Precision luminosity measurement at hadron colliders

Public defense presentation

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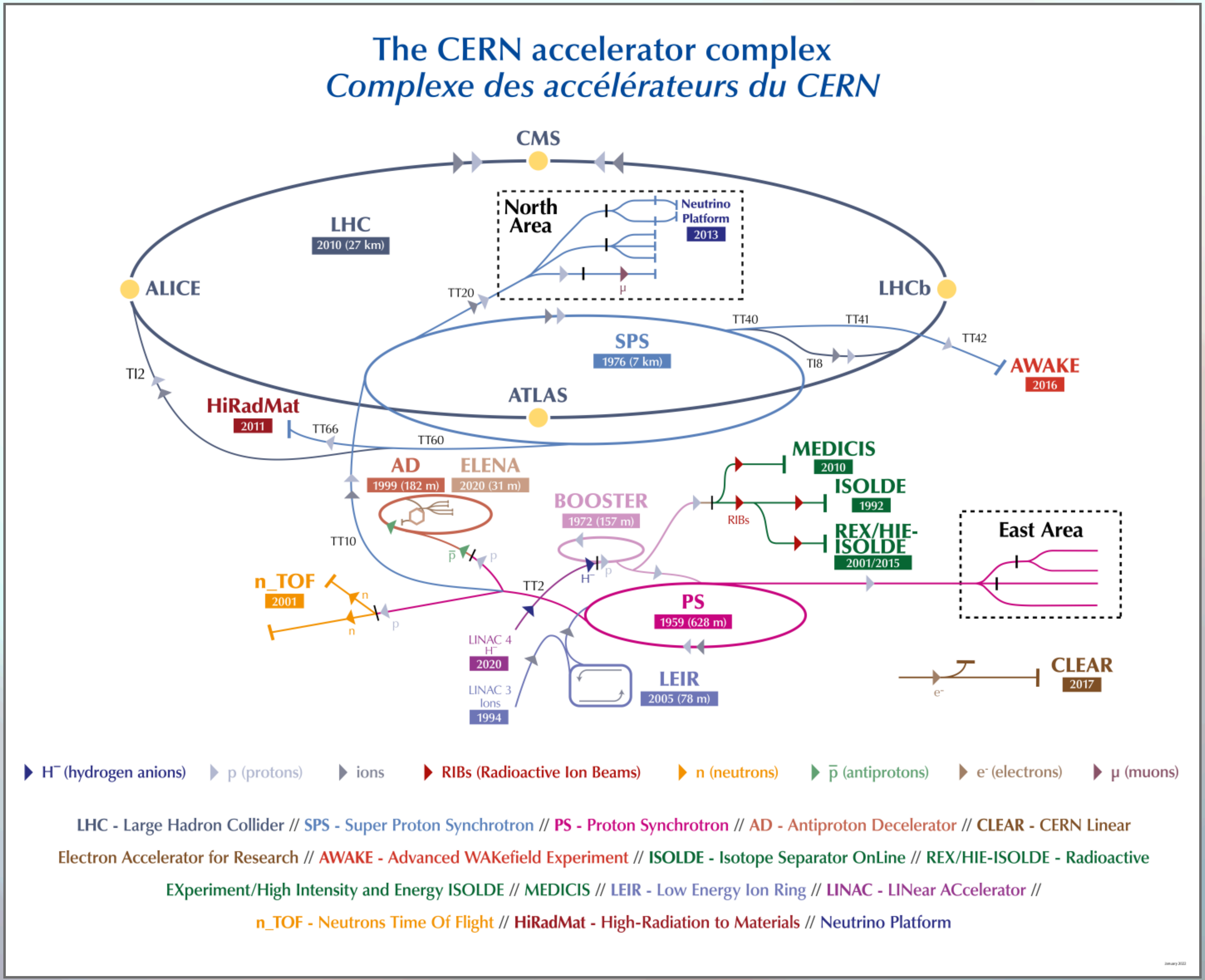
Geneva, 31.05.24

Outline of the presentation

- Introduction & motivation
- Luminosity measurement with the new Beam Conditions Monitor (BCM1F-utca) for the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC)
- Beam-beam effects in the luminosity calibration
- Absolute luminosity scale calibration of BCM1F-utca for 2022 data set

Large Hadron Collider



The CERN accelerator complex

Complexe des accélérateurs du CERN

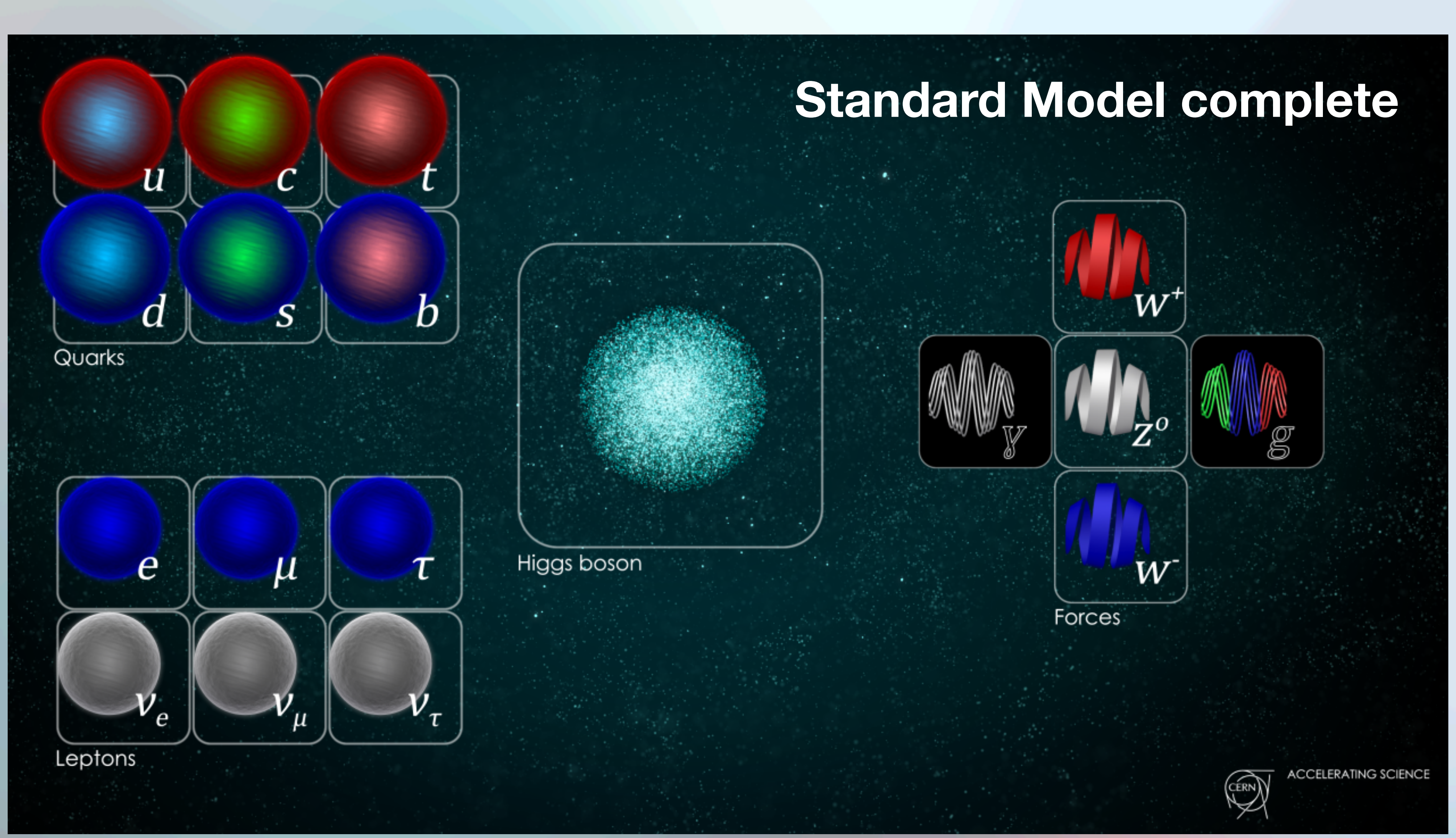
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

high magnetic field and large radius

→ high energy $E = E_{beam1} + E_{beam2} = 13.6$ TeV

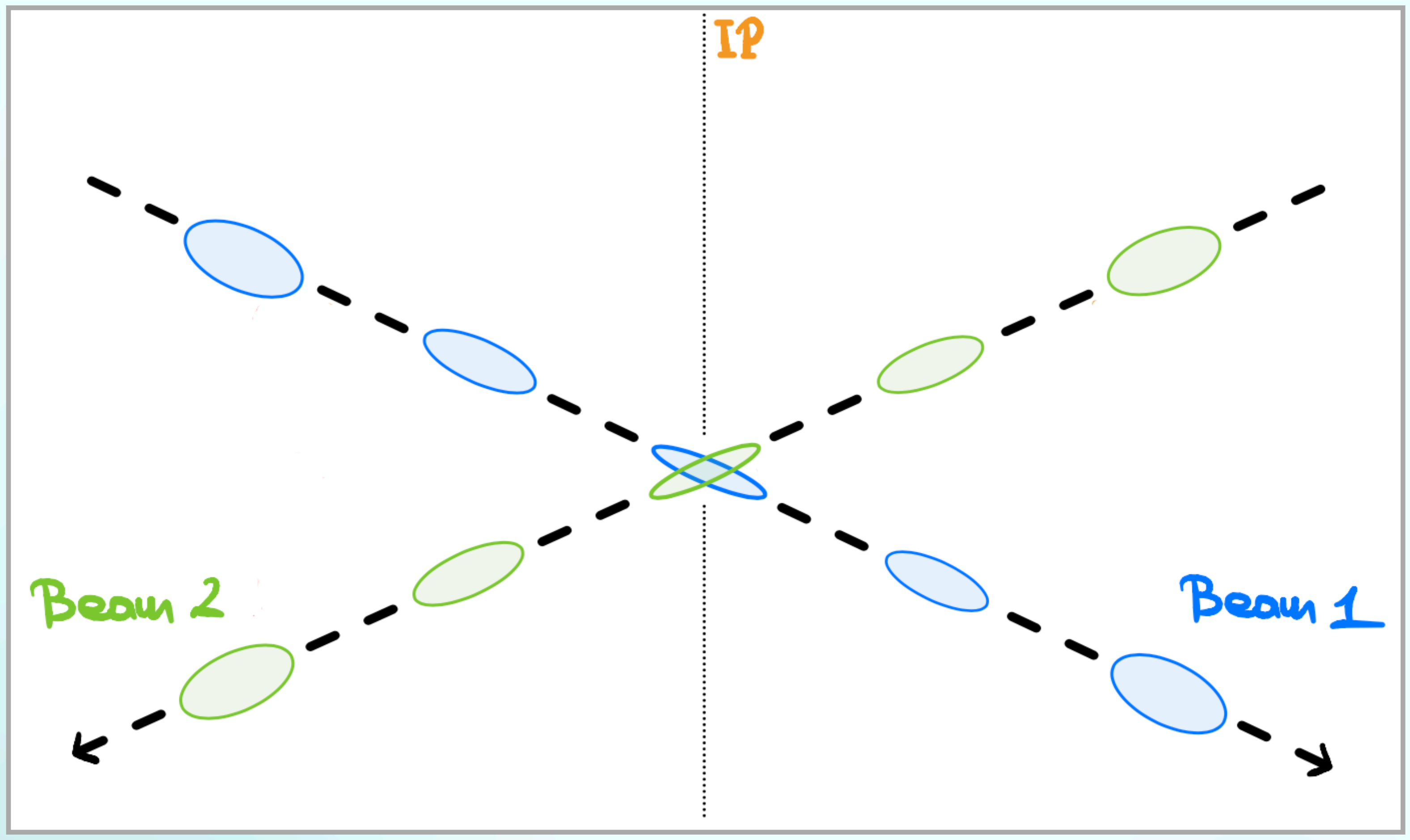
→ smaller scales, heavier particles

→ discovery of the Higgs boson

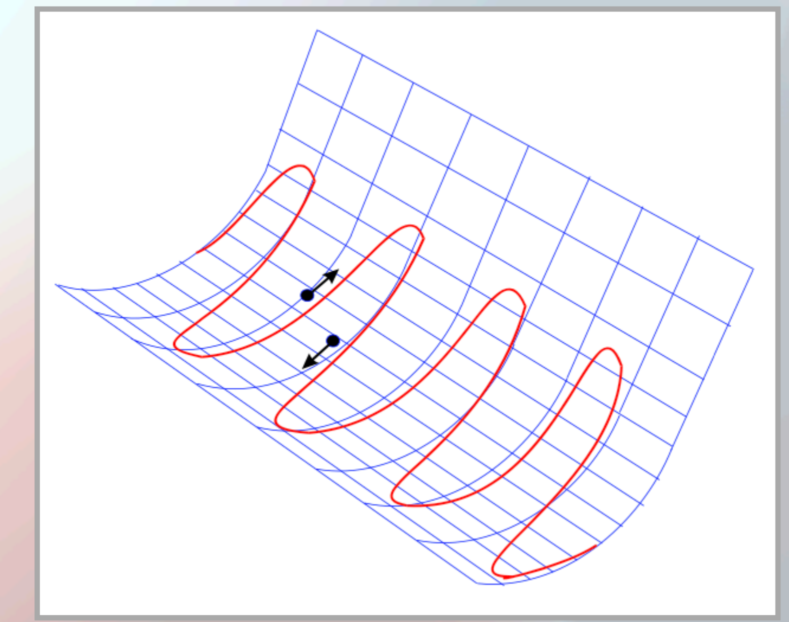


Standard Model complete

Large Hadron Collider

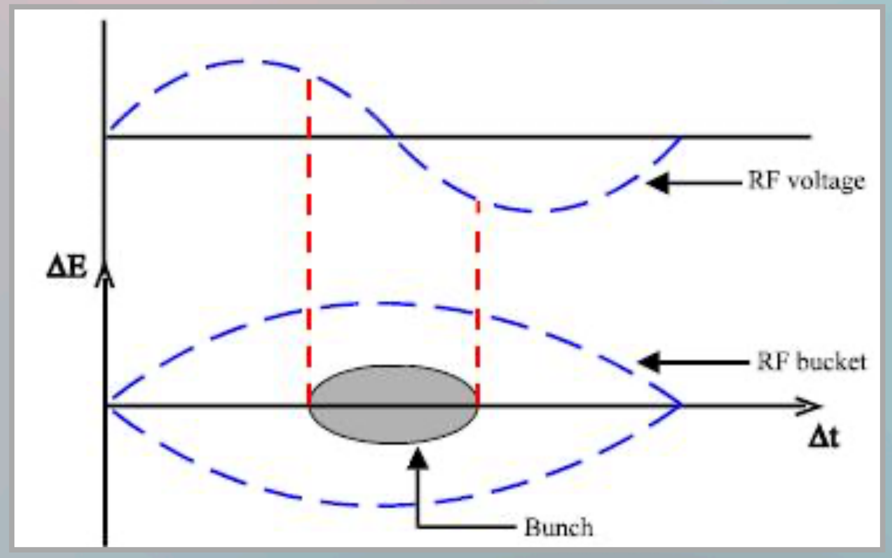


- DIY accelerator: bending, focusing, accelerating components
- beams divided into groups crossing each other resulting in billions of collisions per second
- many other elements providing high quality beams and diagnostic tools

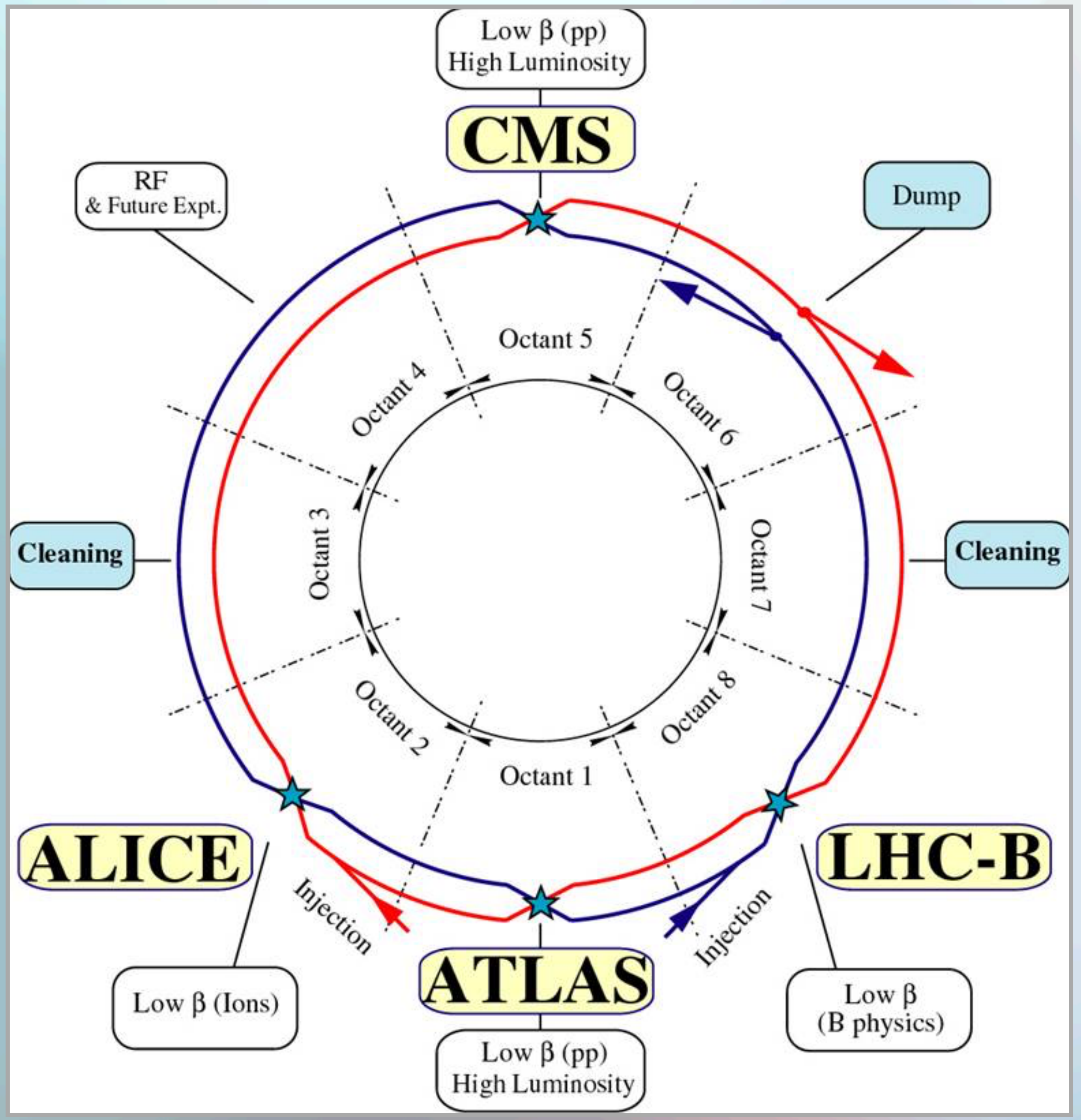


betatron tune Q is defined as the number of transverse oscillations in a single turn

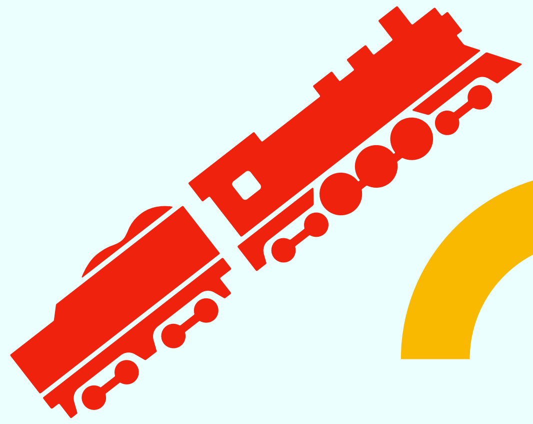
99,9999991% of c

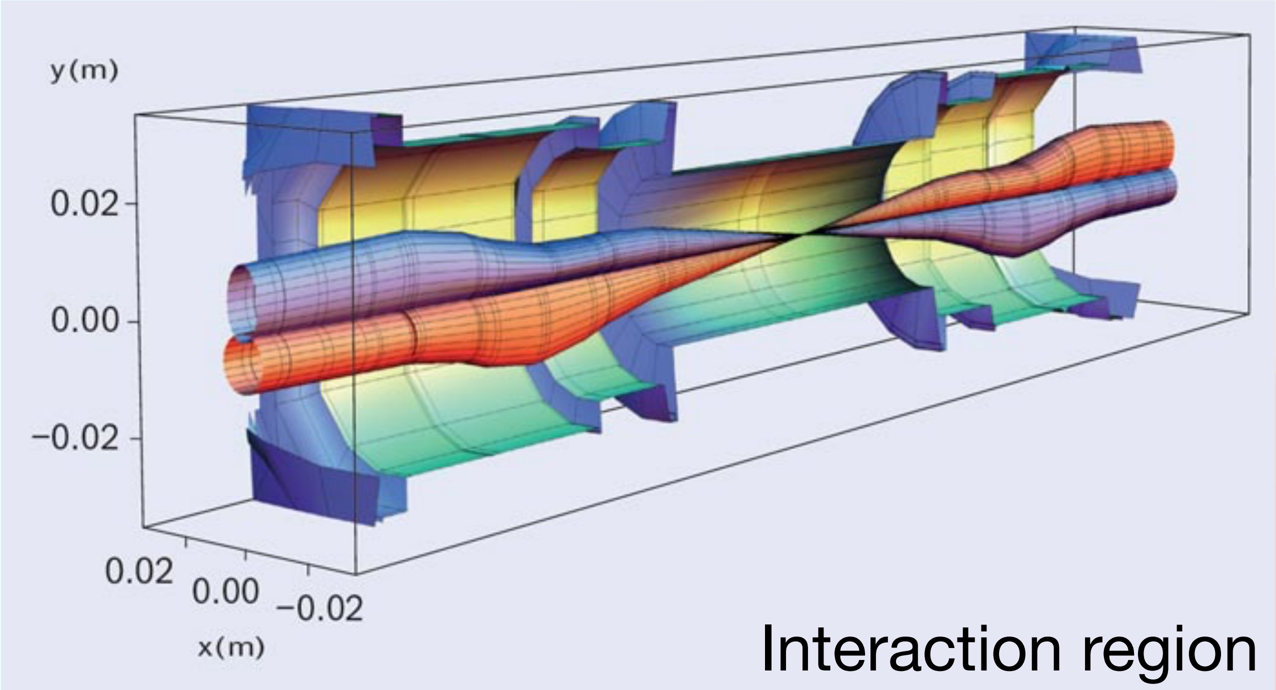


x 35640

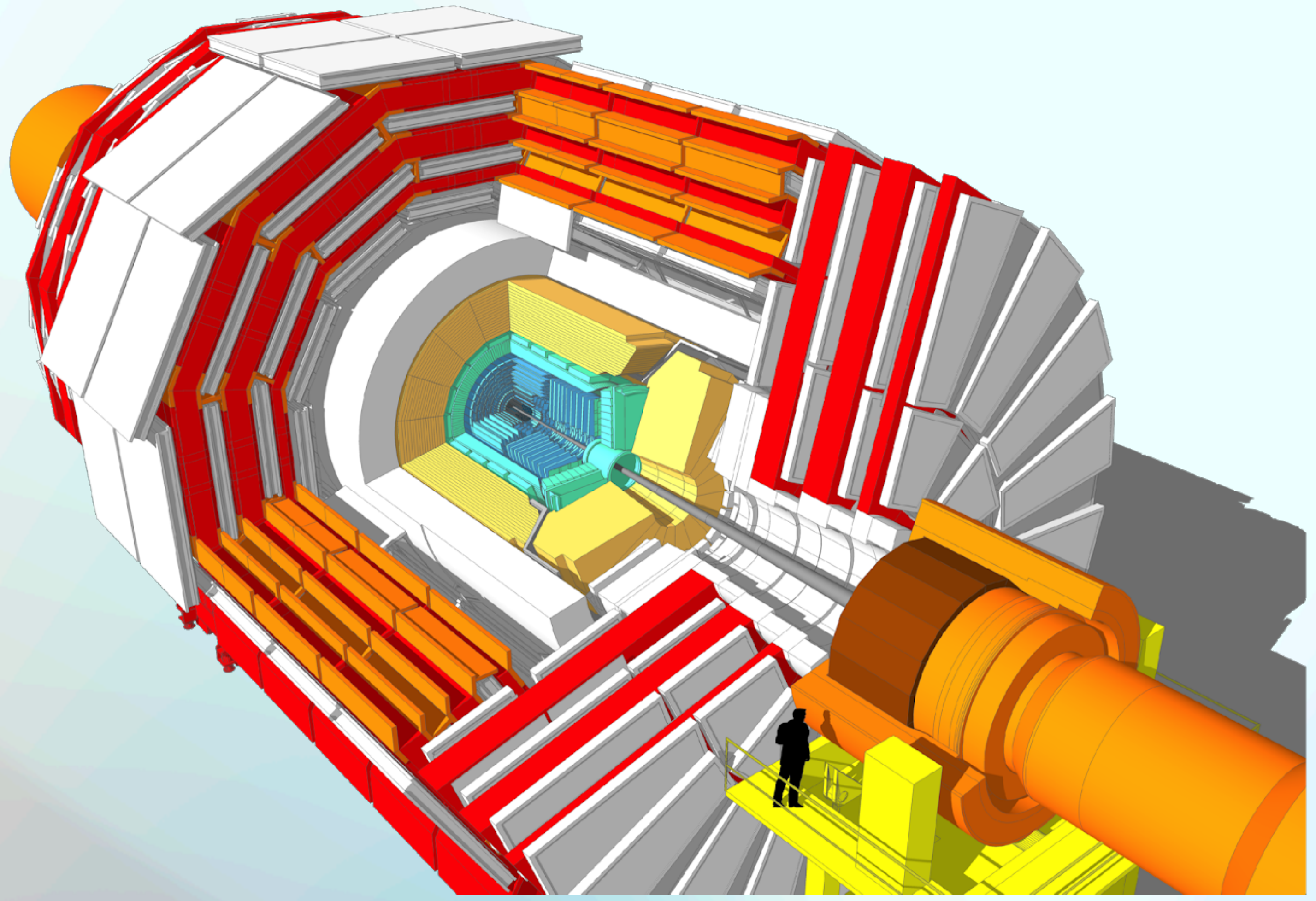


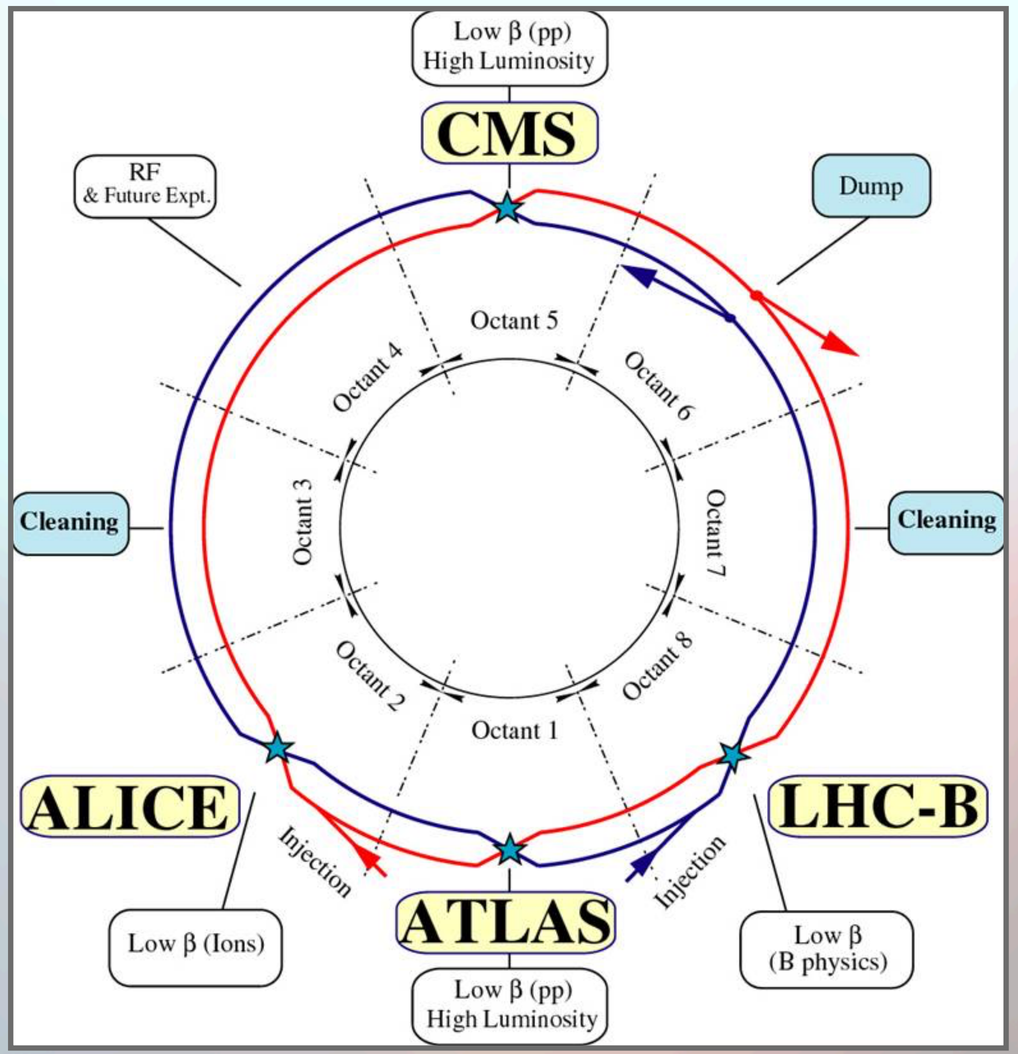
LHC experiments



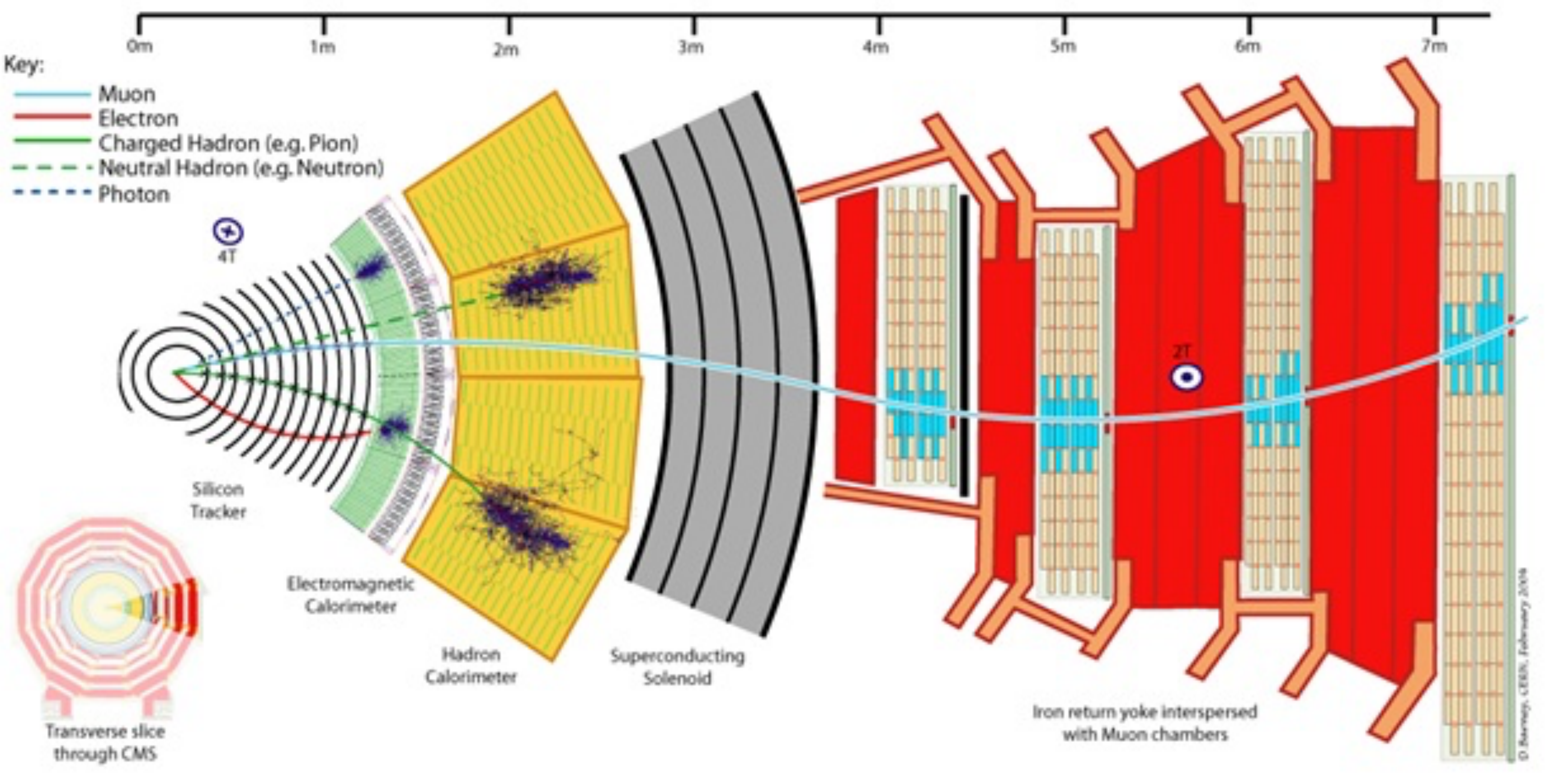


Interaction region





- to study tiny scales and reconstruct events from traces sophisticated detectors are needed



Luminosity

- ‘collisions’ too general for the field of particle physics
- need for quantity that describes the efficiency of the collider independently of a process

$$R = \mathscr{L}_{inst} \cdot \sigma_{ev}$$

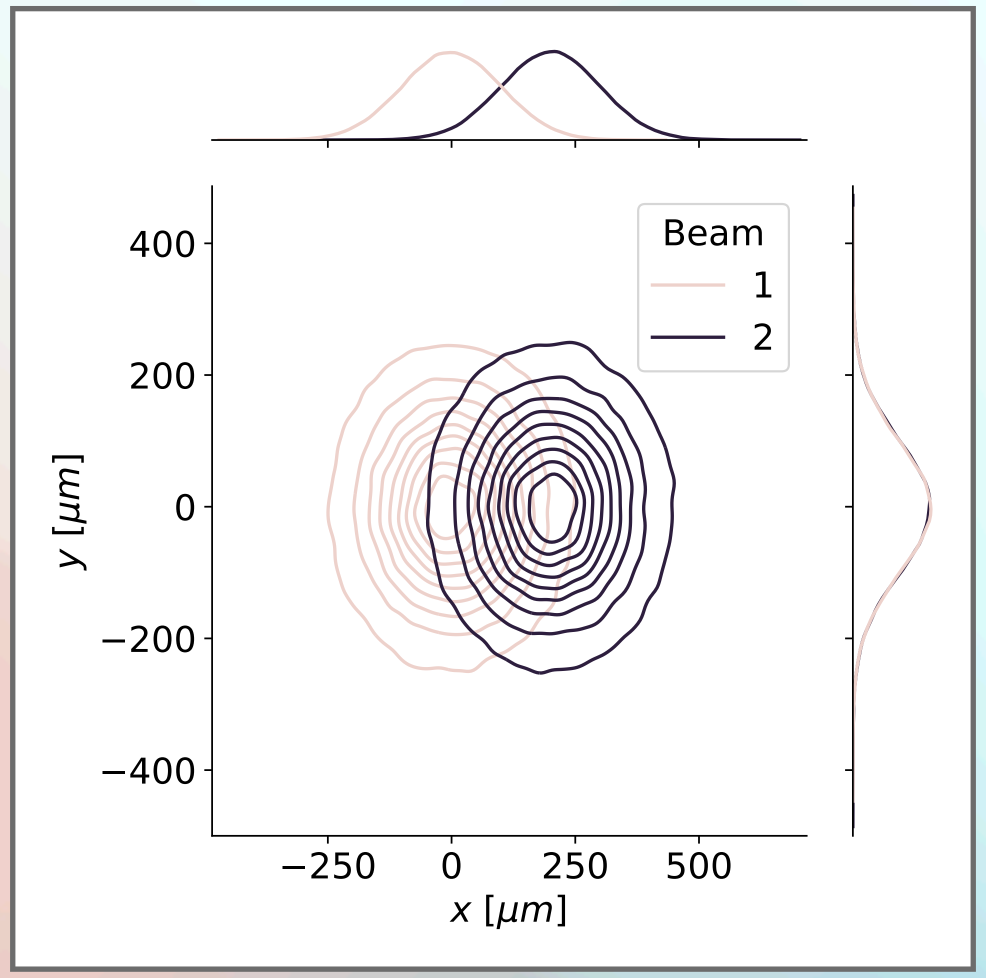
- can be maximized with machine parameters

