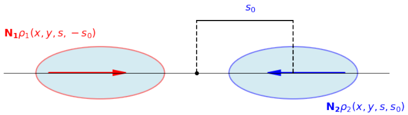
Along the chain MDs - van der Meer beams

MD Days 2025

S. Albright, F. Asvesta, H. Bartosik, M. Bozatzis, G. Franchetti, M. Giovannozzi, P. Hermes, L. Intelisano, S. Kostoglou, W. Kozanecki, **E. Lamb**, I. Mases, D. Miriarchi, C.E. Montanari, G. Papotti, K. Paraschou, T. Persson, T. Prebibaj, **G. Sterbini**, D. Stickland, G. Trad, F. Van der Veken, J. Wanczyk, PSB-OP, LHC-OP

Luminosity

- The figure of merit of colliders for high energy physics are the **energy** and the **luminosity** produced in order to increase the probability of observing rare physics events.



Colliding particle bunches of two counter-rotating beams [1].

$$\sigma = \frac{N_{\text{events}}}{\mathcal{L}_{int}} \tag{1}$$

N_{events}, divided by the luminosity in a time period ($\mathcal{L}_{int}$), yields the cross-section σ.

Luminosity Calibration

- The calibration constant is measured in calibration runs once a year in the LHC, the beams are scanned transversally in a method called **van der Meer scans** [2, 3].

Source	**Uncertainty (%)**
Calibration	
Beam current	0.20
Ghosts & satellites	0.10
Orbit drift	0.02
Residual beam positions	0.16
Beam-beam effects	0.34
Length scale	0.20
Factorization bias	0.67
Scan-to-scan variation	0.28
Bunch-to-bunch variation	0.06
Cross-detector consistency	0.16
Integration	
Cross-detector stability	0.71
Cross-detector linearity	0.59
Calibration	0.89
Integration	0.92
Total	**1.28**

Uncertainty sources and their corresponding percentages in the 2022 p-p van der Meer run of CMS, [4].

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- It is not clear the source of non-factorization, if it comes from the **bunch's history** or a **local source** during collisions (not a linear coupling).
- The experiments asked for an improvement for the non-factorization.

MD Goals and challenges

- Be able to **measure** non-factorization independent of a van der Meer scan.
- Try to understand better non-factorization and if there is any contribution from the **bunch's history** along the **injector chain**.
  1. Make very 'non-factorizable' bunches in the PSB and observe if the distribution is preserved up to the LHC.
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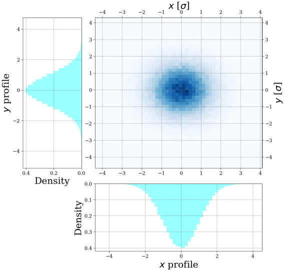
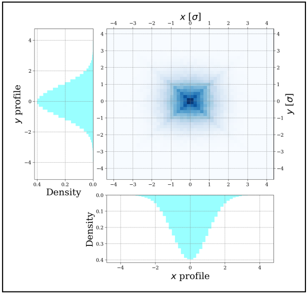
  $\Rightarrow$ **Produce high quality van der Meer bunches for calibration.**

Measuring non-factorization with apertures

Example:



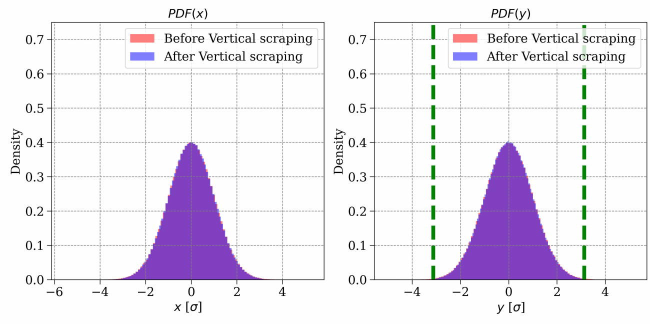
1) $\rho_{X,Y}(x,y) = \rho_X(x)\rho_Y(y)$



2) $\rho_{X,Y}(x,y) \neq \rho_X(x)\rho_Y(y)$

Measuring non-factorization with apertures

Moving an aperture in y into the beam and measuring in **both planes**, with a **normalisation** to the intensity:



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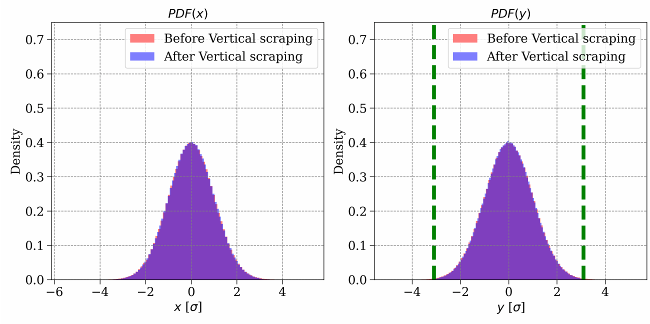

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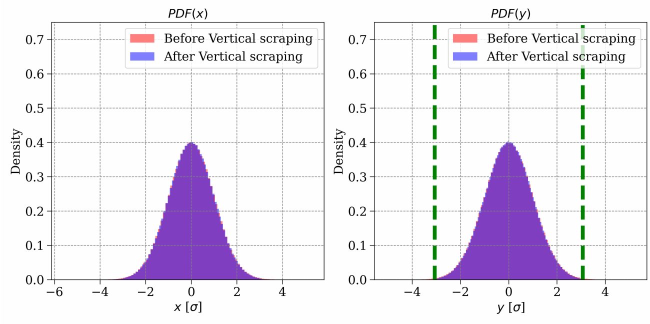

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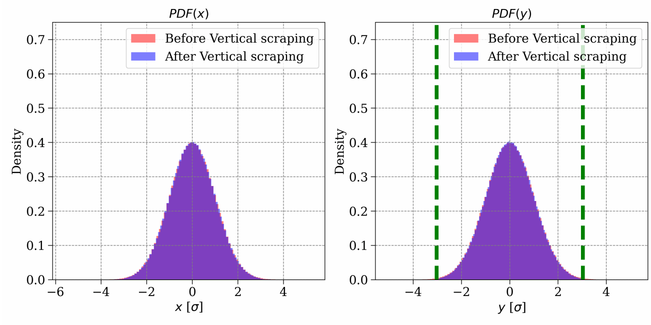

