Absolute luminosity calibration through van der Meer scans in ATLAS

with focus on run 3 2022 vdM scan session

DESY Zeuthen Particle Physics Mini-Retreat

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HELMHOLTZ

Why is a precise luminosity calibration important?

How often does a process happen?

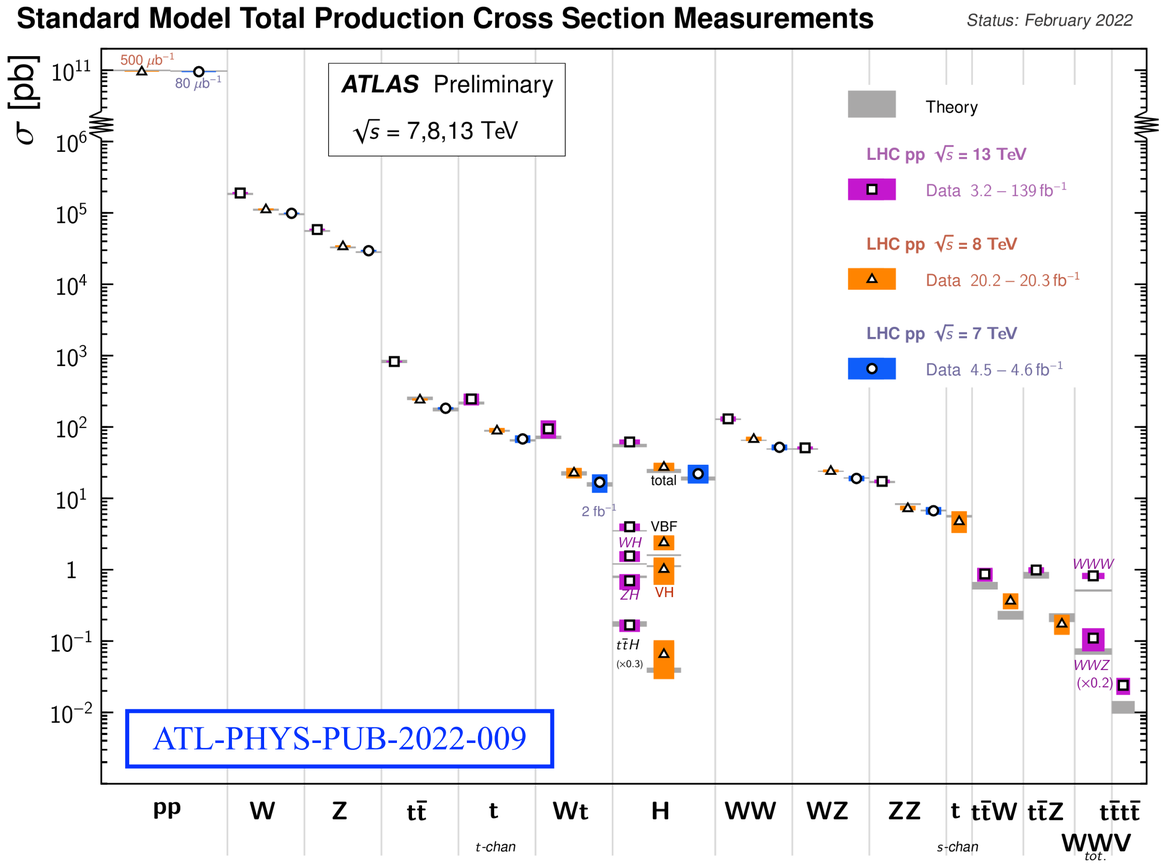
What is the cross section of the process?

$$N = \sigma \cdot L_{int}$$

cross section — σ

number of events — N

integrated luminosity — L_{int}



more precise luminosity ⇒ more precise physics measurement ⇒ possible new discoveries

