Belle II: stato e prospettive

Riunione CSN1 LNF 11/03/2025

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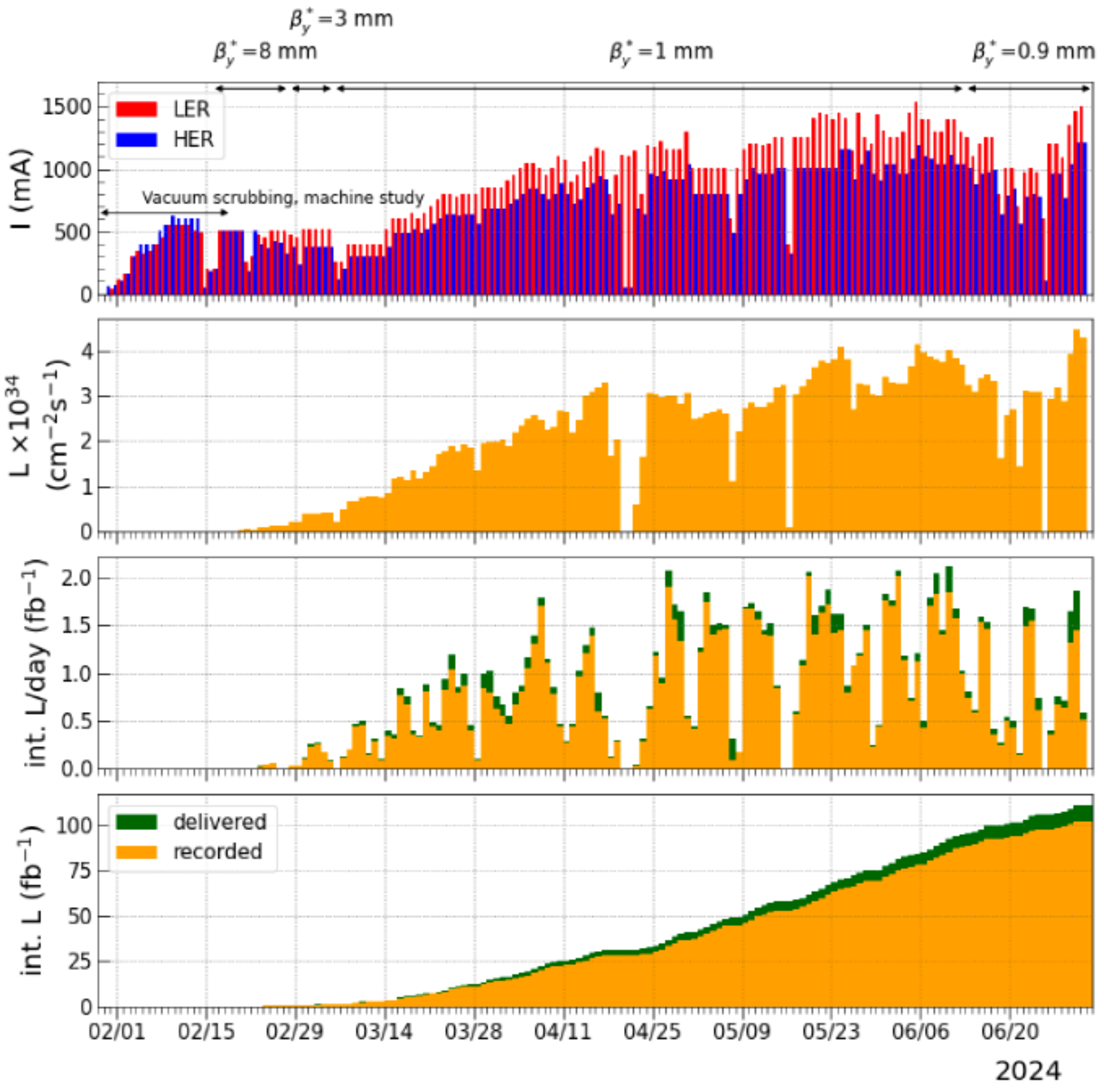
Outline:

- Summary of 2024c Run Period
- Plans for 2025-26
- Latest physics results

Run 2024ab 29 Jan-1 Jul 2024 (155 days)



2022 performances reproduced:

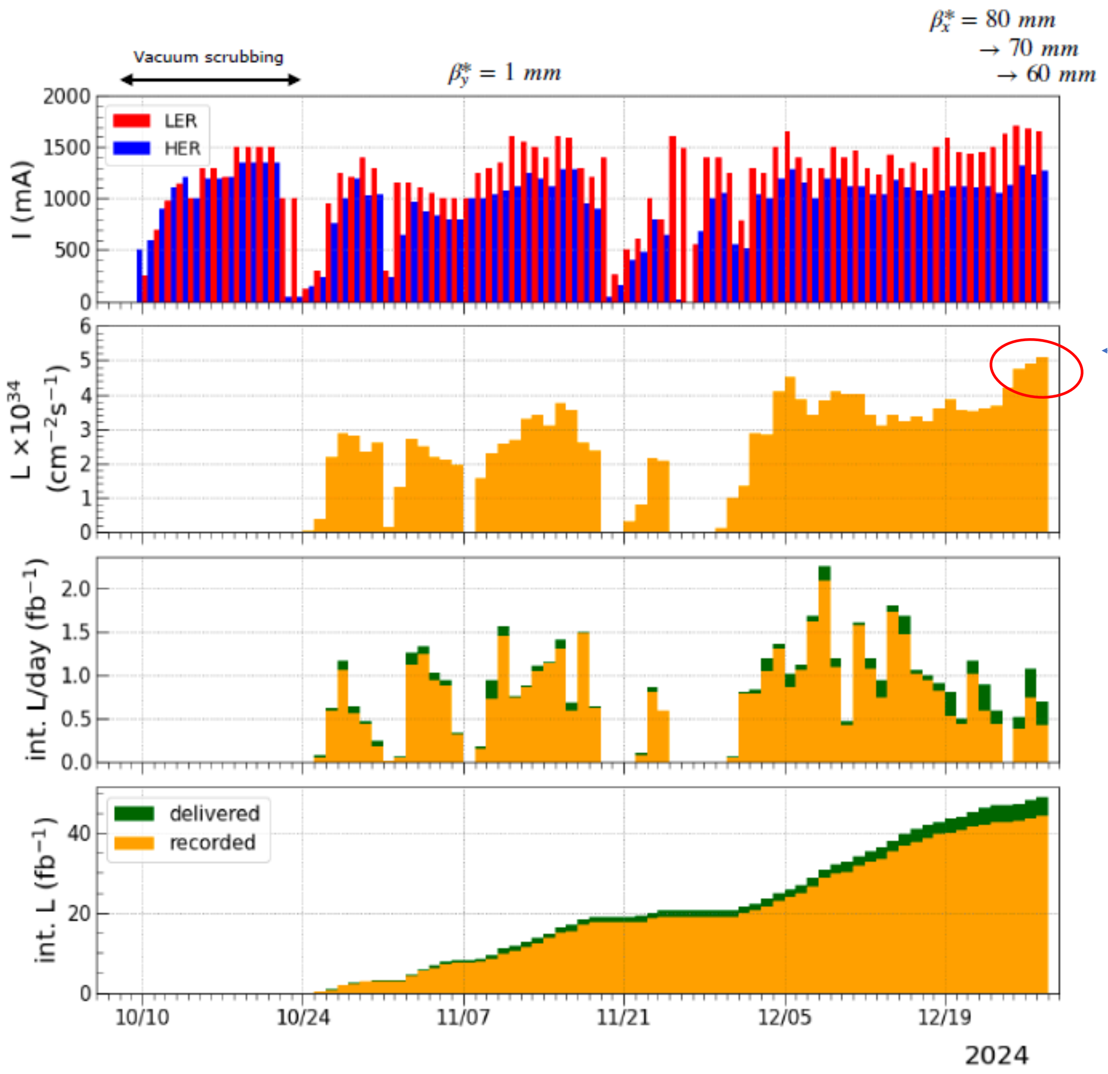
e^+ and e^- currents	1.5 A and 1.21 A
β_y^*	0.9 mm
peak luminosity	4.47×10^{34} cm^{-2}s^{-1}

However:

- Frequent beam losses limited machine operation
- Sudden Beam Losses (SBL) happen with no precursor in less than 1 turn → dangerous for IR detectors (PXD kept off since April)
- Low injection efficiency

Priority given to machine studies: only 103 fb^{-1} integrated for physics

Run 2024c 9 Oct-27 Dec 2024 (80 days)

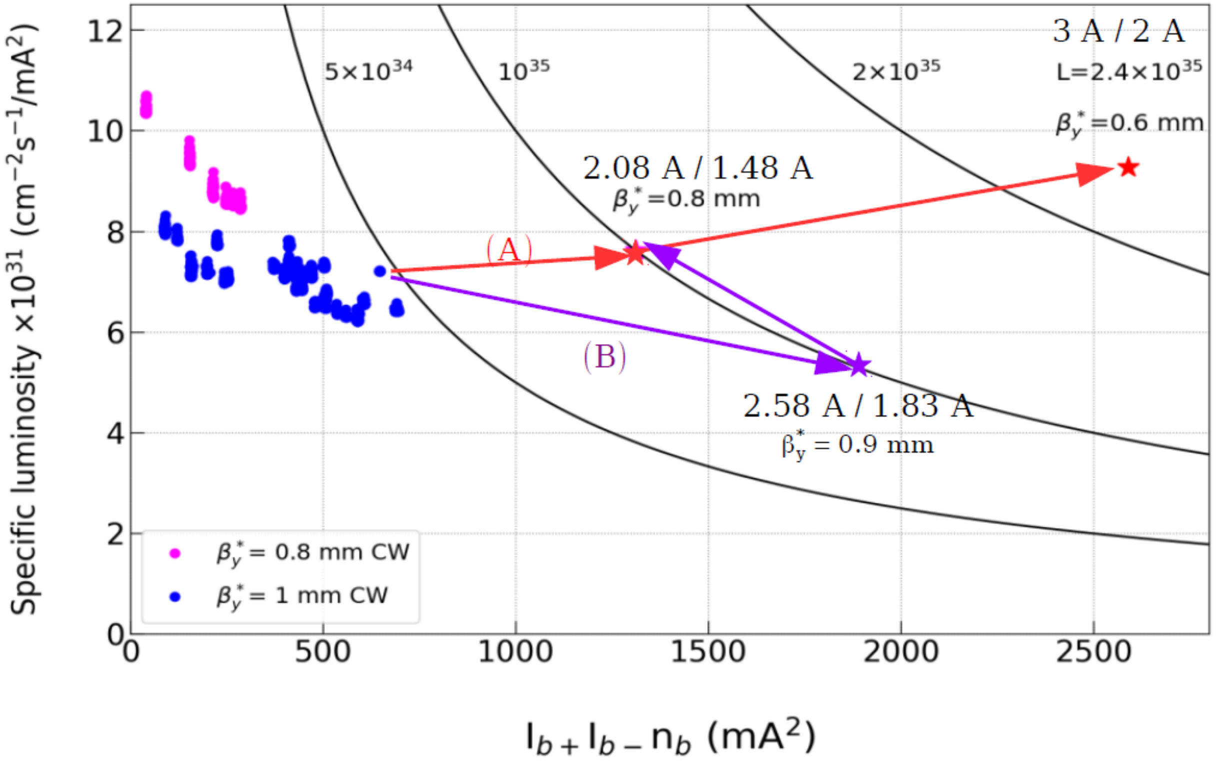


e^+ and e^- currents	1.7 A and 1.3 A
β_y^*	1 mm
peak luminosity	**5.1 x 10^{34} cm^{-1} s^{-1}**

