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APS AND SPS MEETING 2021

PRECISION LUMINOSITY MEASUREMENT AT THE LHC

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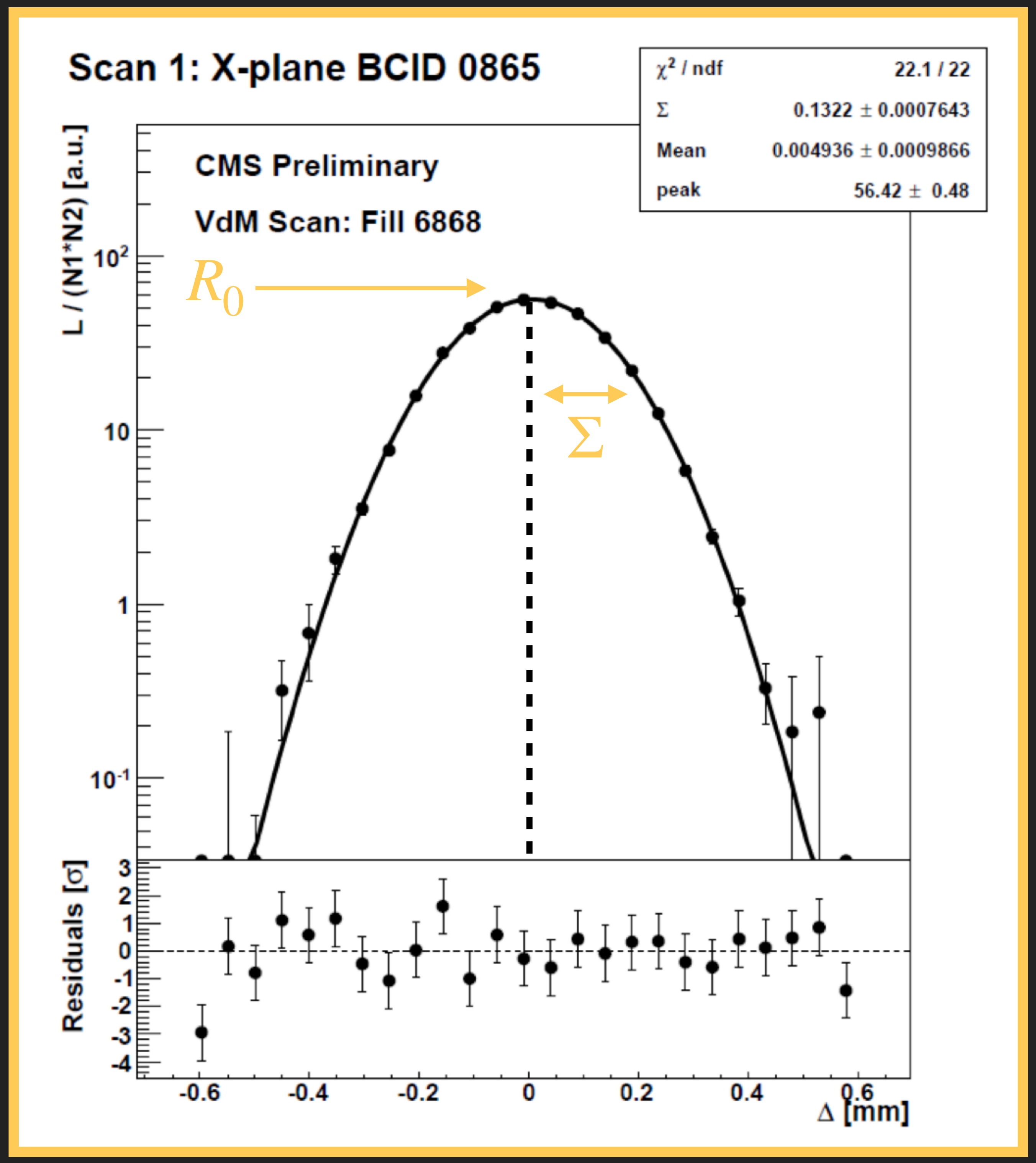
PHYSICS MOTIVATION

- Measurements of production cross sections provide crucial tests of theoretical predictions. Both the measurements and the predictions require the best possible precision in order to determine fundamental parameters of the SM and to constrain new physics phenomena.
- In Run 2, the CMS luminosity uncertainty in proton-proton collisions was $2.3-2.5\,\%$ per year in normal physics data taking using the preliminary calibrations. For the pp case at 13 TeV, the luminosity uncertainty has improved to $1.2-1.6\,\%$ per year with the final high-precision 2015–16 measurements.
- One of the key improvements for the precision calibration were studies for corrections and uncertainties related to the Beam-Beam interaction - the electromagnetic interaction of the two beams while crossing each other.
- Essential to provide the precision measurement in the HL-LHC era.

LUMINOSITY CALIBRATION WITH VAN DER MEER METHOD*



source: CMS-PAS-LUM-18-002

- performed every year in a special low-luminosity fill to obtain the detector-specific visible cross-section σ_{vis}.
- beams are moved across each other in the two collision planes by discrete separation steps,
- the measured visible rate follows Gaussian distribution, under the assumption of uncorrelated x and y planes, the two scans are fitted separately with width $\Sigma_x = \sqrt{\sigma_{x1}^2 + \sigma_{x2}^2}$,
- the combined information from the vertical and horizontal scans supplemented with the information about the revolution frequency and bunch intensities allows to infer the instantaneous luminosity and calculate the visible cross-section:

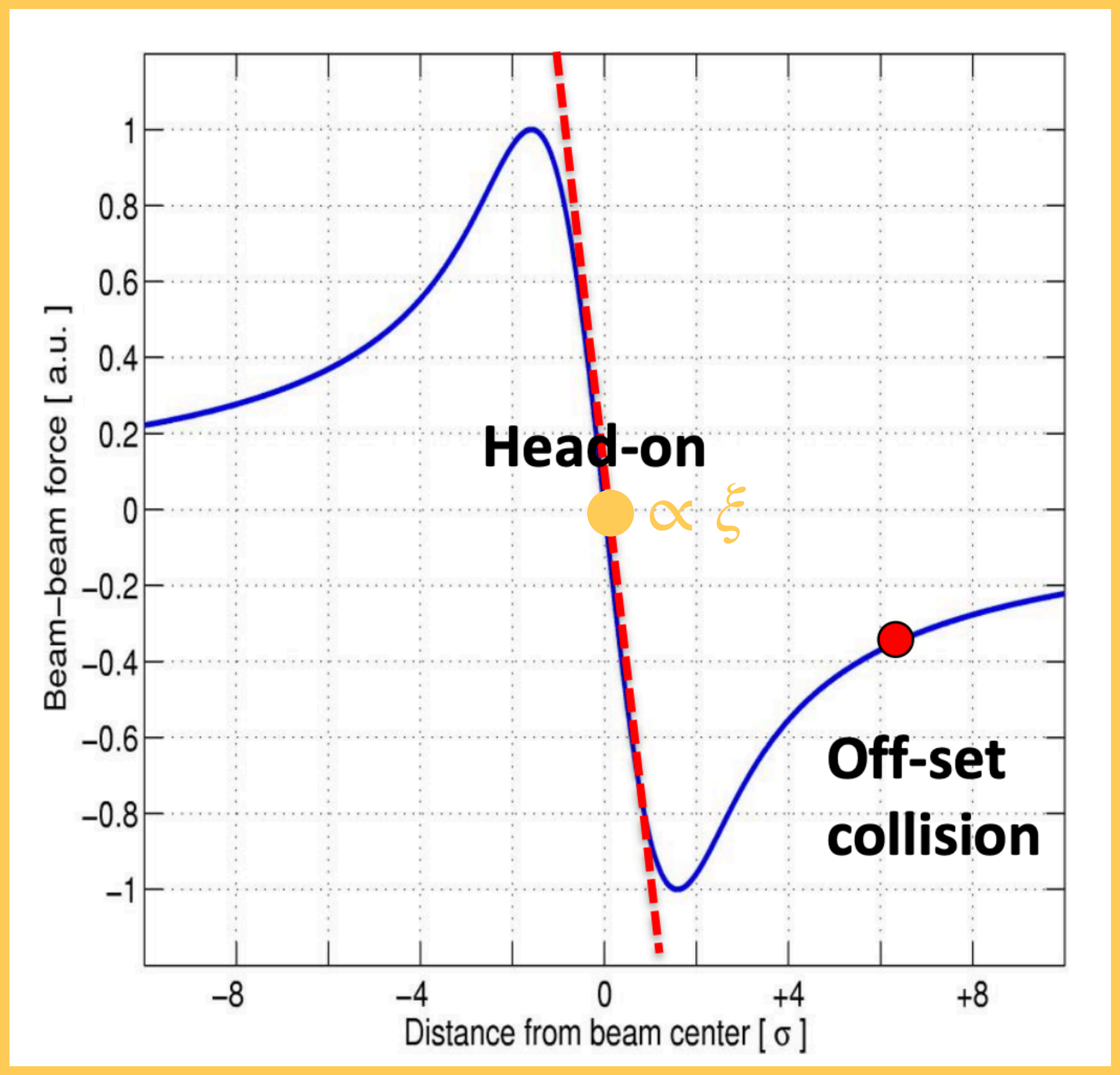
$$\frac{dR}{dt} = \mathscr{L}_{inst} \times \sigma_R \rightarrow \sigma_{vis} = \frac{2\pi\Sigma_x\Sigma_y}{N_1N_2f}R_0$$

- analysis to include corrections and uncertainties from systematic effects such as the beam-beam, orbit drift, etc., as well as the detector specific OOT effects and 'integration' uncertainties: response linearity and long-term stability

*ref: https://cds.cern.ch/record/296752

BEAM-BEAM EFFECTS

- Beams are collection of charges (protons) which interact electro-magnetically: $F \propto -\frac{N}{\gamma} \cdot \frac{x}{r^2}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)$
- Interaction distorts the motion of a whole bunch (coherent) as well as the single particle motion (incoherent)
- the strength of the force is described by the beam-beam parameter: $\xi = \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}$, $\xi = 3 \times 10^{-3}$ for VdM scans, higher for LHC nominal operation and HL-LHC
- Several effects are expected: orbit deflections, beam size effects (dynamic beta), change of betatron tunes (tune shifts and spreads), particle losses, emittance blow up, etc.