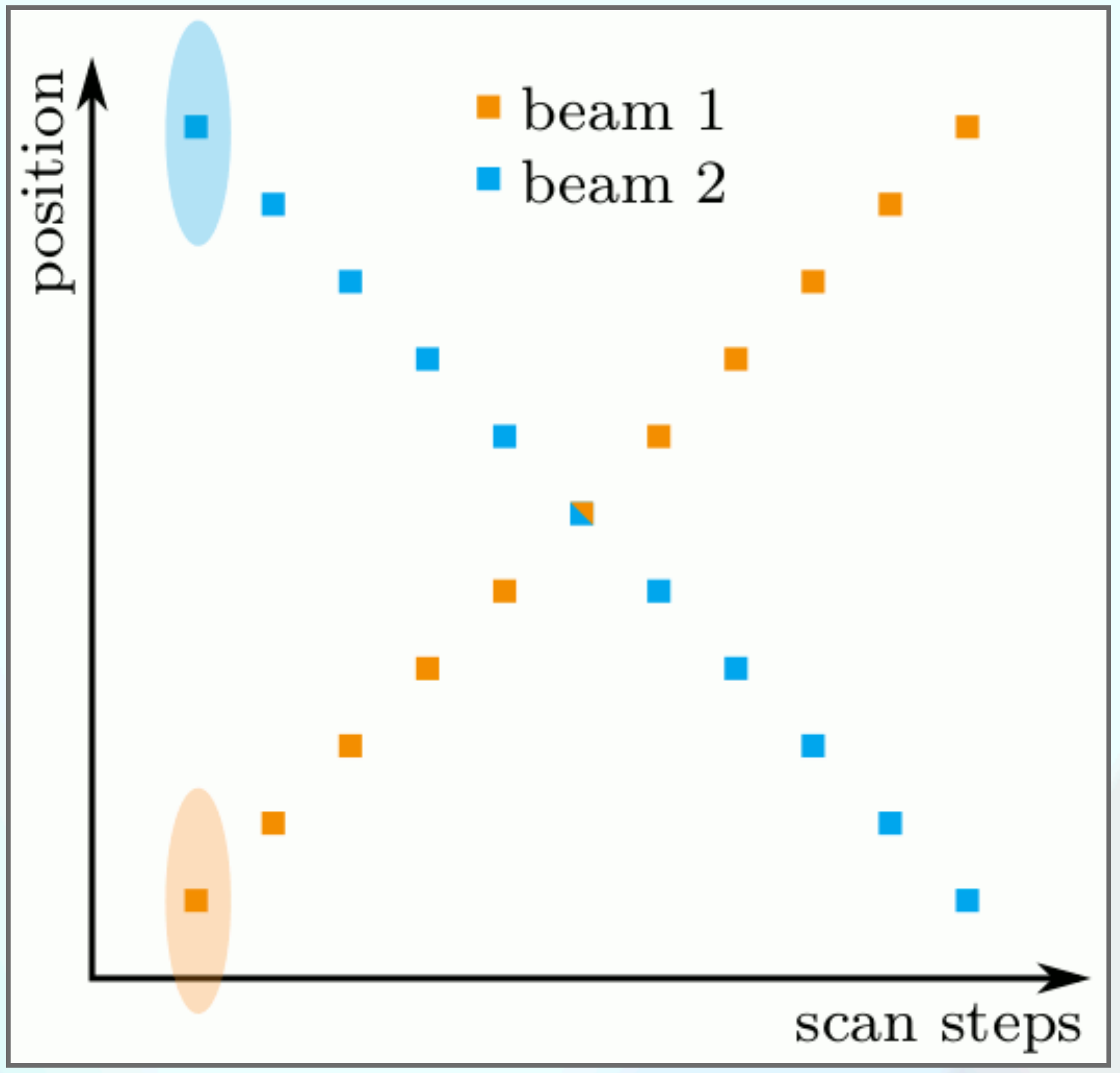
$$\mathscr{L}_{inst} = \sum_{i}^{N_b} \frac{n_{1,i}\, n_{2,i}\, f_{\text{rev}}}{4\pi\sigma_x\sigma_y}$$

- high integrated luminosity makes the observation significant

$$\mathscr{L}_{int} = \int_0^T \mathscr{L}_{inst}\, dt$$

Luminosity calibration



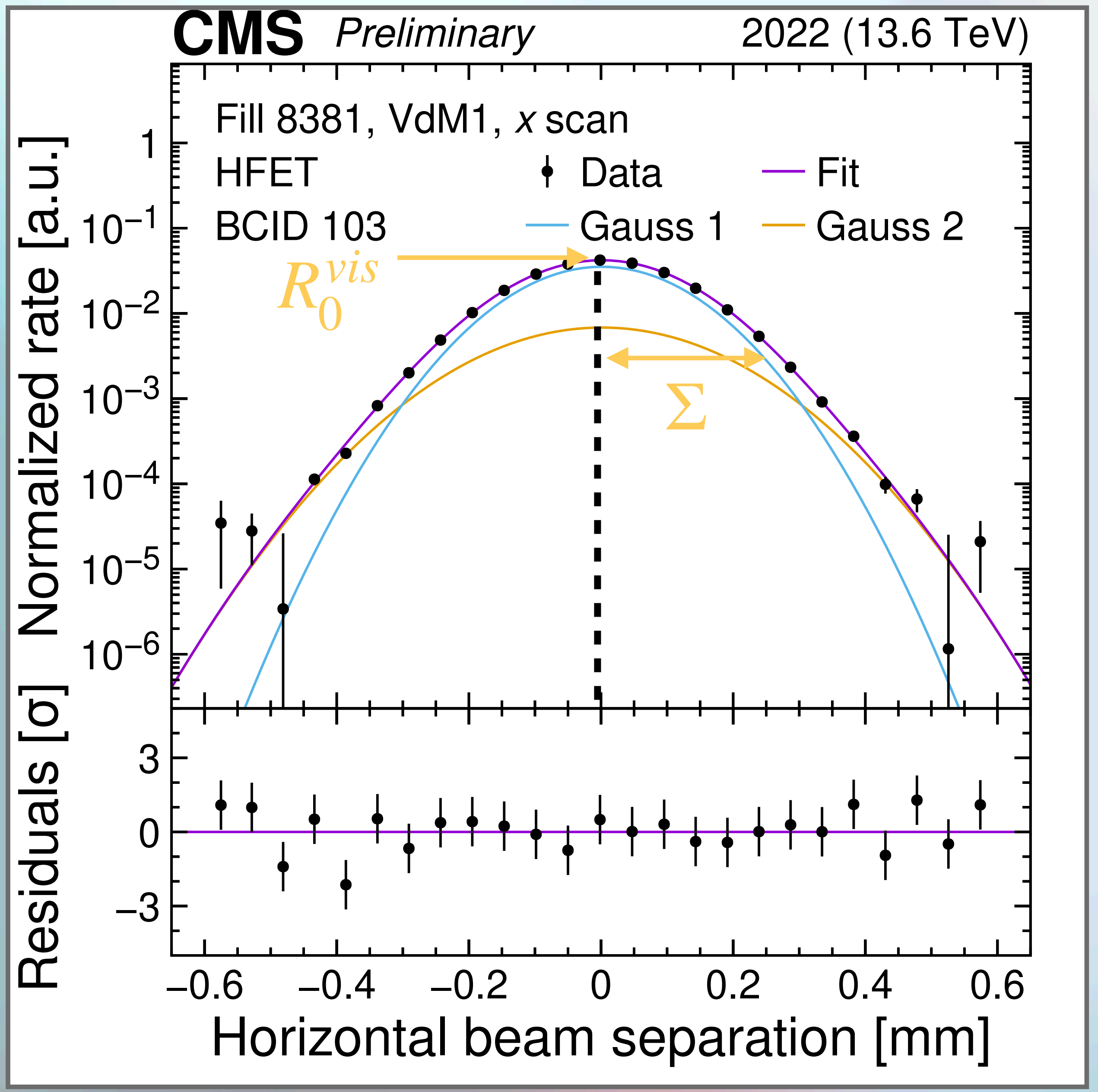


- van der Meer (vdM) scans are performed every year to obtain the detector-specific visible cross-section
- luminosity is a product of the colliding bunch-pair parameters:

$$\mathscr{L}_{inst}^{vdM} = \sum_{i}^{N_b} n_{1,i} n_{2,i} f_{\text{rev}} \iiiint_{-\infty}^{+\infty} \rho_{1,i}(x, y, s, -s_0)\rho_{2,i}(x, y, s, s_0)\, dx\, dy\, ds\, ds_0$$

- beams are moved across each other by discrete separation steps
- the convolved transverse beam size can be extracted from the measured visible rate:

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R(\Delta_x,0)\, d\Delta_x}{R(0,0)}$$



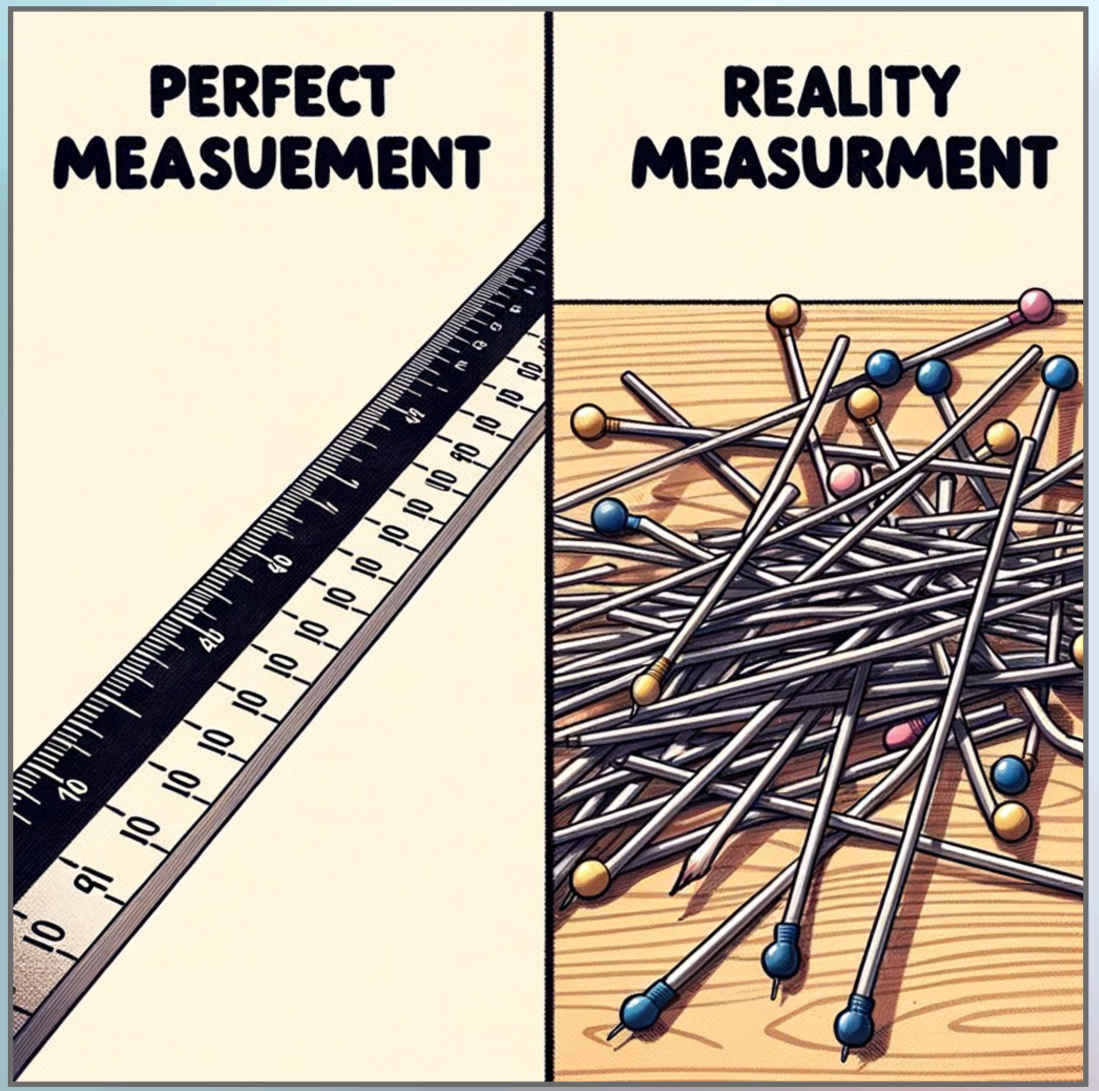
CMS-PAS-LUM-22-001

Luminosity calibration

- two scans in a pair for each of transverse directions and full overlap area
- the absolute head-on luminosity can be computed from the measured bunch parameters, and compared to the measured rate to infer the calibration constant:

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

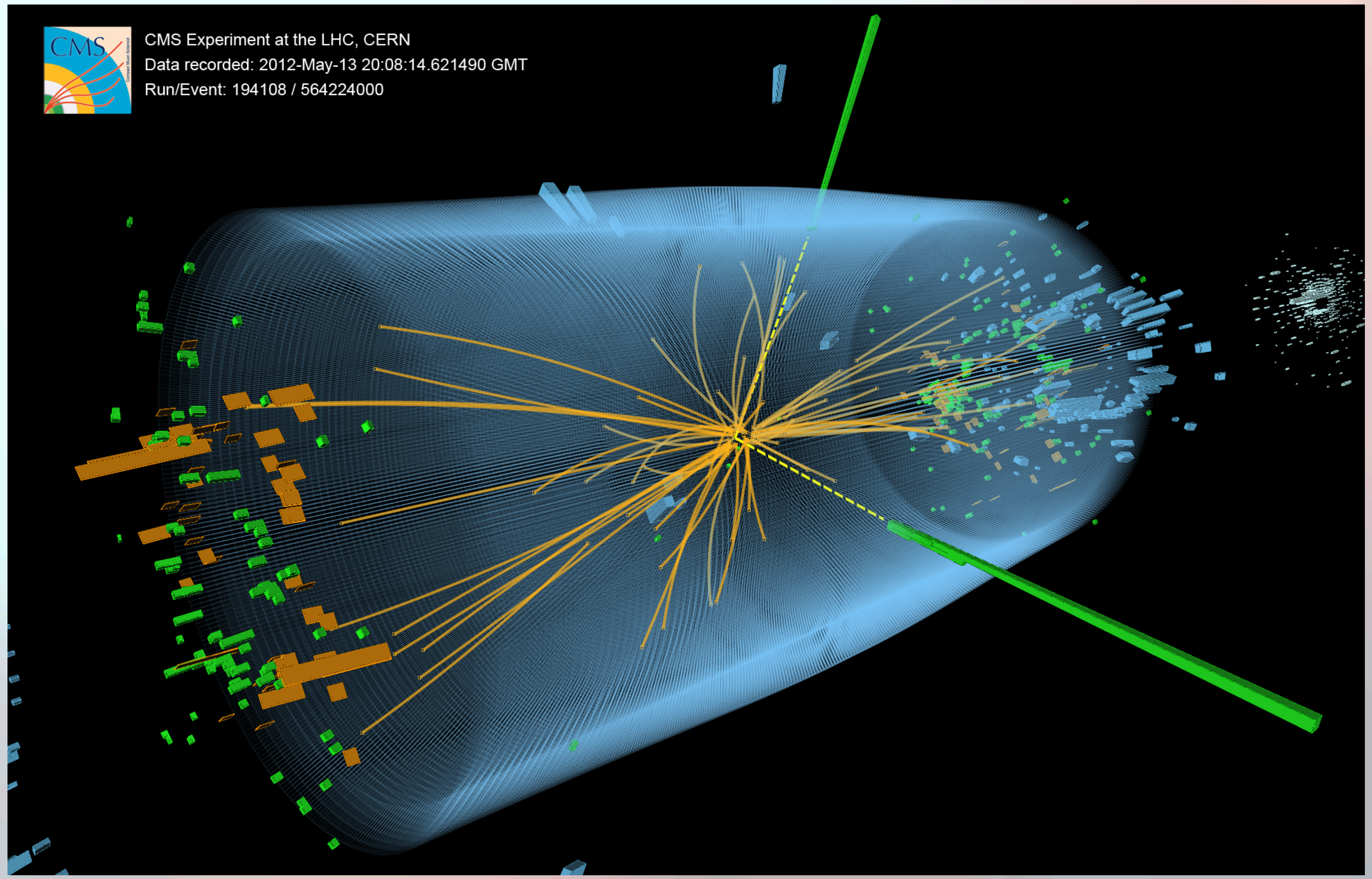
- luminometer calibration can be used to measure luminosity at any conditions



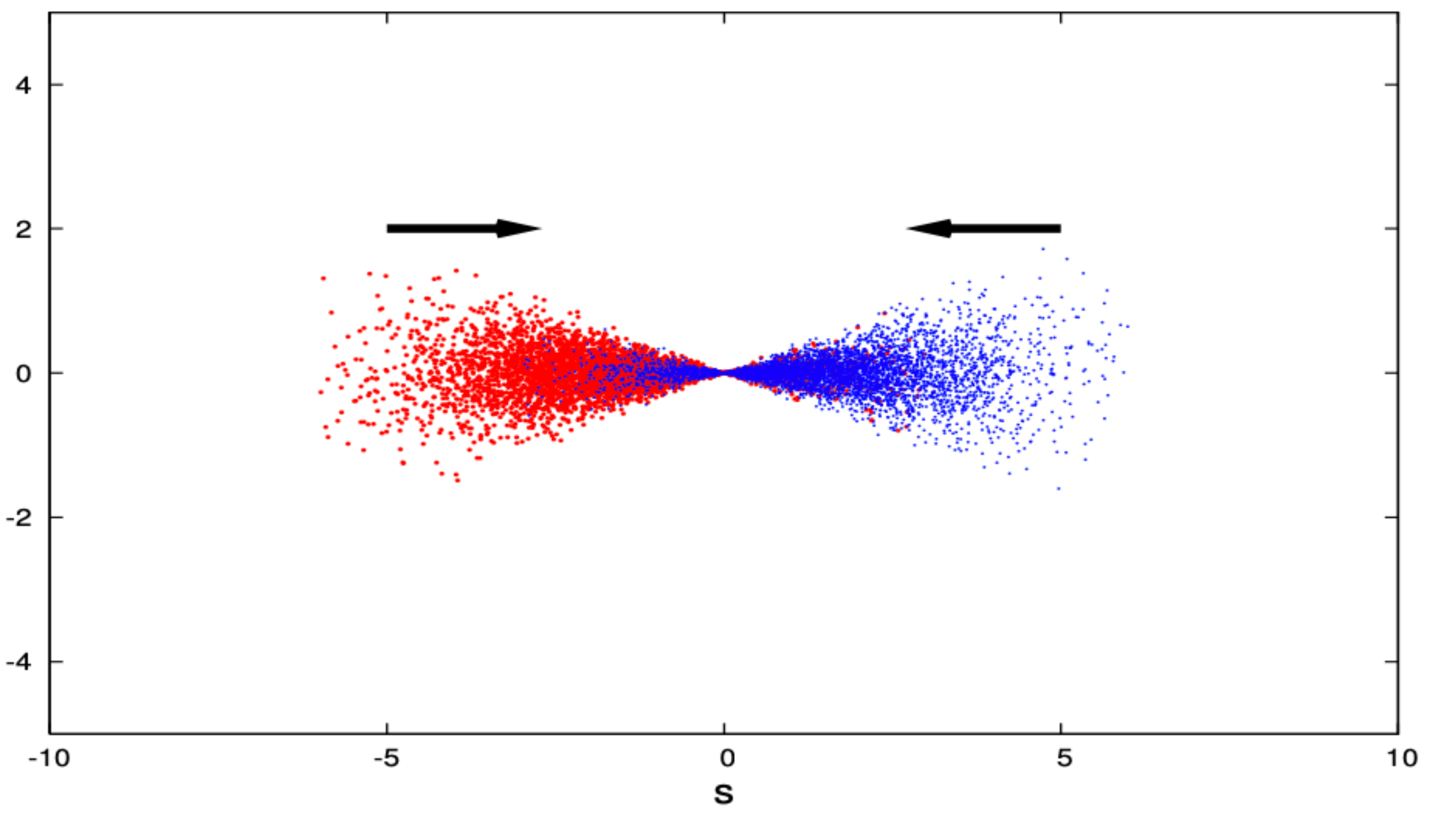
- evaluation of biases from beam-related systematic effects such as the orbit drift, beam-beam interaction, etc.
  - calibration accuracy affected - apply corrections
  - estimate systematic uncertainties down to 0.1%
- extended scan program used with multiple scans for dedicated studies as well as wide range of beam instrumentation

When the beams are brought into collision

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

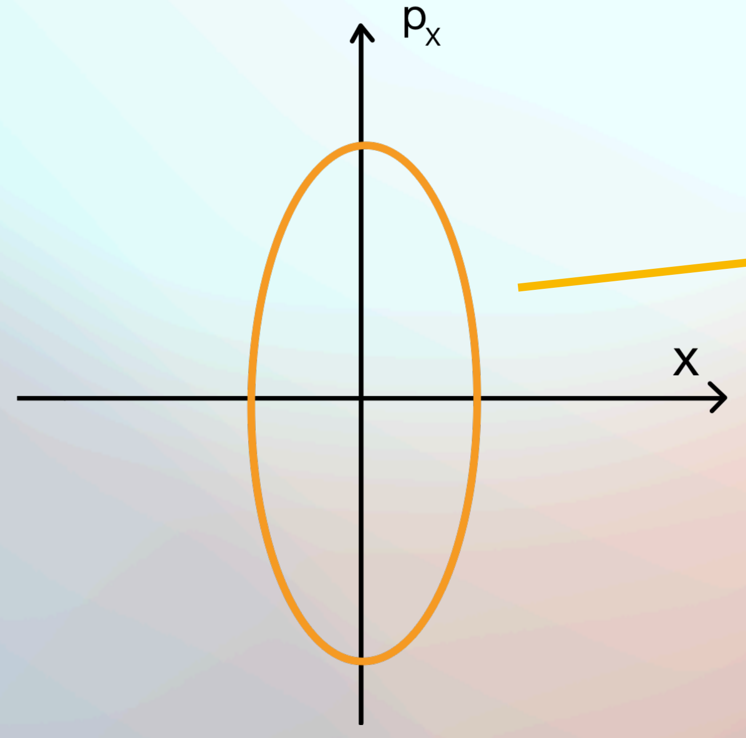


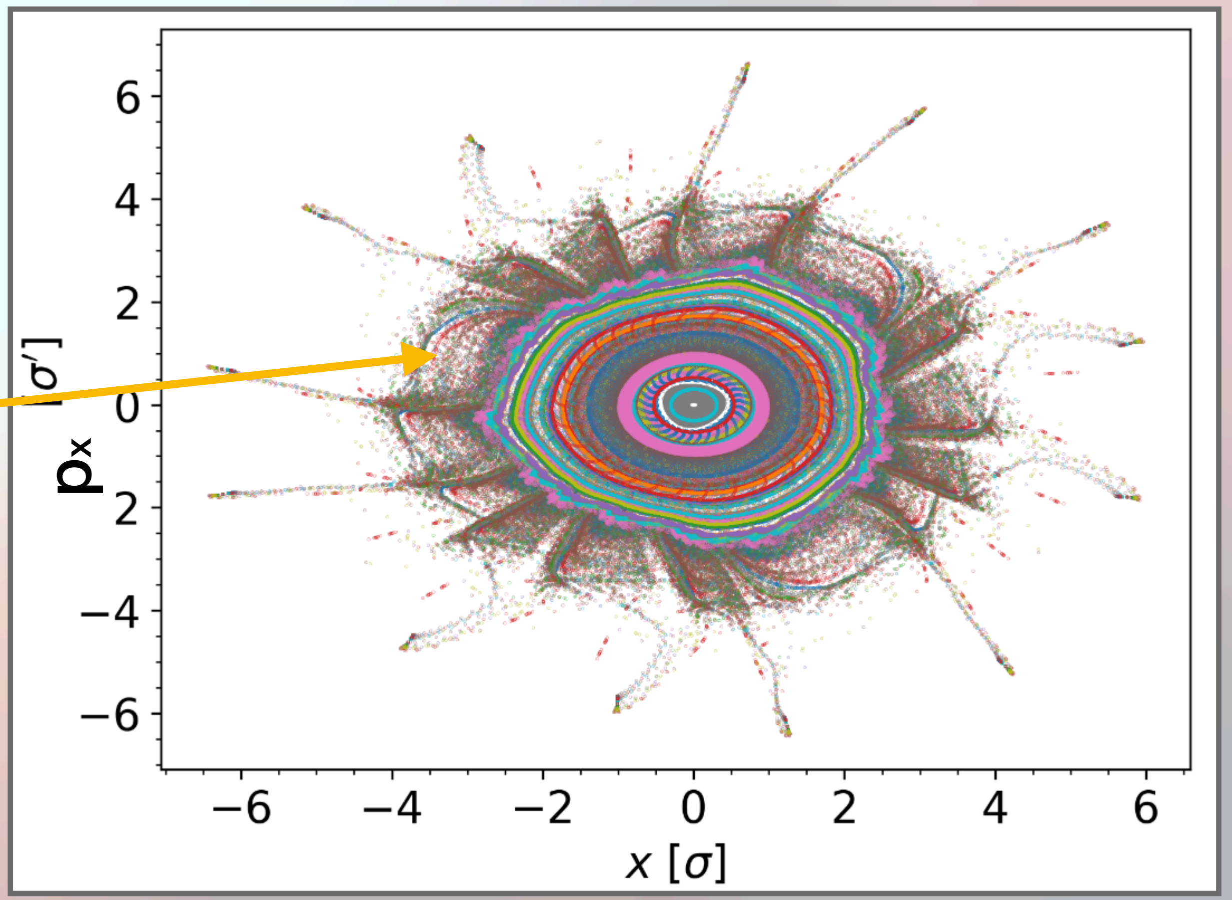
- reality (for ~99.999..% of beam particles): the trajectory is changed due to the electromagnetic interaction with the opposing beam



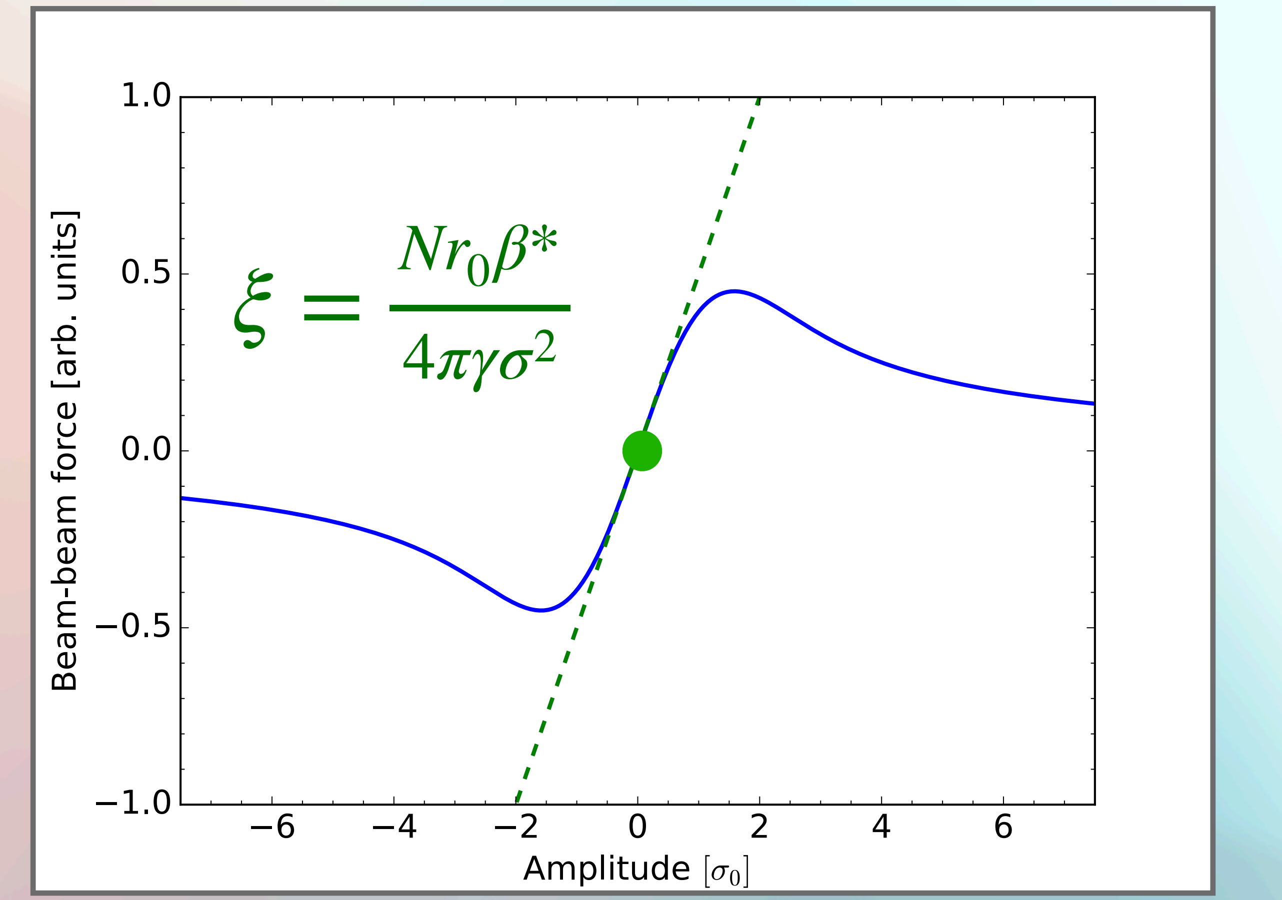
Beam-beam interaction

- Beams are collections of charges that interact electromagnetically
- BB parameter ξ describes the linearized force for small amplitude particles
- single particle trajectory changed depending on its amplitude due to non-linear force

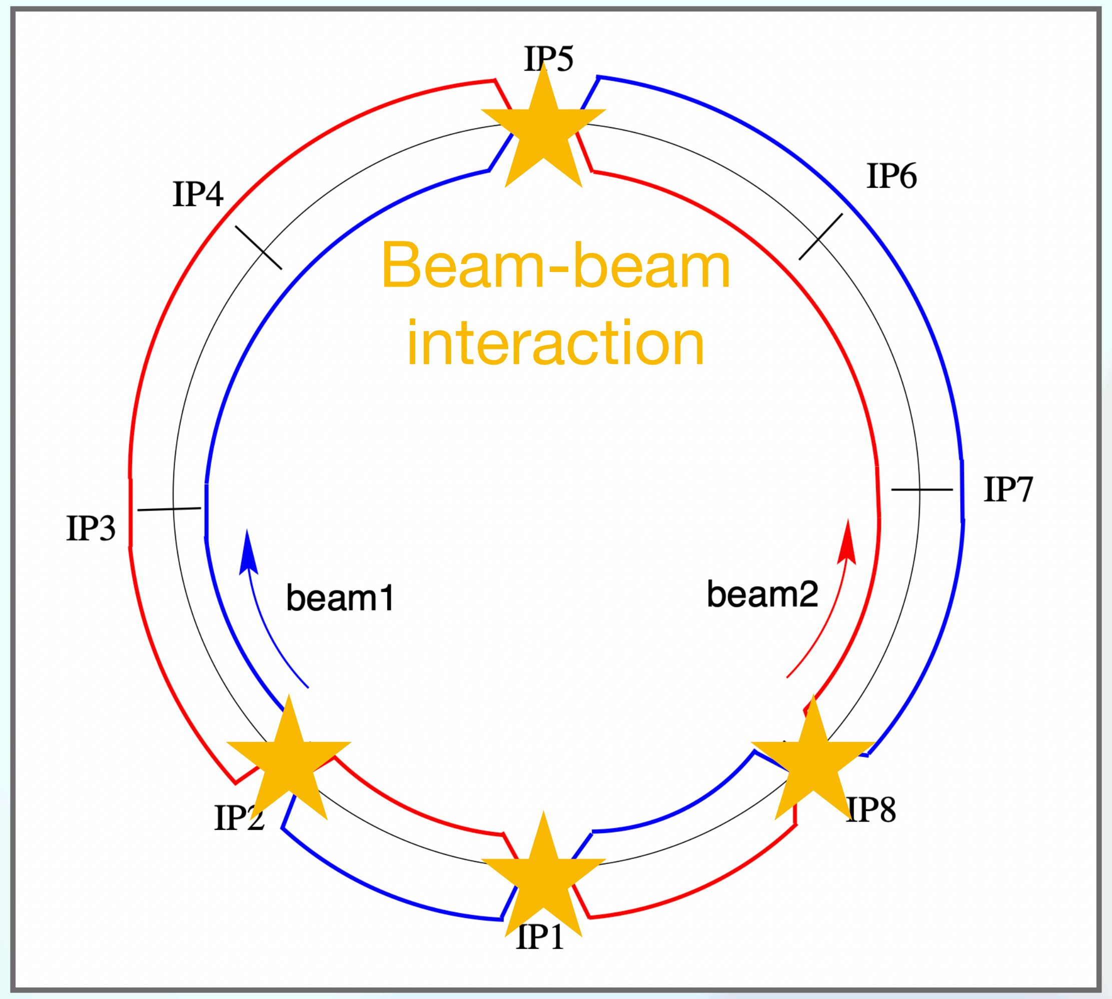


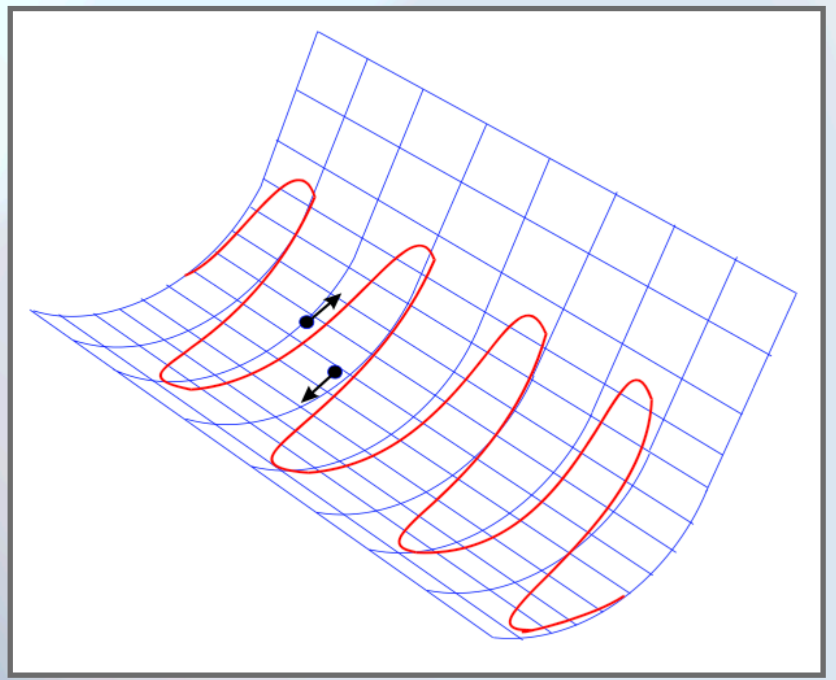


$$F_\perp = \pm \frac{Ne^2(1+\beta_{rel}^2)}{4\pi\epsilon_0 r}\left(1-\exp\left[-\frac{r^2}{2\sigma^2}\right]\right),$$



- as a result, there is a tune spread in the beam $\Delta Q \sim \xi$
- COherent Multibunch Beam-beam Interactions (COMBI) code used to model



