65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders (eeFACT2022)

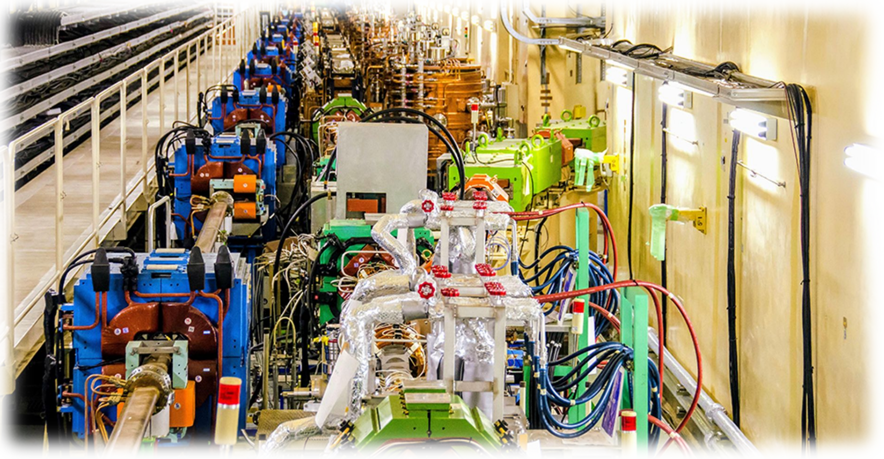
Beam background status of Belle II at SuperKEKB

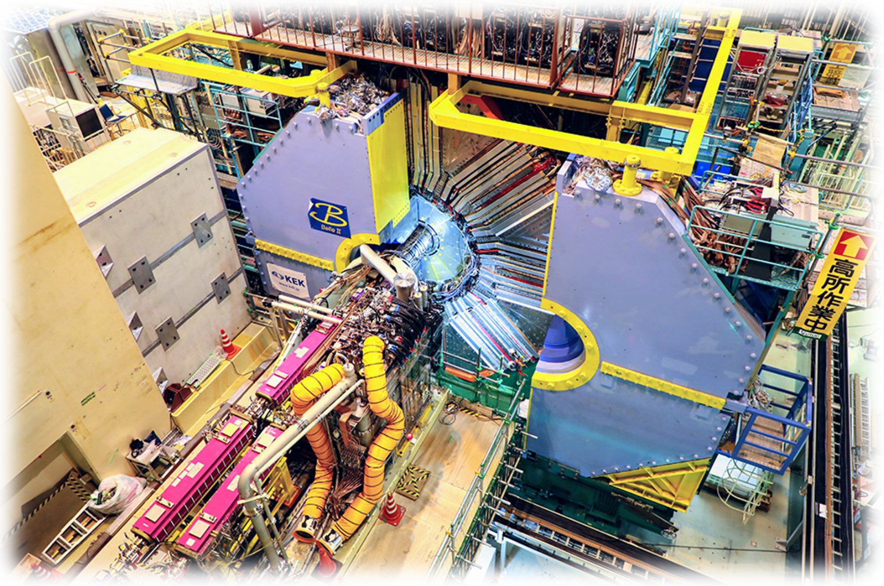
Andrii NATOCHII

On behalf of the beam background and MDI groups

University of Hawaiʻi at Mānoa
natochii@hawaii.edu

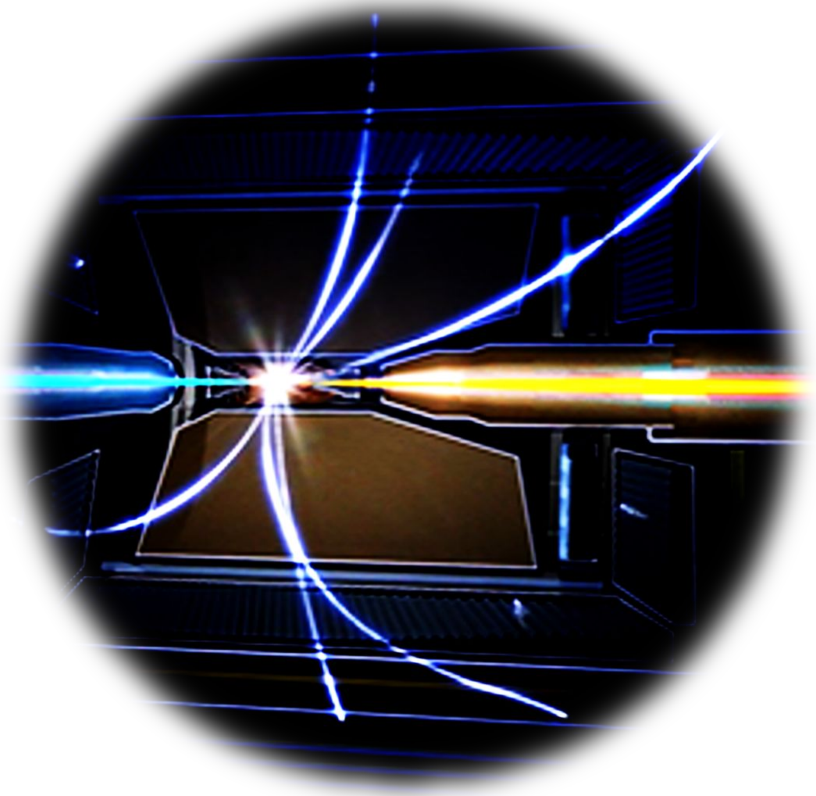
INFN Frascati 2022





Outline

- Introduction
- Belle II and SuperKEKB
- Luminosity gain and consequences
- Beam background overview
  - Sources and mitigation
  - Measurements
  - Current status
  - Simulation
- Future plans and prospects
- Summary