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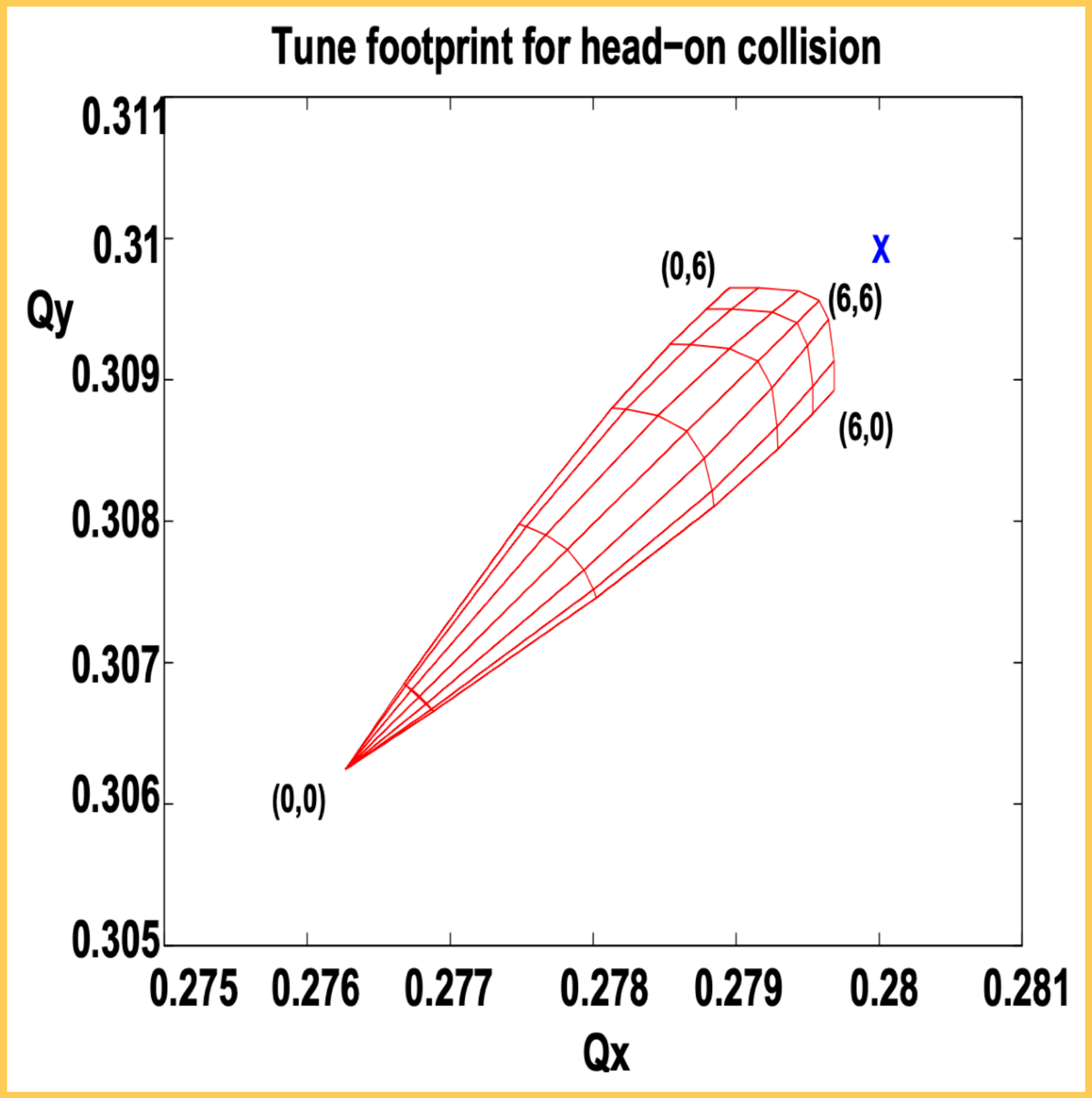
- To study the impact of beam-beam effects on the luminosity we have extended the COherent Multibunch Beam-beam Interaction (COMBI) code to calculate the instantaneous luminosity in the presence of BB.

BEAM-BEAM EFFECTS

- Betatron tunes define oscillation frequency in transverse planes, LHC has a nominal working point of $(Q_x^0, Q_y^0) = (64.31, 59.32)$ but Beam-Beam interaction changes it,
- As a result there is a tune spread in the beam (footprint), tunes shifted in both transverse planes, footprint gets very asymmetric in presence of long-range interactions,
- Multiple BB interactions at all experiments per turn and different bunches involved
- Tune spectra show coherent modes - coupled bunches
- Beam-beam parameter does not describe the non-linear part of the force



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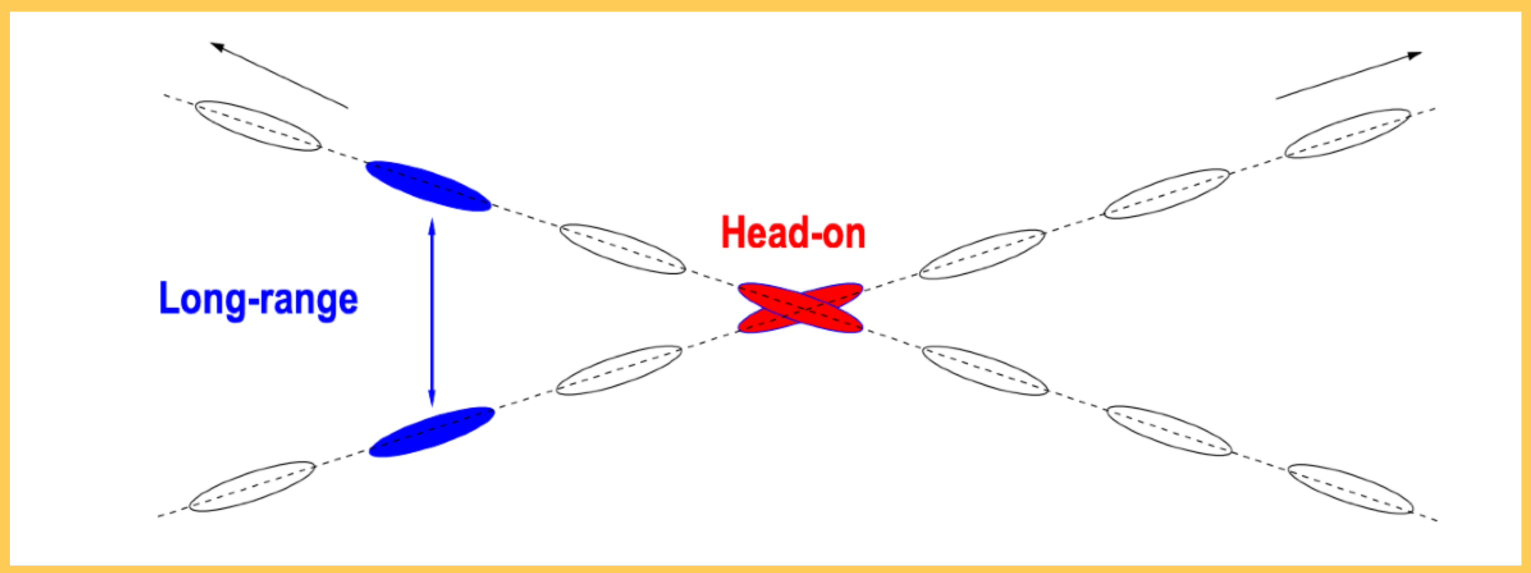

