BB2024 Lausanne

Swiss Accelerator Research and Technology

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03.09.24

Beam-beam effects in the luminosity calibration

On behalf of multiple experts; with Tatiana Pieloni and Witold Kozanecki present and many more experts from the LHC luminosity working group

Outline of the presentation

- Introduction to luminosity measurement and calibration
- Beam-beam effects on luminosity
- Corrections
  - Single IP parametrization + multi-collision tune shift
  - Application examples from experiments
- Uncertainties
  - Points considered in the recently published overview paper
  - Typical vdM uncertainties
- Verification with measurement
- Ongoing studies & open questions

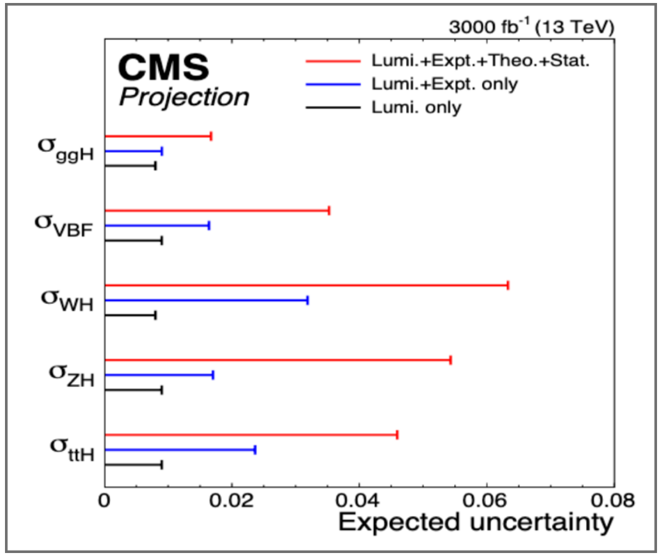
Why is luminosity accuracy and precision important?

- Precision luminosity measurement requirements
  - single largest source of experimental uncertainty in the most precise Standard Model measurements

$$R_{ev} = \mathcal{L}\, \sigma_{ev}$$

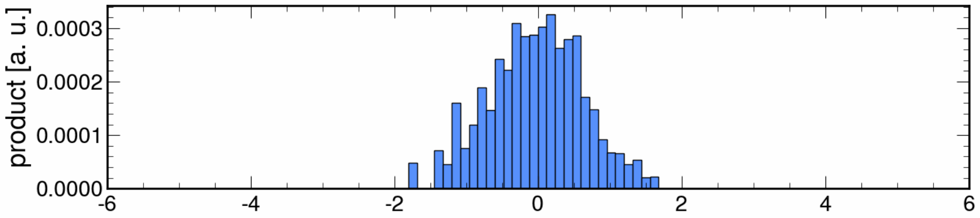
- Accurate luminosity calibration requires a thorough understanding of the beam-related systematic effects to correct for calibration biases
- Evaluation of biases from **systematic effects** such as beam-beam, orbit drift, etc.
  - apply corrections
  - estimate contributions to systematic uncertainty
- Beam instrumentation used whenever possible for bunch and beam currents, beam position at the IP, tunes, …
- Extended scan program used including multiple scans for dedicated studies
- First precision results in 2024 below 1%, DOI: 10.1140/epjc/s10052-023-11747-w
- Every year updated calibration: **(2022 data)** ATL-DAPR-PUB-2023-001, CMS-PAS-LUM-22-001, **(2023 data)** ATL-DAPR-PUB-2024-001, CMS-DP-2024-068, (2024 data) …

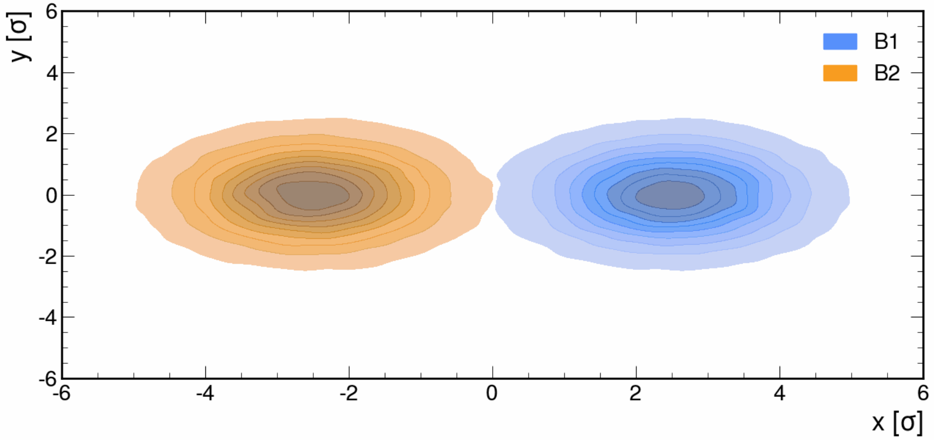
for example, top quark pair production - in the latest CMS publication, the preliminary 2.3% luminosity uncertainty dominates the total experimental uncertainty of 2.5% from other source

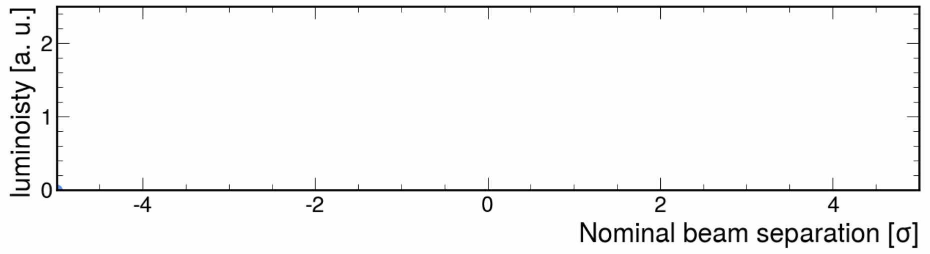


- ➢ will become even more important at HL-LHC with 1% target for absolute Higgs measurements

Luminosity calibration







- van der Meer (vdM) scans are performed every year to obtain the detector-specific visible cross-section σ_{vis}
- beams are moved across each other in discrete separation steps
- luminosity is given by the overlap integral of the particle densities $\rho_{1,i}, \rho_{2,i}$ in bunch-pair i:

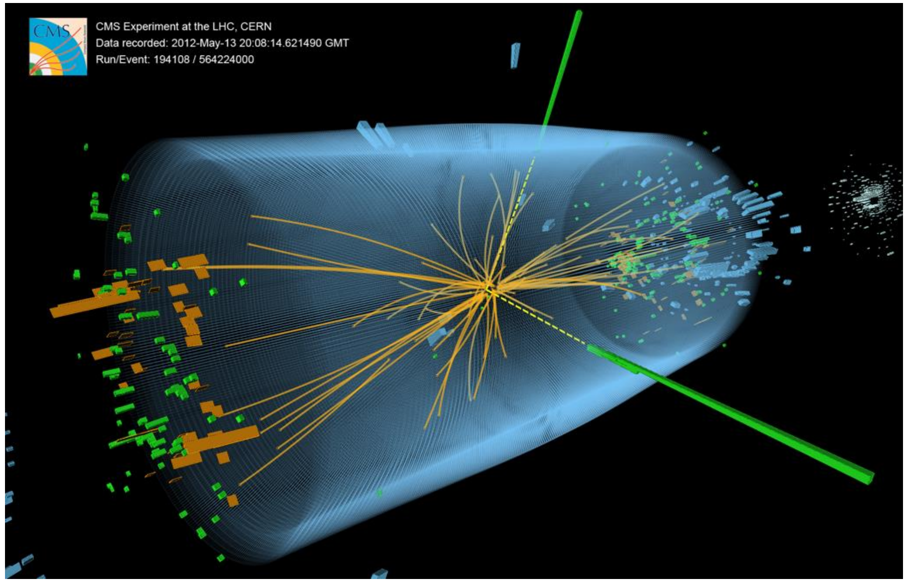
$$\mathcal{L}_{inst}^{vdM} = \sum_{i}^{N_b} n_{1,i} n_{2,i} f_{rev} \int\int\int\int_{-\infty}^{+\infty} \rho_{1,i}(x,y,z,t)\rho_{2,i}(x,y,z,t)\,dxdydzdt$$

- the convolved transverse beam size can be extracted from the measured visible rate along the scan: $$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R(\Delta_x, 0) d\Delta_x}{R(0,0)}$$
- a pair of scans (one for each transverse direction) is performed to obtain the full overlap area $\Sigma_x \Sigma_y$
- the absolute head-on luminosity can be computed from the measured bunch parameters, and compared to the measured rate to obtain the calibration constant σ_{vis}
- σ_{vis} can later be used to measure luminosity directly from the rate:

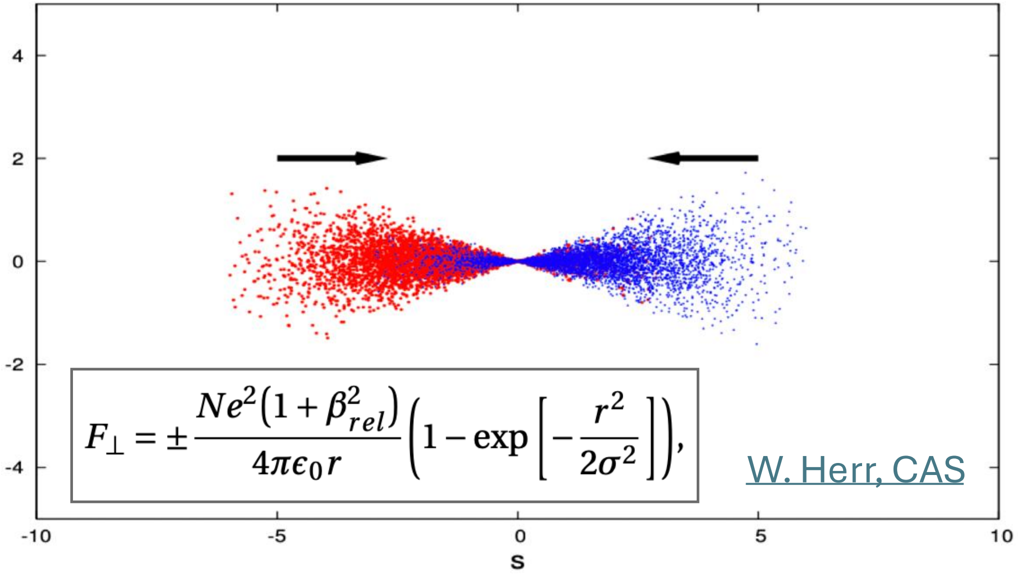
$$\sigma_{vis} = \frac{R_0^{vis}}{\mathcal{L}_{inst}^{vdM}} = 2\pi \frac{R_0^{vis}}{n_1 n_2} \Sigma_x \Sigma_y \rightarrow \mathcal{L}_{inst}^{phys} = \frac{R}{\sigma_{vis}}$$

When the beams are brought into collision

- expectation: high energy collisions between two protons,   p+p = Higgs signatures



- reality (for ~99.999..% of beam particles): the trajectory is changed due to the electromagnetic interaction with the opposing beam



$$F_{\perp} = \pm \frac{Ne^2(1+\beta_{rel}^2)}{4\pi\epsilon_0 r}\left(1-\exp\left[-\frac{r^2}{2\sigma^2}\right]\right),$$

W. Herr, CAS

Calibration accuracy and beam-beam effect

- BB parameter ξ used as a reference to quantify the strength,
- but bunch includes a distribution of particles at different amplitudes,
- single particle trajectory changes depending on its amplitude due to non-linear force,
- as a result, there is a tune spread in the beam $\Delta Q \sim \xi$,
    - **Beam-beam interaction has impact on the absolute luminosity calibration.**
- Big interest from the experiments to implement corrections and estimate uncertainties,
- Various configurations with multiple interaction points need to be considered,
- Simulation codes used to obtain accurate and **self-consistent** results:
    - COherent Multibunch Beam-beam Interactions (COMBI) - strong-strong
    - B*B - weak-strong
    - XSUIT *NEW
    - ~~MADX~~

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10.1140/epjc/s10052-023-12192-5

