Luminosity and inelastic cross section determination for hadronic collisions with ALICE at the LHC

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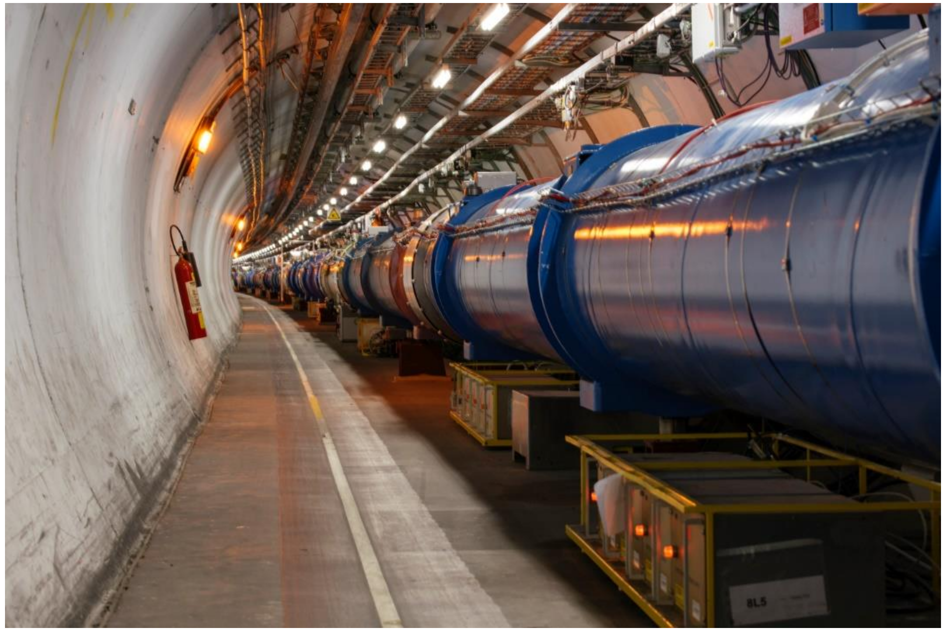
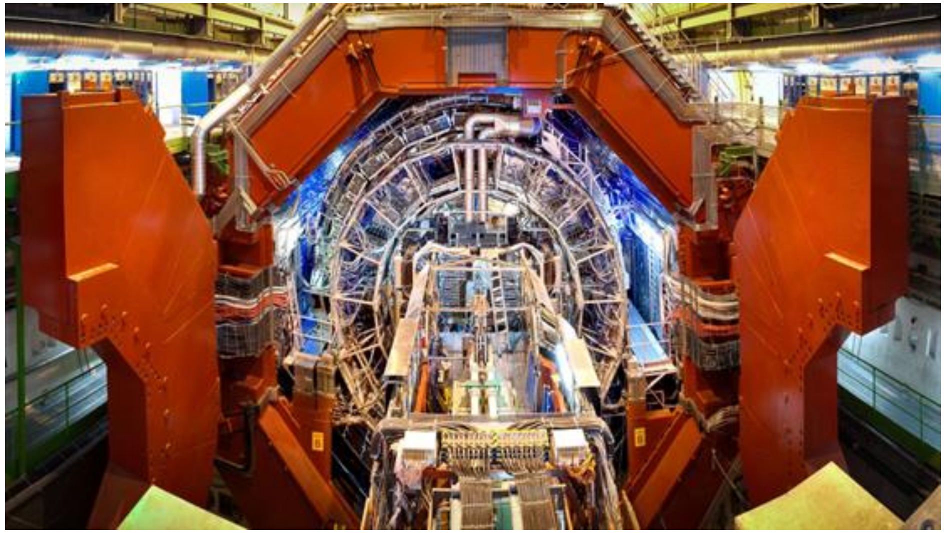
On behalf of the ALICE collaboration

Outline

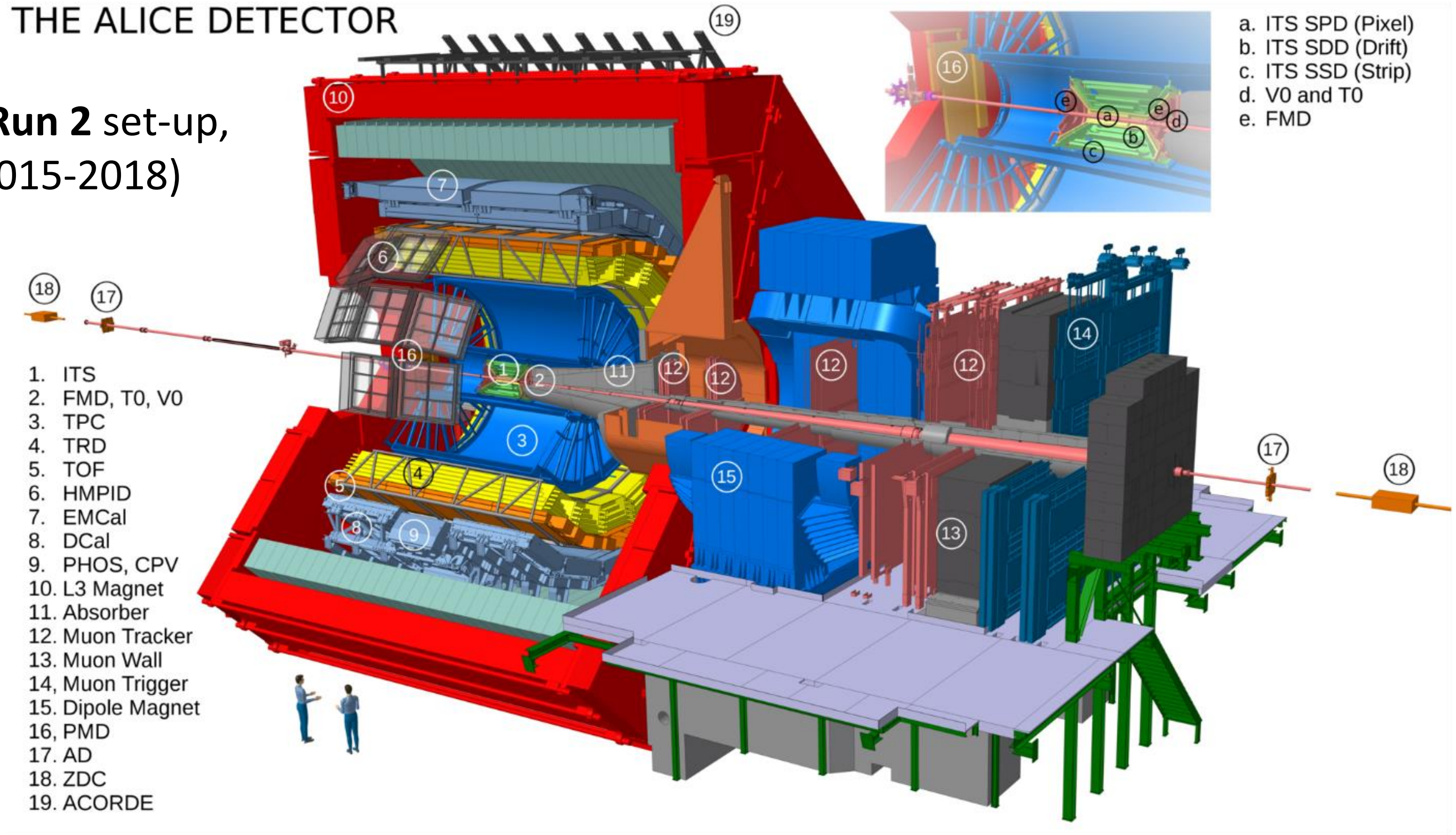
- Cross section measurements in ALICE
- Basics of luminosity and the van der Meer scan
- Luminosity determination and results
  for pp, p-Pb and Pb-Pb collisions at the LHC Run 2
- Measurement of the hadronic inelastic cross section
  for Pb-Pb collisions
- Conclusions

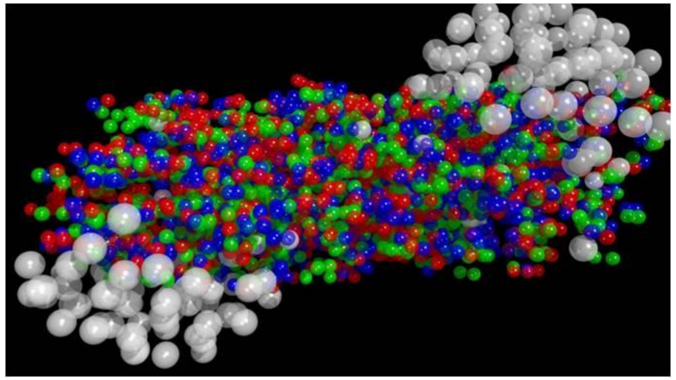


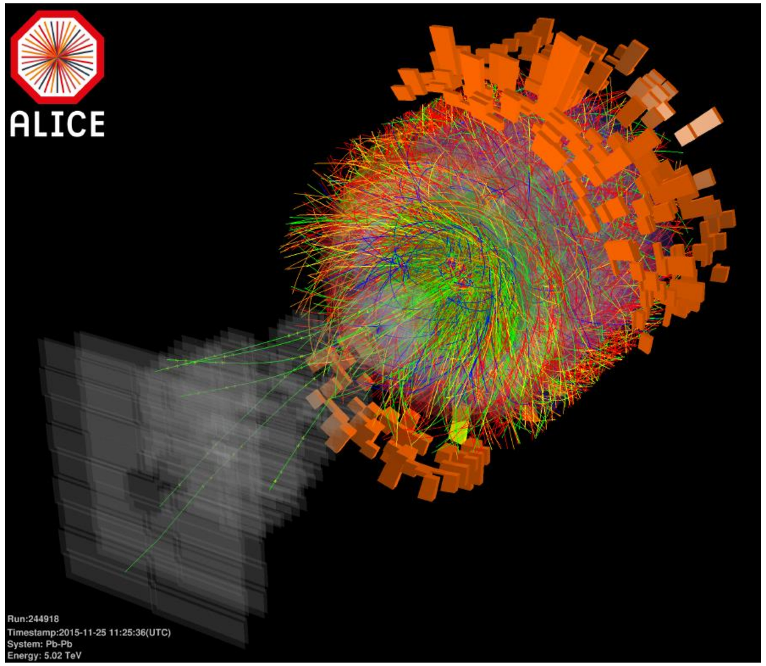


The ALICE experiment

(**Run 2** set-up, 2015-2018)







