Luminosity determination at the LHC: A look at non-factorisation effects through simulations

J. Pucek[1]

[1]Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University of Prague

ZIMÁNYI SCHOOL'18, 3.12.2018
Budapest, Hungary

Luminosity

Luminosity is proportional to interaction rate $L = \frac{R}{\sigma}$ where σ is the cross section of the process.
For bunched beams, as in the LHC, the luminosity can be expressed as:

$$L = K n_b f \underbrace{N_1 N_2}\overbrace{\int_{-\infty}^{\infty} S_1(x,y,z,t) S_2(x,y,z,t) \mathrm{d}V \mathrm{d}t}$$

Luminosity

Luminosity is proportional to interaction rate $L = \frac{R}{\sigma}$ where σ is the cross section of the process.
For bunched beams, as in the LHC, the luminosity can be expressed as:

$$L = K n_b f \underbrace{N_1 N_2} \overbrace{\int_{-\infty}^{\infty} S_1(x,y,z,t) S_2(x,y,z,t) \mathrm{d}V \mathrm{d}t}$$

Kinematic factor

Luminosity

Number of colliding bunches

Luminosity is proportional to interaction rate $L = \frac{R}{\sigma}$ where σ is the cross section of the process.

For bunched beams, as in the LHC, the luminosity can be expressed as:

$$L = K n_b f \underbrace{N_1 N_2} \overbrace{\int_{-\infty}^{\infty} S_1(x, y, z, t) S_2(x, y, z, t) \mathrm{d}V \mathrm{d}t}$$

Kinematic factor

Luminosity

Number of colliding bunches

Luminosity is proportional to interaction rate $L = \frac{R}{\sigma}$ where σ is the cross section of the process.
For bunched beams, as in the LHC, the luminosity can be expressed as:

$$L = K n_b f \underbrace{N_1 N_2} \overbrace{\int_{-\infty}^{\infty} S_1(x, y, z, t) S_2(x, y, z, t) \mathrm{d}V \mathrm{d}t}$$

Kinematic factor

Rev. frequency

Luminosity

Number of colliding bunches

Luminosity is proportional to interaction rate $L = \frac{R}{\sigma}$ where σ is the cross section of the process.

For bunched beams, as in the LHC, the luminosity can be expressed as:

$$L = K n_b f \underbrace{N_1 N_2} \overbrace{\int_{-\infty}^{\infty} S_1(x, y, z, t) S_2(x, y, z, t) \mathrm{d}V \mathrm{d}t}$$

Kinematic factor

Number of particles in a bunch

Rev. frequency

Luminosity

Number of colliding bunches

Integral of bunch shapes

Luminosity is proportional to interaction rate $L = \frac{R}{\sigma}$ where σ is the cross section of the process.

For bunched beams, as in the LHC, the luminosity can be expressed as:

$$L = K n_b f \underbrace{N_1 N_2} \overbrace{\int_{-\infty}^{\infty} S_1(x,y,z,t) S_2(x,y,z,t) \mathrm{d}V \mathrm{d}t}$$

Kinematic factor

Number of particles in a bunch

Rev. frequency

Contents

Motivation

During luminosity calibration, there are several phenomena influencing the measurement.

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%	

Table 1 : Relative uncertainties on the measurement of the T0 and V0 reference process cross section in p–Pb and Pb–p collisions. [Abelev et al. 2014]

The one I am interested in are the transverse correlations (= non-factorisation effects). To study this behavior I have developed a program to simulate the determination of luminosity at the LHC.

Simulation description

- Several classes enabling to convolve different probability distributions.
- Probability distribution represents one bunch.
- The simulation can "collide bunches" under different input conditions.
- The output is the luminosity value of the collision.

