Swiss Accelerator
Research and
Technology

Beam-beam bias to precision luminosity measurement in hadron colliders - LHC case

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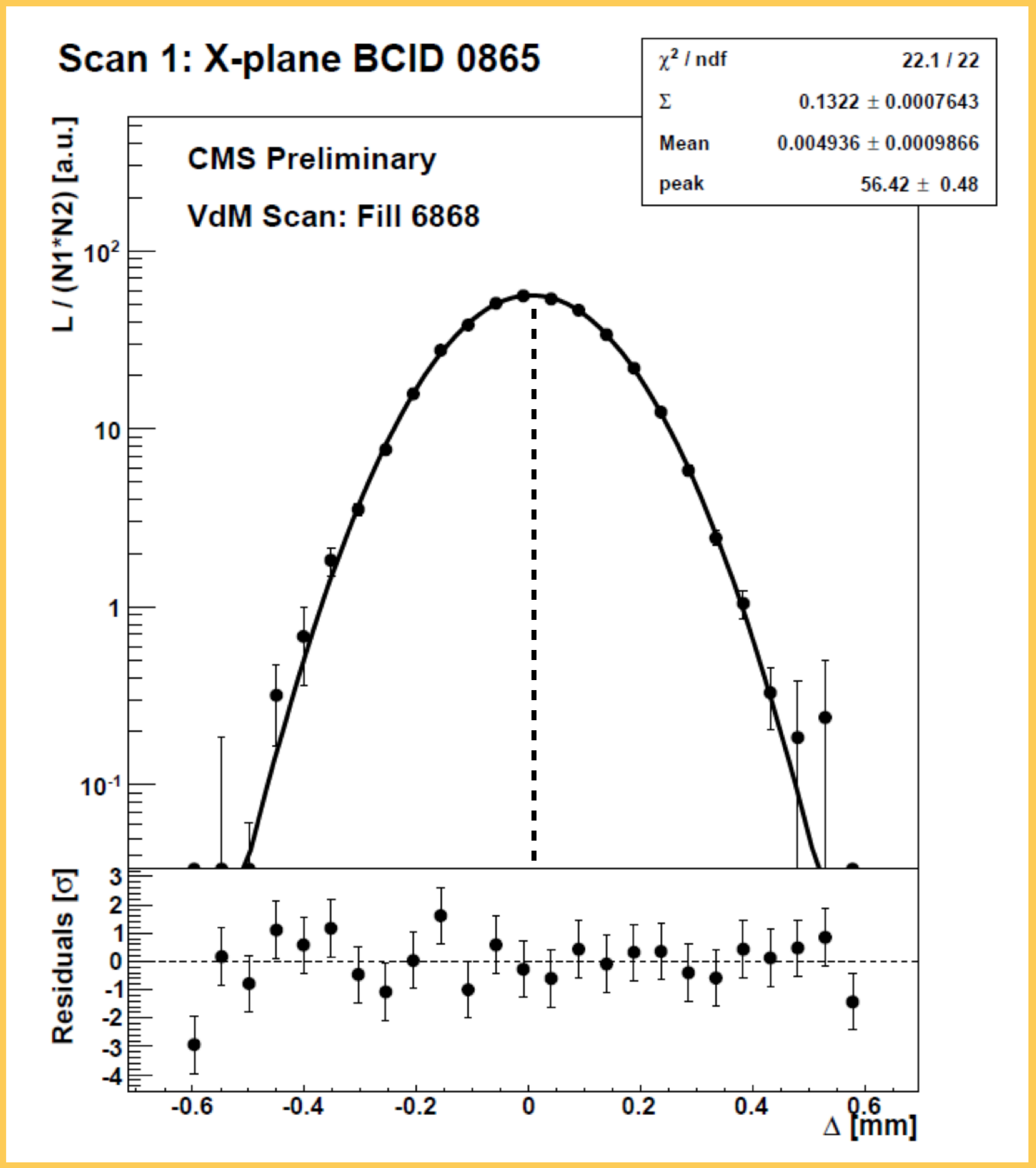
CHART meeting 2023
PSI, 11th October

Luminosity calibration with Van der Meer method*

- aimed to obtain the detector-specific visible cross-section σ_{vis}.
- beams are scanned across each other [1],
- beams overlap width can be extracted Σ, to calculate the transverse luminous area.
- rate can be correlated with instantaneous luminosity from beam parameters:



source: CMS-PAS-LUM-18-002

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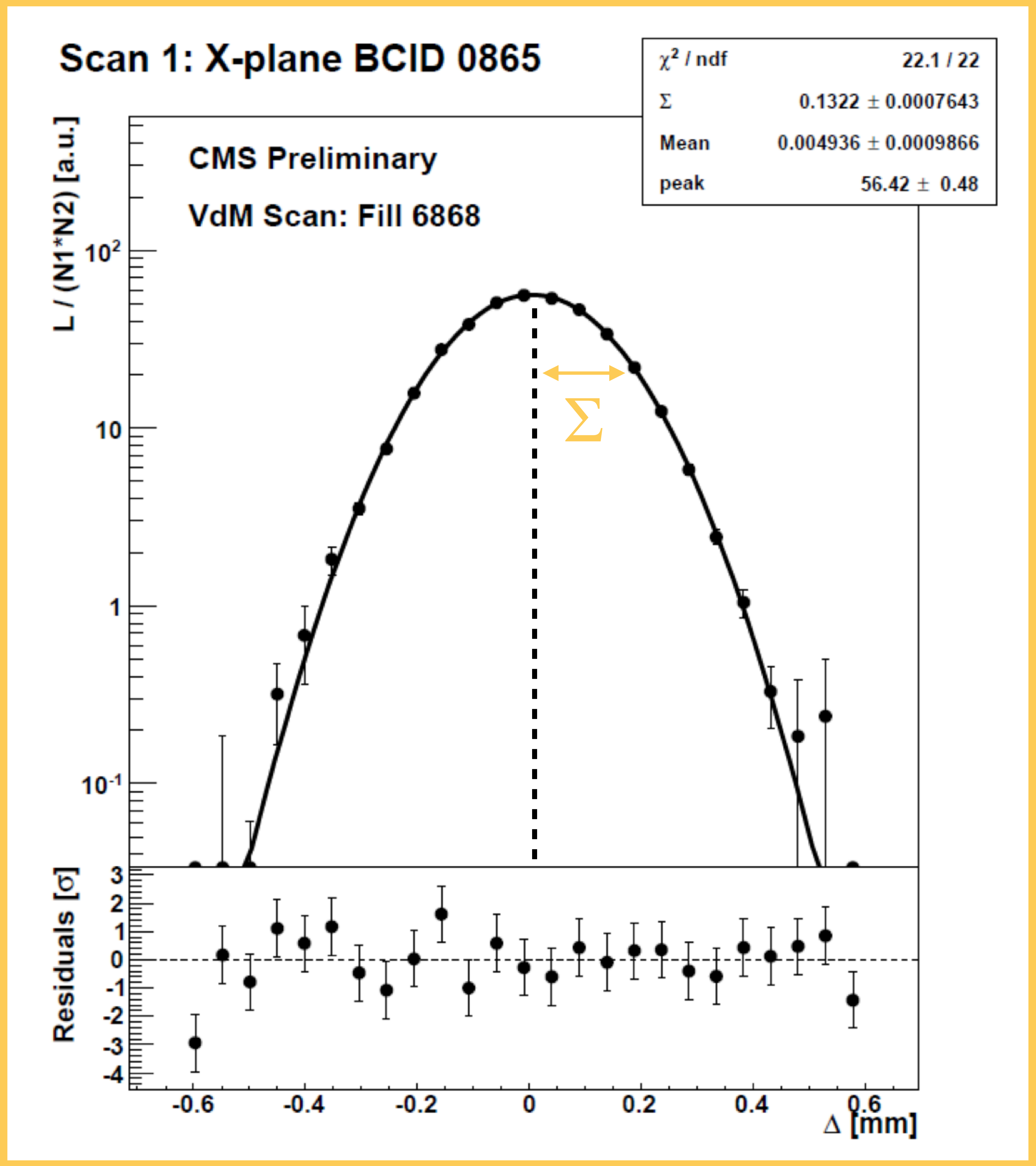

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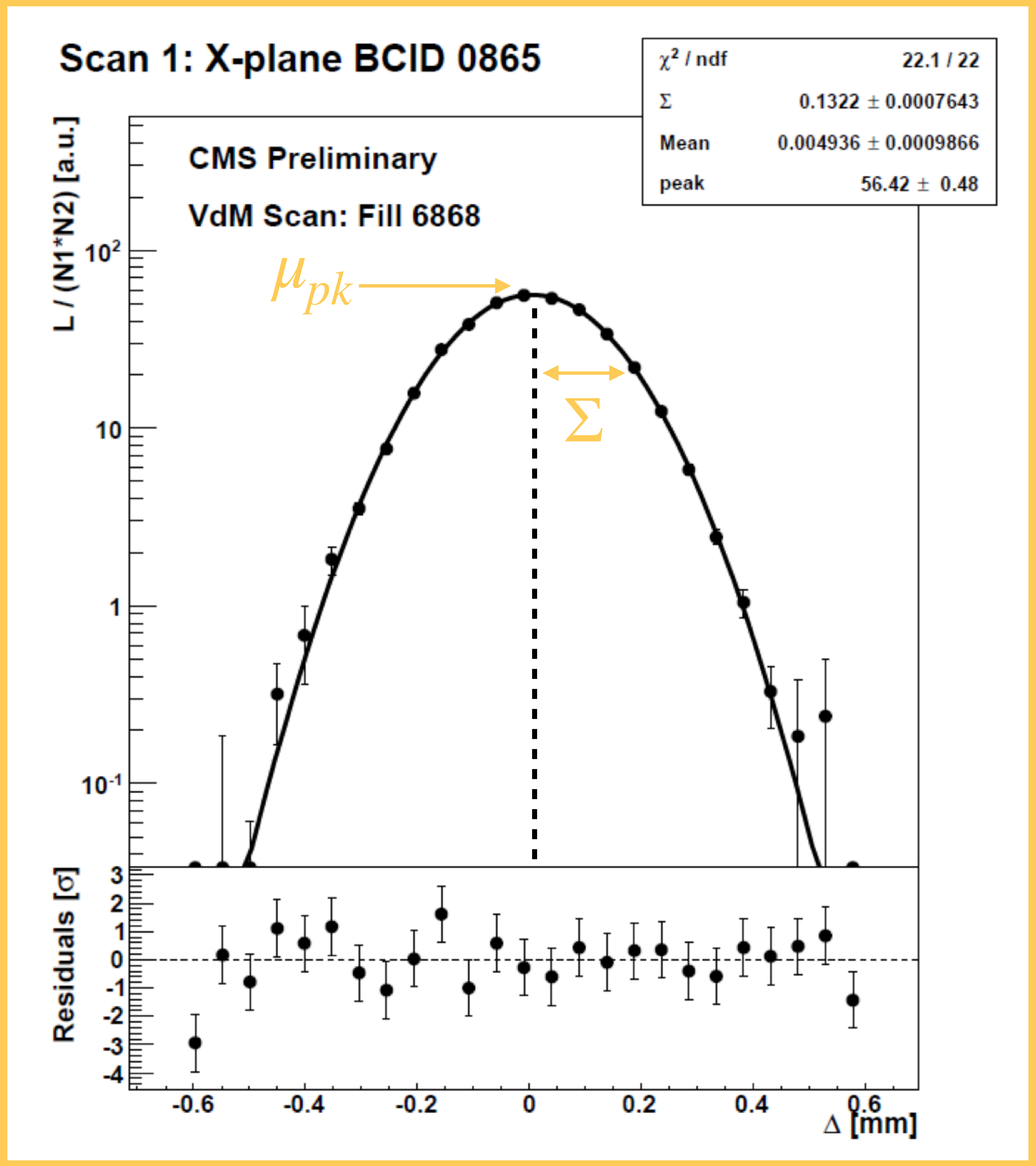

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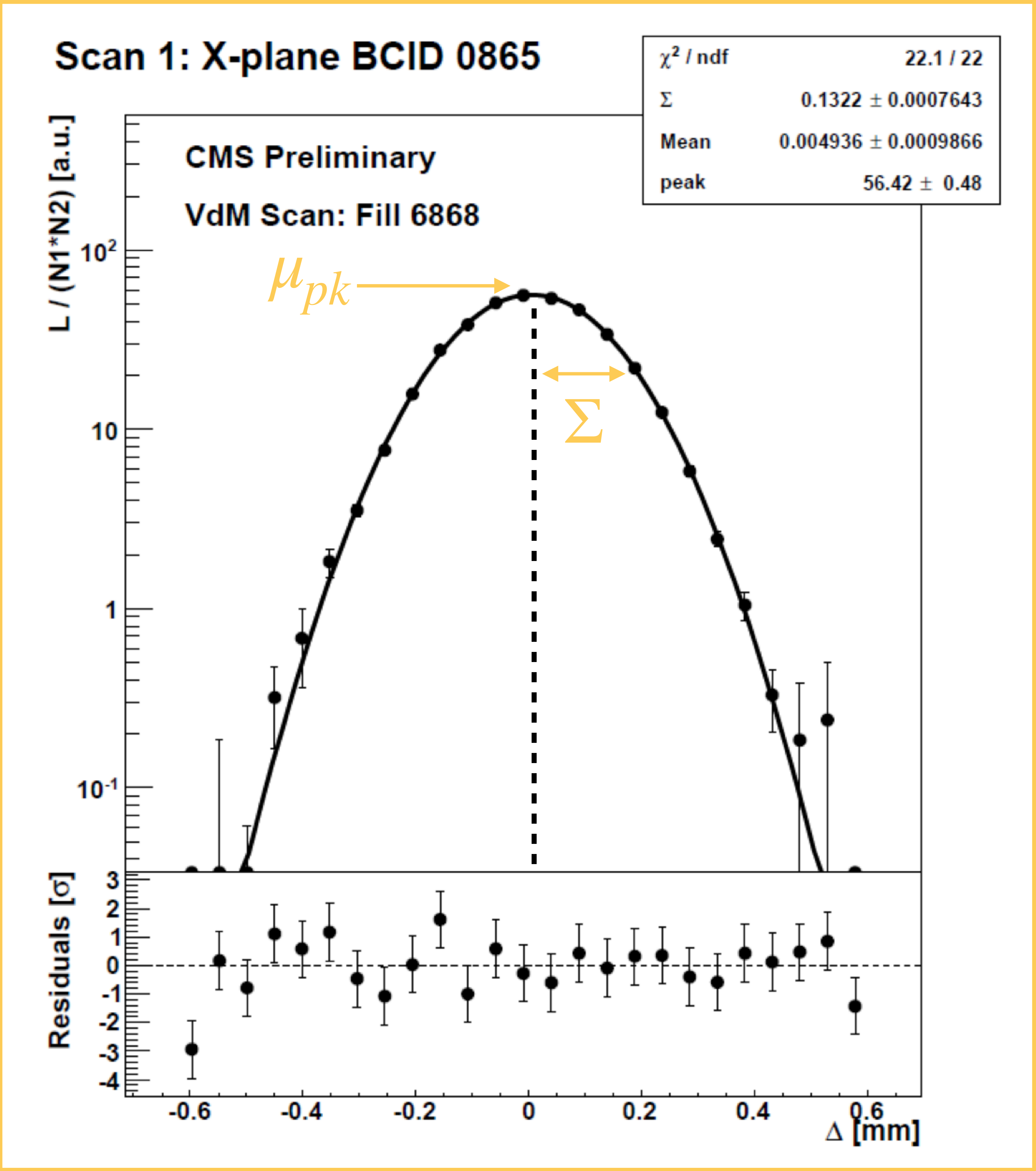
- beam-related systematic effects have to be considered.



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Motivation - Introduction

collaborative work of all LHC experiments within the LLCMWG

- precision luminosity measurement requires a thorough understanding of beam systematics
  - currently aiming at ~1% total uncertainty
  - leading to the shift of the absolute integrated luminosity by ~ -1% [2] (compared to pre-2021)

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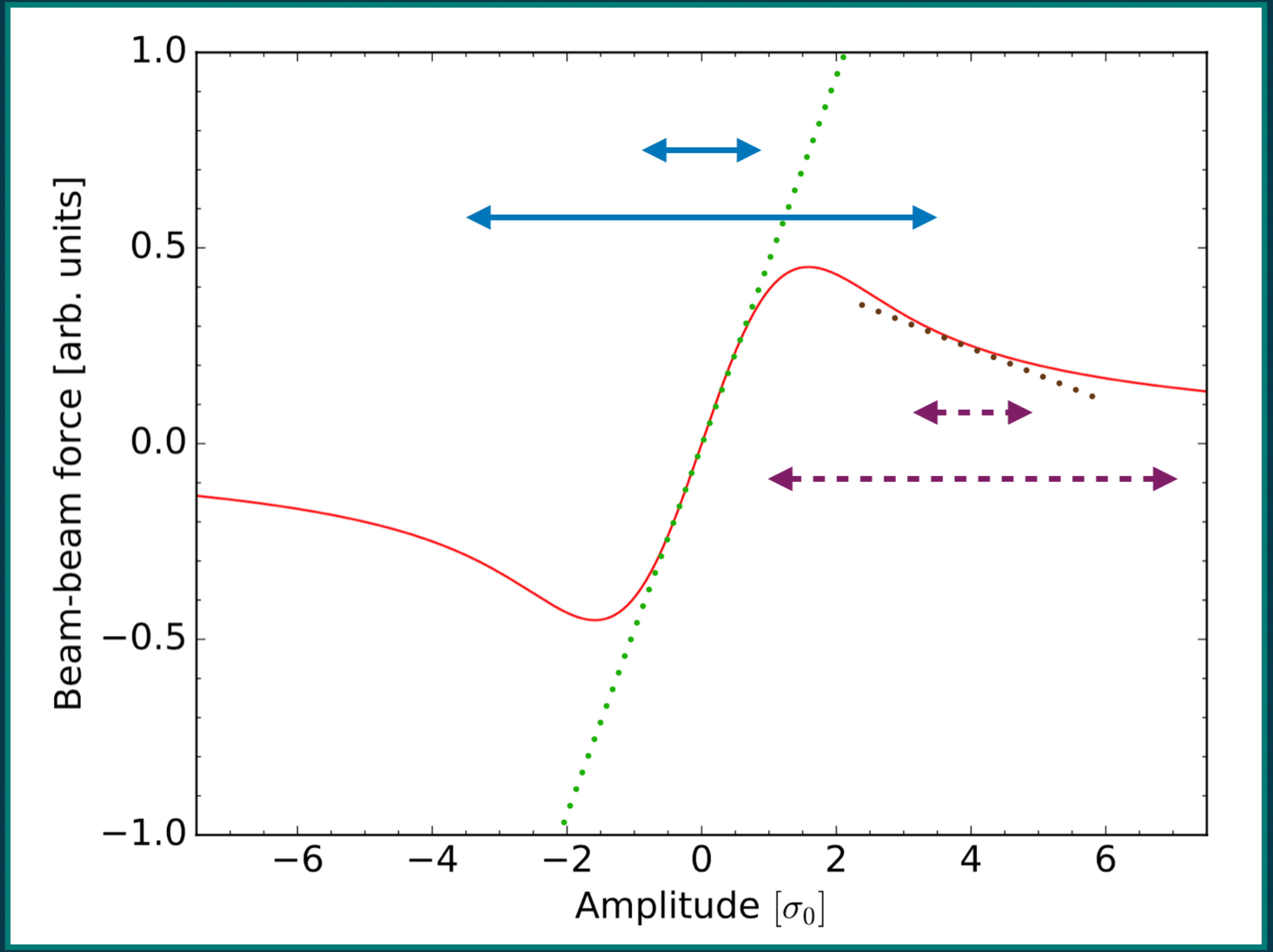
- of particular importance: detailed studies for corrections and uncertainties related to the Beam-Beam (BB) interaction [3]
  - BB optical distortion corrections completely underestimated in Run 2
  - BB deflection known, measured very well
  - year-long studies to derive new model and strategy for systematic uncertainties, resulted in nice publication [3]

Beam-beam interaction

- BB force - electromagnetic interaction of the two beams while crossing each other at the IP



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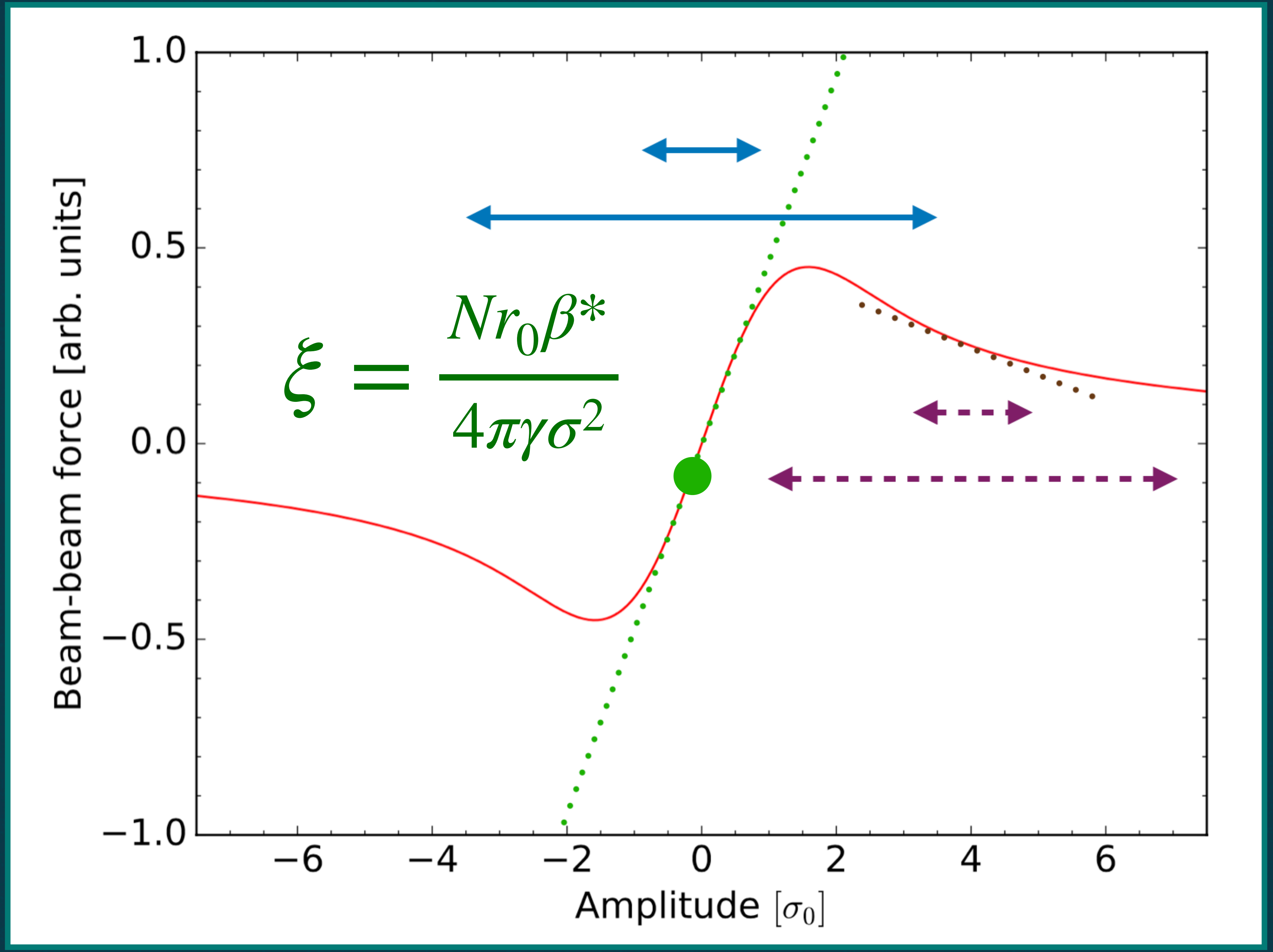

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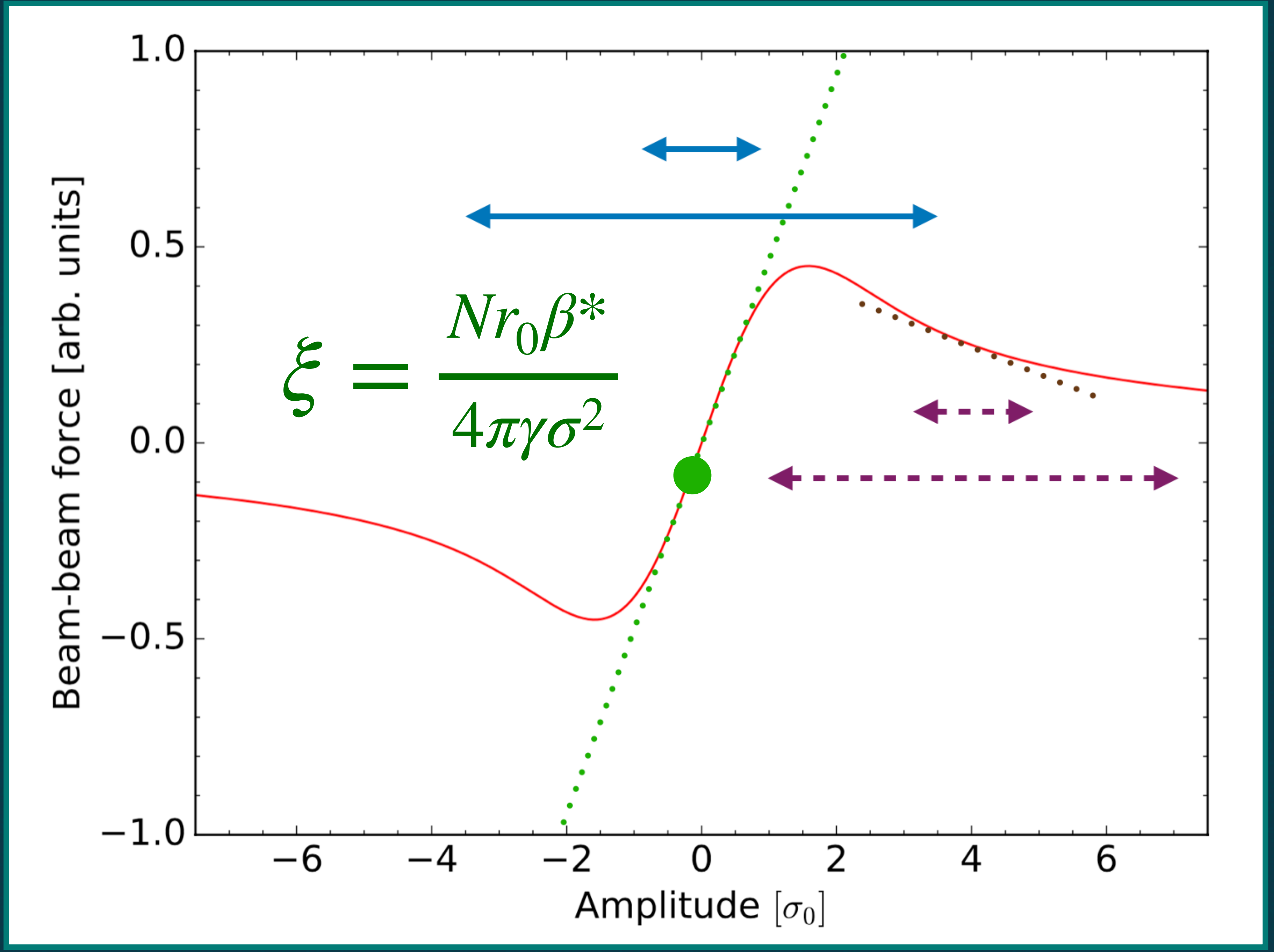