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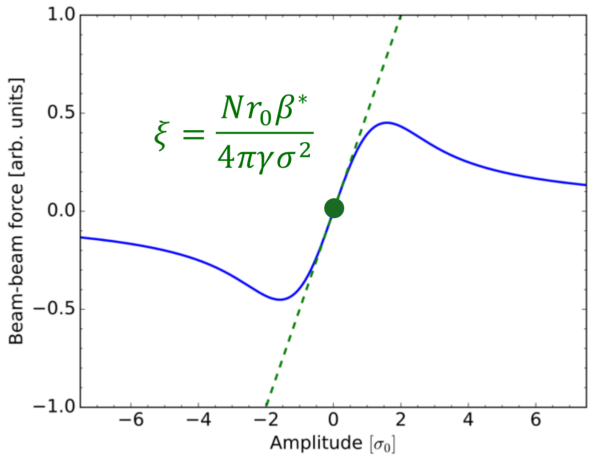
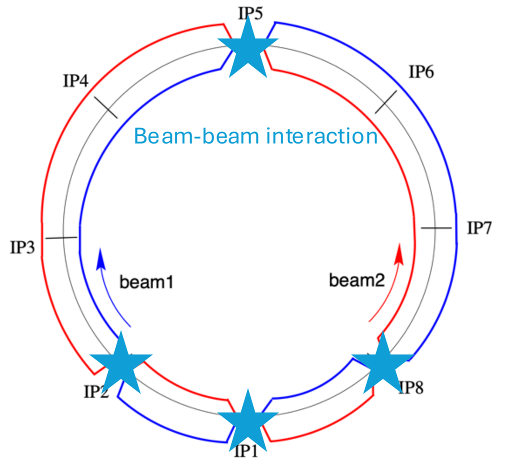
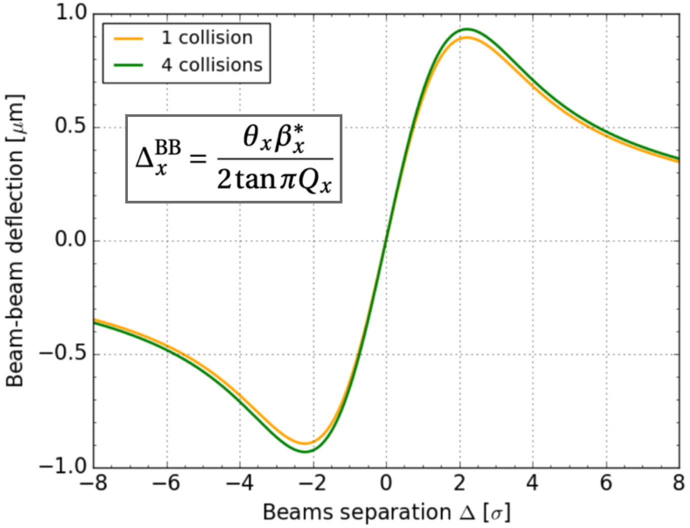
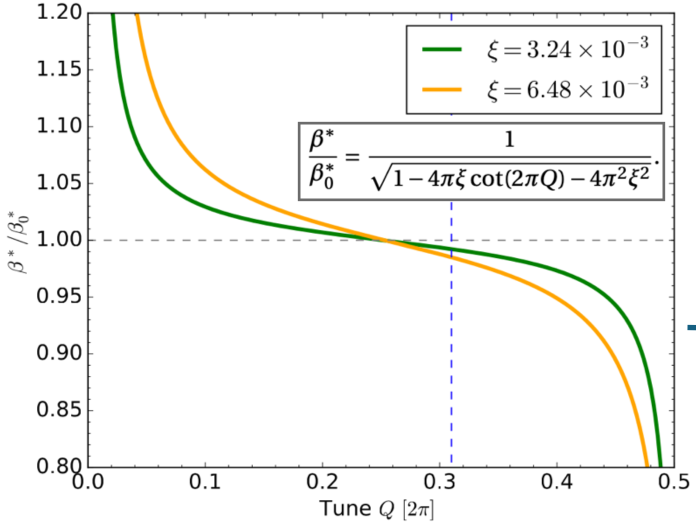




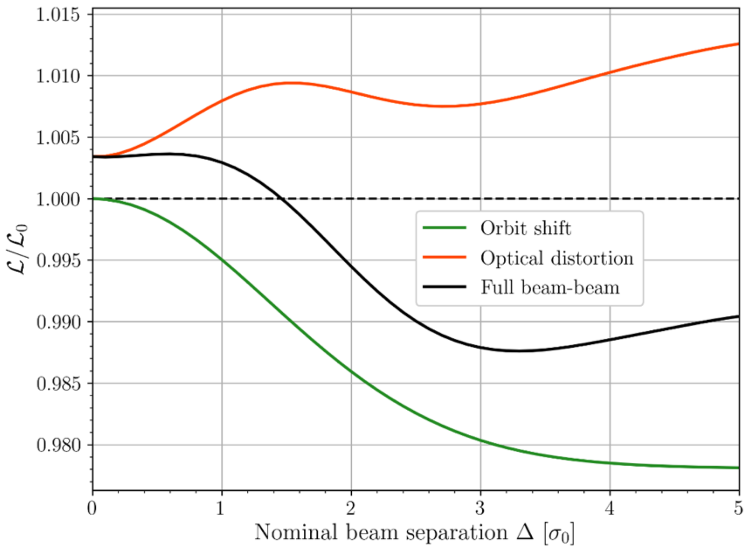
Beam-beam effects on luminosity

- Distinctive BB effects:
  - **deflection** induces change in the orbit
  - **optical distortion**
    - induces changes in the beam widths (dynamic-beta)
    - amplitude-dependent changes - **arbitrary distribution** → need for the lumi. integrator, COMBI development
- At the LHC opposite effects on luminosity
- Overall effect on the calibration constant slightly negative (sign and magnitude are tune-dependent)





$$\Delta x' \simeq -\frac{2Nr_0}{\gamma} \times \frac{1}{d}\left(1 - \exp\left[-\frac{d^2}{2\sigma^2}\right]\left[1 + O(r) + O(r^2) + ...\right]\right),$$



in the first approximation beam size envelope changed

$$\sigma = \sqrt{\beta^* \times \epsilon_g}.$$

$$\frac{\Delta L}{L} \approx -\frac{1}{2}\frac{\Delta\beta_0}{\beta}.$$

for Gaussian particle distrib.

Corrections – beam-beam deflection

- Deflection **calculated analytically** from Bassetti-Erskine closed expression for the electrical field of a two-dimensional Gaussian charge Q distribution:

$$E_x = \frac{Q}{2\epsilon_0\sqrt{2\pi(\sigma_x^2-\sigma_y^2)}}\Im\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)-e^{\left[-\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}\right]}w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right],$$

$$E_y = \frac{Q}{2\epsilon_0\sqrt{2\pi(\sigma_x^2-\sigma_y^2)}}\Re\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)-e^{\left[-\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}\right]}w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right].$$

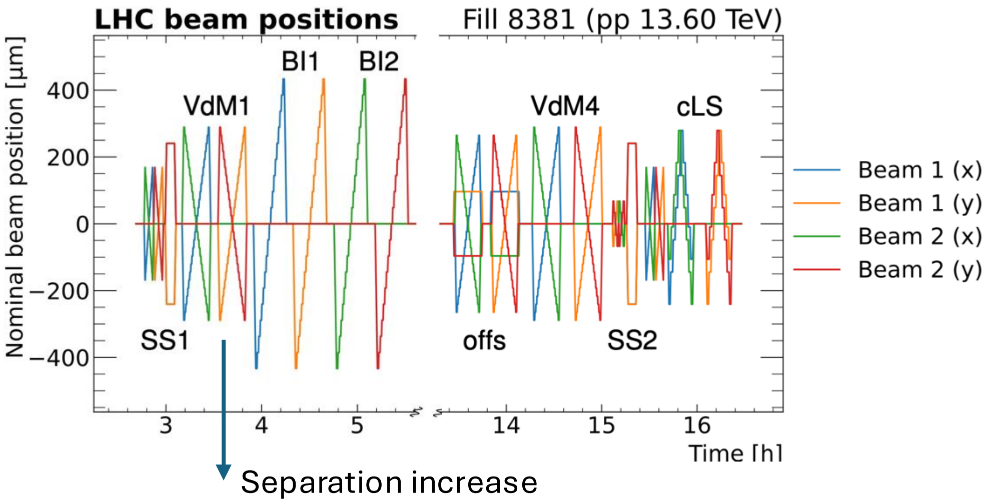
- For the same charged bunches moving in the opposite directions generates repulsive kick whenever the collision occurs with an **offset**:

$$\theta_x = \frac{2Nr_0}{\gamma}E_x.$$

- Causing an **additional orbit offset** at the Interaction Point:

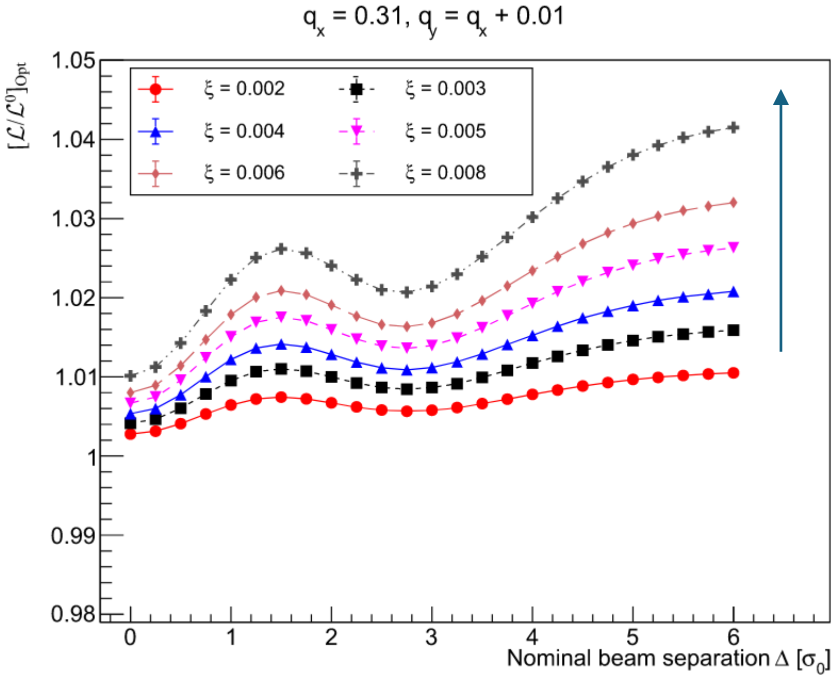
$$\Delta_x^{\mathrm{BB}} = \frac{\theta_x\beta_x^*}{2\tan\pi Q_x}.$$

- It is **added** as correction directly to the nominal beam position



Corrections - single-IP parametrization

- **Optical distortion** including the amplitude dependent changes
  - not possible to evaluate analytically in an accurate way – evaluate with simulation
- Correction model parametrizing the beam-beam effects on luminosity $\mathcal{L}/\mathcal{L}_0(\Delta, \xi, Q_x, Q_y)$ in vdM conditions using:



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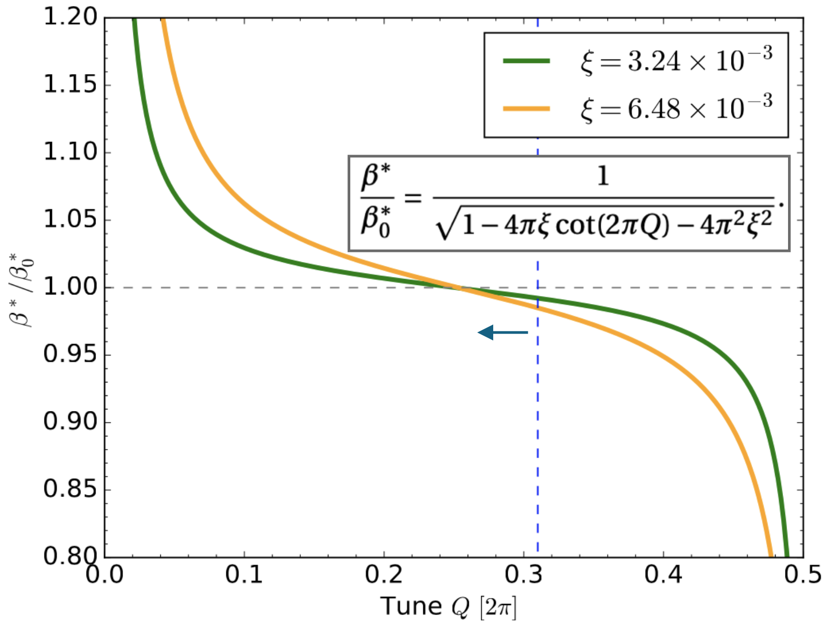
Increasing beam-beam parameter (linear)

