EPFL

Swiss Accelerator Research and Technology

CERN

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

Tatiana Pieloni and Joanna Wańczyk (EPFL)

X. Buffat (CERN), A. Dabrowski (CERN), W. Kozanecki (IRFU-CEA), D. Stickland (Princeton U.), R. Tomas Garcia (CERN), Y. Wu (EPFL), A. Babaev (TPU), C. Tambasco, A. Mehta, O. Karacheban (CERN), G. Pasztor,(Eotvos, U) T. Barklow (SLAC), I. Kralik(IEF), J. Wenninger, LHC OP crews

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

HB2023 workshop
CERN, 10th October

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)

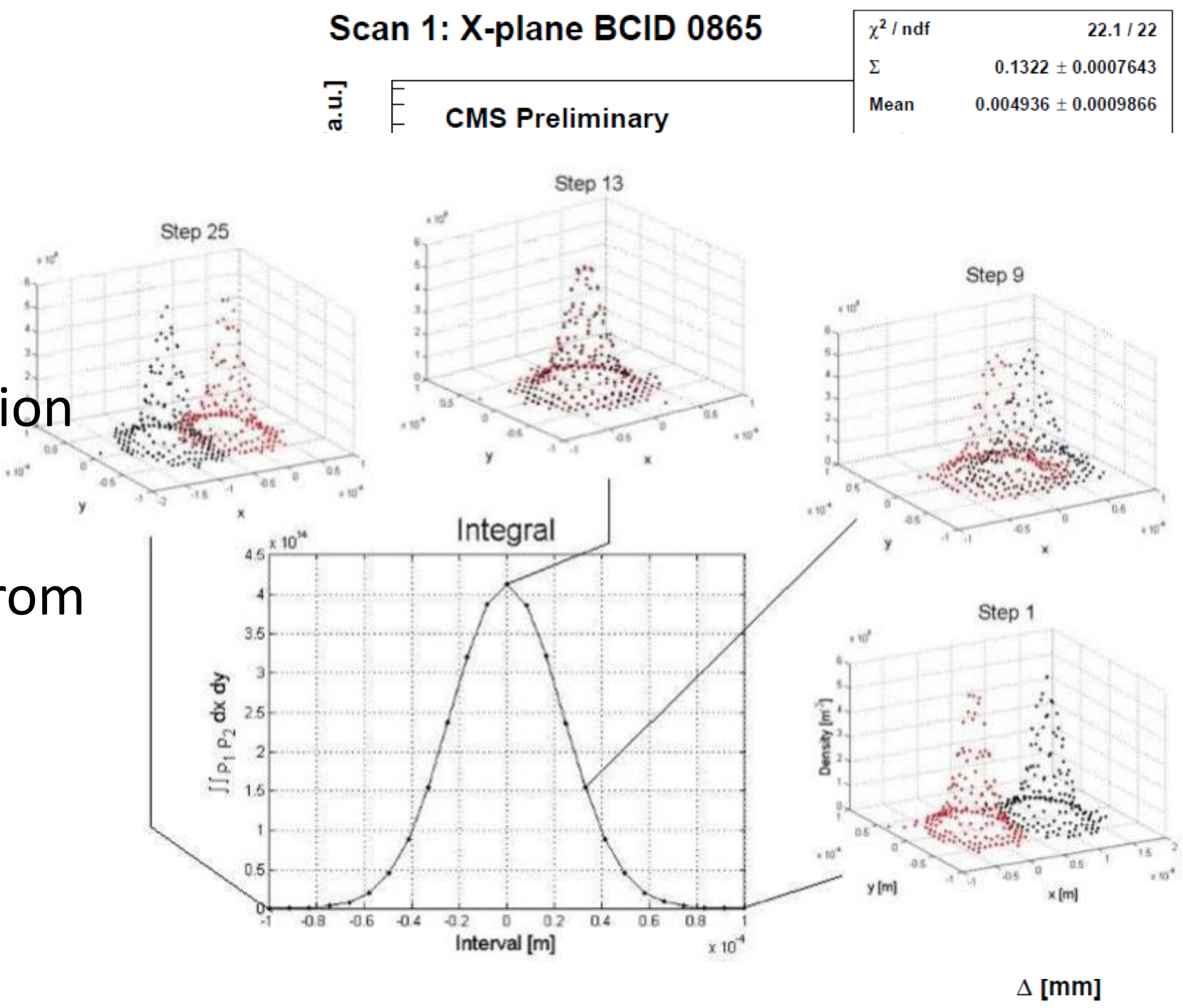
- σ_{vis} is determined in dedicated fills based on beam parameters

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.



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 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)

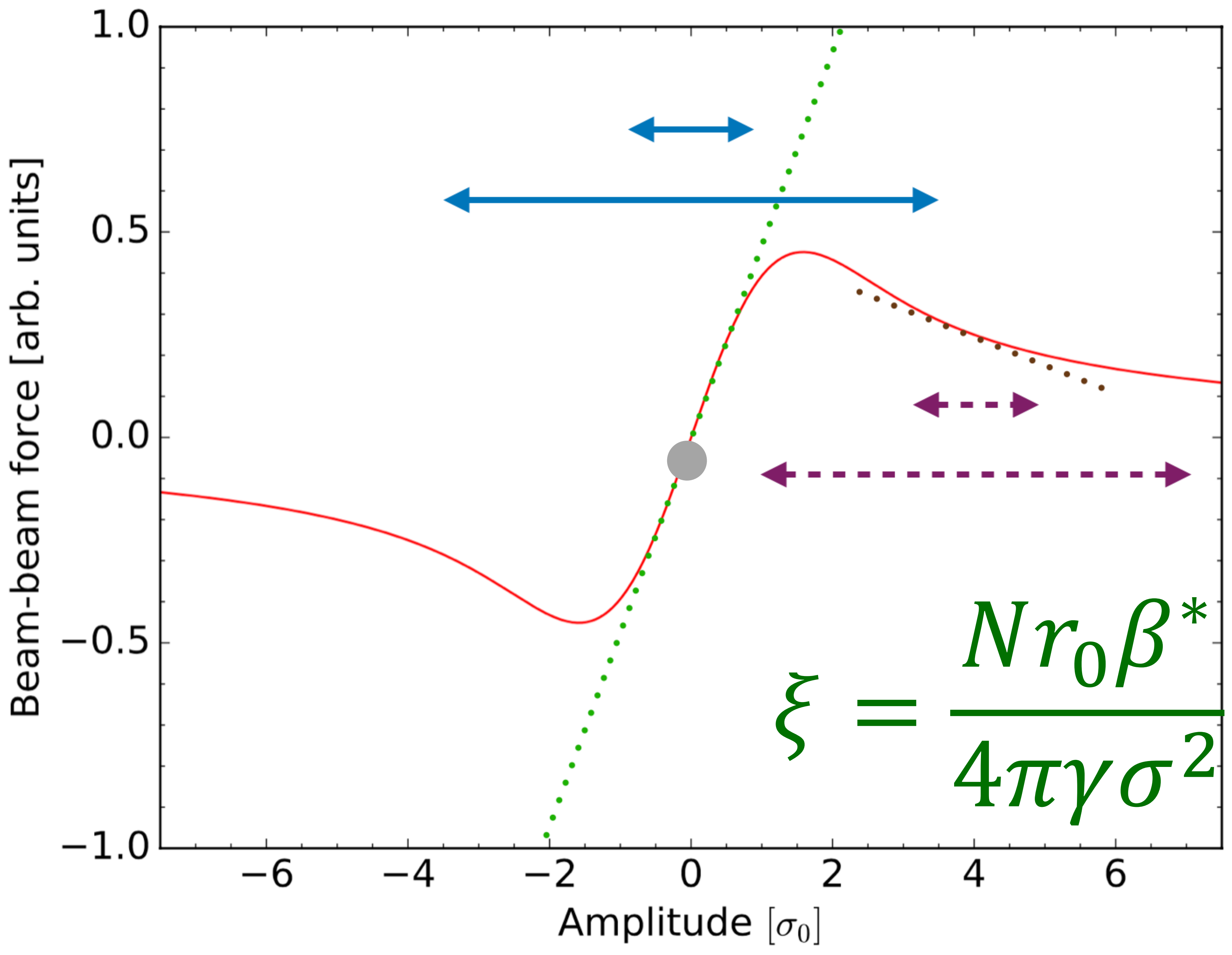
in preliminary Run-2 ATLAS results ~1.5% correction with 0.2% uncertainty (!)