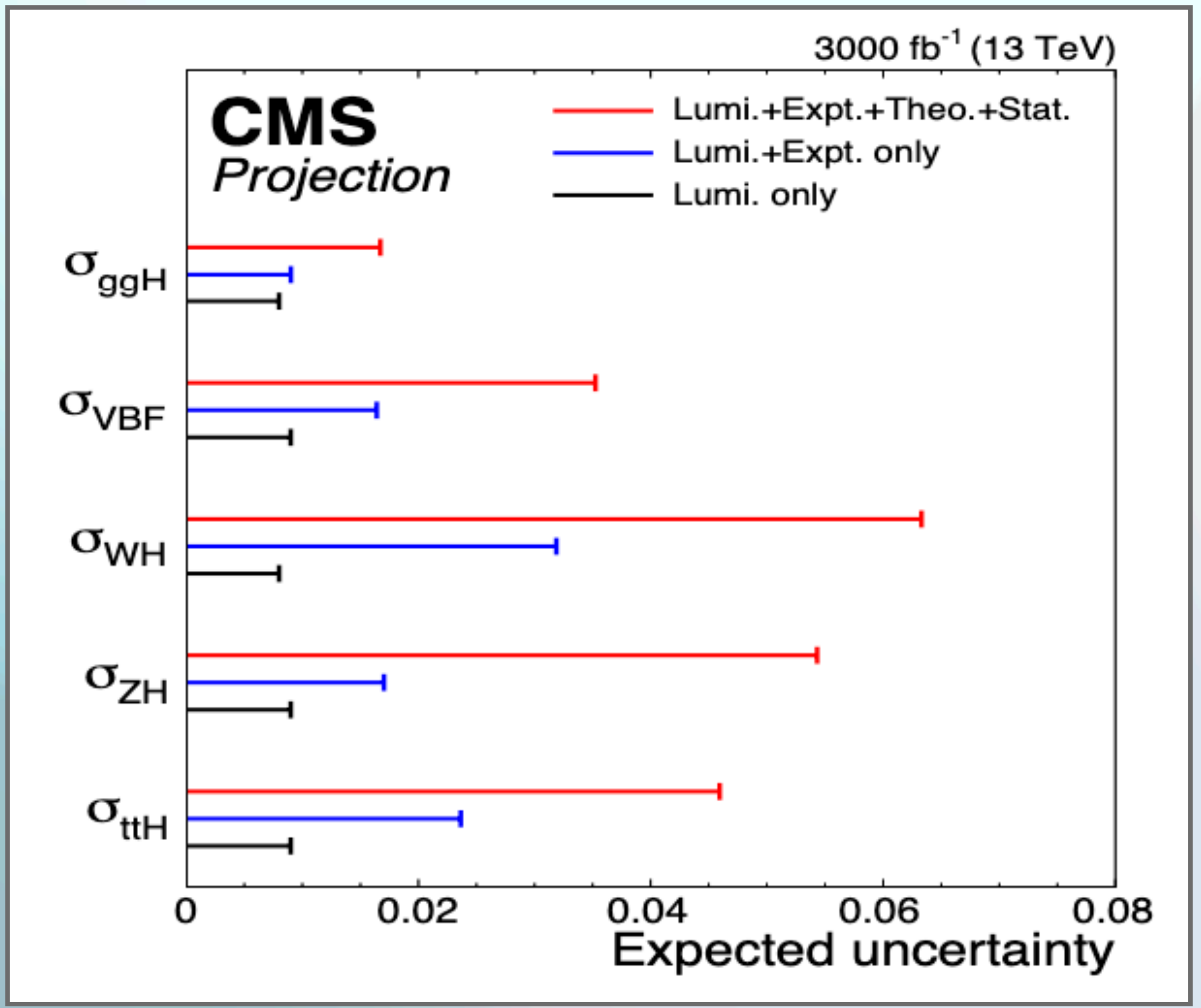


Motivation of the thesis

- A well-designed luminometer is needed with minimized detector-related systematic effects
- Accurate luminosity calibration requires a thorough understanding of the beam-related systematic effects to correct for the biases:
  - motivates detailed studies of corrections and uncertainties related to beam-beam (BB) interaction @ multiple locations
  - experimental validation for simulation models for the effects on the luminosity
- Precision luminosity measurement requirements
  - single largest source of experimental uncertainty in the most precise SM measurements
  - for example top quark pair production - in the latest CMS publication, the 2.3% luminosity unc. dominates the total experimental uncertainty of 2.5% from other sources

Only partial beam-beam correction included in the preliminary Run 2 analyses
➡ picture possibly not complete

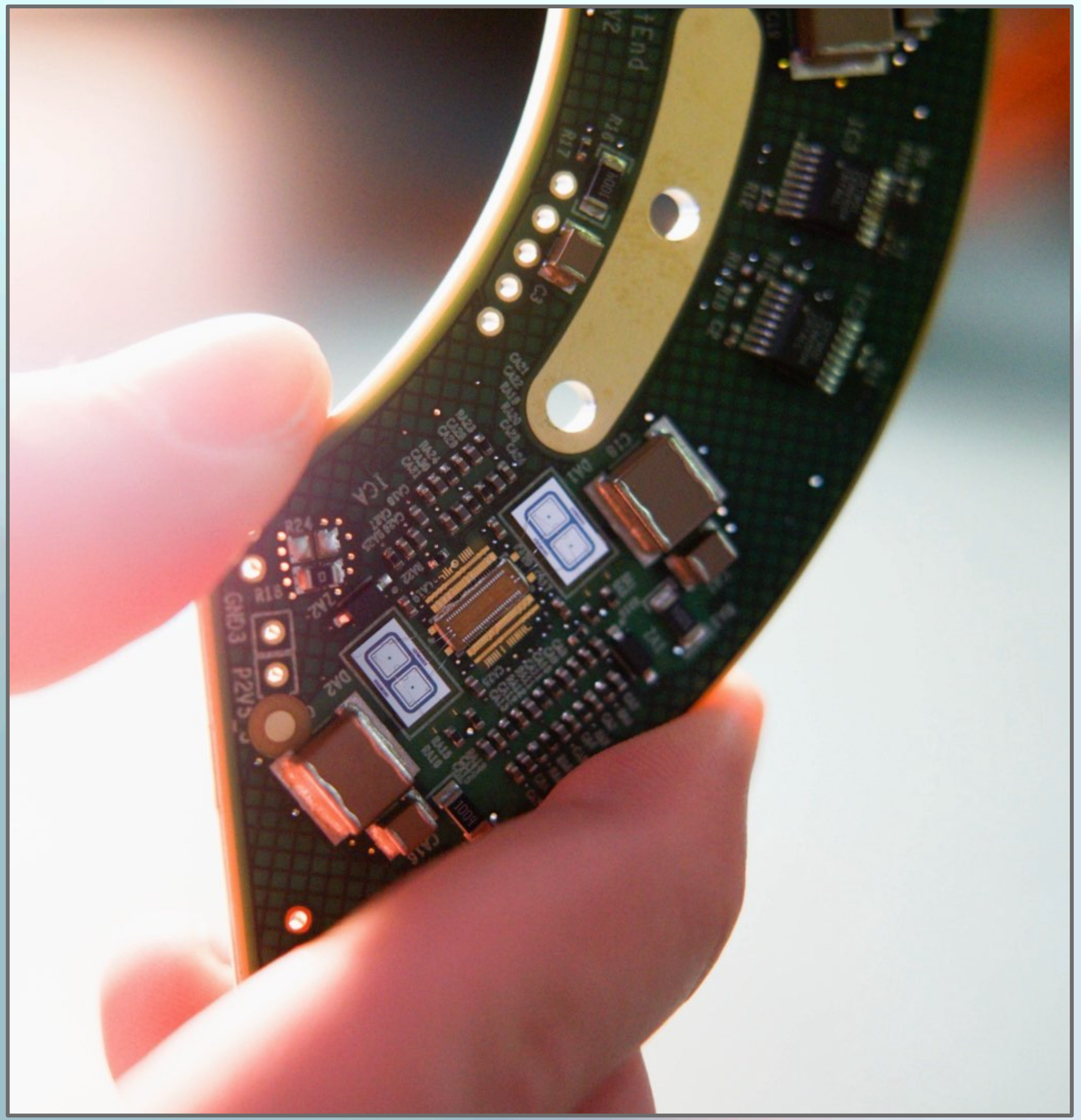
$$R = \mathscr{L}_{inst} \cdot \sigma_{ev}$$



➡ will become even more important at HL-LHC
➡ 1% target for absolute Higgs couplings

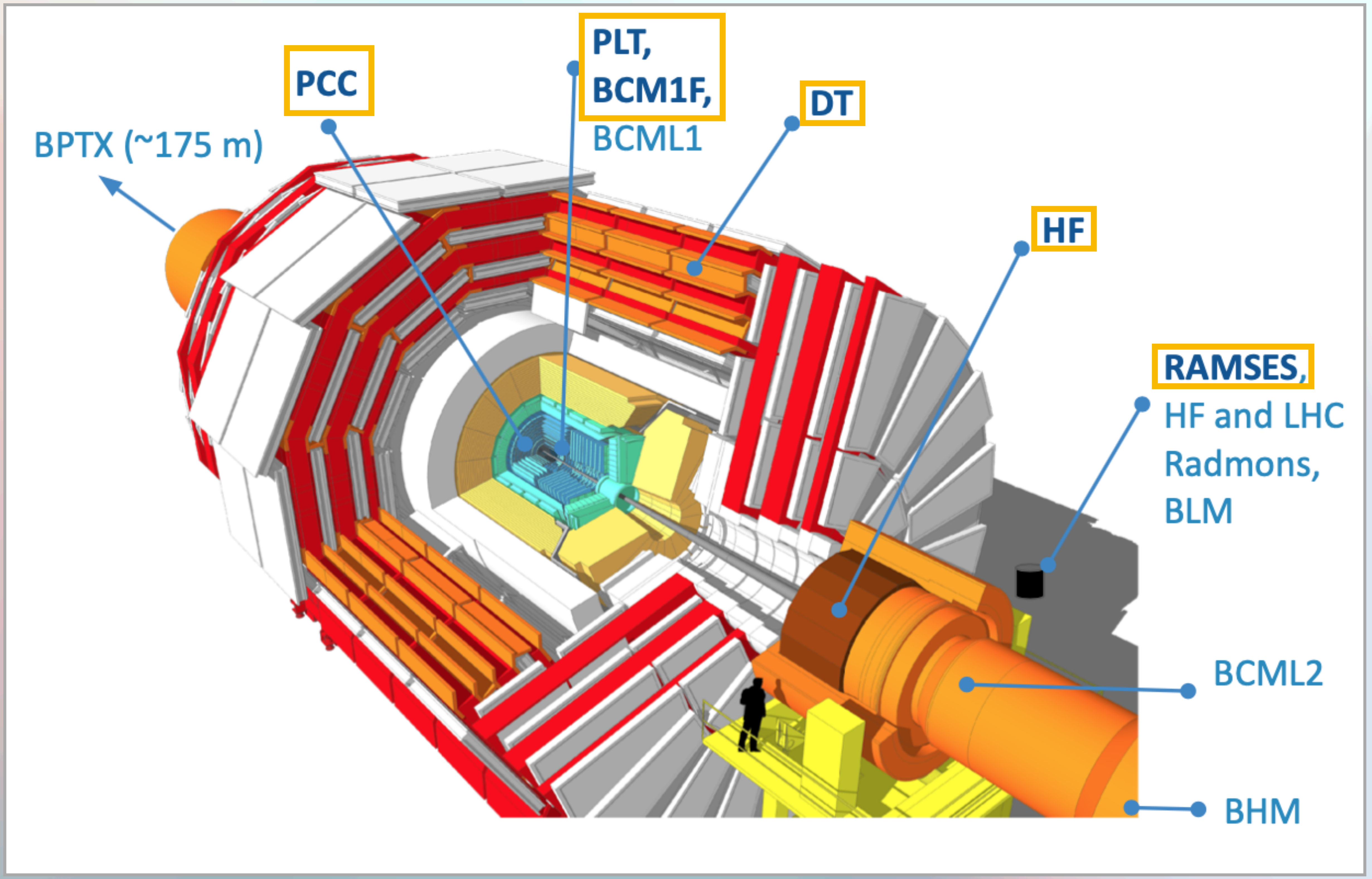
Outline of the presentation

- Introduction & Motivation
- Luminosity measurement with the new Beam Conditions Monitor (BCM1F-utca) for the CMS experiment
- Beam-beam effects in the luminosity calibration
- Absolute luminosity scale calibration of BCM1F-utca for 2022 data set



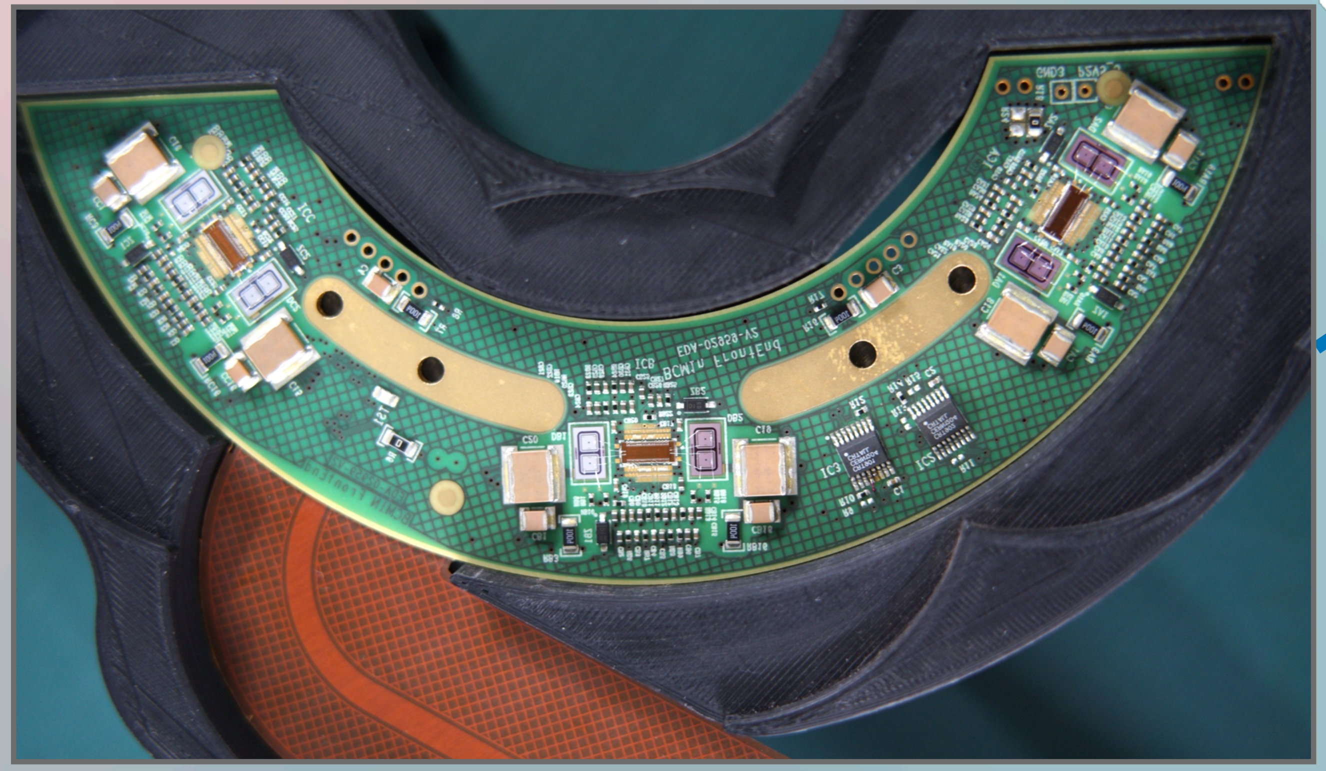
CMS experiment luminometers

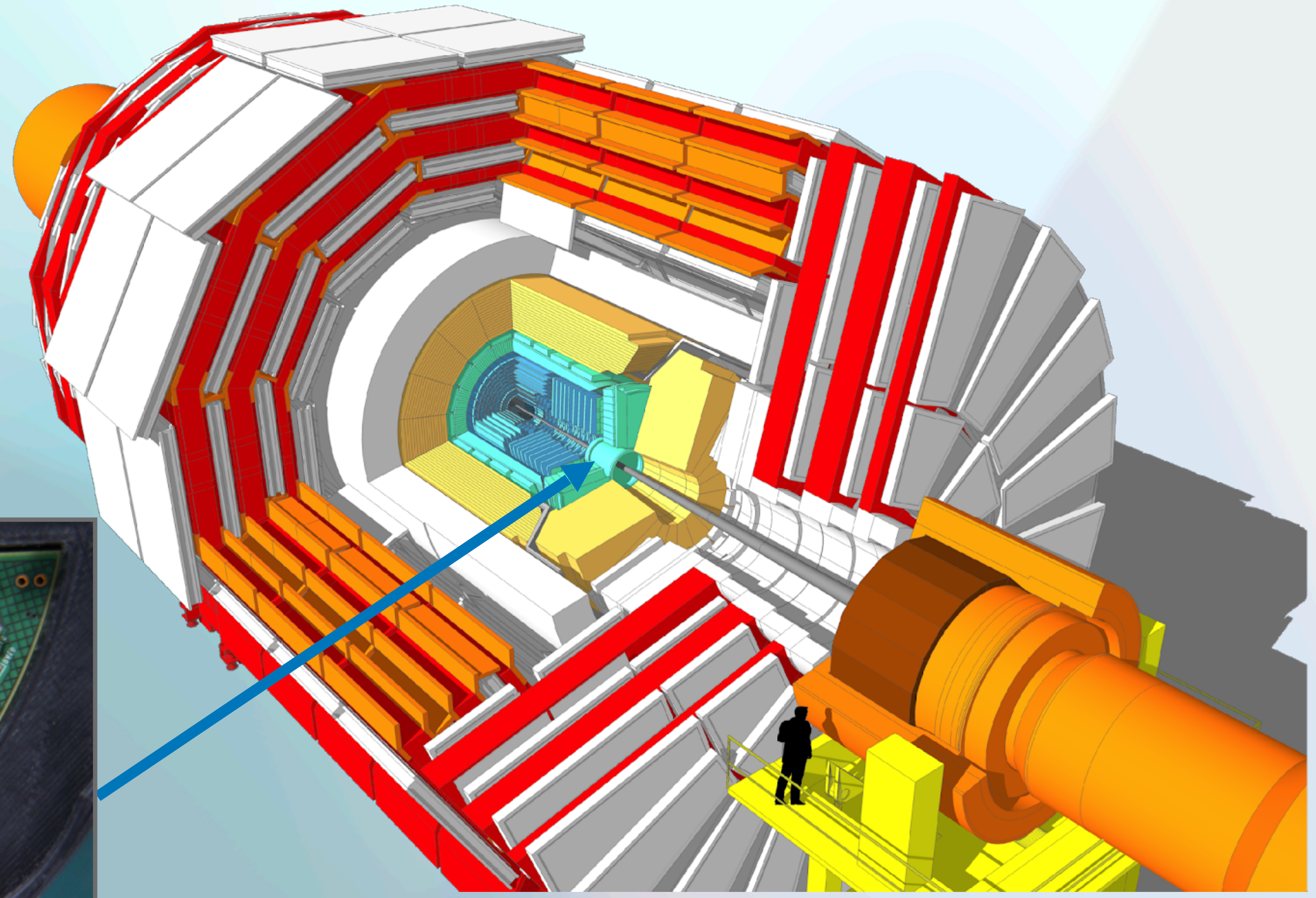
- Beam Radiation Instrumentation and Luminosity (BRIL) Project has the mandate of providing CMS with the luminosity measurement
- 9 luminosity measurements
- BCM1F is one of them
    - dedicated, standalone luminometer, operates independently from central CMS data acquisition system
    - sub-bunch crossing time resolution (< 1 ns), enables the measurement of beam-induced background



BCM1F-utca luminometer

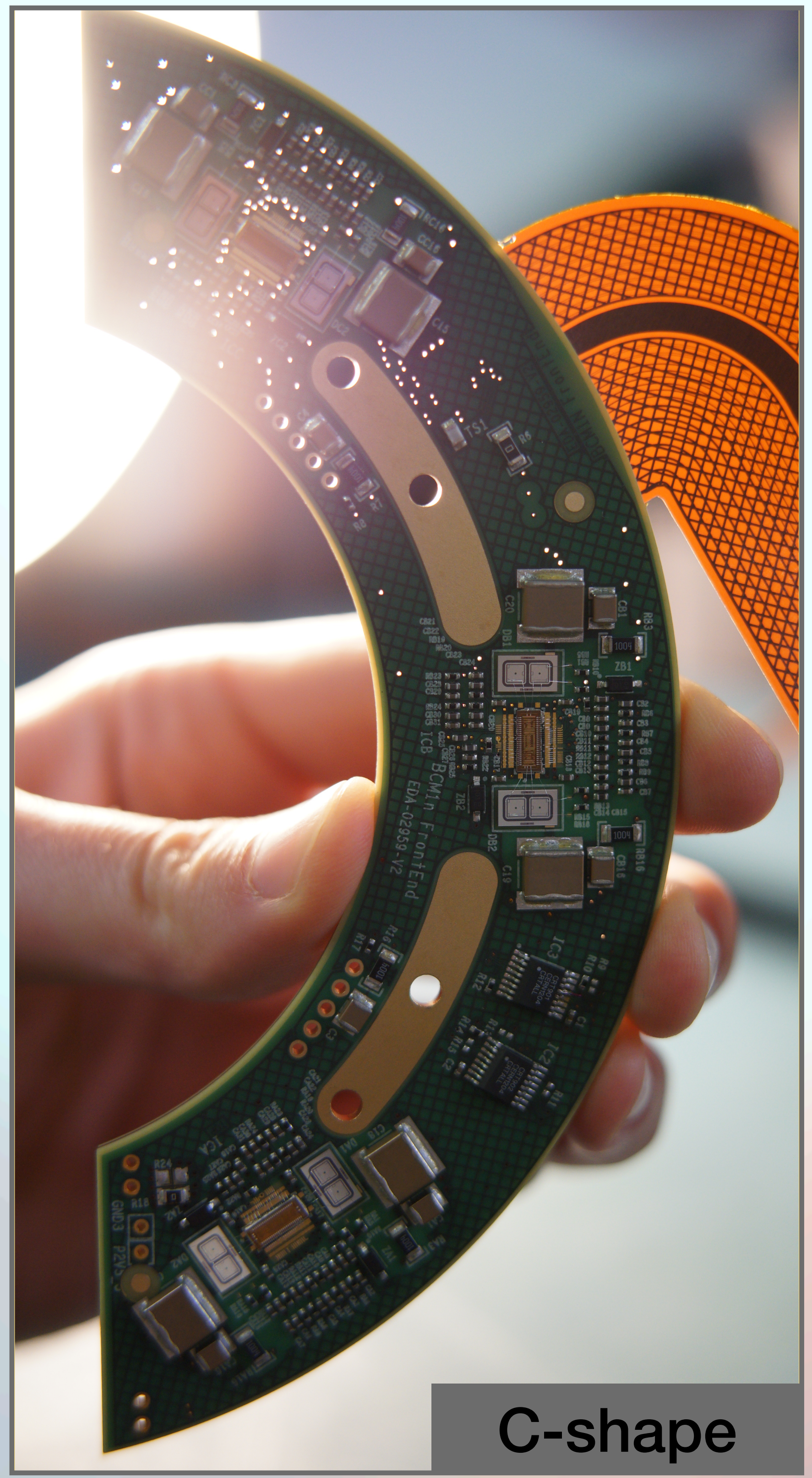
- Good performance achieved in Run 2 with the detector prototype:
  - mixed sensor types were used: diamonds and Silicon
  - signal-noise separation and response linearity much better for the Silicon sensors
  - stable operation, but data quality was limited
- Upgraded during Long Shutdown 2 for LHC Run 3:
  - new Silicon diodes
  - titanium circuit for active cooling to -20°C



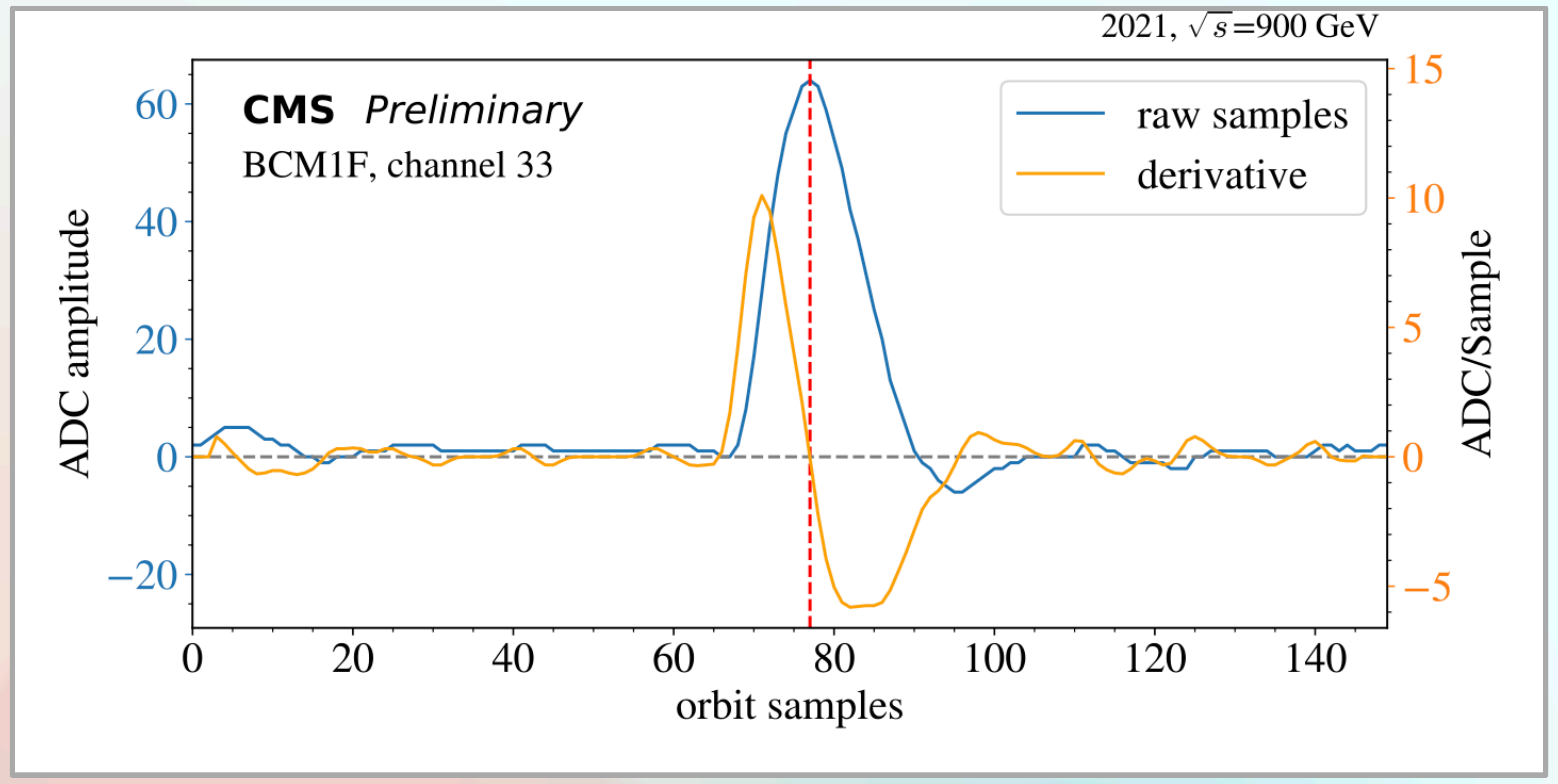


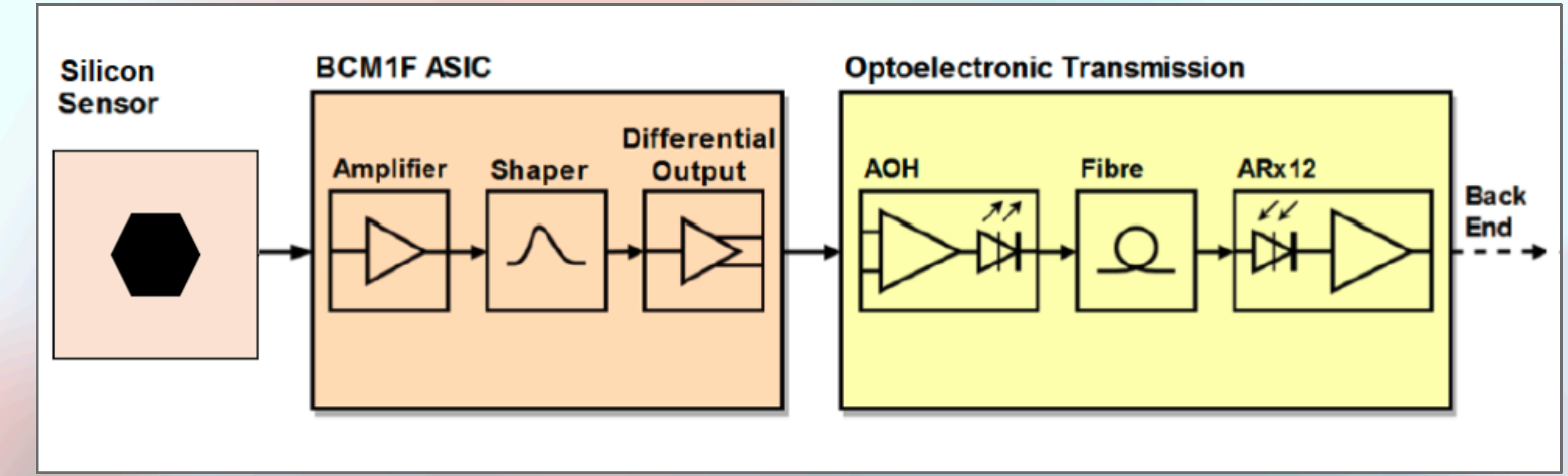
located just outside the beampipe, 1.9 m from the interaction point (IP)

BCM1F-utca luminometer



- ionizing particle generates electrons and holes





new derivative-based peak finding algorithm

Sensors:

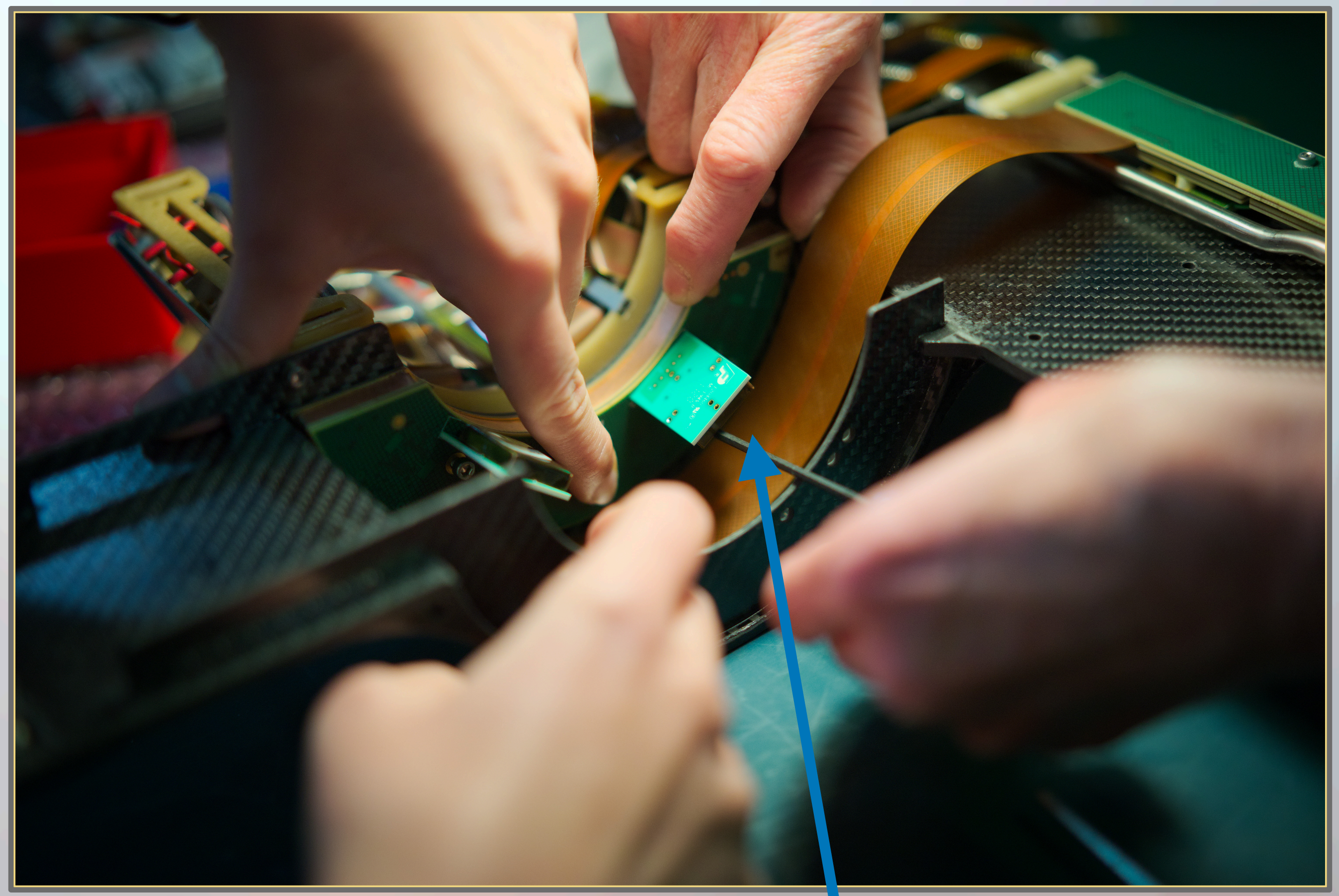
- 290 um thick
- 1.7×1.7 mm^2 area
- AC-coupled

ASIC:

- radiation-hard
- < 10 ns peaking time
- ~10 ns FWHM

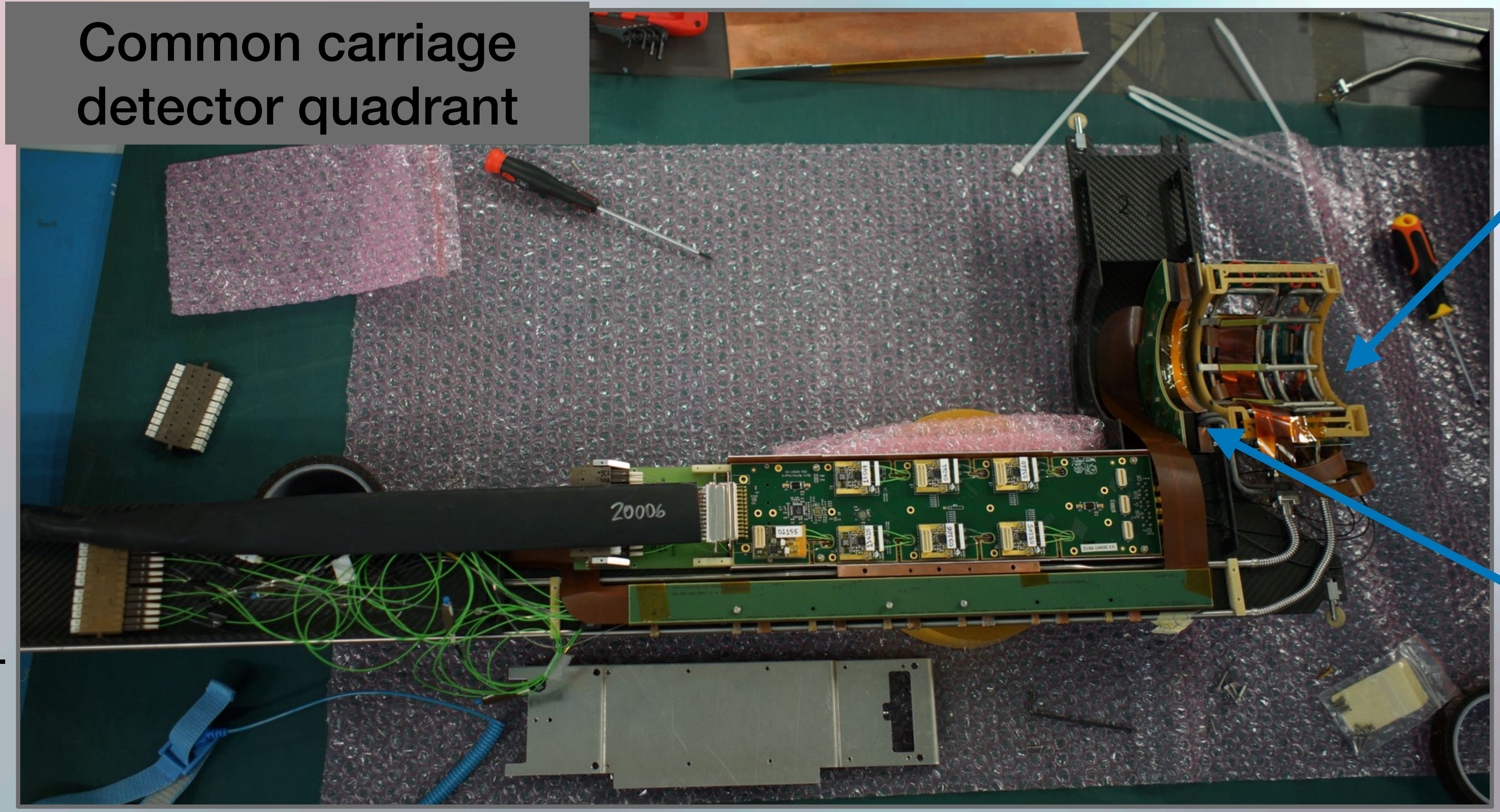
Detector assembly

- laboratory tests for best-quality components
- each C-shape pair forms a ring around the beam pipe at a radius of 7 cm
- total of 48 channels (4x12)
- integration on a common carbon fiber carriage with the Pixel Luminosity Telescope (PLT) and Beam Conditions Monitor for Losses (BCML1)



diamond sensor (BCML1)