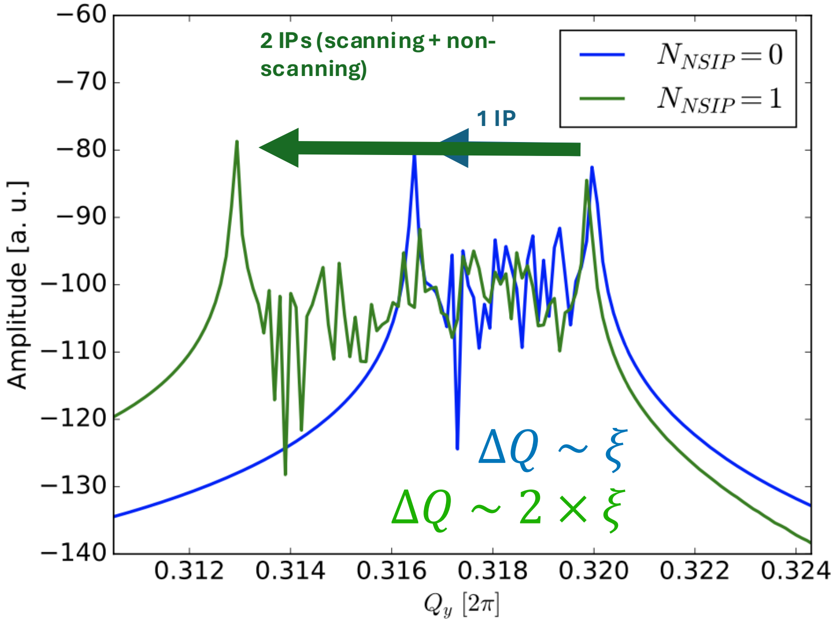


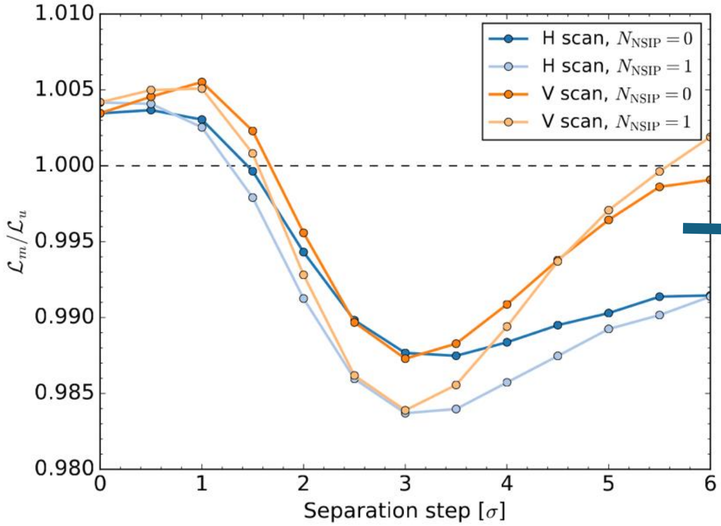
Tune sensitivity: additional tune shift = reduced focusing

✓ Beam-separation dependent corrections

Corrections - multi-collision cases

- contribution from the additional collisions at interaction points (IPs) other than the scanning IP
  - simulation campaign to evaluate them
- quadrupole-like approximation not correct
- additional collision = additional betatron tune shift
  - separation-dependent effect on luminosity changes depending on the collision configuration
  - in the example of 2 IPs - double the effect on σ_{vis}





effect on calibration constant ~integral under the curves of both transverse scans

$$\sigma_{\text{vis}} \sim \frac{1}{\mathscr{L}(0,0)} \int \mathscr{L}(x,0)\,dx \int \mathscr{L}(0,y)\,dy.$$

	relative difference in $\sigma_{vis}/\sigma^0_{vis}$
IP1 scanning	-0.16%
IP1 scanning + IP5	-0.37%

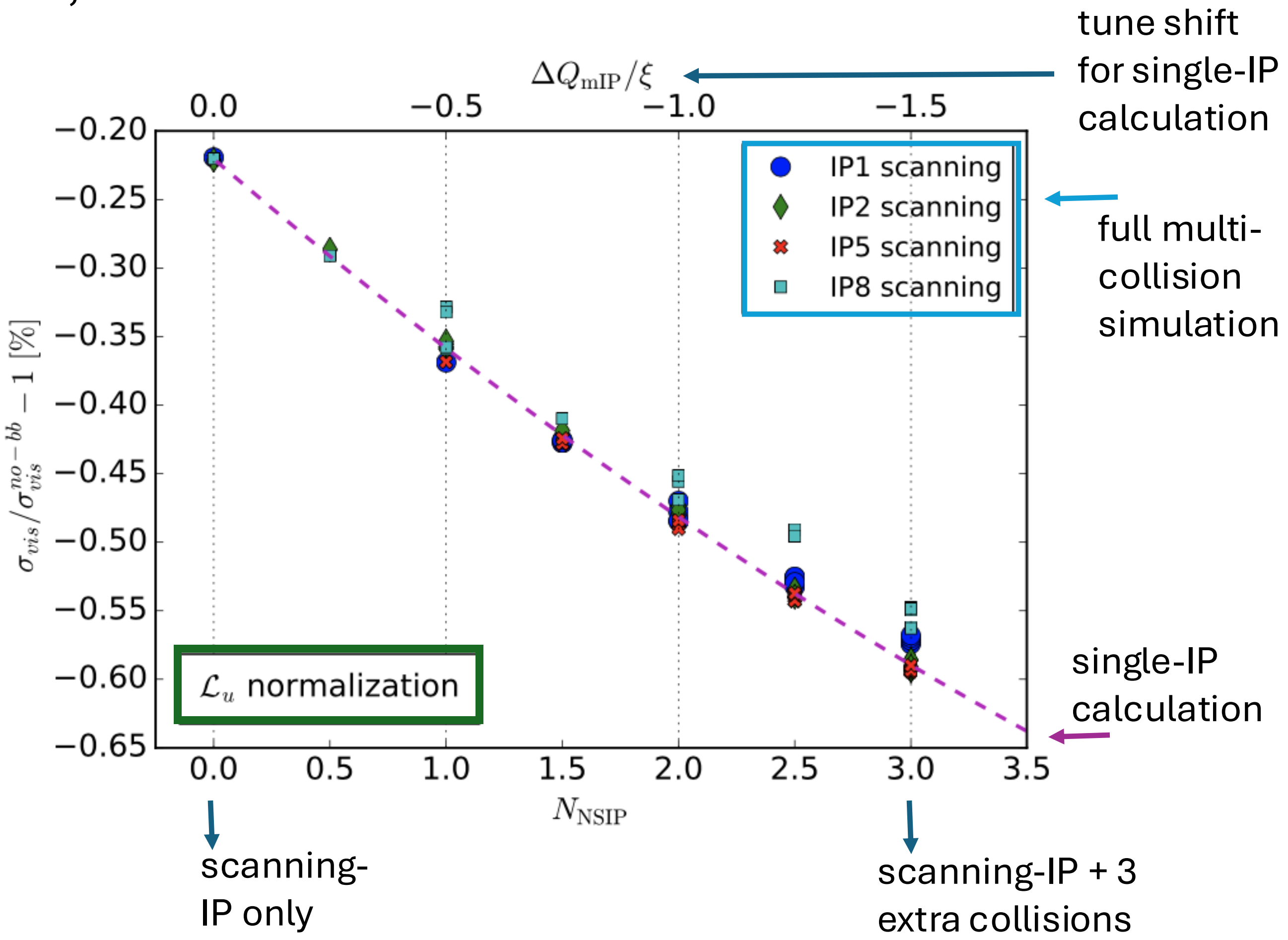
➢ How to include that in the corrections in a universal way?

Impact of multi-IP effects on luminosity calibration

- Luminosity bias correction model based on the single-IP parametrization dependent on beams separation Δ, BB parameter and tunes $\mathcal{L}/\mathcal{L}_0(\Delta, \xi, Q_x, Q_y)$
- effective multi-IP tune shift ΔQ_{mIP} can be used to obtain the equivalent σ_{vis} bias
- simple scaling law derived from strong-strong simulations:

$$\Delta Q_{mIP} = -0.5 \times \xi N_{NSIP}$$

- valid for all LHC IPs
- verified in simulation for vdM regime (ξ<0.01)
- when considering more than single collision there is an ambiguity related to the normalization
  - 'witness' collision perturbed $\mathcal{L}_u$



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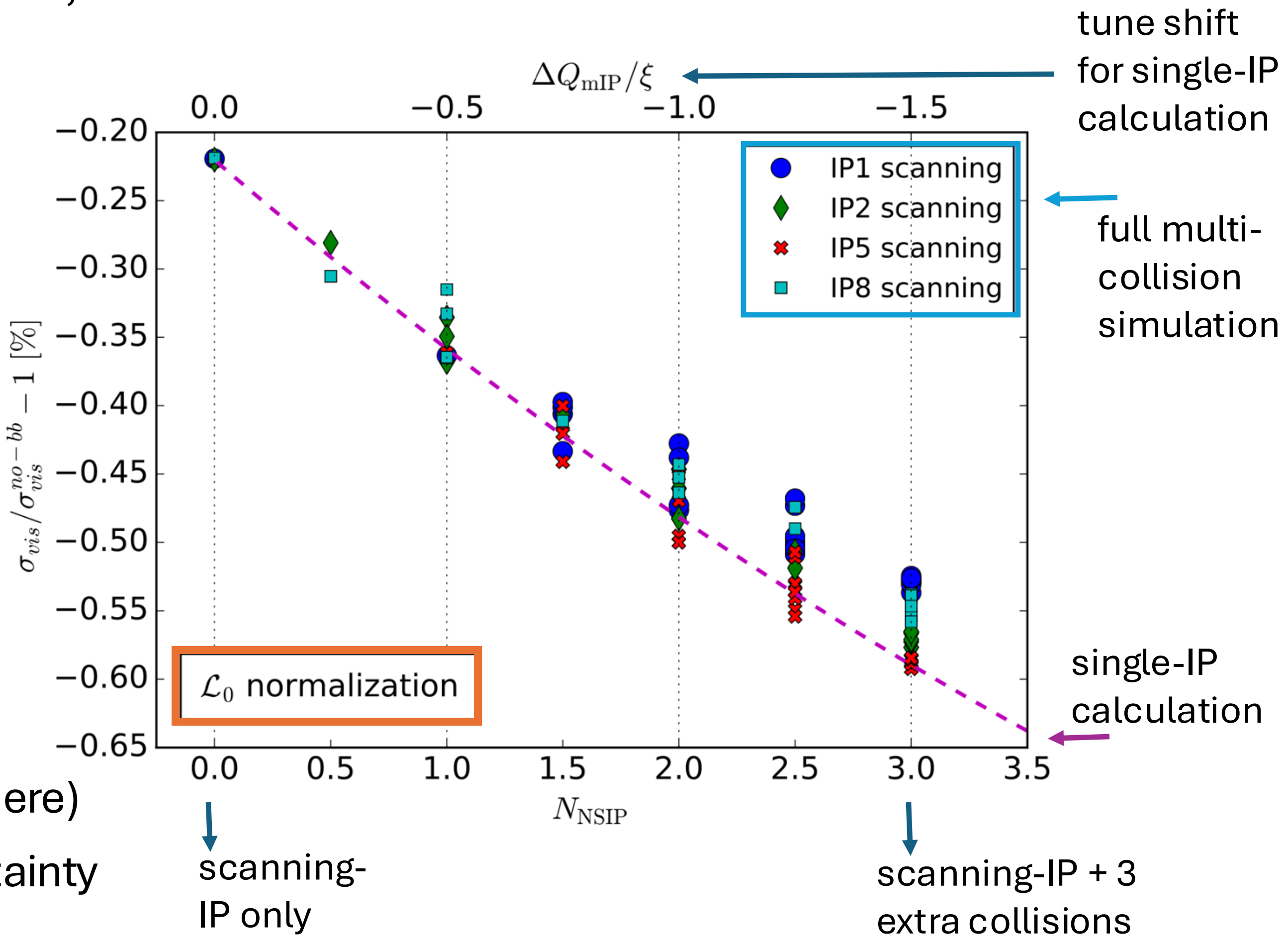
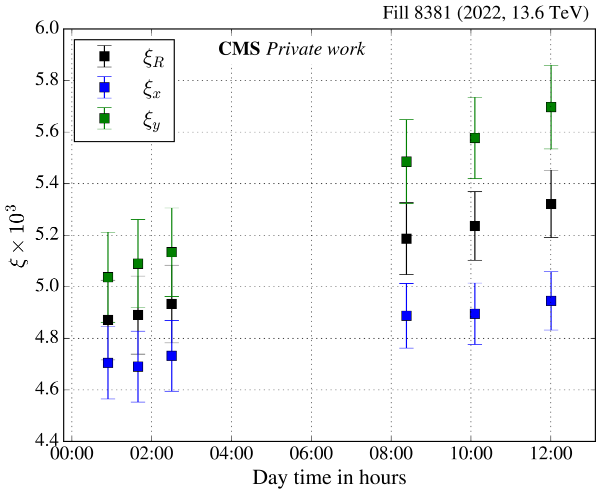
- when considering more than single collision there is an ambiguity related to the normalization
  - 'witness' collision perturbed $\mathcal{L}_u$
  - absolute $\mathcal{L}_0$ (no beam-beam interaction anywhere)
  - phase advance dependence, covered in uncertainty