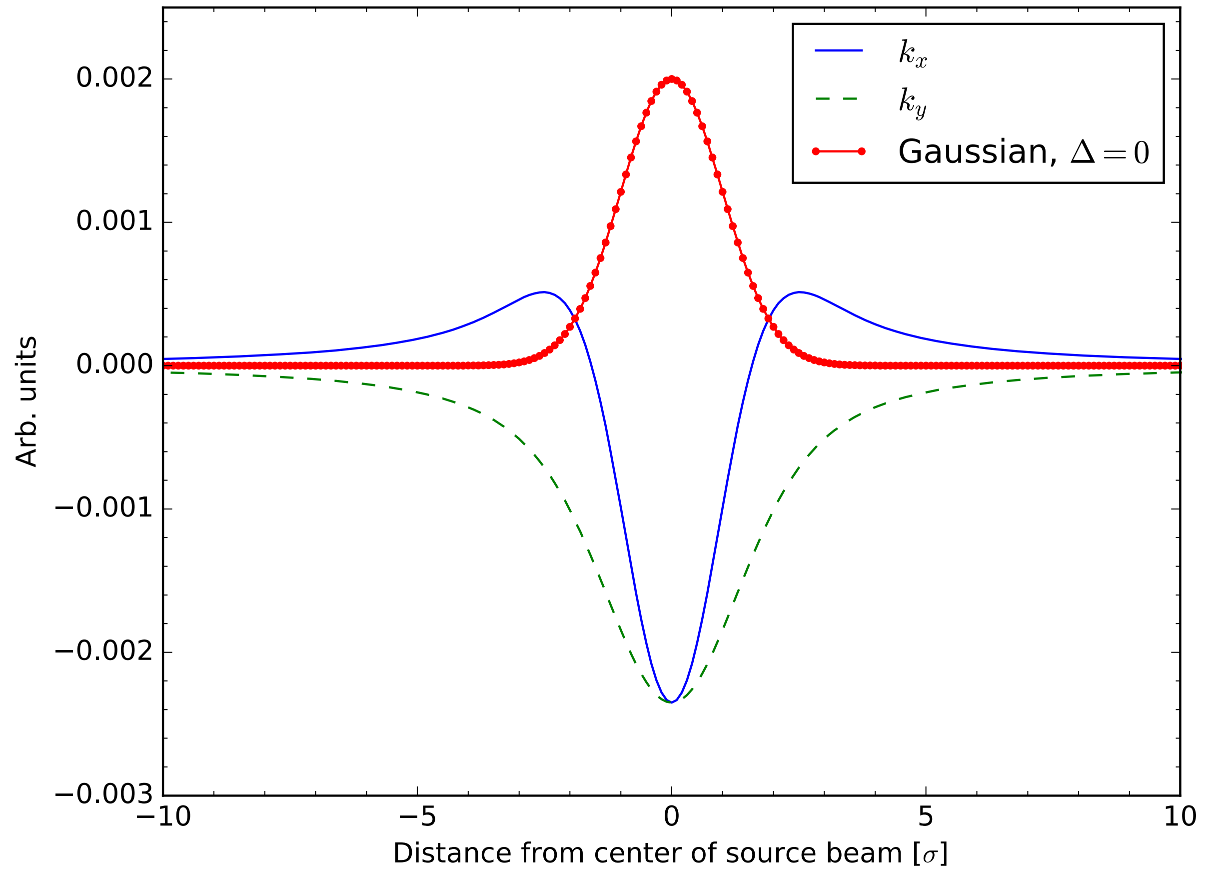
↓

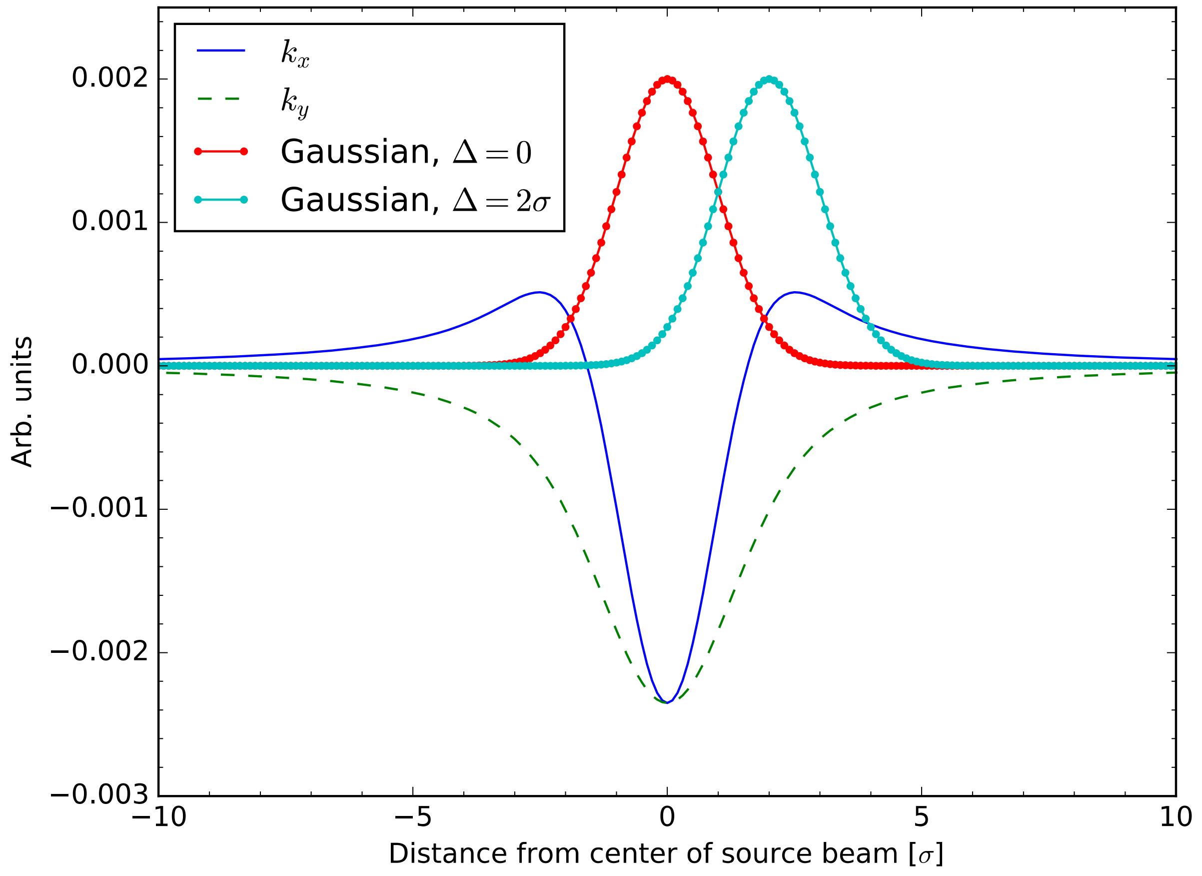
in legacy Run-2 ATLAS results ~0.5% correction with 0.3% uncertainty

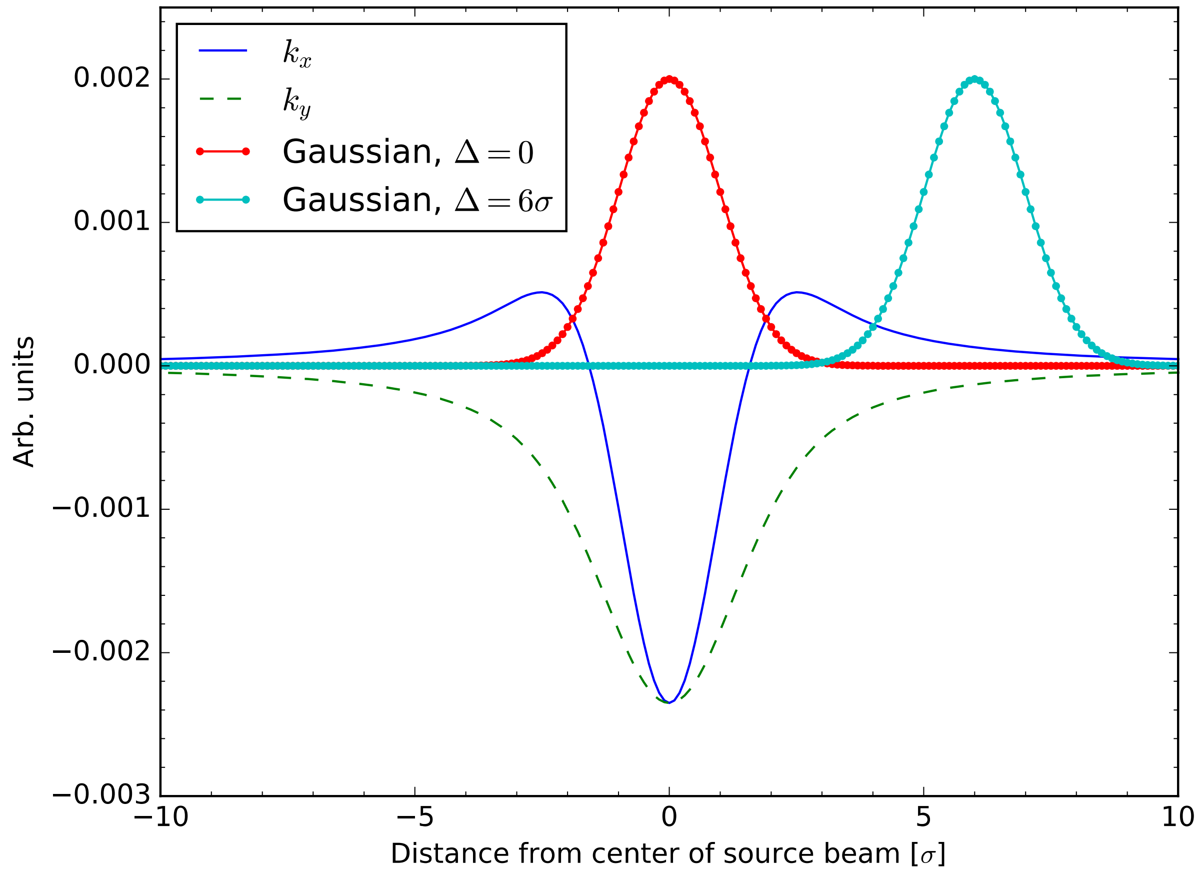
Beam-beam interaction

- 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
- COMBI [4] code used to model self-consistently the interactions to









HB2023

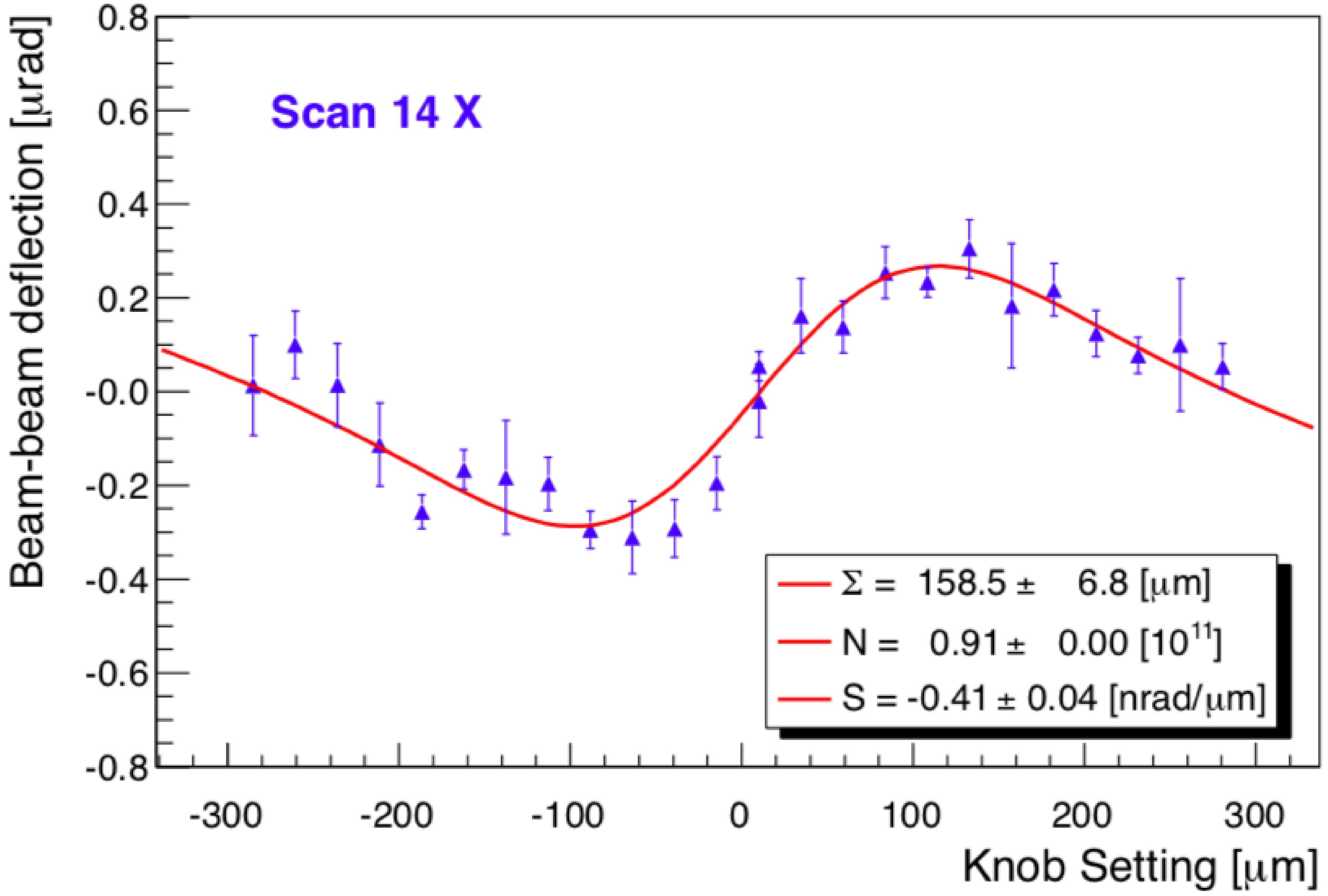
BB bias to luminosity break down for single IP:

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

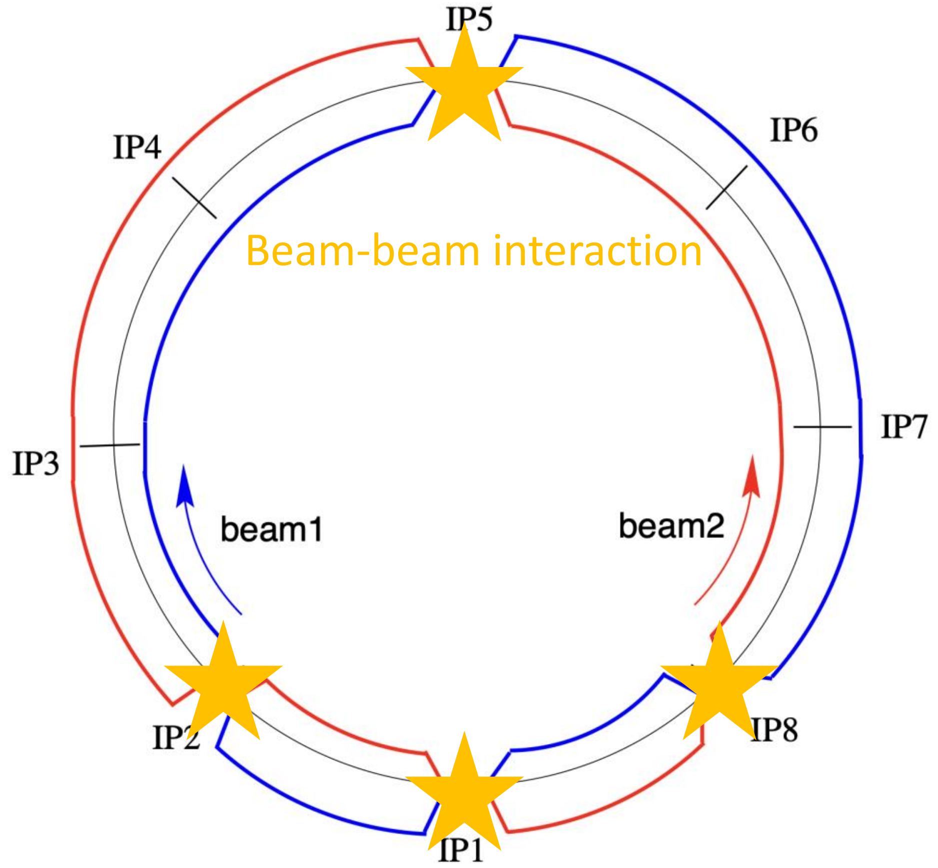
Studied separately in terms of:

