Beam-beam effects: modelling, measurements and correction strategy on the luminosity calibration measurements at the Large Hadron Collider experiments

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HB2023 workshop
CERN, 10th October

This work is supported by the Swiss Accelerator Research and Technology Institute (CHART)

Luminosity Basics

$$N_{events} = L \times \sigma_{event}$$

$\mu_{vis} = \varepsilon * \mu$ = **mean number of interactions per Bunch crossing seen by detector**

$$L = \frac{\mu_{vis} n_b f_r}{\sigma_{vis}}$$

Cross section seen by detector (measured)

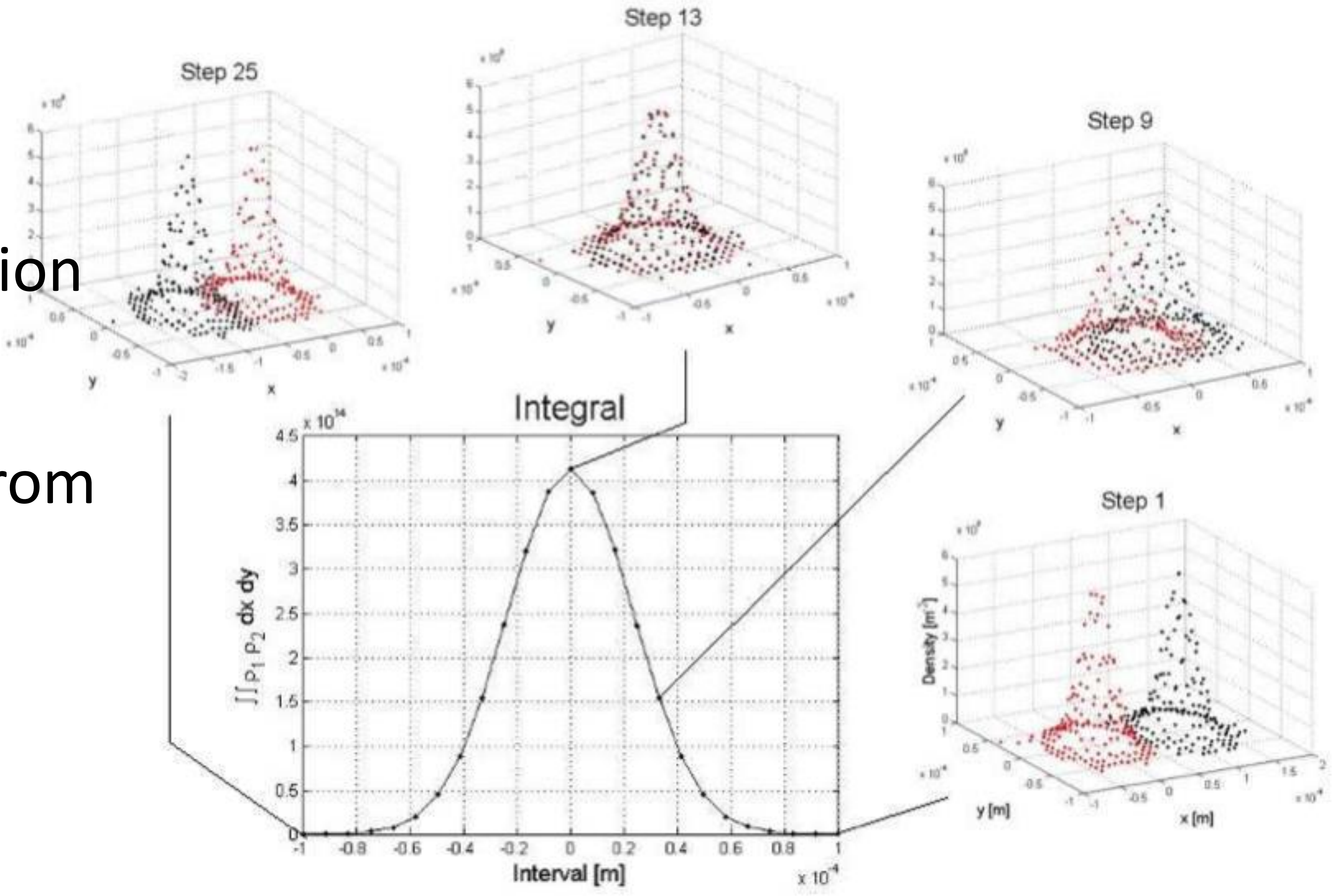
- σ_{vis} is determined in dedicated fills based on beam parameters

Luminosity calibration with van der Meer method

- beams are scanned across each other and luminosity recorded in luminometers [1],
- beams overlap width can be extracted $\Sigma_{x,y}$, to calculate the transverse luminous area.
- aimed to obtain the detector-specific visible cross-section
- rate can be correlated with instantaneous luminosity from beam parameters:

$$\sigma_{vis} = \frac{\mu_{pk}}{n_1 n_2} \times 2\pi\Sigma_x\Sigma_y \rightarrow \mathcal{L}_{inst} = \frac{\mu_{pk} f_{rev}}{\sigma_{vis}}$$

- beam-related systematic effects have to be considered.



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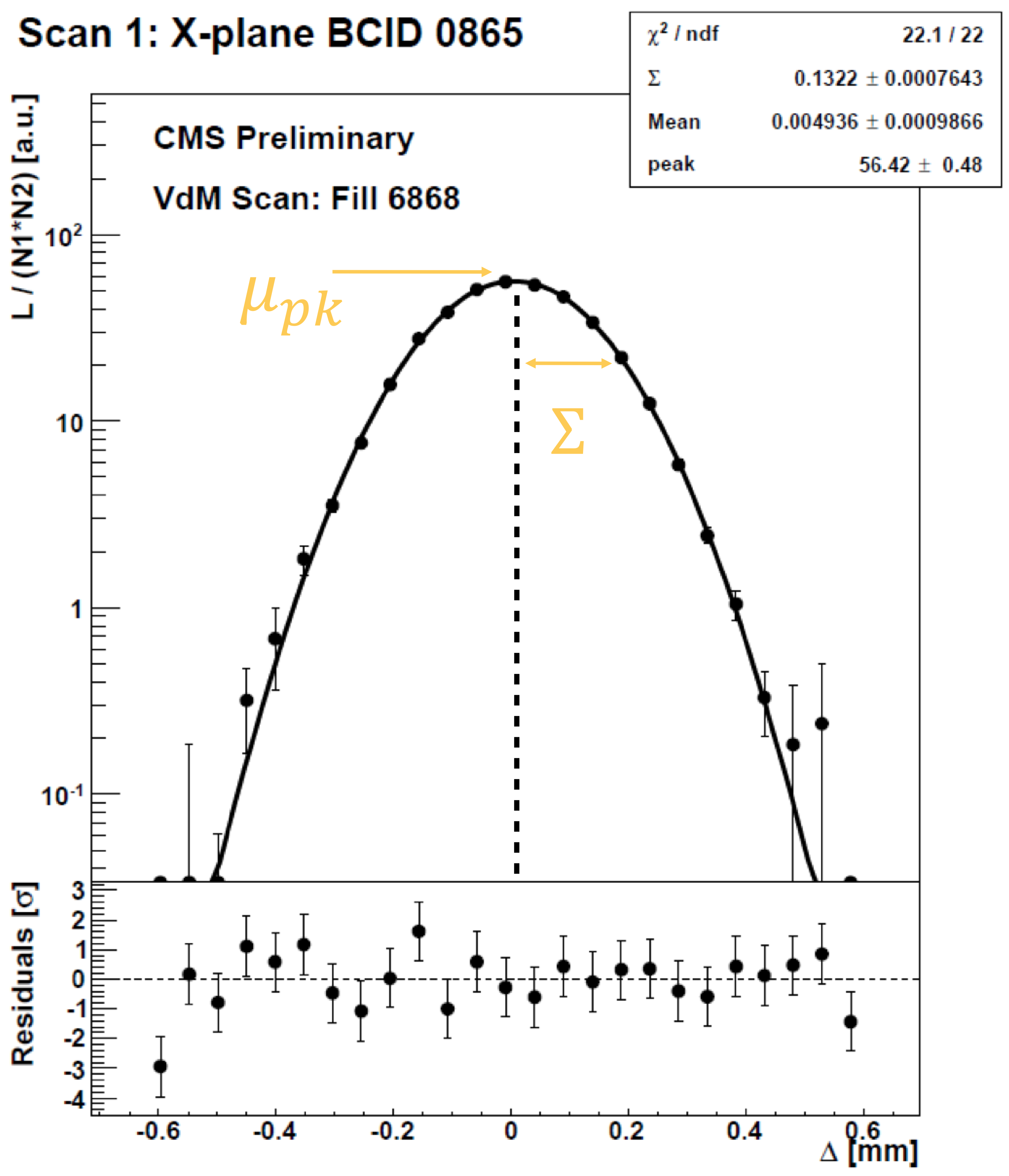


source: CMS-PAS-LUM-18-002

Motivation - Introduction

collaborative work of all LHC experiments within the LLCMWG

- precision luminosity measurement requires a thorough understanding of beam systematics
- of particular importance: detailed studies for corrections and uncertainties related to the Beam-Beam (BB) interaction
  - BB optical distortion corrections underestimated in Run 1-2
  - BB angular deflection known, measured very well and calculated analytical [3b]
  - year-long studies to derive new model and strategy for systematic uncertainties, resulted in nice publication [3]
  - leading to the shift of the absolute integrated luminosity by ~ -1% [2] (compared to pre-2021)

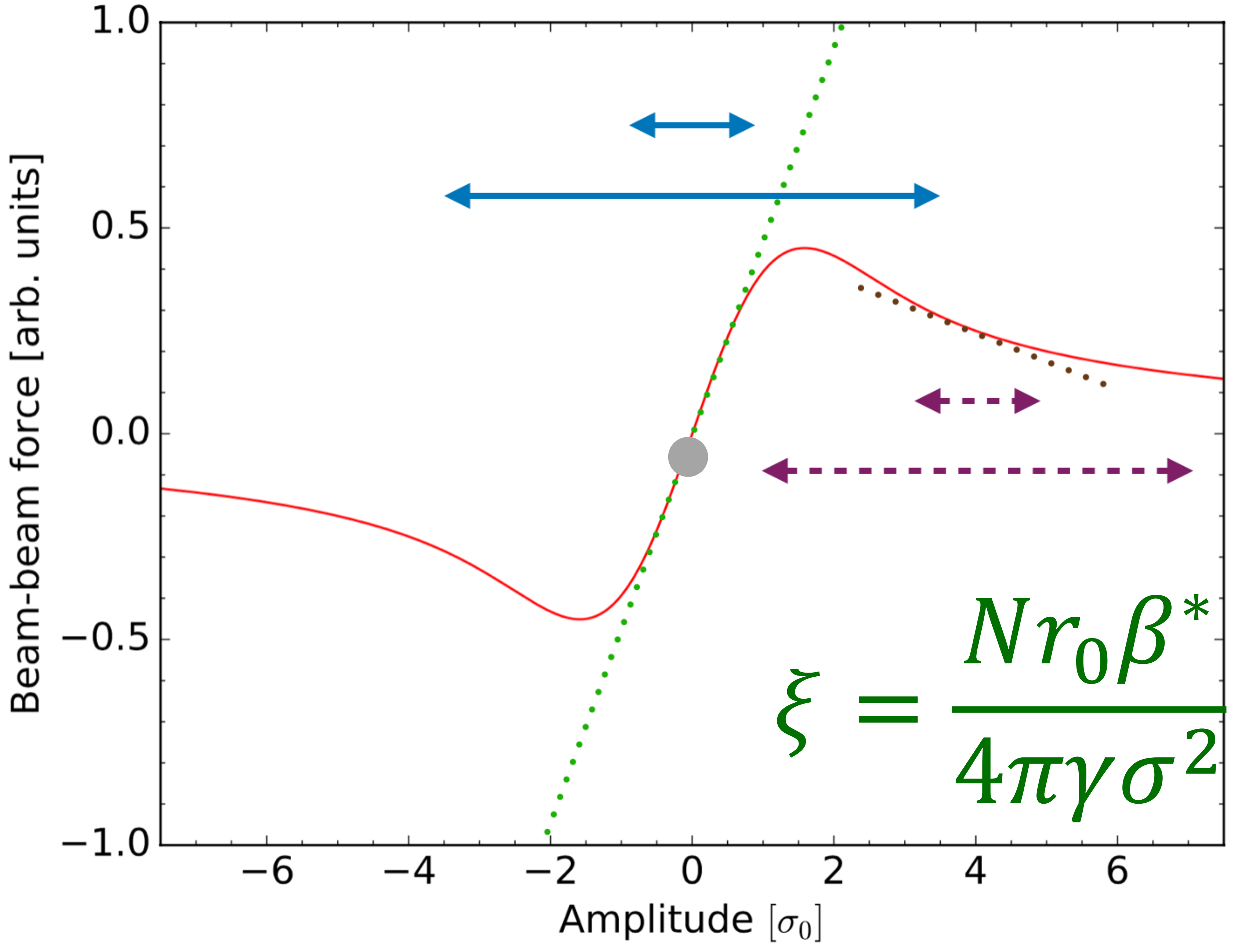
in preliminary Run-2 ATLAS results ~1.5% correction with 0.2% uncertainty (!)

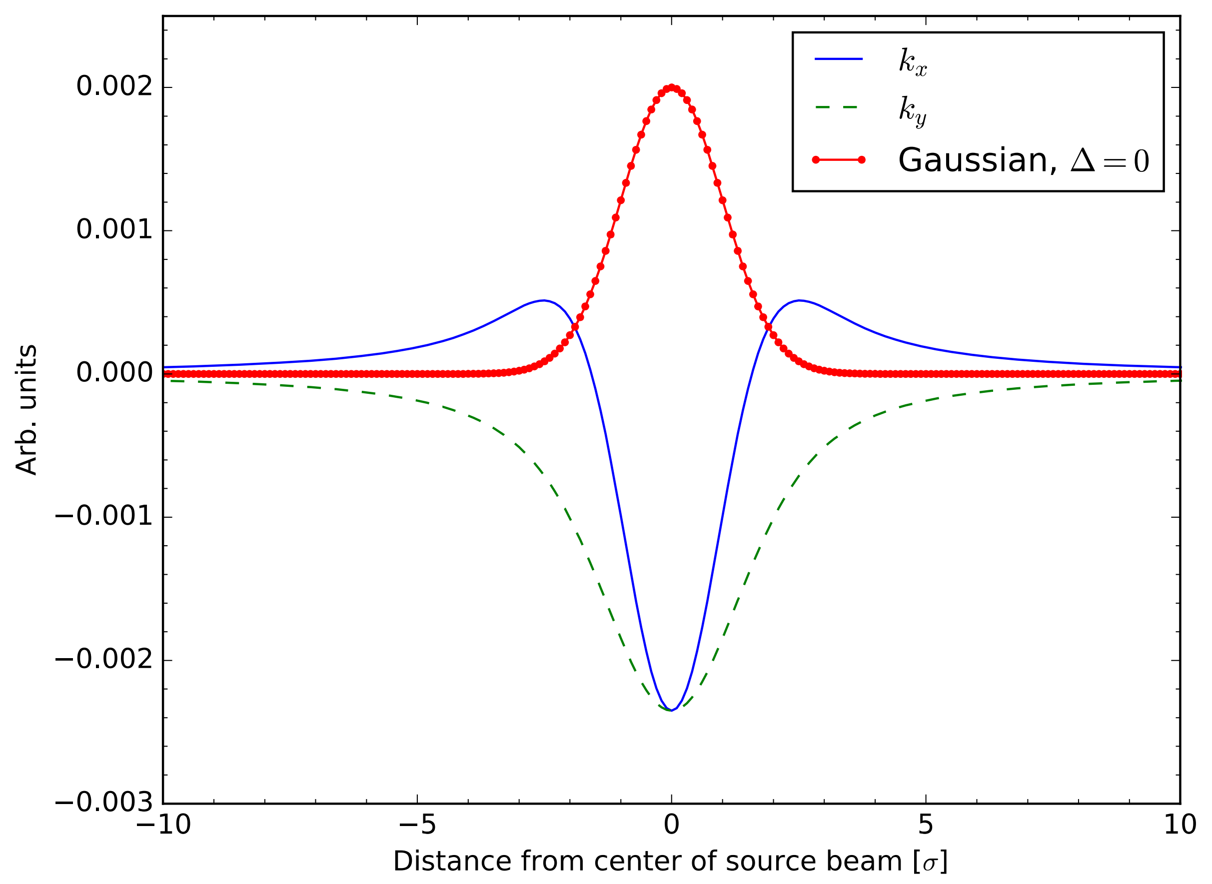
↓

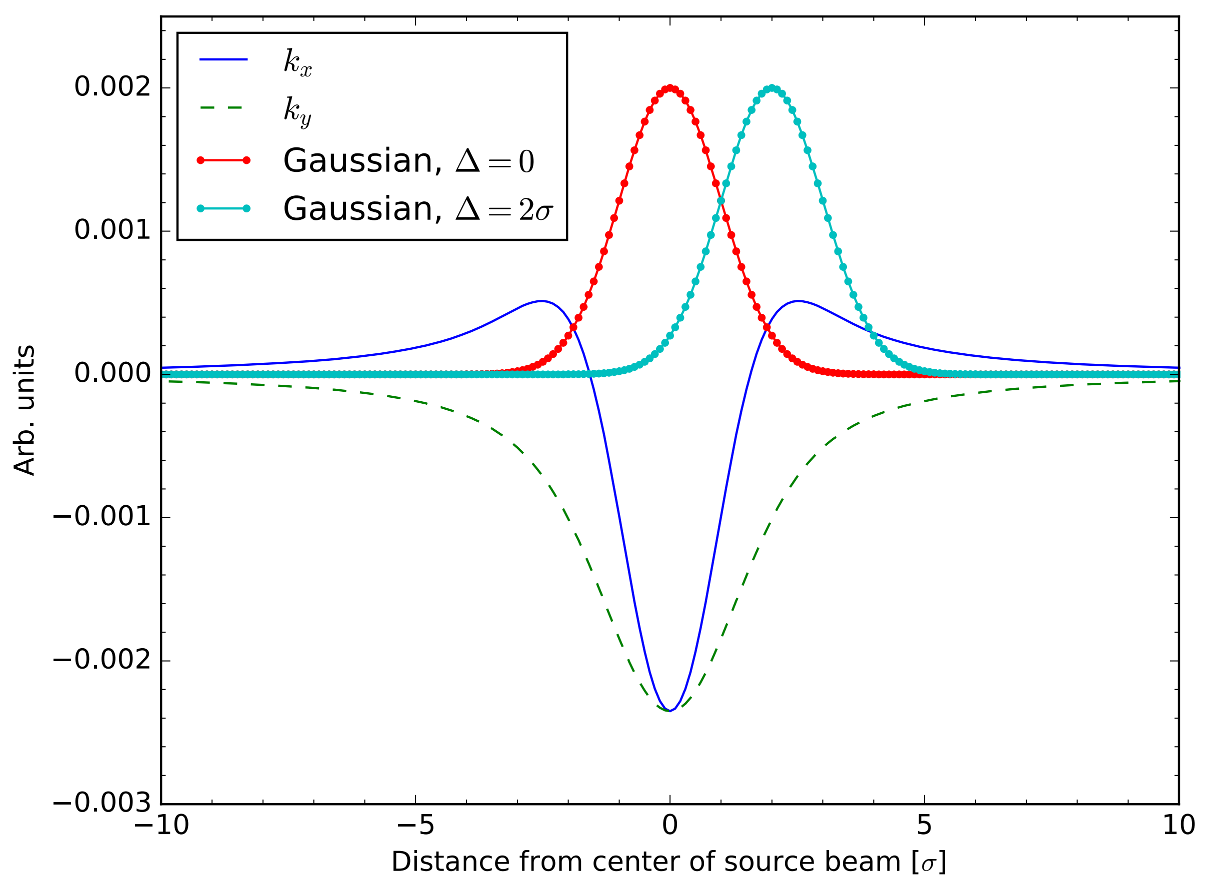
in legacy Run-2 ATLAS results ~0.5% correction with 0.3% uncertainty