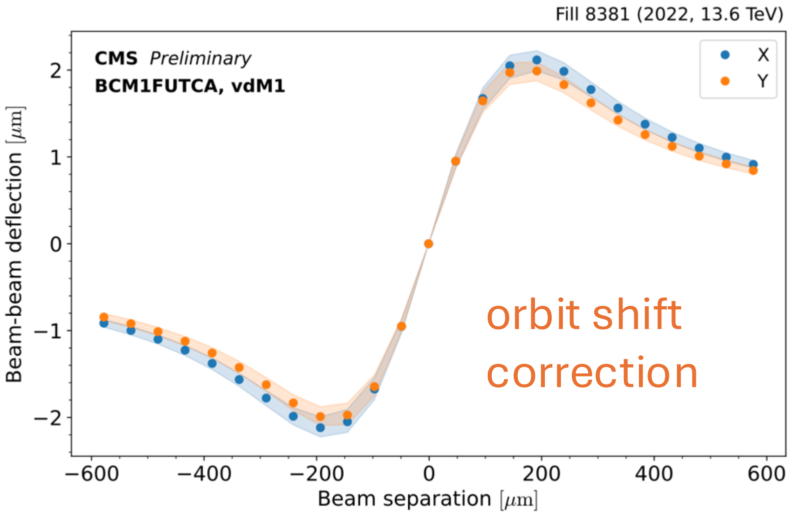


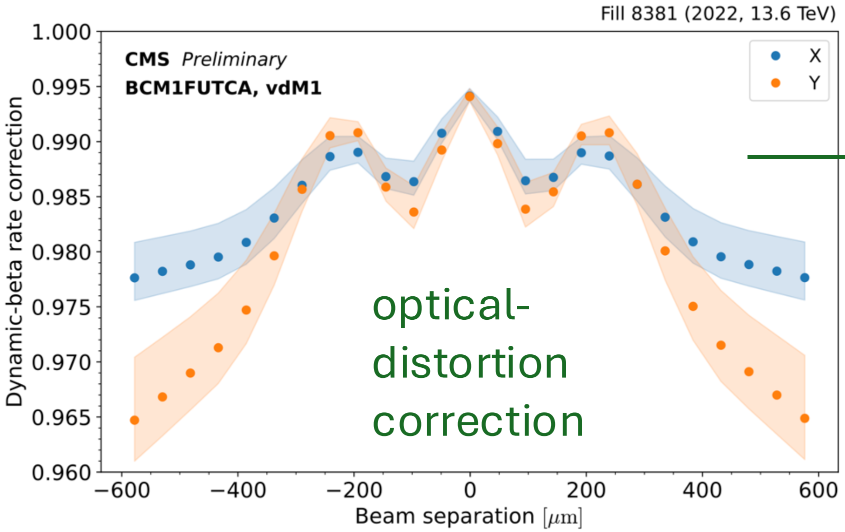
Example luminometer calibration corrections

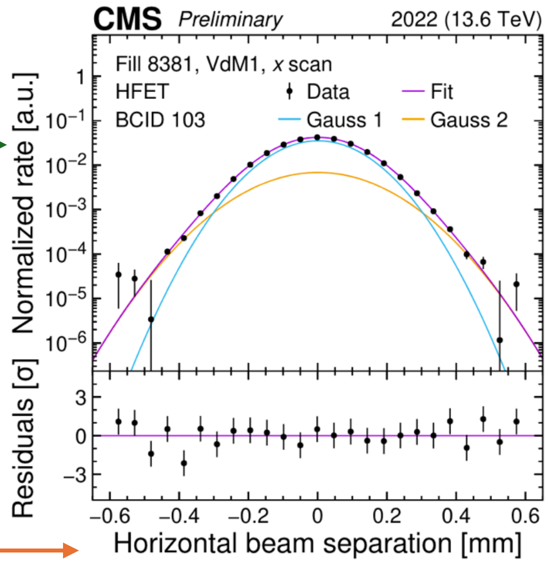
- vdM is the case of very **special beam conditions** that results in the increase of ξ over time in collision, standard ξ~<u>0.003</u> - 0.006
- **per bunch corrections** dependent on its parameters as well as the total number of collisions give spread in corrections (background colors)
- Significant differences in correction for the two scan directions from the sensitivity to tune setpoint (from difference of $0.01\ [2\pi]$)



EPFL, Thesis Nr. 10500, CMS-PAS-LUM-22-001







Systematic effects after beam-beam corrections

- Typical total correction on the level of +1%,
- Beam-beam uncertainty sources considered:
  - nominal (Q_x, Q_y), transverse non-Gaussianity, β^*, beam ellipticity, beam 1/beam 2 emittance imbalance, single & multi-IP modelling, phase advances.
  - Considered negligible in vdM conditions: residual crossing-angle, lattice non-linearities.

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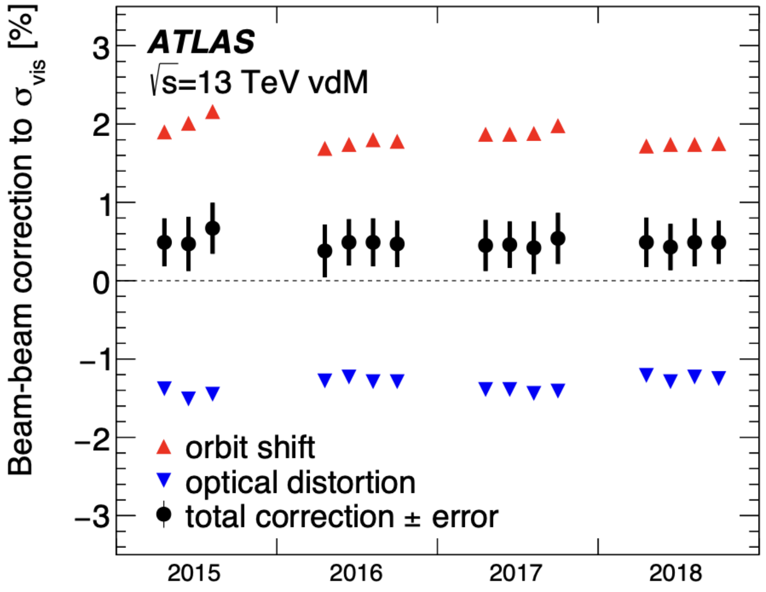
- Procedures available for uncertainty determination can be obtained from:
  - parametrization,
  - or simulation.



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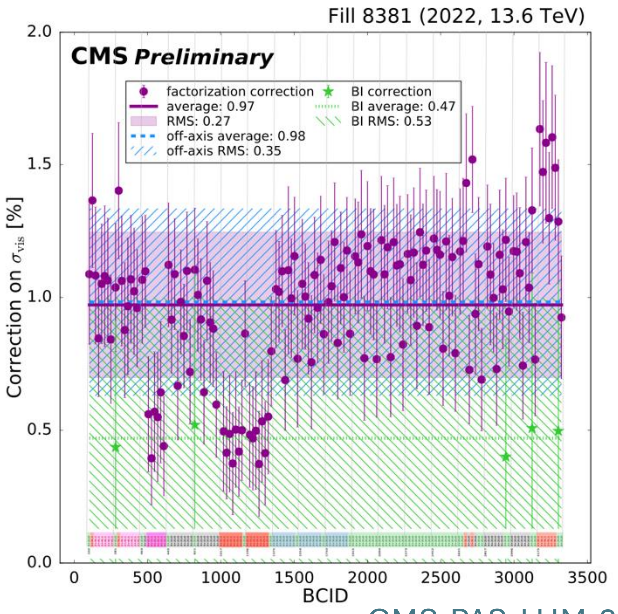
- Typical total uncertainty of ~0.4% contributes directly to the total uncertainty of the calibration,
  - Most sensitive to the conditions (assessed with ξ) but also to the total number of collisions.

Residual beam-beam signatures?

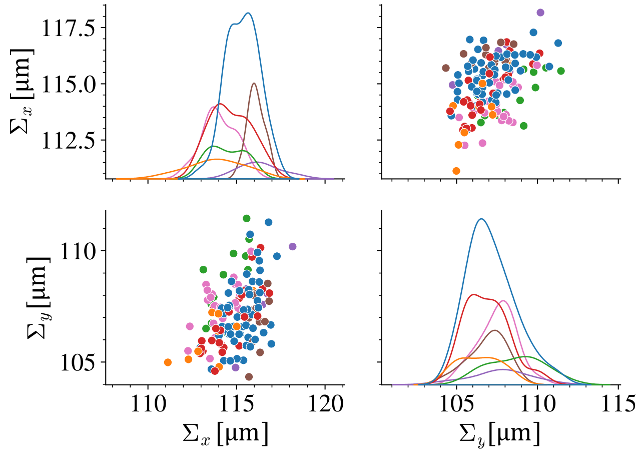
- There are still open questions with regards to the beam-beam interaction and the luminosity calibration
- vdM data shows traces of differences evolving in time that depend on the collision pattern thus could be induced by the beam-beam interaction
- Interplay with other effects such as the linear coupling resonance, and non-factorization of x and y transverse distribution

$$\sigma_{vis} = 2\pi \frac{R_0^{vis}}{n_1 n_2} \Sigma_x \Sigma_y$$



CMS-PAS-LUM-22-001

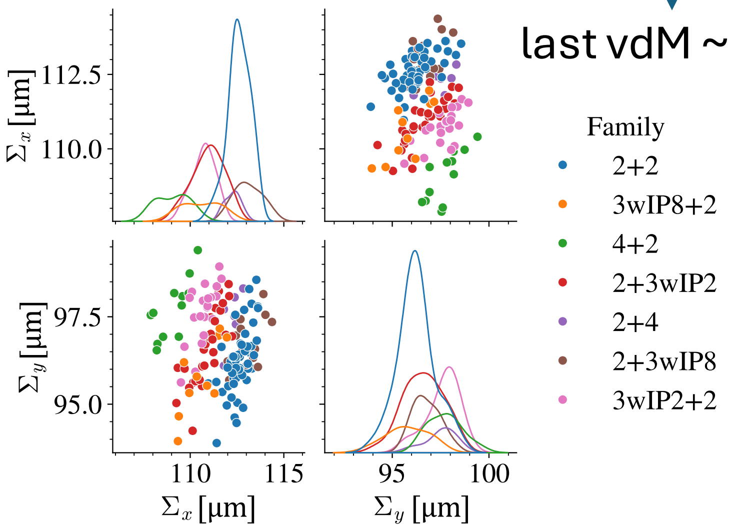
- Full modelling missing in the analysis of the non-standard scans (diagonal, offset, 2D...)
- Accuracy of some of the assumptions, for example Gaussian modelling for calculating the primary EM force, especially in the case of the observed q-Gaussian charge distribution at the LHC



2022: first

↓

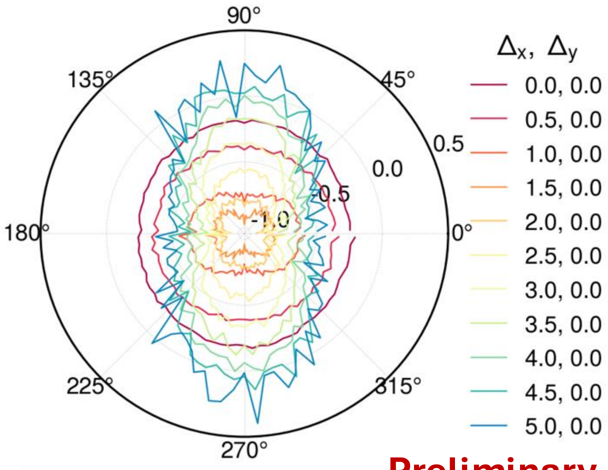
last vdM ~11 h



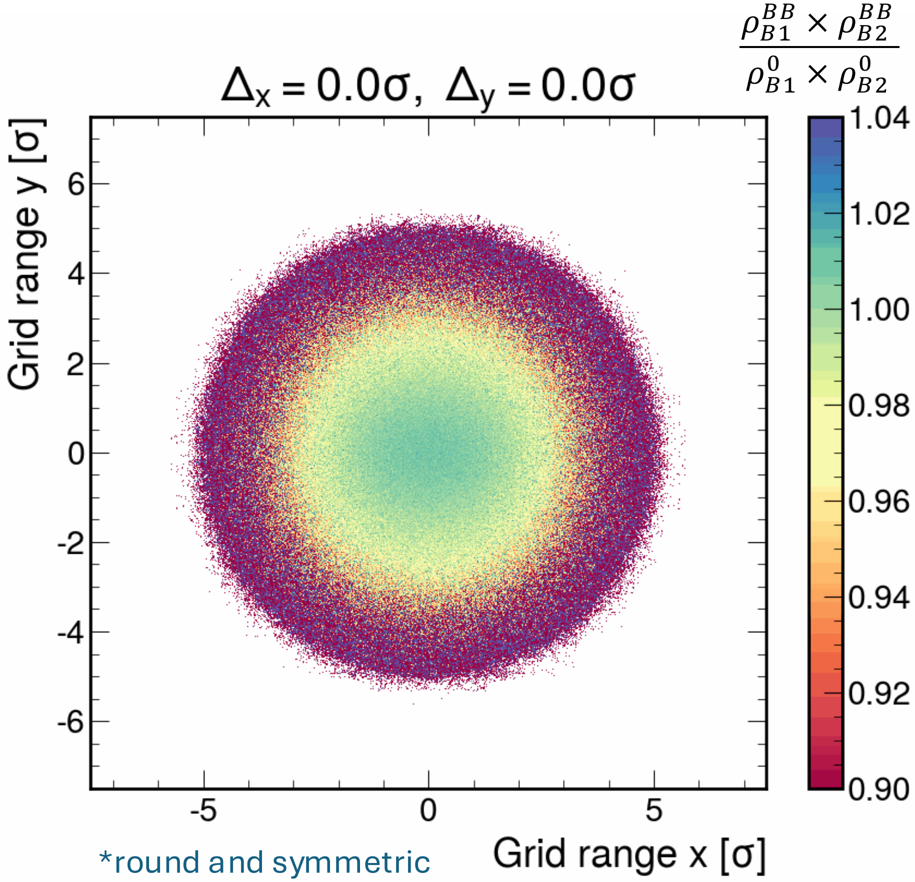
Ongoing studies – BB impact on the luminous region

+ Chenying Zhang, Tatiana Pieloni (EPFL)

- Active code development to study the the impact of beam-beam interaction on the observable available during vdM scans - implemented in XSUIT due to its versatility and reliability
- **Luminous region** is reconstructed with high statistics detectors used to measure primary vertices,
- During vdM it is used to study transverse factorization of the charge distribution within a bunch,
- First insight into the beam-beam induced changes on the luminous region.



