Heavy Flavors at Belle II Status and Plans

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On behalf of the Belle II Collaboration

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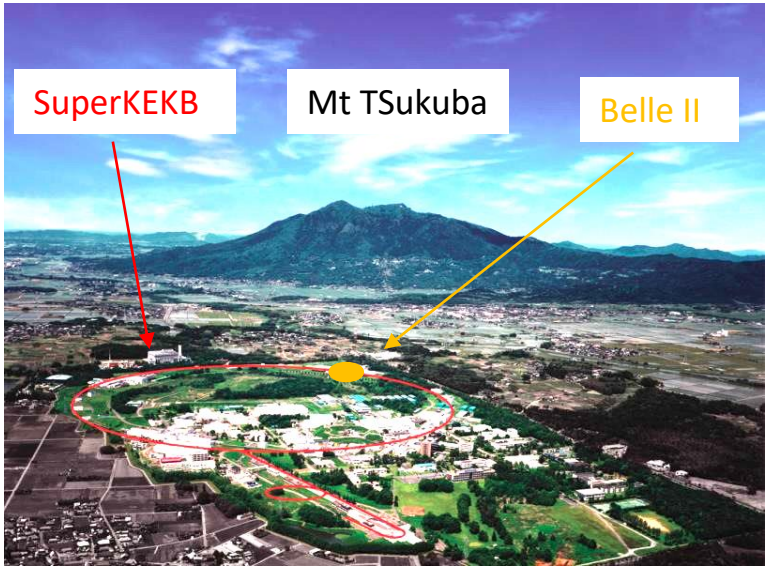
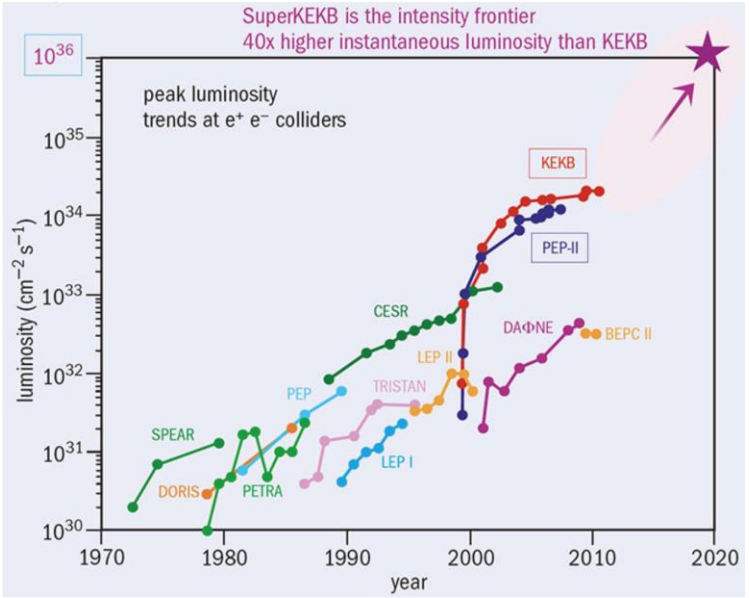
Belle II @ SuperKEKB

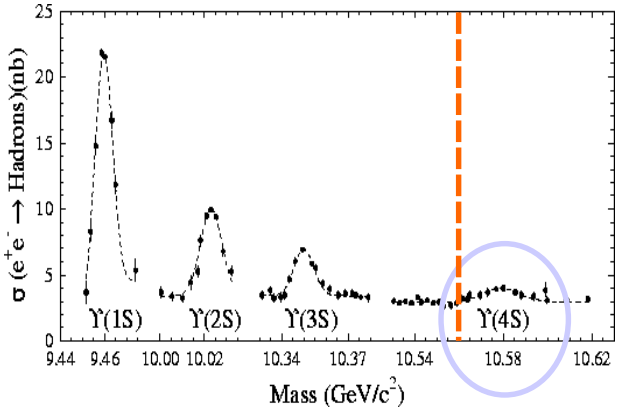
- Belle II at SuperKEKB is the successor of the Belle experiment at KEKB
  - Main mission of the Belle II is to search for beyond the SM via studies of heavy flavors: B, charm and τ
- The target luminosity for SuperKEKB is 8×10^{35} /cm^2/s which is the world's highest and 40 times larger than that for KEKB.

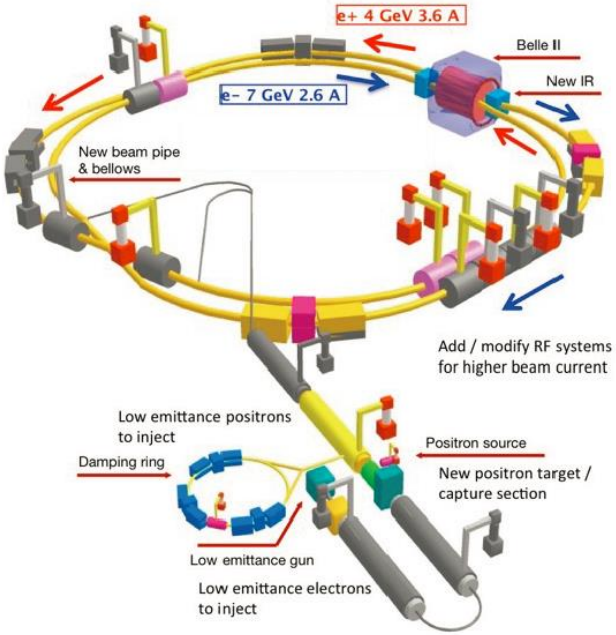


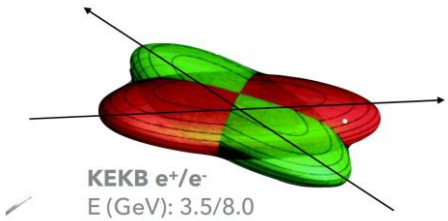


SuperKEKB

- Sitting on Y(4S)
  - To produce B meson pairs efficiently
- Asymmetric e^+e^- Collision
  - Electron : 7GeV, Positron 4GeV
  - To boost B meson to study time dependent CP Violation
    - Difference of two B meson decay vertices $\Delta z \approx 140\ \mu m$
- 40 times larger luminosity
  - Adopted nano-beam scheme by P. Raimondi
  - Beam size in vertical plain 1/20
    - σ_y^*=940nm → 48/62nm (positron/electron)
  - Beam current x2
    - 1.7A/1.2A → 3.6A/2.6A