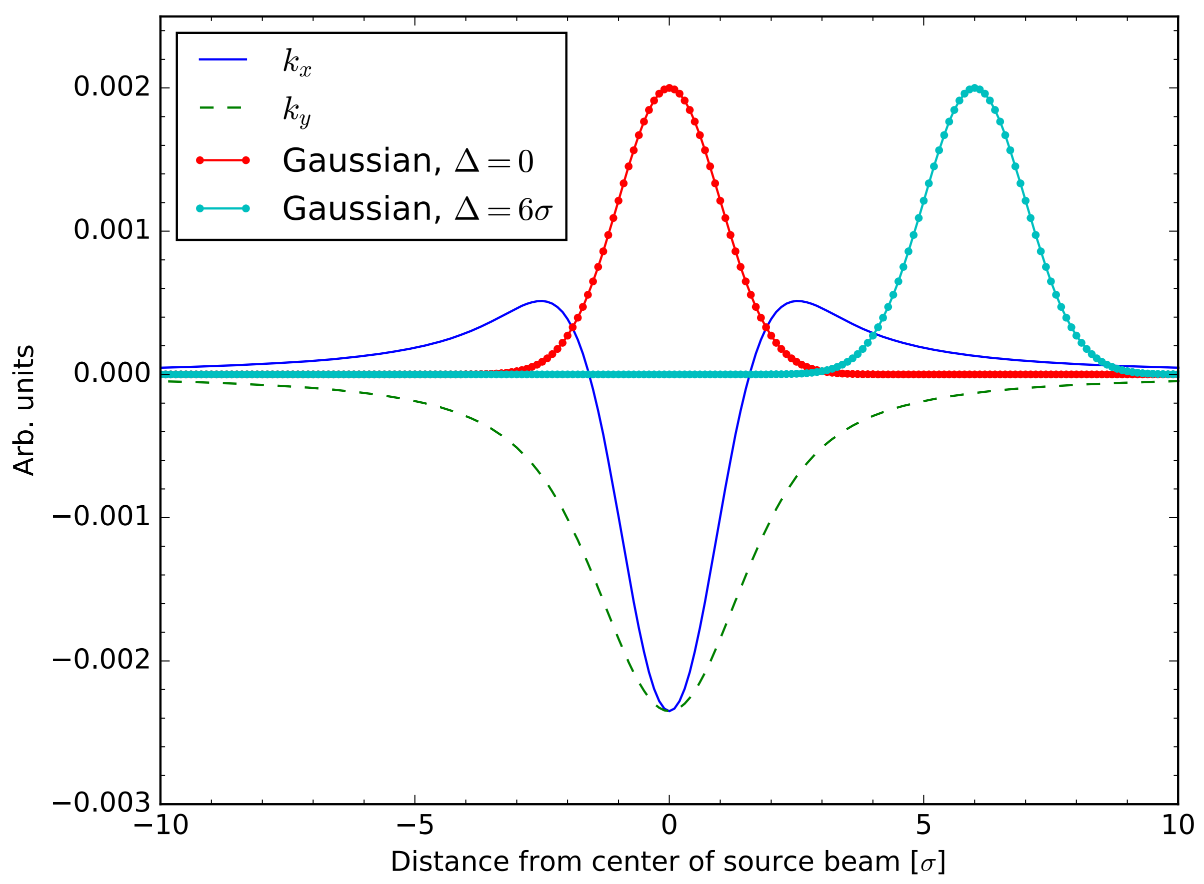
Beam-beam interaction

- BB force : electromagnetic interactions of the two charged beams
  - Change in orbit [3b]
  - Change in optical properties [3]
  - LHC specific vdM with multiple experiments in collision
- BB parameter describes the linearised force for small amplitude particles, separation introduces more complex effects









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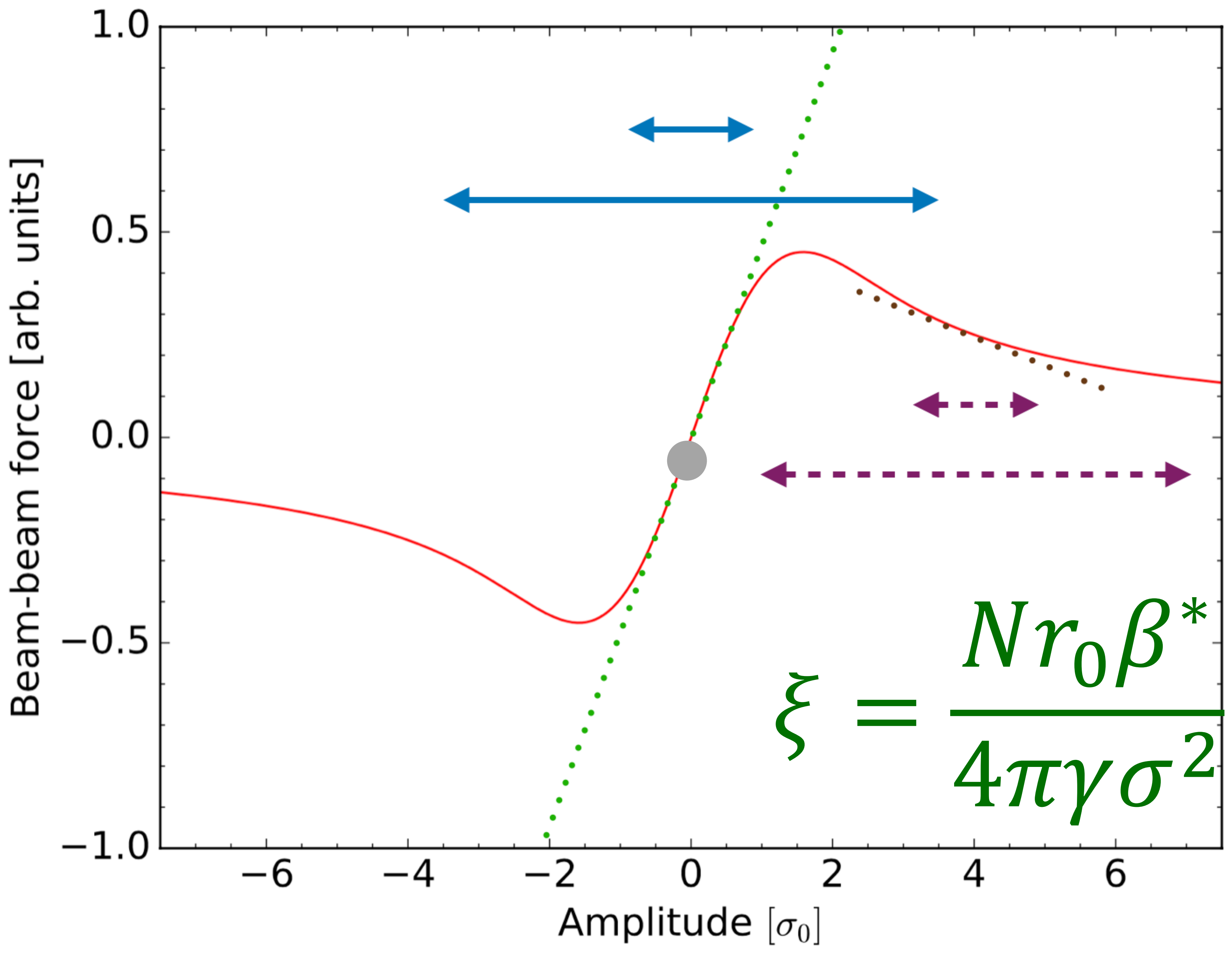
  - LHC specific vdM with multiple experiments in collision
- BB parameter describes the linearised force for small amplitude particles, separation introduces more complex effects
- COMBI [4] code used to model self-consistently the interactions to understand and quantify the bias to absolute luminosity measurements with multiple IPs
- Provide a set of corrections to be used in detectors luminosity analysis :
  - vdM analysis of absolute calibration of luminometers (ξ<0.01/IP)
  - Luminometers non-linearities in high pile-up regime (ξ=0.01/IP)



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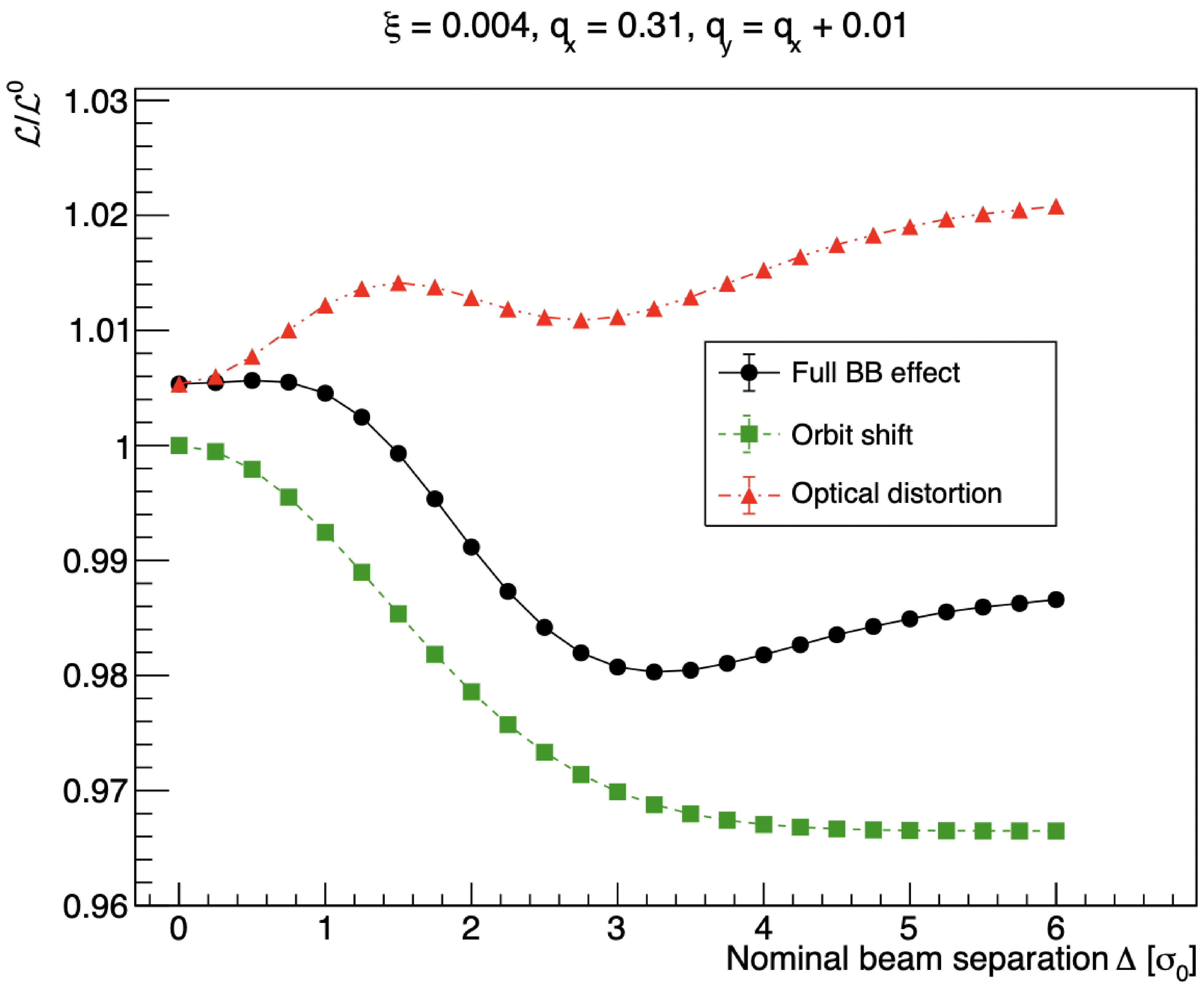
BB bias to luminosity break down for single IP:

Beam-beam force will modify the luminosity while scanning introducing different effects.

Studied separately in terms of:
- Optical effects including dynamic-beta, non linear effects and overlap changes (non-gaussianity and non-factorisation)
- Orbit deflection calculated from Bassetti-Erskine formula [5]

- In addition while one experiment is scanning the others acquire luminosity and introduce further BB effects:
  - Change in tunes
  - Amplitude dependent beta-beating
  - Phase advance dependency…



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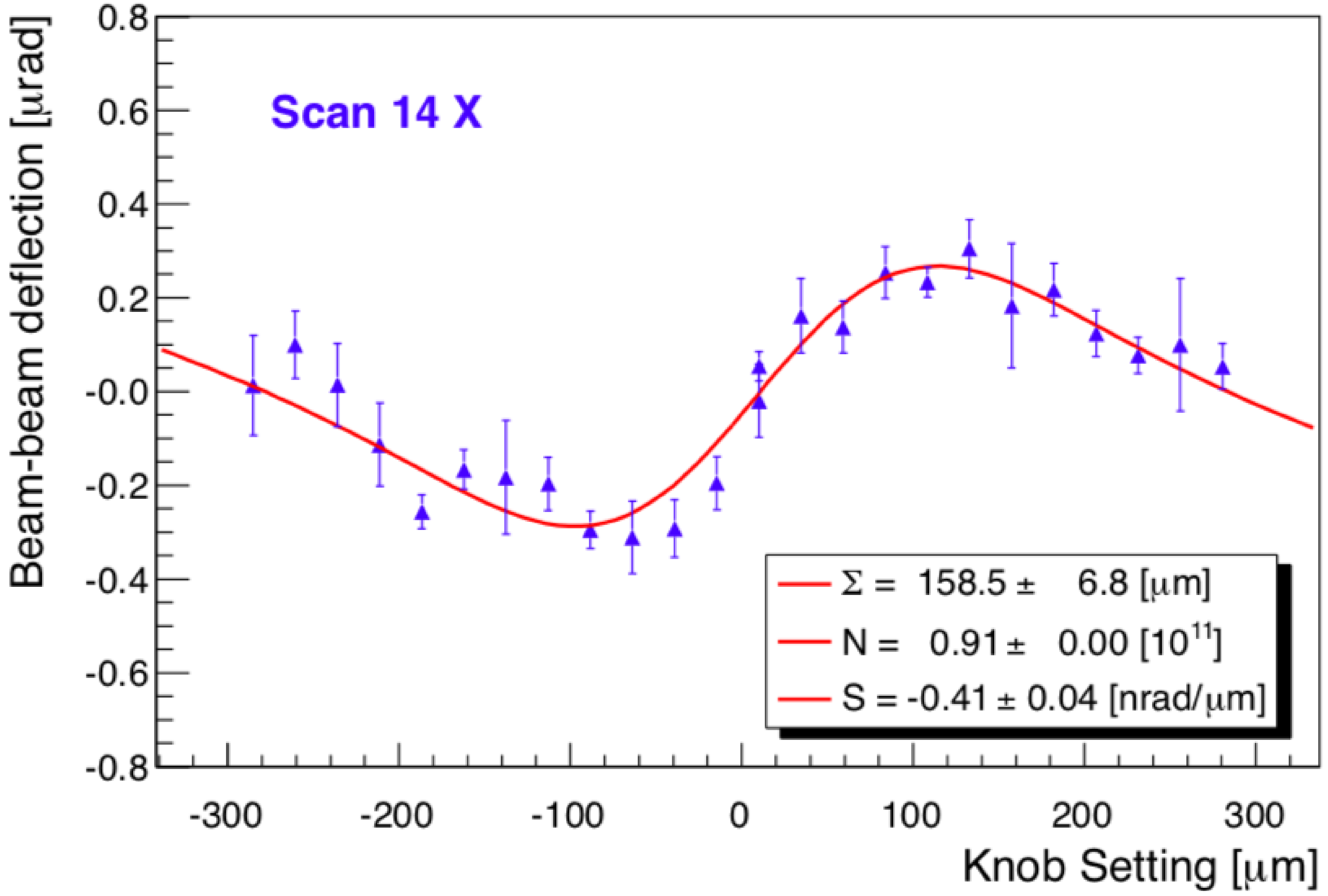
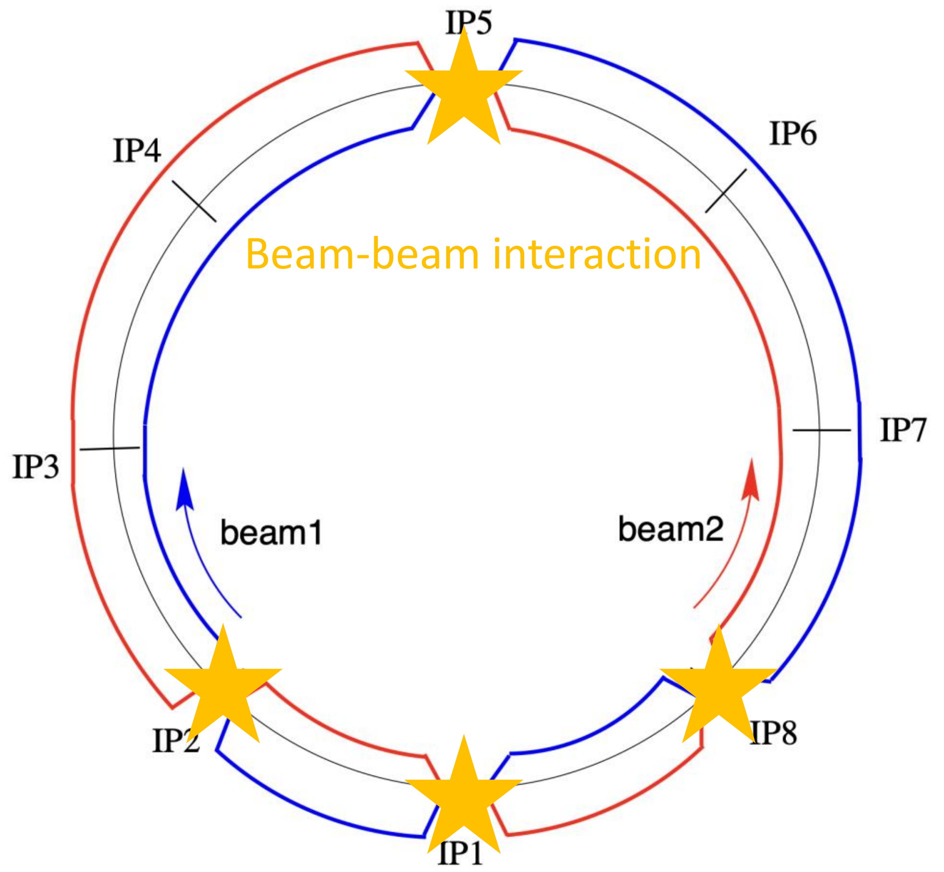


