SuperKEKB/Belle II Experiment

Keisuke Yoshihara

17th October 2022, Zurich HEP seminar

Self introduction

- **LHC-ATLAS**

  2011 - 2014 Higgs to WW search and measurement

  2015 - 2020 SUSY searches (Top squark, Higgsino, …)

  2015 - 2019 TRT detector operation, ITK asic development

- **SuperKEKB/Belle II**

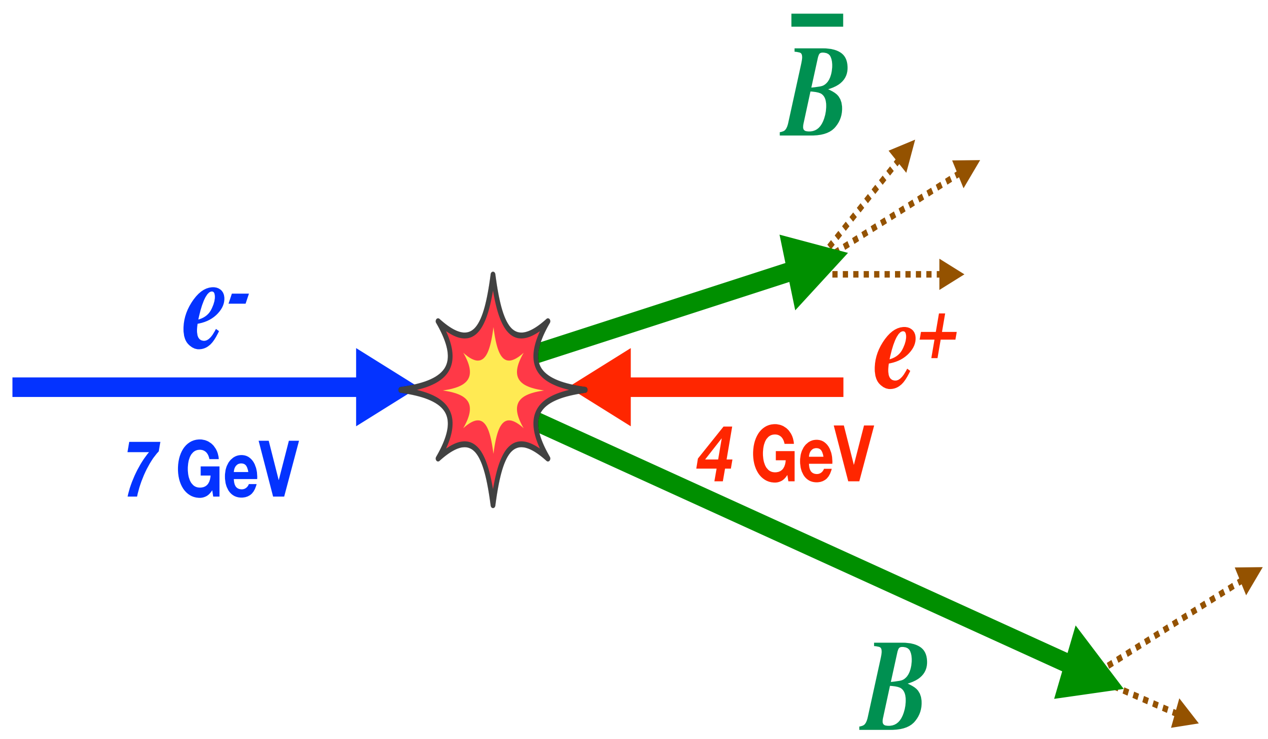
  2019 - 2021 KLM operation

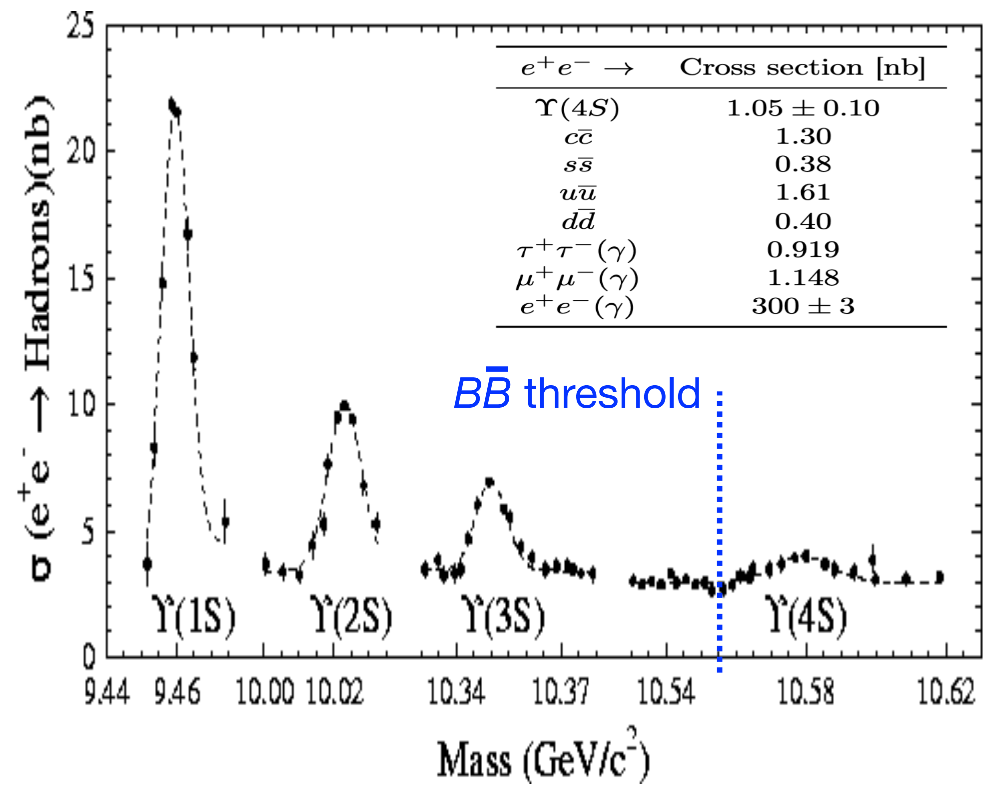
  2020 - Present

  Machine/detector operation (as deputy run coordinator)

  - iTOP operation
  - accelerator (collimator) operation
  - beam background measurement
  - beam diagnosis system development
  - beam abort system upgrade

Introduction — B-factories

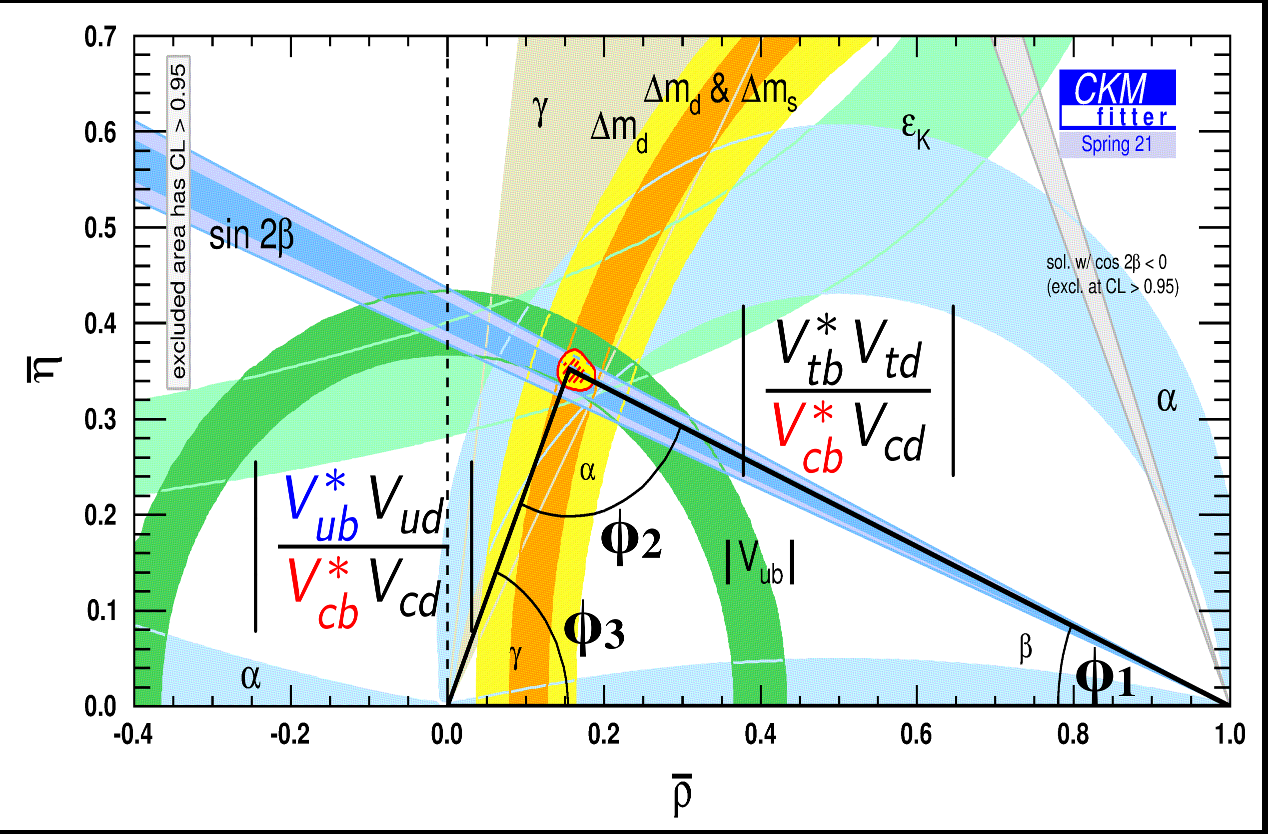




In B-Factories, e^+ and e^- collide at 10.58 GeV to make *Y(4S)* resonance decaying into B^+B^- and $B^0\bar{B}^0$ in 96% of the time. Belle (~1 ab^{-1}) and BaBar (~0.5 ab^{-1}) played a crucial role in establishing large ***CP violation*** in the B-meson system in the SM and constrained on the ***CKM matrix.***

Precision CKM measurement

Current status



If **50 ab^{-1}** of data is collected, CKM parameters can be precisely measured.

A large improvement is expected in not only ϕ_1 but also in **$|V_{ub}|$, ϕ_2 and ϕ_3** .

Precision of $|V_{cb}|$ and $|V_{td}|$ can be improved by phenomenology or better calculation of lattice QCD.

Sensitivity projection

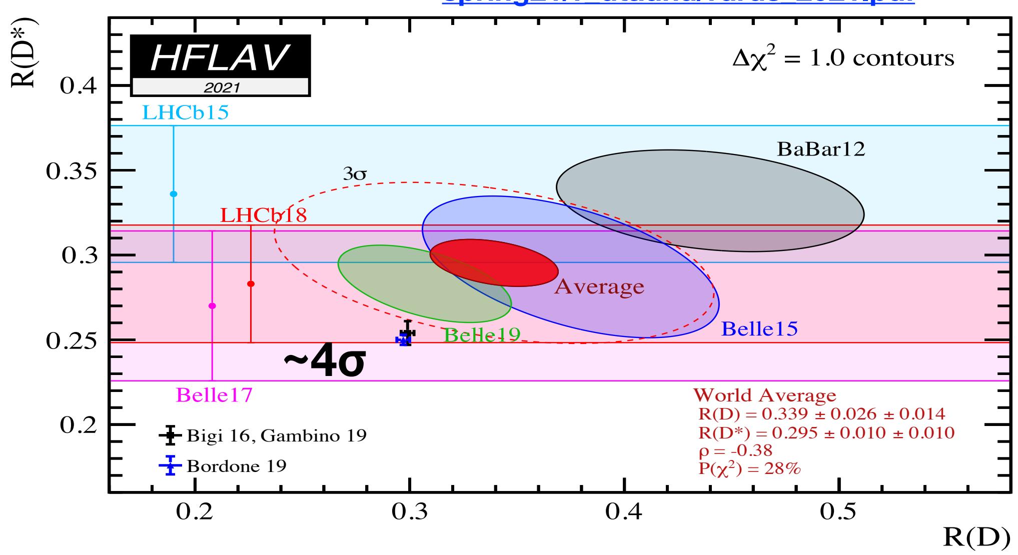
arXiv:1808.10567

Observable	Belle	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
$\|V_{cb}\|$ incl.	1.8%	1.2%	1.2%
$\|V_{cb}\|$ excl.	$3.0_{ex} \pm 1.4_{th}$%	1.8%	1.4%
$\|V_{ub}\|$ incl.	$6.0_{ex} \pm 2.5_{th}$%	3.4%	3.0%
$\|V_{ub}\|$ excl.	$2.5_{ex} \pm 3.0_{th}$%	2.4%	1.2%
$\sin 2\phi_1$ (B->J/ψKs)	**0.667 ± 0.023 ± 0.012**	**0.012**	**0.005**
ϕ_2 [deg]	85 ± 4 (Belle +BaBar)	2	0.6
ϕ_3 [deg] (B->$D^{(*)}K^{(*)}$)	63 ± 13	4.7	1.5

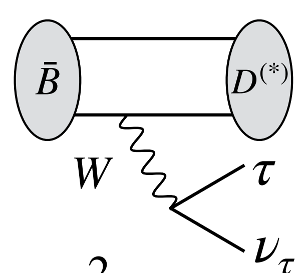
Anomaly

$b \to c\tau\nu$

https://hflav-eos.web.cern.ch/hflav-eos/semi/spring21/r_dtaunu/rdrds_2021.pdf



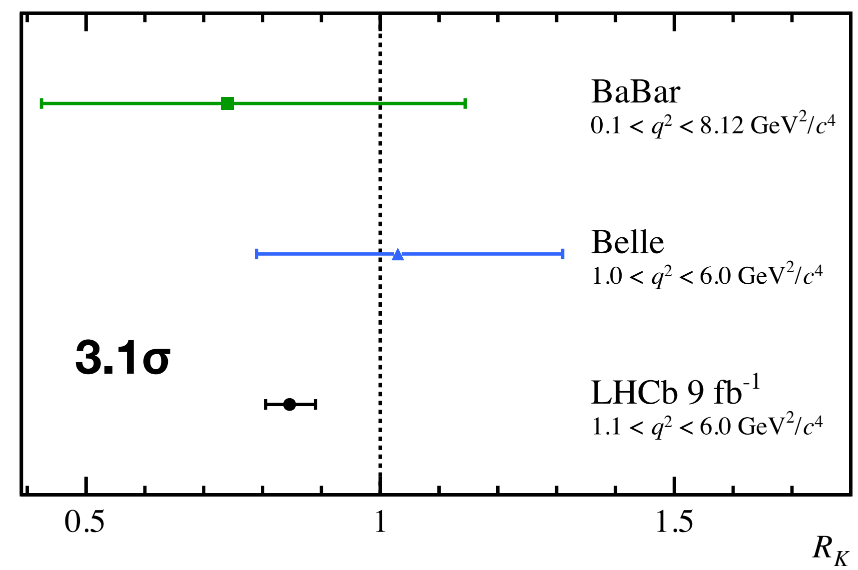
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$



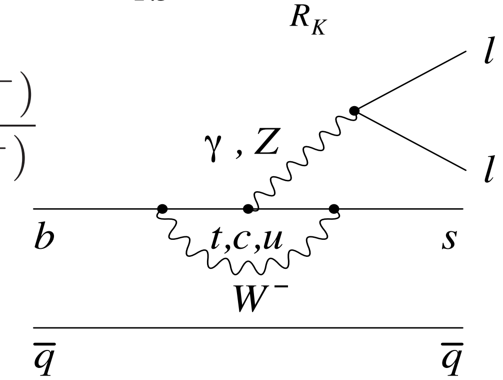
tree BF~O(10^{-2})

$b \to s\ell\ell$

arXiv:2103.11769



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



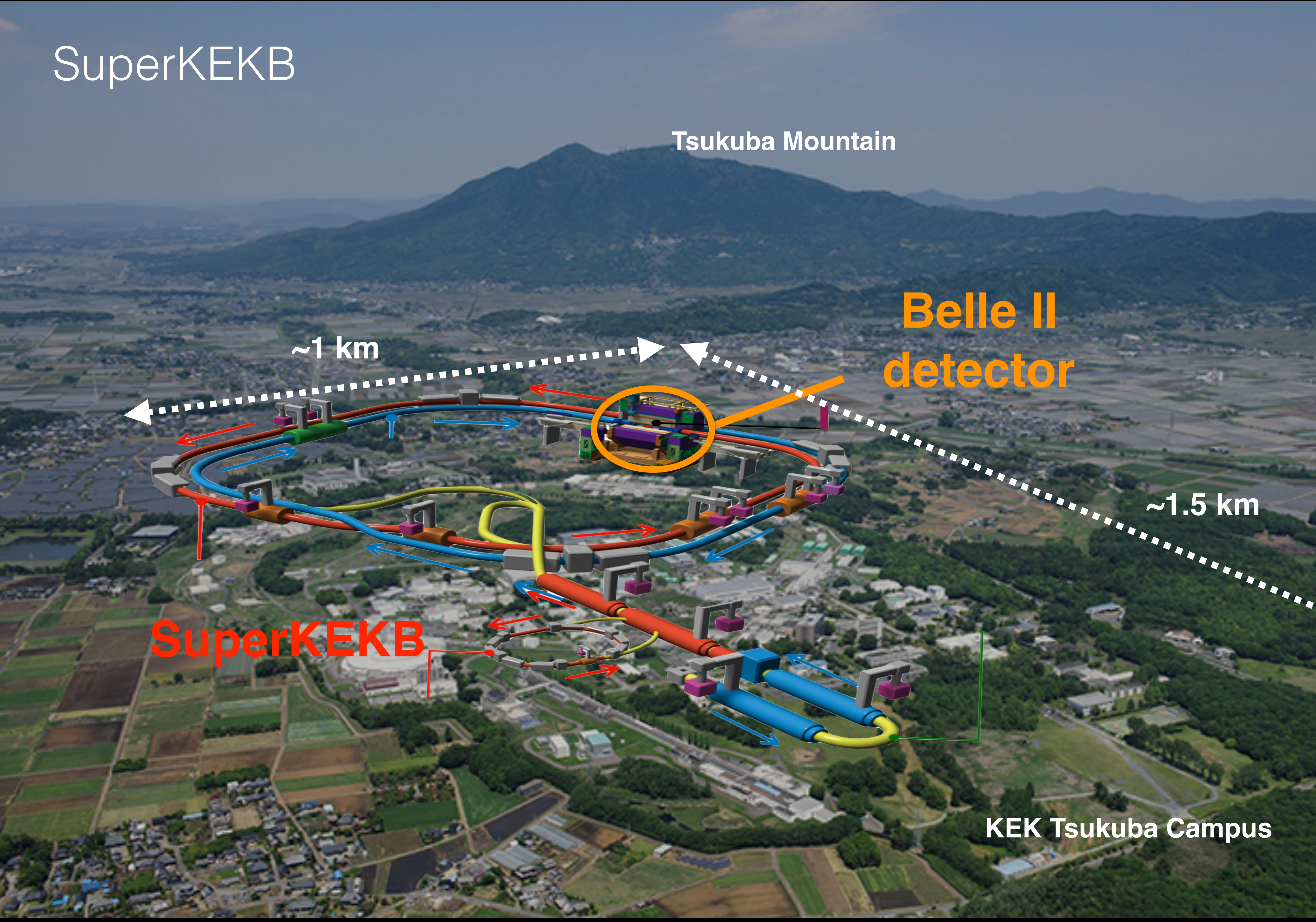
loop, BF~O(10^{-6})

Some deviations from the SM in **lepton universality measurement (LFU)**.

It could be an indication of new physics in *O* (1-10) TeV (e.g. 3rd gen. Z' or W', Leptoquark).

These anomalies must be well verified. Belle II can measure them independently.

SuperKEKB


Tsukuba Mountain
Belle II detector
~1 km
~1.5 km
SuperKEKB
KEK Tsukuba Campus

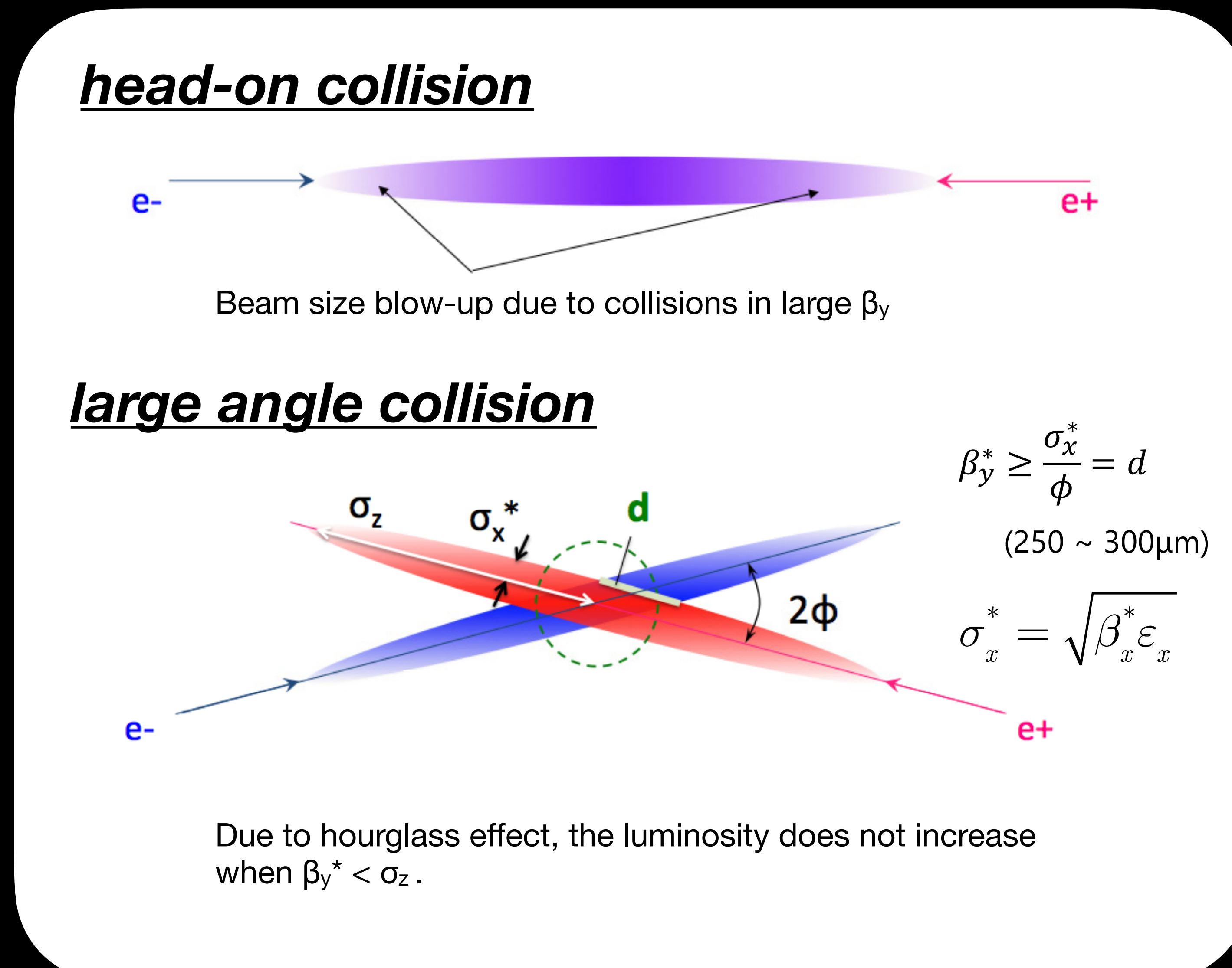
Nano beam scheme

Squeezing vertical β function (β_y^*) at Interaction Point (IP)

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

- Small vertical beam size (σ_y~60 nm): β_y^* ~0.3mm (x 1/20)
- Larger beam current (x 2)

- In the nano-beam scheme with large crossing angle, effective bunch length (*d*) can be much shorter (β_y^* ~σ_z)
- Small β_x^* and small emittance (ε_x) are also the key → positron DR
- Positron beam energy from 3.5 to 4.0 GeV to increase beam lifetime (still ~O(10) min maximum)