- Sudden Beam Losses not solved, but new clues detected

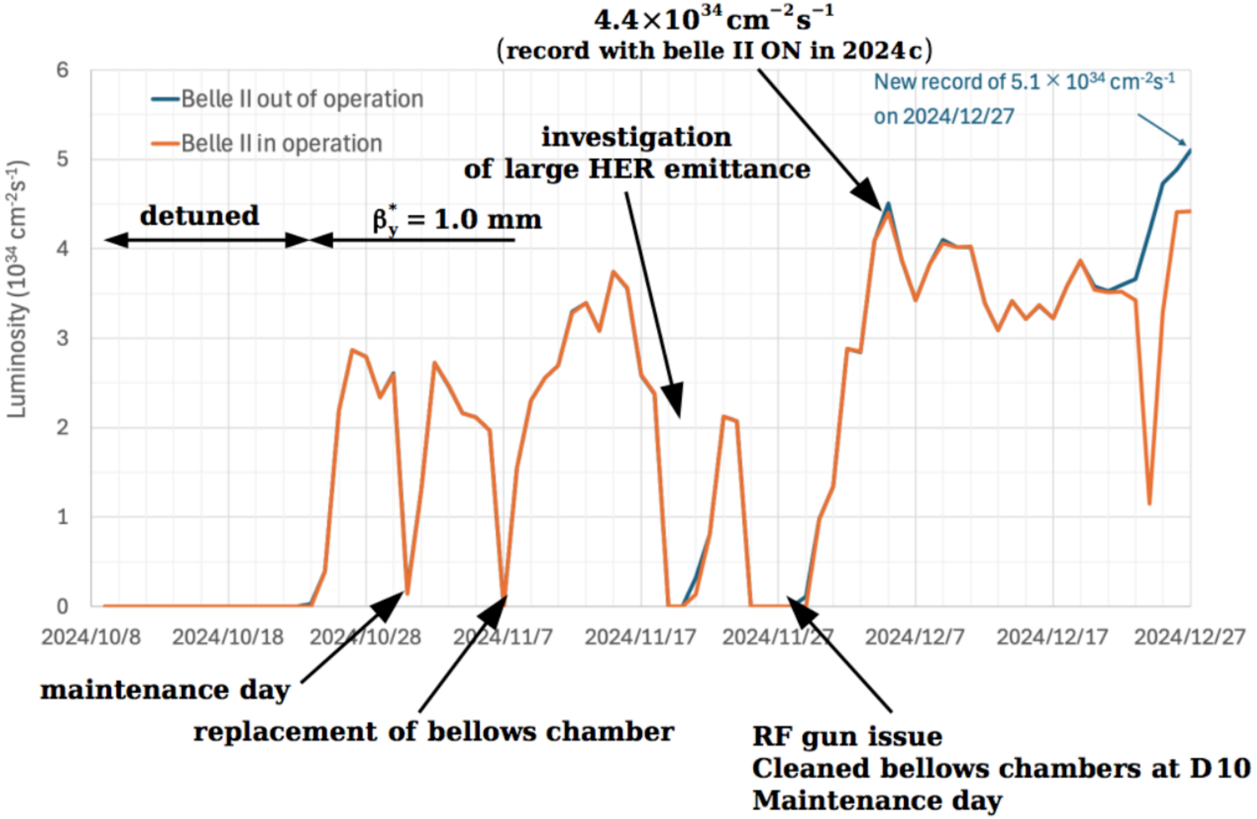
- PXD kept off for safety
- Discharging RF-gun to be replaced
- HER emittance increased significantly
- High radiation levels but improved background collimators and threshold tuning.

The strategy….



more runs are needed to implement the strategy

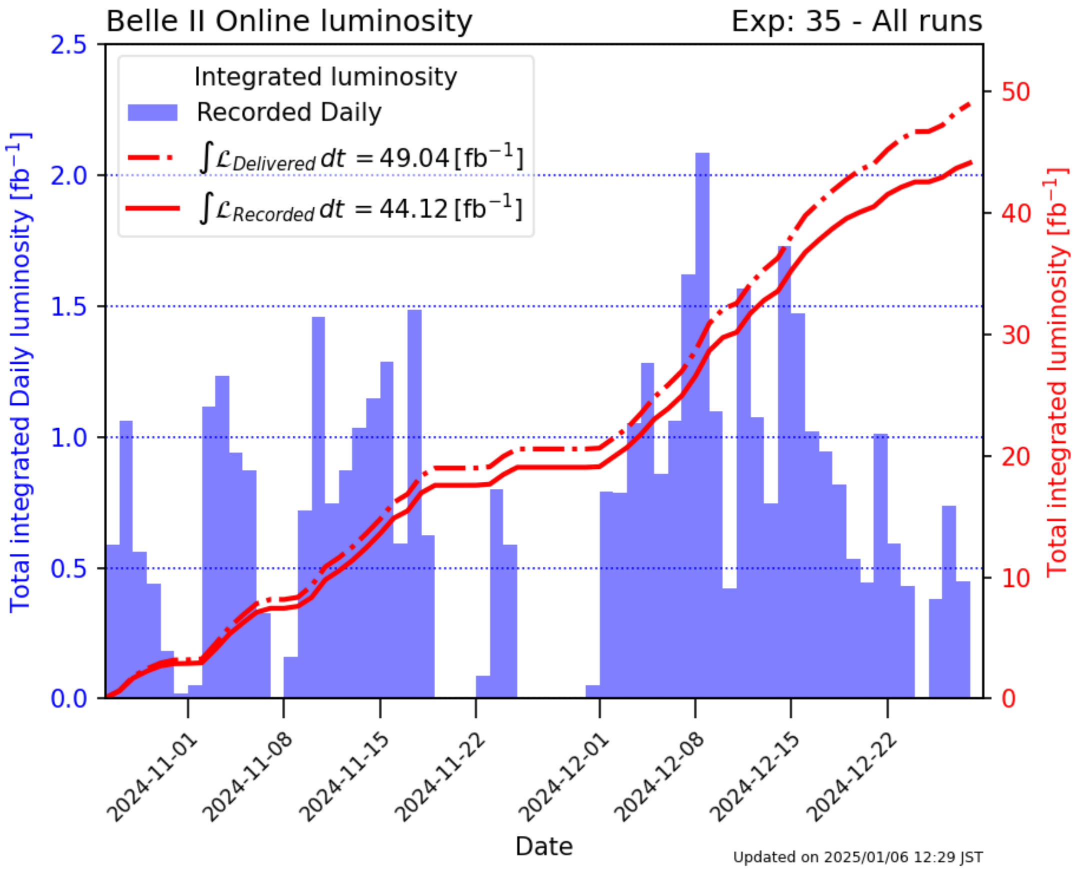
….the reality in 2024c



Peak luminosity record on the last day of the run

	Old record	New record
Date and time	2022/06/22	2024/12/27
Luminosity	4.71×10^{34} cm^{-2}s^{-1}	5.105×10^{34} cm^{-2}s^{-1}
Specific luminosity	6.95×10^{31} cm^{-2}s^{-1}mA^{-2}	5.83×10^{31} cm^{-2}s^{-1}mA^{-2}
LER current	1460 mA	1632 mA
HER current	1145 mA	1259 mA

Priority always given to machine studies



MDI group

Leader: Hiro Nakayama

MDI group includes not only **Belle II collaborators** but also several experts from **SuperKEKB** vacuum, monitor, control, commissioning, injection, RF groups, as well as from **LINAC** group.

Beam background subgroup

Leader: Andrii Natochii
(10 staff, 7 postdoc, 7 students)

- **BKG simulation**
  - simulate storage and injection background
  - Find optimal collimator settings
- **BKG machine studies**
  - validate BKG simulation based on machine study data
  - understand and improve injection BG duration which causes DAQ deadtime
- etc..

Beam loss monitor subgroup

Leader: TakShun Lau
(8 staff, 3 postdoc, 7 students)

- **Sudden beam loss (SBL)**
  - beam loss monitors with fast readout
  - acoustic sensors
  - post-mortem abort timing analysis
  - BOR timing analysis
- **Faster abort delivery**
  - NLC CLAWS as a new abort source
  - Abort delivery using laser transmission in air
- etc..

new!

Machine learning activities (*)

ML application to accelerator parameter tuning

Big data analysis using machine PV data

There also exist other MDI-related topics which are directly reported to MDI meetings, such as **beam injection, collimator R&D, diamond abort system, etc…**

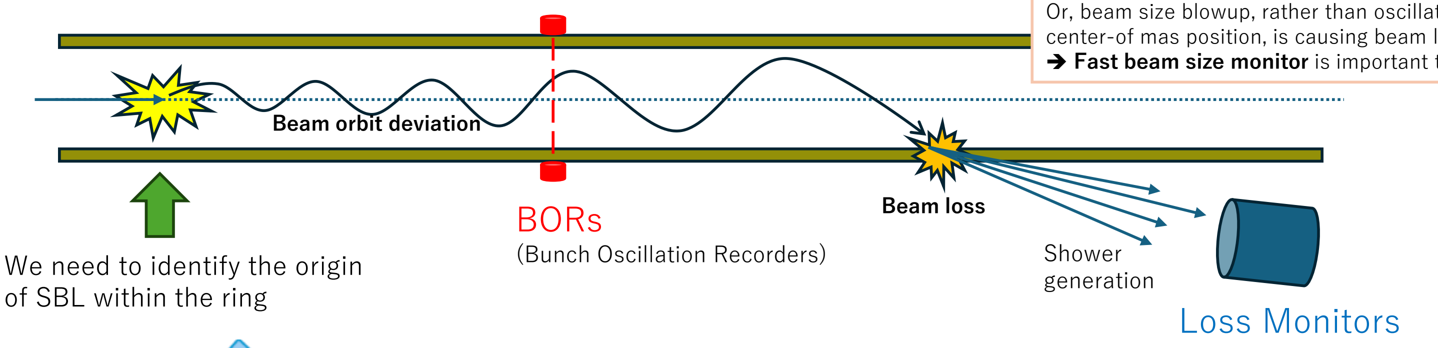
Smaller beam BKG | Longer beam life | Larger beam currents | Better injection performance

