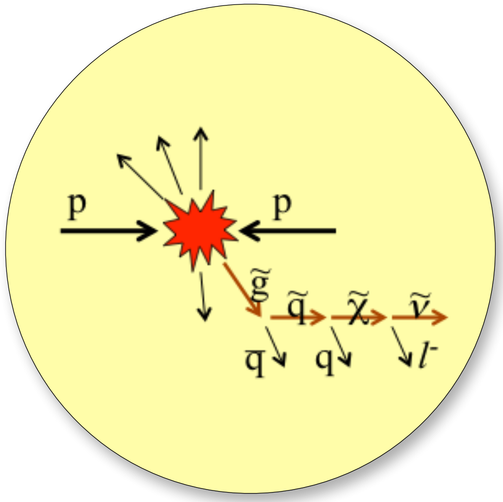
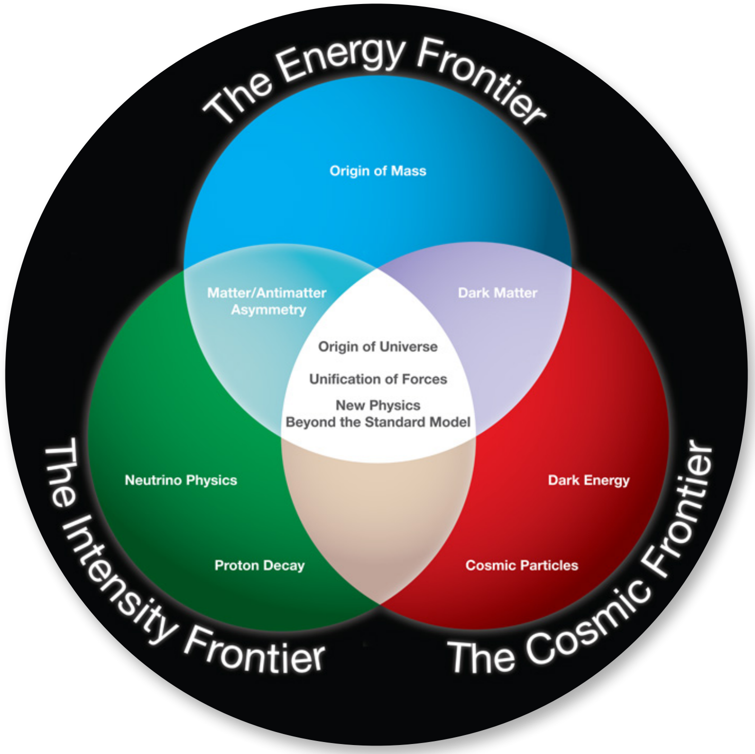
SuperKEKB & Belle II
Status and Prospects

Motivation

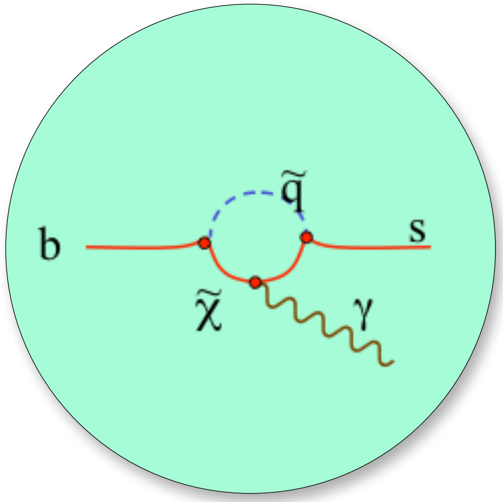
Energy frontier



Direct production of new particles



Intensity frontier

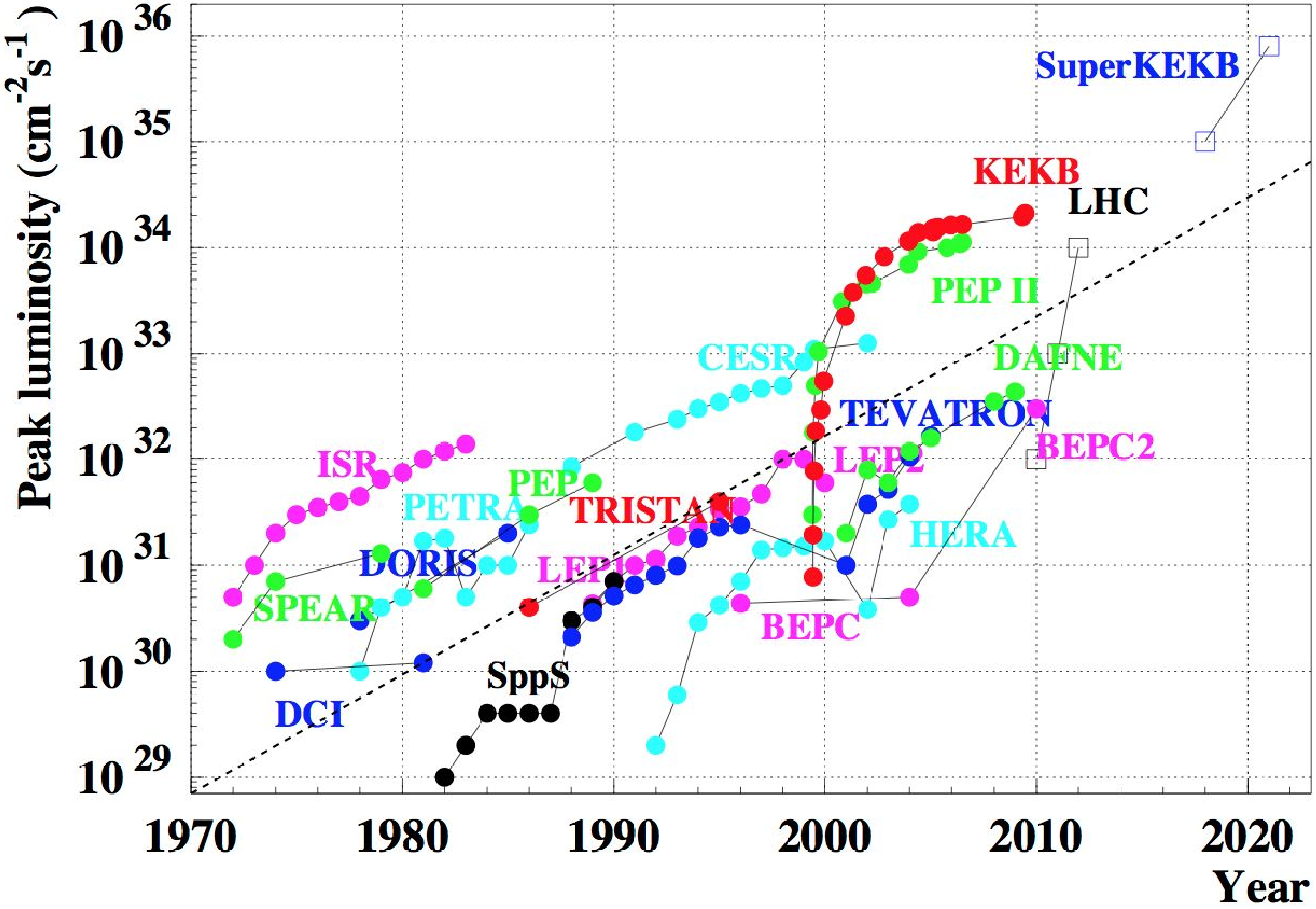


Indirect sensitivity through loops

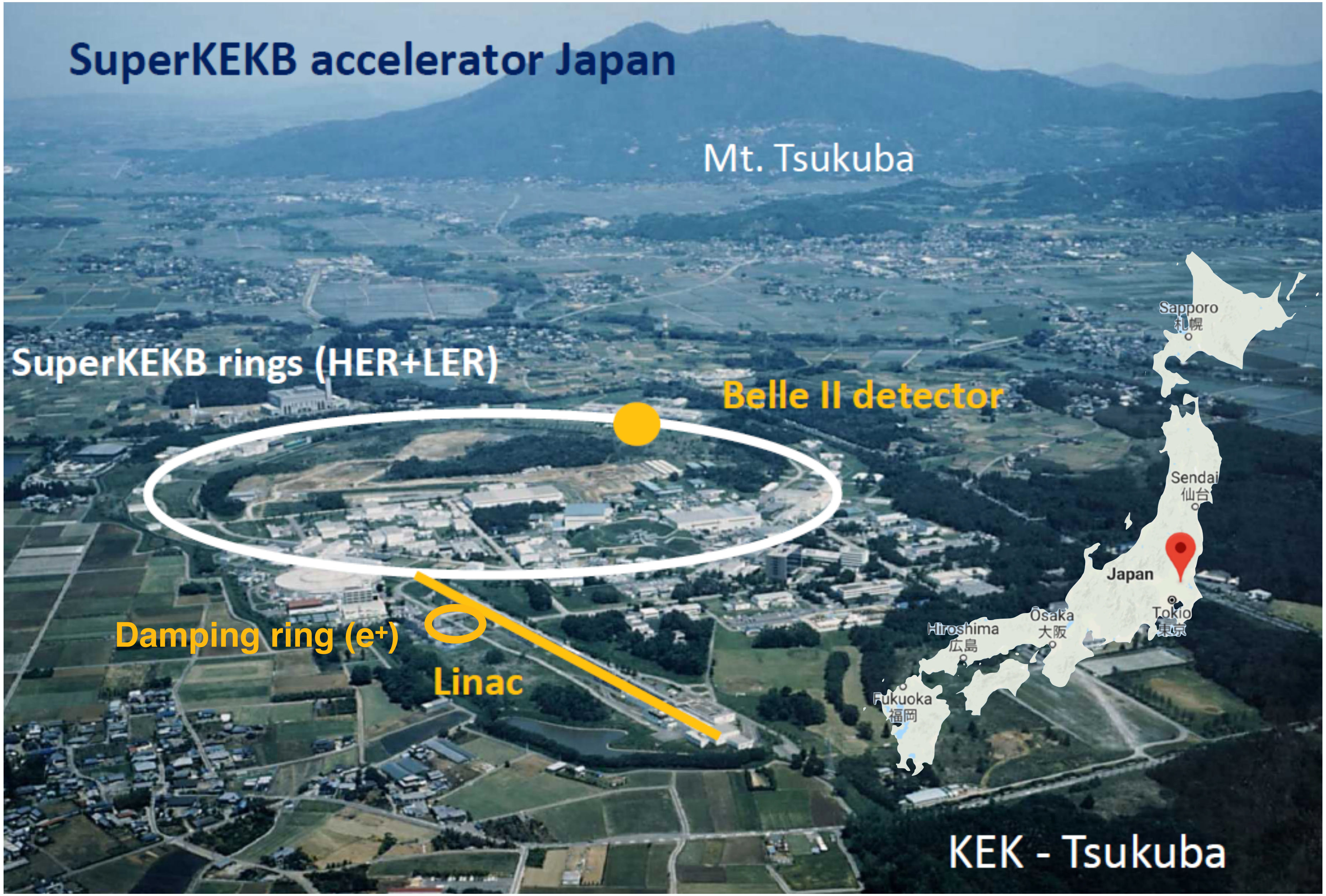
Current experimental situation

- No clear evidence for Beyond Standard Model (BSM) physics at the high energy frontier
- Intensity frontier offers **indirect** sensitivity to **very high** scales: recent observation of **"Flavour Anomalies"**
- **Direct and indirect searches are complementary**

Ambitious Next Step at Luminosity Frontier: SuperKEKB



SuperKEKB and Belle II at the Intensity Frontier



提言

第24期学術の大型研究計画に関する

マスタープラン

（マスタープラン2020）

令和２年（２０２０年）１月３０日

日 本 学 術 会 議

科学者委員会

研究計画・研究資金検討分科会

KEK submitted 10 year SuperKEKB project to the SCJ Master plan 2020.

The project was ranked as one of the 31 most important projects and is among 15 projects with grade A-A.

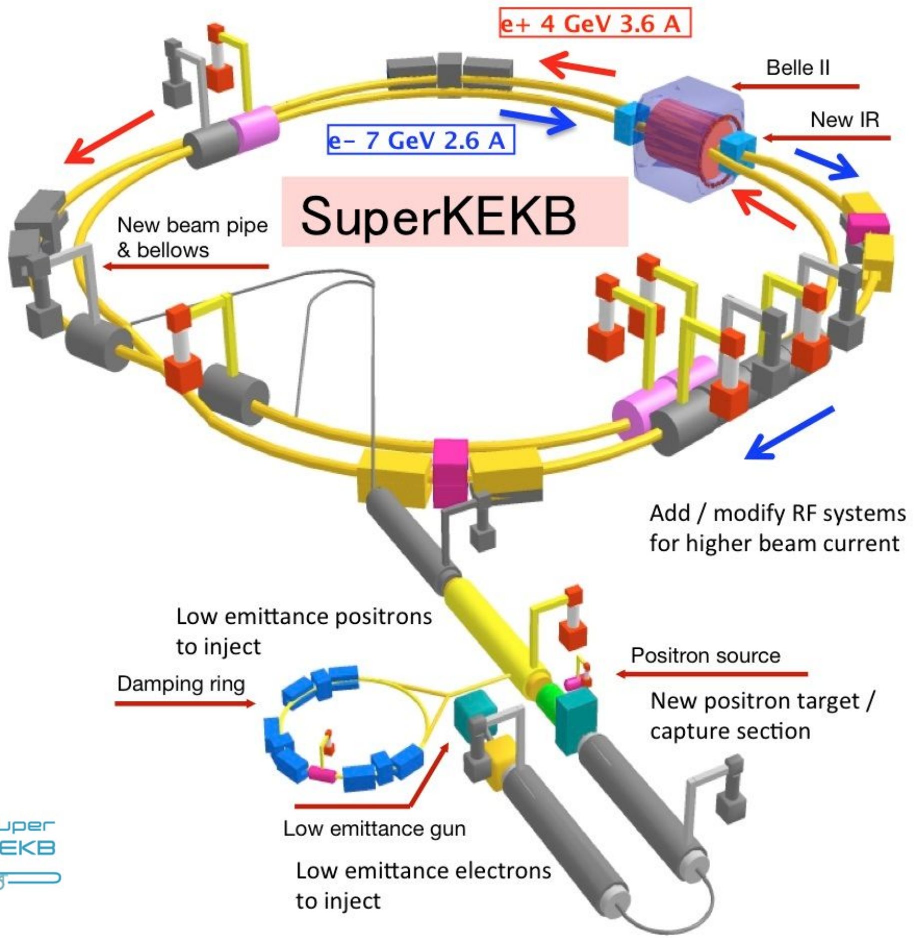
SuperKEKB and Nano-Beam Scheme

beam current **x2**

beam-beam param. **x1**

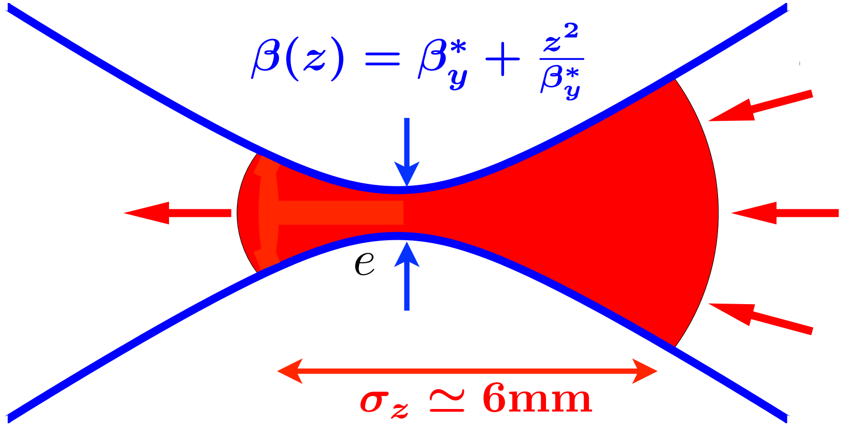
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{R_L}{R_\xi}\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}$$

vertical beta function **x 1/20**



LER / HER	KEKB	SuperKEKB	L-Factor
Energy [GeV]	3.5 / 8	4.0 / 7.0	
Crossing angle $2\phi_x$ [mrad]	22	**83**	
β_y^* [mm]	5.9 / 5.9	**0.27 / 0.30**	**x 20**
β_x^* [mm]	1200	**32 / 25**	
$I_\pm$ [A]	1.64 / 1.19	**3.6 / 2.6**	**x 2**
$\varepsilon_x = \sigma_x \times \sigma_{x'}$ [nm]	18 / 24	**3.2 / 4.6**	
$\varepsilon_y = \sigma_y \times \sigma_{y'}$ [pm]	140 / 140	13 / 16	
$\xi_y \sim (\beta_y^*/\varepsilon_y)^{1/2} / \sigma^*_x$	0.129 / 0.09	**0.09 / 0.09**	**x 1**
# of bunches	1584	2500	
Luminosity [10^{34} cm^{-2} s^{-1}]	2.1	**80**	**x 40**