Preliminary

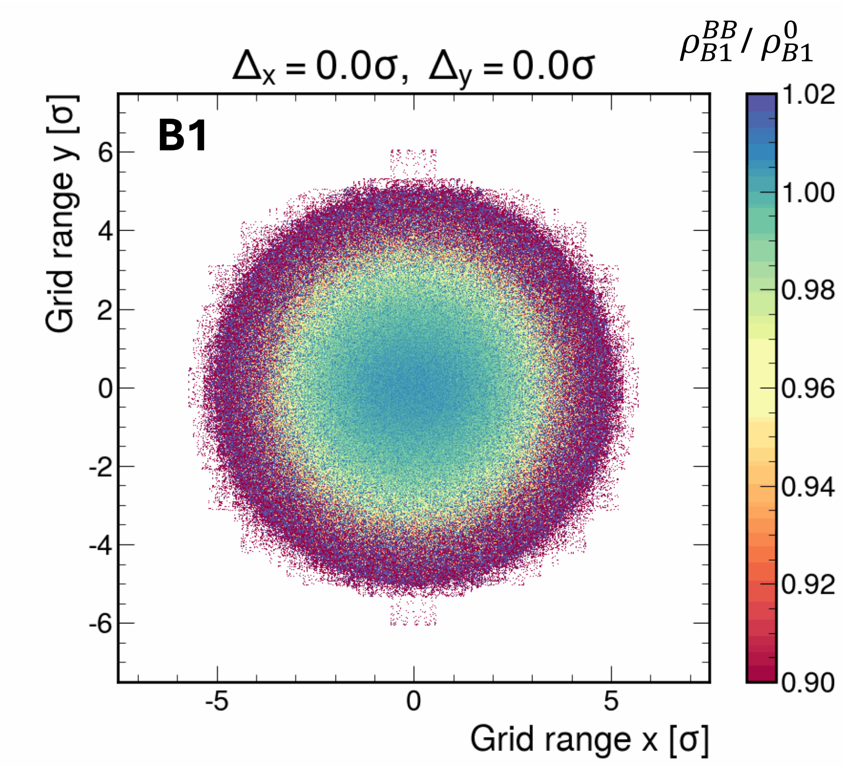


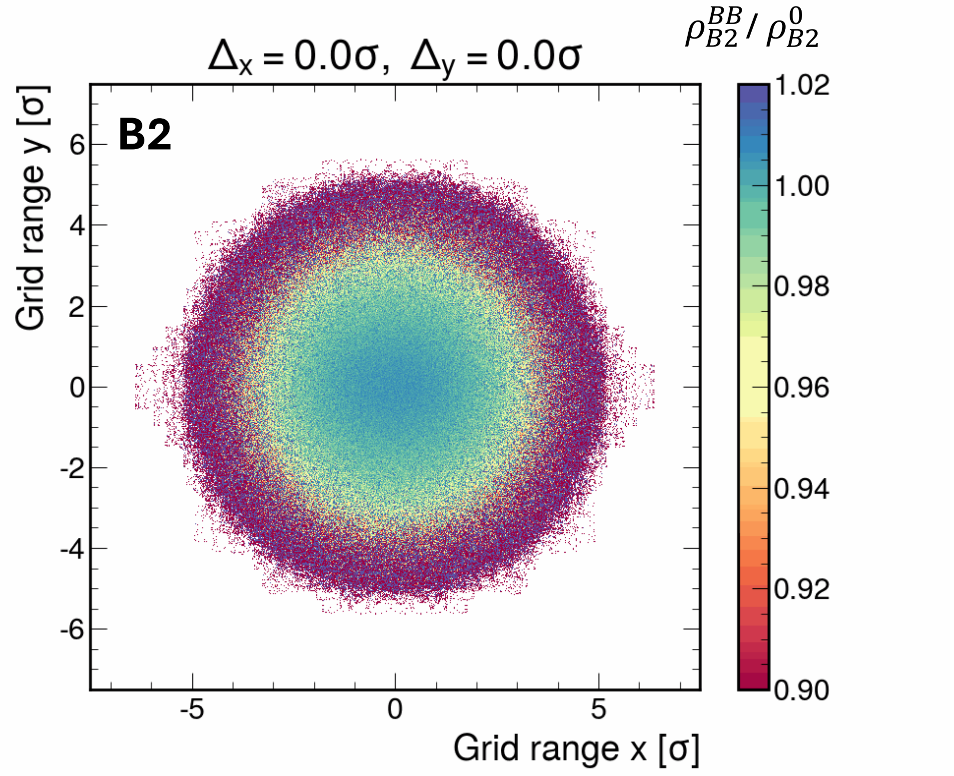
*round and symmetric Gaussian beams, $\xi = 0.003$

Ongoing studies – Possibility to study the BB induced non-factorization

New student
Lia joined!

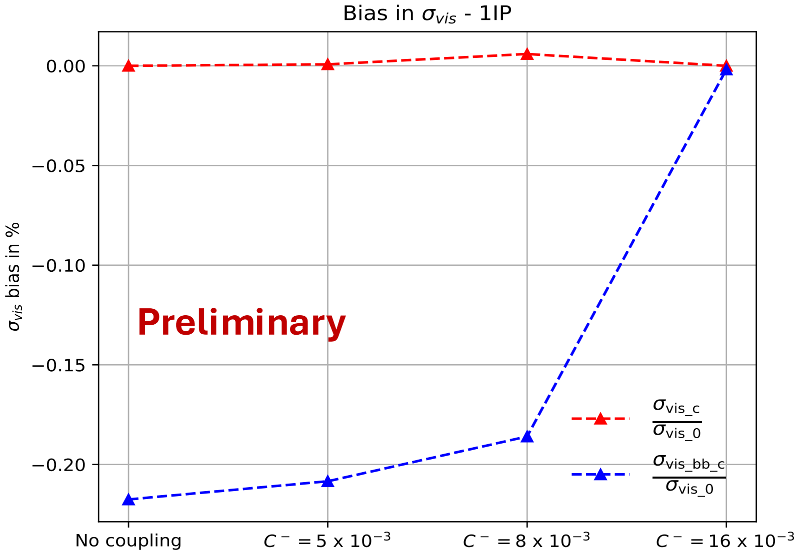
- Developments with the goal to study the changes to charge distributions



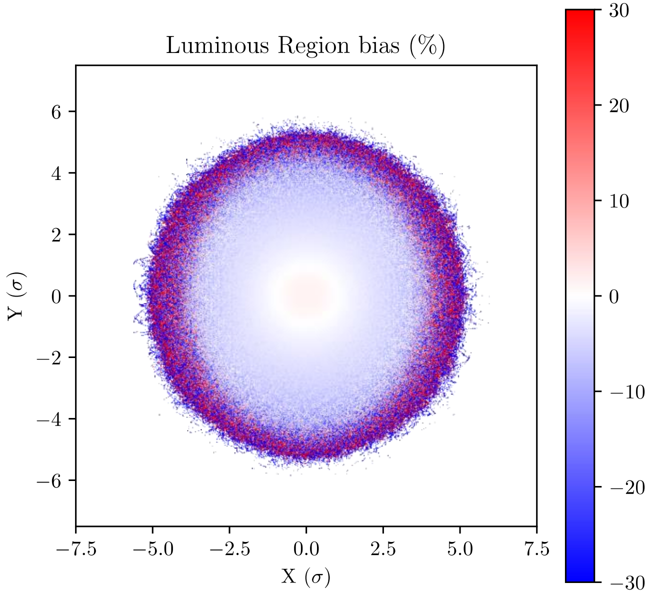


Ongoing studies – BB + linear coupling resonance

- By incorporating a skew quadrupole to introduce linear coupling the $x - y$ charge distribution product is modified
- Thus, luminosity bias curve from beam-beam effects is also changed

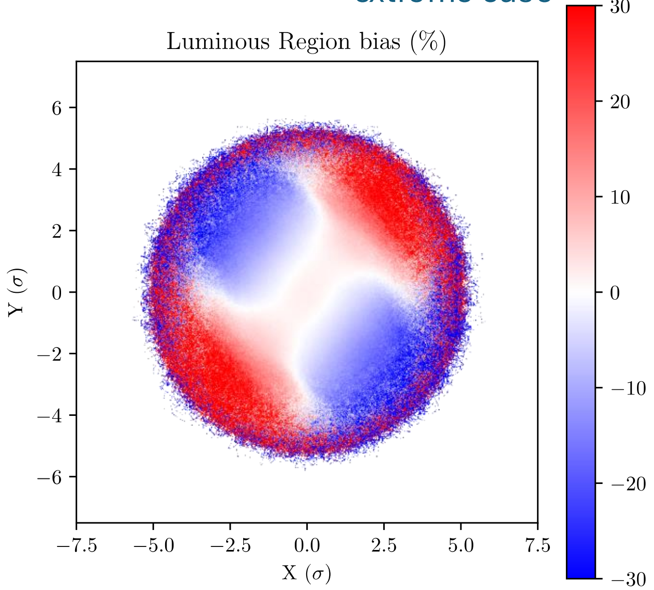


Bias from beam-beam



Bias from beam-beam and coupling with $C^- = 16 \times 10^{-3}$

* extreme case

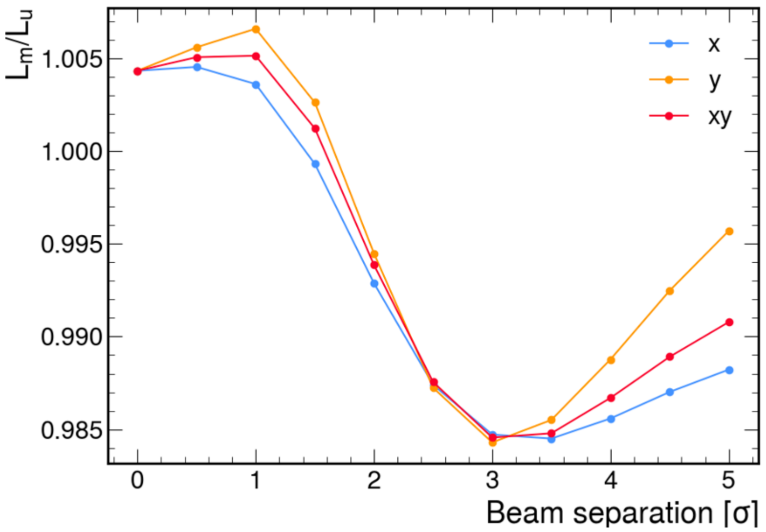


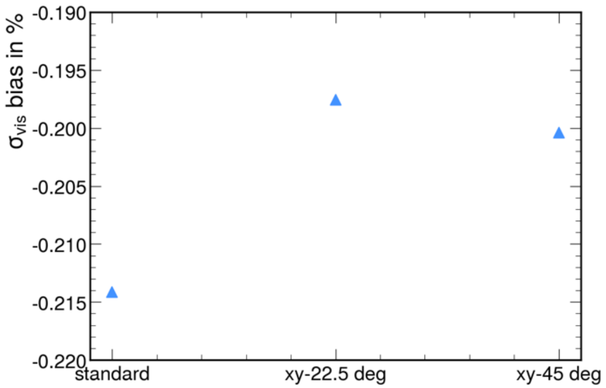
*data aggregated over full horizontal scan, Chenying Zhang (EPFL/IC)