→ **Higher luminosity**

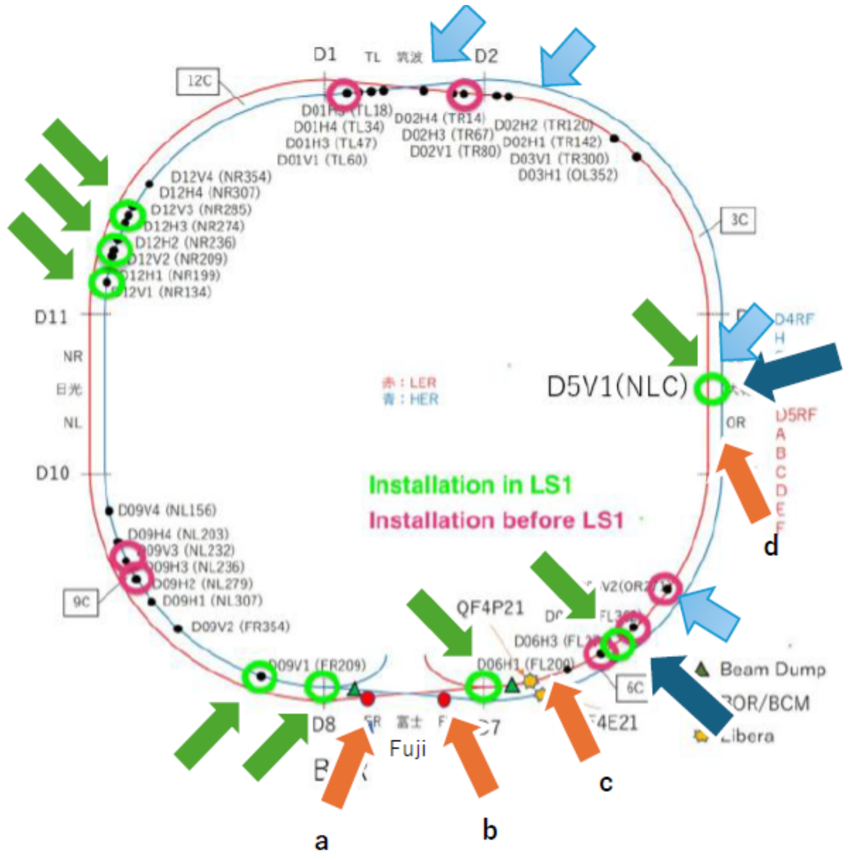
(*) B2/SKB/LINAC management has agreed to promote our further collaborations on "machine-learning application to accelerator tuning". Kickoff seminars are held to recruit (remote) Belle II collaborators and activities are started.

Sudden Beam Losses investigation

SBL tracking is made possible by a number of sensors added in 2024c:



Or, beam size blowup, rather than oscillation of beam center-of mas position, is causing beam loss?
➔ **Fast beam size monitor** is important to check it out



New loss monitors
(at NLC, D6H4, HER masks, injection points)

New CLAWS scintillators at D5V1, D6V1

Acoustic sensors
(at D6V2,D2V1,D5V1, and QCS beam pipes)

New BOR (Bunch Oscillation Recorders)
(based on iGp12,RFSoC)

a (D8, Fuji upstream), **b** (D7, Fuji downstream)
c (D6, before D6 masks) or **d** (D5, before D05V1)

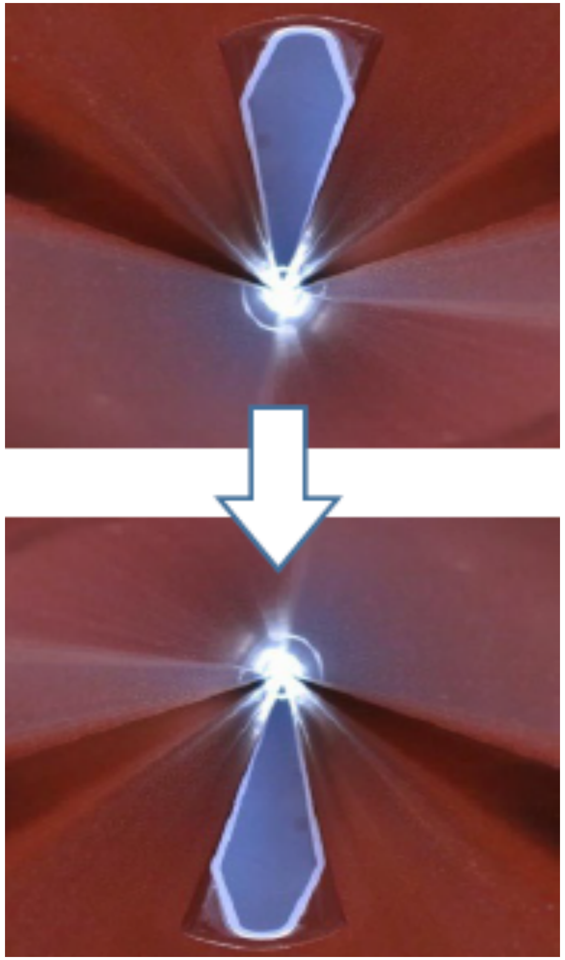
Fighting *Sudden Beam Losses* (SBL)

i.e. losses which happen in 1 turn (10 μs) or less

- Dust from keramic electrodes in wiggler sections spotted as possible SBL source in 2024ab

  15/50 beam pipes turned upside down during summer shutdown

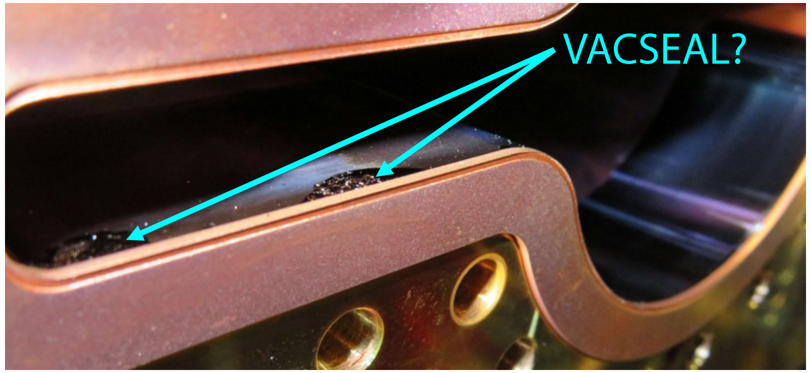
  In 2024c frequency of SBL with pressure burst in the «flipped» area increased with beam currents….. Definitely was not the right solution.

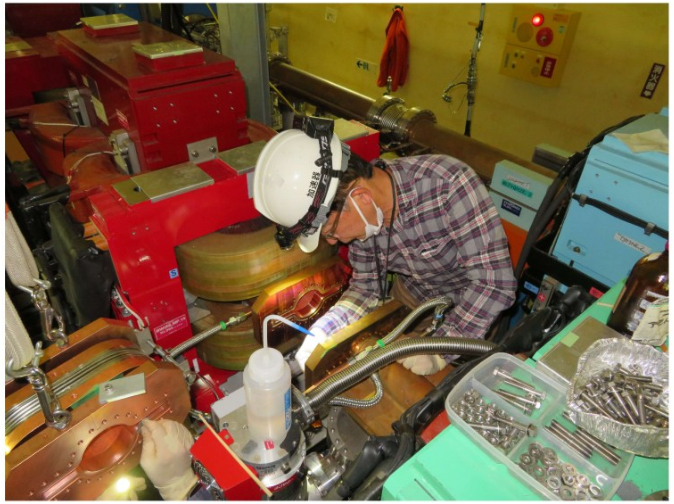


- Black deposits due to vacuum sealant and small dust particles were found in the bellows of a region where many *pressure bursts* occurred.

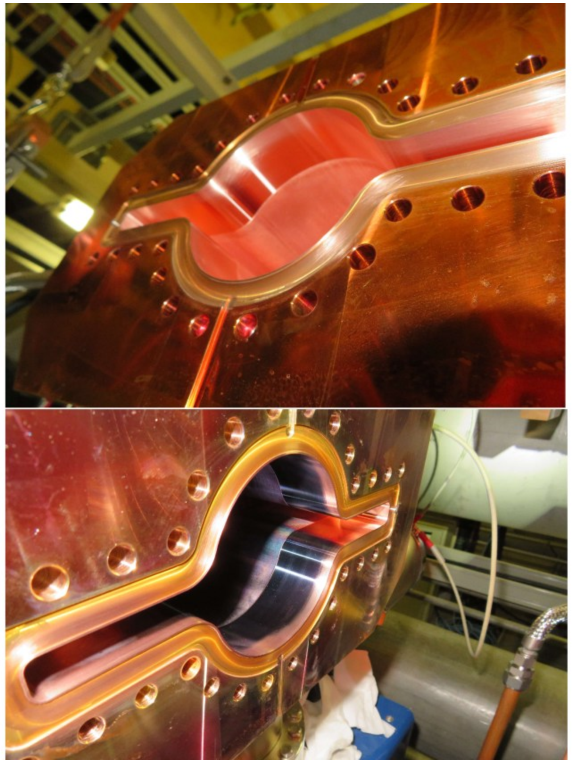
Effect of VACSEAL removal on SBL events

Before removal





After removal



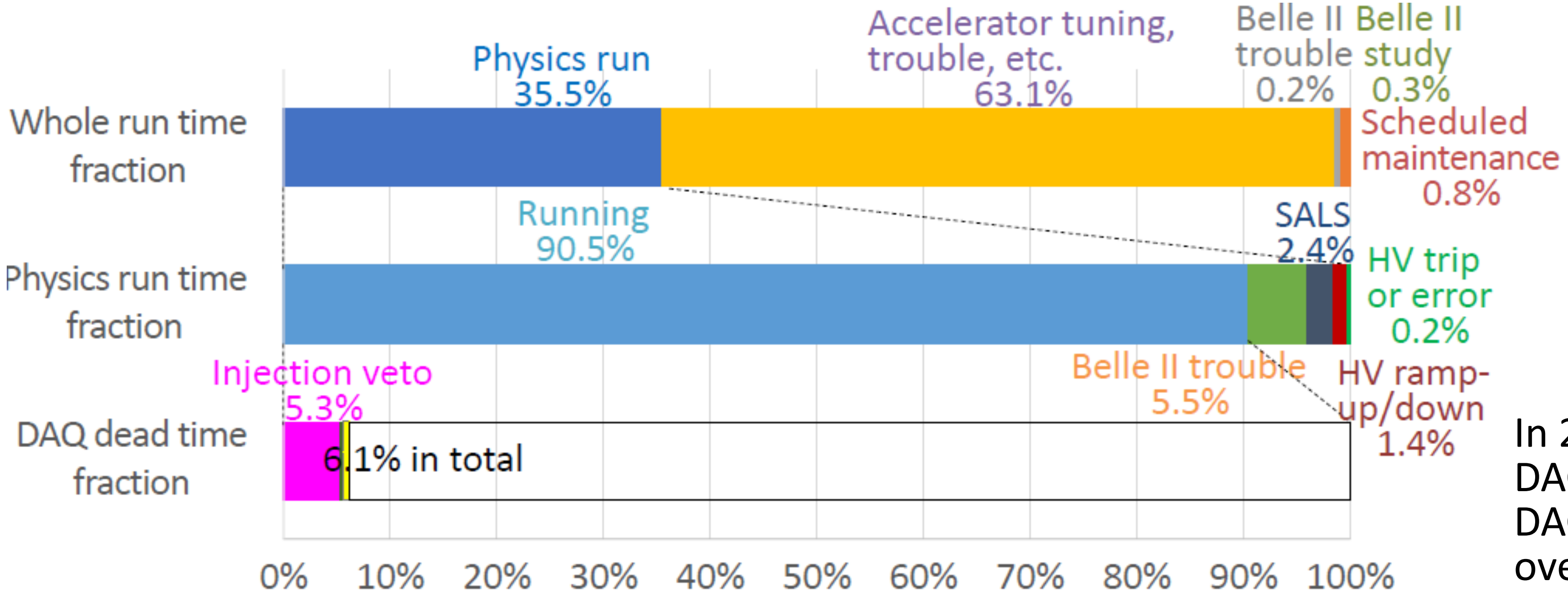
VACSEAL removal reduces SBL events accompanied by pressure bursts