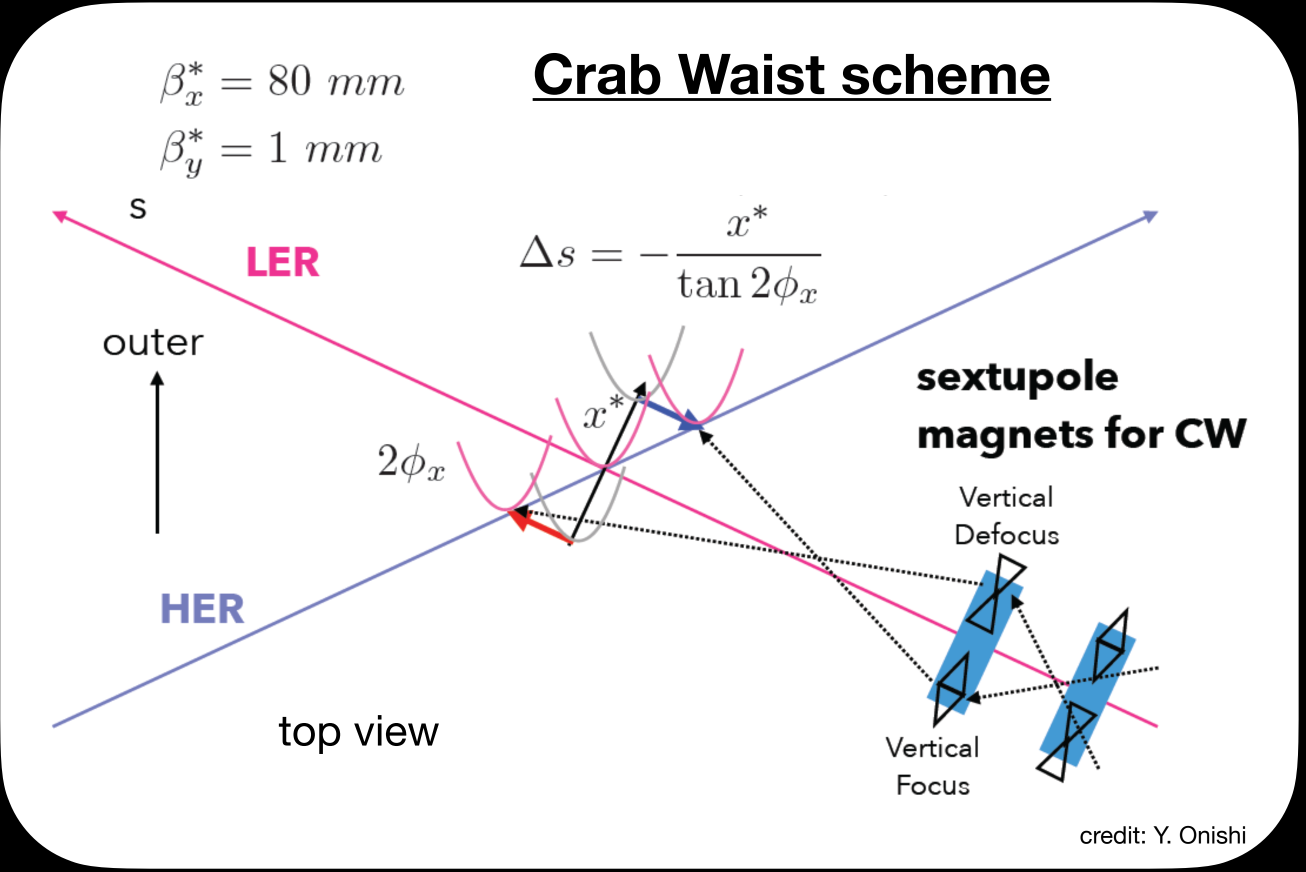


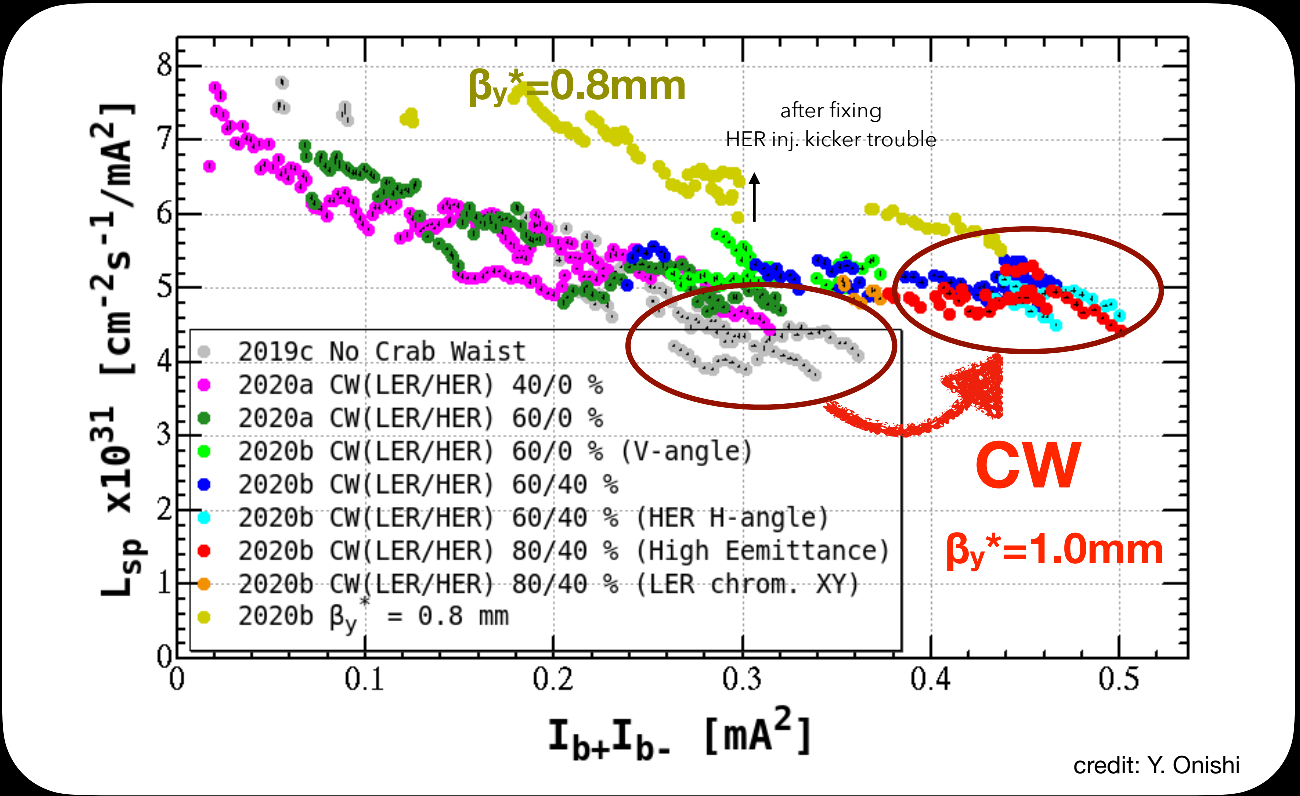
Specific luminosity

- Beam waist (minimum of vertical beam size) is aligned with the other beam axis by rotatable sextupole magnets
  → **Crab waist (CW)**

- CW mitigates ***beam size blow-up due to beam-beam effect***
  → background mitigation and higher (specific) luminosity at IP

- Luminosity performance is evaluated to be independent of total beam current (specific luminosity, ***L_{SP}***).
  → **Significant improvement with CW and/or beam size squeezing**





Machine parameters (at design)

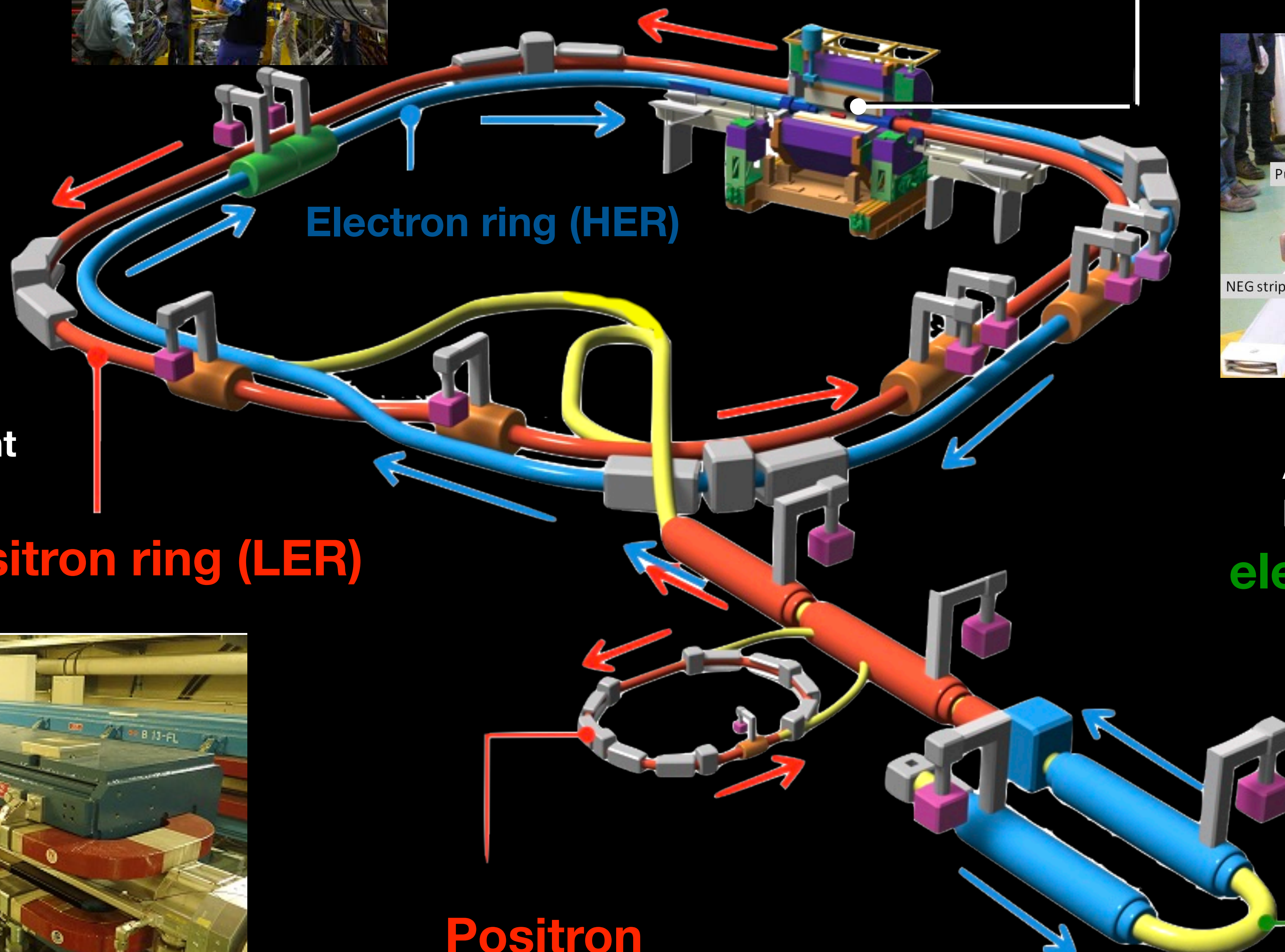
parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	**3.5**	**8**	**4**	**7.007**	GeV
Half crossing angle	ϕ	11		41.5		mrad
# of Bunches	N	1584		2500		
Horizontal emittance	ε_x	18	24	3.2	5.3	nm
Emittance ratio	κ	0.88	0.66	0.27	0.24	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		3.2/0.27	2.5/0.30	mm
Beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam param.	ξ_y	0.129	0.090	0.0886	0.081	
Bunch Length	sz	6.0	6.0	6.0	5.0	mm
Horizontal Beam Size	sx*	150	150	10	11	um
Vertical Beam Size	sy*	0.94		0.048	0.062	um
Luminosity	**L**	**2.1×10^{34}**		**8×10^{35}**		**$cm^{-2}s^{-1}$**

Note: beam energy changed because positron beam (Touschek) lifetime is too short while accepting smaller boost (**$\beta\gamma$ = 0.42 → 0.28**) of decayed particles.

Upgrading to “**Super**”KEKB

QCS magnets

RF reinforcement



Belle II detector

Interaction Point

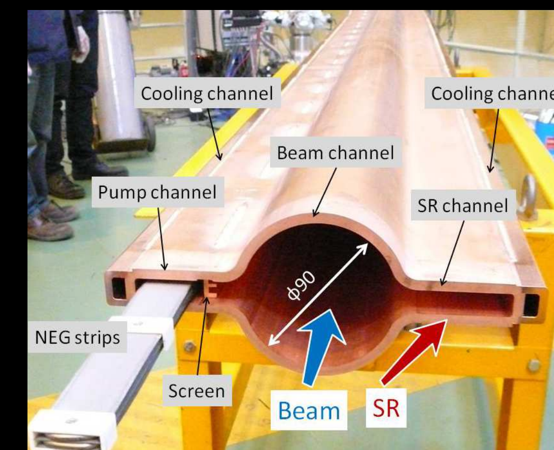
Electron ring (HER)

Positron ring (LER)

Positron dumping ring

electron/positron injector

Low-emittance RF gun

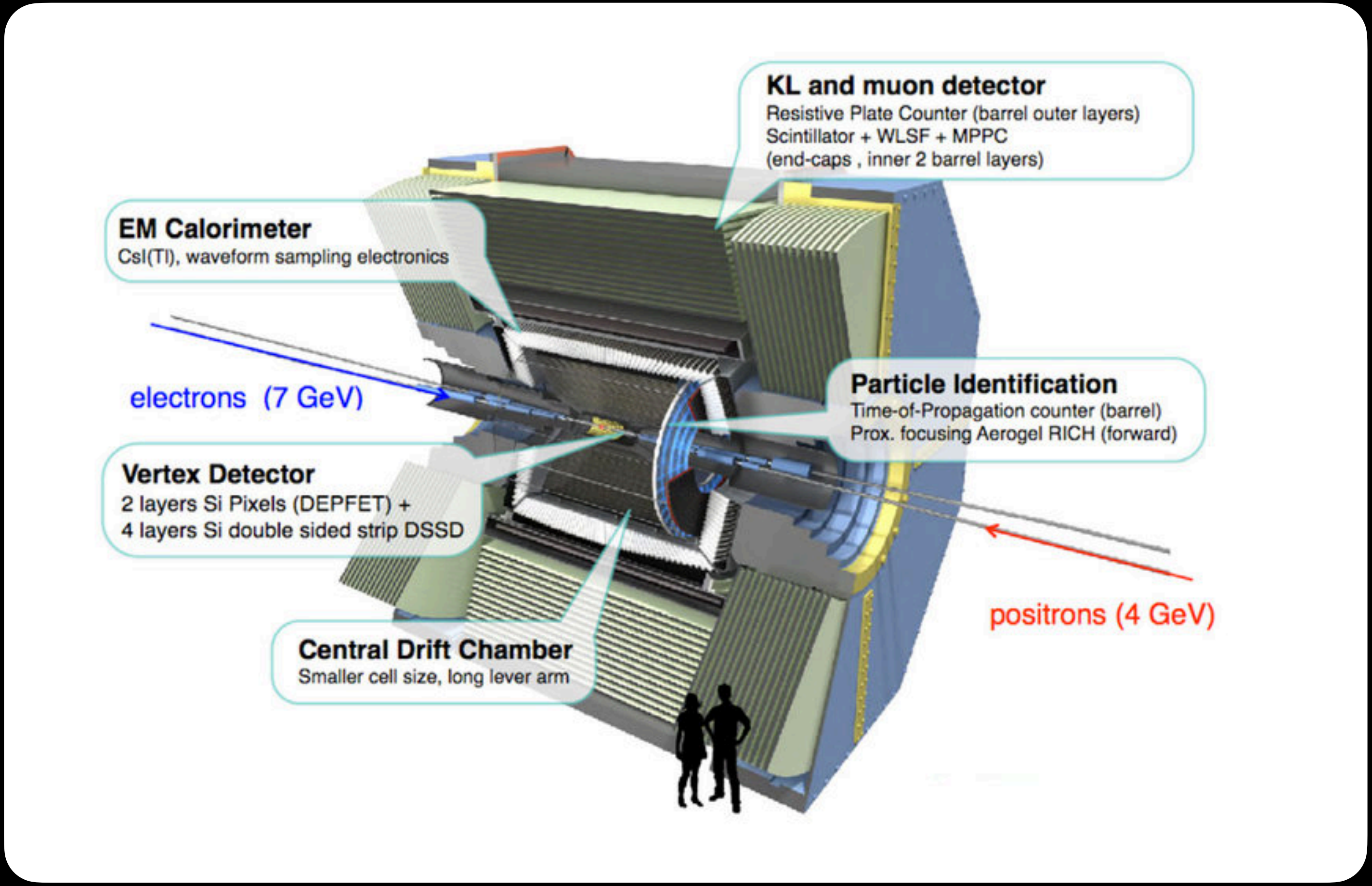


Ante-chamber beam pipe

dipole magnets newly installed in LER (~4 m)

Belle II detector

Detector looking similar to Belle, but it is practically a brand new!



Belle II TDR, arXiv:1011.0352

Improved vertex reconstruction

- Smaller beam pipe (ϕ7.5 → 5)
- A 2-layer silicon pixel detector (PXD)
- 4-layer silicon strip detector (SVD) extended to a larger radius
- Larger volume and smaller drift cell in tracking chamber (CDC)

Improved PID and energy measurement

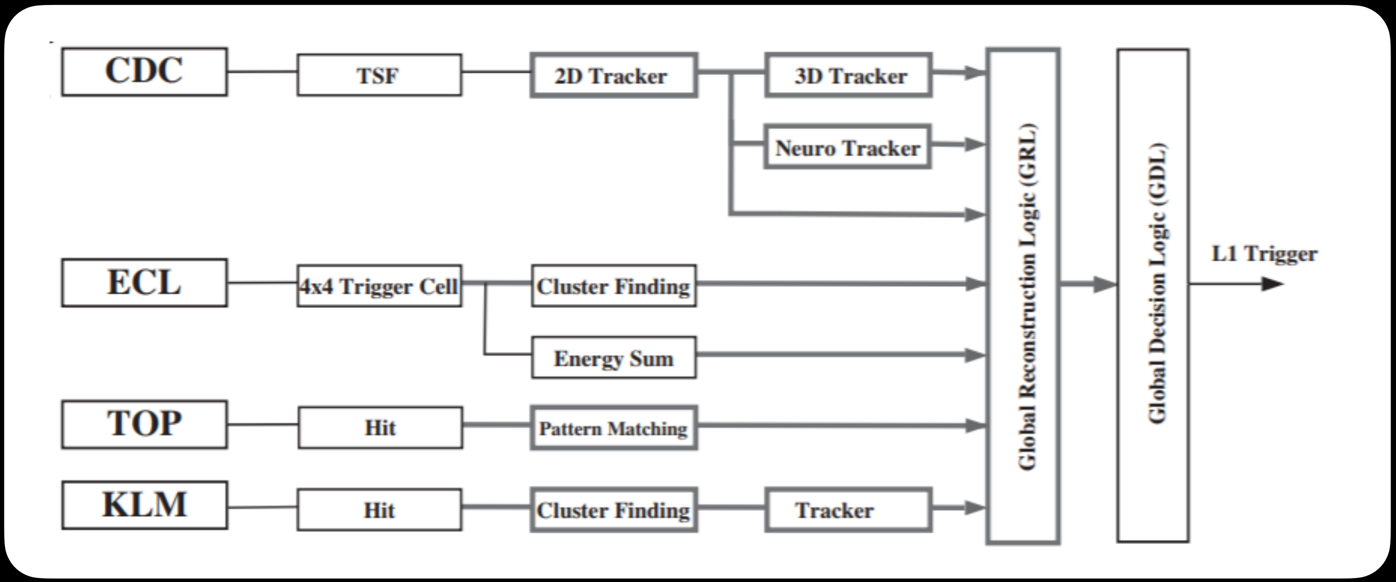
- Improved K/π separation (TOP and ARICH)
- Wave-form sampling robust against pile-up (ECL)
- Endcap RPC was replaced by scintillator in Muon/K_L detector (KLM)

Other improvements

- New triggers (e.g. dark sector searches)
- Analysis tools with decent machine learning techniques
- Grid computing

Trigger system

- Trigger system has the capability to handle ***L1~30 kHz***, while physics event rate is expected to be ***~15kHz*** @ L= 8 x 10^{35} cm^{-2} s^{-1}.

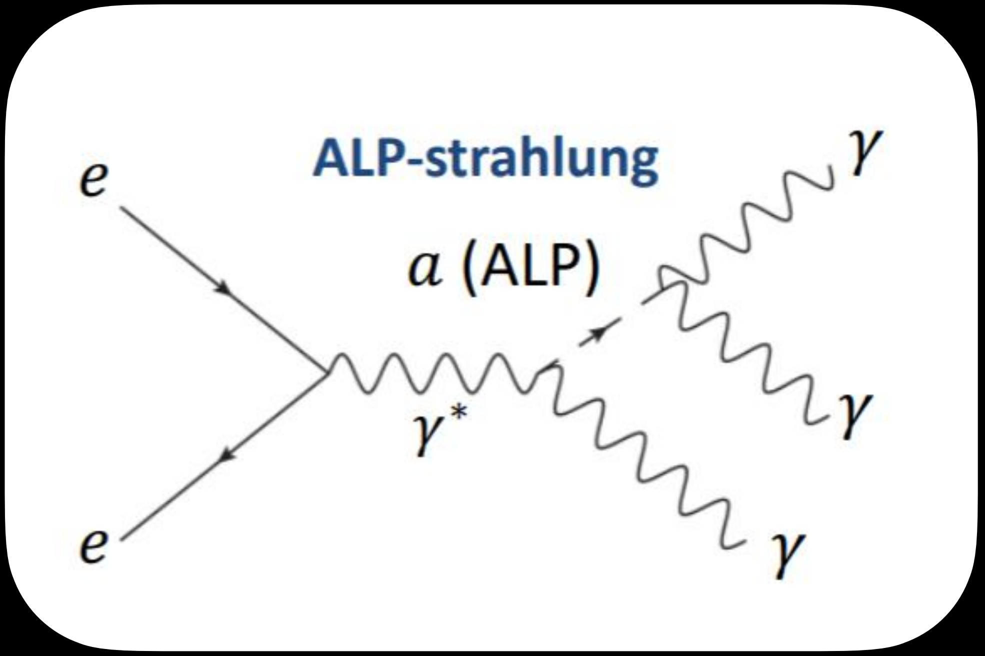


process	σ [nb]	Rate [Hz] @ L= 8 x 10^{35} cm^{-2} s^{-1}
Υ(4S)	1.2	960
Continuum	2.8	2200
μμ	0.8	640
ττ	0.8	640
Bhabha (*)	44.0	350
γ-γ (*)	2.4	19
Two photon (**)	13.0	10,000
Total	67	~15,000

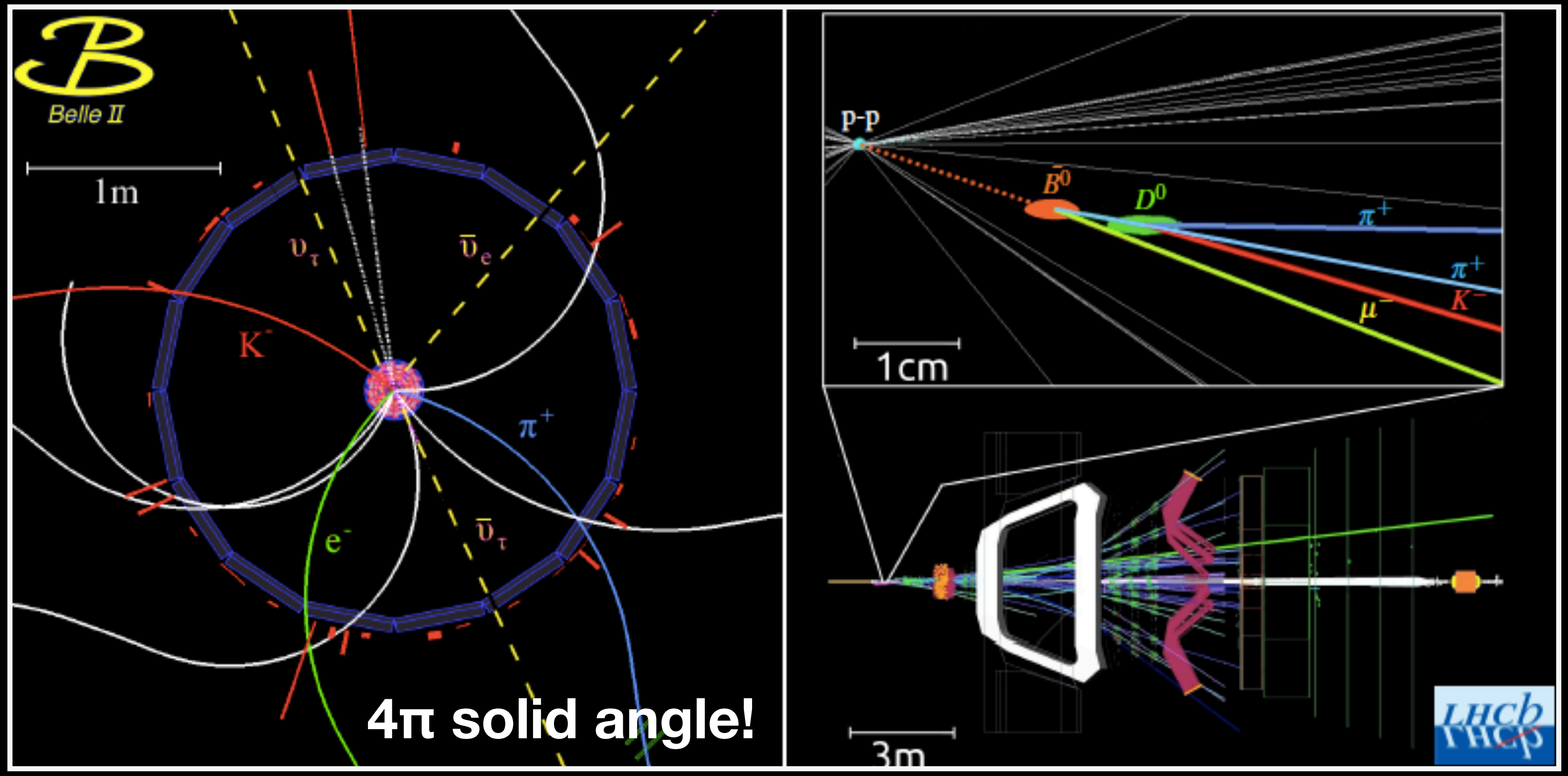
(*) Rate of Bhabha and γ-γ are pre-scaled by a factor of 100
(**) Rate are estimated by the luminosity component in Belle L1 rate

- Υ(4S) events have to be > 99.9% efficient.
  - #CDC track >=3
  - #CDC track >=2 & Δϕ > 90 deg.
  - ECL energy sum > 1GeV
  - #ECL cluster >= 4

- **Dedicated triggers for dark sector searches**
  - #CDC-KLM matching >=1 (Z' search)
  - ECL cluster back-to-back, E < 2GeV (ALP, two-photon fusion)
  - … and more



