SuperKEKB/Belle II:

design, status and prospect

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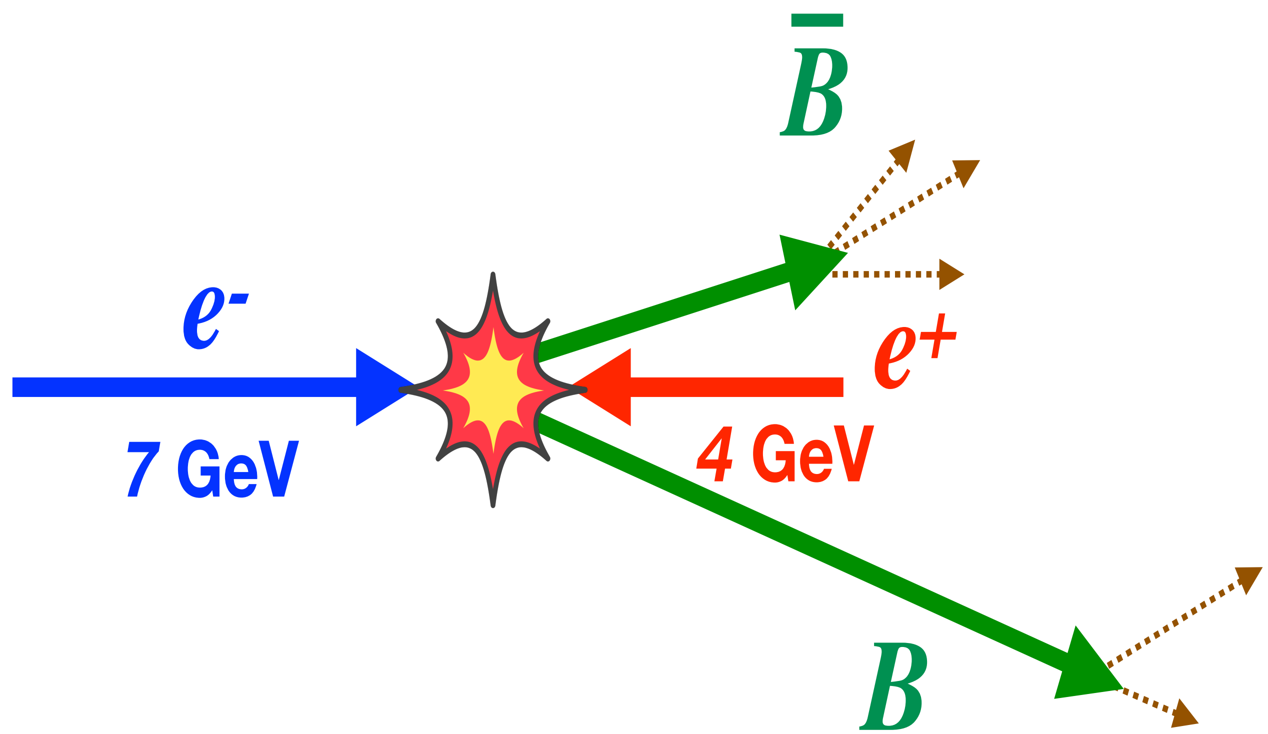
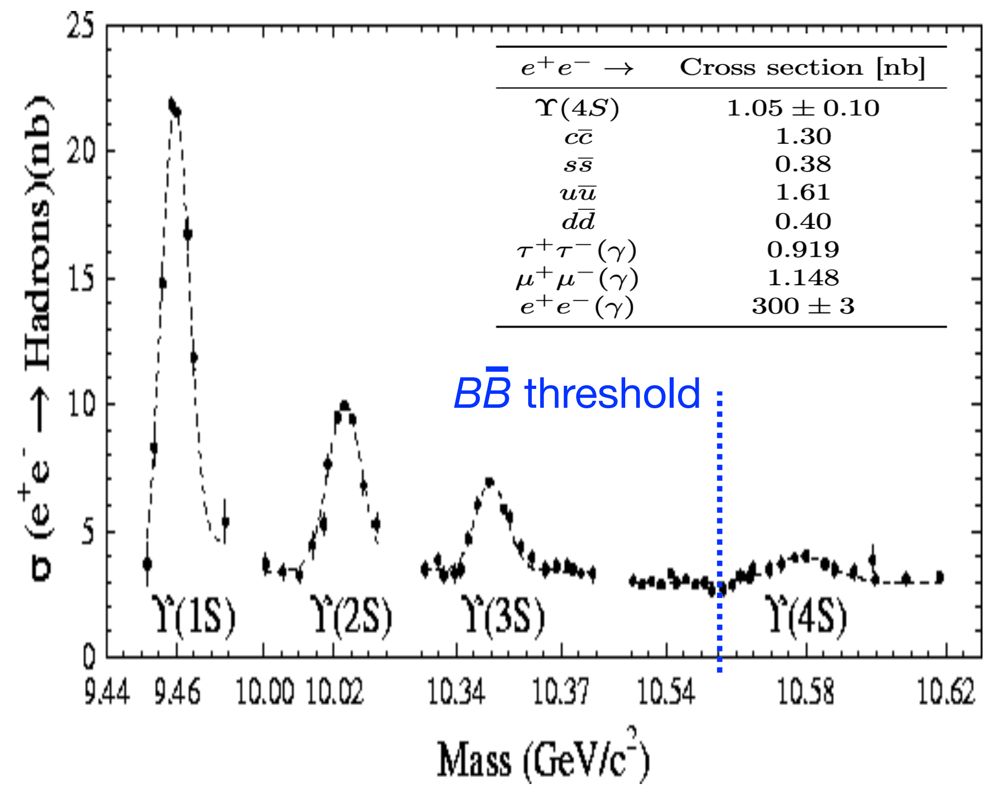
25th August 2022, APPC15

Introduction — B-factories

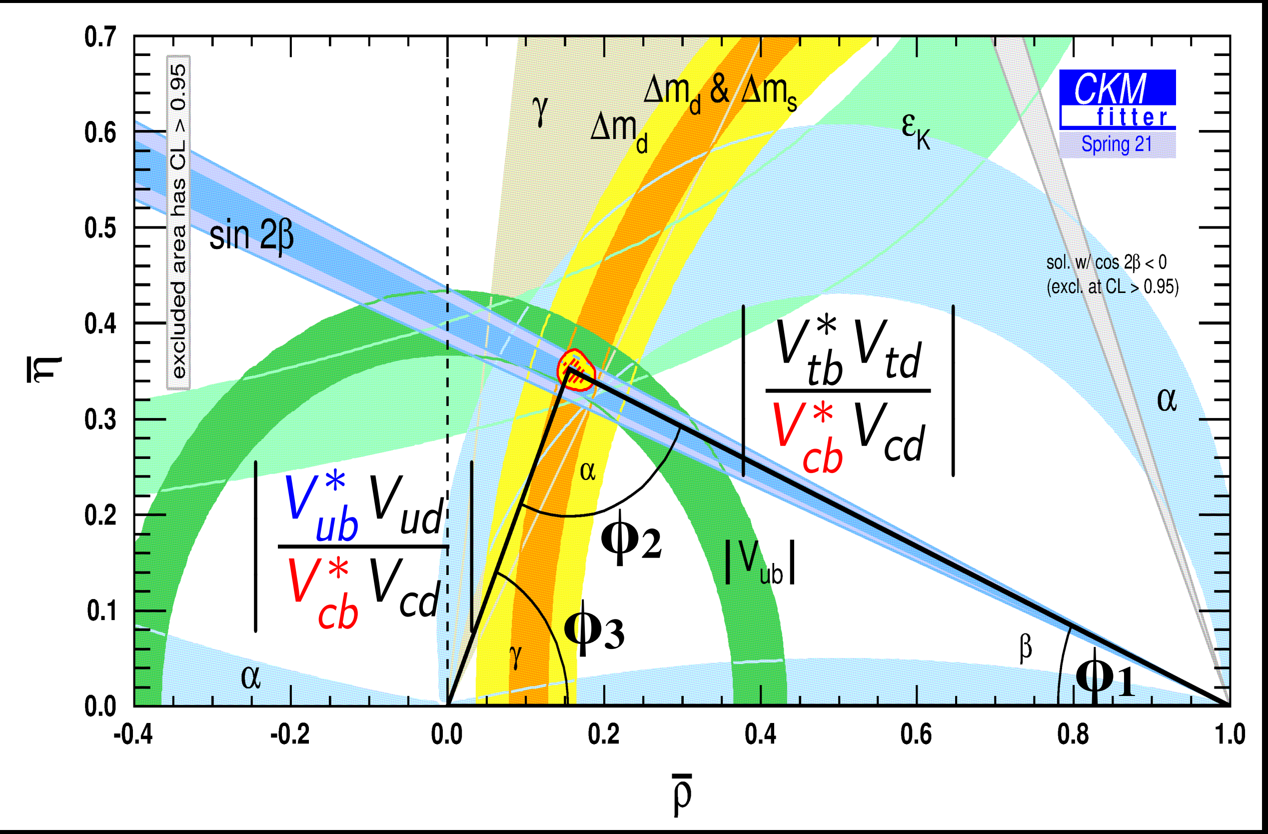




In B-Factories, e^+ and e^- collide at 10.58 GeV to make *Y(4S)* resonance decaying into B^+B^- and $B^0\bar{B}^0$ in 96% of the time. Belle (~1 ab^{-1}) and BaBar (~0.5 ab^{-1}) played a crucial role in establishing large ***CP violation*** in the B-meson system in the SM and constrained on the ***CKM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

Introduction — 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

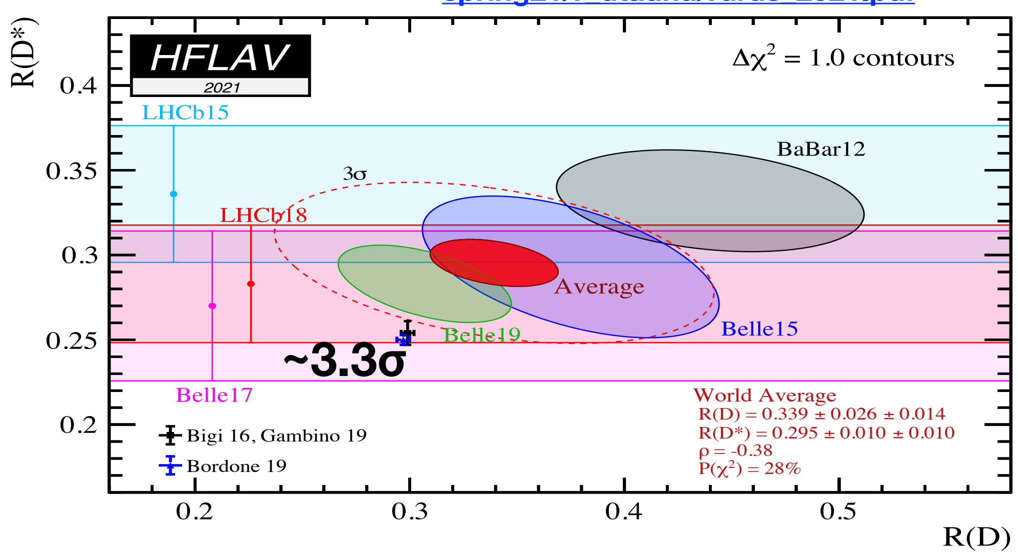
arXiv:1808.10567

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

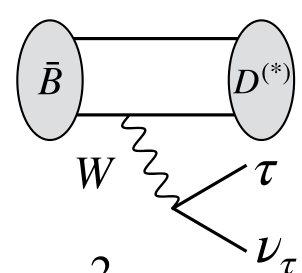
Introduction — B anomaly

$b \to c\tau\nu$

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



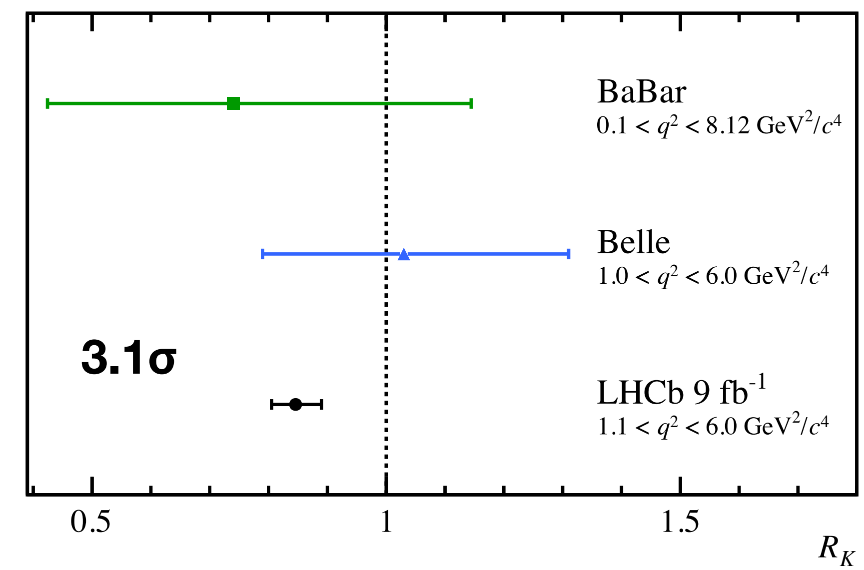
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$



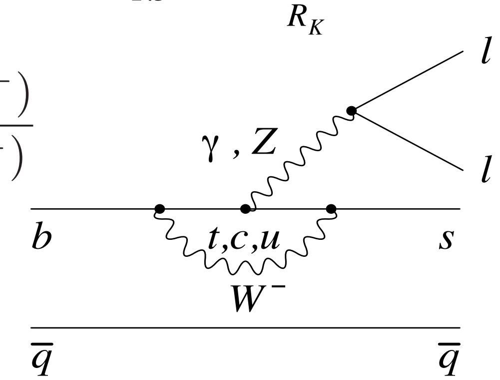
tree BF~O(10^{-2})

$b \to s\ell\ell$

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 flavor universality (LFU)**.