Hourglass effect



$$\Rightarrow \text{goal} : \sigma_z^{\text{eff}} < \beta_y^*$$

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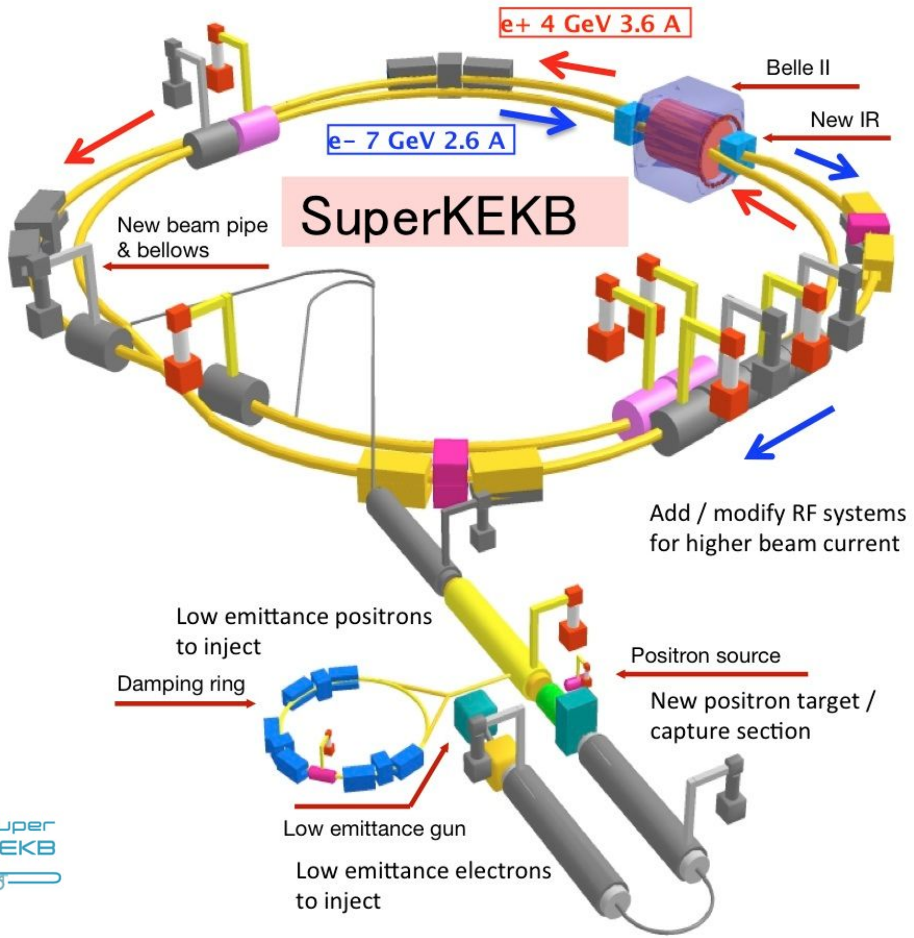
vertical beta function **x 1/20**



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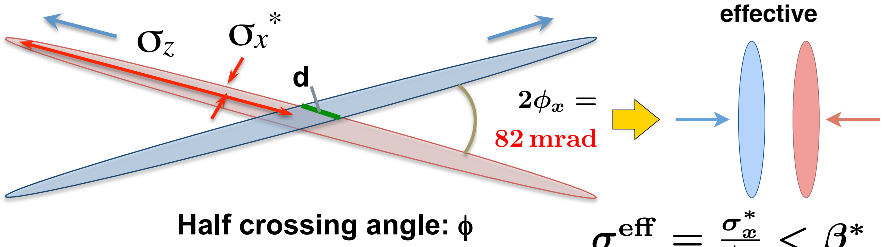
Nano-Beam scheme (P. Raimondi, DAΦNE):
Squeeze beta function at the IP (β_x^*,β_y^*) and minimize longitudinal size of overlap region to avoid penalty from hourglass effect.



$$\sigma_z^{\mathrm{eff}} = \frac{\sigma_x^*}{\phi_x} < \beta_y^*$$

overlap region (≠ bunch length)

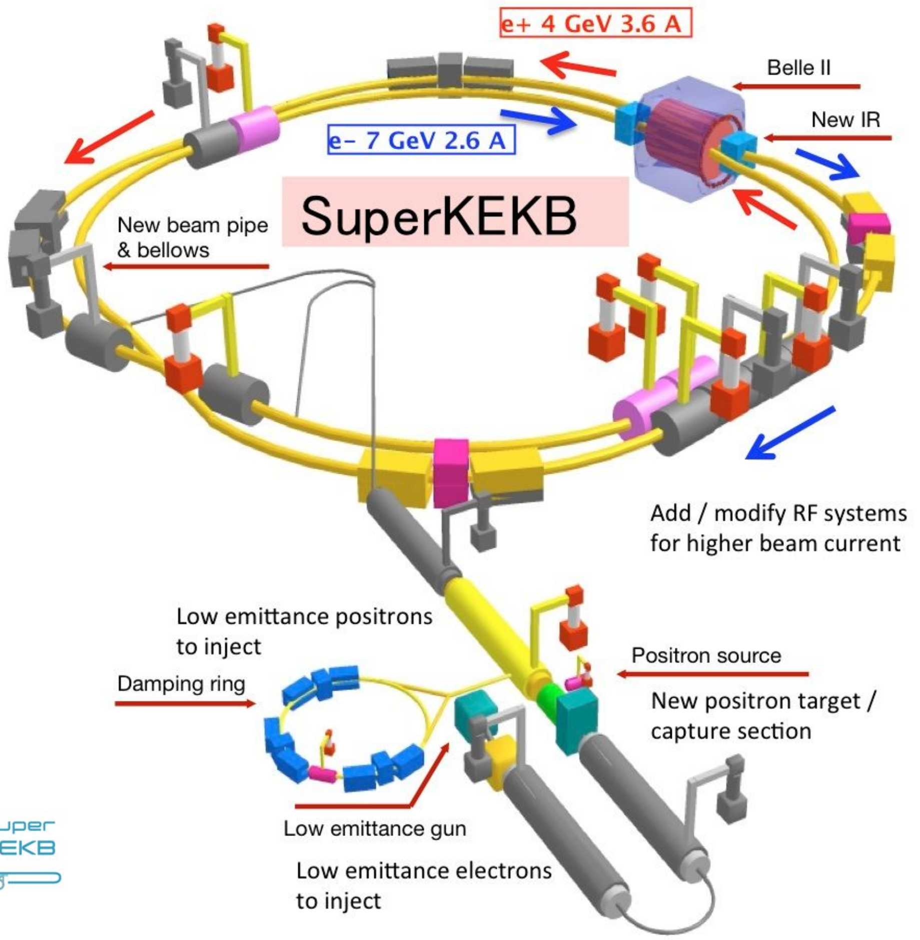
Strong focusing of beams down to vertical size of ~ **50 nm** requires **very low emittance beams** and **large crossing angle (83 mrad)** ⇒ Need **sophisticated final focus** system (QCS)

SuperKEKB and Nano-Beam Scheme

beam current **x2**   beam-beam param. **x1**

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{R_L}{R_\xi}\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}$$

vertical beta function **x 1/20**



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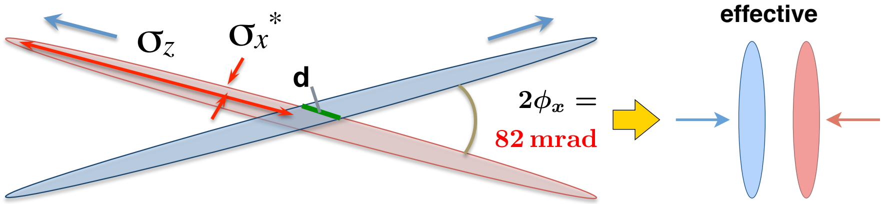
$I_\pm$ [A]	1.64 / 1.19	**2.8 / 2.0**	**x ~1.5**
$\varepsilon_x = \sigma_x \times \sigma_{x'}$ [nm]	18 / 24	**3.2 / 4.6**	
$\varepsilon_y = \sigma_y \times \sigma_{y'}$ [pm]	140 / 140	13 / 16	
$\xi_y \sim (\beta_y^*/\varepsilon_y)^{1/2} / \sigma_x^*$	0.129 / 0.09	**0.09 / 0.09**	**x 1**
# of bunches	1584	1800	
Luminosity [10^{34} cm^{-2} s^{-1}]	2.1	**60**	**x 30**

Roadmap2020

Nano-Beam scheme (P. Raimondi, DAΦNE):
Squeeze beta function at the IP (β_x^*,β_y^*) and minimize longitudinal size of overlap region to avoid penalty from hourglass effect.



Half crossing angle: φ

$$\sigma_z^{\text{eff}} = \frac{\sigma_x^*}{\phi_x} < \beta_y^*$$

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Strong focusing of beams down to vertical size of ~ **50 nm** requires **very low emittance beams** and **large crossing angle (83 mrad)** ⇒ Need **sophisticated final focus** system (QCS)

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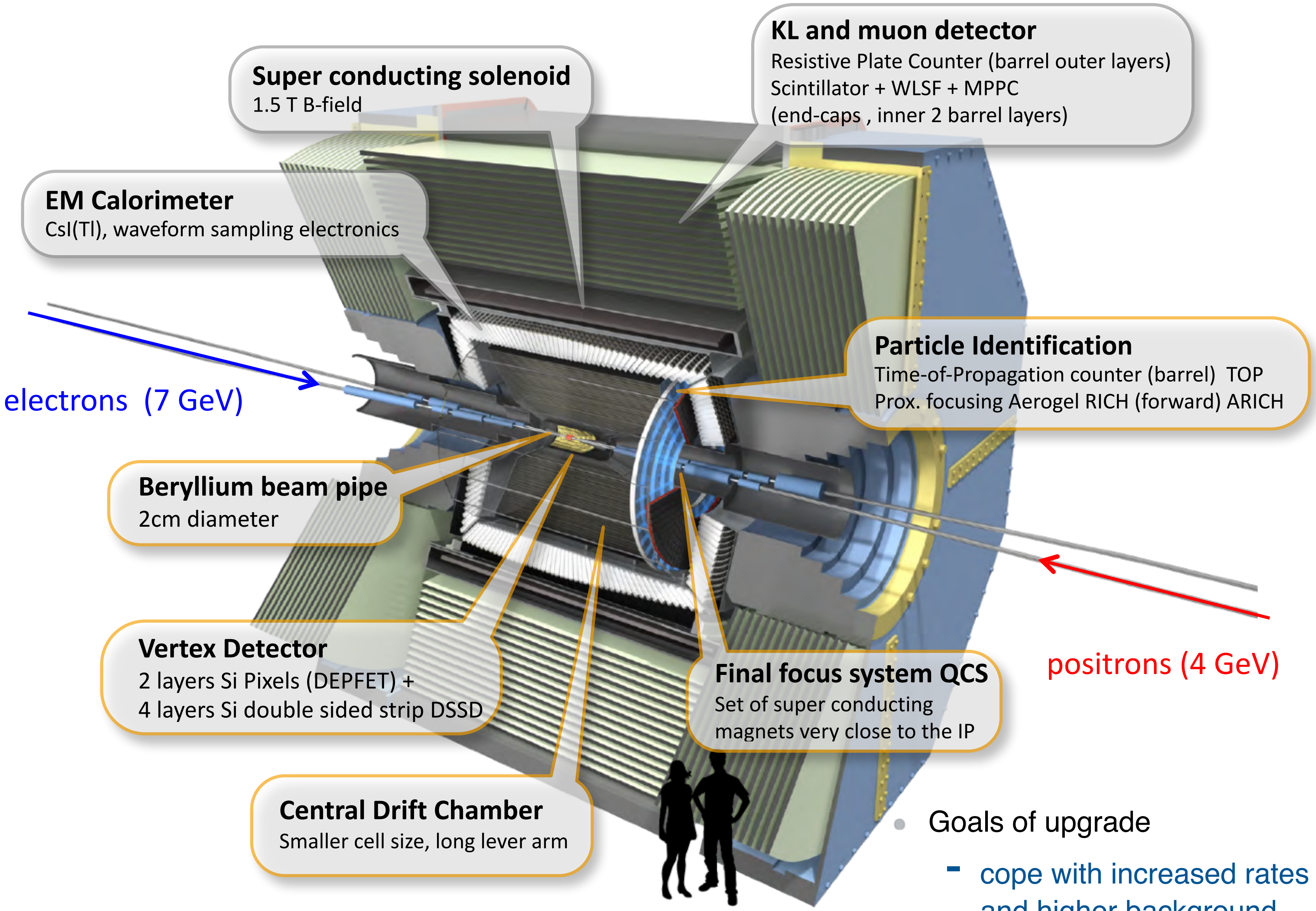
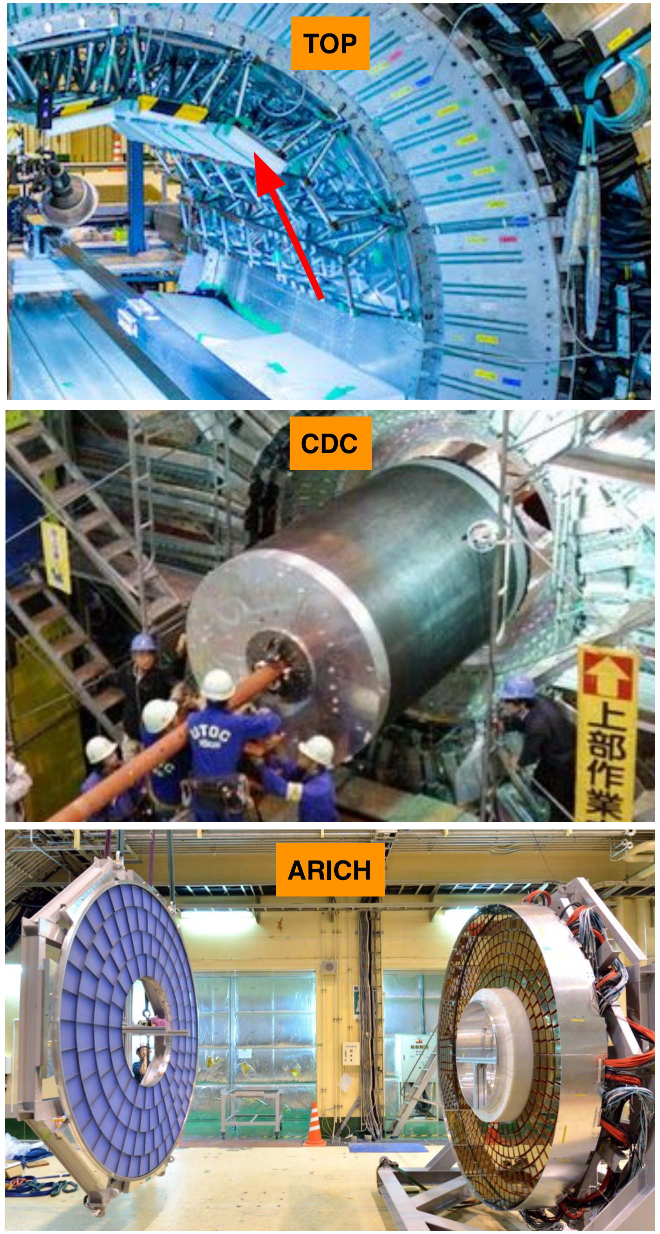
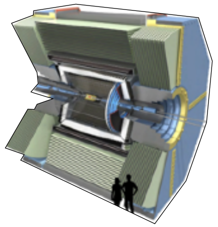
Belle II



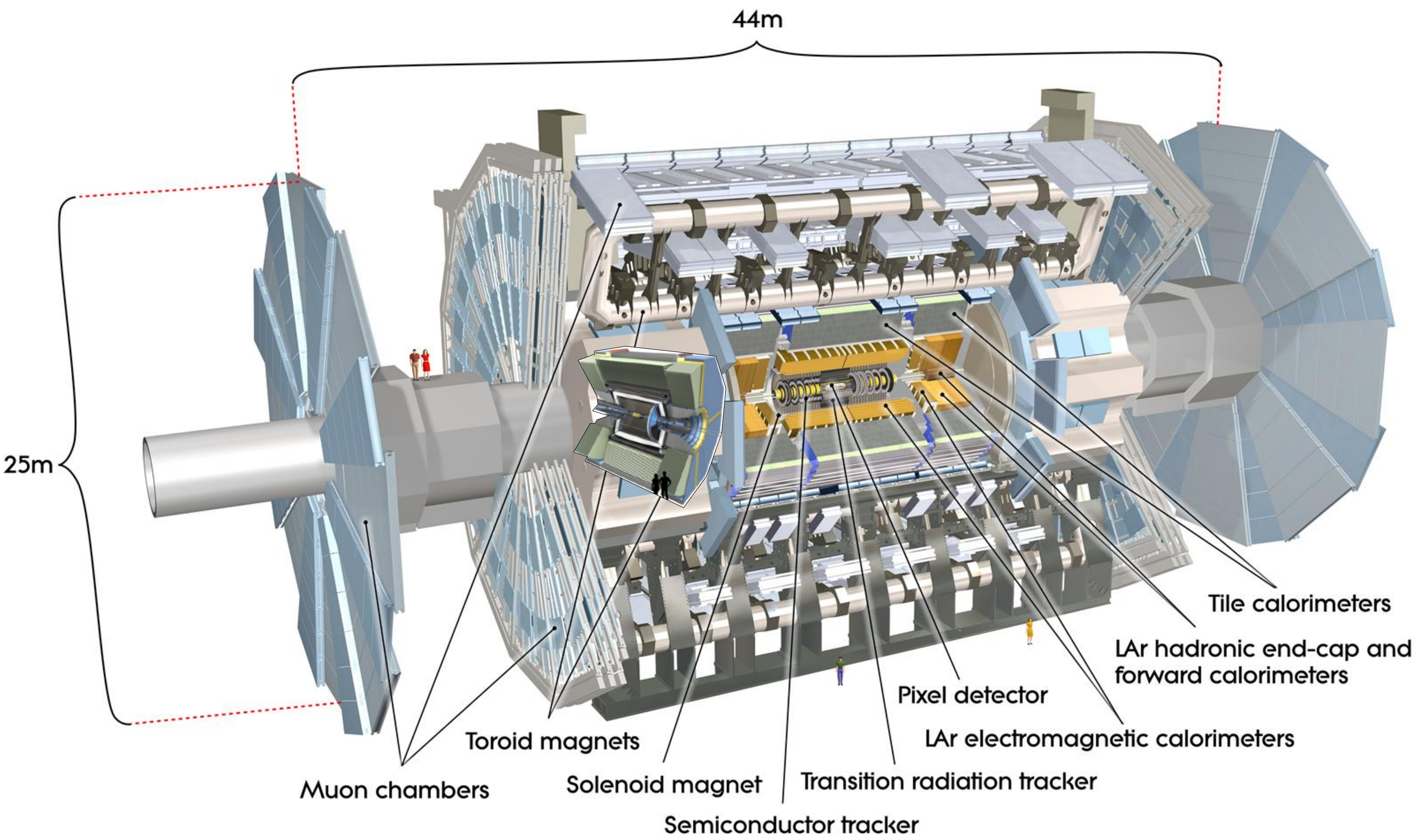


- Goals of upgrade
  - cope with increased rates and higher background
  - improve performance