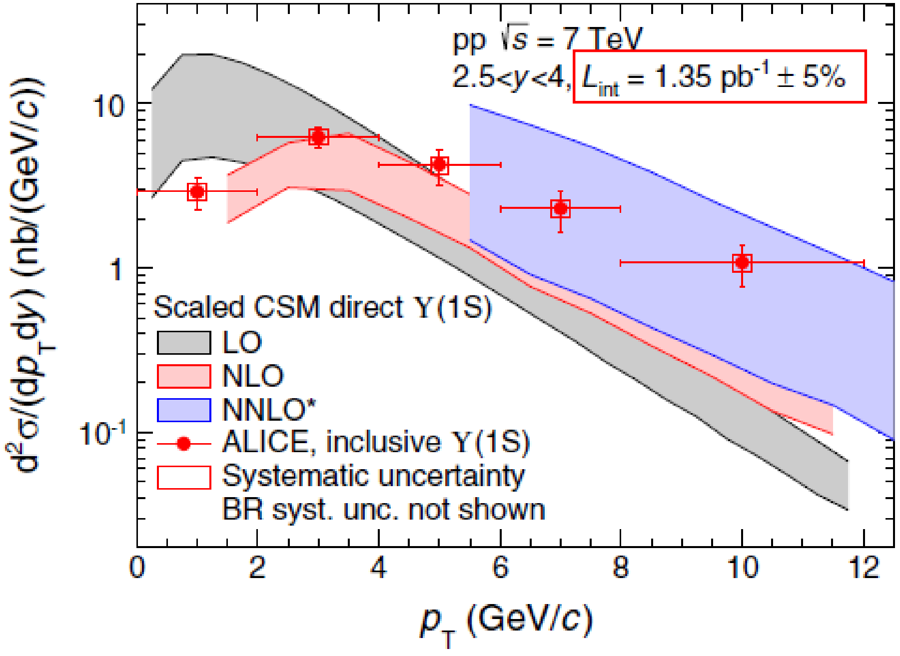
- Study the **hot and dense medium** formed in **Pb-Pb collisions** at the LHC
- Study **pp and p-Pb collisions**, both as a **reference** for Pb-Pb and to gather insights on **QCD** mechanisms

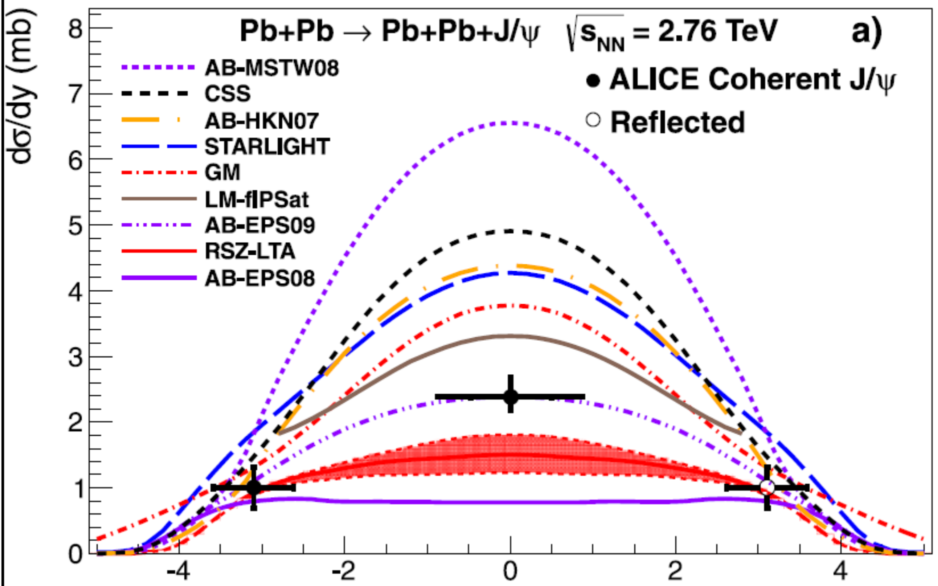
Luminosity: why does it matter?

Cross-section measurements are essential to the ALICE physics program:

- Production of **hard probes of the QCD medium** such as quarkonia, jets, heavy-flavour, direct photons..
- **Electromagnetic processes** in p-Pb and Pb-Pb collisions (e.g. vector meson photoproduction, EM dissociation..)

Eur. Phys. J. C 74 (2014) 2974





Eur. Phys. J. C 73 (2013) 2617

Source	Uncertainty for coh. J/ψ
Luminosity	$^{+5\%}_{-3\%}$
Trigger dead time	$\pm 2.5\%$
Signal extraction	$^{+7\%}_{-6\%}$ $\left(^{+6\%}_{-5\%}\right)$
Trigger efficiency	$^{+3.8\%}_{-9.0\%}$
$(Acc \times \varepsilon)$	$\pm 2.5\%$ $(\pm 1\%)$
$\gamma\gamma \to e^+e^-$ background	$^{+4\%}_{-0\%}$
e/μ separation	$\pm 2\%$
Branching ratio	$\pm 1\%$
Neutron number cut	$^{+2.5\%}_{-0\%}$
Hadronic J/ψ	-
Total	$^{+14.0\%}_{-9.6\%}$ $\left(^{+13.4\%}_{-8.8\%}\right)$

Luminosity uncertainty for LHC **Run 1**: **3-5%** depending on data sets

- Non negligible
- **Limit for precision measurements** (e.g. total inelastic cross section)

Luminosity: the basics

For **cross-section measurements,**

$\sigma = N / \mathscr{L}_{int}$

N = efficiency-corrected yield for a given physics process

$\mathscr{L}_{int} = \int \mathscr{L}(t)dt$ = integrated luminosity

For two counter-rotating bunches at a collider:

$$\mathscr{L} = \nu_{rev} N_1 N_2 \iint \rho_1(x,y)\rho_2(x,y)dxdy$$

Factorisation assumption: $\rho(x,y) = \rho(x)\rho(y)$ → $\mathscr{L} = \frac{\nu_{rev} N_1 N_2}{\Sigma_x \Sigma_y}$

$$1/\Sigma_x = \int \rho_{1x}(x)\rho_{2x}(x)dx$$

$$1/\Sigma_y = \int \rho_{1y}(y)\rho_{2y}(y)dy$$

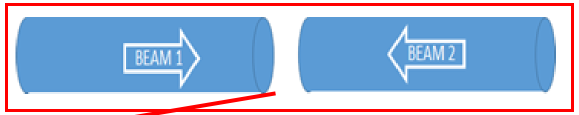
Σ_x , Σ_y : **effective widths** of the beam overlap region

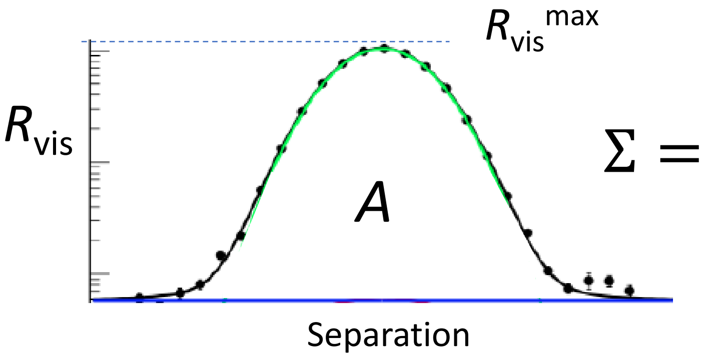
- can be calculated from machine parameters, with poor precision (> 10%)
- can be measured directly in dedicated sessions
  - beam-gas imaging (LHCb)
  - **van der Meer (vdM) scan** (all large LHC experiments)