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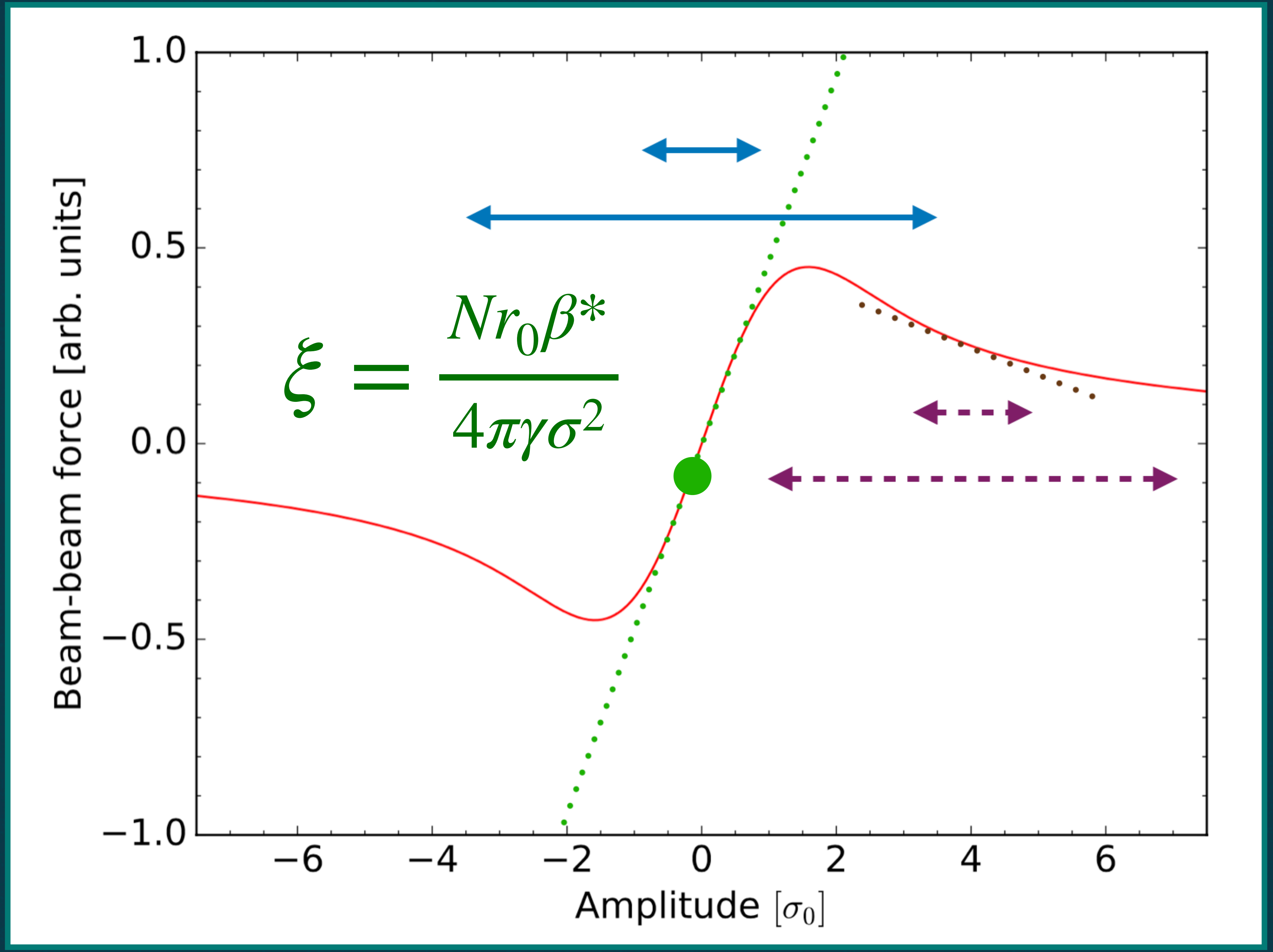

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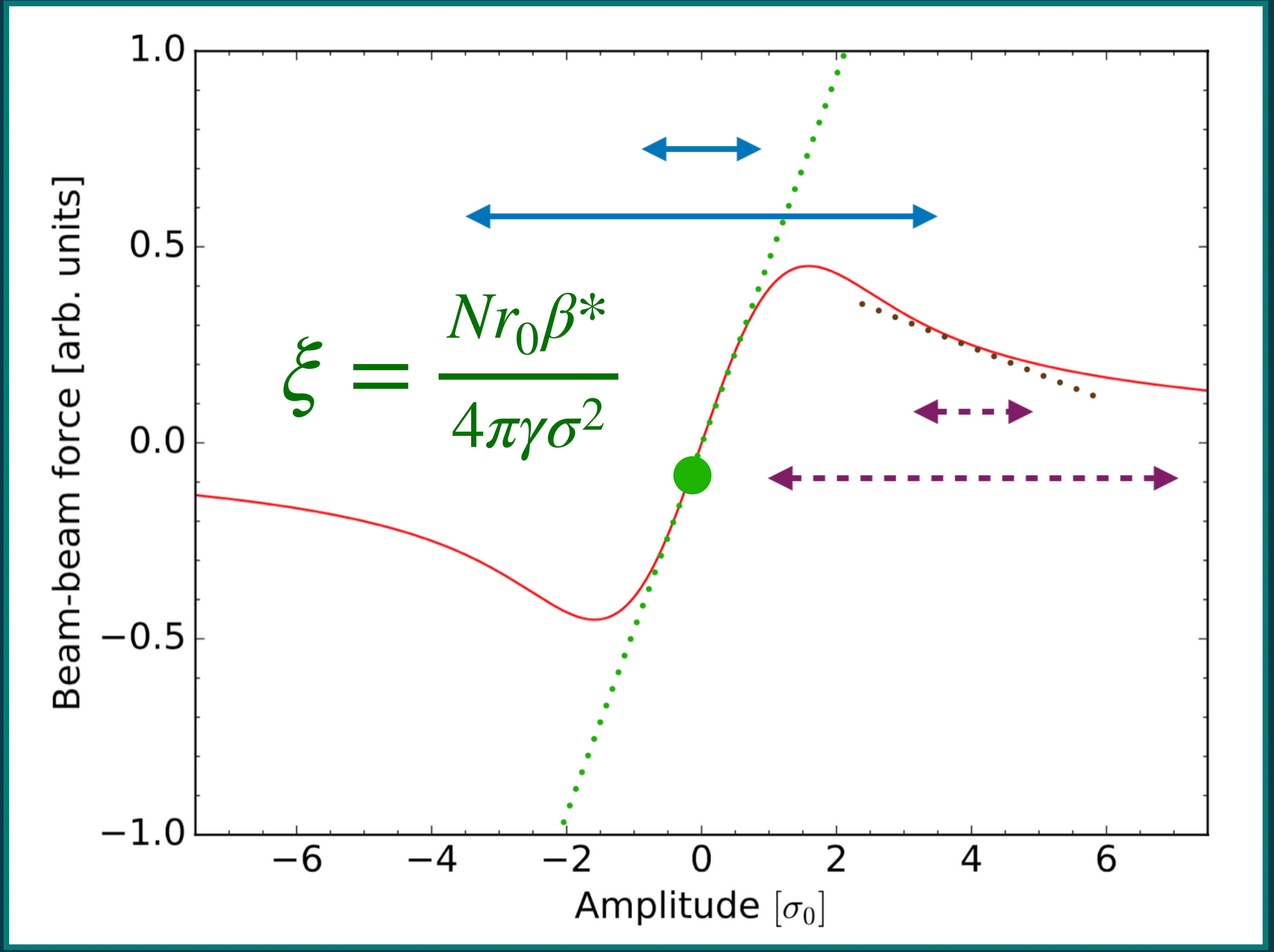

$$\xi = \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}$$

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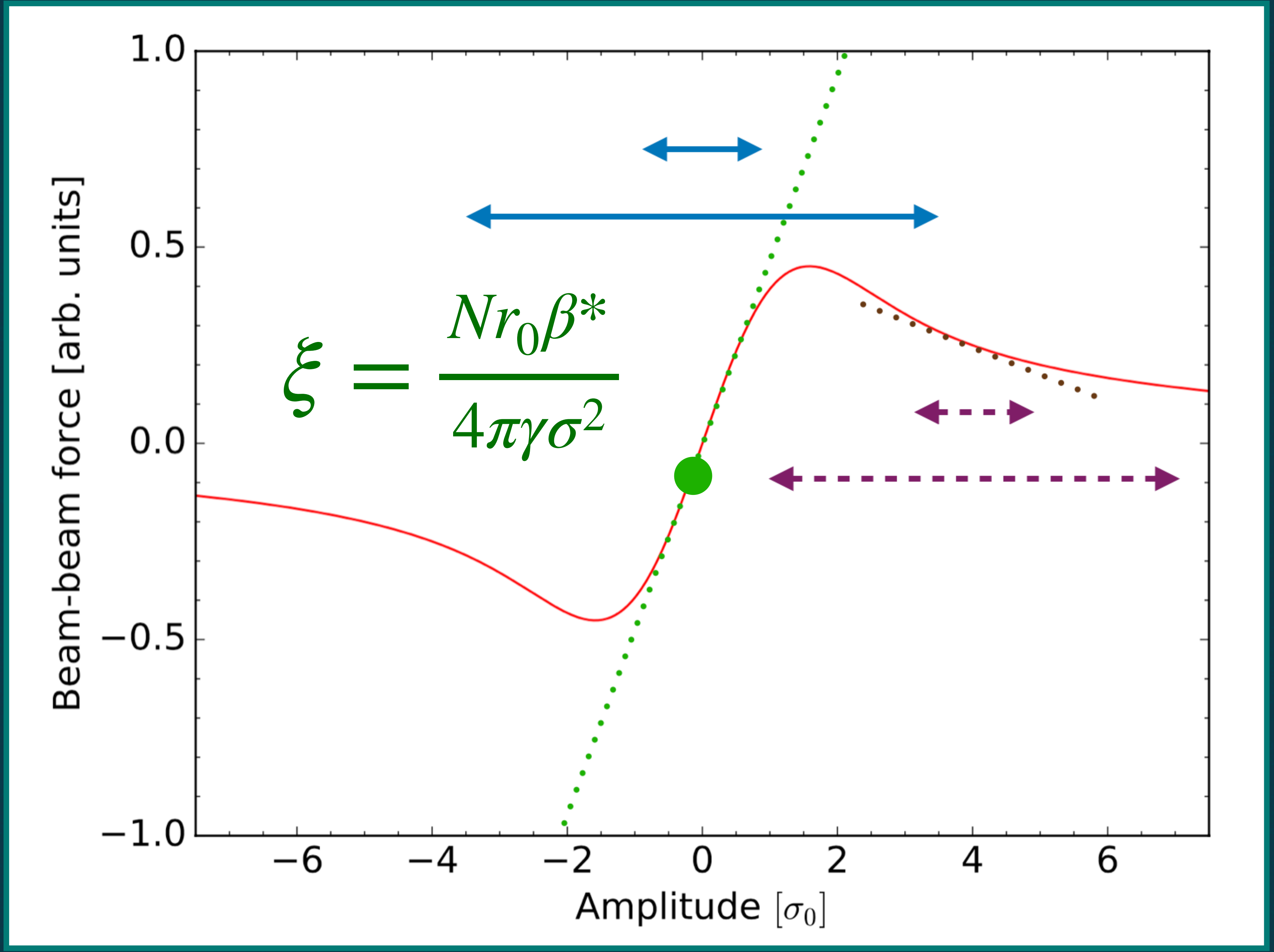
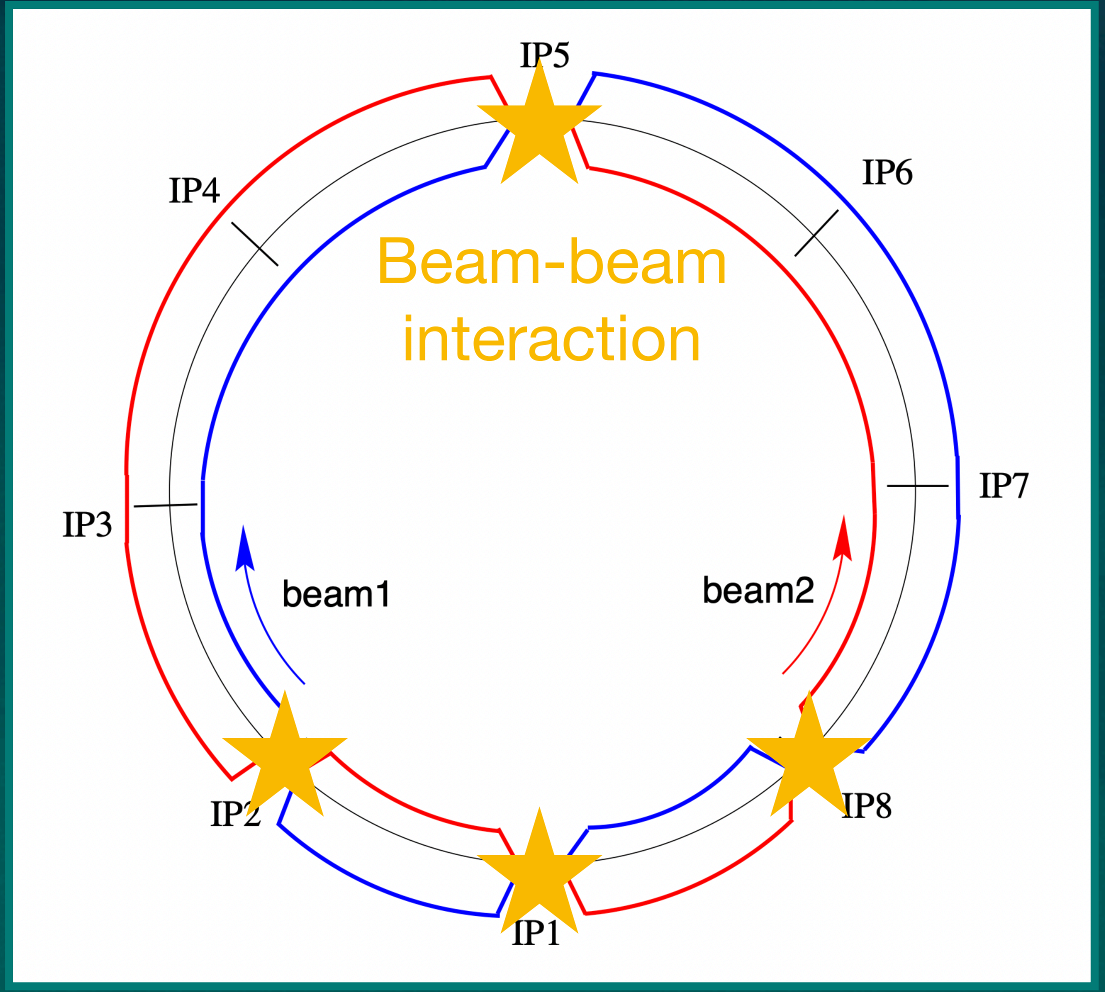
    - optical effect including dynamic-beta   and overlap changes (non-gaussianity and non-factorisation from coupling)





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)

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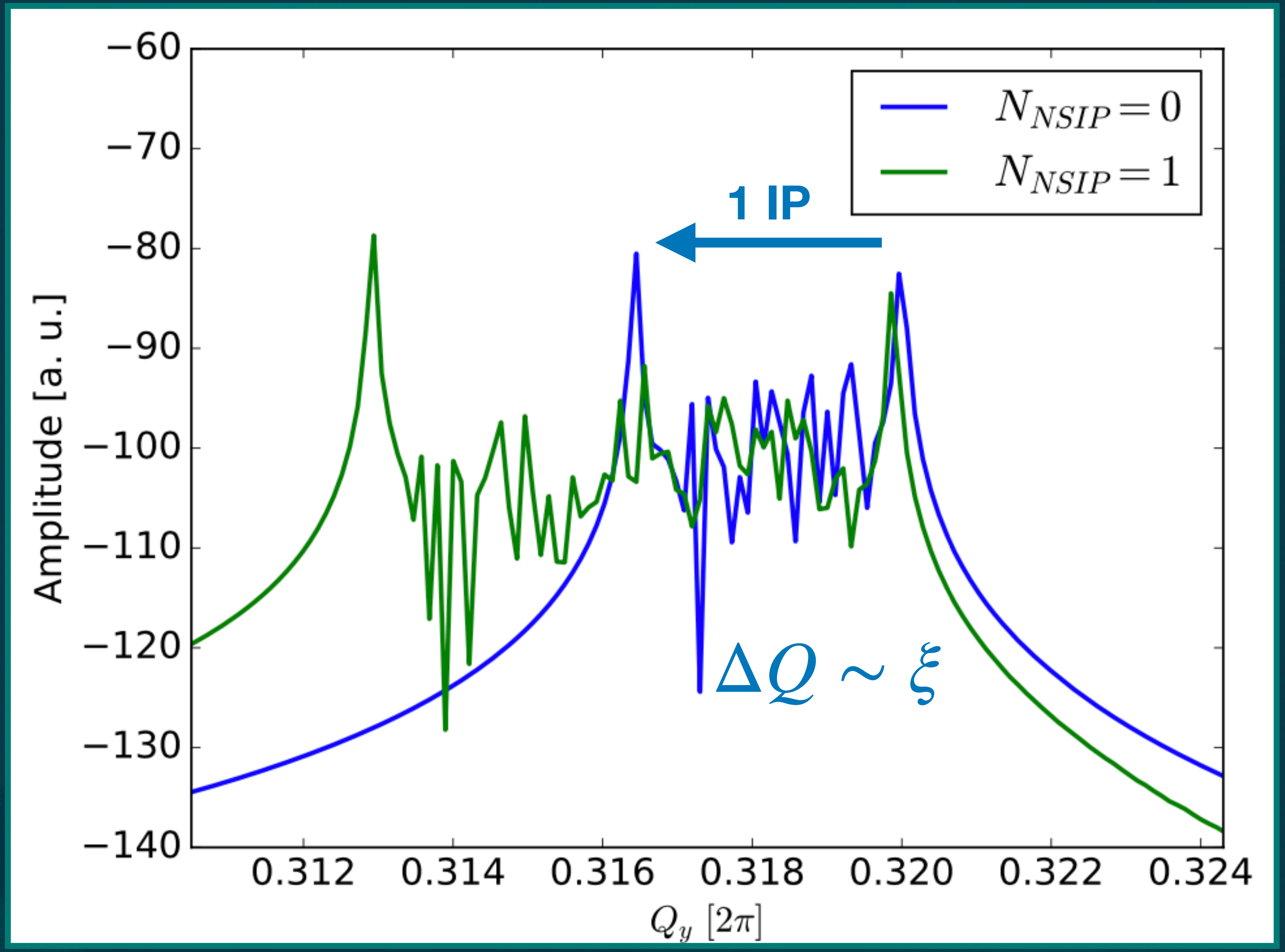

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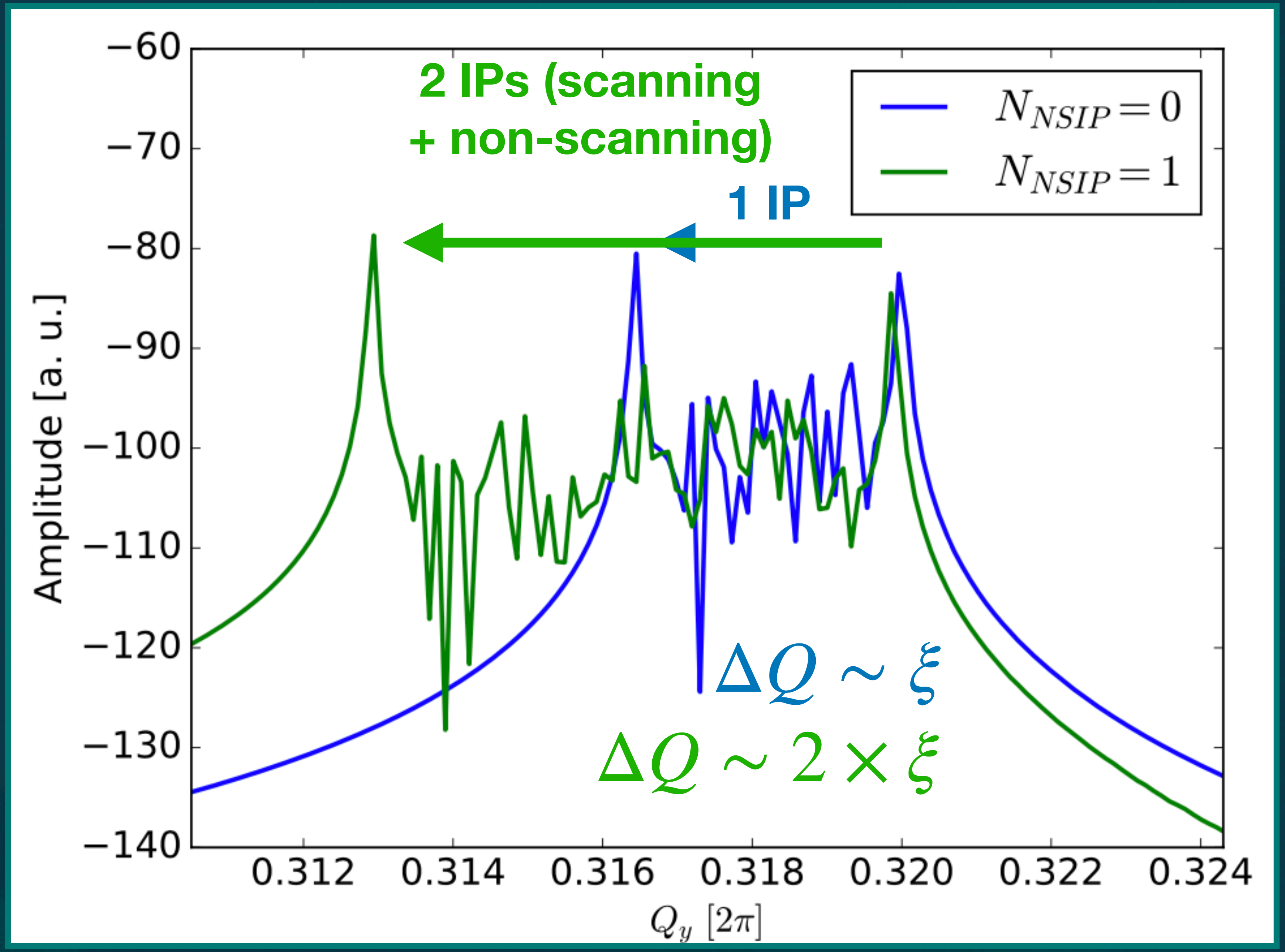

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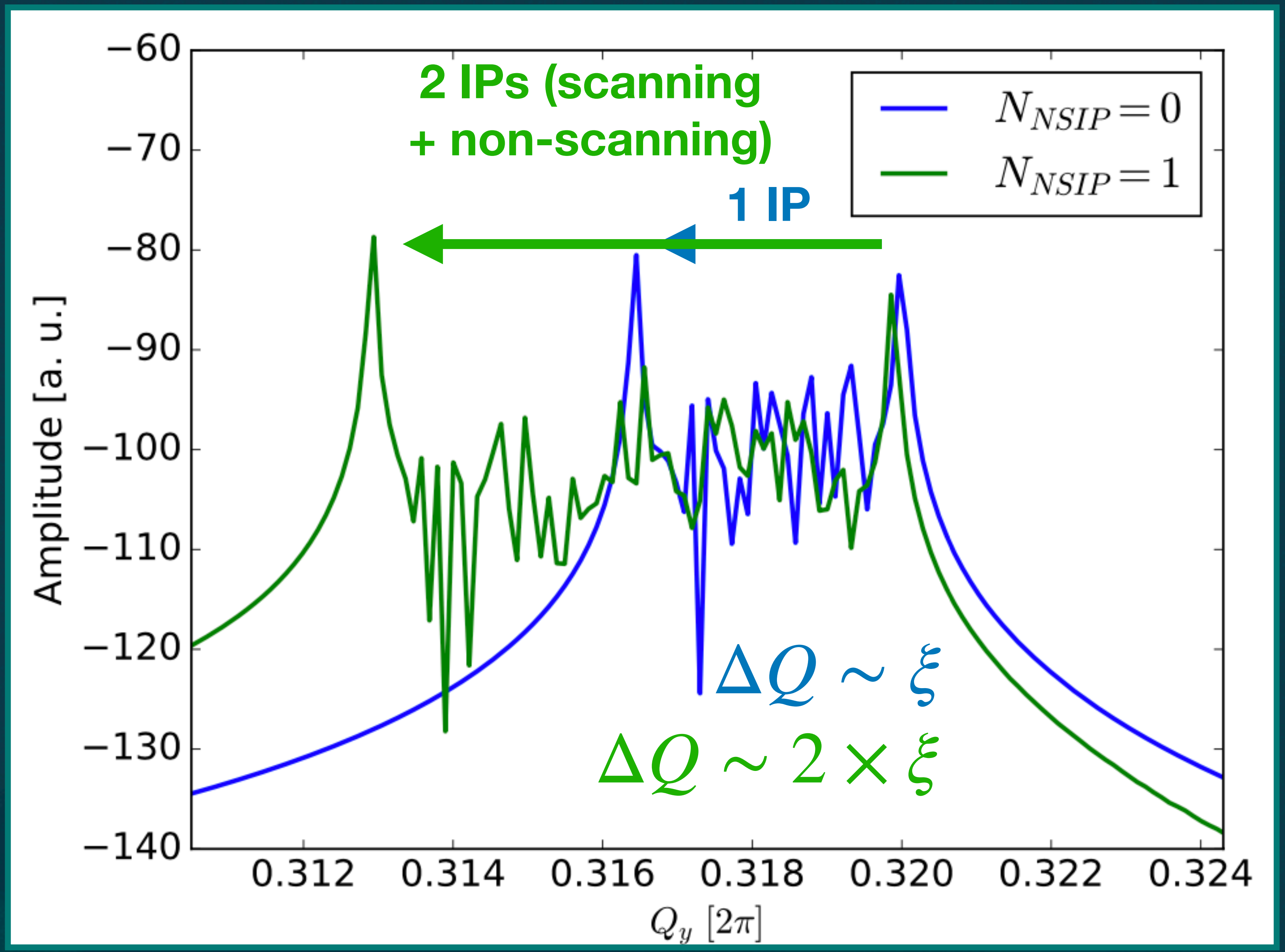
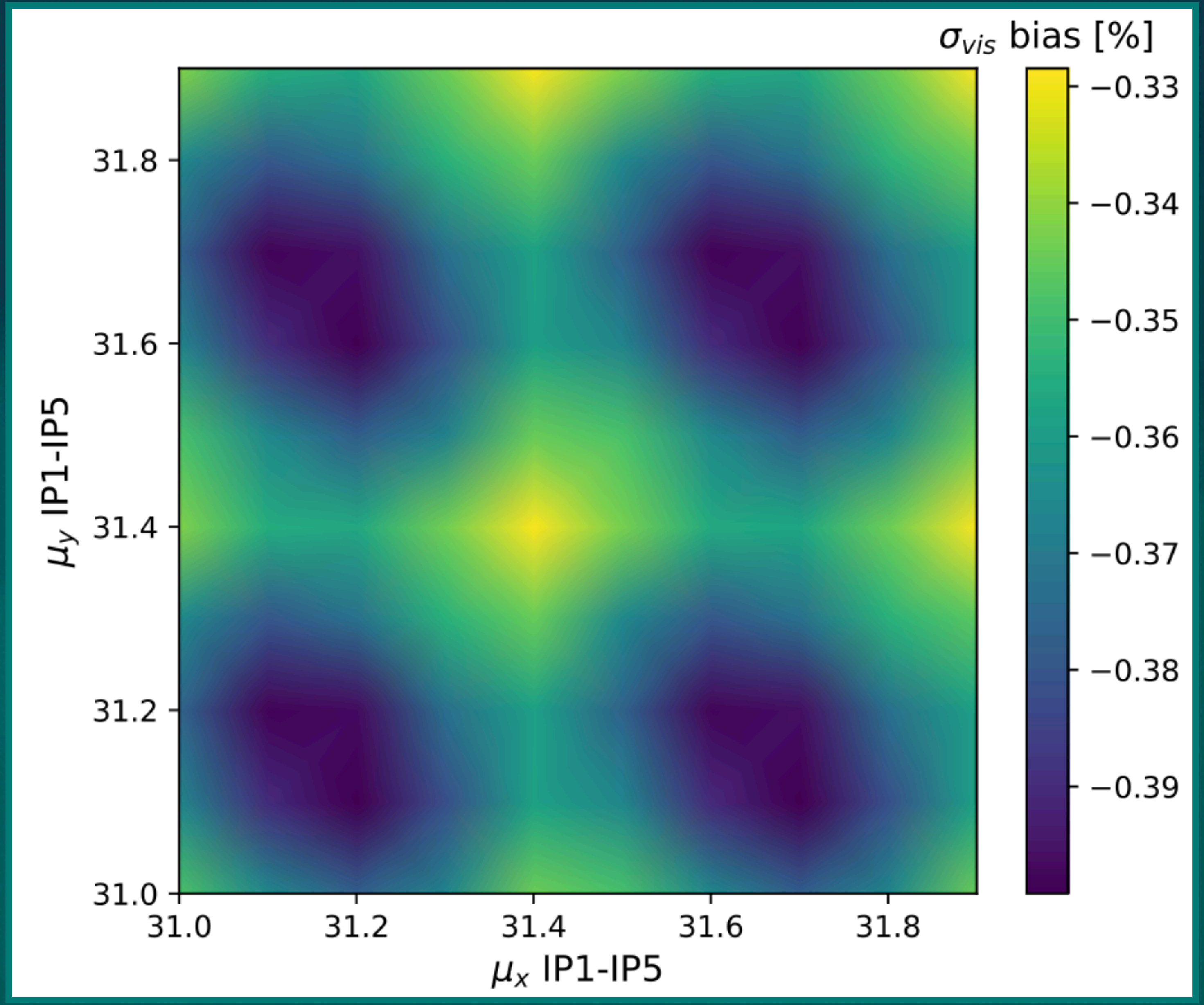