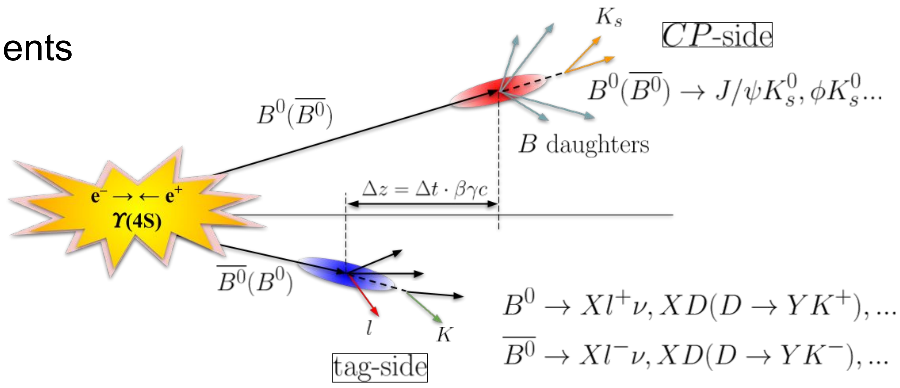


Introduction: *B*-factories

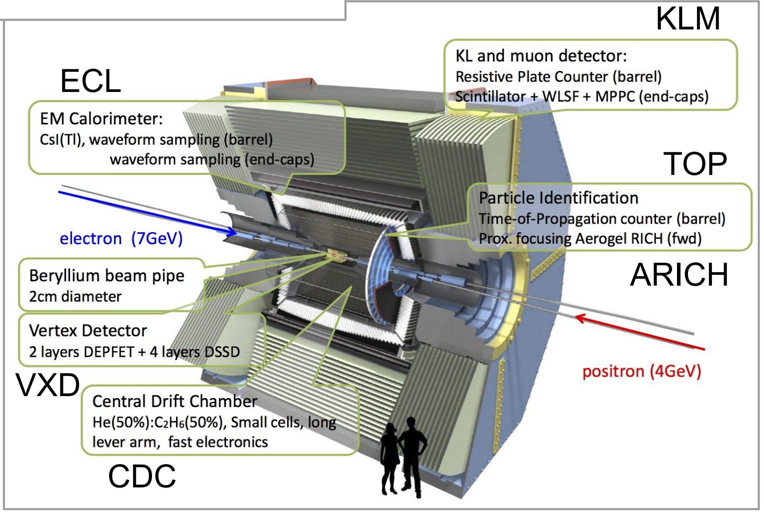
1999-2010

Since 2016

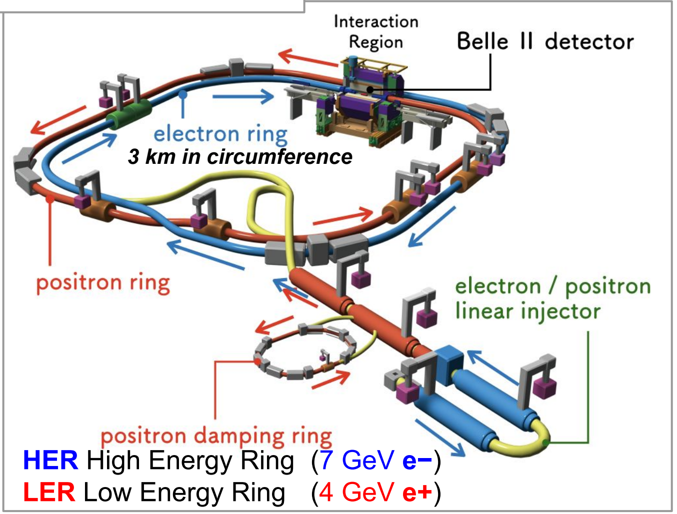
- Goals of **Belle** and **Belle II** experiments
  - Study the *CP*-symmetry violation in the *B*-meson system
  - Searching for New Physics beyond the Standard Model
- Requirements for **KEKB** and **SuperKEKB** colliders
  - Produce a large number of $B\overline{B}$-pairs
    - *High collision luminosity*
  - *B*-meson decay time difference (Δt) measurements
    - *Asymmetric collider*
  - Precise measurements of the $B\overline{B}$-mixing rate
    - *High quality spectrometer*