Belle II

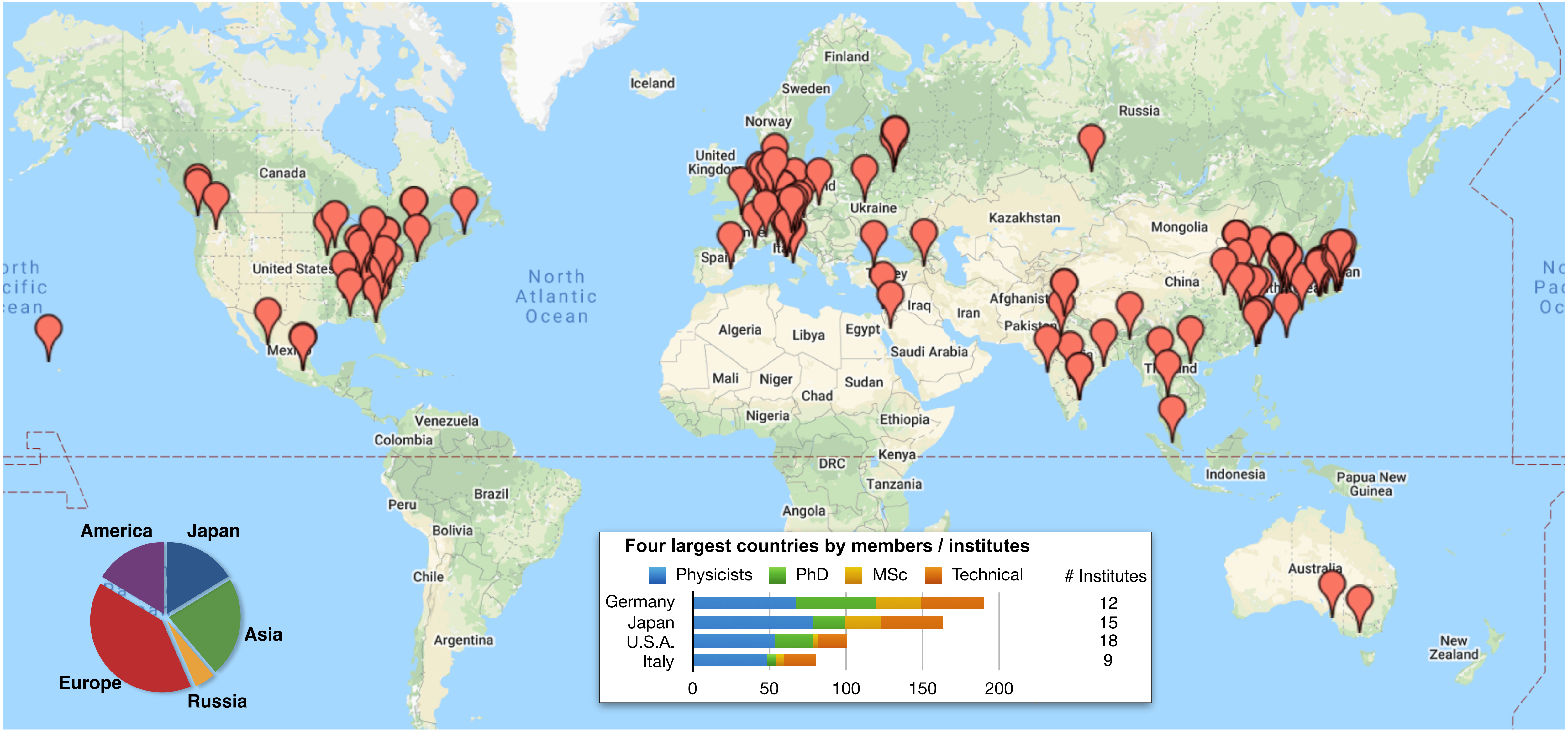


Belle II



44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Solenoid magnet
Transition radiation tracker
Muon chambers
Semiconductor tracker

Belle II Collaboration

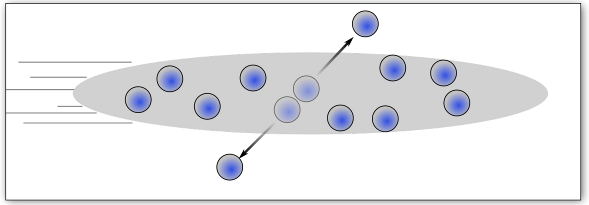


1060 members from 123 institutes in 26 countries

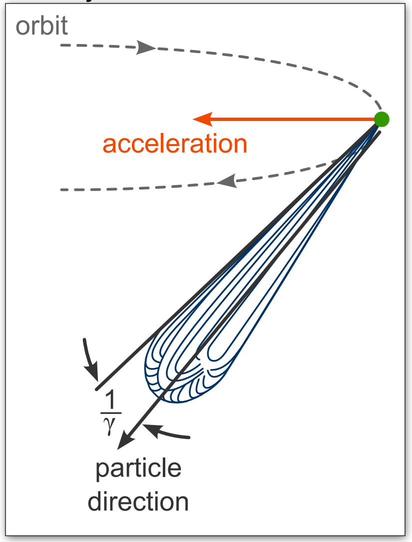
Main Background Sources at SuperKEKB

- Single beam (LER and HER)
  - Touschek: single scattering within same bunch → particles get lost when they drop out of momentum acceptance of the machine
    - rate $\propto I_{\pm}^{2} / (n_b \sigma_x \sigma_y E_{\pm}^{3}) \propto 1/\tau_{\text{beam}}$ ⇒ reduced energy asymmetry
    - nano beam ⇒ increased background
  - beam gas: rate $\propto I_{\pm}\, p\, Z_{eff}^{2}$ (approx. $\propto I_{\pm}^{2}$)
    - elastic Coulomb scattering
    - bremsstrahlung
  - synchrotron radiation: $P_{\gamma} \propto E_{\pm}^{4}\, I_{\pm}\, \rho^{-1}$
  - injection background (2 x 25 Hz)
- Beam-beam (irreducible): rate $\propto L$
  - radiative Bhabha: $e^+e^- \rightarrow e^+e^- \ (\gamma)$
    - (a) emitted photon (neutrons), (b) spent e+/e-
  - 2-photon process: $e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-e^+e^-$

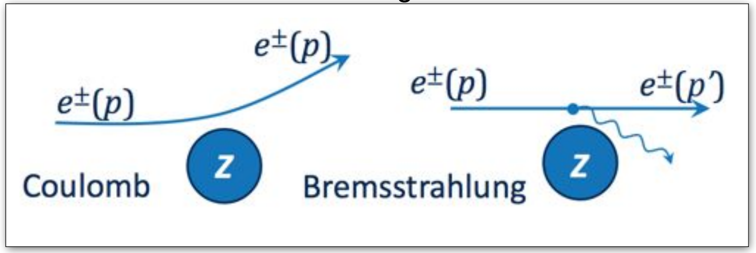
Touschek



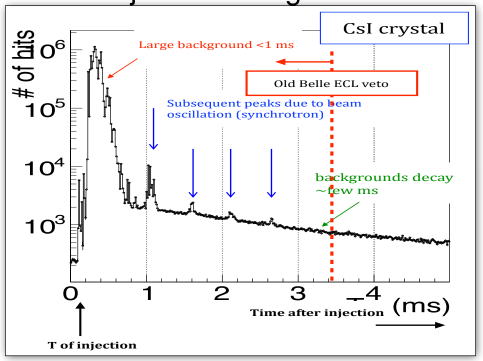
Synchrotron radiation



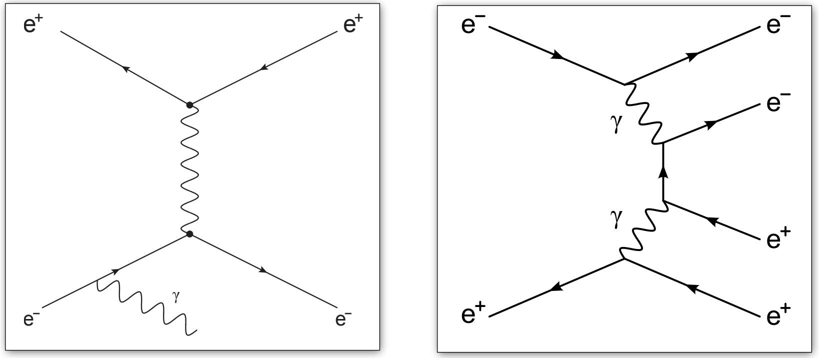
Beam gas



Injection background

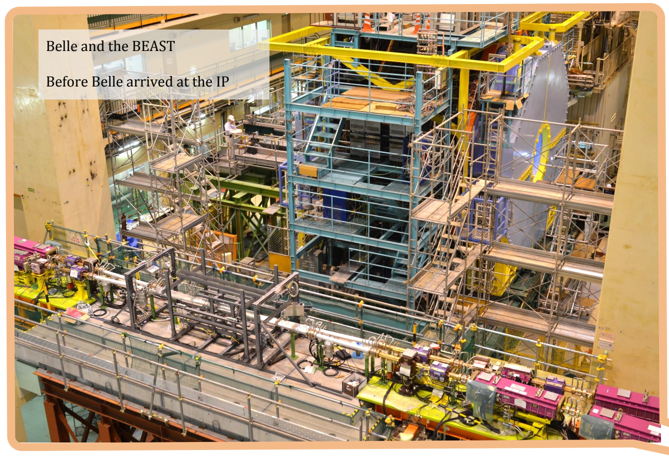


Beam beam

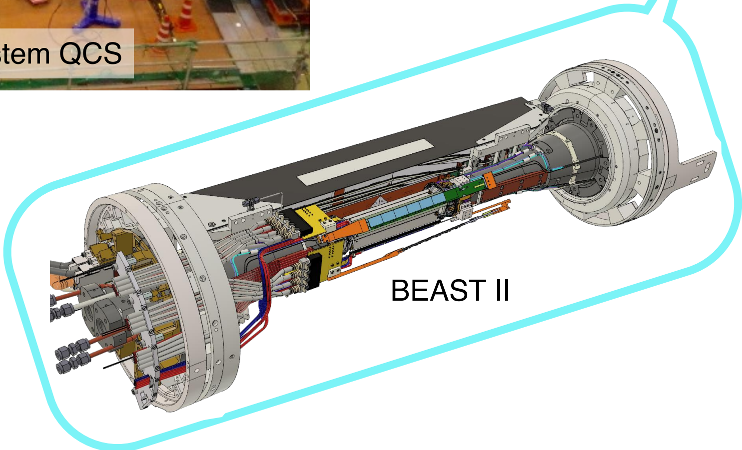


Overview SuperKEKB / Belle II Commissioning

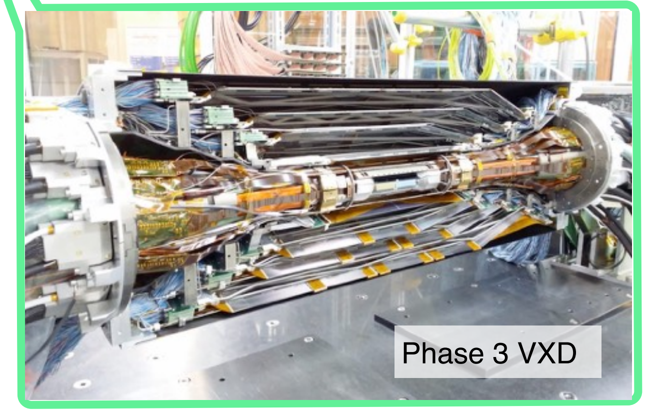
- Phase 1
  - only MR without final focussing magnets and without Belle II
- Phase 2
  - with final focussing magnets, but without final VXD detectors
  - establish nano-beam scheme
  - study background
- Phase 3
  - start physics data taking with full* Belle II



In total 55 individual super conducting coils



Background studies



* only partial PXD L2

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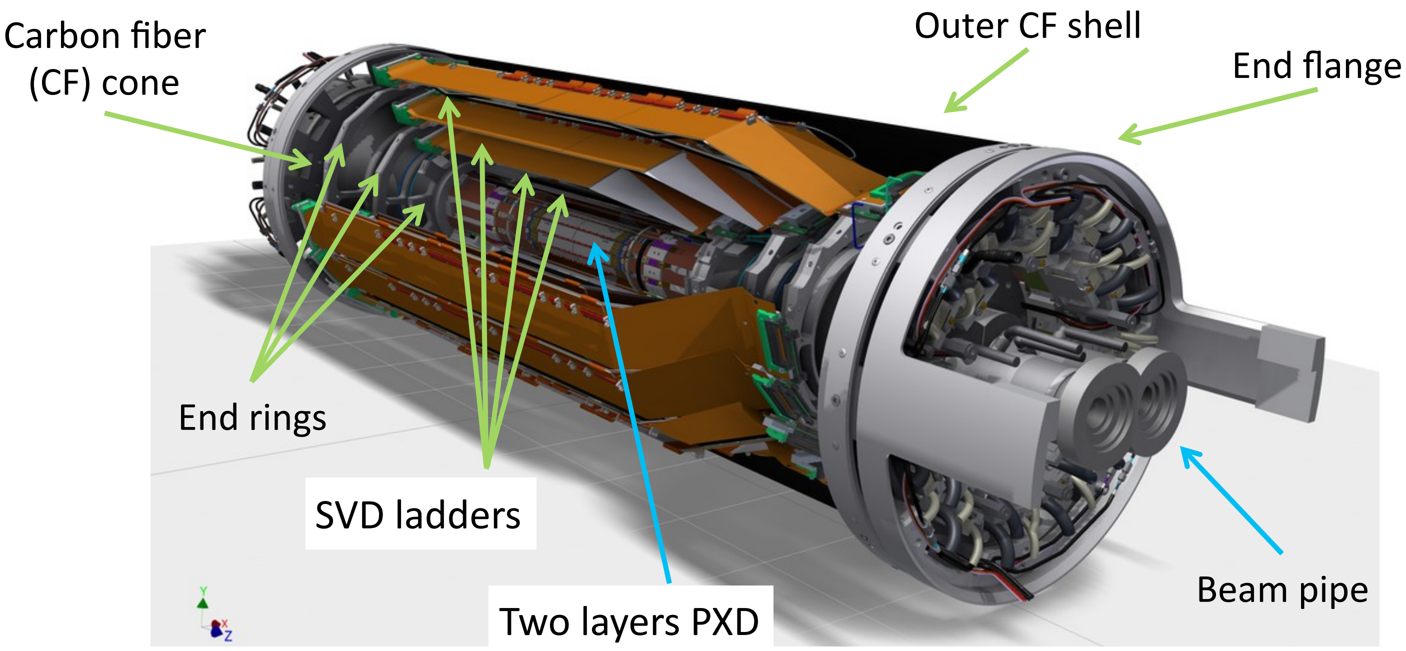
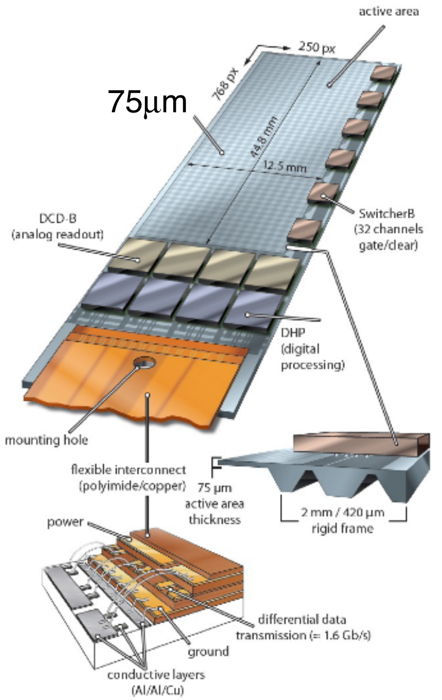
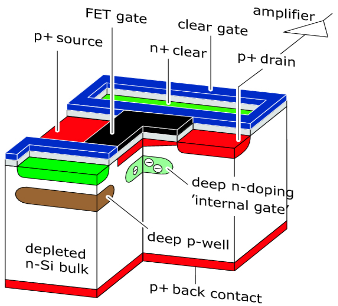
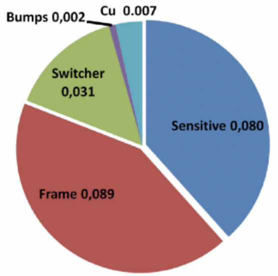
Belle II Vertex Detector VXD