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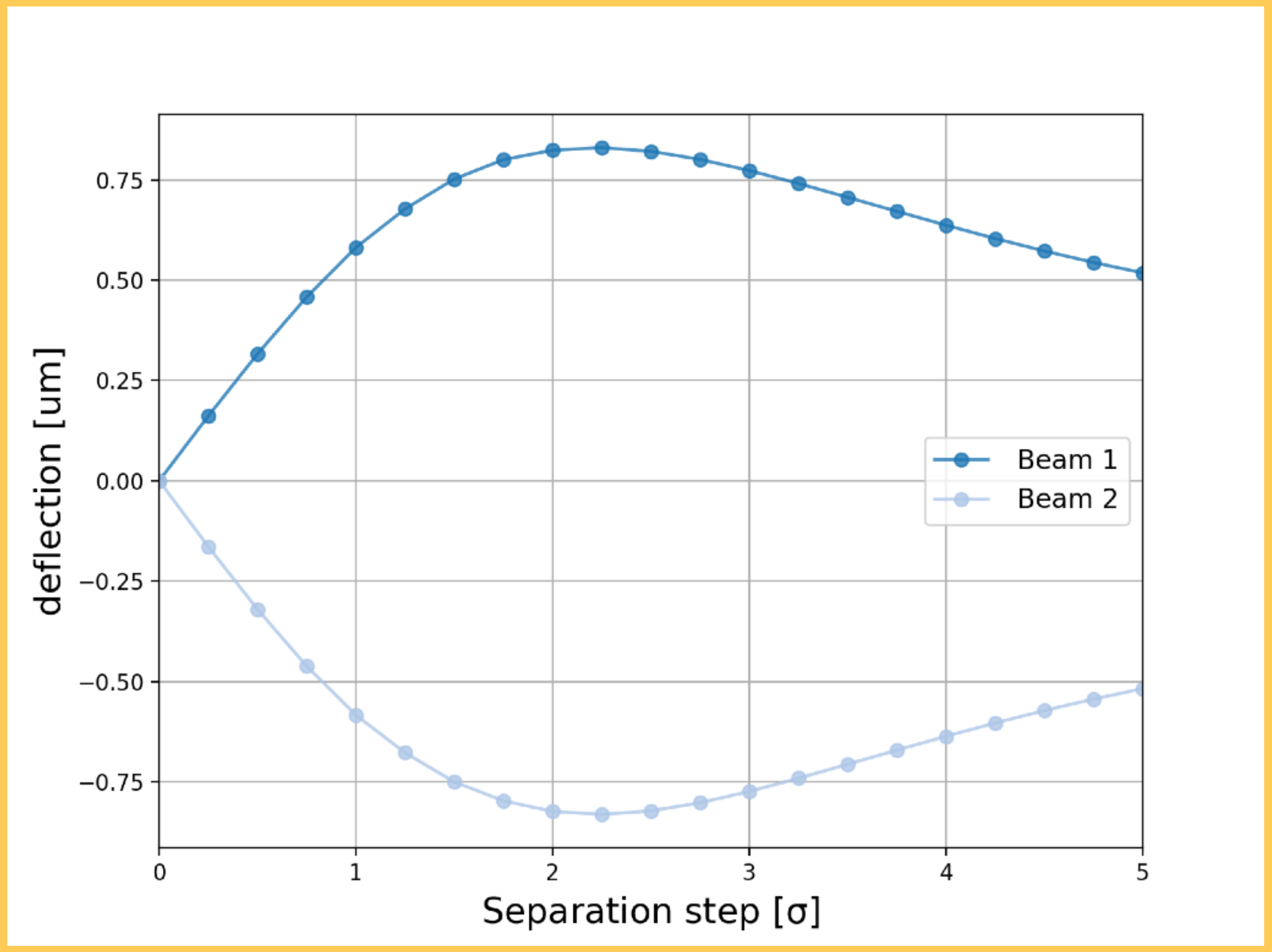
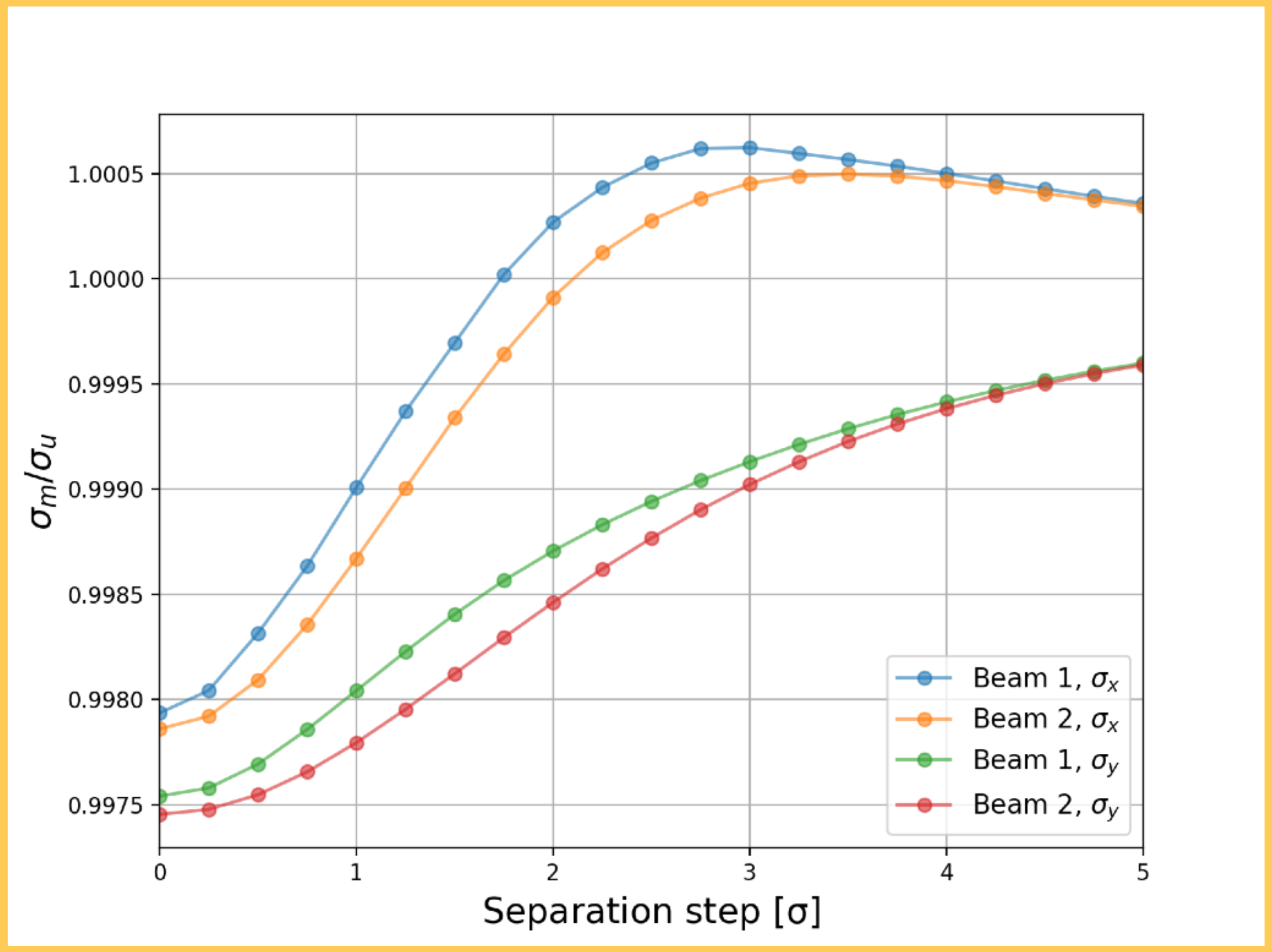
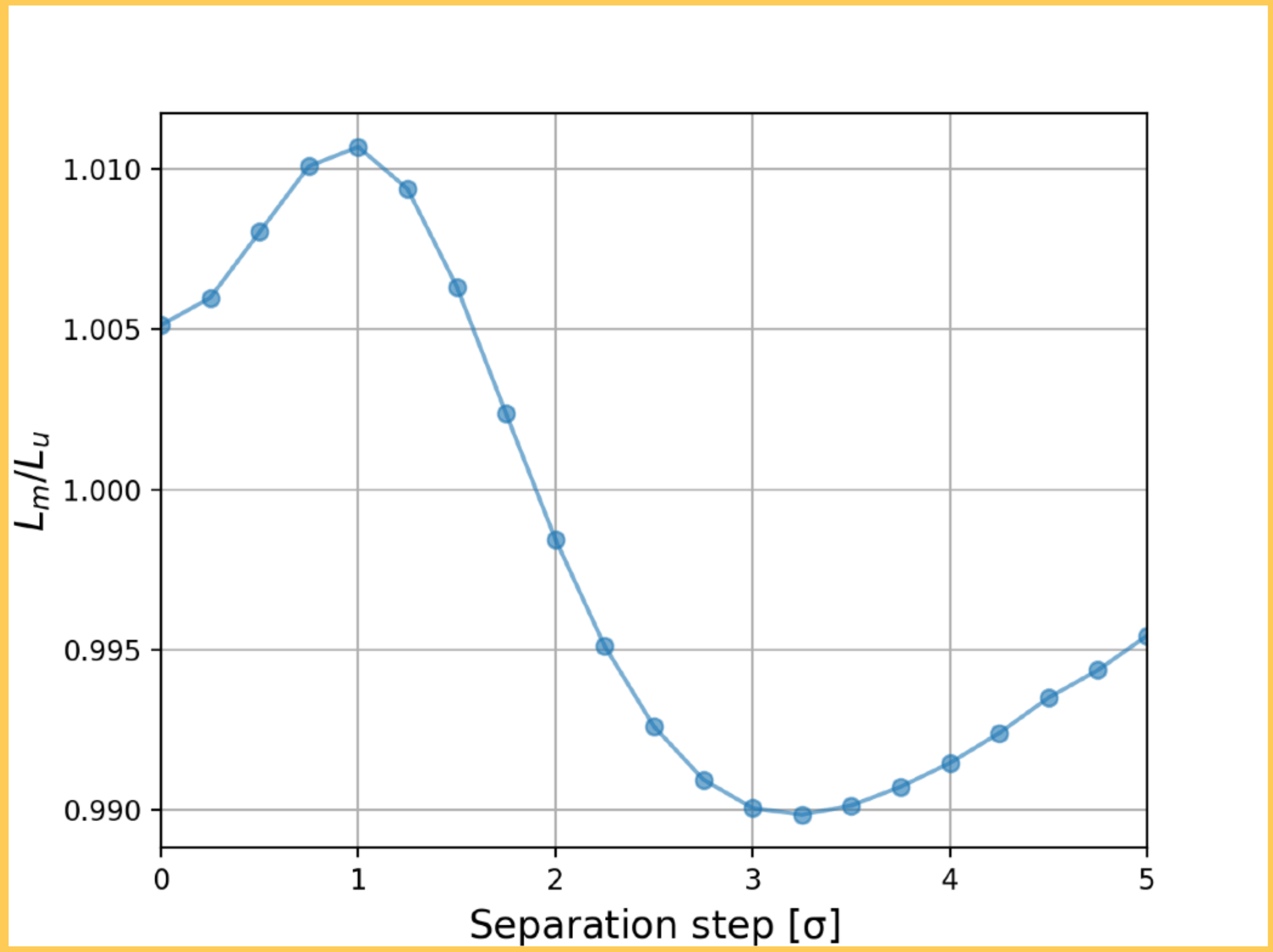
SIMULATION RESULTS

BEAM-BEAM INTERACTION CORRECTIONS IN LUMINOSITY MEASUREMENT

- currently luminosity measurement corrected for two separate effects computed in a semi-analitical way:
  - orbit offset caused by electromagnetic deflection
  - beam optics change - dynamic beta
- resulting full beam-beam luminosity bias