Belle II detector



SuperKEKB collider



ab ≡ attobarn = 10^{-42} cm^2

KEKB/Belle

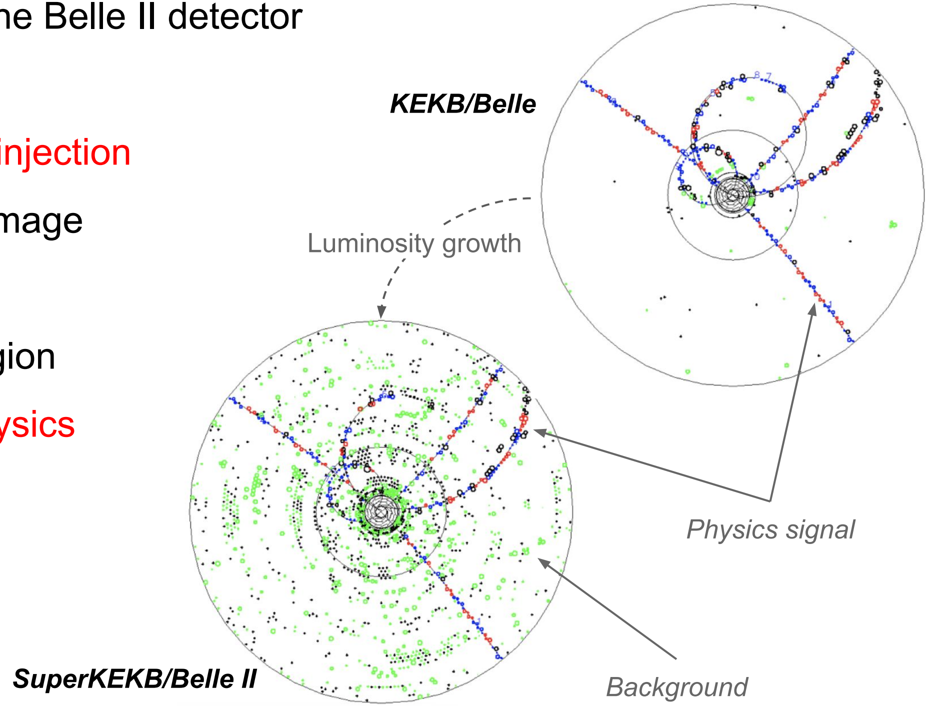
- Collected **~1 ab^{-1}** of data ~10^9 of *$B\bar{B}$-pairs*
- Along with PEP-II/BaBar, observed large time-dependent *CP*-asymmetries
  - Contributed to the 2008 Physics Nobel Prize

SuperKEKB/Belle II

- Almost all subsystems are upgraded for better performances
- Nano-beam and Crab waist collision scheme
- Aims to collect **50 ab^{-1}** of data by the 2030s

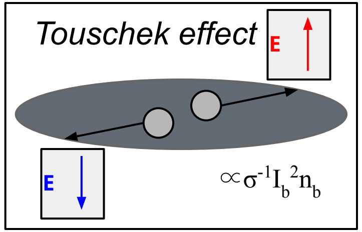
Luminosity gain and consequences

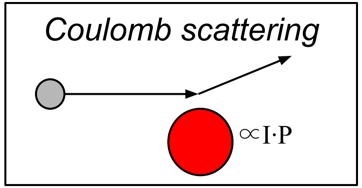
- The SuperKEKB **design** has x40 higher luminosity ($L \sim I_{\pm}/\beta^{*}_{y}$ [cm^{-2}s^{-1}]) than KEKB with x2 higher beam currents ($I_{\pm}$ [A]) and x20 smaller vertical beta functions (β^{*}_{y} [m]) at the interaction point (IP).
- This implies higher beam-induced backgrounds in the Belle II detector
  - High rate of particles leaving the beam
    - Requires a more frequent top-up beam injection
  - Sensitive detector and collider component damage
    - Reduces components longevity
  - High rate of beam losses in the interaction region
    - Increased Belle II hit occupancy and physics analysis backgrounds

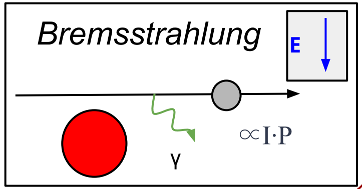


Background sources

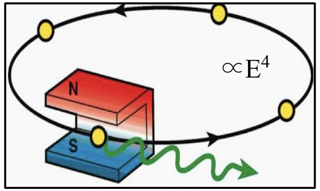
Particle scattering



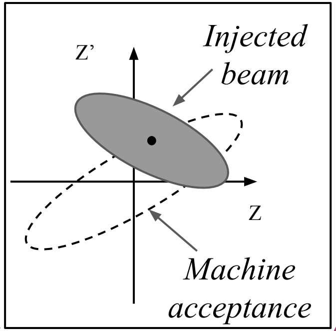




Synchrotron radiation

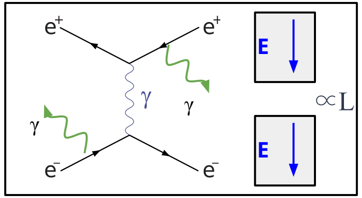


Injection (top-up, continuous)