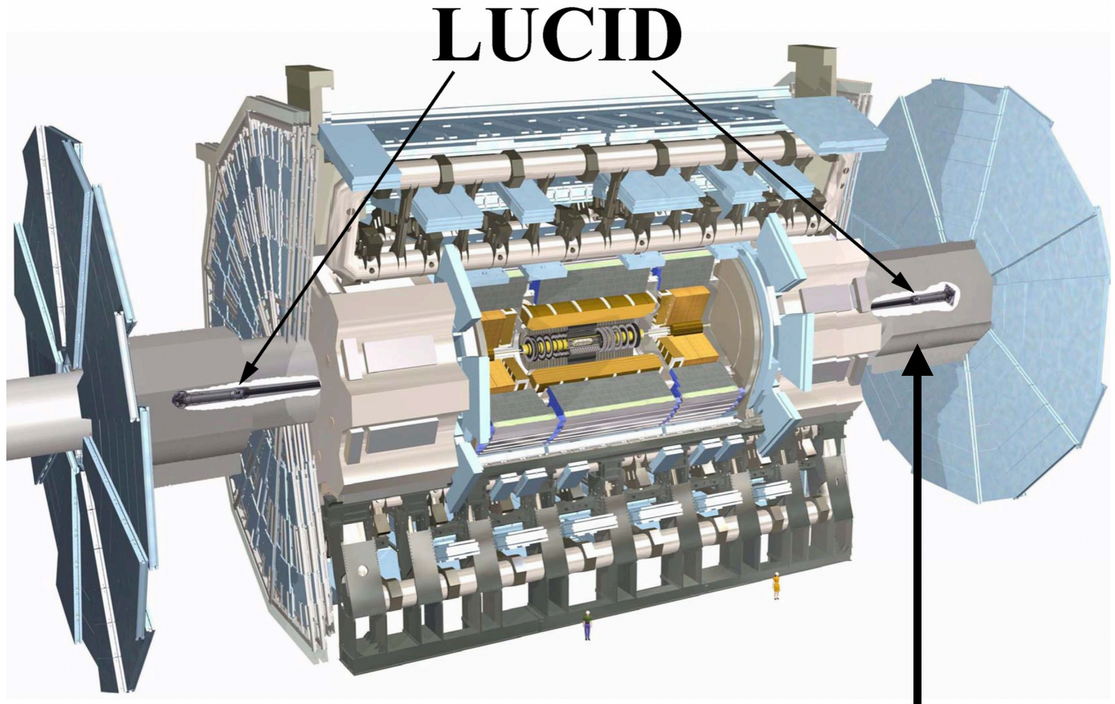
How is luminosity measured in ATLAS?

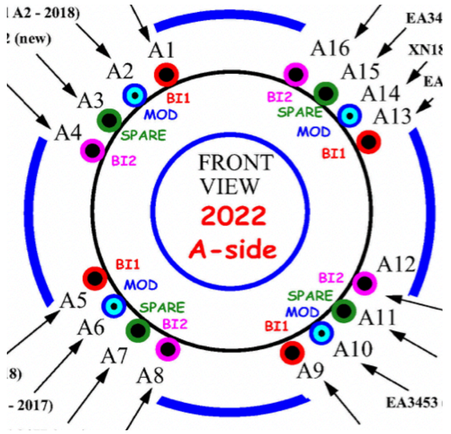
Detectors measure a quantity proportional to luminosity, e.g. the number of hits in a bunch-crossing

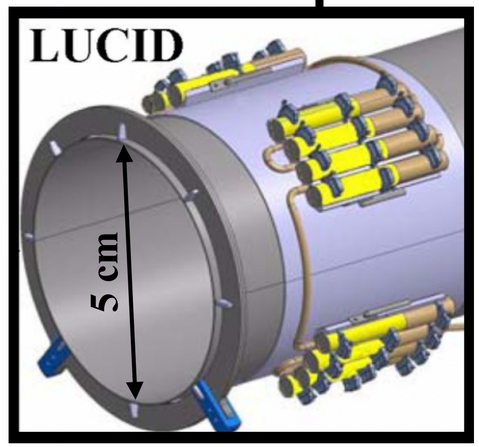
ATLAS' preferred luminosity detector: LUCID