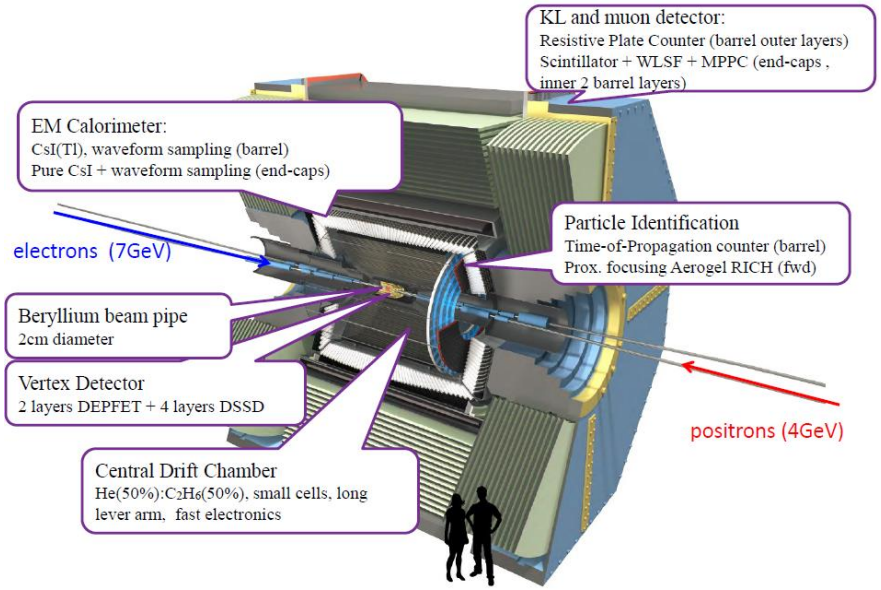


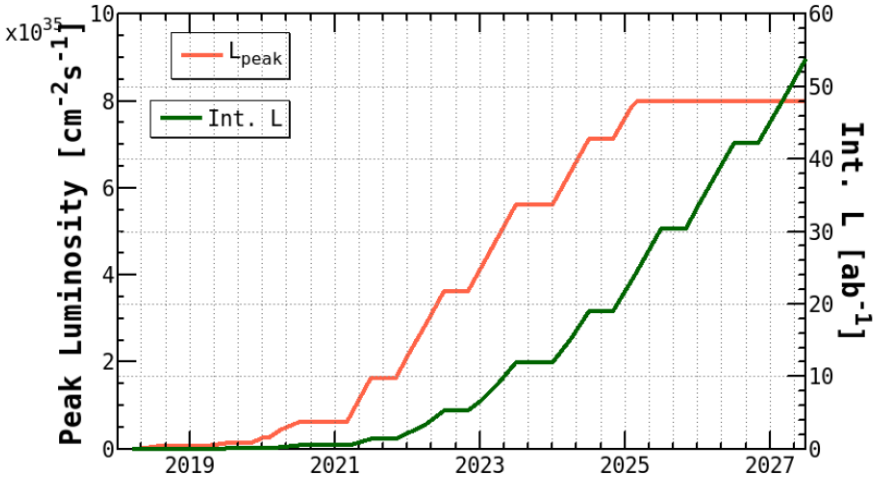




Belle II Detector

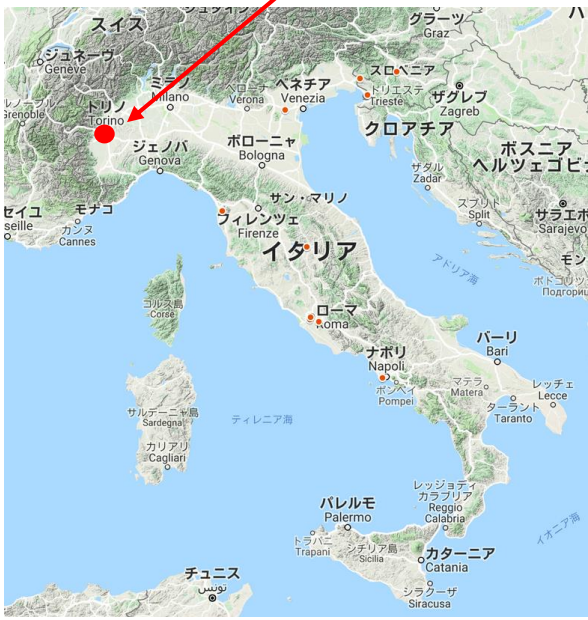
- All subdetectors had been upgraded
  - Work under 40 times larger instantaneous luminosity.
- General purpose 4π detector
  - Excellent momentum and energy resolution
  - Good PID capability to separate π/K/p
- Accumulate 50ab^{-1} data in 2027
  - Containing 10^{11} B mesons, 3×10^{11} charm hadrons, 0.8×10^{11} tau leptons





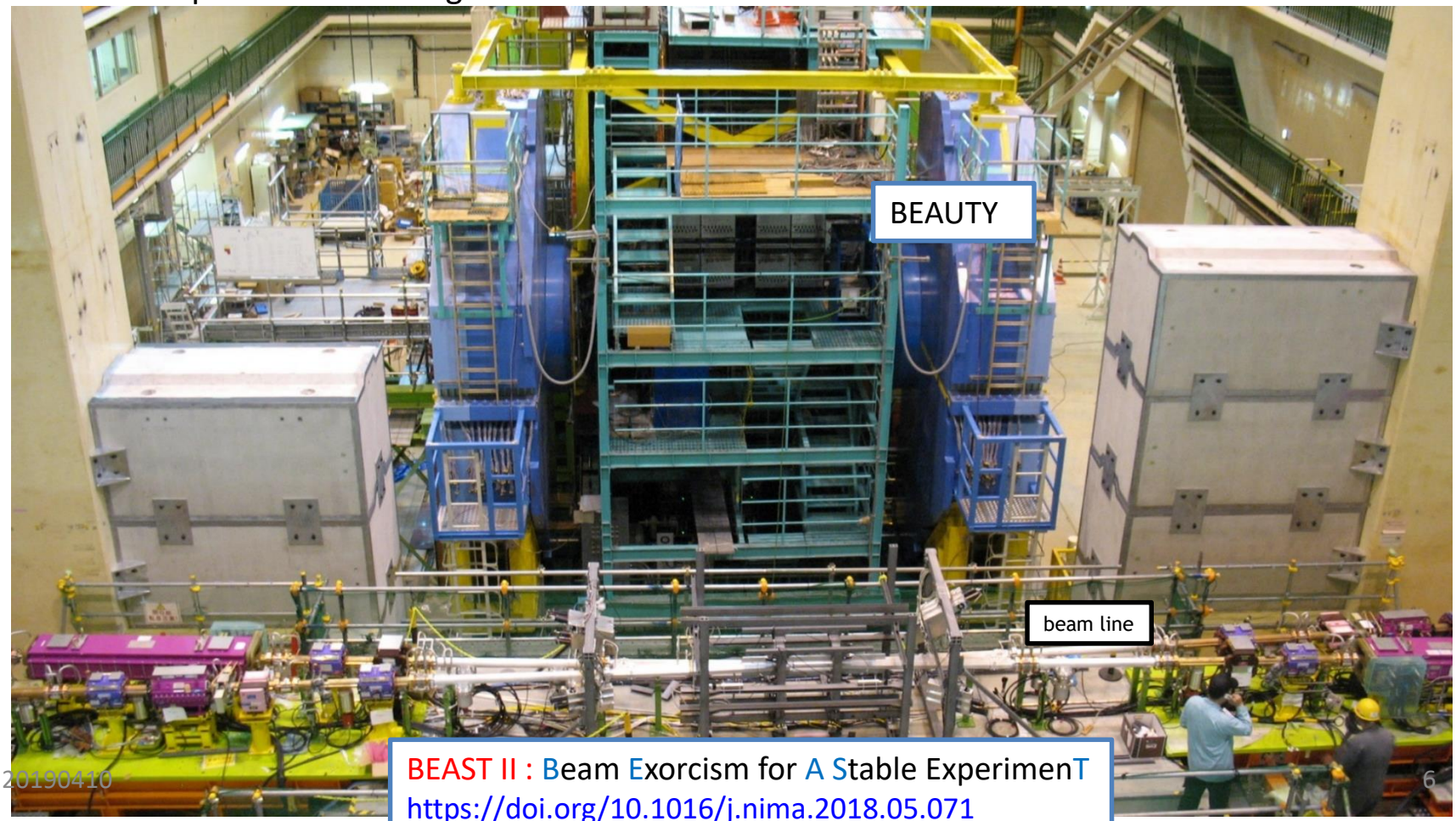
Belle II Collaboration

- Worldwide collaboration
  - ~800 researchers (including ~320 graduate students) from 113 institutions and 26 countries.
    - 10 Italian institutions : Frascati, INFN, Napoli, Padova, Perugia, Pisa, Roma Uno, Roma Tre, Torino and Trieste



Phase1 : Commissioning Run

- 2016 : Phase 1 Commissioning Run
  - First SuperKEKB operation
  - No final focus, no collisions, Belle II detector roll out from the beam line
  - Special beam background monitor detector called BEAST II was installed