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

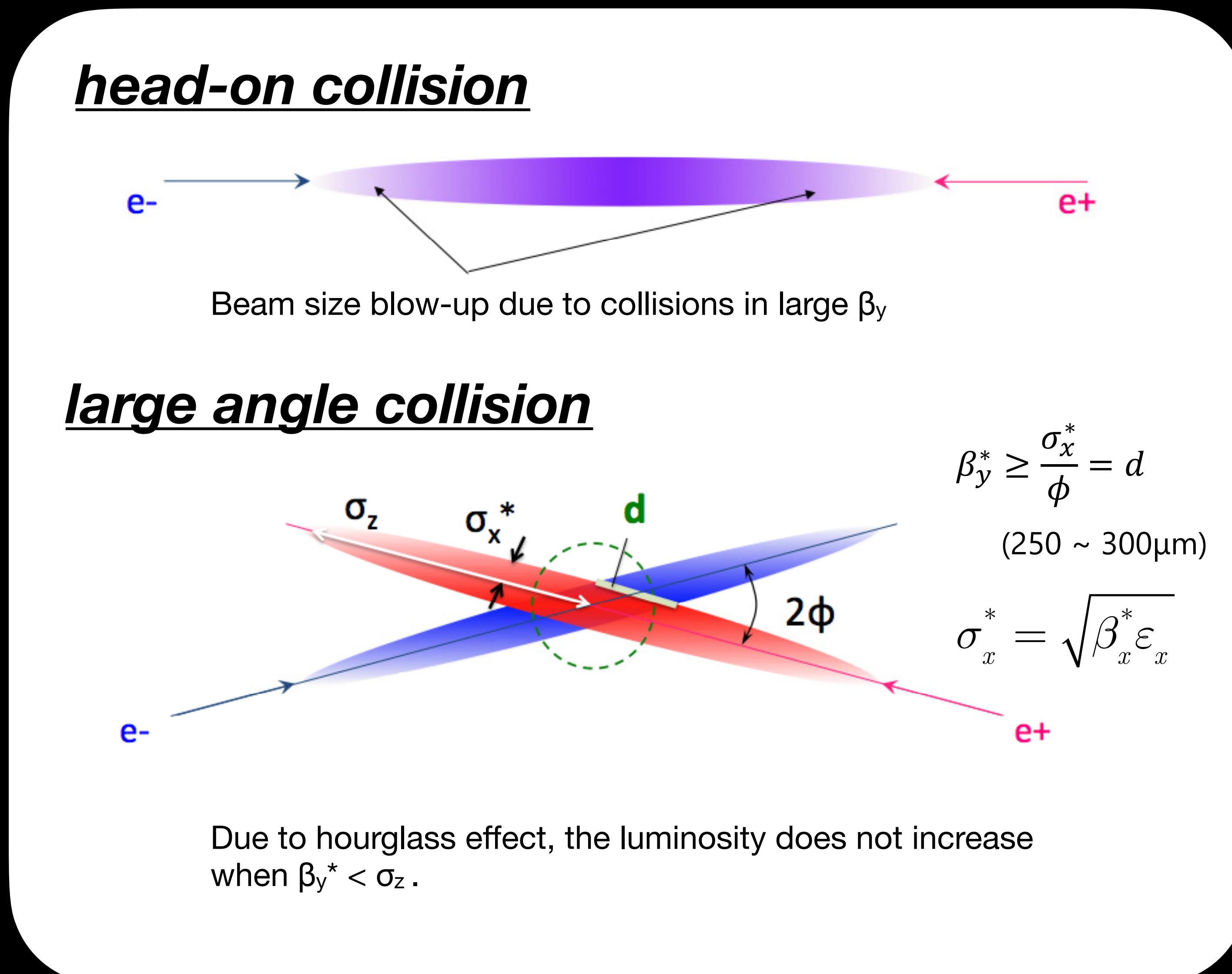
These anomalies must be well verified. Belle II can measure them independently.

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)**

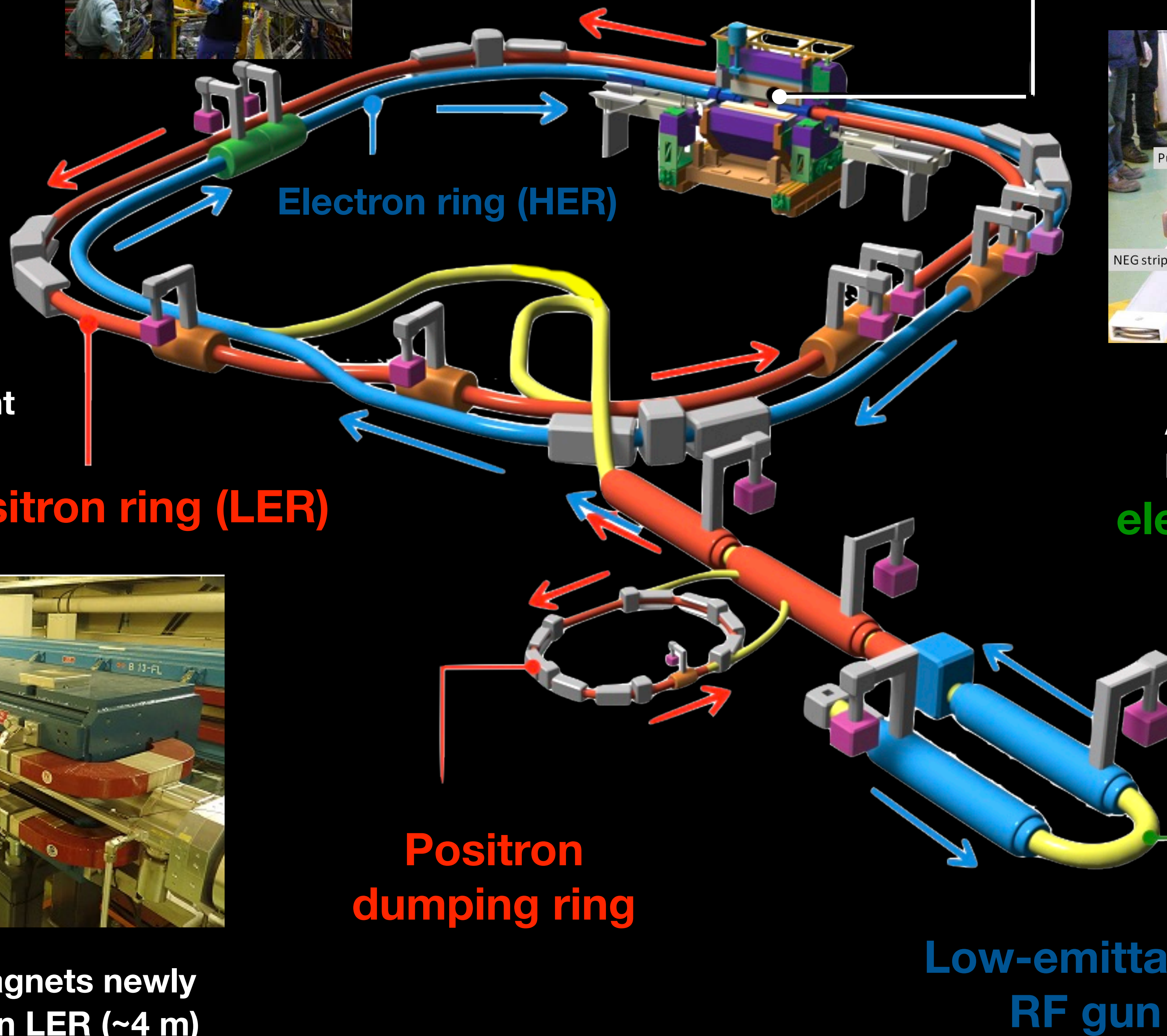


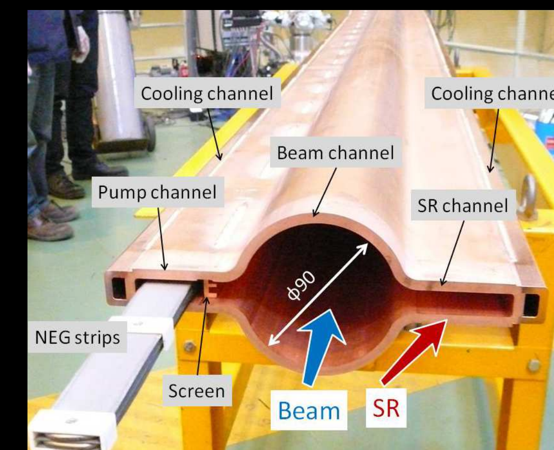
- In the nano-beam scheme with large crossing angle, effective bunch length (*d*) can be much shorter (β_y^* ~σ_z)
- Small β_x^* and small emittance (ε_x) are also the key → **positron DR**
- Positron beam energy from 3.5 to 4.0 GeV to increase beam lifetime (still ~O(10) min maximum)

Upgrading to “**Super**”KEKB

QCS magnets

RF reinforcement



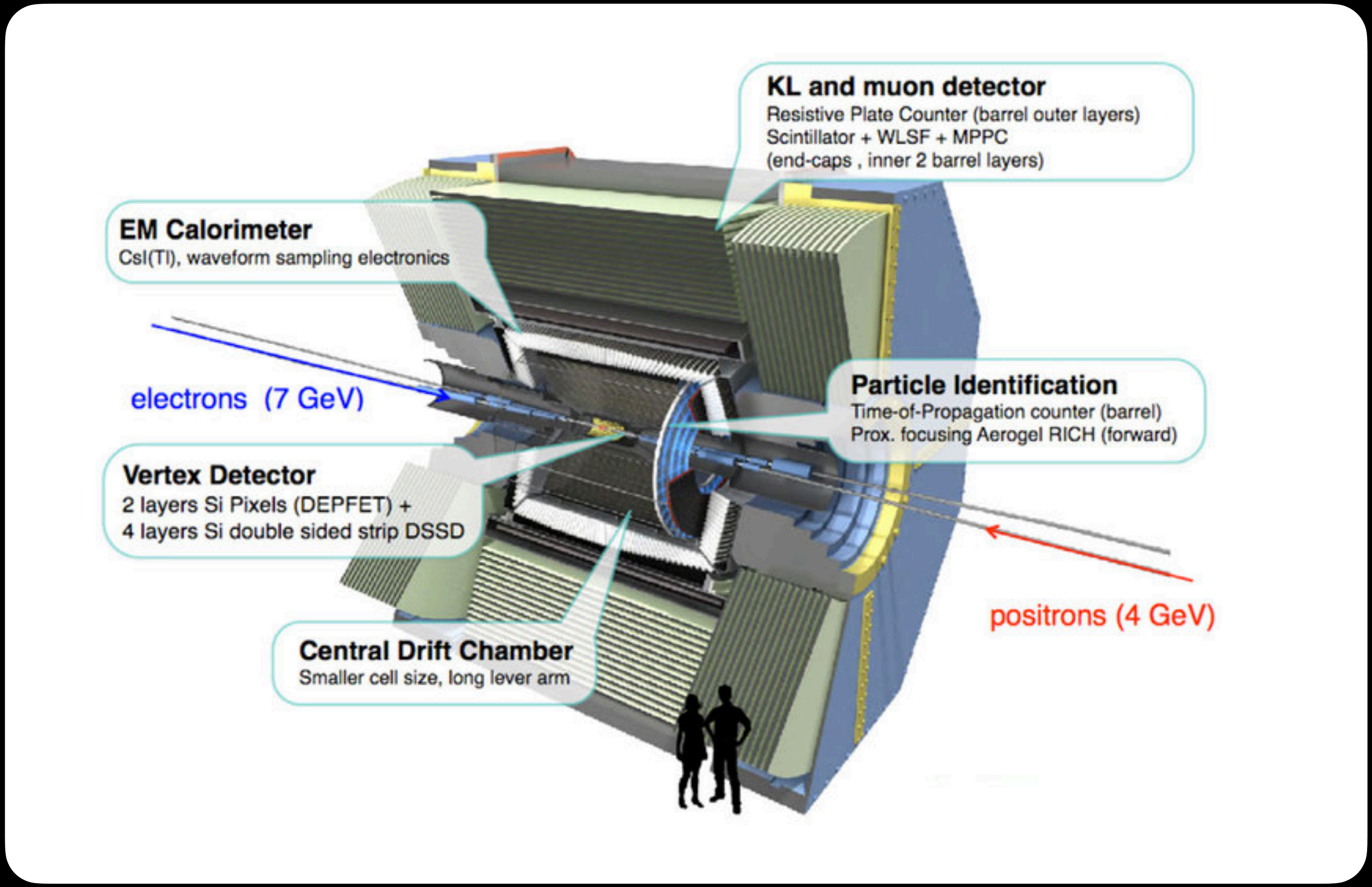


Ante-chamber beam pipe

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)