LUminosity Cherenkov Integrating Detector (LUCID):

- **16 photomultipliers** (PMTs) on each side
- particle detection based on **Cherenkov radiation** and readout by PMTs
- if signal is above threshold ⇒ we have a hit!
- 16 PMTs x2 can be combined in multiple ways ⇒ different luminosity algorithms







Luminosity

$$L = \frac{dN}{dt}\frac{1}{\sigma} \Longrightarrow L = \frac{\mu}{\sigma} f_r \Longrightarrow L = \frac{\mu_{inelastic} f_r}{\sigma_{inelastic}} \Longrightarrow L = \frac{\epsilon \mu_{inelastic} f_r}{\epsilon \sigma_{inelastic}} \Longrightarrow L = \frac{\mu_{visible} f_r}{\sigma_{visible}}$$

for inelastic pp interactions

for one bunch crossing: $\frac{dN}{dt} = \mu f_r$

what is visible to LUCID

LUCID measures

we know

constant we need to find

Luminosity can also be expressed by beam parameters:

$$L = \frac{n_1 n_2 f_r}{4\pi \sigma_x \sigma_y} \Longrightarrow L = \frac{n_1 n_2 f_r}{2\pi \Sigma_x \Sigma_y}$$

with $\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int \mu_{vis}(\Delta x) d(\Delta x)}{\mu_{vis}(\Delta x = 0)}$ where Δx is the beam-beam separation