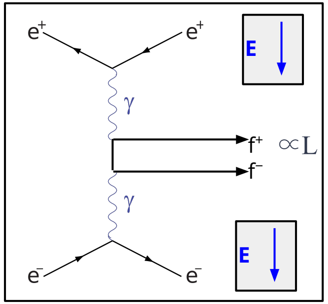


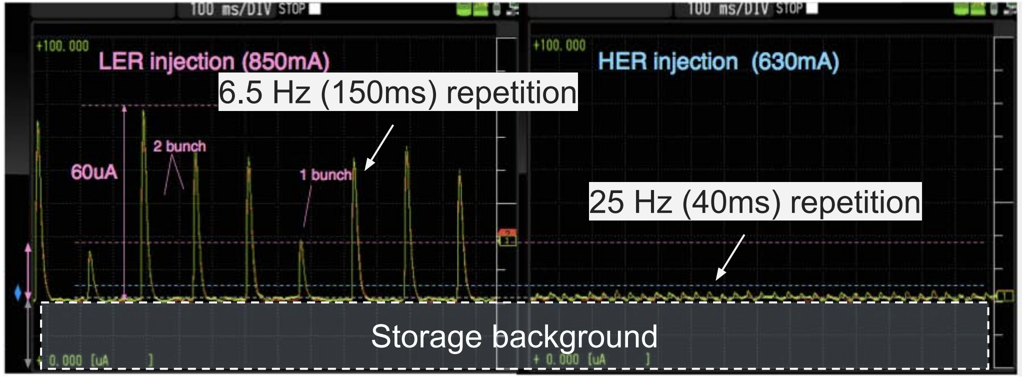
Colliding beams (Luminosity)

Radiative Bhabha proc.



Two-photon proc.



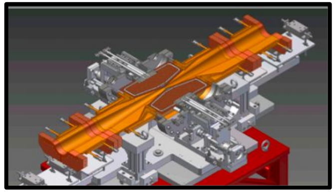


CDC background during injection (2021)

Background countermeasures

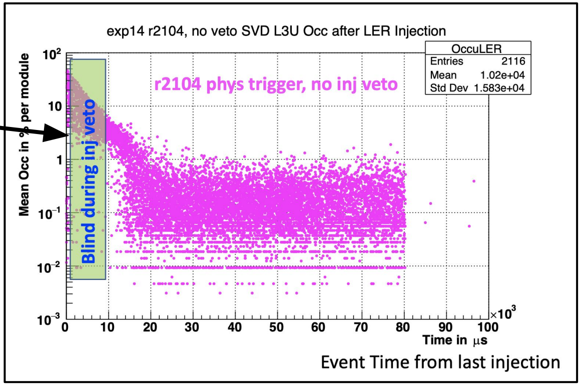
Particle scattering

Collimators *(off-trajectory particles stop)*, Vacuum scrubbing *(residual gas pressure reduction)*, Heavy-metal shield outside the IR beam pipe *(detector protection against EM showers)*



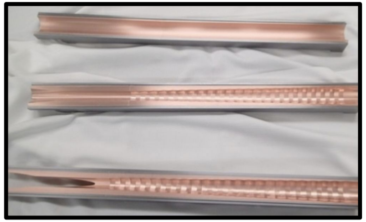
Injection

- Injection trigger veto
- Injection chain tuning
- Damping ring for positrons
(to reduce the emittance)



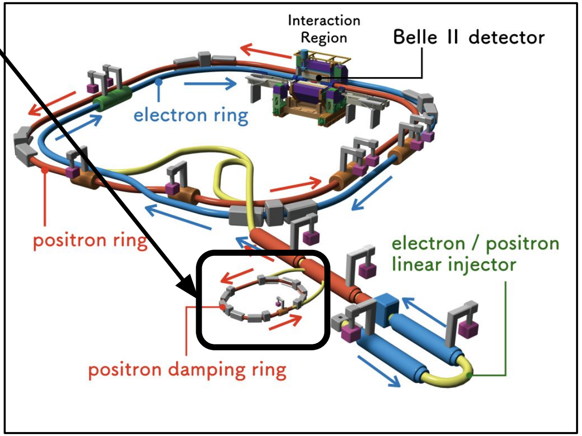
Synchrotron radiation

Beryllium beam pipe is coated with a gold layer + ridge surface of the beam-pipe + variable incoming beam pipe radius
(to avoid direct SR hits at the detector)