Nov. 2020 - April 2021



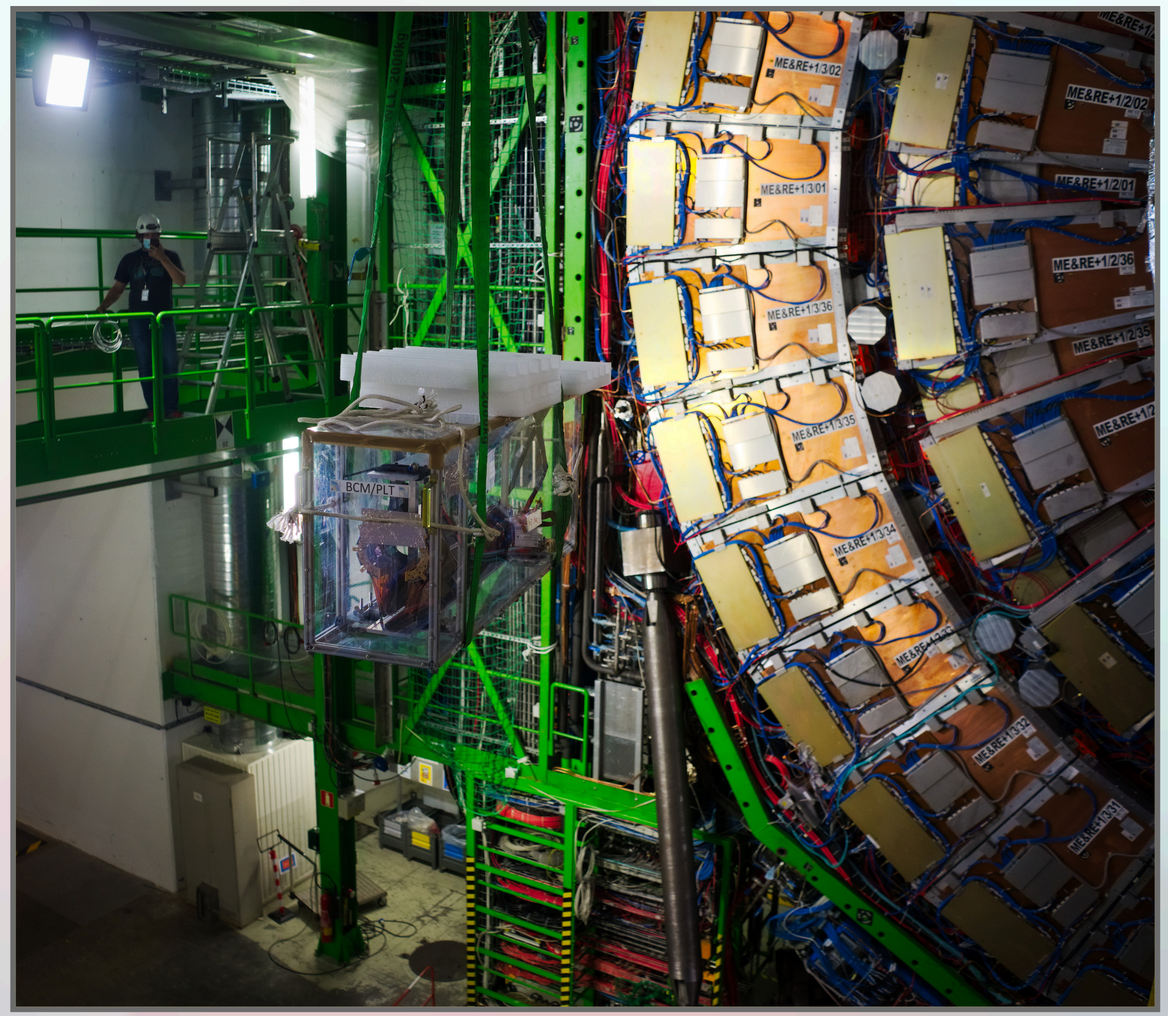
Common carriage detector quadrant

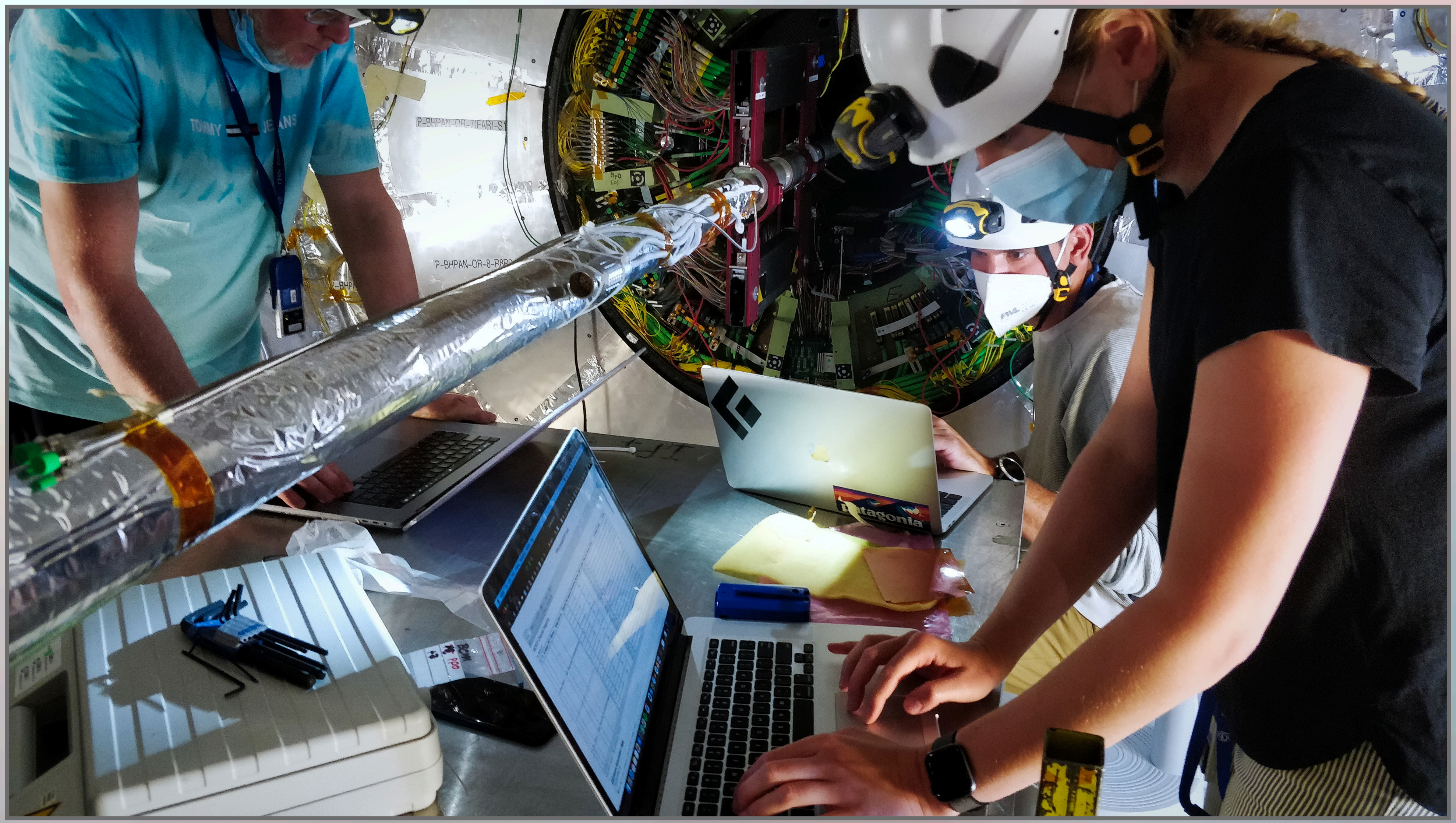
PLT cassette

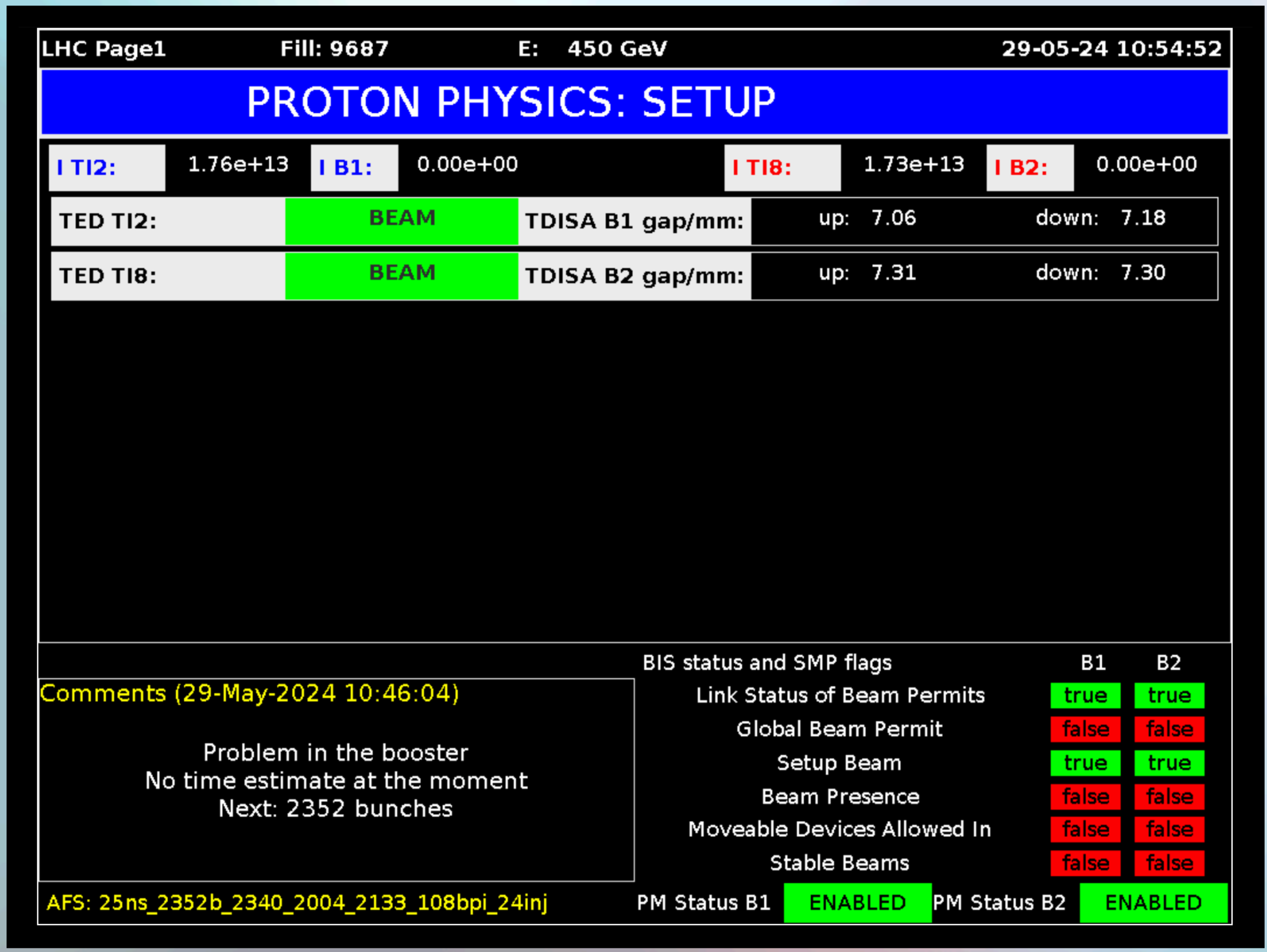
new BCM1F cooling loop

Detector installation

- installation behind the CMS pixel detector, on both ends
- commissioning of
    - new front-end during the 2021 LHC pilot beam test
    - new back-end during the 2022 LHC ramp up
- online operations







LHC Page1 Fill: 9687 E: 450 GeV 29-05-24 10:54:52

PROTON PHYSICS: SETUP

I TI2:	1.76e+13	I B1:	0.00e+00	I TI8:	1.73e+13	I B2:	0.00e+00

TED TI2:	BEAM	TDISA B1 gap/mm:	up: 7.06	down: 7.18
TED TI8:	BEAM	TDISA B2 gap/mm:	up: 7.31	down: 7.30

Comments (29-May-2024 10:46:04)

Problem in the booster
No time estimate at the moment
Next: 2352 bunches

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	false	false
Setup Beam	true	true
Beam Presence	false	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

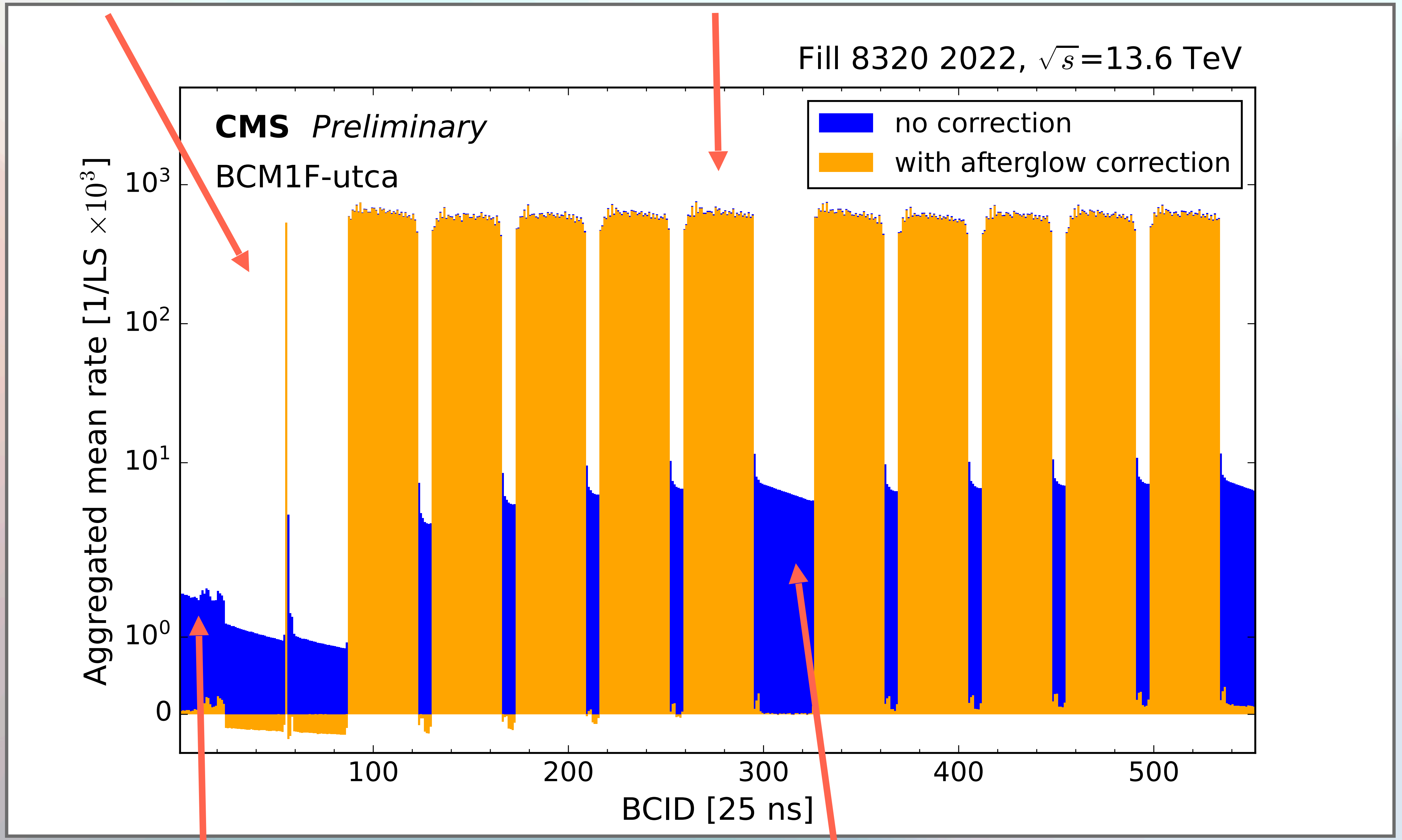
AFS: 25ns_2352b_2340_2004_2133_108bpi_24inj PM Status B1 ENABLED PM Status B2 ENABLED

Measurement with BCM1F

- ➔ Detector configuration optimized to measure direct collision products and beam induced background
- ➔ Additional out-of-time hit count requires corrections
- ➔ BCM1F has been operational including the new backend system since the beginning of the LHC commissioning period for Run 3

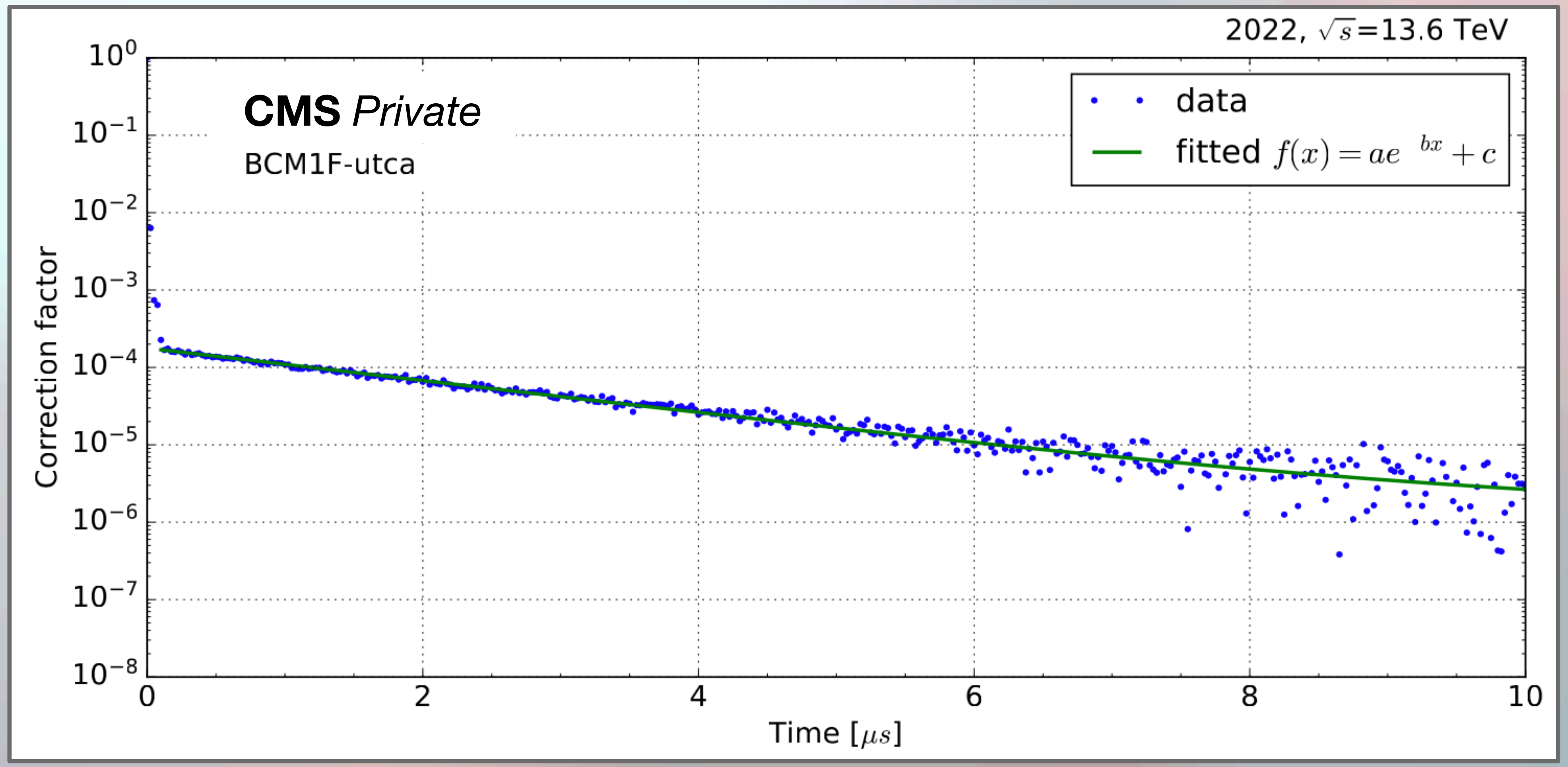
individual
colliding bunch

set of four
bunch trains



beam induced background
from non-colliding bunches

afterglow tail



Early performance reported in
the contributed talk at IBIC'22

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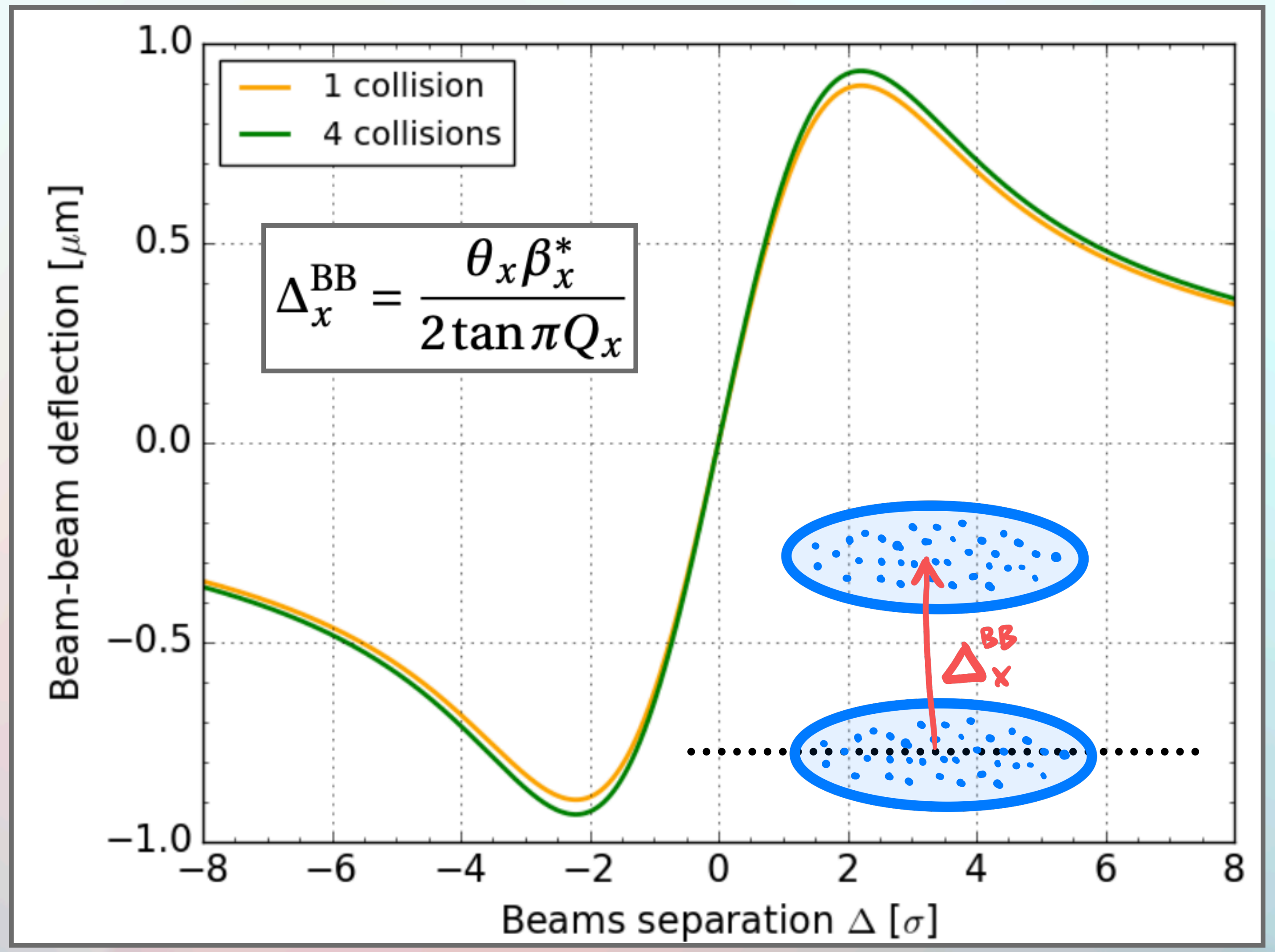
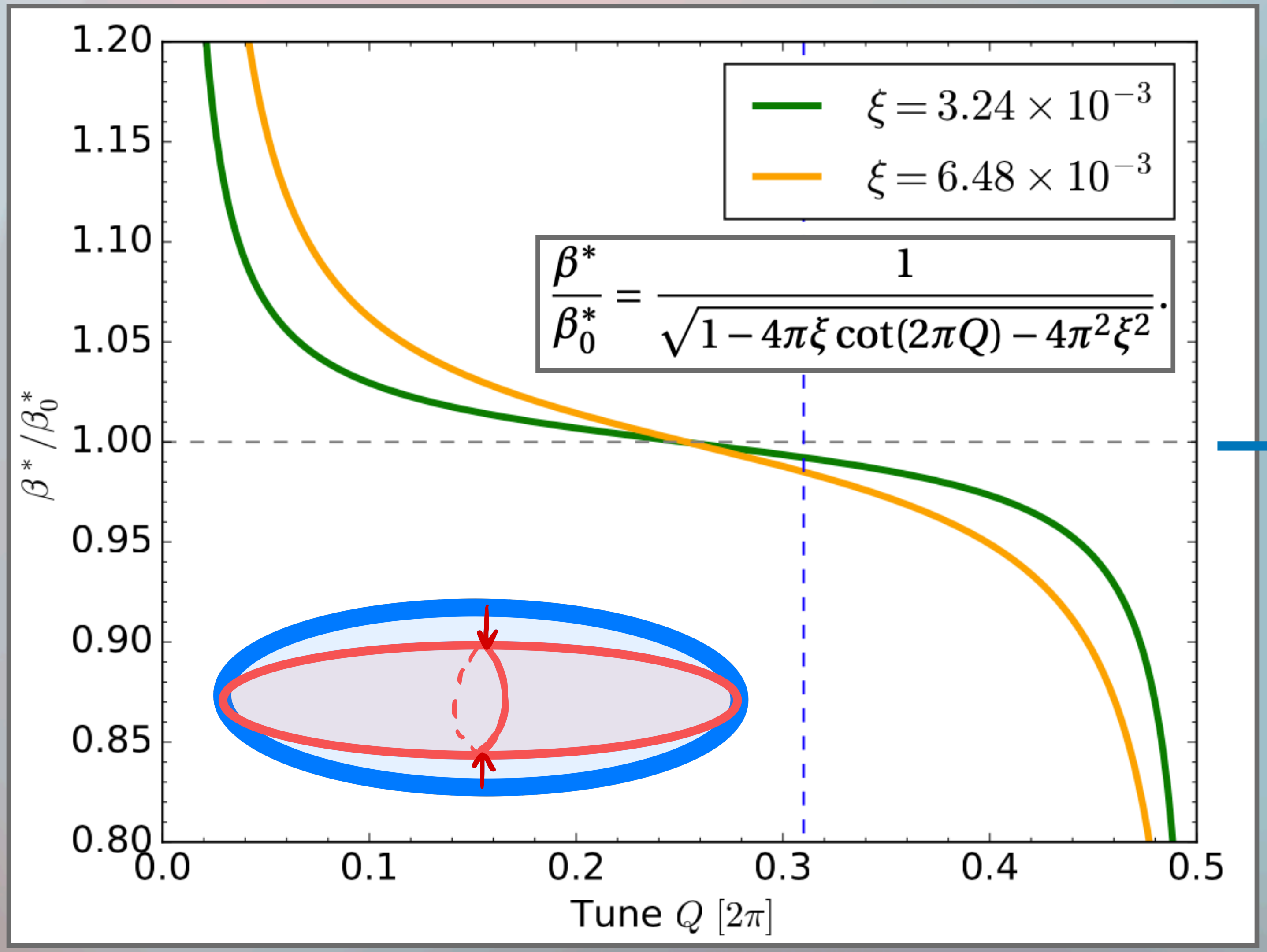
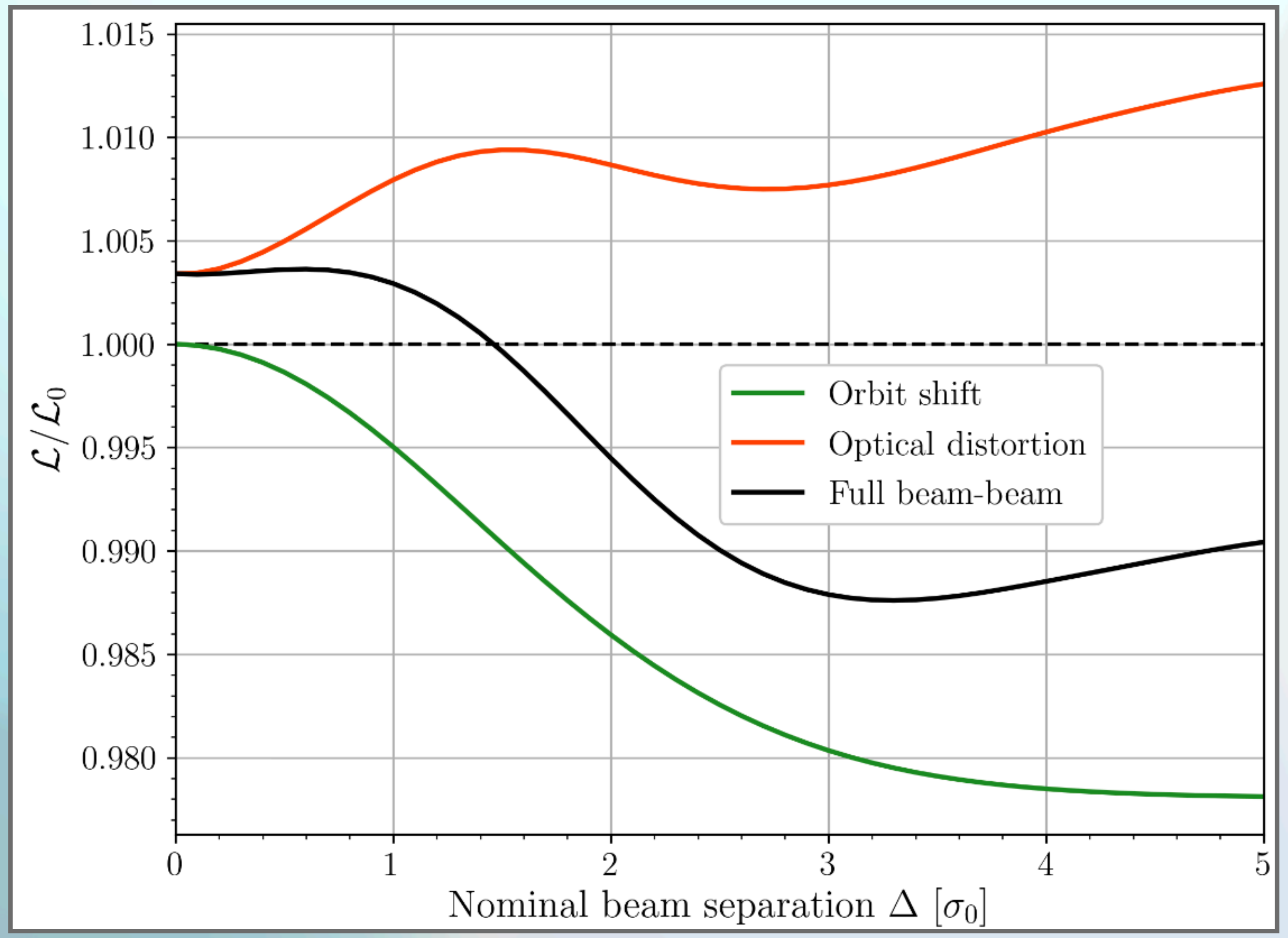
- Introduction & motivation
- Luminosity measurement with the new Beam Conditions Monitor (BCM1F-utca) for the CMS experiment
- Beam-beam effects in the luminosity calibration
  - simulation studies for corrections and quantification of systematic effects in luminosity calibration
  - dedicated experiment at the LHC for correction model validation
- Absolute luminosity scale calibration of BCM1F-utca for 2022 data set

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
- Beam-separation dependent corrections
- Overall effect on the calibration constant slightly negative (sign and magnitude are tune-dependent)







beam size envelope

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

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

for Gaussian particle distrib.

Beam-beam effects on luminosity

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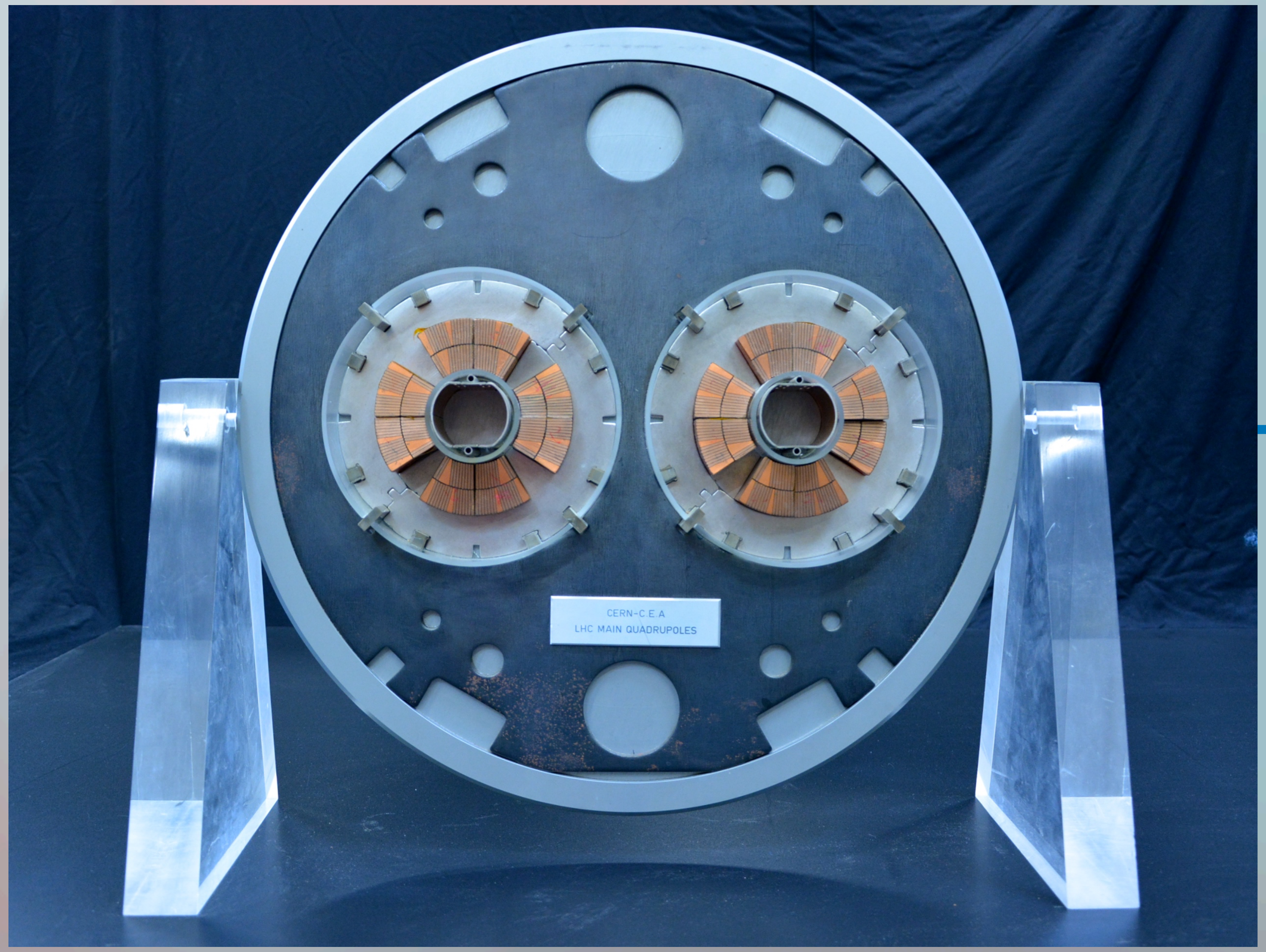

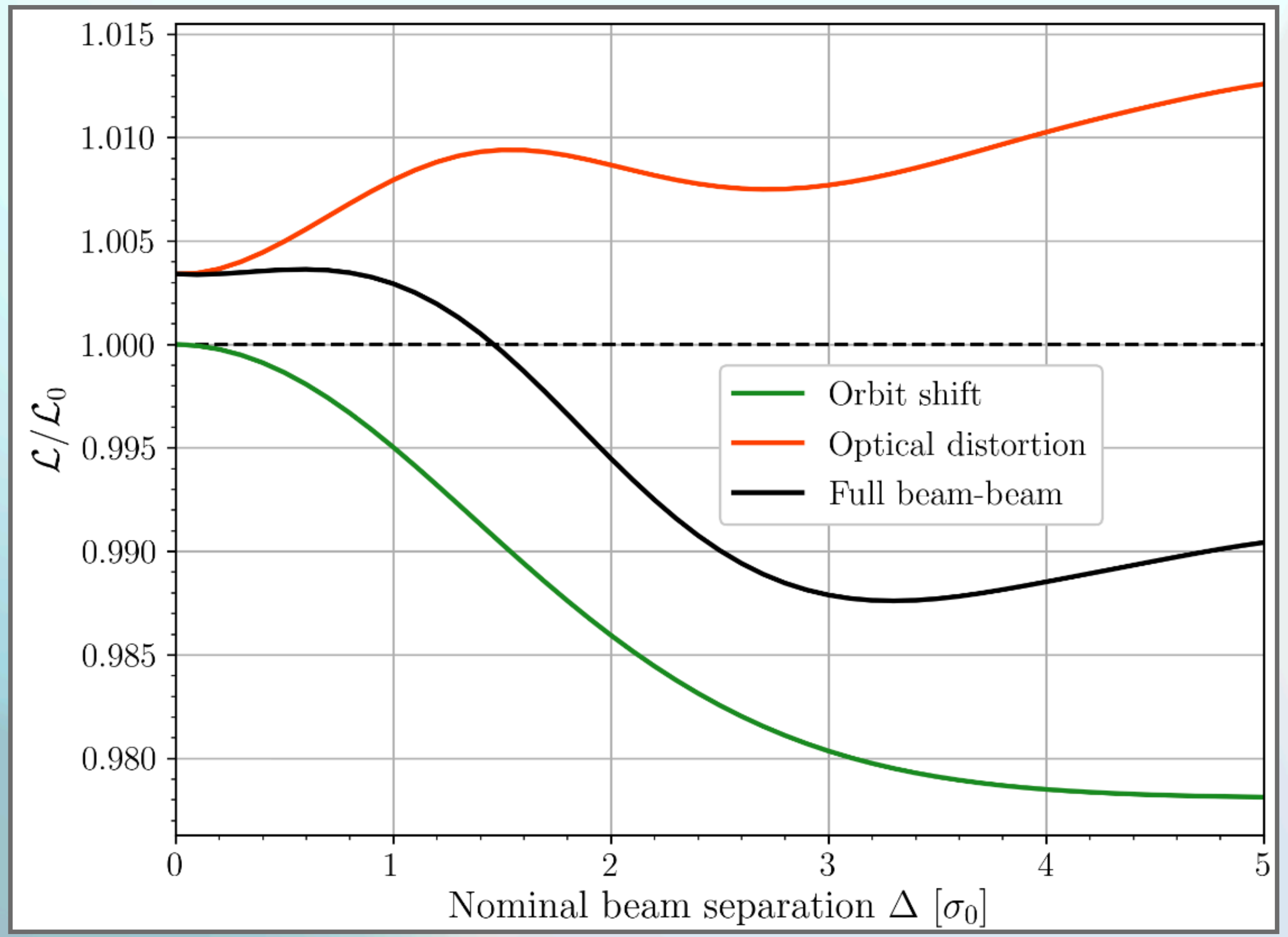

beam size envelope

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for Gaussian particle distrib.