Oct. 9 - Nov. 6 : #SBL/Beam Dose = 0.141 (1/Ah)

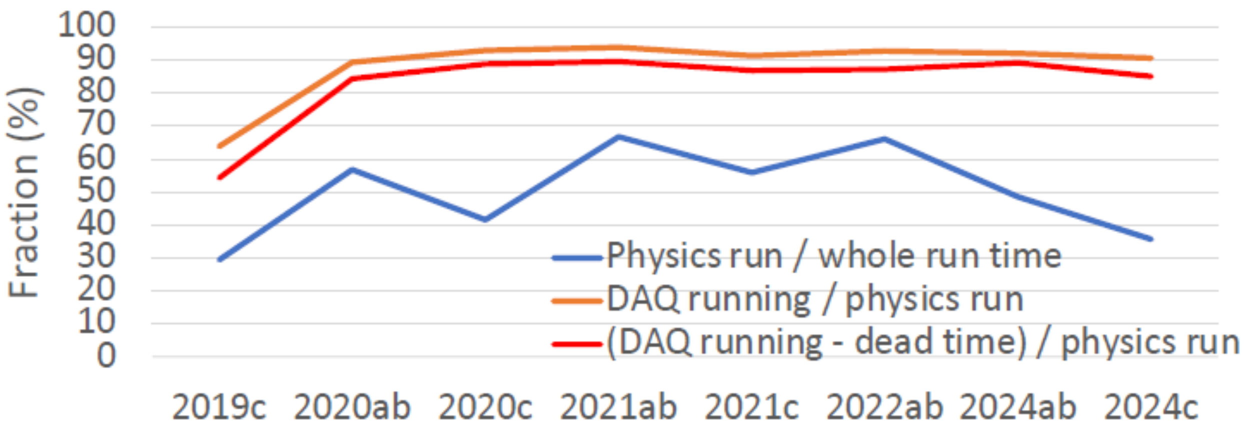
// Bellows chamber at Nikko wiggler section was exchanged on Nov. 6.

Nov. 6 - Dec. 27 : #SBL/Beam Dose = 0.043 (1/Ah) ← including not-removed flanges

Belle II run time fraction



In 2024ab:
DAQ running: ~92%
DAQ deadtime: 3.1%,
overall efficiency: 89.1%



~2/3 of time for machine tuning

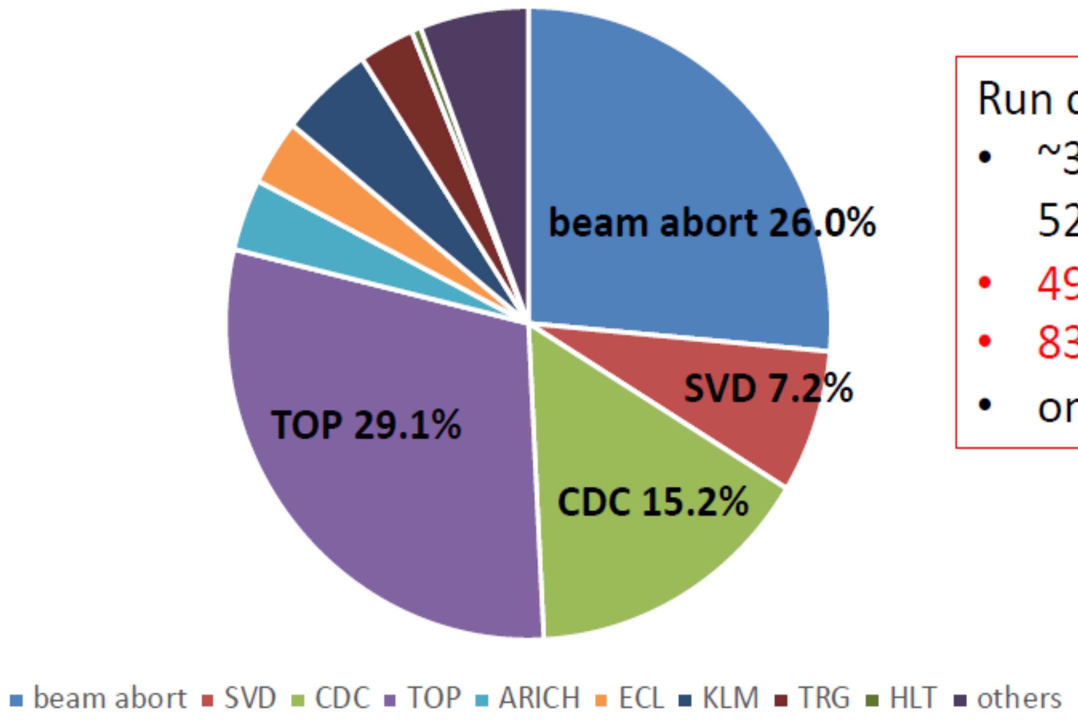
Overall data taking efficiency = 85.0%
(Target 90%)

Belle II run stop statistics

Belle II sub-detectors generally stable

- Run stop reason:
  - TOP: 29.1%
  - beam abort 26.0%
  - CDC: 15.2%
  - SVD: 7.2%
  - KLM: 4.9%
  - ARICH: 3.6%
  - ECL: 3.3%
  - TRG: 2.9%.
  - HLT: 0.5%
  - others: 5.7%

run stop reason of physics runs



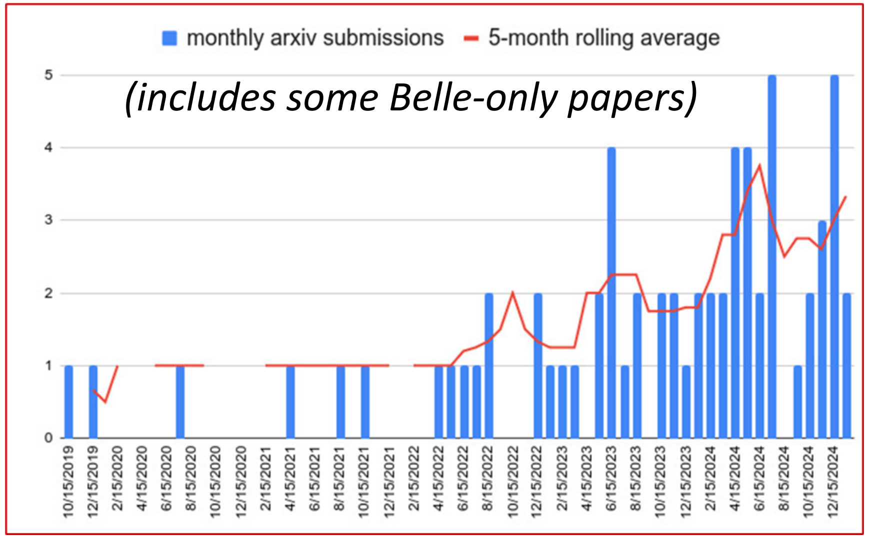
Run duration for physics runs:
- ~33mins/run on average. (vs. 52mins/run in 2024ab)
- 49% of runs are less than 10 minutes
- 83% of runs are less than 1 hour
- one run reached 8 hours (run1754)

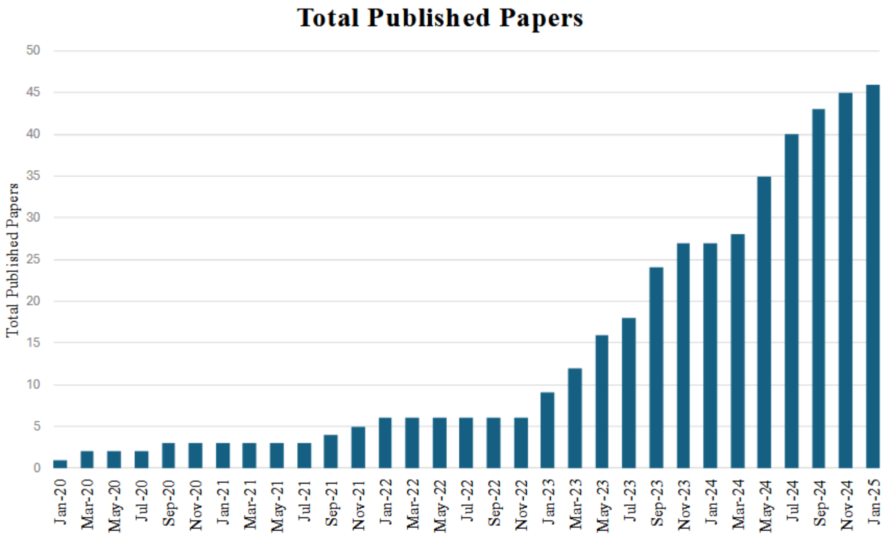
- Frequent TOP b2link lost and SVD errors occurred due to high injection background.
- SEU induced FEE errors are also main part of run stoppers by CDC, TOP.

Belle II Physics Analysis keeps competitive

- Journal papers statistics:
  - **52 published papers + 3 accepted for publication**;
  - + 9 more submitted;
  - + ~20 more in the pipeline
- First results using 2024 data in Summer 2025.

Few highlights in the following slides, with an eye to results more «Belle2-specific»