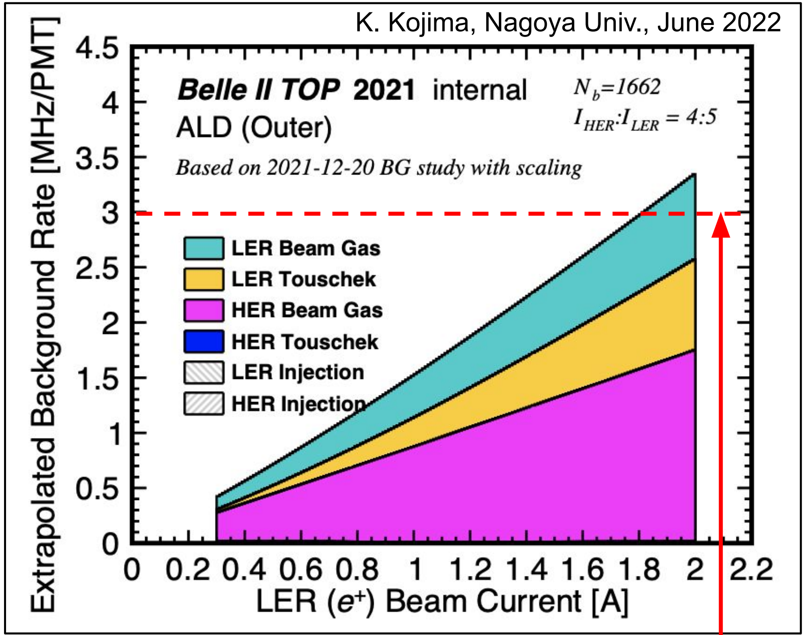
Colliding beams (Luminosity)

Lead and polyethylene shields
(neutron flux reduction)



Current background level in Belle II

One of the most vulnerable sub-detectors is the Time of Propagation (TOP) particle ID system



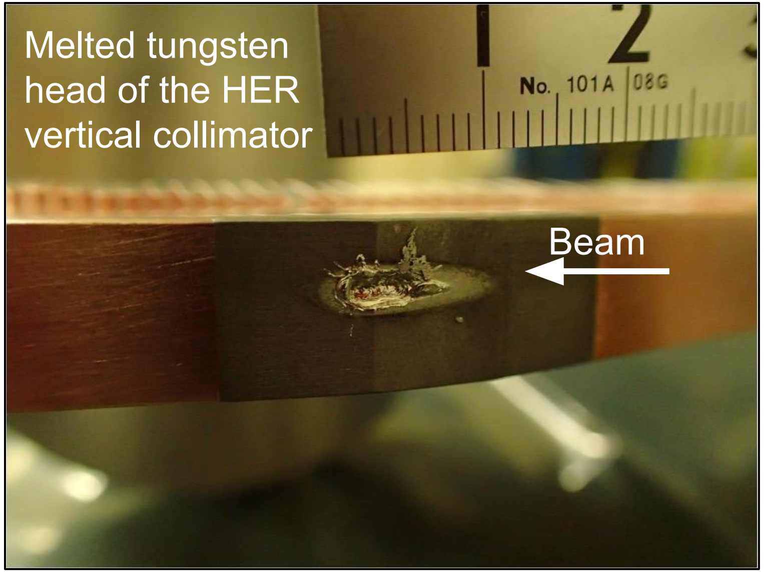
Excludes the luminosity background

- Current background rates in Belle II at ~1.2 A are acceptable and below limits
- Belle II did not limit beam currents in 2021 and 2022
  - It will limit SuperKEKB eventually, without further background mitigation
- To reach the **target** luminosity of 6.3×10^{35} $cm^{-2}s^{-1}$ an upgrade of crucial detector components is foreseen (e.g. TOP short lifetime conventional PMTs)

Snowmass Whitepaper arXiv:2203.11349

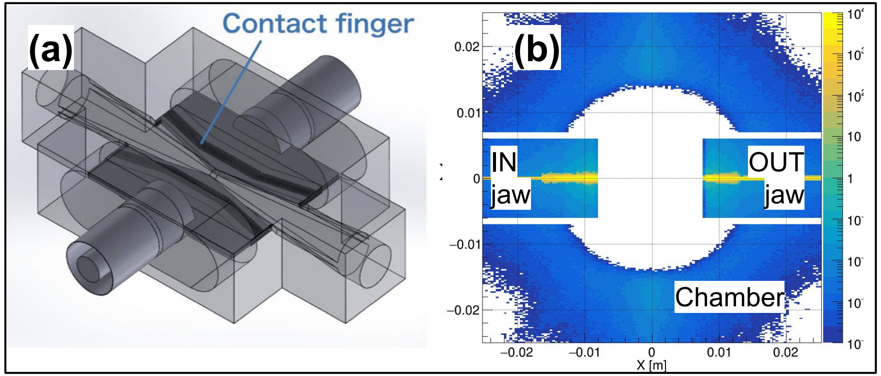
Uncontrolled beam losses

- During stable machine operation unexplained beam instabilities and beam losses may occasionally occur in one of the rings causing **sudden beam losses (SBLs)** at a specific location around the ring due to
    - Machine element failure
    - Beam-dust interaction
    - Vacuum element defects
- **Consequences**
    - Detector and/or collimators damage, see Figure
        - Belle II background increase
    - Superconducting magnet quenches
- Usually only a few such catastrophic beam loss events happen per year in each ring
    - In 2022, we had many (>50) SBLs in the LER trying to go beyond 0.7 mA/bunch
- **Cures**
    - Upgraded abort system → fast abort signal
    - Low-Z materials for collimator heads (MoGr, Ta+Gr) → robust collimators
    - Understand the source of the unstable beam (vacuum system inspection, beam dynamics study, installation of additional beam loss monitors around the rings)