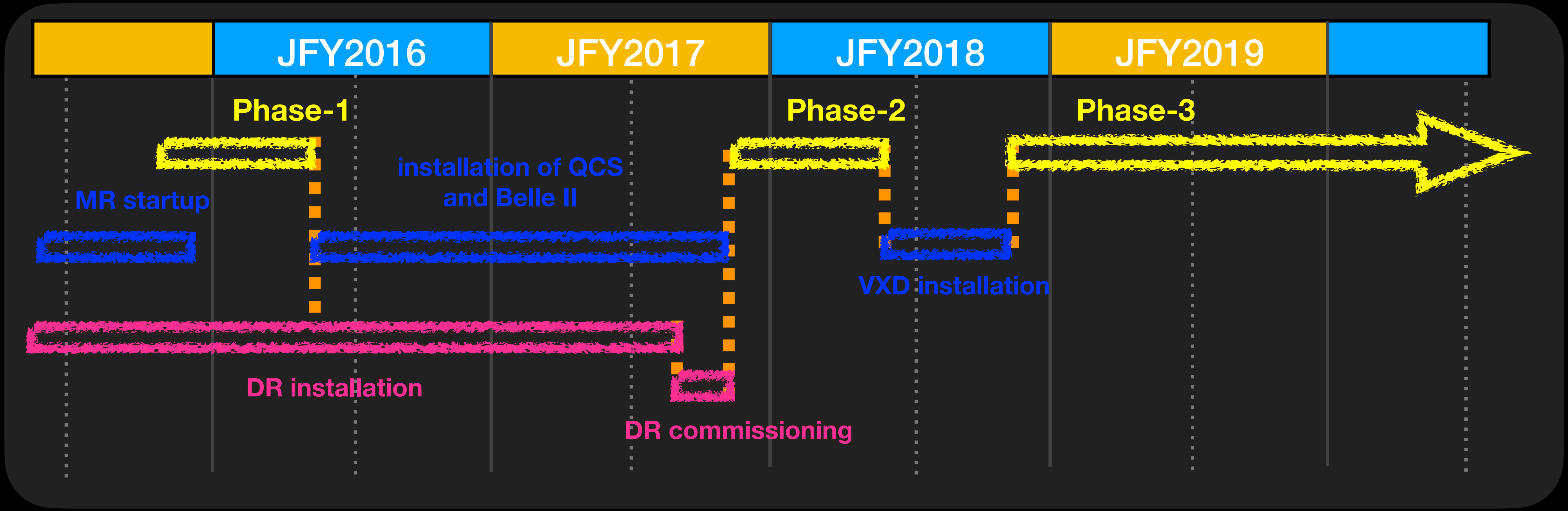
LHCb vs Belle II



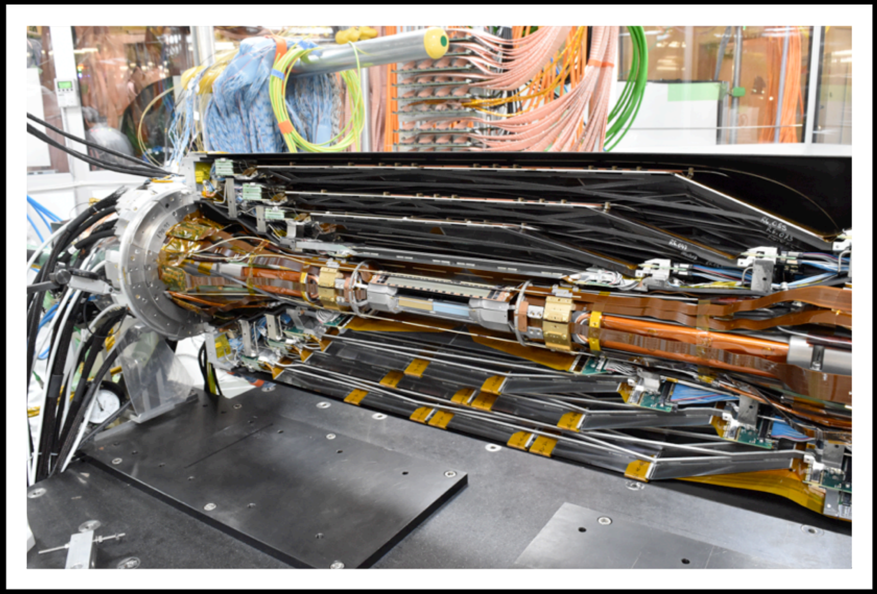
Credit: G. Ciezarak et al, Nature 546, 227 (2017)

- LHCb:
  - Large B-meson cross section (roughly 1 ab^{-1} @Belle II ~ 1 fb^{-1}@LHCb)
  - Good sensitivity to all charged final states.
- Belle II: (simpler environment with no additional particles)
  - High reconstruction efficiency of B meson (tagging)
  - ***Inclusive processes*** can be measured
  - ***Neutral particles*** (photons, K_s, and neutrinos) can be measured
  - High statistics for electron channels as well as muons' → ***lepton universality test***

Machine and detector commissioning

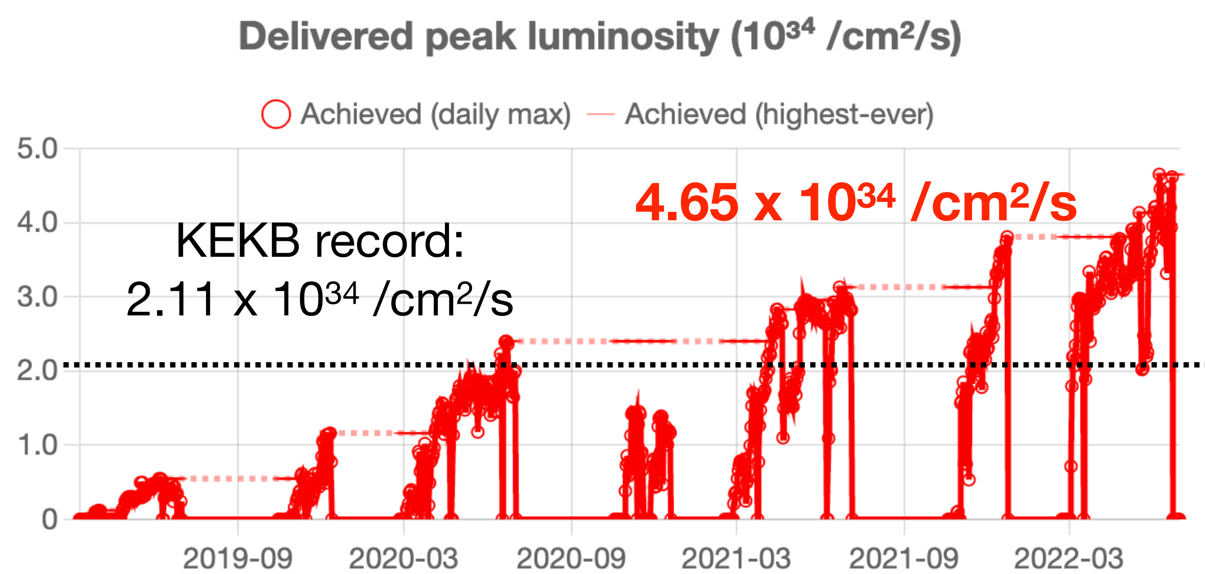


- **Phase-1: Startup of the machine:**
  - commissioning without collision
  - low emittance beam tuning
  - vacuum scrubbing
- **Phase-2: Commissioning w/o VXD**
  - β^* squeezing at IP
  - DR commissioning
  - collision tuning
- **Phase-3: Commissioning w/ full Belle II detector**
  - collision tuning
  - collimator tuning and background study
  - continuous injection

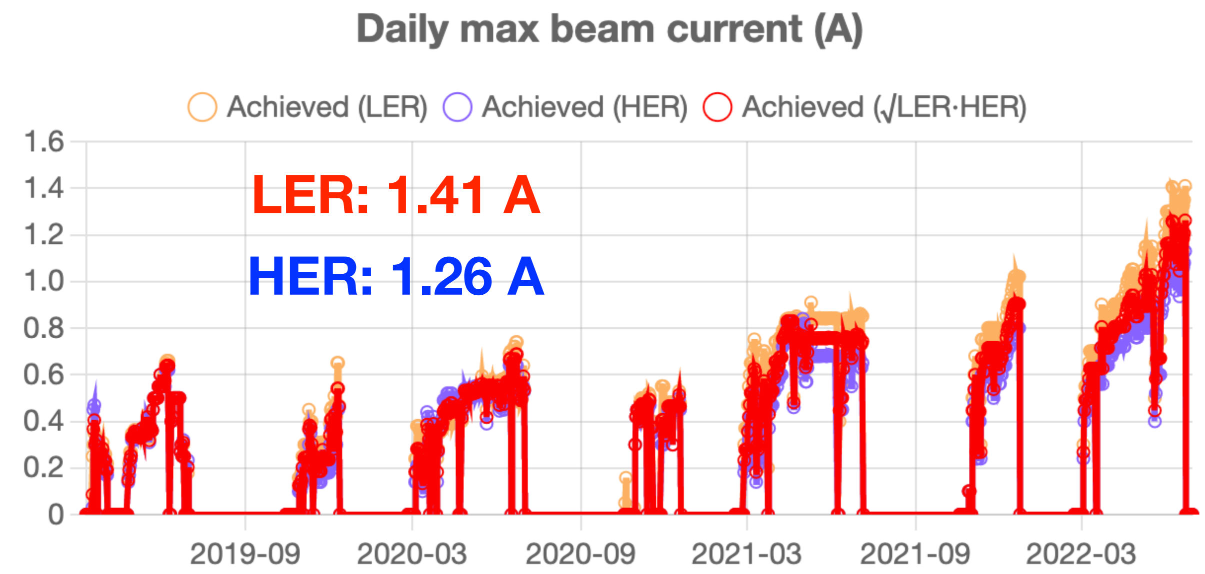


VXD detector

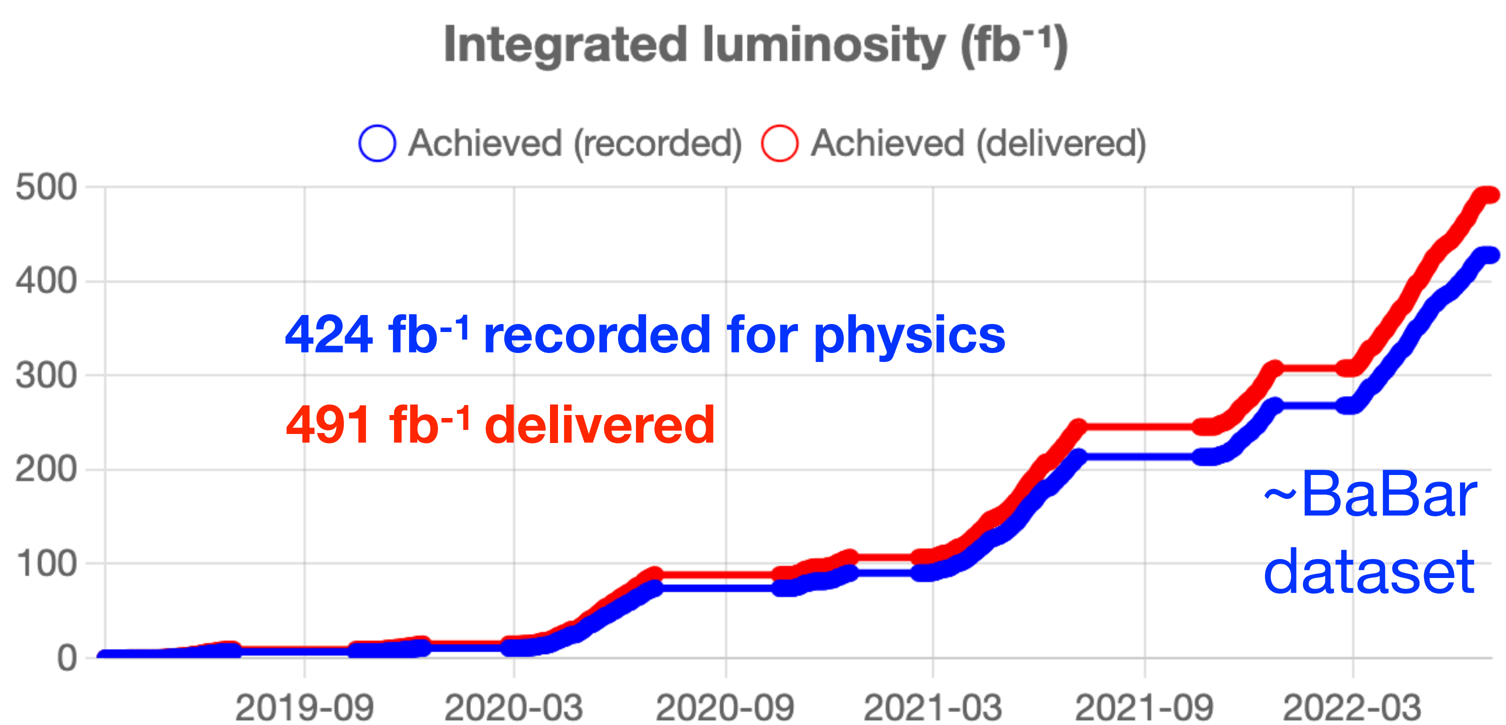
Phase-3 operation summary



Delivered peak luminosity during physics runs



[beam current] = $\sqrt{I_{LER}\, I_{HER}}$, I_{LER}, or I_{HER} when the HV permission is given.



[Delivered $\int L$(plan)] = Σ [Daily delivered $\int L$(plan)]

With remote+local operation scheme, we have been running during the pandemic. A new record for peak luminosity while integrating ~BaBar dataset.

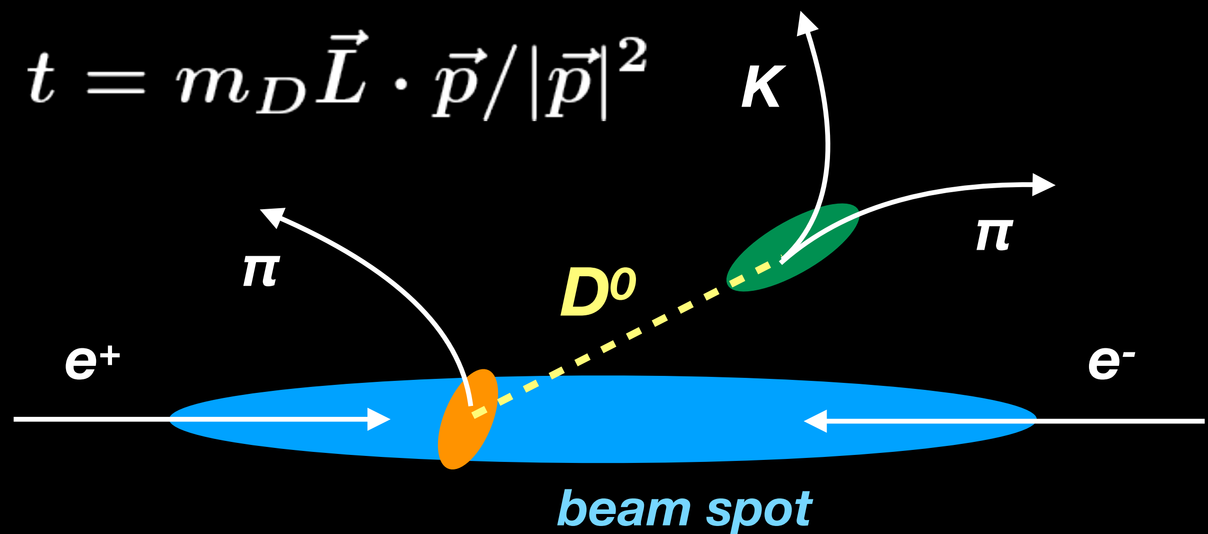
Vertexing performance — charm lifetime

The lifetime meas. nicely demonstrates performance of vertex reconstruction.

$e^+e^- \to c\bar{c}$ events are used:

$$\begin{cases} D^{*+} \to D^0(\to K^-\pi^+)\pi^+ \\ D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0 \\ \Lambda_c^+ \to pK^-\pi^+ \end{cases}$$

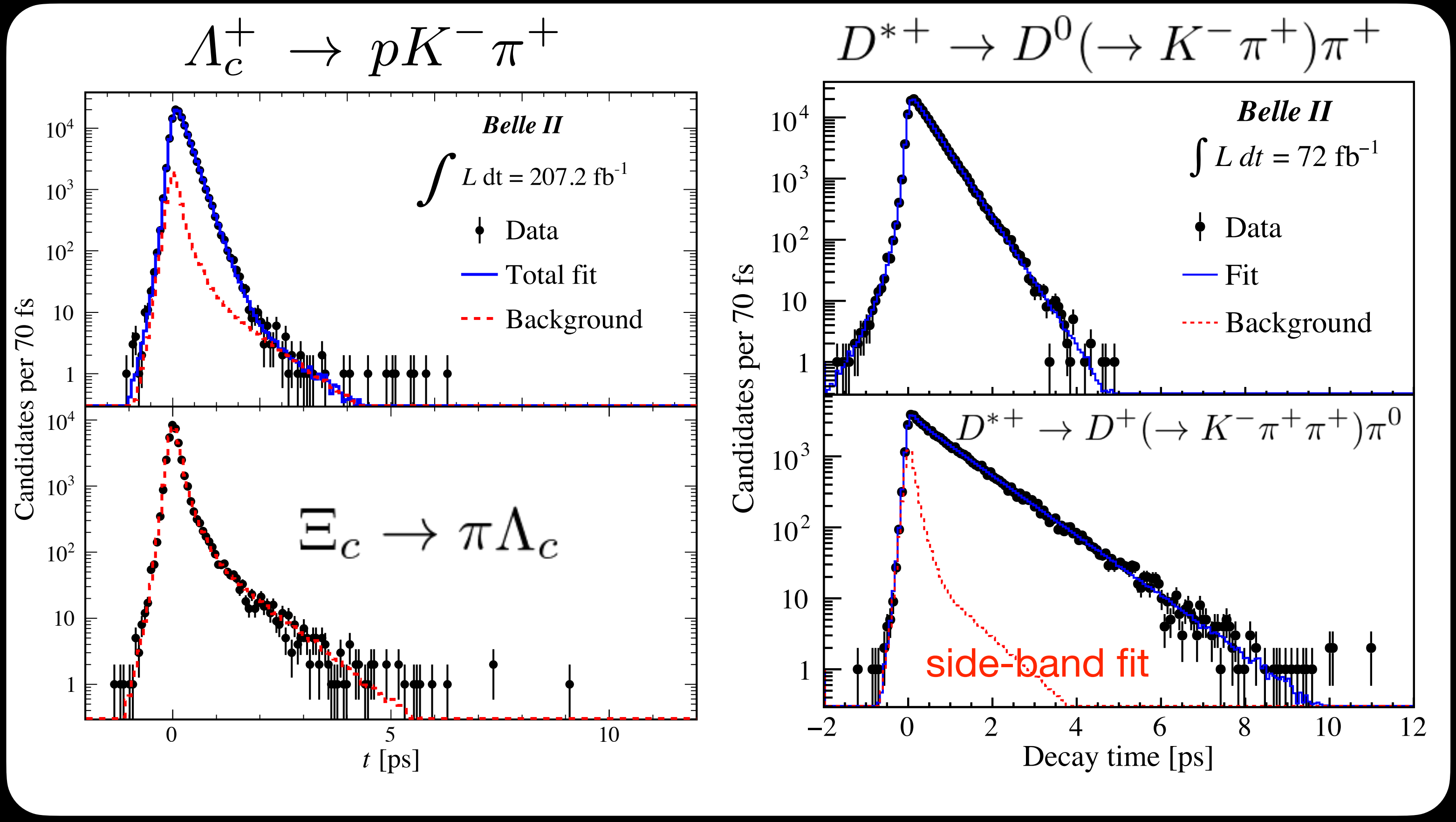
$$t = m_D \vec{L} \cdot \vec{p}/|\vec{p}|^2$$



Backgrounds are estimated from the side-band or simulation.

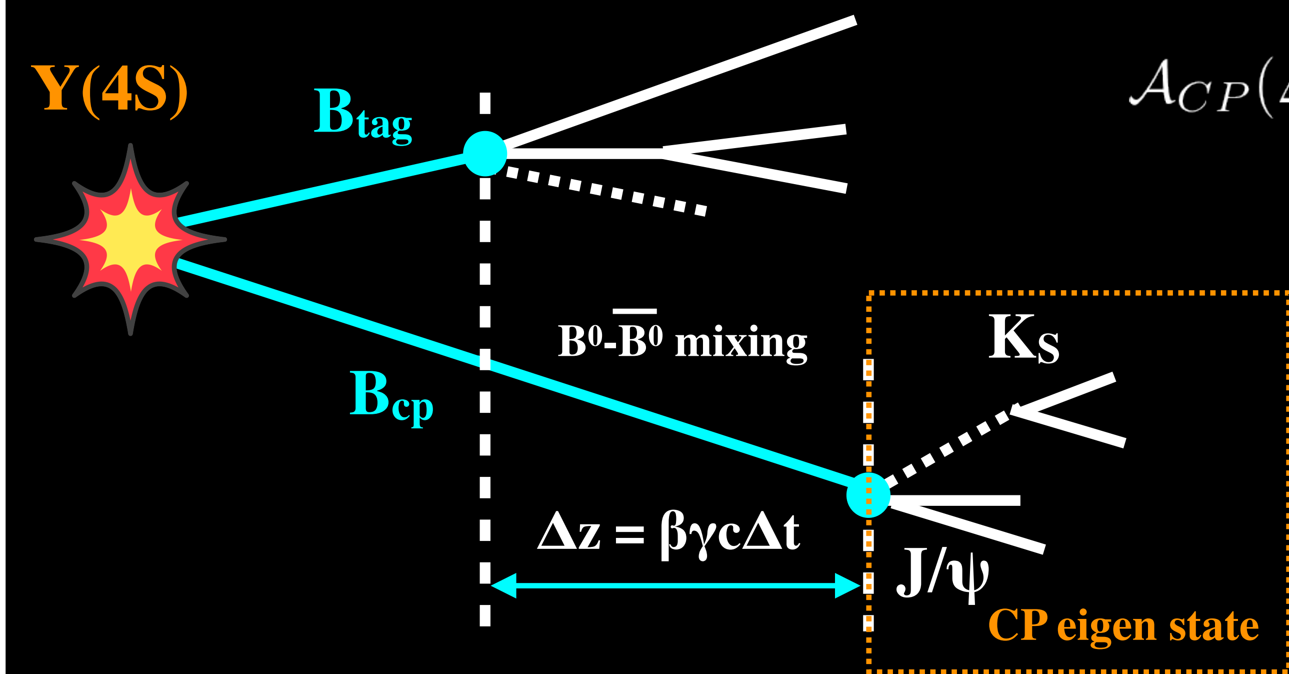
$$\begin{cases} \tau(D^0) = (410.5 \pm 2)\text{fs} \\ \tau(D^+) = (1030.4 \pm 5.6)\text{fs} \\ \tau(\Lambda_c^+) = (203.2 \pm 1.1)\text{fs} \end{cases}$$

World best meas. achieved thanks to new PXD layers.



arXiv:2206.15227, Phys. Rev. Lett. 127 (2021), 211801

Time dependent CP asymmetry



$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0 \to J/\psi K_S^0) - \Gamma(B^0 \to J/\psi K_S^0)}{\Gamma(\bar{B}^0 \to J/\psi K_S^0) + \Gamma(B^0 \to J/\psi K_S^0)}$$

$$= S_{CP}\sin(\Delta m_B \Delta t) + A_{CP}\cos(\Delta m_B \Delta t)$$

mixing induced CPV

$S_{CP} = \sin(2\phi_1)$

B → $J/\psi K_S$, B → $\overline{B}$ → $J/\psi K_S$

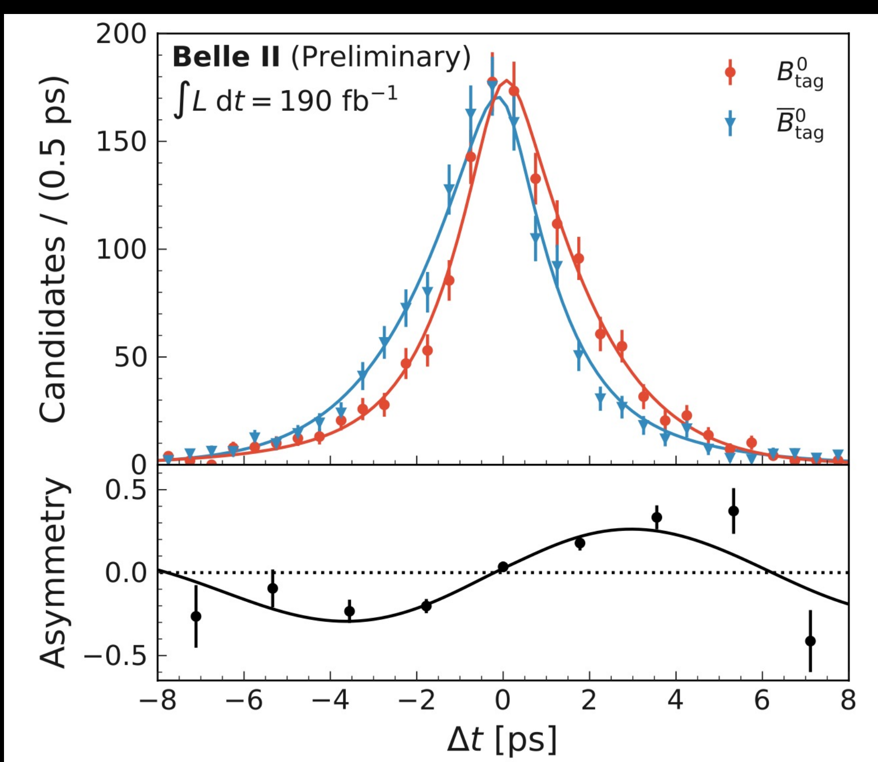
Direct CPV

$\mathcal{A}_{CP} = -\mathcal{C}_{CP}$

|B> → |f> ≠ |$\overline{B}$> → |f>

$A_{CP} = 0$ (tree level)

＊ S, A: defined by final state



$J/\psi \to e^+e^-, \mu^+\mu^-, K_S^0 \to \pi^+\pi^-$

$S_{CP}(J/\psi\ K_S) = \sin(2\phi_1)$ measurement：

b→c$\bar{c}$s has a small unc. on theo. and exp.
→ golden mode for ϕ_1

<u>First measurement at Belle II</u>

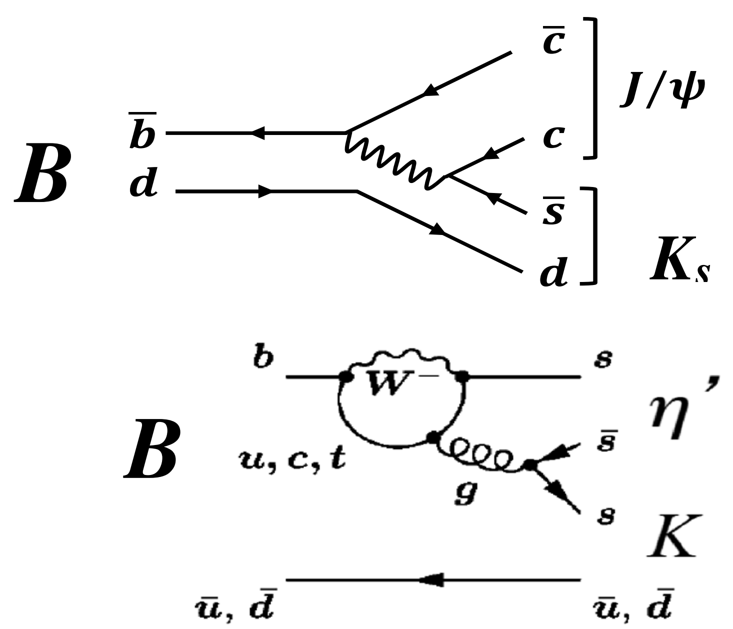
S_{CP} = 0.720 ± 0.062 (stat.) ± 0.016 (syst.)