- 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…



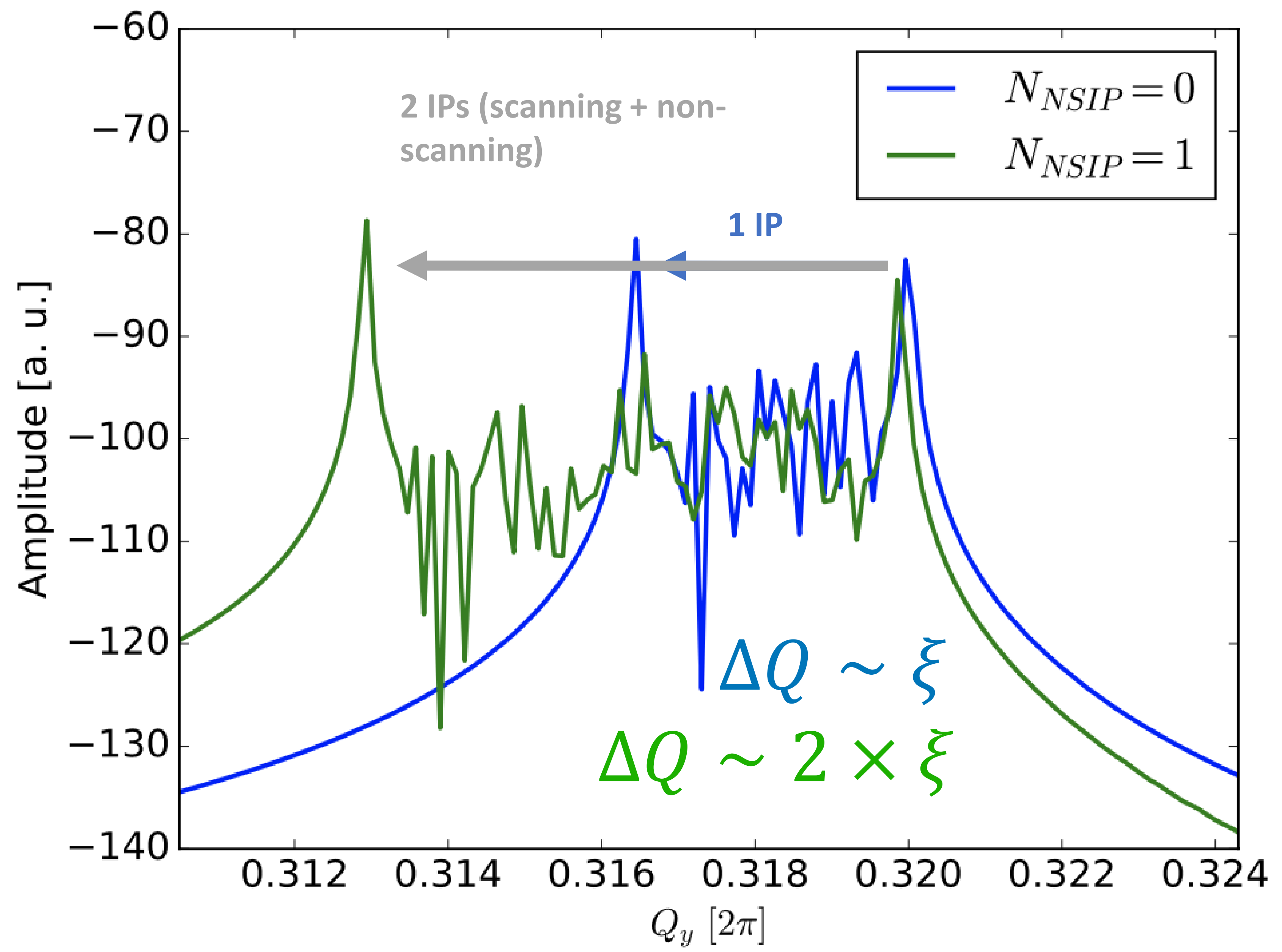
Measurements in VdM
CERN-ACC-NOTE-2013-0006
J. Wenninge, Kozanecki, Pieloni



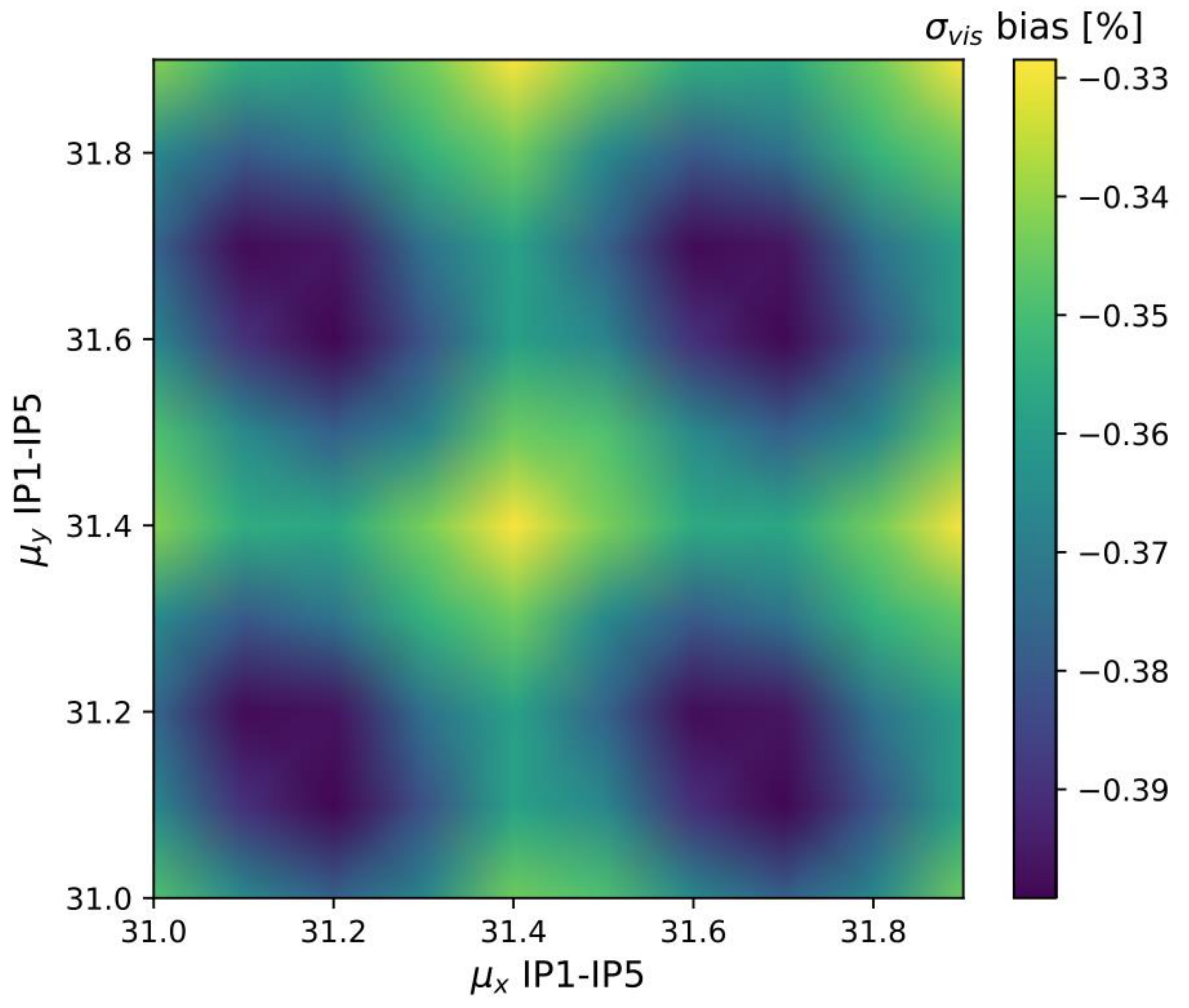
Multi-collision study for vdM calibration

- 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



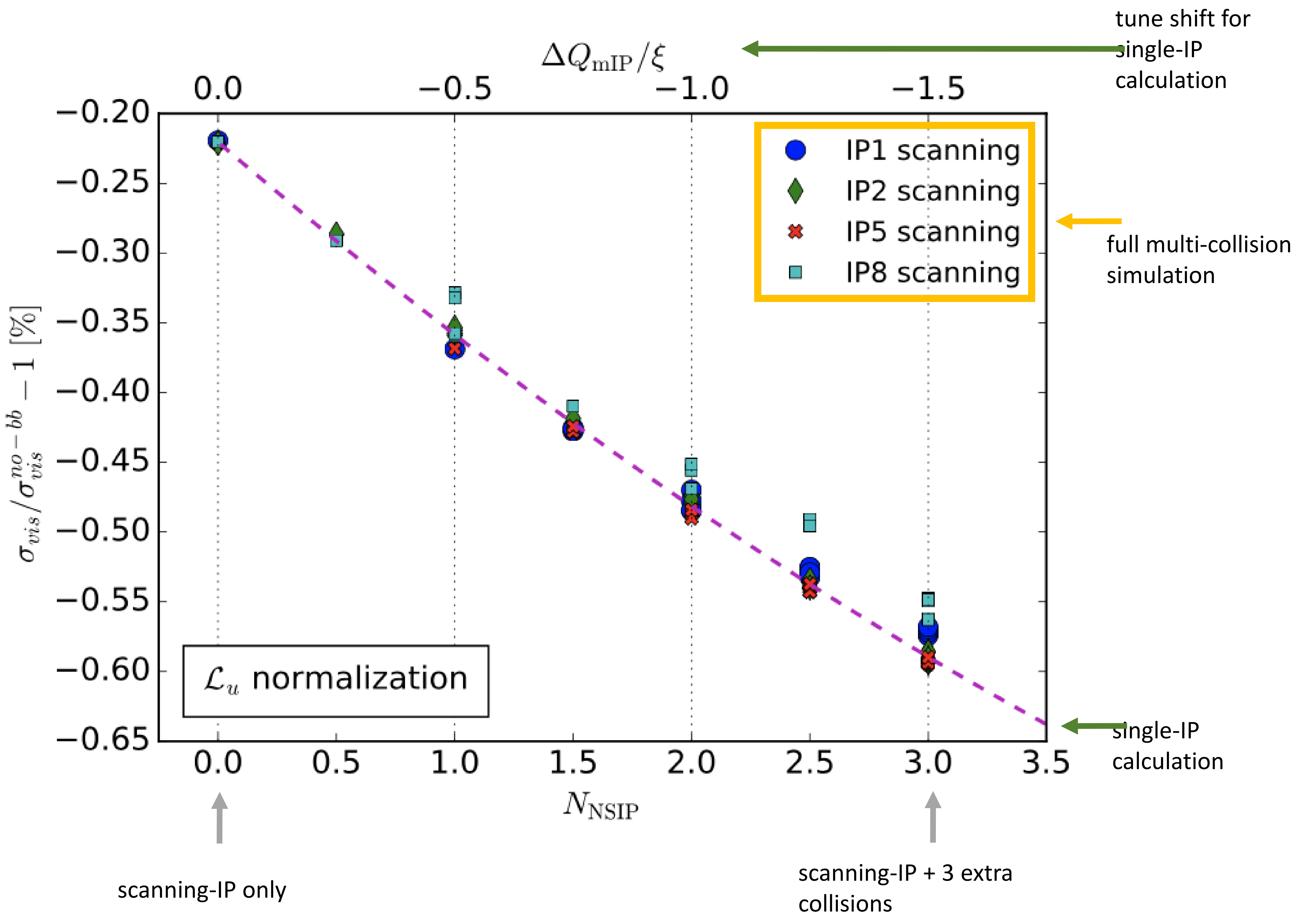
Additional collisions → IPs are coupled via BB

- 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

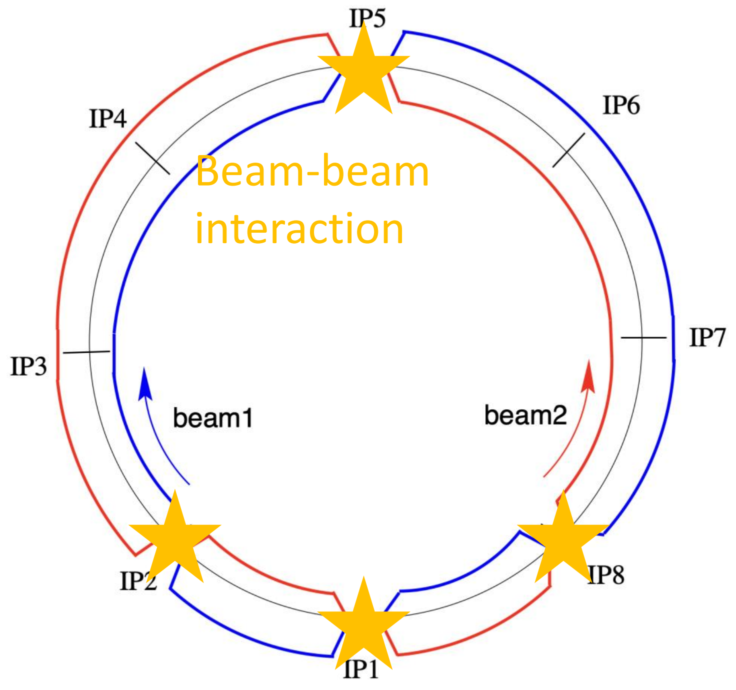
- dependent on beams separation, BB parameter and tunes [3]
- effective multi-IP tune shift can be used to obtain the equivalent calibration constant bias (mimic the extra HO with a tune shift 0.5∗ξ/NSIP)
- simple scaling law derived from strong-strong simulations
  - valid for all LHC IPs
  - verified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



