac{P_i - p_{\mathrm{sat},i}}{P_i}\right)} + \boxed{t_i \ln P_i + (n_i - t_i)\ln(1 - P_i)}$$

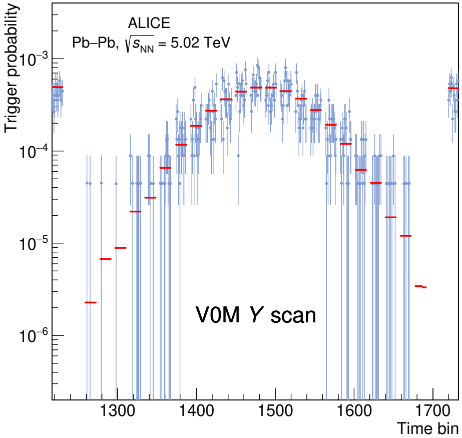


- Satellite information at each step is averaged over all colliding bunches due to small statistics
- Likelihood to estimate conditional satellite probability for each scan step
- Likelihood is modified to estimate satellites for each bunch: discrepancy between fit and data is considered potentially due to satellites

arXiv:2204.10148

$\log \mathcal{L}$ fits for Pb-Pb 2018

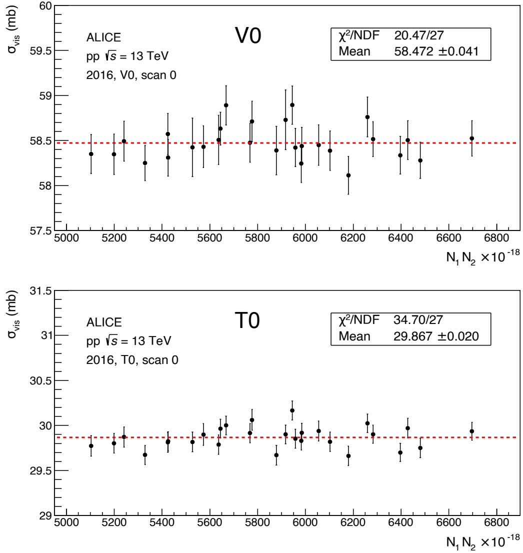




- Good description of the trigger probabilities despite low statistics
- Satellite contribution is dominant in Y scans at large separation
- 7-13 fit parameters to describe tails to reach $\chi^2/ndf \sim 1$

arXiv:2204.10148

Cross section results for pp and Pb-Pb



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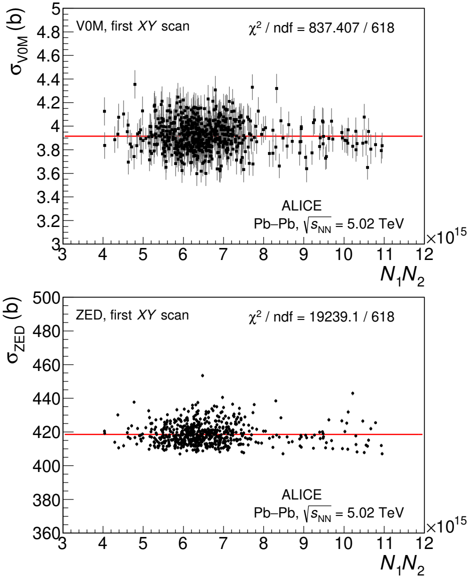


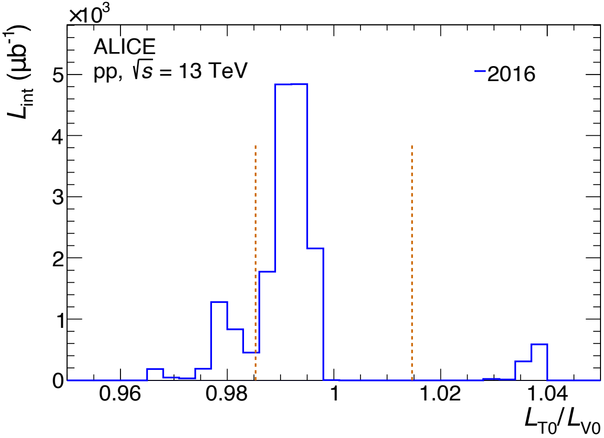
arXiv:2204.10148

No dependence on the product of bunch intensities

Fluctuations beyond statistical uncertainties in Pb-Pb $\Rightarrow$ systematics

$$\int \mathcal{L} = n_{\text{events}}/\sigma_{\text{visible}} = n_{\text{events}}/\left(\boxed{\epsilon_{\text{detection}}}\,\sigma\right)$$

Distribution of the run-by-run ratio of luminosities measured by the two luminometers



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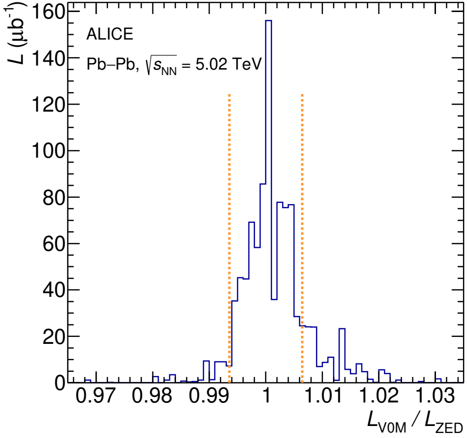