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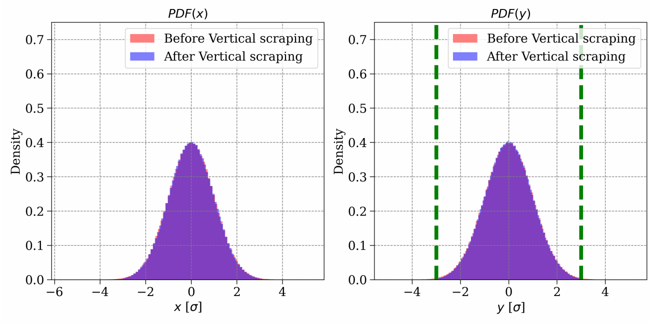

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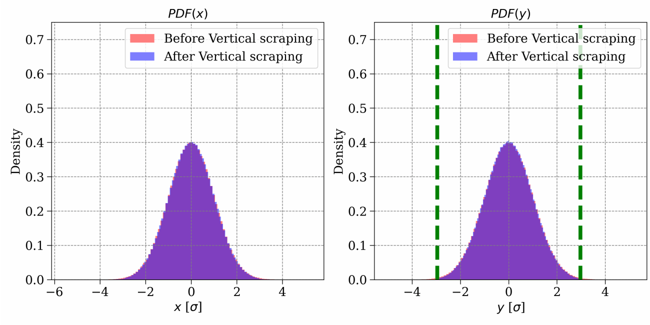

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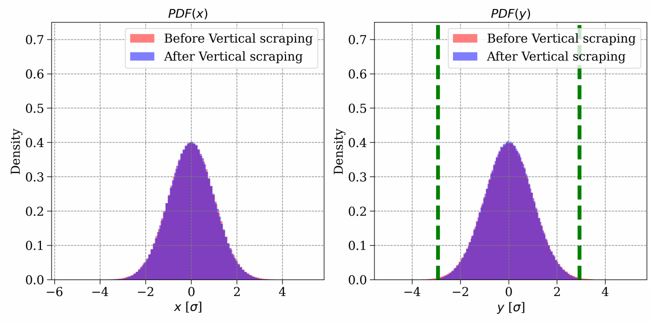

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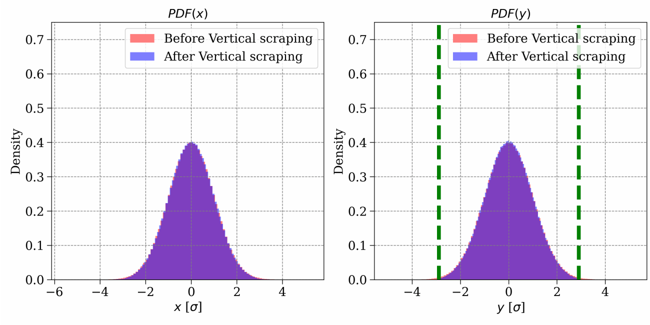

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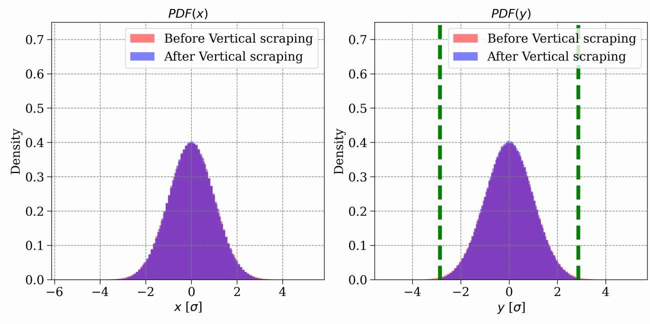

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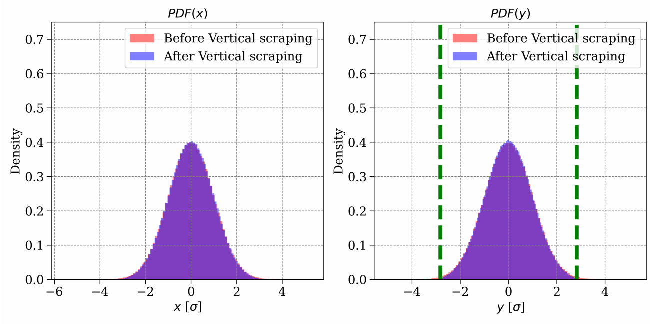

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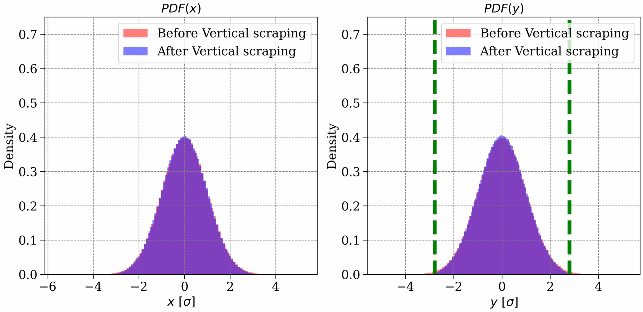

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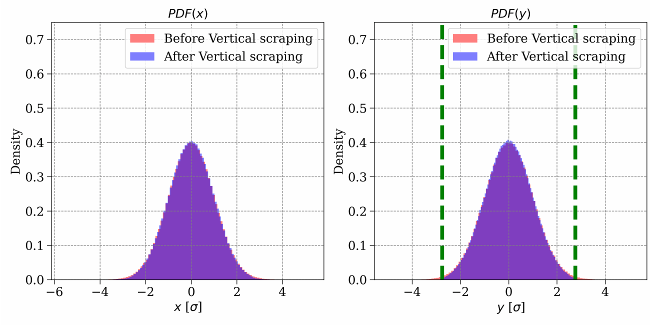

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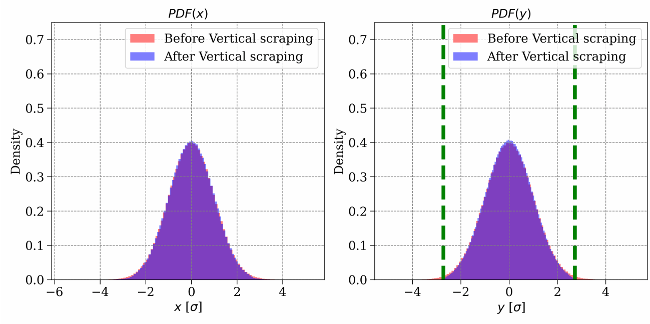