PXD DEPFET

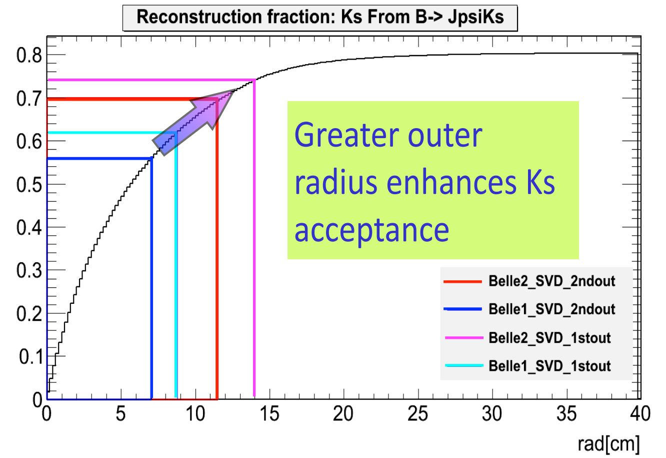




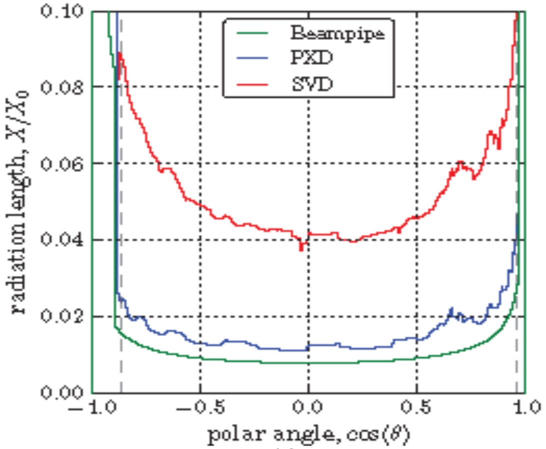


0.21% X_0 per layer

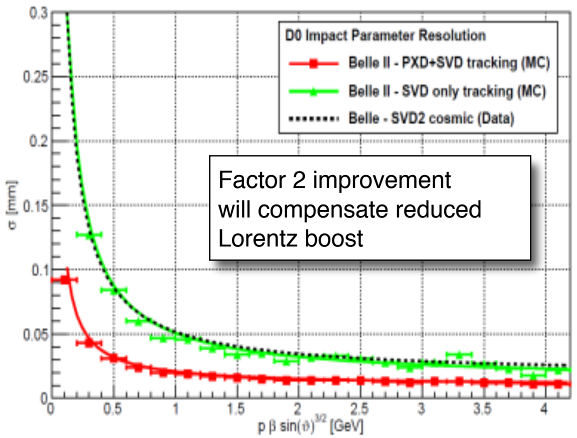
Acceptance



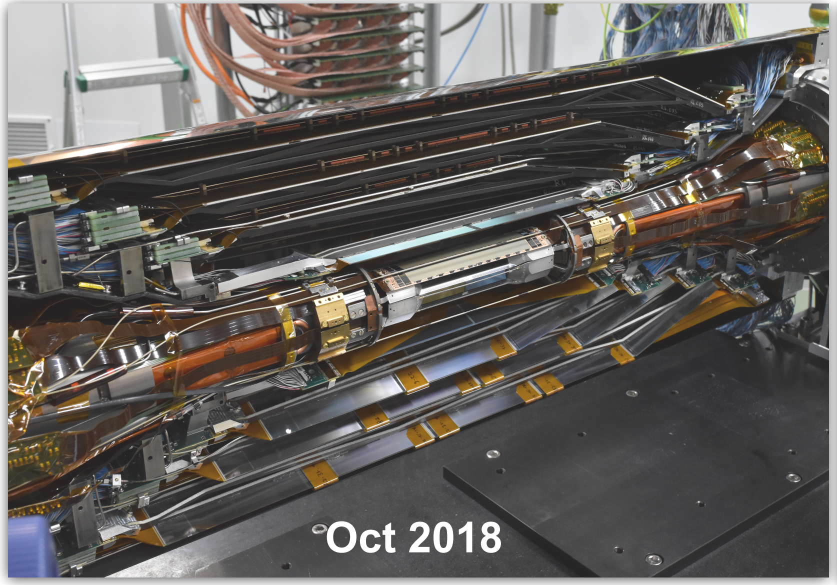
Material budget

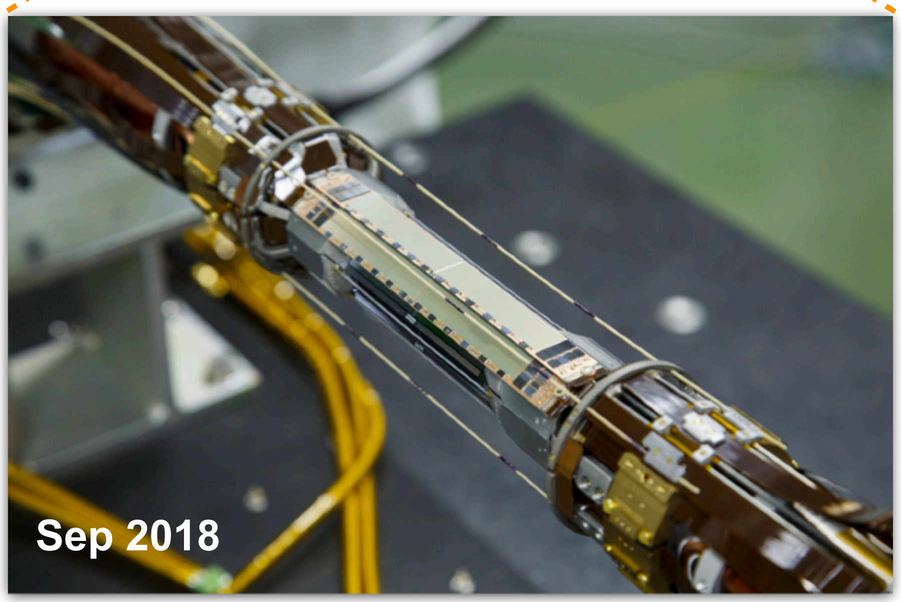


Resolution

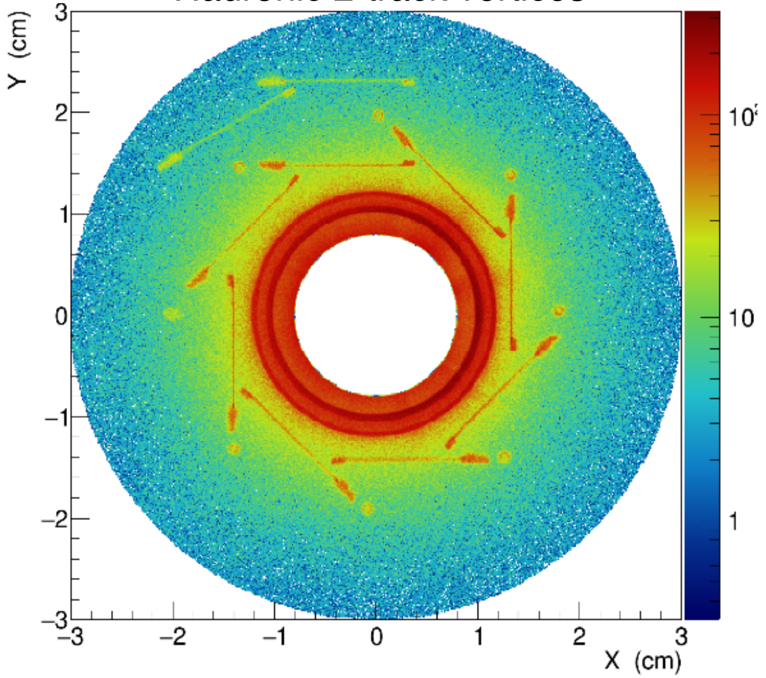


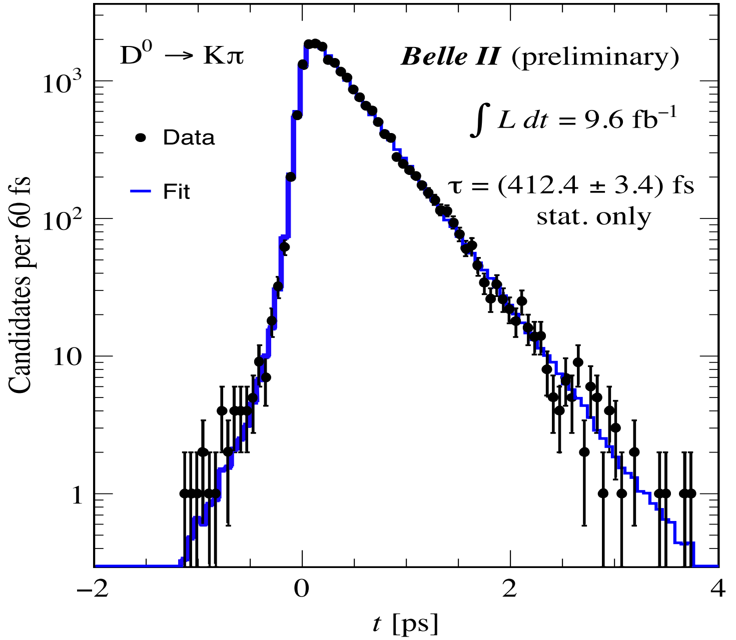
Phase 3 VXD Installation and Performance





Hadronic 2-track vertices





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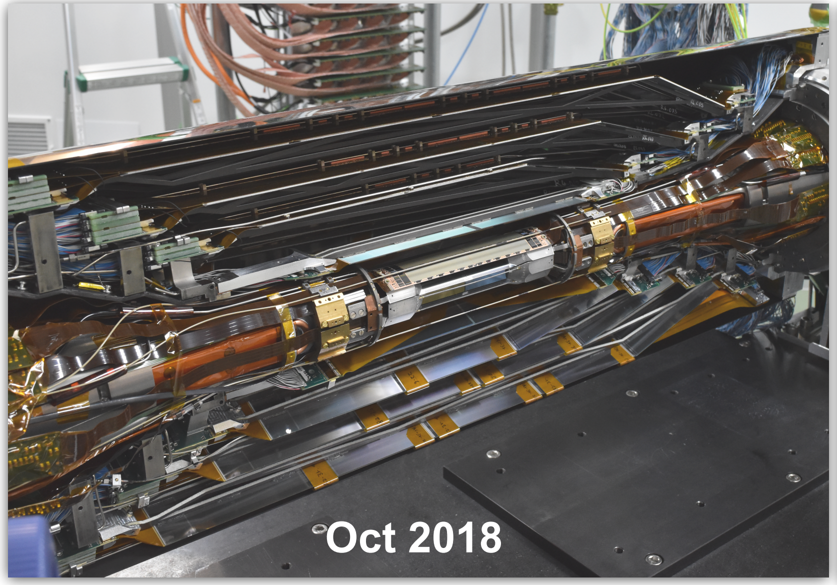

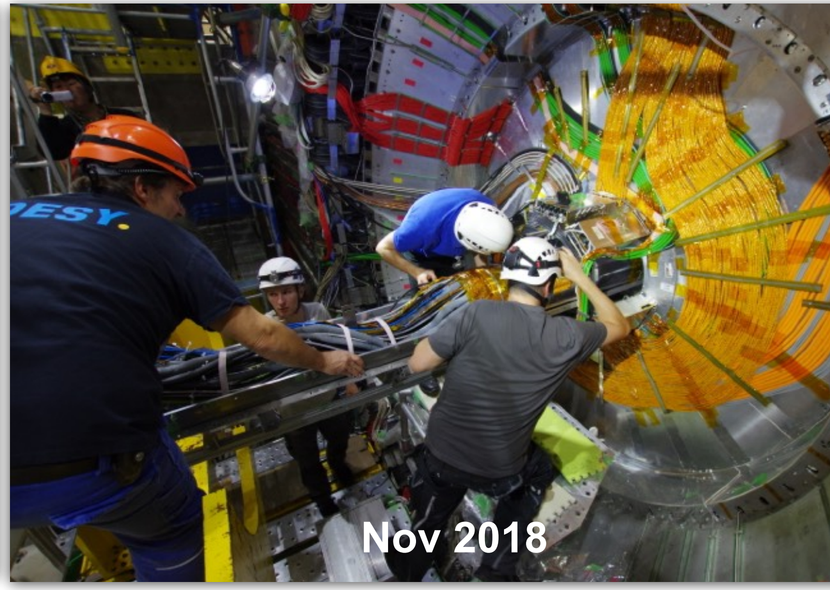

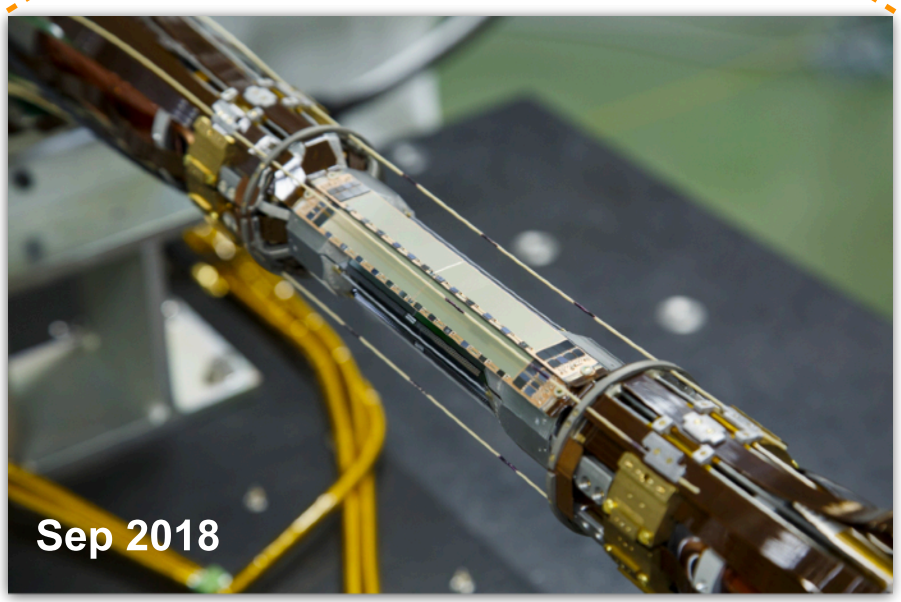

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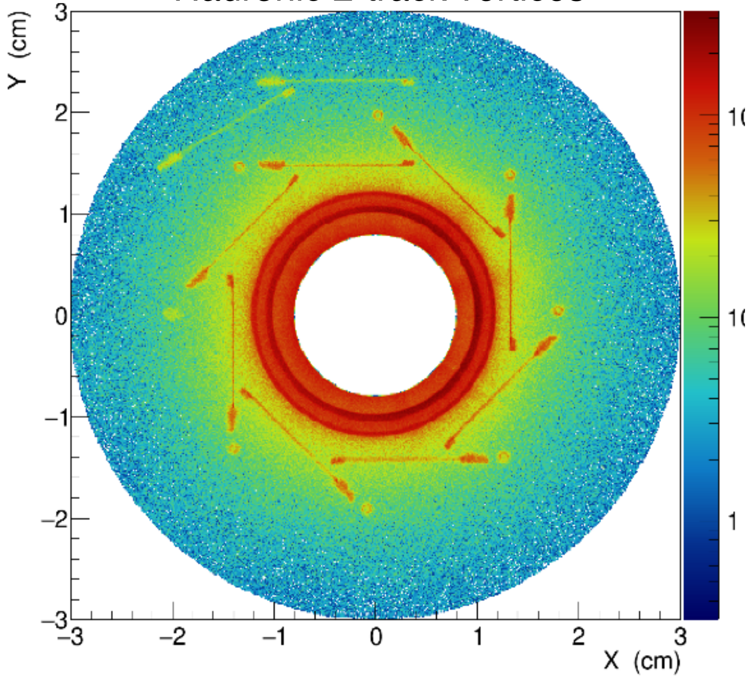