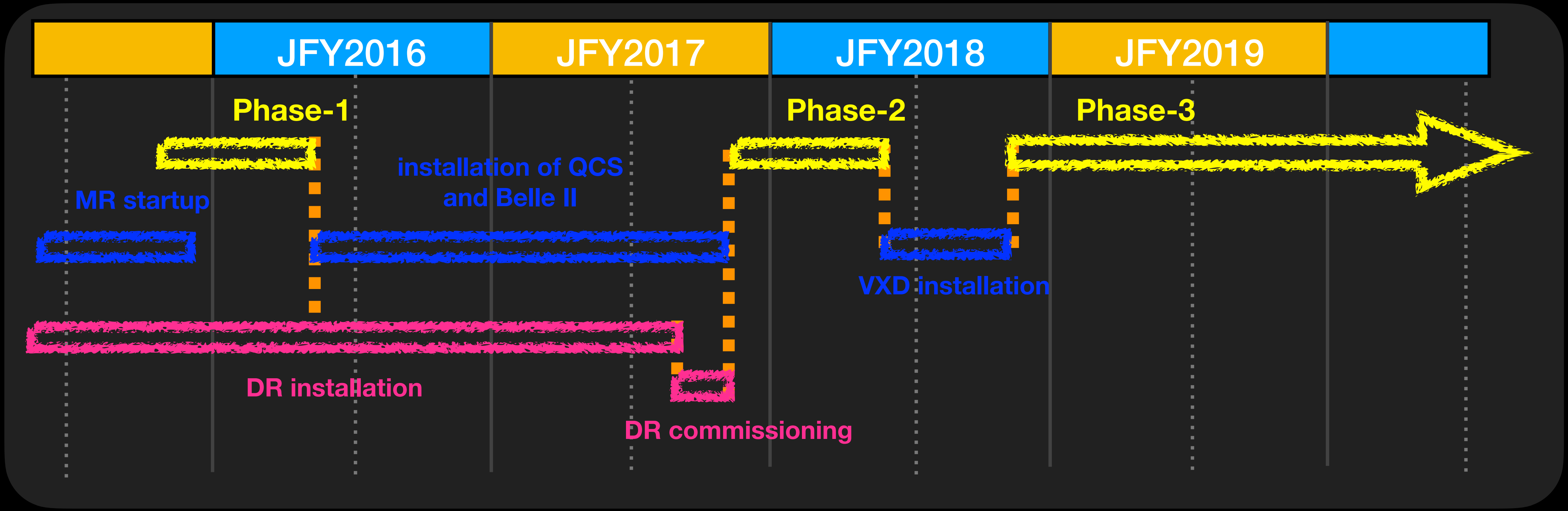
Improved PID and energy measurement

- 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)

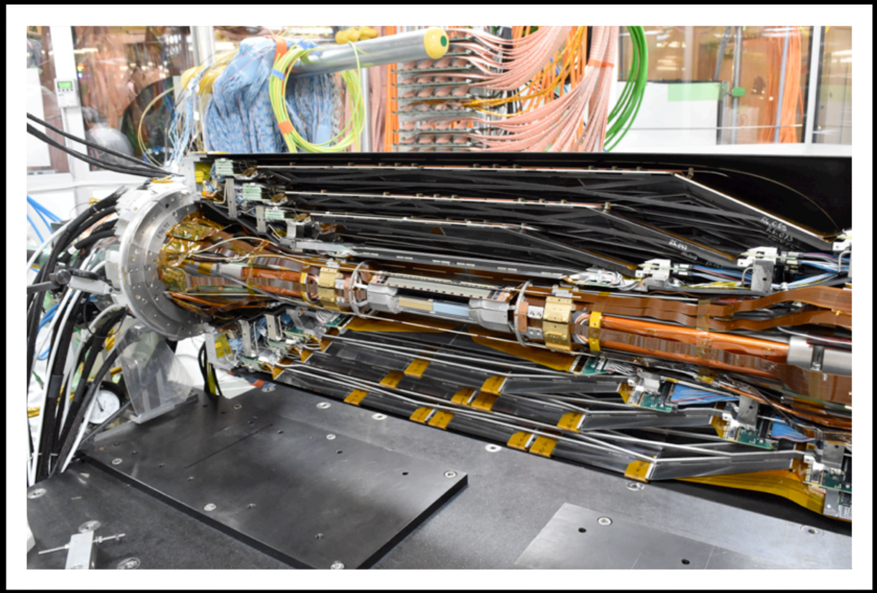
Other improvements

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

Machine and detector commissioning

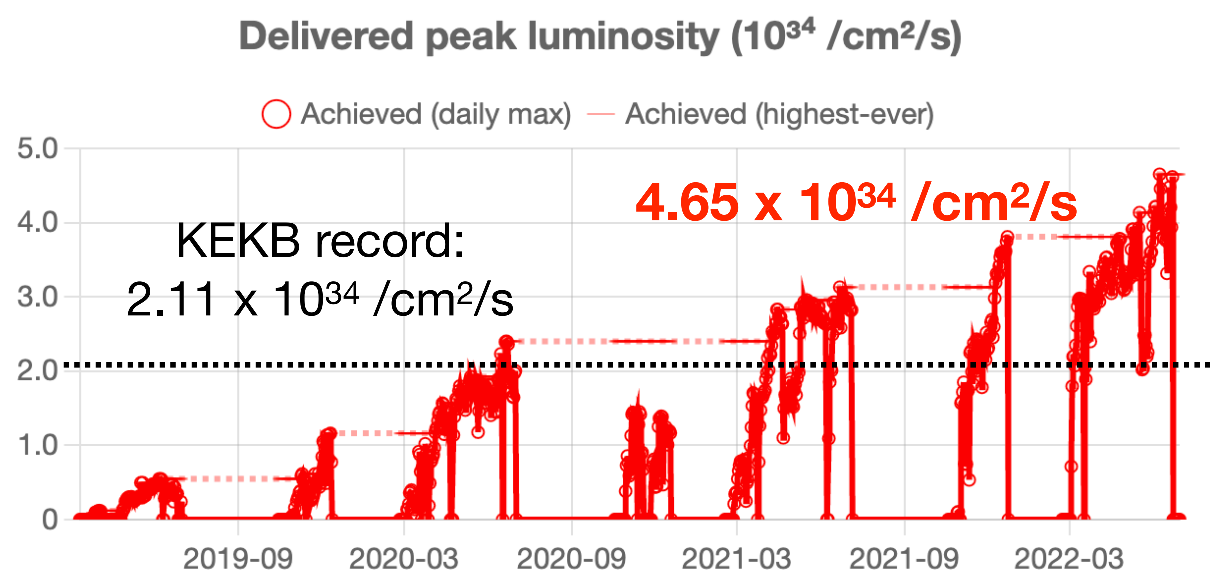


- **Phase-1: Startup of the machine:**
  - commissioning without collision
  - low emittance beam tuning
  - vacuum scrubbing
- **Phase-2: Commissioning w/o VXD**
  - β* squeezing at IP
  - DR commissioning
  - collision tuning
- **Phase-3: Commissioning w/ full Belle II detector**
  - collision tuning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

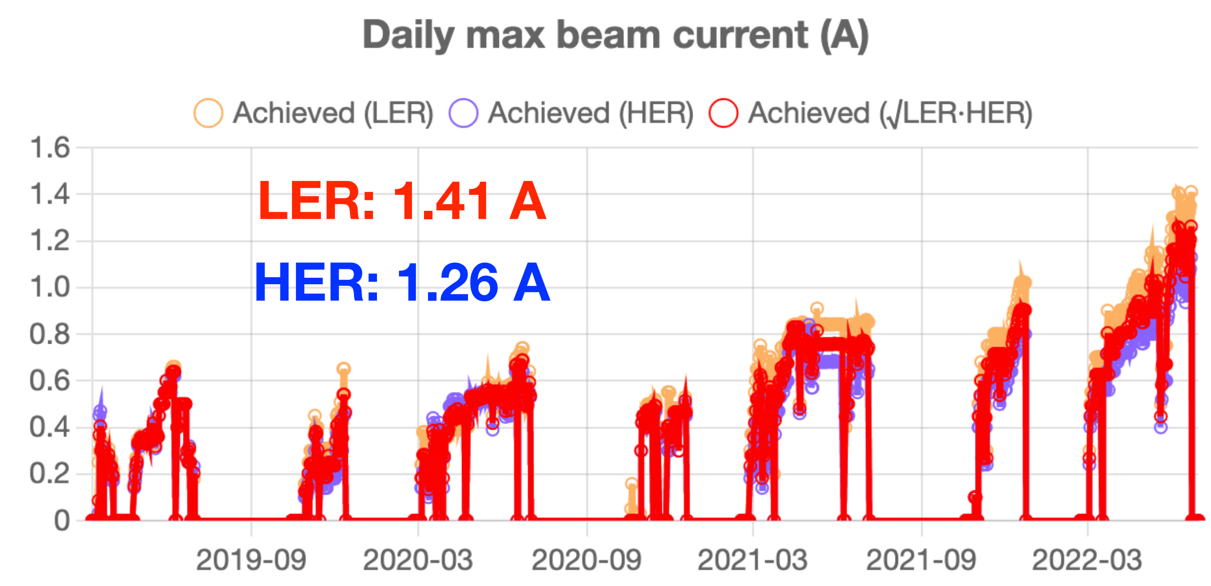


VXD detector

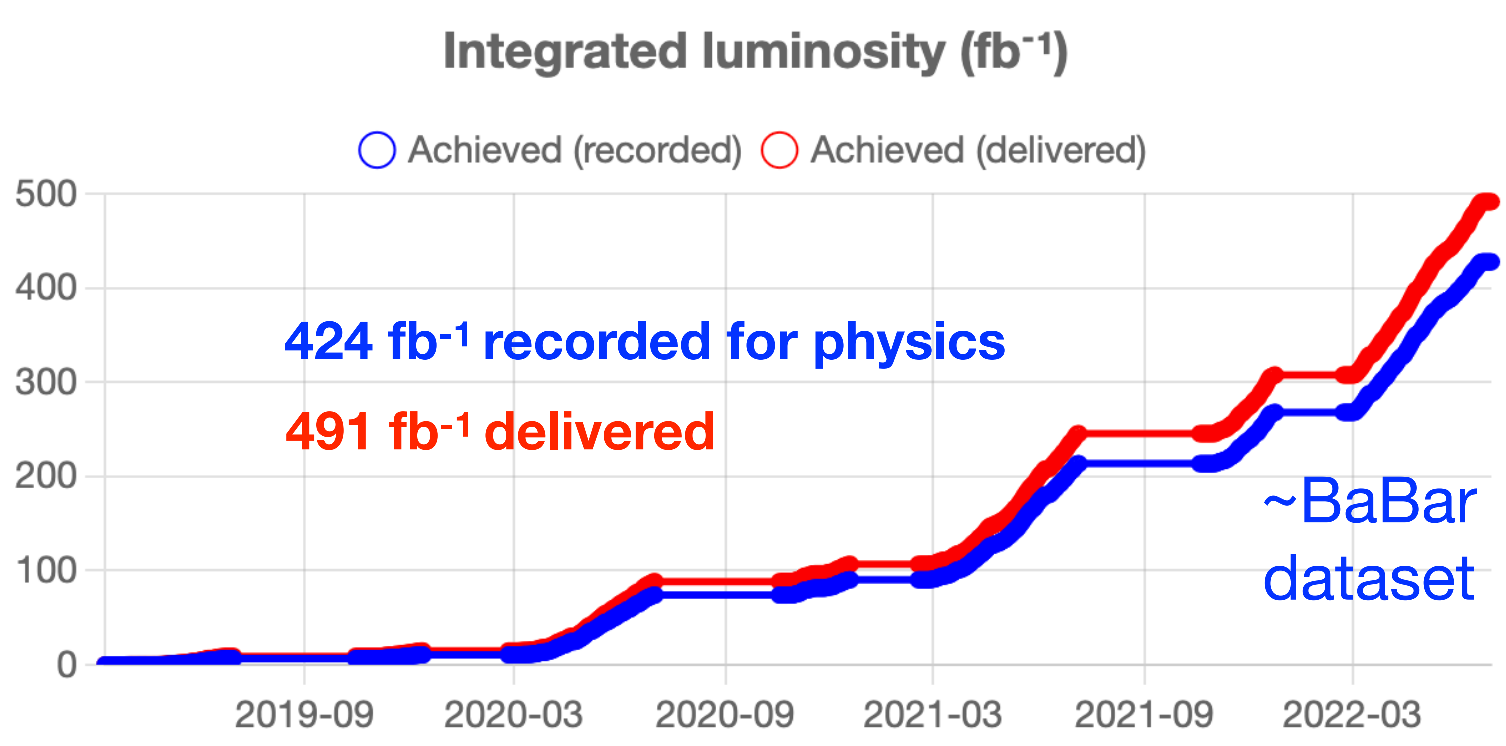
Phase-3 operation summary



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

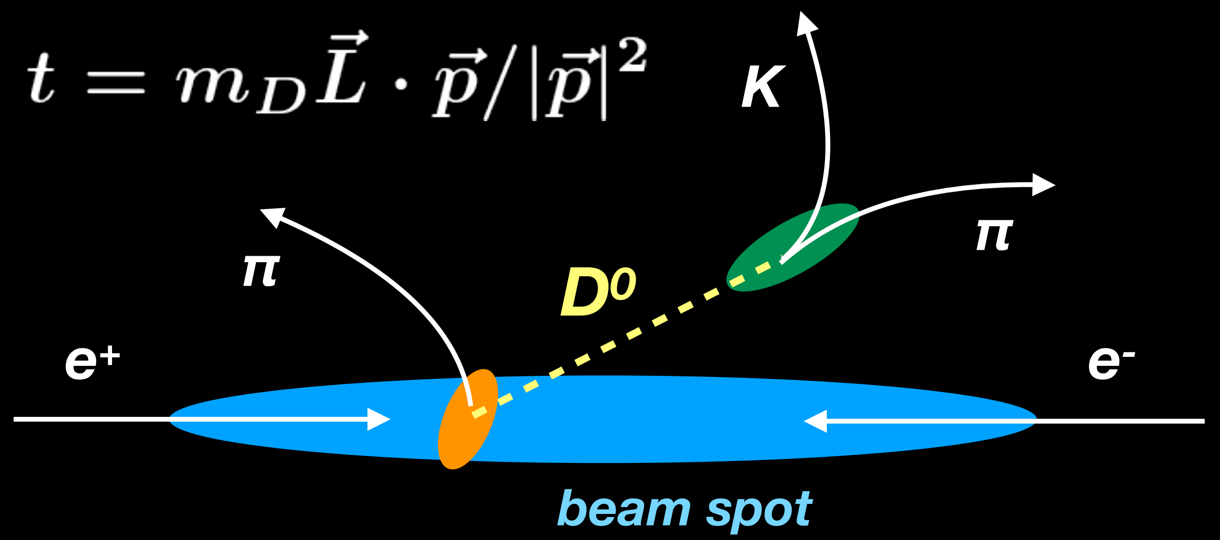
K11.02: Measurements of charm lifetimes at Belle II by Doris Kim

The lifetime meas. nicely demonstrates performance of vertex reconstruction.