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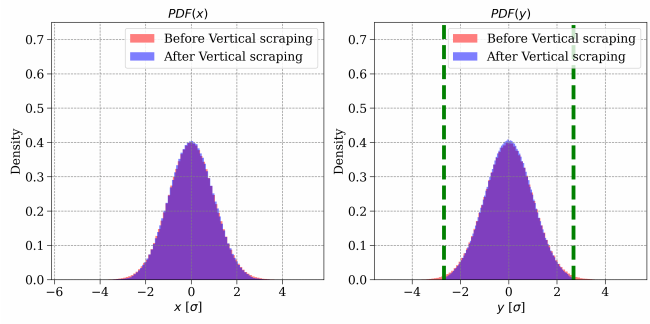

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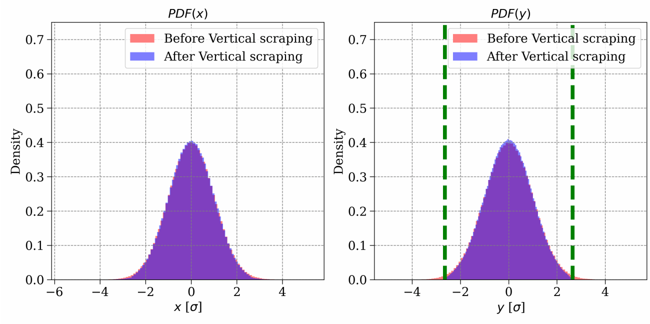

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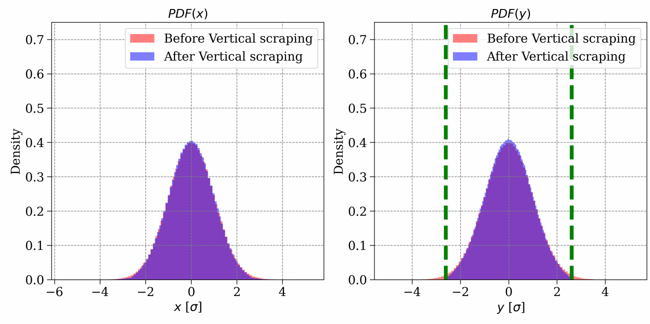

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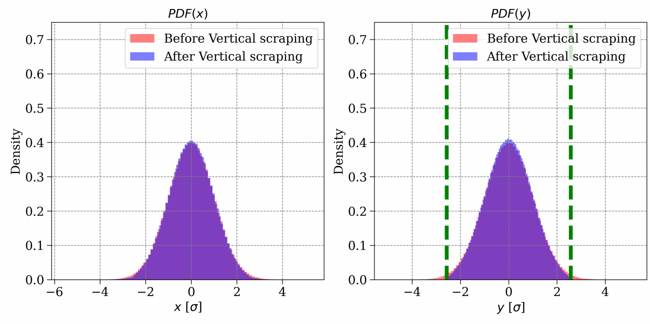

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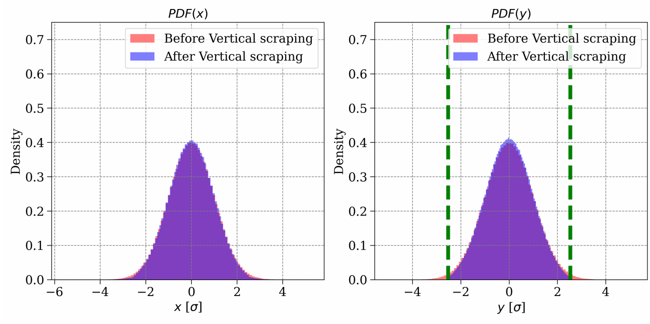

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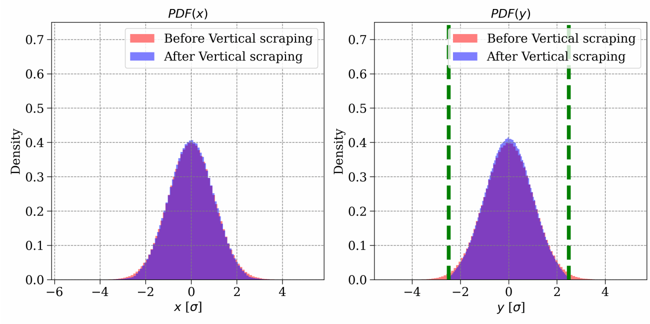

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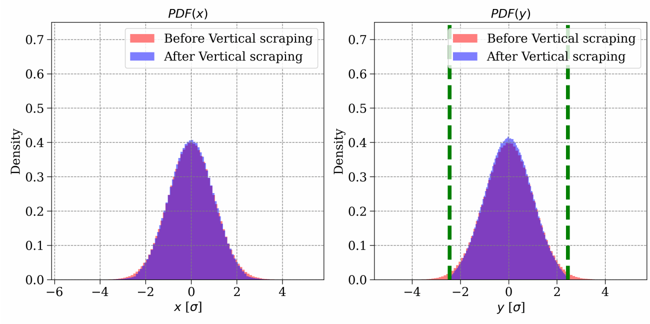

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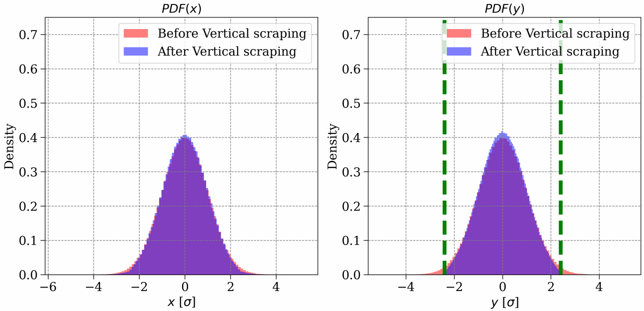

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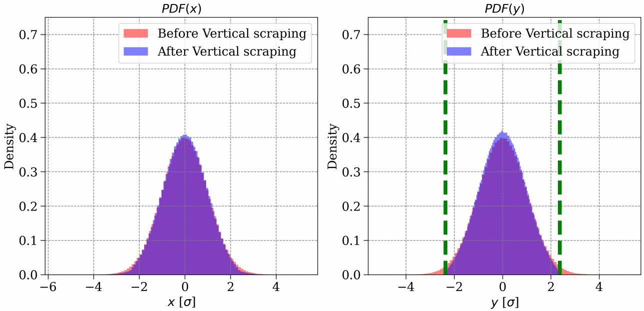