phase-modulated calibration constant σ_{vis} bias



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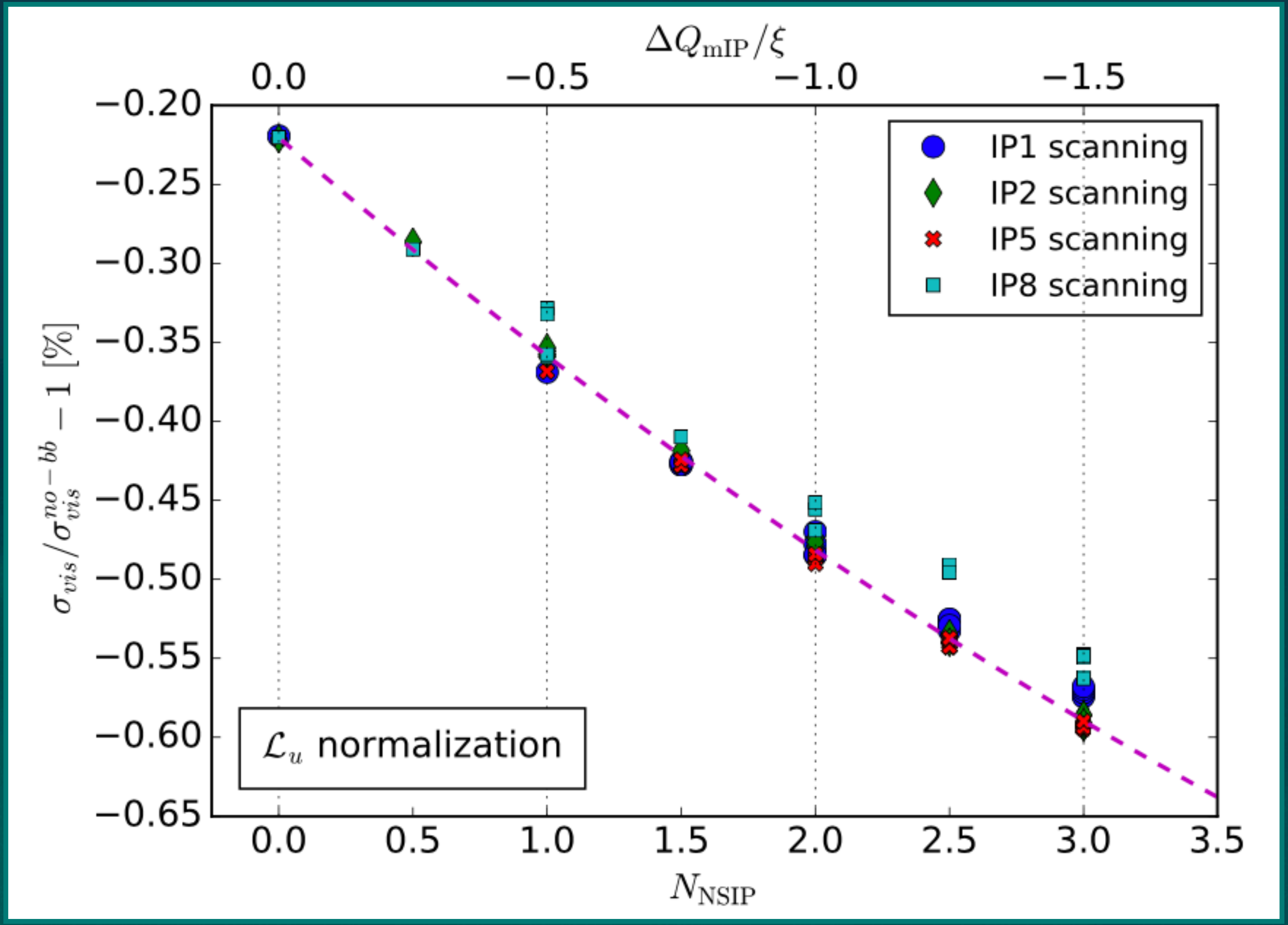
- phase advance between IPs (μ_x, μ_y) causes modulation on tune shift → propagates into the calibration constant [7]

to be published in EPJC

Mimicking multi-IP impact

- luminosity bias correction model based on the single-IP parametrization dependent on beams separation Δ, BB parameter and tunes $\mathscr{L}/\mathscr{L}_0(\Delta, \xi, Q_x, Q_y)$ [3]



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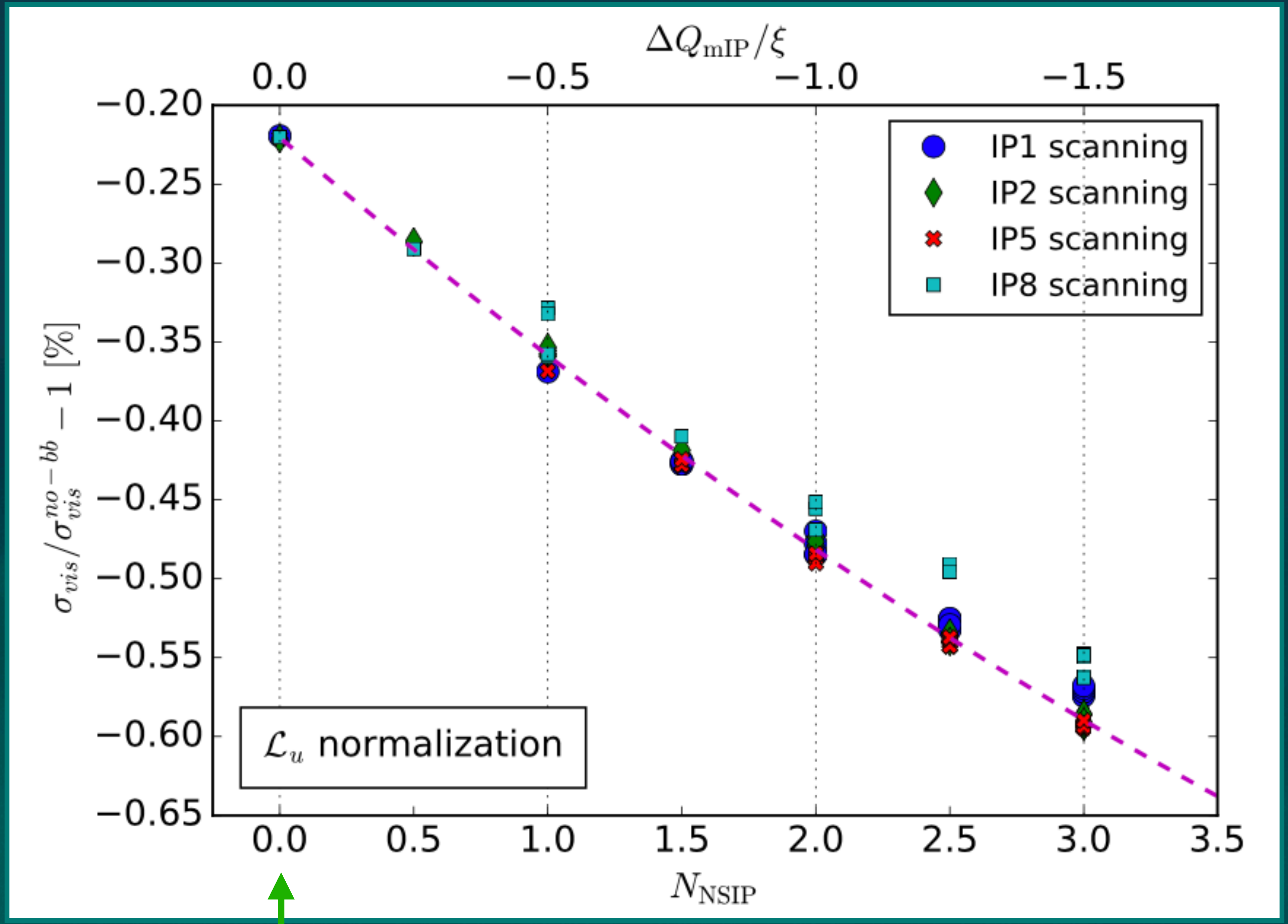

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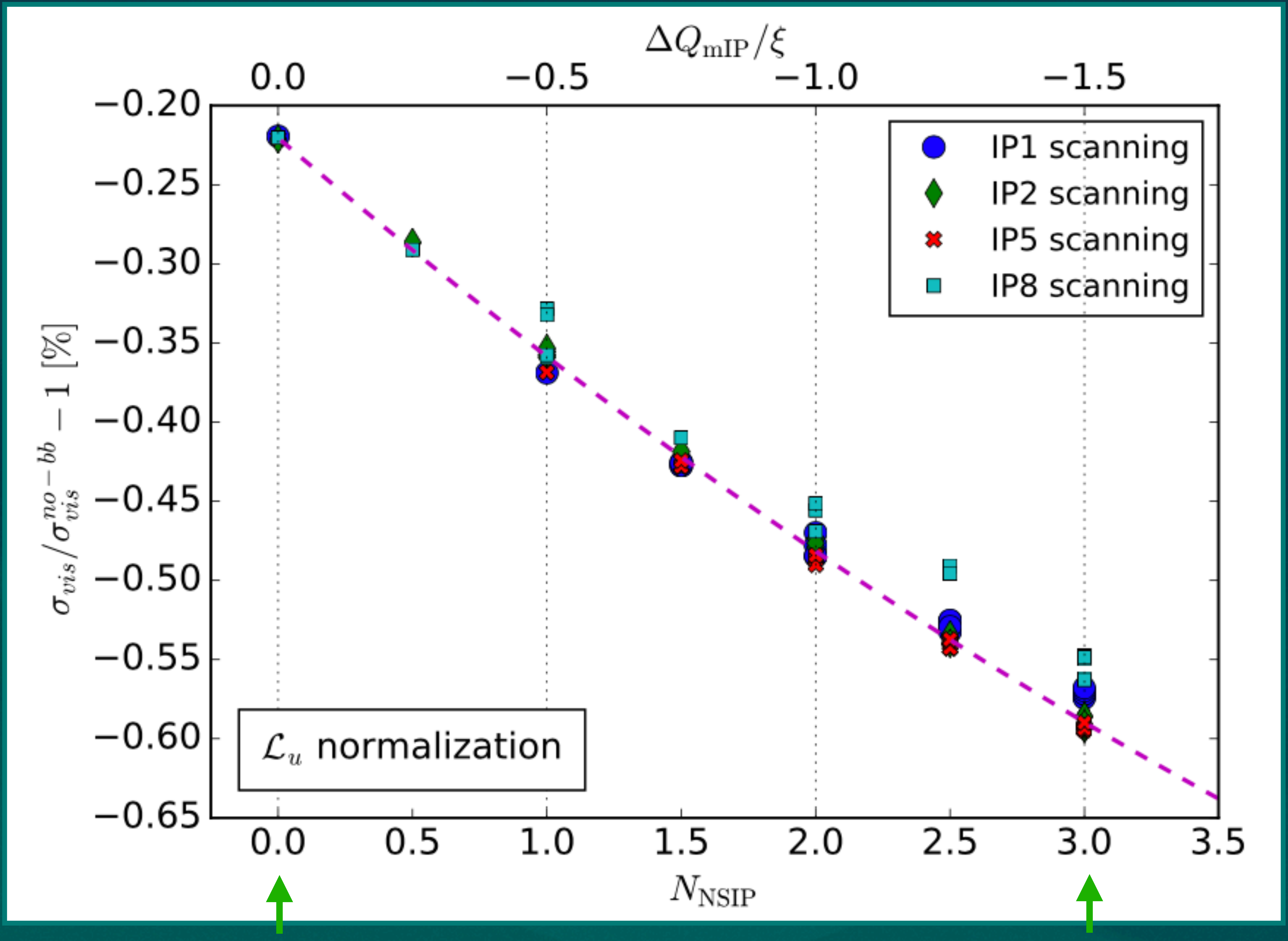

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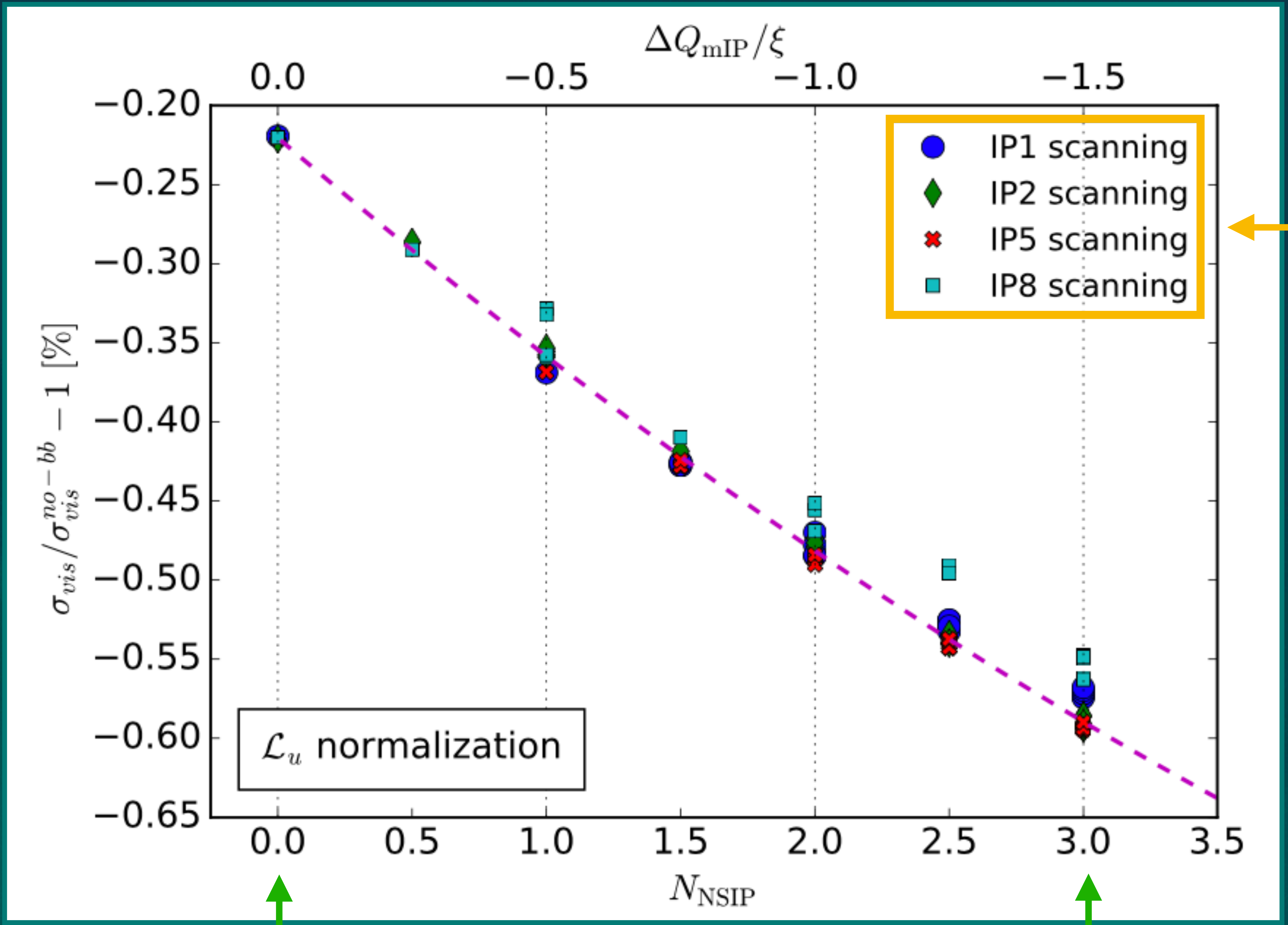

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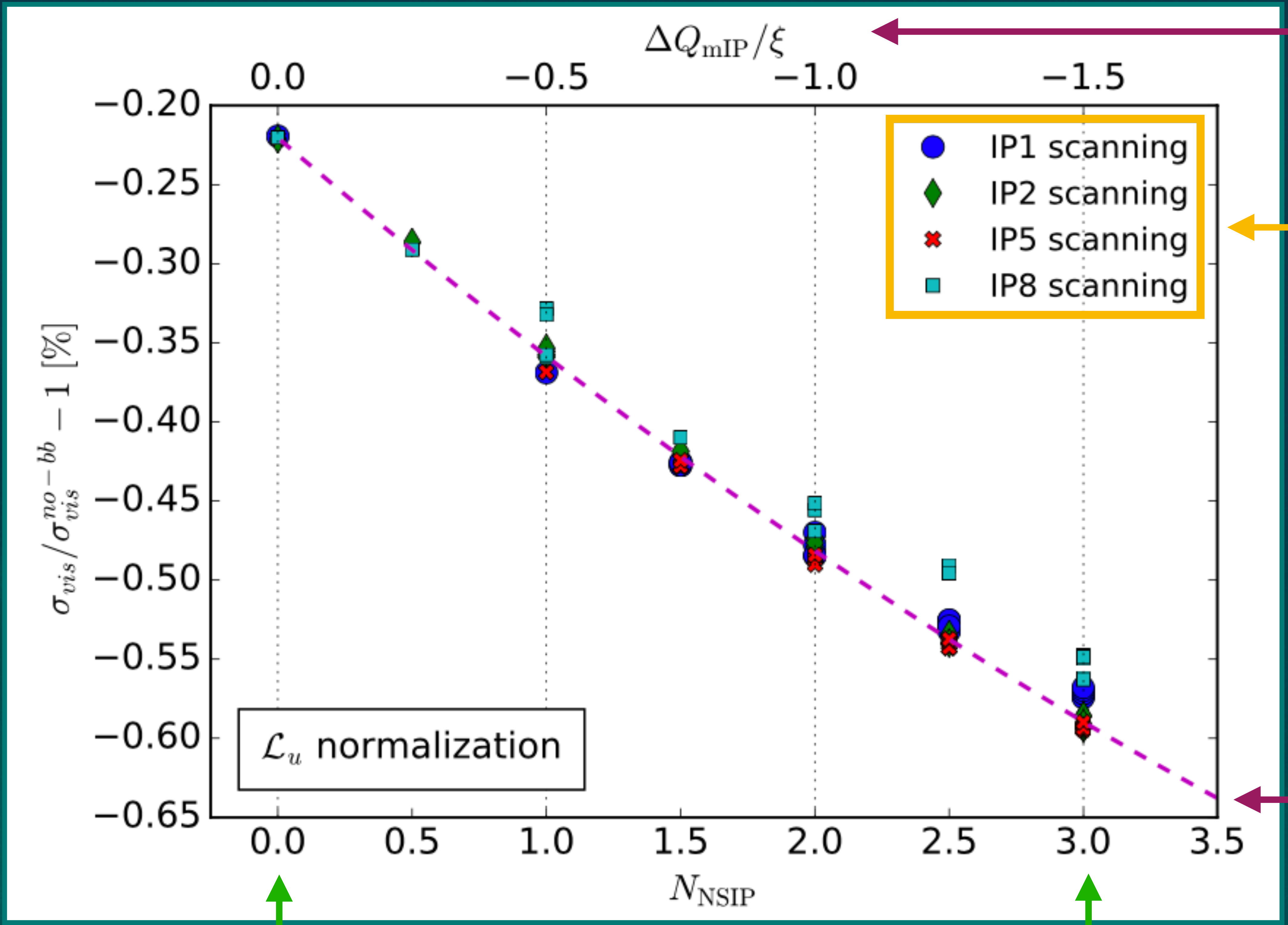

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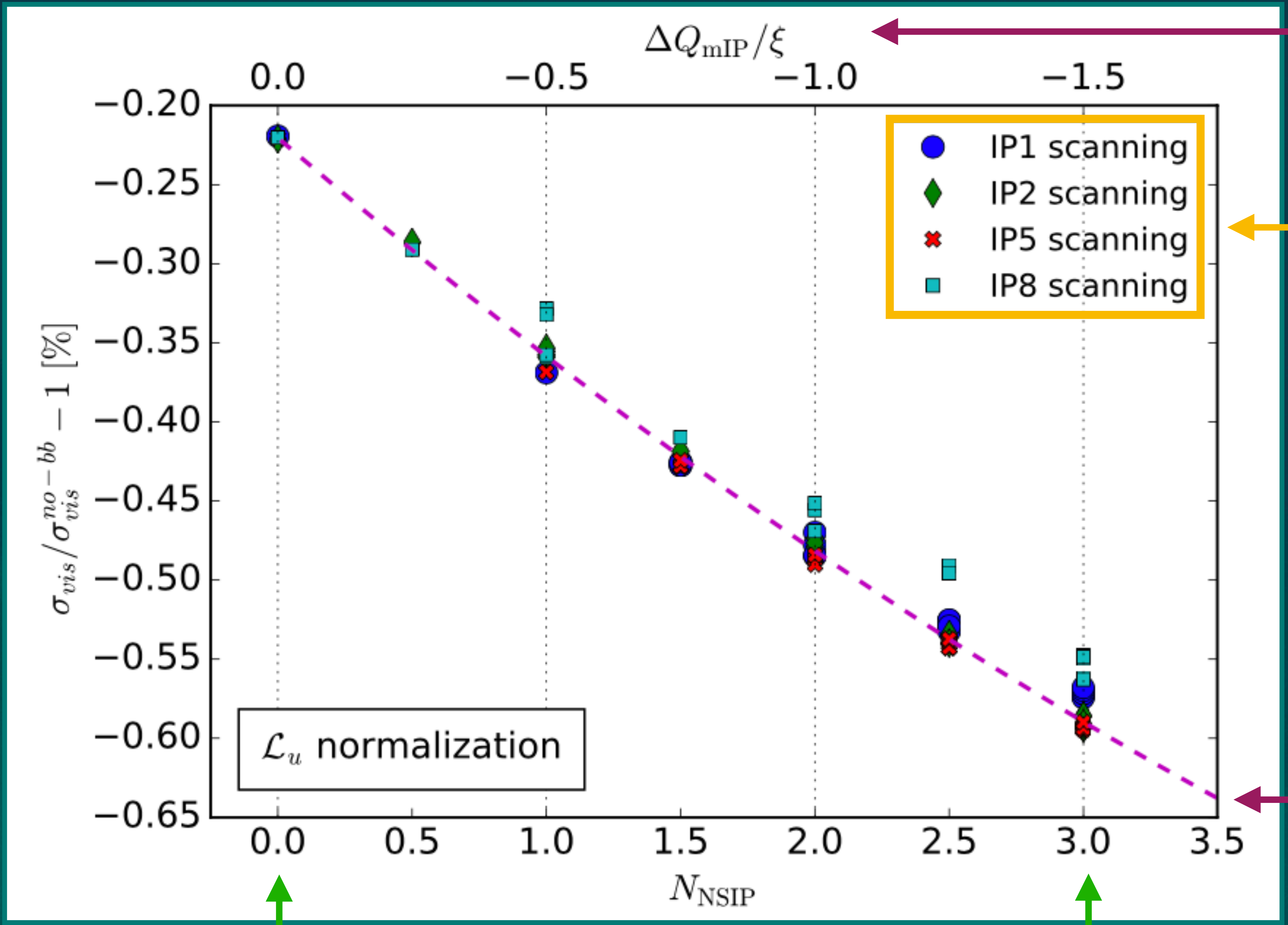
- simple scaling law derived from strong-strong simulations
  - valid for all LHC IPs