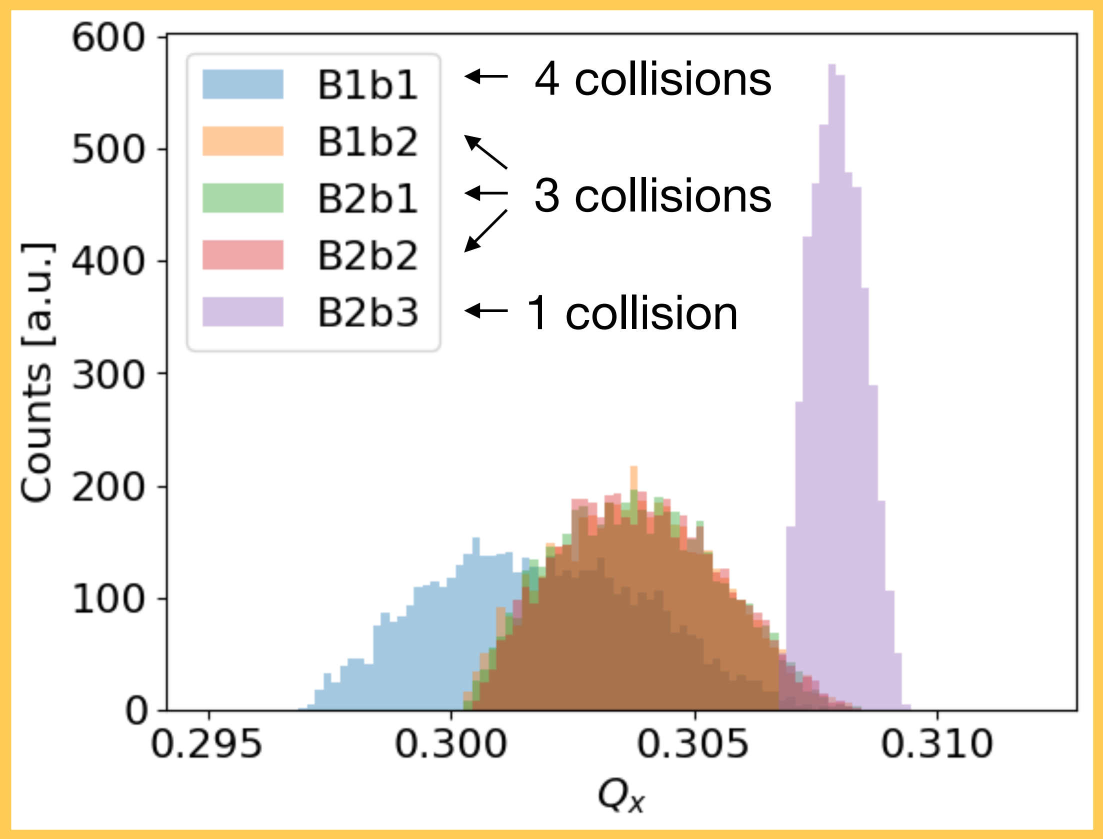


- need to include other uncertainty sources such the machine tune, crossing-angle, magnet lattice non-linearities, beams imbalance and ellipticity, non-factorization and non-Gaussian distributions

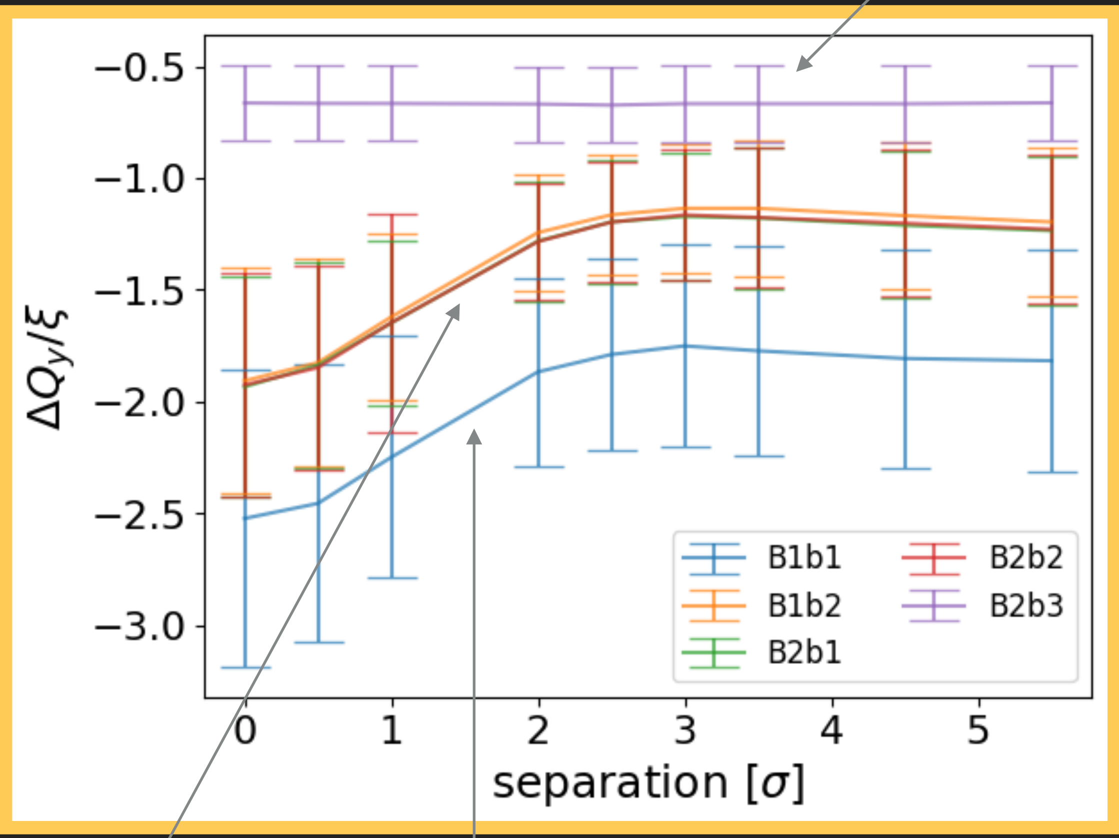
SINGLE PARTICLE MOTION

- 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



Bunch not colliding at scanning IP

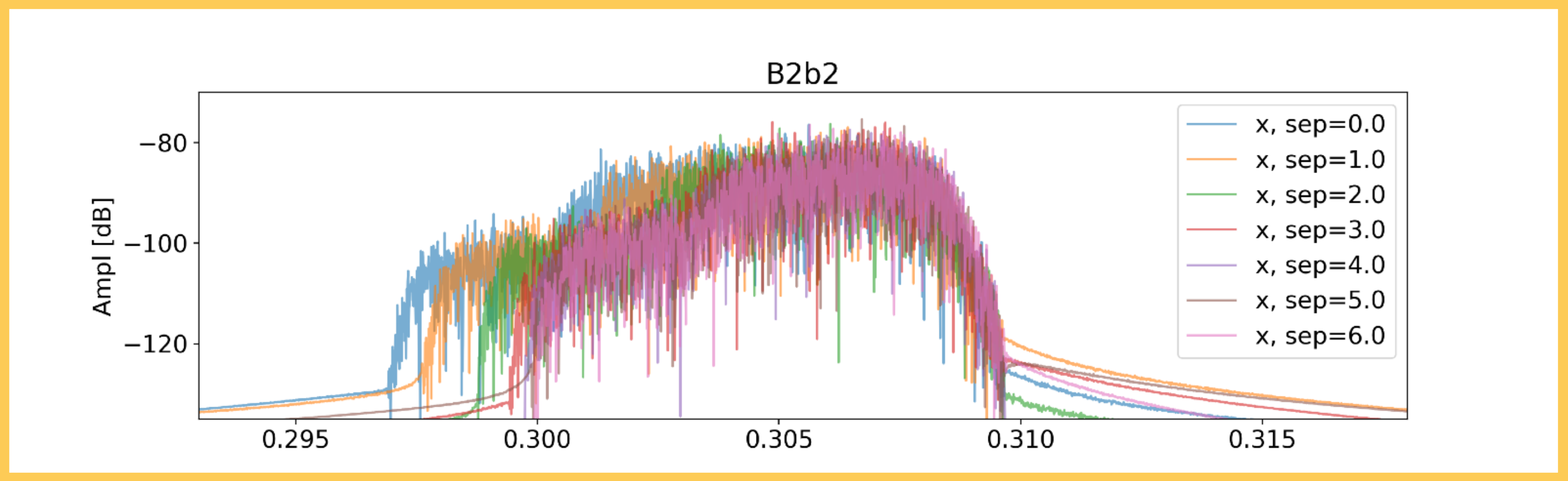
Bunches with 3 collisions very similar, both with IP2 and IP8