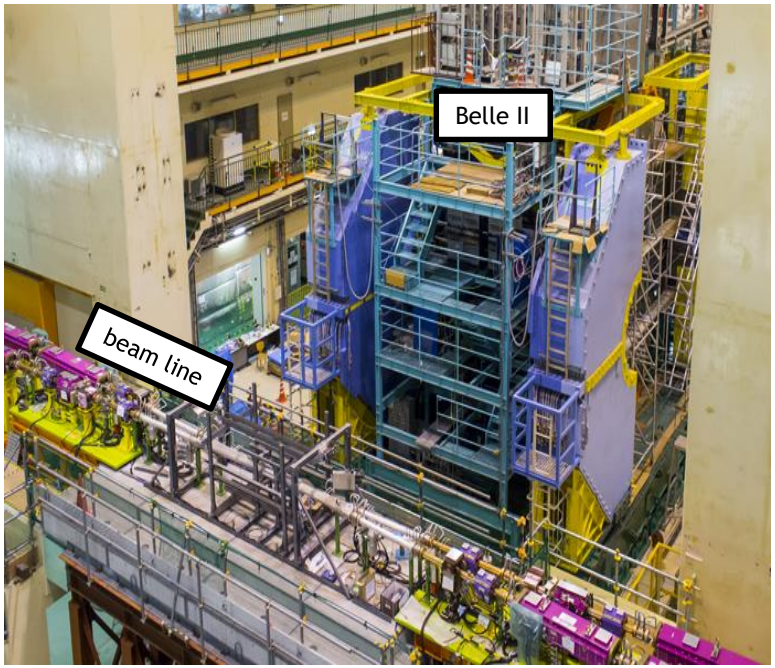


BEAST II : Beam Exorcism for A Stable ExperimenT
https://doi.org/10.1016/j.nima.2018.05.071

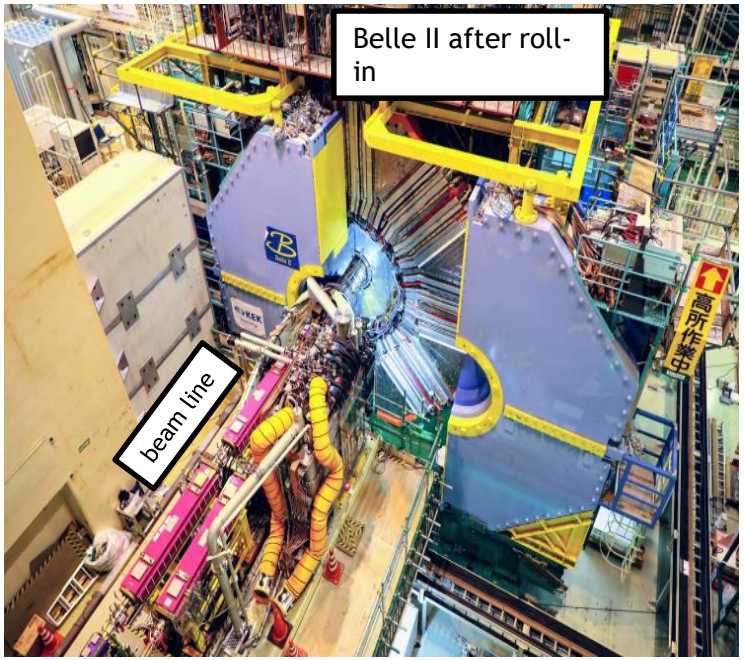
Rolling in Belle II Detector

- April 2017 : After Phase 1, Belle II detector was rolled into the beam line
  - Only 1 ladder of vertex detector

2016

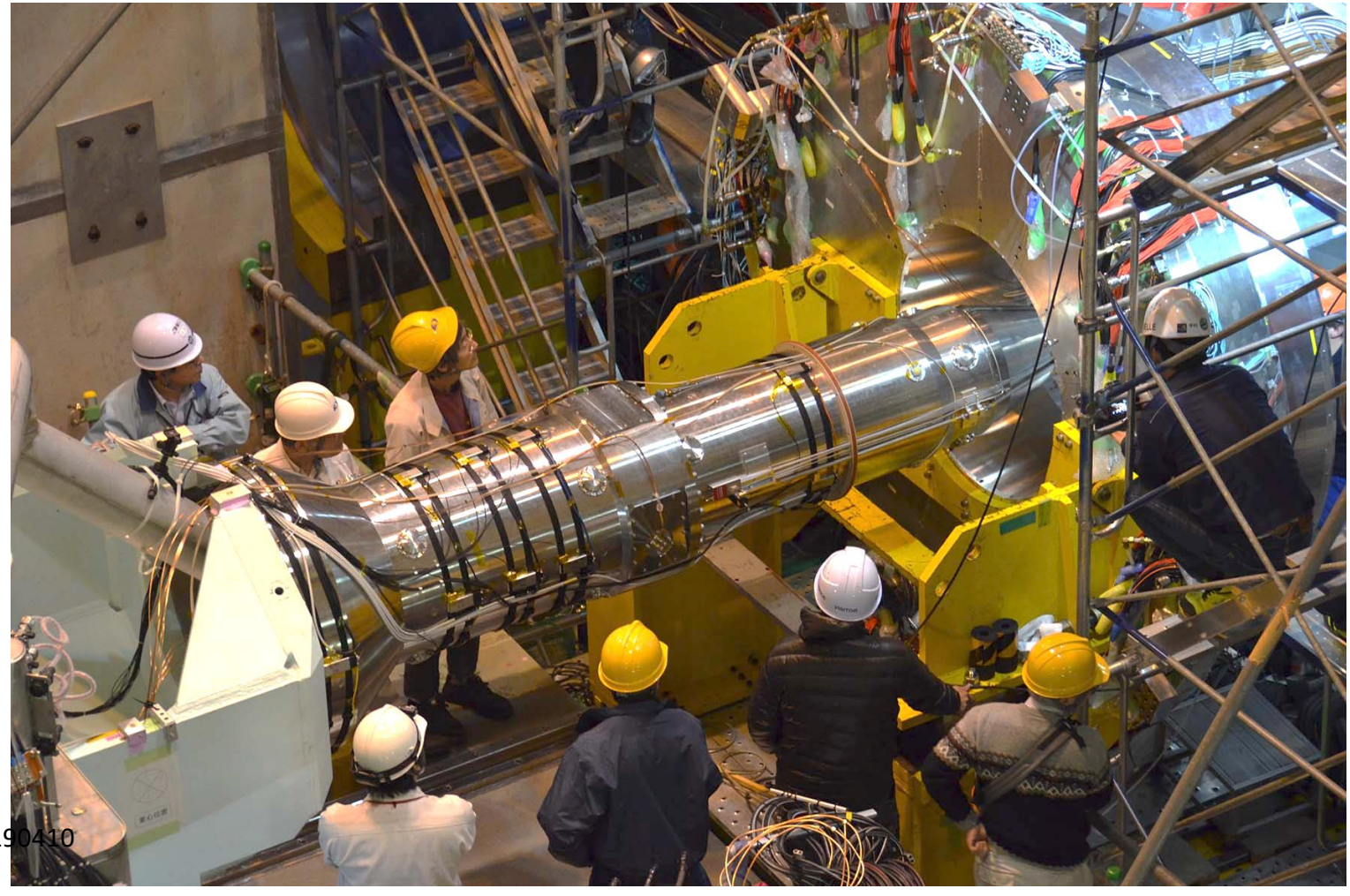


2017

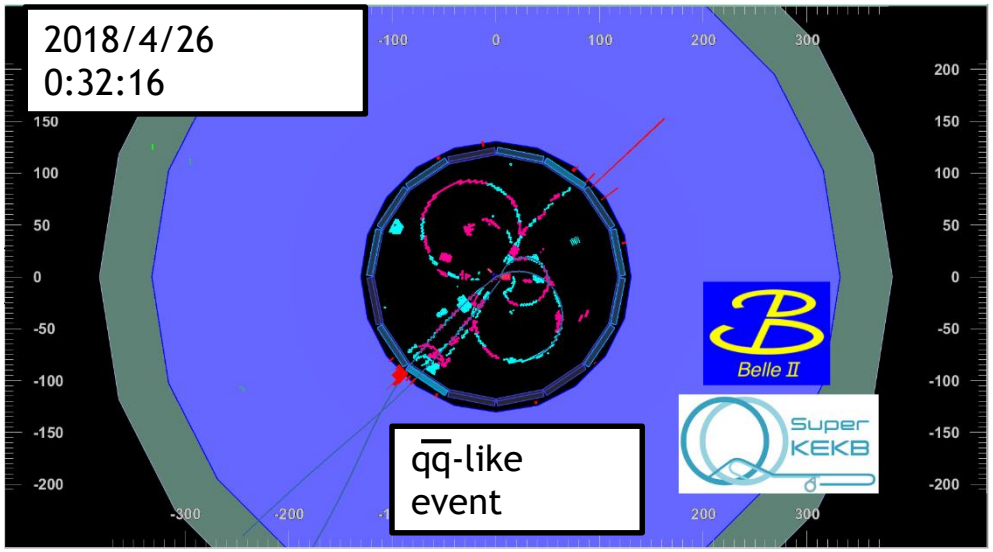


Final Focus Magnet Moving in

- January 2018: The superconducting magnets for final focusing of the beams were moved to the core of the Belle II detector