Bunch intensities $N_1 N_2$: measured by LHC instrumentation

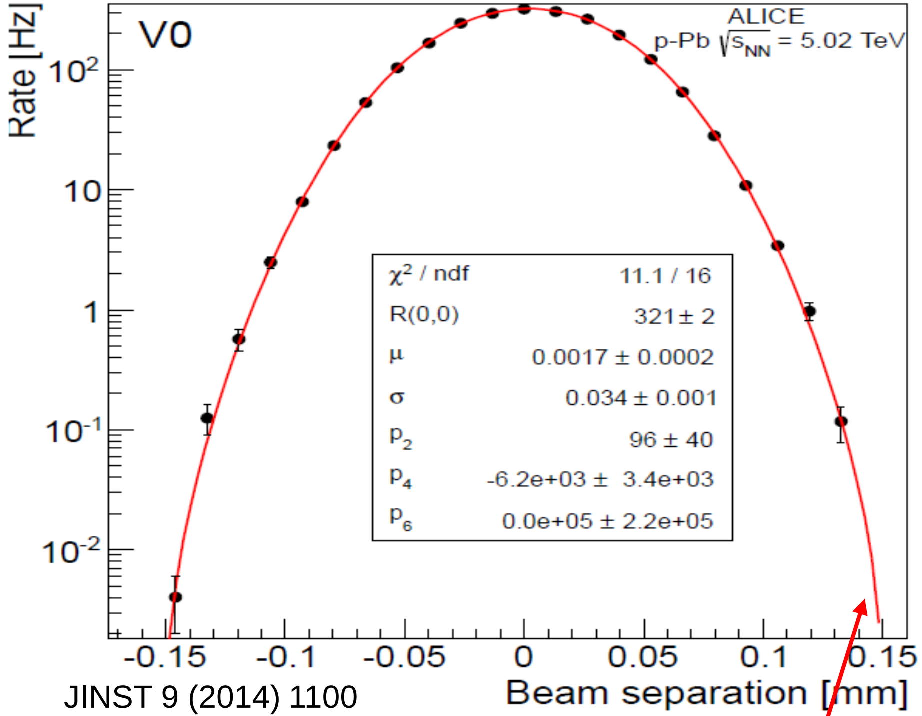
The vdM scan method

- Choose a suitable **«visible»** reference **process**
- **Measure** its rate $\boldsymbol{R_{vis}}$ **vs beam separation** in a dedicated scan





$$\Sigma = \frac{A}{R_{vis}^{max}} \qquad \mathscr{L} = \frac{\nu_{rev} N_1 N_2}{\Sigma_x \Sigma_y}$$



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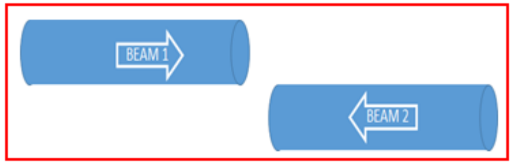
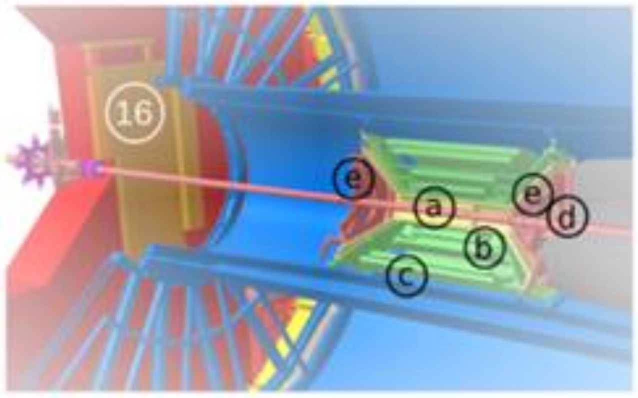


- $\boldsymbol{R_{vis}}$ **is corrected** for both detector- and beam-related effects:
  - noise + afterglow
  - separation-dependent acceptance
  - beam-gas and beam-satellite collisions
- Both R_{vis} and the separation need to be corrected for beam-beam effects (mutual EM interaction between beams) and beam drifts

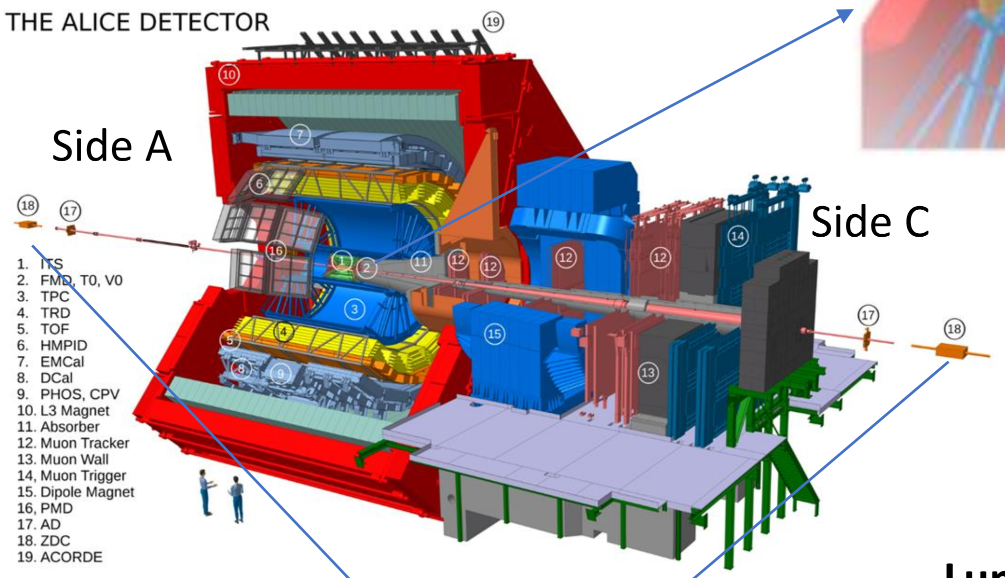
vdM scan output: $\sigma_{vis} = \frac{R_{vis}^{max,vdM}}{\mathscr{L}_{vdM}}$ → used for indirect measurement of luminosity during physics data taking → $\mathscr{L} = \frac{R_{vis}}{\sigma_{vis}}$

ALICE luminometers (Run 2)



a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

Provide vertexing for vdM scan analysis (a–c)



ZN

V0 detector: two **scintillator** arrays (V0A, V0C)

T0 detector: two **Cherenkov counter** arrays (T0A, T0C)

ZN detector: two **Cherenkov calorimeters** for neutrons (ZNA, ZNC)

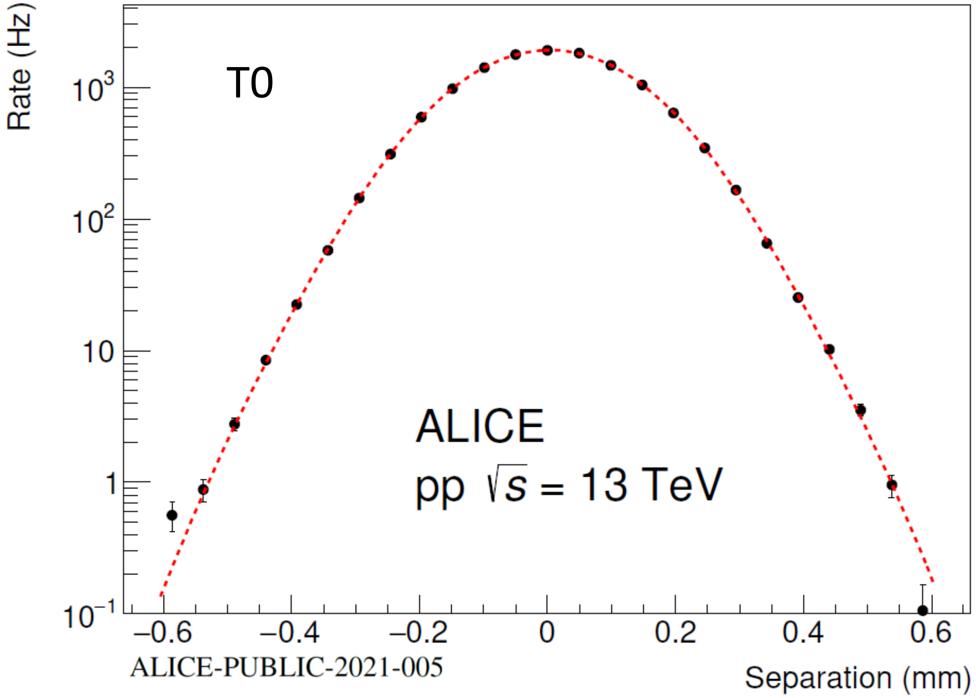
Luminosity signals:
V0A & V0C (pp, p-Pb)
T0A & T0C + timing (pp, p-Pb)
V0M = total amplitude trigger (Pb-Pb)
→ Signal from hadronic collisions

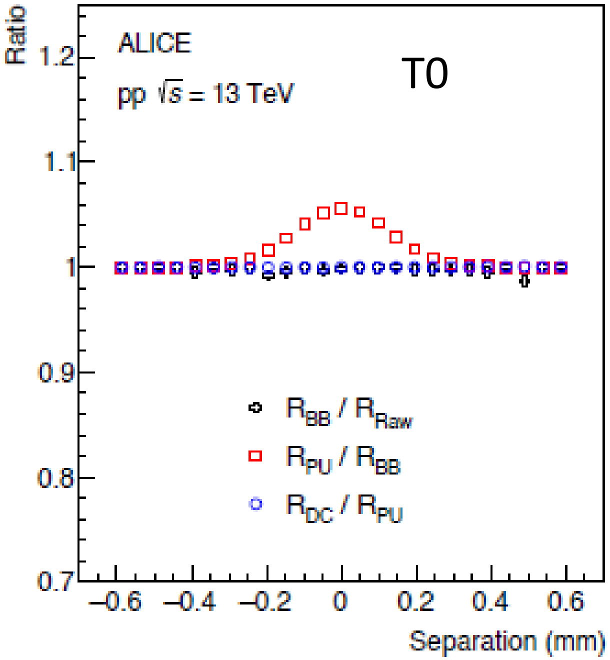
ZED = ZNA | ZNC (Pb-Pb) → Signal mainly from EM dissociation