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

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

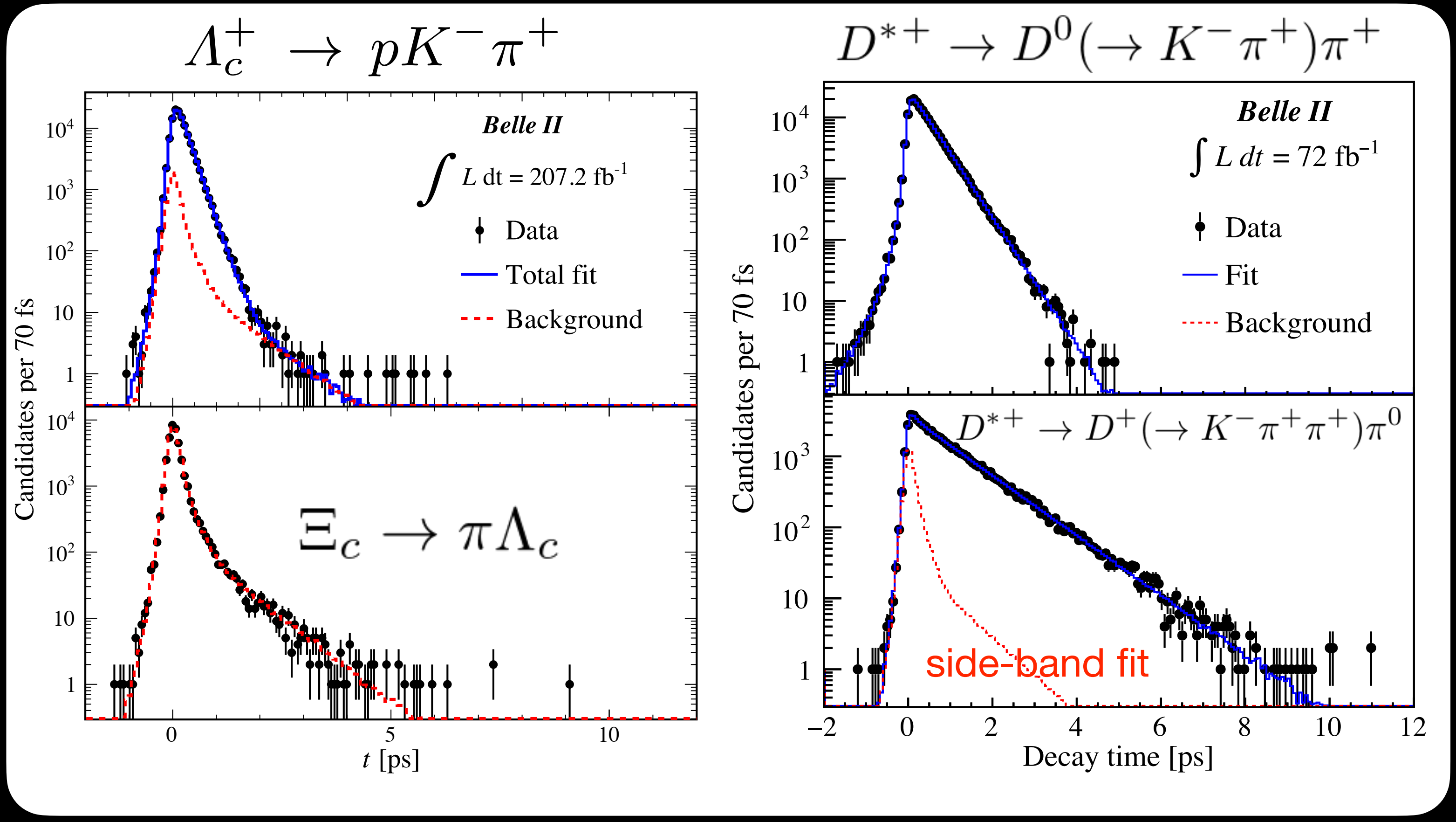
$$t = m_D \vec{L} \cdot \vec{p}/|\vec{p}|^2$$



Backgrounds are estimated from the side-band or simulation.

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

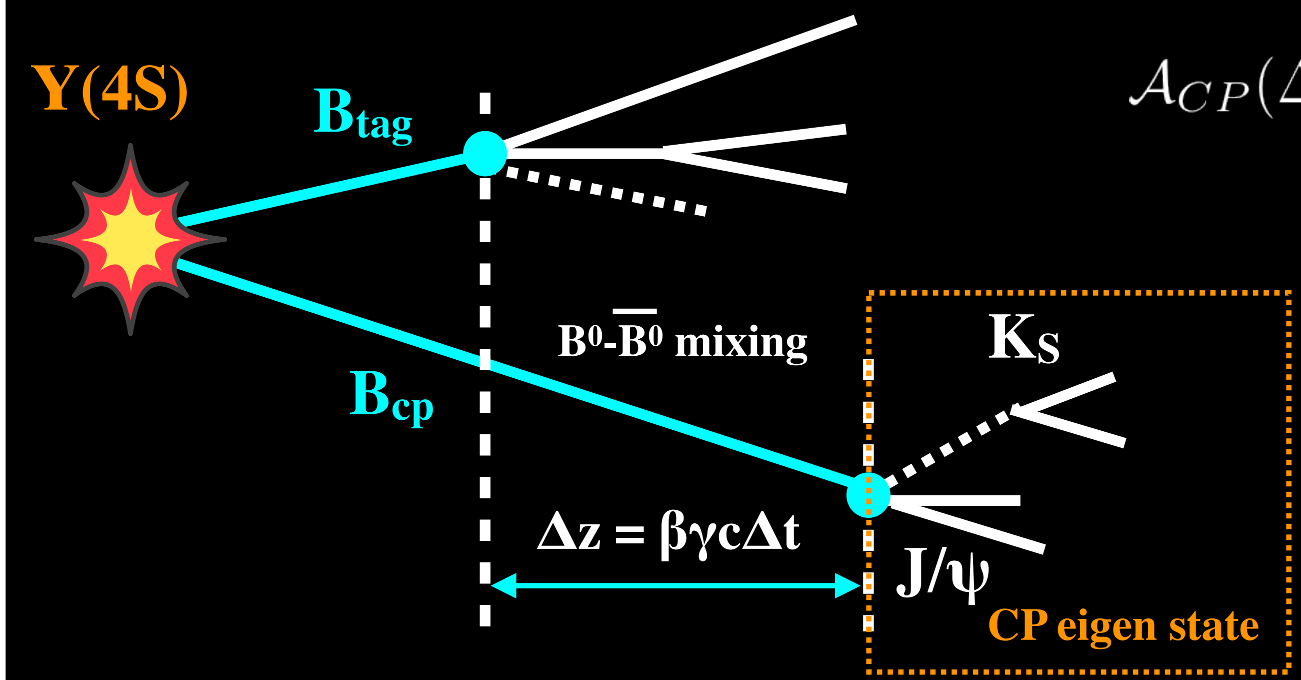
World best meas. achieved thanks to new PXD layers.



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

Time dependent CP asymmetry

K11.03: Recent Belle II results on decay-time-dependent CP violation by Ming-Chuan Chang



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

$$= \mathcal{S}_{CP}\sin(\Delta m_B \Delta t) + \mathcal{A}_{CP}\cos(\Delta m_B \Delta t)$$

mixing induced CPV

$\mathcal{S}_{CP} = \sin(2\phi_1)$

B → $J/\psi K_S$

B ↘ B̄ ↗ $J/\psi K_S$

Direct CPV

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

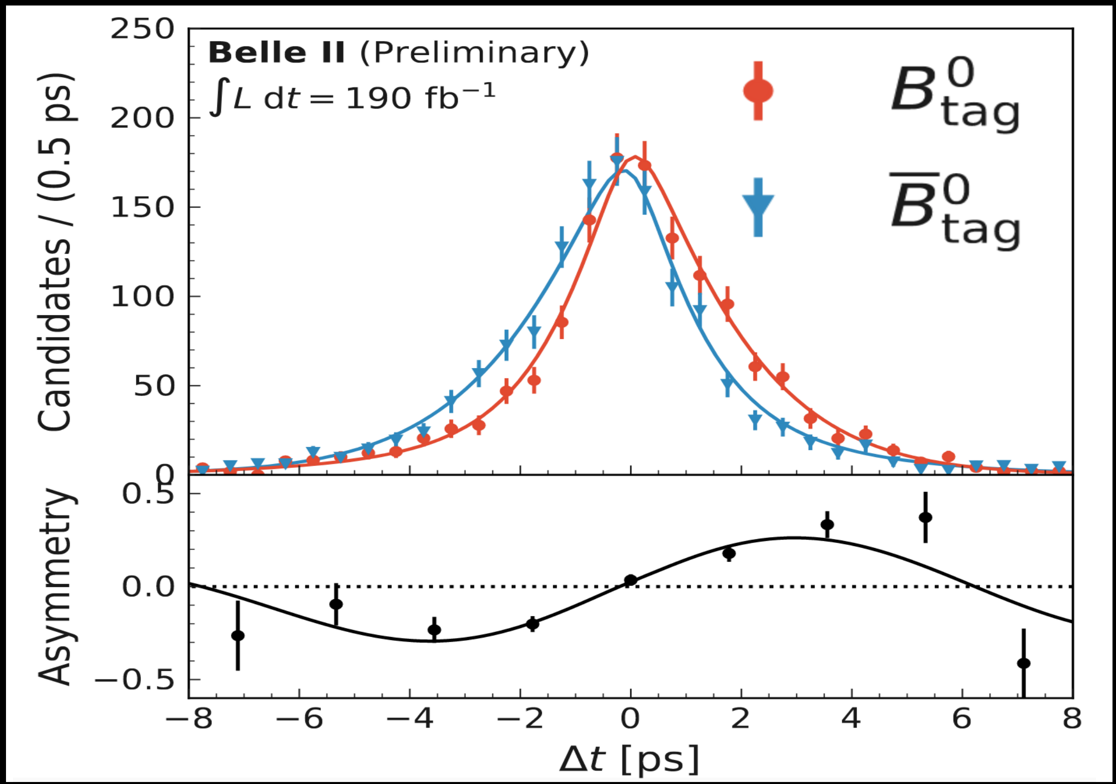
|B> → |f>

≠

|B̄> → |f>

* S, A: defined by final state

A_{CP} = 0 (tree level)



BELLE2-TALK-CONF-2022-080

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

b→cc̄s has a small unc. on theo. and exp.

→ golden mode for ϕ_1

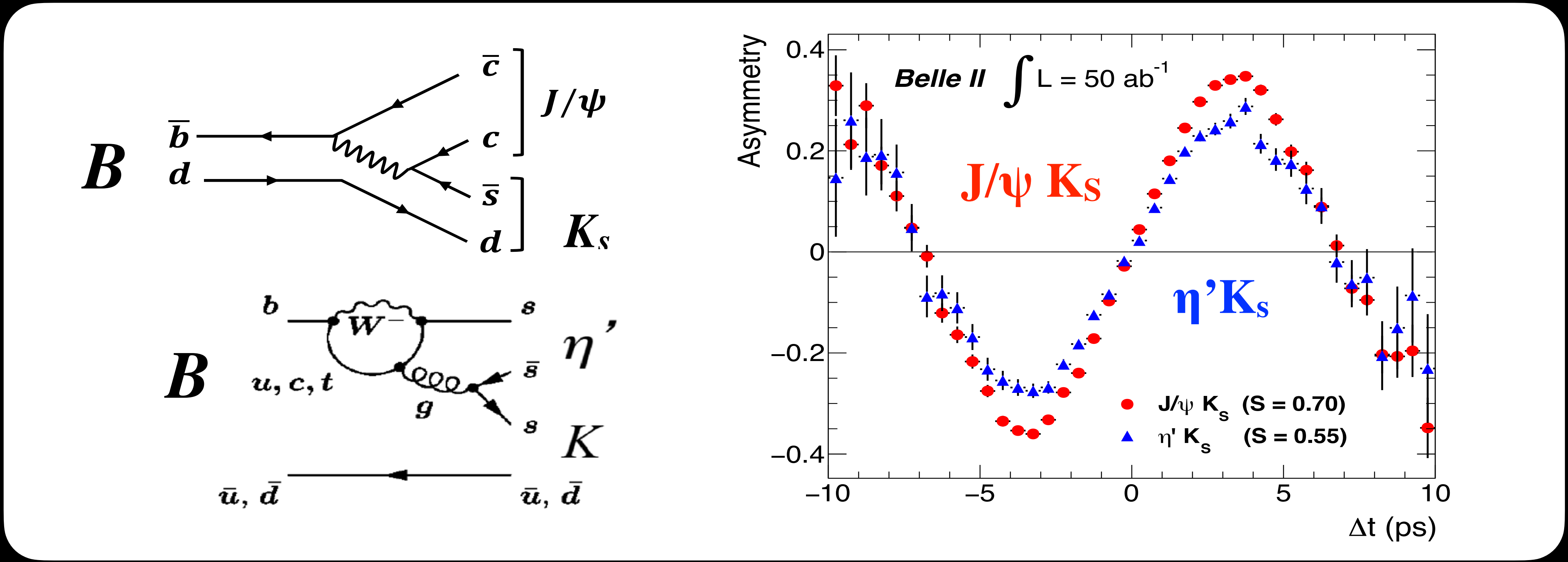
First meas. (190 fb^{-1}) of $J/\psi\ K_S$ at Belle II