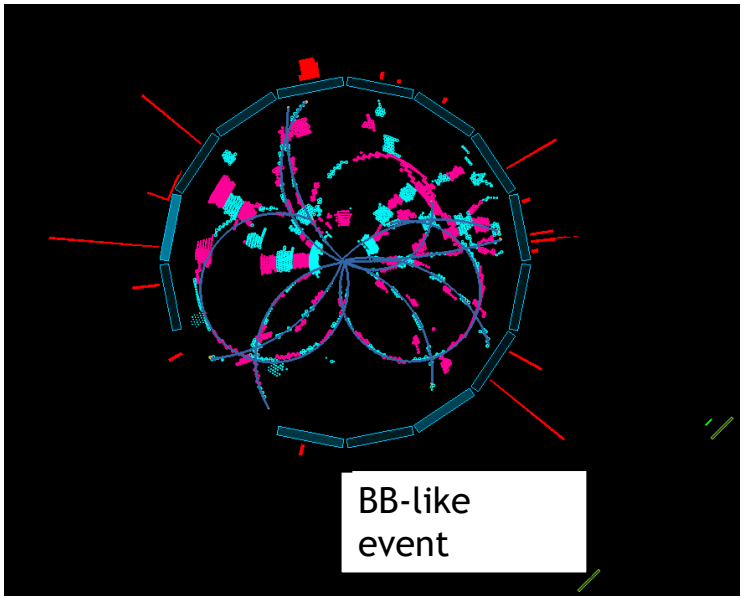
Phase 2 Commissioning Run



- 2018 March-July
- First e^+e^- collisions were achieved
- Data taking with Belle II minus VXD (vertex detector)
  - To avoid serious damage of VXD
- Beam backgrounds are high but tolerable
  - Synchrotron radiation (VXD background) observed for first time

→ All goals achieved. Safe to proceed and install full VXD

Phase 2 Commissioning Run



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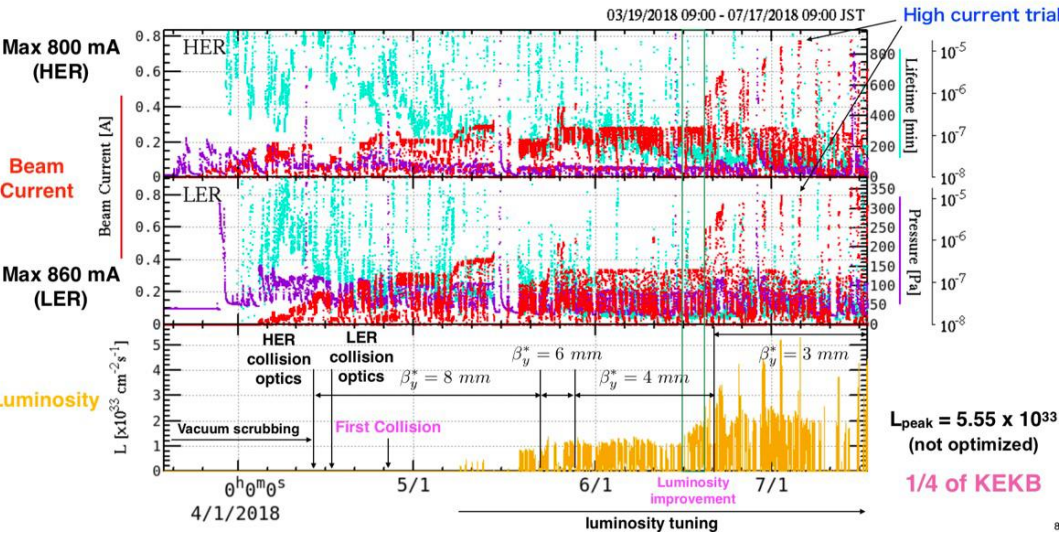
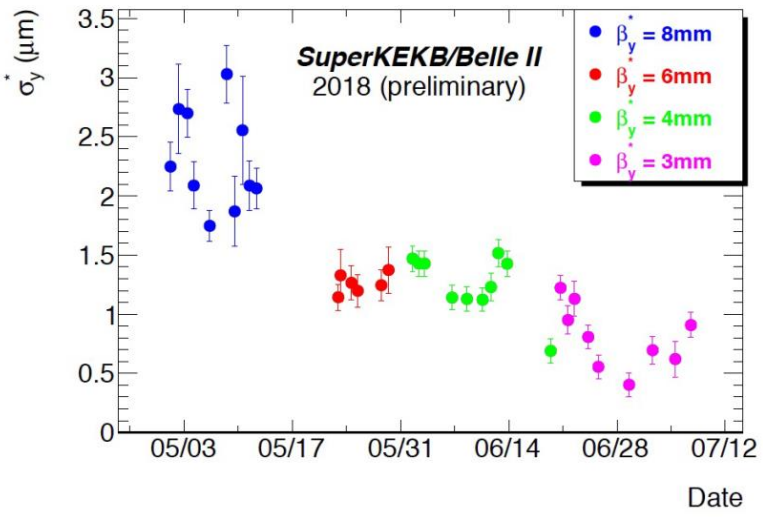
SuperKEKB in Phase2



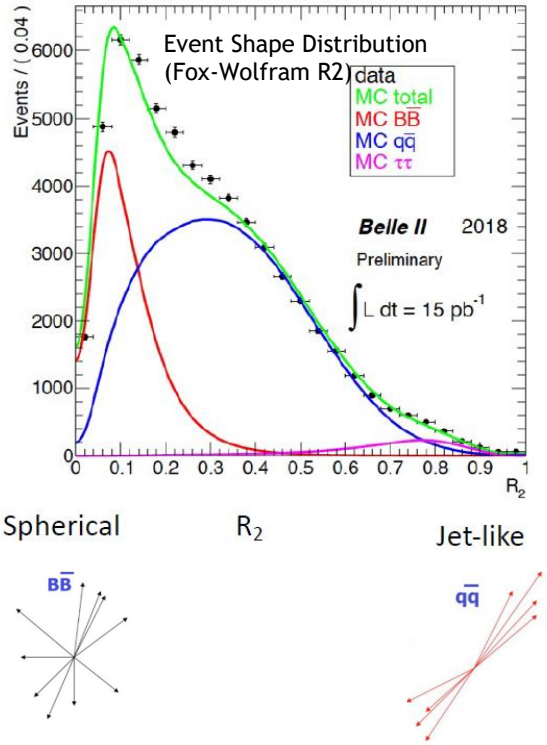
Ramping up the beam currents

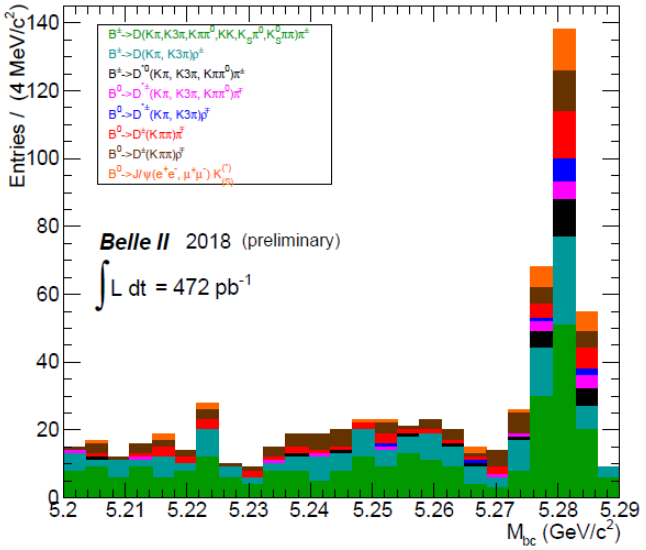


Squeezing the beams at the interaction point

- Achieved
  - Lpeak = 5.55 x 10^{33} /cm^2/s
  - Belle II recorded ~ 500 pb^{-1}
  - Confirmed the nano-beam scheme
  - Reduced β_y^* to 3 mm, σ_y^* ~ 400 nm (Final target β_y^* = 0.3 mm)