Benchmarking

Two models are used: Gaussian (G) and Double Gaussian (DG).

$$G(\vec{x}) = \frac{\exp\left(-\frac{1}{2}(\vec{x}-\vec{\mu})^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}(\vec{x}-\vec{\mu})\right)}{\sqrt{(2\pi)^k|\boldsymbol{\Sigma}|}} \tag{1}$$

$$DG(\vec{x}) = wG_1 + (1-w)G_2 \tag{2}$$

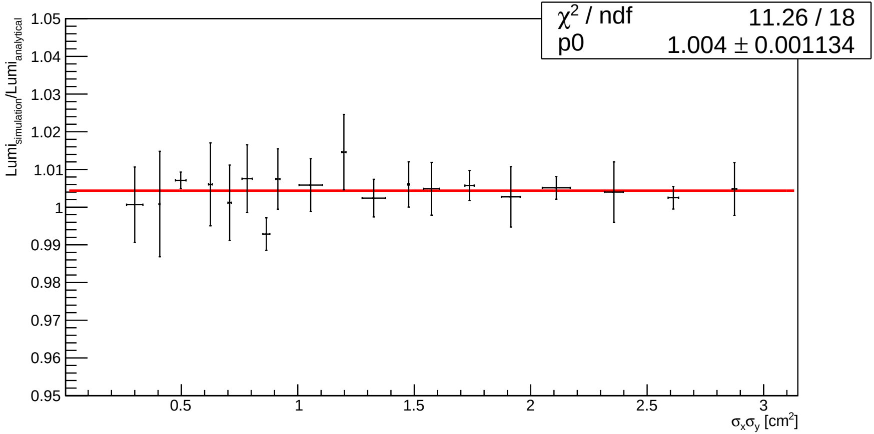
Comparing simulation output with analytical computation for several cases:

- Head-on collisions
- Offset collisions (in backup)
- Collisions with a crossing angle (in backup)
- Collisions with a crossing angle and an offset

First tested for single Gaussian bunches, later verified with double Gaussian bunches.

Benchmarking

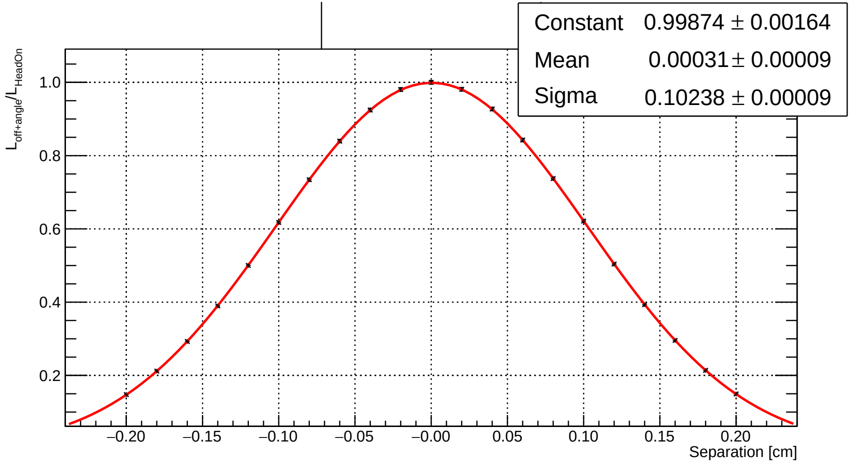
Head-on collisions



The average ratio between simulated and computed luminosity is $\frac{L_s}{L_a} = (1.004 \pm 0.001)$.

Benchmarking

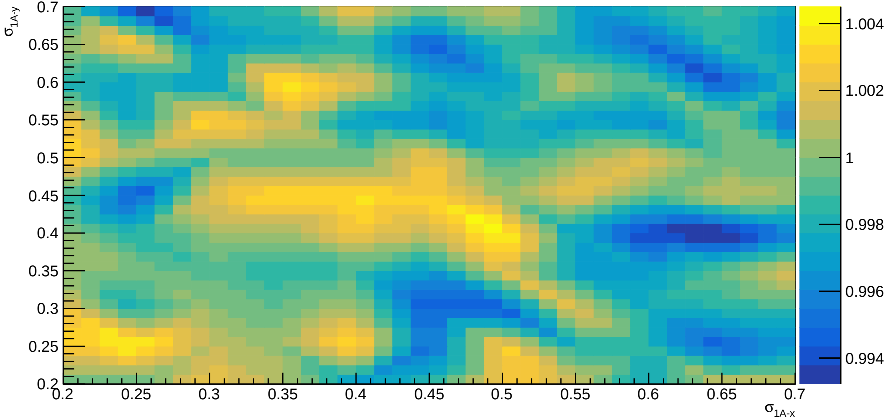
Collisions with a crossing angle and an offset