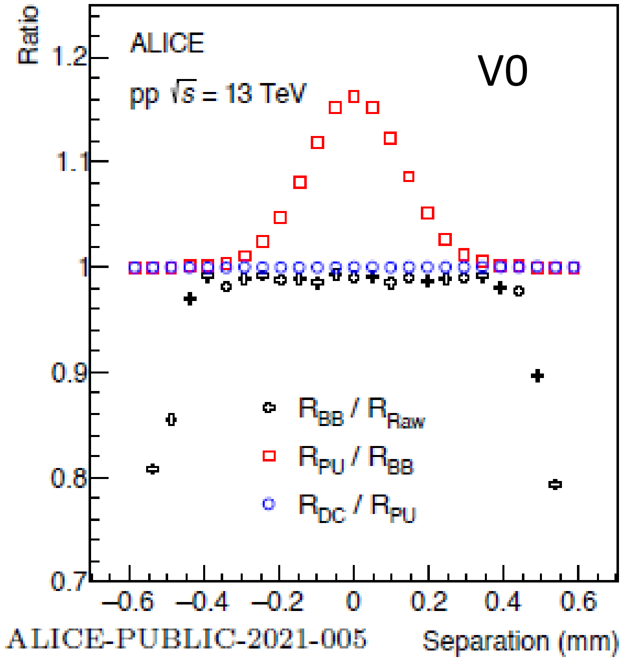
pp/p-Pb vdM scans: corrections & fit

pp and p-Pb scans:
χ^2-based fit to trigger rate vs separation, for each bunch pair, after correction for:

- beam-induced background (use timing)
- Poissonian pile-up
- beam intensity decay







Curves are fitted with a **Gaussian x polynom. function** to extract head-on rate and width

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

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

$\Sigma_{x,y}$ measured by T0 and V0 typically agree to the per-mil level

Fit strategy for Pb-Pb vdM scans

Pb-Pb scans:

- **χ^2-based fit not reliable** due to low number of counts in the tails

- For each bunch pair: binomial likelihood fit to the number of trigger counts (t_i) in n_i sampled orbits in time bin i

- **μ_i = average number of triggers per bunch crossing** in time bin i, includes all known effects
  - luminosity dependence on intensity (N_1N_2) and beam separation (Δx_i, Δy_i)
  - contamination from
    beam-gas collisions
    satellite collisions (next slide)
    noise
  - σ_{vis} extracted as a fit parameter

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

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

$$\mu_{\text{vis}}(\Delta x_i, \Delta y_i) = \nu_{\text{rev}} N_1 N_2 \frac{\sigma_{\text{vis}}}{\Sigma_x \Sigma_y} f(\Delta x_i) g(\Delta y_i)$$

Luminosity dependence on separation modeled by the $f(\Delta x_i)$ and $g(\Delta y_i)$ functions:

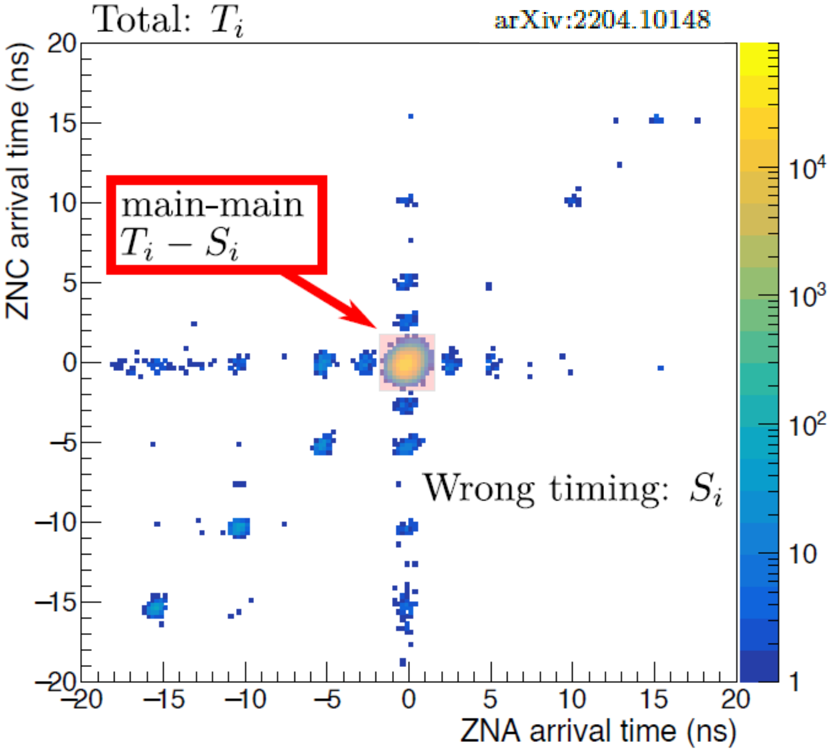
- Gaussian core

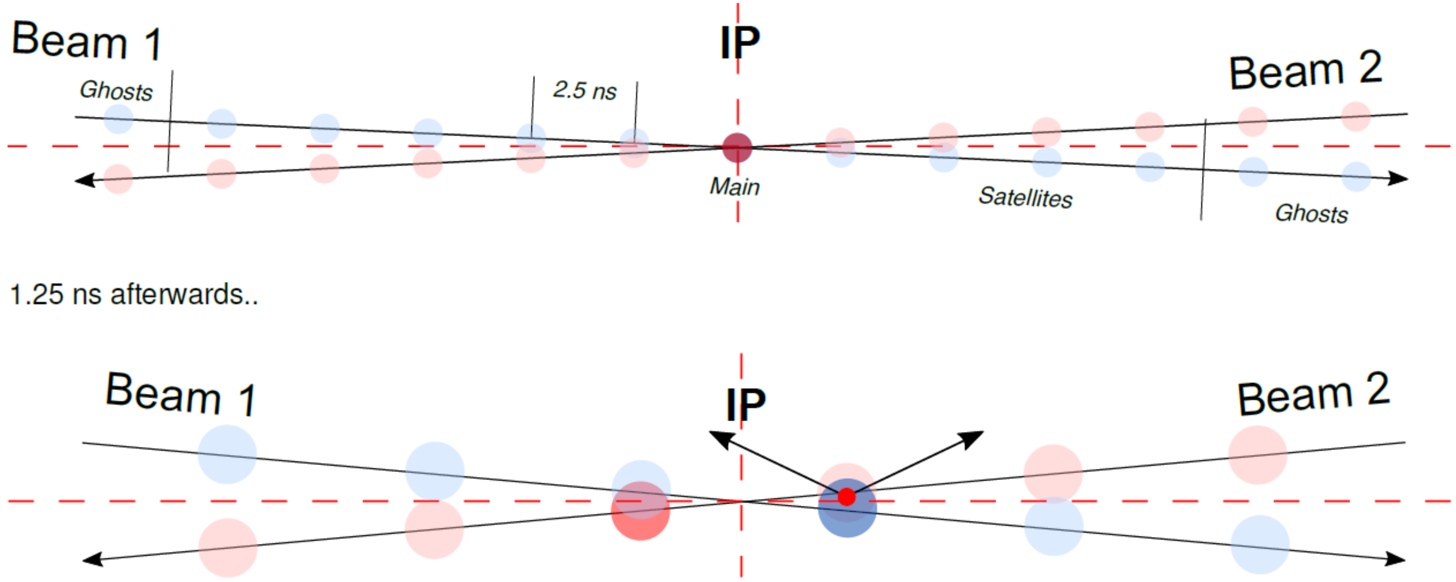
- variable number of (symmetric) free parameters to describe the tails

Treatment of satellite collisions for Pb-Pb scans

Satellites: charge circulating in non-nominal RF buckets, close in time and space to the main bunch
-> ~**6% of total charge** in the 2018 vdM scan

They collide at (sat.-sat.) or near (main-sat.) the nominal interaction point
-> can trigger the luminosity signal