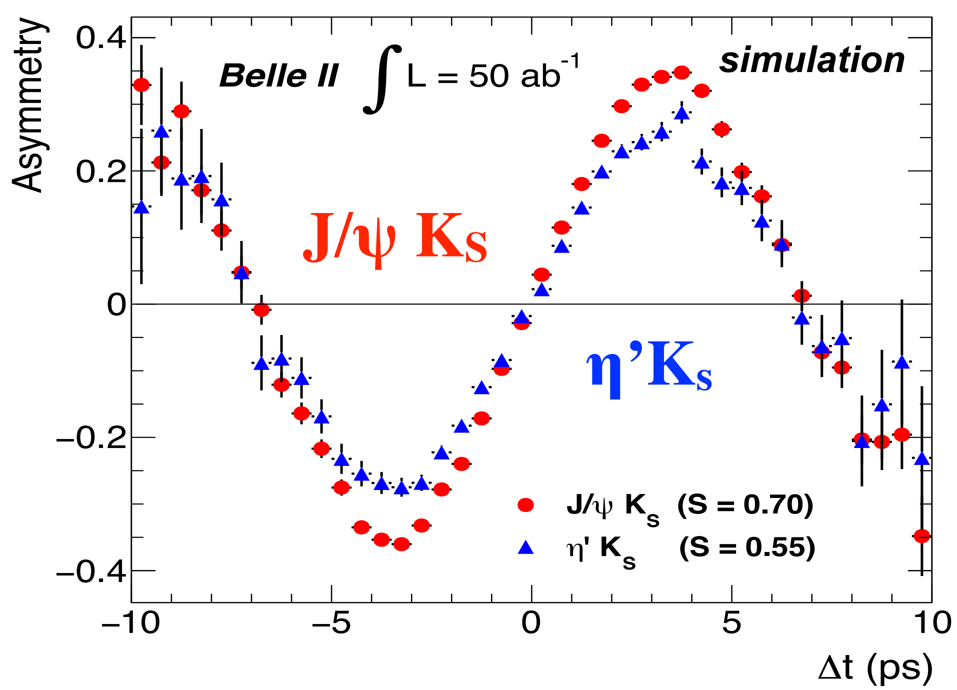
A_{cp} = 0.094 ± 0.044 (stat.) $^{+0.042}_{-0.017}$ (syst.)

(S_{PDG} = 0.695 ± 0.019, A_{PDG} = 0.000 ± 0.020)

ϕ_1/β measurement in penguin

- Size of CP asymmetry in $b \to s q\bar{q}$ (loop) is expected to be similar to $b \to c\bar{c}s$ (e.g $J/\psi\ K_S$) (tree). However, if a new particle contributes to the loop, **size of CP asymmetry may change** ($\phi_1^{eff} = \phi_1 + \delta\phi_1^{NP}$)

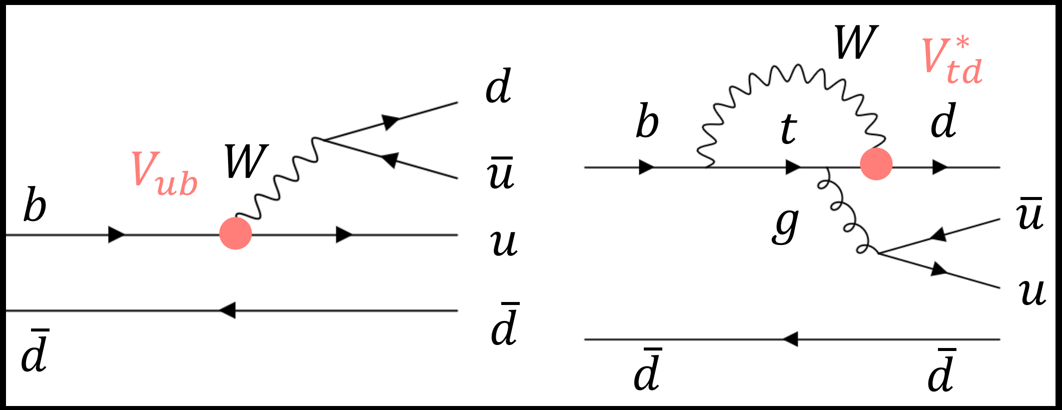




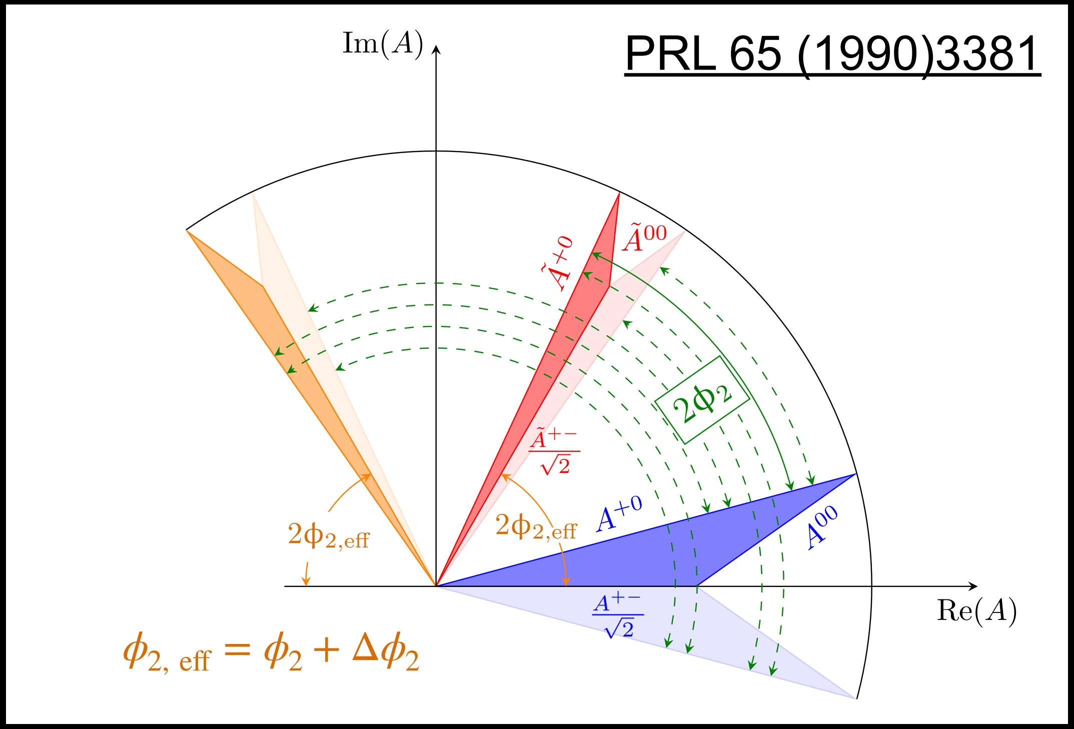
- $B \to \phi K$, **$\eta' K_s$, $K_s K_s K_s$** are golden mode (small theory unc.)
  - First measurement (63 fb^{-1}) of $\eta' K_s$ *Br* is consistent with World Average (see arXiv:2104.06224)
  - First measurement (190 fb^{-1}) of $K_s K_s K_s$ mode is consistent with unity: **$S_{CP} = -1.86\ ^{+0.91}_{-0.46}$ (stat.) $\pm$ 0.09 (syst.)**

ϕ_2/α measurement

- ϕ_2 is the least constrained CKM parameter: $\phi_2 = (85.2\,^{+4.8}_{-4.3})$ due to **large interference between tree and penguin diagram**.



- $B \to \pi\pi$ and $B \to \rho\rho$ are the most sensitive final state for ϕ_2. **Isospin analysis** (+0,+-, 00) is performed to resolve the interference and extract ϕ_2



2φ2: angle between the CP-conjugate charged amplitudes.

- These decay modes are also sensitive to direct CP violation.

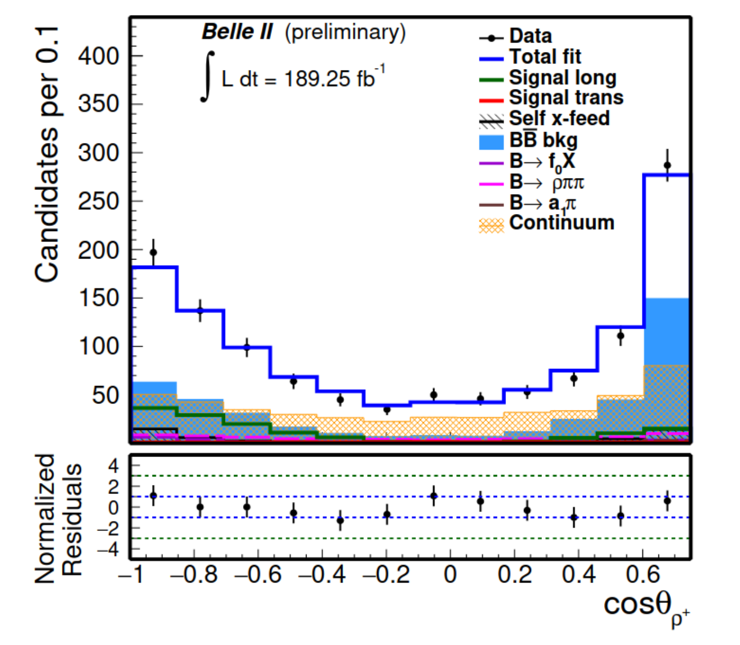
$$S_{CP} = \sqrt{1 - A_{CP}^2}\,\sin(2\phi_2 - 2\Delta\phi_2),\ A_{CP} \neq 0$$

ϕ_2/α measurement

- $B \to \rho\rho$ decay is characterized by three helicity states (longitudinal H_0 and transverse H_+ and H_-). Longitudinal polarization fraction ($|H_0|^2/\Sigma|H_i|^2$) is an observable in angular analysis.
- Multidimensional fit in kinematic variables to extract branching fraction, longitudinal polarization fraction (***f_L***), charge asymmetry (***A_{cp}***)

Belle II 190 fb^{-1} result

	$\mathcal{B}\ (\times 10^6)$	f_L	A_{CP}
$B \to \rho^+\rho^-$	$26.7 \pm 2.8 \pm 2.8$ (27.7 ± 1.9)	$0.956 \pm 0.035 \pm 0.033$ $(0.990^{+0.021}_{-0.019})$	$(\mathcal{A} = 0.00 \pm 0.09,\ \mathcal{S} = -0.14 \pm 0.13)$
$B \to \rho^+\rho^0$	$23.2^{+2.2}_{-2.1} \pm 2.7$ (24.0 ± 1.9)	$0.943^{+0.035}_{-0.033} \pm 0.027$ (0.950 ± 0.016)	$-0.069 \pm 0.068 \pm 0.060$ (-0.05 ± 0.05)
$B \to \pi^+\pi^0$	$6.12 \pm 0.53 \pm 0.53$ (5.5 ± 0.4)		$0.085 \pm 0.085 \pm 0.019$ (0.03 ± 0.04)
$B \to \pi^0\pi^0$	$1.27 \pm 0.25 \pm 0.17$ (1.59 ± 0.26)		$0.14 \pm 0.46 \pm 0.07$ (0.33 ± 0.22)

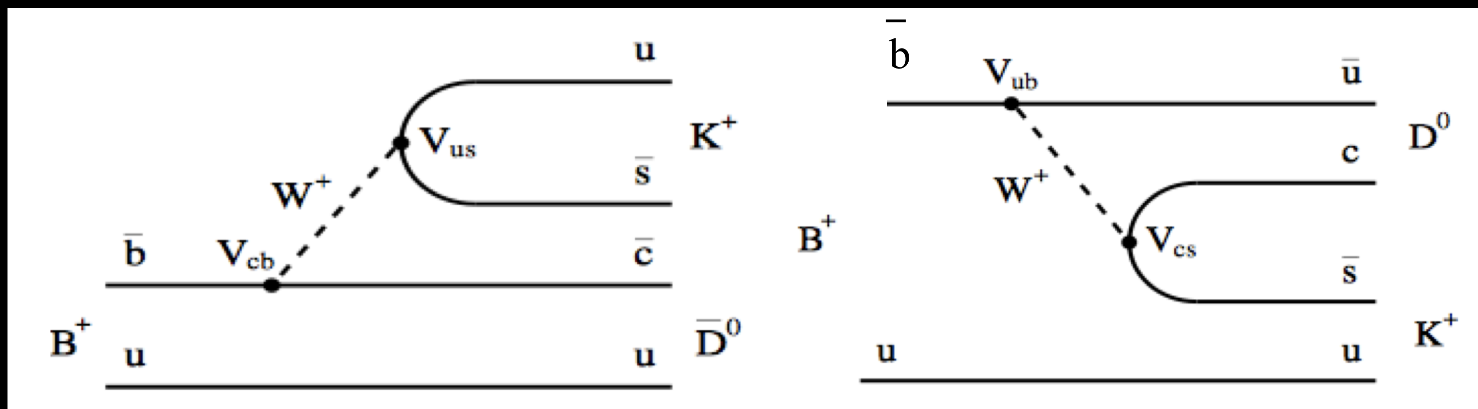


helicity angle distribution

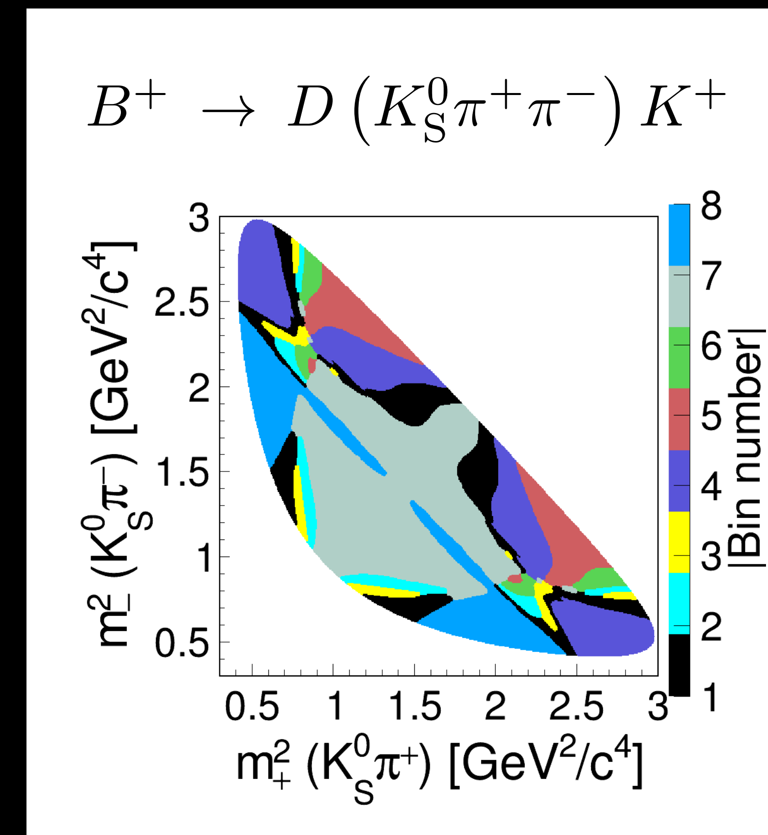
See arXiv:2106.03766, 2107.02373, 2206.12362

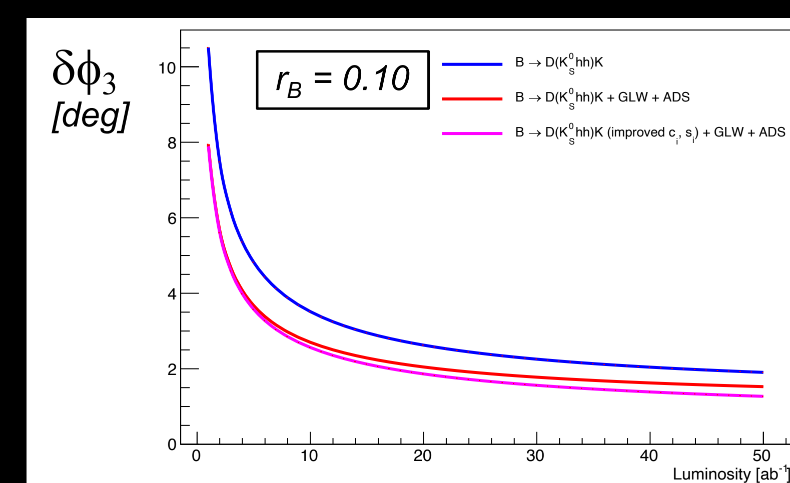
φ3/γ measurement : $B^+ \to D(K_S^0 h^+ h^-)h^+$

$B^+ \to \bar{D}^0 K^+$ $\quad$ $B^+ \to D^0 K^+$



arXiv:2110.12125



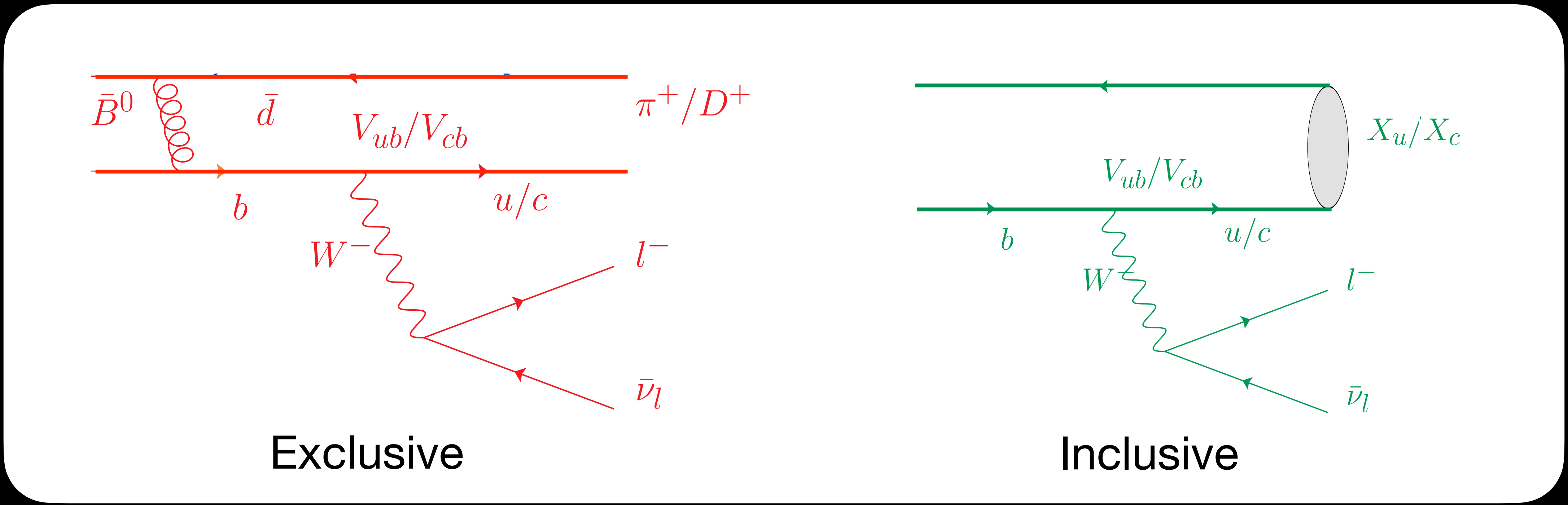


- Φ_3 can be measured via interference between b →c and b →u transition.
    - Decay rate depends on interference btw the two amplitudes and can be determined in bins of D-decay Dalitz plot (**model-independent**).
    - External input (BESIII, CLEO) for D-decay strong-phase parameters.
- **First joint Belle (711fb^{-1}) and Belle II (128fb^{-1}) analysis**

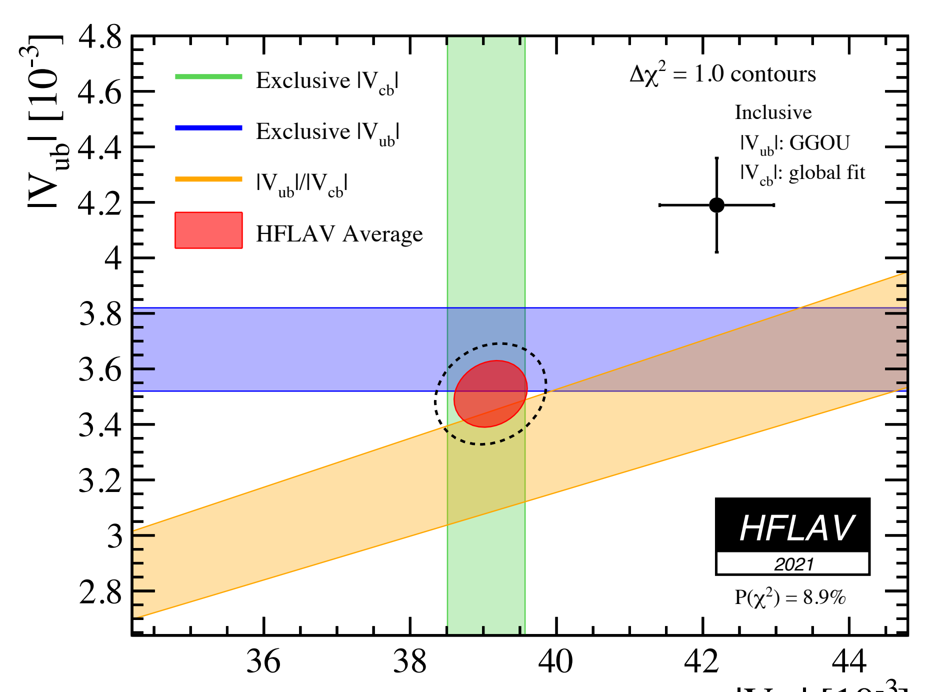
$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)deg.$$
$$r_B = 0.129 \pm 0.024 \pm 0.001 \pm 0.002$$
$$\delta_B = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)deg.$$

$|V_{ub}|$ and $|V_{cb}|$ measurement

- Semi-leptonic B decays are used to extract the CKM parameters $|V_{ub}|$ and $|V_{cb}|$.

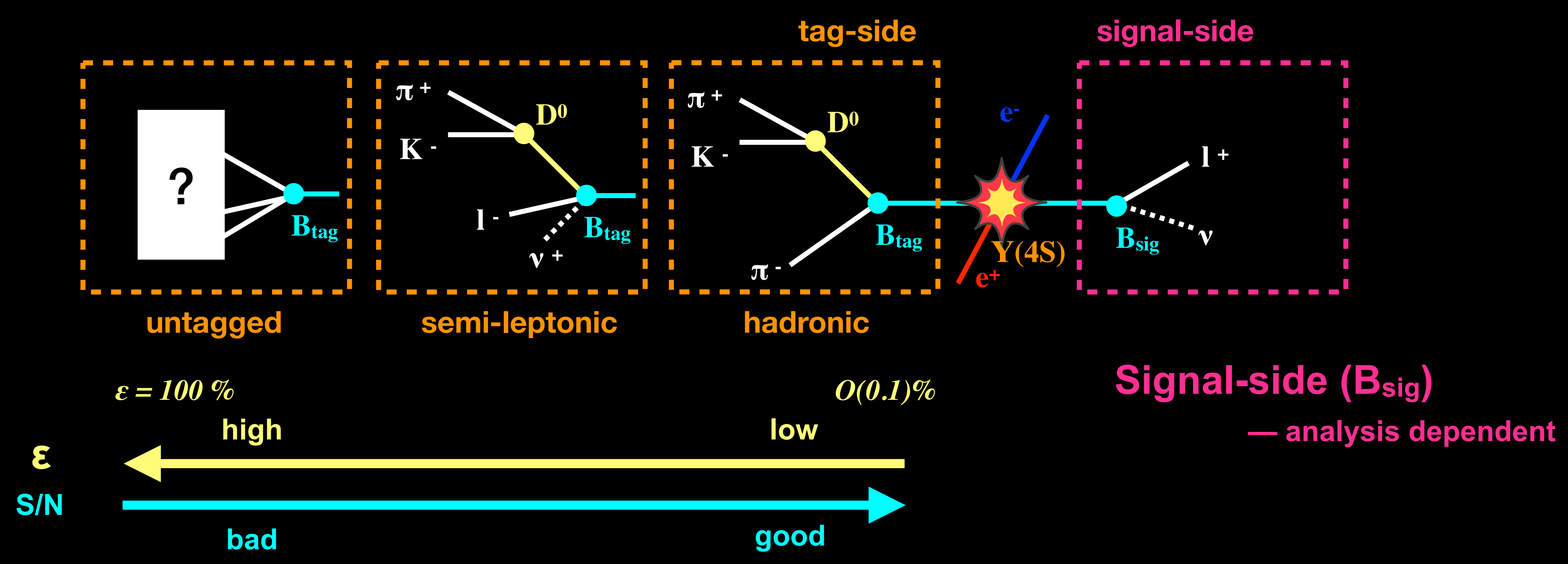


- $B \to \pi\ell\nu$ and $B \to D\ell\nu$ are golden modes for $|V_{ub}|$ and $|V_{cb}|$ measurements.
- There exists a longstanding discrepancy (~3.3σ) between exclusive and inclusive meas.



arXiv:2206.07501

B tagging technique



- Reconstruction of the B-meson in Tag-side (B_{tag})
  - **Large statistics from B-factory is required** because the reconstruction efficiency of B_{tag} is not so high.
  - B_{tag} is very important when there is a neutrino in final state in your signal.
- **Full Event Interpretation** (**FEI**, machine learning algorithm) improved the reconstruction efficiency compared to Belle's algorithm.