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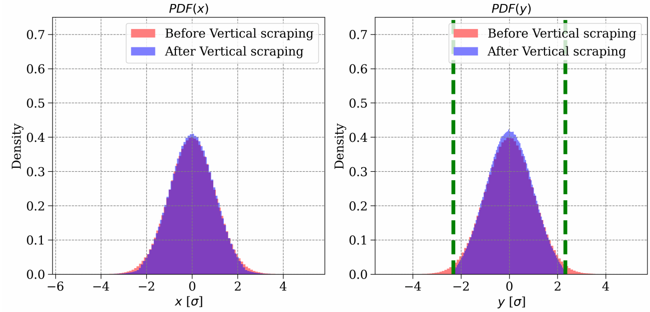

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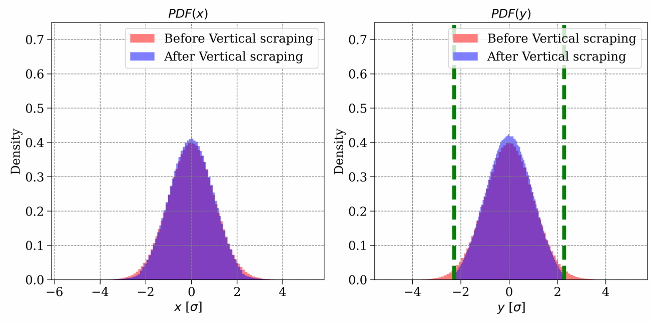

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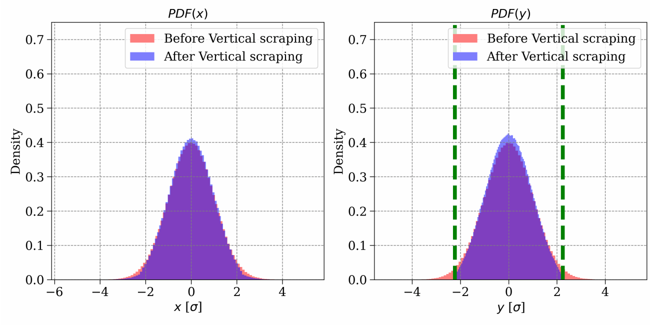

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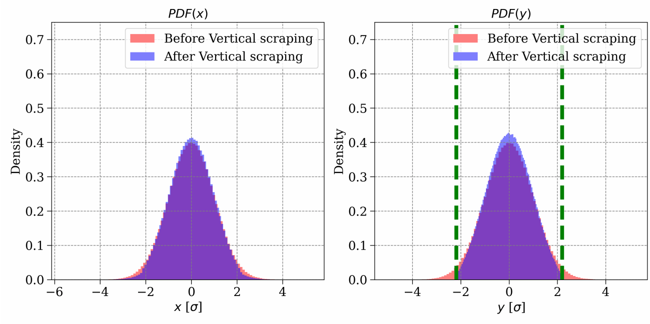

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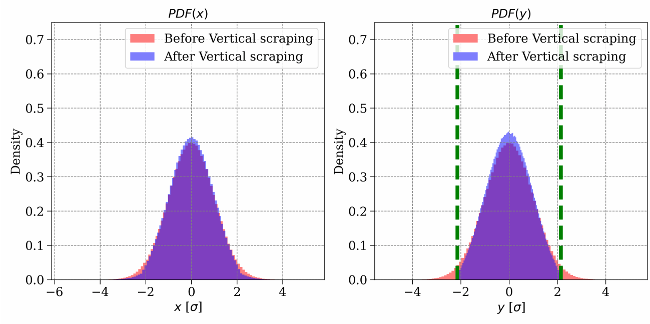

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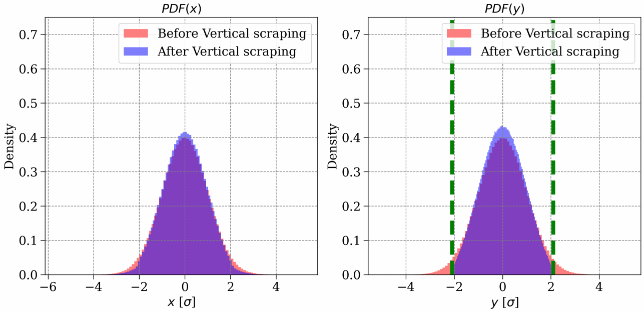

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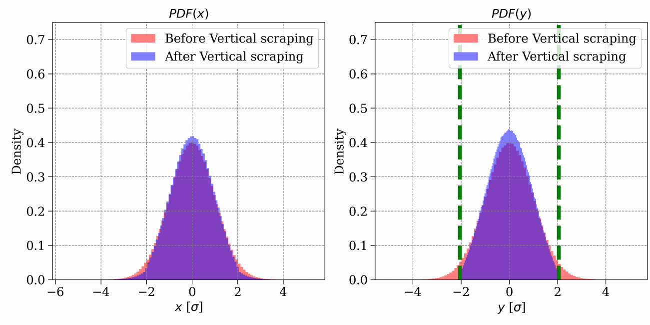

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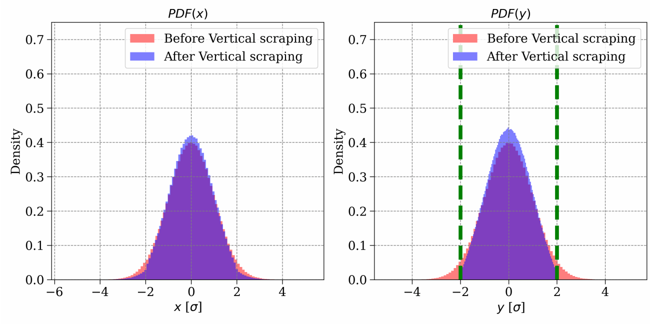

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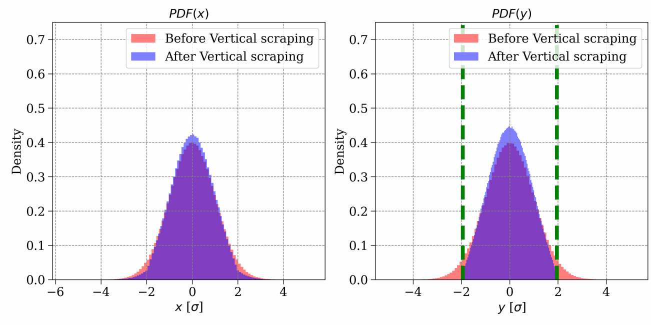