	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

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

Measured beta-beating along the LHC ring from the knob

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

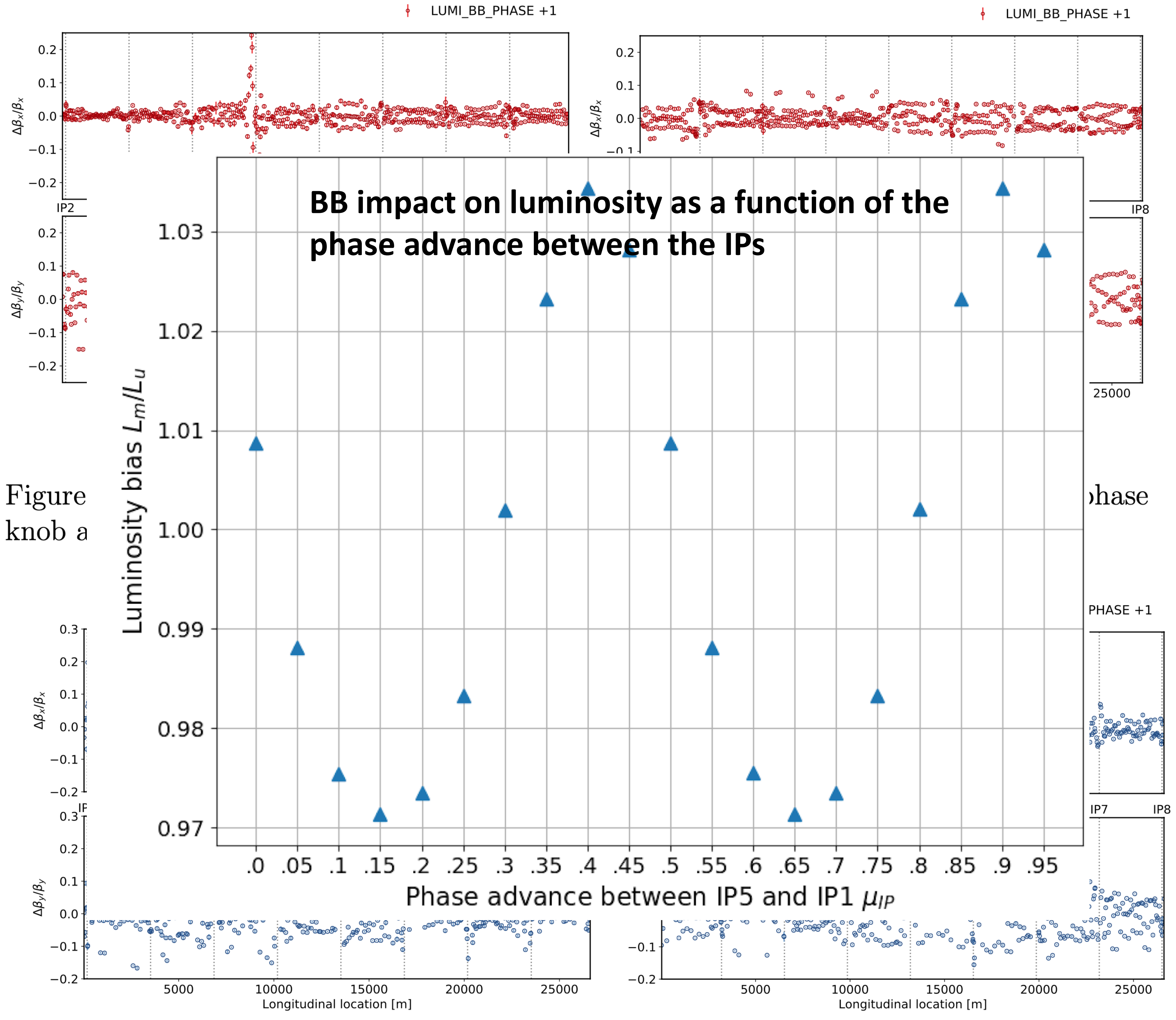


Figure 5: Measured beta function differences along the LHC ring with respect to the MADX model with included maximizing (+1) phase knob, for Beam 1 (left) and Beam 2 (right).

Phase optimisation validated with optics measurements:

Benchmark experiment

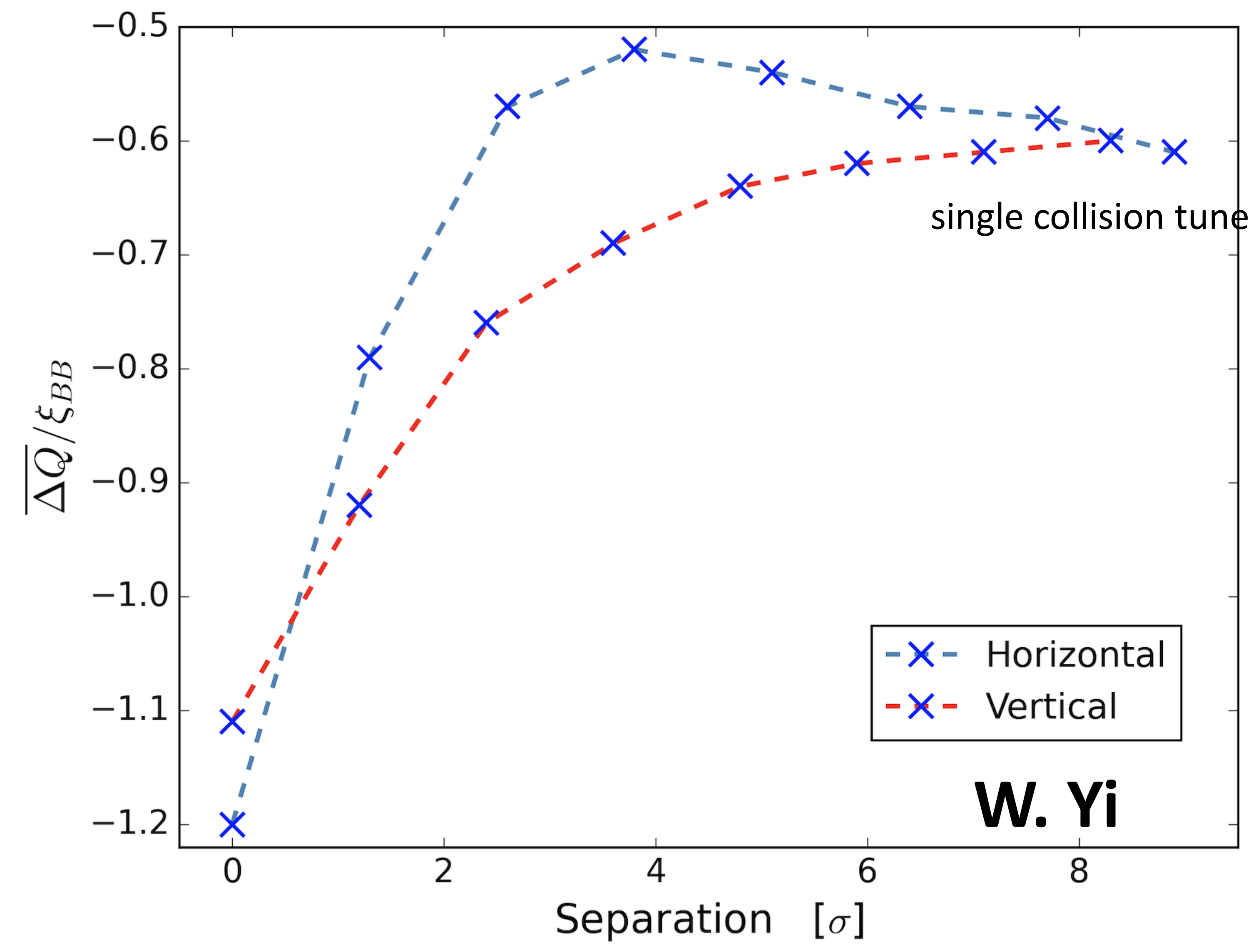
Series of tests:

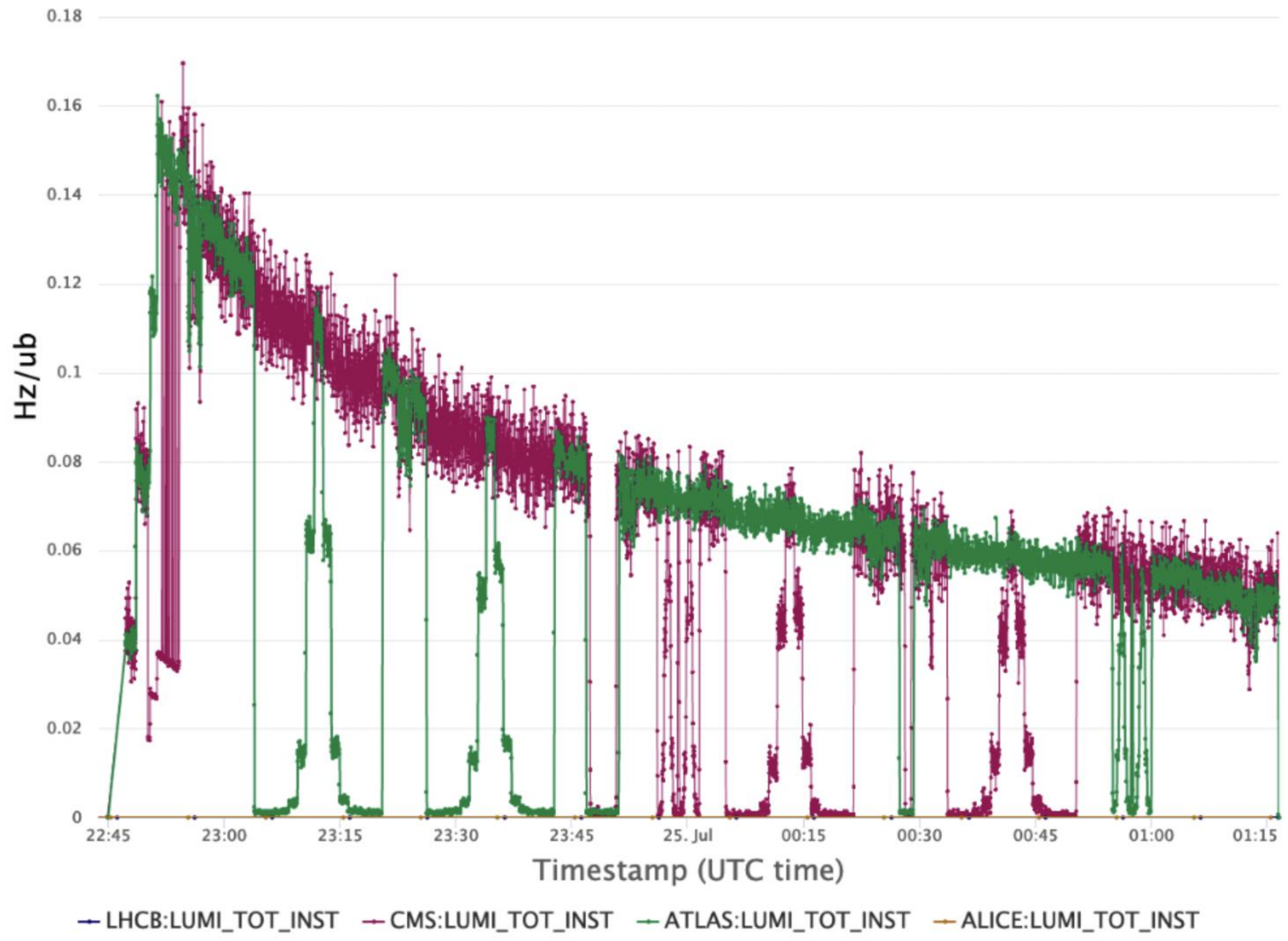
- Scanning IP : in and out collision and transverse scan

→ propagation

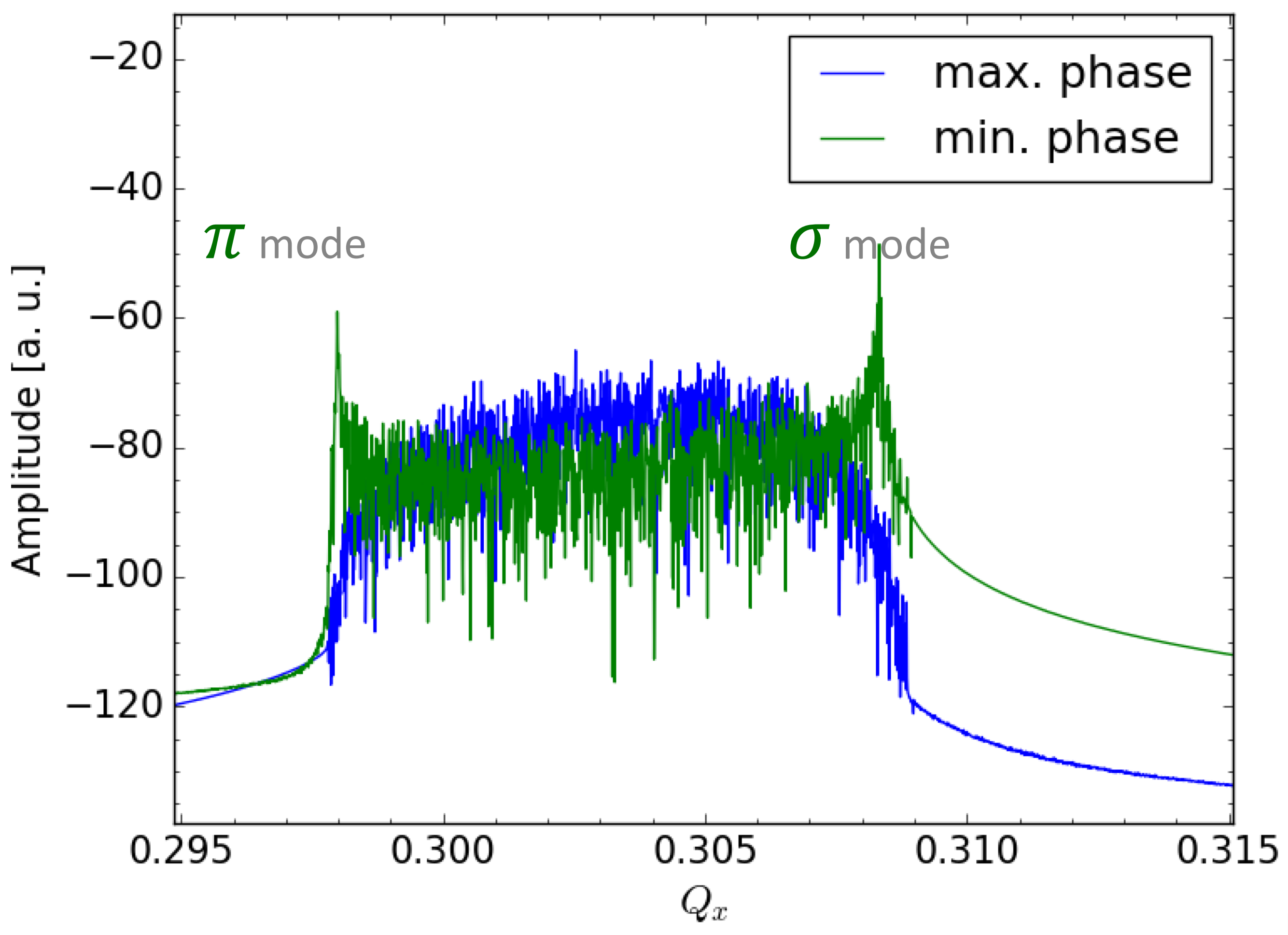
- Witness IP: in HO collision, observation point to see bias on luminosity