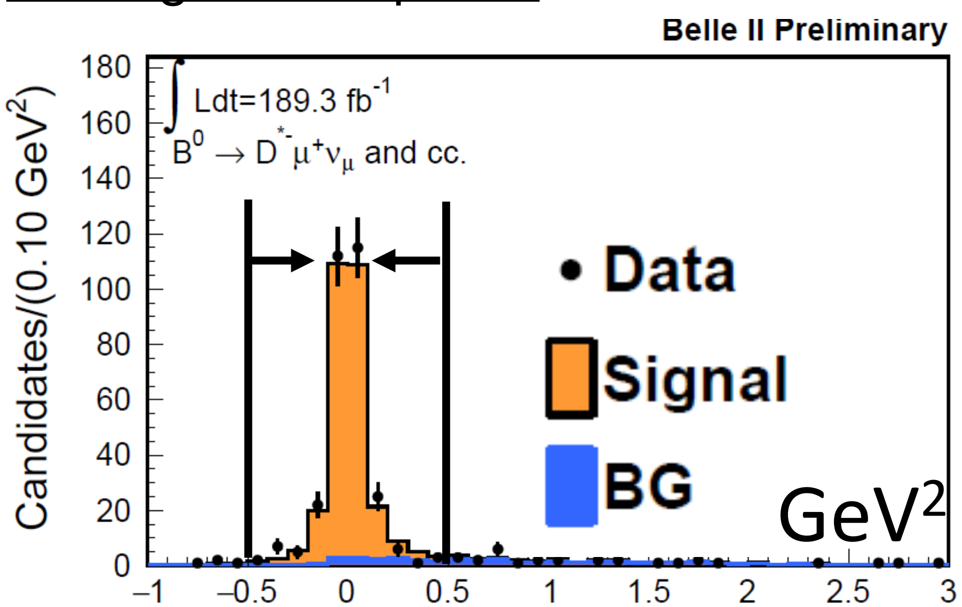
$B \to D^{(*)} \ell \nu$ for $|V_{cb}|$

- Untagged and hadronic tagged analyses were performed with 190 fb^{-1}.
- The reconstruction of low momentum pions from D* is challenging.
- For the tagged analysis, the missing mass squared (i.e. neutrino) is calculated from visible particles (B_{tag}, D*, ℓ) and beam energy.
- Differential decay width is fit to extract **$|V_{cb}|$** and a **form factor**.

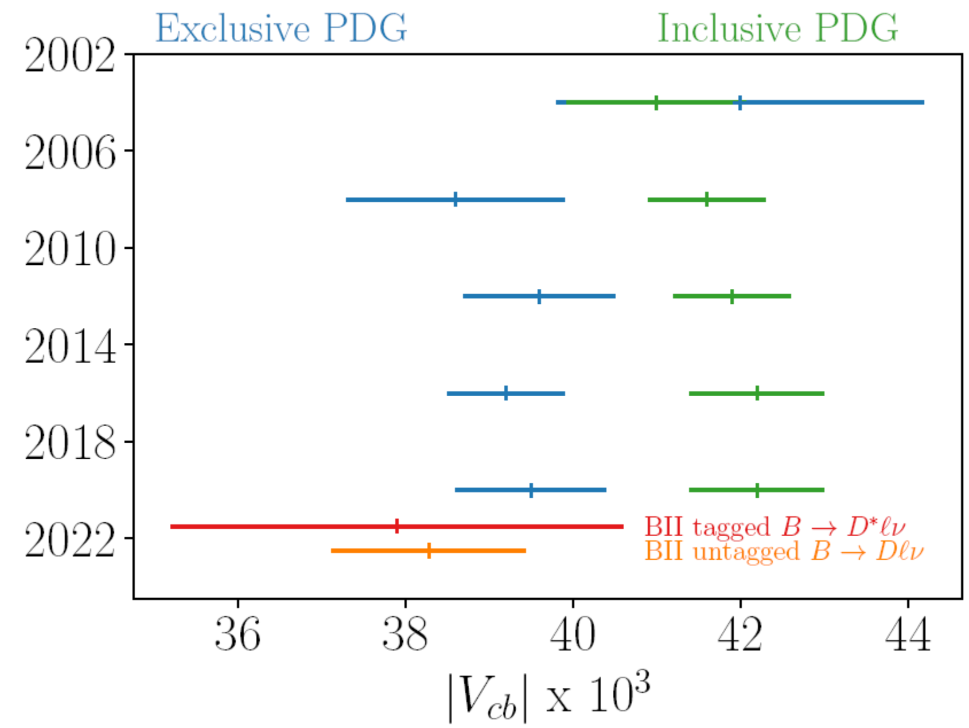
$$\frac{d\Gamma}{dw} = \frac{\eta_{EW}^2 G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 g(w) F^2(w) |V_{cb}|^2$$

$$w = \frac{m_{D^{*+}}^2 + m_{B^0}^2 - q^2}{2 m_{B^0} m_{D^{*+}}}$$

missing mass squared

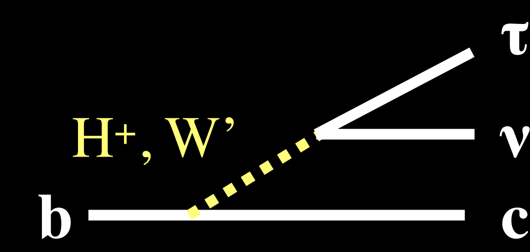


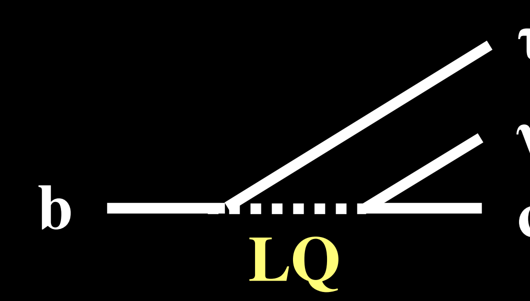
$$m_{\rm miss}^2 = (P_{\rm beam} - P_{B_{\rm tag}} - P_{D^*} - P_l)^2$$

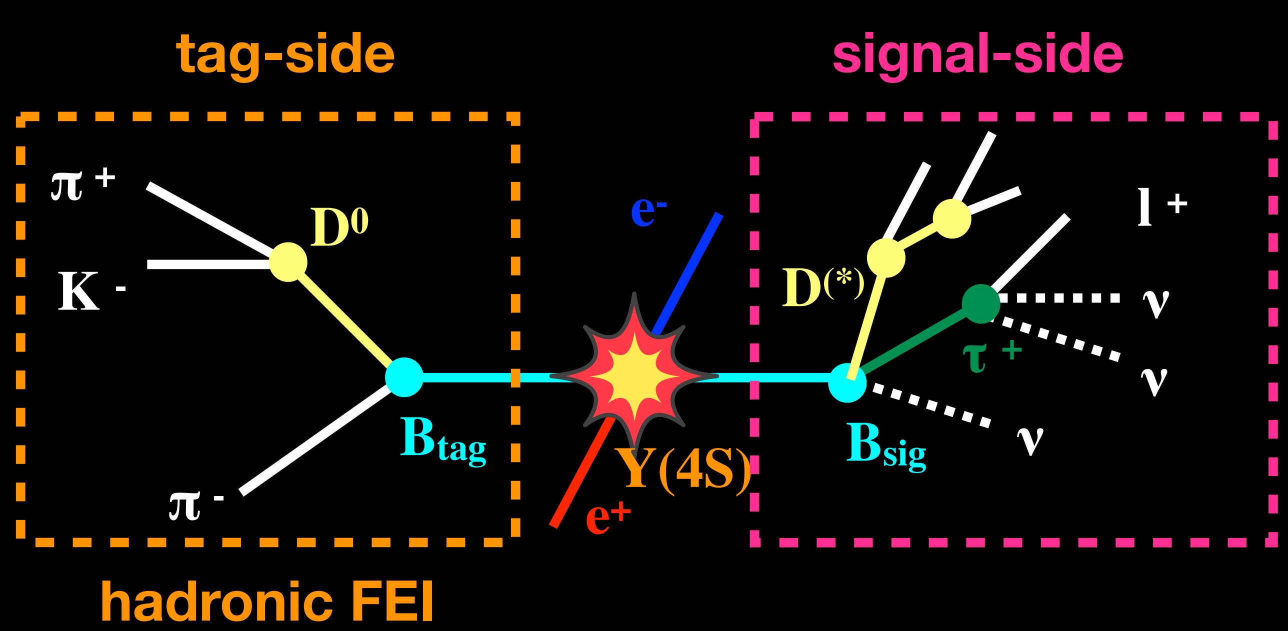


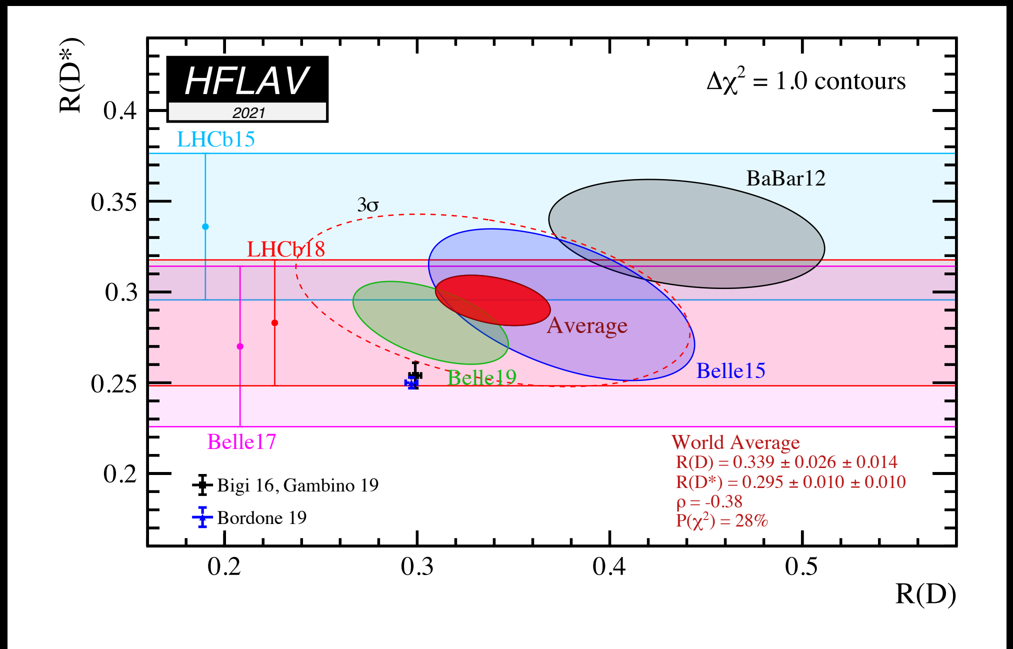
$B \to D^{(*)}\tau\nu$

- Since B meson decays via W in the SM, the BF is large *O* (1) %
- This is a decay of 3rd gen. quark to 3rd gen. lepton
  - large coupling to heavy particle (e.g. charged Higgs)
  - large coupling to 3rd gen. particles (e.g. LQ, Z' model)
- > 1 neutrino in the final state → **Flavor tagging is a key**









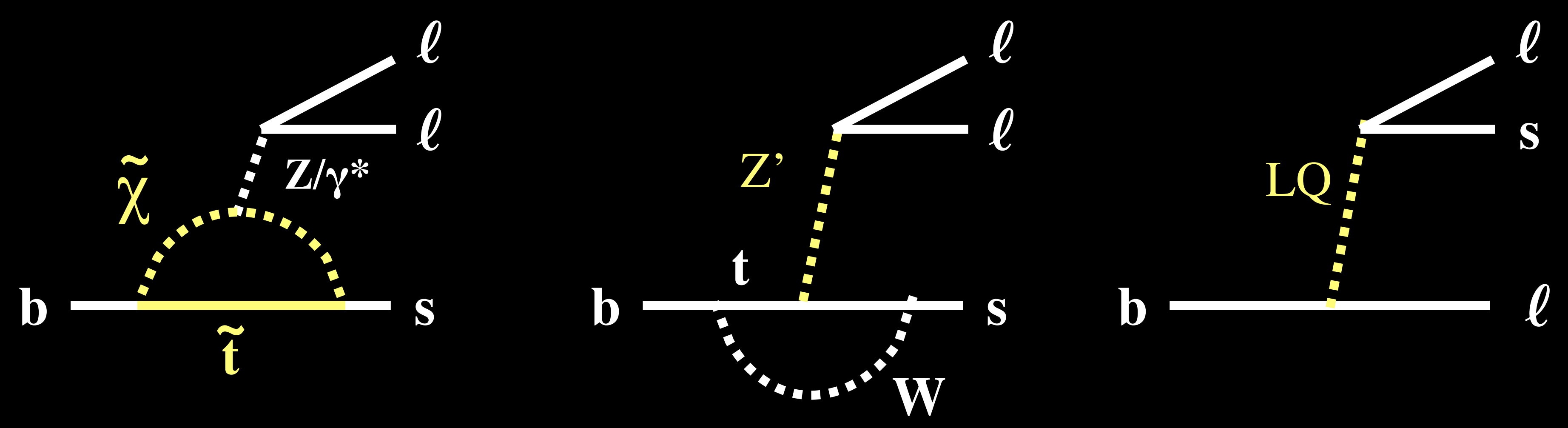
- Unc. can be suppressed by taking a ratio (LFU)

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
R_D	±6.0±3.9%	±2.0±2.5%
$R_{D(*)}$	±3.0±2.5%	±1.0±2.0%

$b \to s\ell^+\ell^-$

- Flavor changing neutral current (FCNC) *b→s (d)* decay proceeds with a loop diagram. Hence it is suppressed in the SM.
  - Enhancement of new physics contribution (e.g. SUSY, Z', LQ model etc)



- $b \to s\ell^+\ell^-$ is experimentally a clean signature. Unc. can be suppressed by taking a ratio:

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

- In Belle II, in addition to R(K*), an **inclusive measurement** of R(Xs) is also possible

(*)all possible final states taken into account.

Sensitivity at Belle II

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K $([1.0, 6.0]\,\mathrm{GeV}^2)$	28%	11%	3.6%
R_K $(> 14.4\,\mathrm{GeV}^2)$	30%	12%	3.6%
R_{K^*} $([1.0, 6.0]\,\mathrm{GeV}^2)$	26%	10%	3.2%
R_{K^*} $(> 14.4\,\mathrm{GeV}^2)$	24%	9.2%	2.8%
R_{X_s} $([1.0, 6.0]\,\mathrm{GeV}^2)$	32%	12%	4.0%
R_{X_s} $(> 14.4\,\mathrm{GeV}^2)$	28%	11%	3.4%

* Statistical uncertainty is dominant. Systematic unc. is negligible.

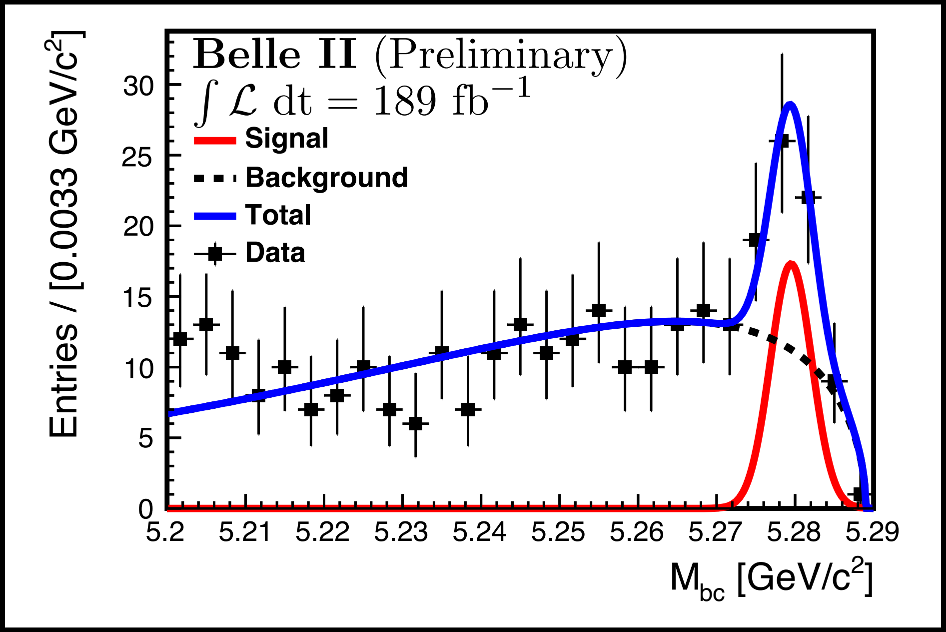
Branching fraction of $B \to K^* \ell^+ \ell^-$

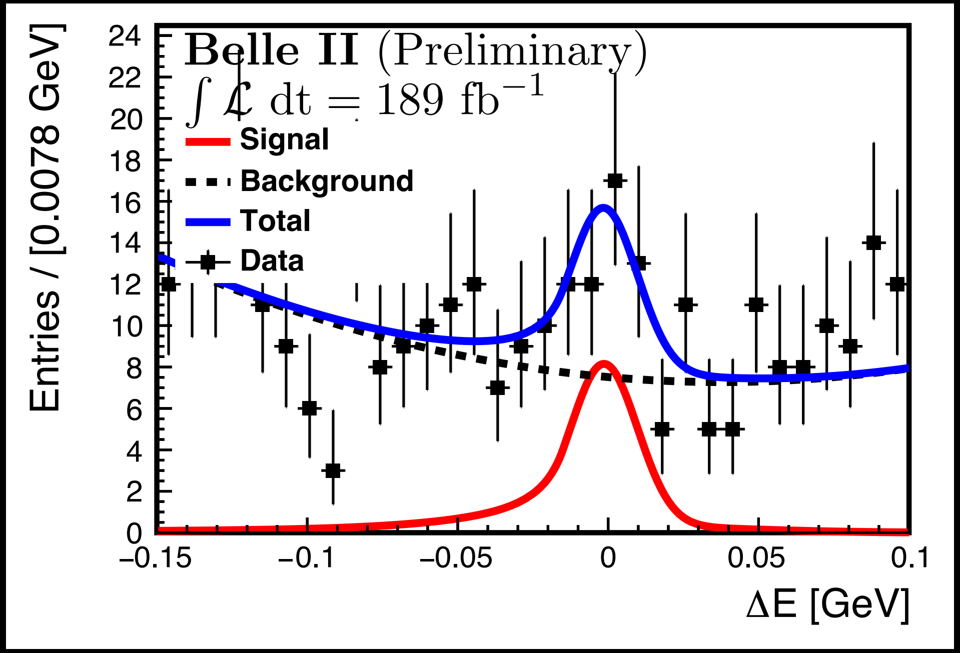
- First measurement of branching fraction with 190 fb^{-1}.
- *K*(892) → Kπ (100%)*
    - invariant mass cut: 796<M<996 MeV
- BG → *MVA discriminant (Fast BDT)*
    - Charmonium resonances: *J/ψK, ψ(2S)*
    - Continuum BG: light quark pairs
    - inclusive B meson decay: semi-leptonic B decays
- M_{bc} and ΔE are used for signal extraction
- Main source of systematic unc. : particle ID

Branching fraction:

$$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}.$$

arXiv:2206.05946



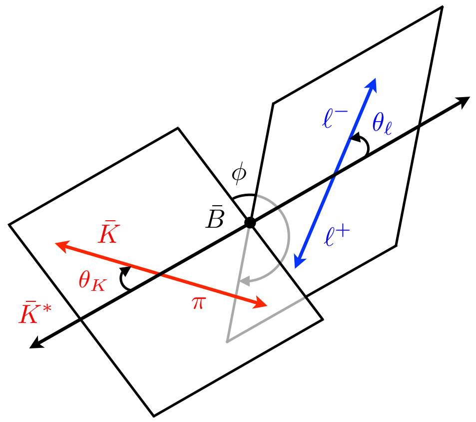


Angular analysis

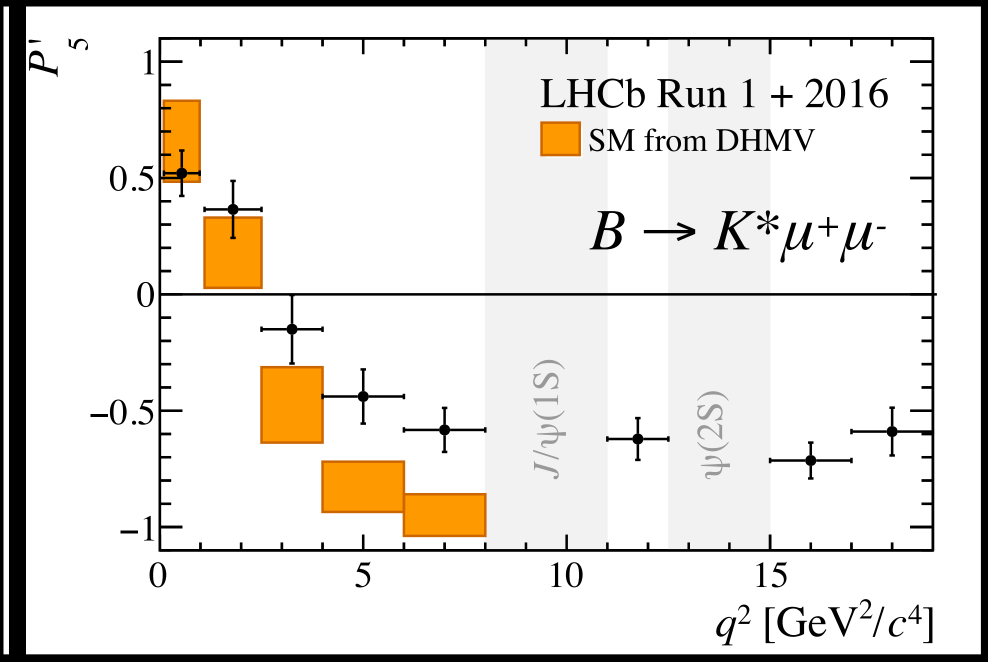
Measurement of $B \to K^* \ell^+ \ell^-$ at Belle II is an important cross check for $B \to K^* \mu^+ \mu^-$ anomaly

angular variables P'$_{i=4,5,6,8}$ are sensitive to ***C$_7$*, *C$_9$* and *C$_{10}$***

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$



$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}},$$



PRL125.011802(2020)

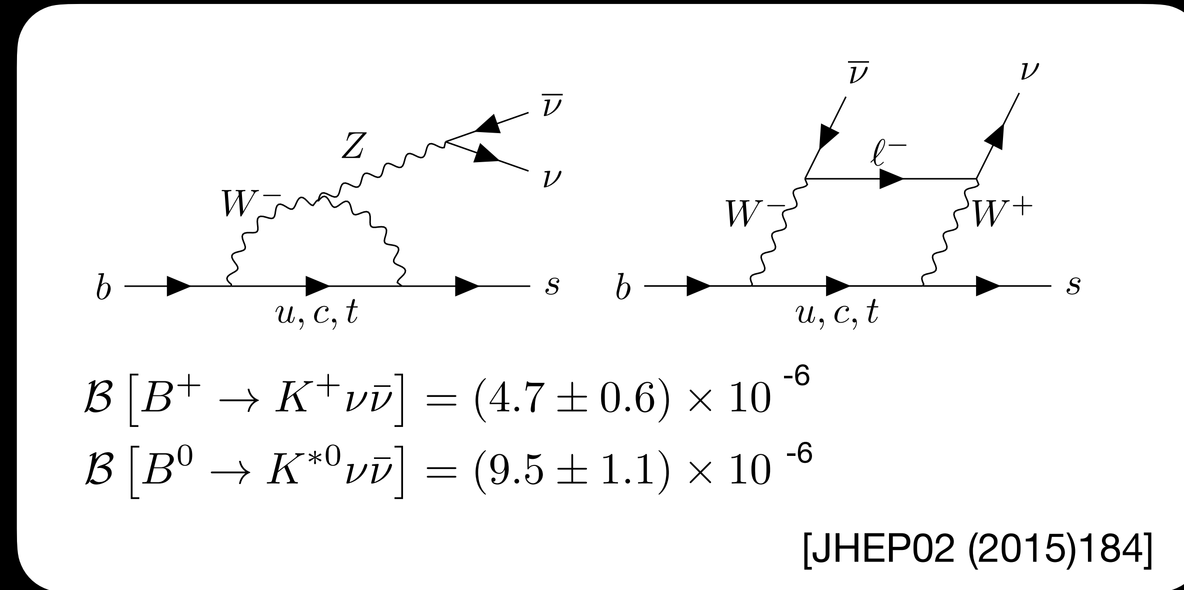
Belle II sensitivity

Observables	Belle 0.71 ab^{-1}	5 ab^{-1}	50 ab^{-1}
P'_5 ([1.0, 2.5] GeV^2)	0.47	0.17	0.054
P'_5 ([2.5, 4.0] GeV^2)	0.42	0.15	0.049
P'_5 ([4.0, 6.0] GeV^2)	0.34	0.12	0.040
P'_5 (> 14.2 GeV^2)	0.23	0.088	0.027