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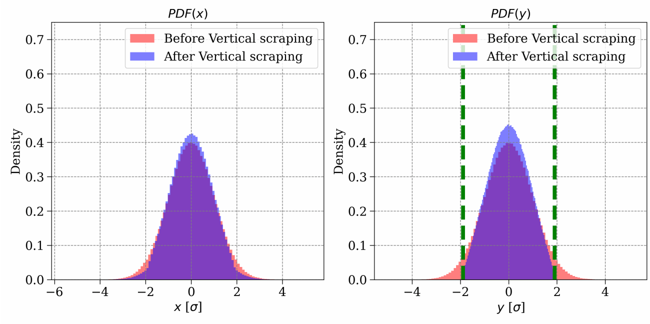

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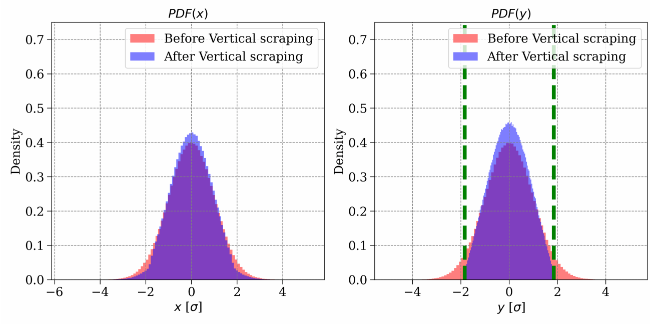

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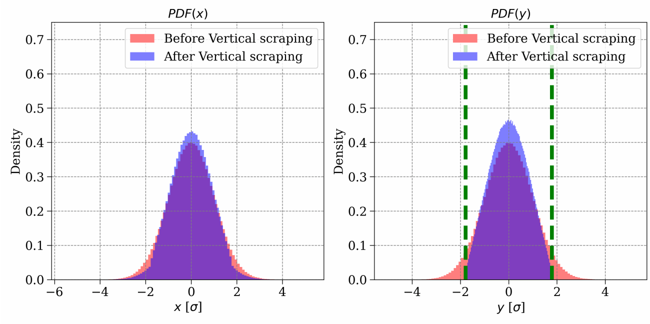

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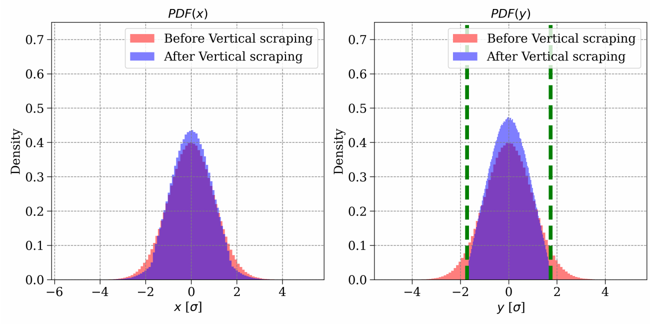

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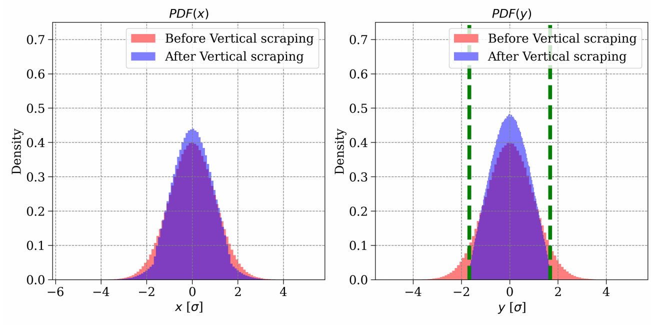

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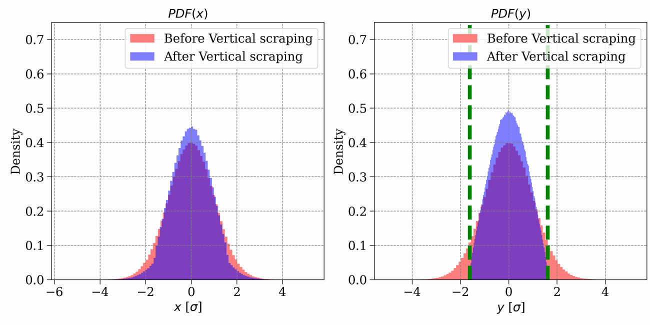

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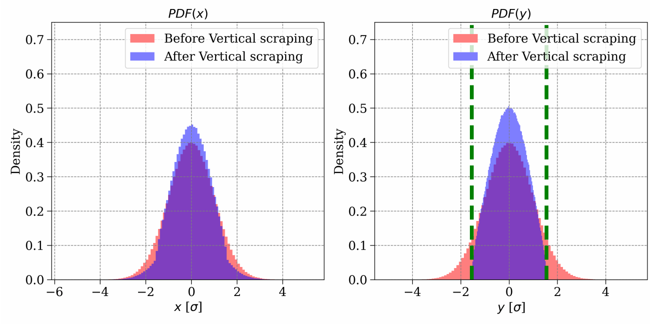

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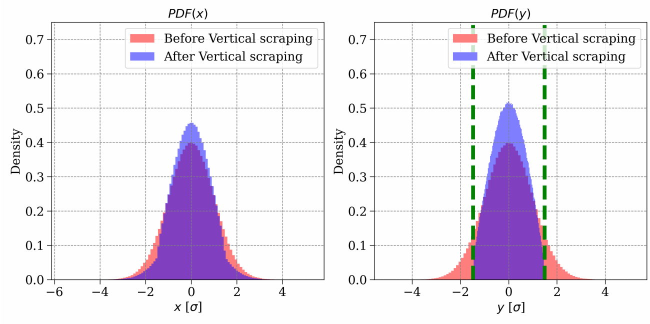

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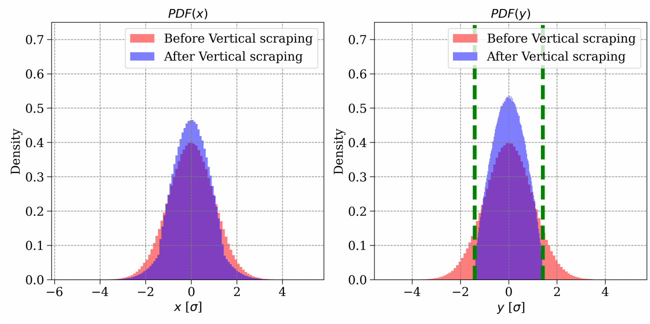