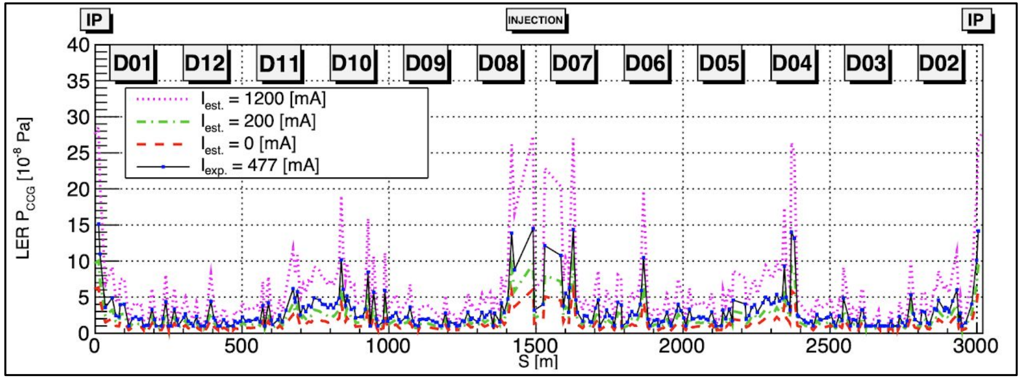


Background simulation: Tools

- **Single-beam background** (Beam-gas & Touschek)
  - Strategic Accelerator Design (`SAD`@KEK) (multi-turn particle tracking)
    - *Realistic collimator profile and chamber*
    - *Particle interaction with collimator materials*
    - *Measured residual gas pressure distribution around each ring*
  - `Geant4` (detector modelling)
- **Luminosity background:**
  - `Geant4` (single-turn effect, colliding bear
- **Synchrotron radiation background:**
  - `Geant4` (close to the Belle II detector)



Collimator chamber 3D model (a) and simulated absorbed particles at a collimator (b)

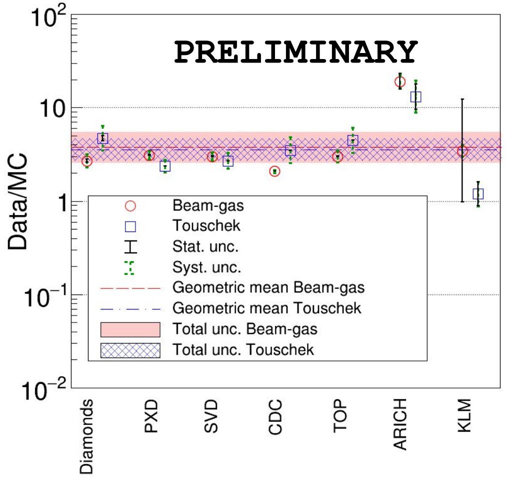


Measured and estimated vacuum pressure distribution around the LER

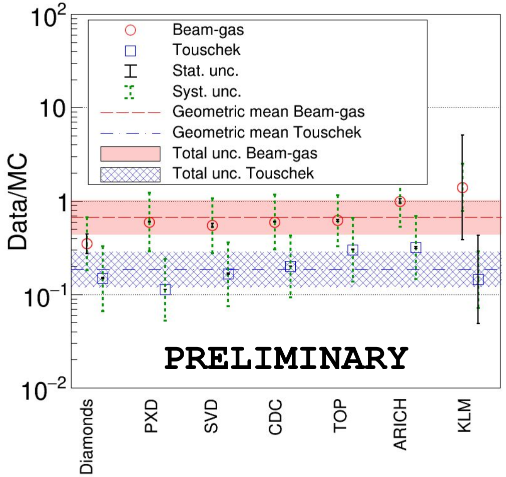
Background simulation: Accuracy

Ratios of measured (**data**) to simulated (**MC**) backgrounds based on dedicated studies in 2020-2021