Sensitivity of Belle II ~5 ab^{-1} is expected to be similar to LHCb's 4.7 fb^{-1}

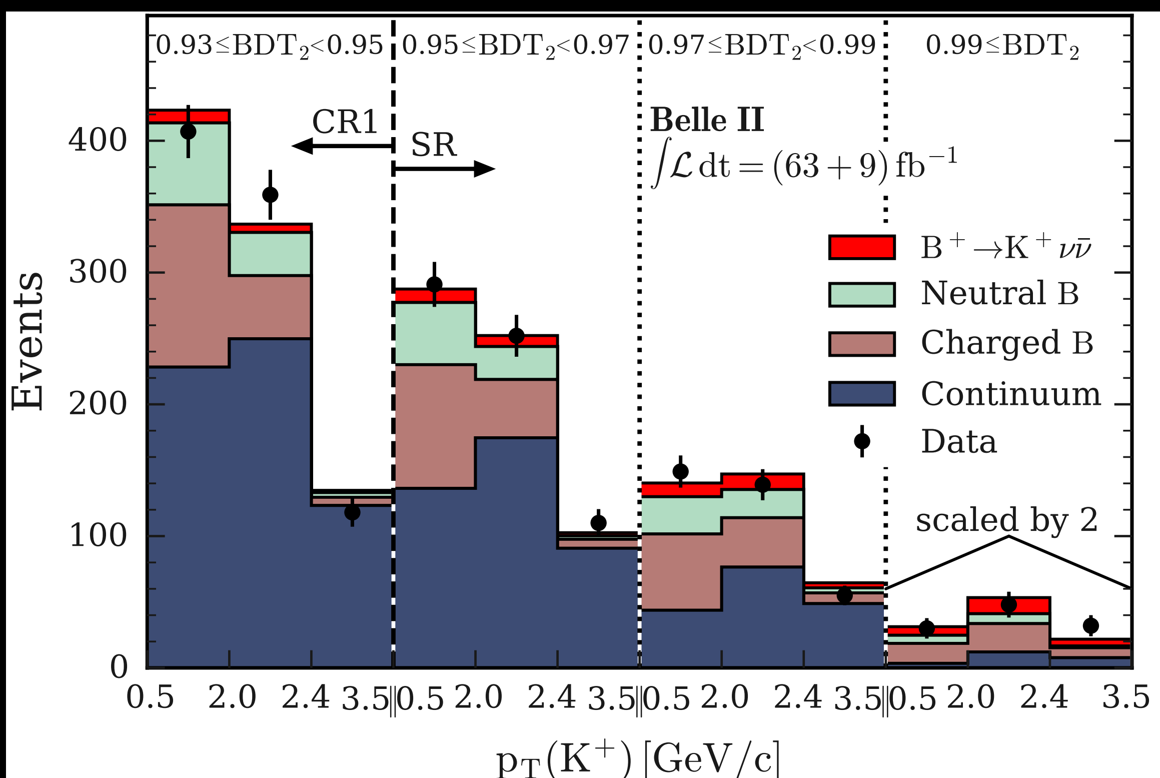
B→K$^{(*)}$νν

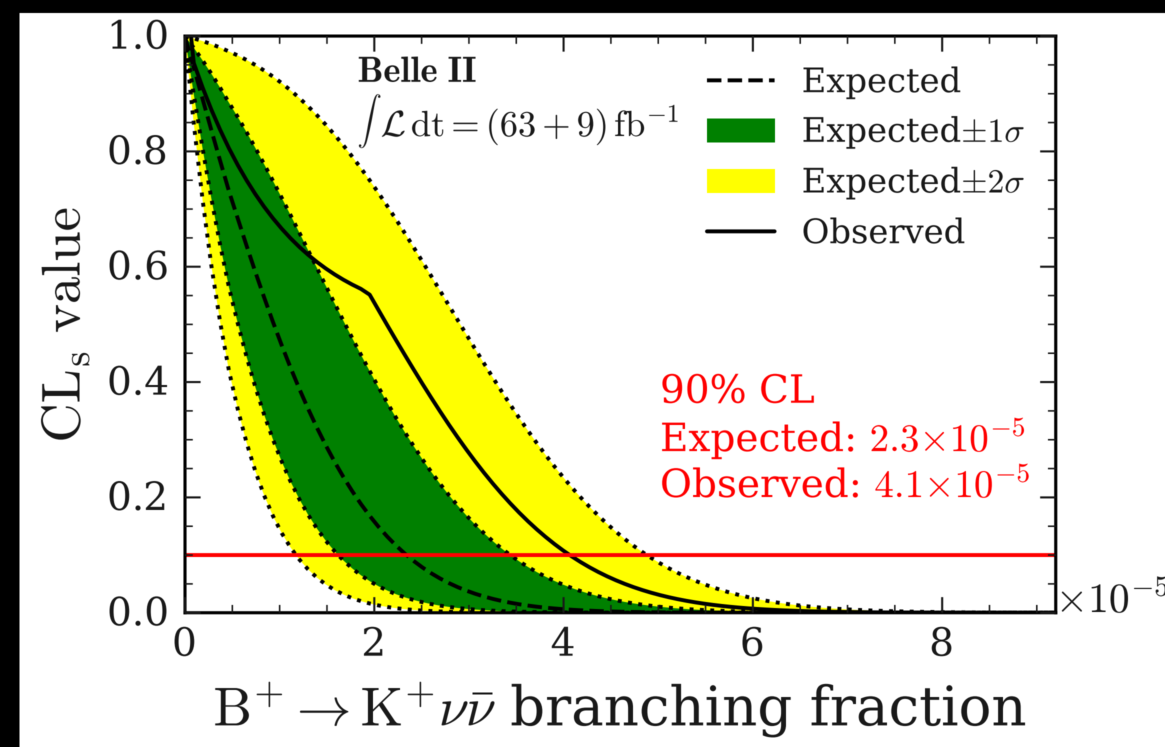
- FCNC *b→s (d)* process
- **Independent probe against *b→sℓ⁺ℓ⁻ anomaly***



- B_{tag} is a key since two neutrinos are in the final state. MVA analysis is employed to further improve the Belle II sensitivity.

PhysRevLett.127.181802





- Binning with Kaon P_T to maximize the sensitivity
- Continuum BG is estimated by CR

Discovery with 5-10 ab⁻¹ of Belle II data?

g-2 anomaly and vacuum polarization

- **4.2σ** deviation from the SM in $(g\text{-}2)_\mu$
  - new physics? (e.g. SUSY, LQ, ALP, …)
- Dominant theo. unc. arises from QCD term (HVP term)

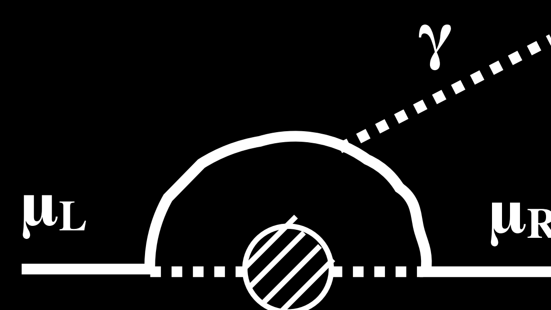
HVP : **H**adronic **V**acuum **P**olarization

$$a_\mu = \frac{g-2}{2} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD}$$

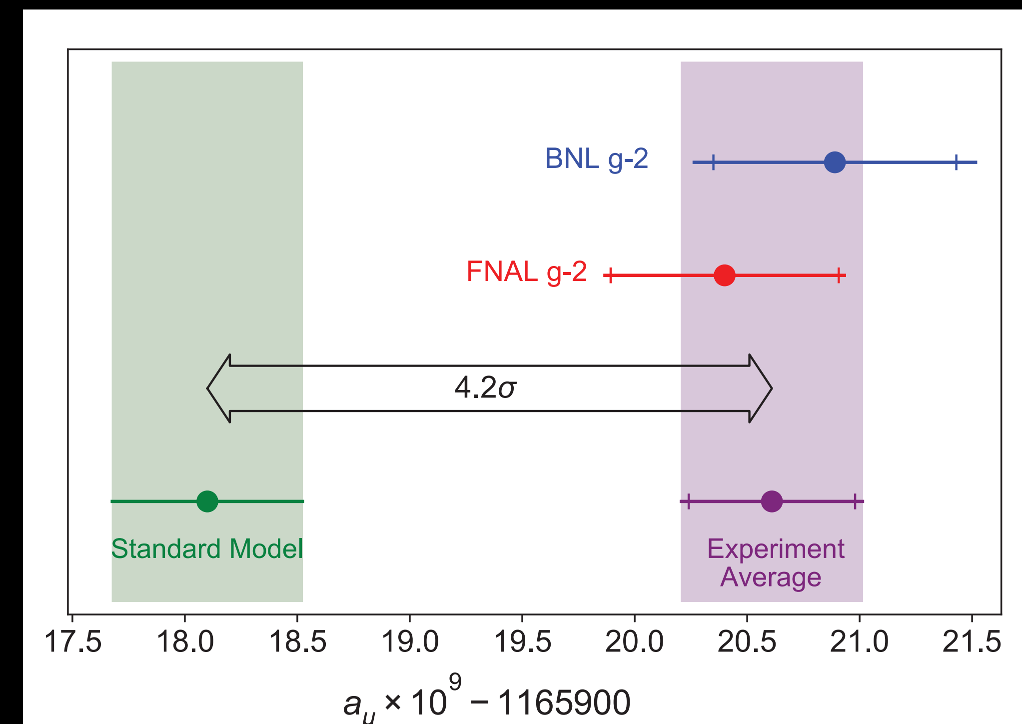
$$a_\mu^{QCD} = a_\mu^{HVP} + a_\mu^{HLbL}$$

$$a_\mu^{HVP,LO} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty}\frac{ds}{s}R(s)K(s)$$

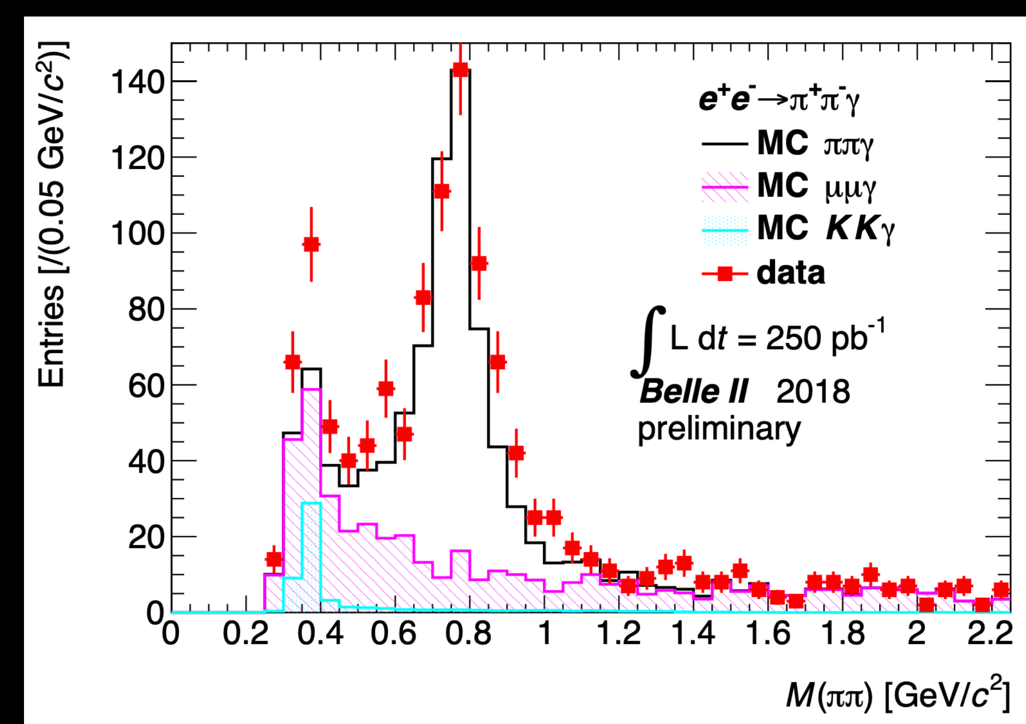
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



PhysRevLett.126.141801



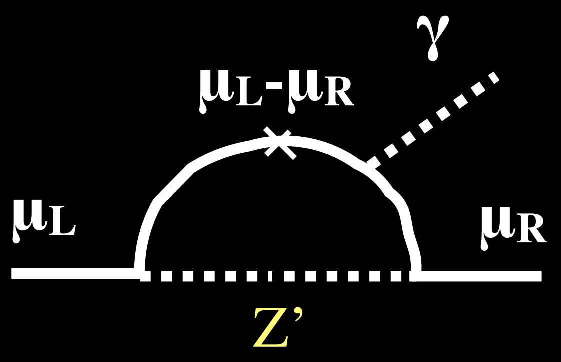
- Large diff. in measured xsec btw BaBar and KLOE
- **$e^+e^- \to$ hadrons (e.g. $\pi^+\pi^-$) cross section at Belle II**
  - Energy of hadrons scales with ISR γ recoil energy
  - Small statistics is OK?



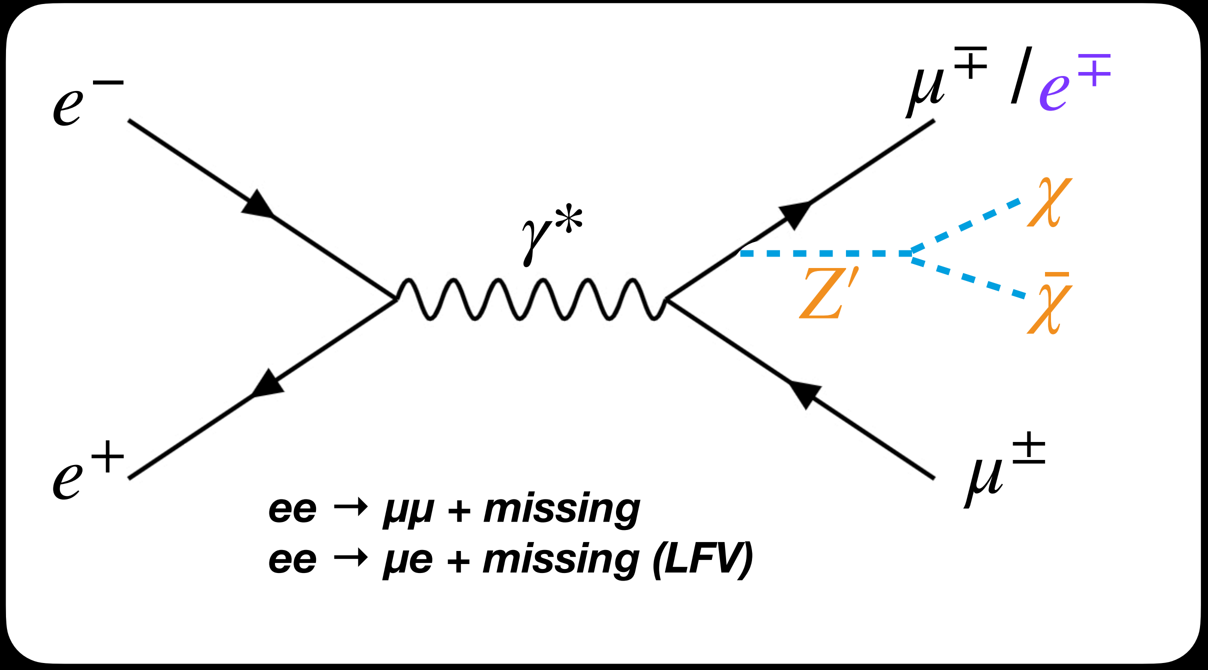
BELLE2-NOTE-PL-2018-023

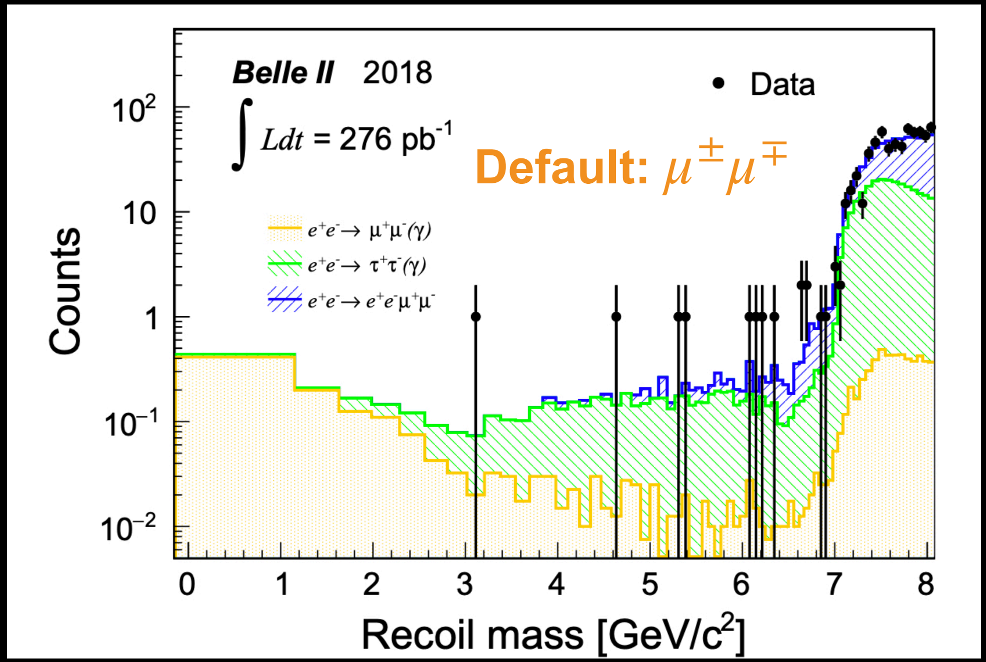
Invisible decay

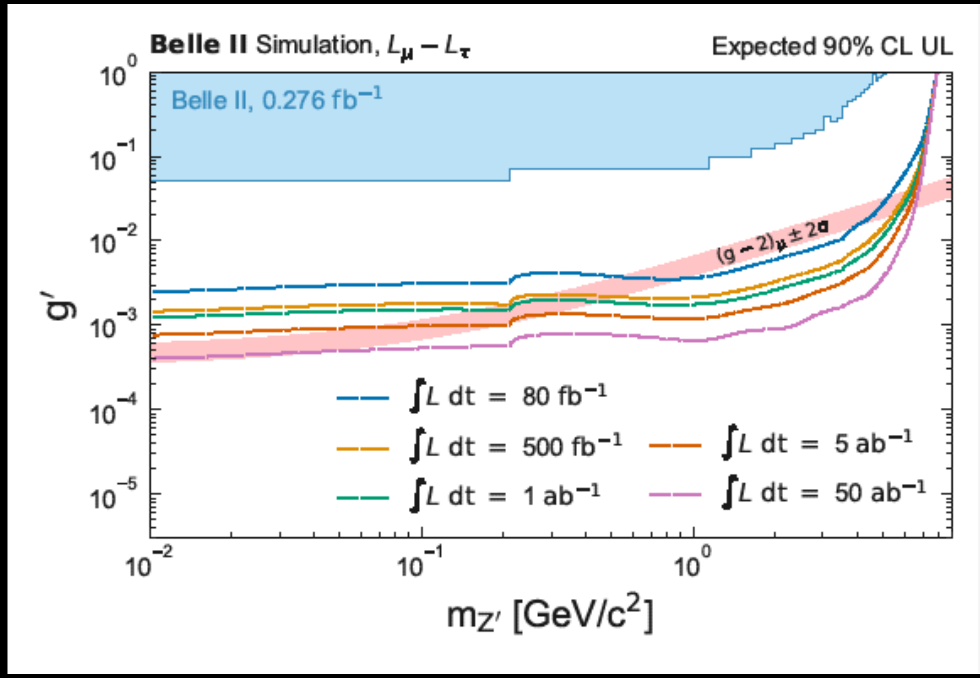
- $U(1)_{L\mu-L\tau}$ model considers L_μ-L_τ as a new charge:
  - Sensitive to **$(g\text{-}2)_\mu$ anomaly** or $b \to s\mu^+\mu^-$
  - Z' couples to only τ, μ, $\nu_{\tau,\mu}$ in the SM



Phys. Rev. Lett. 124, 141801 (2020)



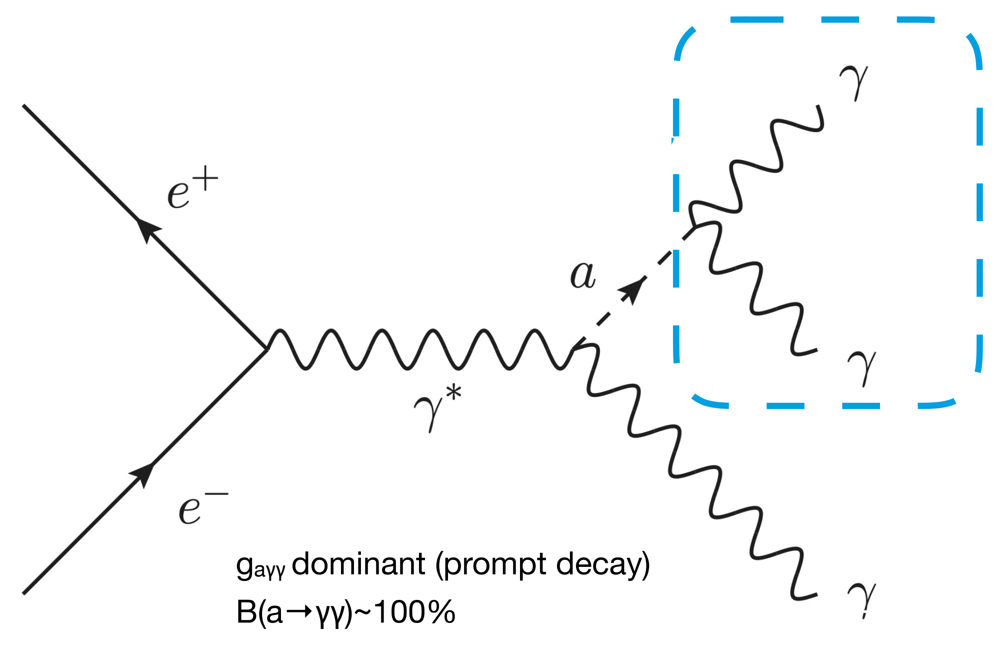




- Main BG
  - $\tau^+\tau^-$ (1-prong) + missing energy (neutrino)
  - $\mu^+\mu^-$ + γ (being missing)

- Limit on Z'—SM coupling (g')
  g'> 5 x 10^{-2} @ 90% CL

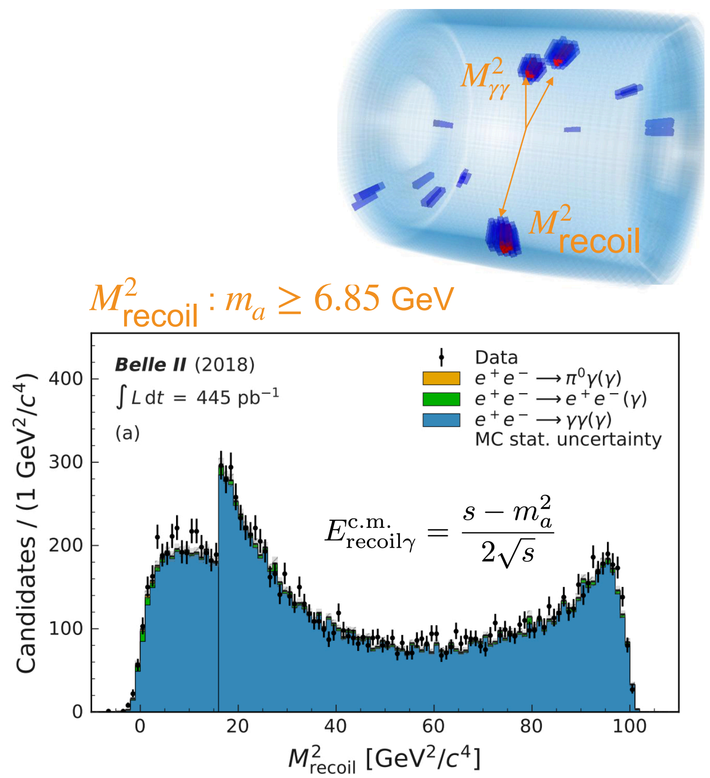
ALP search



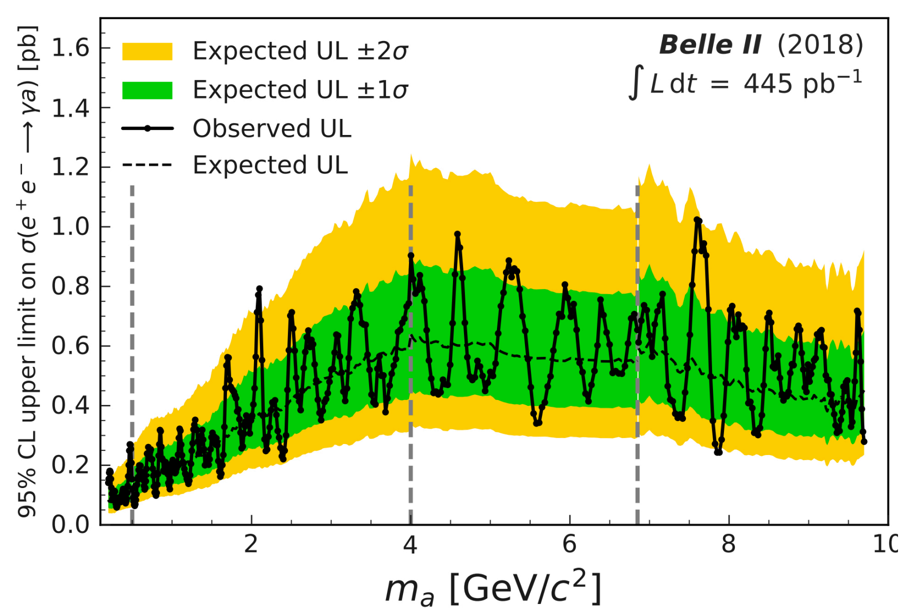
$g_{a\gamma\gamma}$ dominant (prompt decay)
$B(a \to \gamma\gamma) \sim 100\%$