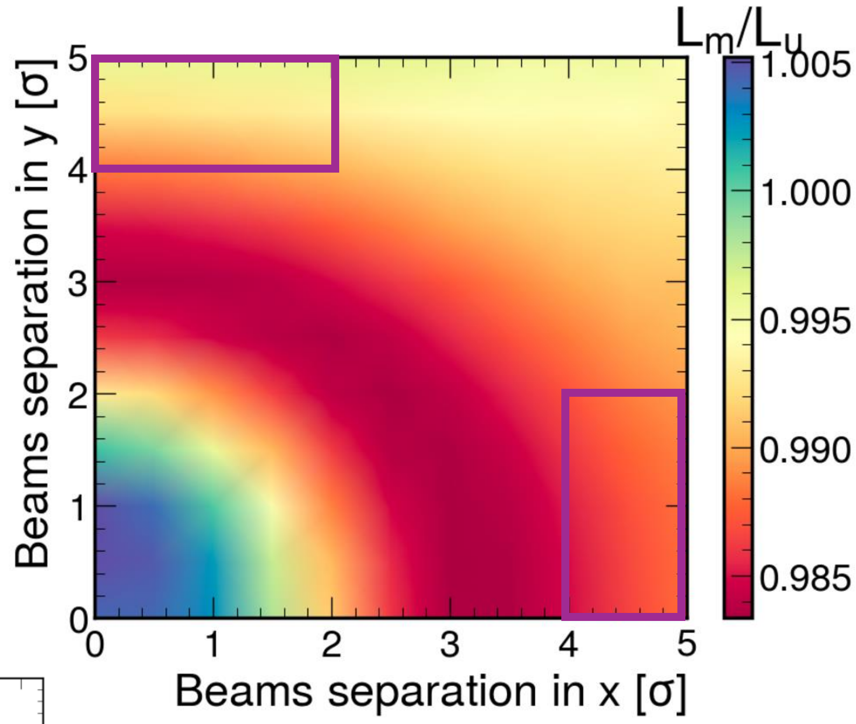
- This results in a corresponding reduction in σ_{vis} bias
- The effects of beam-beam effects and linear coupling resonance begin to cancel each other out (case of a horizontal 1IP scan)

Ongoing studies – diagonal, offset, 2D scans

- Non-standard scans are not covered by the parametric model
- Angular symmetry broken with differences in tunes and phase advances
- Beam-beam bias on luminosity during a diagonal scan comes out in between the standard x and y directions
- Results in slightly reduced bias on σ_{vis} when compared to the standard scan pair



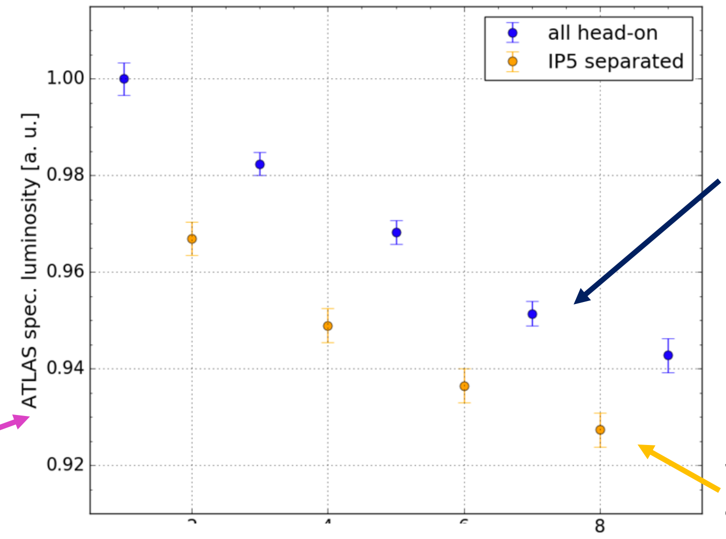




- Bias for 2 IPs cases changes when evaluated in full 2D

Beam-beam **measurement**

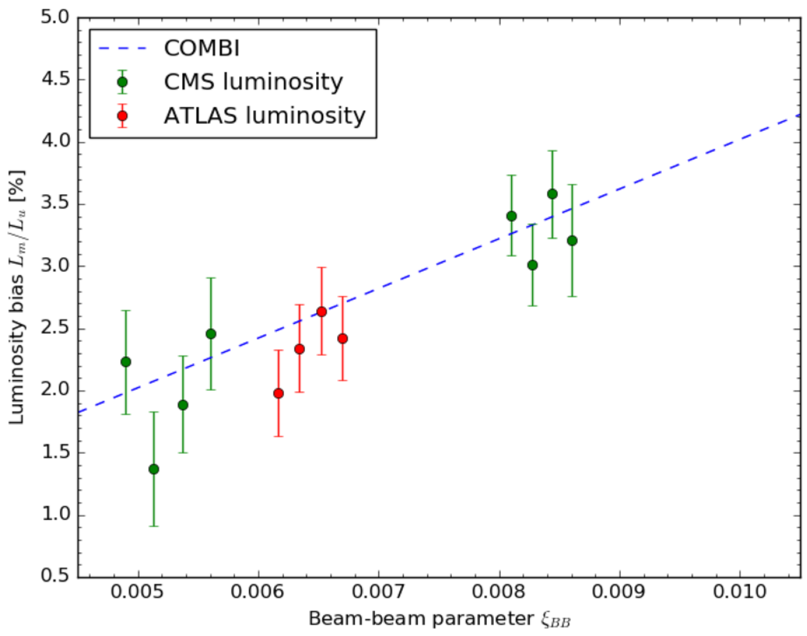
- Aimed at validation of the correction strategy used in the vdM calibration
- phase advance between IP1 & IP5 optimized for **maximizing** the effect on luminosity $(1 \rightarrow 3\%)$ at the witness IP at LHC injection energy 450 GeV
- methodology using the **witness IP** with configuration changes at other location
- repetitive steps used for validation
- **first measurement** of the impact of BB effects on the luminosity at the LHC
- scaling law with BB parameter verified
  - wire scanner measurements used as a reference to evaluate ξ_{BB}
  - **very good agreement with simulation** ⟶



witness

repetitive change of configuration

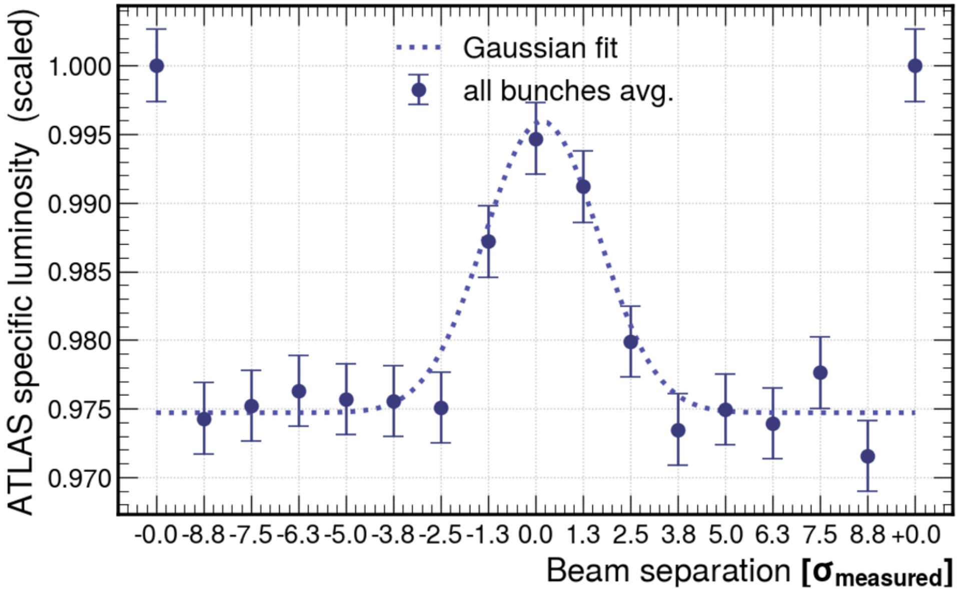
separation at another location

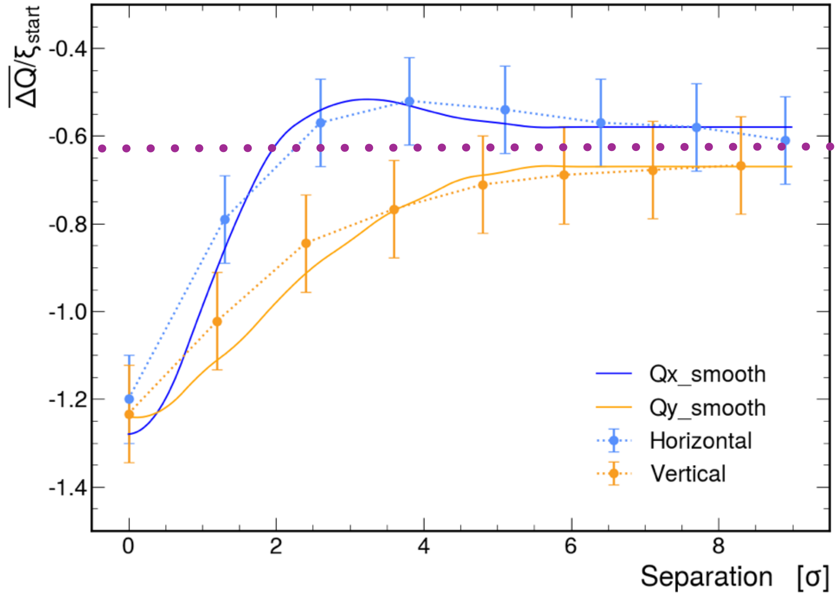


Luminosity enhancement in head-on configuration caused by additional BB interaction (at another IP) as measured by both **ATLAS** and **CMS** (observer IP), as a function of the single-IP BB parameter, compared to **COMBI** simulation predictions

BB experiment - results

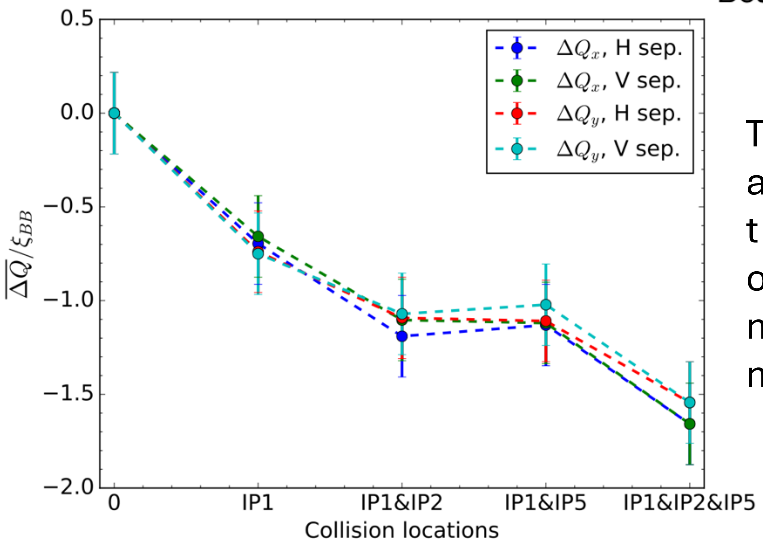
- observations of BB-induced changes during a separation scan
  - very clear on the mean tunes extracted from the spectra as well as on the luminosity
- observed scaling with the number of collision supports the multi-IP modeling strategy
- overall good agreement of all beam-beam tests with expectations
- quality of the results can be improved by optimized scan program





← single collision tune shift

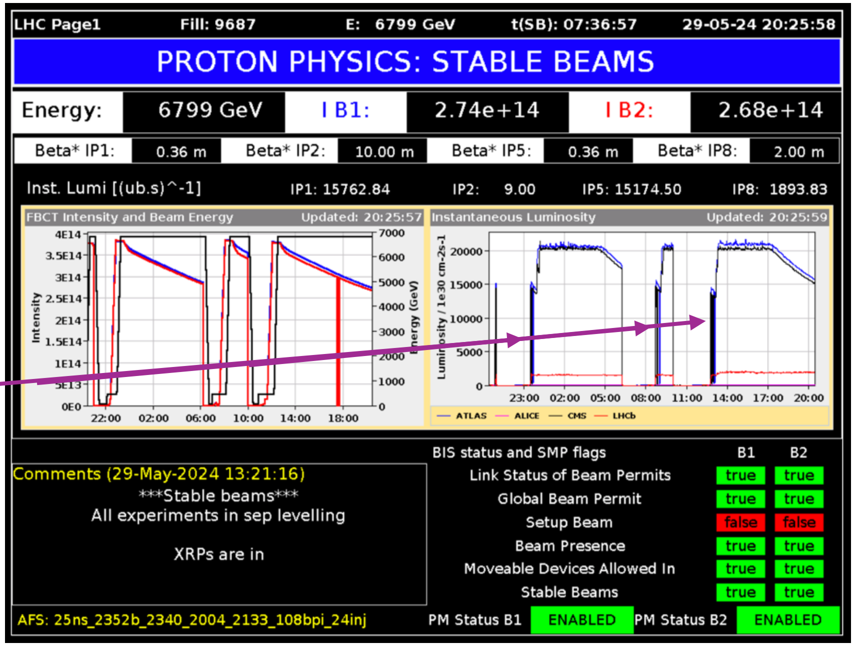
Tune shift:
- induced by BB during horizontal-separation scan
- measured using the ADT