Bunch colliding at all IPs

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

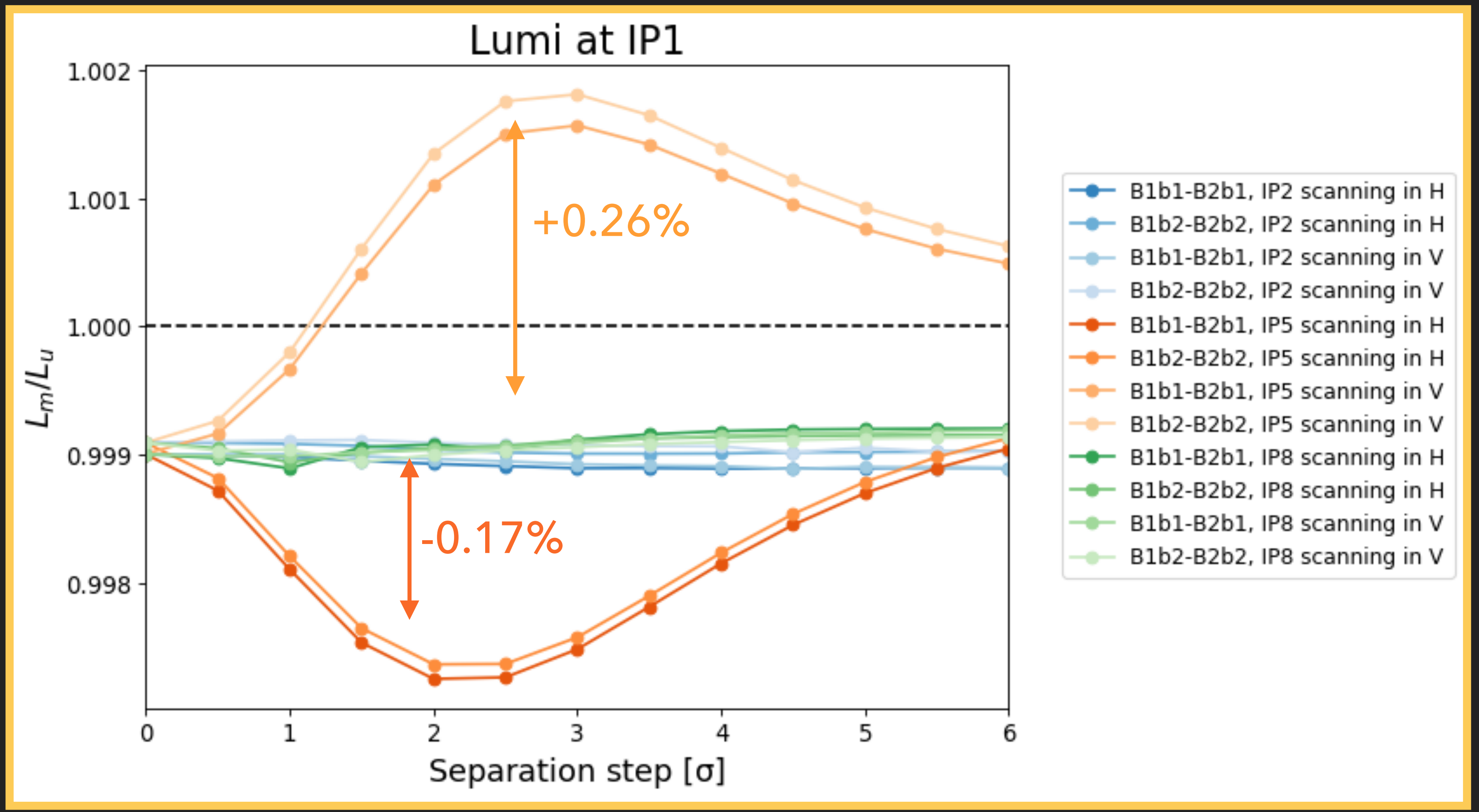
Vertical scan



betatron frequencies change caused by the multiple collisions has to be taken into account when evaluating beam-beam corrections

COMBI INSIGHT FOR ALL EXPERIMENTS

- New COMBI version with parallel processes per each bunch code developed and optimised to be able to simulate full machine description in preparation for setups with multiple bunches colliding all 4 LHC collision points
- Van der Meer scans possible at each Interaction Point (IP) independently.
- 2 bunch pairs with different collision patterns - colliding at ATLAS (IP1) and CMS (IP5): - slight differences between the families
- effects very similar for Interaction Points at the opposite sides of the LHC, Vertical scan has bigger impact
- bias from other IPs can be corrected 0-separation, at other experiments dependence more complex



one colour per IP, including Horizontal (darker shades) and Vertical (lighter shades) scans

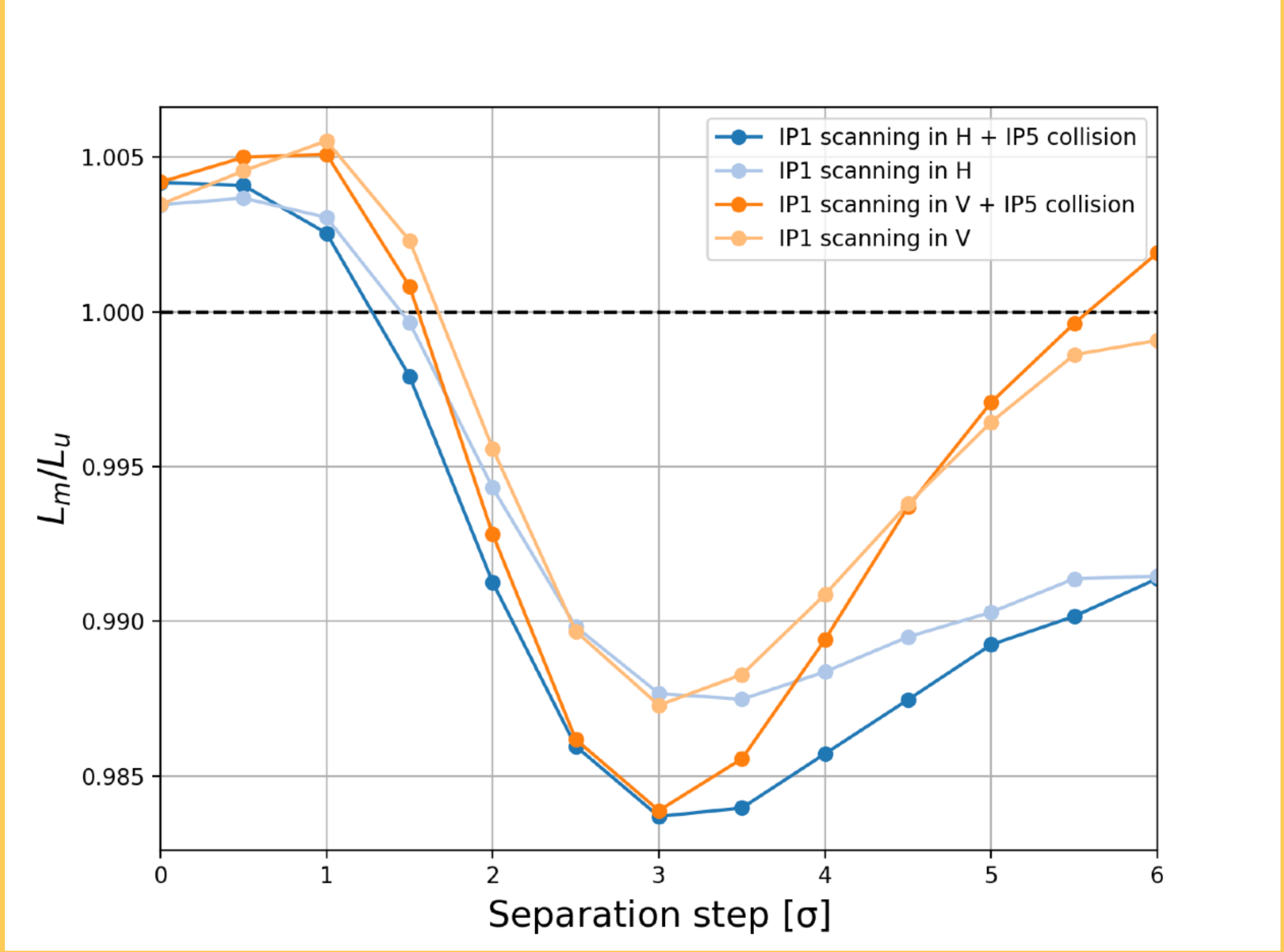
B1b1-B2b1: 4+3 with LHCb (IP8)

B1b2-B2b2: 3 with LHCb + 3 with ALICE (IP2)

Total bias up to $0.6\,\%$ was found for other experiments at the VdM conditions ($\xi = 0.0032$)

IMPACT OF WITNESS COLLISION

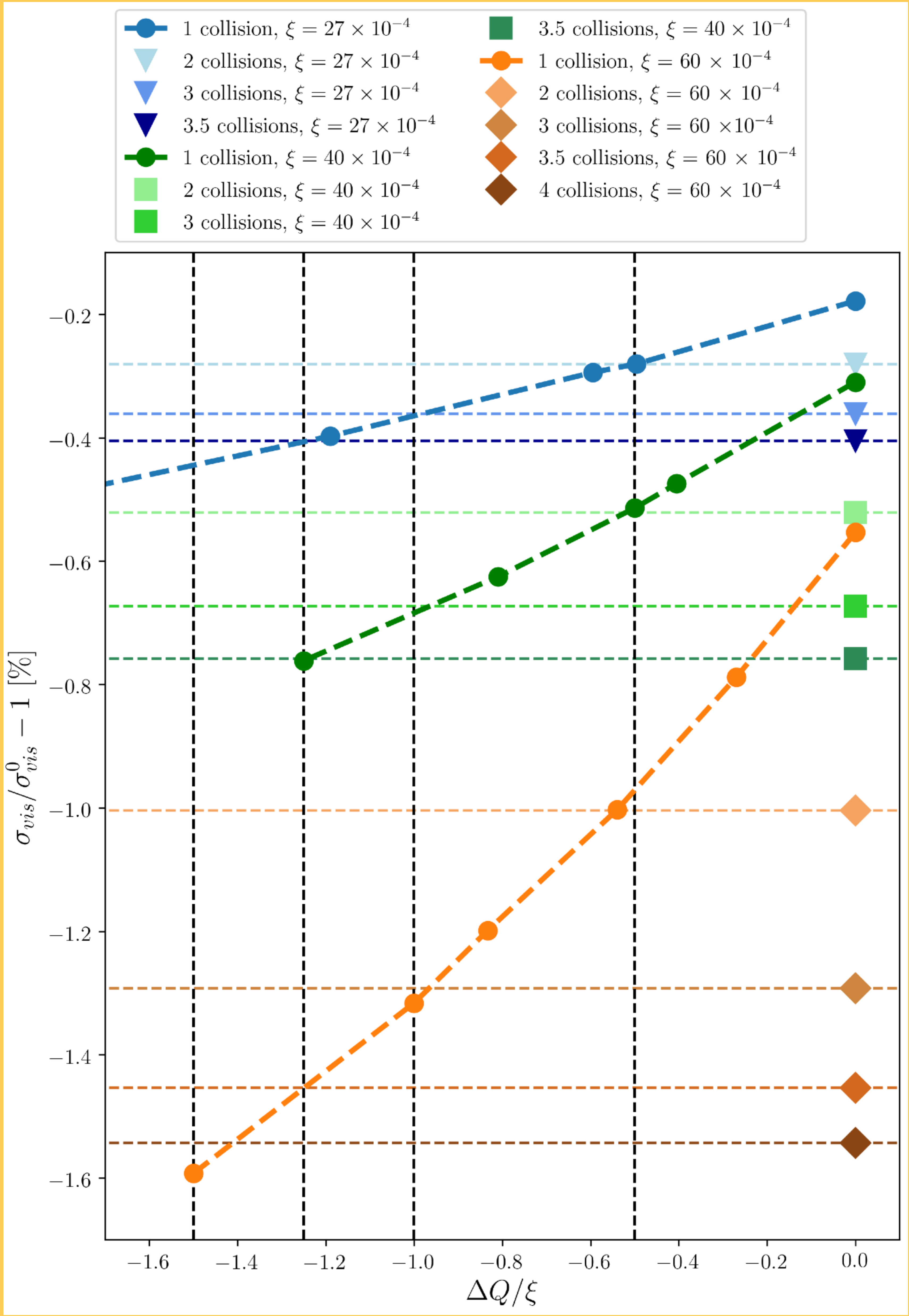
- Comparison of the simplified picture when there is just scan, and the same scan with additional collision at another IP
- Additional beam-beam interaction at the witness collision adds $0.21\ \%$ to the induced effect on the visible cross section during a VdM scan
- How to include that in the corrections in a universal way?