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

(S_{PDG} = 0.701 ± 0.017)

ϕ_1 measurement in penguin

- Size of CP asymmetry in $b \to s\bar{q}$ (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** ($\phi_1^{eff} = \phi_1 + \delta\phi_1^{NP}$)



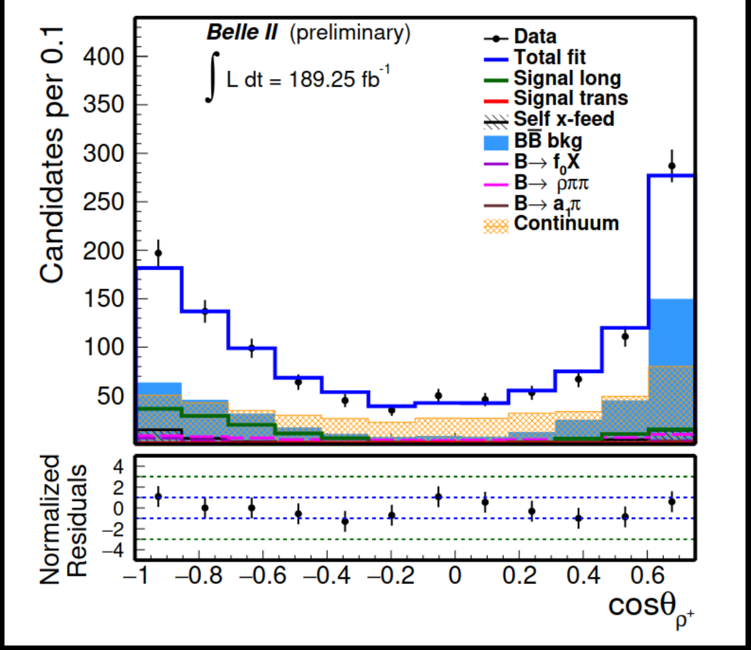
- $B \to \phi K$, **$\eta' K_s$, $K_s K_s K_s$** are golden mode (small theory unc.)
    - First measurement (63 fb^{-1}) of $\eta' K_s$ *Br* is consistent with World Average (see arXiv:2104.06224)
    - First measurement (190 fb^{-1}) of $K_s K_s K_s$ mode is consistent with unity: **$S_{CP} = -1.86\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

ϕ_2 measurement

- $B \to \pi\pi$ and $B \to \rho\rho$ are sensitive to ϕ_2 which is the least constrained CKM parameter. These decays are also sensitive to direct CP violation. Isospin analysis (+0,+-, 00) is performed to resolve interference between tree and penguin diagrams and extract ϕ_2
- 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)

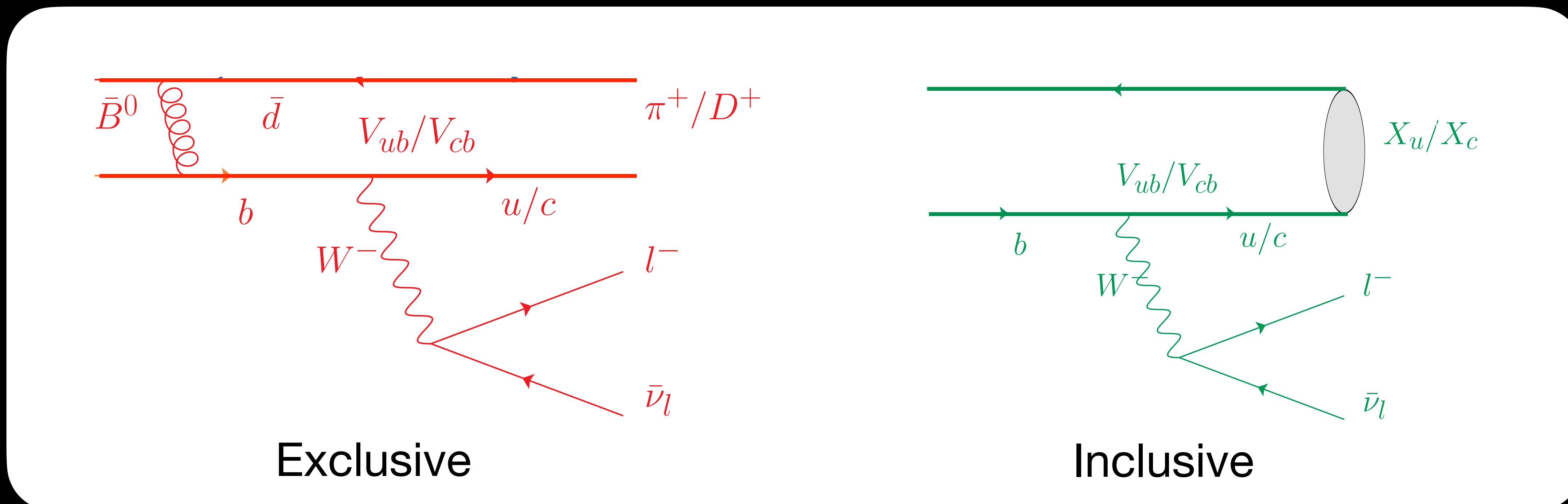


helicity angle distribution

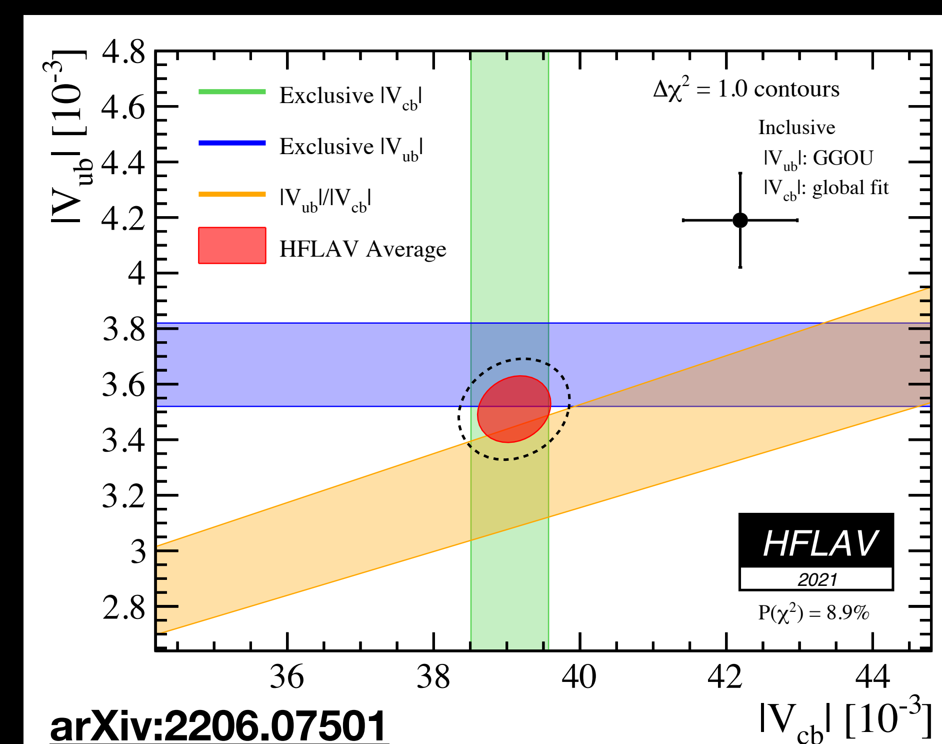
See arXiv:2106.03766, 2107.02373, 2206.12362

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

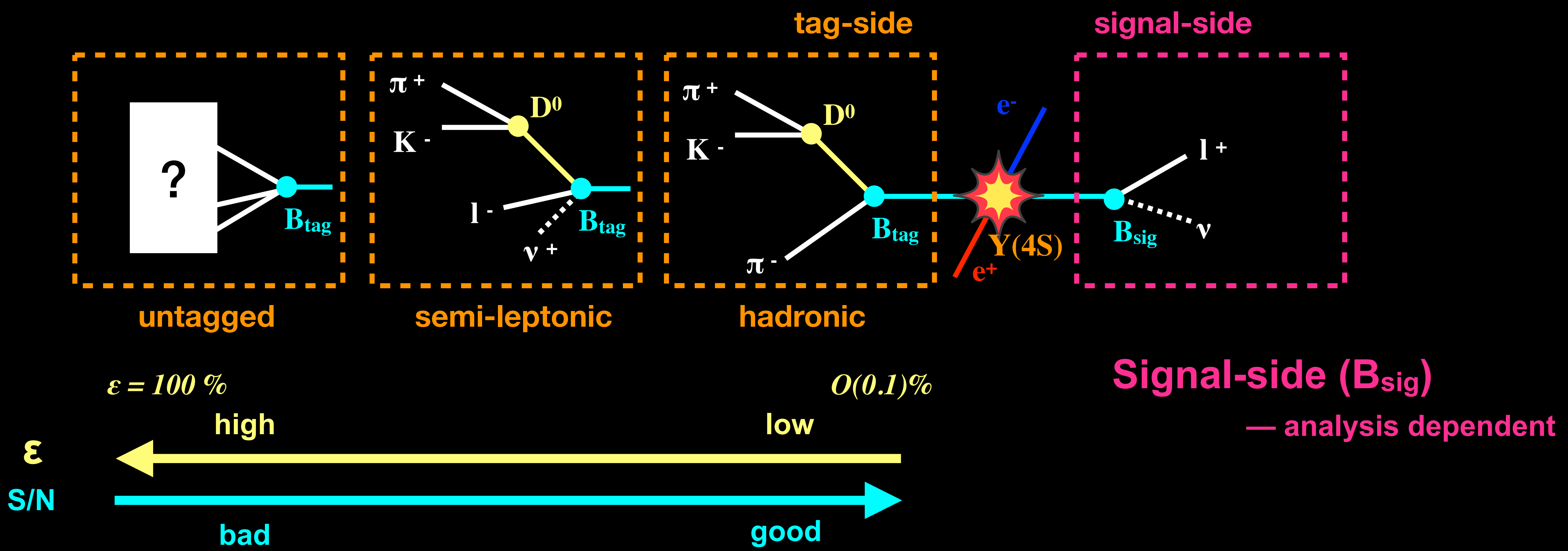
- Semi-leptonic B decays are used to extract the CKM parameters $|V_{ub}|$ and $|V_{cb}|$.



- $B \to \pi \ell \nu$ 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.



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.

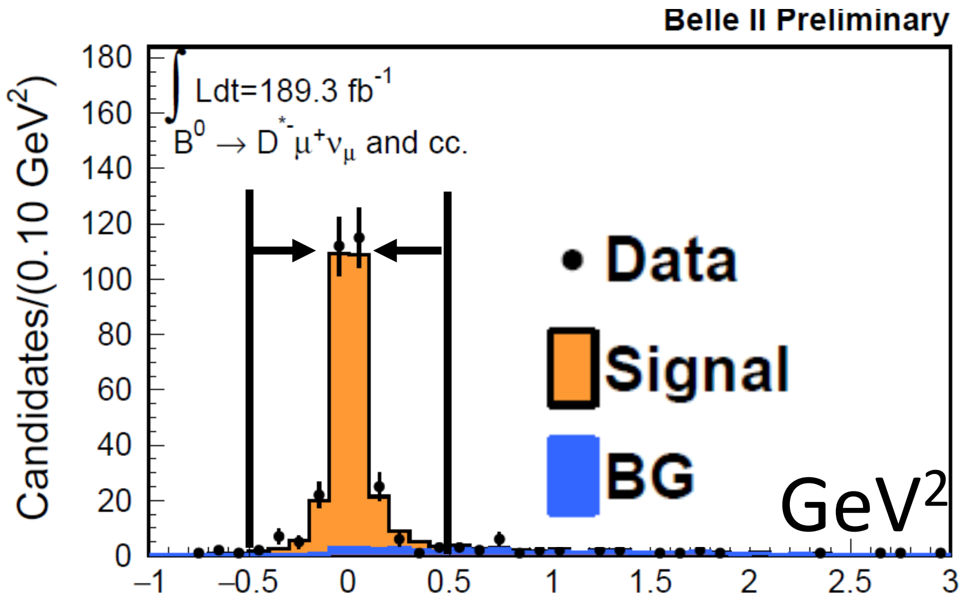
$B \to D^{(*)} \ell \nu$ for $|V_{cb}|$

- 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**.