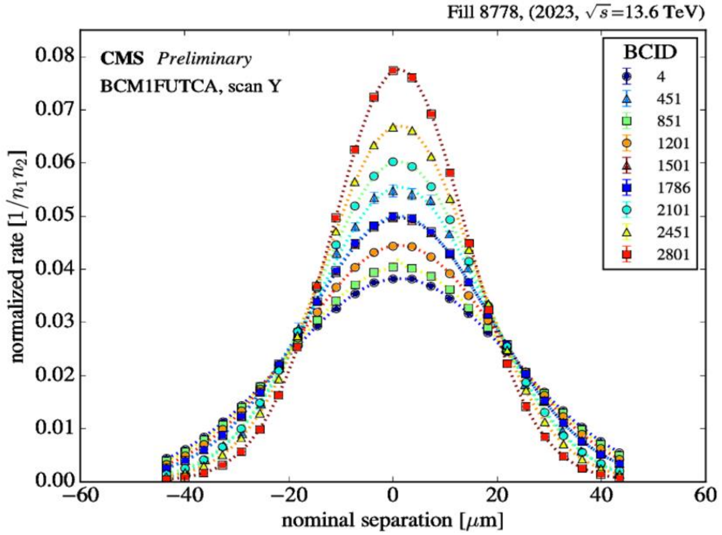


Tune shift as a function of the number of collisions, measured in multiple tests

Application in the nominal conditions

- Possible to evaluate impact of beam-beam interaction in the **high pileup conditions** with 6D implementation: CERN-ACC-NOTE-2019-0032
- Can be used to remove the systematic bias in the detector response linearity measurement in **emittance scans**
- These scans are performed regularly at the LHC and are used to study the luminometer response

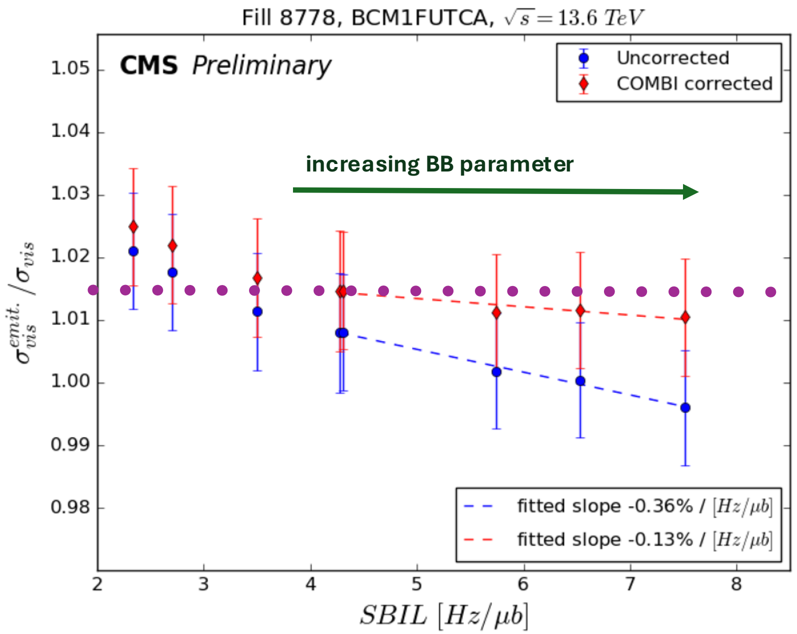




- By reconstructing the vdM-like calibration constant it is possible to study its dependence on the pileup (luminosity)

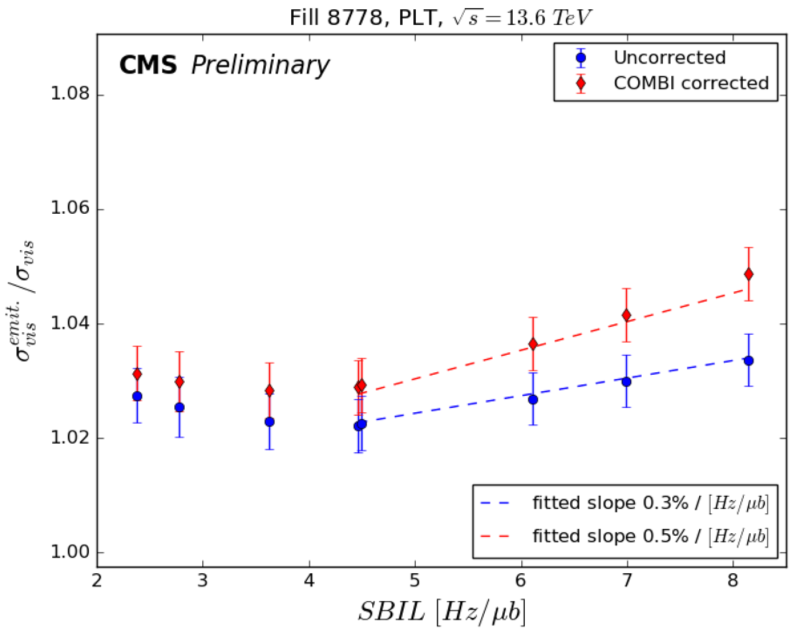
DOI: https://doi.org/10.1051/epjconf/201920104001

Application in the nominal conditions



perfectly linear luminometer = flat response across SBIL

two independent systems with different behaviour



DOI: https://doi.org/10.22323/1.449.0624

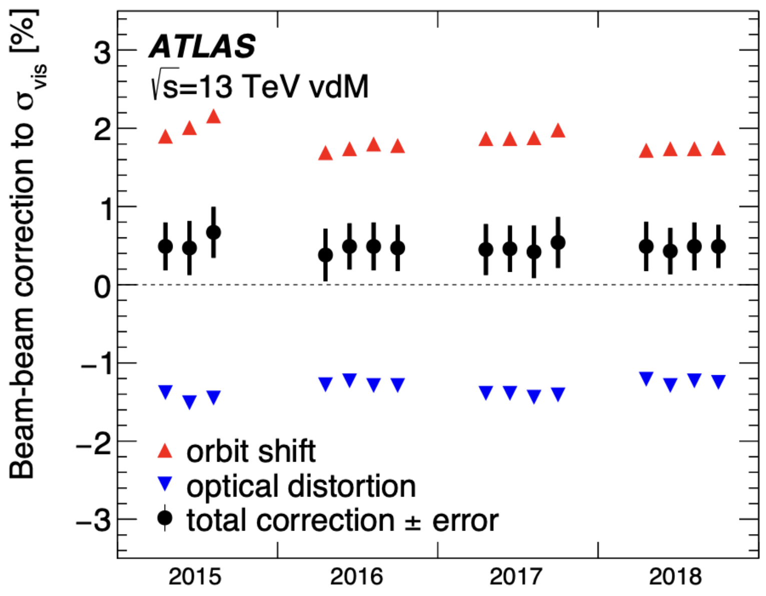
- main contributions to the measured non-linearity:
  - apparent BB-induced slope - removed with COMBI simulation
  - intrinsic detector response inefficiencies

- possible additional biases from non-factorisation
- challenging fit quality
- operational limitations - to be improved in the future

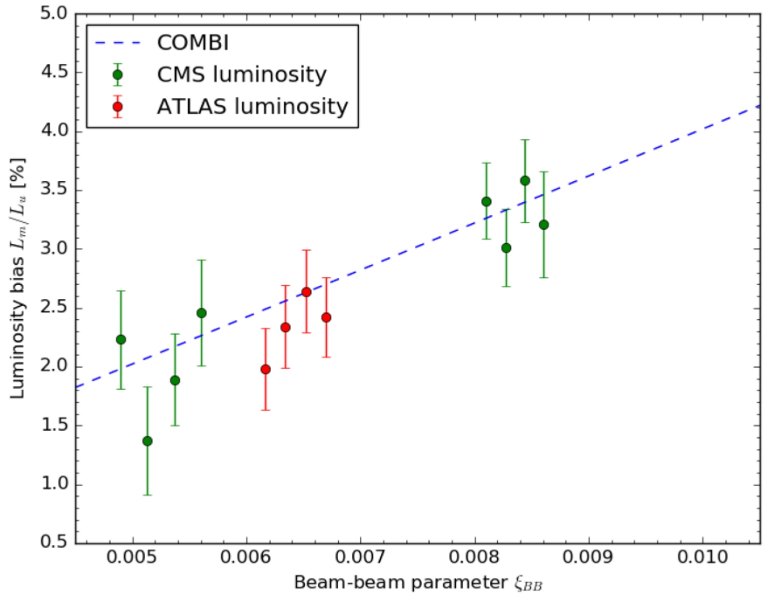
- possibility for an independent measurement
- valuable for HL-LHC
- further studies needed to make it precise

Conclusions

- Beam-beam interaction significantly impacts the luminosity calibration's systematic uncertainty using the vdM method
  - In the past, it was neglected or partially modeled wrongly
  - Extensive investigations within the LHC Luminosity Working Group during LHC's Long Shutdown 2 improved the understanding of luminosity calibration biases
    - A parametrized correction strategy was developed for multi-collision beam-beam bias modeling
    - A recipe was established for estimating beam-beam related systematic uncertainties based on beam conditions
  - These corrections and uncertainties are currently applied in ATLAS and CMS results, with successful benchmarking at the LHC.

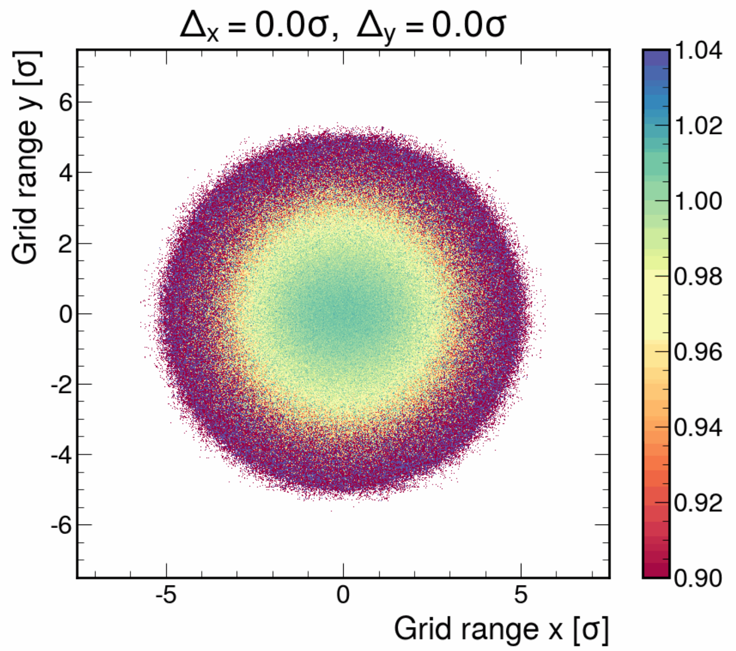


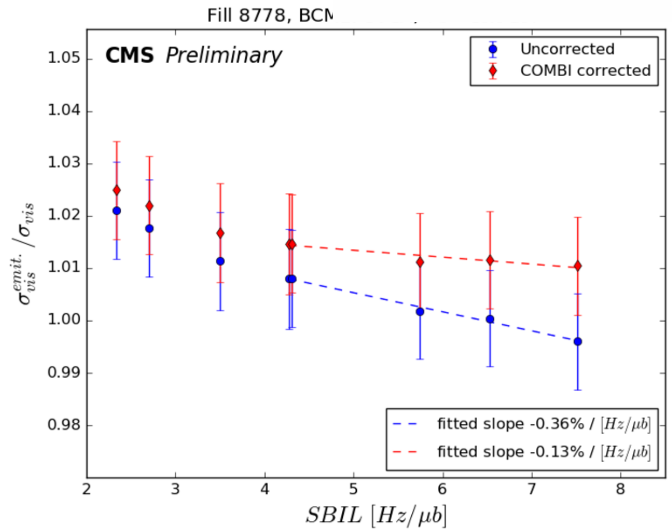
DOI: 10.1140/epjc/s10052-023-11747-w



Conclusions

- Ongoing studies explore the interplay of beam-beam interactions with other effects
- Recent simulation code advancements enable the inclusion of new observables and the simulation of the nominal LHC and HL-LHC conditions
  - Results have applications in emittance scans to correct for beam-beam induced slopes in detector non-linearity measurements
- Findings are applicable to any hadron collider.





Thank you for your attention!
May the beam-beam force be with you!