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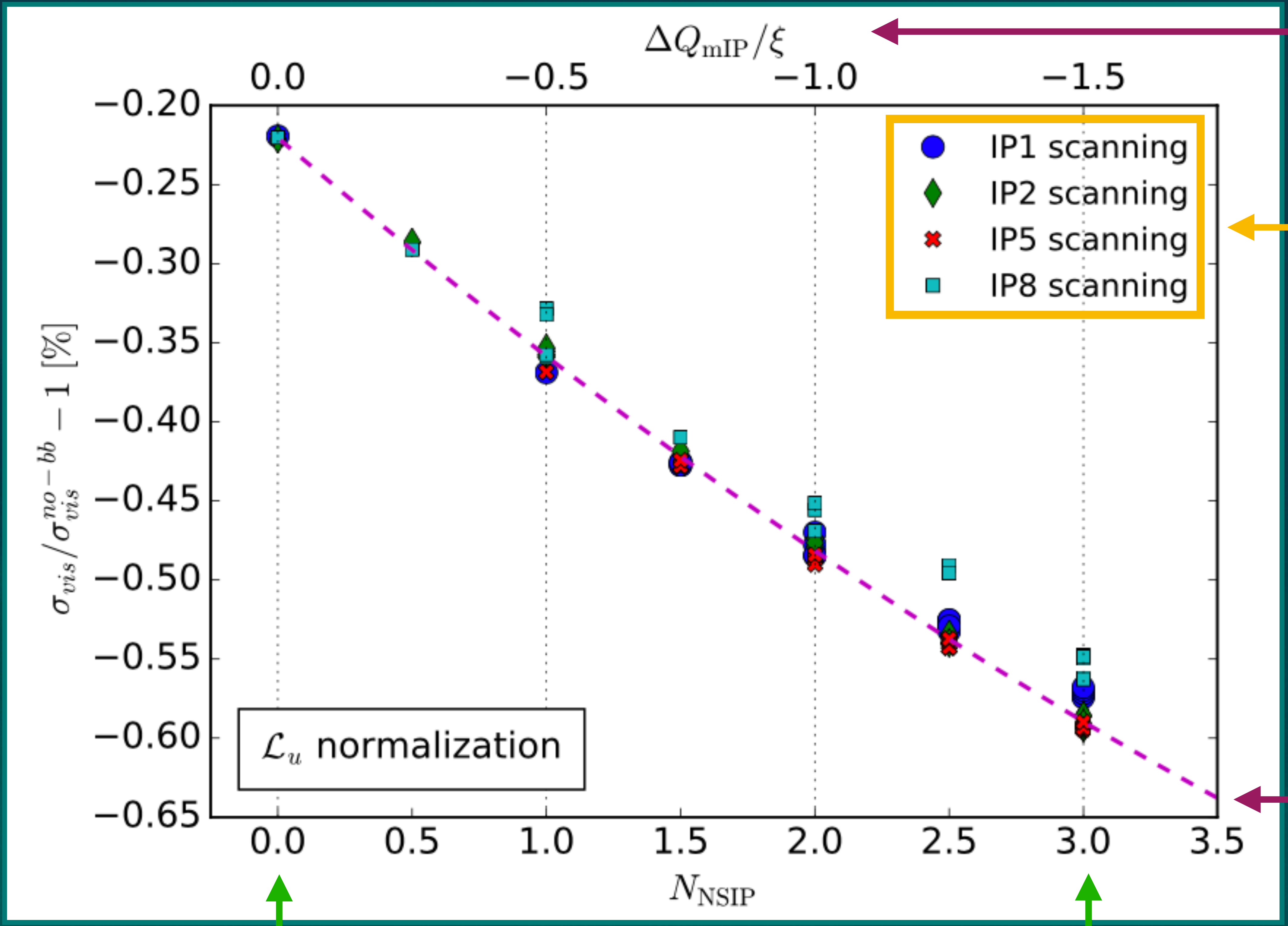
- verified in simulation for vdM regime $(\xi < 0.01)$



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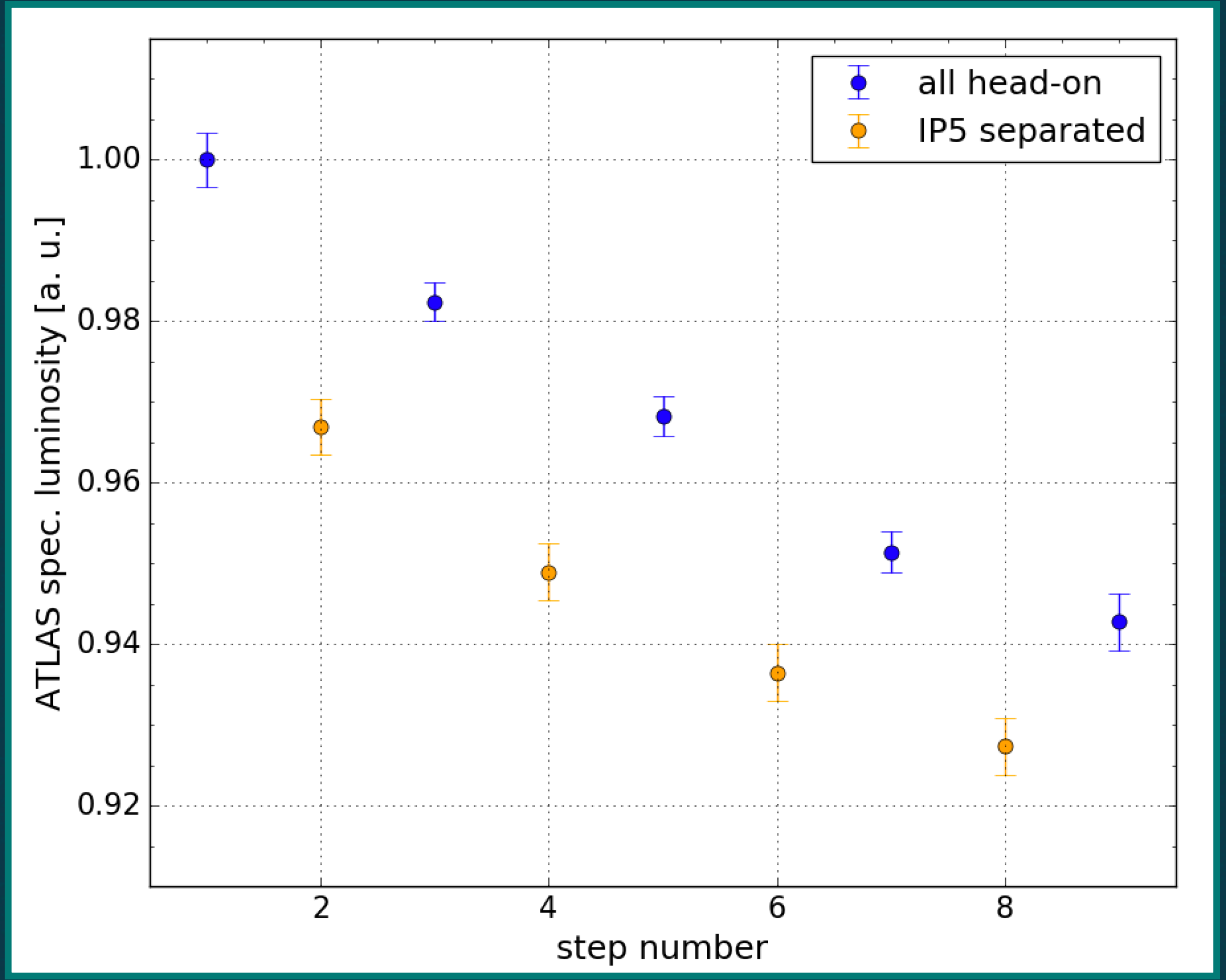
Benchmark experiment

- 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 $(1 \rightarrow 3\%)$
    - lattice validated up to 1°
  - suppression of coherent modes

Luminosity observations



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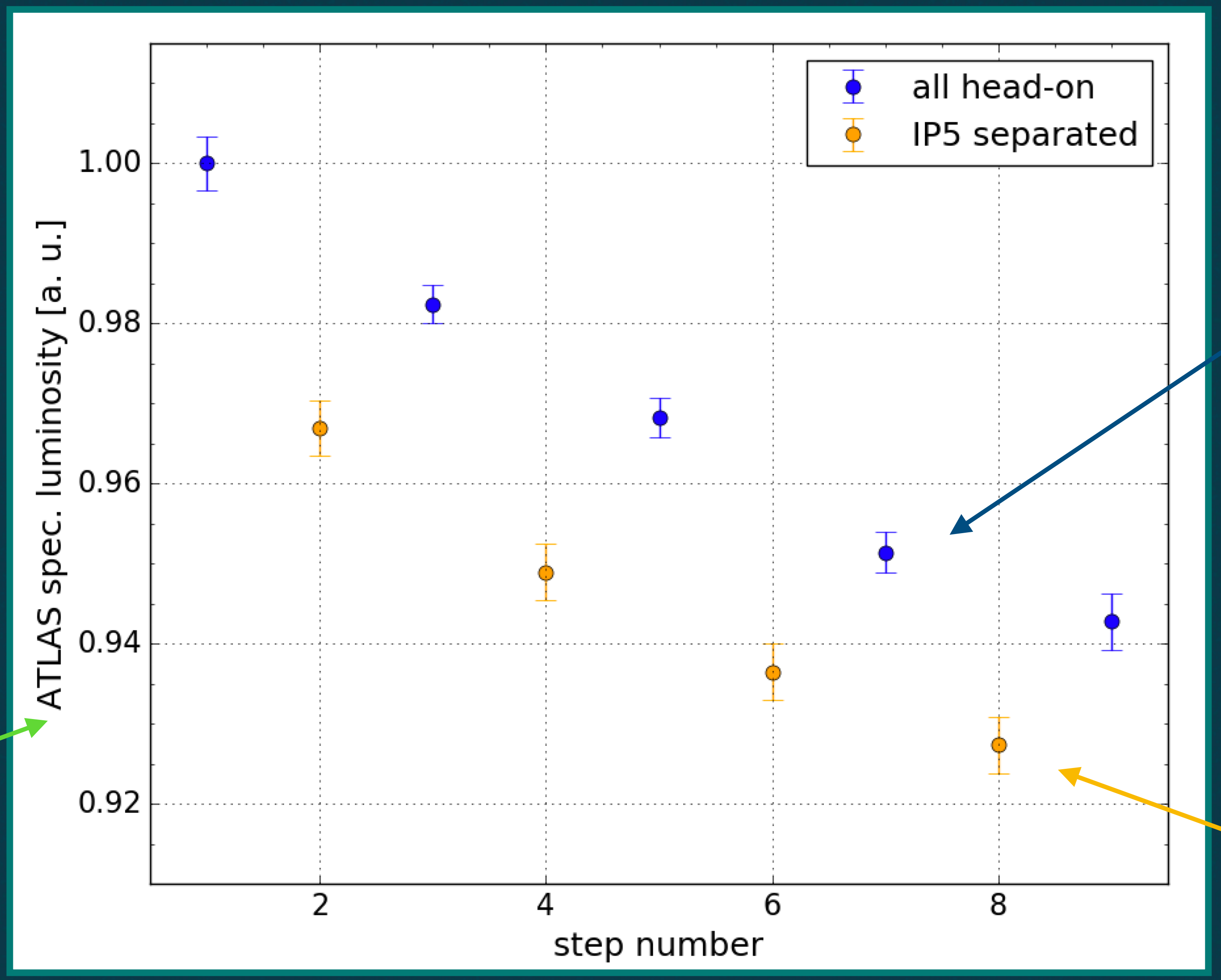

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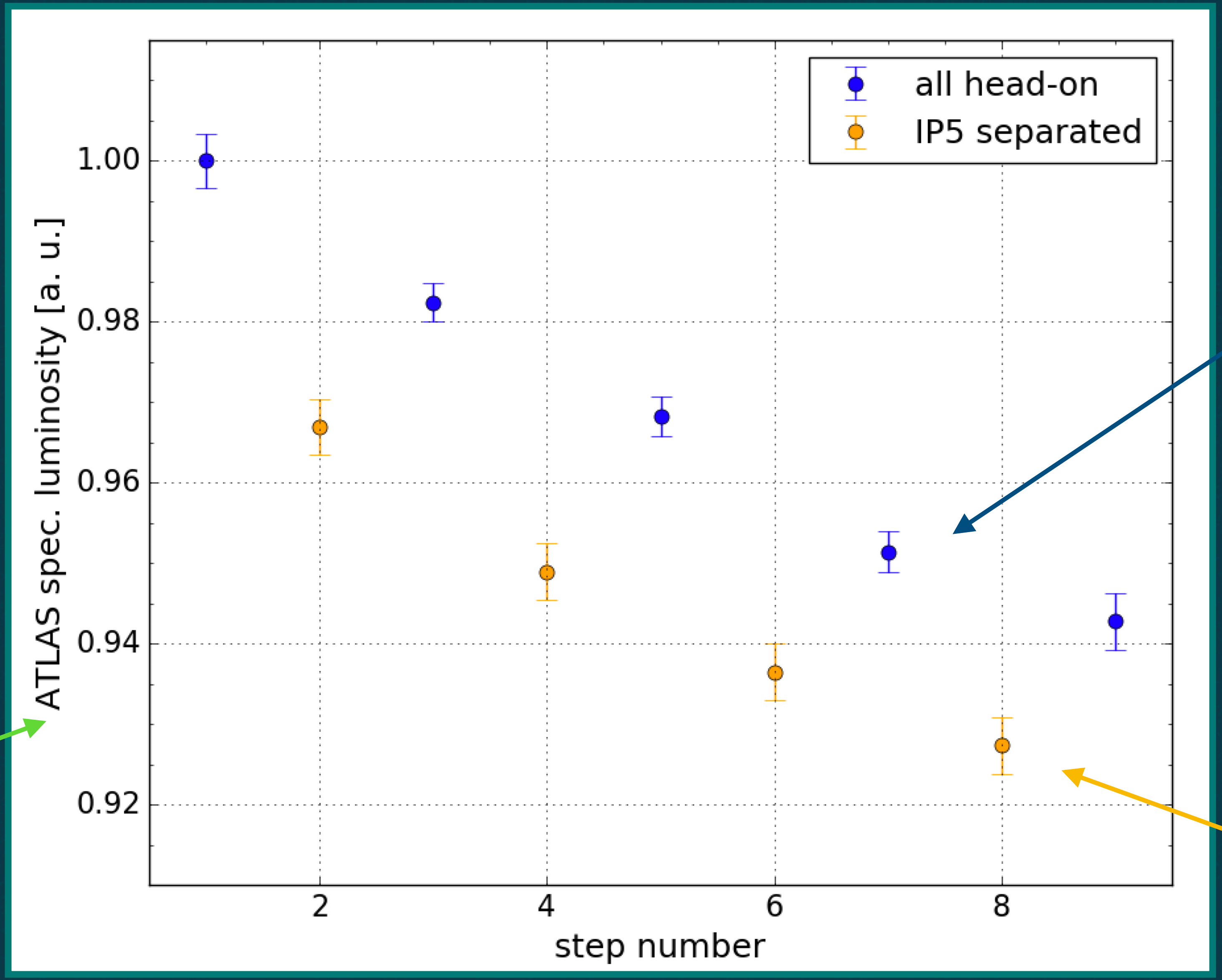

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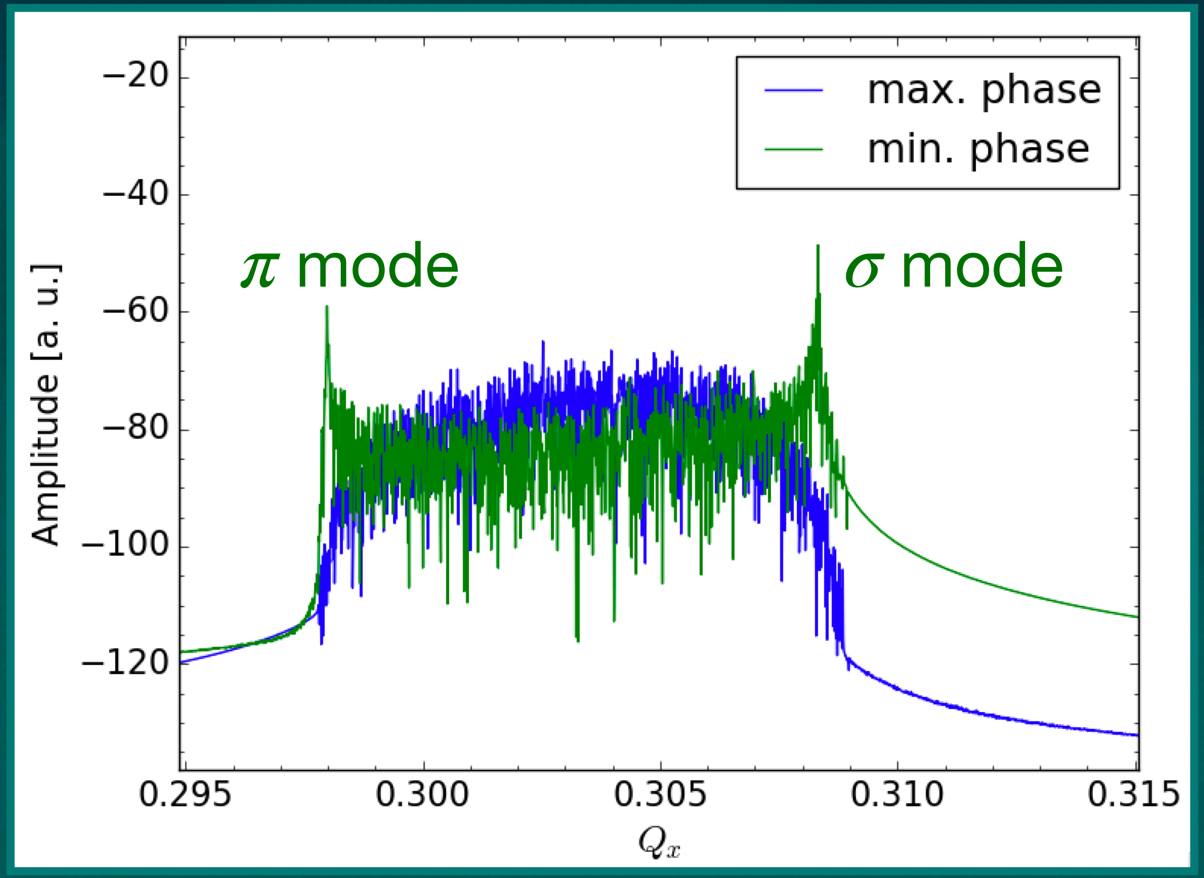

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    - lattice validated up to 1°
  - suppression of coherent modes
- multiple instruments were used to measure the effects on:
  - luminosity from ATLAS and CMS luminometers
  - tune spectra (Q_x, Q_y) from ADT, BBQ
  - transverse beam sizes σ with synch. light monitors and wire scanners
  - orbit at the IPs with BPMs

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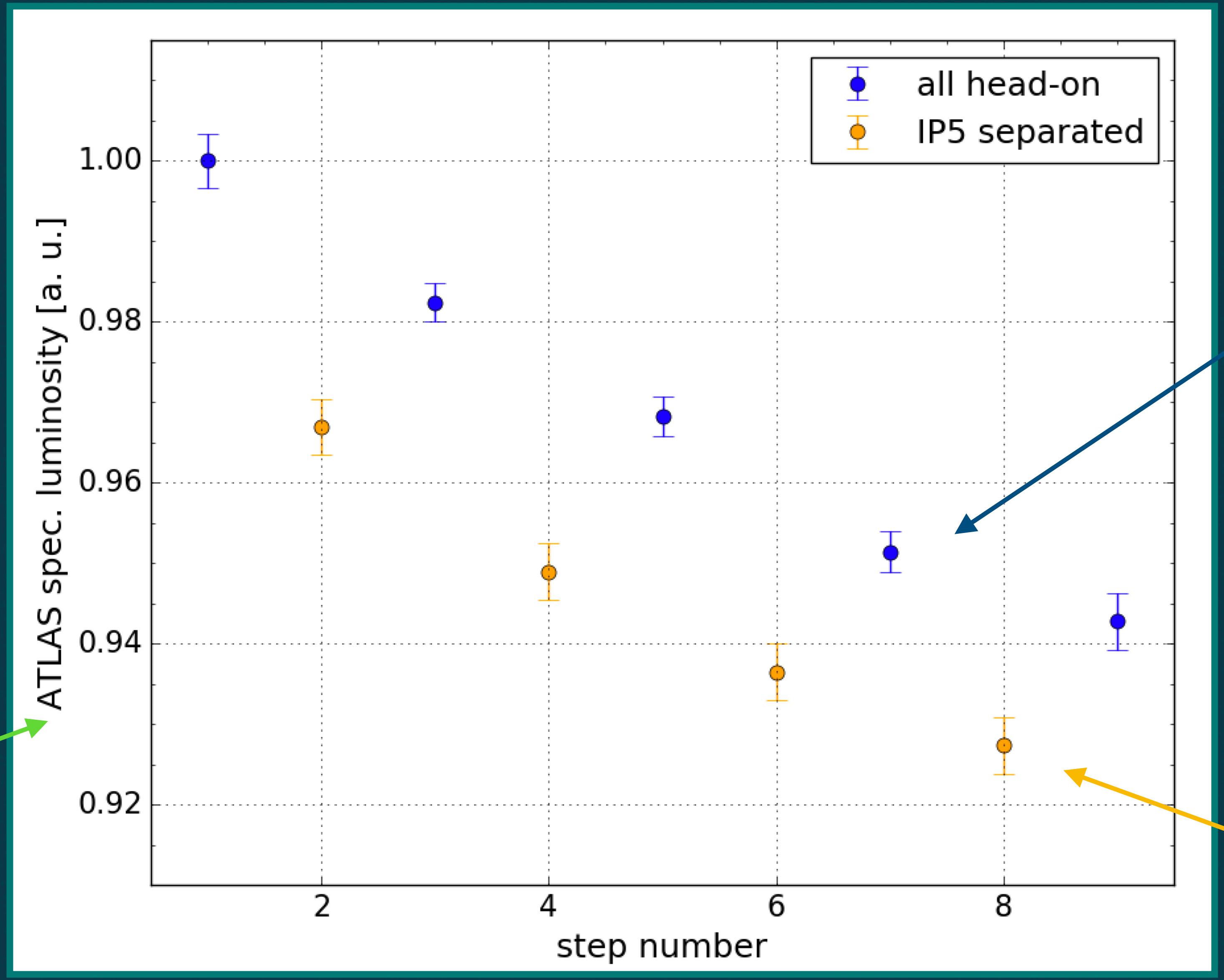

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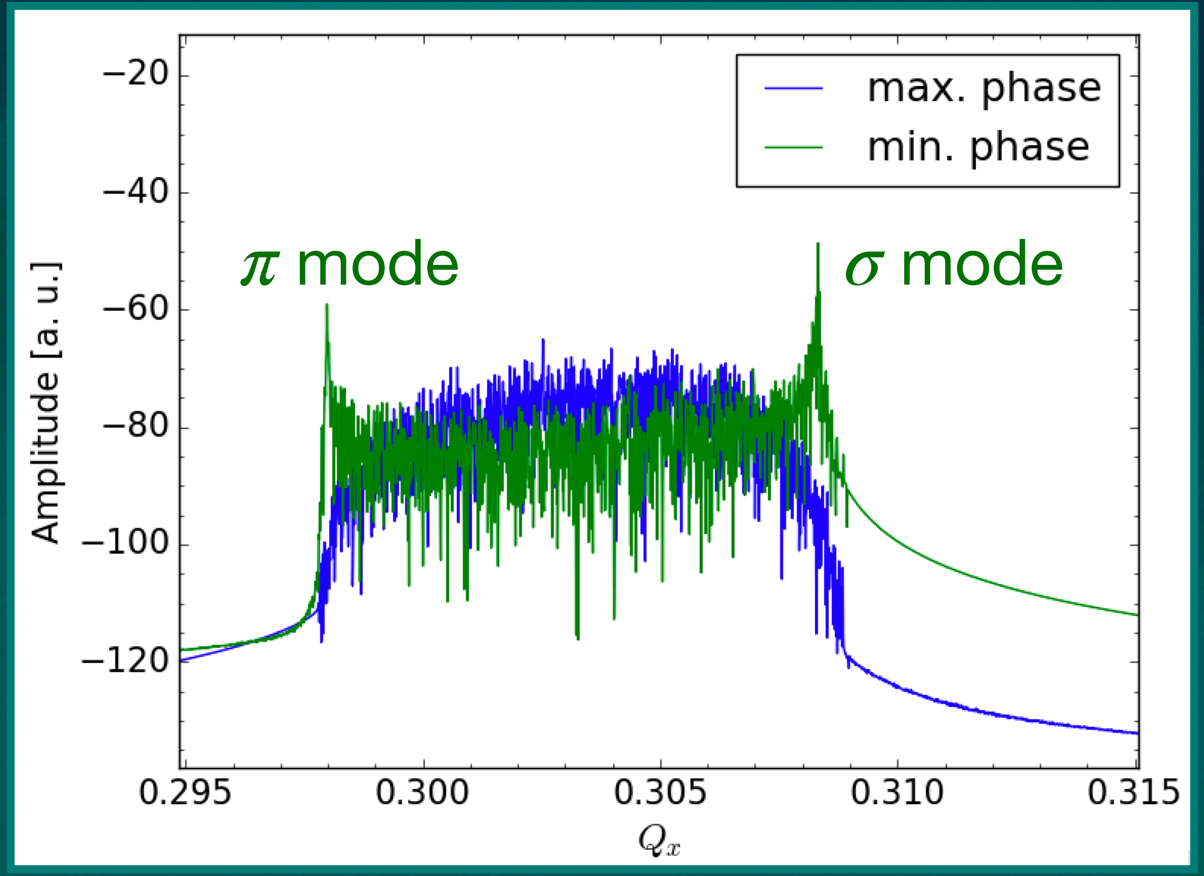
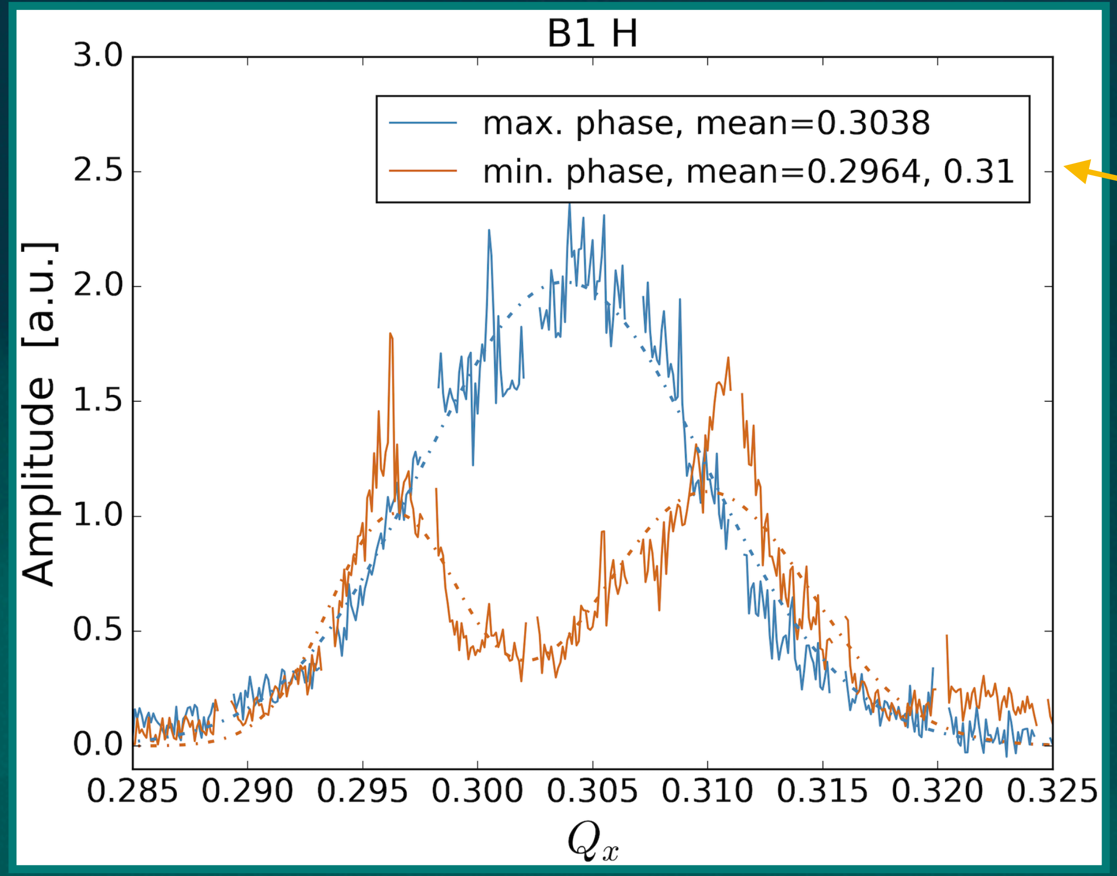