Beam-beam effects on luminosity calibration

- LHC working group effort including all experiments and accelerator experts

EPJ C

2022 Impact factor **4.4**

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10 most recent **Browse issues** **Topical issues** **Reviews** **Letters**

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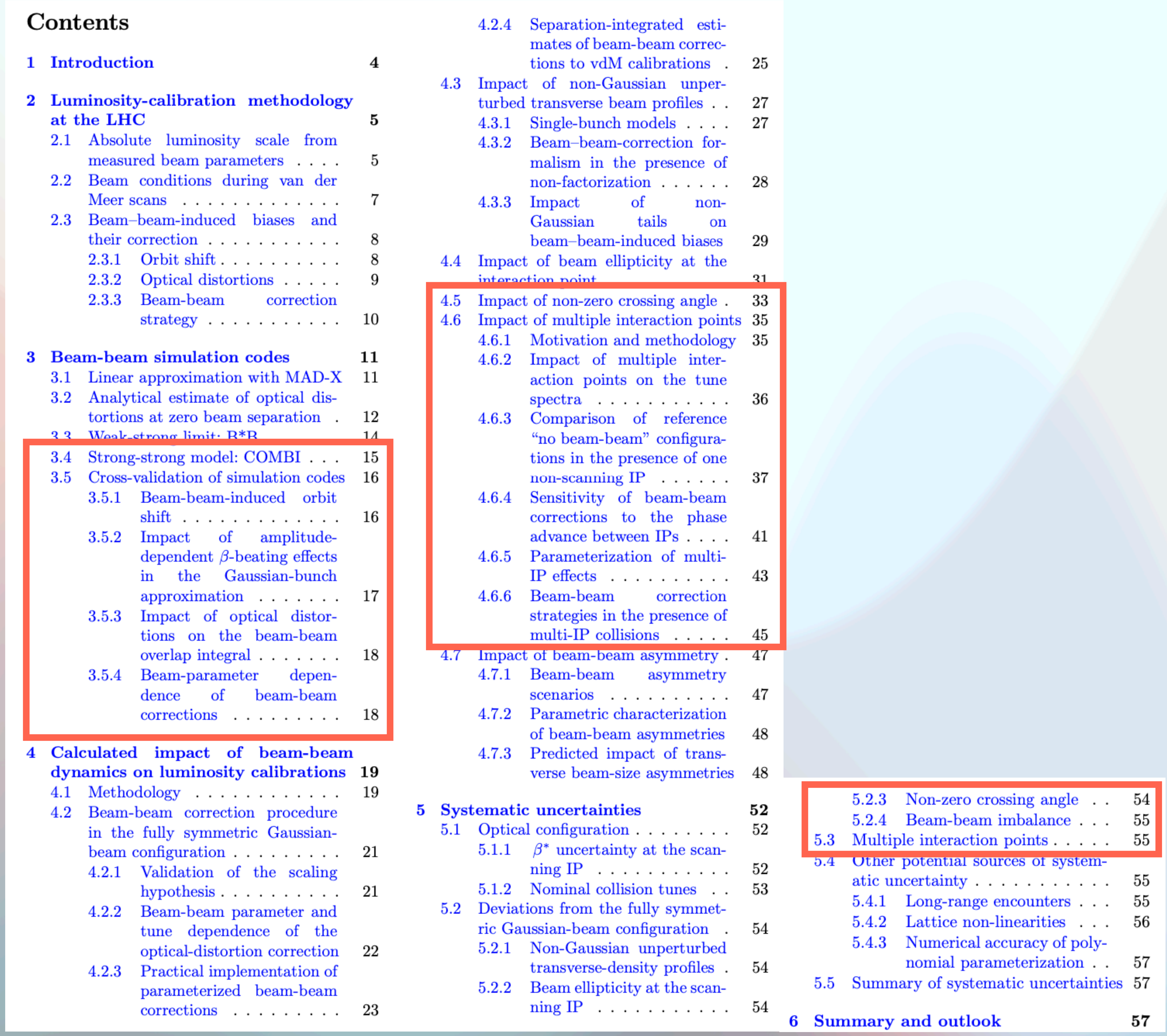
https://doi.org/10.1140/epjc/s10052-023-12192-5

Regular Article - Experimental Physics

Impact of beam–beam effects on absolute luminosity calibrations at the CERN Large Hadron Collider

A. Babaev[1], **T. Barklow**[2], **O. Karacheban**[3,4], **W. Kozanecki**[5], **I. Kralik**[6], **A. Mehta**[7], **G. Pasztor**[7], **T. Pieloni**[8h], **D. Stickland**[9], **C. Tambasco**[8], **R. Tomas**[4] and **J. Wańczyk**[4,8]

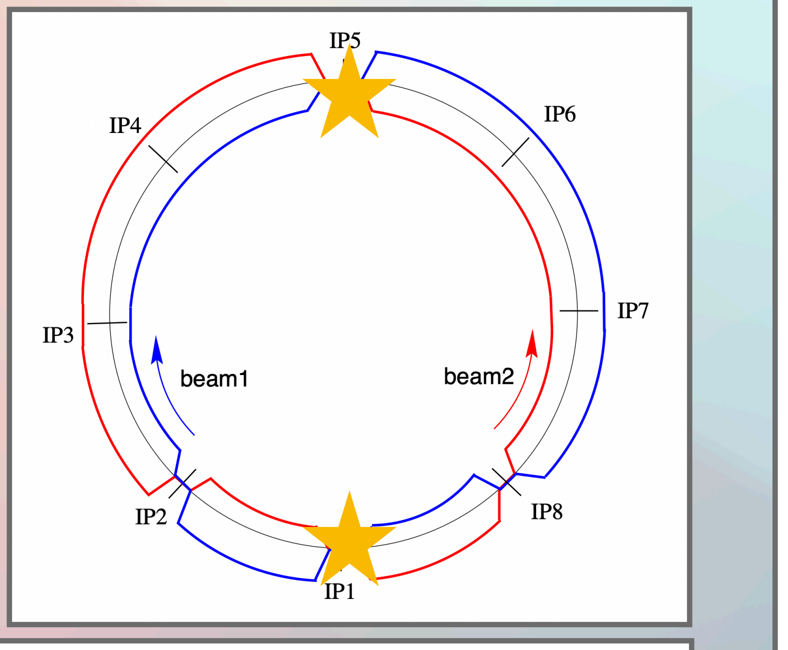


Contents

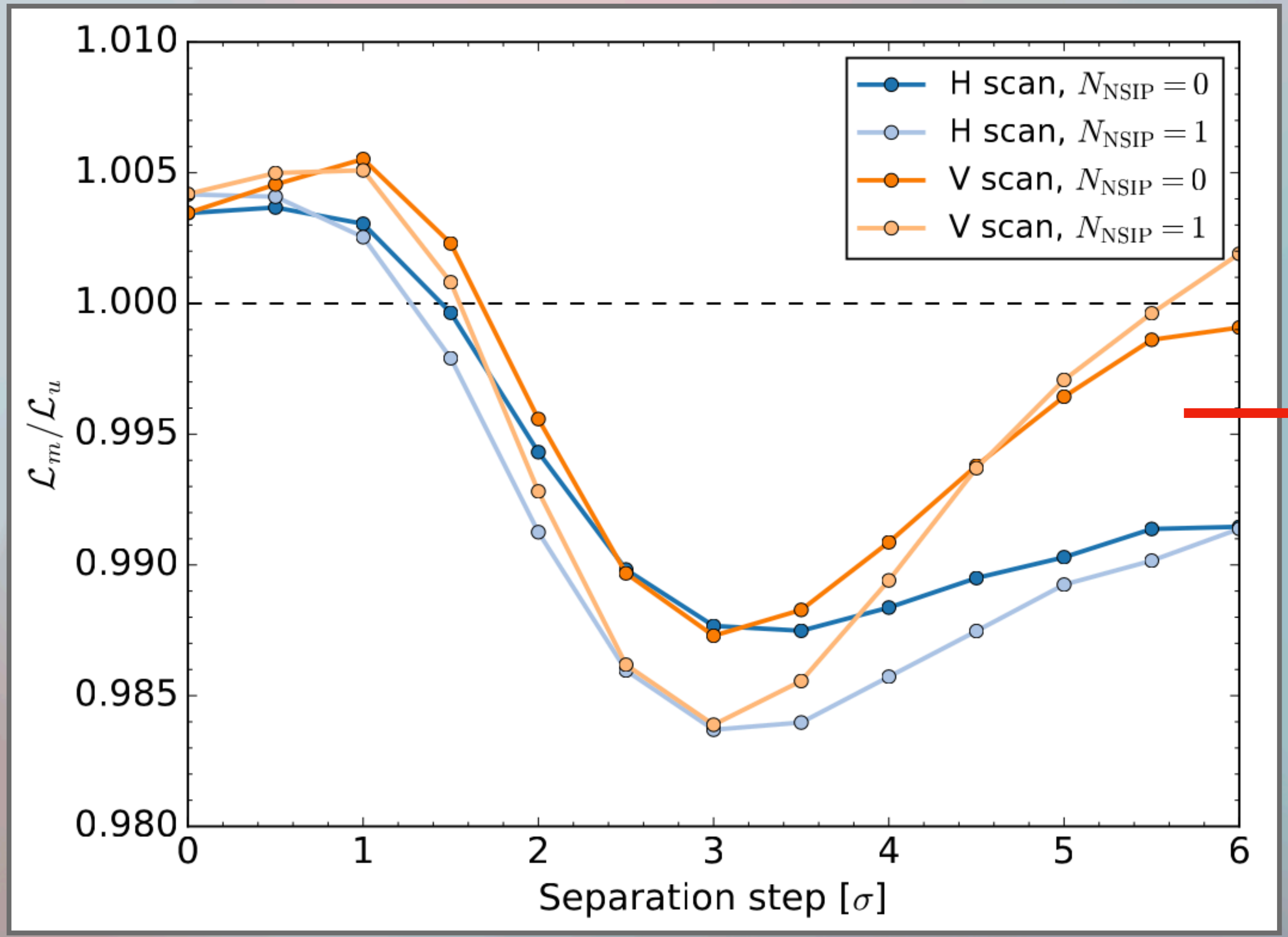
- Extensions of this work:
  - Poster at IPAC'23
  - Talk at EPS'23

Multi-collision study for vdM calibration

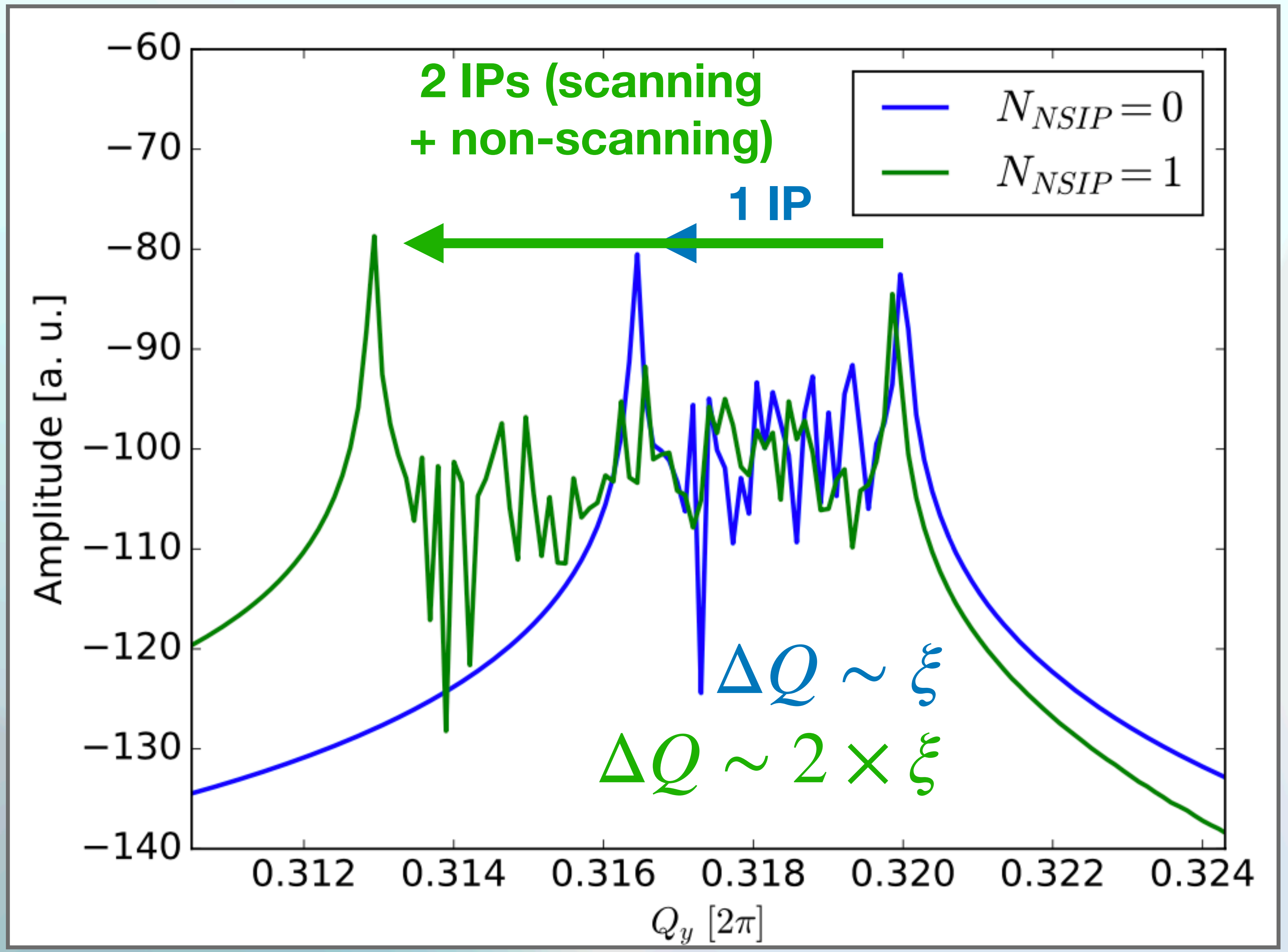
- Starting point: correction model parametrizing the beam-beam effects on luminosity $\mathscr{L}/\mathscr{L}_0(\Delta, \xi, Q_x, Q_y)$
- contribution from the additional collisions at interaction points (IPs) other than the scanning IP <u>not considered previously</u>
  - simulation campaign to evaluate them
- additional collision = additional betatron tune shift
  - separation-dependent effect on luminosity depends on the collision configuration
  - in the example of 2 IPs - double the effect on the calibration constant



	relative difference in $\sigma_{vis}/\sigma^0_{vis}$
1 IP	-0.16%
2 IPs	-0.37%



whole bunch motion = coherent spectra



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

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

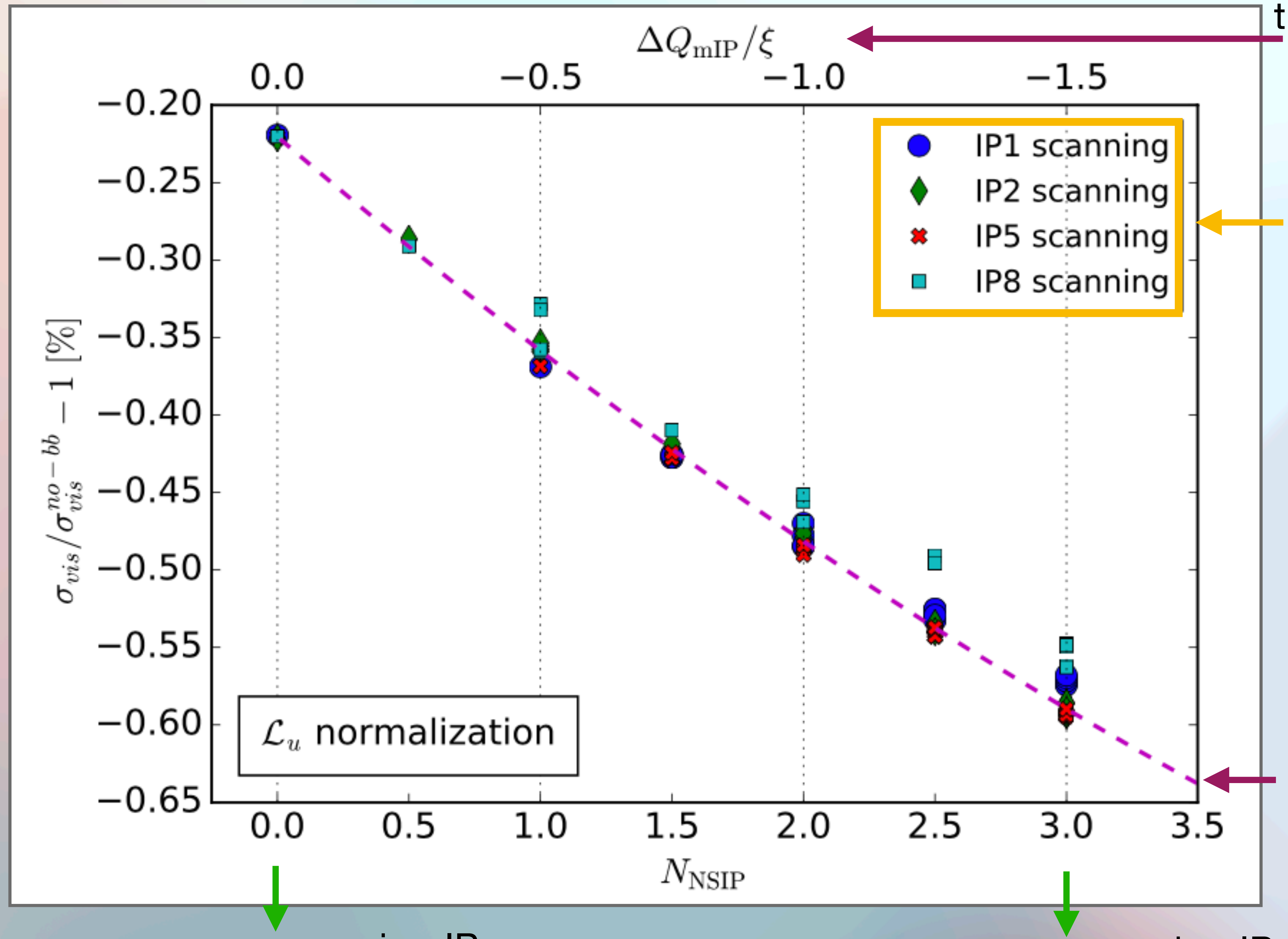
- How to include that in the corrections in a universal way?

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 $\mathscr{L}/\mathscr{L}_0(\Delta, \xi, Q_x, Q_y)$
- 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:

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

  - valid for all LHC IPs
  - verified in simulation for vdM regime $(\xi < 0.01)$



tune shift for single-IP calculation

full multi-collision simulation

single-IP calculation

scanning-IP only

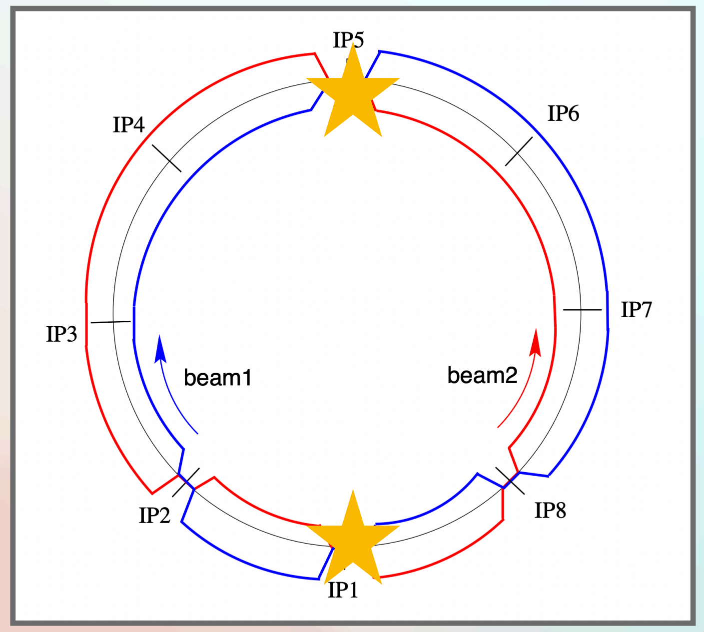
scanning-IP + 3 extra collisions

Outline of the presentation

- Introduction & motivation
- Luminosity measurement with the new Beam Conditions Monitor (BCM1F-utca) for the CMS experiment
- Beam-beam effects in the luminosity calibration
  - simulation studies for corrections and quantification of systematic effects in luminosity calibration
  - dedicated experiment at the LHC for correction model validation
- Absolute luminosity scale calibration of BCM1F-utca for 2022 data set

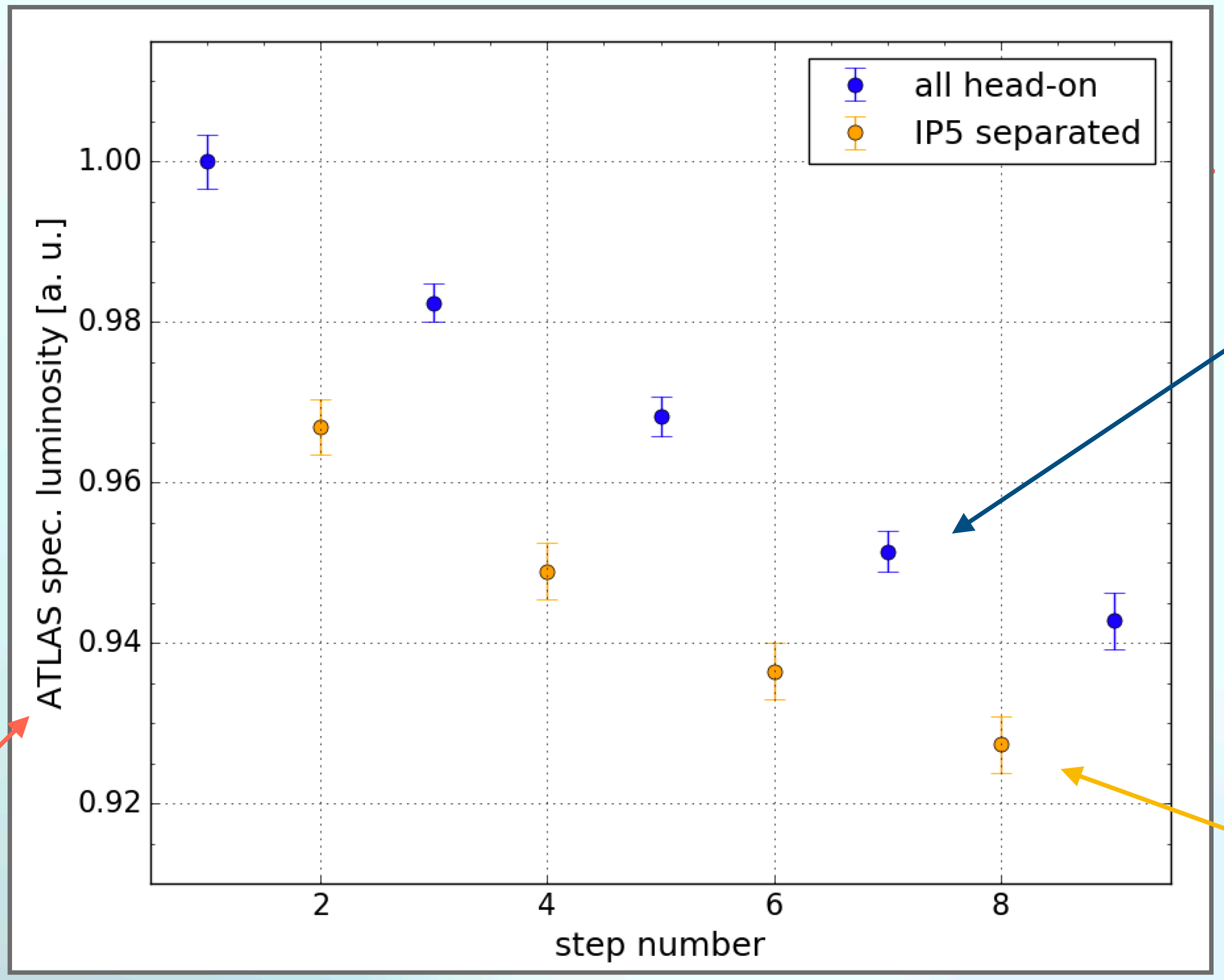
Beam-beam experiment results

- dedicated experiment at the LHC aimed at validation of the correction strategy used in the vdM calibration
- methodology using the witness IP with configuration changes at other location and optimized phase advances
- first measurement of the impact of BB effects on the luminosity at the LHC
- scaling law with BB parameter verified
  - very good agreement with simulation
  - stat. uncertainties could be rendered negligible if experiment could be repeated at nominal energy (both luminosity & σ_{vis} several times larger)



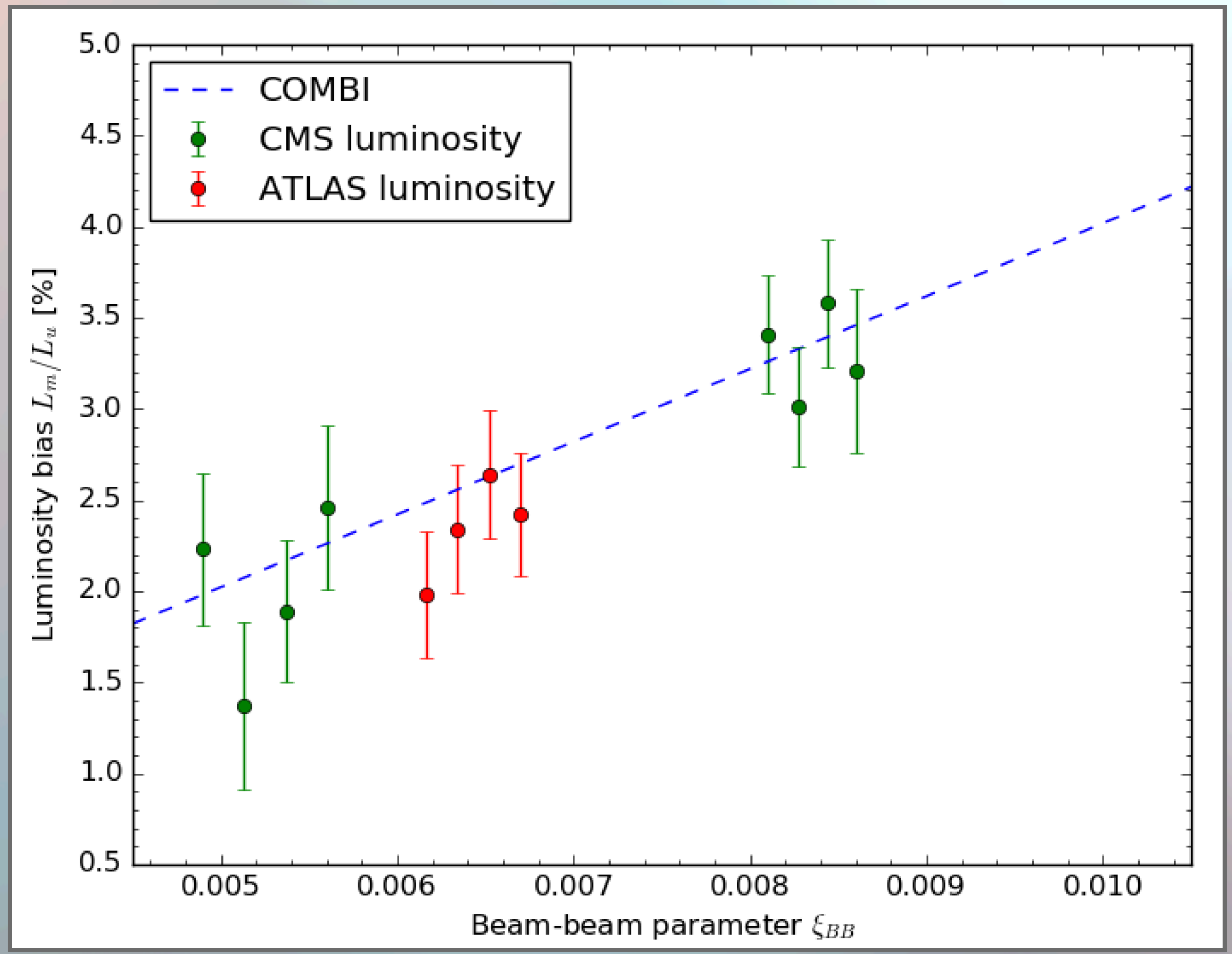
witness

Luminosity observations



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

Outline of the presentation

- Introduction & motivation
- Luminosity measurement with the new Beam Conditions Monitor (BCM1F-utca) for the CMS experiment
- Beam-beam effects in the luminosity calibration
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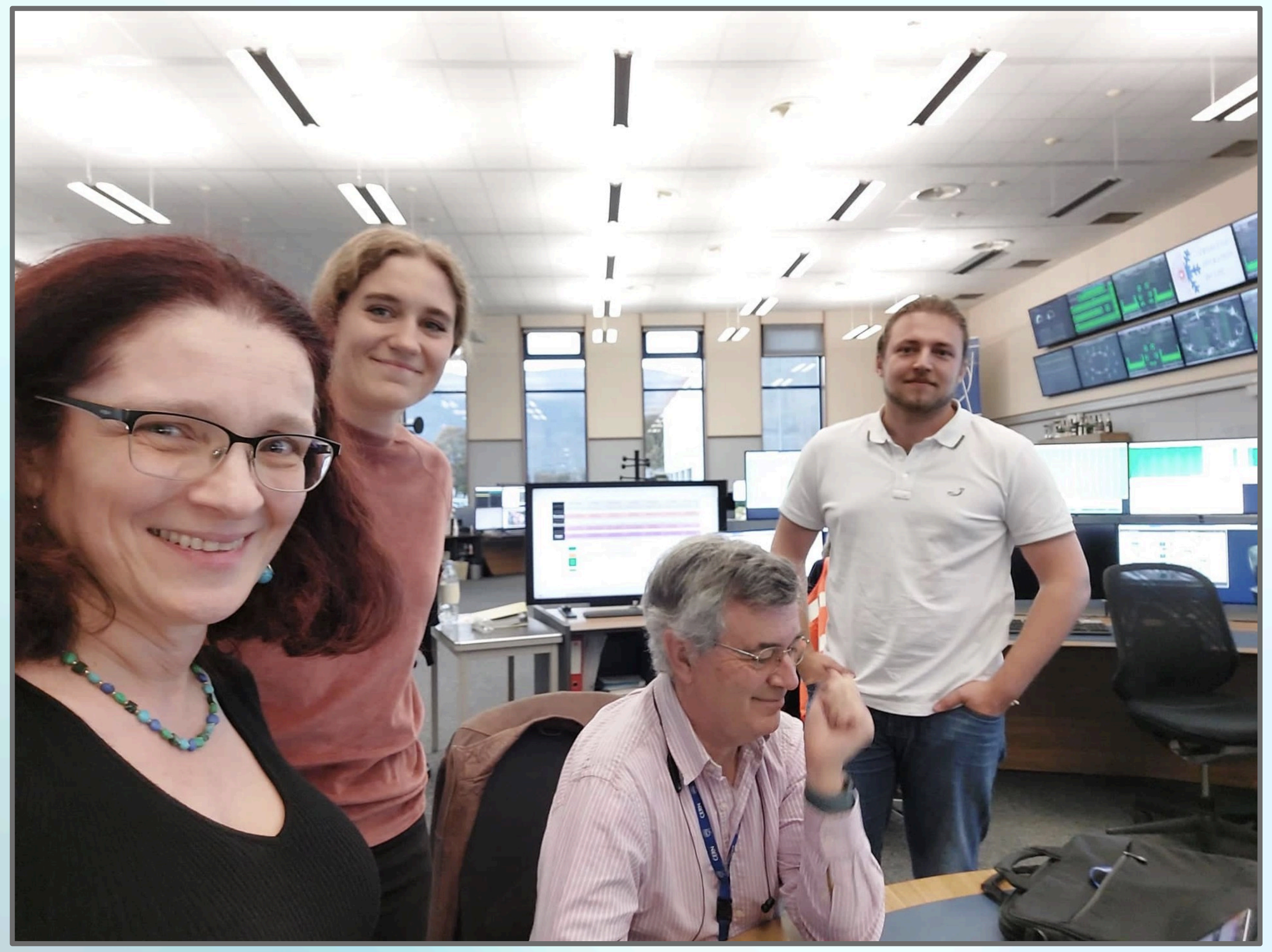
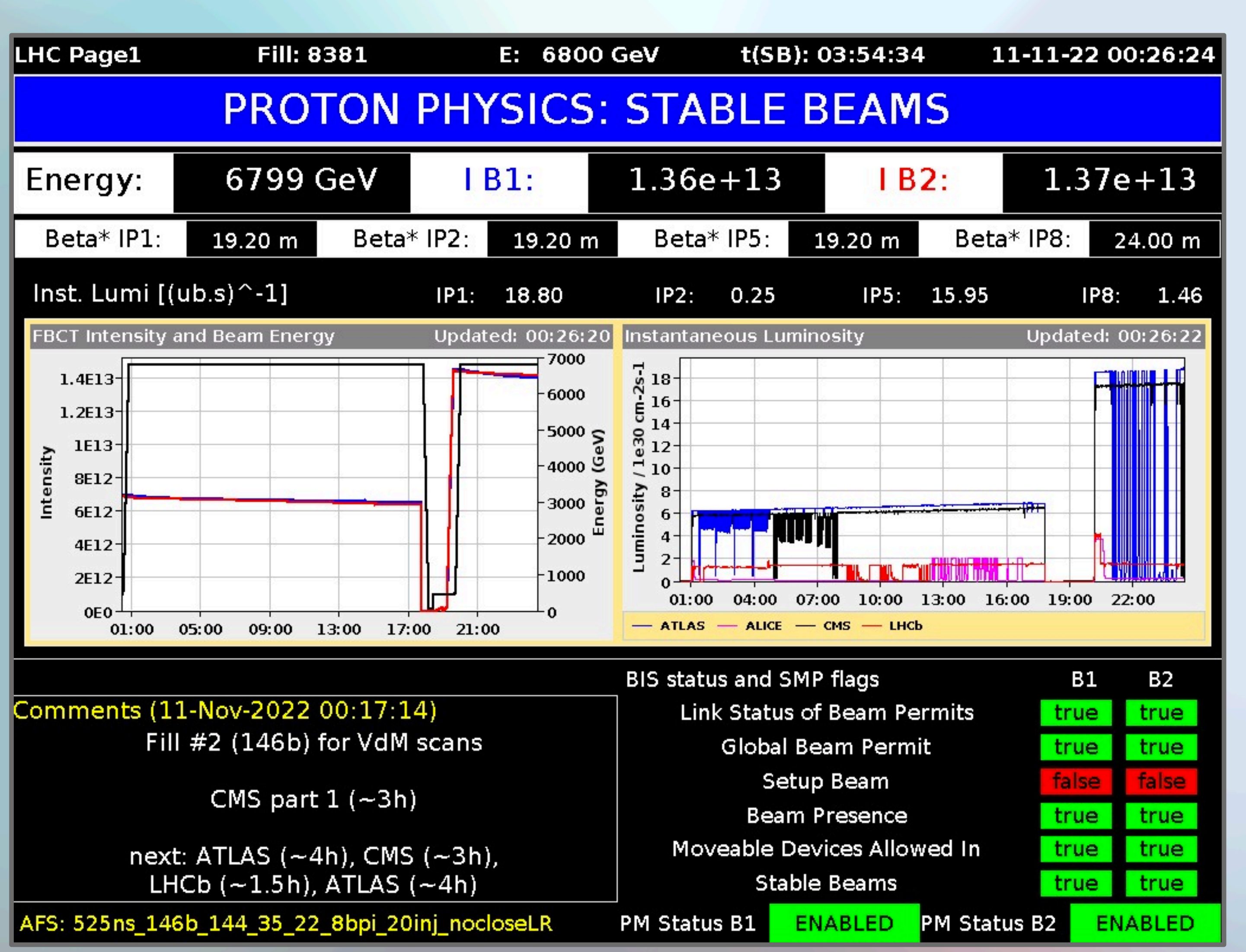