The difference here between the analytical prediction and the simulation is 0.4%, which is comparable to the head-on uncertainty.

Benchmarking

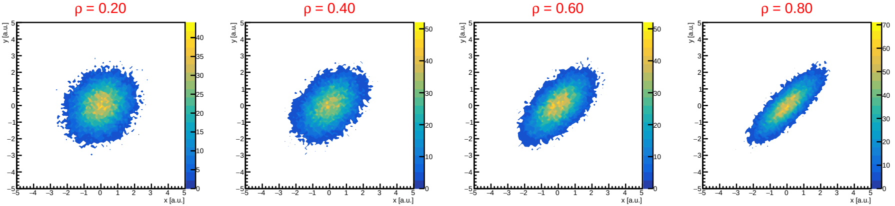
Head-on collisions - Double Gaussian model



From standard formula the predicted uncertainty of two colliding Double Gaussians should be 0.25% and was measured to be 0.27%.

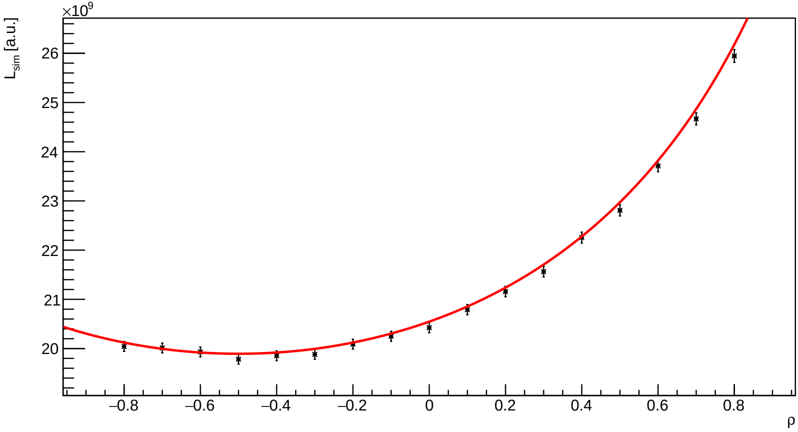
Transverse correlations

If the bunch has an xy correlation the luminosity value changes. See figure for the visual representation of 2D single Gaussian with correlation for different correlation factors.



$$G(x,y) = \exp\left[-\frac{1}{2(1-\rho^2)}\left(\frac{(x-\mu_x)^2}{\sigma_x^2} + \frac{(y-\mu_y)^2}{\sigma_y^2} - \frac{2\rho(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y}\right)\right]$$

Effect of transverse correlations on luminosity



The other bunch had a correlation of 0.5, that is the reason why the minimum is shifted.

Non-factorisation

Non-factorisation ratio

At the LHC one method to determine luminosity relies on so-called van der Meer (vdM) scans, which assume that the transverse profile of bunches factorises.
If they do not factorise, the cross section determined from vdM scans has to be corrected.
The value of delivered luminosity divided by the value obtained from vdM method is called non-factorisation ratio, noted R.

$$R = \frac{\int\int S_1(x,y)S_2(x,y)\mathrm{d}x\mathrm{d}y}{\int S_1(x)S_2(x)\mathrm{d}x \int S_1(y)S_2(y)\mathrm{d}y} \tag{3}$$