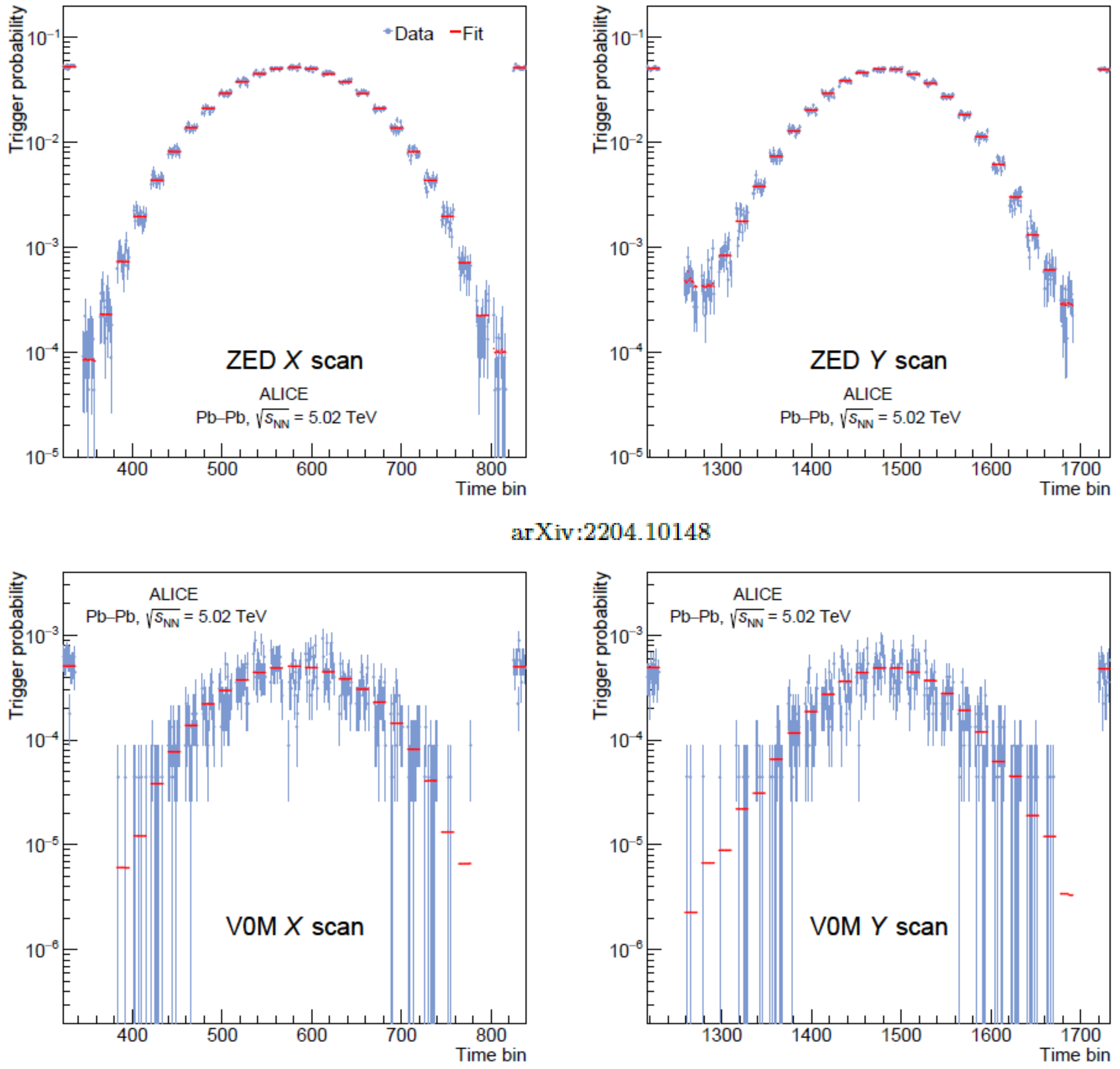
Satellite collisions nicely tagged by ZN timing capabilities

However, method statistically limited -> only bunch-pair-integrated S_i

-> use measurement as input to a **combined likelihood**, whose other input is the likelihood of the current trigger probability given the current parameters

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

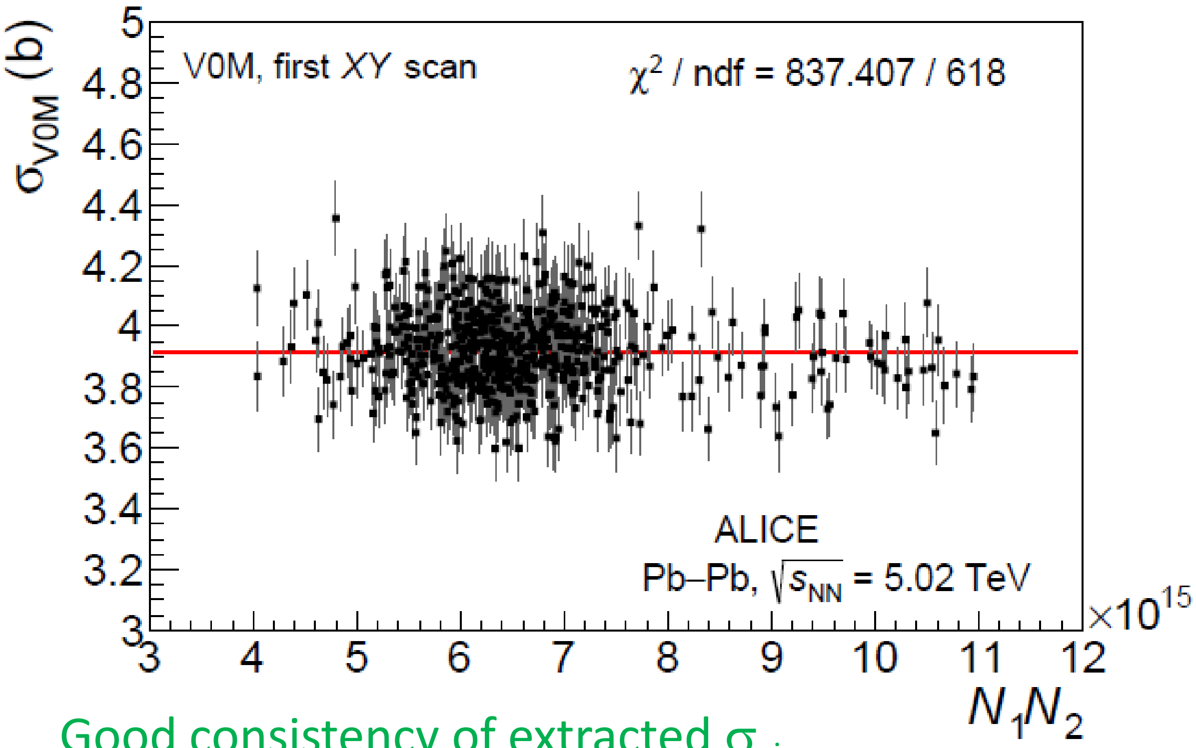
Likelihood fits for the Pb-Pb vdM scans



Good description of the trigger probabilities despite low statistics

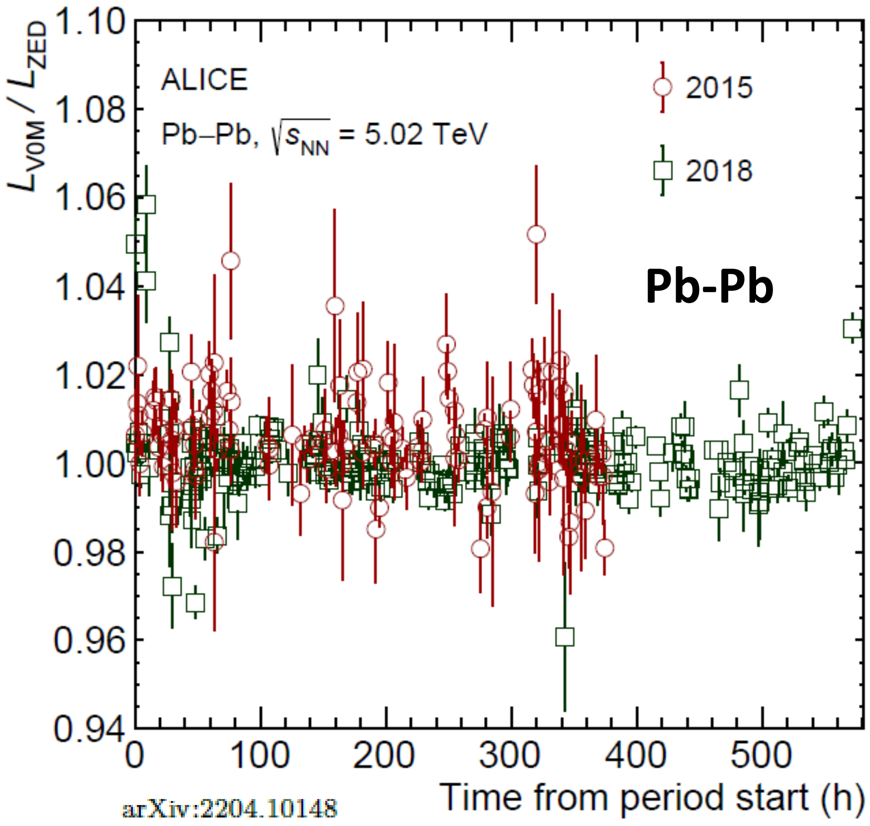
7-13 tail parameters needed to achieve $\chi^2/ndf \sim 1$

$\Sigma_{x,y}$ measured by V0 and ZN agree to the per-mil level



Good consistency of extracted σ_{vis} across bunch pairs (~0.1%)