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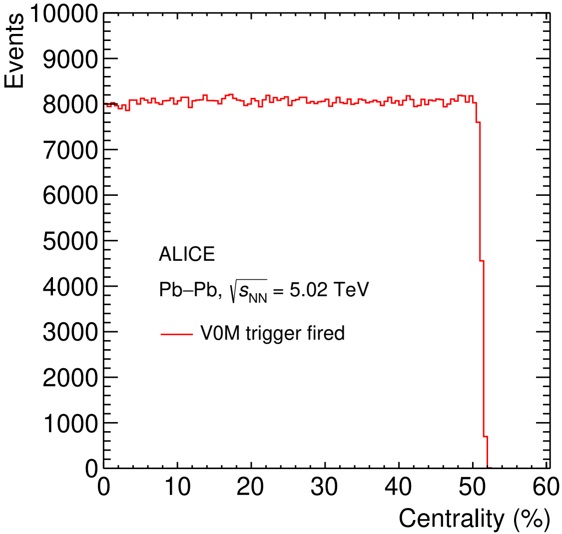
Vertical dashed lines represent the RMS difference from unity of the ratio
Better agreement for Pb-Pb (lower μ, large bunch spacing. . .) than pp

vdM cross section uncertainties

Source \ Uncertainty (%)	2016 pp T0 | V0	2017 pp T0 | V0	2018 pp T0 | V0	2018 Pb-Pb ZED | V0M
Statistical	0.05 | 0.05	0.07 | 0.07	0.05 | 0.05	0.04 | 0.09
$\Sigma_x \Sigma_y$ consistency (V0M vs T0/ZED)	0.1	0.4	0.4	0.13
Length-scale calibration	0.2	0.3	0.3	1
Non-factorisation	0.5	0.2	0.4	1.1
Bunch-to-bunch consistency	<0.1 | <0.1	0.1 | 0.1	0.1 | 0.1	0.4 | 0.1
Scan-to-scan consistency	0.2 | 0.1	0.1 | 0.1	0.5 | 0.5	1
Background subtraction	0.1 | 0.6	0.1 | 0.8	0.1 | 0.7	0.8 | 0.5
Bunch intensity	0.5	0.6	0.4	0.8
Luminosity decay	0.5	0.5	0.3	n.d.
Magnetic non-linearities	0.1	0.2	0.2	0.2
Orbit drift	0.1	0.1	0.2	0.15
Beam–beam deflection and distortion	0.3	0.3	0.3	0.1
Fitting scheme	0.2	0.6	0.4	0.4
Pile-up	0.1 | < 0.1	0.5	0.2 | < 0.1	n.d.
Stability and consistency	1.5	2.3	1.6	0.7
Total of luminosities	1.8 | 1.9	2.6 | 2.7	2.9 | 2.1	2.3 | 2.2

Pb-Pb hadronic cross section



Centrality distribution of events triggered by V0

arXiv:2204.10148

- Centrality distribution of vdM V0 trigger is uniform in 0-50% centrality
- Systematic uncertainties on trigger efficiency $\epsilon_{\rm had}$
  - $\pm 1.4\%$ by varying the centrality at the 90% "anchor point"
  - $\pm 1.8\%$ by comparing Glauber fit with T$_{\rm R}$ENTo
- $\sigma_{\rm V0M}$ uncertainty $\pm 2.1\%$

$$\boxed{\sigma_{\rm had} = \frac{\sigma_{\rm V0M}}{\epsilon_{\rm had}} = 7.67 \pm 0.24 \ \ {\rm b}}$$

Glauber model estimation $\sigma_{\rm had} = 7.62 \pm 0.15 \ \ {\rm b}$ (arXiv:2011.14909) is in agreement with ALICE measurement

Summary

- Three luminometers were calibrated in vdM scans
  - T0 and V0 for pp 2015, 2016, 2018 $\sqrt{s} = 13$ TeV
  - V0 and ZDC for Pb-Pb 2015 and 2018 $\sqrt{s_{\rm NN}} = 5.02$ TeV
  - uncertainty on the integrated luminosity measurement $\sim 2\%$
- Likelihood technique to address low statistics in Pb-Pb data sample
- Introduction of beam-related effects in the fit
- Measured hadronic cross section for Pb-Pb $\sqrt{s_{\rm NN}} = 5.02$ TeV
  - $\sigma_{\rm had} = 7.67 \pm 0.24 \;\; \mathrm{b}$
  - Glauber model estimation is compatible with ALICE result

For further information:

- pp 5 TeV 2015 - ALICE-PUBLIC-2016-005
- p-Pb 8.16 TeV 2016 - ALICE-PUBLIC-2018-002
- pp 13 TeV 2016-2018 - ALICE-PUBLIC-2021-005
- PbPb 5.02 TeV 2015/2018 - arXiv:2204.10148