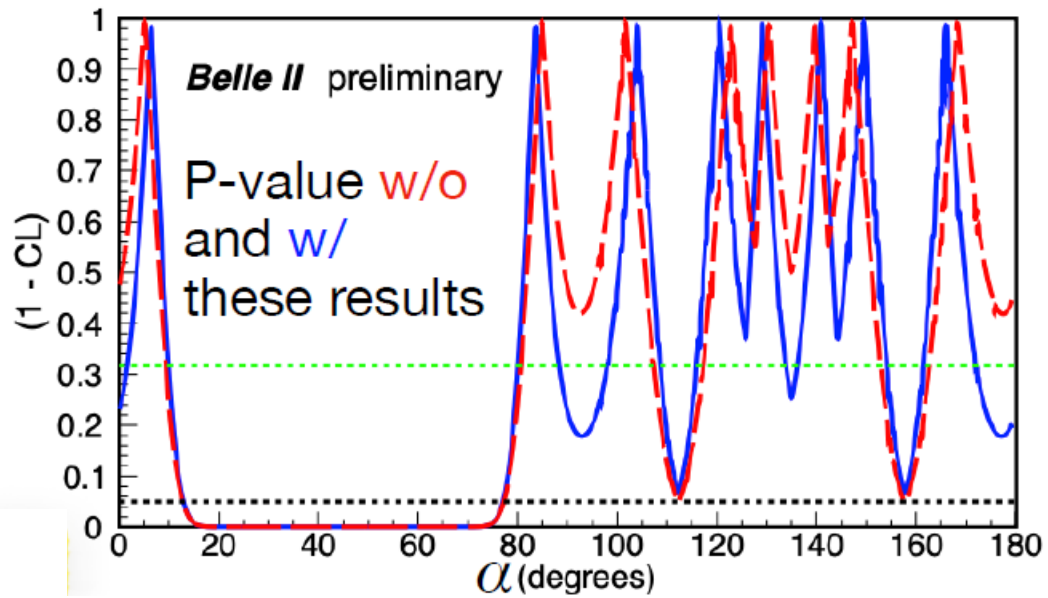


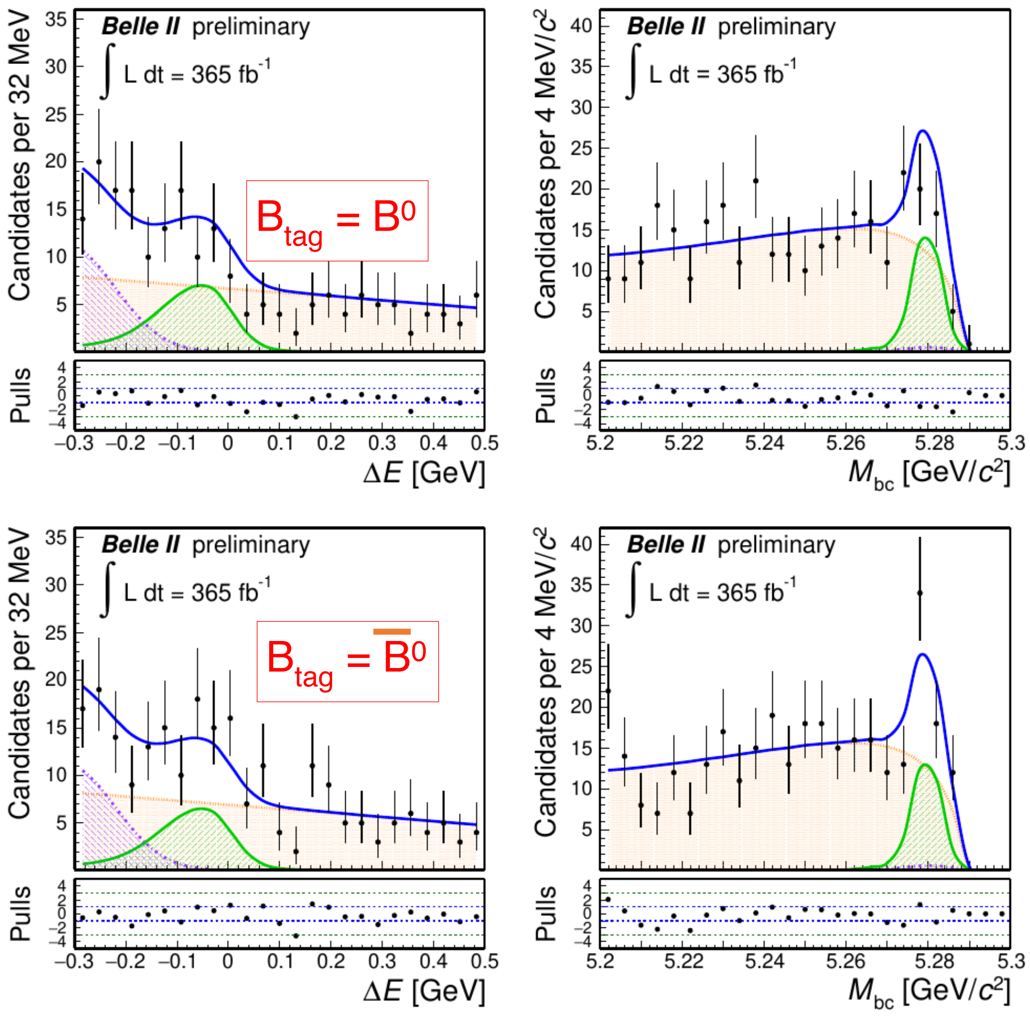
$B^0 \to \pi^0\pi^0$

[Arxiv:2412.14260 accepted by PRD]

- Four-photon final state, no vertex: only at Belle II!
- Branching ratio and direct ACP are fundamental inputs for α/ϕ_2;
- Continuum suppressed with dedicated BDT. Tag the flavour to measure the CP asymmetry. Extract signal from a 4D fit

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.03 \pm 0.30 \pm 0.05$$





Best precision on BR and same accuracy as WA on the CP asymmetry!

CPV in $B^0 \to J/\psi\pi^0$

PhysRevD 111, 012011 (2025)

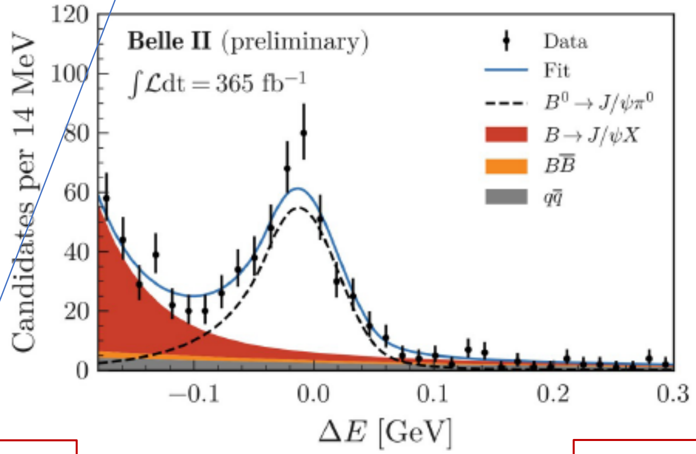
- Color suppressed b → c$\bar{c}$d tree-level decay → loop contribution plays a role
- Important input to correct for the penguin contamination in the $B^0 \to J/\psi K^0_S$ (tree only: S=-sin 2ϕ_1 ~ -0.71)

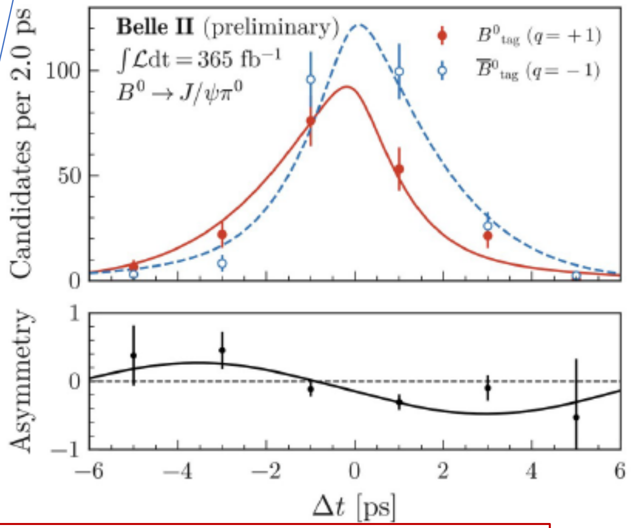
203±17 ($J/\psi \to \mu\mu$)
186±16 ($J/\psi \to ee$)

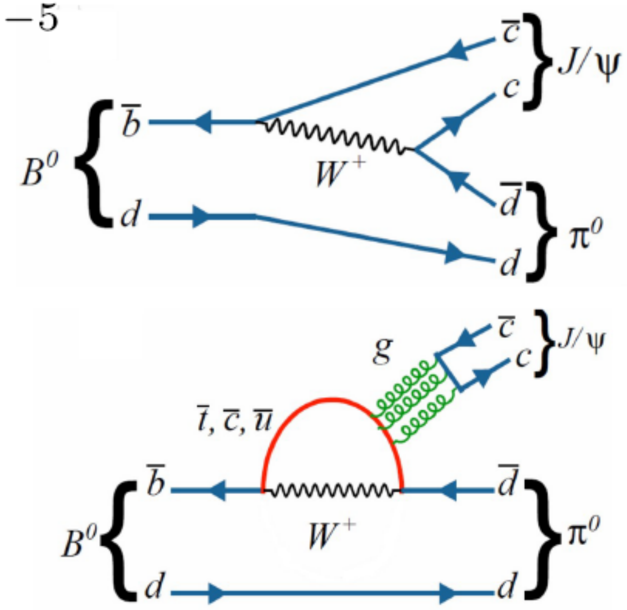
Best precision

$$S = -0.88 \pm 0.17 \pm 0.03$$
$$C = +0.13 \pm 0.12 \pm 0.03$$

$$\mathrm{BR} = (2.00 \pm 0.12 \pm 0.10) \pm 10^{-5}$$







5 σ from zero

Consistent with WA.
Precision similar to other measurement.

Evidence of $B \to \tau\nu$

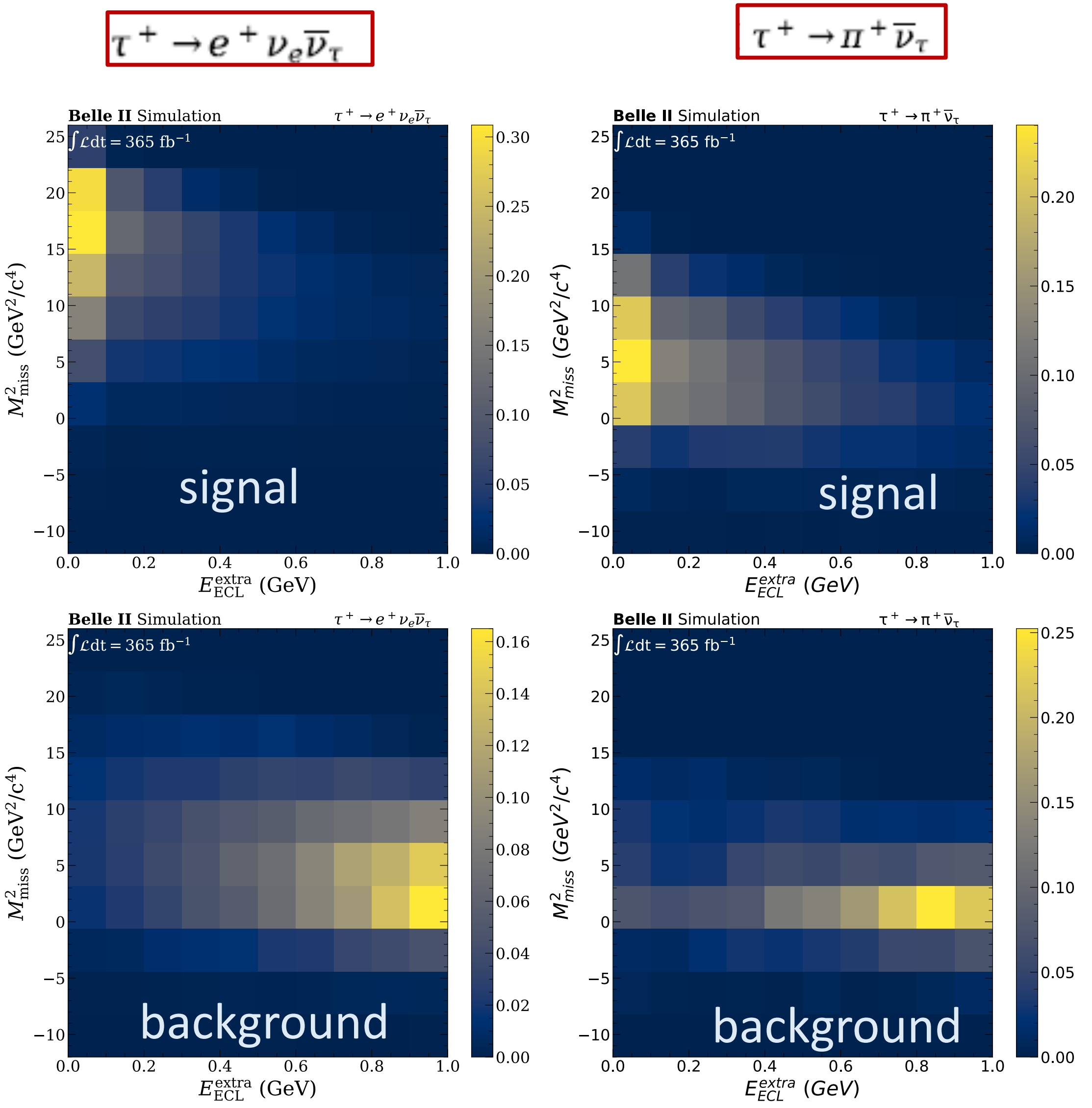
Arxiv: 2502.04885

Ideal process to measure V_{ub}, but helicity suppressed.