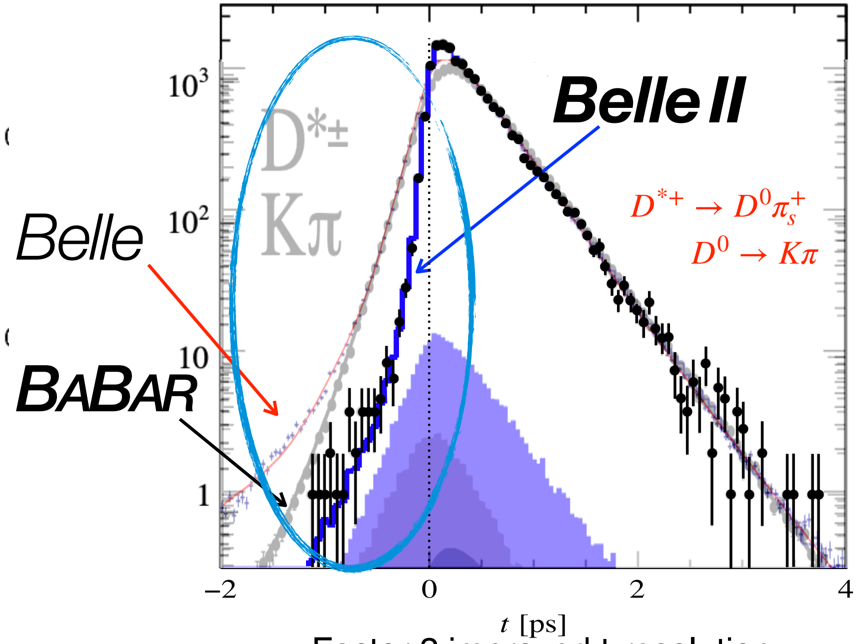

Factor 2 improved t-resolution

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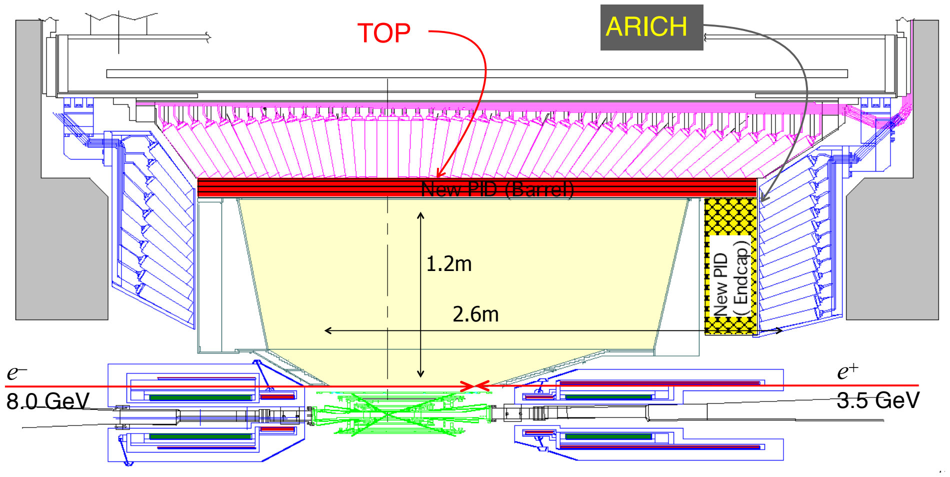
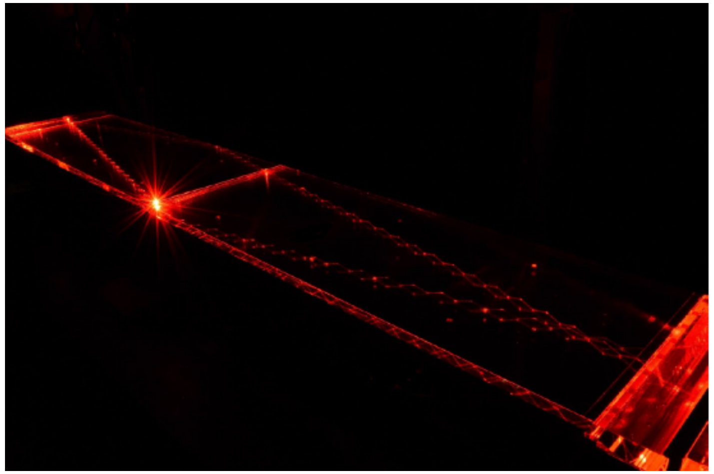
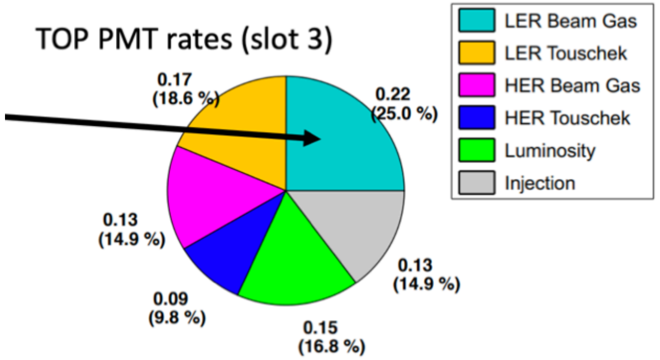
Time Of Propagation Detector TOP

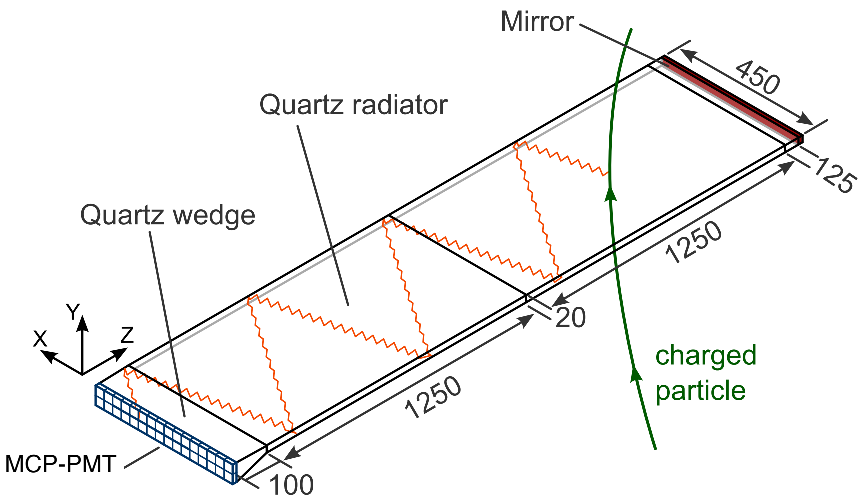


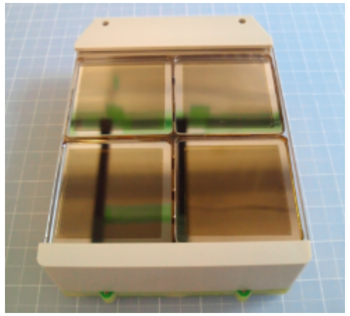


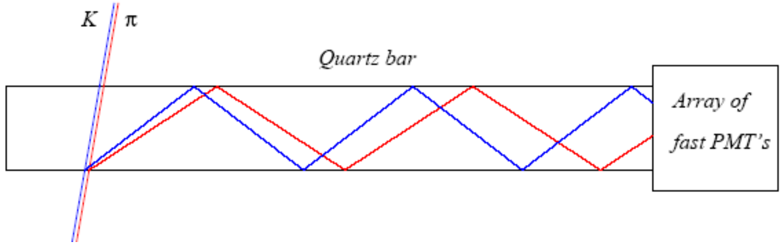
Present background decomposition in TOP



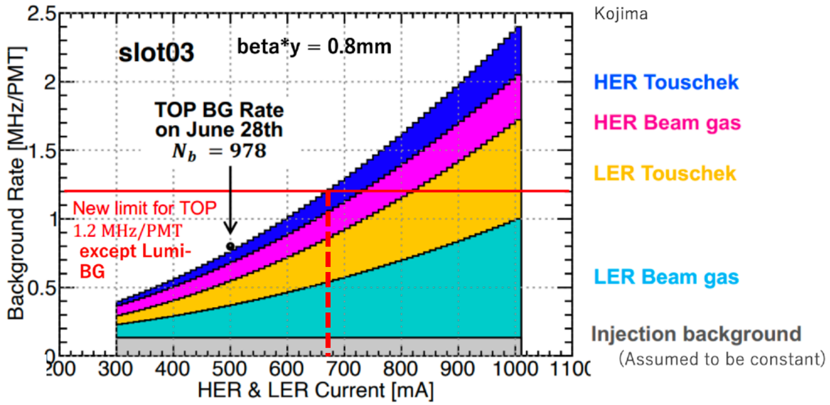
- 16 quartz bars: 2x1.25 m x 0.45 m x 2 cm
- 32 (segmented anode 4x4) Micro-channel plate PMTs Hamamatsu SL-10 MCP PMT
- 60 ps time resolution







θ_c is reconstructed from hit position (x,y) in the PMT and from time of propagation

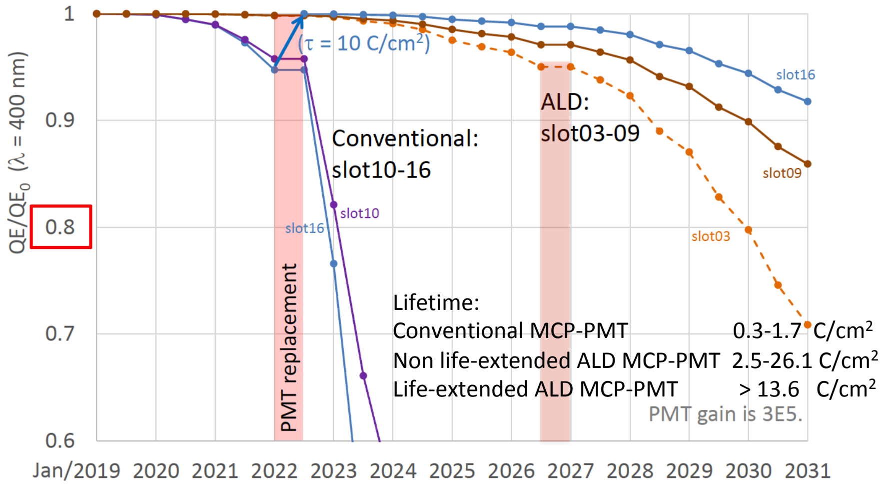


Beam current limit w/o further background mitigation

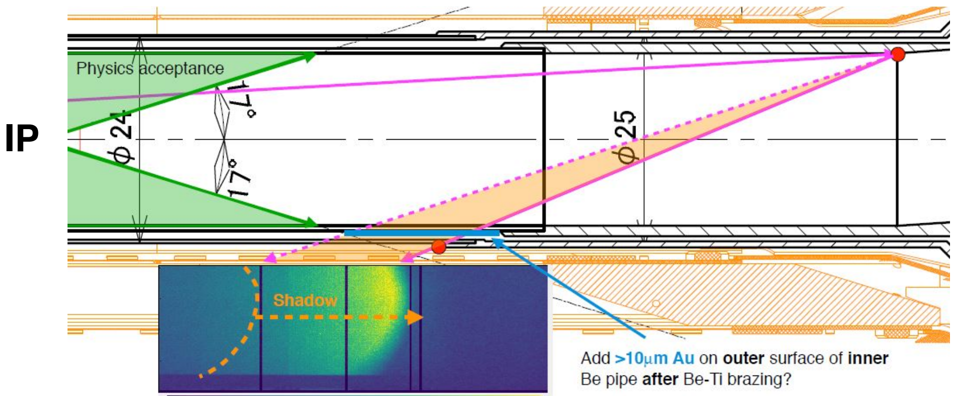
Operational Challenges

- Detector background
  - high rates in TOP MCP-PMT's
    - Quantum Efficiency degrades with integrated charge
    - conventional PMTs have to be replaced in 2022 shutdown
    - TOP background (and injector) presently limits beam currents
    - further background reduction essential to ramp up luminosity
      - additional and more robust collimators
      - extra shielding, vacuum scrubbing
  - synchrotron radiation background in PXD (HER injection)
    - construction of improved IP beam pipe is ongoing at KEK
    - installation together with PXD2 in 2022
- Uncontrolled beam losses close to the IR
  - some beam losses are not detected early enough by SKB beam loss monitors or Belle II diamond system
    - origin of these events still unclear (dust particles?)
    - ⇒ collimator damage and QCS quenches
    - ⇒ permanent damage in PXD (→ 2.5% inefficient gates)
      - implement faster beam abort and emergency shutdown of PXD

Projected development of TOP-PMT Quantum Efficiency



We have 220 no life-extended ALD, there's a window for their replacement in 2026.



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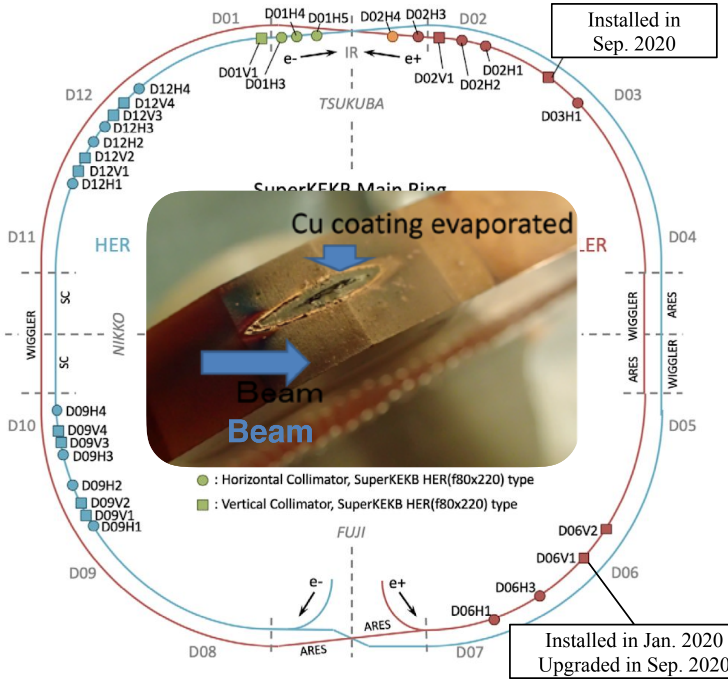
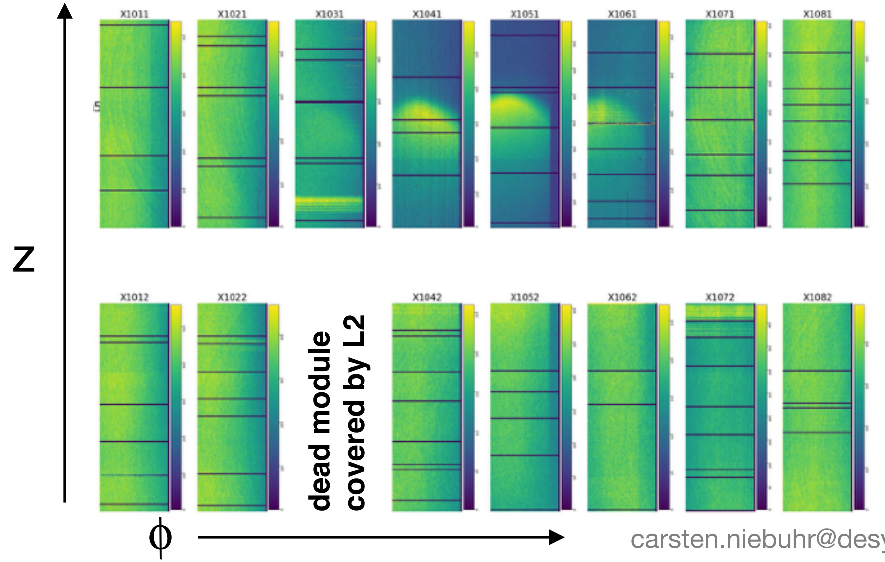
  - synchrotron radiation background in PXD (HER injection)
    - construction of improved IP beam pipe is ongoing at KEK
    - installation together with PXD2 in 2022
- Uncontrolled beam losses close to the IR
  - some beam losses are not detected early enough by SKB beam loss monitors or Belle II diamond system
    - origin of these events still unclear (dust particles?)
    - ⇒ collimator damage and QCS quenches
    - ⇒ permanent damage in PXD (→ 2.5% inefficient gates)
      - implement faster beam abort and emergency shutdown of PXD