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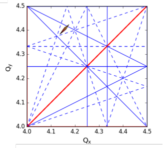
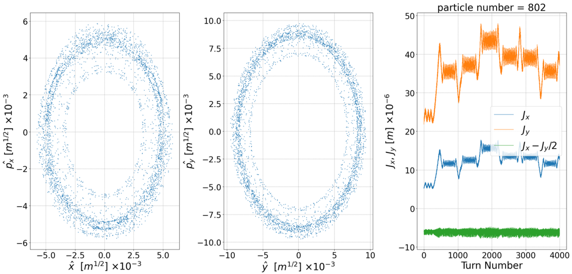
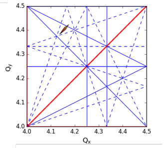
Bunch history - making non-factorizable bunches in the PSB



- We want to check if beam dynamics earlier on in the chain effects the measurement
- Use interaction with a coupling resonance, $Q_x + 2Q_y = 13$:



Bunch history - making non-factorizable bunches in the PSB



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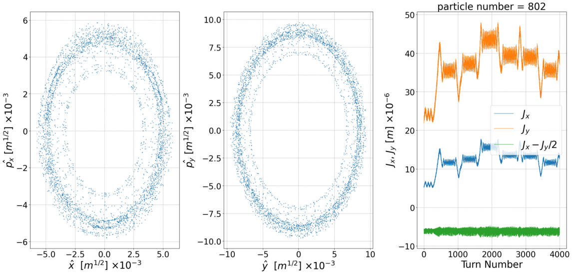
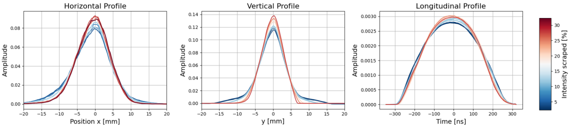


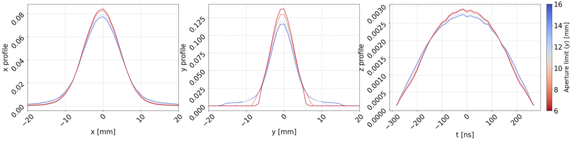
- The effect on many particles in a bunch results in a non-factorization.

Experimental measurement of non-factorization in the PSB

- Observing the bunch exposed to a coupling resonance with the aperture method, we see a non-factorization for the full distribution.



Experiment in PSB



Simulation in PSB

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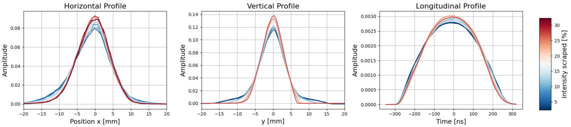

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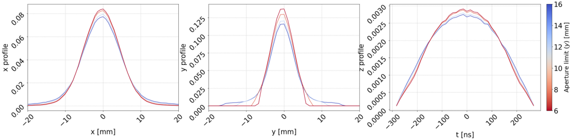
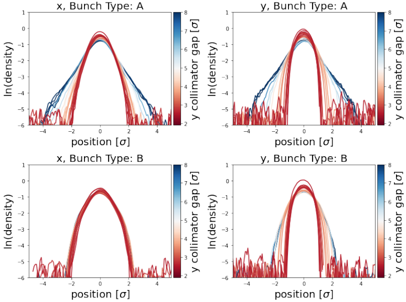


Simulation in PSB

- Is it **preserved** up to the LHC as a **bunch property**?

Along the chain

- The bunch from the previous slide, plus an optimised bunch (avoiding resonance conditions), was transported along the chain to the LHC.
- Required optimisation of tune and steering in all machines along the chain to preserve $\rho(x, y)$.



Experiment at LHC injection

- The two bunches differ in their factorization even though they see the **same lattice in the LHC** $\Rightarrow$ Non-factorization transported from lower machines.

Conclusions

- Non-factorization of a bunch can be preserved from the injectors to the LHC.
- Exposure to coupling resonances can lead to non-factorization in a bunch.
- The non-factorization of a bunch was measured for the first time for a van der Meer campaign by the injectors (PSB, SPS) before sending it to the LHC.
- **The 2024 van der Meer bunch was created with a new method with tunes away from resonances.**

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⇒ Ensuring a high quality factorizable bunch requires control of parameters all along the chain, mainly tune and injection steering.

⇒ We are waiting for the results of the calibration measurement from 2024.

Thank you!

References (I)

Werner Herr and B Muratori.
Concept of luminosity.
2006.

C. Rubbia.
Measurement of the luminosity of pp collider with a (generalized) van der meer method.
Technical Report CERN-pp-Note-38, CERN, 1977.

S. van der Meer.
Calibration of the effective beam height in the isr.
ISR Report CERN-ISR-PO-68-31, CERN, 1968.

CMS collaboration.
Measurement of the offline integrated luminosity for the CMS proton-proton collision dataset recorded in 2023.
CMS performance note, 2024.

References (II)

Andrzej Wolski.
Alternative approach to general coupled linear optics.
Phys. Rev. ST Accel. Beams, 9:024001, Feb 2006.

Kevin Shing Bruce Li.
Collective effects ii.
Presentation at CAS, September 2024.
27 Sept 2024.

Justin Matejka and George Fitzmaurice.
Same stats, different graphs: Generating datasets with varied appearance and identical statistics through simulated annealing.
pages 1290–1294, 05 2017.

Henri Poincaré.
Les Méthodes Nouvelles de la Mécanique Céleste, volume 1–3.
Gauthier Villars, Paris, 1899.

- In the linear approximation, the dynamics of the **storage ring**, can be represented by a **symplectic** matrix, 'one turn map' M_{OTM} acting on the coordinates of the particles.
- ρ has a matrix of **second order moments**, Σ.
- For ρ to be preserved under linear transport, it has to be **matched**:

$$\Sigma = M_{\mathrm{OTM}} \Sigma M_{\mathrm{OTM}}^T$$

[5]

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- There are infinite ρ that have the required Σ matrix.
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van der Meer scan

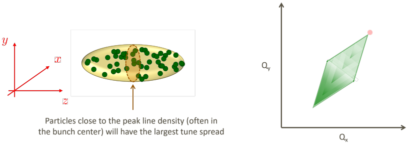
$$\mathcal{L}_b = \frac{R_{\text{vis,pk}}}{\sigma_{\text{vis}}} = f_r \frac{\mu_{\text{vis,pk}}}{\sigma_{\text{vis}}} = f_r \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

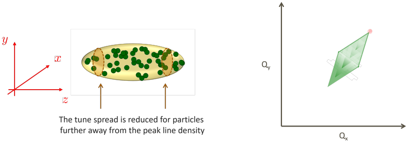
$$\sigma_{\text{vis}} = 2\pi \frac{\mu_{\text{vis,pk}}}{n_1 n_2} \Sigma_x \Sigma_y$$