Data



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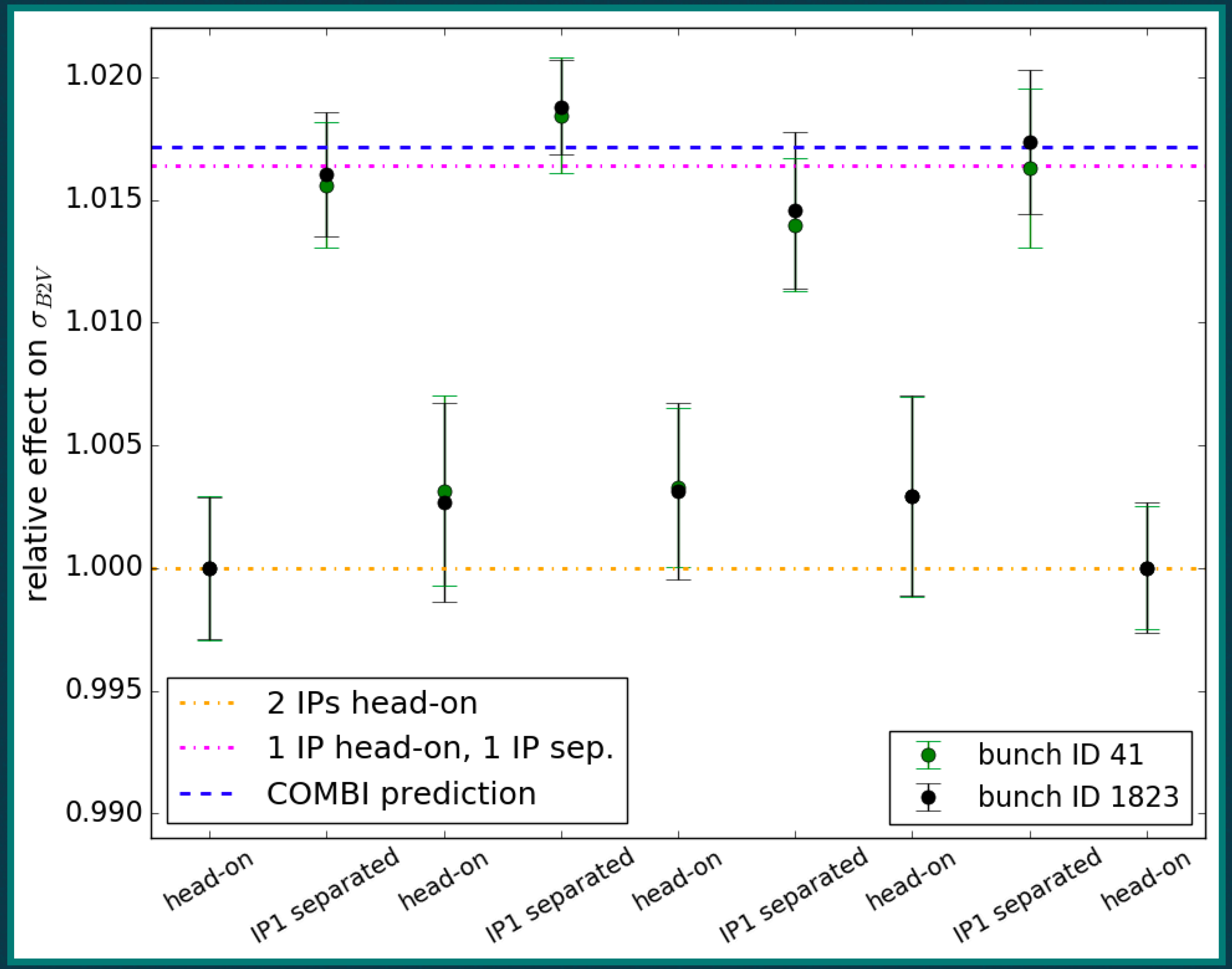

Beam width reduction caused by moving IP1 from fully separated to head-on position, as measured by synchrotron light monitor [8] and compared to COMBI

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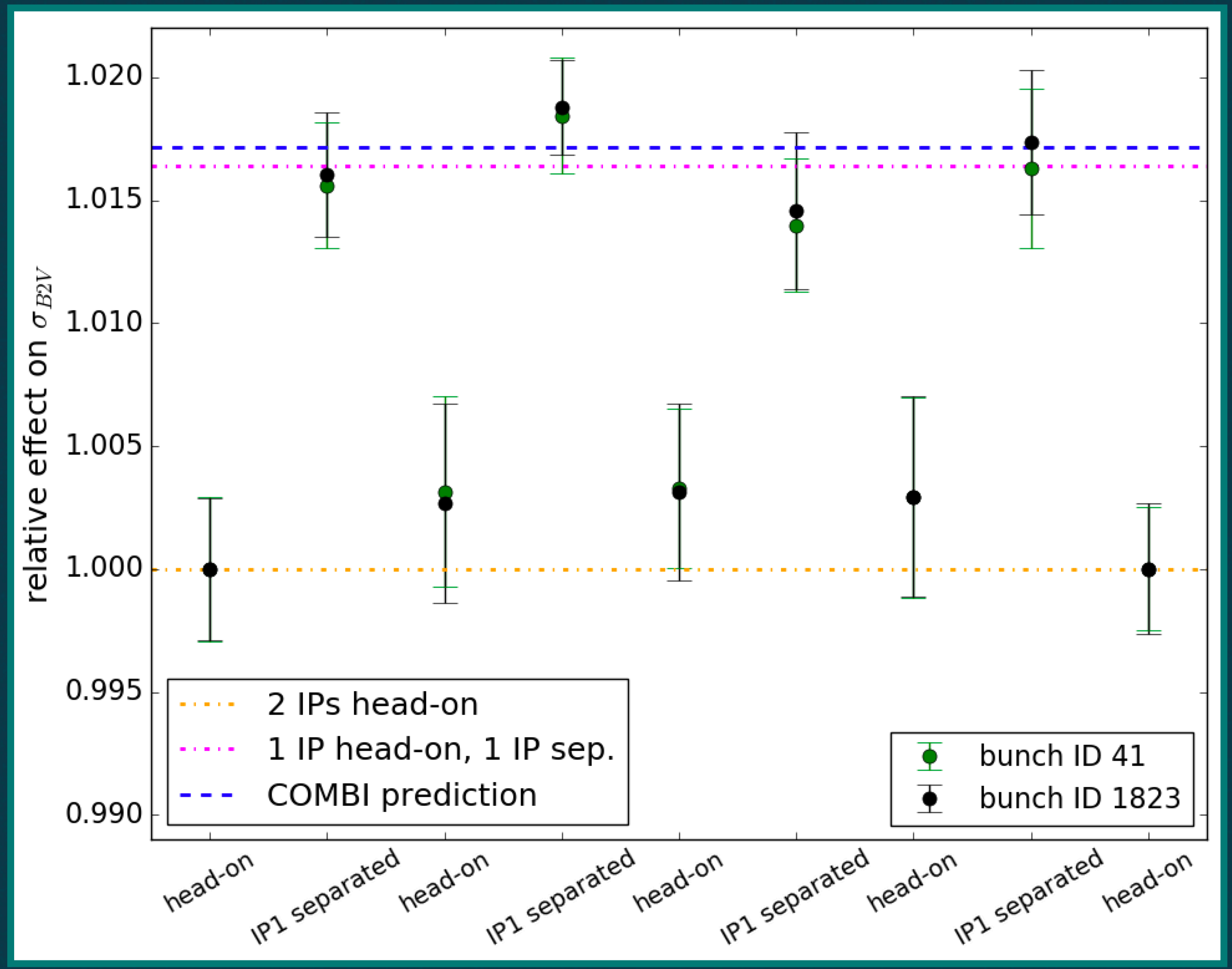
  - support for the multi-IP modelling
  - scaling law with BB parameter verified



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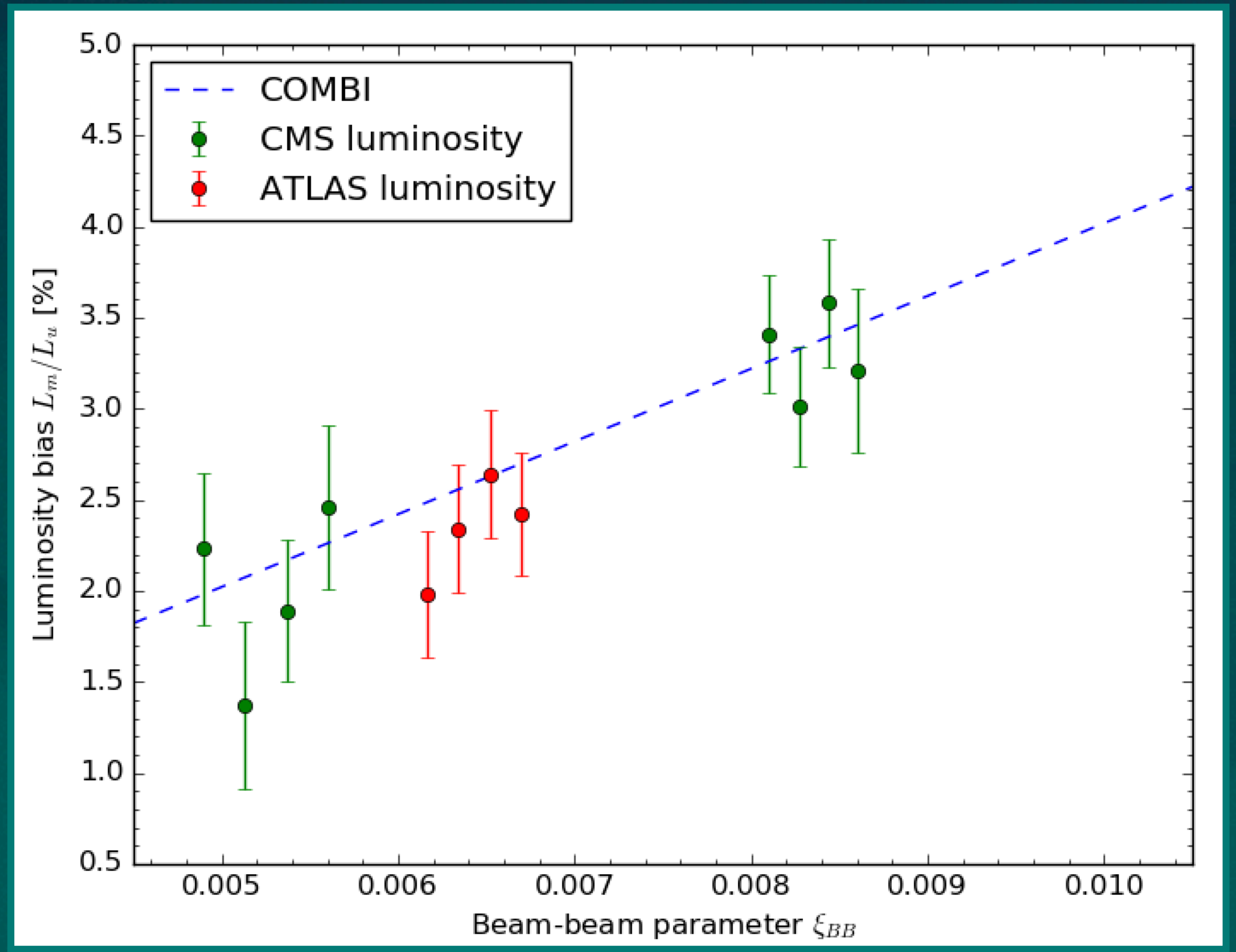

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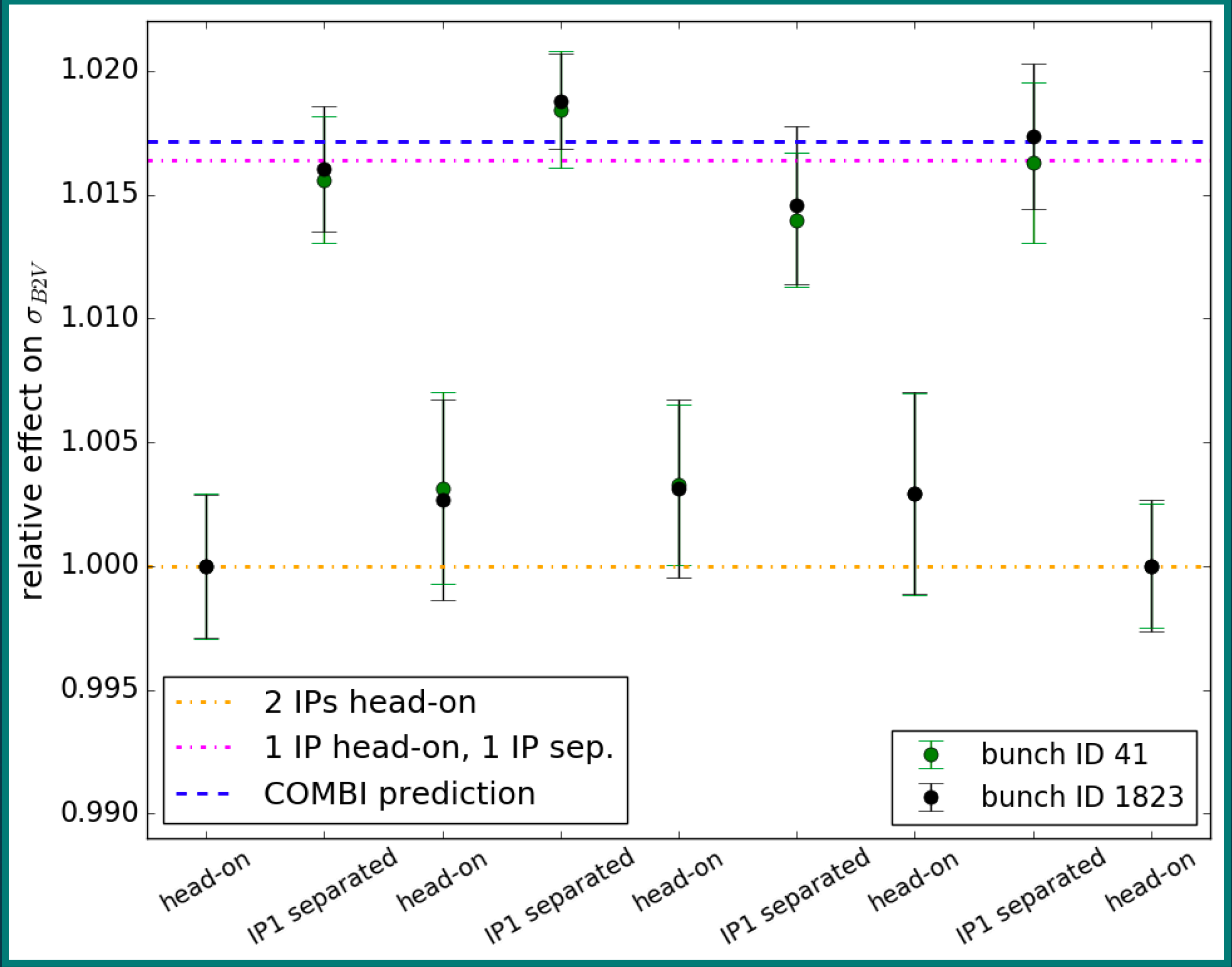

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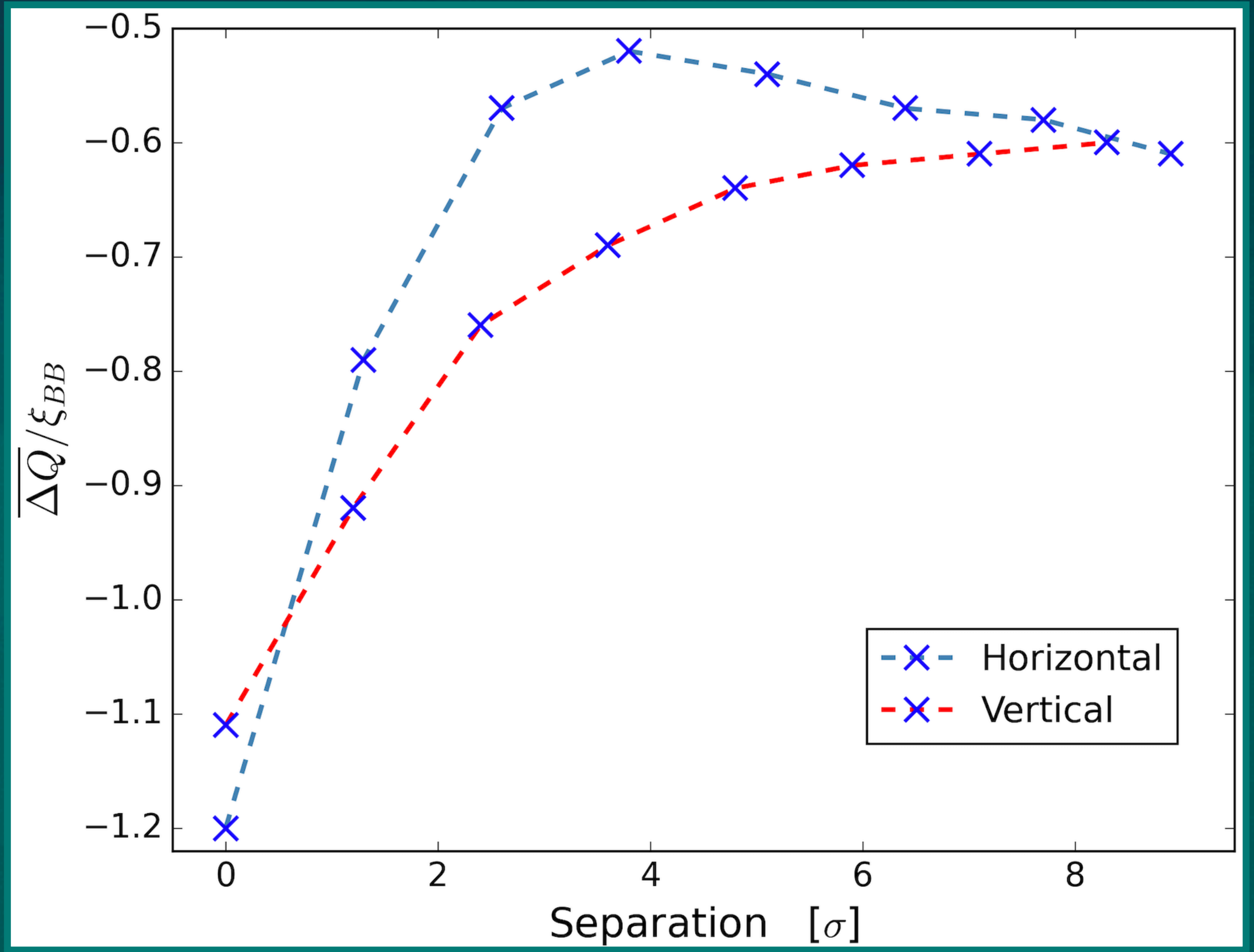
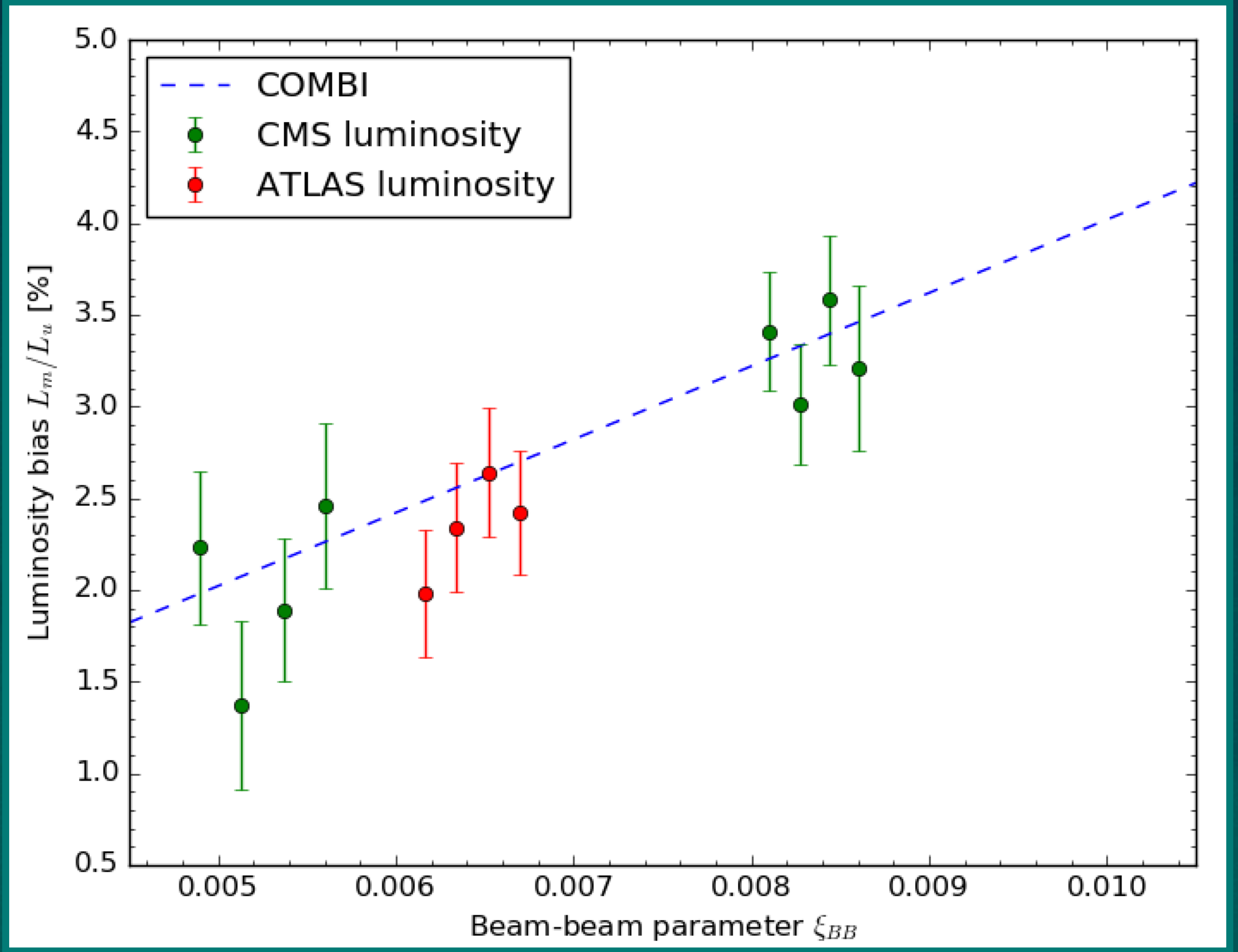


← single collision tune shift

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 [9]



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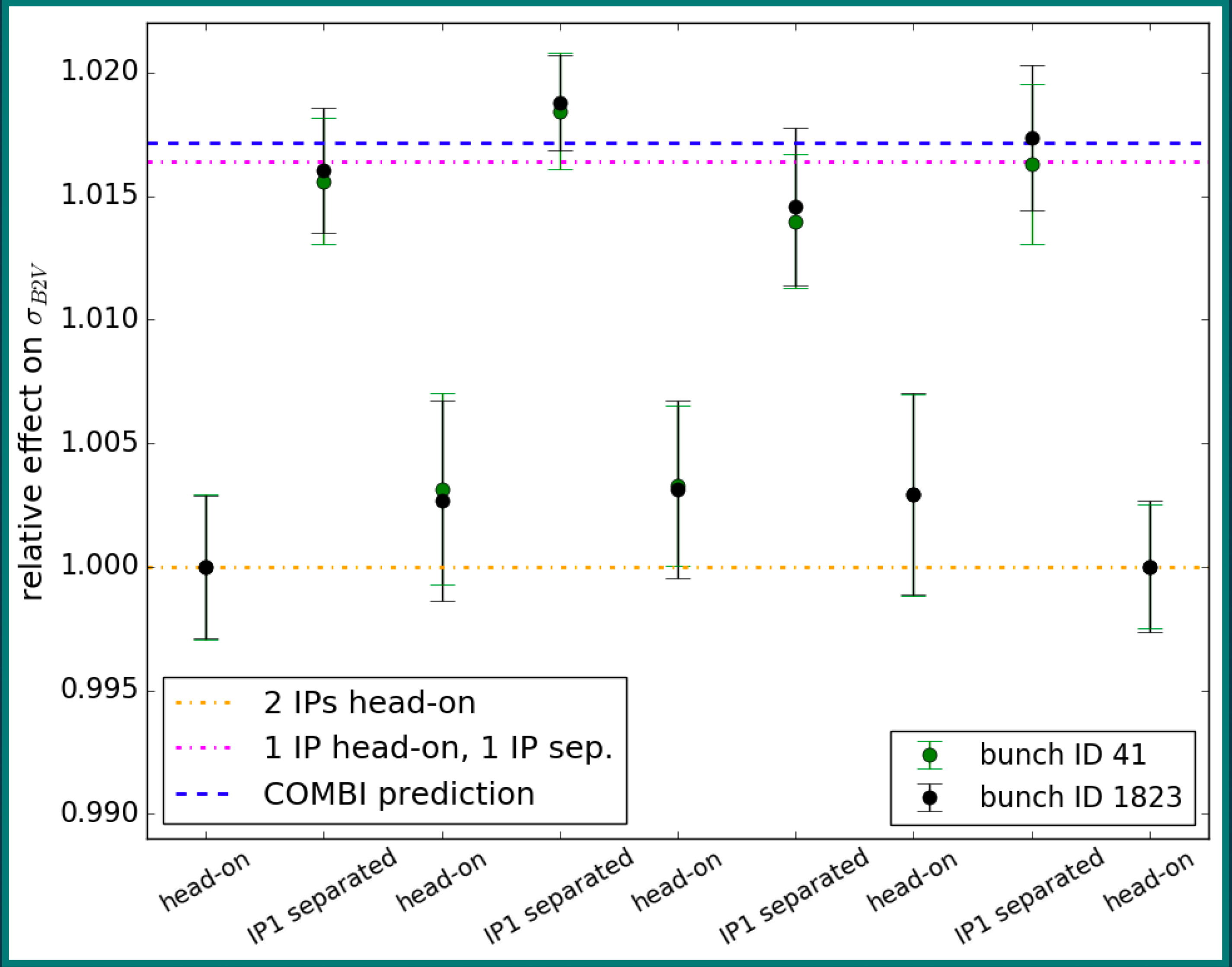
  - support for the multi-IP modelling
  - scaling law with BB parameter verified
  - observations of BB-induced changes during a separation scan
- first measurement of the impact of BB effects on the luminosity