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]

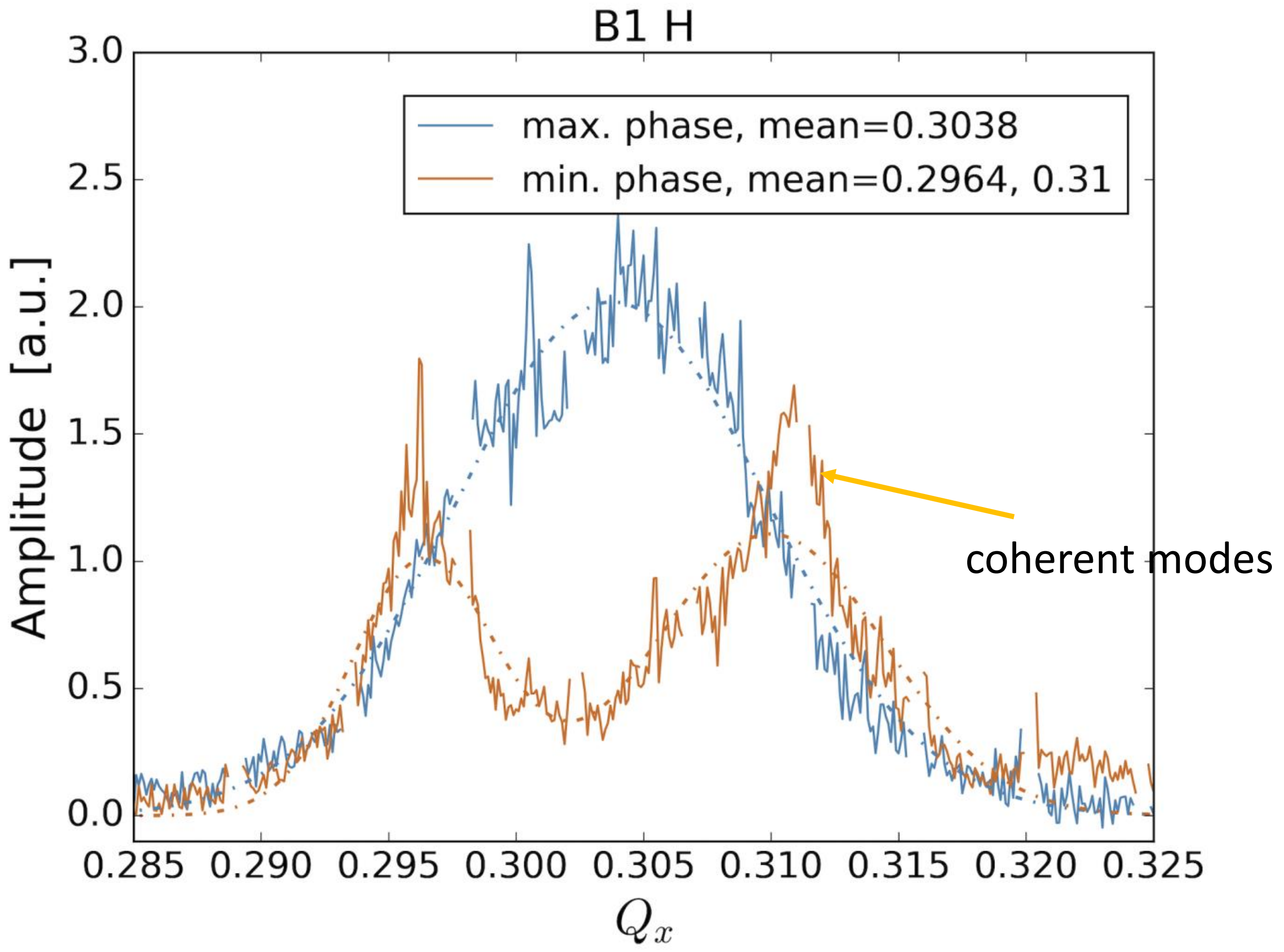




COMBI simulated



Data



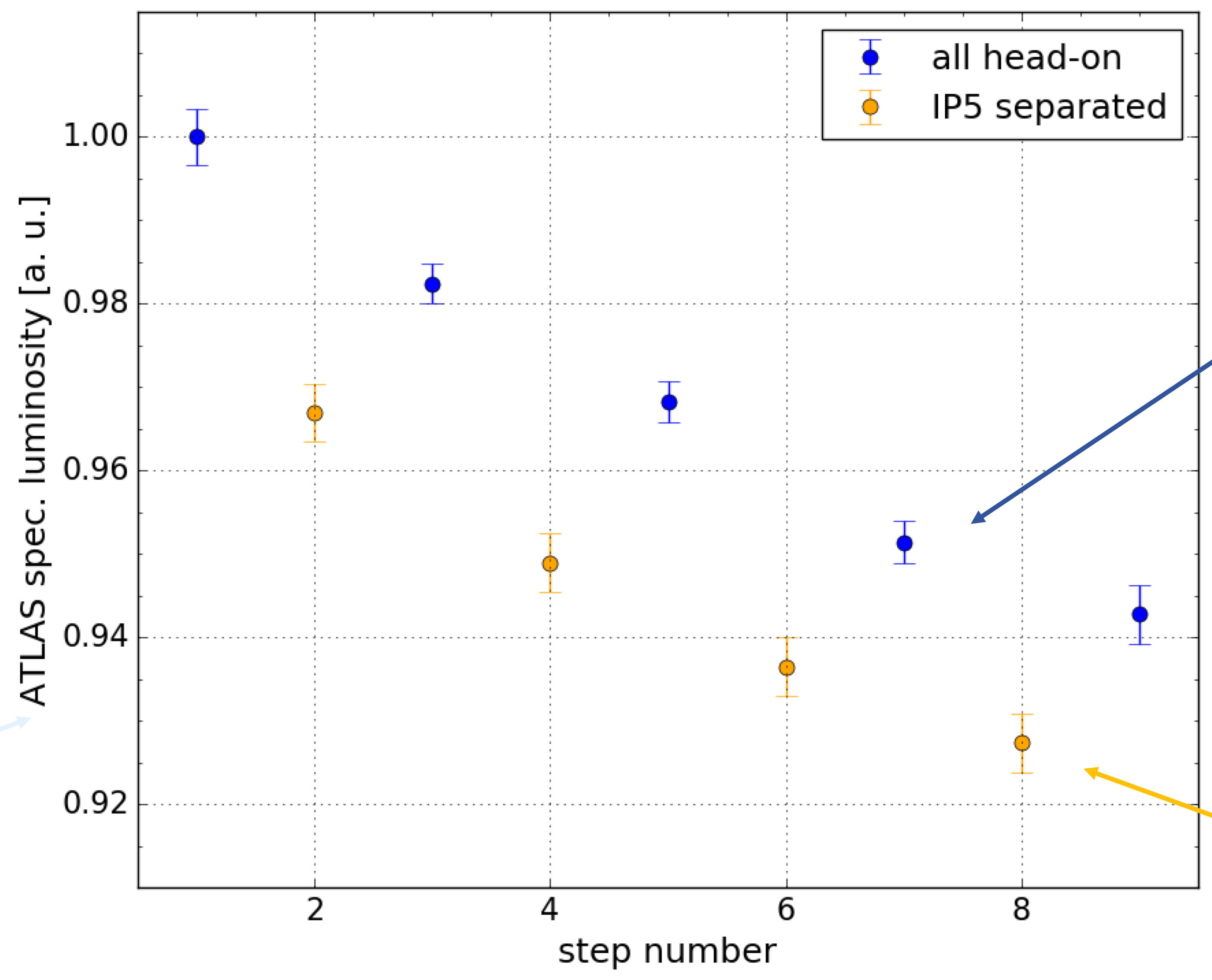
Benchmark experiment

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

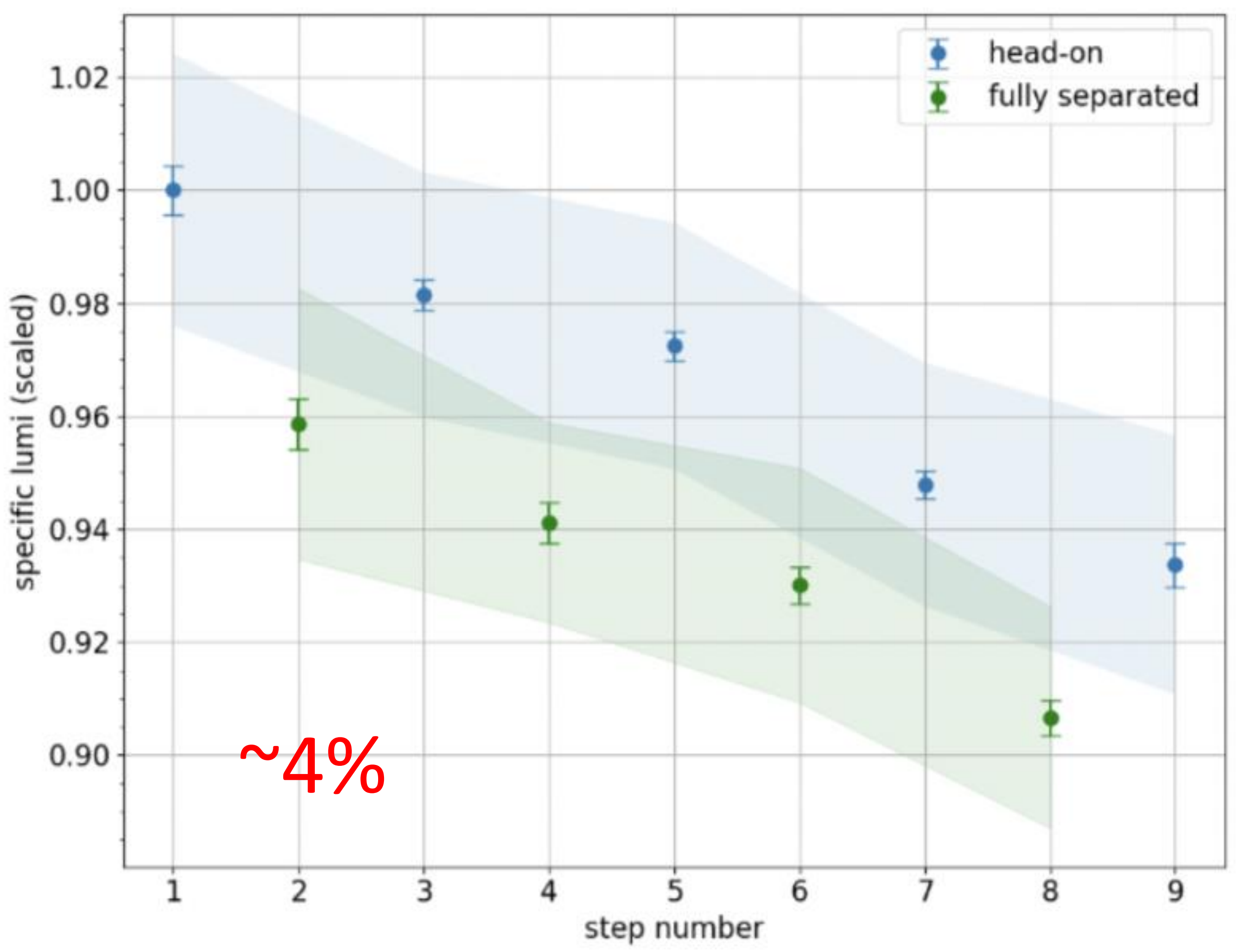
ξ = 0.007/IP

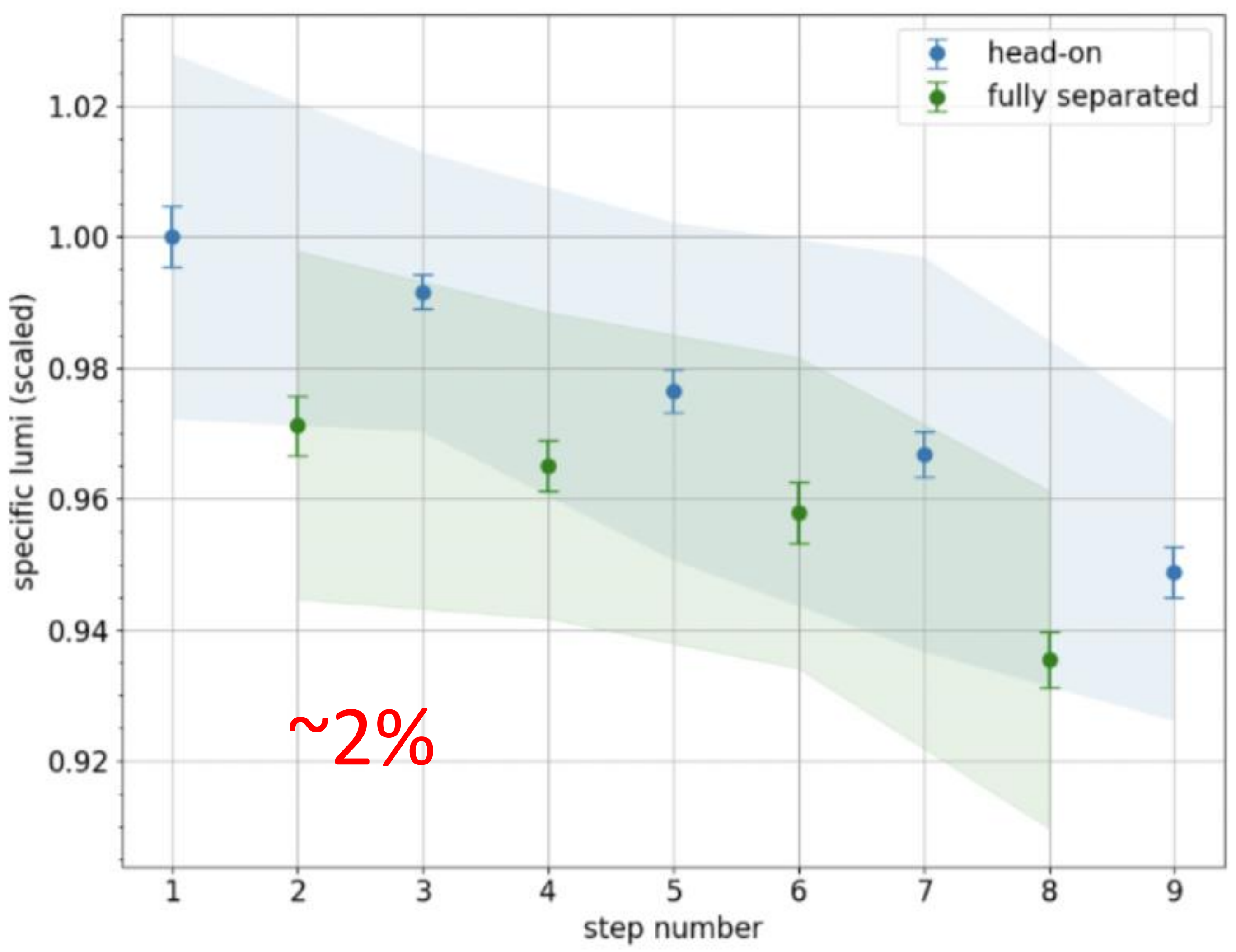