Inefficient gates in PXD L1 hit map due to beam losses



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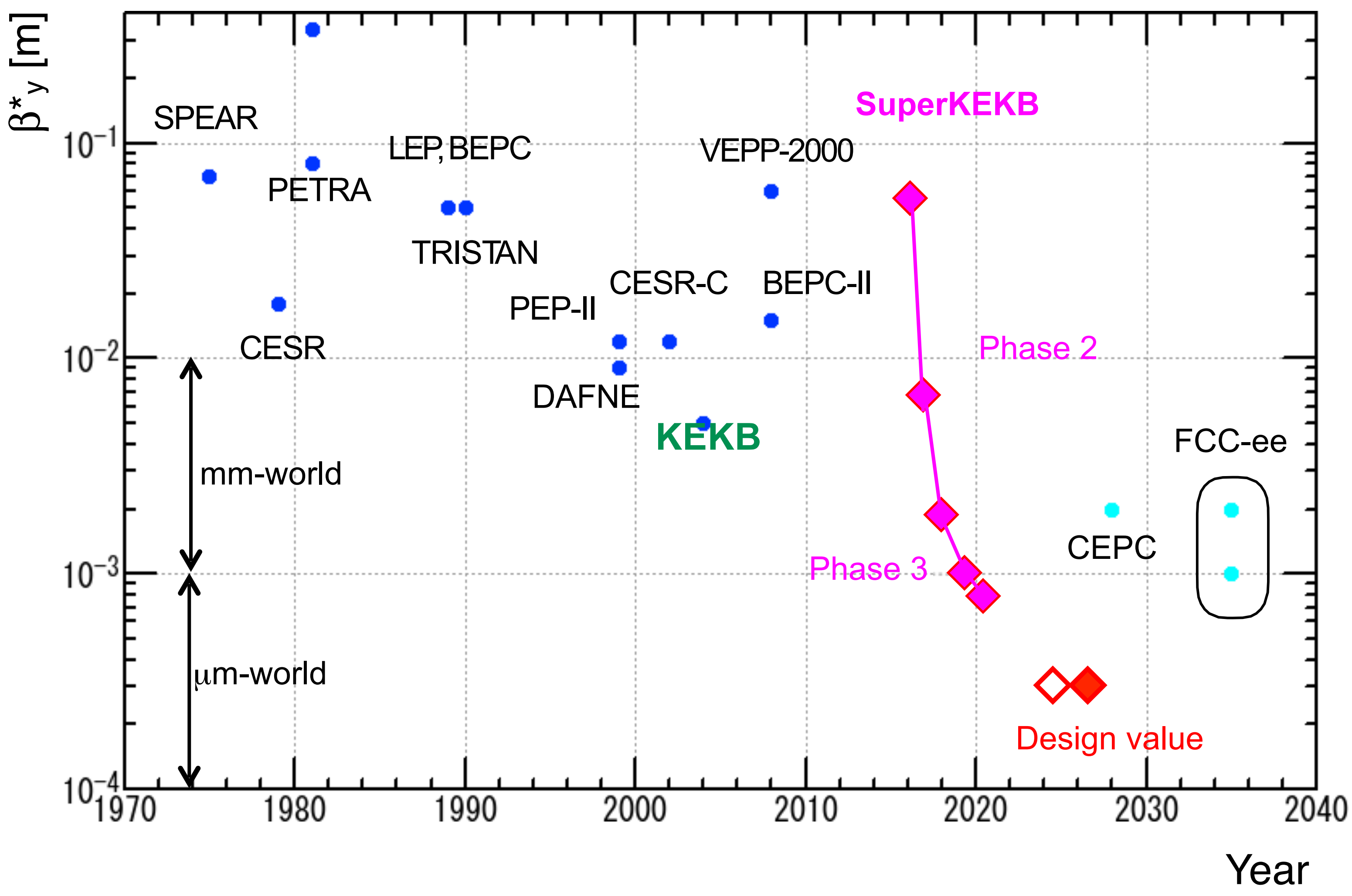
Entering new Territory in β^*_y and L_{peak}

Plot adapted from Y.Suetsugu



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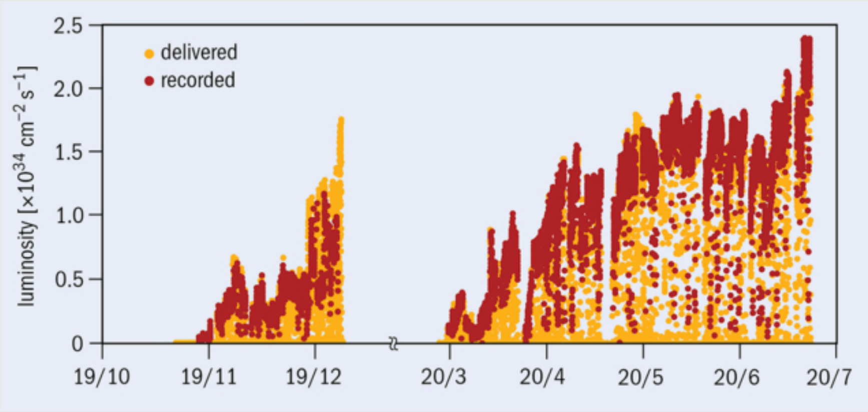
ACCELERATORS | NEWS

KEK reclaims luminosity record

30 June 2020



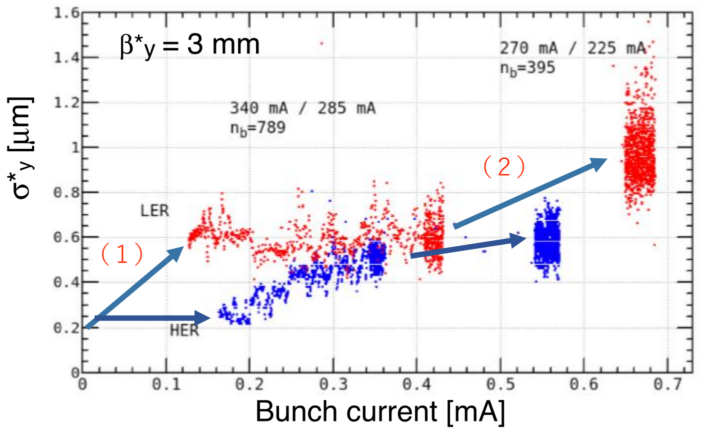
Record breaker The instantaneous luminosity of SuperKEKB measured at 5-minute intervals from late 2019 to 22 June 2020. Values are online measurements and contain an approximate 1% error. Credit: KEK

We can spare no words in thanking KEK for their pioneering work in achieving results that push forward both the accelerator frontier and the related physics frontier

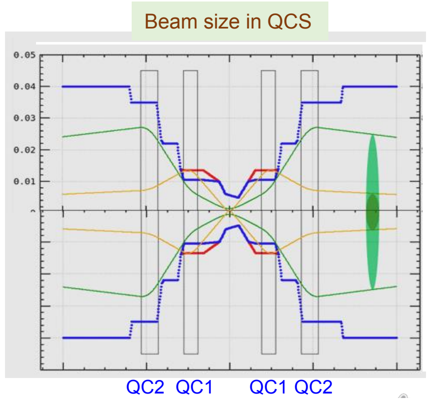
Pantaleo Raimondi

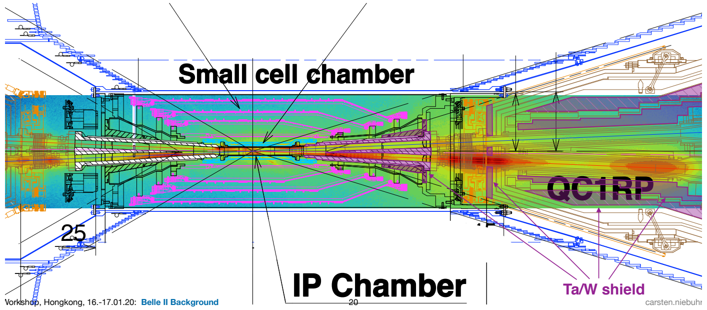
Challenges in SuperKEKB Operation and Roadmap2020

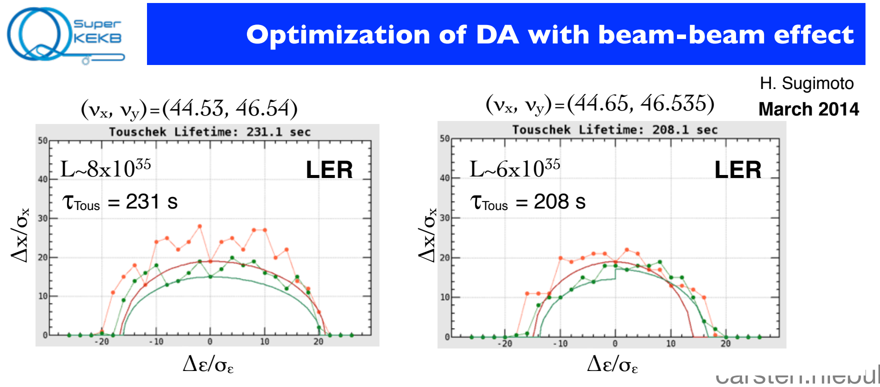
- MEXT Roadmap2020 selection is the fundamental plan of MEXT for the promotion of large-scale projects
  - KEK has submitted the SuperKEKB Roadmap2020 proposal in February
- Main arguments for strategy update
  - operation at design currents requires substantial increase in electricity costs (x1.6) ↯ running time
  - major challenges encountered during first year of phase 3 operation
    - strong beam-beam effects for high bunch-currents emittance blow-up in LER ↘ **luminosity**
    - narrow physical aperture in the QCS → **quenches** and **collimator damage**
    - **high background** in Belle II
  - small dynamic aperture in high bunch-current regime at β_y^*~0.3 mm
    - LER Touschek **lifetime** will be reduced to <4 min



$$L_{sp} = \frac{1}{2\pi e^2 f_0 \Sigma_x^* \Sigma_y^*}$$



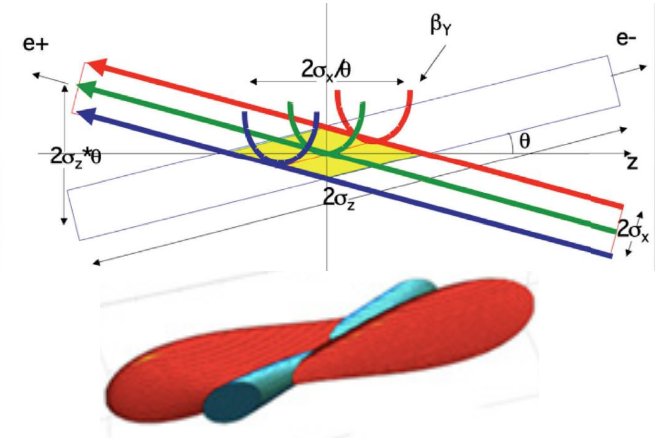




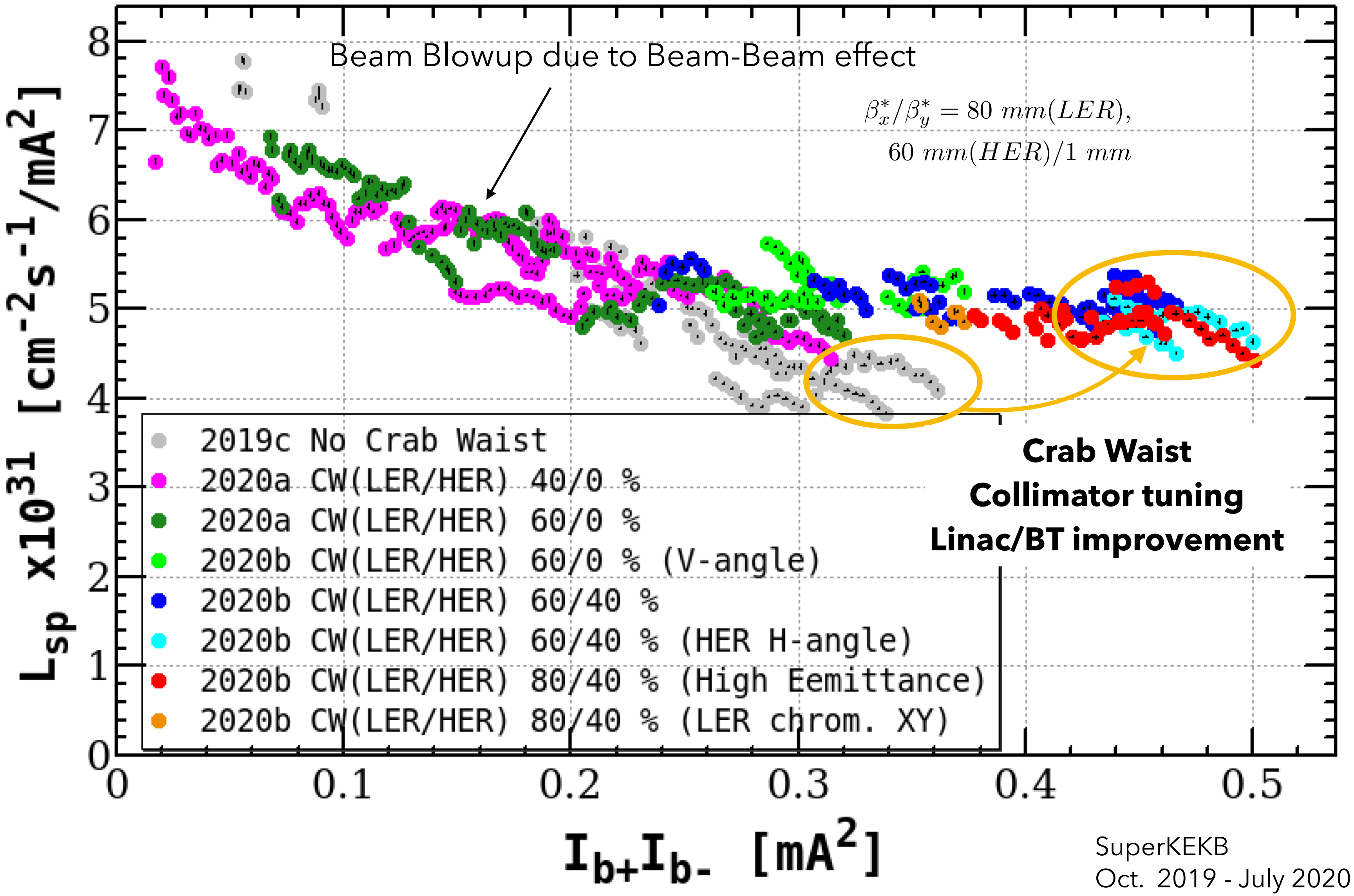
Performance Improvement with Crab Waist Optics

$$L_{sp} = \frac{L}{I_{b+}I_{b-}n_b} = \frac{1}{2\pi e^2 f_0 \Sigma_x^* \Sigma_y^*}$$

Crab waist principle



$\beta_y^* = 1\ mm$



SuperKEKB
Oct. 2019 - July 2020

Performance Improvement with Crab Waist Optics

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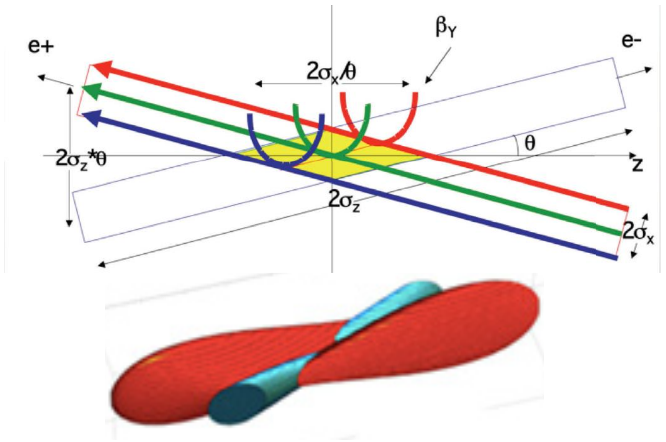
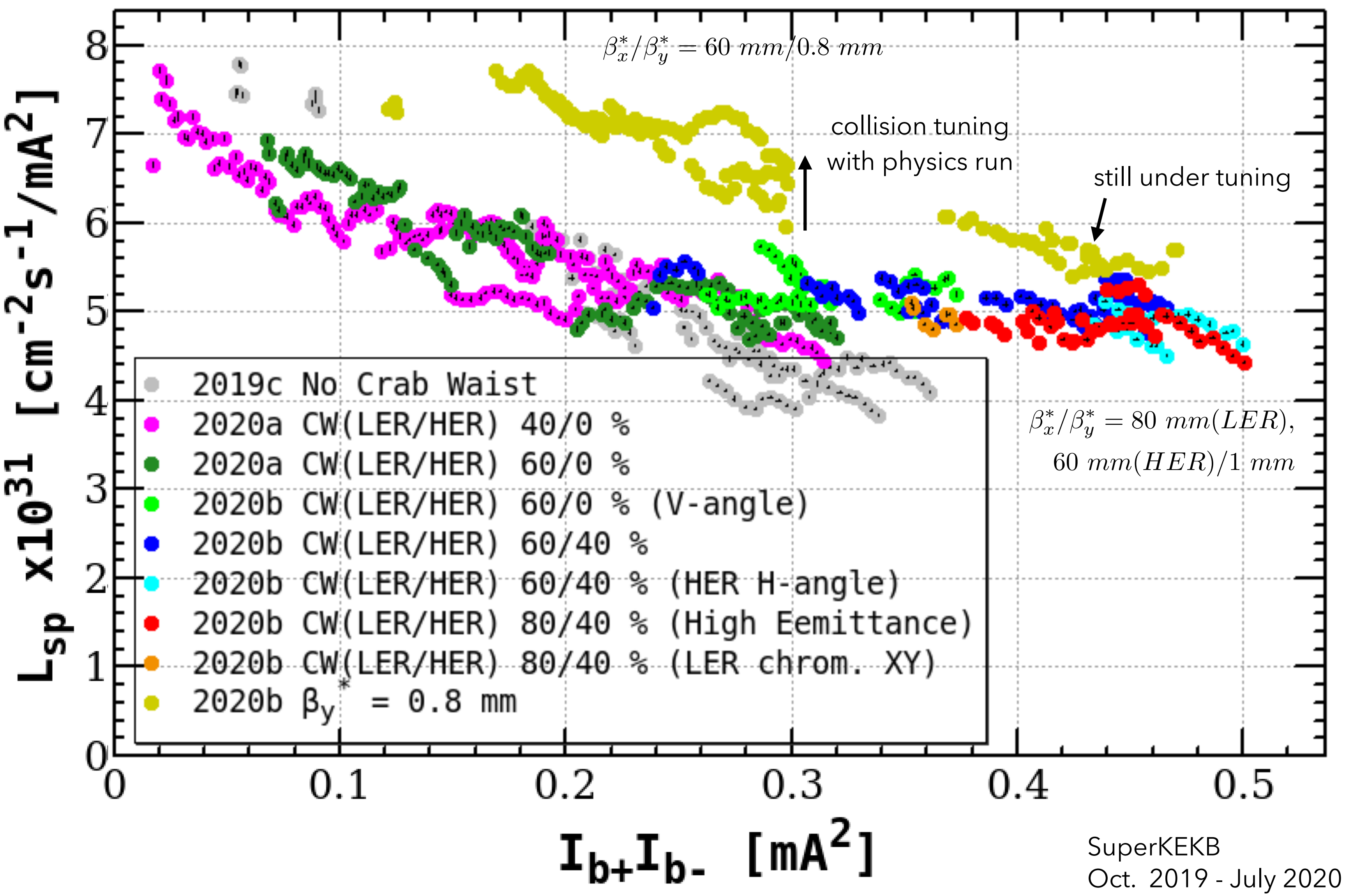