measure with some detectors

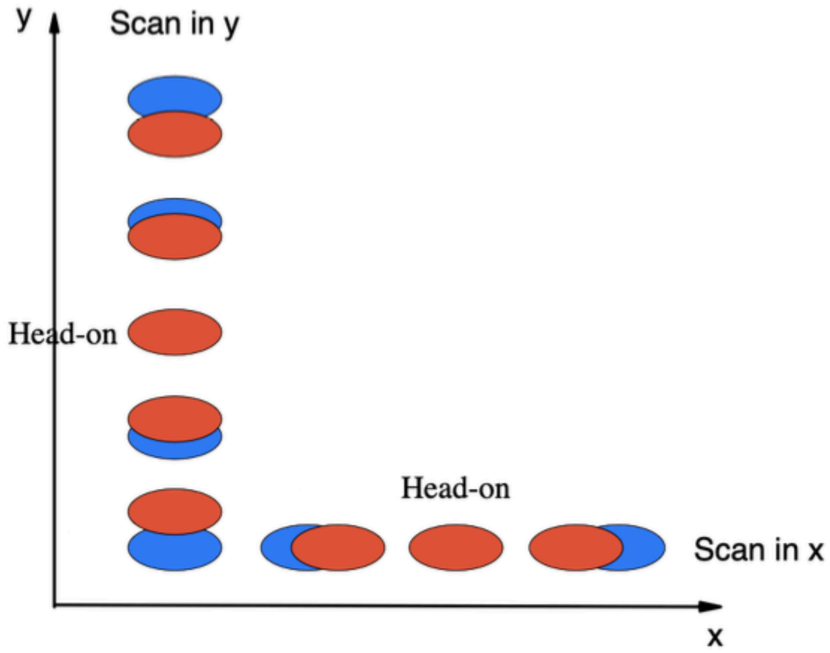
we know

width of beams in x and y planes we do not know

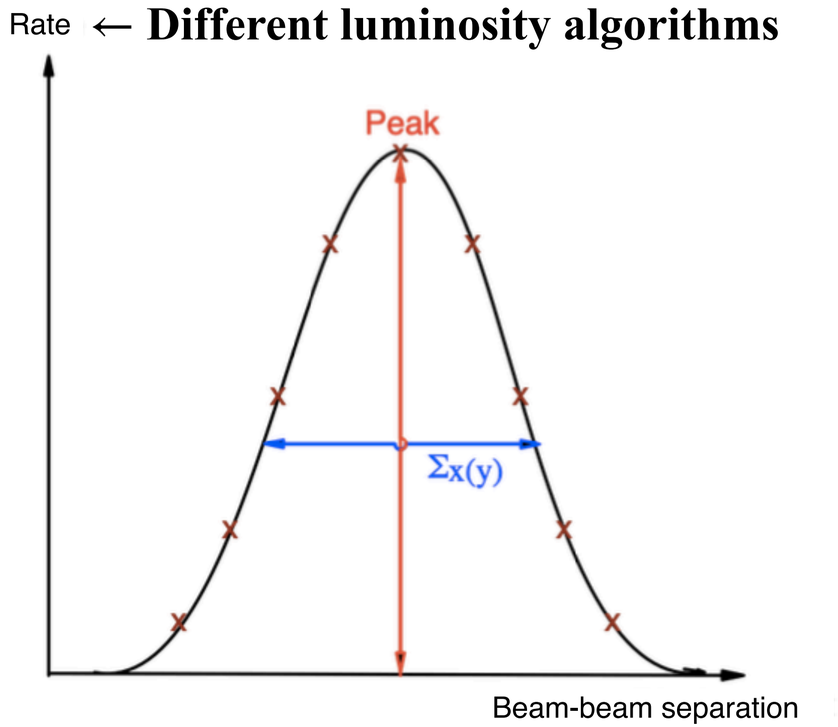
vdM formalism: no crossing angle and x,y factorisation

width of the luminous region measured through van der Meer analysis !!!

What is a van der Meer scan?



A van der Meer (vdM) scan is a transverse scan of the beams through each other performed in special runs



Interaction rates are measured at different beam-beam separations

Rate ~ counting hits in the detector

From van der Meer scan to an absolute calibration of luminosity

After calibration, luminosity at any point in time can be determined: $L = \frac{\mu_{visible} f_r}{\sigma_{visible}}$

Rates and beam-beam separations need to be corrected for several effects before extracting a precise σ_{vis}