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

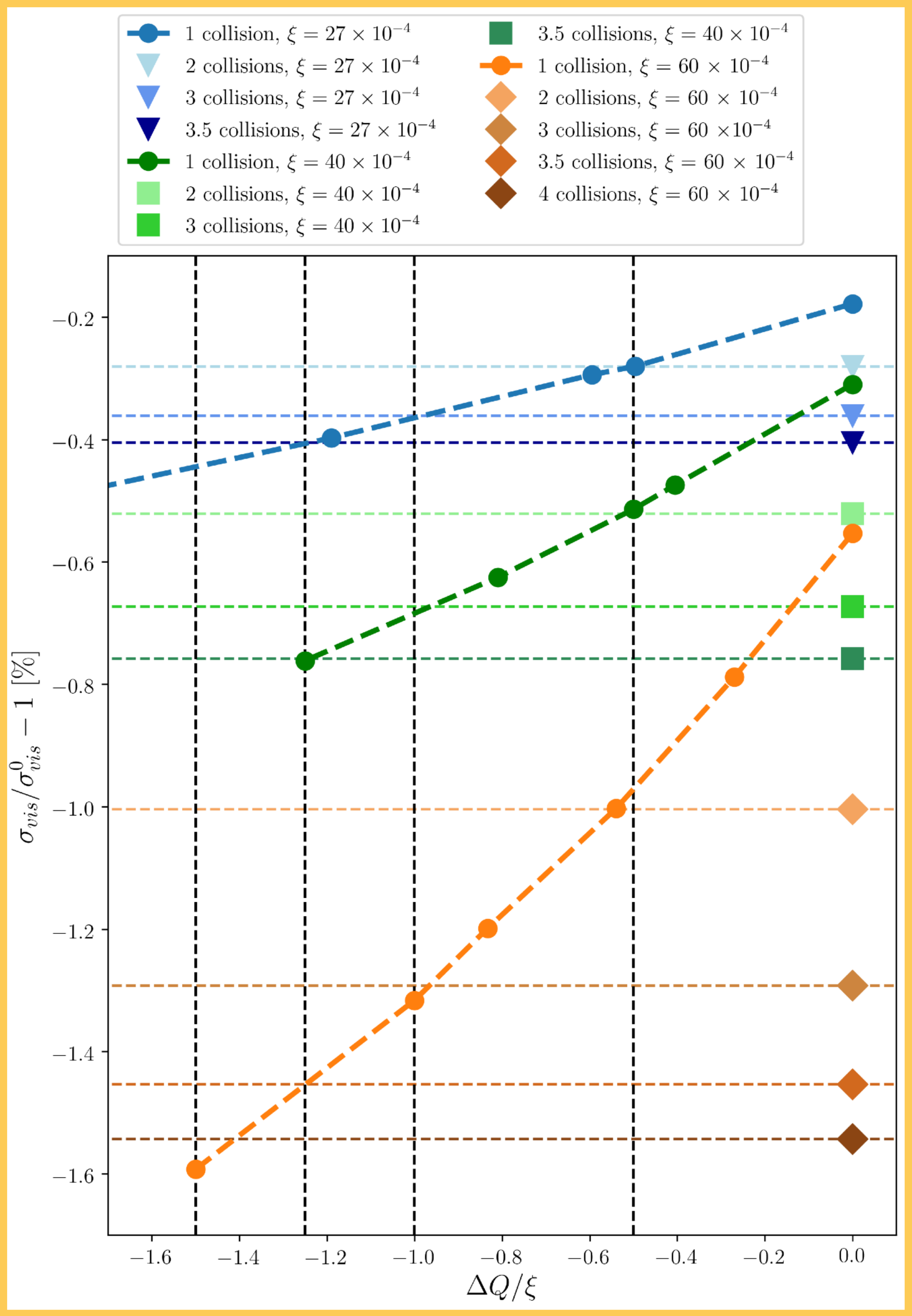
SINGLE IP TUNE SCAN FOR MULTI-IP $\sigma_{vis}/\sigma^0_{vis}$ SHIFT COMPENSATION

- aim: finding tune shift needed in the single collision setup to mimic the effect of multiple collisions
- three groups of colours intend to make the distinction between BB parameter ξ values
- in the single IP setup (lines) tunes $(Q^0_x,\ Q^0_y)$ are shifted in the same way, for both planes by $\Delta Q/\xi$
- multi-collision cases simulated separately (marked with symbols) fixed at the nominal unperturbed tune values $(Q^0_x,\ Q^0_y) = (64.31,\ 59.32)$, in the figure at $\Delta Q/\xi = 0.0$



SINGLE IP TUNE SCAN FOR MULTI-IP $\sigma_{vis}/\sigma_{vis}^0$ SHIFT COMPENSATION

- scaling law found for the impact of witness IPs on the relative difference in $\sigma_{vis}/\sigma_{vis}^0$
- for beam-beam parameter up to $\xi = 0.01$, the nominal tune shift in the single collision setup can be changed by $\Delta Q/\xi \approx -0.50 \pm 0.02$ per witness collision to induce the correct bias in the parametrisation model
- the results can be applied directly in the luminosity corrections since the beam-beam effect parametrisation depends on (Q_x, Q_y, ξ)