$\beta_y^* = 1\ mm$ and $0.8\ mm$



SuperKEKB
Oct. 2019 - July 2020

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Updated Luminosity Projection

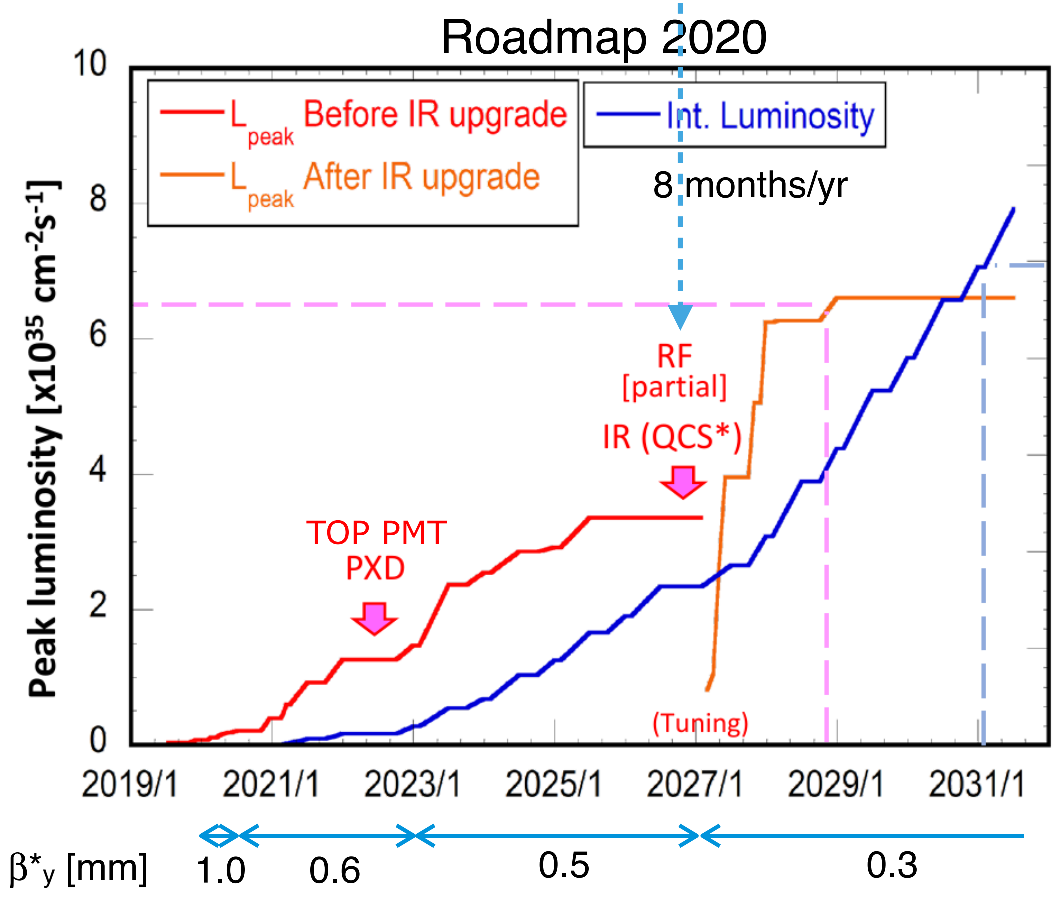
Key elements of the update (details still under study):

- Aim at an ecological operation by limiting running cost
  - priority on integrated luminosity, rather than peak luminosity
    - L_{peak}: $8x10^{35}$ $cm^{-2}s^{-1}$ → ~ $6x10^{35}$ $cm^{-2}s^{-1}$
    - integrate 50 ab^{-1} by ~2030/31
- Modify QCS
  - relocate magnets inside cryostat
    - be able to squeeze β_y* down to **0.3 mm**
    - mitigate beam-beam effect in high bunch-current regime
  - enlarge radius of QCS beam pipes
    - protect QCS against off-orbit particles → reduce risk of fatal quenches
    - reduce detector background (mainly TOP and CDC)
- Partial upgrade of RF power (2 stations)
  - store beam currents of LER 2.8A and HER 2.0A
- Keep essential investments for upgrade of Linac, Belle II and collimators

Opportunity for detector upgrade in 2026
- increase resilience against background
- improve performance

Goal: prepare EoI's by end of 2020

Polarization and/or luminosity upgrades?



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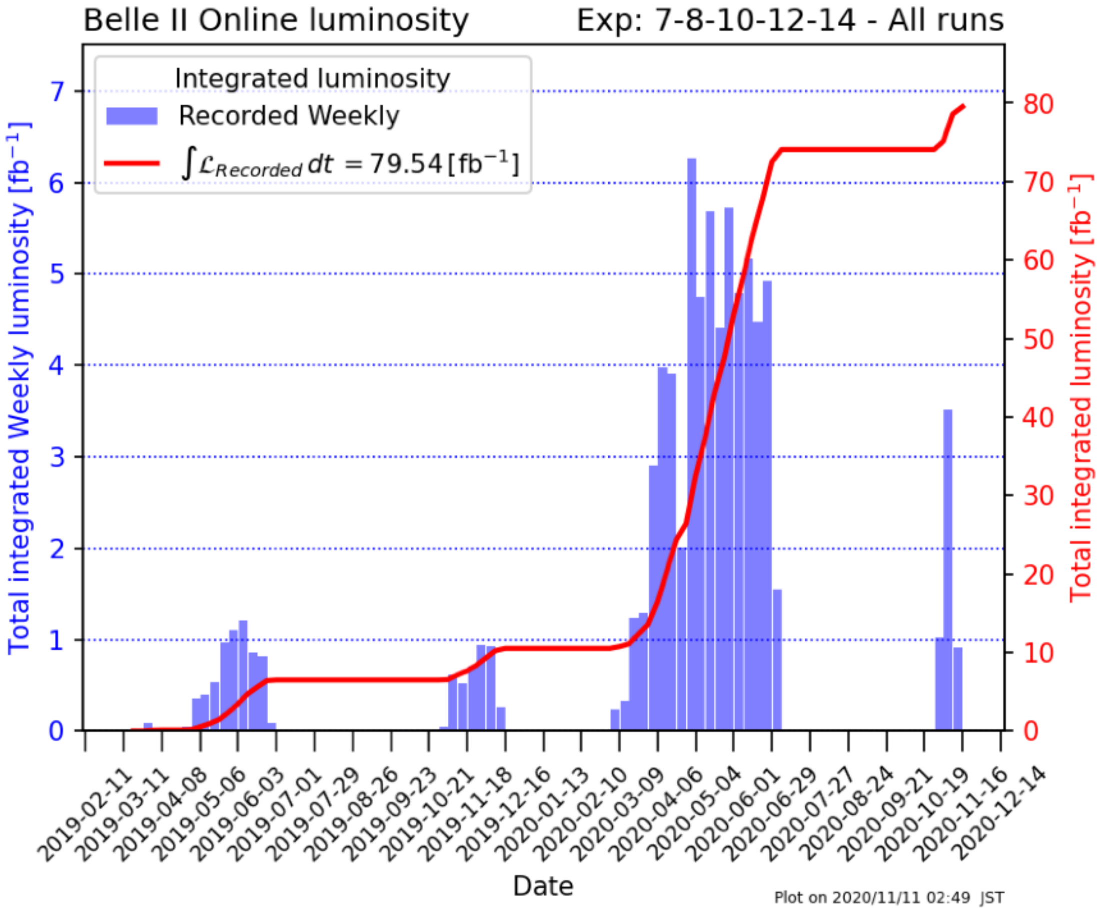
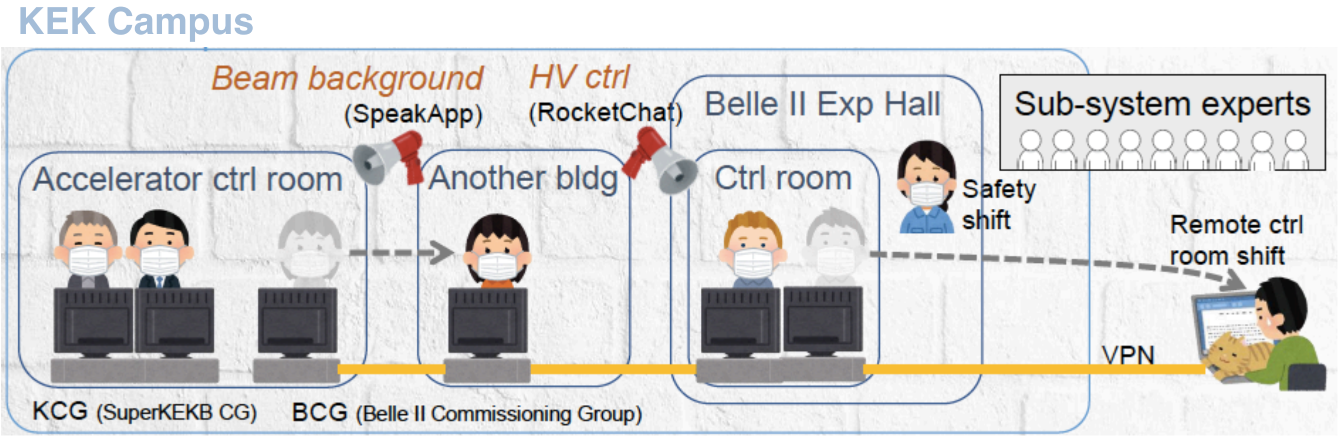
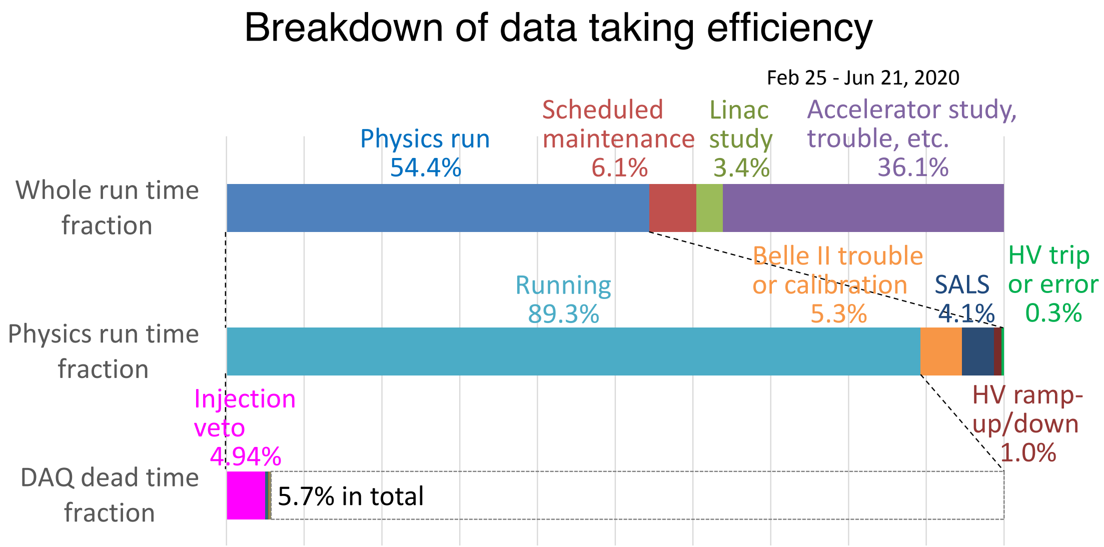
ICHEP2020 Results based on first Belle II Data

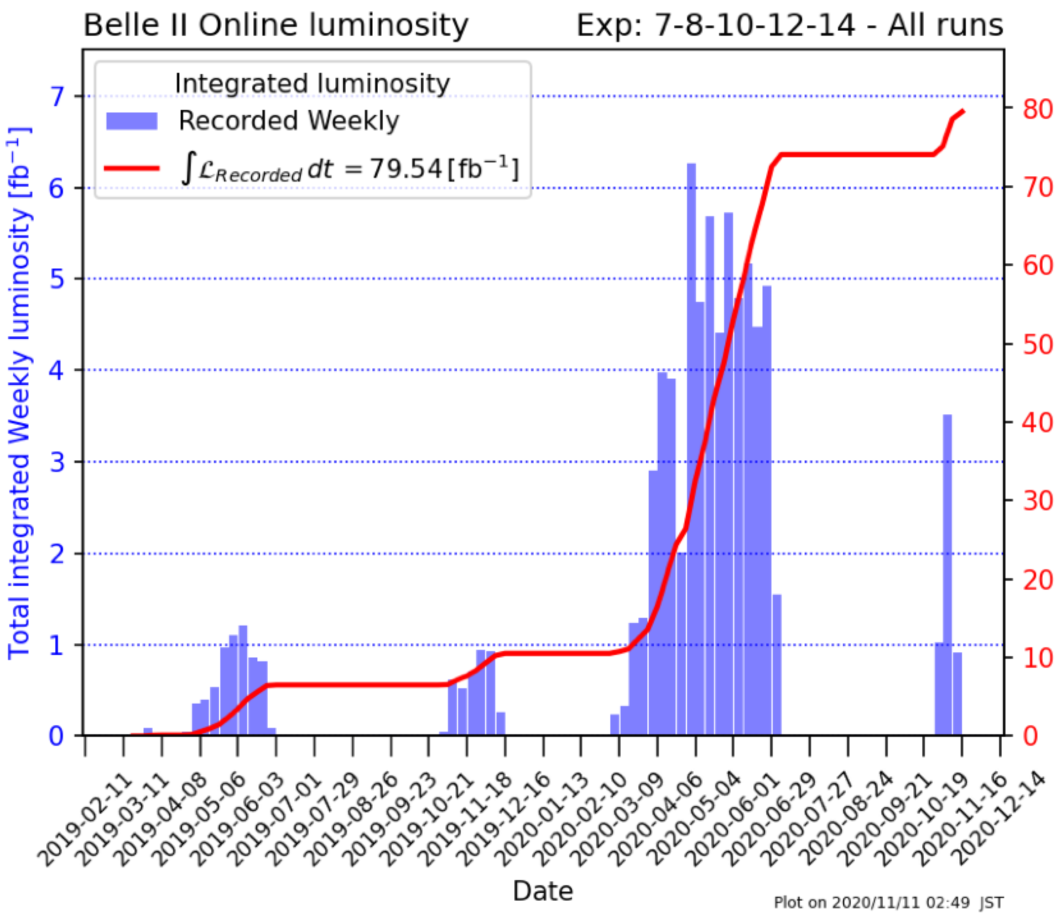
SuperKEKB/Belle II were operating during the COVID-19 pandemic with protocols in place to maximize safety and minimize the risk of infection



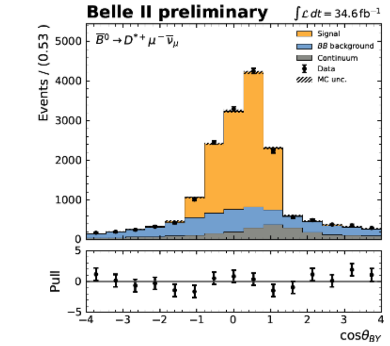




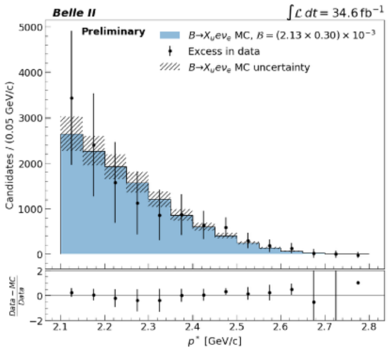
ICHEP2020 Results based on first Belle II Data