LHC Page1 Fill: 8381 E: 6800 GeV t(SB): 03:54:34 11-11-22 00:26:24

PROTON PHYSICS: STABLE BEAMS

Energy:	6799 GeV	I B1:	1.36e+13	I B2:	1.37e+13

Beta* IP1:	19.20 m	Beta* IP2:	19.20 m	Beta* IP5:	19.20 m	Beta* IP8:	24.00 m

Inst. Lumi [(ub.s)^-1] IP1: 18.80 IP2: 0.25 IP5: 15.95 IP8: 1.46

Comments (11-Nov-2022 00:17:14)
Fill #2 (146b) for VdM scans

CMS part 1 (~3h)

next: ATLAS (~4h), CMS (~3h),
LHCb (~1.5h), ATLAS (~4h)

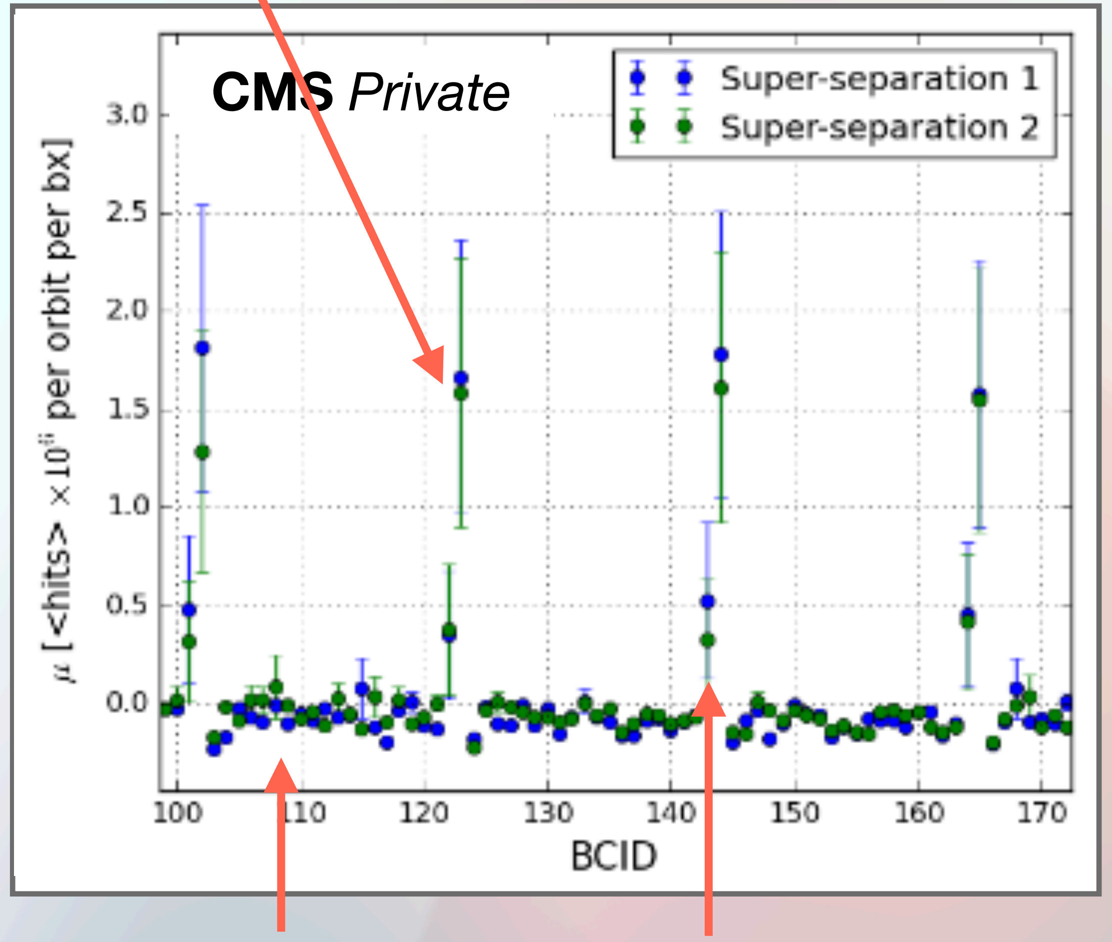
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 525ns_146b_144_35_22_8bpi_20inj_nocloseLR

PM Status B1 ENABLED PM Status B2 ENABLED

BCM1F-utca vdM calibration corrections

- Detector specific
    - high sensitivity to beam background
    - measured in super-separation ≈ 7σ
- Beam-related
    - bunch-charge: per bunch (FBCT) measurement normalised to full beam current (DCCT) + ghosts & satellite corrections
    - beam position: length-scale, linear & residual drifts corrections
    - non-factorisation of the transverse distributions
    - beam-beam effects



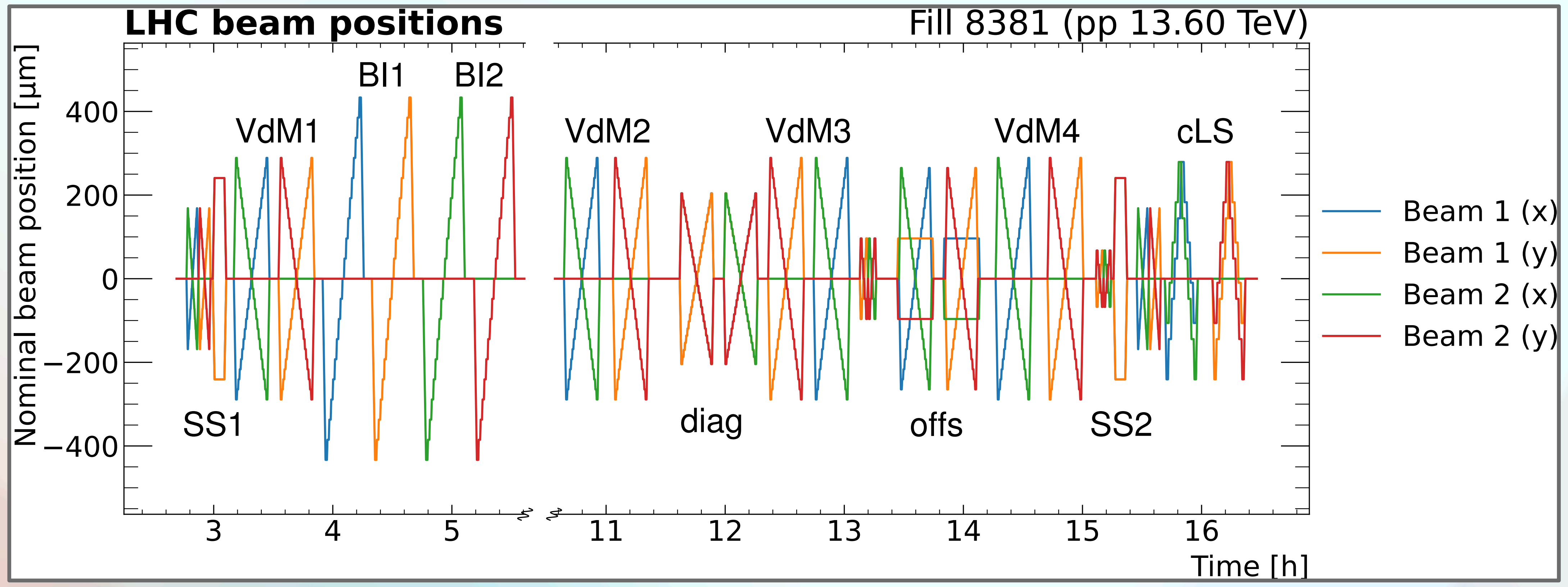
outgoing beam background

luminosity signal x1000 higher @ head-on

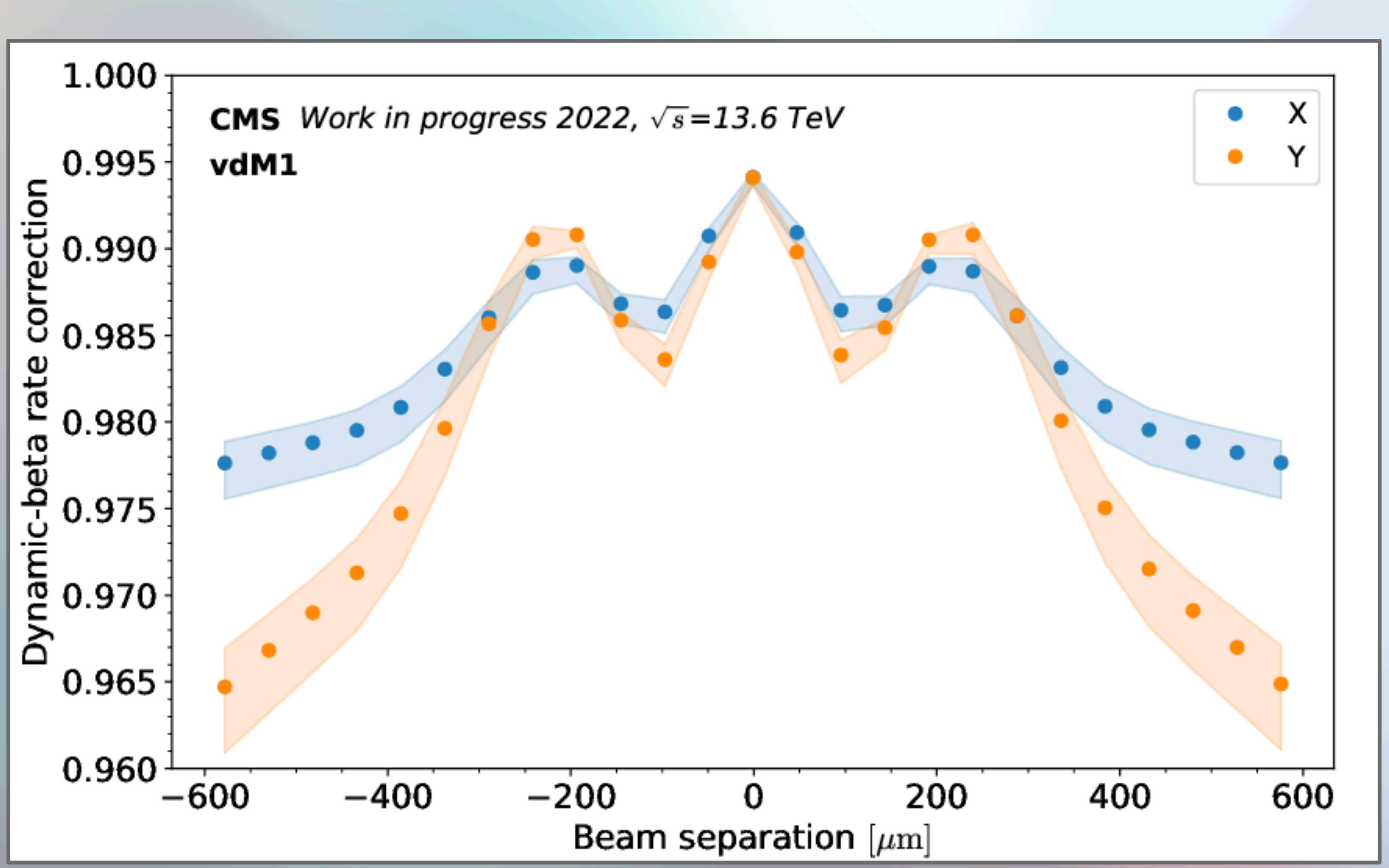
detector noise

incoming beam background

→ new corrections shift the result with respect to the past by +1%

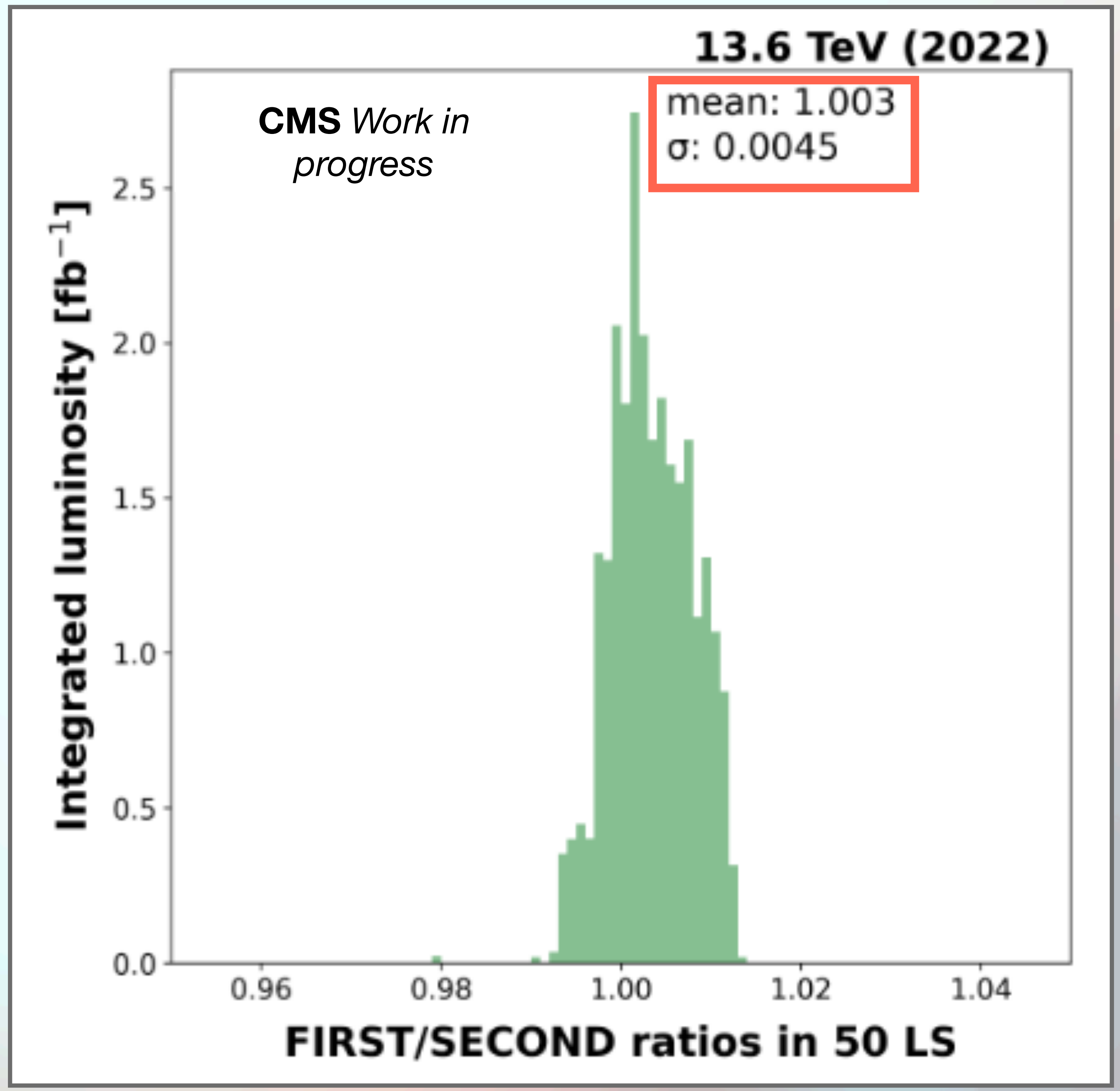


vdM 2022 CMS scan program



Integration of 2022 luminosity

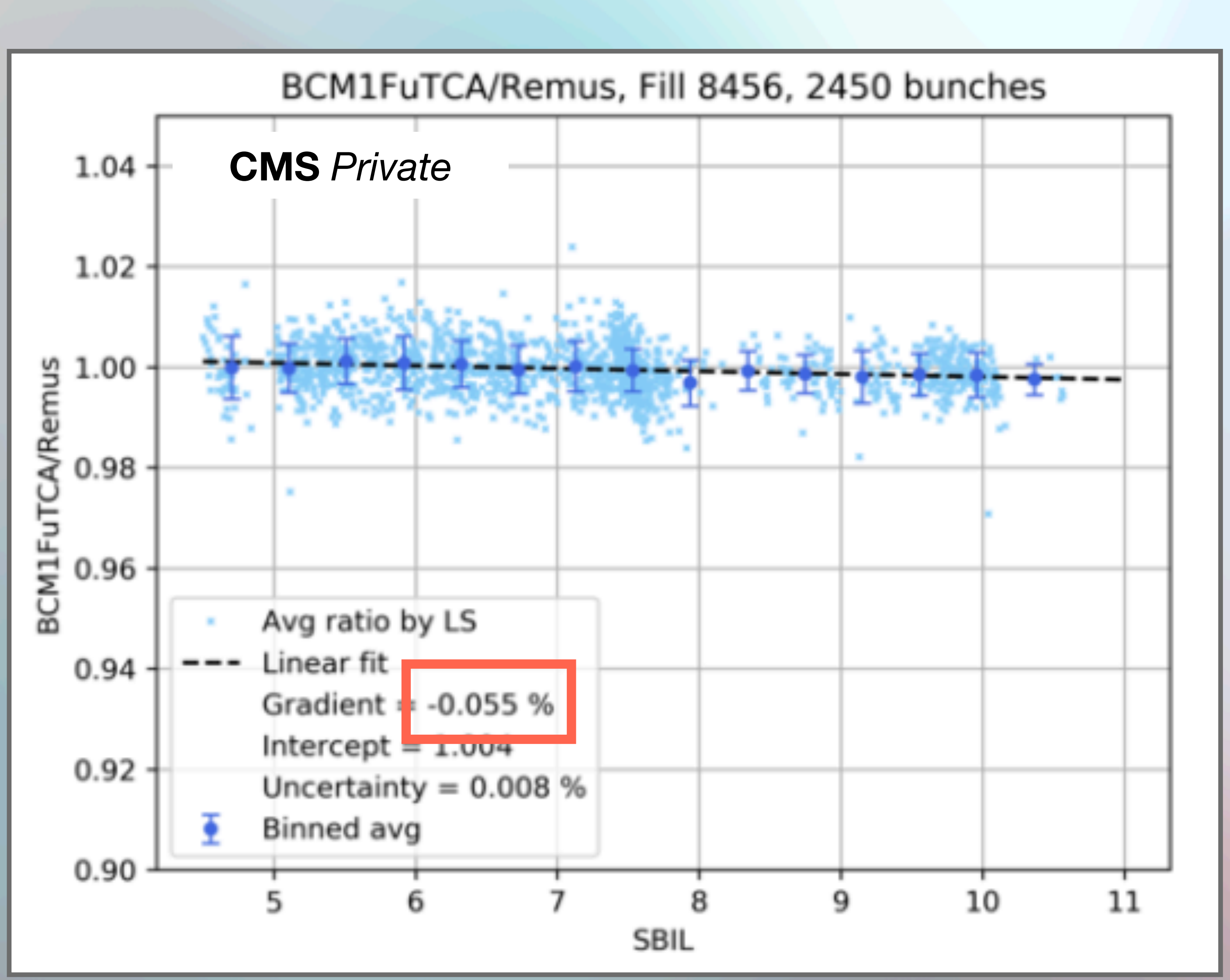
- Very good overall 2022 data quality



BCM1F-utca compared to other available CMS luminom. for total 2022 data sample (HFET, DT, PCC…)

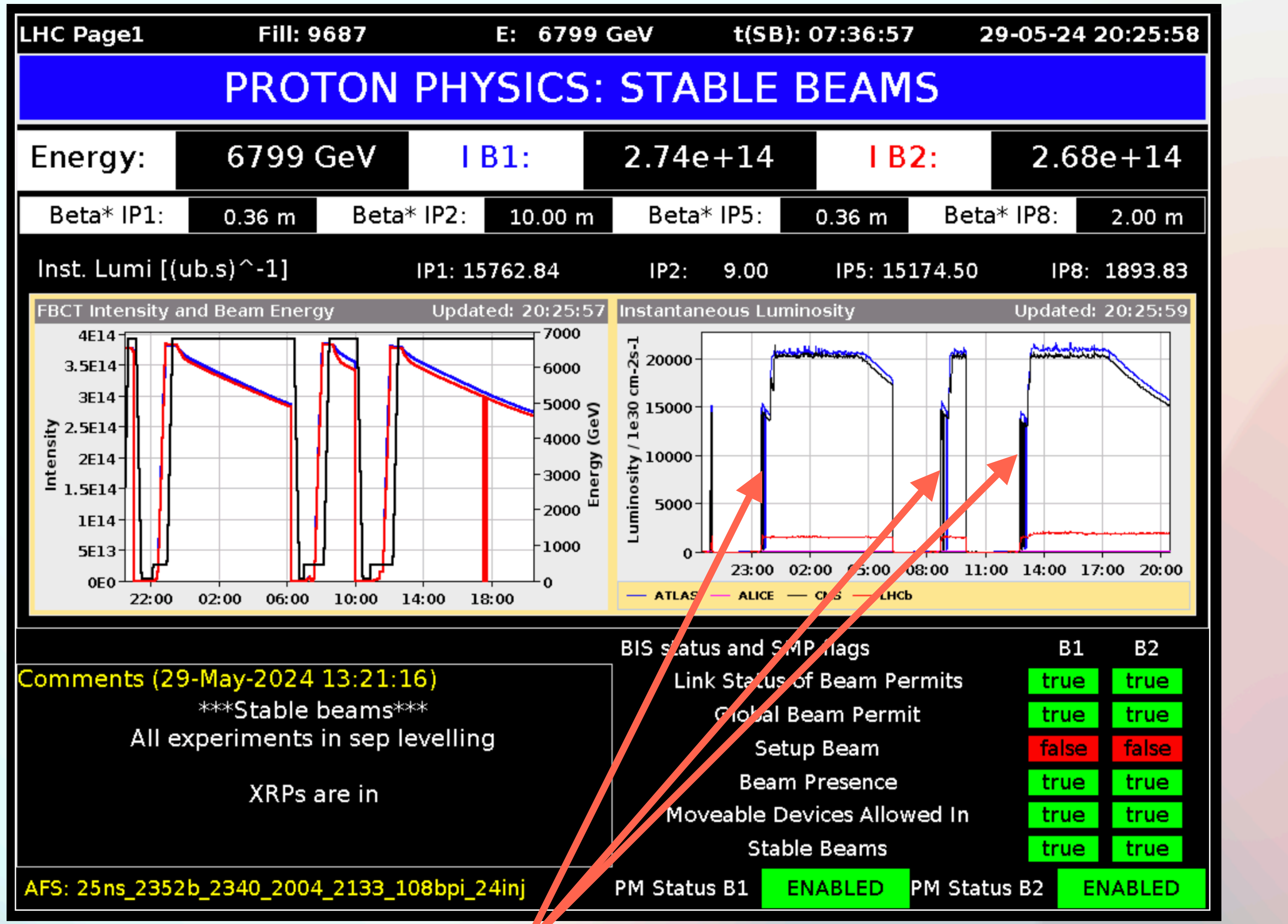
- Non-linearity estimated from comparisons to other reliable systems
  - assumption needed on a perfect luminometer (3 independent CMS systems used)
  - BCM1F-utca non-linearity measured below 0.1%/SBIL

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



Relative linearity across SBIL 4-11 [Hz/ub] with reference to Remus

Dedicated beam-beam corrections



LHC Page1 Fill: 9687 E: 6799 GeV t(SB): 07:36:57 29-05-24 20:25:58

PROTON PHYSICS: STABLE BEAMS

Energy:	6799 GeV	I B1:	2.74e+14	I B2:	2.68e+14

Beta* IP1:	0.36 m	Beta* IP2:	10.00 m	Beta* IP5:	0.36 m	Beta* IP8:	2.00 m

Inst. Lumi [(ub.s)^-1] IP1: 15762.84 IP2: 9.00 IP5: 15174.50 IP8: 1893.83

Comments (29-May-2024 13:21:16)
Stable beams
All experiments in sep levelling

XRPs are in

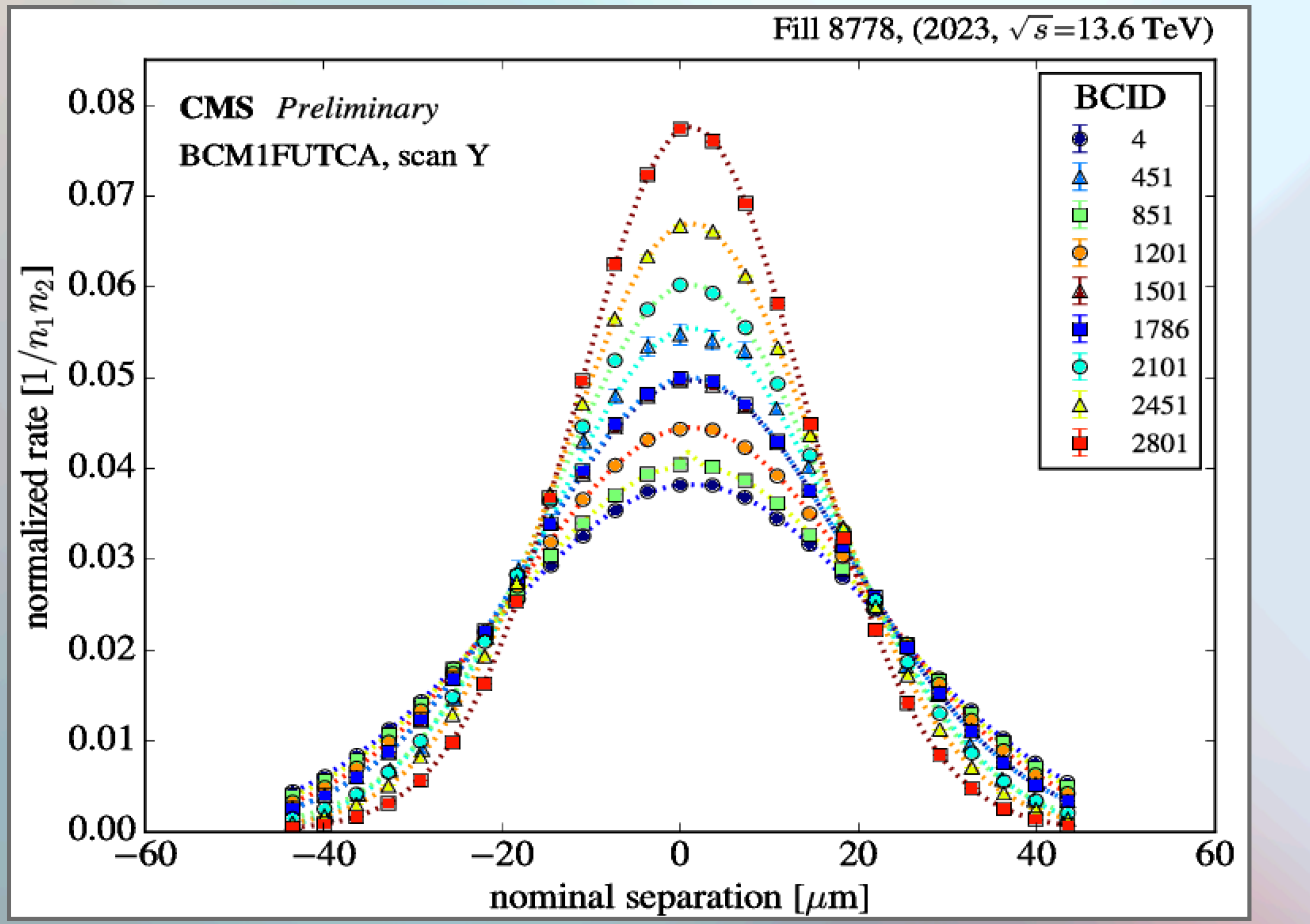
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_2352b_2340_2004_2133_108bpi_24inj

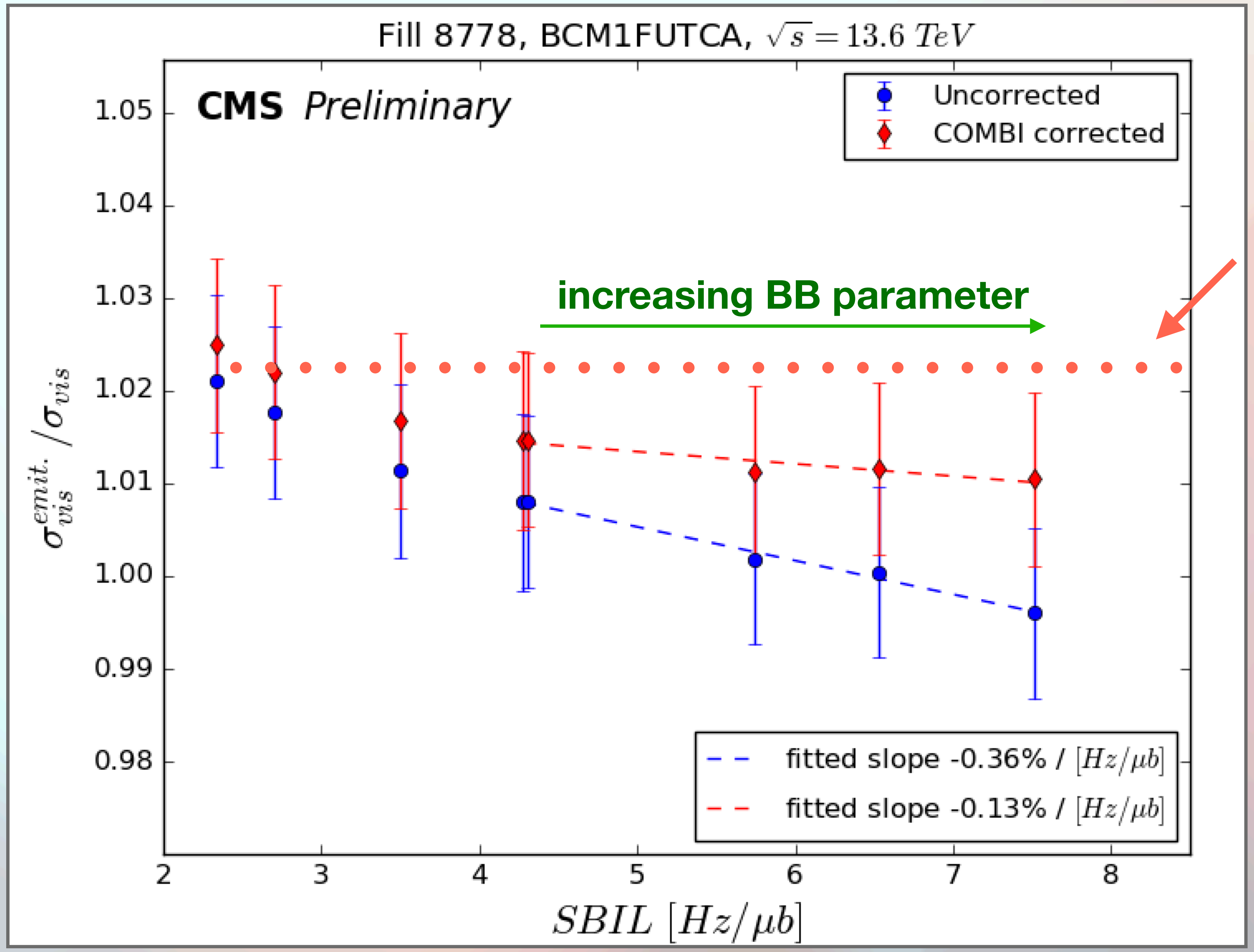
PM Status B1 ENABLED PM Status B2 ENABLED

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

- equivalent of the calibration constant $\sigma_{vis}^{emit.}$ from emittance scans with reference to σ_{vis} measured in vdM calibration
- COMBI upgrades are useful to produce dedicated corrections - minimising the associated extra systematic from per bunch differences



Impact of beam-beam on measured linearity



perfectly linear luminometer = flat response across SBIL

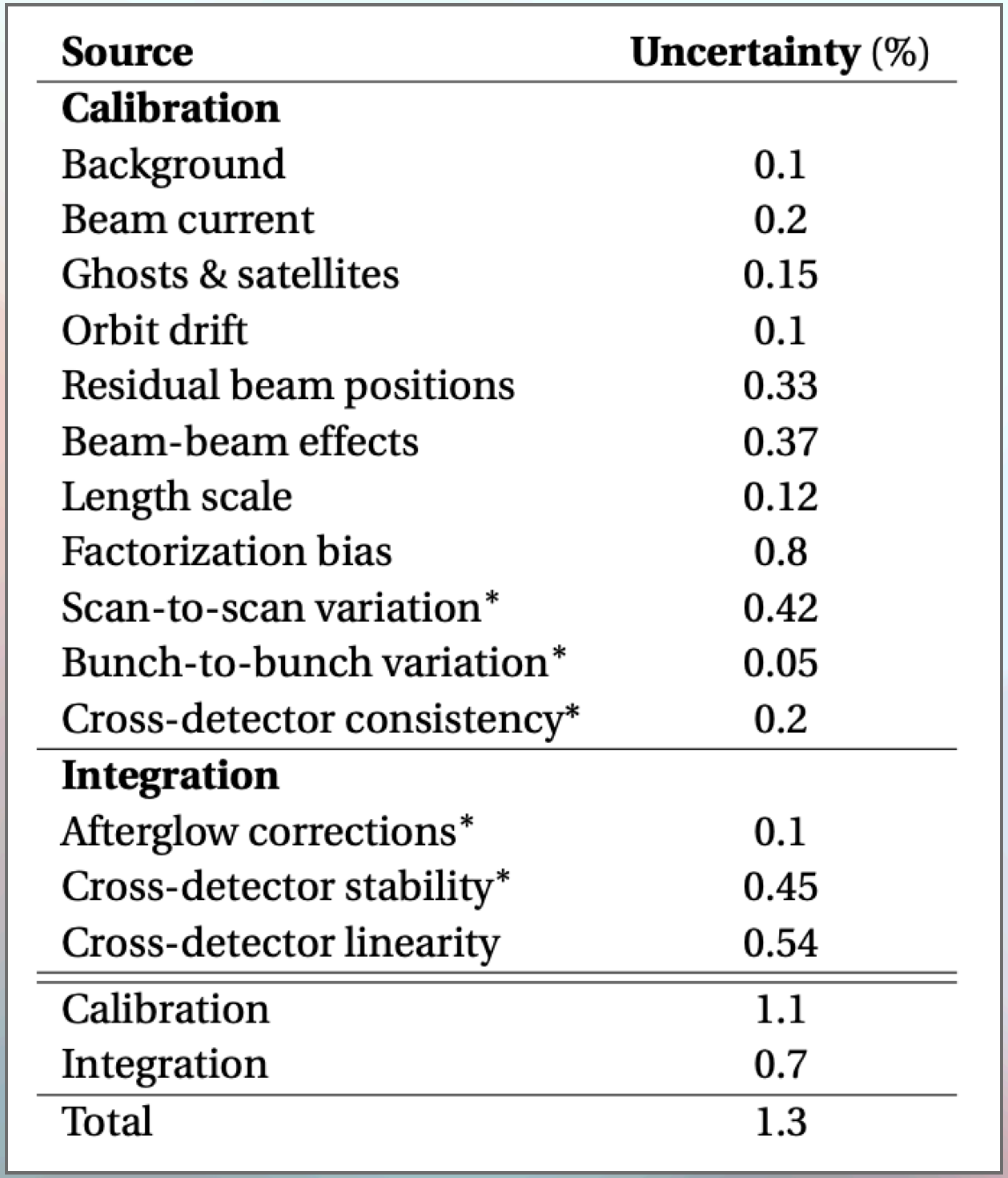
- main contributions to the measured non-linearity:
  - apparent BB-induced slope - removed with COMBI simulation
  - intrinsic detector response inefficiencies

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

Independent measurement → further studies needed for precise measurement

Final BCM1F-utca calibration results

- Overview of all the contributions to the final systematic uncertainty
- preliminary result already at 1.3%
  - in the past typically > 2%
- can be directly combined with Run 2 data samples
- possible further improvement with extended analysis of non-factorisation and detector data
- demonstration that BCM1F-utca can be used as the primary luminometer