plot rate vs separation

⇓

make a fit

⇓

extract Σ_x, Σ_y and μ_{vis}^{max}

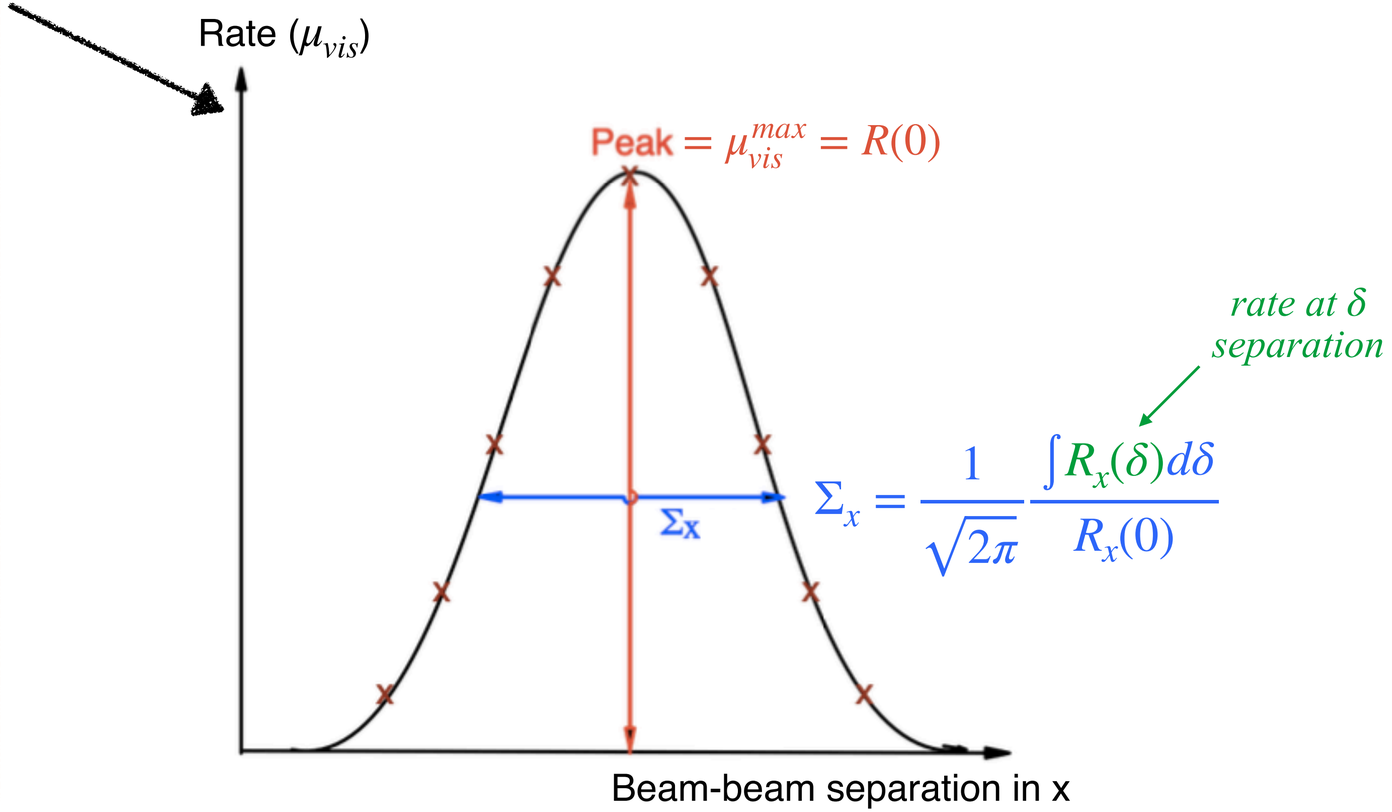
⇓

$$L = \frac{n_1 n_2 f_r}{2\pi \Sigma_x \Sigma_y} \text{ and } \mu_{vis}^{max}$$

⇓

$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y \mu_{vis}^{max}}{n_1 n_2 f_r}$$

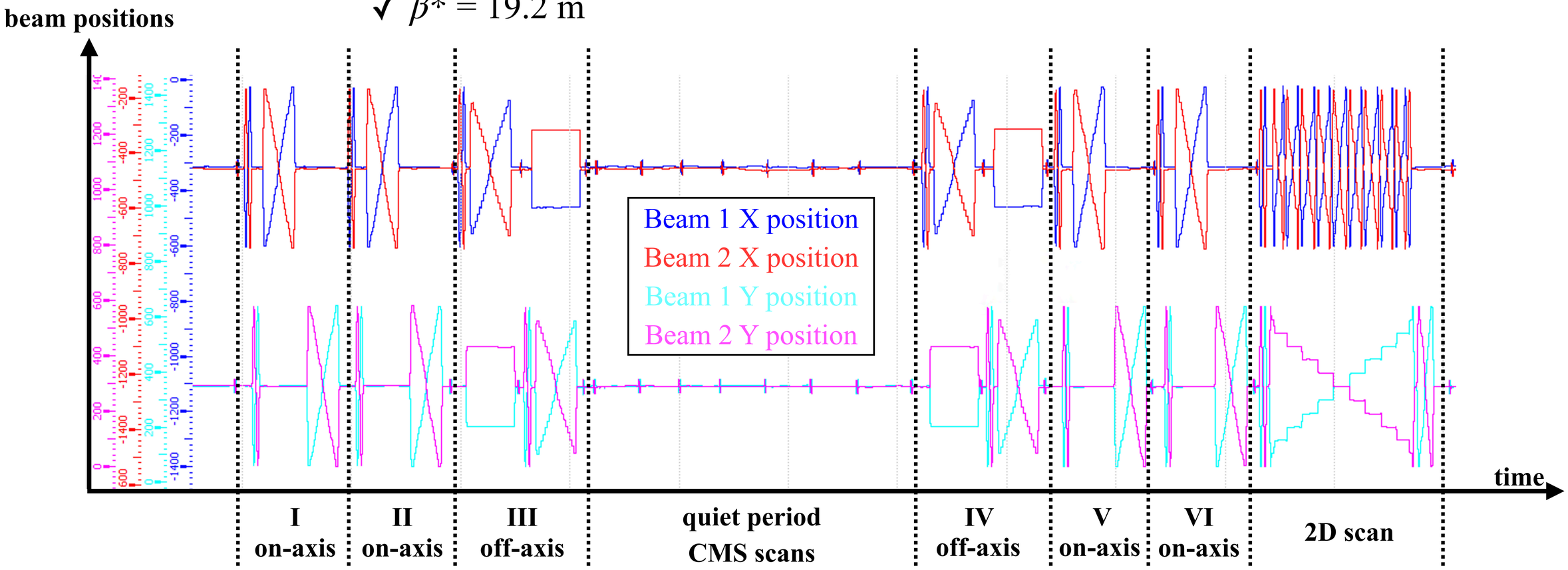
vdM methodology assumes that the beams are factorizable in x and y plane