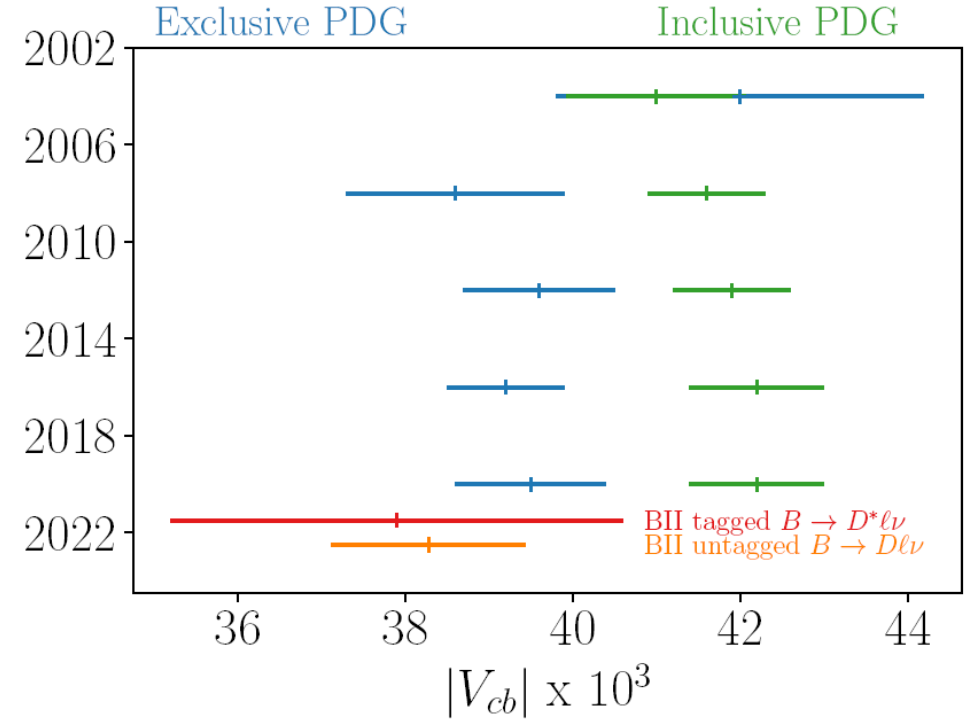
$$\frac{d\Gamma}{dw} = \frac{\eta_{EW}^2 G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 g(w) \underline{F^2(w)} |V_{cb}|^2$$

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

missing mass squared

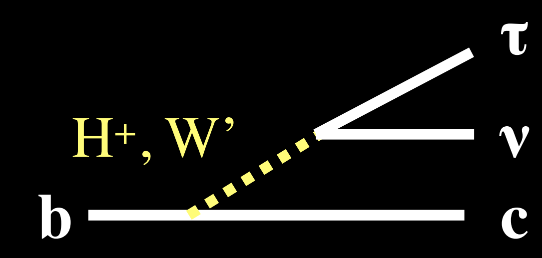


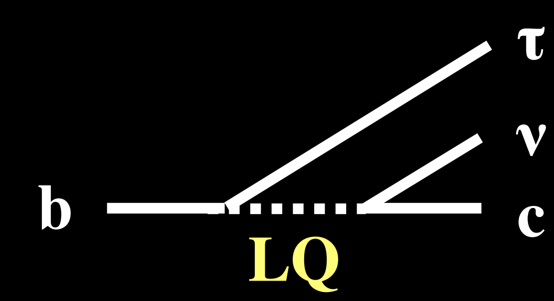
$$m_{miss}^2 = (P_{beam} - P_{B_{tag}} - P_{D^*} - P_l)^2$$

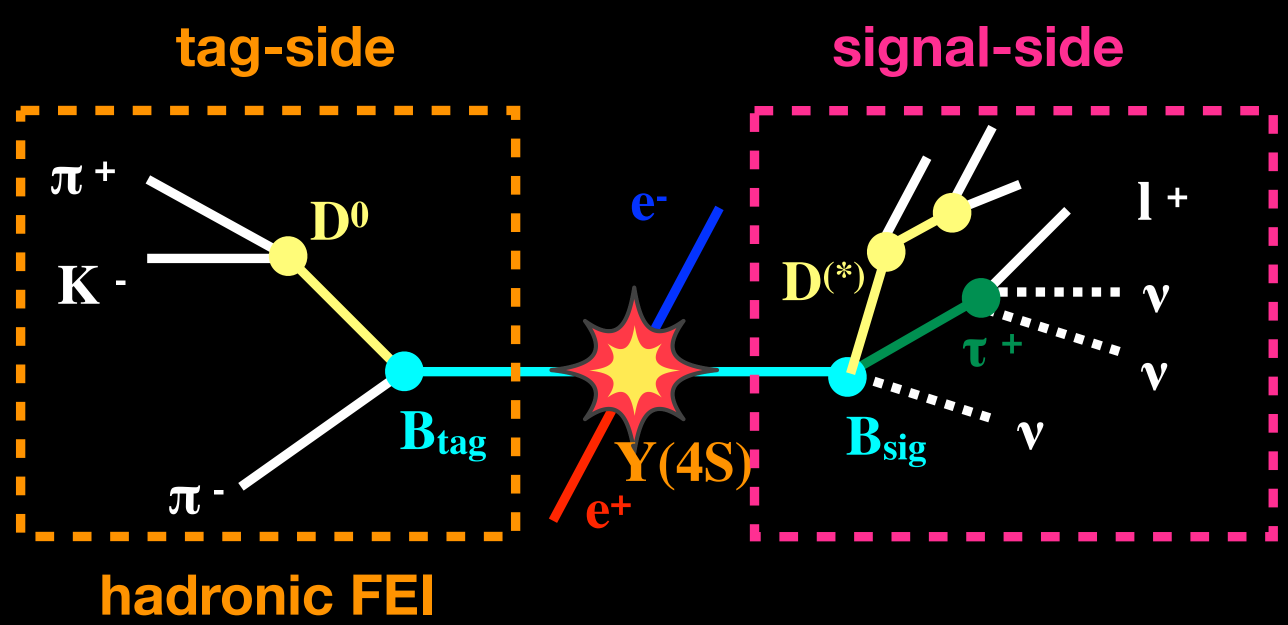


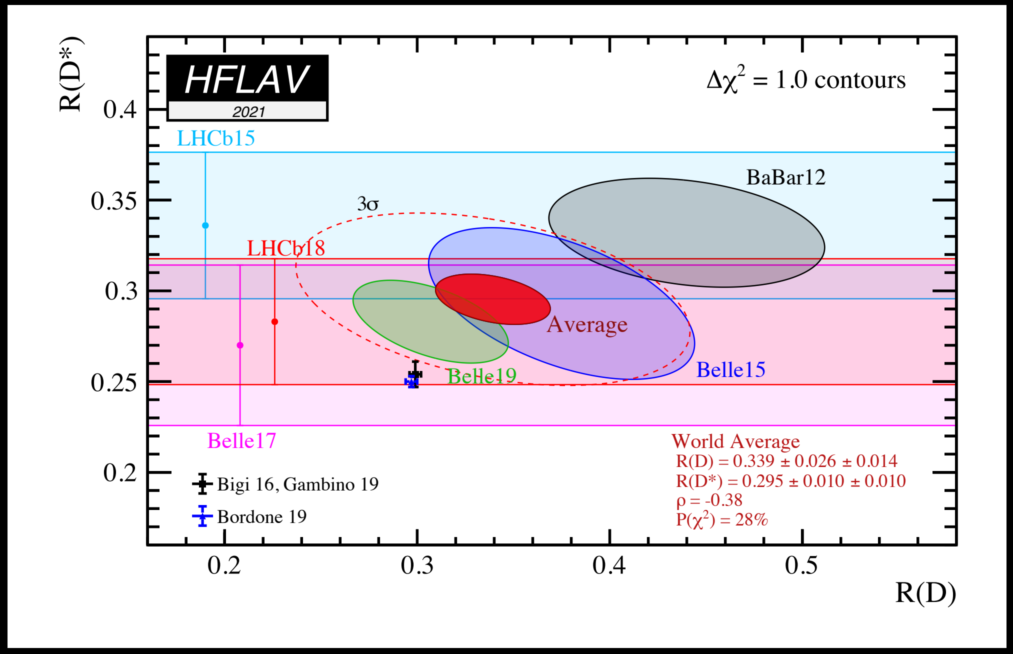
$B \to D^{(*)}\tau\nu$

- 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 or Z' model)
- > 1 neutrino in the final state → **Flavor tagging is a key**









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

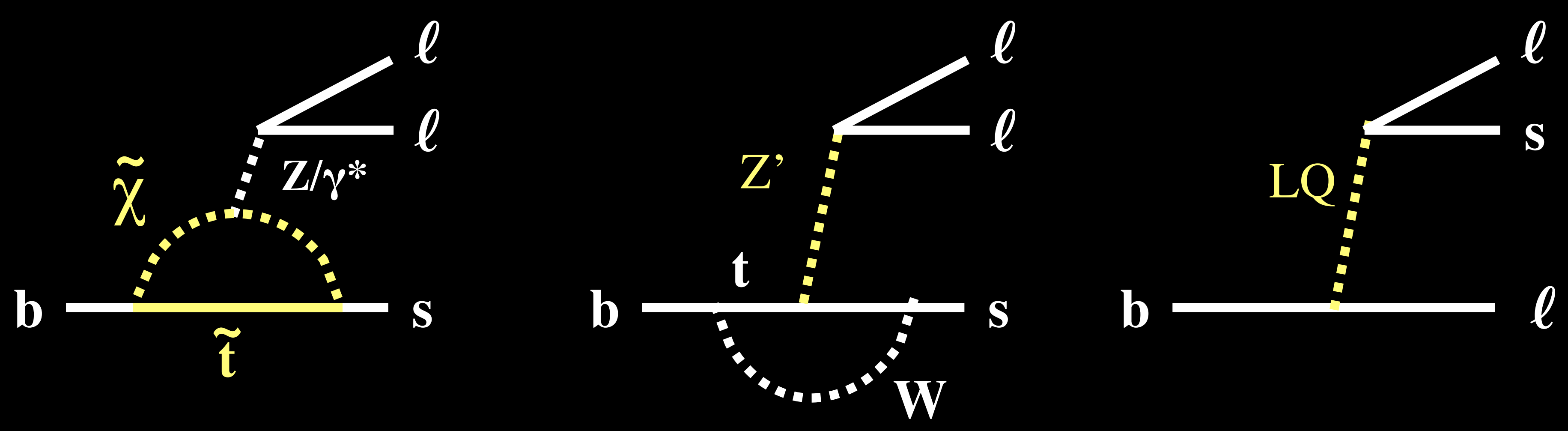
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

Sensitivity at Belle II

	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. **Flat sensitivity over q²**.

(*) all possible final states taken into account.

Sensitivity at Belle II

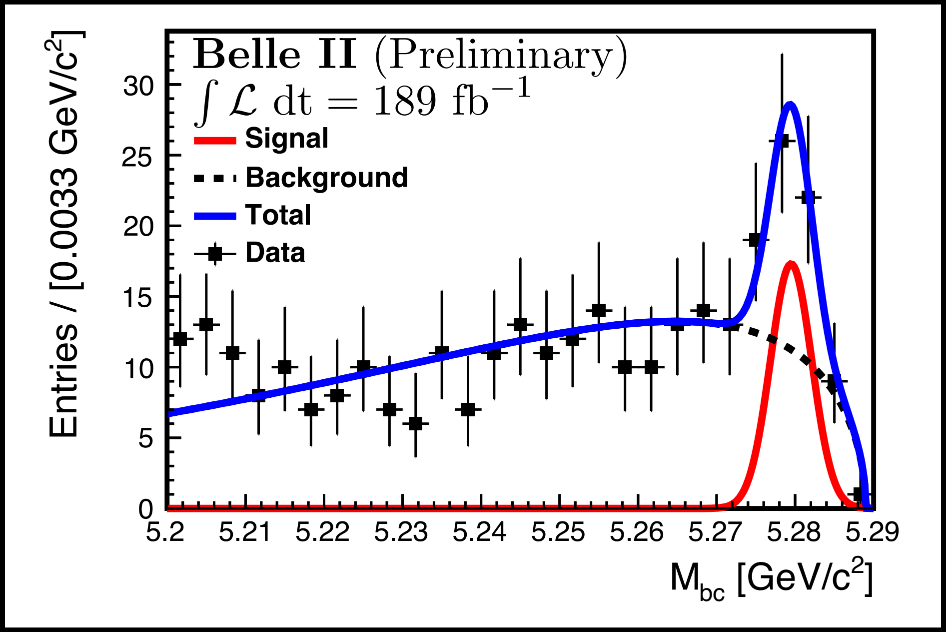
Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
R_K ($[1.0, 6.0]\,\mathrm{GeV}^2$)	28%	11%	3.6%
R_K ($> 14.4\,\mathrm{GeV}^2$)	30%	12%	3.6%
R_{K^*} ($[1.0, 6.0]\,\mathrm{GeV}^2$)	26%	10%	3.2%
R_{K^*} ($> 14.4\,\mathrm{GeV}^2$)	24%	9.2%	2.8%
R_{X_s}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

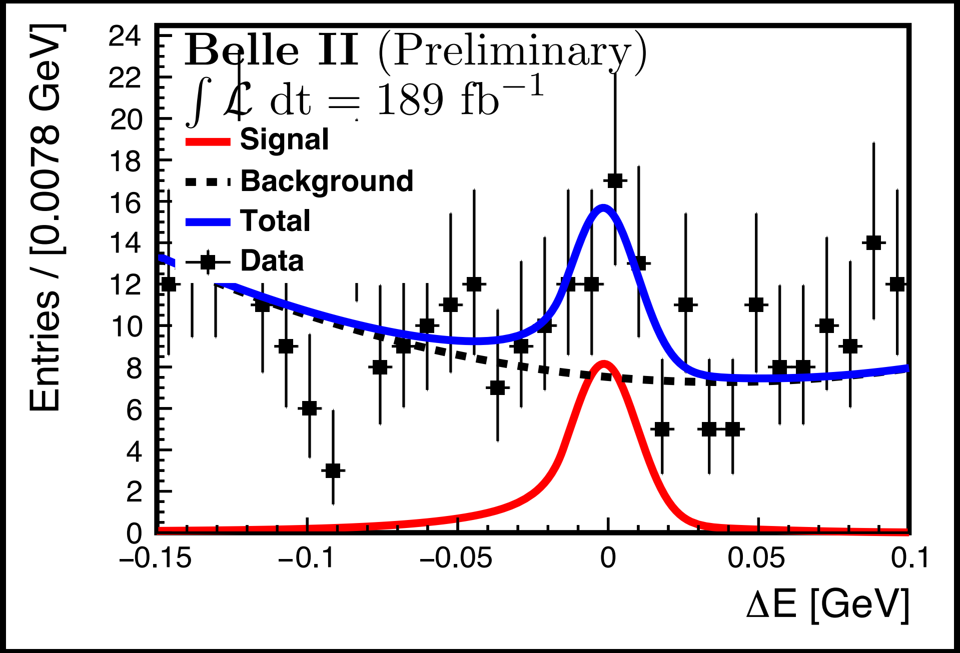
* Statistical uncertainty is dominant. Systematic unc. is negligible.