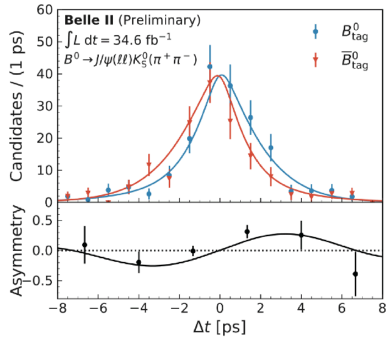
Exclusive B→D*lν



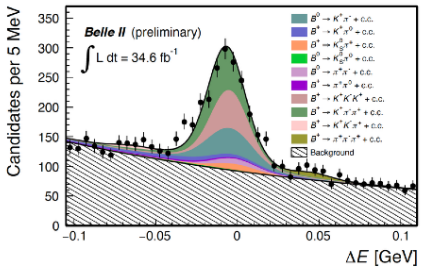
Inclusive b→u



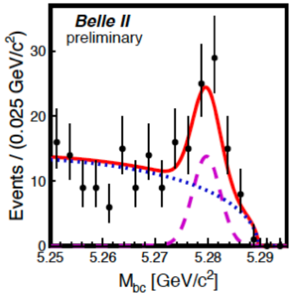
TDCPV (B→J/ψK$_S^0$)



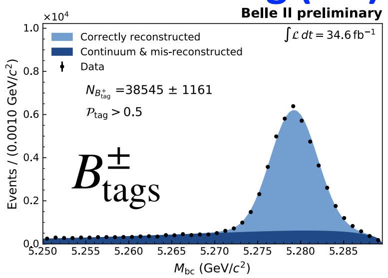
Charmless B decays



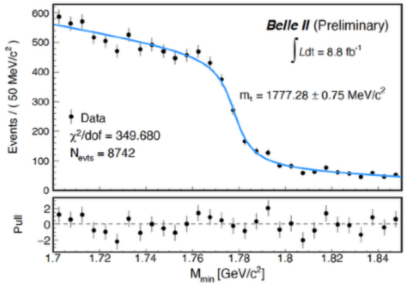
B → ΦK$^{(*)}$



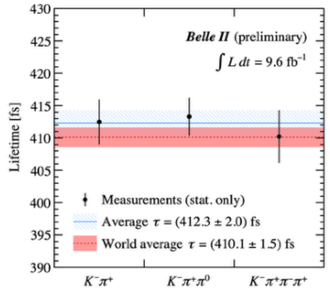
Hadronic tag (FEI)



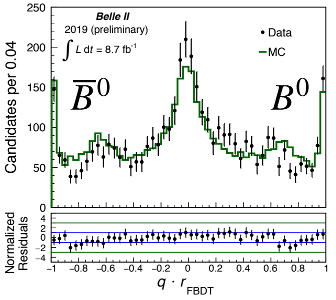
τ mass measurement



D^0 lifetime



Flavortag $B^0/\overline{B}^0$



First Belle II Physics Results

2 Dark Sector PRL publications on Phase2 data:

- Search for an Invisibly Decaying Z′ Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States, PRL 124, 141801 (2020);
- Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II, PRL 125, 161806 (2020);

12 conference papers posted on arXiv:

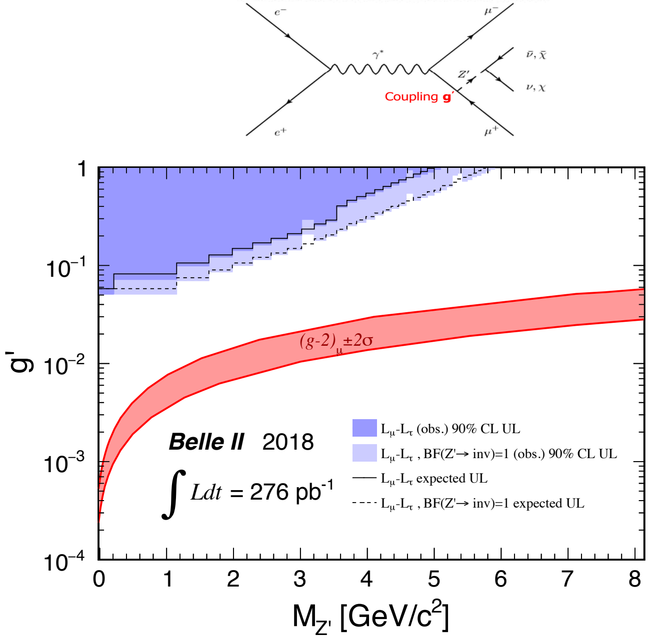
Spring

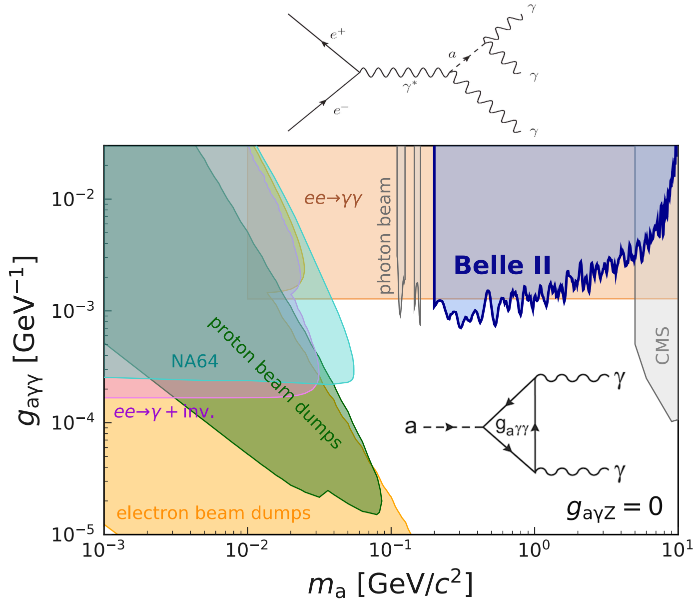
- Charmless B decay reconstruction, arXiv:2005.13559 [hep-ex];
- Measurement of the branching fraction $B(\text{anti-}B^0 \to D^{*+} l^- \nu_l)$, arXiv:2004.09066 [hep-ex];
- Measurement of the B^0 lifetime using fully reconstructed hadronic decays, arXiv:2005.07507 [hep-ex];

Summer

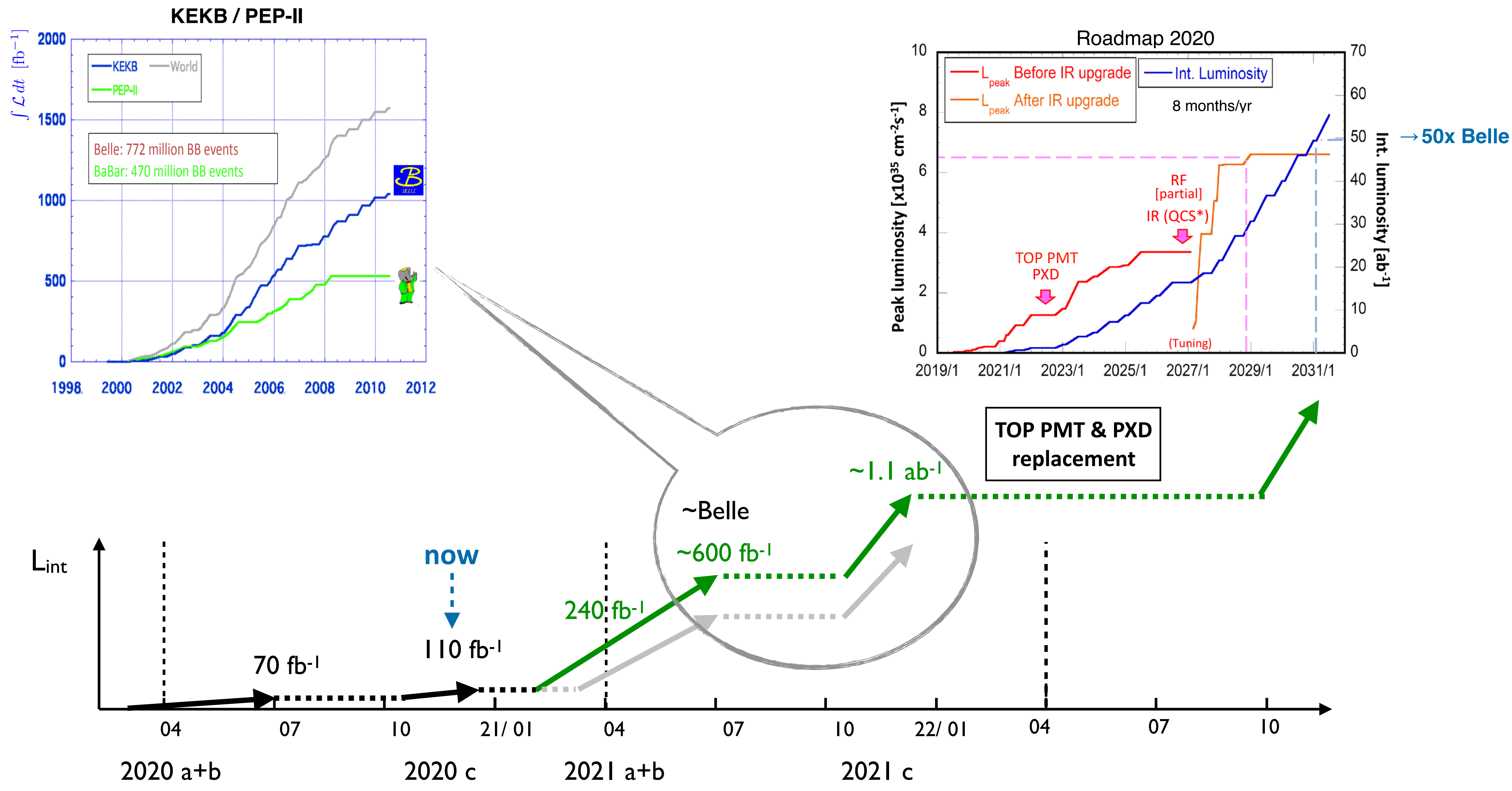
- Measurement of the branching ratios of $B^0 \to D^{(*)-} l^+ \nu$ (untagged analysis), arXiv:2008.07198 [hep-ex];
- Calibration of the Belle II hadronic Full Event Interpretation (FEI), arXiv:2008.06096 [hep-ex];
- Measurement of the hadronic mass moments of $B \to X_c l^+ \nu$ decays, arXiv:2009.04493 [hep-ex];
- Measurement of the branching ratios of $B^0 \to D^{*-} l^+ \nu$ (using the hadronic FEI), arXiv:2008.10299 [hep-ex];
- Rediscovery of $B^0 \to \pi^- l^+ \nu$ (using the hadronic FEI), arXiv:2008.08819 [hep-ex];
- Calibration of the Belle II B FlavorTagger, arXiv:2008.02707 [hep-ex];
- Rediscovery of $B \to \phi K^{(*)}$ decays, and measurement of the longitudinal polarization fraction of $B \to \phi K^*$, arXiv:2008.03873 [hep-ex];
- Branching ratios and direct CP asymmetries of B → Charmless decays, arXiv:2009.09452 [hep-ex];
- Measurement of the τ lepton mass, arXiv:2008.04665 [hep-ex];

… plus many other public physics results, see our public confluence page.



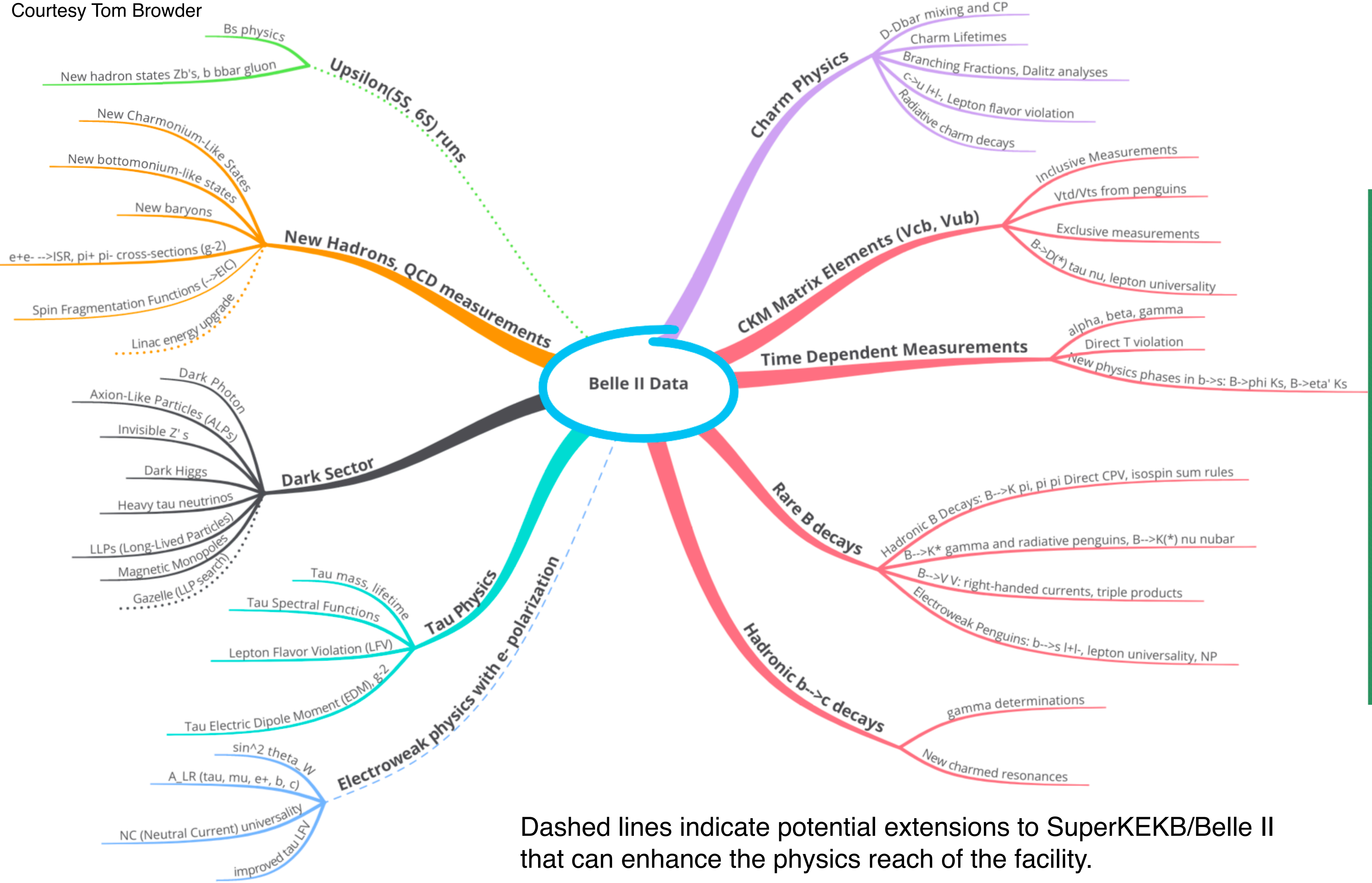


Mid-term Luminosity Projection



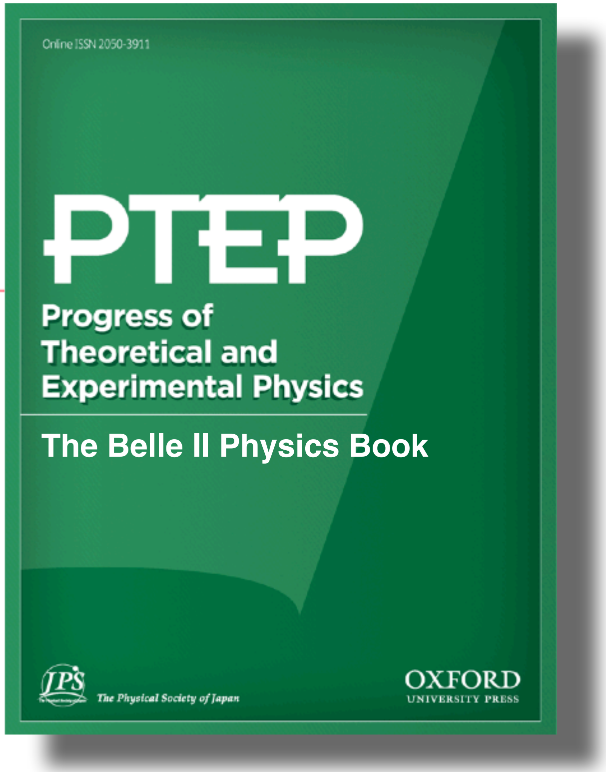
Rich Belle II Physics Program

Courtesy Tom Browder



Dashed lines indicate potential extensions to SuperKEKB/Belle II that can enhance the physics reach of the facility.

Recently published



Prog. Theor. Exp. Phys. 2019, 123C01 (654 pages) DOI: 10.1093/ptep/ptz106

Summary

- SuperKEKB has set a new world record in peak luminosity

- Entering this new regime of a „Super B factory" revealed several operational challenges
  - The recent strategy update addresses these issues and outlines a viable pathway to the original luminosity goals of 50 ab^{-1}
  - Despite the COVID-19 restrictions Belle II managed to take data with good efficiency

- The detector is working well and is already producing very promising physics results
  - World-leading results already in the dark sector (Searches for $Z' \to$ invisible and ALPs published)
  - Rediscovering many of the signals seen at the B factories: semi-leptonic decays, improving FEI, establishing "missing energy" and time-dependent capabilities, and beginning to see hints of time-dependent CP violation. Need more data to make further progress

- Within the next decade expect a new, exciting era of discoveries, and a friendly competition and complementarity of Belle II and LHCb