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \int \frac{\mu_{\text{vis}}(\Delta x)\, d\Delta x}{\mu_{\text{vis}}(0)}, \quad \Sigma_y = \dots$$

Tune, resonances and space charge

- The particles may not all have the same tune, the most dominant effect in lower energy machines is from **space charge**
- The charged particles fields interact, and there is a nonlinear force, space charge, causing **amplitude dependent detuning**
- In bunched beams, depending on the longitudinal position (oscillating due to longitudinal motion in phase space), the detuning is different[1]:

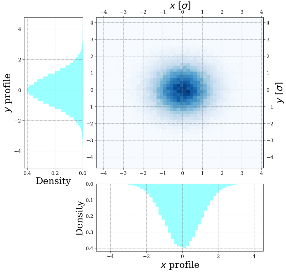




[1] Image taken from [6]

Non-factorization in a synchrotron

$$\rho_X(x) = \int \rho_{6D}(x, p_x, y, p_y, z, p_z)\, dp_x\, dy\, dp_y\, dz\, dp_z \tag{3}$$



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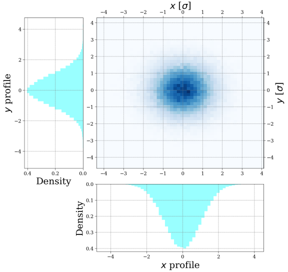

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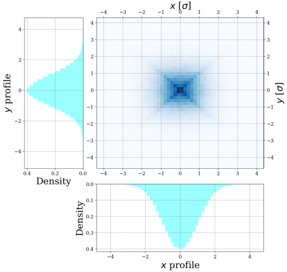


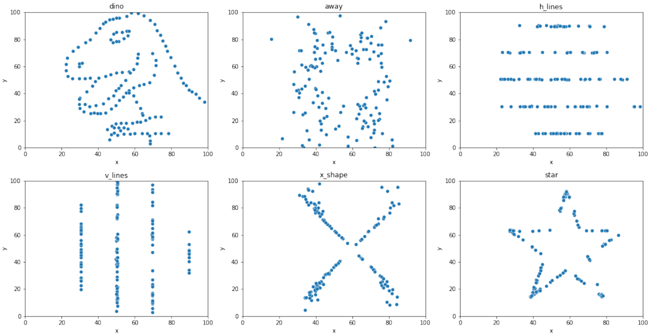
2) NF $x - y$ distribution with Gaussian marginal distributions, **stationary**

Stationary (turn by turn) distributions are **not unique** given a beam profile. They can be **non-factorizable**.

LINAC4 $\rightarrow$ **PSB** $\rightarrow$ PS $\rightarrow$ **SPS** $\rightarrow$ **LHC** $\rightarrow \star$ **Collisions**

Interlude

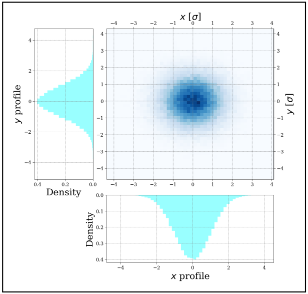
- Distributions cannot be singularly described by statistical observables.



All the distributions have the same correlation, mean, and standard deviation [7].

Non-factorization measurement with scraping

In the absence of an instrument to measure $\rho_{X,Y}(x,y)$, at CERN, a measurement protocol was developed using **moveable apertures** (beam scraping) to measure non-factorization
Example:



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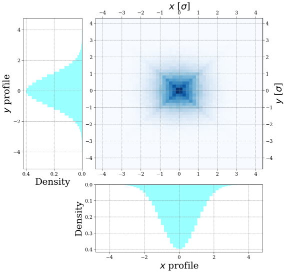

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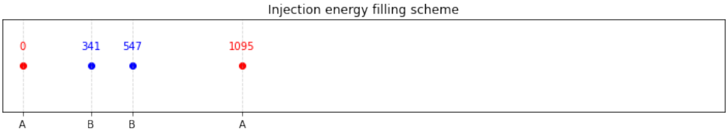
Non-factorization transport experiments in the LHC

Experiment at LHC injection

LINAC4 → PSB → PS → SPS → **LHC** → ★ **Collisions**

Inject different bunches with **different non-factorization at the PSB** into the LHC and measure their non-factorization at **LHC injection**:

1. **A) Highly non-factorizable:**
   - Excited coupling resonances to enhance non-factorization in the PSB
2. **B) Factorizable as possible:**
   - Avoid resonant tune conditions in the PSB



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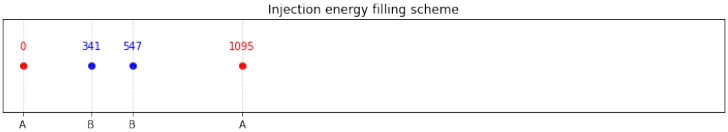
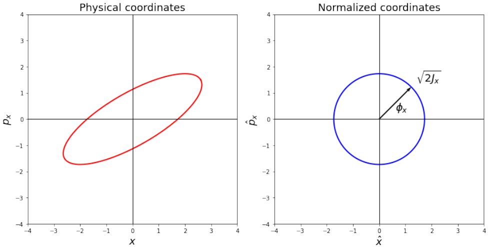


Will the non-factorization **beam property** be transported along the machines?

Single particle dynamics

- The phase space can be inspected to observe the behaviour of a single particle (x, p_x) near resonance conditions turn by turn.
- It is useful to transform to **action-angle** coordinates.



The Poincaré ellipse [8] of a particle in x phase space and a normalisation to action-angle variables turn by turn in an accelerator.

- Under linear motion the 'action' J_x is constant.

Tune, resonances

- The **tune** of an accelerator is the number of oscillations a particle makes per turn around the accelerator.
- It is defined as:
$$Q_x = \frac{\nu_x}{2\pi}, \quad Q_y = \frac{\nu_y}{2\pi} \tag{4}$$
where Q_x and Q_y are the horizontal and vertical tunes, and ν_x and ν_y are the respective phase advances per turn.
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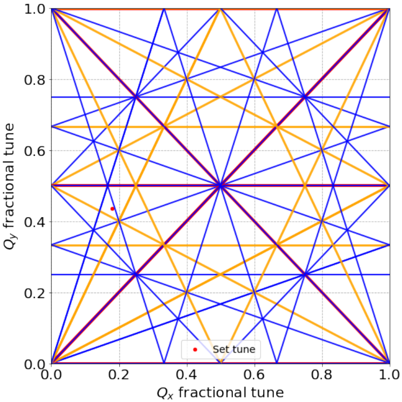
- The magnetic fields determine the tune and the working point is the set tune of the accelerator.
- A **resonance condition** occurs when the **tune of a particle** satisfies the condition:

$$mQ_x + nQ_y = p, \tag{5}$$

  where m, n, and p are integers. This condition can cause particles to receive kicks in or out of phase each turn.