CMS luminosity change as a function of the ATLAS collision

ξ = 0.01/IP

ξ = 0.006/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

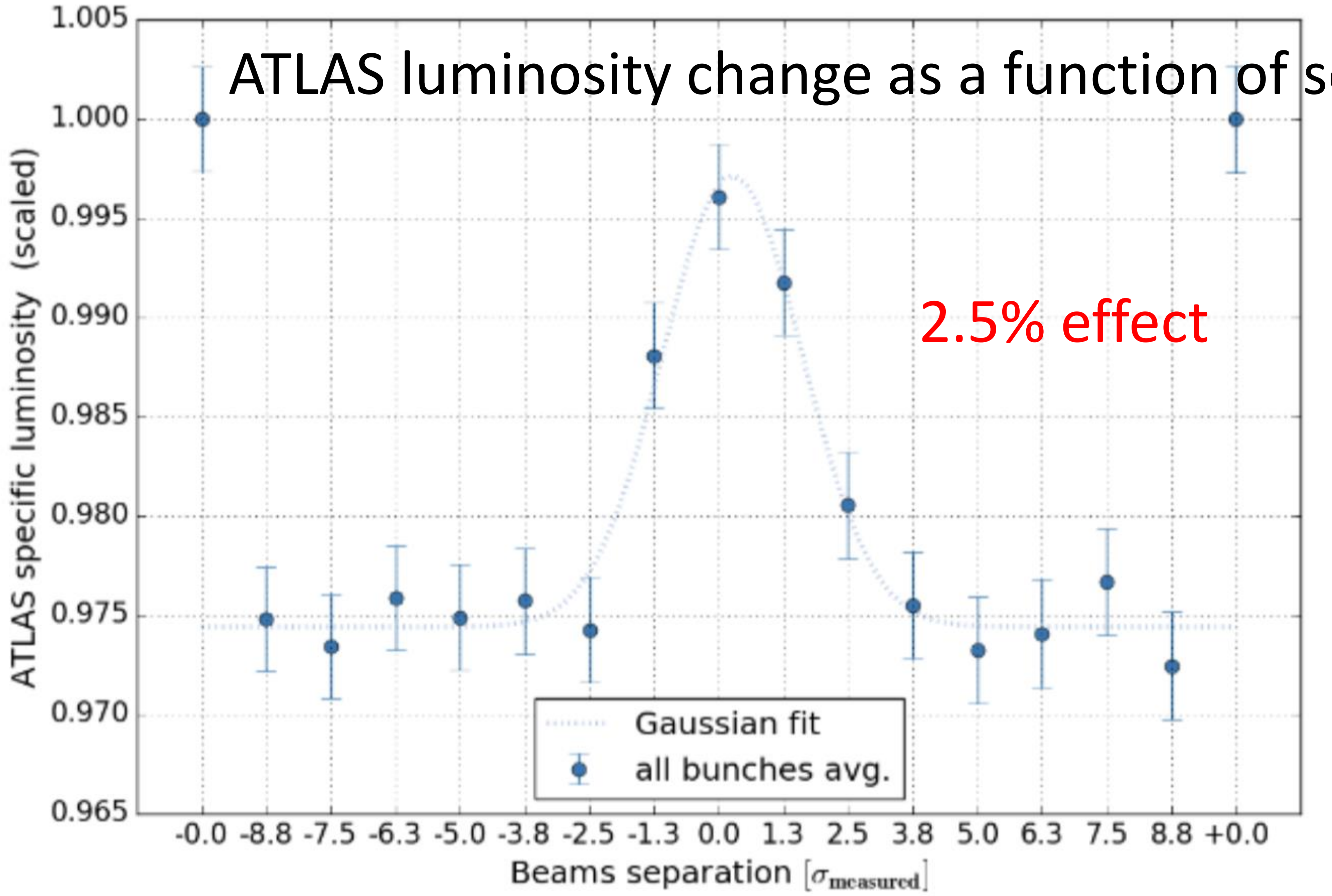
presented at EPS-HEP 2023

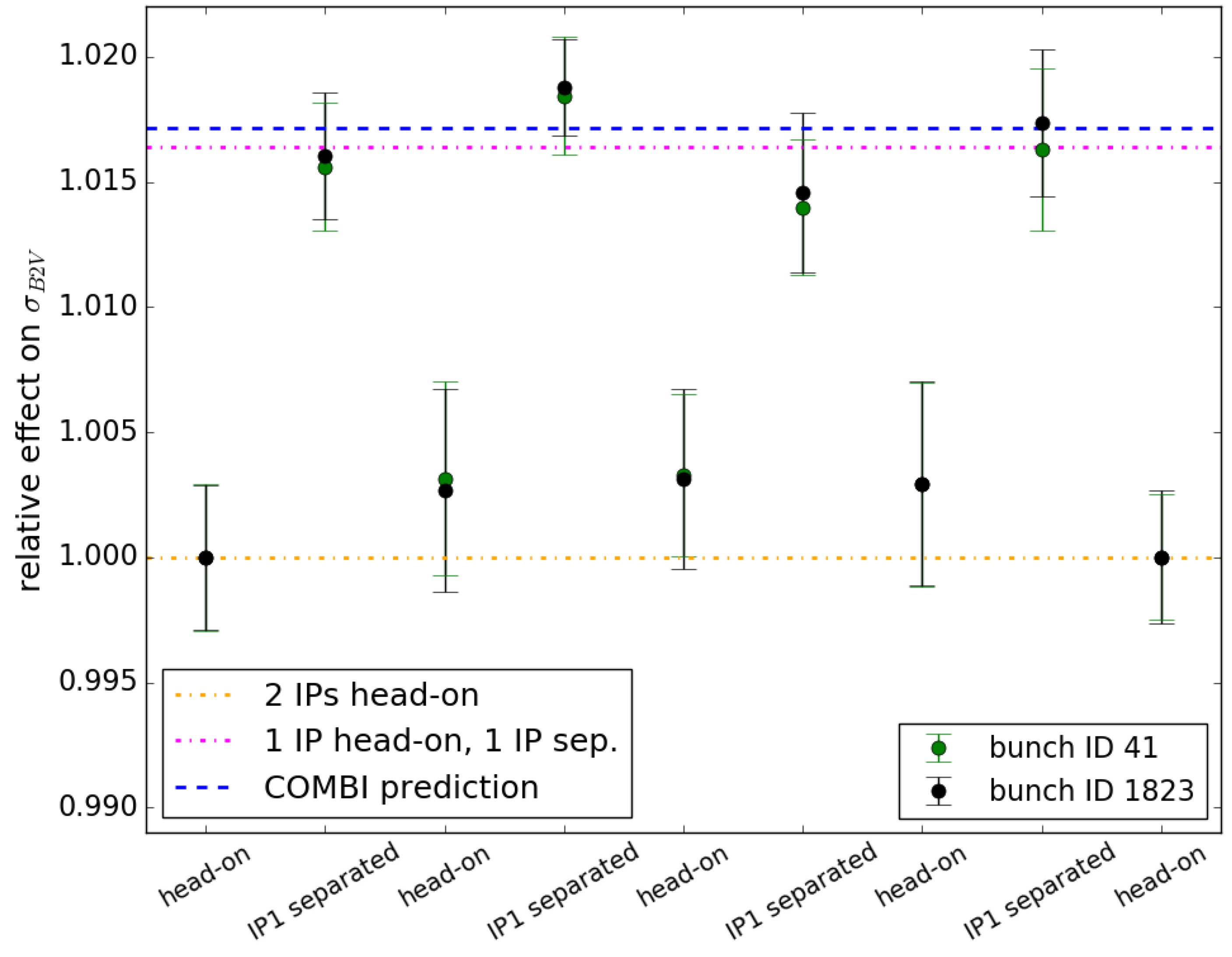
Aim: validation of the correction strategy used in the vdM calibration