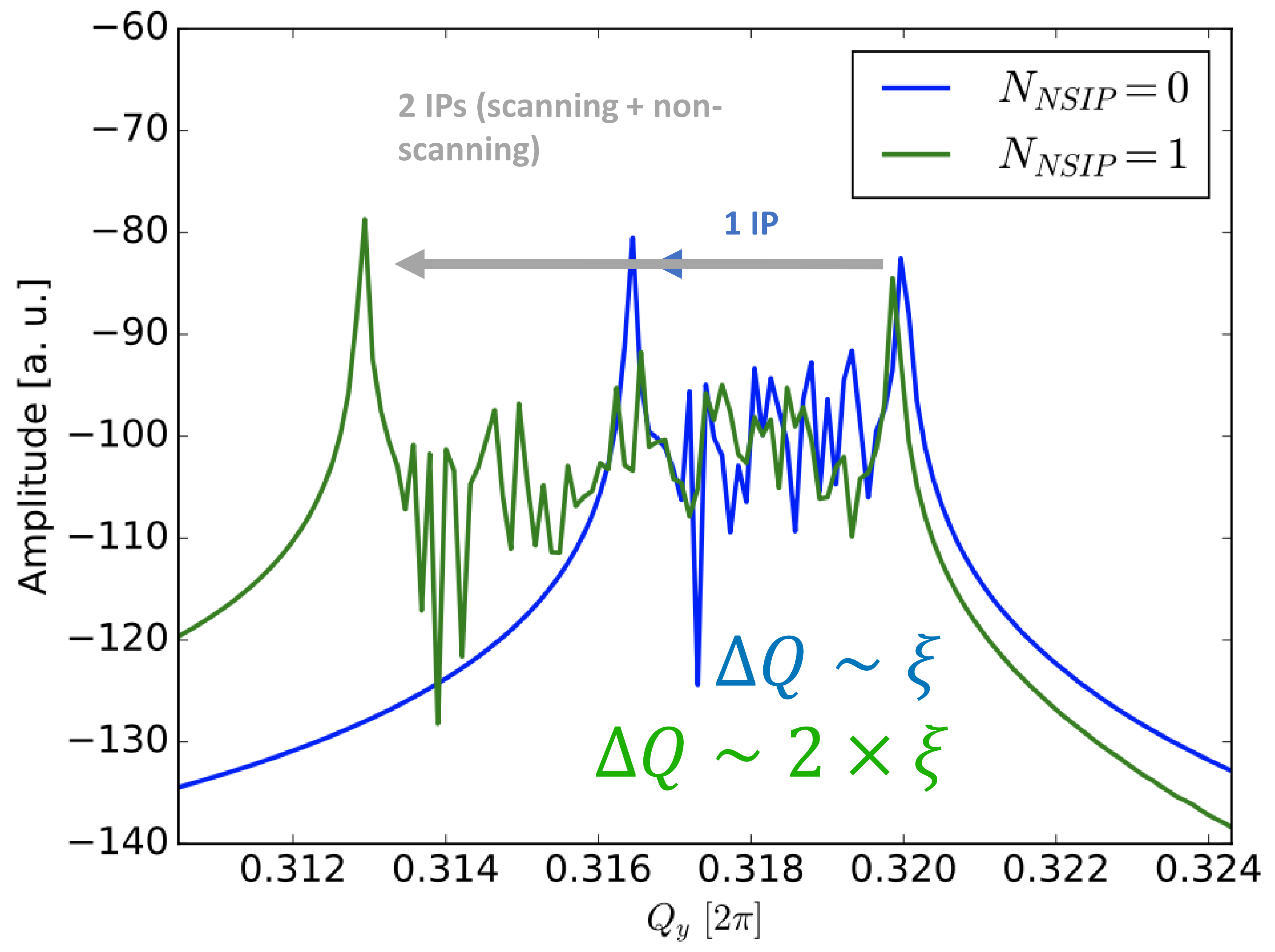
Measurements in VdM
CERN-ACC-NOTE-2013-0006
J. Wenninge, Kozanecki, Pieloni



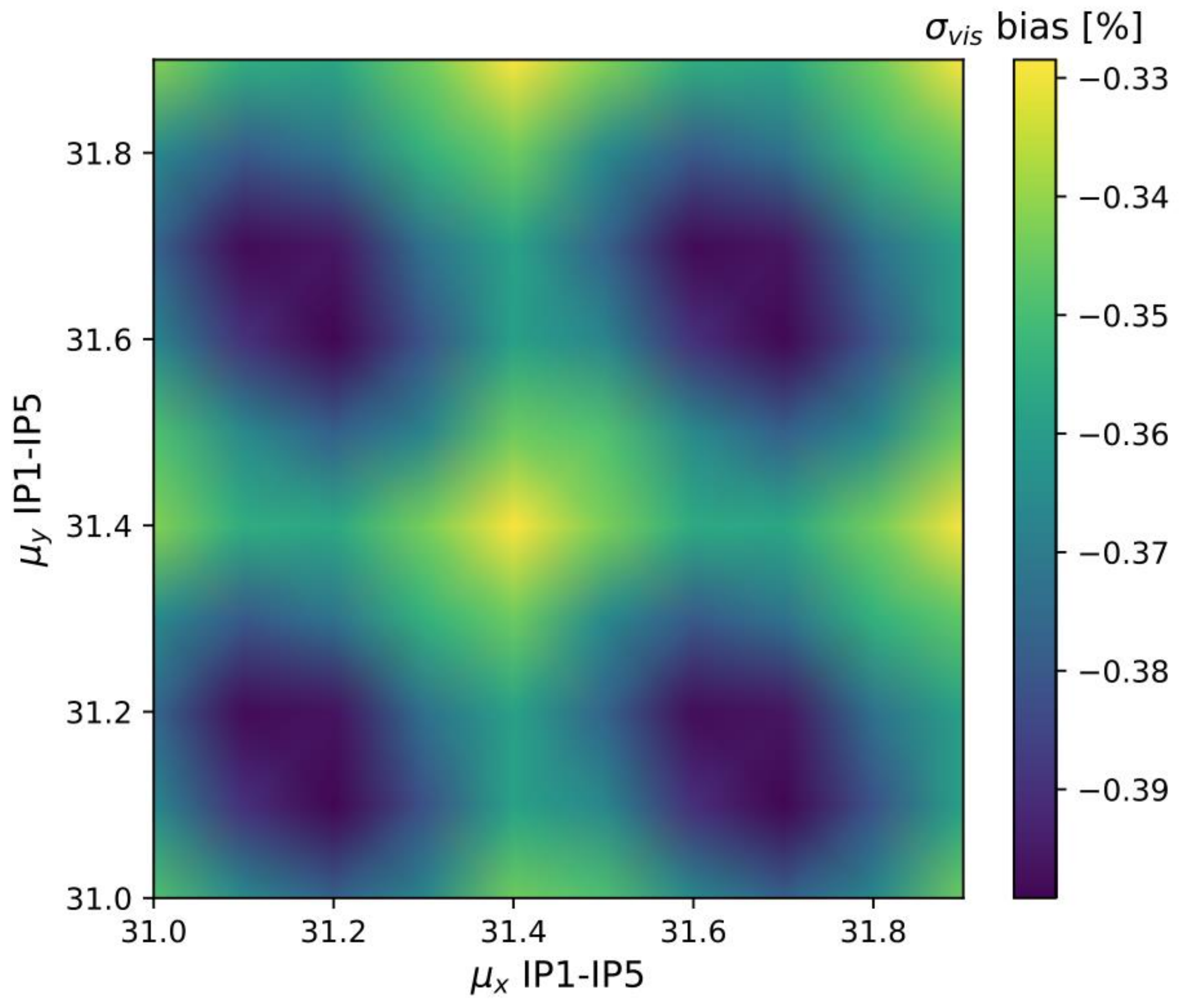
Multi-collision study for vdM calibration

- focus on the additional collisions at interaction points (IPs) other than the scanning IP
- separate corrections for beam-separation dependent deflection-induced orbit shift and optical distortion (aka dynamic-beta)

whole bunch motion = coherent spectra



phase-modulated calibration constant bias



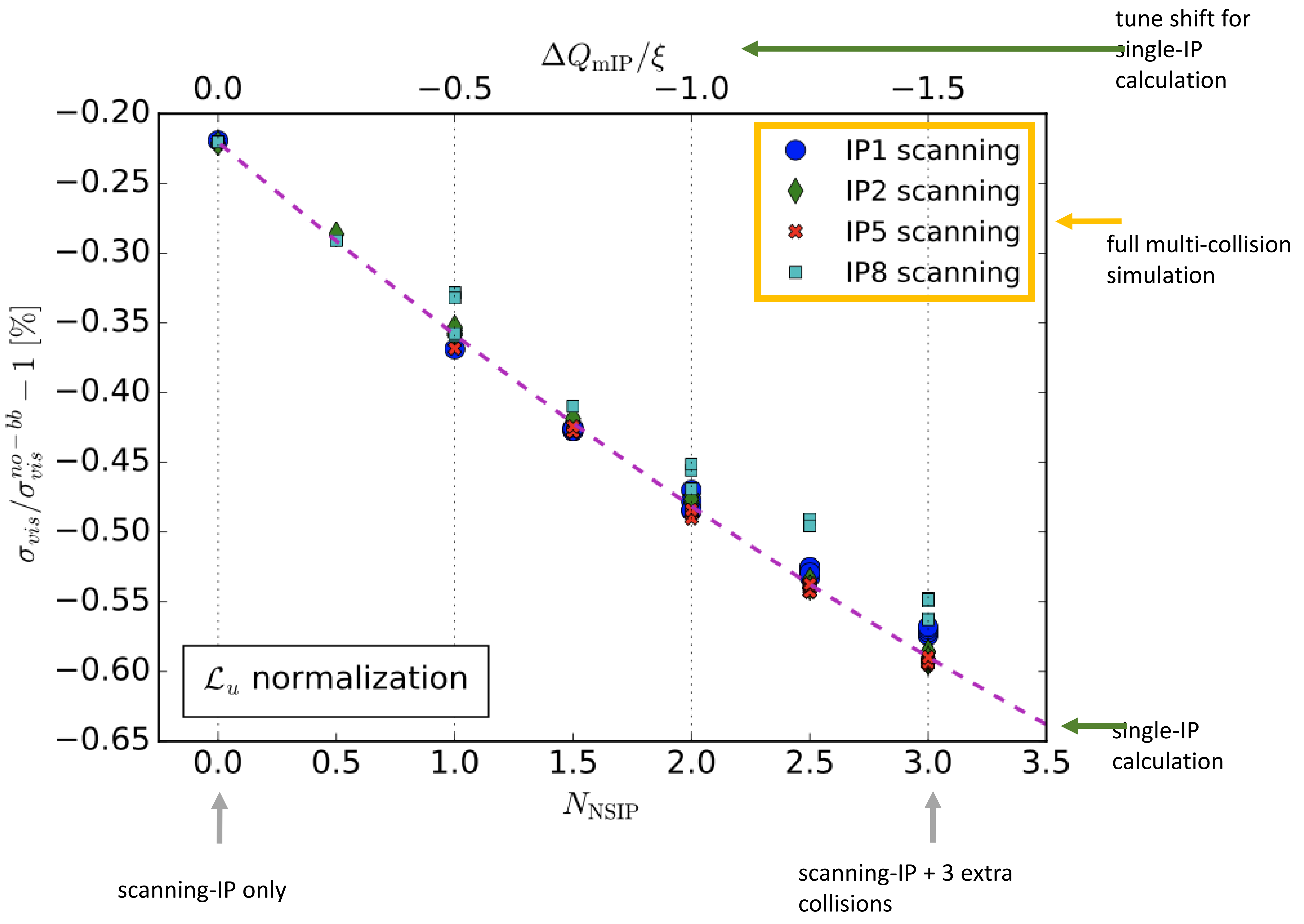
Additional collisions → IPs are coupled via BB

- additional betatron tune shift [6]
- Amplitude dependent beta-beating propagated
- Propagates from one Ip to the others: phase advance between IPs causes modulation calibration constant [7]

Mimicking multi-IP impact

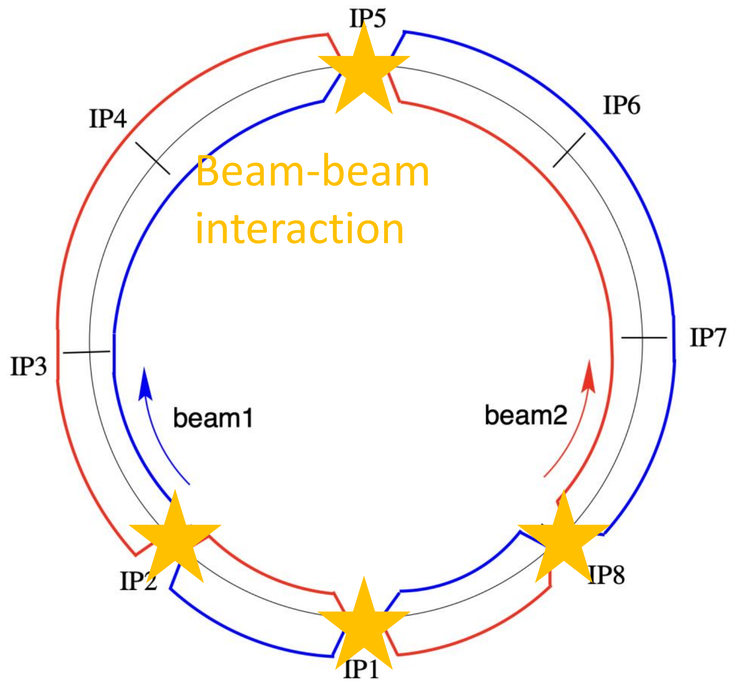
luminosity bias correction model based on the single-IP parametrization

- dependent on beams separation, BB parameter and tunes [3]
- effective multi-IP tune shift can be used to obtain the equivalent calibration constant bias (mimic the extra HO with a tune shift 0.5∗ξ/NSIP)
- simple scaling law derived from strong-strong simulations
  - valid for all LHC IPs
  - verified in simulation for vdM regime ξ~0.004/IP



If you cannot measure it, it doesn't exist!