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

arXiv:2206.05946

- 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



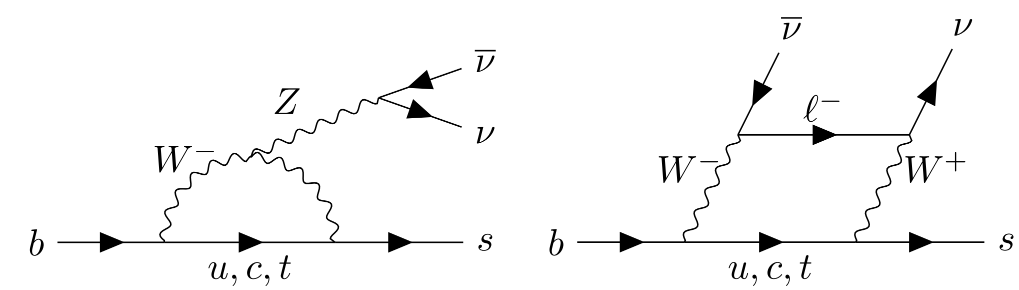


Branching fraction:

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

$B \to K^{(*)}\nu\nu$

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

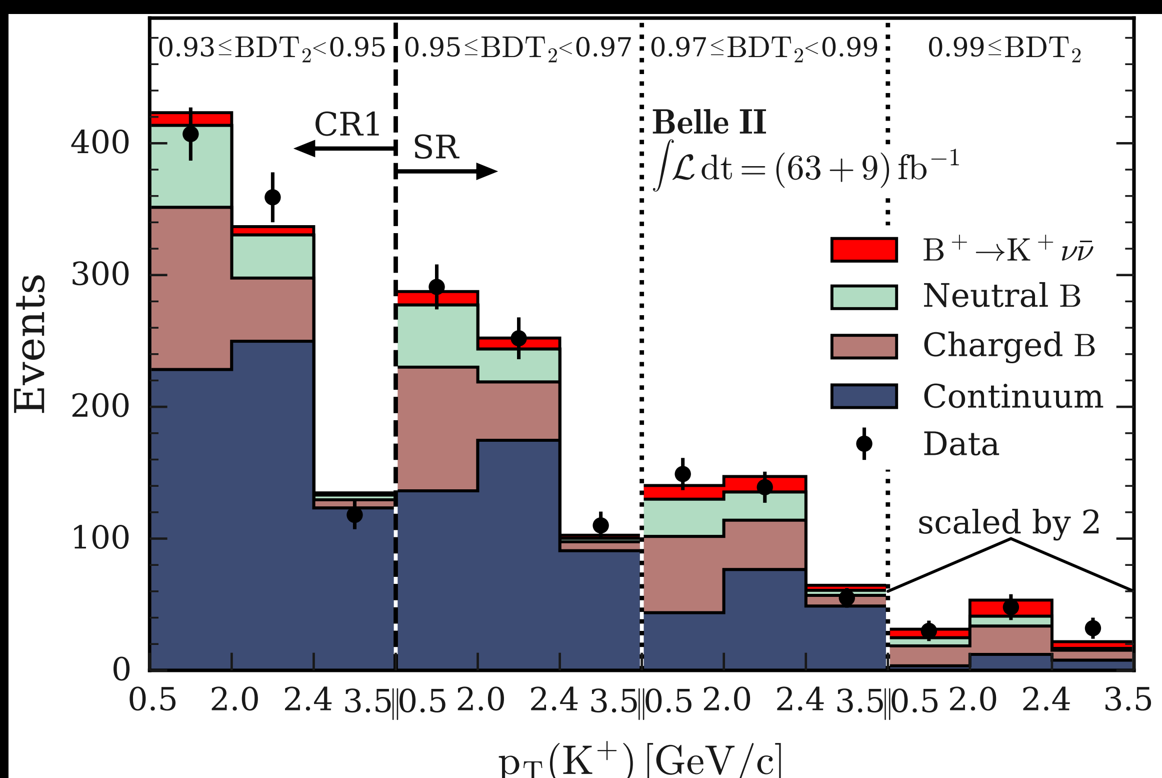


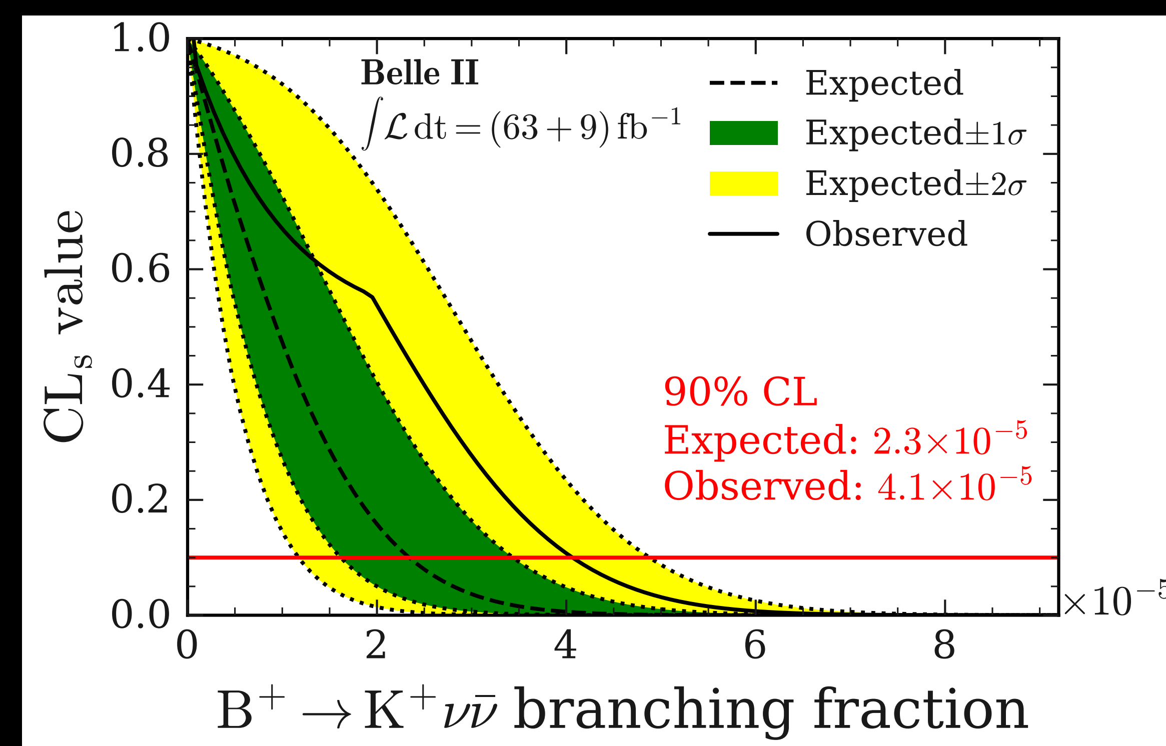
$$\mathcal{B}\left[B^+ \to K^+\nu\bar{\nu}\right] = (4.7 \pm 0.6) \times 10^{-6}$$
$$\mathcal{B}\left[B^0 \to K^{*0}\nu\bar{\nu}\right] = (9.5 \pm 1.1) \times 10^{-6}$$

[JHEP02 (2015)184]

- 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



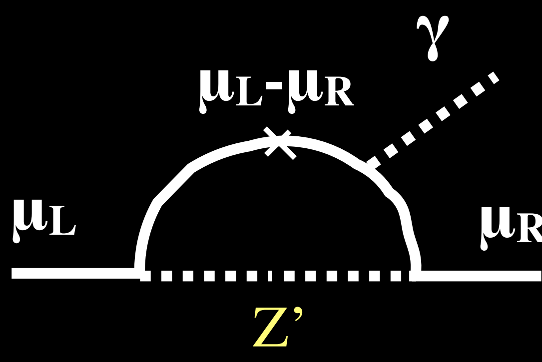


- Binning with Kaon P_T to maximize the sensitivity
- Continuum BG is estimated by CR

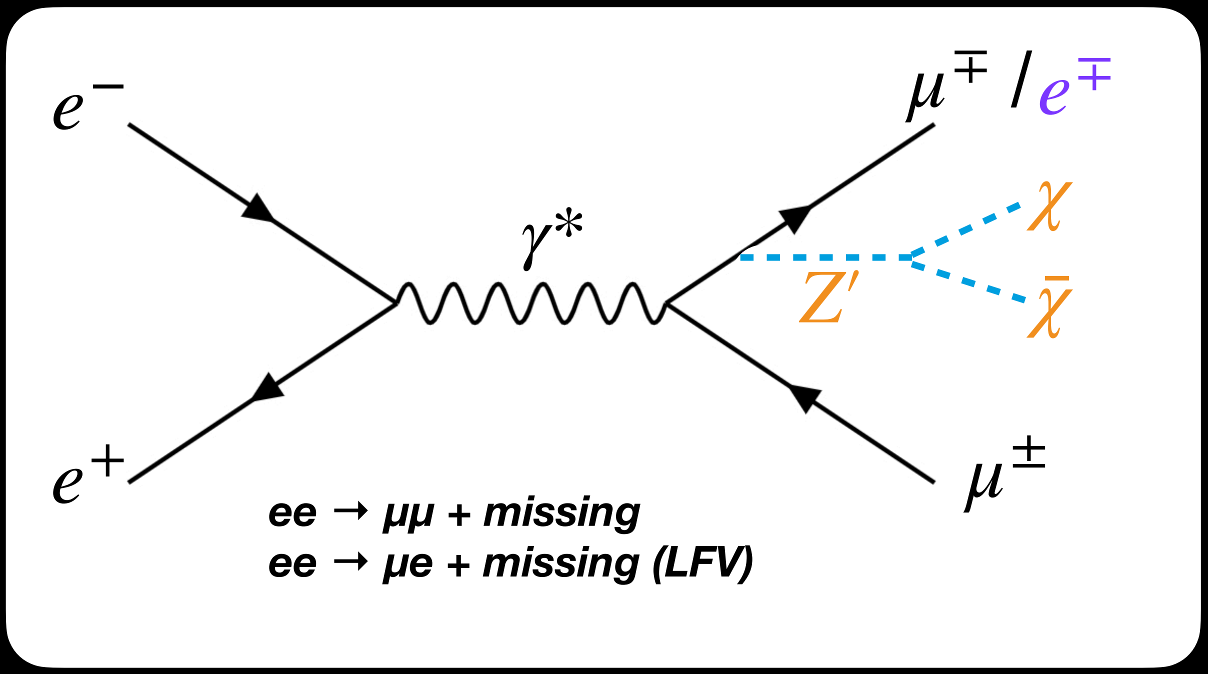
Discovery with 5-10 ab⁻¹ of Belle II data?

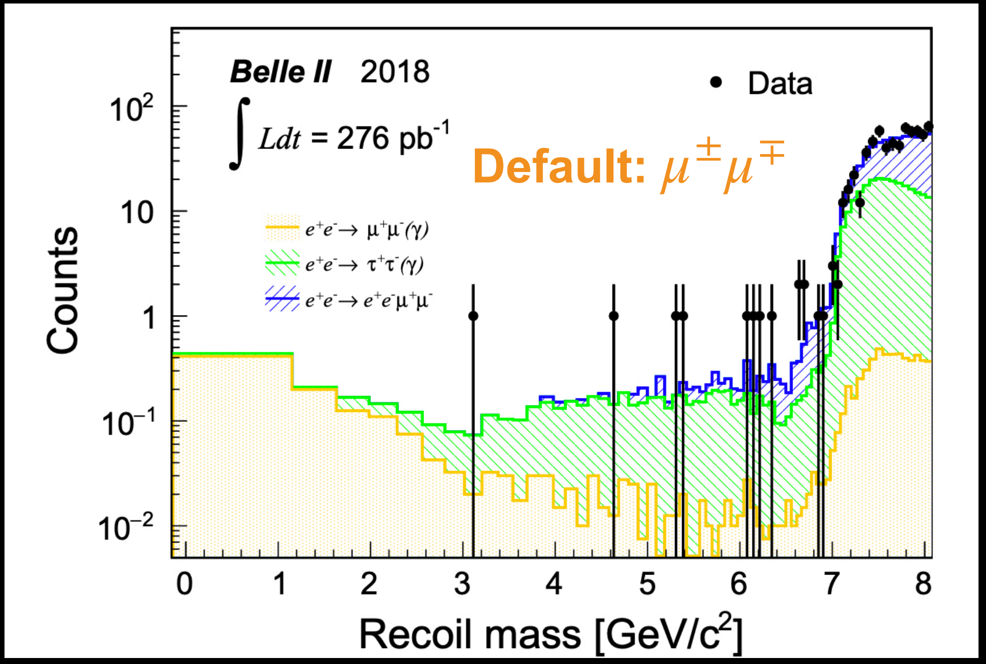
Z’ → invisible

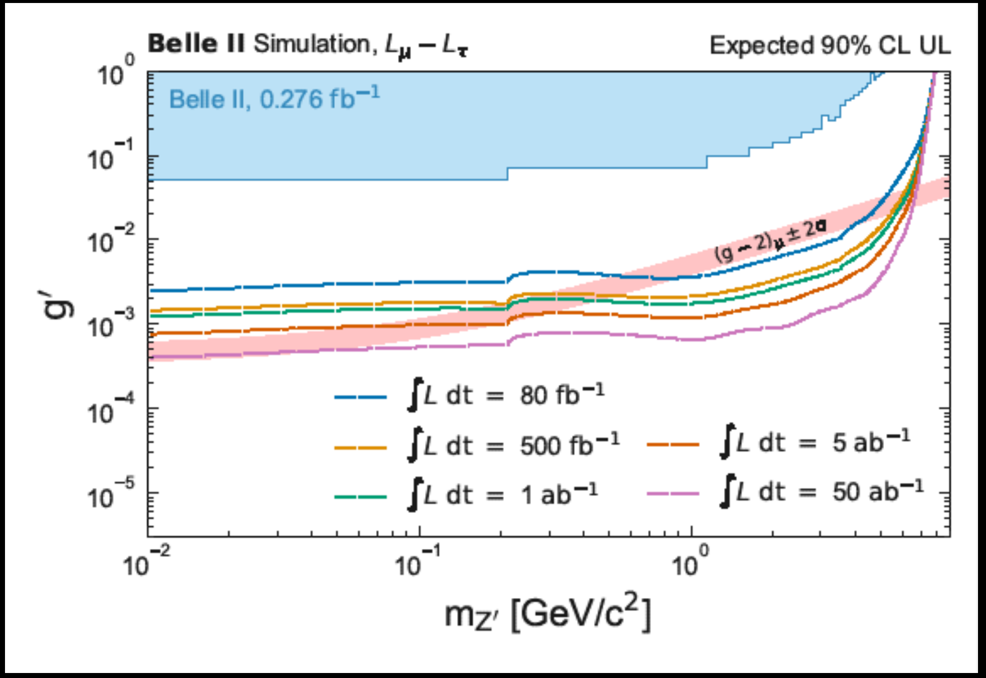
- U(1)$_{L\mu-L\tau}$ model considers L_μ-L_τ as a new charge:
  - Sensitive to **$(g\text{-}2)_\mu$ anomaly** or *b→sμ⁺μ⁻ anomaly*
  - Z’ couples to only τ, μ, $\nu_{\tau,\mu}$ in the SM