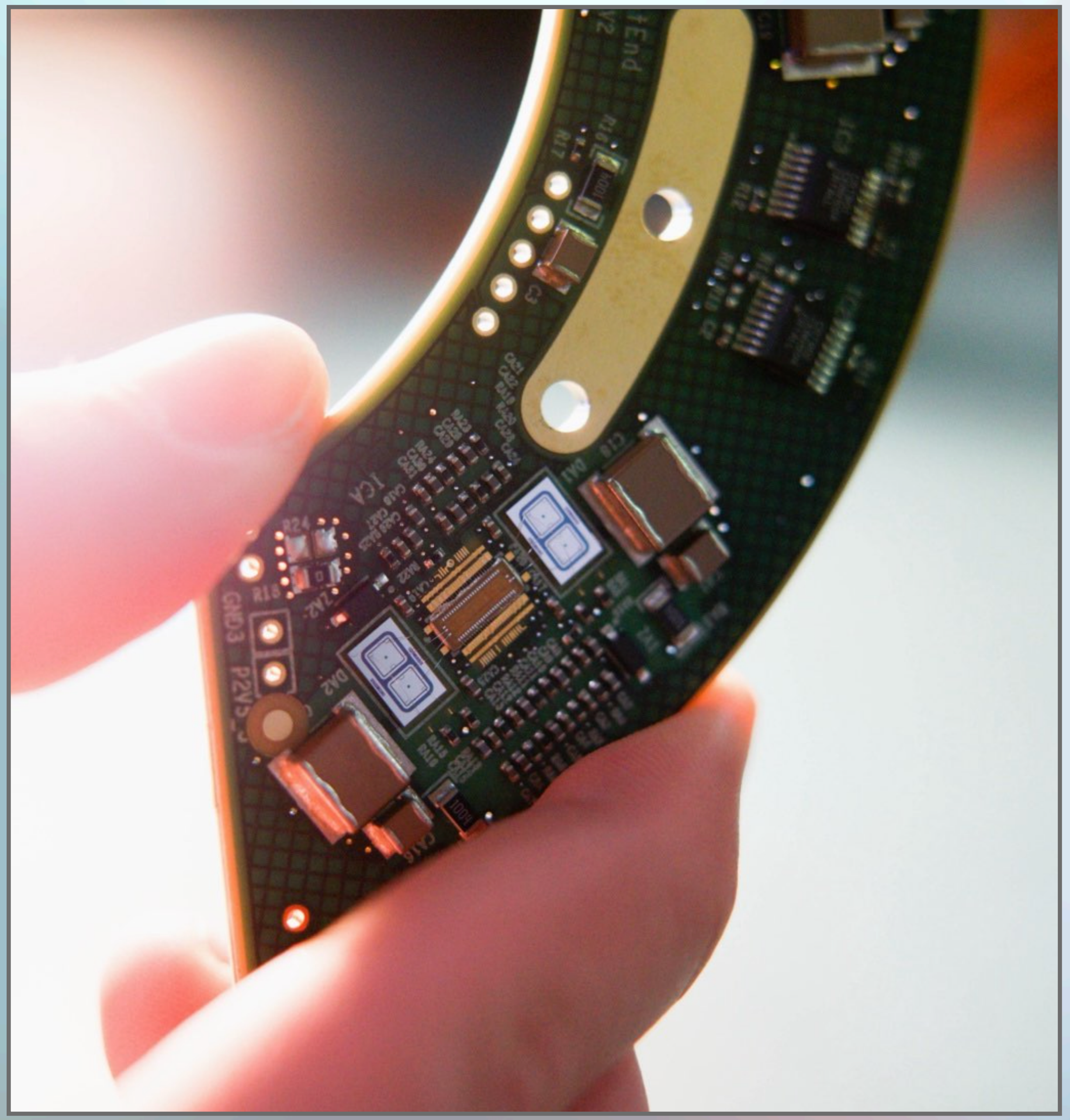


Source	**Uncertainty** (%)
Calibration	
Background	0.1
Beam current	0.2
Ghosts & satellites	0.15
Orbit drift	0.1
Residual beam positions	0.33
Beam-beam effects	0.37
Length scale	0.12
Factorization bias	0.8
Scan-to-scan variation*	0.42
Bunch-to-bunch variation*	0.05
Cross-detector consistency*	0.2
Integration	
Afterglow corrections*	0.1
Cross-detector stability*	0.45
Cross-detector linearity	0.54
Calibration	1.1
Integration	0.7
Total	1.3

*indicates differences with respect to the CMS LUM PAS 2022

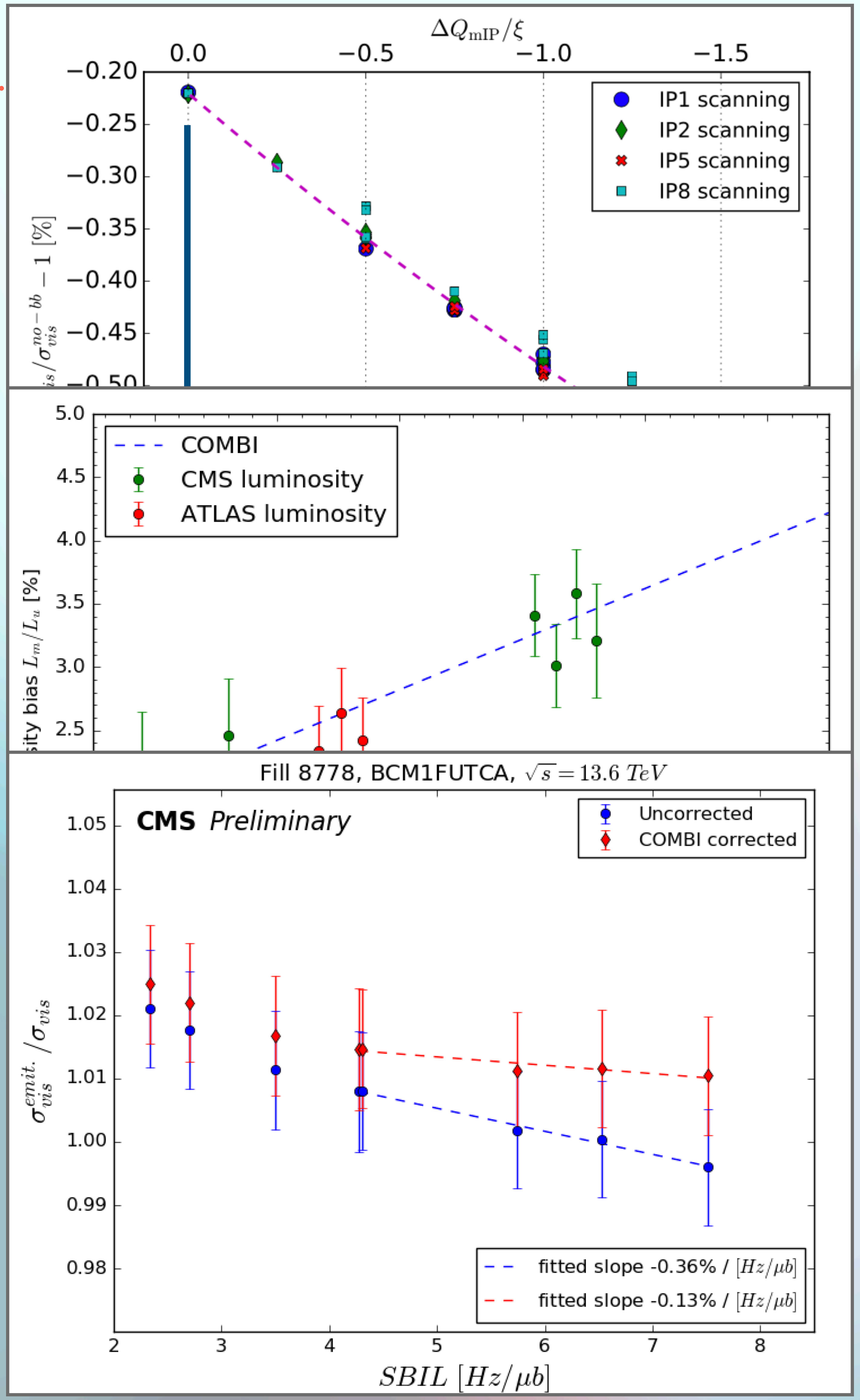
Conclusions (1/2)

- ➔ The upgraded BCM1F was built, installed and commissioned successfully
- ➔ Since the beginning of LHC Run 3, it has proven to be robust and reliable, the configuration was optimised, with the focus of employing the new peak finding algorithm
- ➔ It has continuously provided CMS and LHC with:
  - ◆ online beam-induced background, and luminosity measurements
  - ◆ regular emittance scans allow for independent, non-destructive transverse-profile and orbit-shift measurements on a bunch-by-bunch basis
- ➔ BCM1F-utca performance was investigated to achieve the best precision in luminosity measurement:
  - ◆ corrections for both vdM and nominal physics conditions were derived
  - ◆ first vdM calibration was performed at the end of 2022 resulting in a luminosity measurement with a very competitive systematic uncertainty of 1.3%



Conclusions (2/2)

- Extensive simulations of BB effects on the luminosity led to a much better understanding, minimising the related systematic uncertainty on absolute luminosity calibrations
- Improved corrections by accounting for the multiple collisions
  - additional ~0.4% correction for typical $\xi = 0.003$
  - methodology applicable to all LHC experiments
- Dedicated BB experiment at the LHC allowed to validate some key aspects of the simulation model
  - first measurement of the BB-induced biases on luminosity at the LHC
  - agreement with the simulation to the level of 0.1%
- Beam-beam simulation model improvements allow for dedicated corrections at the physics conditions
  - possible to remove the apparent beam-beam induced slope for measuring intrinsic detector non-linearities in an independent way
  - valuable for HL-LHC studies with high pile-up
- The results apply to any current and future hadron colliders, for example FCC-hh

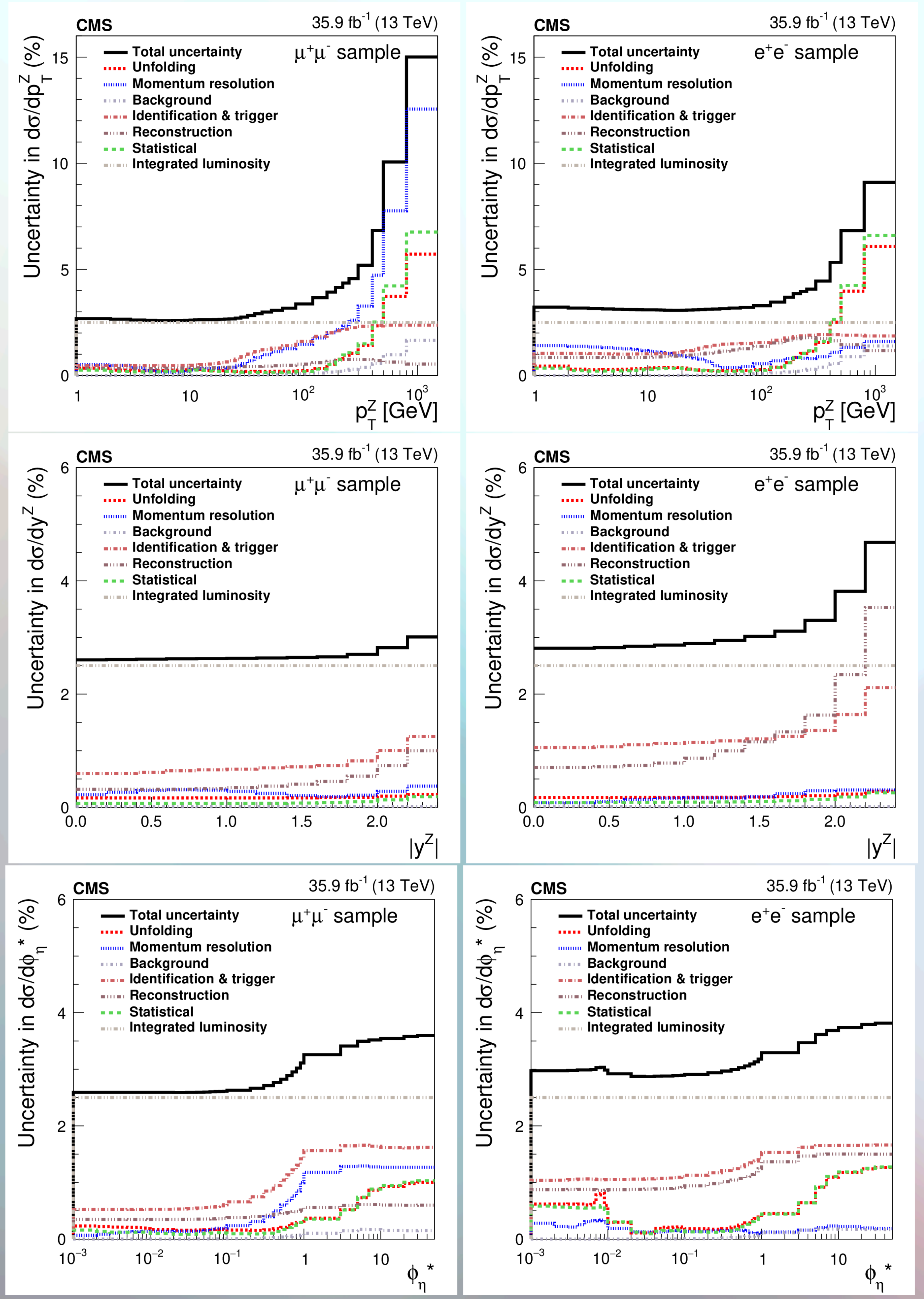


Backup - motivation

top quark pair production cross section systematic uncertainty table

Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.6
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.5
ME scale, backgrounds	0.2
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Top quark p_T	0.5
tW background	0.7
t-channel single-t background	0.4
Z+jets background	0.3
W+jets background	<0.1
Diboson background	0.6
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.5
Integrated luminosity	2.3

Z boson production cross section uncertainty

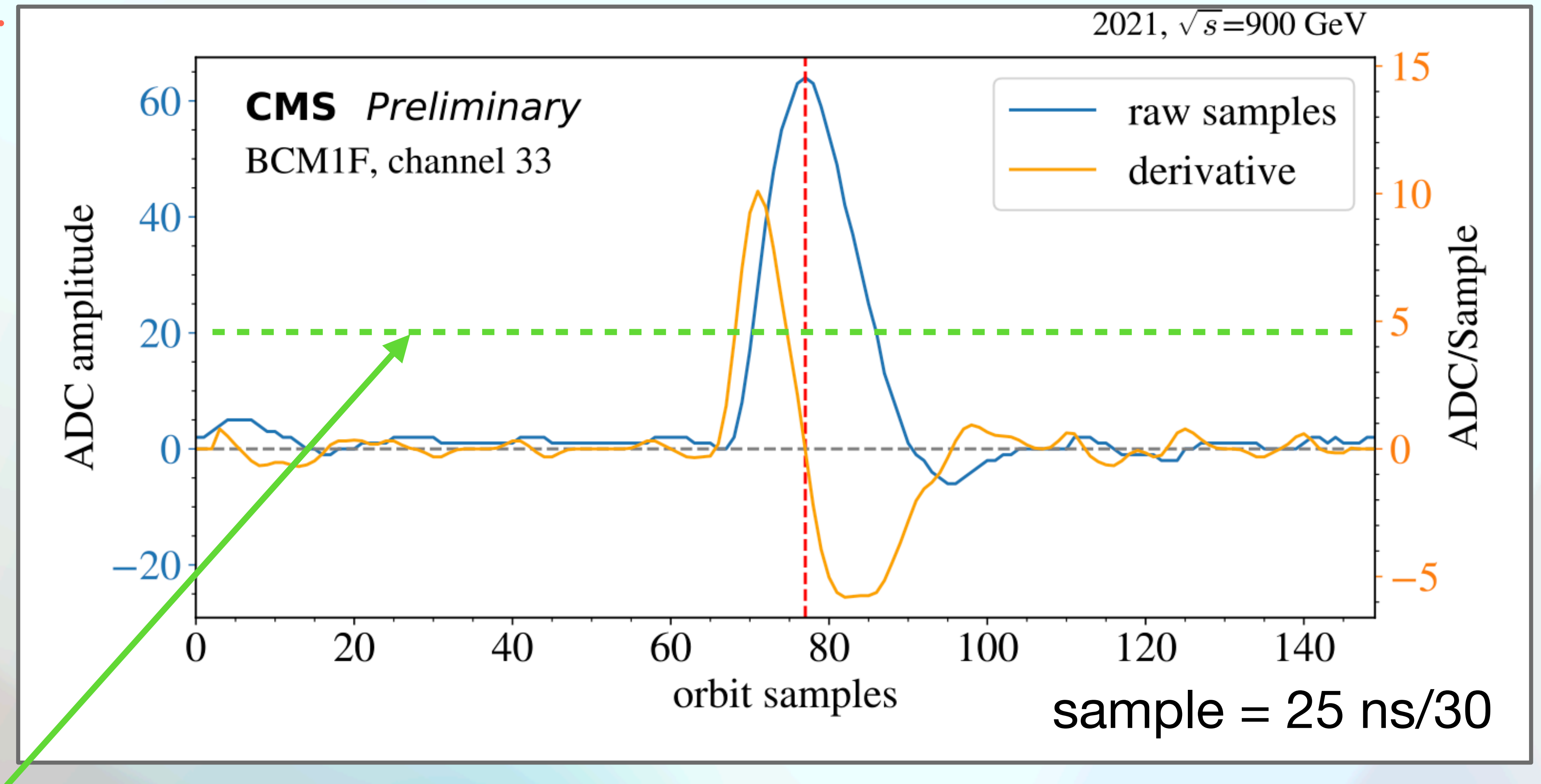


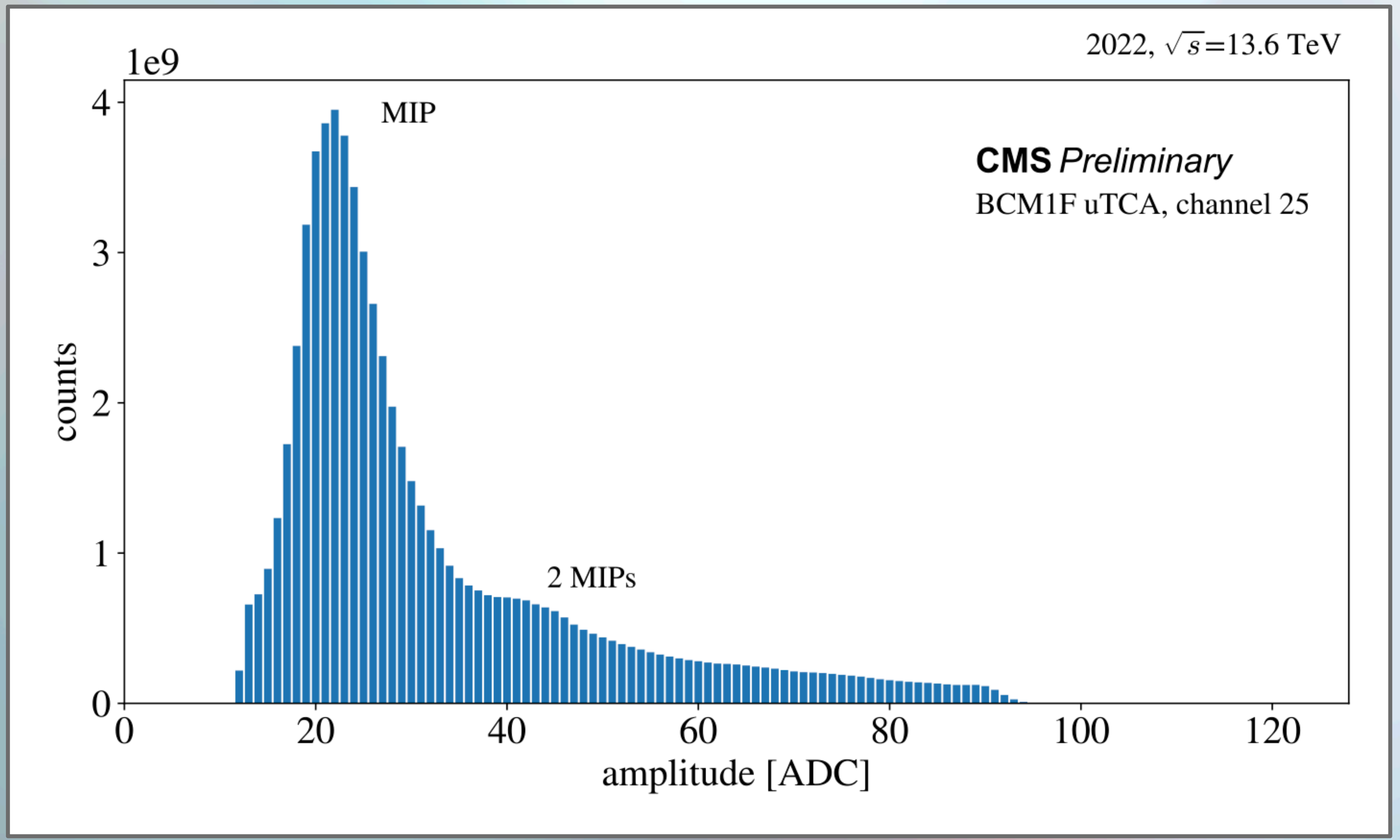
The new BCM1F-utca peak finding algorithm

➔ New peak finding algorithm designed to differentiate the overlapping pulses to maintain the detection efficiency at high pileup:

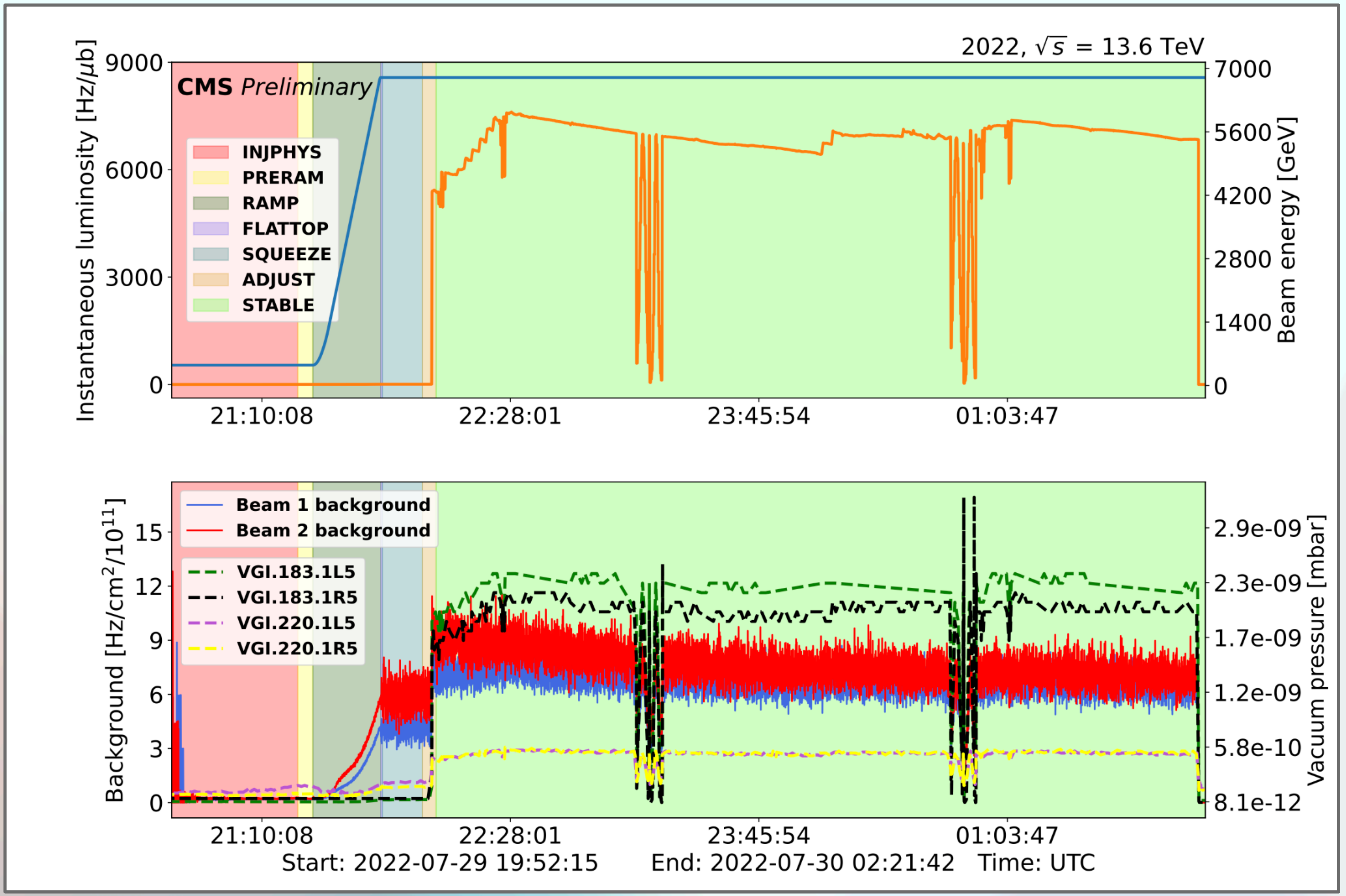
- derivative calculated with a smooth noise-robust differentiator (N=7): $\boxed{\frac{5(f_1-f_{-1})+4(f_2-f_{-2})+f_3-f_{-3}}{32h}}$
- designed to provide noise suppression at high freq. with efficient implementation into a digital system.
- peak detection based on the derivative threshold level crossing,
- further noise separation based on the low value of the signal derivative, and by applying the amplitude cut off.

➔ The amplitude spectrum is a Landau distribution with the most probable value corresponding to the energy loss of the minimum-ionizing particle. The low amplitude Gaussian noise contribution removed with back-end thresholds.





BCM1F-utca measurements



- ➔ luminosity measurement is based on the sum of counts within a colliding BCID,
- ➔ zero counting algorithm is used:

$$\mu = -ln\left[p(0)\right] = -ln\left[1 - p(n \neq 0)\right] = -ln\left[1 - \frac{N_{hit}}{N_{bc}}\right]$$

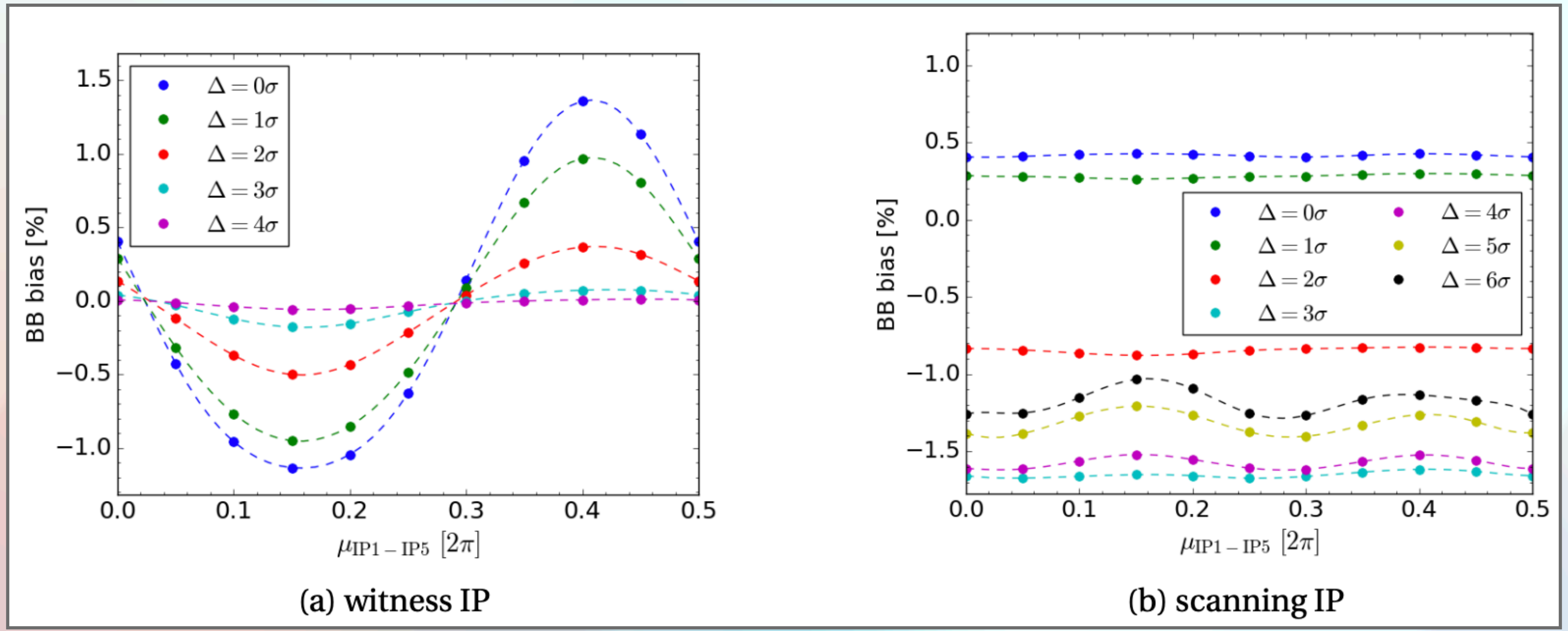
- ➔ BCM1F has been the main online luminometer since the beginning of the LHC commissioning period for Run 3,

- BIB particles are measured by different BCM1F channels, based on their location with reference to the CMS IP and the particle arrival time,
- based on the BCM1F background measurements are used to assess beam conditions

  → guarantee safe operation for the other CMS subsystems.
- Real-time feedback of the beam conditions prevalent close to the CMS experiment to the LHC.
- Additionally, per-bunch orbit displacement and transverse widths can be measured with high accuracy in beams separation scans.

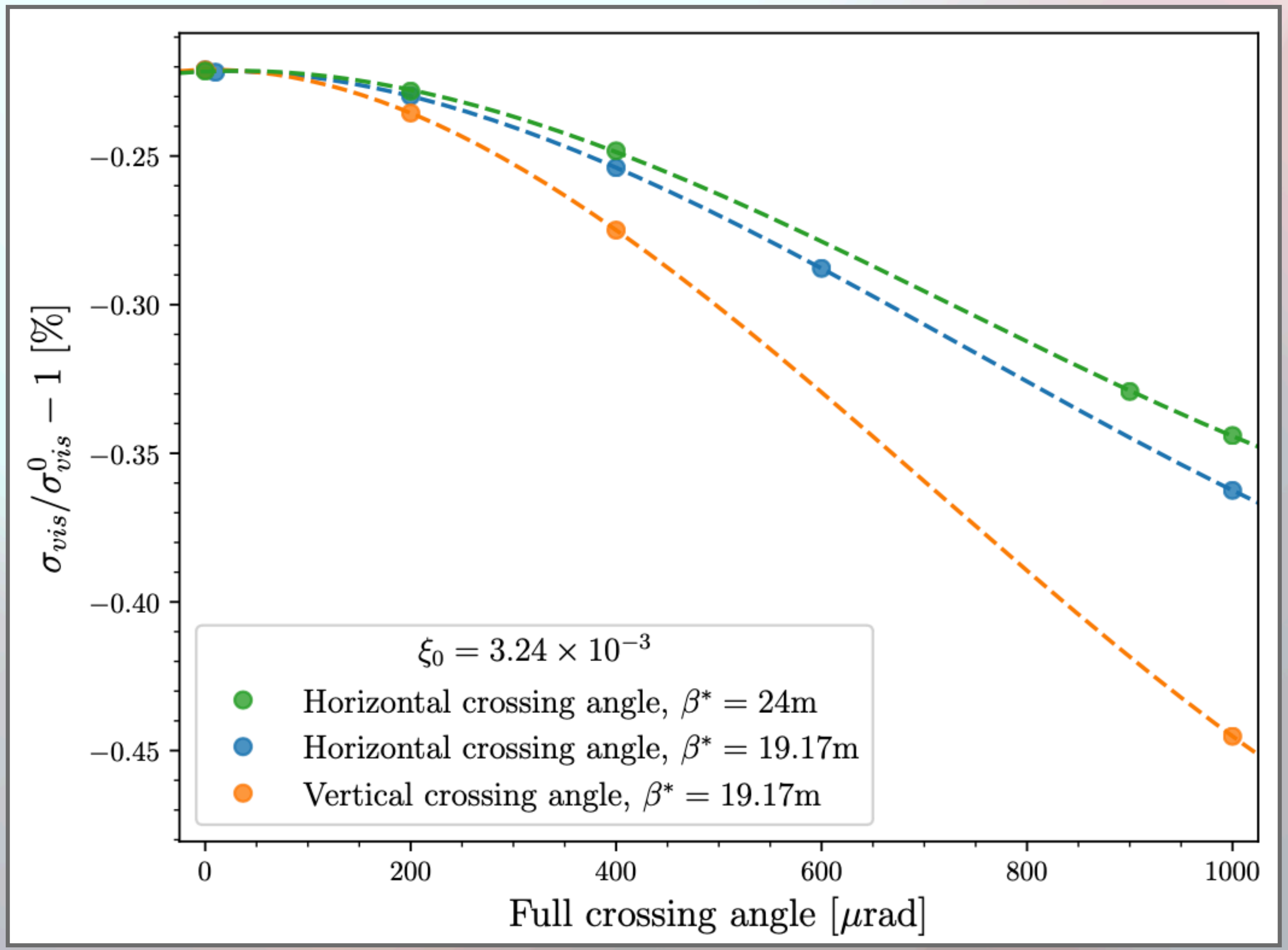
Backup - simulation studies

- phase advance luminosity changes different for scanning and the witness IP



(a) witness IP

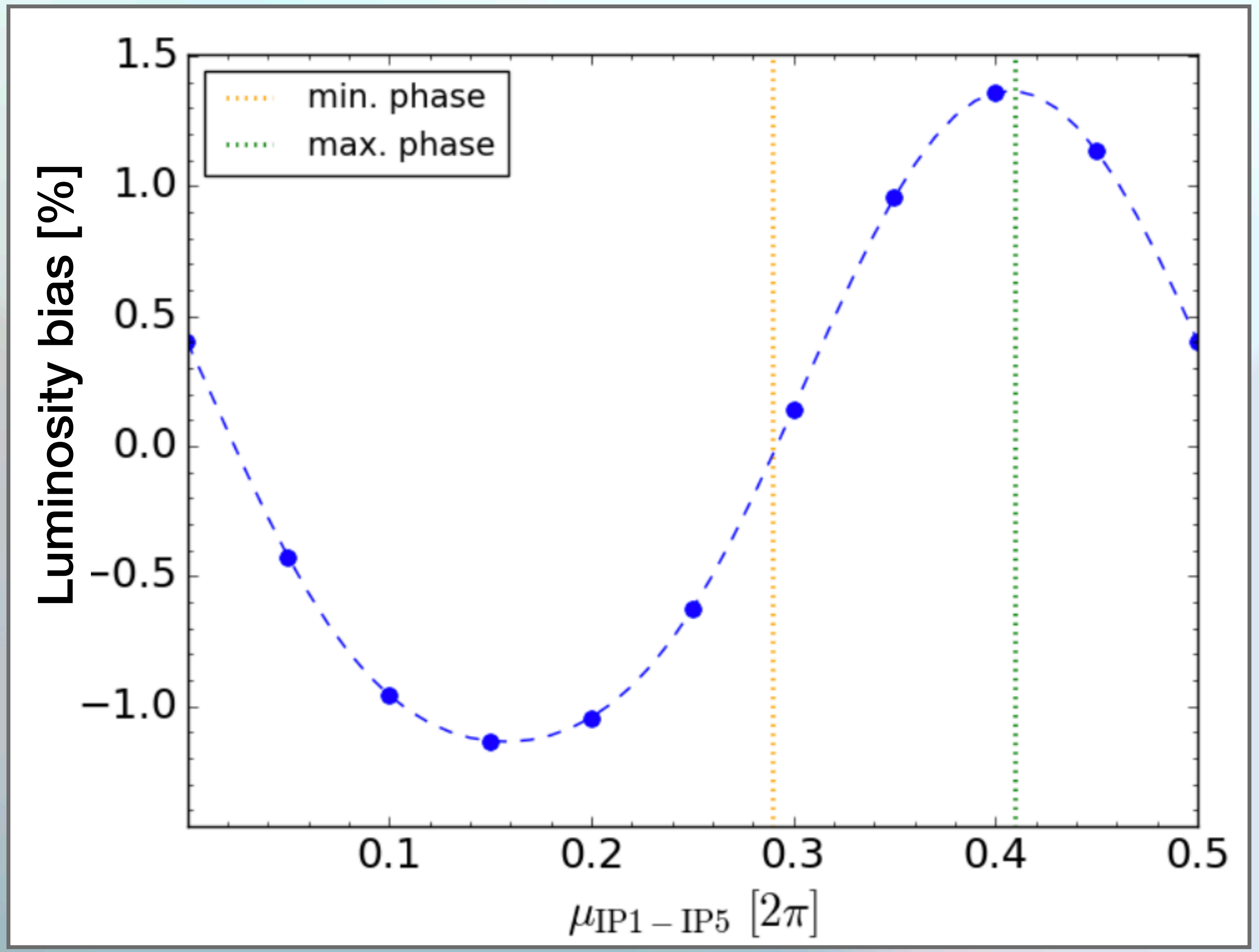
(b) scanning IP



- COMBI Model development needed to study the impact of crossing-angle configurations
- Additional beam-beam induced bias in the configuration with the crossing-angle, non-negligible even at high β^*