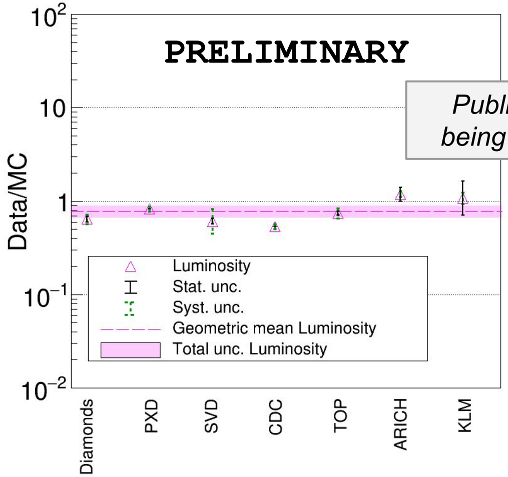
LER single-beam



HER single-beam



Luminosity



Publication is being prepared

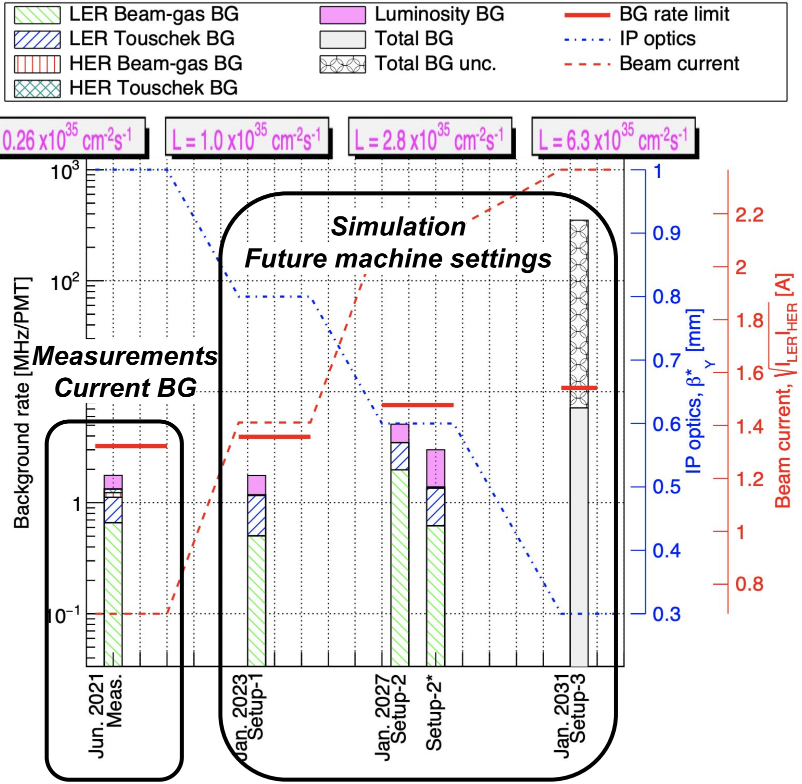
- Current data/MC ratios are within one order of magnitude from unity
  - **Substantial improvement** compared to measurements in 2016 [*link*] and 2018 [*link*]
  - It confirms our good understanding of beam loss processes in SuperKEKB
- These ratios are used to rescale simulated backgrounds toward higher luminosities

Background simulation: Benefits

Our simulation with a good data/MC agreement helps us to

- Study an impact of beam optics parameters on Belle II backgrounds
- Develop new collimators
- Better mitigate backgrounds through machine or detector adjustments and upgrades
- Predict background evolution at future machine settings
    - Backgrounds will remain high but acceptable until the luminosity of about 2.8x10^{35} cm^{-2}s^{-1}
    - For the **target** luminosity of about 6.3x10^{35} cm^{-2}s^{-1} machine condition is very uncertain to make an accurate background prediction

Snowmass Whitepaper arXiv:2203.05731

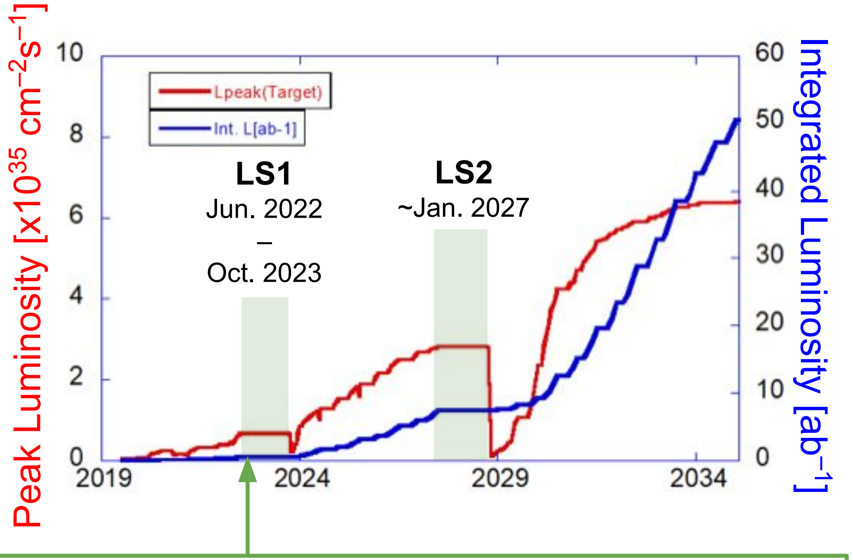


Measured and predicted Belle II backgrounds

Future plans and prospects

To reach the **target** luminosity of 6.3×10^{35} $cm^{-2}s^{-1}$ by 2030s we plan

- Detector upgrades (e.g. PXD, TOP PMTs) [LS1]
  - *Damage sensors replacement*
  - *Fully assembled PXD with two layers*
  - *Replaced short-lifetime conventional PMTs in the TOP*
- Additional shielding in/outside Belle II against SR, EM-showers and neutrons [LS1]
  - *More polyethylene and concrete shieldings on endcaps and around the final focusing magnets*
  - *New IP beam pipe*
- Collimation system upgrade [LS1, LS2]
  - *Nonlinear collimation (NLC) insertion in the LER*
    - *Low impedance budget*
    - *Better background control*
  - *More robust collimator heads installation (MoGr, Ti, Ta+Gr)*
- IR redesign [LS2]
  - *To use the crab waist scheme at* $\beta^*_y = 0.3$ *mm*
- Injection chain and feedback system upgrade [LS1, LS2]
  - *For stable machine operation at low injection backgrounds*