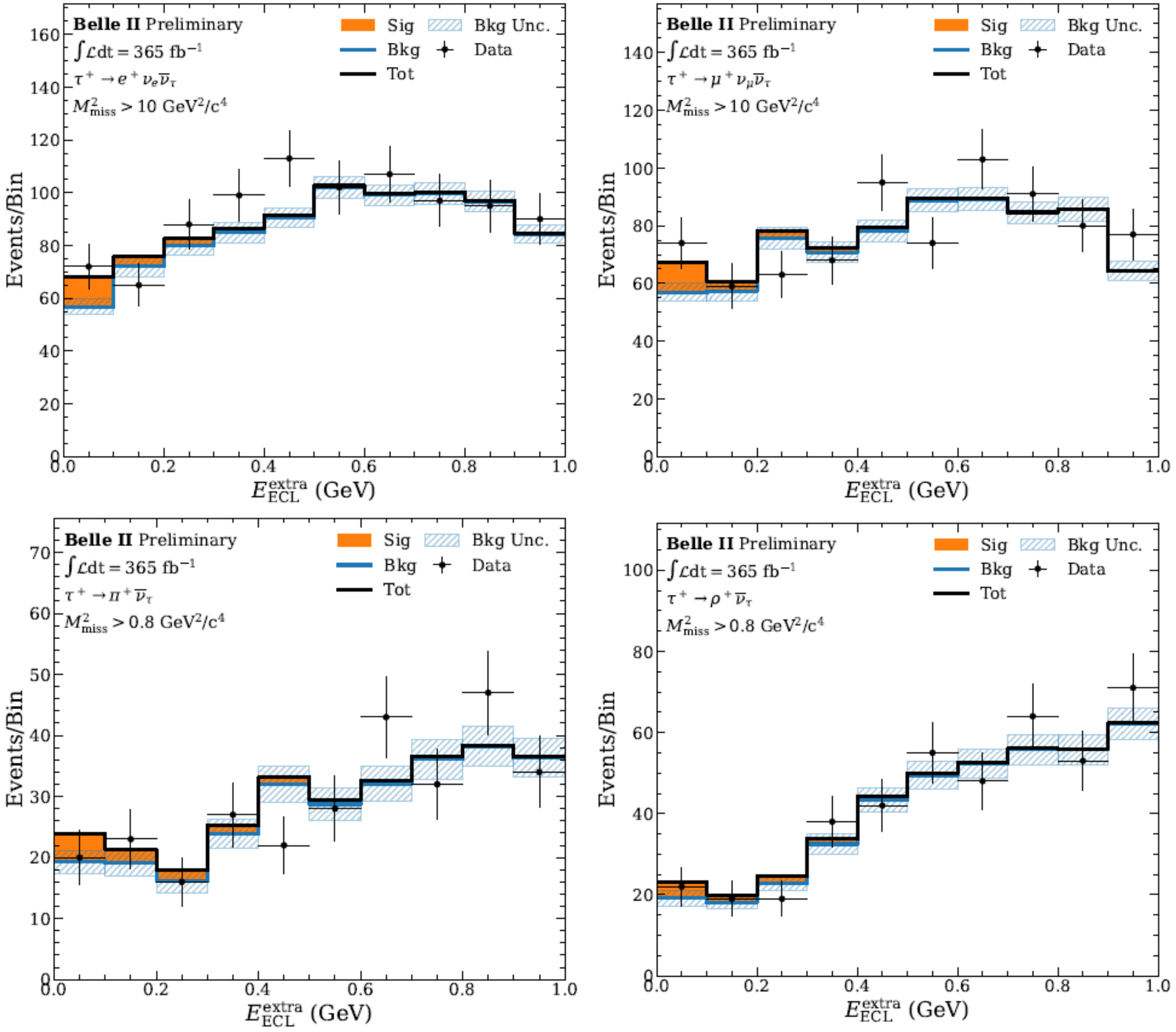
Sensitive to BSM contributions.

- Hadronic tagging
- τ decay reconstruction in leptons, π, ρ
- Large missing energy
- Nothing else: no residual energy in calorimeter

Signal extracted by a fit to the 2-dim distribution of E_{extra} and M^2_{miss}

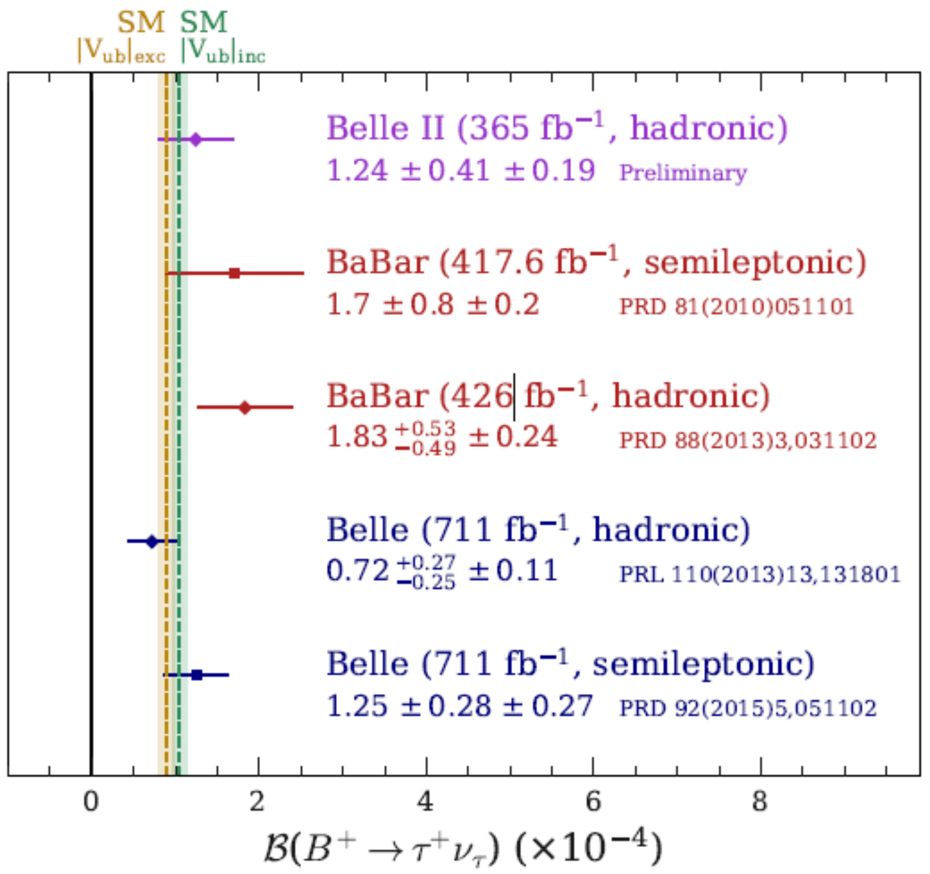


Evidence of $B \to \tau\nu$



E_{ECL}^{extra} in the M_{miss}^2 signal-enriched region

Fit 94 ± 31 events: result in agreement with SM and previous measurements



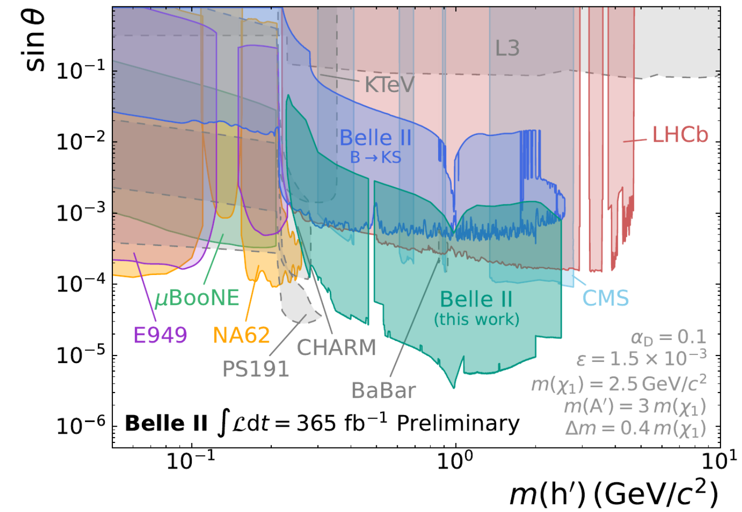
Inelastic Dark Matter with a dark Higgs

to be submitted to PRL

Expanded dark sector with two dark matter states with a small mass splitting and a dark photon

χ_1 is stable, χ_2 is long-lived $m_{A'} > m_{\chi 1} + m_{\chi 2}$

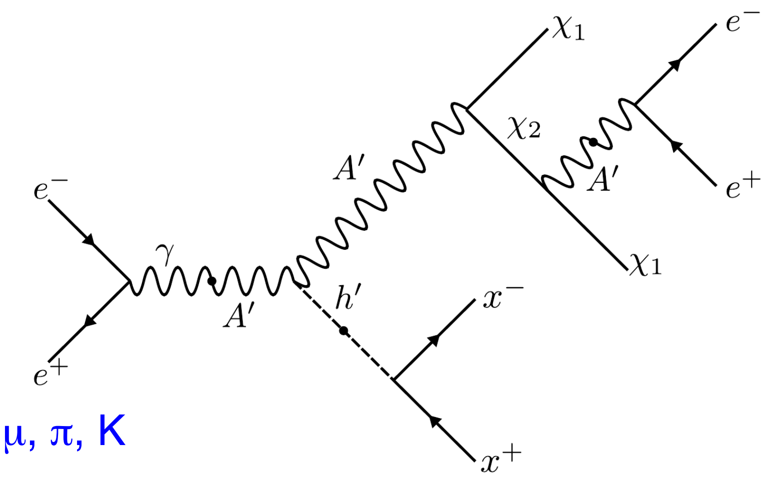
θ: mixing angle between dark and SM Higgs's