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

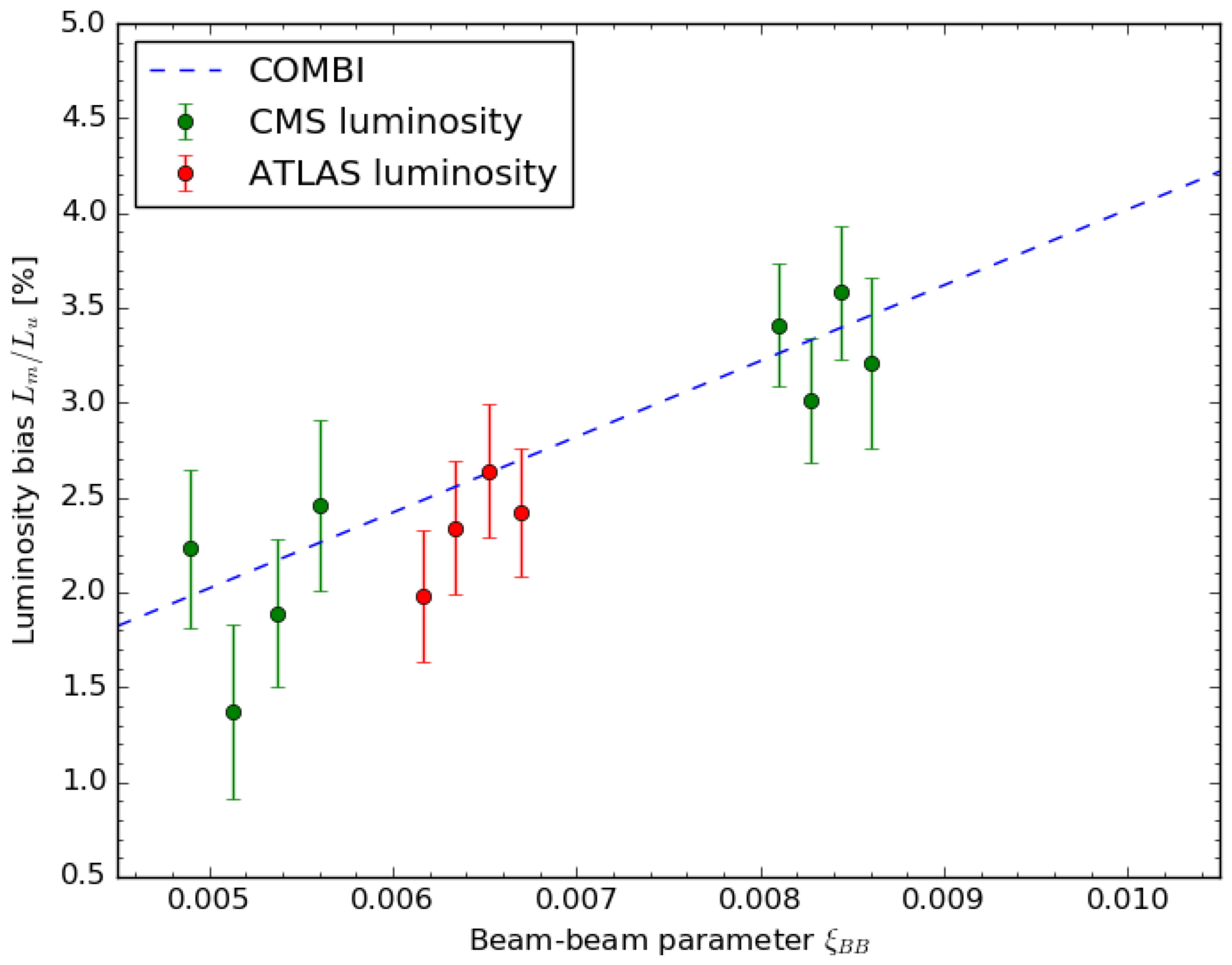
- first measurement of the impact of BB effects on the luminosity in LHC

ATLAS luminosity change as a function of separation step





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



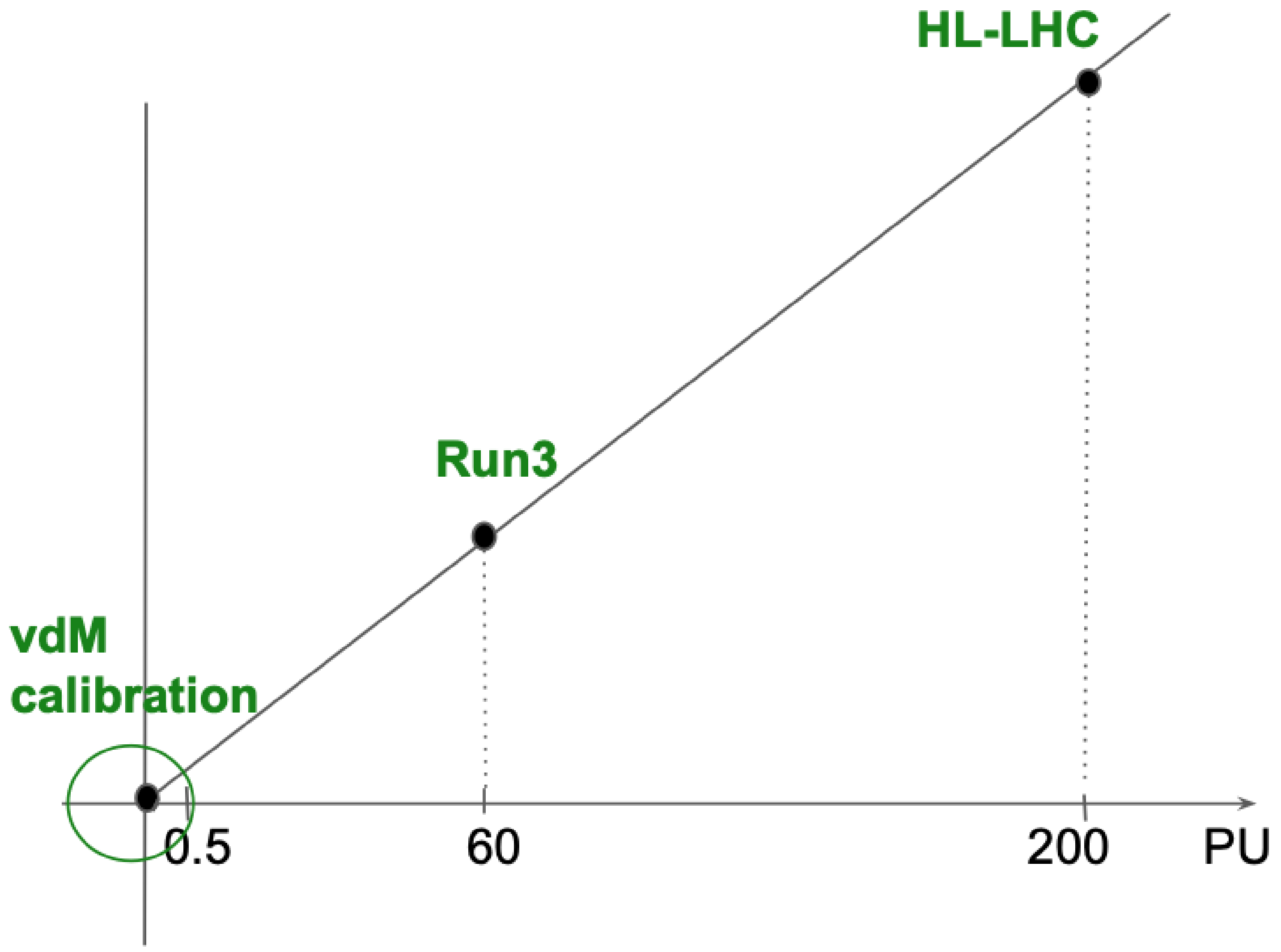
Luminosity enhancement at head-on configuration caused by additional BB interaction (at another IP) as measured by both ATLAS and CMS (observer IP), as a function of the single-IP BB parameter, compared to COMBI simulation predictions

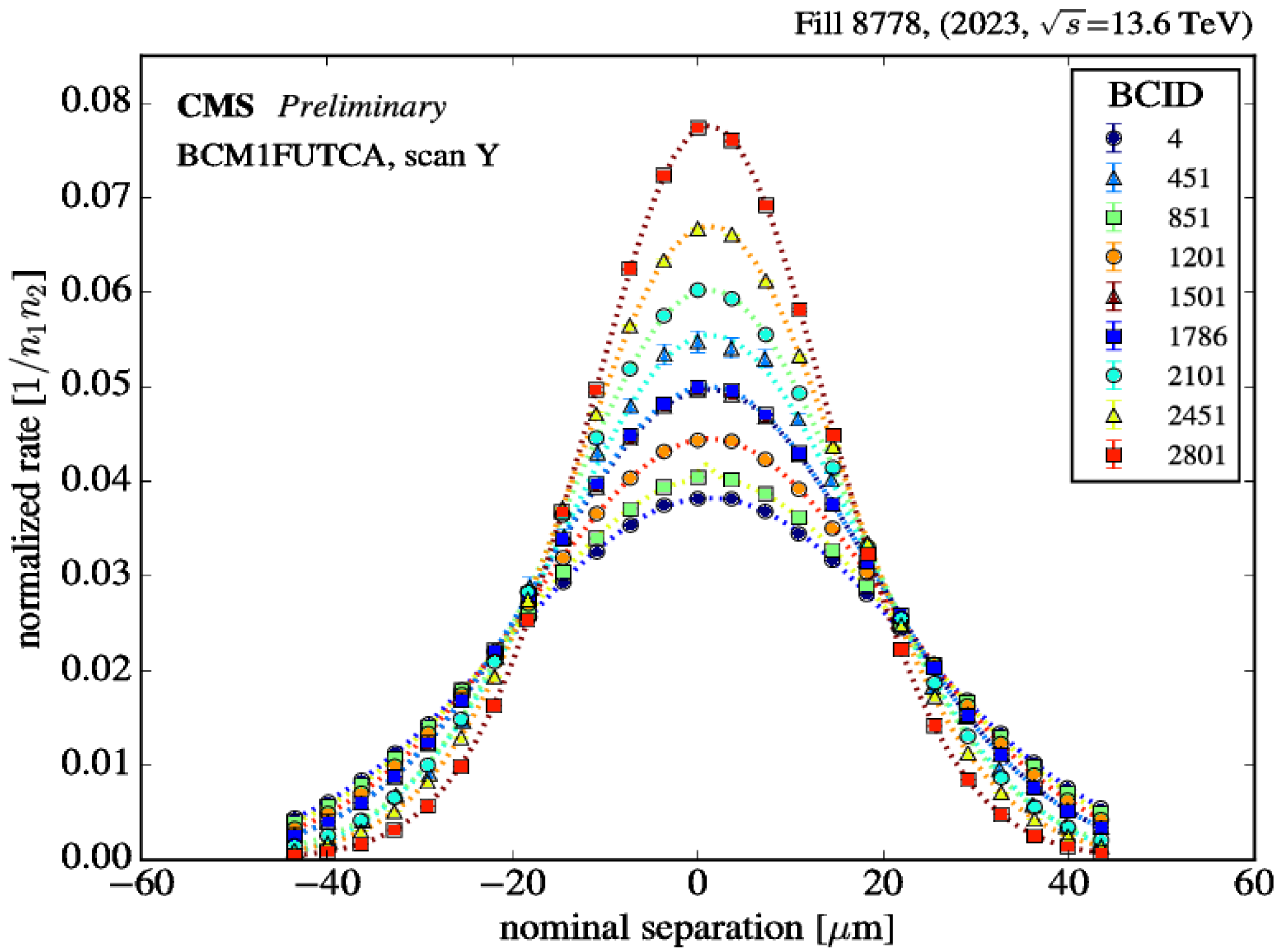
Extrapolation to nominal conditions

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

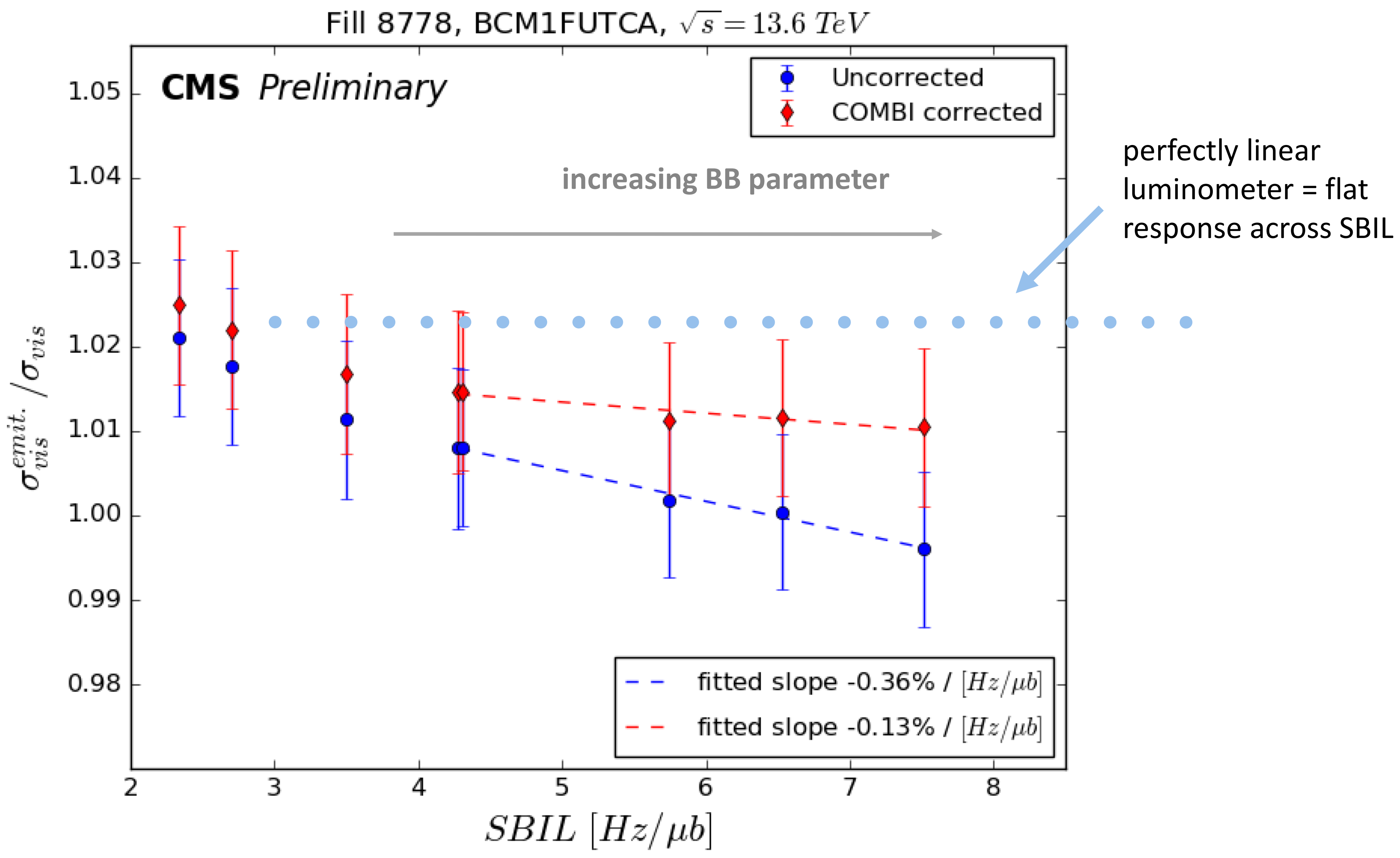
- BB simulations useful to produce dedicated corrections - minimising the associated extra systematic from bunch by bunch differences
- Tested/used for a specific measurement fill (BSRT calibration fill 2023)