Rediscovery of B mesons





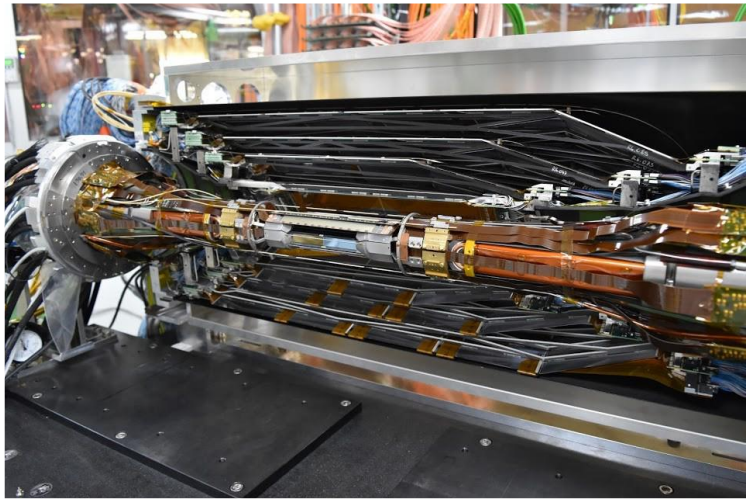
$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p^2_{recon}}$$

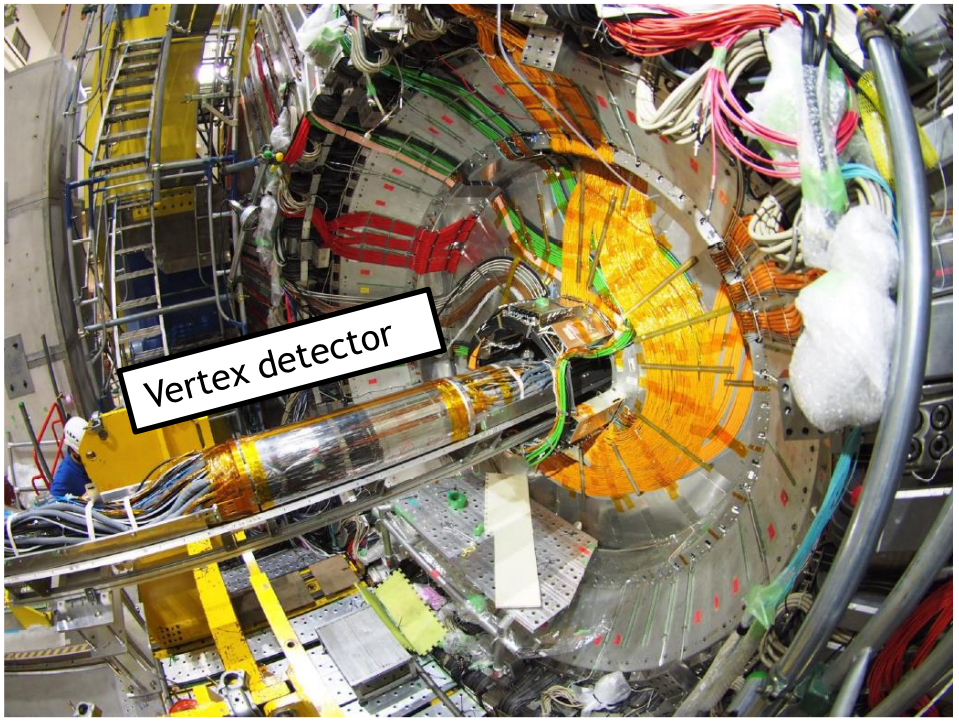
- Clearly observed an excess of BB events
- Detector and full reconstruction analysis chain working well.

Vertex Detector Installed

- Nov 2018 : After phase2, vertex detector was installed
  - Layer 2 of Pixel detector partially, full SVD 3-6 layers.
- Ready for time dependent measurements