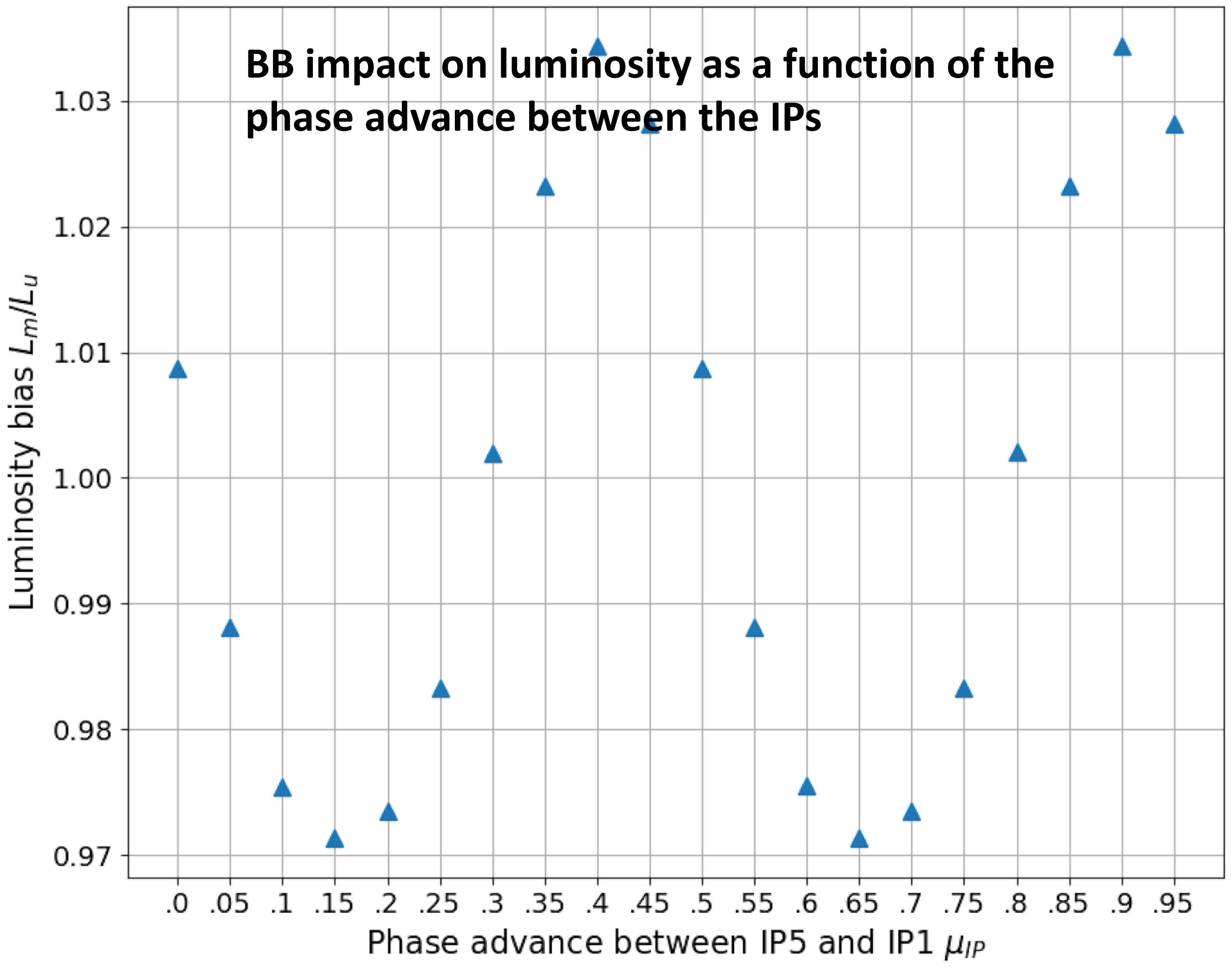
Benchmark experiment



- Test designed especially to measure the BB effects
  - phase advance between IP1 & IP5 optimised so as to maximize the effect on luminosity at the observer IP at injection energy
    - lattice validated (R. Tomas, T. Person, OP crew)

Multiple instruments were used to measure the BB effects on:

- luminosity from ATLAS and CMS luminometers
- tune spectra from ADT, BBQ
- transverse beam sizes with synch. light monitors and wire scanners
- orbit at the IPs with BPMs



W. Yi EPFL TPIV projects 2022

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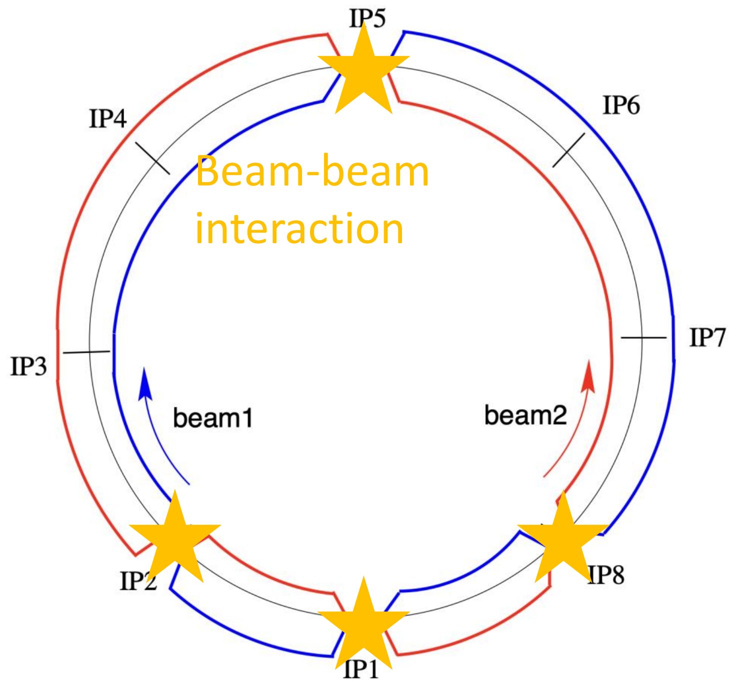


	Beam 1		Beam 2	
	$\Delta\mu_x$ $[2\pi]$	$\Delta\mu_y$ $[2\pi]$	$\Delta\mu_x$ $[2\pi]$	$\Delta\mu_y$ $[2\pi]$
IP1-IP5	30.977	29.649	31.062	29.762
IP1-IP5 adjusted	30.9	29.9	30.9	29.9
expected change	-0.077	0.251	-0.162	0.138
measured change	-0.076 ± 0.003	0.240 ± 0.002	-0.162 ± 0.002	0.137 ± 0.002

Measured beta-beating along the LHC ring from the knob

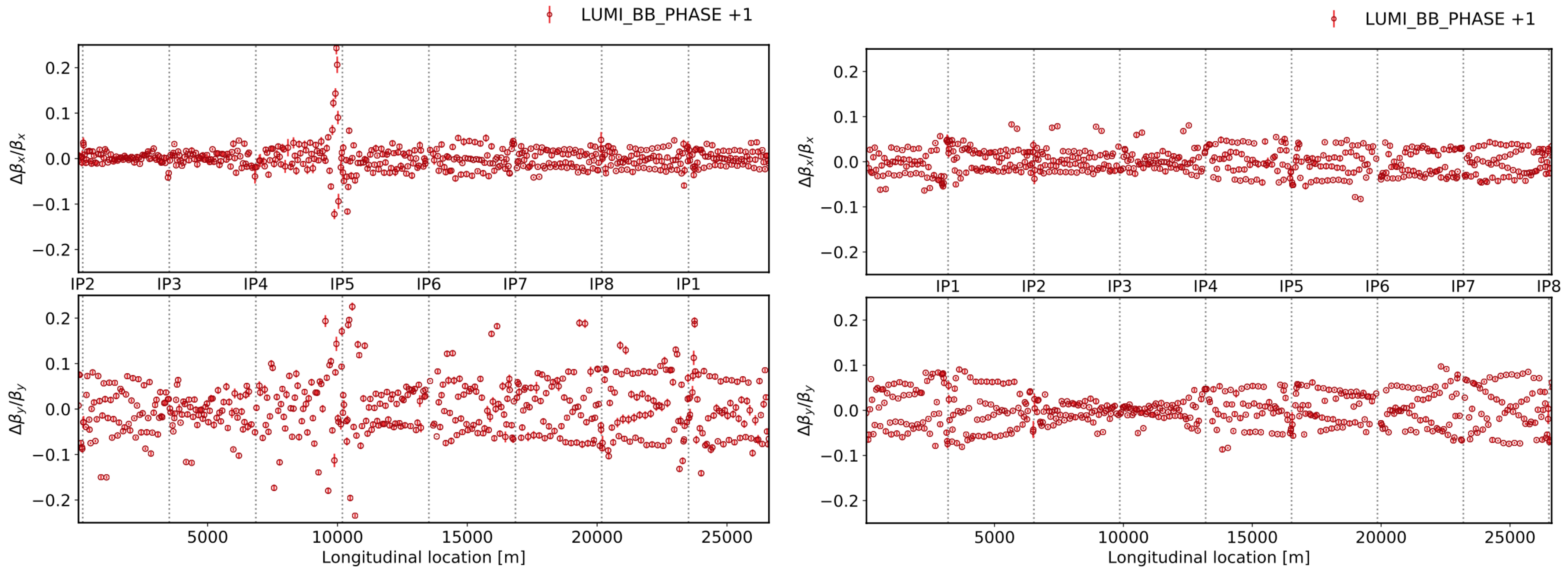


Figure 2: Measured beta difference between the lattice with the maximizing (+1) phase knob and nominal lattice along the LHC ring, for Beam 1 (left) and Beam 2 (right).

Measured beta-beating along the LHC ring from the knob with reference to the MADX model predictions

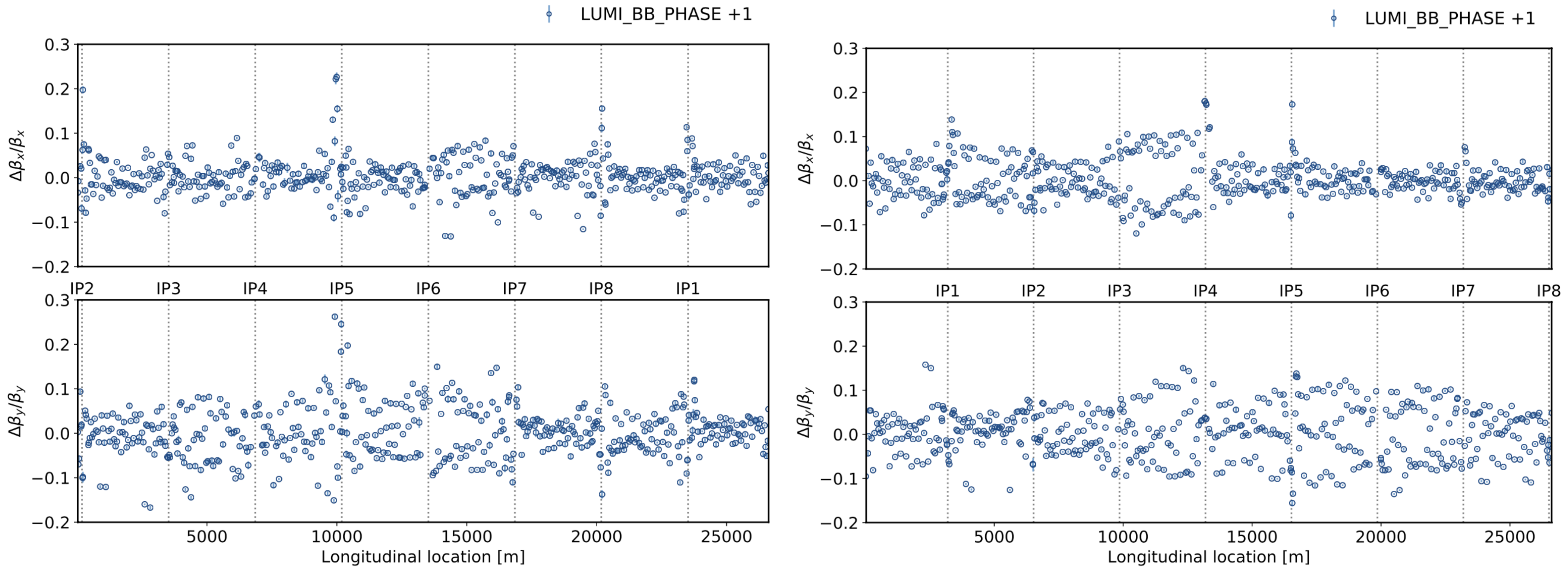


Figure 5: Measured beta function differences along the LHC ring with respect to the MADX model with included maximizing (+1) phase knob, for Beam 1 (left) and Beam 2 (right).

Phase optimisation validated with optics measurements:

Benchmark experiment

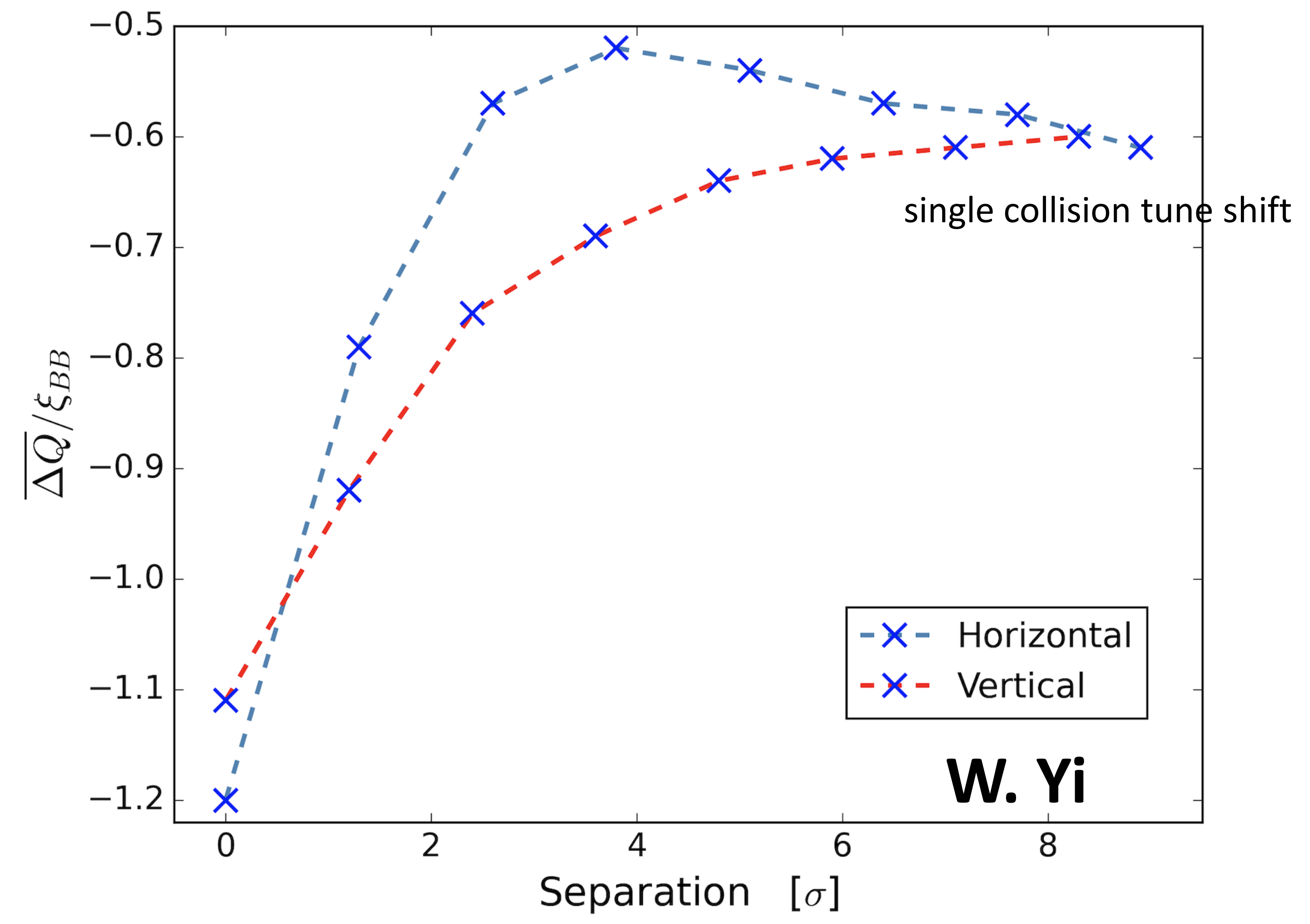
Series of tests:

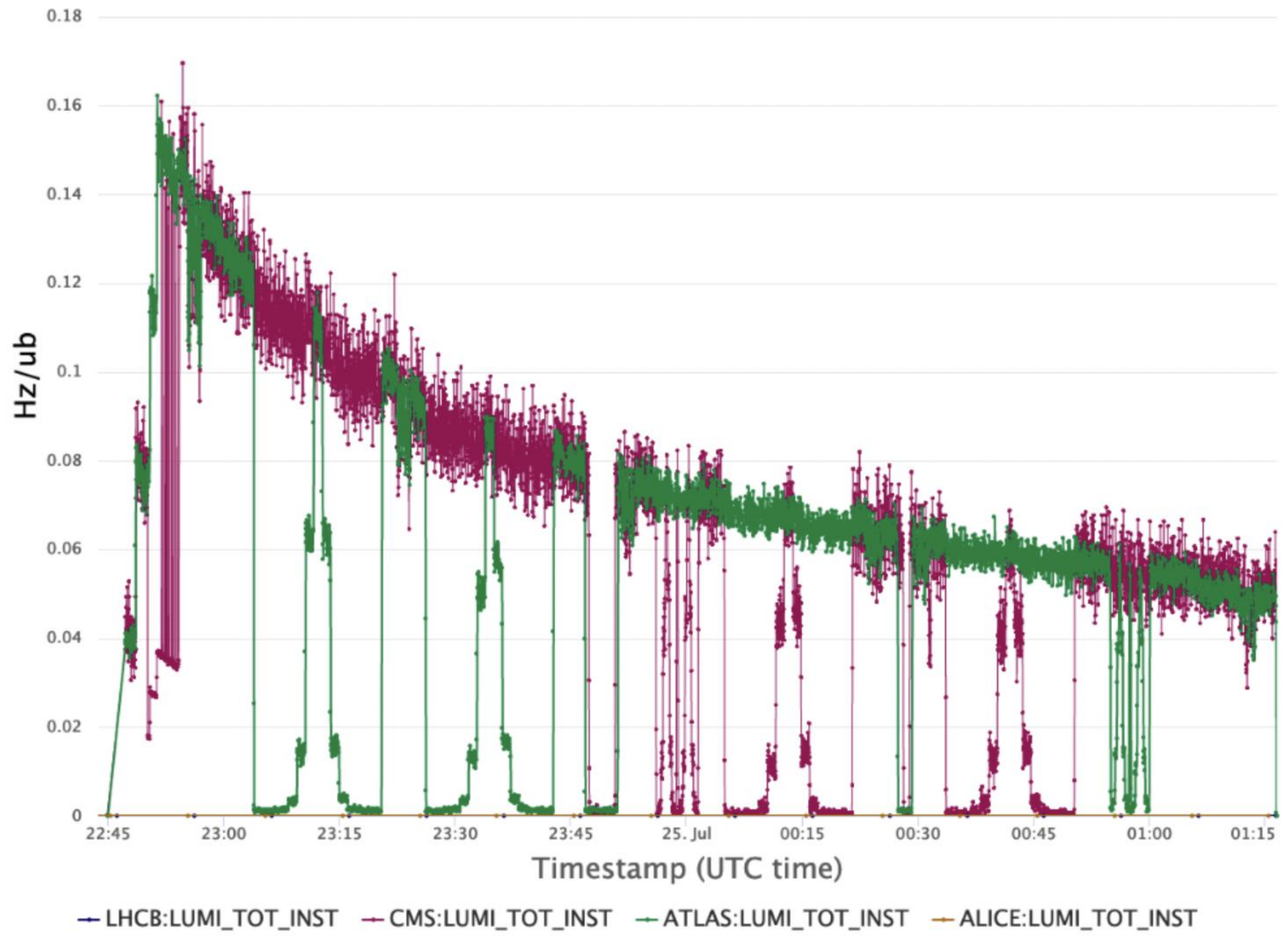
- Scanning IP : in and out collision and transverse scan