Stability and consistency of the luminosity calibration

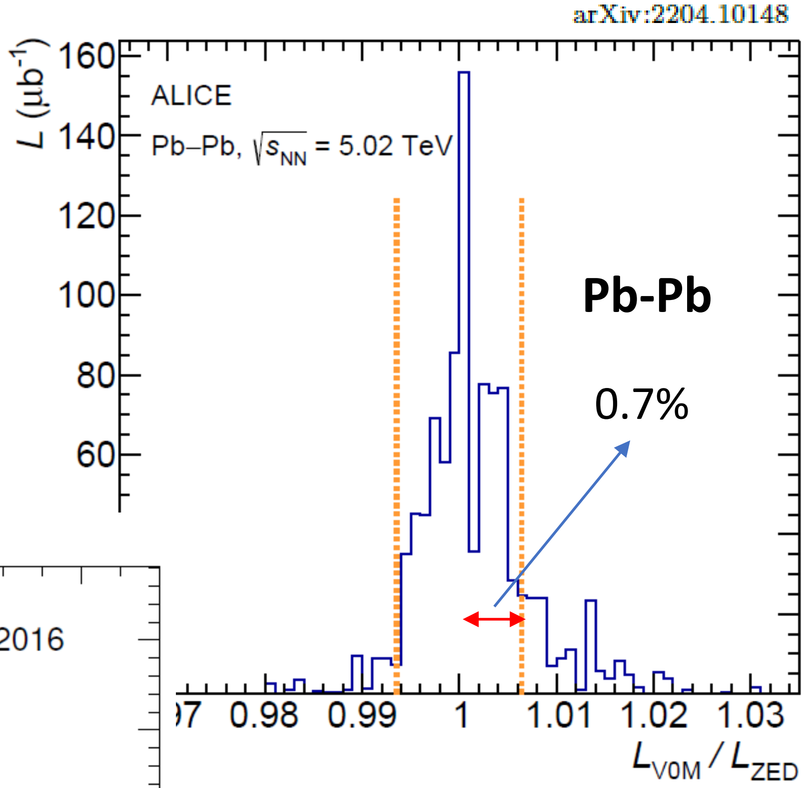


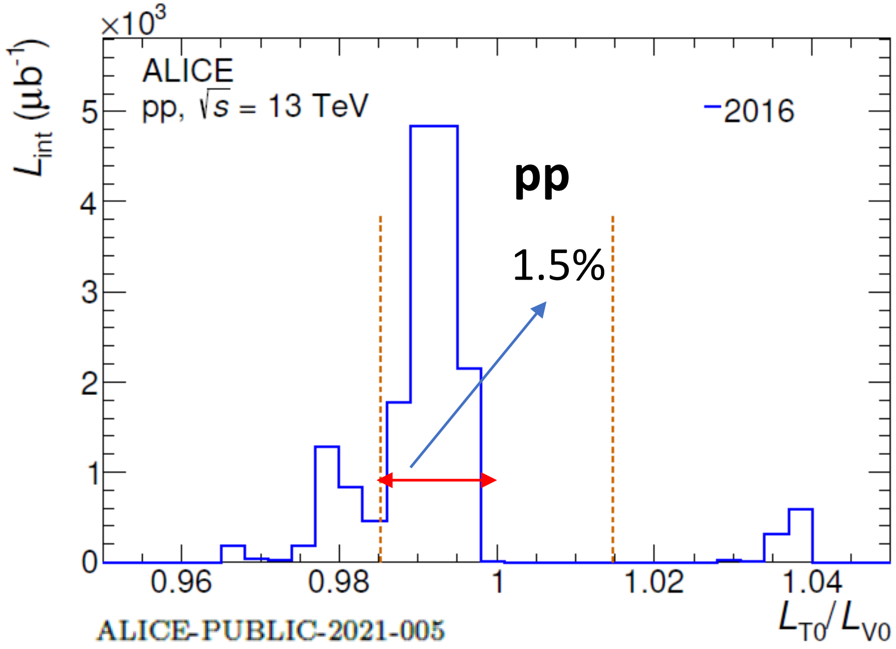
$$\mathscr{L} = \frac{R_{vis}}{\sigma_{vis}}$$

R_{vis} → from physics runs

σ_{vis} → from vdM scan

Stability assessed by **comparing two luminometers**





Uncertainty:
the RMS difference from unity of the distribution of the luminosity ratio

Pb-Pb typically better than pp

(shorter data-taking period, smaller pile-up, less dense filling scheme..)

Luminosity results: pp collisions

Uncertainty ($\sqrt{s}$ = 13 TeV)	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

Source ($\sqrt{s}$ = 5 TeV (2017))	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)

ALICE-PUBLIC-2018-014

Uncertainties mostly uncorrelated across years -> **unc. for combined 13 TeV sample ~1.6%**

Luminosity results: p-Pb and Pb-Pb collisions

p–Pb $\sqrt{s_{NN}}$ = 8.16 TeV (2016)

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)	

ALICE-PUBLIC-2018-002

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

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

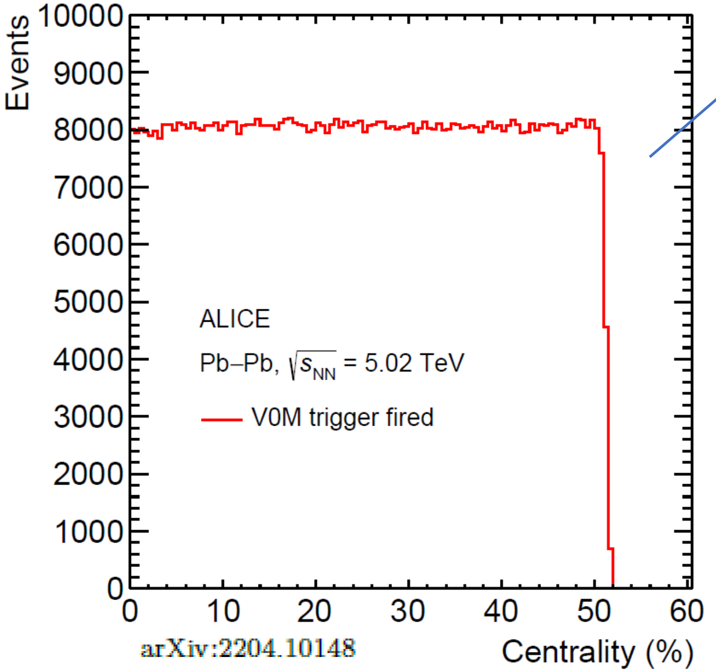
arXiv:2204.10148

Measurement of the hadronic Pb-Pb cross section (I)

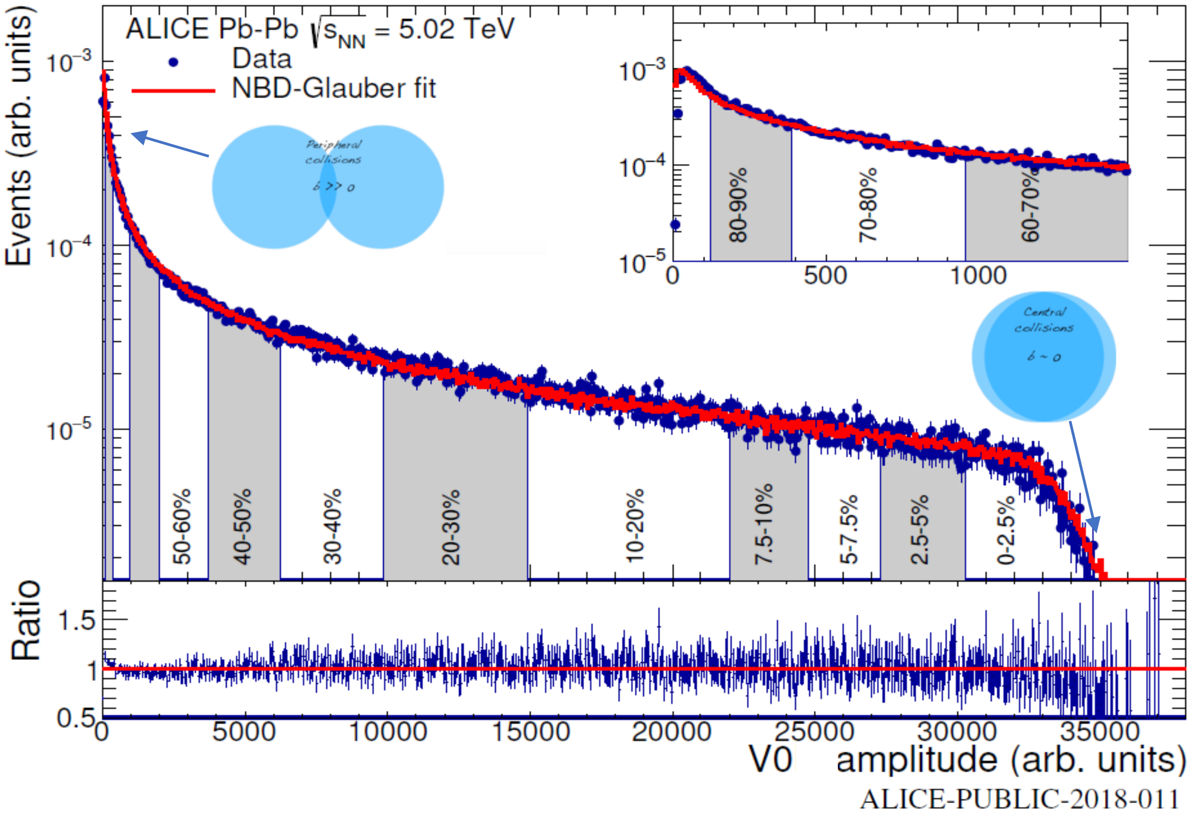
The **V0M visible cross section** is corrected for its **efficiency ε_{had}**, determined via the **centrality distribution of V0M events**

Centrality is:

- expressed in **percentiles of the total cross section**
- **determined via the total amplitude of V0 signal**
  →distribution fitted with geometrical (Glauber) + ancestor model to **get rid of EM contamination in the most peripheral events**



Centrality distribution of V0M-triggered events



The integral of the distribution, properly normalised, gives the **V0M efficiency for hadronic collisions**:

$$\varepsilon_{had} = 0.513 \pm 0.012$$

Uncertainty = 2.3% from variation of Glauber fit range and exploring different fit models

Measurement of the hadronic Pb-Pb cross section (II)

Hadronic Pb-Pb cross section at $\sqrt{s_{NN}}$ = 5.02 TeV:

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

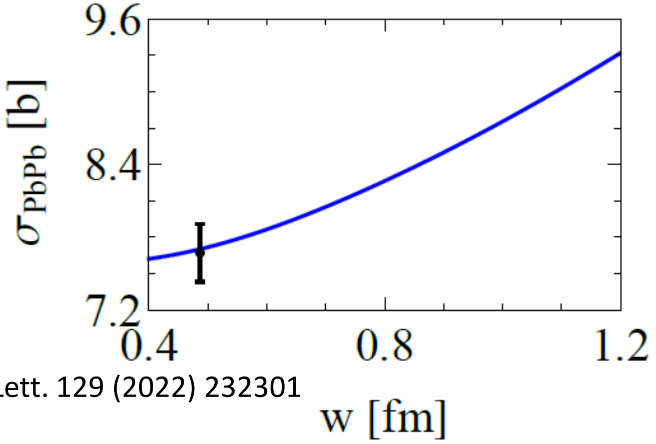
Prediction from the **Glauber model***: 7.62 ± 0.15 b
→**good agreement** with our result