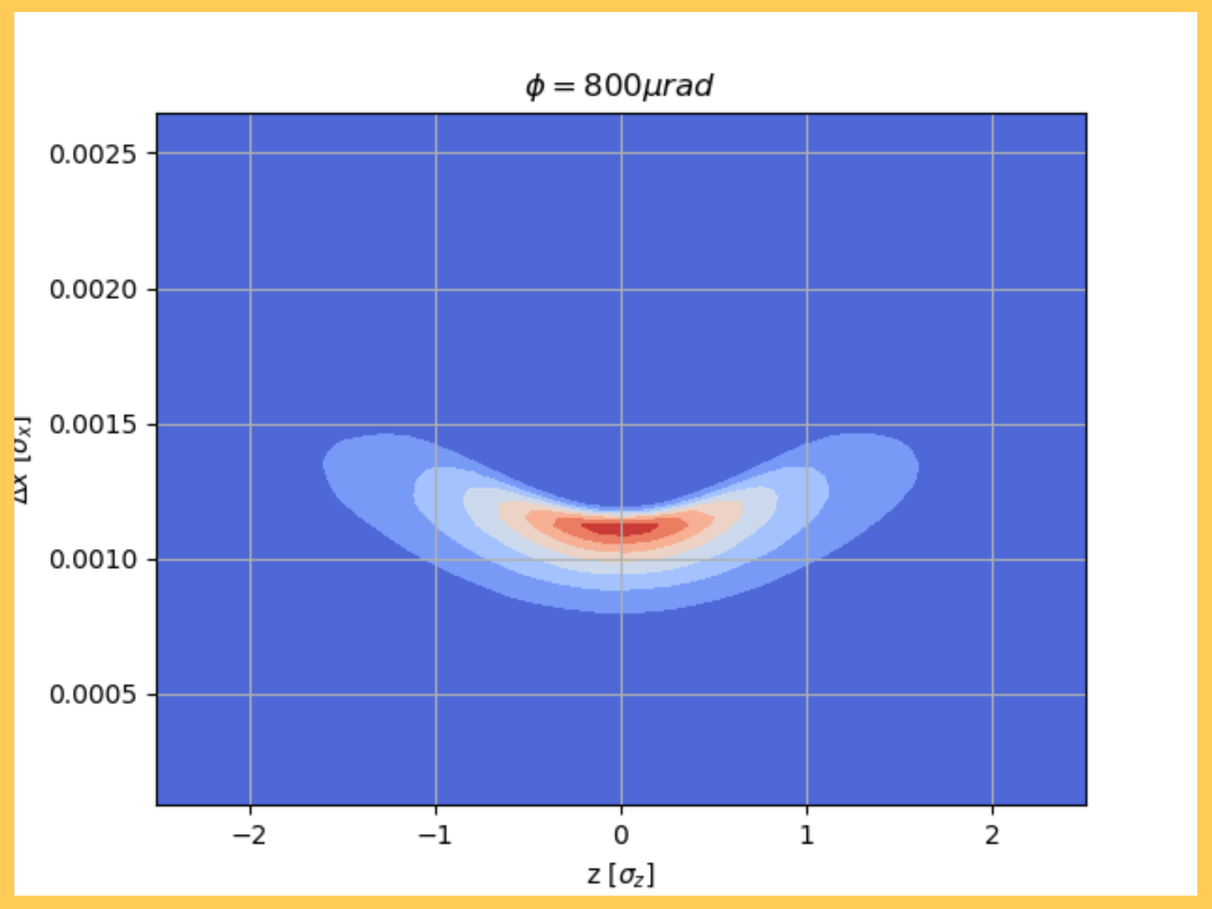
SUMMARY AND NEXT STEPS

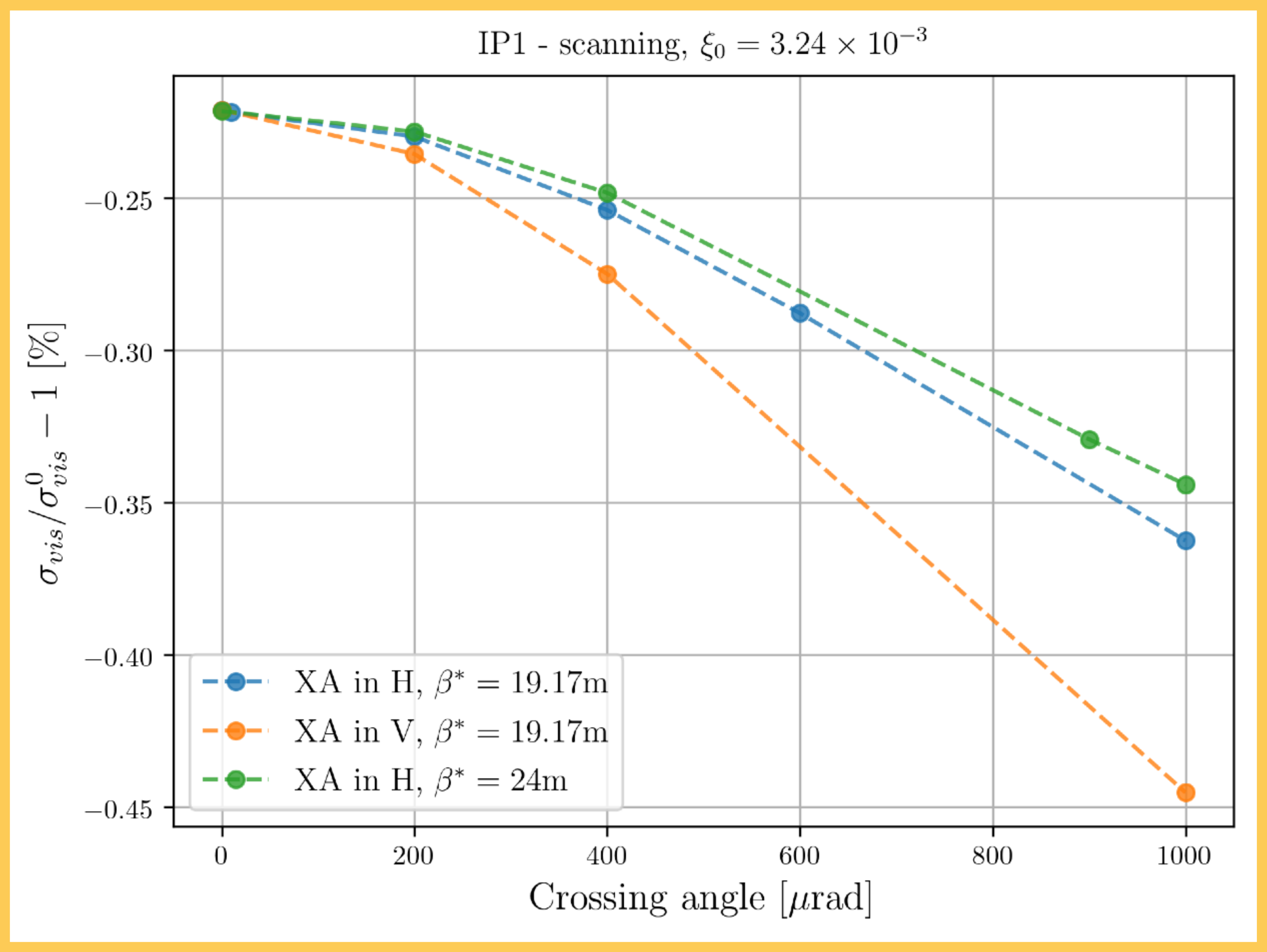
- Successful improvement in the VdM normalisation corrections and benchmark of the beam-beam related uncertainties
- Implementation of 4D luminosity integrator ongoing

- Cross-check with non-Gaussian longitudinal distributions
- Extrapolation to multiple bunches to consider train effects with long-range interactions in the common vacuum chamber around the IP
- Studies with 6D beam-beam kick in nominal conditions including the crossing-angle and low β^* can provide corrections in the emittance scans for response linearity evaluation

ONGOING CROSSING-ANGLE STUDIES

- The effect of crossing angle as well as the transverse beam size variations using the 6D beam-beam strong-strong model.
- VdM regime: beam-beam induced bias especially important for the LHCb, for which the total angle can reach $1000\ \mu\text{rad}$.
- The absolute value of the bias increases with the angle. It depends on the plane in which the angle is applied - caused by the difference in the nominal betatron tunes.
- Bias for different $\beta*$ diverge slightly when the angle is present, introducing the dependence on the $\beta*$ value.
- Considering the uncertainty on the zero crossing angle to be in the order of $10\ \mu\text{rad}$, the impact on the σ_{vis} was quantified to be below $0.01\ \%$, for classical VdM scan with no XA.





XA - crossing angle

THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

TYPICAL LUMINOSITY CALIBRATION SYSTEMATIC UNCERTAINTIES

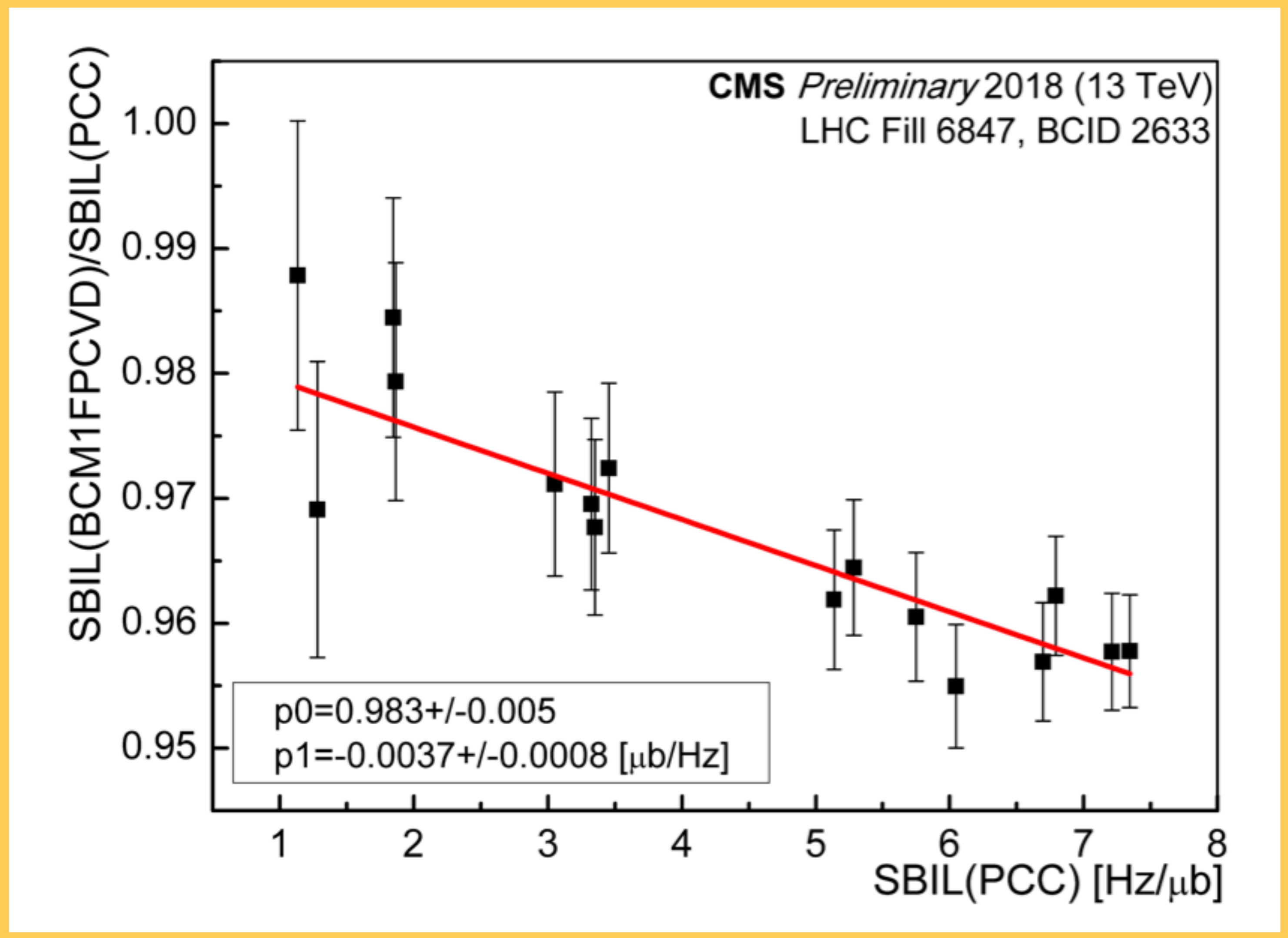
- the latest CMS luminosity measurement has a total systematic uncertainty of 2.5% which comprises the normalization and integration uncertainties
- simulation campaign aim to validate and improve VdM fit and its consistency, and the beam-beam effect corrections
- detector upgrade and performance studies should provide better linearity and stability

	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	−1.6 to −0.5	0.2–0.5
	Orbit drift	+0.2 to +0.6	0.1–0.2
	Transverse nonfactorization	+0.6 to +1.5	0.5–1.6
	Beam-beam deflection	+1.5 to +1.8	0.2–0.3
	Dynamic-β	−0.5 to −0.3	
	Beam current calibration	+2.3	0.2
	Ghosts and satellites	+0.2 to +0.4	0.1
	Scan-to-scan variation	—	0.3
	Bunch-to-bunch variation	—	0.1
	Cross-detector consistency	—	0.5–0.6
Integration	Afterglow (detector specific)	−4.0 to 0	0.3–0.5
	Cross-detector stability	—	0.5–0.6
	Linearity	—	0.3–1.5
	CMS deadtime	—	<0.1

CMS NOTE -2019/008

LINEARITY AND STABILITY

- Linearity uncertainty comes from the extrapolation of calibrated during the VdM scan σ_{vis} to the nominal conditions
- both estimated form cross-detector comparison and also from measuring the visible cross-section of a particular detector at VdM conditions and nominal conditions (emittance scans) and seeing how the value changes with pileup and instantaneous luminosity