→ propagation

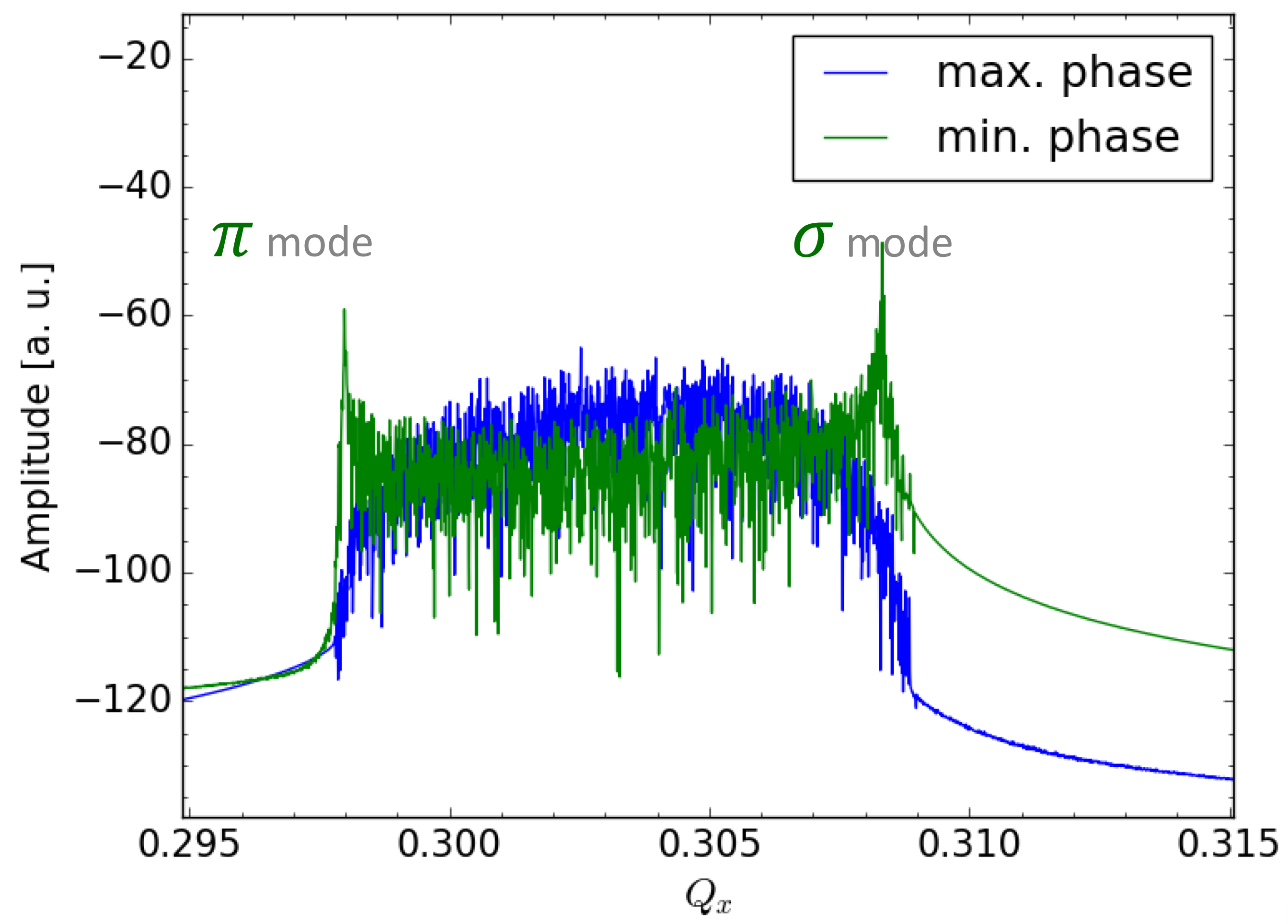
- Witness IP: in HO collision, observation point to see bias on luminosity

Tune shift induced by BB during separation scan in horizontal plane at one IP, while the other is colliding head-on as measured by the ADT ObsBox[9]

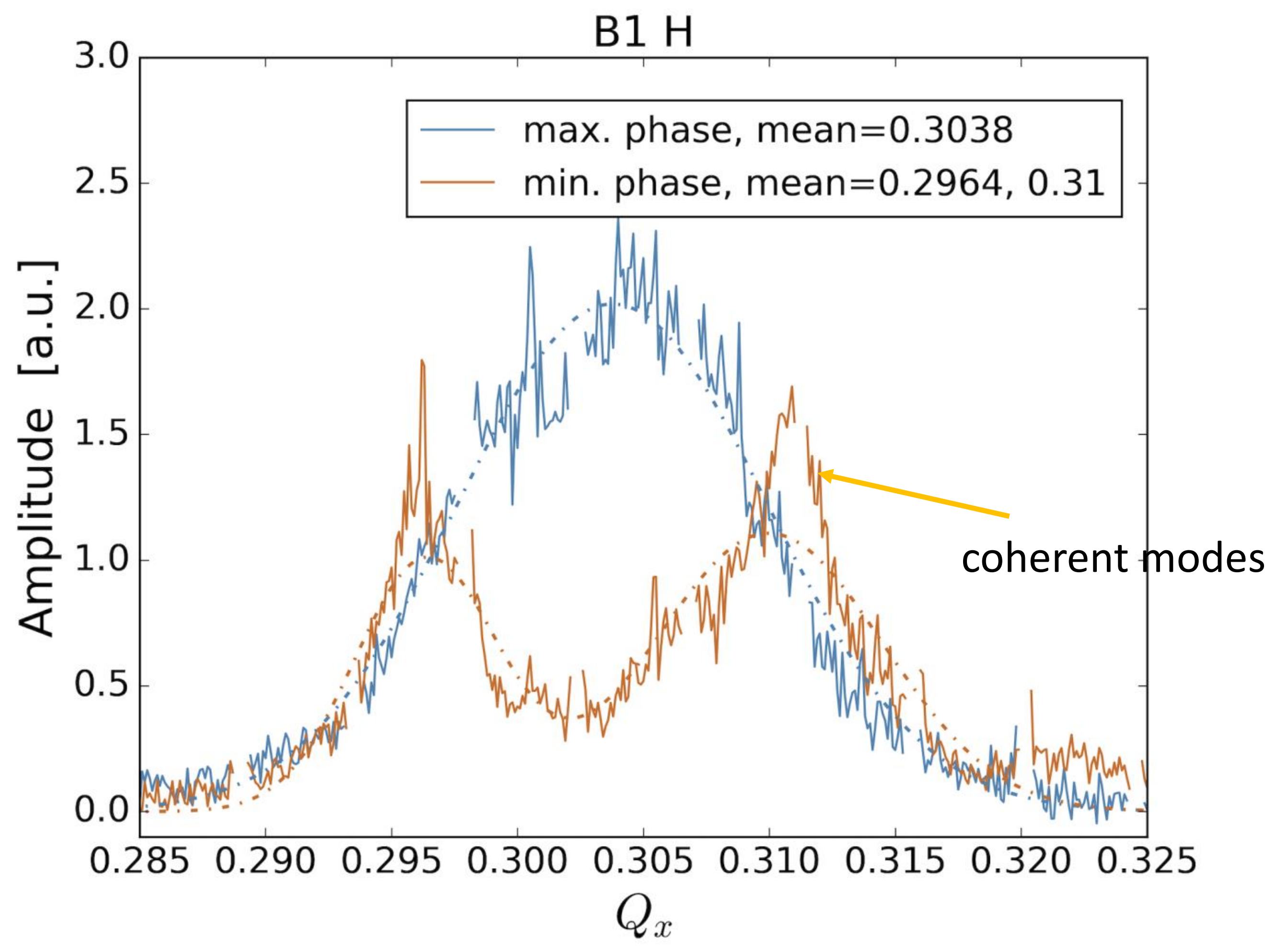




COMBI simulated



Data



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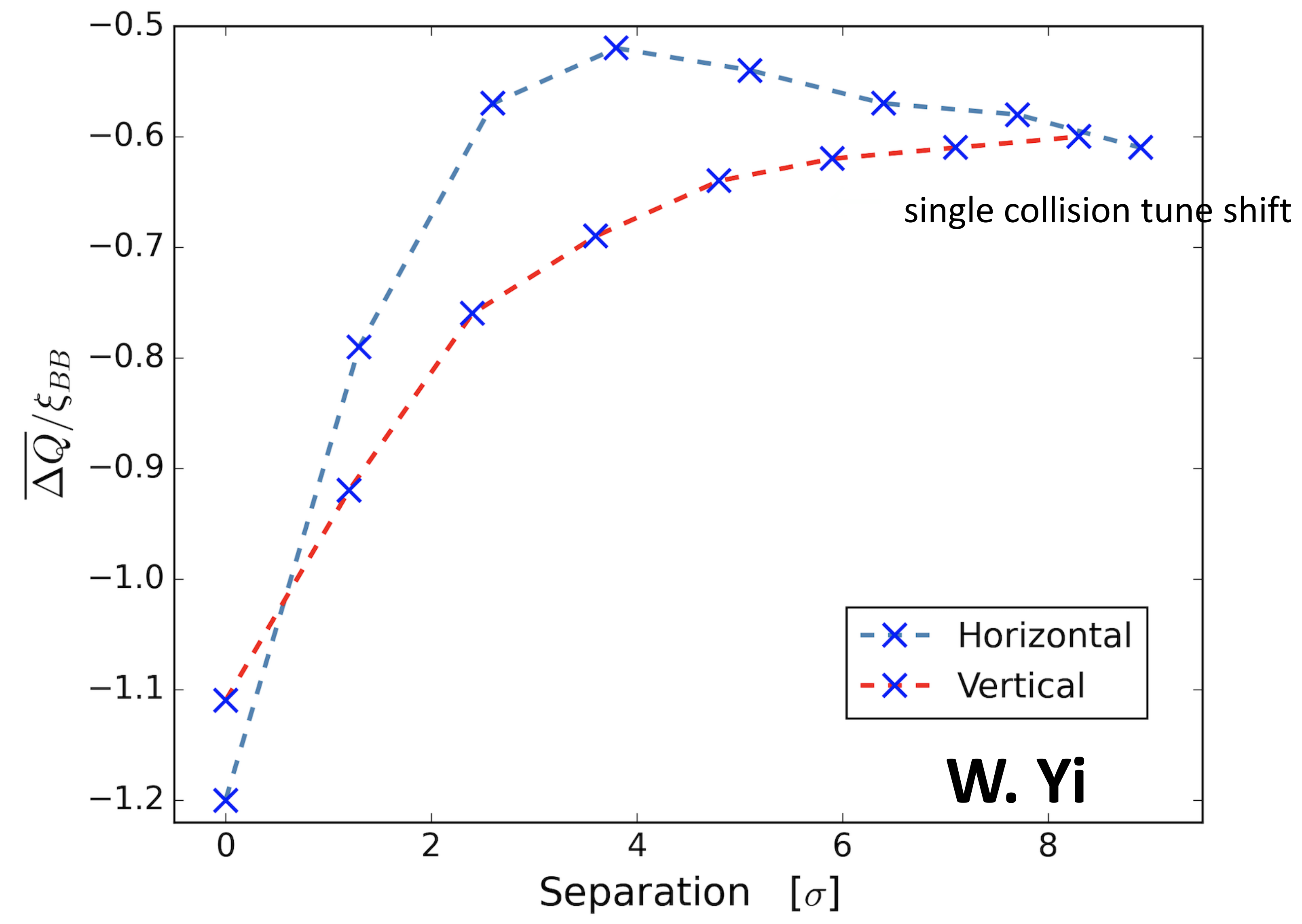
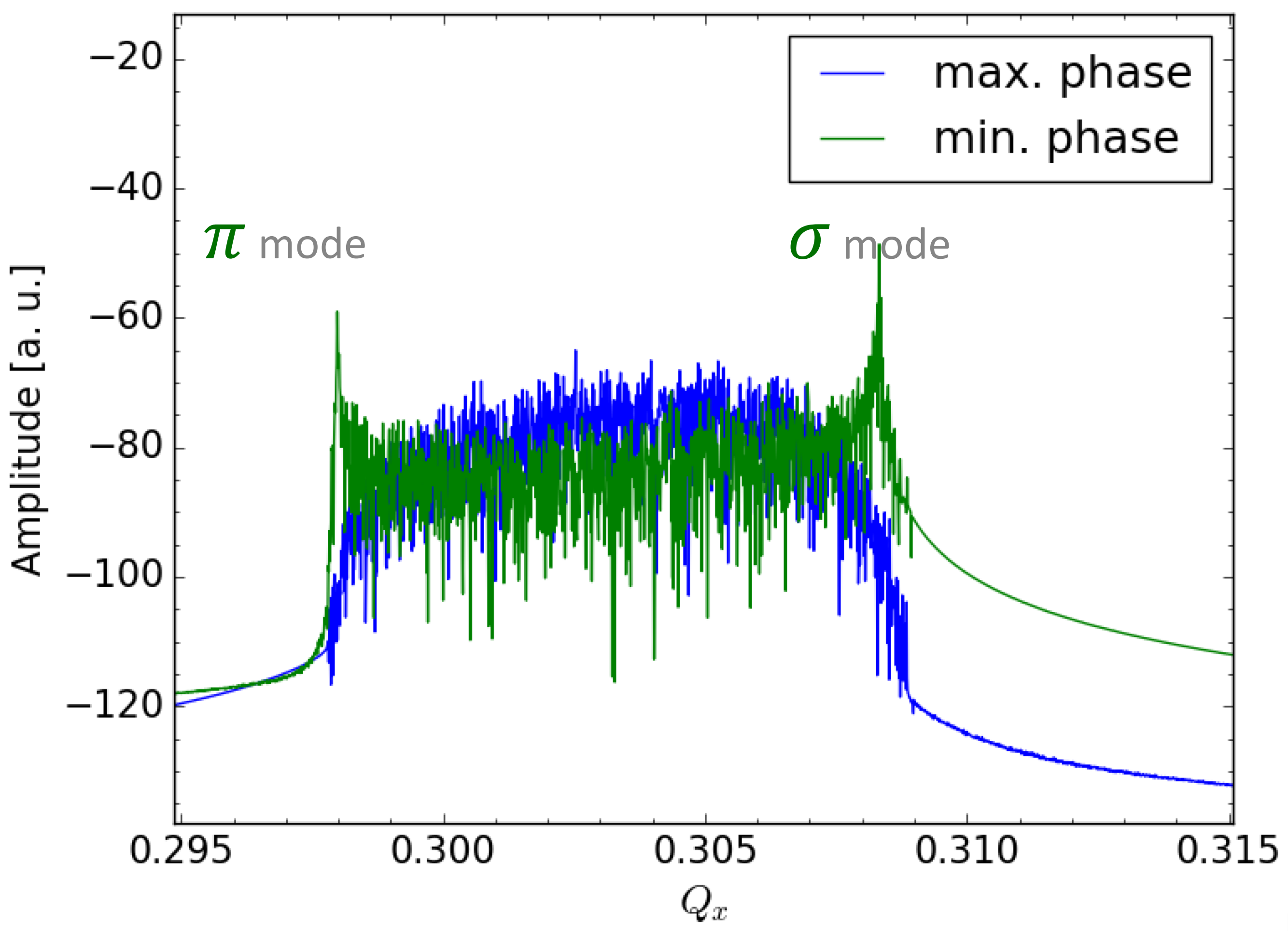