Non-factorisation

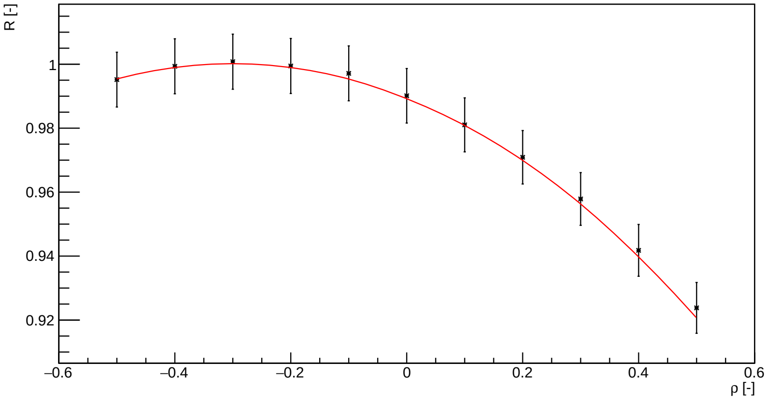


Figure 1 : Ratio dependence on correlation factor ρ for single Gaussian model.

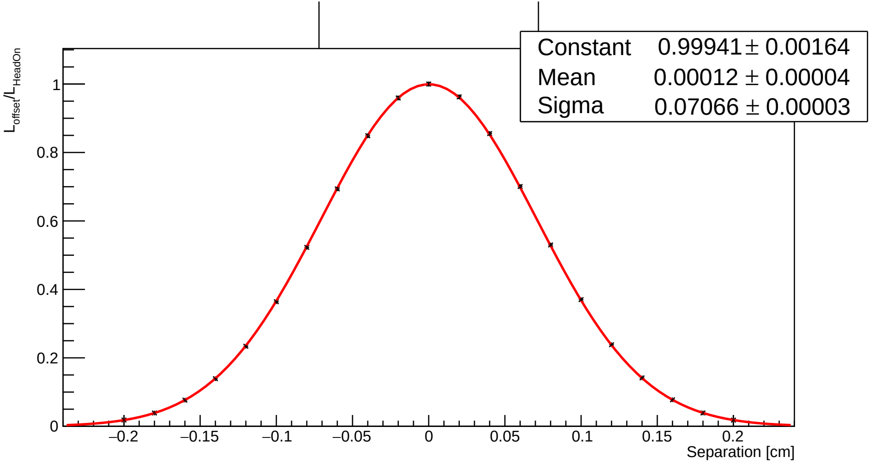
Summary and outlook

- A program to simulate the luminosity determination at the LHC has been developed
- The program has been benchmarked with several cases that have an analytical solution
- The program has been used to explore the size of non-factorisation effects when using the van-der-Meer method to determine the luminosity
- The next step is to include detector effects in the simulation and use it to improve the understanding of non-factorisation effects at the LHC

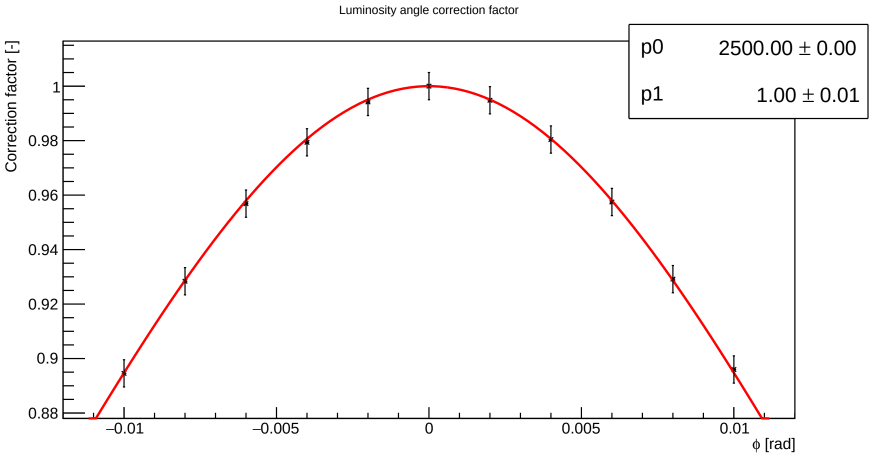
Thank you for your attention!