* *Ann. Rev. Nucl. Part. Sci.* 71 (2021) 315–44

Important input for models, e.g. *Trajectum*

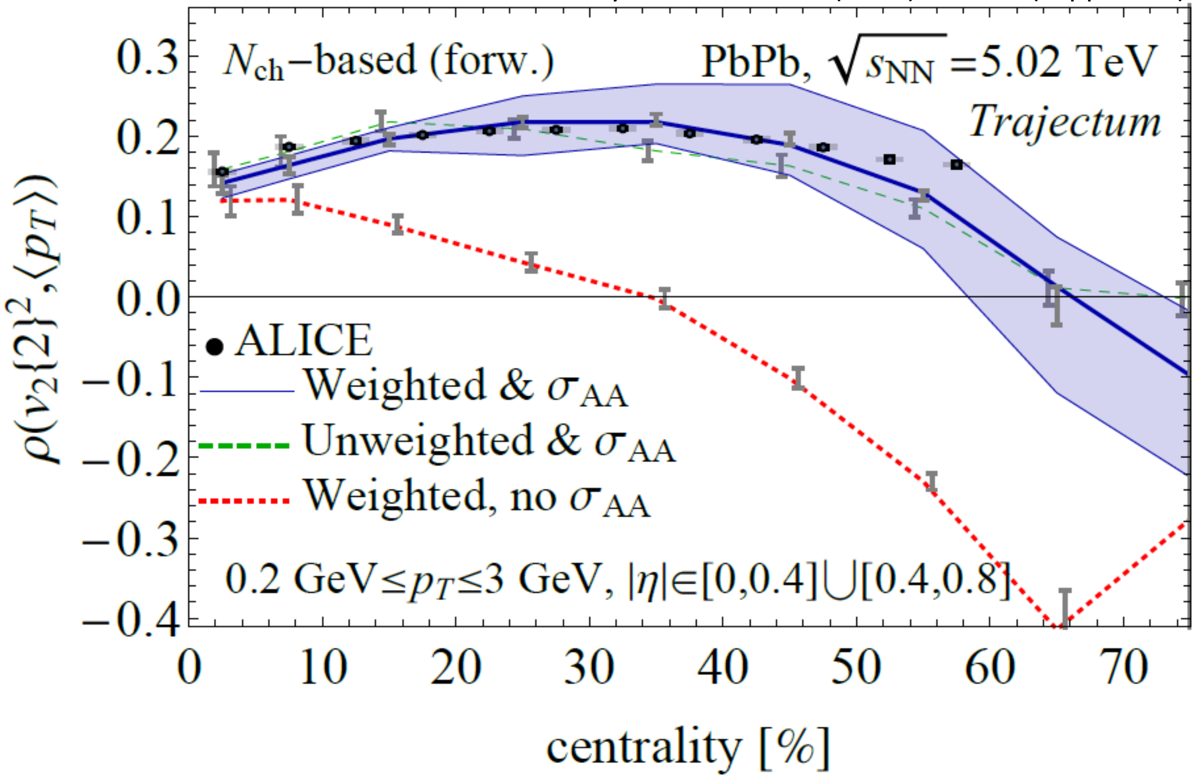
- couple **initial geometry of the collision** with the hydrodynamic evolution of the deconfined QCD medium
- fit parameters to particle distribution and correlation data

Measurement of σ_{had} provides a strong constraint on the nucleon width parameter and improves description of correlation data



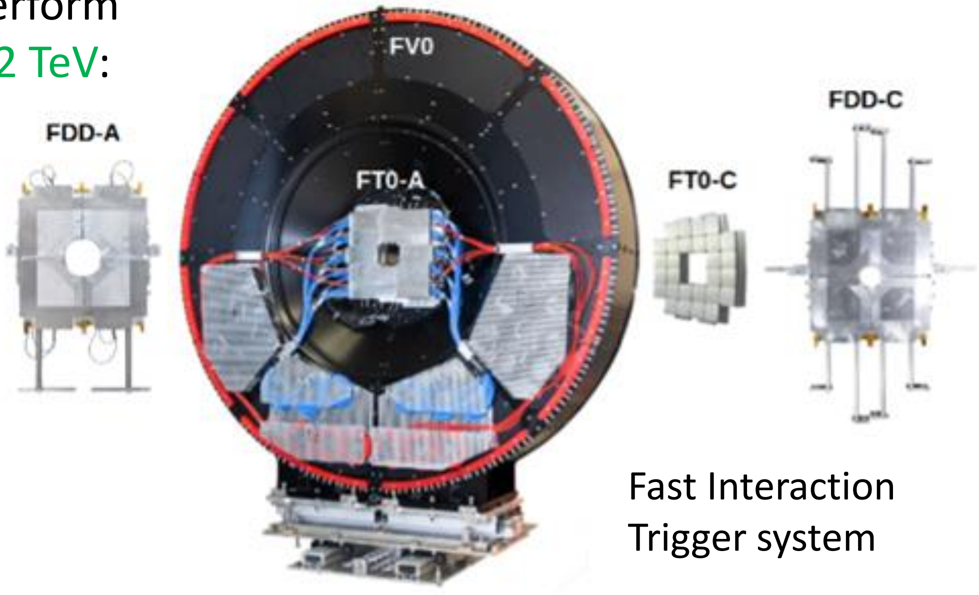
Phys. Rev. Lett. 129 (2022) 232301

Phys. Rev. Lett. 129 (2022) 232301 (supp. mat.)



Conclusions

- Precise **luminosity determination is crucial** to the ALICE physics program
- Although based on a very **simple principle**, vdM scan -based luminosity calibration requires a detailed data-taking and analysis procedure to have good control of **several subtle effects**
- The precision of the ALICE luminosity measurements has improved from 3-5% in Run 1 to 2-3% in Run 2
- Uncertainty mainly **driven by long-term stability for pp**, and by a **mix of effects for p-Pb and Pb-Pb**
- Precise luminosity measurement in Pb-Pb collisions allowed ALICE to perform a significant measurement of the hadronic inelastic cross section at 5.02 TeV:
  $\boldsymbol{\sigma_{had} = 7.67 \pm 0.25}$ **b**
  → important input for models
- **LHC Run 3**: increased interaction rates (factor ~2 for pp, factor ~10 for Pb-Pb) pose new challenges for luminosity determination
  → new luminometers (Fast Interaction Trigger project)
  → upgraded ZN read-out



Fast Interaction Trigger system

References for ALICE luminosity measurements

Run 1:

Eur. Phys. J. C 73 (2013) 2456 (pp 2.76 TeV 2011, pp 7 TeV 2010)
Int. J. Mod. Phys. A 29 (2014) 1430044 (pp 2.76 TeV 2011, pp 7 TeV 2010, Pb-Pb 2.76 TeV 2010-11)
*JINST **9** (2014) P11003* (p-Pb 5.02 TeV 2013)
ALICE-PUBLIC-2017-002 (pp 8 TeV 2012)

Run 2:

ALICE-PUBLIC-2016-002 (pp 13 TeV 2015)
ALICE-PUBLIC-2021-005 (pp 13 TeV 2016-17-18)
ALICE-PUBLIC-2016-005 (pp 5 TeV 2015)
ALICE-PUBLIC-2018-014 (pp 5 TeV 2017)
ALICE-PUBLIC-2018-002 (p-Pb 8.16 TeV 2016)
arXiv:2204.10148, accepted by *JINST* (Pb-Pb 5.02 TeV 2015-18)

Back-up

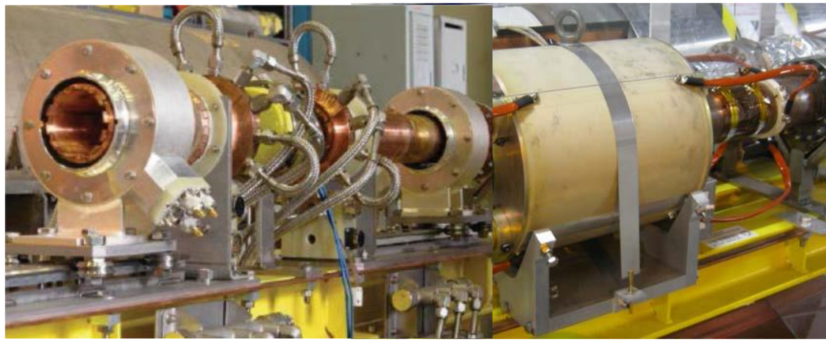
Bunch-intensity measurement

$$\mathscr{L} = \frac{f_{rev} N_1 N_2}{2\pi \Sigma_x \Sigma_y}$$

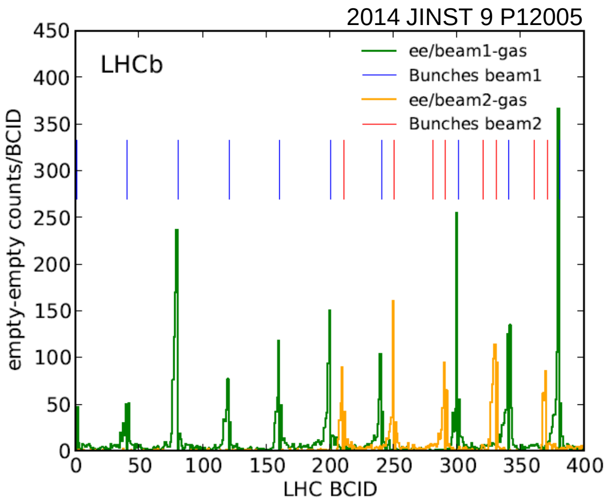
- LHC **current transformers**:
  - **DCCT** for the total beam intensity
  - **fastBCT** for relative bunch populations