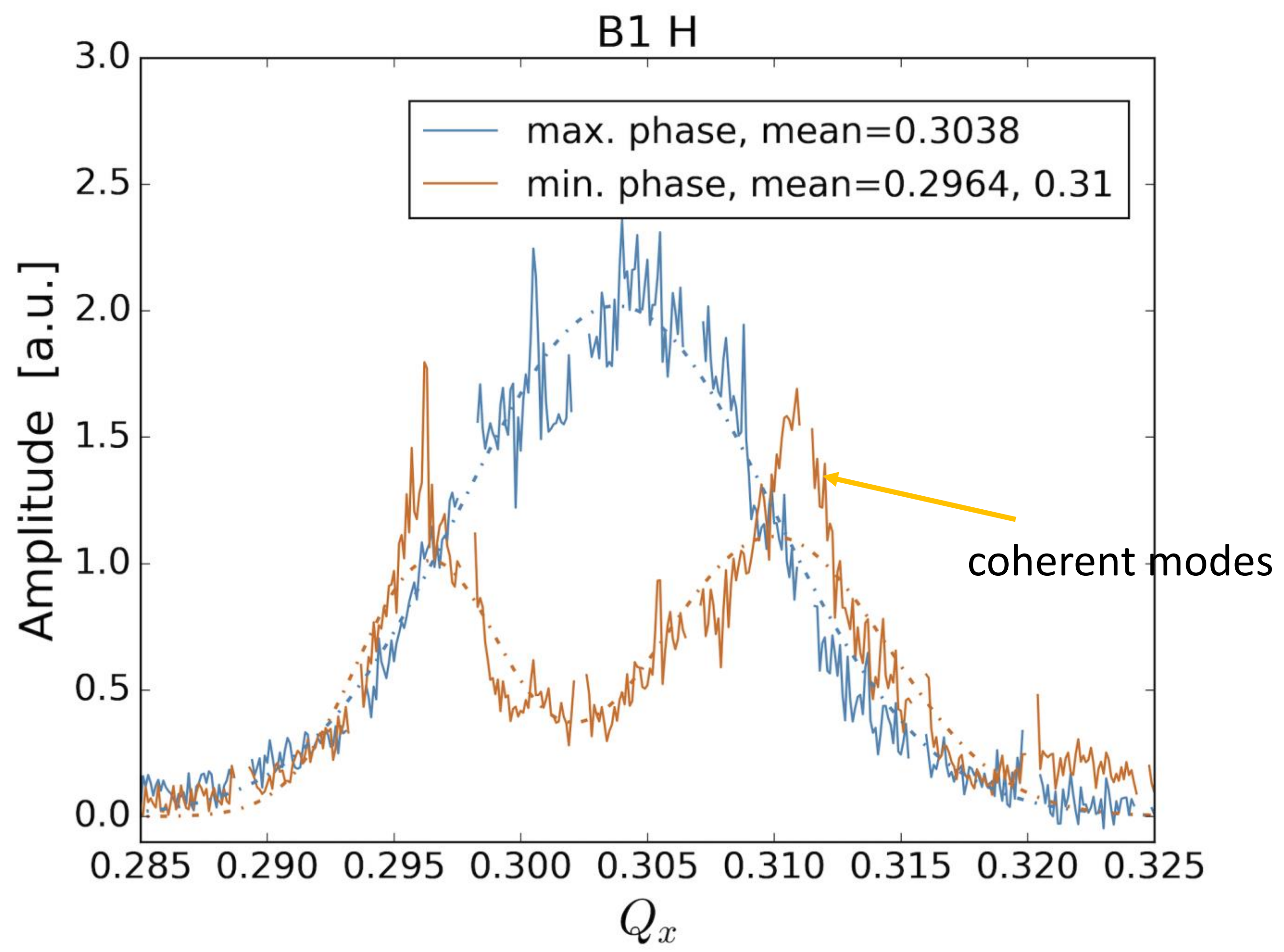
Tune shifts and coherent modes

- Tune spectra and coherent modes
- Tune shift versus separation scan

COMBI simulated



Data



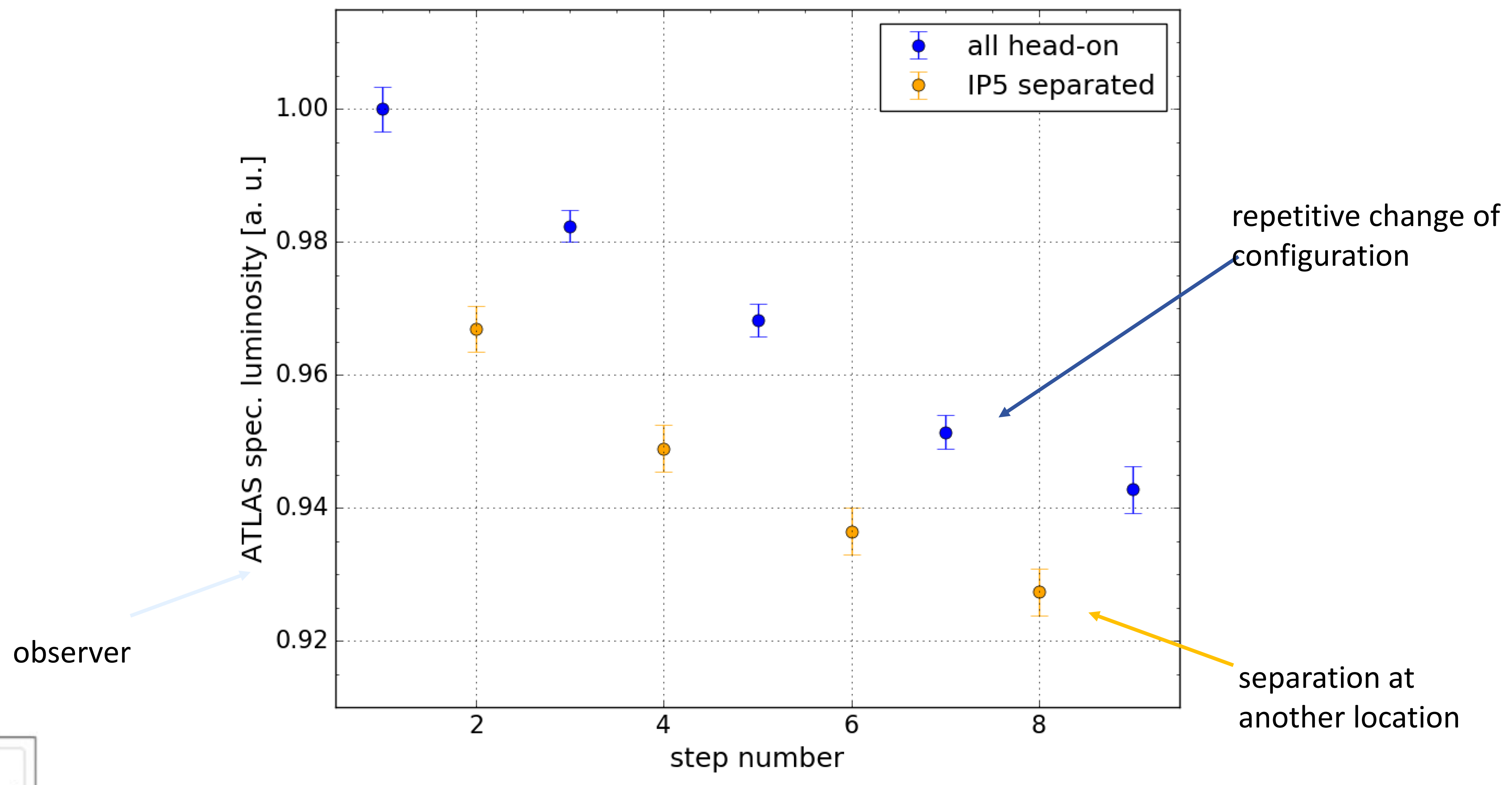
Benchmark experiment

witness	IP5				IP1				IP5			
ξ_{start}	0.010				0.007				0.006			
step #	2	4	6	8	2	4	6	8	2	4	6	8
bias [%]	3.21	3.58	3.01	3.41	2.42	2.64	2.34	1.98	2.46	1.89	1.37	2.23
stat. [%]	0.45	0.35	0.33	0.32	0.34	0.35	0.35	0.35	0.45	0.39	0.46	0.42

ATLAS luminosity change as a function of the CMS collision

Luminosity observations

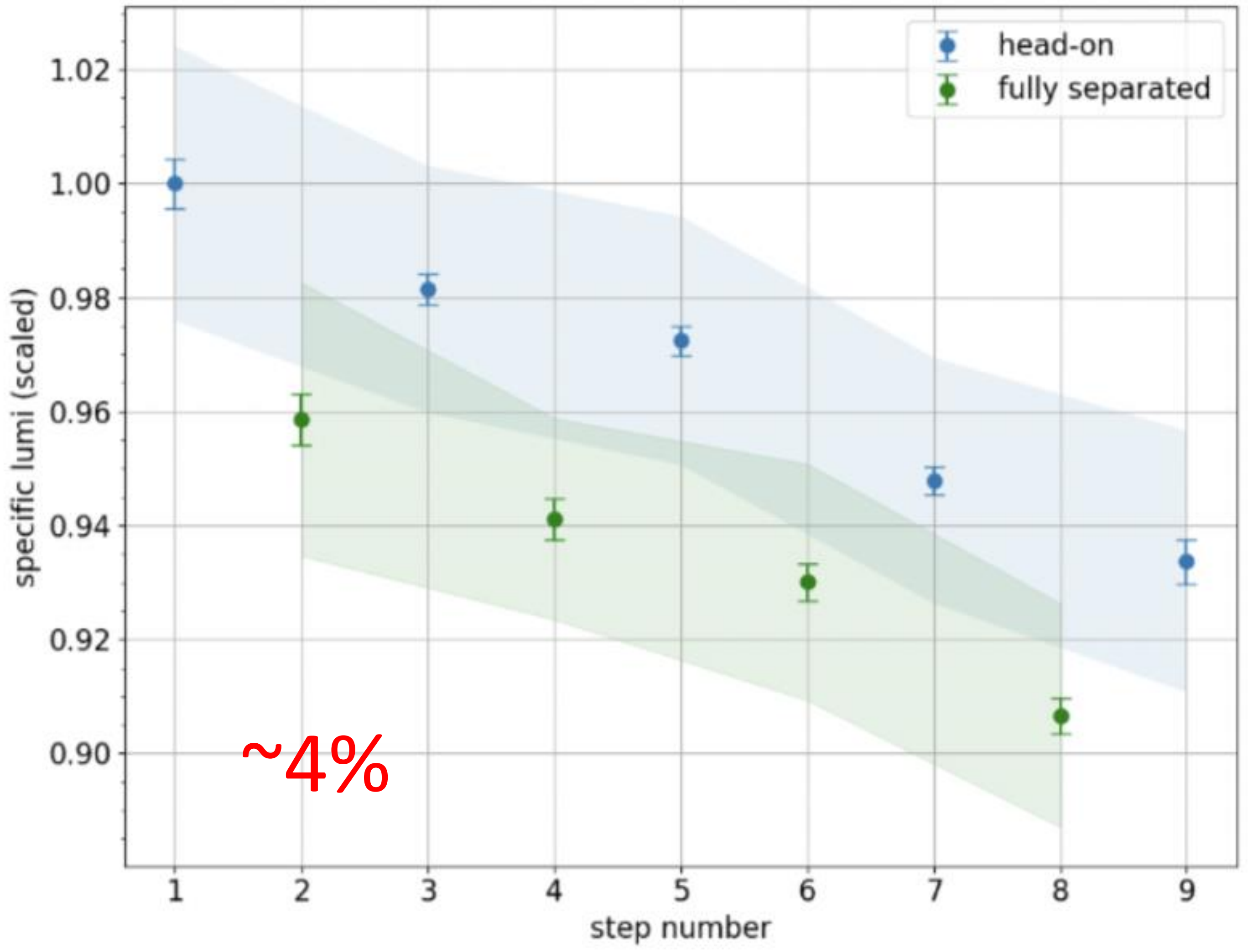
$\xi = 0.007/\text{IP}$

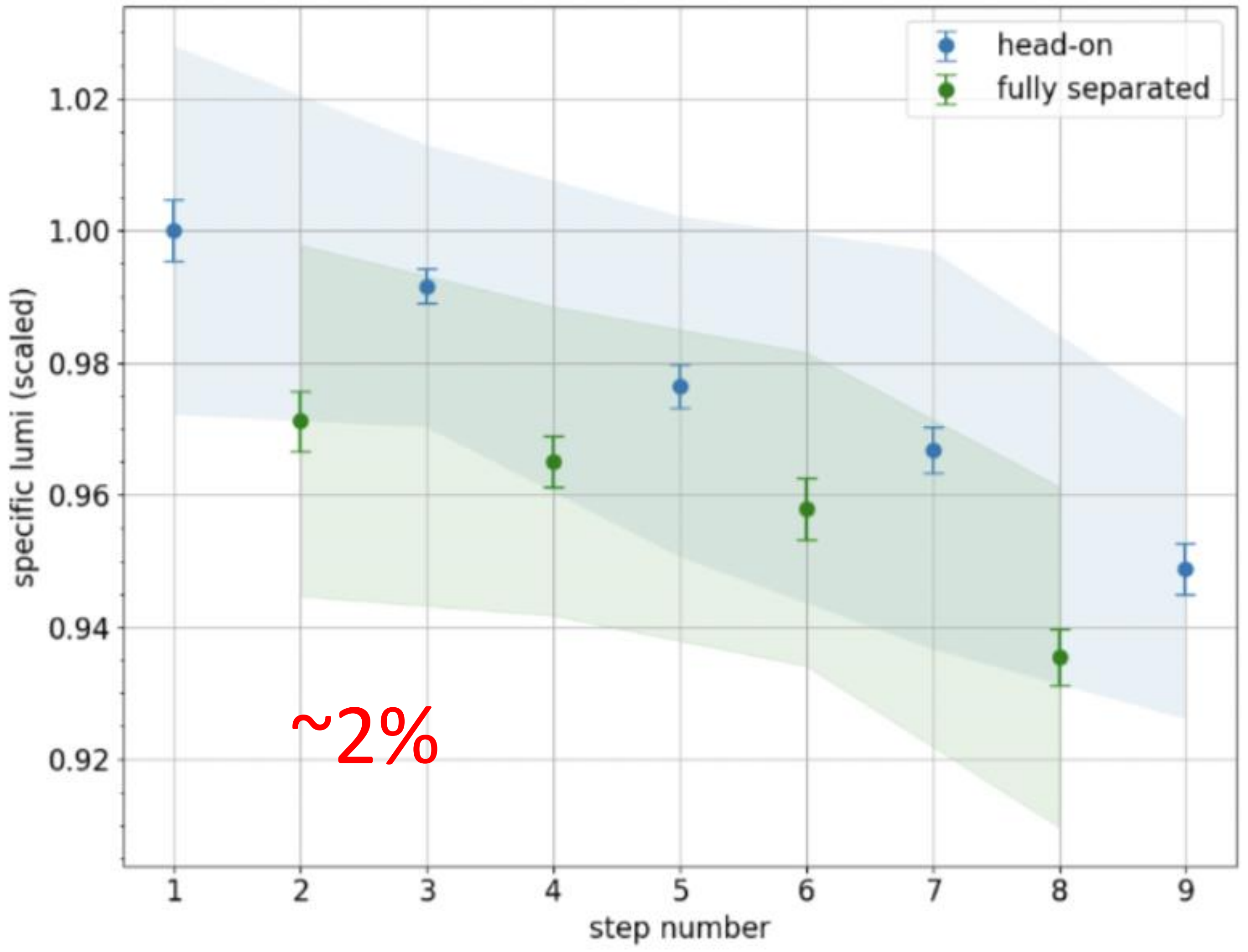


CMS luminosity change as a function of the ATLAS collision

$\xi = 0.01/\text{IP}$

$\xi = 0.006/\text{IP}$





- Luminosity bias due to BB has been observed in both observing IPS and the resulting effect is in within expectations
- The expectation varies with ξ_{bb}
- Phase advance impact to the observed effect visible