- GeV scale ALP (a) as a pseudo portal mediator btw Dark Sector and SM
- Peak hunting by selecting events with three photons with invariant mass consistent with √s.
- Background dominated by (irreducible) ee →3γ
- Set upper limits on σ(ee→γa)
  — no excess in $0.2 < m_a < 9.7$ GeV/c²

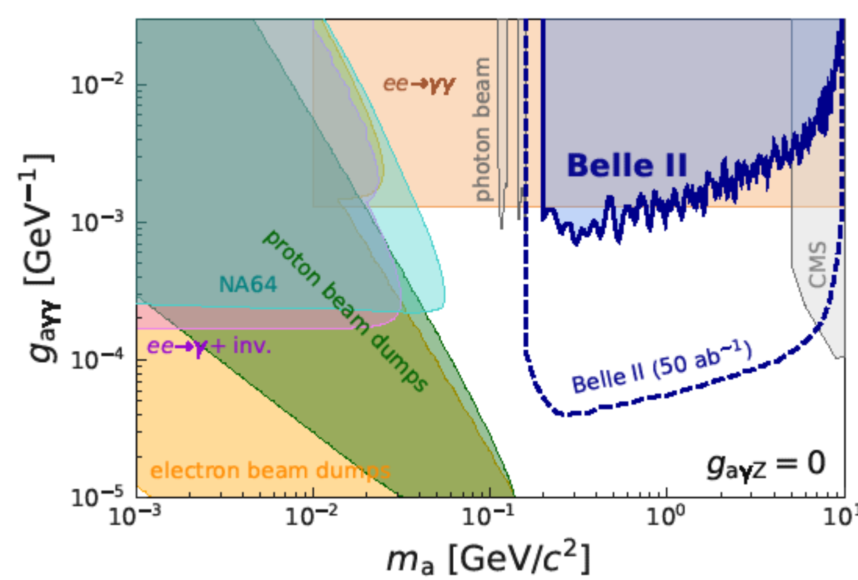
Phys. Rev. Lett. 125, 161806 (2020)



Upper limit on σ(ee → γa)



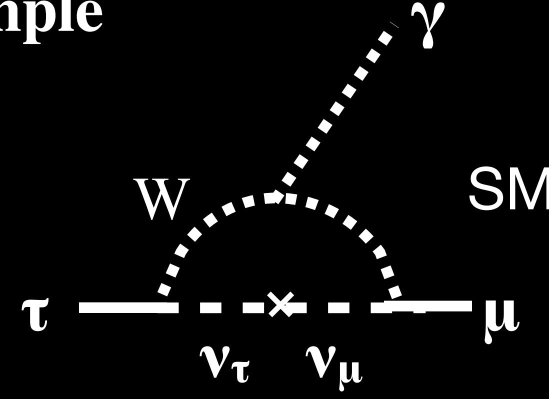
Upper limit on m_a vs $g_{a\gamma\gamma}$

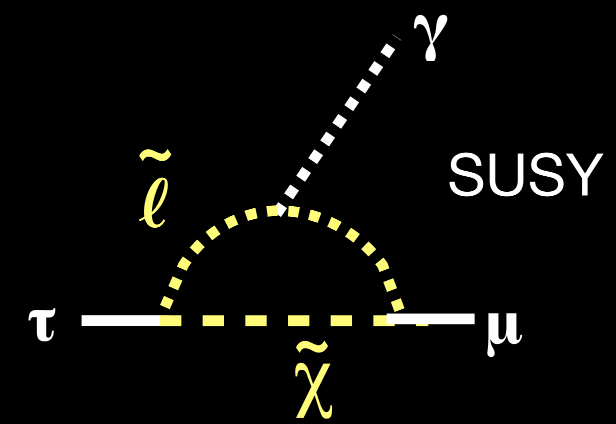


τLFV search

- Taus are also pair-produced at SuperKEKB — **σ(ττ): 0.9nb, σ(Y(4S)): 1.2nb**
- τLFV decay proceeds via neutrino oscillation in the SM (~10^{-54}) which is expected to be much smaller than **new physics contribution (10^{-7} - 10^{-10} ?)**

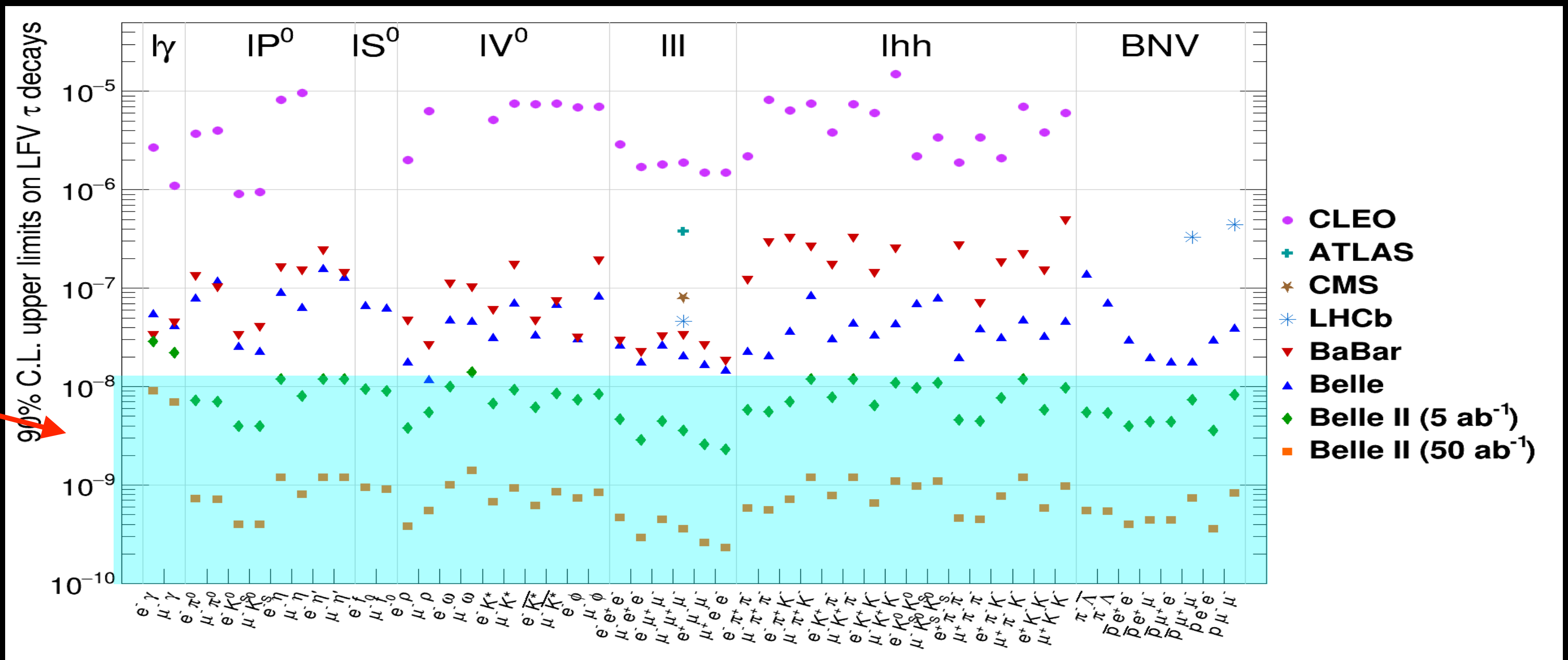
τ→μγ example





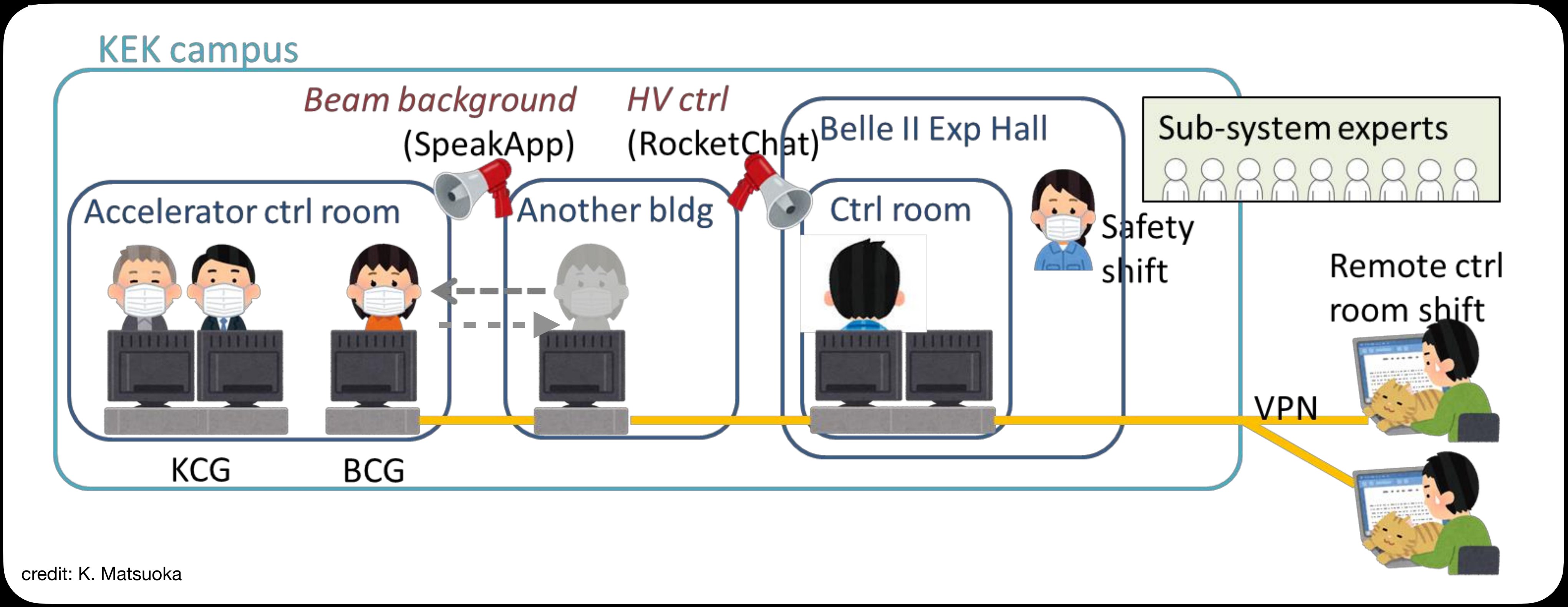
arXiv:2203.14919

Belle II is a unique experiment for τLFV



Challenges and prospect

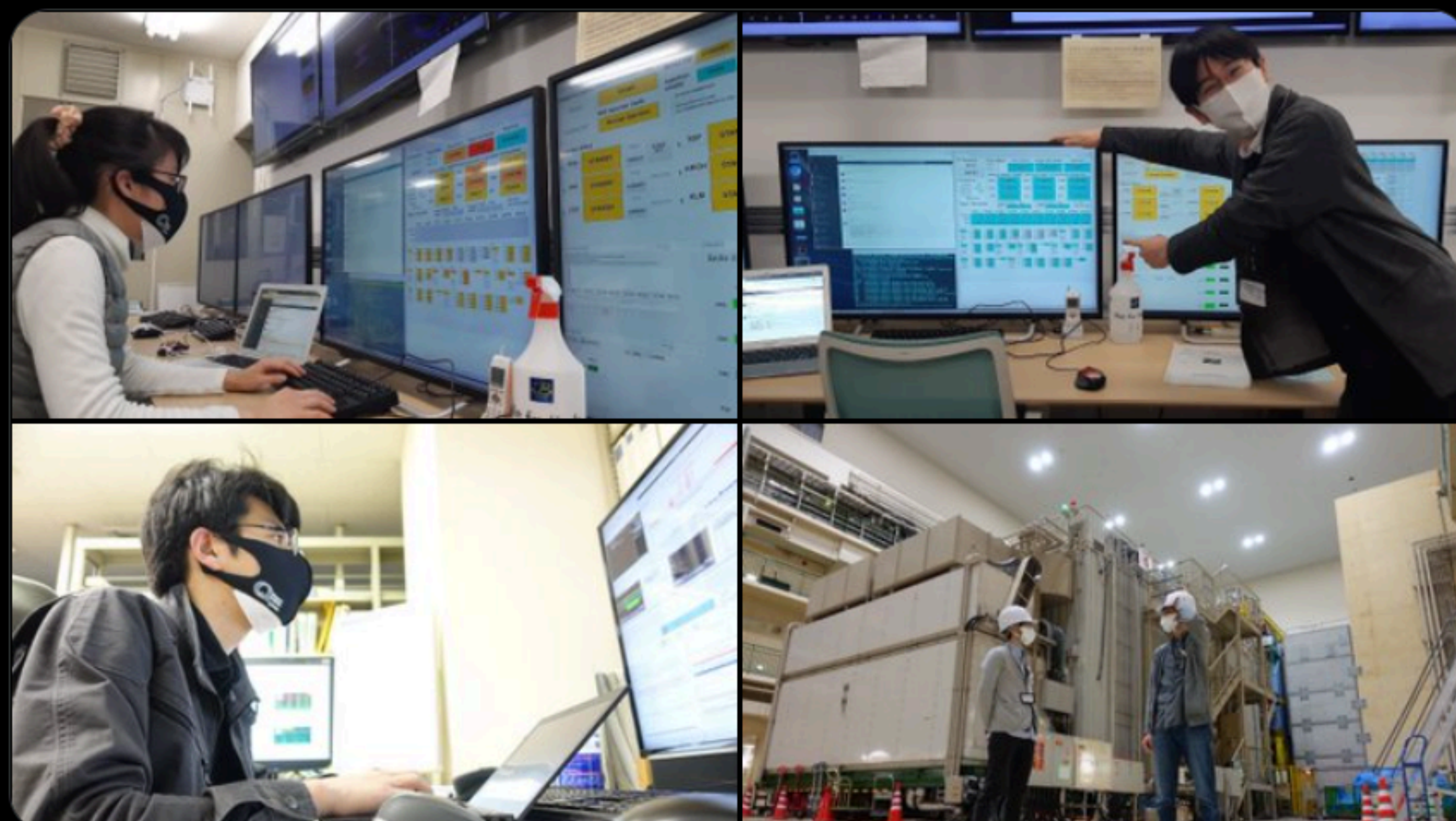
Operation in during the pandemic



- **Key to minimize the risk of infection**
- **Limited number of people (~40 people) available at KEK**
- New shift scheme implemented for detector operation
  - One operation shifter in ctrl room
  - **Two remote operation shifters (off campus)**
  - BCG shifter (going back and forth btw acc. room and another bldg)
    - Beam background monitoring
    - Lead communication with acc. operators (KCG)
  - Safety shifter and detector sub-system experts support them online

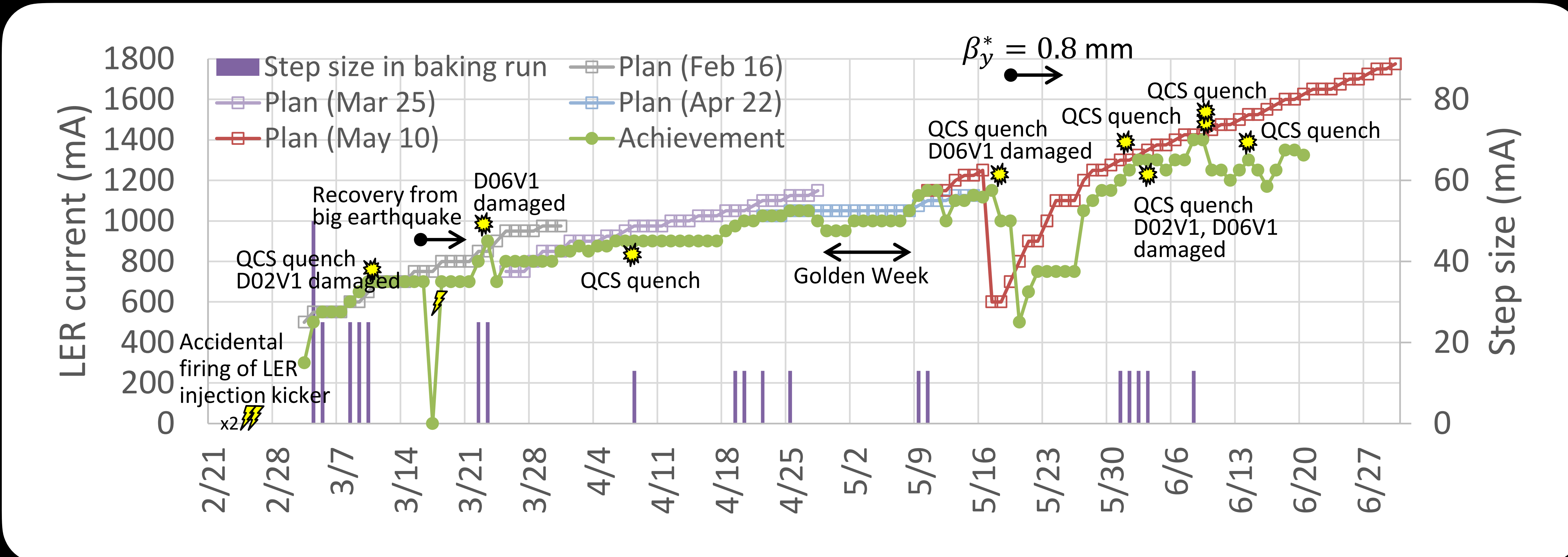
Belle II Experiment
@belle2collab

At Belle II, we work together as one team on our experiment, cooperating to prevent the spread of COVID-19, including by wearing our new #Belle2 & #SuperKEKB face masks. In these images you can see members of the Nagoya University Belle II group wearing the #Belle2Mask.



Ref: https://twitter.com/belle2collab/status/1376800773397307396

2022 run operation summary

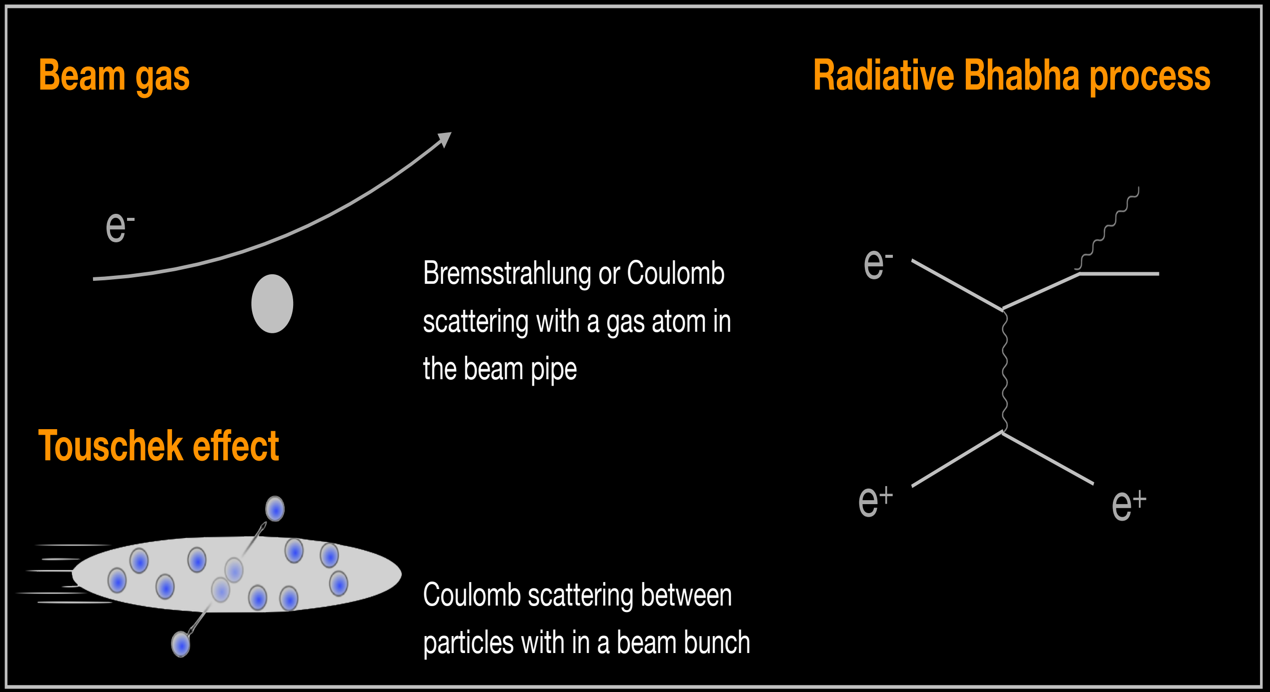


- QCS quench and/or collimator damage
  - the machine condition sometimes changes after these accidents
  - collimator damage increased the beam background and the frequency of **sudden beam loss** events.
- β_y^* = 0.8 mm operation for short period of time.
  - It was very difficult to increase the beam current because **the beam injection performance was poor** (due to short lifetime and collimator damage)

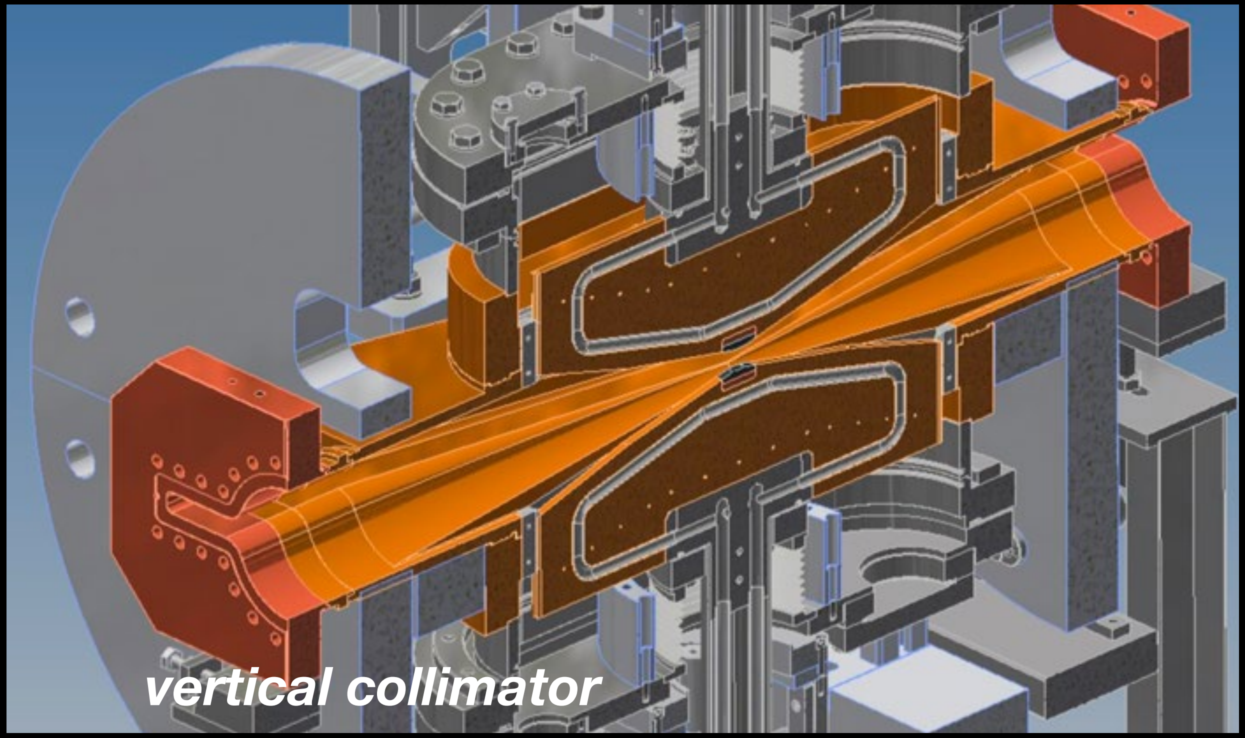
Beam Background

Beam background crucial to maintain Belle II detector performance

- Single-beam background
  - Touschek, beam-gas, synchrotron radiation, injection background
- Luminosity background
  - radiative Bhabha, two photon process



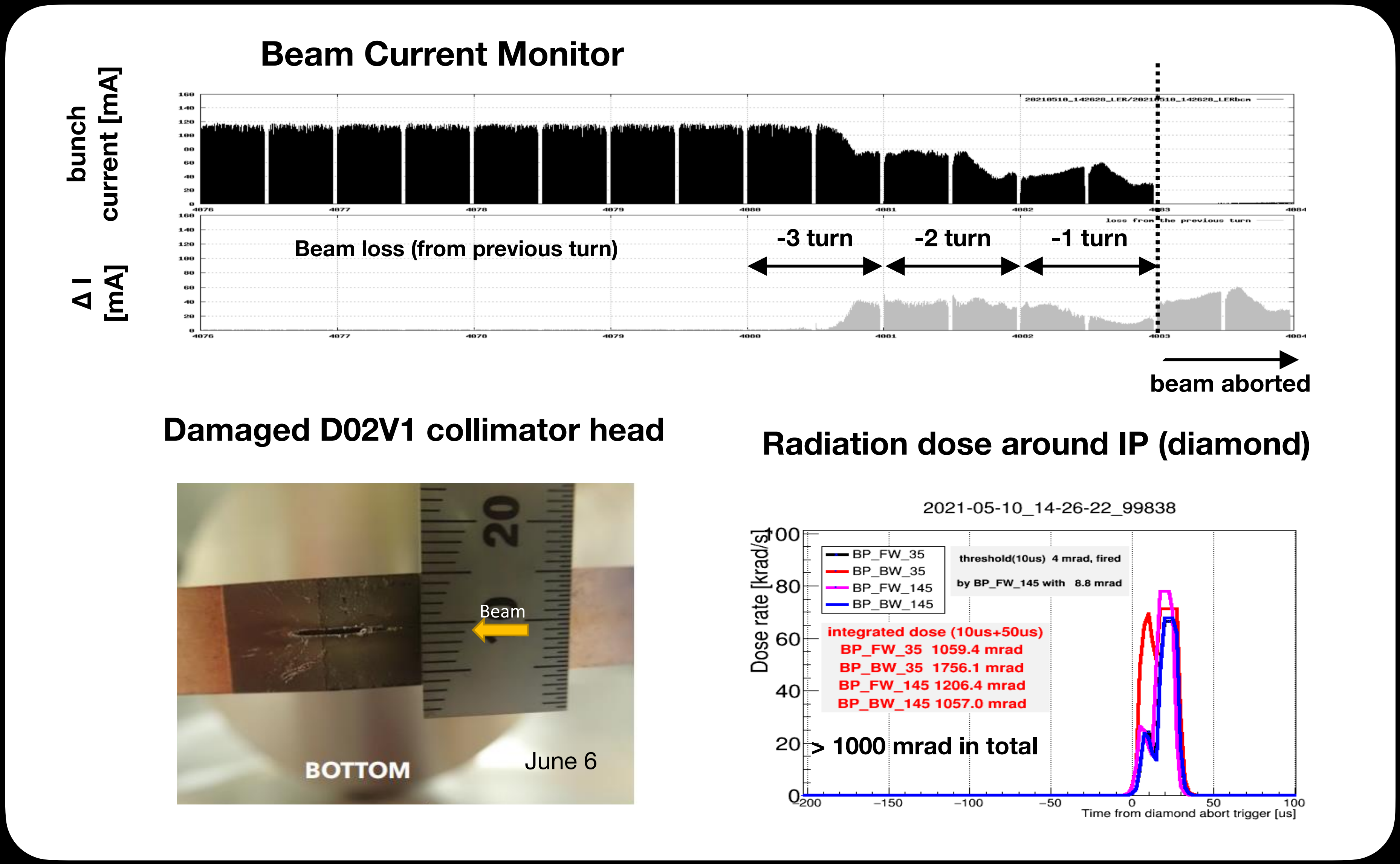
credit: K. Kojima



How to reduce beam background?