- Correction for
  ghost and satellite charge:

DCCT fBCT

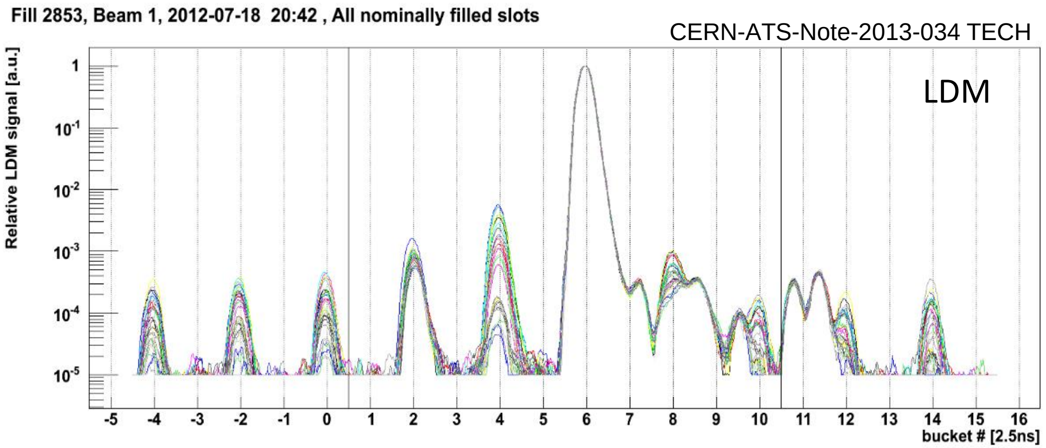


LHCb (as a by-product of beam-gas imaging)



Ghost charge-induced counts vs LHC bunch slot

LHC Longitudinal Density Monitor (LDM)



Satellite charge-induced counts vs LHC RF bucket
(1 bunch slot = 10 RF buckets)

Bunch intensity was **initially dominating the luminosity uncertainty** ⟶ **great effort** in calibrating and understanding these devices → per-mil level uncertainties

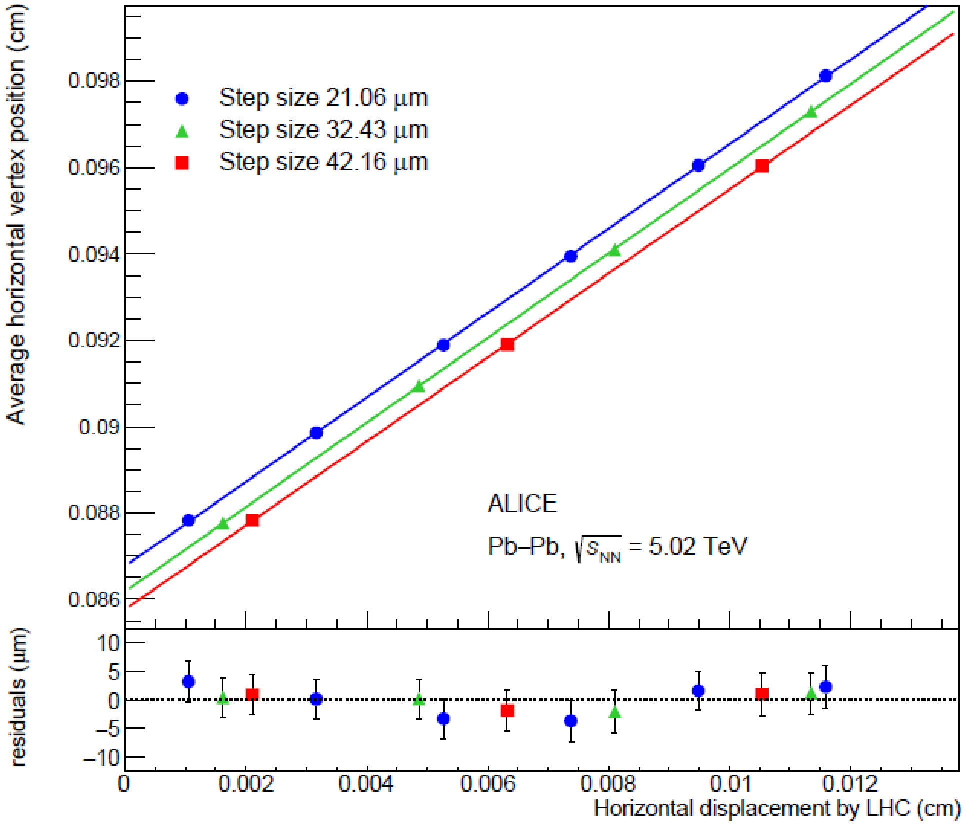
Length-scale calibration and non-factorisation corrections

Length-scale calibration:

How many μm is a LHC μm?

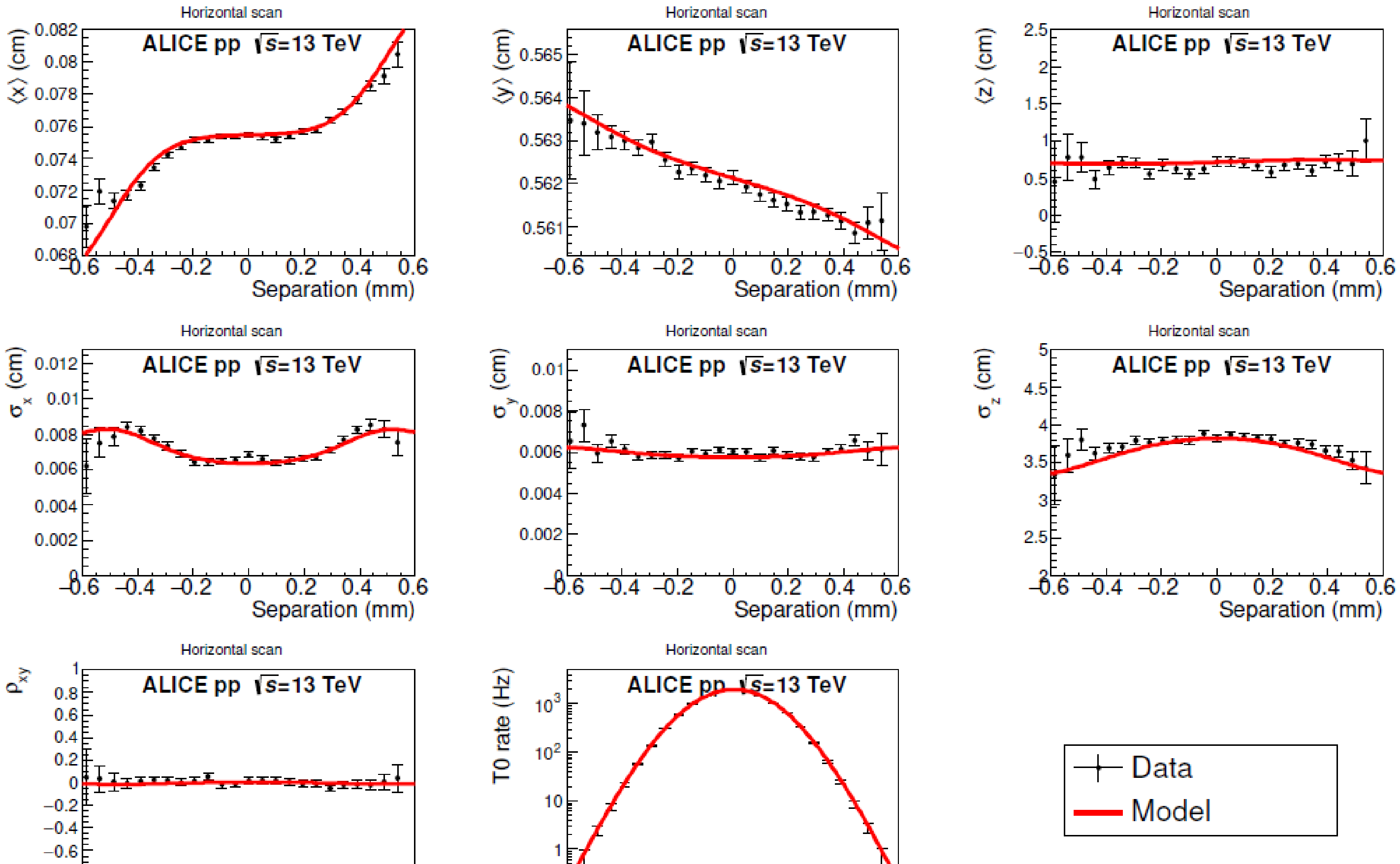
→ **measure vertex displacement vs nominal beam displacement** in a dedicated scan (few per-mil to ~3% effect)

arXiv:2204.10148



Non-factorisation: $\rho(x, y) \overset{?}{=} \rho(x)\rho(y)$

- **potential bias** (up to a few %) on vdM-based cross section, estimated by **fitting the luminous-region parameters to a non-factorisable model**



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