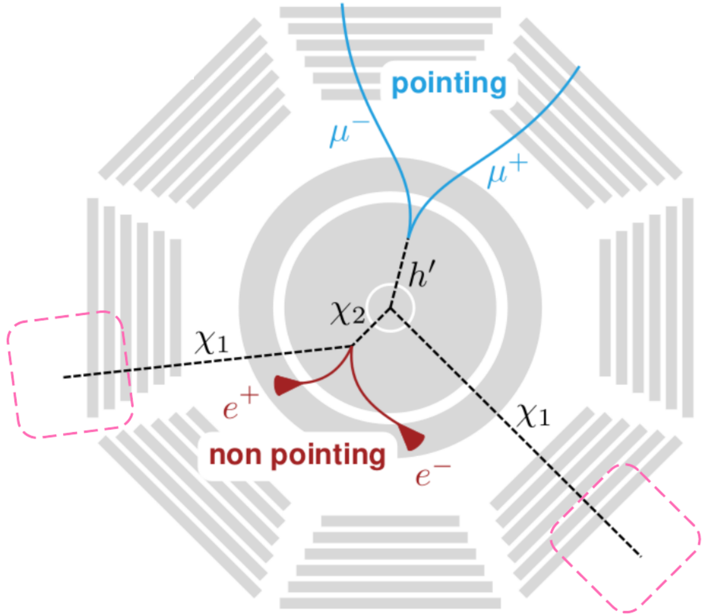
- 4 tracks + missing Energy
- 2 displaced vertex: one pointing, one non-pointing
- Challenging for tracking and *trigger*
- Almost zero background

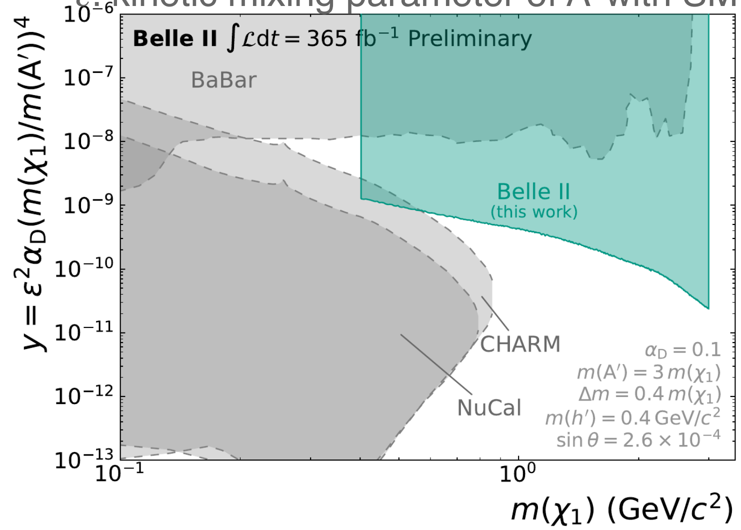
α_D: coupling strength between DM and A'

ε: kinetic mixing parameter of A' with SM γ



x = μ, π, K





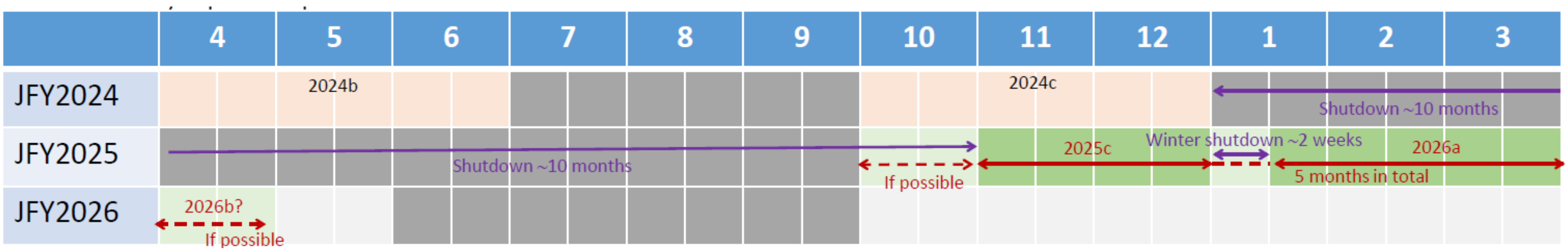
What next in 2025 ?

Increased electricity cost produce a reduction of the SuperKEKB yearly operation time that MEXT can guarantee:
==> 5 months for the next fiscal year is a reasonable expectation

SuperKEKB needs still a number of hardware works to be implemented to cure its present limitations

On the other hand a longer run durations is desirable to allow machine optimisation.

The Belle II Executive Board has recently approved the following plan for 2025-26:



10 months shutdown to implement all the HW works + 7/8 months continuous running

Plans:

- Next run period will be 2025c, starting October or November
  - Only 2 week winter break, transition into 2026ab (until ~ end of May?)
  - Path to PXD re-inclusion under discussion
- Accelerator:
  - Remove vacseal to avoid SBL
  - mitigate beam background/IR loss from SBL (e.g. collimator relocation, faster aborts)
- Detector:
  - Tsukuba Hall roof renovation
  - ARICH cooling work
  - mitigate SEU-related downtimes (SVD, CDC, TOP, DAQ)
  - work on accepting higher backgrounds (all)

Conclusions

- Run 2 started in 2024 showed some important machine instabilities which are being studied. A number of countermeasures are being implemented.
- A 10 months shutdown is planned in 2025 to allow all hardware works to be completed. Run will restart in November 2025 for 8 months.
- Belle II is getting the most out of Run 1 data sample, often surpassing the sensitivity of previous *B* factories, despite having a significantly smaller data set;
- SuperKEKB program is planned to continue beyond 2040, with a second long shutdown around 2032, up to integrate 30-50 ab^{-1} . A strategic collaboration with future e+e- accelerator R&D can be established
- Belle II detector upgrade project is progressing with R&D toward a TDR.

Backup slides

MDI important improvements in 2024c

5-10 μs faster beam abort

1. **Faster beam abort**
   - Additional abort sensors (CLAWS) installed to LER D6, D5
   - Shorter abort delivery path to the LER abort kicker
2. **SBL analysis utilizing BORs(Bunch Orbit Recorders) data**
   - Multiple BORs enable timing/phase analysis of SBL origin
3. **Relaxed Belle II diamond abort threshold during injections**
   - Smoother operation startup and reduced injection-aborts
4. **Collimator operations**
   - LER NLC (Non-Linear Collimator) put into action
   - D02V1 orbit drift alarm implemented
5. **Machine learning application to SuperKEKB operation**
   - Automized injection parameter tuning based on Bayesian optimization
6. **Beam background machine studies**
   - Dedicated single-beam BKG machine studies in Apr. and Oct.
   - Detailed injection BKG simulation now available, dedicated machine studies for comparison

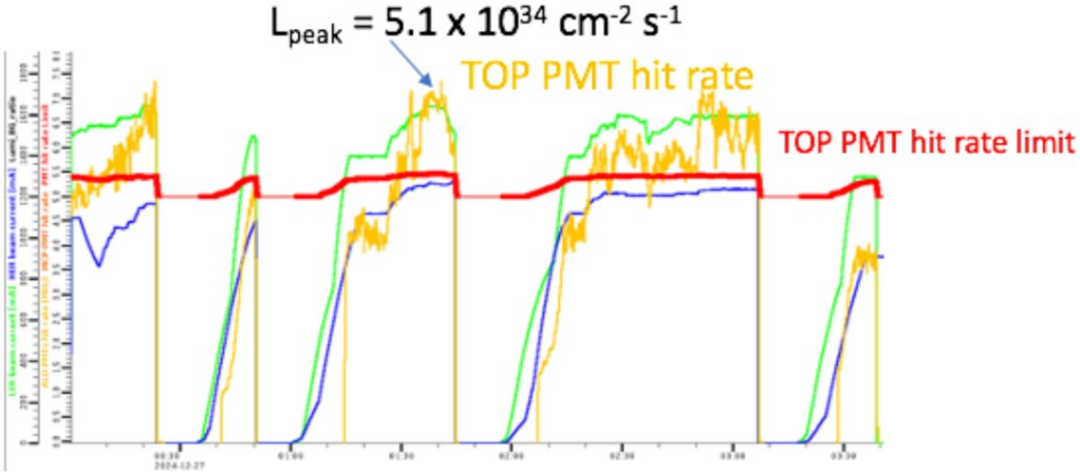
Pressure burst location

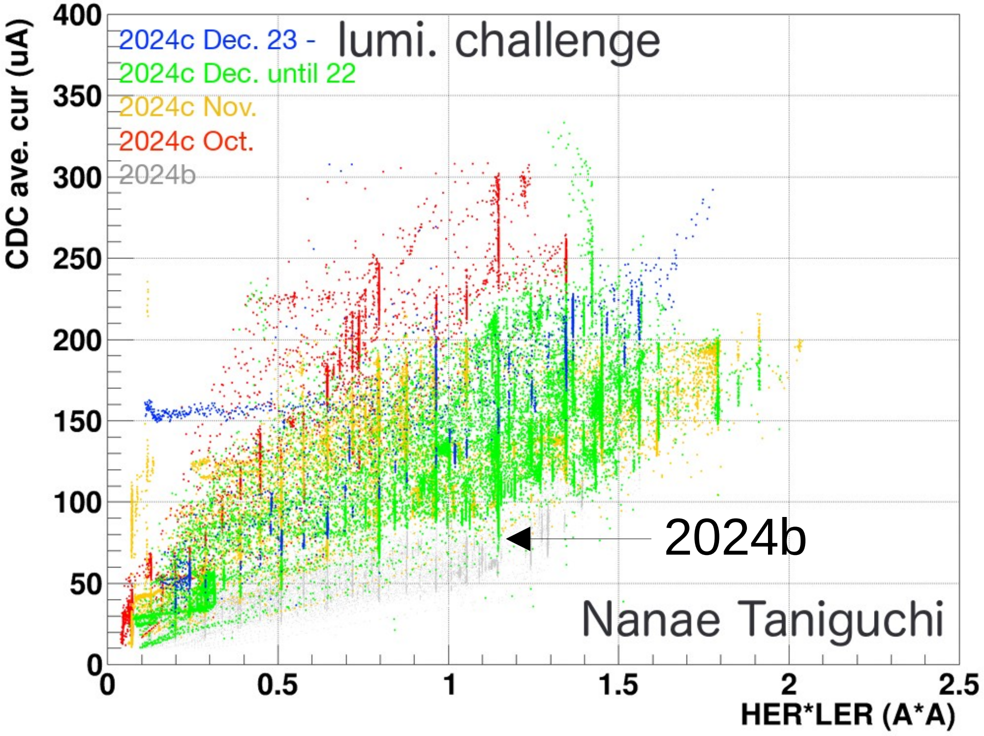
Thanks to new diamond DCU firmware.