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





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

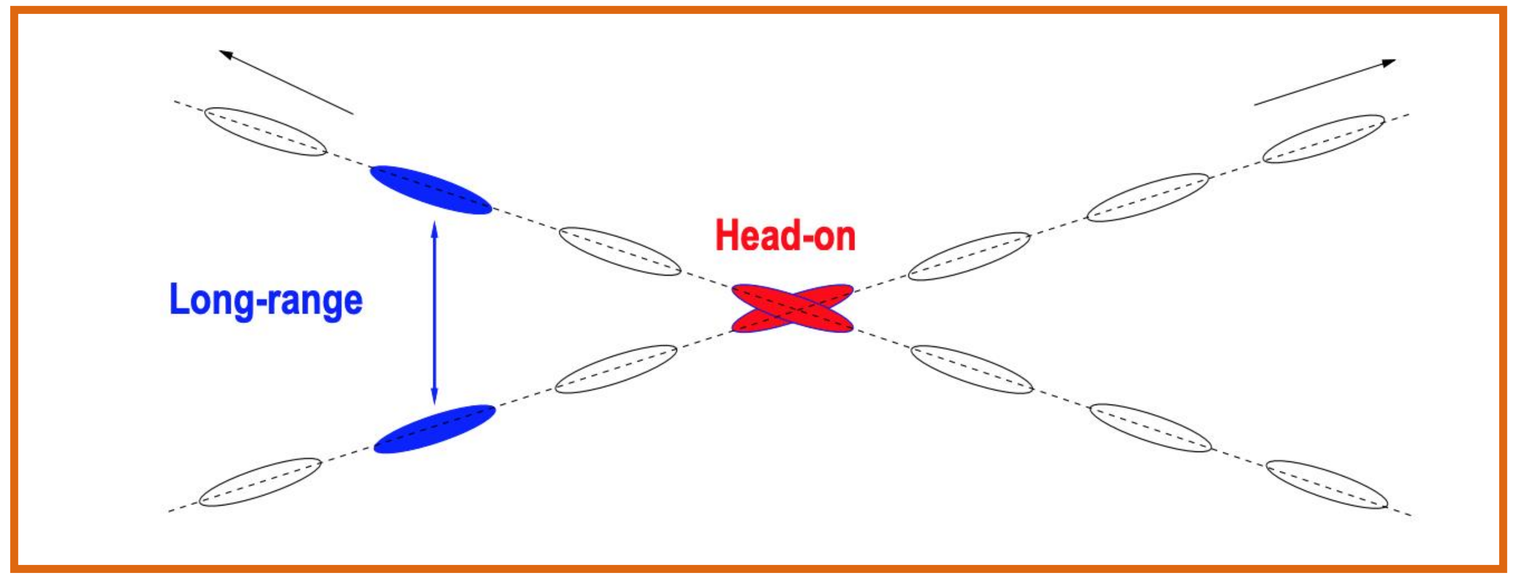
Uncertainties from BB

Beam-beam (b-b) uncertainty source	ξ_{sim} $[10^{-3}]$	Uncertainty-determination procedure	$\sigma_{\rm vis}$ uncertainty [%] for $N_{\rm NSIP}$ = 0	1	2	Comments	See Sec.
Absolute ξ scale: β^* uncertainty at the scanning IP	5.60	Vary β^* by $\pm10\%$ in the simulation or parameterization (Sec. 4.2.3), for each beam and in each plane	0.06	0.10	0.13	β^* uncertainty assumed uncorrelated between beams, correlated between planes	4.2.1 + 5.1.1
			(total for both beams and both planes)				
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	0.20	Tune uncertainty assumed correlated between beams and between planes	4.2.2 + 5.1.2
			(total for both beams and both planes)				
Non-Gaussian transverse-density distributions	5.60	B*B (or COMBI) simulations	0.13	0.22	0.30	Simulated for $N_{\rm NSIP} = 0$, extrapolated to $N_{\rm NSIP} \geq 1$ 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 $\pm15\%$ 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 $\sigma_{\rm vis}$	5.5
Total b-b correction	5.60	Parameterization (Secs. 4.2.3 & 4.6.5)	+0.52	+0.86	+1.17	% of $\sigma_{\rm vis}$	5.5

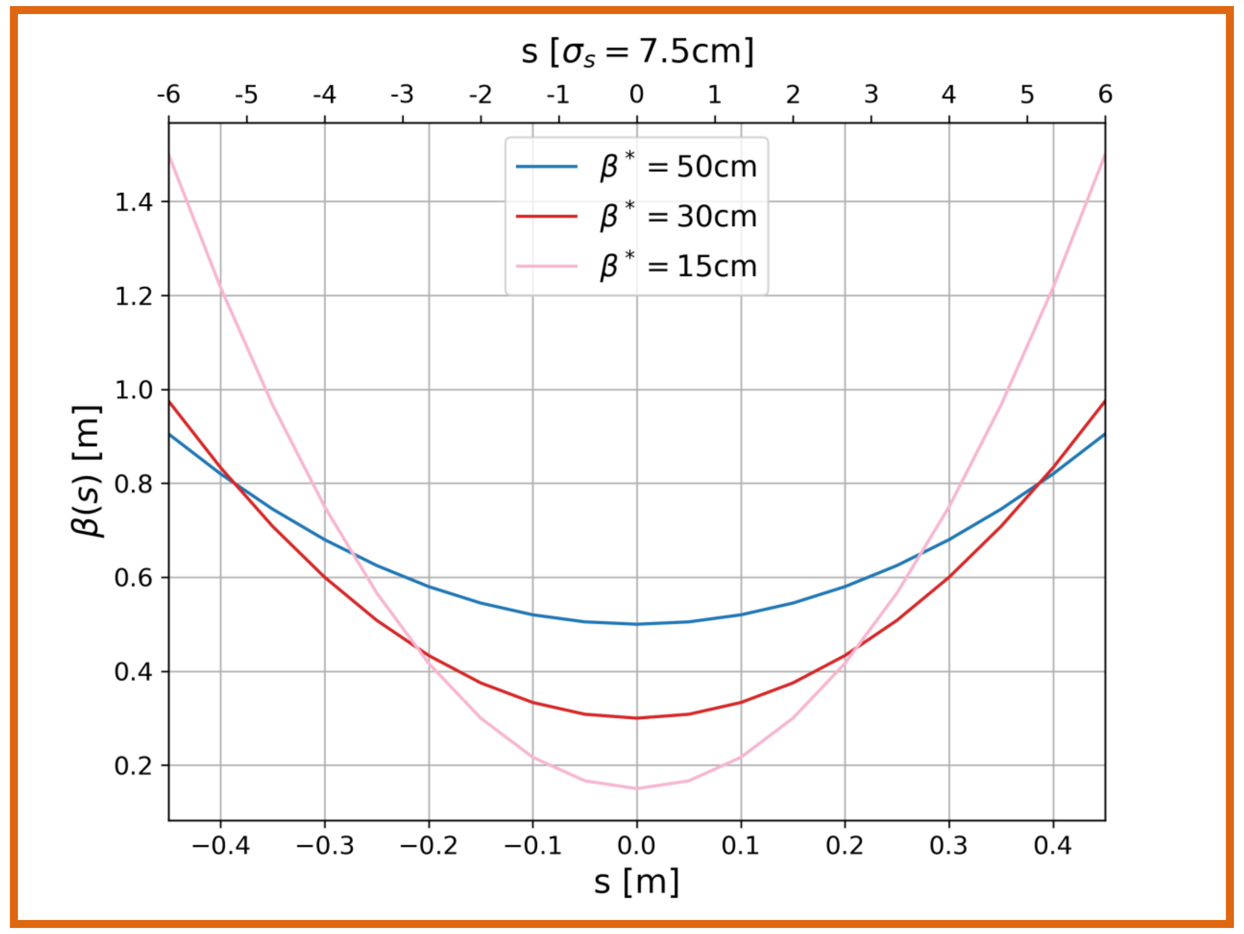
Table 8: Typical systematic uncertainties affecting beam-beam corrections to a hypothetical *pp vdM* calibration in a fully symmetric Gaussian-beam configuration, with the round–beam-equivalent beam-beam parameter set equal to ξ_{sim}, for three values of $N_{\rm NSIP}$. For each source, the uncertainty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

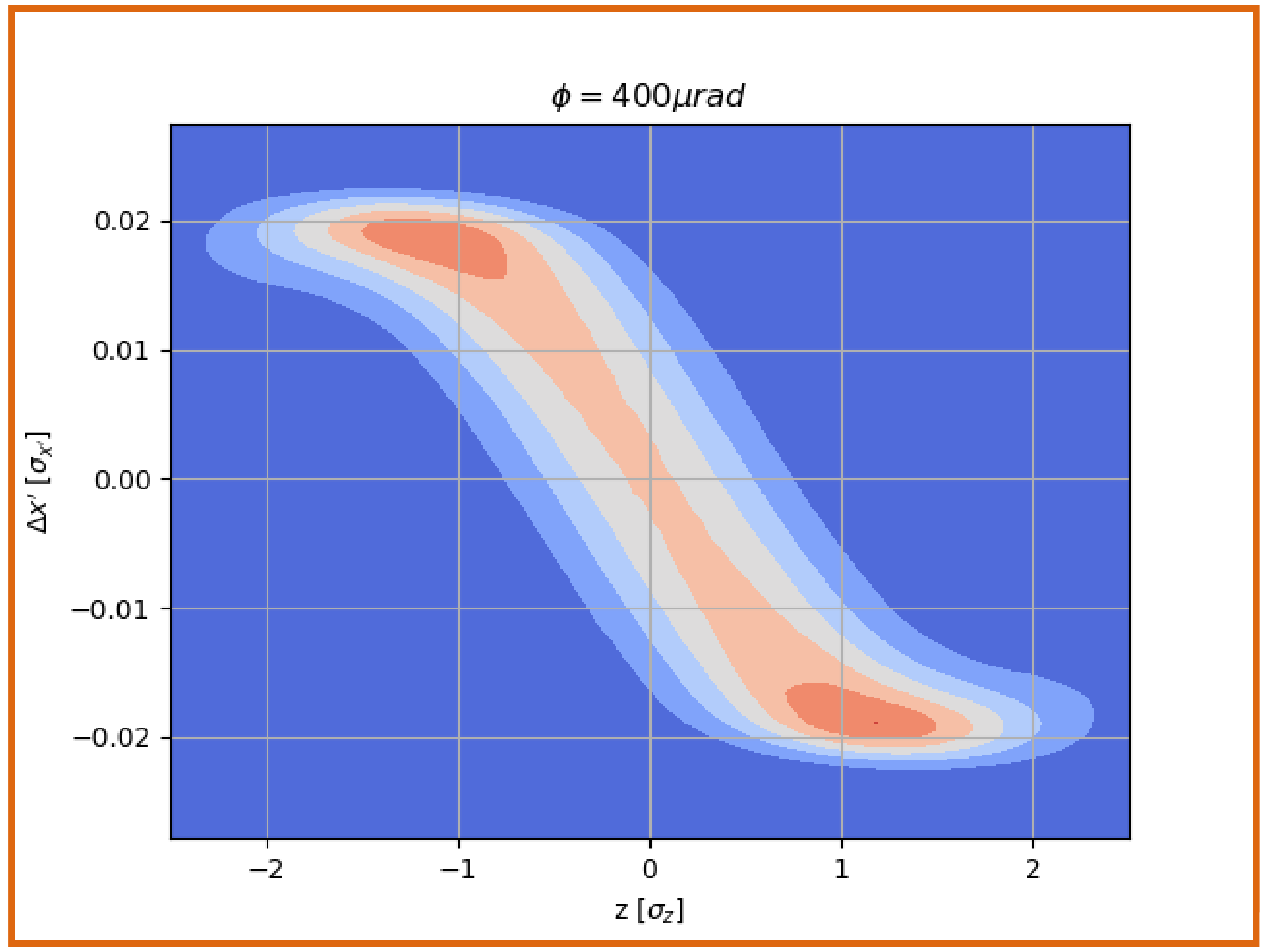
- not only measurement but also simulation challenge
- changes with respect to the vdM regime:
  - pile-up x 100
  - higher BB parameter x 1.5-2
  - non-zero crossing-angle
  - trains - long-range interactions
  - hour-glass effect
- using 6D BB strong-strong soft Gaussian [9]
- developed sliced luminosity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

HB2023