van der Meer scan calibration Run 3 2022

van der Meer scans are taken in special “vdM conditions”:

- ✓ low μ (μ~1)
- ✓ isolated bunches
- ✓ no crossing angle
- ✓ β^* = 19.2 m



Corrections

Rates and beam-beam separations need to be corrected for several effects before extracting a precise σ_{vis}

vdM methodology assumes that the beams are factorizable in x and y plane

plot rate vs separation

$\Downarrow$

make a fit

$\Downarrow$

extract Σ_x, Σ_y and μ_{vis}^{max}

$\Downarrow$

$$L = \frac{n_1 n_2 f_r}{2\pi \Sigma_x \Sigma_y} \text{ and } \mu_{vis}^{max}$$

$\Downarrow$

$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y \mu_{vis}^{max}}{n_1 n_2 f_r}$$

Corrections to apply:

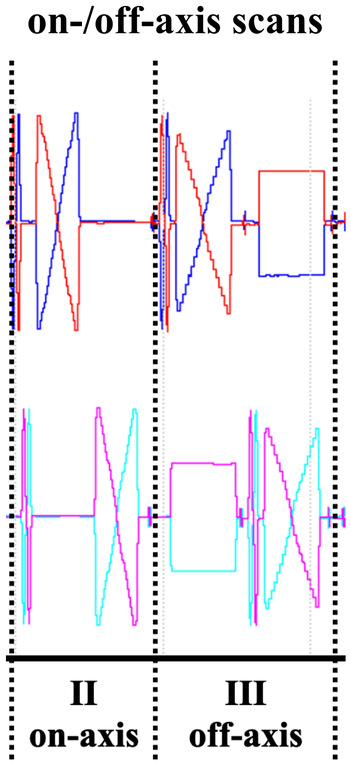
- Non-factorisation correction
- Length Scale Calibration correction
- Beam-Beam corrections
- Ghost and satellite charge corrections
- Background subtraction
- Orbit Drift Correction
- Emittance growth correction
- Bunch current offset