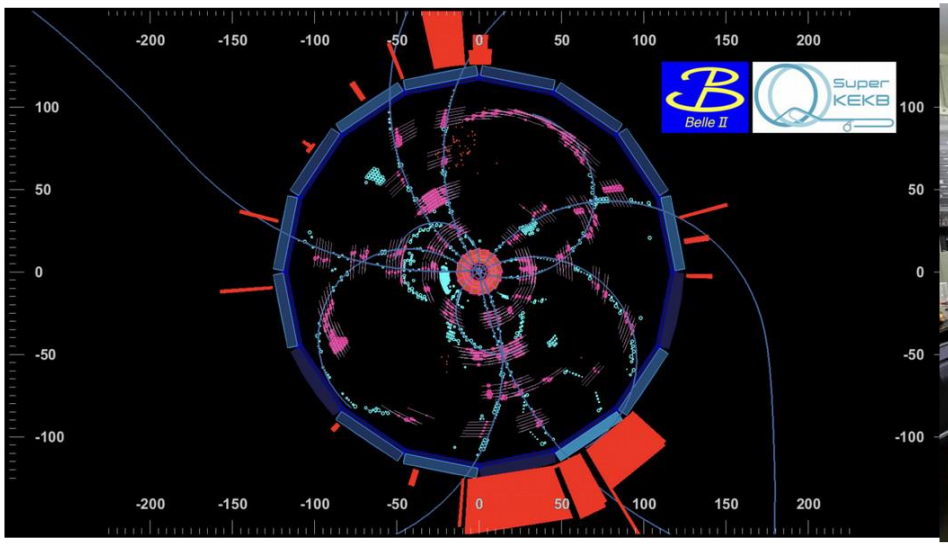
Half ladder





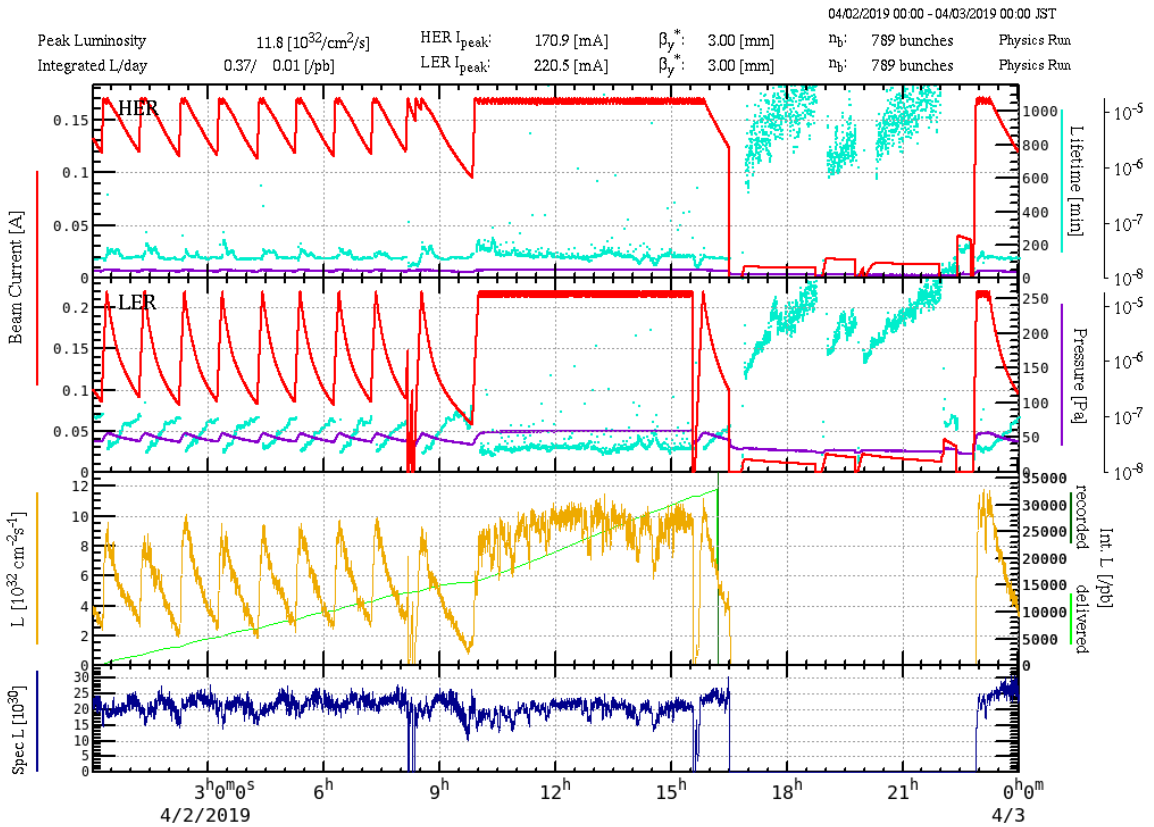
2019 March : Phase 3 started

- First collision in phase 3 on 25th Mar 2019.



Machine Tuning

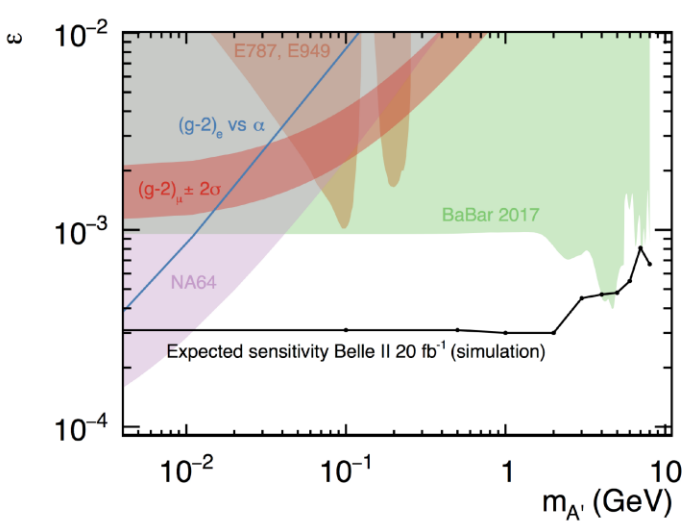
- Reached 1x10^{33} /cm^2/s
- Additional beam collimators work fine to reduce beam background which limited the beam current in phase 2

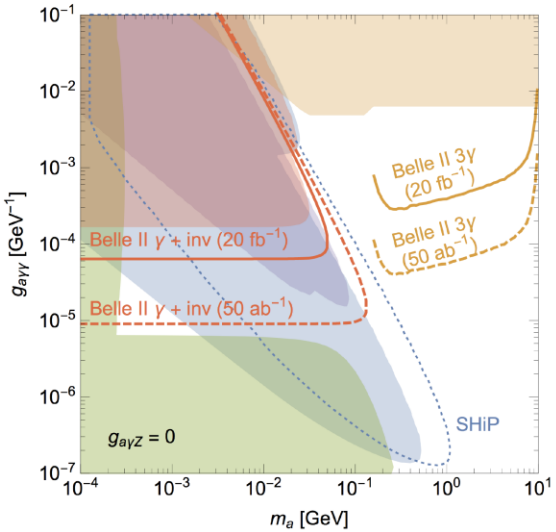


Belle II Physics

- As Super B-factory
  - B physics: CPV beyond CKM picture, LFV in B decays, and more.
- Heavy flavors
  - Not only B but charm and τ can be studied
- Light dark matter searches
  - Vector portal, scalar portal
- Others
  - EW measurements at low energy
    - Hadronic vacuum polarization
  - Hadron physics

Early Physics Target: Dark Sector





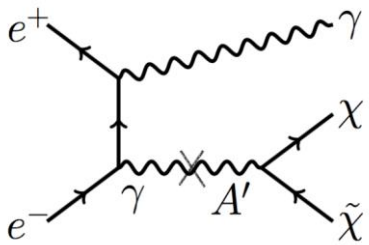


FIG. 4. Projected Belle II sensitivity to $e^+e^- \to \gamma A', A' \to$ invisible (left), and to production of axion-like particles that couple to photons (right). In both cases Belle II has world-leading sensitivity with only 20 fb^{-1} of data, which should be collected within the first year of running. (Figures are taken from the Belle II Physics Book and Ref. [73].)

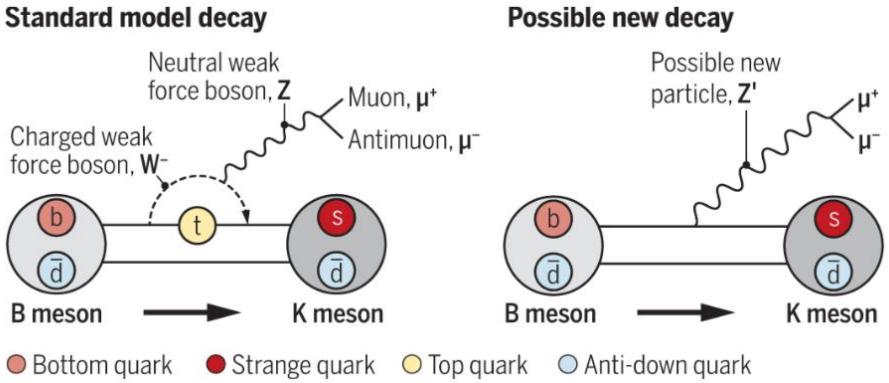
- Belle did not have single photon trigger required for this search
- BaBar sensitivity reduced due to lack of hermiticity of projective crystals in calorimeter

B→K(*)l+l-

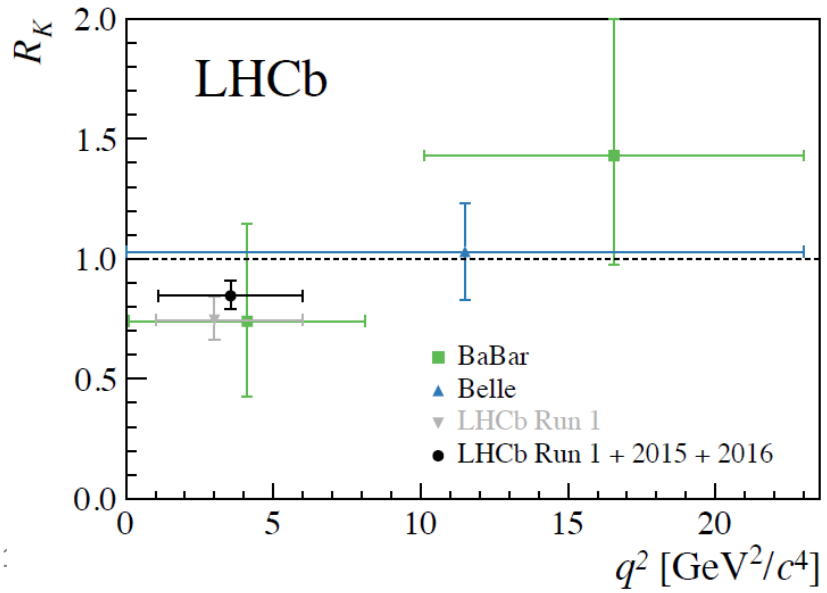
- Recent LHCb results on $R_{K(*)}$ have tensions with the SM