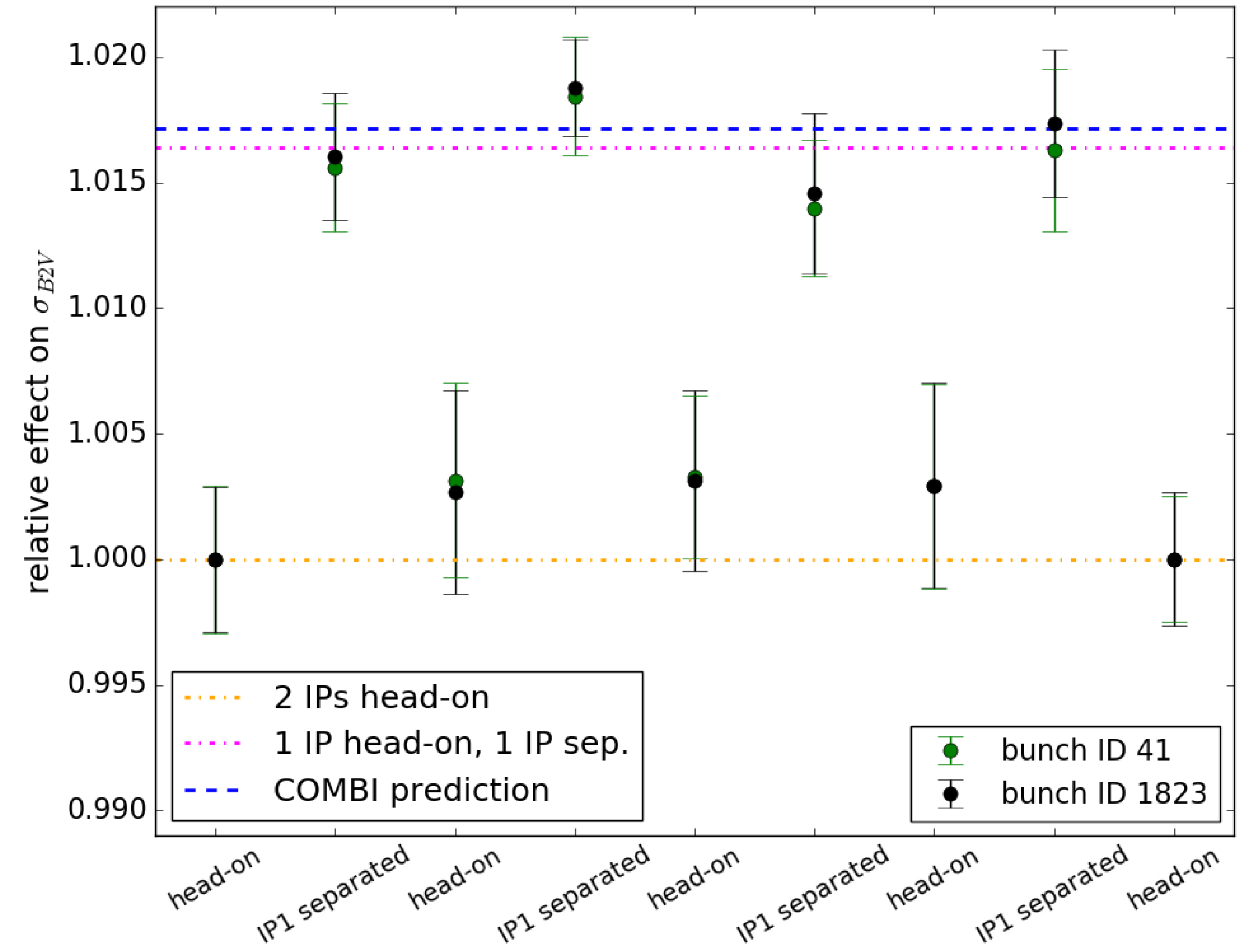
Benchmark experiment

presented at EPS-HEP 2023

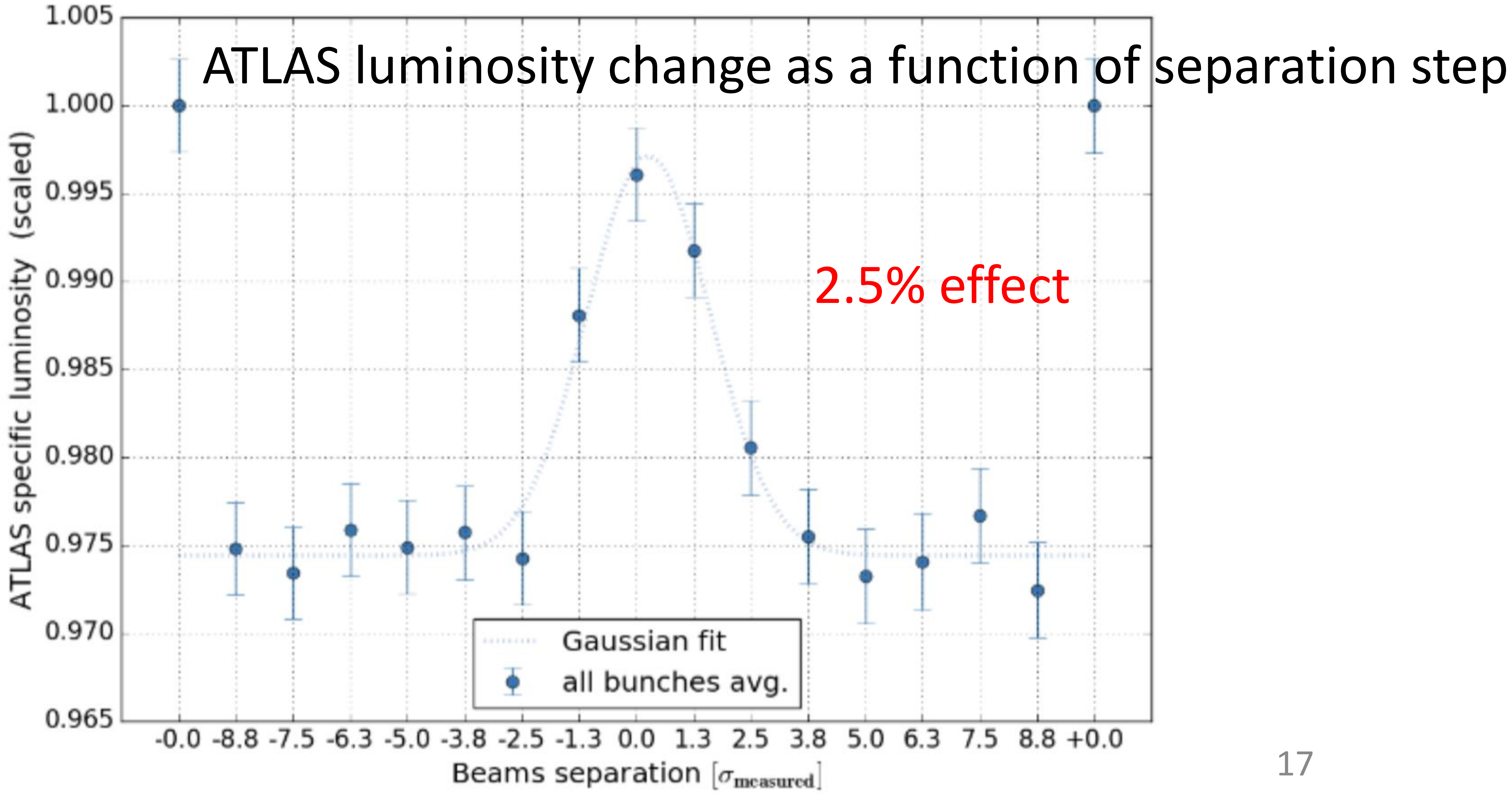
Aim: validation of the correction strategy used in the vdM calibration

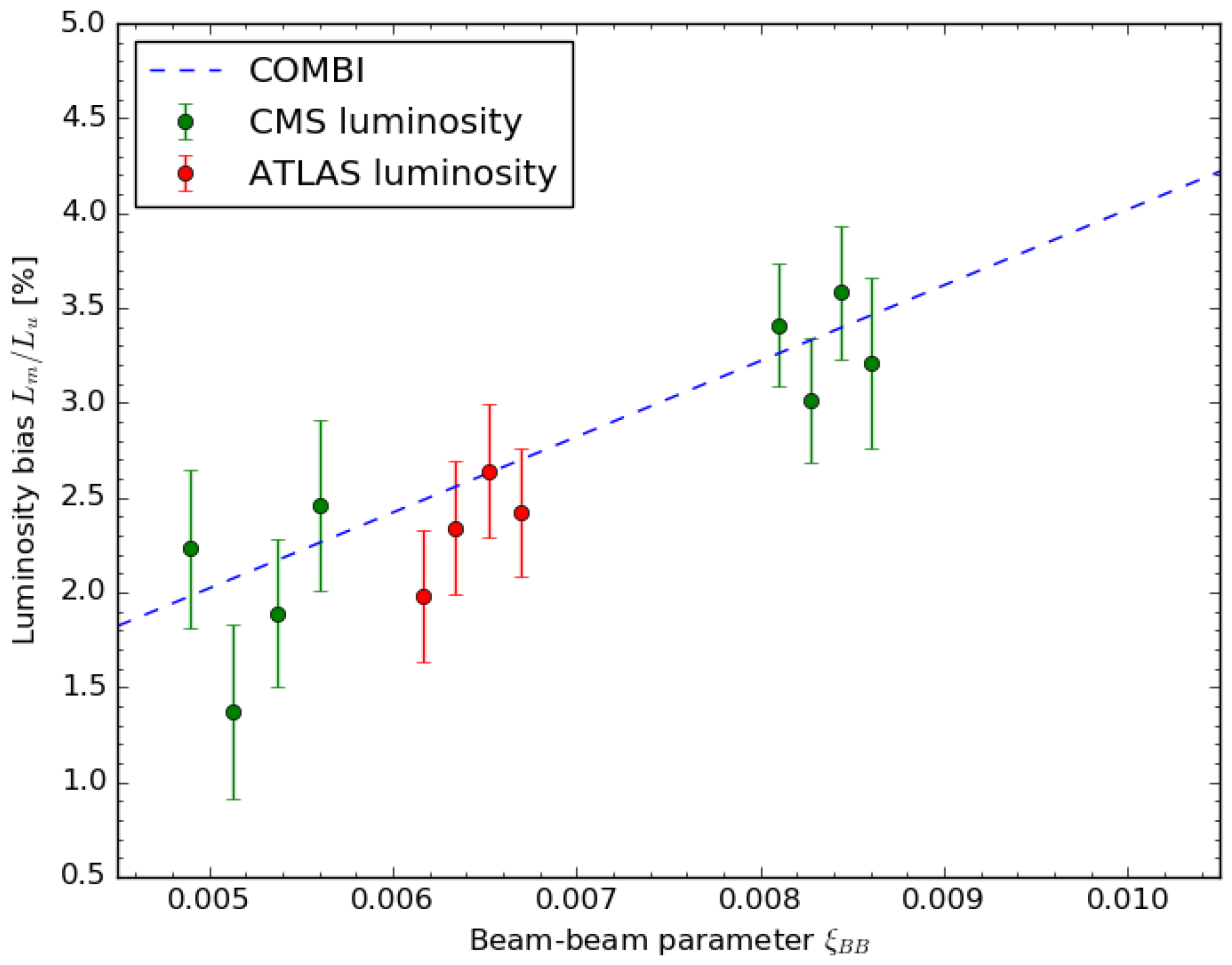
- support for the multi-IP modelling
- scaling law with BB parameter verified
- observations of BB-induced changes during a separation scan

- first measurement of the impact of BB effects on the luminosity in LHC



Beam width reduction caused by moving IP1 from fully separated to head-on position, as measured by synchrotron light monitor [8] and compared to COMBI





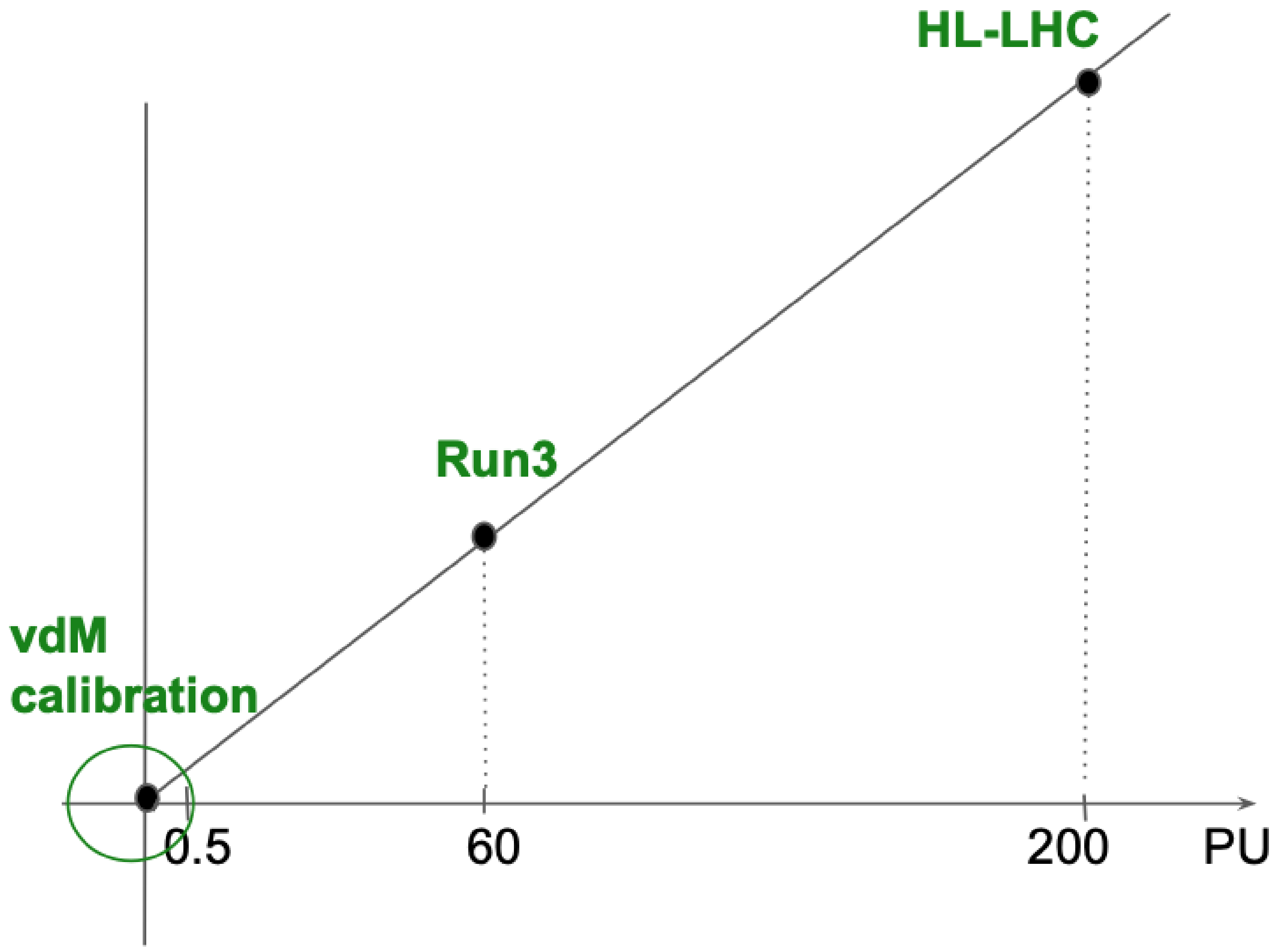
Luminosity enhancement at head-on configuration caused by additional BB interaction (at another IP) as measured by both ATLAS and CMS (observer IP), as a function of the single-IP BB parameter, compared to COMBI simulation predictions

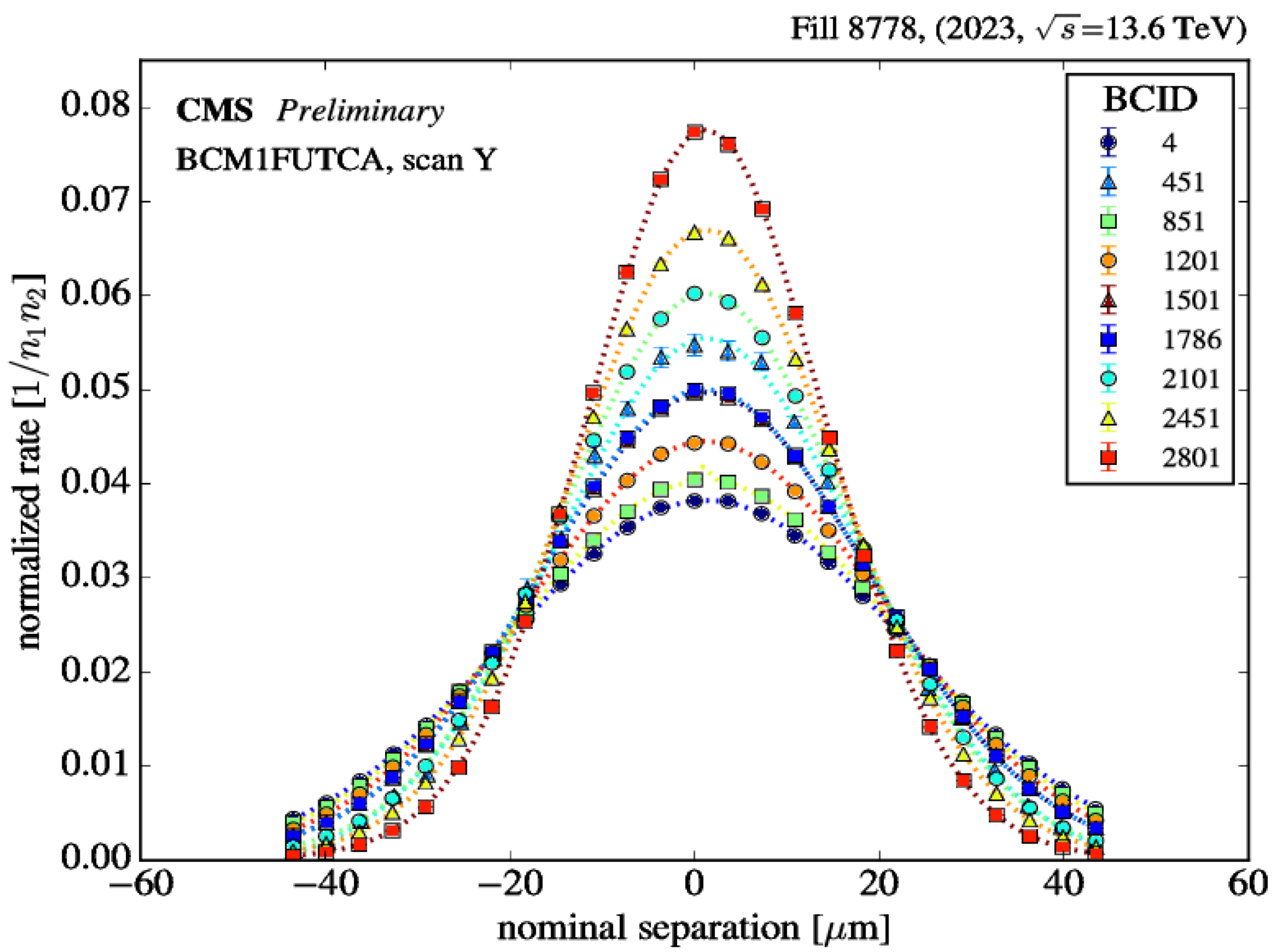
Extrapolation to nominal conditions

At nominal conditions the luminosity measurement can be biased with a non-linearity of a detector response over a wide pile-up range