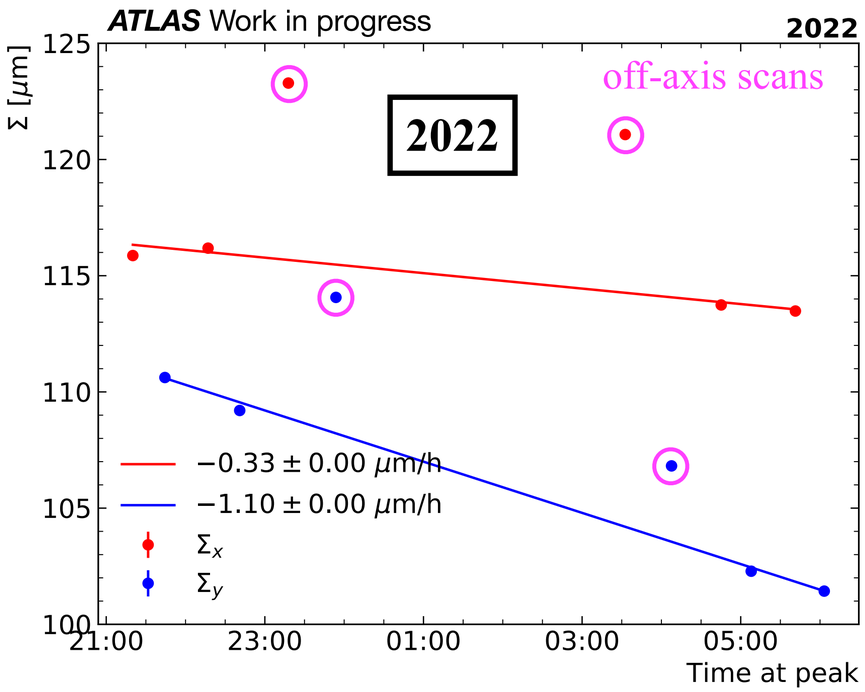
Importance in 2022

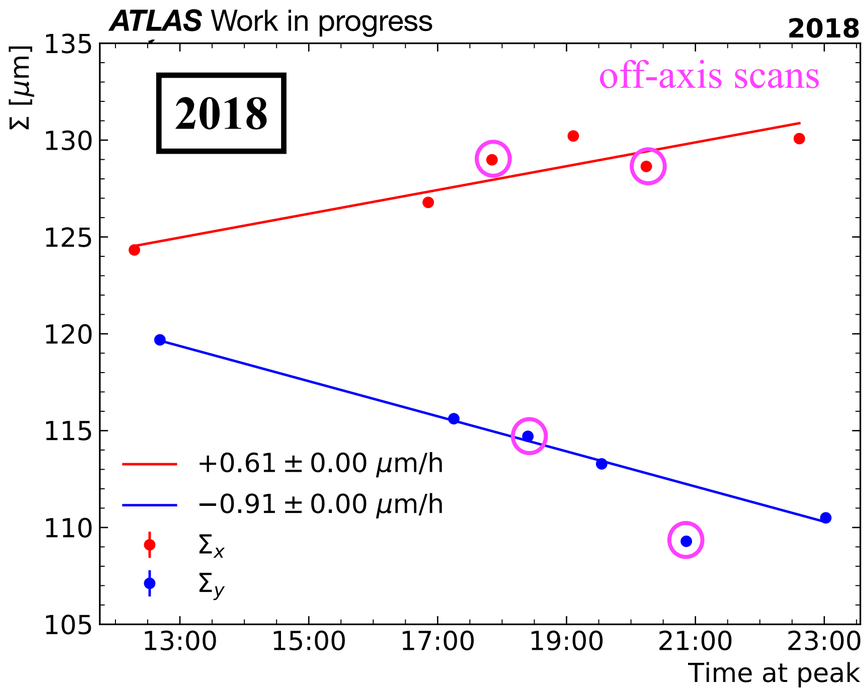
Non-factorisation effects

The van der Meer scan formalism assumes that the beams are factorizable in x and y plane

In reality this is not exactly the case







In these plots one can see the radiation damping effect in both planes for 2022

The non-factorisation effects are significantly bigger in 2022 than in 2018

Non-factorisation correction and uncertainty

Dominant corrections to the van der Meer analysis

non-factorization correction	1-2%
length scale calibration	1%
beam-beam corrections	1%

Big non-factorisation correction in this vdM scan session: ~ 1-2%

Other dominant corrections are length scale calibration and beam-beam corrections (~ 1%)

Dominant systematic uncertainties to the van der Meer analysis

Non-factorization effects	1.1%
Bunch-by-bunch consistency	0.5%
Differences between algorithms	0.4%
Other contributions (ind. <0.4%)	0.7%
Subtotal vdM calibration	**1.5%**

Non-factorisation is also the dominant systematic uncertainty!

How to get to the luminosity used for the physics analyses?

low pileup, no crossing angle and isolated bunches

vdM calibration: special vdM conditions

calibration transfer

data taking: physics conditions

high pileup, crossing angle and bunch trains

Subtotal vdM calibration	1.5%
Calibration Transfer	1.5%
Long-term stability	0.4%
Total uncertainty	2.2%

Summary

Why is it important?