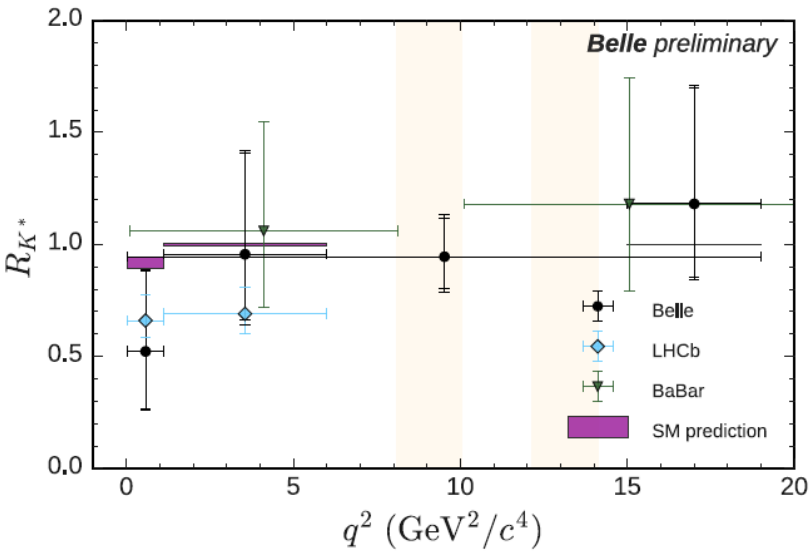
$$R_{K^{(*)}}(q^2) = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}$$

  - ~2.6σ each
  - Simple combination ~4σ
  - Can be explained by Leptoquark or flavorful Z'



- New Belle results have large uncertainty





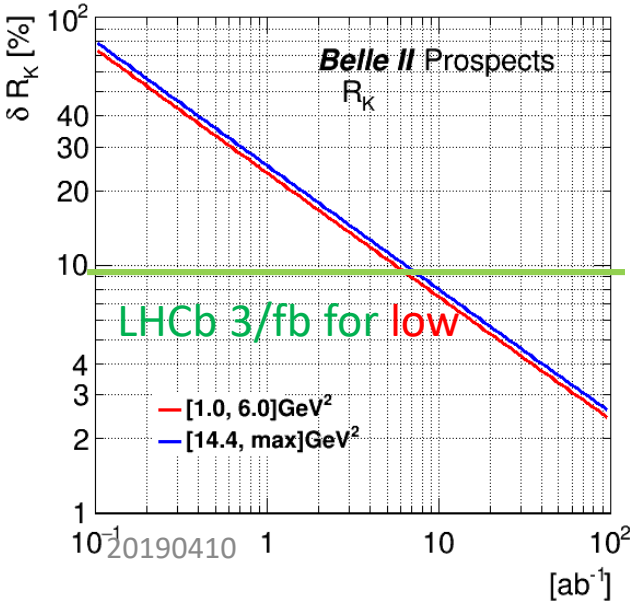
R_K, R_{K^*} and R_{Xs}

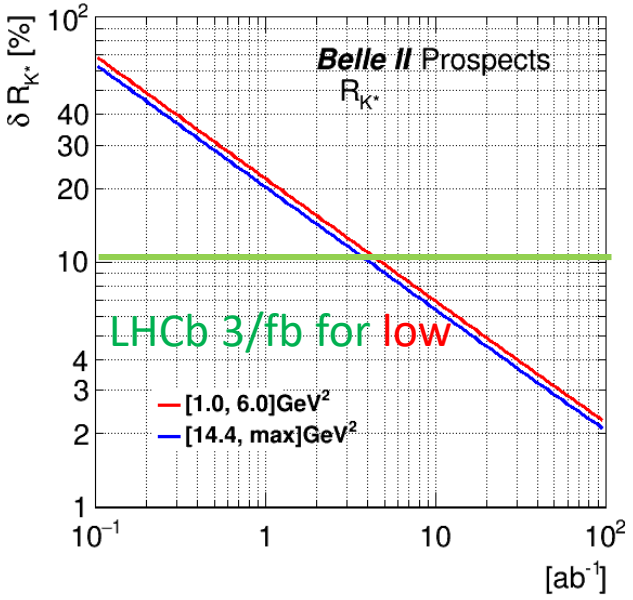
$$R_H = \frac{\mathcal{B}(B \to H\mu^+\mu^-)}{B(B \to He^+e^-)}$$

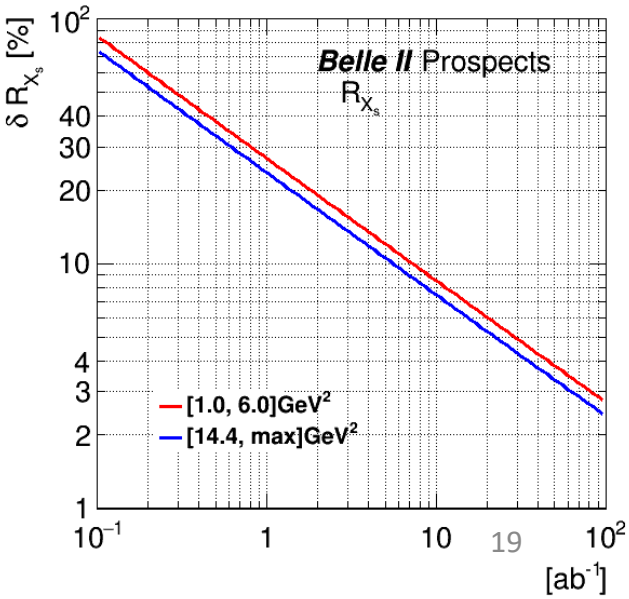
- Ideal measurements at e^+e^- B-factory : Belle II
  - Effiicency for electron and muon similar
    - No problem on bremstrahlung recovery
  - Both low and high q^2 Lcan be accessible
  - Inclusive mode R_{Xs} possible

Low $1<q^2<6GeV^2$
High $q^2>14.4GeV^2$

- In 2022, we can reach the sensitivity of LHCb with 3/fb for low q^2

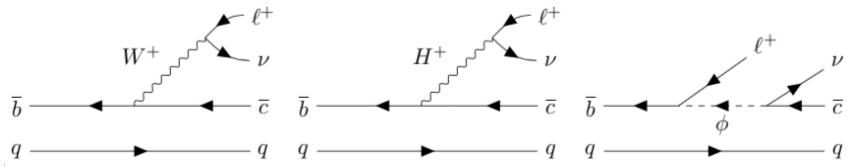






B→D(*)τν

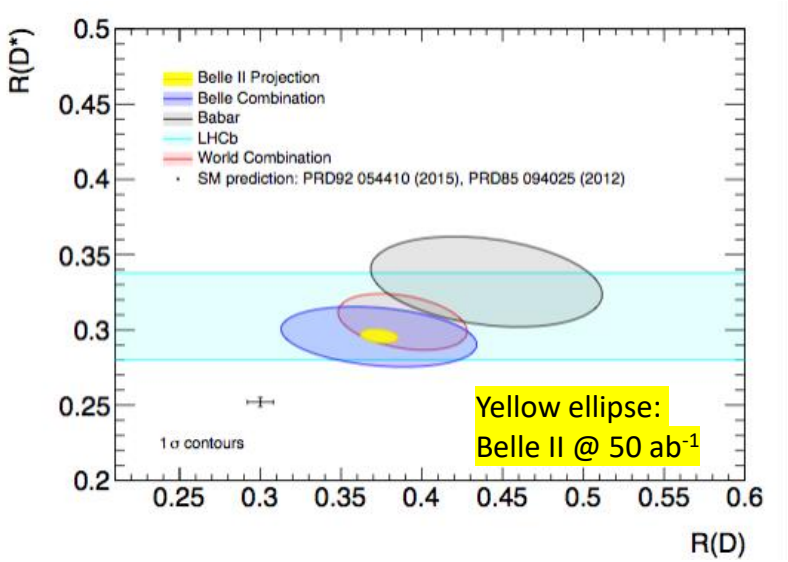
- B → Dτν and B → D*τν are tree-level SM decays containing 3rd generation quarks and leptons