Tune, resonances

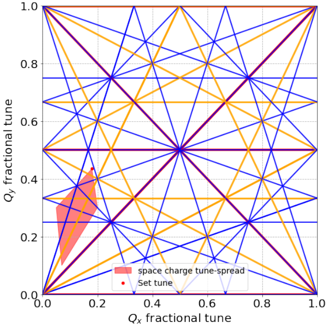
The working point of an accelerator can be visualised on a resonance diagram, plotted up to 4th order:

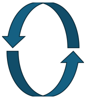


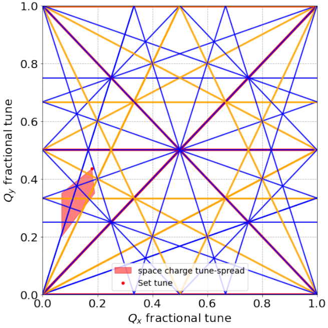
Tune, resonances

- Nonlinear forces can cause the tune of an individual particle to be dependent it's amplitude, causing a **tune spread**

- The tune spread can oscillate, if the nonlinear effect is space charge then it oscillates with **synchrotron motion**.



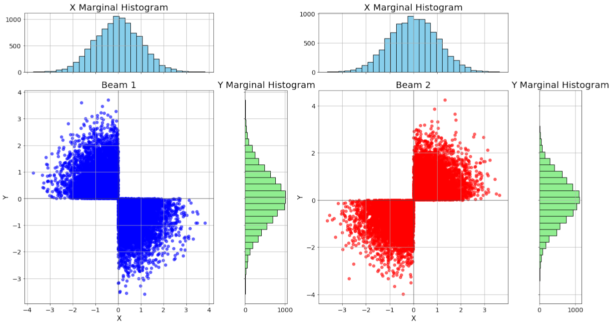




Visualisation of non-factorization

A pathological example:

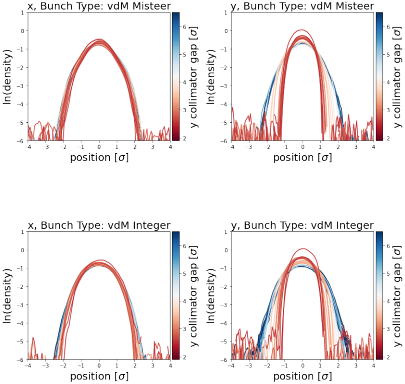
Two bunches with extreme non-factorization, when overlapped (colliding) have zero luminosity:



Two bunches with Gaussian $\rho_X(x)$, $\rho_Y(y)$ projections, when colliding have zero luminosity.

Conclusions

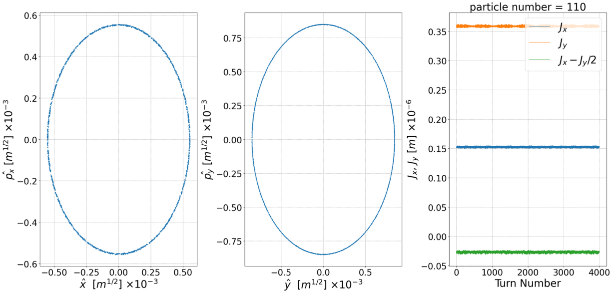
We were able to test multiple configurations for the calibration bunch at LHC injection, which were monitored for their NF in the PSB and the SPS:



We decided on the bunch type to use for the 2024 calibration run using this method and avoiding resonances in the preparation scheme.

Single particle dynamics - non-resonant

- Simulating the PSB for a number of turns, and observing one particle **away** from a resonance condition:



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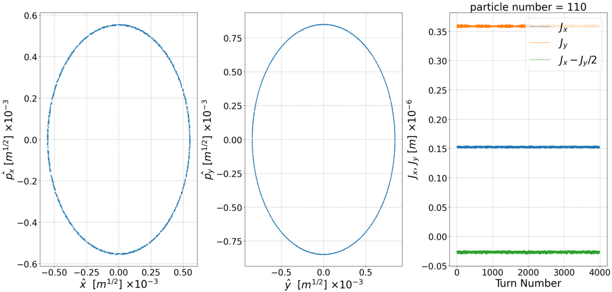
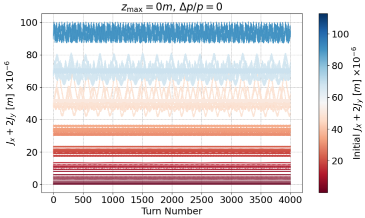


- The tune oscillates due to the synchrotron motion and space charge, but a resonance condition is never met, thus J_x, J_y are constant.

Multi-particle dynamics

- Observing a number of particles at different amplitudes which do not cross a coupling resonance condition:



- The **distribution** is not changing

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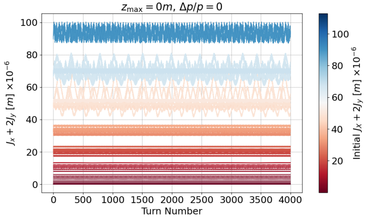
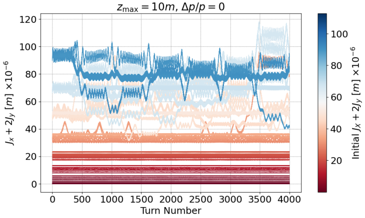


- The **distribution** is not changing

- Observing an ensemble of particles for which some cross the coupling resonance condition:



- Over time, the 'scattering' of the x and y amplitudes becomes **statistical non-factorization**.

Single bunch non-factorization experiments in the PSB

LINAC4 $\rightarrow$ **PSB** $\rightarrow$ PS $\rightarrow$ SPS $\rightarrow$ LHC $\rightarrow \star$ **Collisions**

- We can now measure non-factorization along the accelerator chain with apertures. We want to try and introduce it into the bunch, measure it and control it to prove that it can be a property of the bunch's history, not the calibration scan itself.

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- It was decided to use the lowest energy synchrotron, and experiment with **coupling resonances** to try and artificially introduce in order to measure and characterize it.