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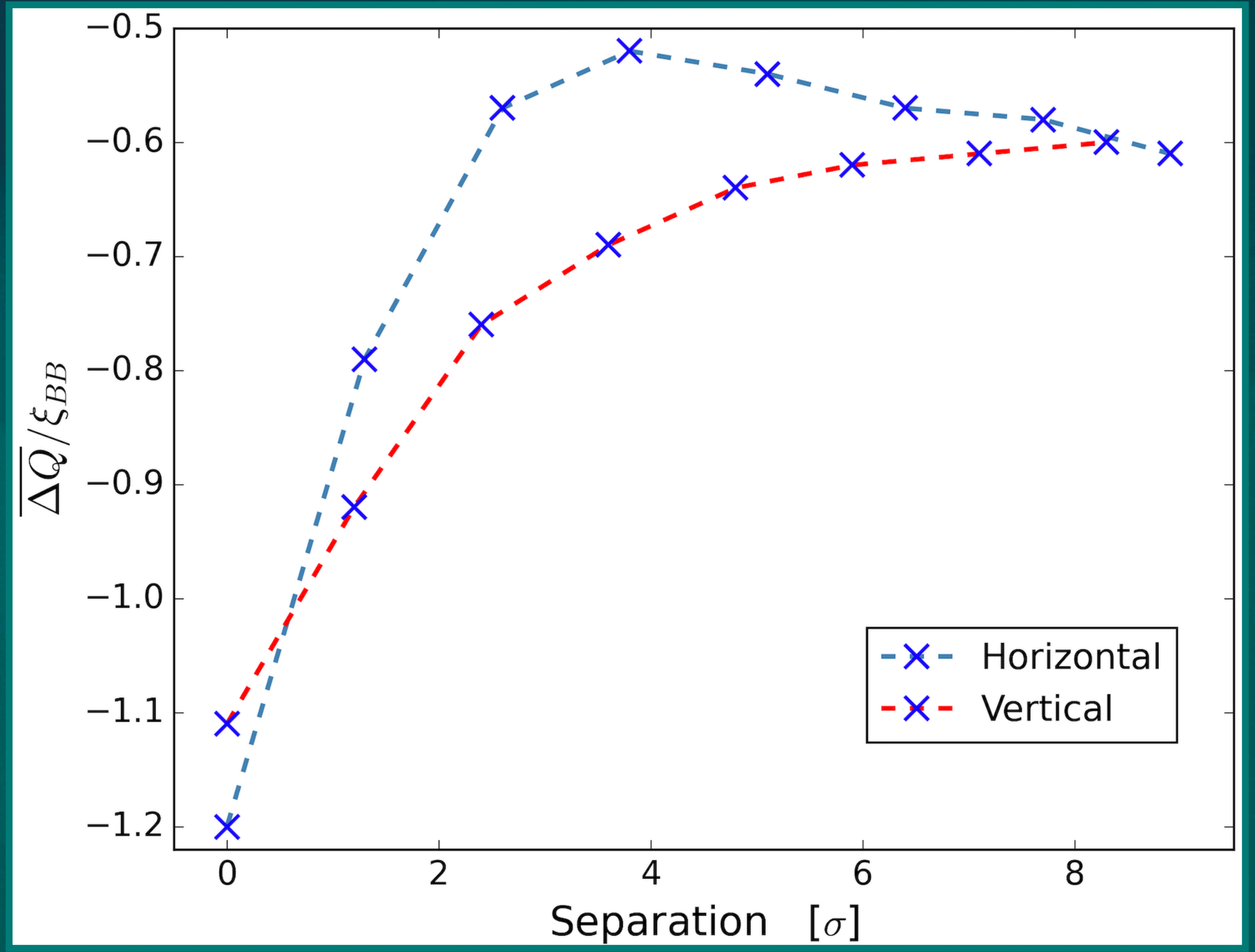

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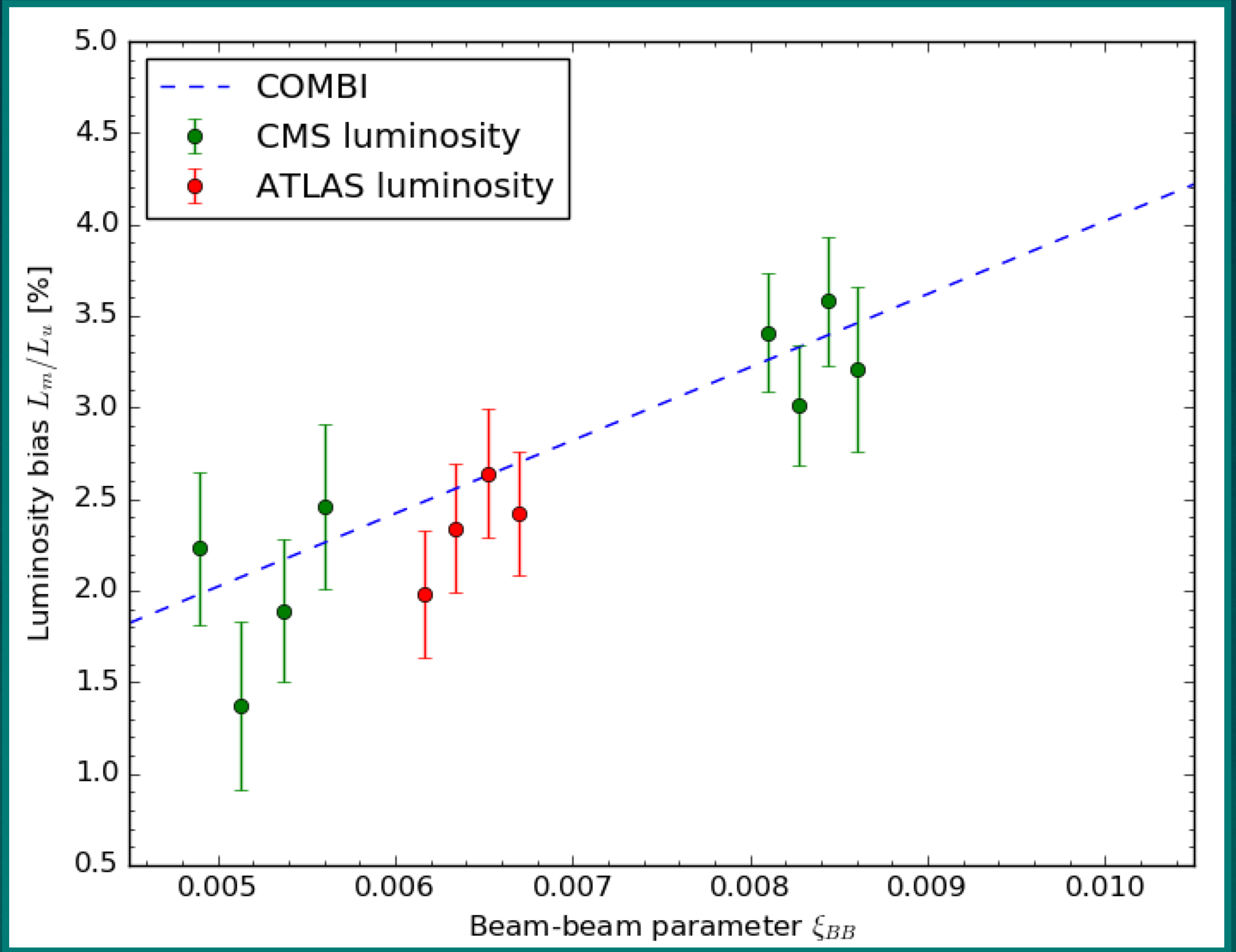

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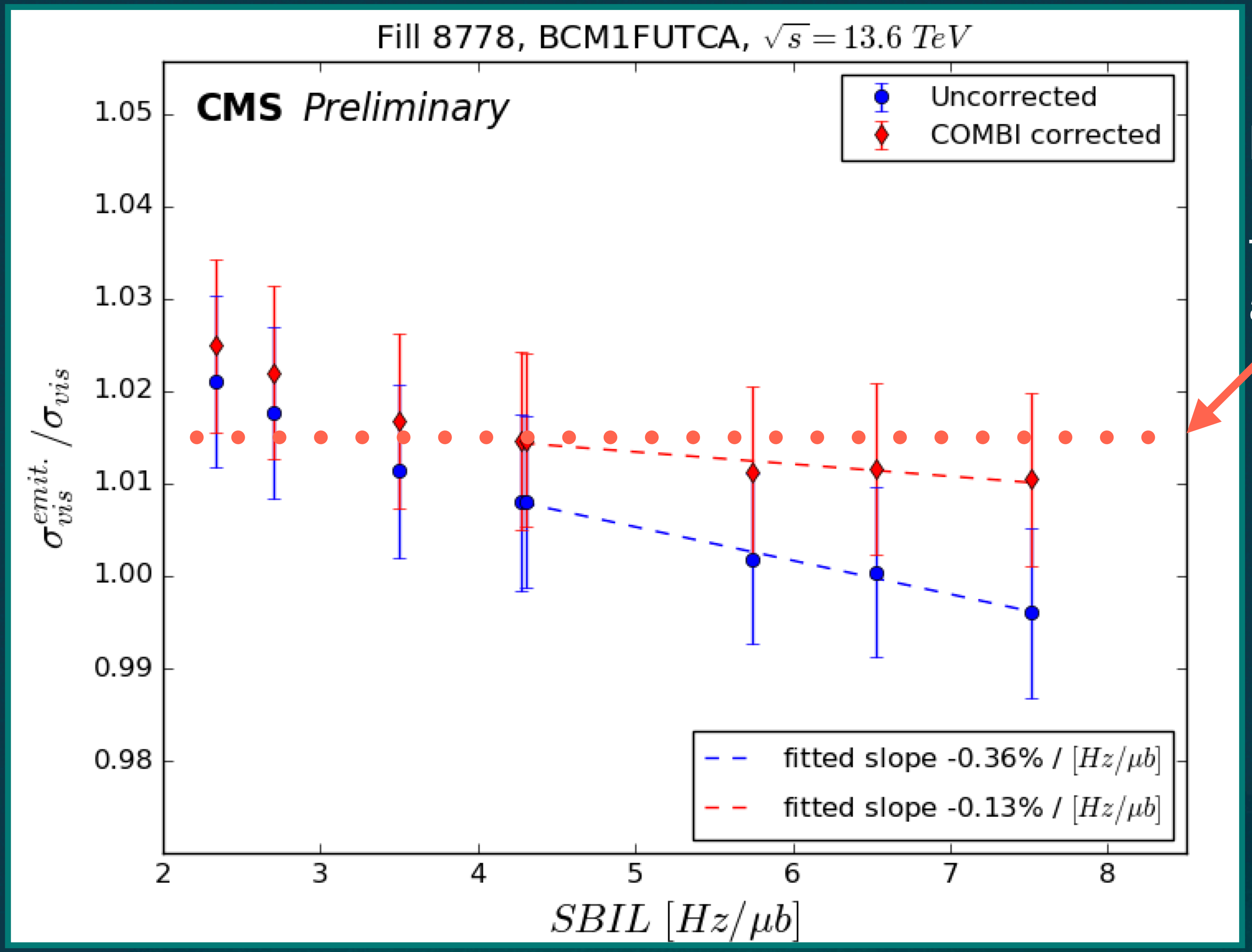

perfectly linear luminometer = flat response across SBIL

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

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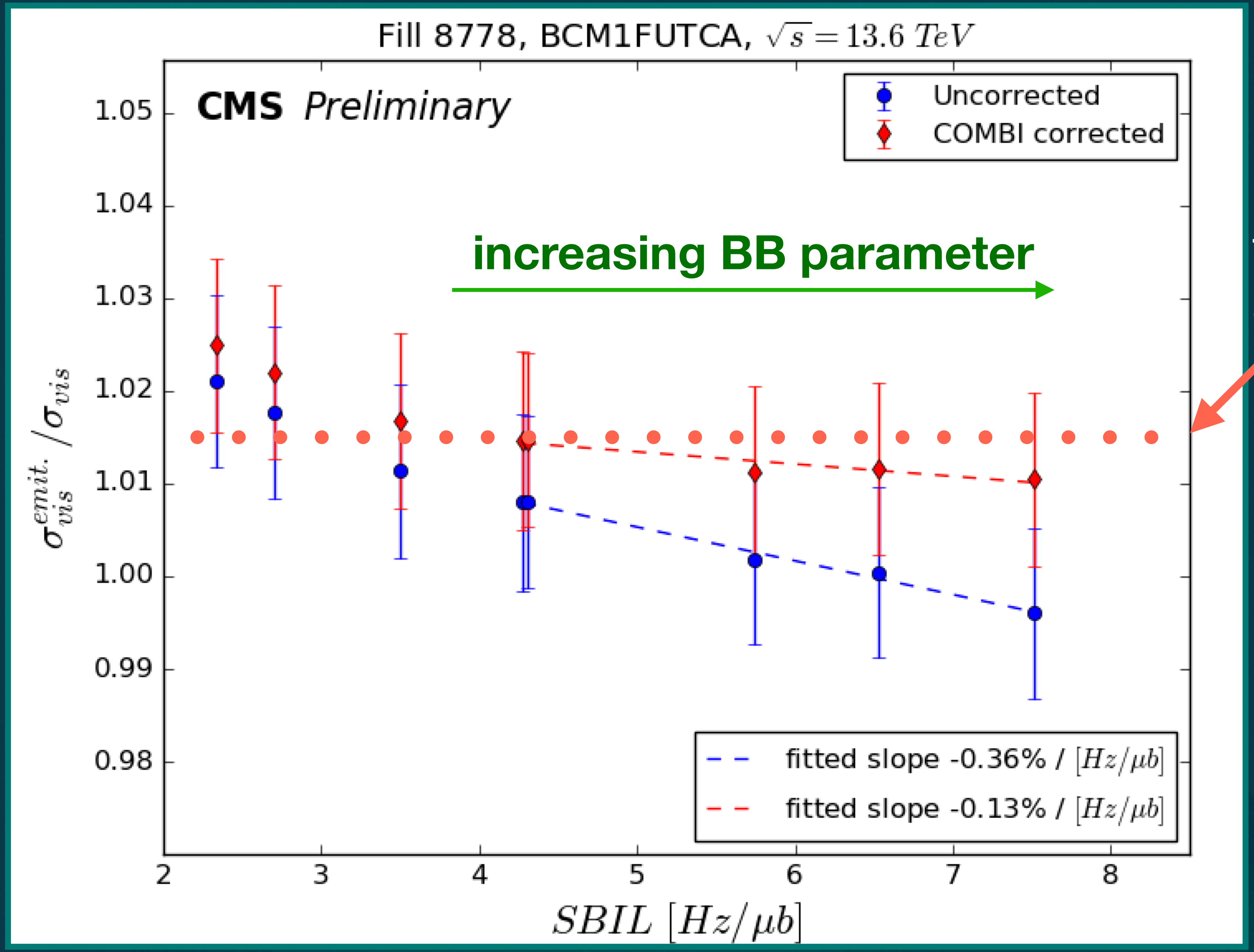

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Pile-up (PU) = ~7 x Single Bunch Instantaneous Luminosity (SBIL)

- main contributions to the measured non-linearity:
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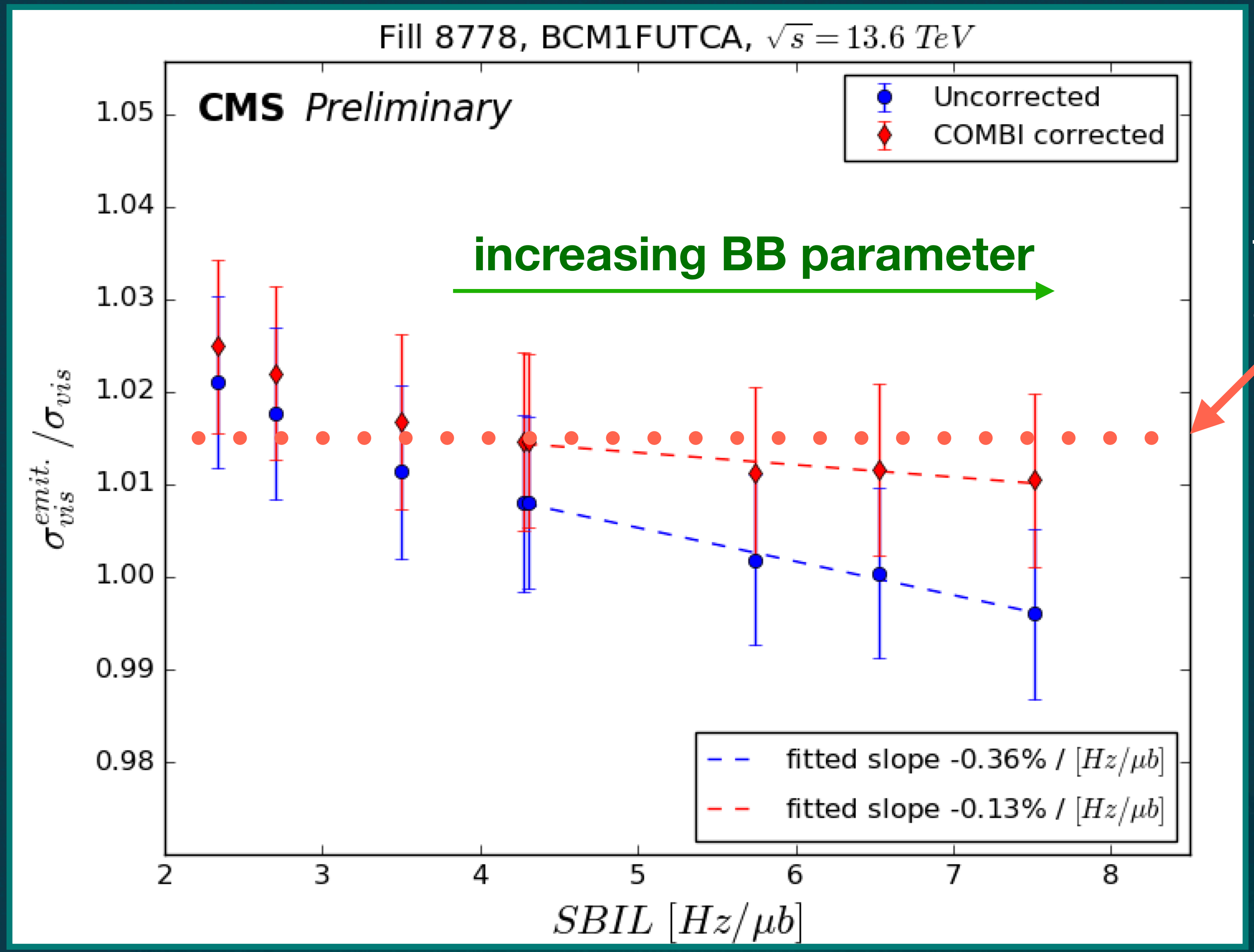
Impact of BB on measuring linearity



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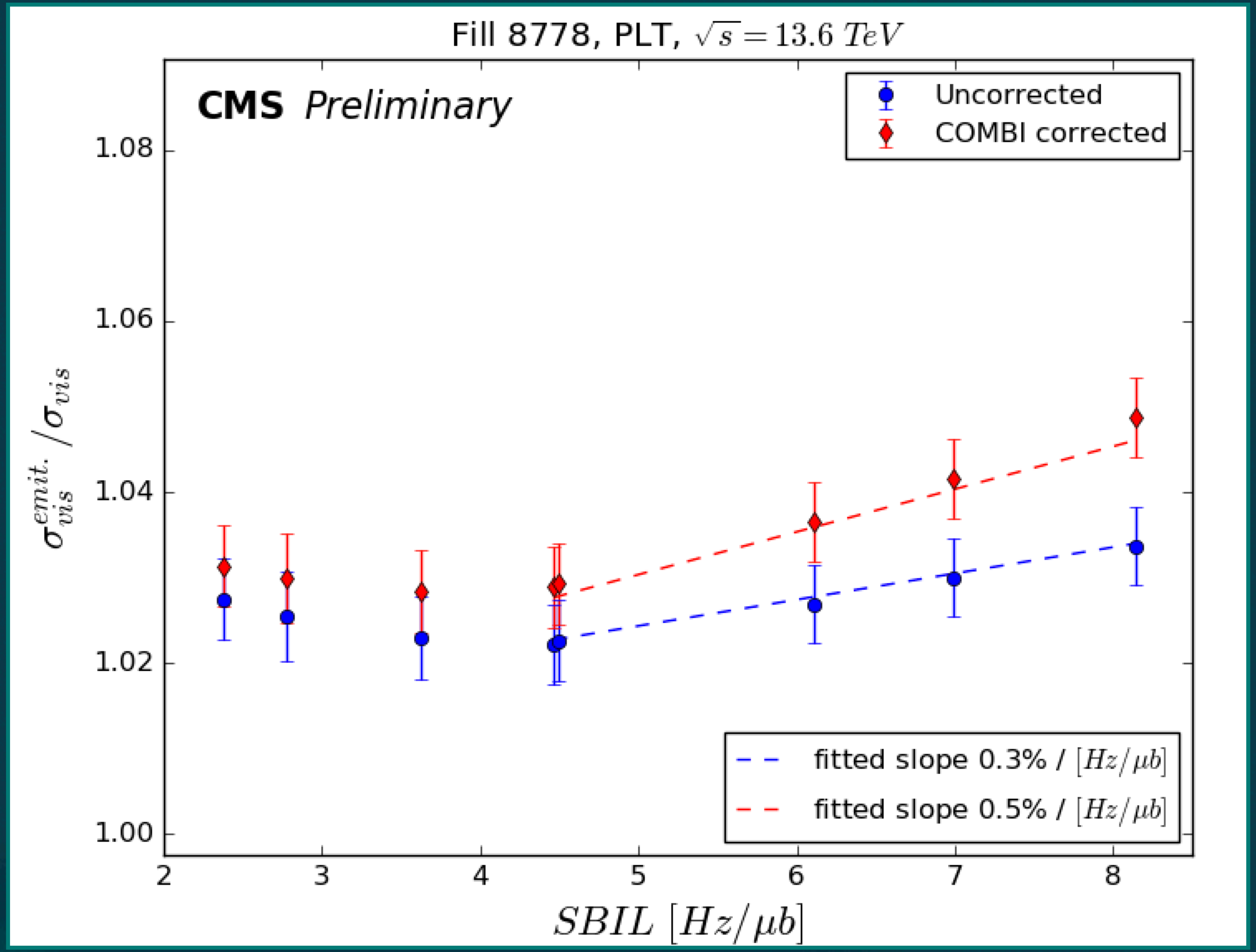

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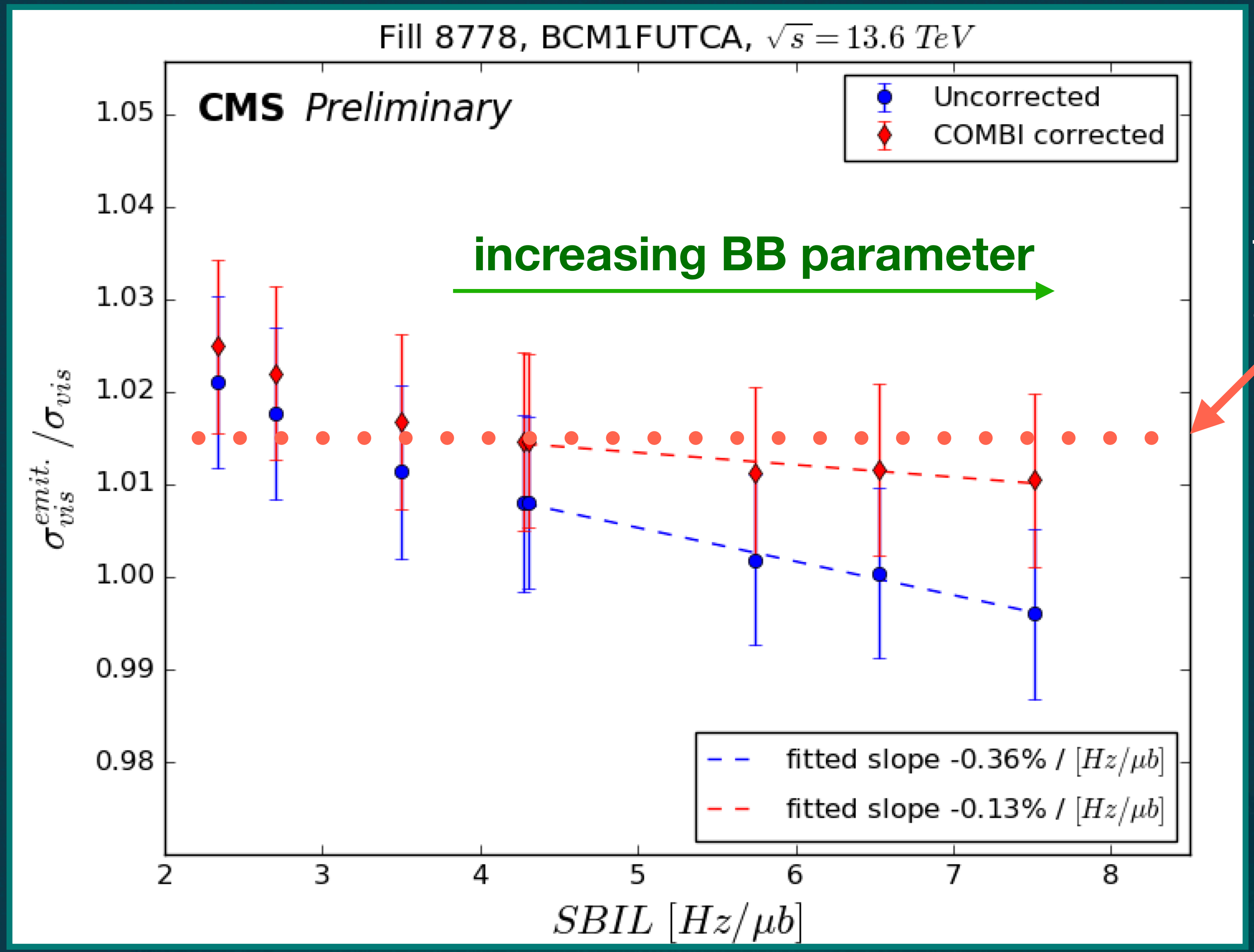