We are currently here

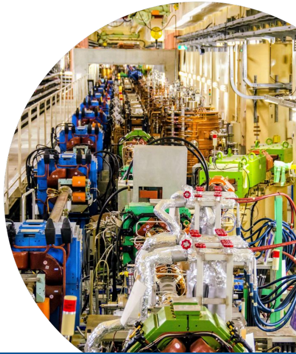
- L_{peak} $\sim0.5\times10^{35}$ $cm^{-2}s^{-1}$ ← *World record*
- L_{int} ~0.4 ab^{-1} ← *BaBar's dataset size*

LS stands for the **L**ong **S**hutdown, which is the period of no beam used for machine and detector upgrades

Summary

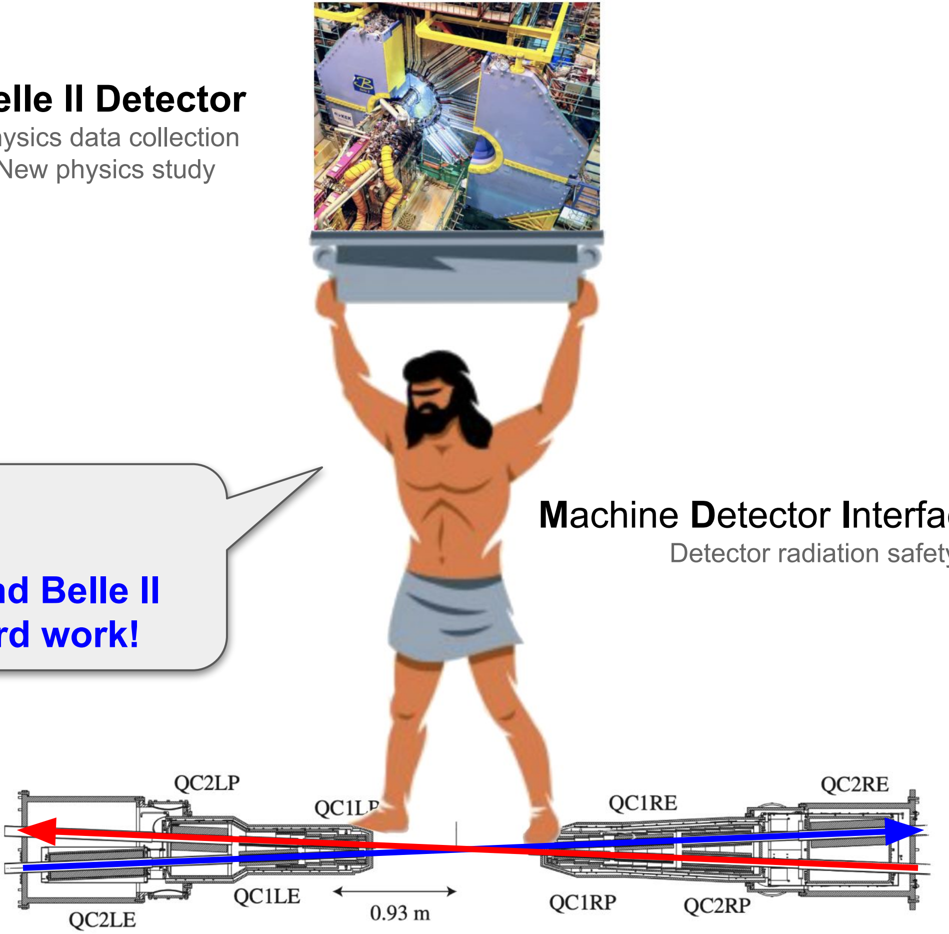
- In 2022, SuperKEKB and Belle II reached the world record luminosity of ~4.7×10^{34} $cm^{-2}s^{-1}$
    - **This success required a close collaboration between machine and detector experts** to keep the balance between high collision rate and acceptable background level in Belle II avoiding unwanted detector and machine damages
- We have successfully reached a good agreement between measured and simulated beam-induced backgrounds which helps us to study future background evolutions [*link*]
- In the next decade, at stable machine operation, backgrounds in Belle II are expected to remain acceptable until at least the luminosity of 2.8×10^{35} $cm^{-2}s^{-1}$ [*link*]
- Further machine and detector improvements are foreseen
- We are closely collaborating with other accelerator laboratories around the globe on optimizing upgrades of SuperKEKB and reaching the **target** luminosity of about 6.3×10^{35} $cm^{-2}s^{-1}$

The Belle II beam background and MDI groups are open to new people motivated and willing to bring their fresh ideas and unique expertise in beam background mitigation for safe and productive machine and detector operation



Acknowledgements

Belle II Detector
Physics data collection
New physics study



Machine Detector Interface (MDI)
Detector radiation safety

Thank you for attention!

And thanks a lot to all SuperKEKB and Belle II people for their contribution and hard work!

SuperKEKB Collider
High rate of particles collisions
Factory of new particles