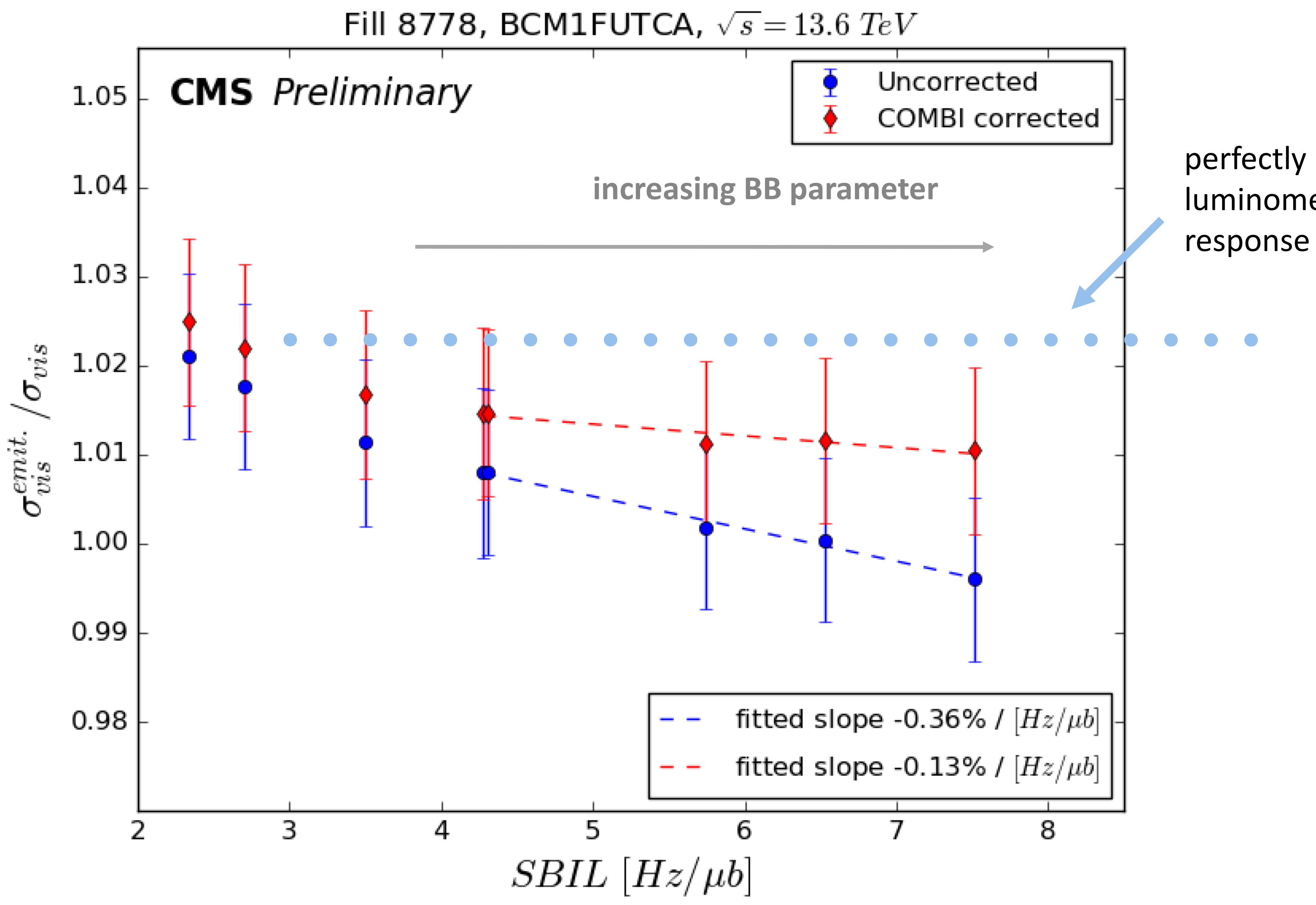
- BB simulations useful to produce dedicated corrections - minimising the associated extra systematic from bunch by bunch differences
- Tested/used for a specific measurement fill (BSRT calibration fill 2023)

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





Impact of BB on detector non-linearity



Pile-up (PU) = ~7 x Single Bunch Instantaneous Luminosity (SBIL)

Proof of concept (EPS-HEP 2023 J. Wanczyk)

- apparent BB-induced slope - removed with BB simulation predictions (ξ~0.008)
- fundamental to understand for HL-LHC

Other luminometers behave differently

Independent measurement → further studies needed for precise measurement

Conclusions

- Extensive simulation campaign of BB effects on the luminosity led to a much better understanding, minimising the related systematic uncertainty on absolute luminosity calibrations at LHC exp
- Improved corrections
  - optical effect shifted pre-2021 central values by -1% - improved results from ATLAS already published [2], CMS results on the way
  - by accounting for the multiple collisions effects - additional 0.4% correction for typical vdM BB parameter ξ~0.004/IP
- Dedicated BB experiment at the LHC allowed to validate some key aspects of the simulation model at the % level
  - First measurement of the beam-beam-induced biases on luminosity
  - agreement with the simulation to the level of 0.1%
- Beam-beam simulations allow for dedicated corrections at the physics conditions (dedicated mini scan at ξ~0.01/IP)
- Possible to remove the apparent beam-beam induced bias to detector response → measuring intrinsic detector non-linear response in an independent way
  - luminometers non-linearities are expected to be one of the main challenges at HL-LHC
- Numerical simulations are invaluable tools to improve understanding, quantify effects and push higher precisions → full exploitation of LHC luminosity and learn more in preparation for the high pile-up era
- BB induced Lumi enhancement by tuning the IPs can be applied also to LHC and HL-LHC case → 3-7% depending on leveling at IPs

Thank you!

References

[1] S. Van der Meer, "Calibration of the Effective Beam Height in the ISR " *CERN-ISR-PO-68-31*, 1968.

[2] ATLAS Run 2 luminosity calibration / CMS on the way

[3] A. Babaev et al., arXiv:2306.10394, submitted to EPJC

[3b] J. Wenninger, SL Note 96-01 (OP)

[3b] M. Venturini and W. Kozanecki, SLAC-PUB-8700

[4] T. Pieloni, COMBI

[5] X. Buffat, 6D BB models:

[6] W. Herr, CAS proceedings

[7] J. Wanczyk, Phase modulation

[8] G. Trad, BSRT

[9] M. Söderén et al., ADT

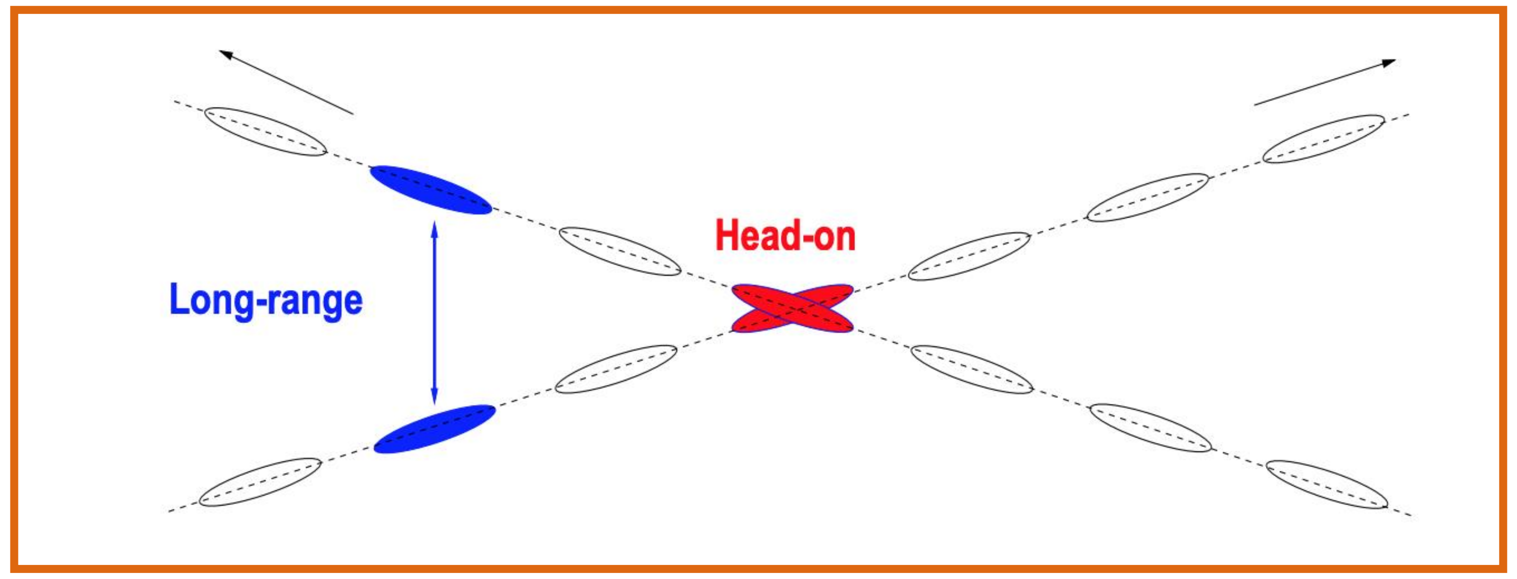
Uncertainties from BB

Beam-beam (b-b) uncertainty source	ξ_{sim} $[10^{-3}]$	Uncertainty-determination procedure	σ_{vis} uncertainty [%] for N_{NSIP} = 0	1	2	Comments	See Sec.
Absolute ξ scale: β^* uncertainty at the scanning IP	5.60	Vary β^* by $\pm 10\%$ in the simulation or parameterization (Sec. 4.2.3), for each beam and in each plane	0.06 (total for both beams and both planes)	0.10	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 (total for both beams and both planes)	0.23	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 $N_{\text{NSIP}} = 0$, extrapolated to $N_{\text{NSIP}} \geq 1$ using Eq. (41)	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			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	$< 0.01^*$ < 0.02			for $\theta_c \leq 10\,\mu$rad* for $\theta_c \leq 150\,\mu$rad	4.5 + 5.2.3
Beam-beam imbalance	5.60	B*B and COMBI simulations	0.016* 0.059 0.136	0.012* 0.045 0.104	0.008* 0.032 0.072	for $\sigma_2/\sigma_1 > 0.95^*$ for $\sigma_2/\sigma_1 > 0.90$ for $\sigma_2/\sigma_1 > 0.85$	4.7 + 5.2.4
Multiple IPs: phase advance	5.60	COMBI (or B*B) simulations	0	< 0.20		Worst case: arbitrary phase advances between IPs	4.6.4 + 4.6.5 + 5.3
multi-IP tune shift	5.60	Vary p_1 in Eq.(41) by $\pm 15\%$ in single-IP simulations. Ignore if using multi-IP simulation	0	0.05	0.09		
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* 0.03			for $E_B \geq 6.5\,$TeV* at lower beam energies	5.4.2
Numerical accuracy of parameterization	-		< 0.10			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 (Secs. 4.2.3 & 4.6.5)	+0.52	+0.86	+1.17	% of σ_{vis}	5.5

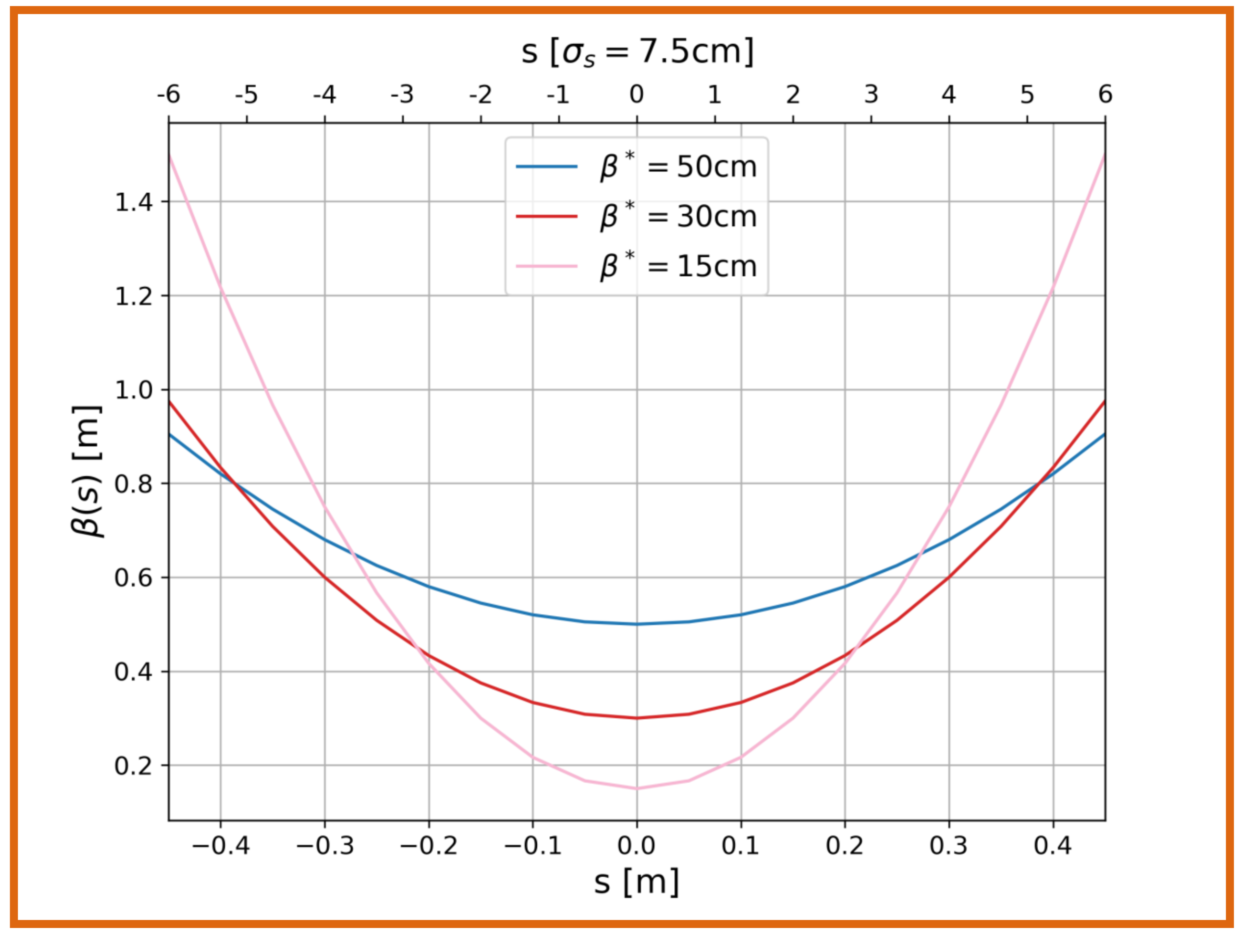
Table 8: Typical systematic uncertainties affecting beam-beam corrections to a hypothetical *pp vdM* calibration in a fully symmetric Gaussian-beam configuration, with the round–beam-equivalent beam-beam parameter set equal to ξ_{sim}, for three values of N_{NSIP}. For each source, the uncertainty is 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.

Simulation challenges in physics conditions

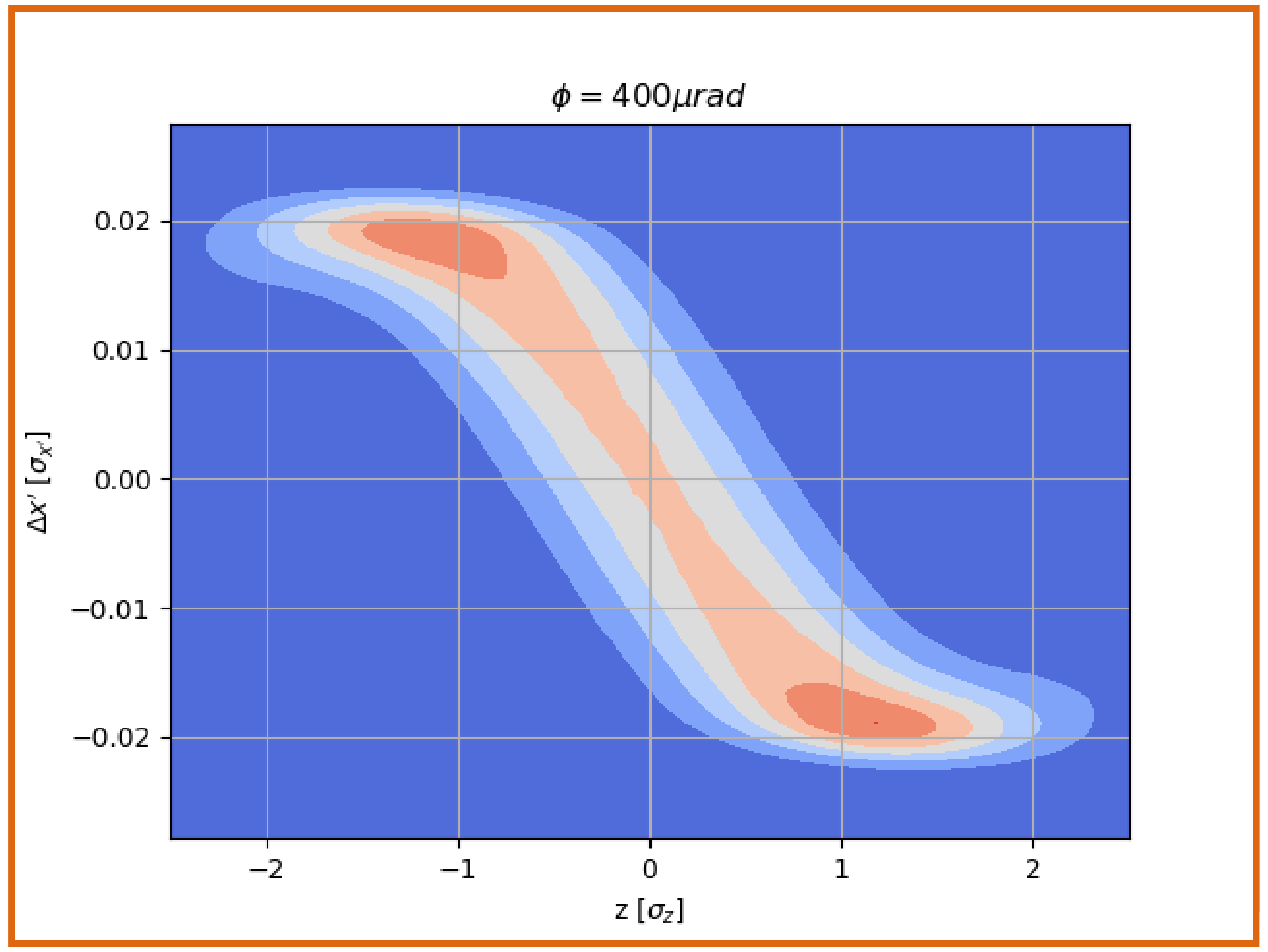
- not only measurement but also simulation challenge
- changes with respect to the vdM regime:
  - pile-up x 100
  - higher BB parameter x 1.5-2
  - non-zero crossing-angle
  - trains - long-range interactions
  - hour-glass effect
- using 6D BB strong-strong soft Gaussian [9]
- developed sliced luminosity integrator for full overlap description along the bunch during collision



multiple long-range interactions around the IP



small non-constant transverse beam widths



longitudinal description of the kick with the crossing-angle