Abelev, Betty Bezverkhny et al. (2014). "Measurement of visible cross sections in proton-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in van der Meer scans with the ALICE detector". In: *JINST* 9.11, P11003. DOI: 10.1088/1748-0221/9/11/P11003. arXiv: 1405.1849 [nucl-ex].

Backup



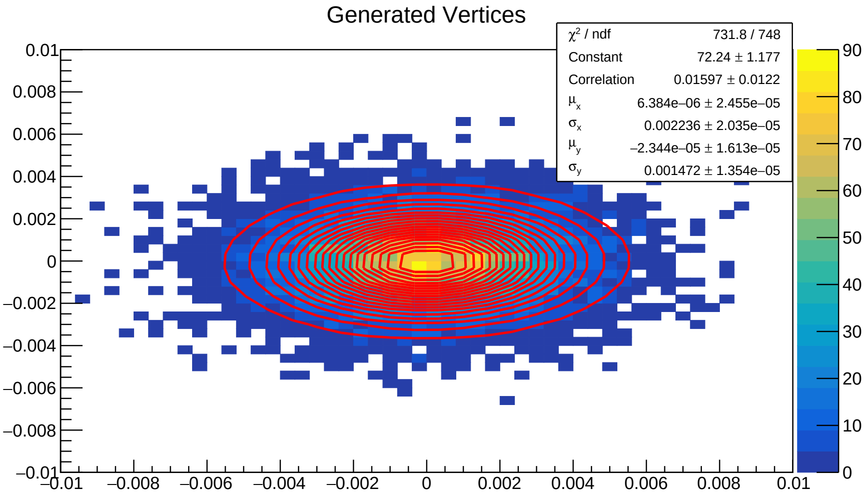
Expected $\sigma_a = 0.07071$, obtained $\sigma_{fit} = (0.07066 \pm 0.00003)$, difference of 0.07%.



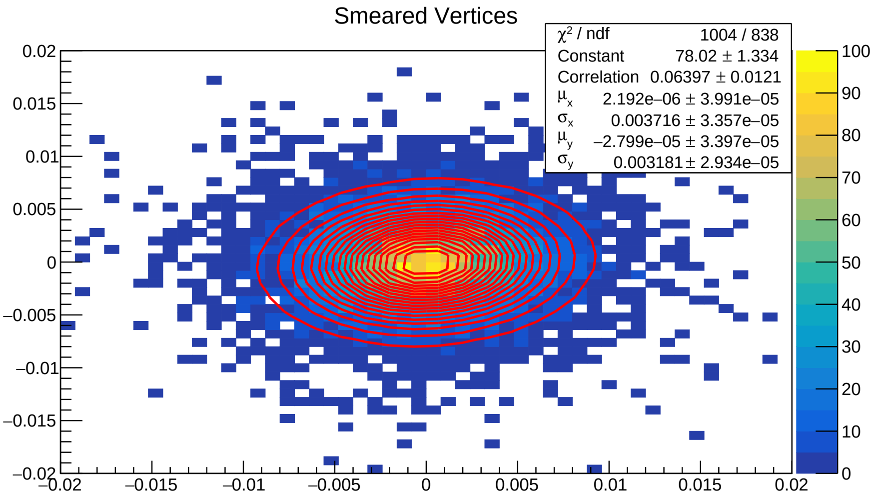
The overall uncertainty is 1%, although the errors are overestimated.

Simulation with a realistic primary vertex resolution

Can the detector's effects change the measured vertices? Generated vertices are smeared by real-world data and the fits are compared.



Simulation with a realistic primary vertex resolution



A correlation emerged after smearing, generated (0.01 ± 0.01), smeared (0.06 ± 0.01).