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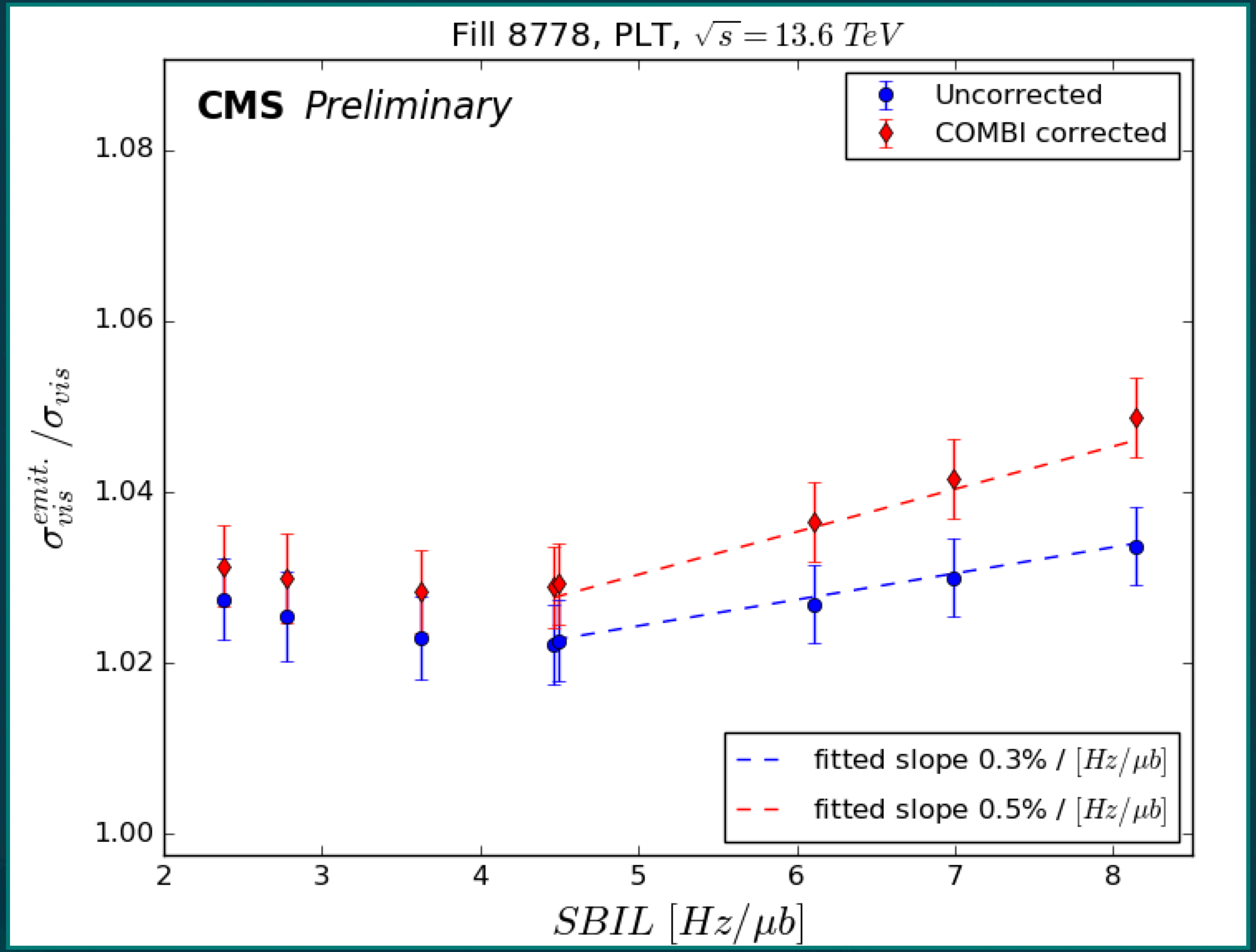

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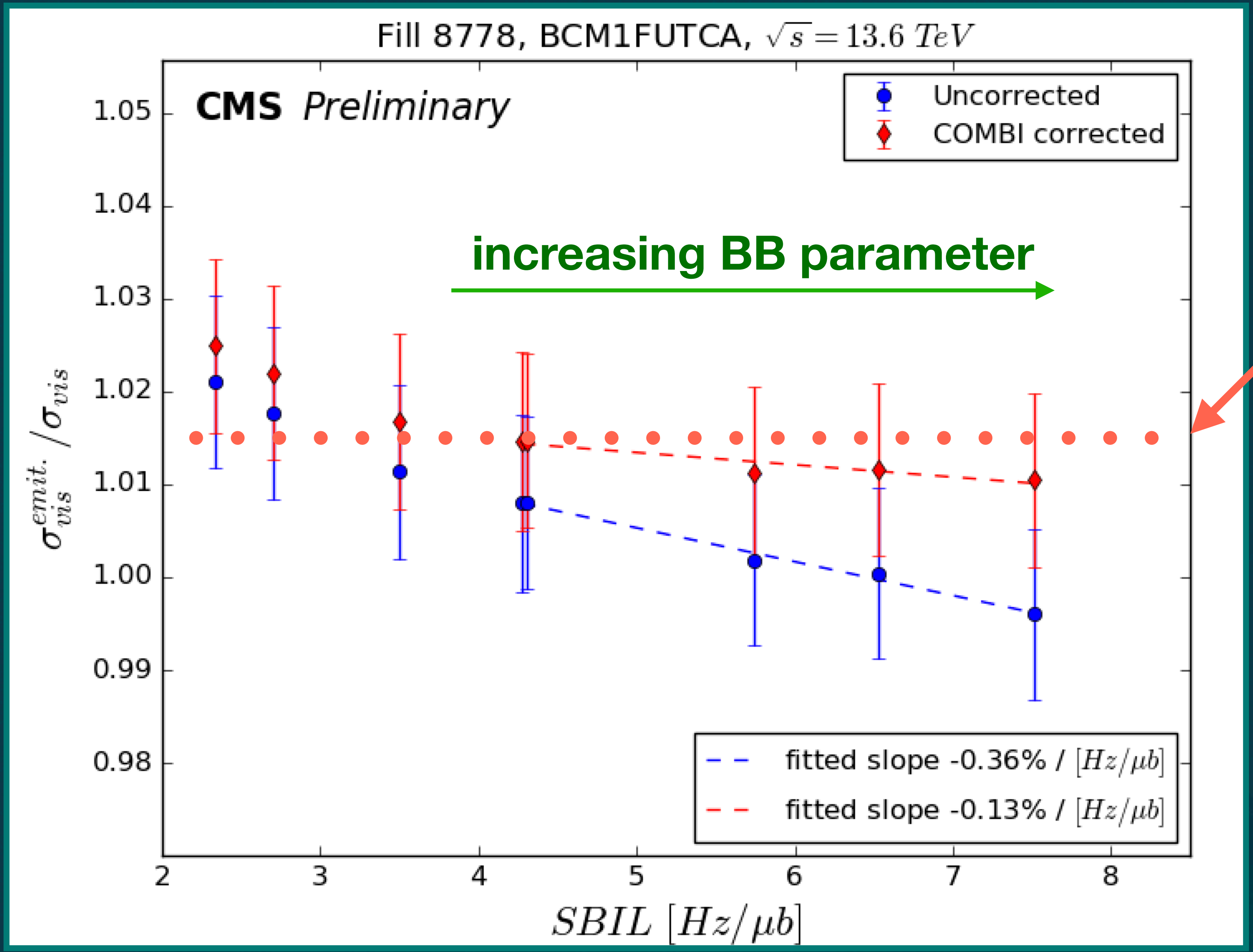

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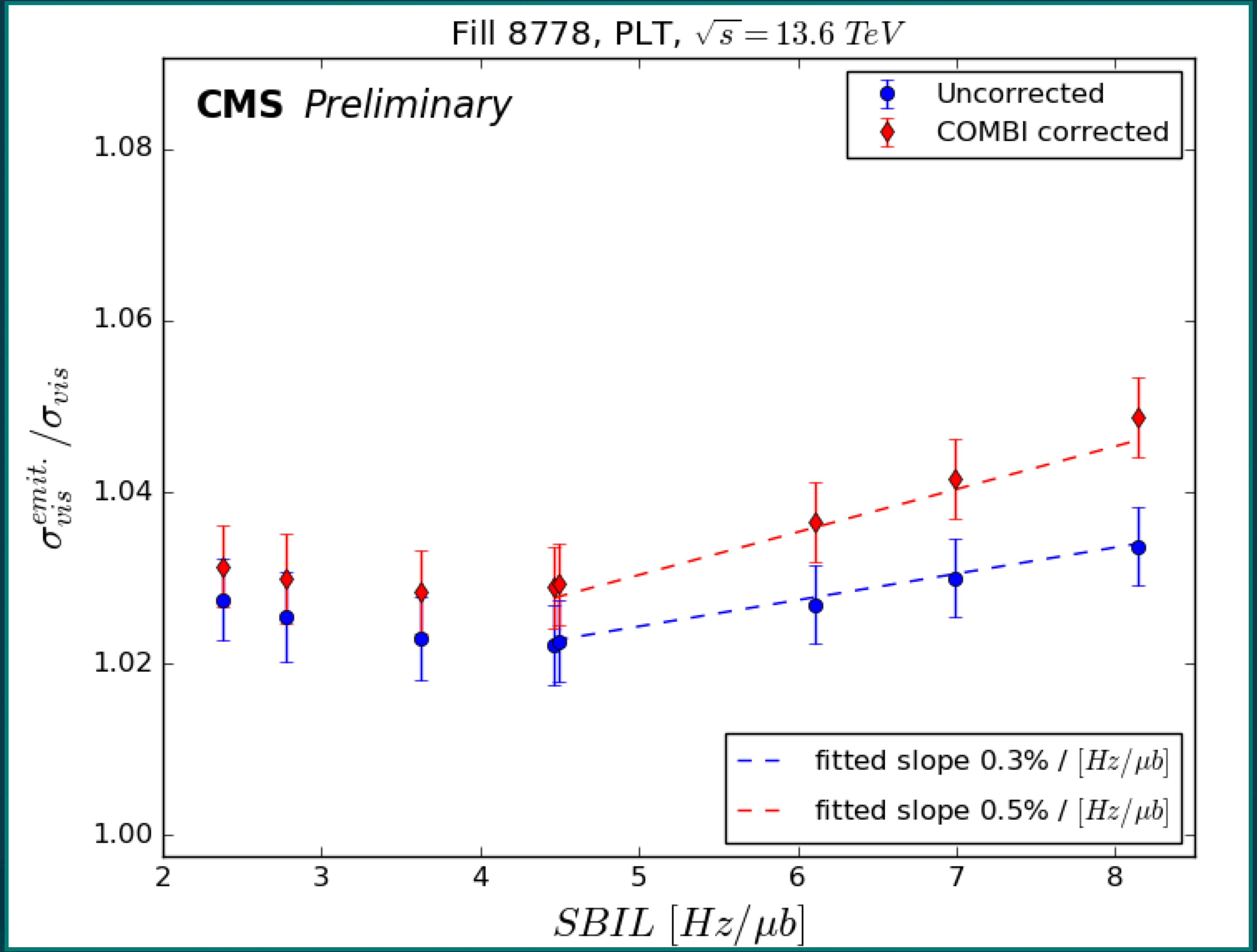

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Independent measurement → further studies needed for precise measurement

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- The phase advance adjustment can be used to increase the peak luminosity in HL-LHC
- The results apply to any current and future hadron colliders (including FCC-hh)

References

[1] vdM

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

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

[4] T. Pieloni, COMBI

[5] BE

[6] W. Herr, CAS proceedings

[7] J. Wanczyk, Phase modulation

[8] G. Trad, BSRT

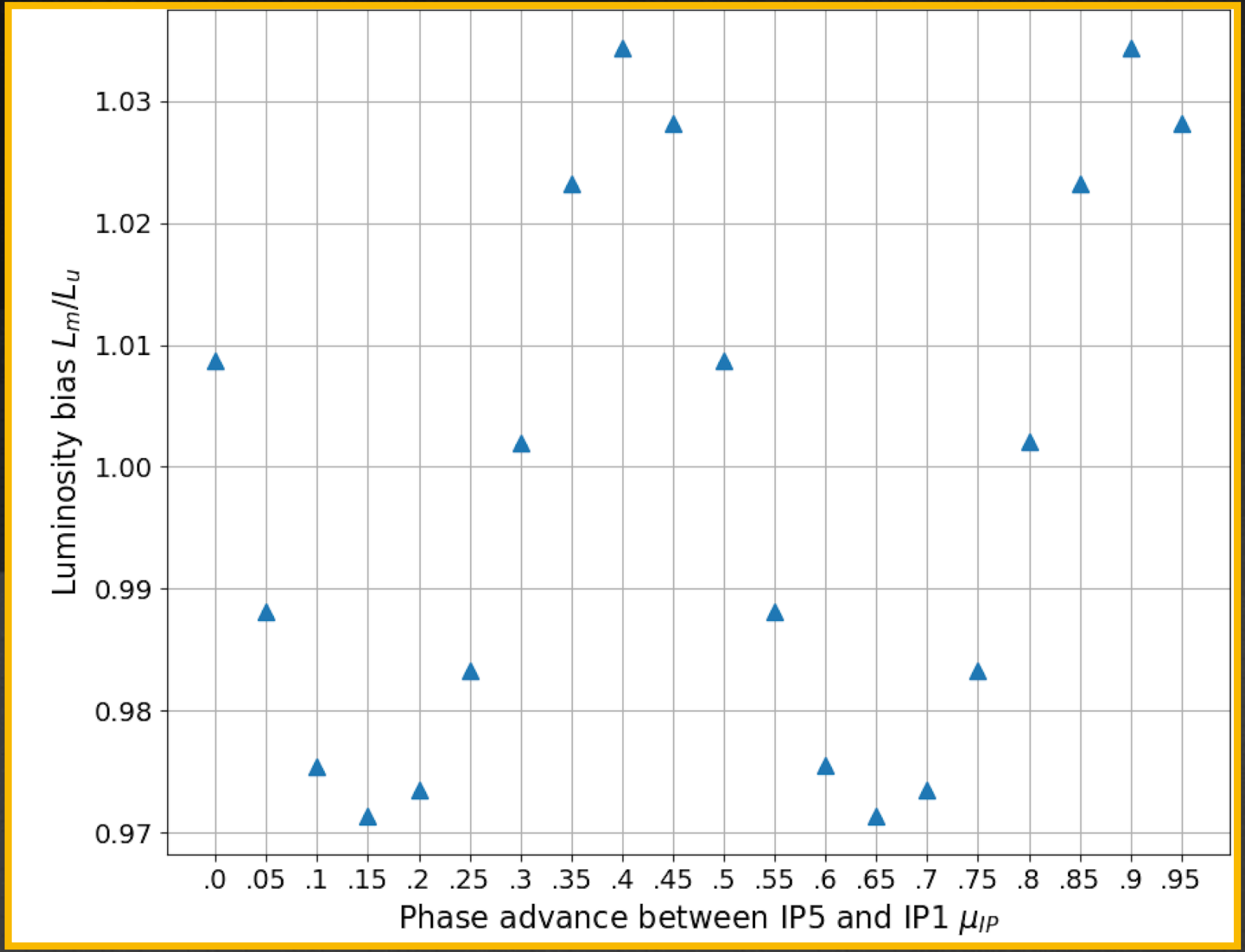
[9] M. Söderén et al., ADT

Acknowledgement

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

Backup - optics measurements for the BB experiment

BB impact on luminosity as a function of the phase advance between the IPs



Phase optimisation validated with optics measurements:

	Beam 1		Beam 2	
	$\Delta\mu_x$ [2π]	$\Delta\mu_y$ [2π]	$\Delta\mu_x$ [2π]	$\Delta\mu_y$ [2π]
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

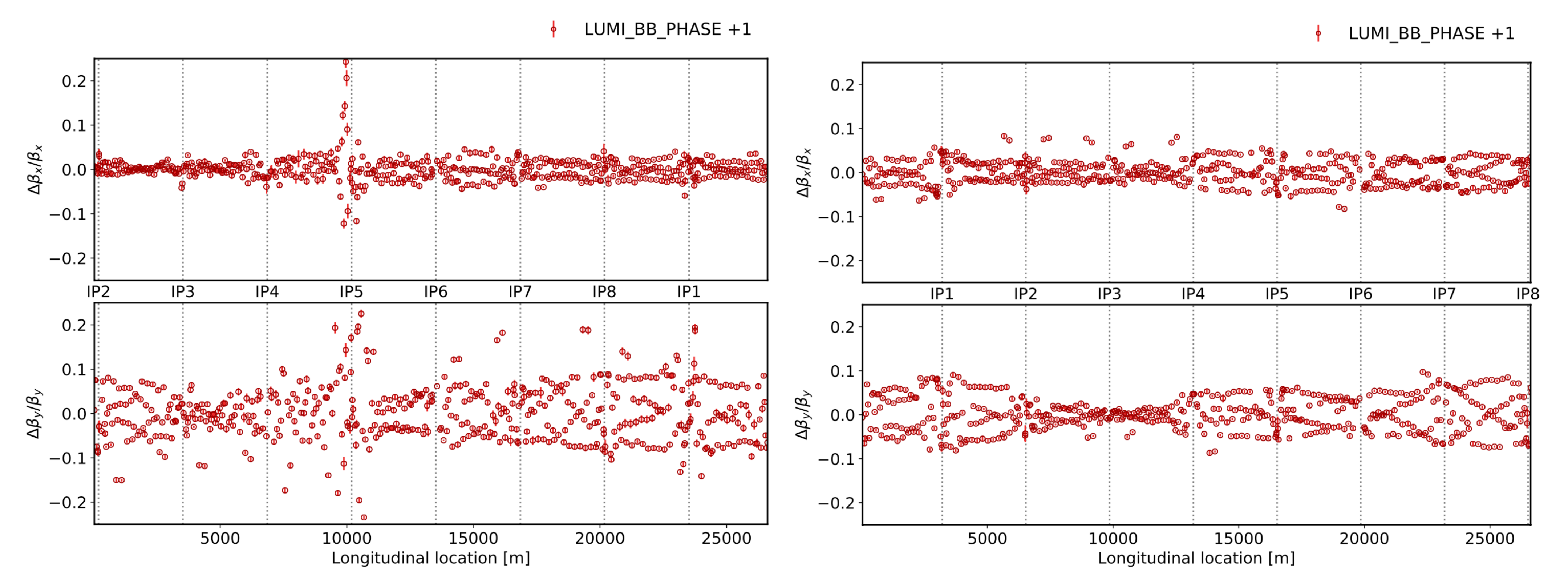


Figure 2: Measured beta difference between the lattice with the maximizing (+1) phase knob and nominal lattice along the LHC ring, for Beam 1 (left) and Beam 2 (right).

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

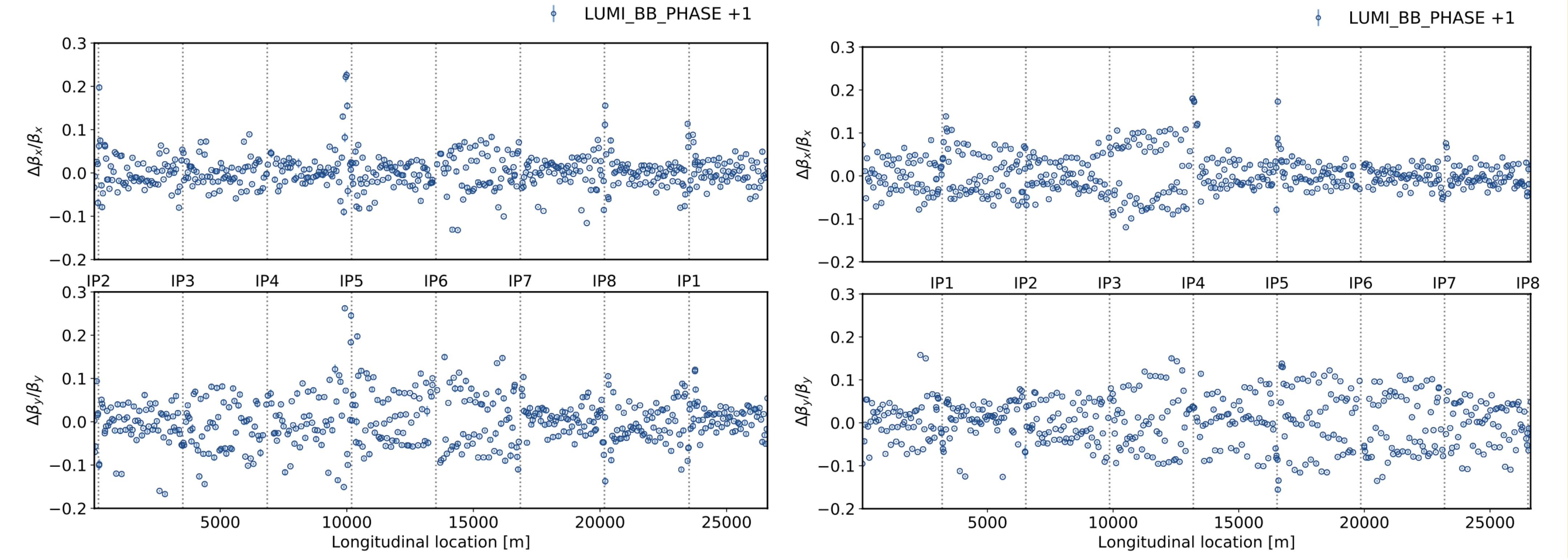
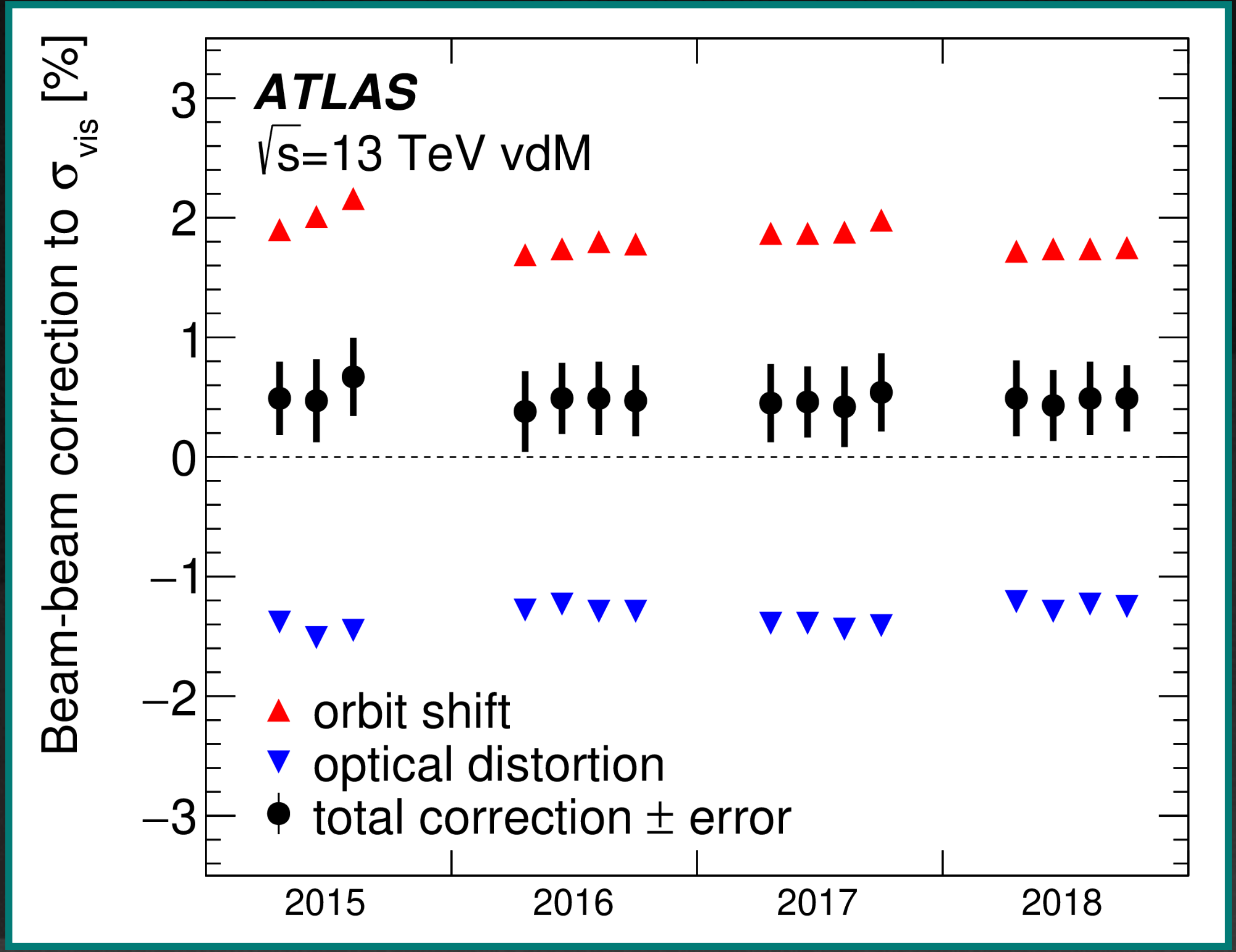
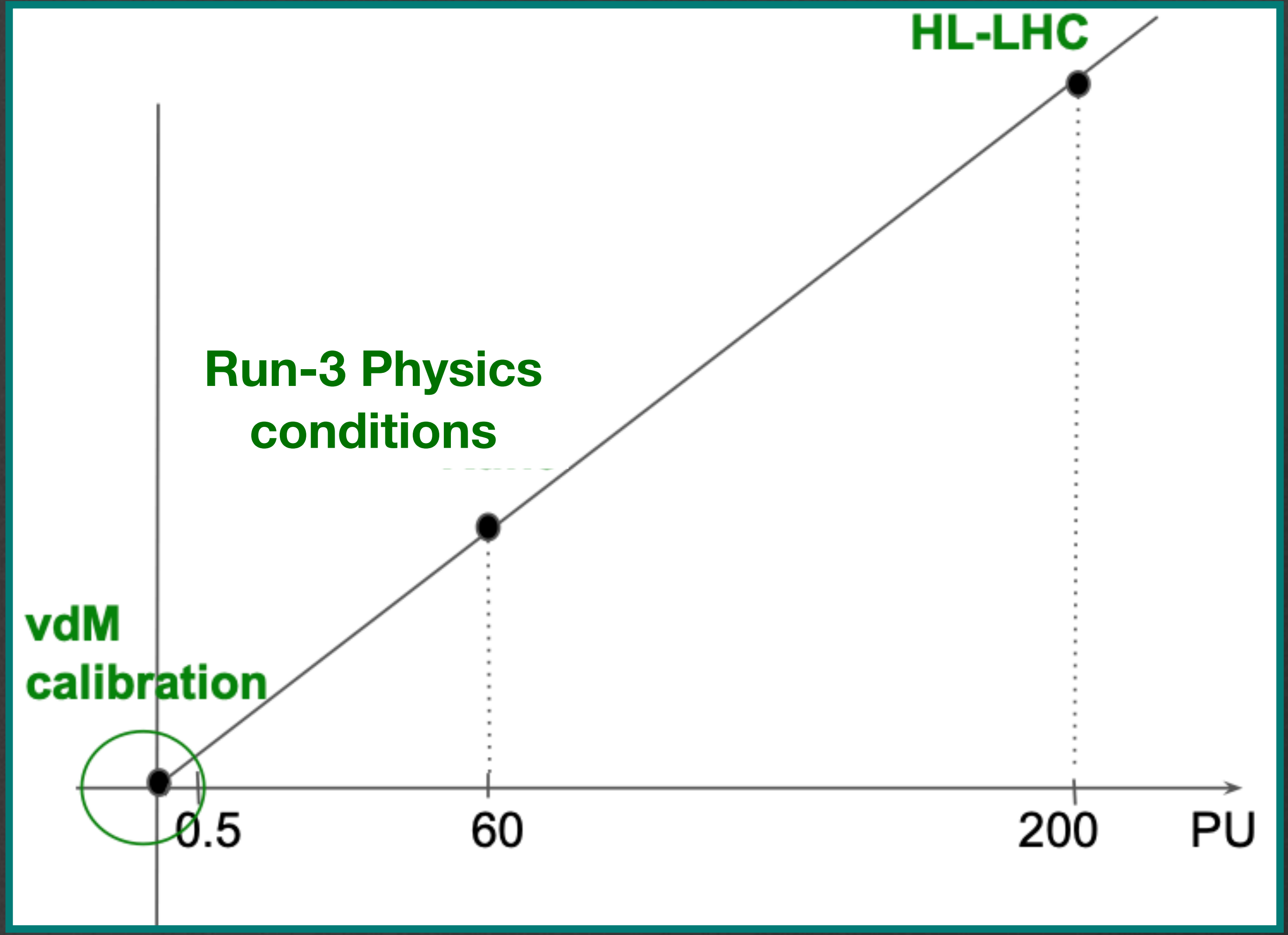


Figure 5: Measured beta function differences along the LHC ring with respect to the MADX model with included maximizing (+1) phase knob, for Beam 1 (left) and Beam 2 (right).