Backup – exhaustive list of systematic effects

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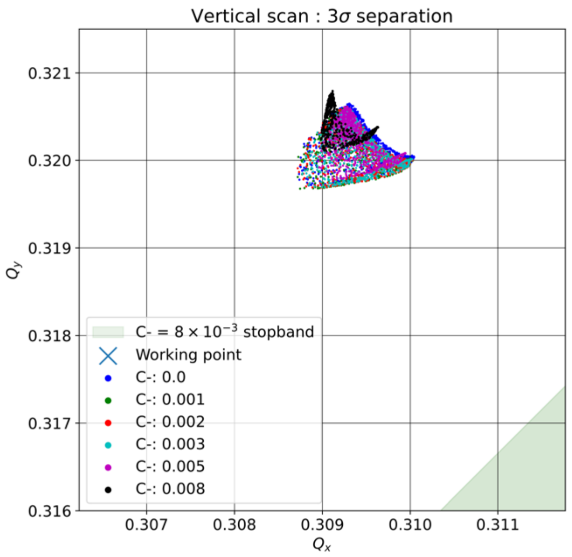
Table 8 Typical systematic uncertainties affecting beam–beam corrections to a hypothetical *pp vdM* calibration in a fully symmetric Gaussian-beam configuration, with the round–beam-equivalent beam–beam parameter set equal to ξ_{sim}, for three values of N_{NSIP}. For each source, the uncertainty is either evaluated at, or scaled linearly to, the value of ξ_{sim} indicated in the second column; if no value of ξ_{sim} is specified, the uncertainty listed covers the full range of ξ values encountered during *pp vdM* scans at the LHC. When an uncertainty is assumption-dependent, the value flagged by an asterisk is that used in computing the total uncertainty; the latter is compared to the overall beam–beam correction itself in the bottom two rows of the Table. The rightmost column indicates the chapter(s) where the corresponding issues are discussed in detail

Beam–beam (b-b) uncertainty source	$\xi_{sim}[10^{-3}]$	Uncertainty-determination procedure	σ_{vis} uncertainty [%] for N_{NSIP} = 0	1	2	Comments	See Sect.
Absolute ξ scale: β^* uncertainty at the scanning IP	5.60	Vary β^* by ±10% in the simulation or parameterization (Sect. 4.2.3), for each beam and in each plane	0.06	0.10 (total for both beams and both planes)	0.13	β^* uncertainty assumed uncorrelated between beams, correlated between planes	4.2.1 + 5.1.1
Nominal collision tunes	5.60	Vary q_x, q_y by ±0.002 in the simulation or parameterization, for each beam	0.26	0.23 (total for both beams and both planes)	0.20	Tune uncertainty assumed correlated between beams and between planes	4.2.2 + 5.1.2
Non-Gaussian transverse-density distributions	5.60	B*B (or COMBI) simulations	0.13	0.22	0.30	Simulated for $N_{NSIP} = 0$, extrapolated to $N_{NSIP} \geq 1$ using Eq. (42)	4.3 + 5.2.1
Beam ellipticity at the scanning IP	5.60	B*B (or COMBI) simulations. Uncertainty scaled linearly from ξ_R to ξ_{sim}		0.03 (for all values of NNSIP)		Simulated for $\xi_R \leq 4.2 \times 10^{-3}$, $0.7 < \Sigma_y/\Sigma_x < 1.4$	4.4 + 5.2.2
Non-zero crossing angle	≤ 5.60	COMBI simulations		< 0.01*(for all values of NNSIP)		For $\theta_c \leq 10\,\mu$rad*	4.5 + 5.2.3
				< 0.02 (for all values of NNSIP)		For $\theta_c \leq 150\,\mu$rad	
Beam-beam imbalance	5.60	B*B and COMBI simulations	0.016*	0.012*	0.008*	For $\sigma_2/\sigma_1 > 0.95$*	4.7
			0.059	0.045	0.032	For $\sigma_2/\sigma_1 > 0.90$	+
			0.136	0.104	0.072	For $\sigma_2/\sigma_1 > 0.85$	5.2.4
Multiple IPs:							
Phase advance	5.60	COMBI (or B*B) simulations	0	< 0.20 (for N_{NSIP}) > 0)		Worst case: arbitrary phase advances between IPs	4.6.4 +
Multi-IP tune shift	5.60	Vary p_1 in Eq. (42) by ±15% in single-IP simulations. Ignore if using multi-IP simulation	0	0.05	0.09		4.6.5 + 5.3
Long-range encounters	–	None at the scanning IP during *pp vdM* scans at the LHC		–			5.4.1
Lattice non-linearities	–	COMBI simulations, with sextupoles and octupoles included		0.01* (for all values of NNSIP) 0.03 (for all values of NNSIP)		For $E_B \geq 6.5$ TeV* at lower energies	5.4.2
Numerical accuracy of parameterization	–			< 0.10 (for all values of NNSIP)		Ignore if using simulation rather than parameterization	5.4.3
Total uncertainty	5.60	Uncertainties summed in quadrature	±0.32	±0.41	±0.46	% of σ_{vis}	5.5
Total b-b correction	5.60	Parameterization (Sects. 4.2.3 and 4.6.5)	+0.52	+0.86	+1.17	% of σ_{vis}	5.5

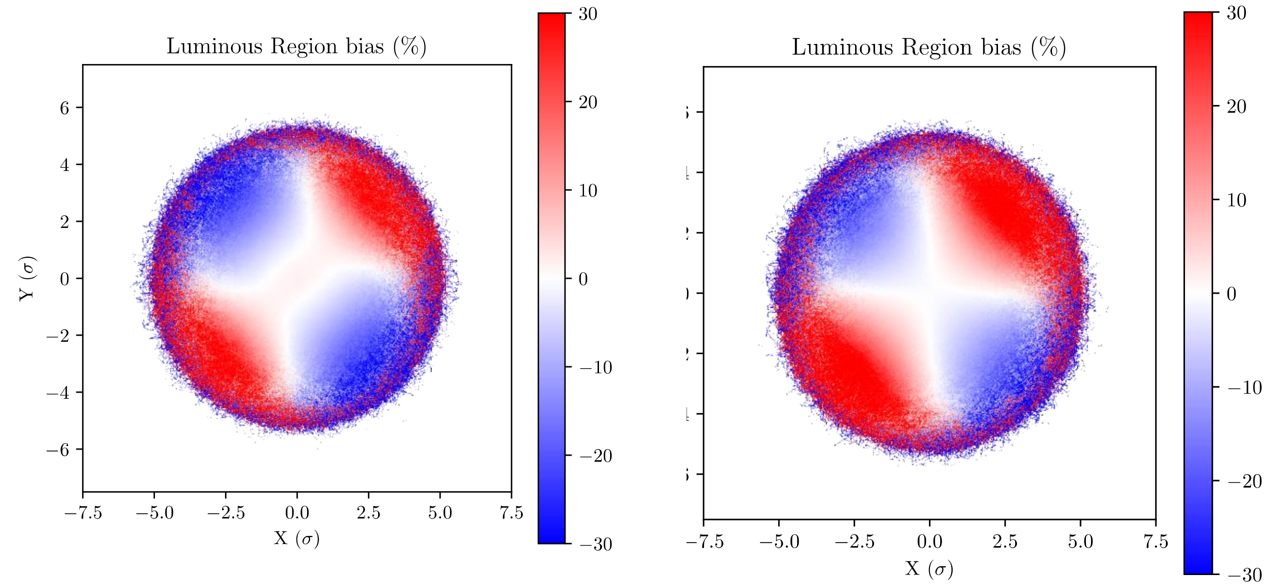
Backup – BB + linear coupling resonance

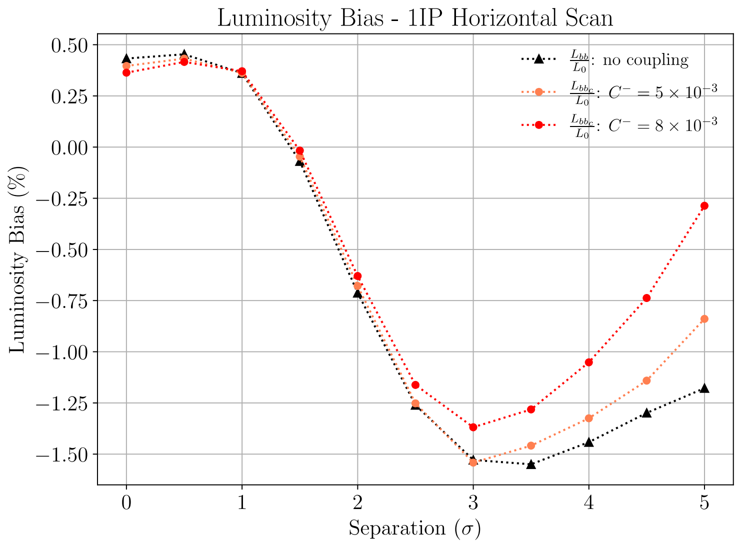


- At smaller separations the (positive) bias is slightly reduced, at larger separations the magnitude of the negative bias is strongly reduced

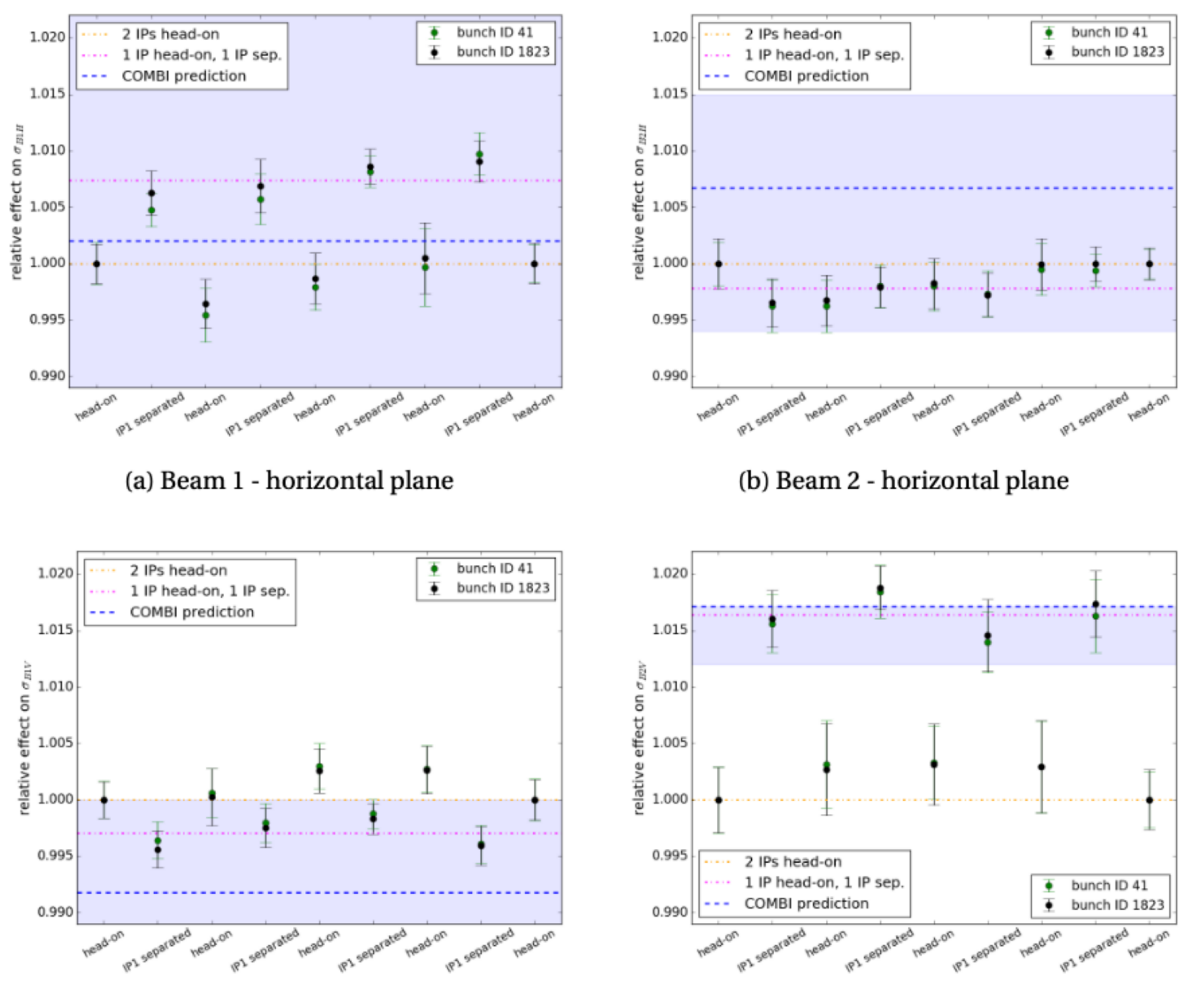
Bias from beam-beam and uncorrected coupling with $C^- = 16 \times 10^{-3}$

Bias from coupling with $C^- = 16 \times 10^{-3}$





Backup – BB experiment – COMBI vs. synchrotron light monitor for transverse beam size



(a) Beam 1 - horizontal plane
(b) Beam 2 - horizontal plane
(c) Beam 1 - vertical plane
(d) Beam 2 - vertical plane