- Ratio of heavy-to-light lepton modes provides robust theoretical prediction

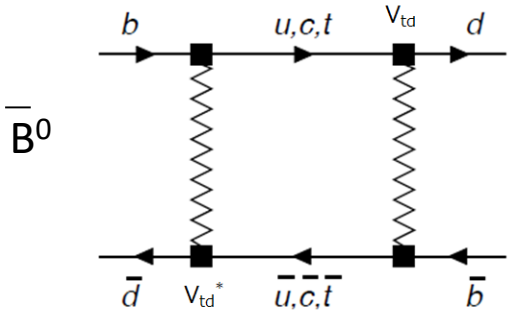
$$R = \frac{\mathcal{B}(b \to q\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(b \to q\,\ell\,\bar{\nu}_\ell)}$$
$$\ell = e, \mu$$

- Measurements from BaBar, Belle and LHCb deviate from SM (combined 3.1σ)
  - Can be explained by leptoquark, flavorful W' or extension of Higgs sector



- Belle II can precisely measure R(D) and R(D*) to constrain or identify BSM physics
- Both charged and neutral B and various final states

CKM Matrix and Unitarity Triangle



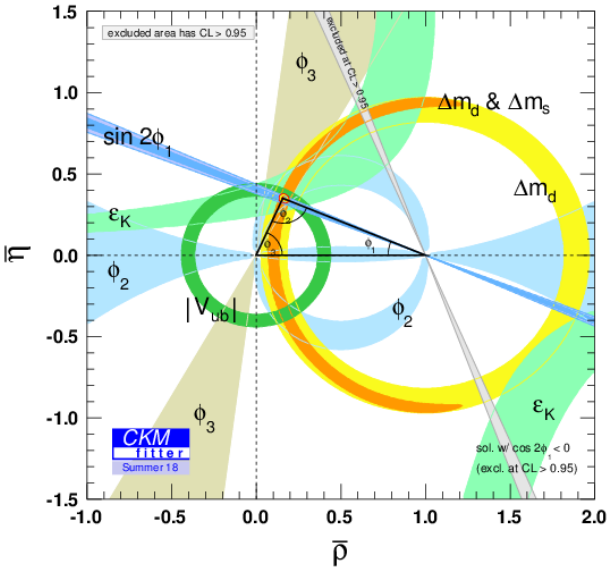
mass eigenstate → Flavor eigenstate

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \Rightarrow \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Product of V_{id} and V_{ib}^* of CKM matrix

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

  - Triangle can be drawn in the complex plain
  - To test new physics in B0-B0bar mixing ΔB=2
    - Three observable from tree, another three from loop



Mixing + B→ππ, ρπ , ρρ

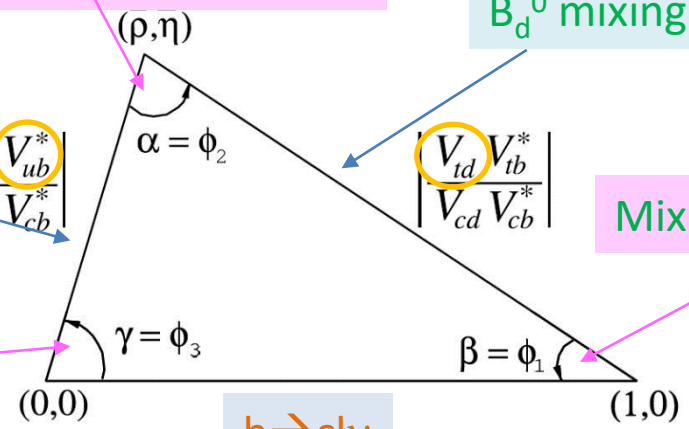
B_d^0 mixing

b→ulν

Mixing + B→J/ψKs

B→DK

b→clν



Tree Loop side angle

CPV phase

Unitarity Triangle Measurements

- Precision will be limited by theory or lattice QCD except ϕ_3
  - Uncertainties of all the sides ~1%
  - Uncertainties of all the angles ~1deg
- 200TeV NP scale can be accessible with EFT analysis
- >10 TeV in SUSY

Including theory and LQCD uncertainties

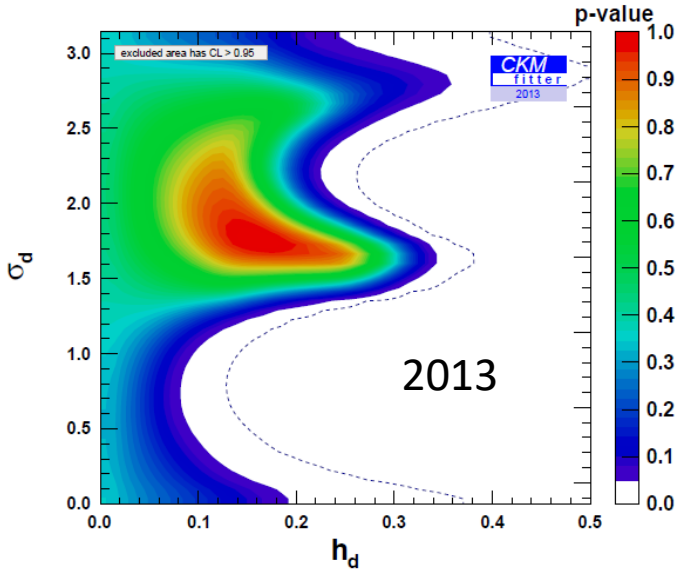
arXiv:1309.2293

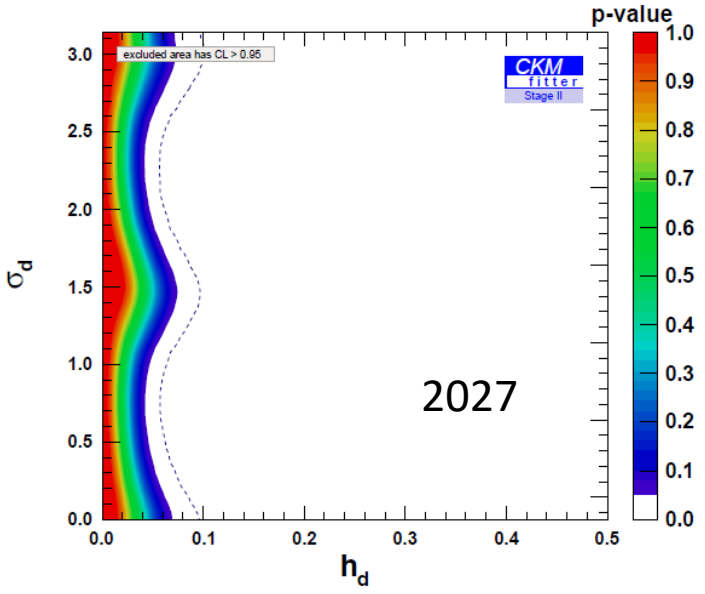
Tanimoto and Yamamoto (2014)

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

$$\frac{C_{ij}^2}{\Lambda^2}\,(\bar{q}_{i,L}\gamma^{\mu}q_{j,L})^2$$

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40





Summary

- Belle II recorded first data without vertex detector in Phase2
  - Instantaneous luminosity of 5.5×10^{33} $cm^{-2}s^{-1}$
  - Integrated luminosity of $0.5 fb^{-1}$
- Phase 3 Physics run is just started in March 2019
  - Early physics target : dark sector search
  - Some rediscoveries in this summer
    - $B \rightarrow K^* \gamma$ etc
  - Aim to supersede existing B factory data set by ~2021
- Stay tuned

Backup