Picoscope to monitor injection background

Backgrounds

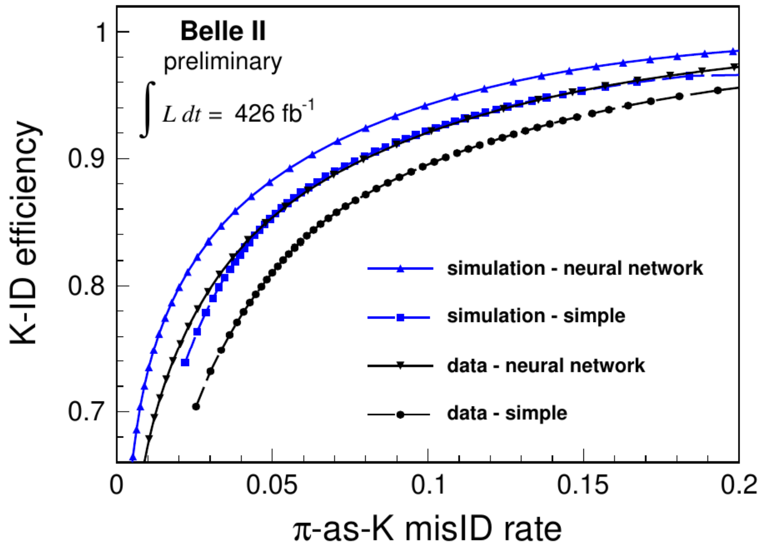
- Storage and injection backgrounds started much higher than before
  Storage background improved to 2024b quality, injection background did not
- LER 2-bunch injection: second bunch is worse
- Flipped beam pipes → higher pressure
- Non-linear collimator (NLC) use limited
  by Oho hall radiation levels
- More shielding and new NLC position for 2025c

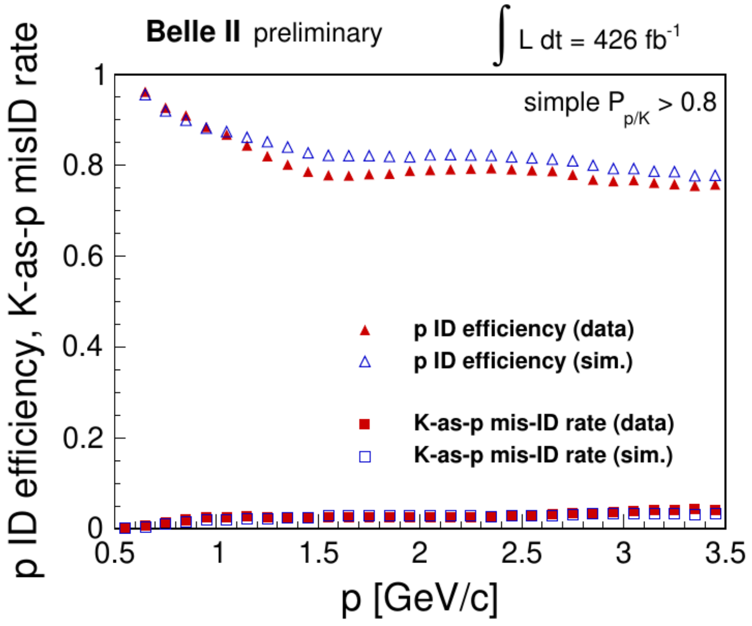




Hadron ID (π, K, p) performance paper (CNS1 milestone 2025)

- Motivations: describe hadron ID at Belle II, with particular reference to what we achieved during Run1 data taking (2019-2022);
- We describe:
  - the sources of PID information and how they are combined into variables made available to analysts;
  - the software tools and data samples used to measure efficiencies and misID rates;
  - how corrections and (systematic) uncertainties are derived;
- We show the performance in terms of K vs π and K vs p separation;
- We critically discuss problems encountered, mitigation strategies, and future developments;
- Target journal: EPJC;
- CWR1 ended on February 24th.

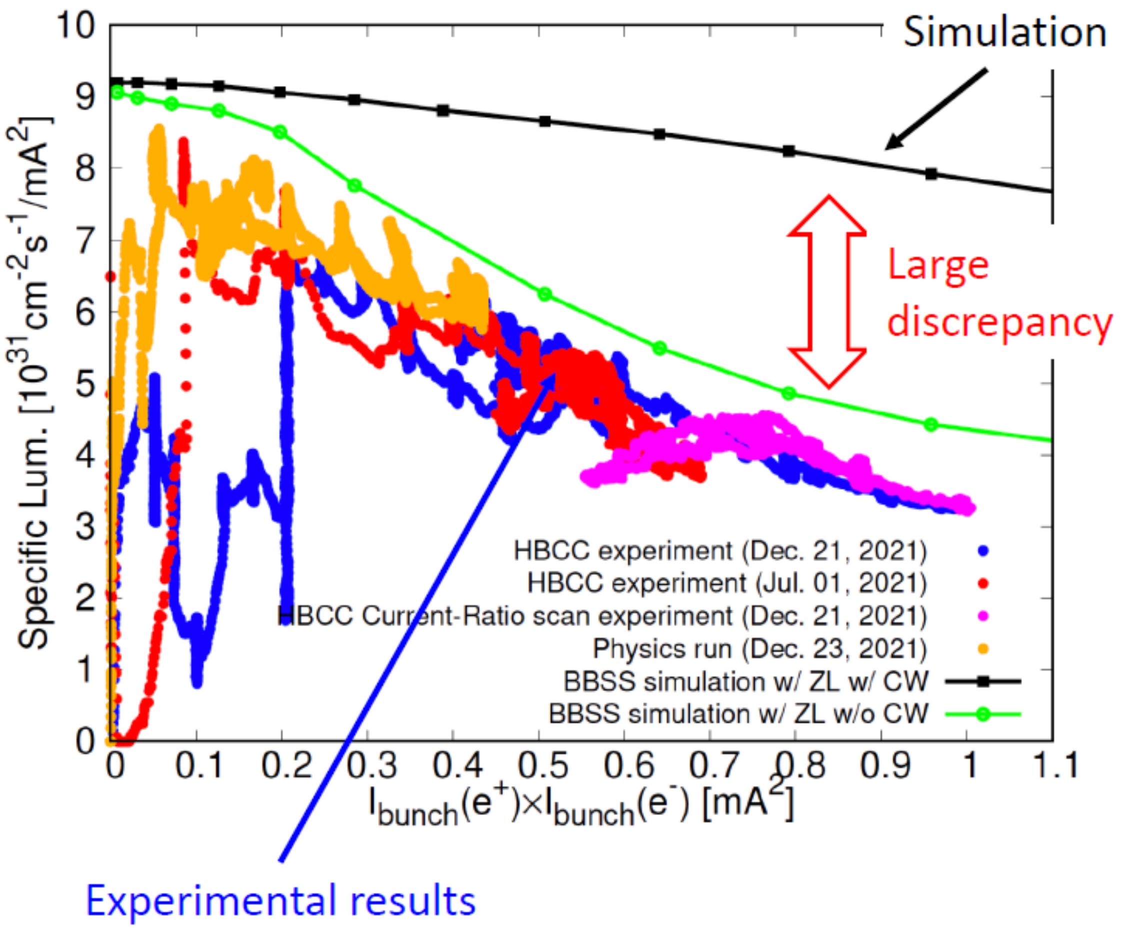




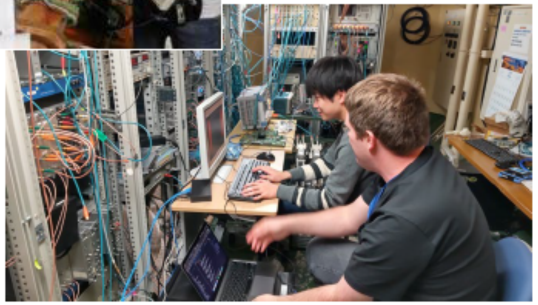
Synergy with future colliders studies

- Beam-Beam simulation shows much higher specific luminosity
  - It is still unclear why experimental results are much smaller than the simulation.
    - Can simulation miss some important factors?
  - There should be hints to increase luminosity of SuperKEKB.
    - If we identify the cause of the reduction in the luminosity, measures can be taken to improve luminosity.
- Important issue not just for SuperKEKB, but for future colliders with nano-beam collision scheme.
- Currently working on establishing a framework for international collaboration with CERN, IHEP, etc. especially on Beam-Beam simulations.
  - Several researchers will join SuperKEKB beam-beam team for 1-2 years to solve the mystery of SuperKEKB.

Strong-Strong Beam-Beam simulation (D. Zhou)

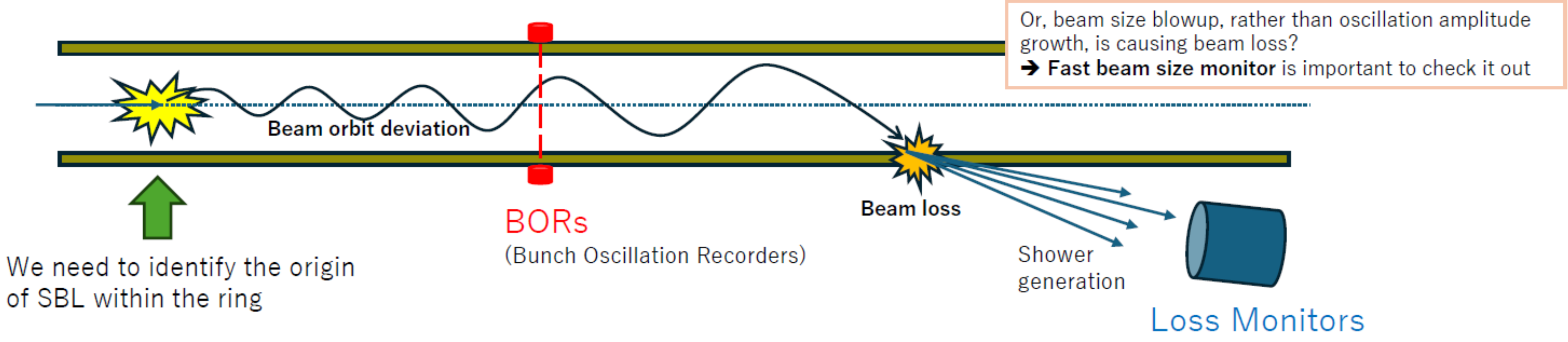


KEK accelerator R&D collaboration opportunities



- International collaboration framework (existing)
  - Multi-National Partnership Project (KEK MNPP)
    - R&D for high luminosity colliders (MNPP-01)
    - Partnership between KEK and INFN, CERN, CNRS/IN2P3, SLAC, IHEP-Beijing
    - Visa support, daily life support, etc.
  - Europe-America-Japan Accelerator Development Exchange Program (EAJADE)
    - Exchanging accelerator scientists and experts between Europe, America (Canada and USA), and Japan
    - Exchange of ideas on R&D and implementation of future accelerators for particle physics
  - US-Japan collaboration on High Energy Physics
    - R&D for SuperKEKB and the next generation high luminosity colliders
    - Development of the SuperKEKB Interaction Region Nb_3Sn Quadrupole Magnet
    - Development of superconducting magnets and the quadrupole field vibration measurement system for SuperKEKB upgrade
  - And more (under consideration)
    - Professor S. Asai, Director General of KEK, have asked several accelerator laboratories, such as CERN, DESY, IHEP, to support SuperKEKB accelerator.
- We surely welcome international collaboration to improve performance of the SuperKEKB accelerators.
  - We would be very grateful if you or your colleague could visit KEK and help us.
  - We would appreciate your consideration of the following points.
    - We are facing an extreme shortage of human resources.
    - During operation period, commissioning staff are often pressed for time and it can be difficult to respond adequately. Therefore, we may have to decline visits for “educational purposes”.

Sensors to find the origin of SBL events



- **Loss Monitors**
  - Equipped with fast readout and provide chronological order of beam loss along the ring
  - Many LMs have been installed before LS1
- **BORs**
  - Can observe earlier stage of beam orbit deviation, prior to the beam loss
  - Multiple LER BORs are installed from 2024, making timing/phase analysis possible
  - This provides new and unique insights into understanding the origin of SBL
- Fast beam size monitors are also important to detect possible beam size blowup just before the abort