Example of applications by LHC experiments



ATLAS summary of BB corrections to Run-2 vdM calibration scans at 13 TeV [1]

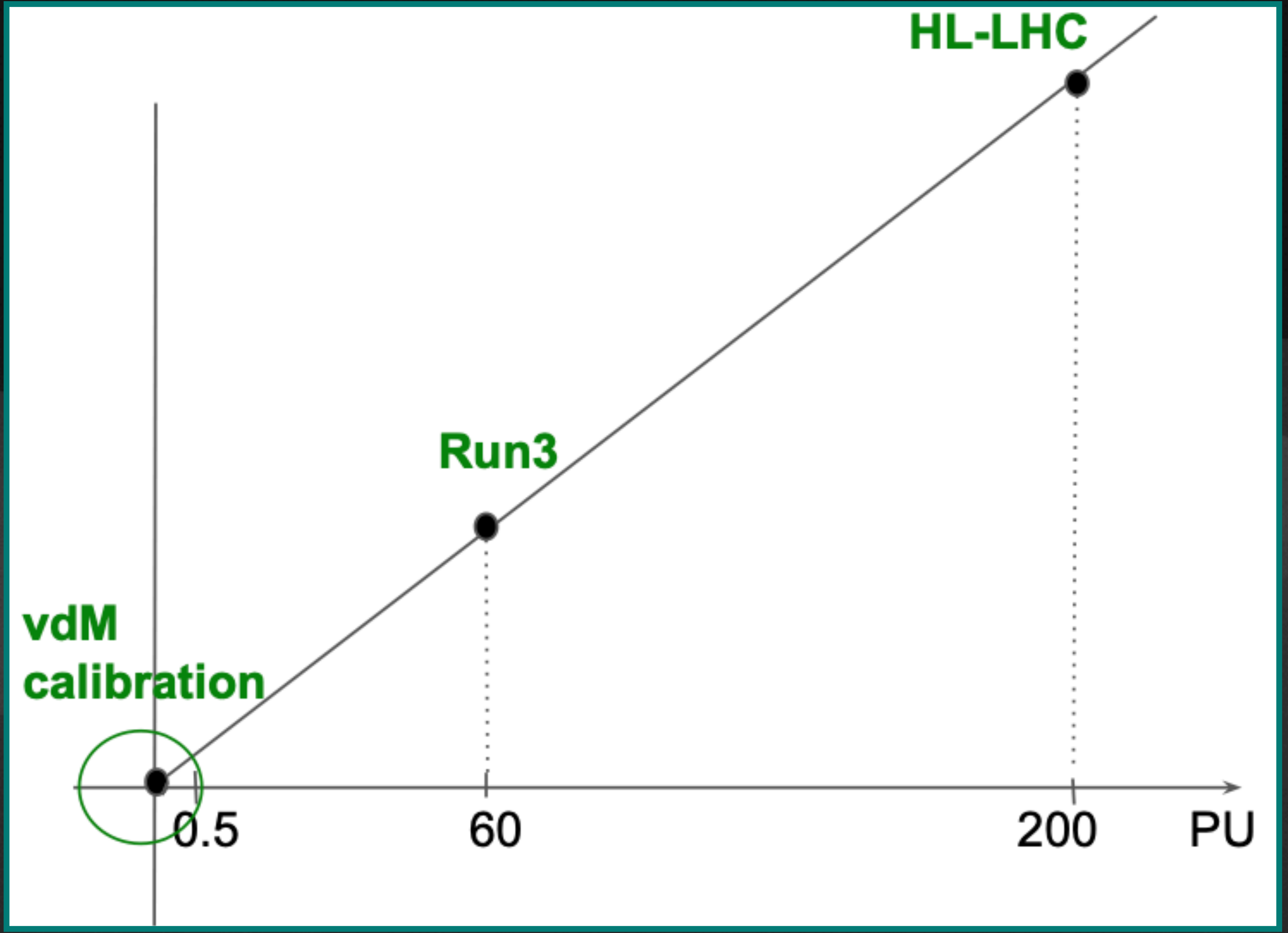


CMS study on impact of the BB effects on the observed luminometer linearity

- vdM conditions
  - Significant corrections in opposite directions result in small total effect
- Extrapolation to physics conditions
  - Luminosity measurement can be biased by an instrumental non-linearity of the detector response over a wide pile-up (PU) range
  - Mostly relying on cross-detector comparisons, with an assumption of an ideal luminometer
    - Typical uncertainty ~0.5% for both CMS [8] and ATLAS (with O(10%) correction) [1]
  - Expected to be one of the dominant issues at HL-LHC

Extrapolation to nominal conditions

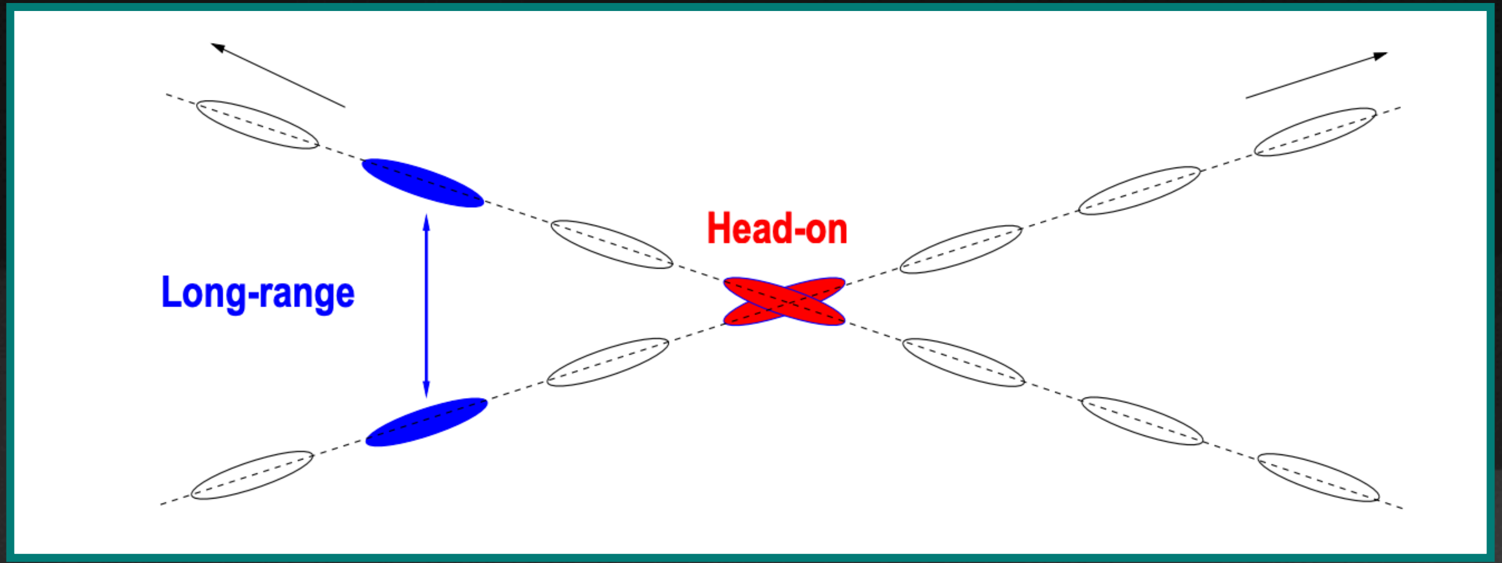
- at nominal conditions the luminosity measurement can be biased with a non-linearity of a detector response over a wide pile-up range
- sources of inefficiencies, e.g.:
  - zero-starvation/saturation
  - accidentals
  - activation
  - electronics inefficiencies
- mostly relying on cross-detector comparisons, with an assumption of an ideal luminometer
- various detectors can suffer from different effects → different sign of the slope



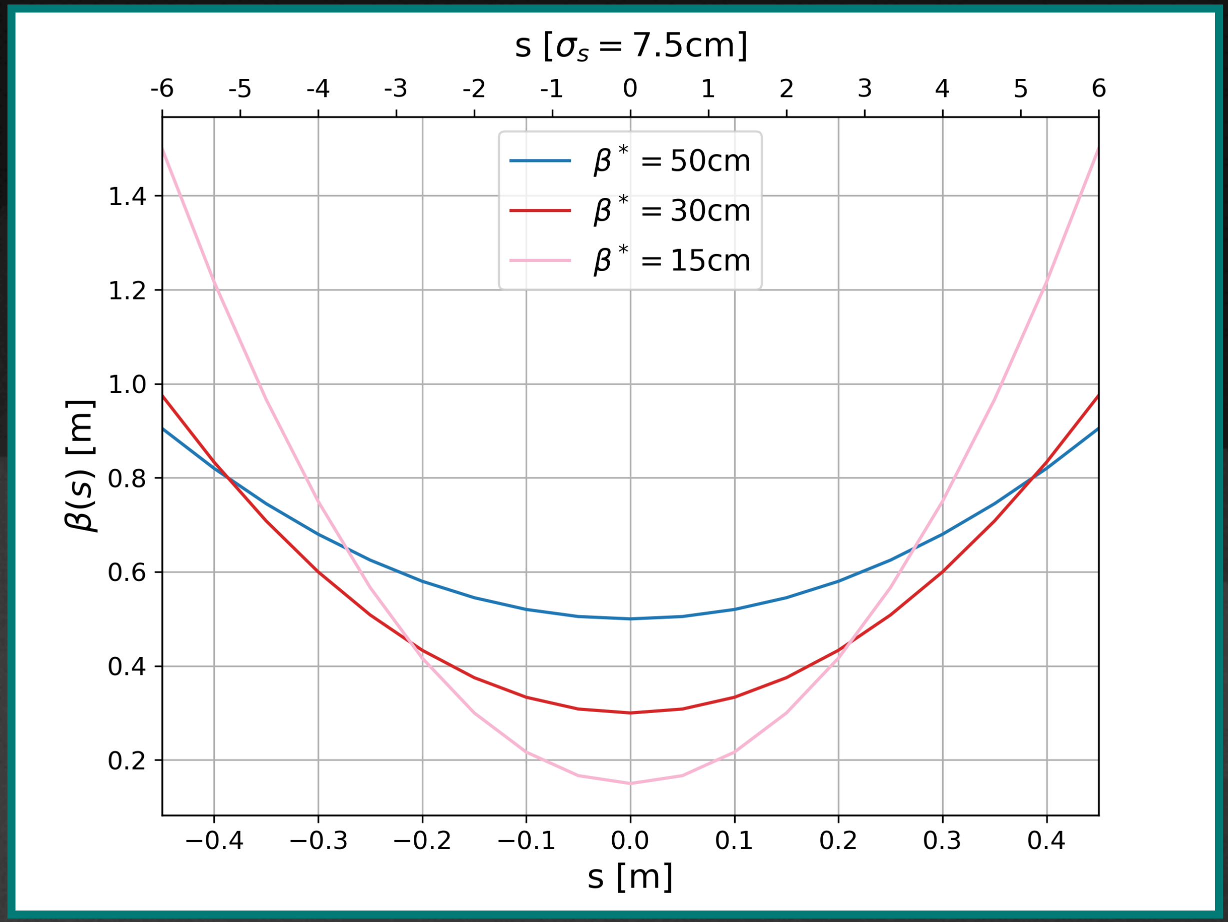
- excellent CMS performance - multiple systems on the level of 0.1%/SBIL

Simulation challenges in physics conditions

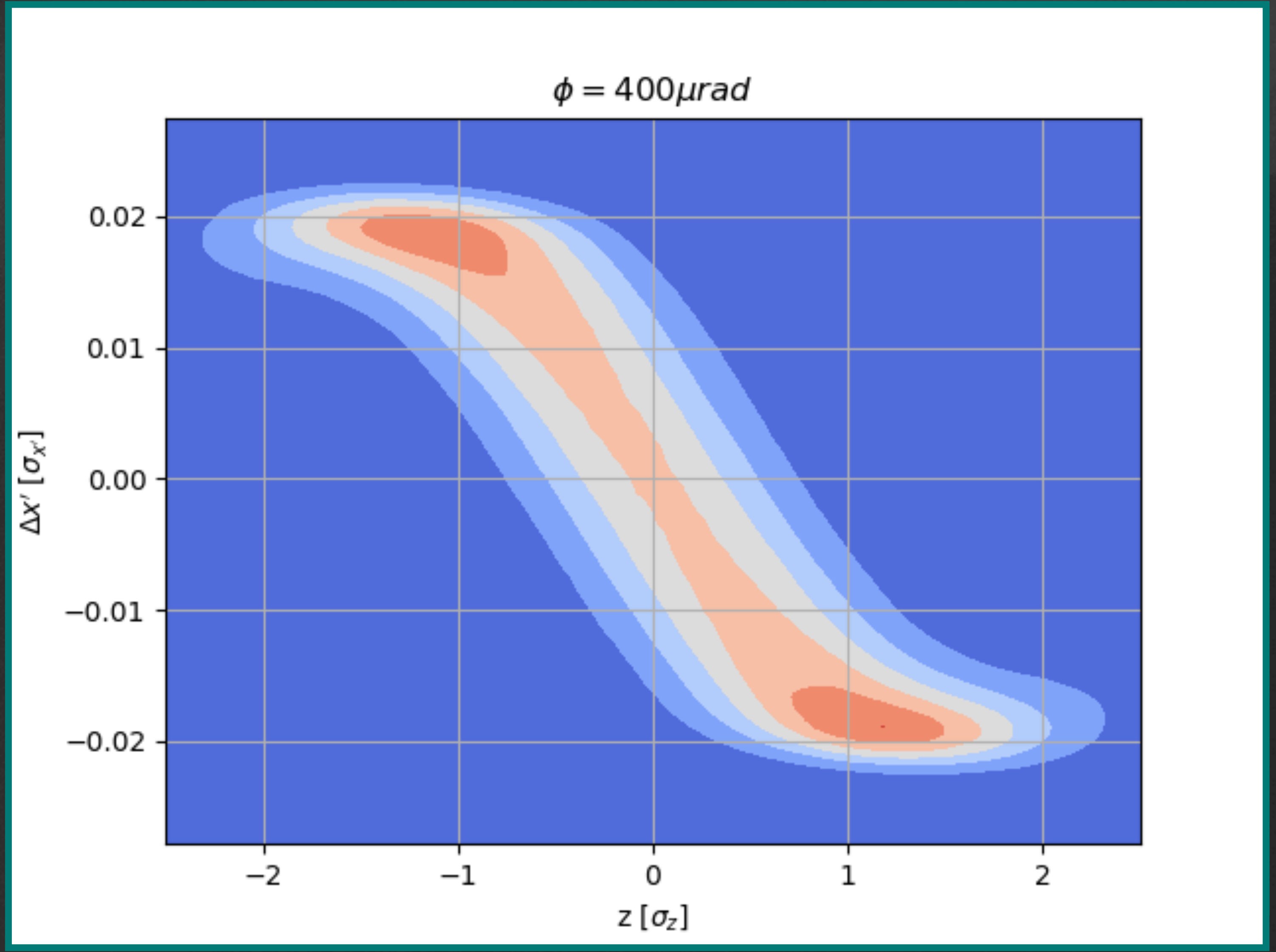
- not only measurement but also simulation challenging
- changes with respect to the vdM regime:
  - pile-up x 100
  - higher BB parameter x 1.5-2
  - non-zero crossing-angle
  - trains - long-range interactions
  - hour-glass effect
- using 6D BB strong-strong soft Gaussian [9]
- developed sliced luminosity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



multiple long-range interactions around the IP



small β^* → non-constant transverse beam widths



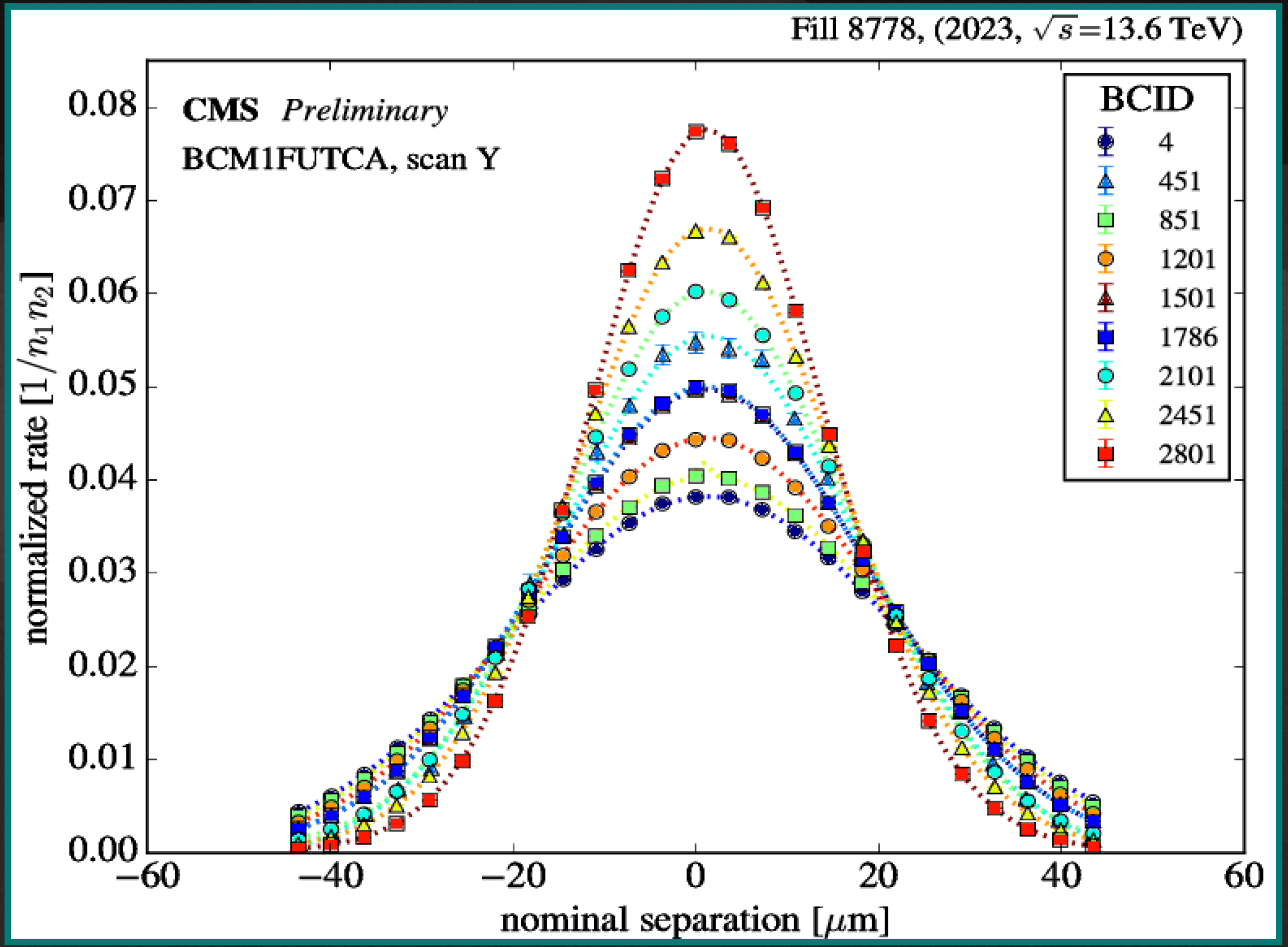
longitudinal description of the kick with the crossing-angle

Dedicated BB corrections for linearity measurement

- COMBI upgrades are useful to produce dedicated corrections - minimising the associated extra systematic from per bunch differences

- used for a specific measurement - special conditions without trains - avoiding the systematic from LR BB:
  - wide range of per bunch emittance gives wide PU/SBIL* range
  - equivalent of the calibration constant $\sigma_{vis}^{emit.}$ from emittance scans with reference to σ_{vis} measured in vdM calibration [10]

emittance scan is a transverse beam separation scan in physics conditions, primarily designed to measure emittance



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

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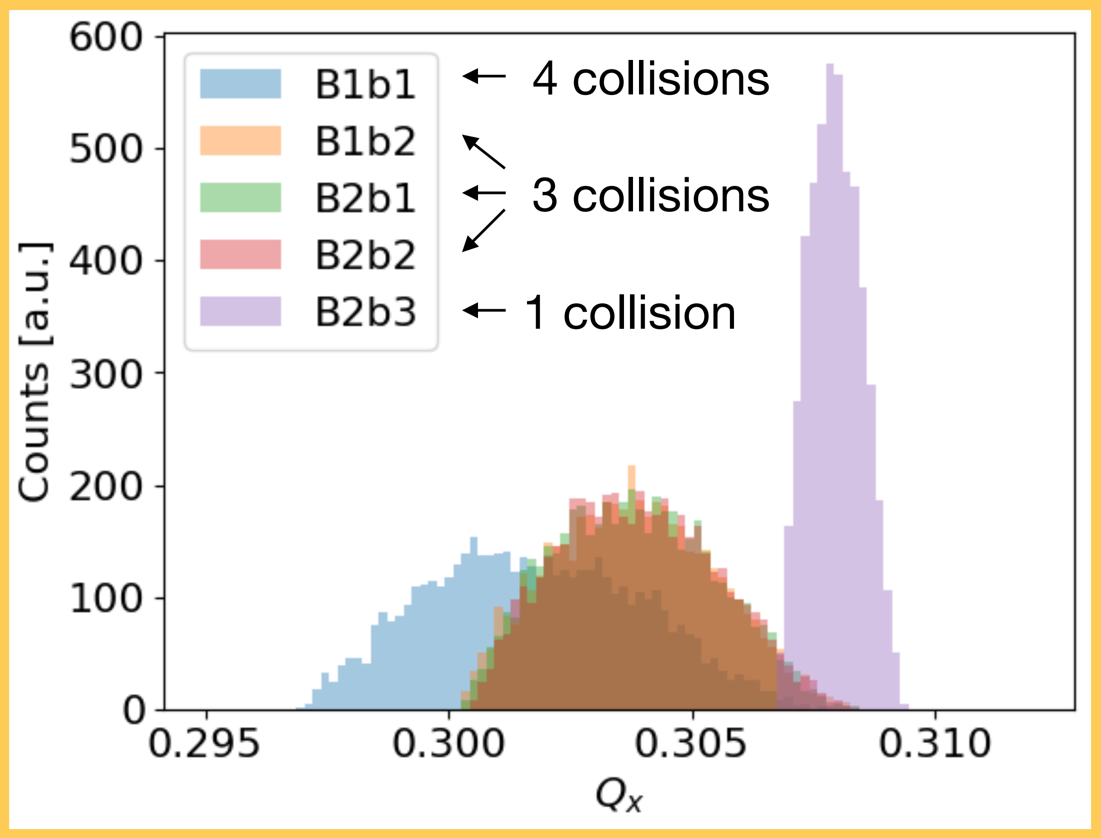
Backup slides - motion

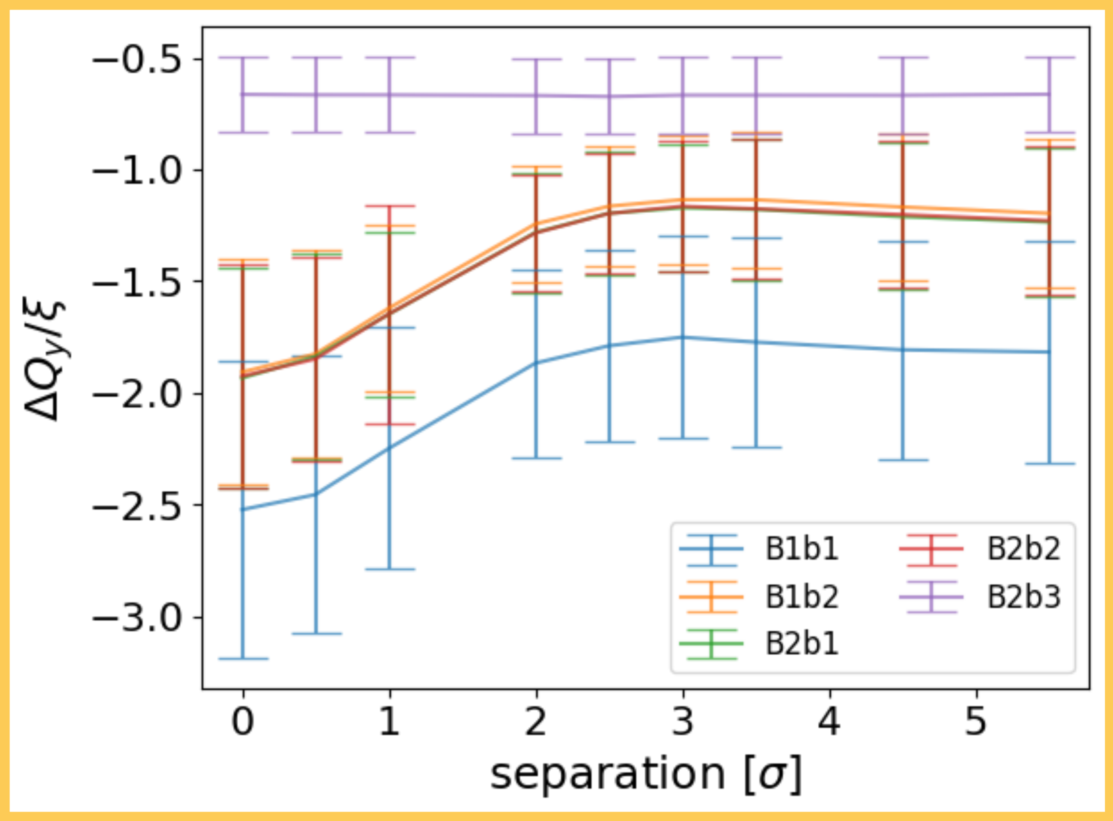
SINGLE PARTICLE MOTION

- Incoherent tune distributions based on the amplitude of single particle in the bunch
- distinctive separation between the bunch groups depending on the number of collisions they undergo
- maximum tune spread proportional to the number of collisions and the beam-beam parameter
- tune shift gets squeezed along the separation scan

Head-on collision



Vertical scan



WHOLE BUNCH MOTION

- spectra based on the bunch centroid position, turn after turn in the machine ring (coherent modes damped)
- spectra have main spread similar to the single particle distributions but also second-order contribution from the collision partner

Vertical scan