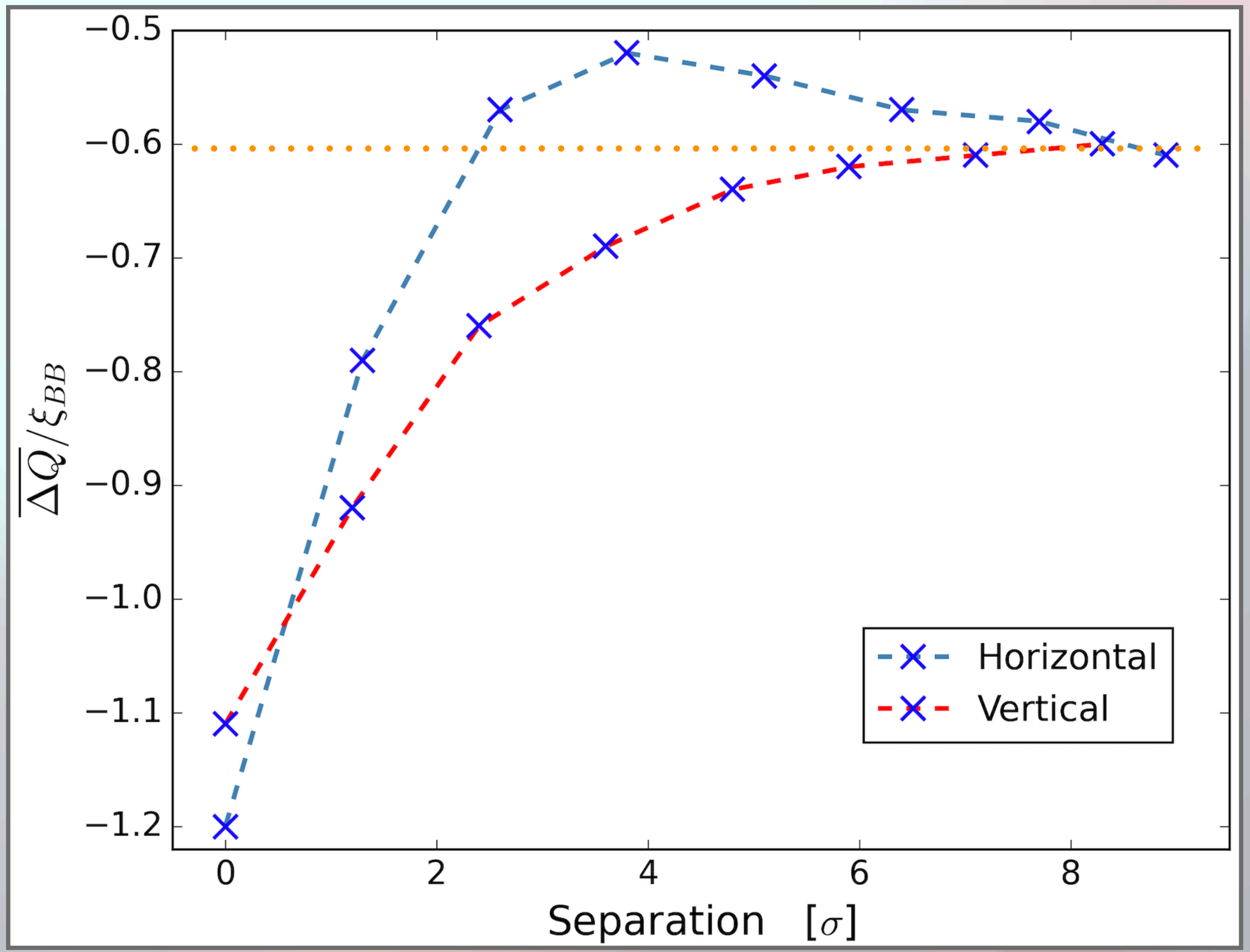
Simulation model benchmark experiment

- Test specifically designed to measure BB effects
- idea to use one of the IPs as ‘the witness’ (observer) to enable observations of beam-beam induced luminosity shifts
- phase advance between IP1 & IP5 optimized for maximizing the effect on luminosity at the witness IP at injection energy $(1 \rightarrow 3\%)$
  - lattice validated up to 1°
- dedicated physics time in 2022 LHC commissioning, BB experiment valuable for all LHC experiments
- multiple instruments were used to measure the BB effects:
  - luminosity from ATLAS and CMS luminometers
  - tune spectra (Q_x, Q_y)
  - transverse beam sizes σ with synch. light monitors and wire scanners
  - orbit at the IPs with BPMs



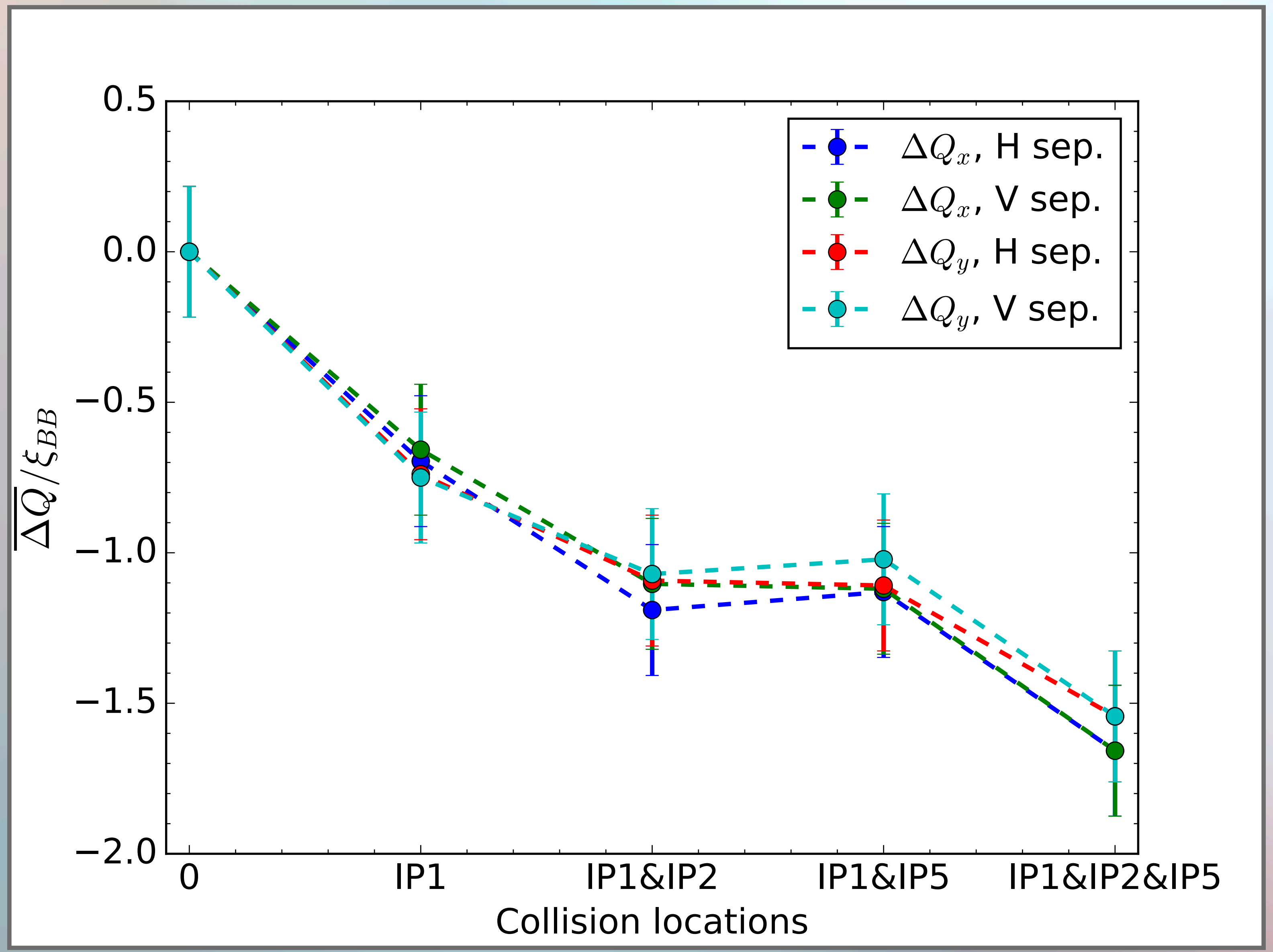
BB experiment: results (2)

- observations of BB-induced changes during a separation scan
    - very clear on the mean tunes extracted from the spectra
- 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

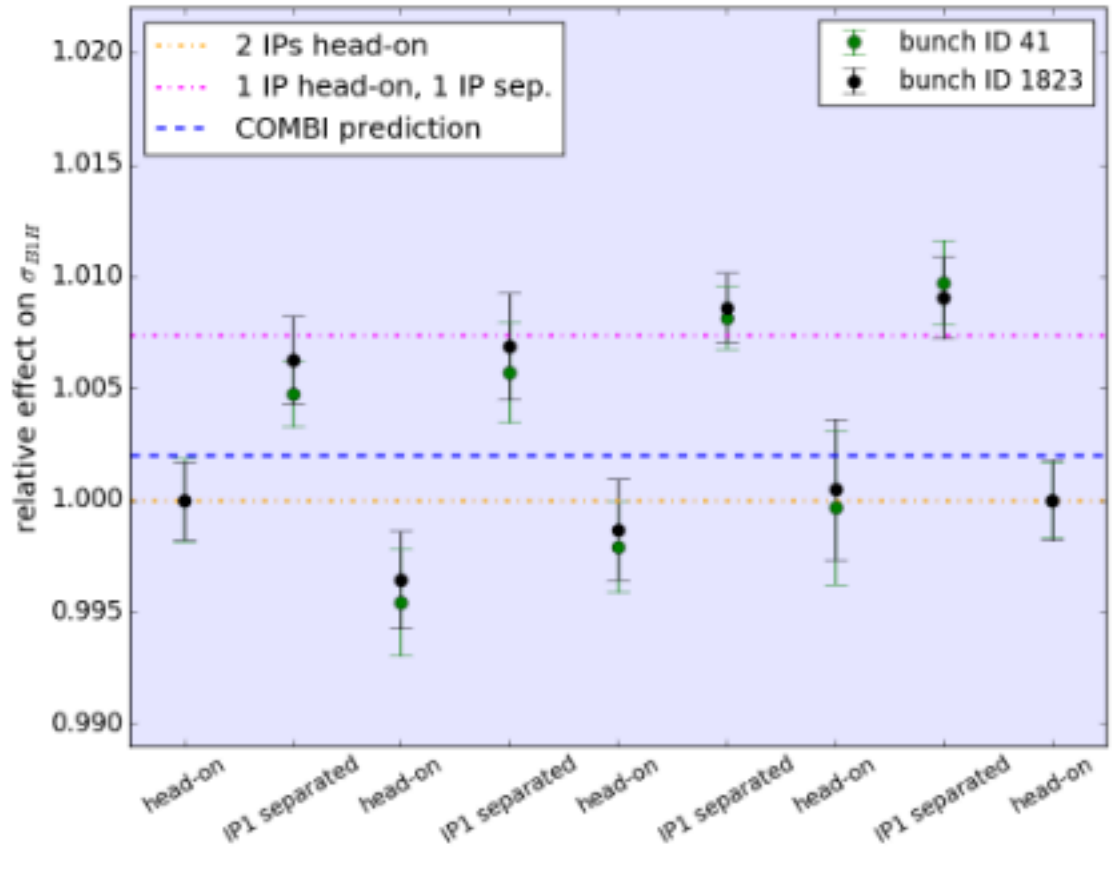
Tune shift:
- induced by BB during horizontal-separation scan
- measured using the ADT



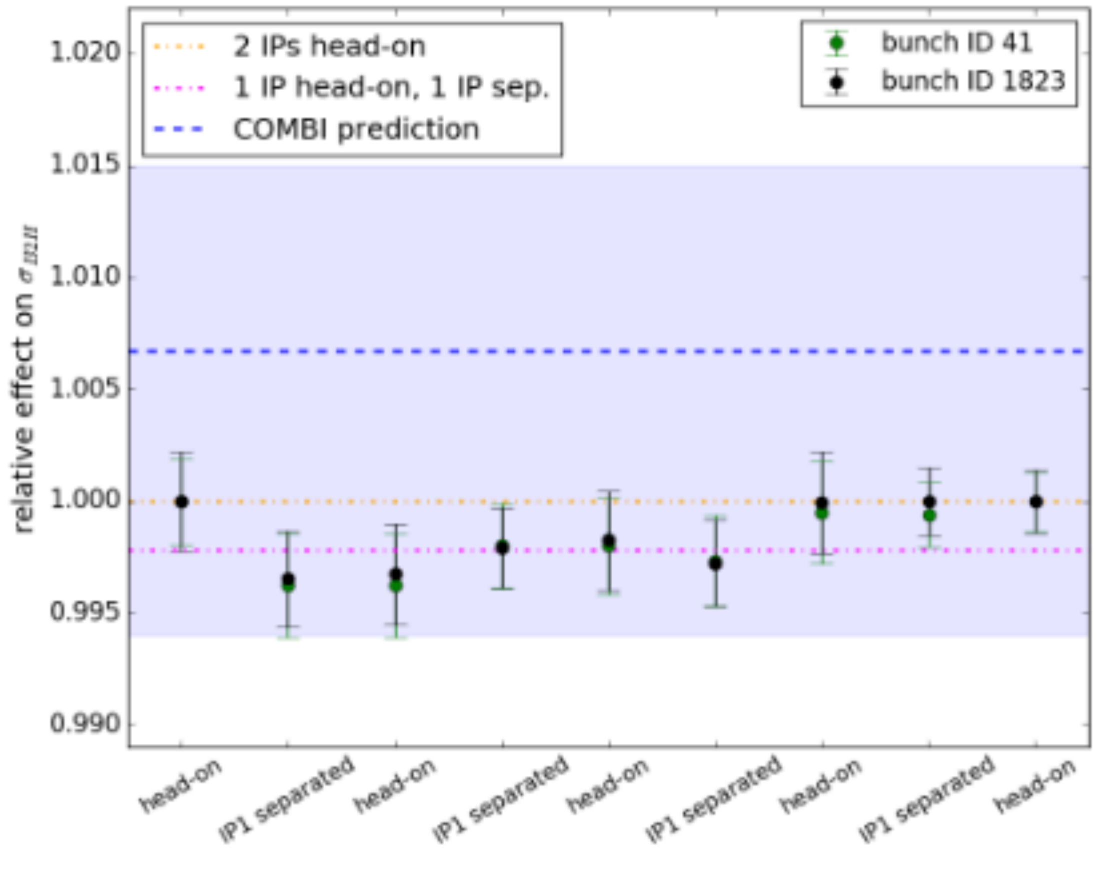
Tune shift as a function of the number of collisions, measured in multiple tests

Backup - BB experiment results (3)

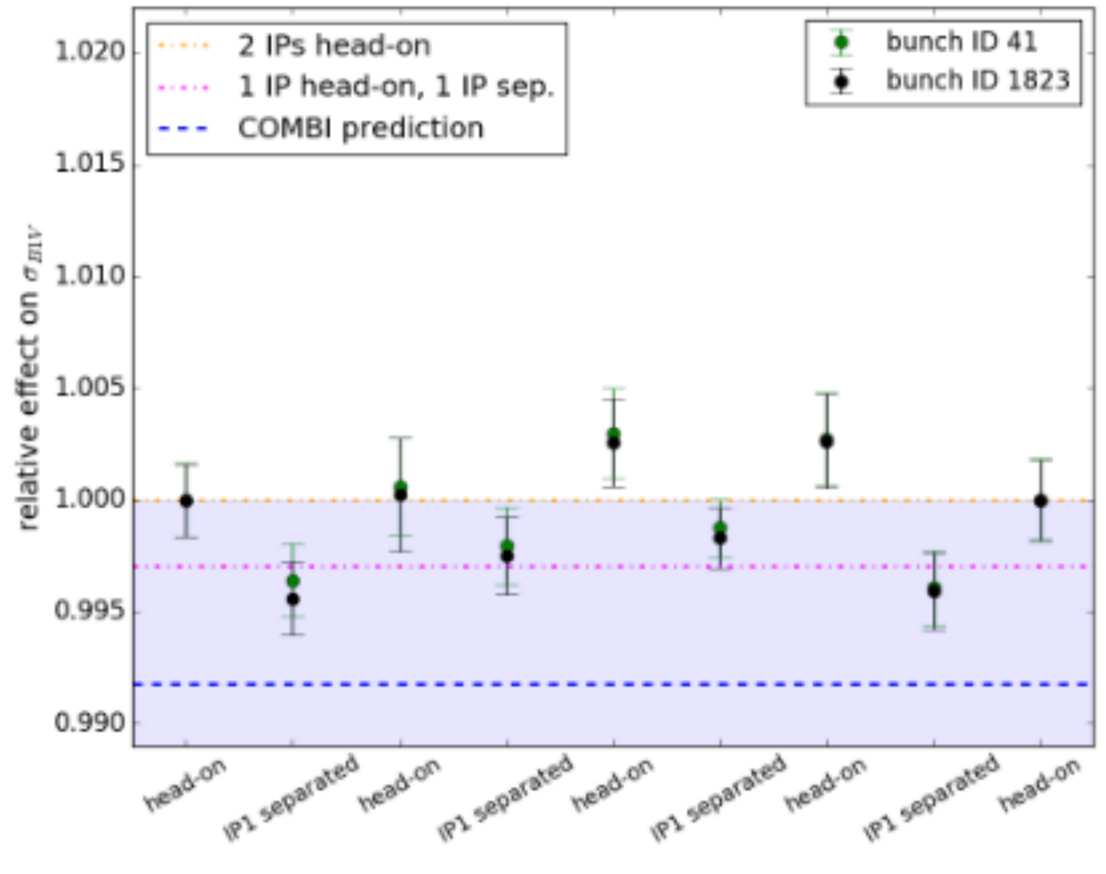
- beam width changes caused by moving IP1 from fully separated to head-on position, as measured by synchrotron light monitor and compared to COMBI
- the most significant effect in B2V with smallest uncertainty (from phase advance set point)
- phase advances could be further optimized for the observations at the synch. light monitor
  - potentially useful to reduce systematic error in standard operation



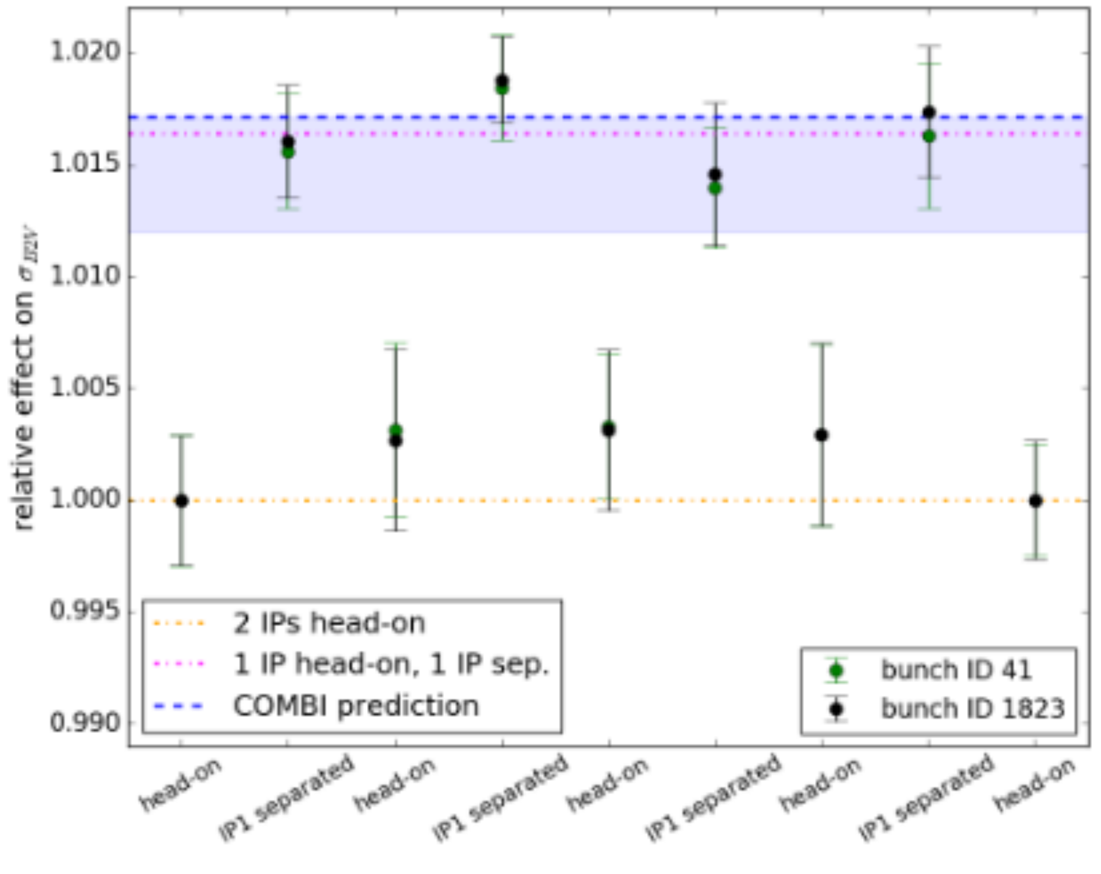
(a) Beam 1 - horizontal plane



(b) Beam 2 - horizontal plane



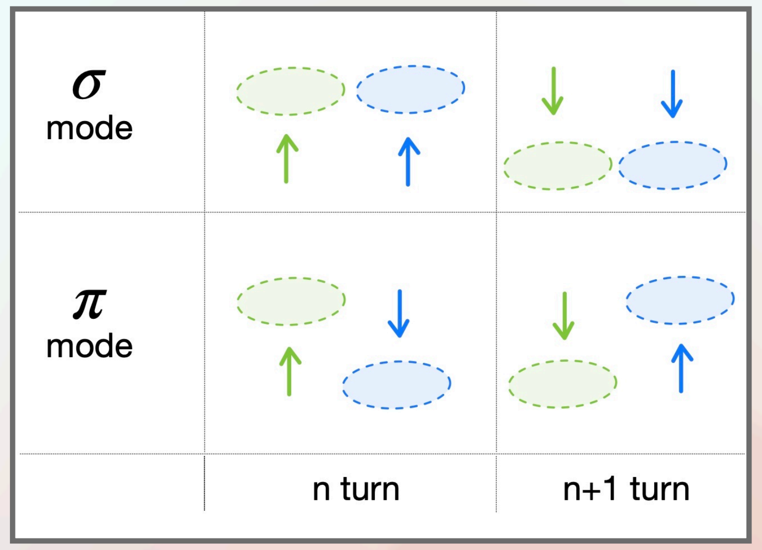
(c) Beam 1 - vertical plane



(d) Beam 2 - vertical plane

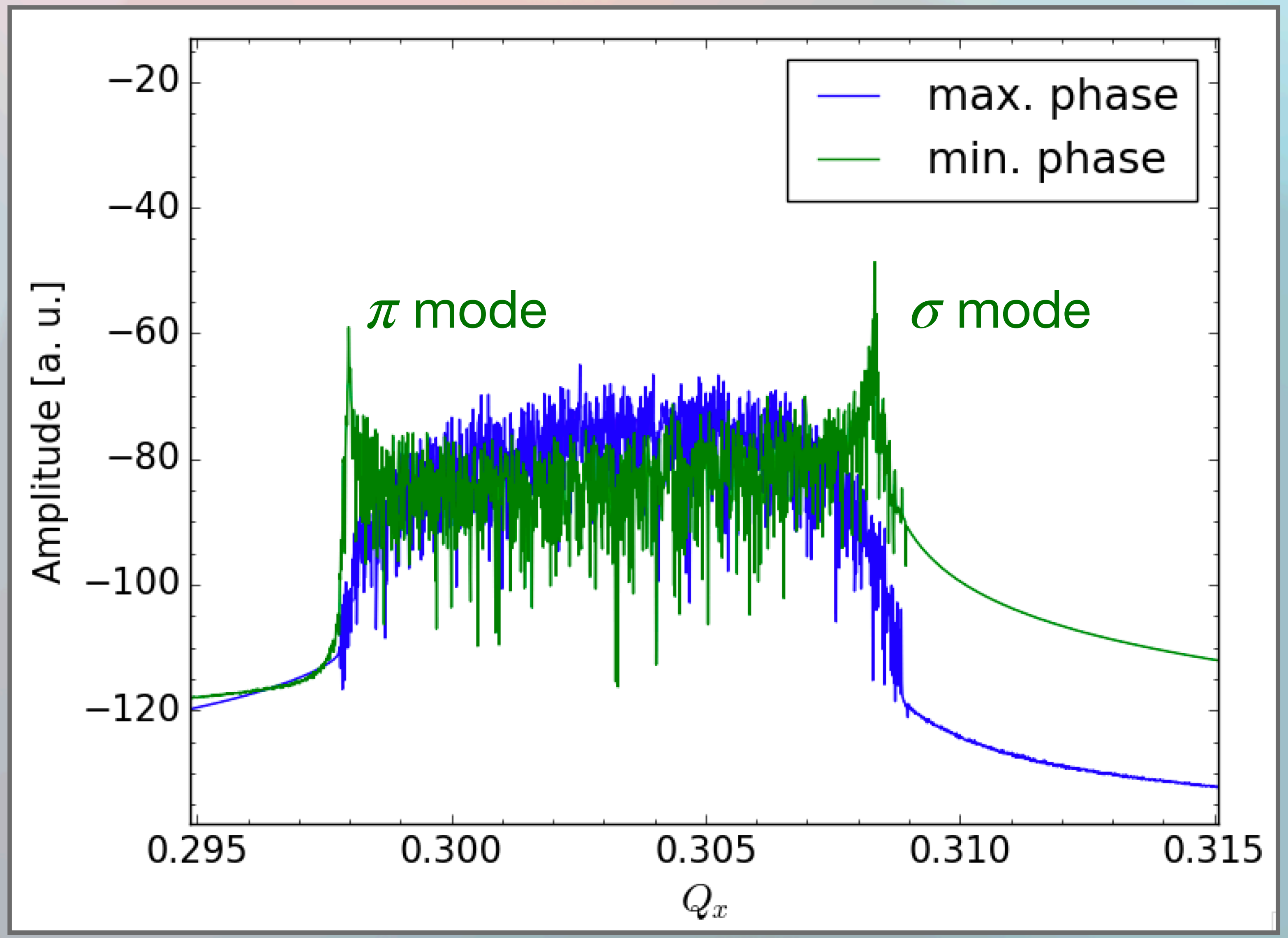
BACKUP - coherent modes

- Tune spectra show coherent modes - beam-beam interaction additionally couples bunches
- effective suppression of coherent modes
  - easier analysis of the spectra

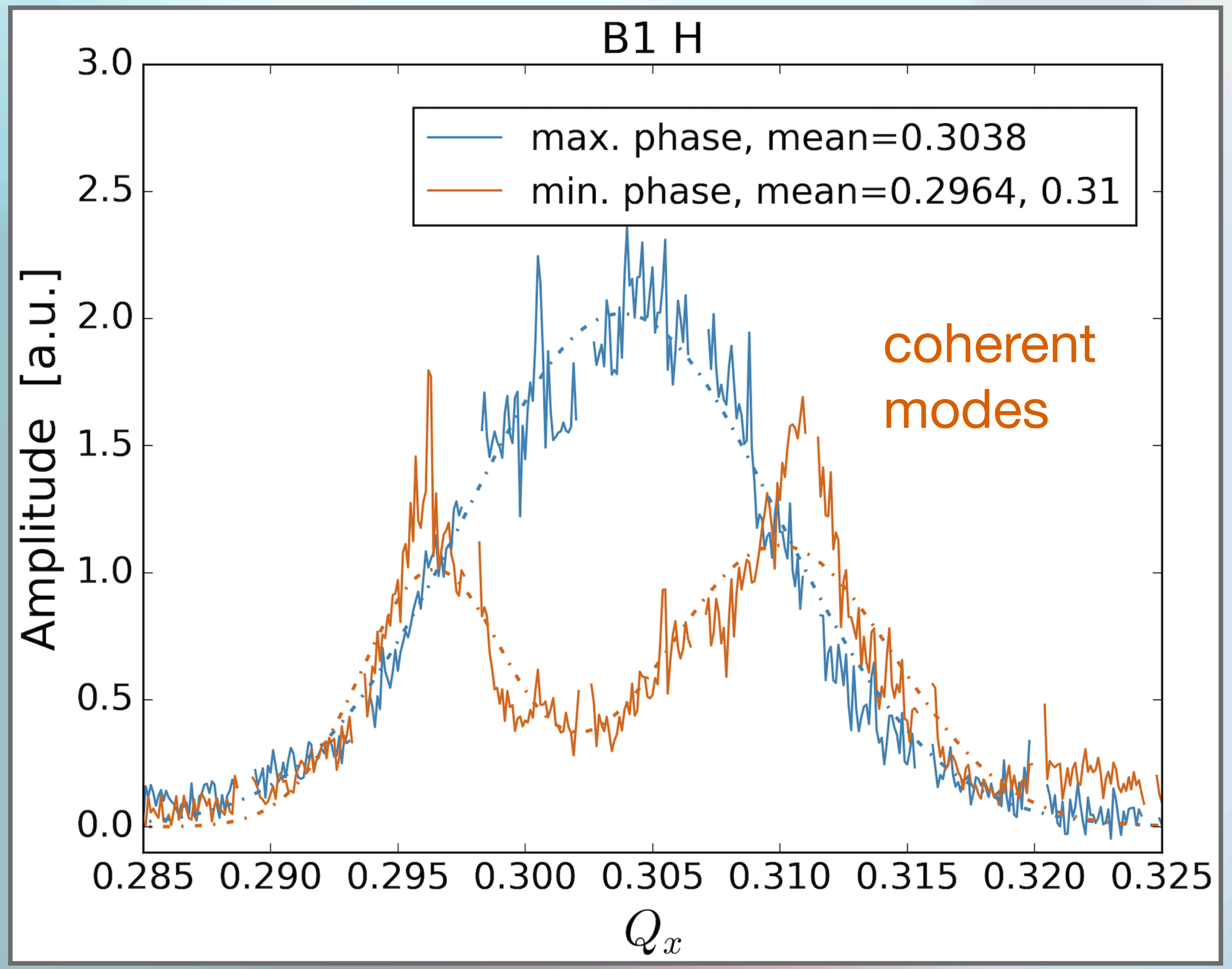


Coherent spectra

COMBI simulated



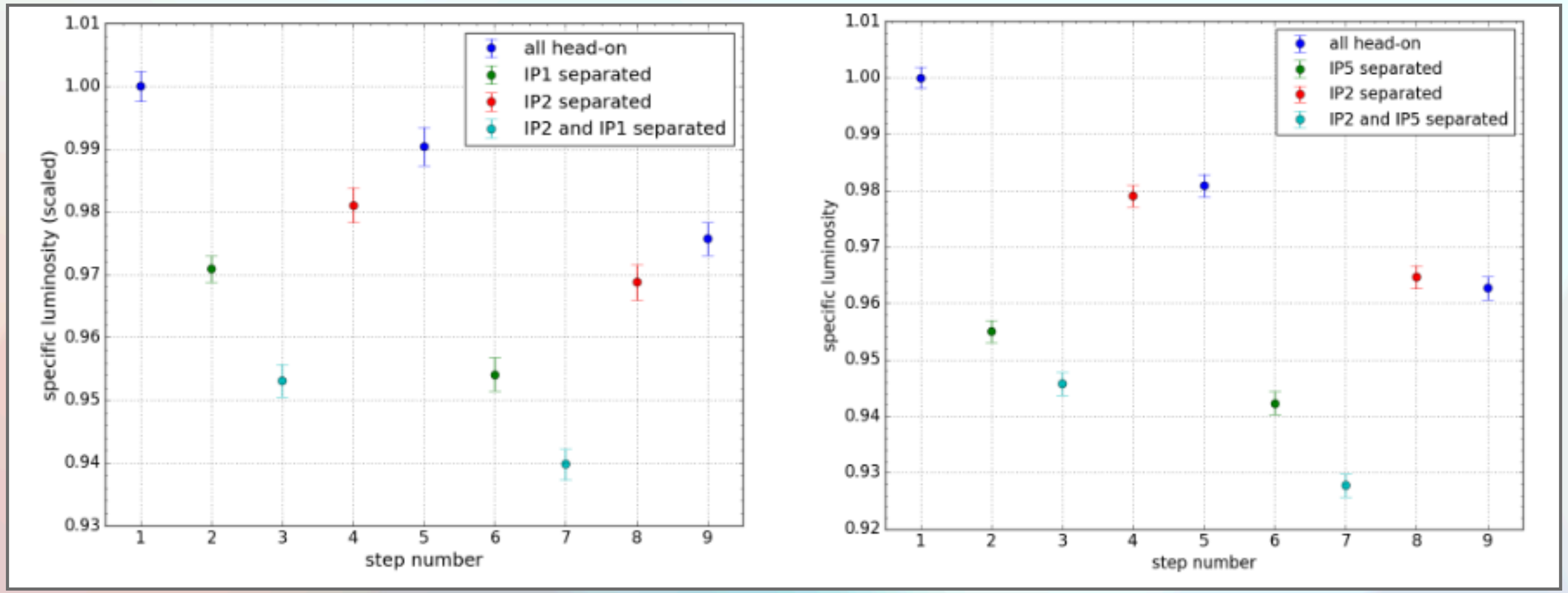
Data

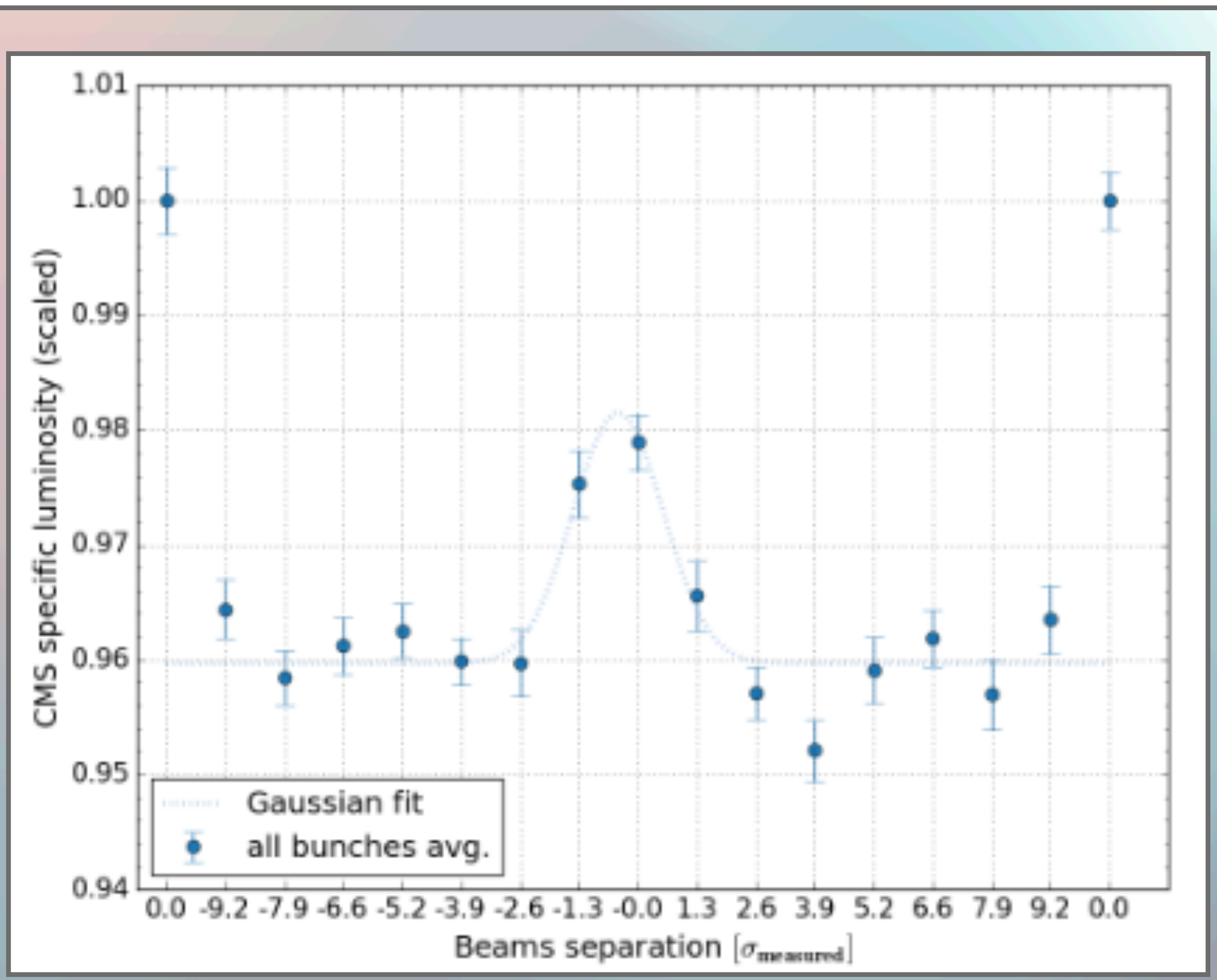


min. → max. phase = phase optimisation

BACKUP - beam-beam experiment

- optics requirement for high crossing-angle at IP2 reduces the observable effect,
    - phase advances not optimised giving different results for different observer IP,
- most of the observations on luminosity in agreement with predictions within 1%.





Luminosity changes during a separation scan

Outlook

- BCM1F-utca performance
  - application of the per channel efficiency corrections from amplitude analysis
  - simulation studies of prompt background source for afterglow components
  - automatisation and centralisation of performance tools
- Simulations
  - dedicated corrections for emittance scans with trains
  - insights for HL-LHC
  - dedicated corrections for non-factorisation scans
- BB Experiment
  - better precision needed for verification of correction dependence on the separation steps
  - optimising the phase advances for all BSRT observations
  - detailed consideration of the systematic effects