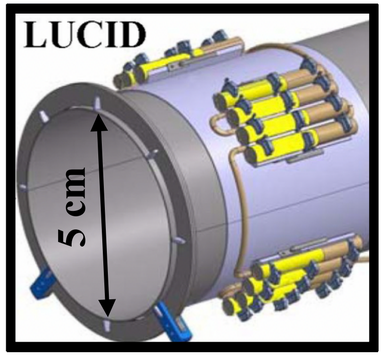
$$N = \sigma \cdot L_{int}$$

cross section → σ

number of events → N

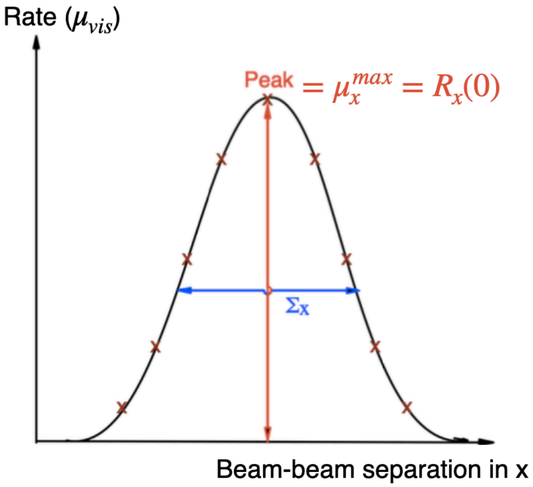
integrated luminosity → L_{int}

How do we measure it?

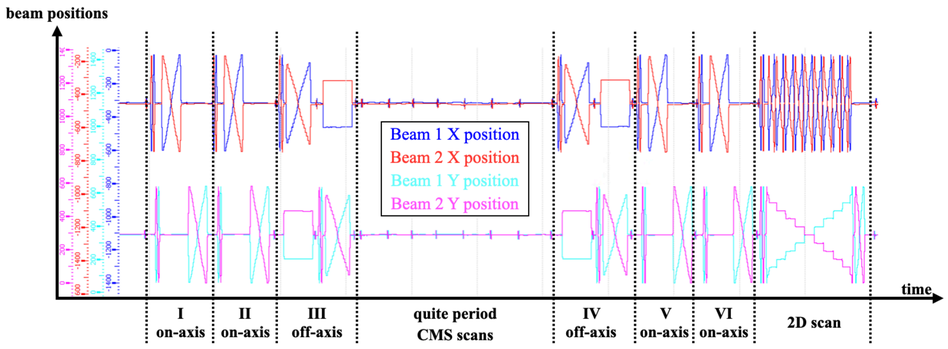


$$L = \frac{\mu_{visible} f_r}{\sigma_{visible}}$$

$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y \mu_{vis}^{max}}{n_1 n_2 f_r}$$



van der Meer scan session Run 3 2022



Main challenge: non-factorization effects

Corrections to apply:

- Non-factorisation correction
- Length Scale Calibration correction
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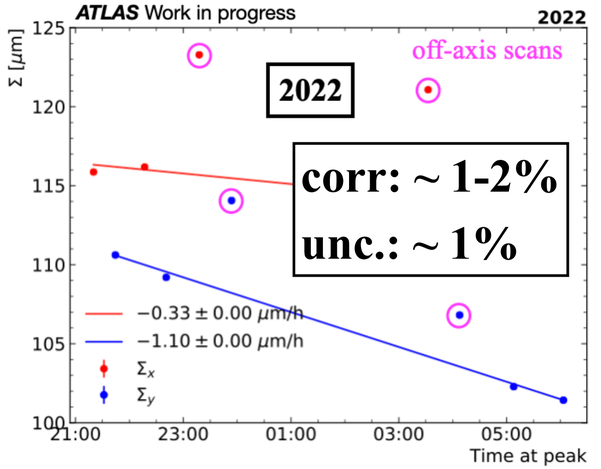
Importance in 2022



luminosity uncertainty: 2.2%!

Thank you for listening!