- Movable collimators
  - arc and horizontal collimators near IP
  - vertical collimators
- Shielding structures
  - tungsten in QCS and VXD volume
  - polyethylene shield for neutrons

Sudden beam loss



- "Sudden Beam Loss" (SBL) : stored beam is suddenly lost for unknown cause. It sometimes occurs in association with a QCS quench or causes severe damage on collimator head or VXD detector.
- **SBL has been a major limitation in machine operation, in particular when going for higher beam current.**

Our approaches against SBL

What can cause SBL events? We don't know the reason yet.

0. International SBL taskforce

- SBL was also observed in previous machines
- An internal task force (CERN, SLAC, IHEP, etc) was created to tackle SBL issue better understanding the mechanism behind it

But is there something we can do?

1. Beam diagnosis system

- Can we identify the location of initial beam loss? Adding beam loss monitors may give us a hint for SBL mechanism?

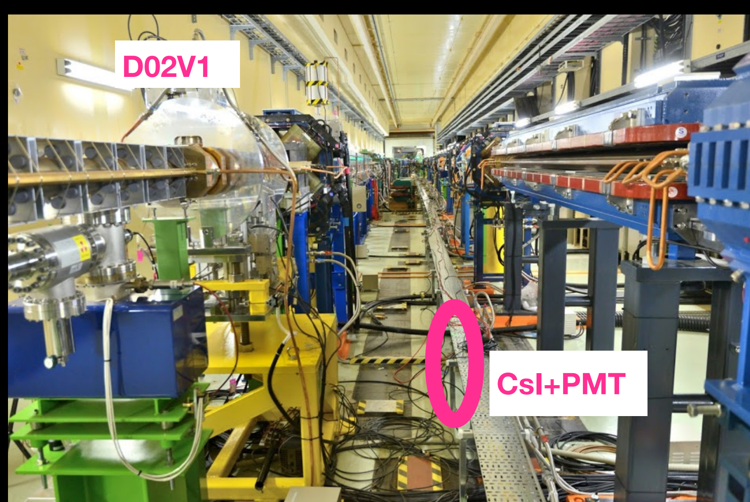
2. Fast beam abort

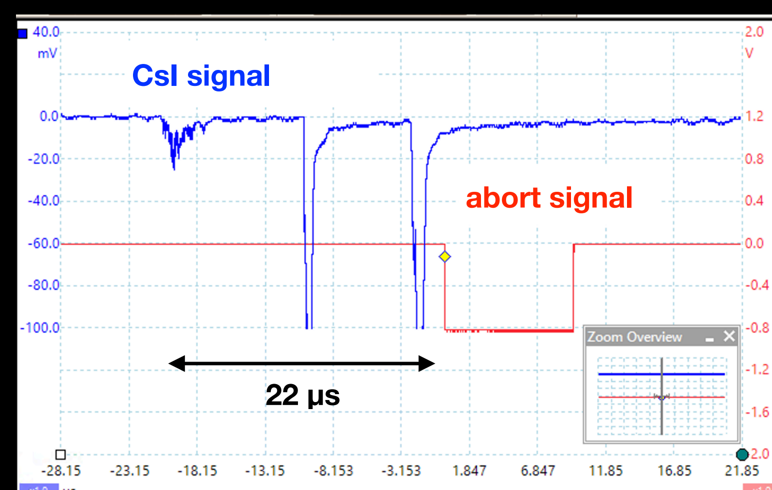
- We have to protect our hardware and detector from SBL. Radiation dose lost in the ring can be reduced by improving the speed of the beam abort.

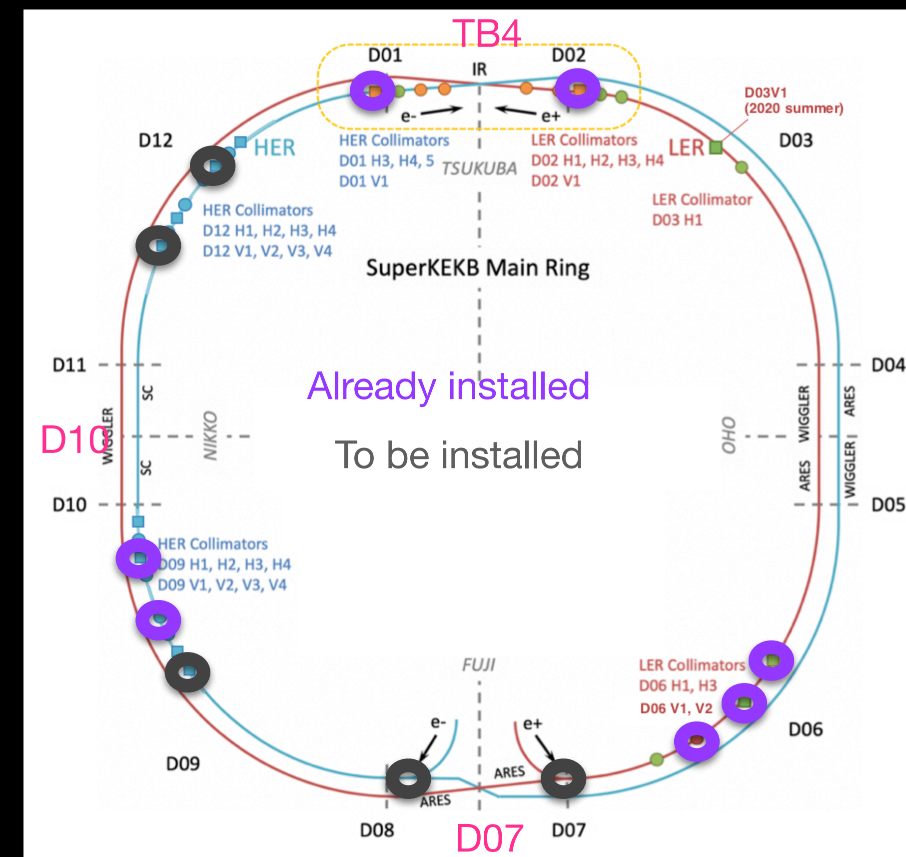
Beam diagnosis system

Adding more "eyes" to find the hint for the cause of the loss!

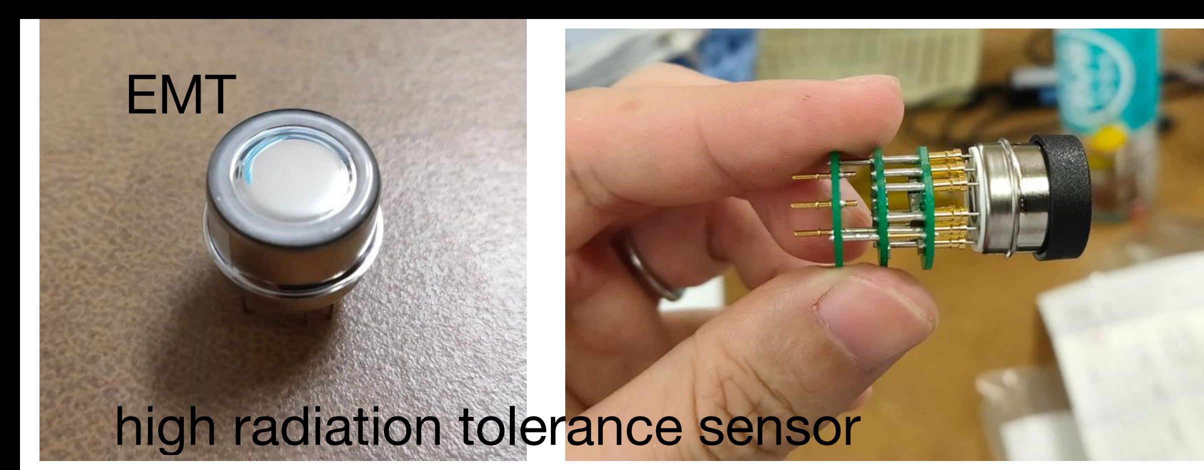
- A new beam diagnosis system is developed to identify the location of the loss w/ accuracy of 20 m in the MR (corresponding to ~100 ns)







- At present, 7 loss monitors (CsI+PMT or EMT) have been newly installed in the main ring. White Rabbit (CERN) is used for time synchronization.



Fast beam abort

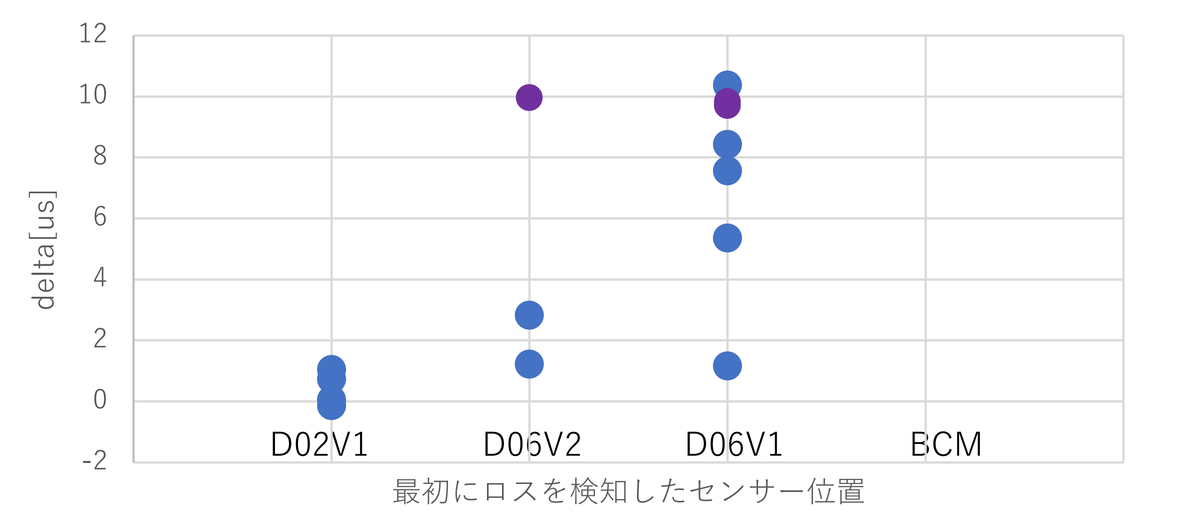
- According to the abort analysis, the first beam loss tends to be detected by D06 sensors (except for QCS quench events).

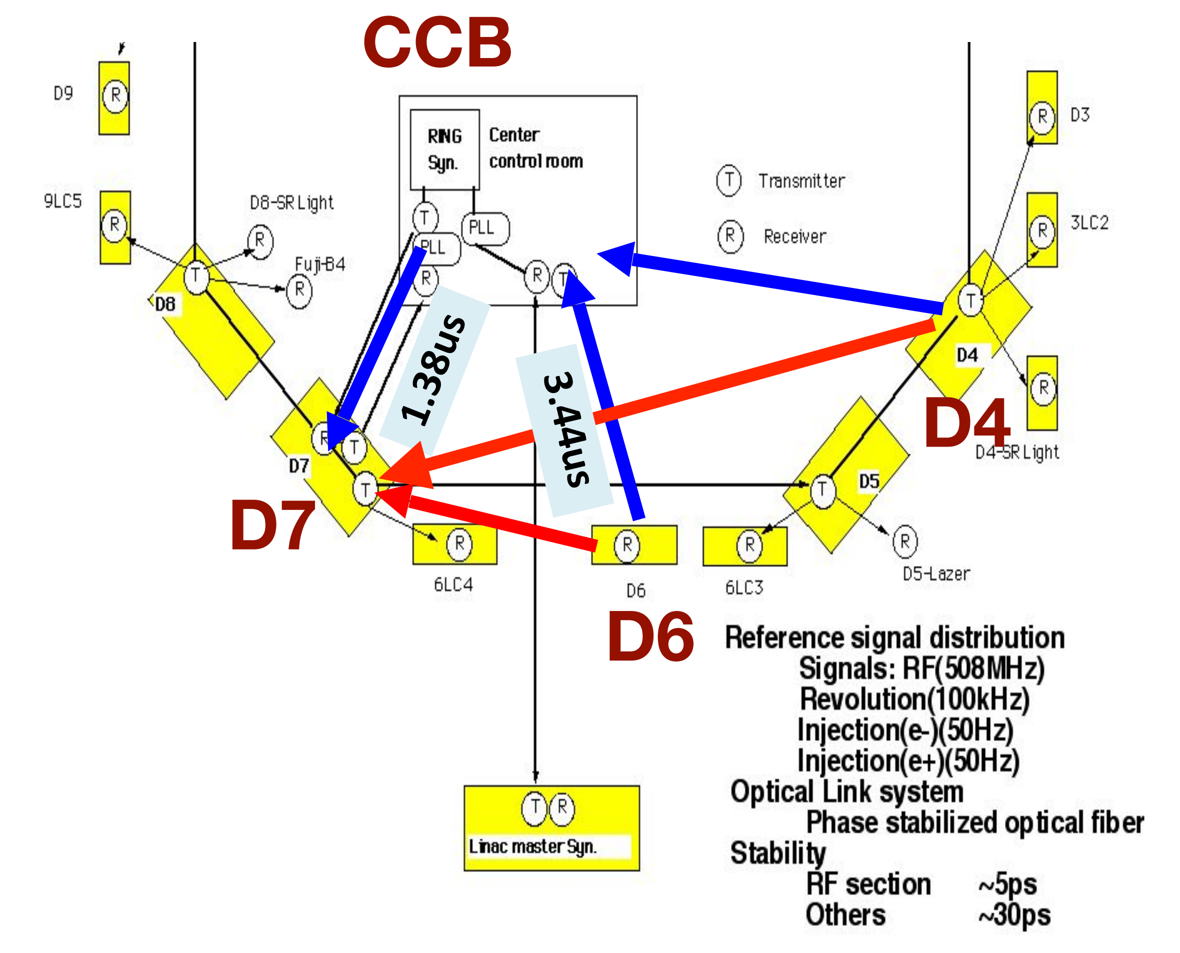
- The faster abort can be achieved by:

  ① having a sensor at better location

  ② faster sensor

  ③ shorter transmission path

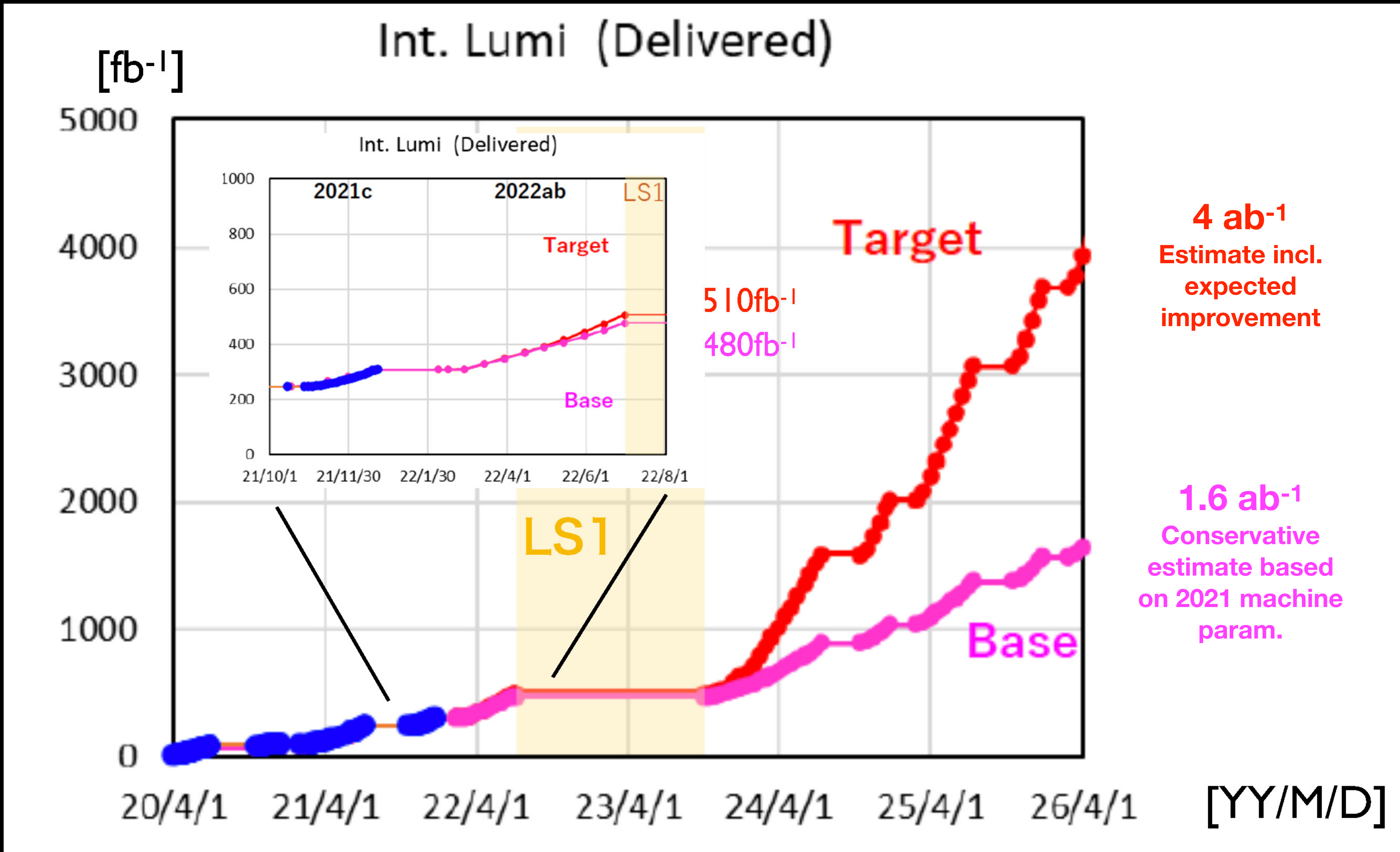




A transmission path changes

from → to →

Luminosity projection



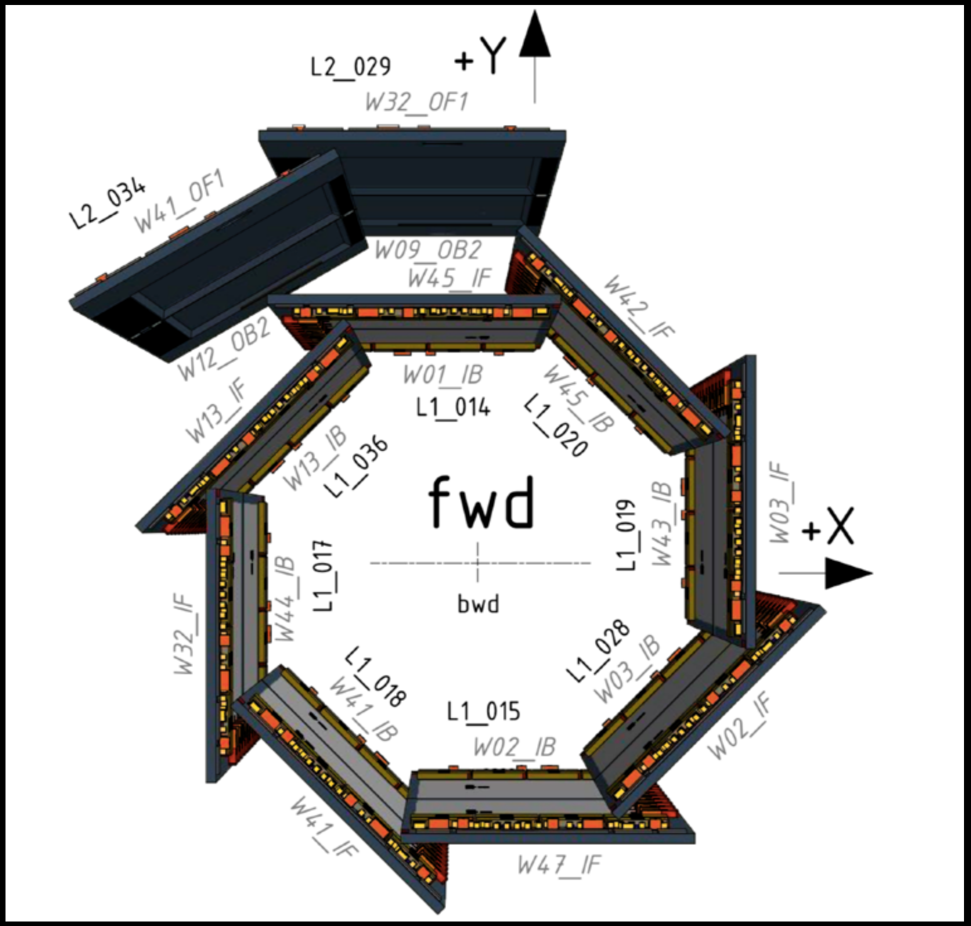
https://confluence.desy.de/display/BI/Belle+II+Luminosity

Detector/machine work in LS1

- PXD2 installation
  - Current PXD is incomplete (10 out of 20 ladders installed)
  - PXD will be fully re-installed in 2022 shutdown (→PXD2).
  - New IP chamber also in production
    - Additional synchrotron radiation/neutron shielding

→ **Belle II detector will be complete!**

- TOP MCP-PMT replacement
  - Large beam background causes QE degradation on old type PMTs.
  - Some PMT will be replaced by life-extended ALD PMTs
- Collimator system upgrade
  - Non linear collimator installation (LER)
  - Robust collimator head (LER)
- Beam pipe upgrade at injection point (HER)



Due to problems in ladder gluing, only half of designed PXD (full L1+ 2 L2 ladders) was installed in 2018/2019.

IR upgrade (long term)

- IR upgrade (QCS and its beam pipes) is essential to achieve 50 ab^{-1} (and peak luminosity of > 6 x 10^{35} $cm^{-2}s^{-1}$)
  - Strong beam-beam effect observed at high-bunch current
  - Narrow physical aperture in QCS beam pipes
  - Large beam background at Belle II
  - Narrow dynamic aperture at high-bunch current at small β_y^*

Details are still under discussion, these items are challenging

	Aim	Possible countermeasures
(1)	Increase injection power (efficiency)	Linac upgrade to designed specification
		Large physical aperture at electron injection point (HER)
		Linac upgrade beyond designed specification
(2)	Improve dynamic aperture	Rotatable sextuplole magnets
		Perfect matching
		QCS modification (Option#1): Move QC1RP to far side of IP
		Large scale QCS modification (Option #8)
(3)	Improve physical aperture Lower BG	QCS cryostat front panel modification and additional shield to IP bellows
		Optimization of collimator location
		QCSR beam pipe enlargement (Option#3)
(4)	Relax TMCI limit	Non-linear collimator
(5)	Improve stability	Robust collimator
		Upgrade of beam abort system and loss monitor system
(6)	Anti-aging measures	Preparation of standby machines and spares, repair of facilities, etc.

credit: Y. Suetsugu

Summary

- SuperKEKB/Belle II is a new generation B-factory having unique capabilities for new physics search.
    - CP violation
    - Rare decay
    - Dark sector
    - tau physics

- Machine operation going well so far and 427 fb^{-1} has been collected.
    - LER/HER: 1460/1143 mA
    - n. bunch: 2346 bunches (2-bucket spacing)
    - Peak luminosity: 4.65×10^{34} $cm^{-2}s^{-1}$

- During the LS1, detector and machine upgrade going on.

stay tuned.

Thank you!