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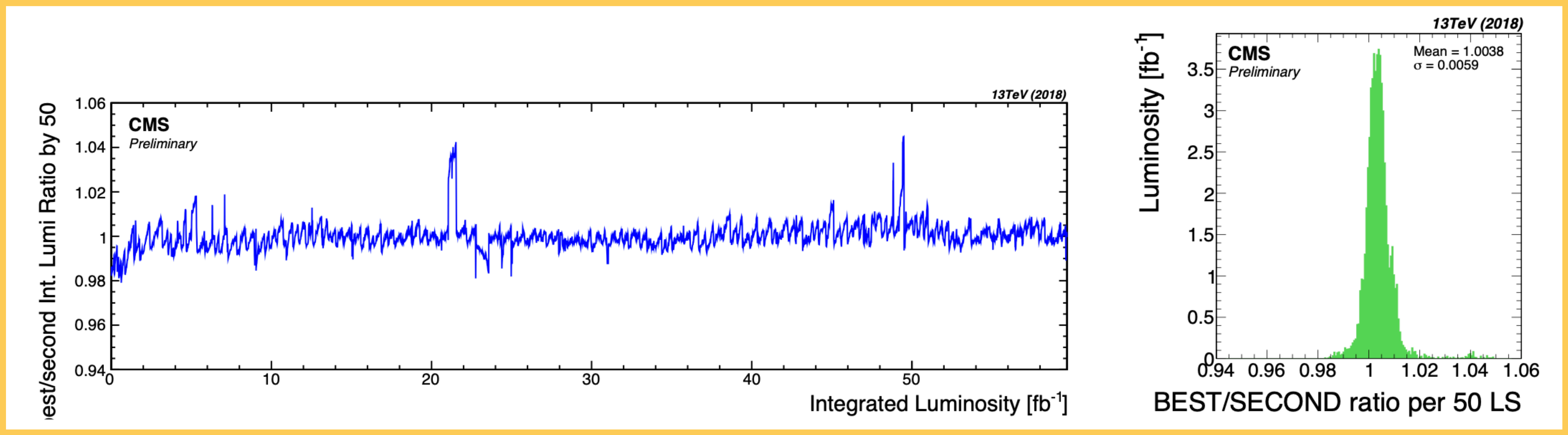
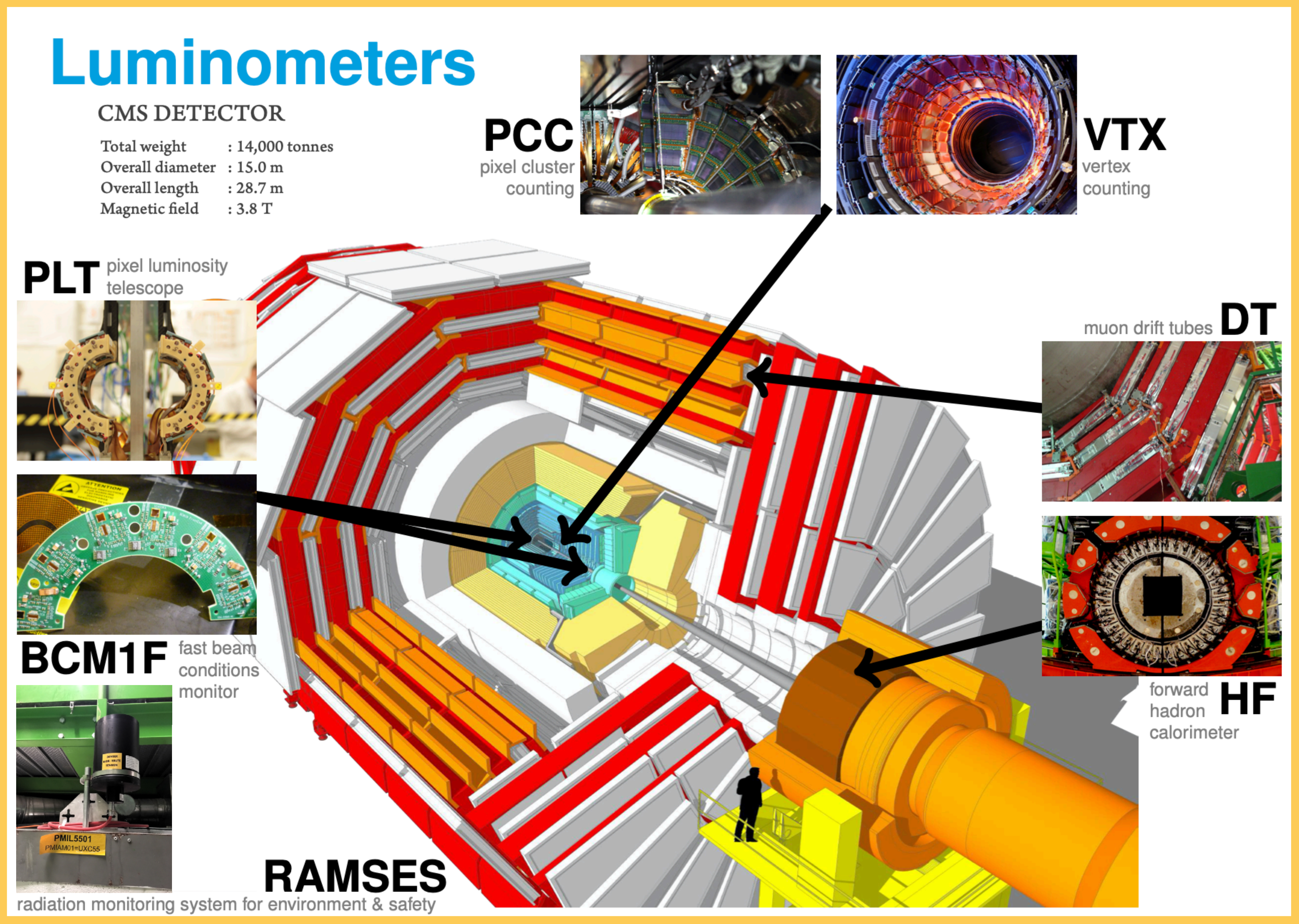
- Stability uncertainty to include the changes over time in the luminometer performance



all 2018 fills, source: CMS-PAS-LUM-18-002

CMS RUN 3 LUMINOMETERS

- At the Compact Muon Solenoid (CMS) experiment the luminosity is measured with both:
  - dedicated luminometers: Pixel Luminosity Telescope (PLT), Fast Beam Condition Monitor (BCM1F)
  - and by exploiting the information collected by the main CMS subsystems
- Multiple instruments necessary for definitive measurement
- Based on the lessons learned from the previous operation, requirements for an ideal luminometer were defined - BCM1F was upgraded and installed for the Run 3 (starting 2022)



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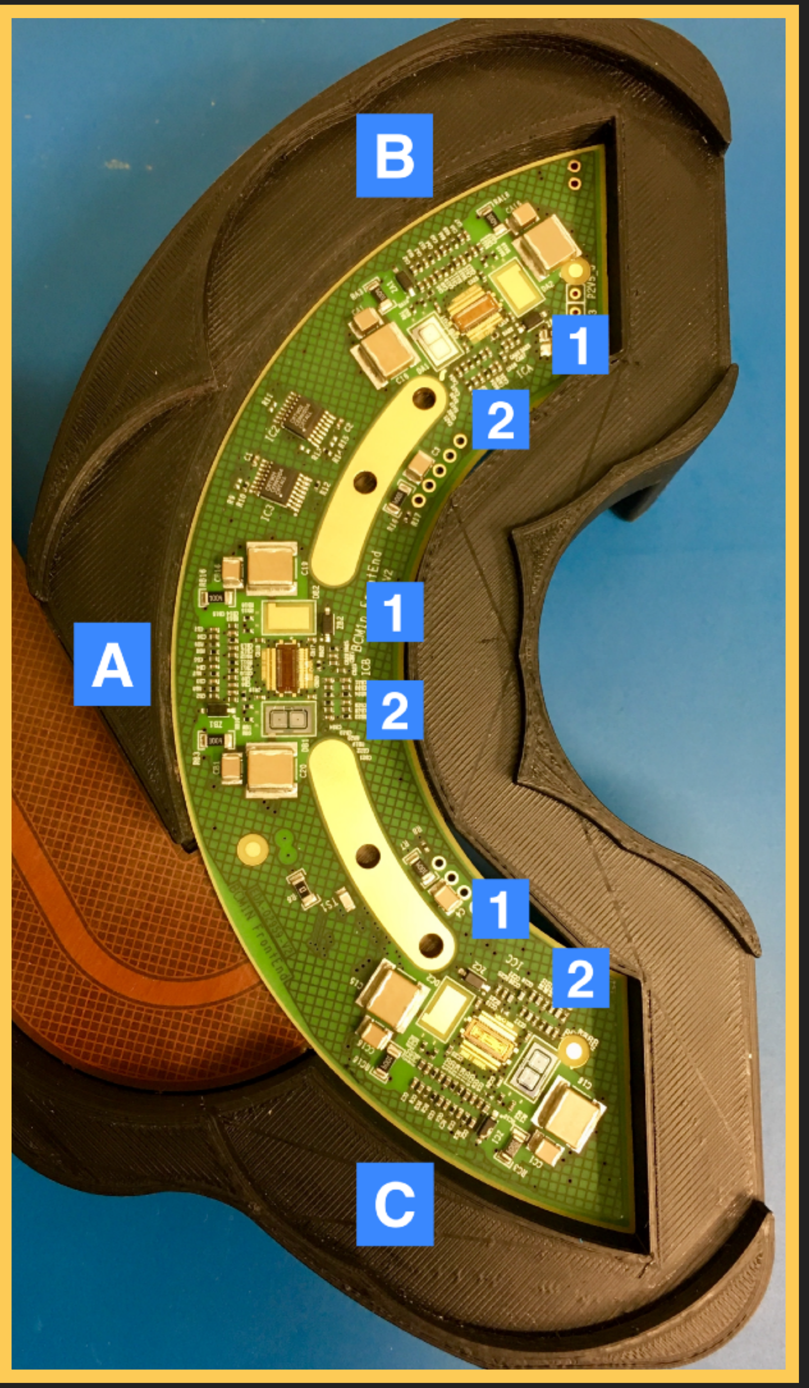
INTRODUCTION – BCM1F UPGRADE



- sensors exchanged from the mixture of pCVD diamonds and silicon pads to new generation silicon, that should provide large signal with improved background separation, AC-coupling to prevent undesired biasing due to leakage current
- newly implemented peak finder algorithm is introduced to improve the double hit resolution
- new μTCA backend system
- 48 independent channels, when combined should give measurement with excellent statistical significance
- The test version printed circuit board and ASIC chips were tested with internal electric pulses and the sensors with a radiation source
- assembly, integration with other subsystems and installation finalised in July 2021