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





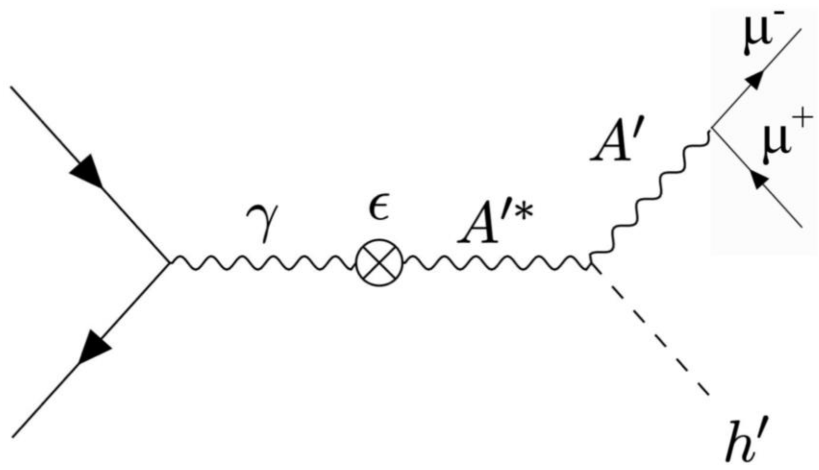


- Main BG
  - $\tau^+\tau^-$ (1-prong) + missing energy (neutrino)
  - $\mu^+\mu^-$ + γ (being missing)

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

Dark Higgs strahlung

arXiv:2207.00509

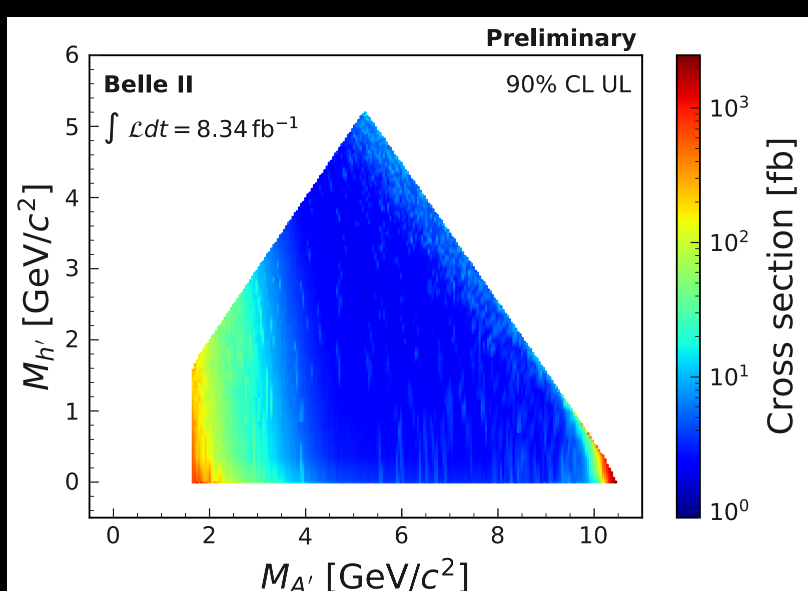


Signature:

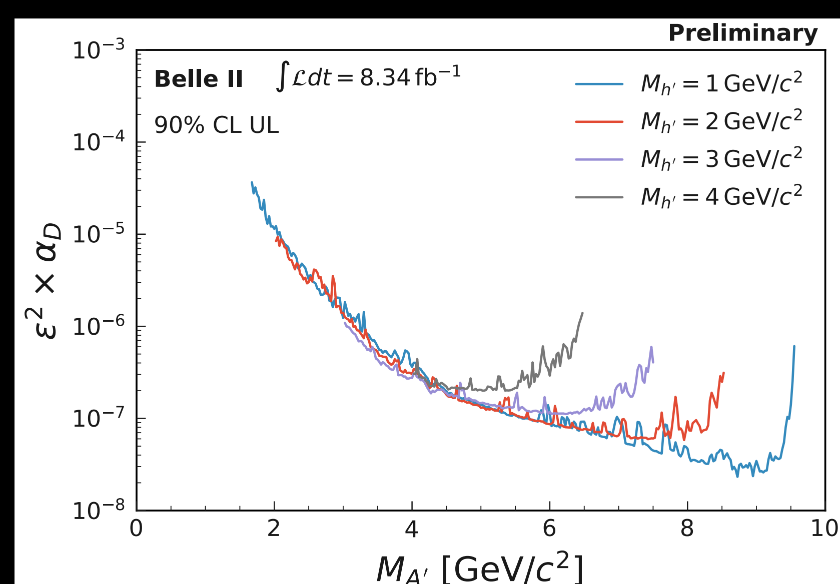
$\mu^+\mu^-$ + h' (being missing)

- U(1)' vector portal extension of SM
- Dark photon (A') couples through kinematic mixing ε to SM and its mass can arise from SSB, introducing a dark higgs boson (h')
- **h' becomes a long-lived particle** if m(h') < m(A').
- Recoil mass M_{recoil} (~m(h')) is defined against $M_{\mu\mu}$. Analysis scans 2D plane: M_{recoil} vs $M_{\mu\mu}$.
- Main BG : $\mu^+\mu^-$ + γ (being missing), $\tau^+\tau^-$ (1-prong) + missing energy (neutrino),

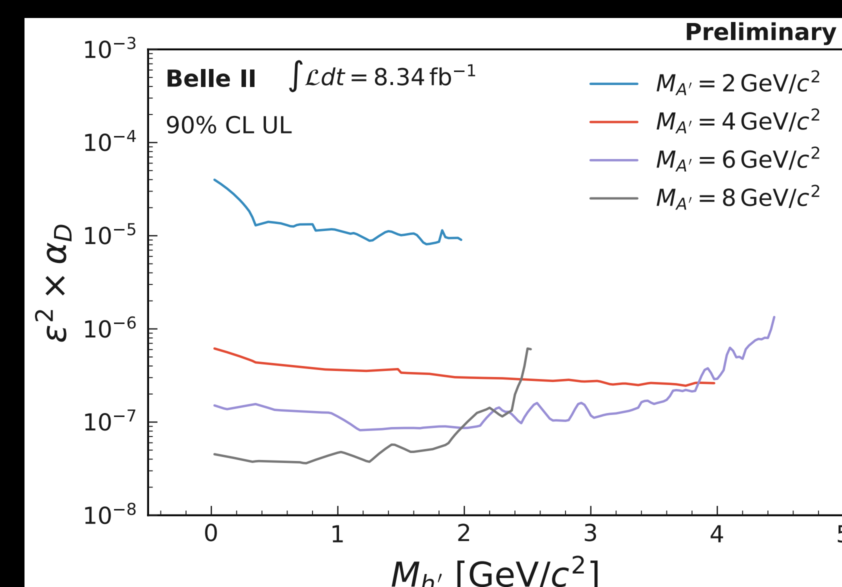
M_{recoil} vs M_{μ}



A' vs coupling



h' vs coupling

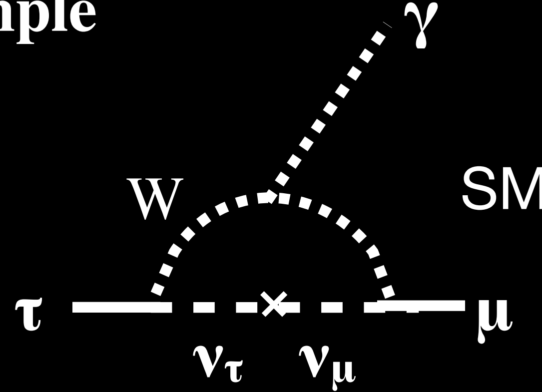


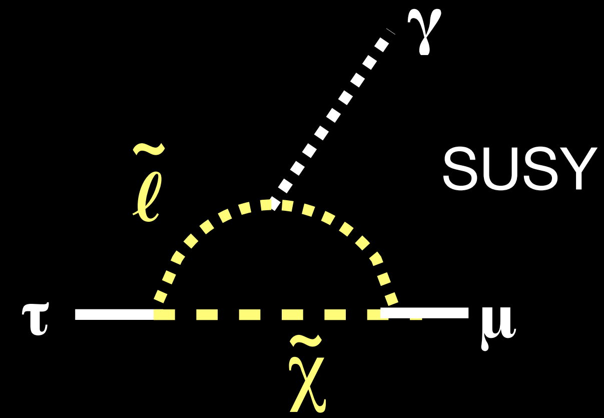
τLFV search

K11.05: Recent highlights with tau leptons from Belle by Youngjoon Kwon

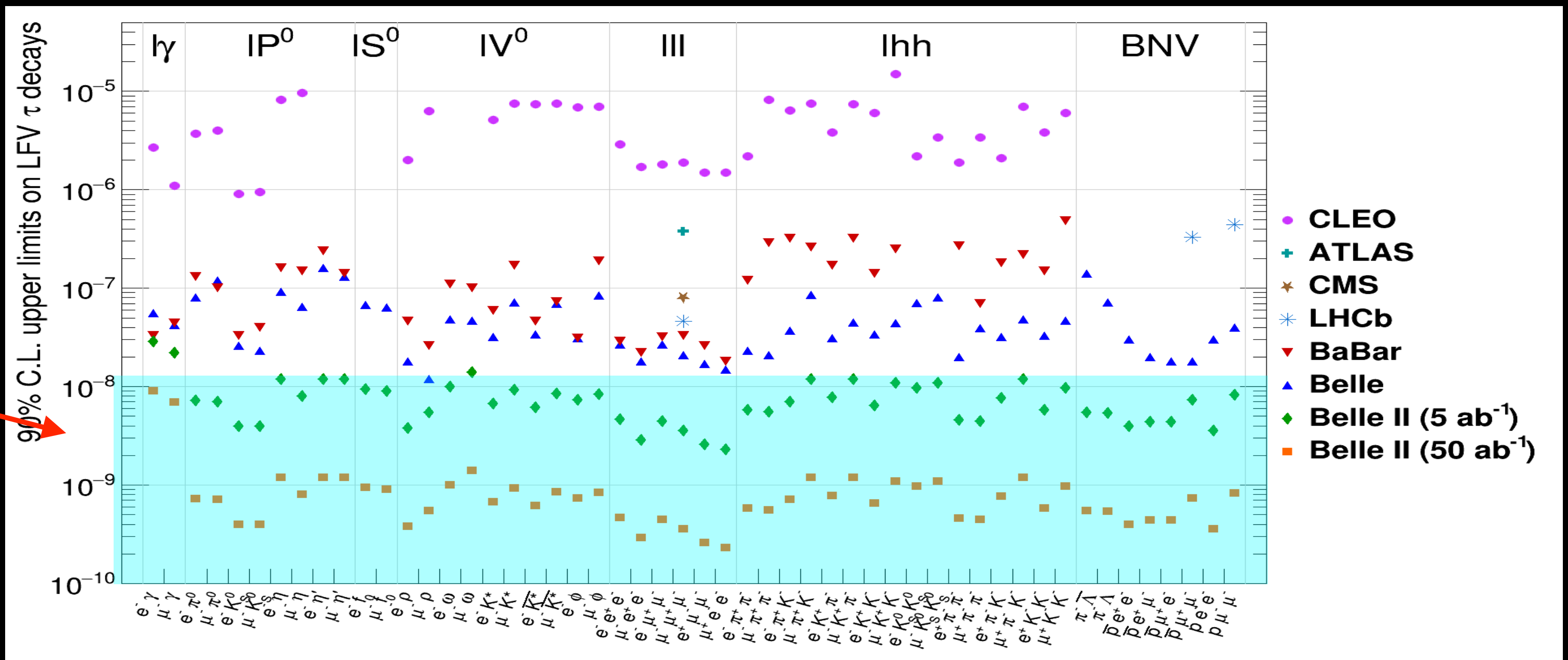
- Taus are also pair-produced at SuperKEKB — **σ(ττ): 0.9nb, σ(Υ(4S)): 1.2nb**
- τLFV decay proceeds via neutrino oscillation in the SM (~10^{-54}) which is expected to be much smaller than **new physics contribution (10^{-7} - 10^{-10} ?)**

τ→μγ example





arXiv:2203.14919



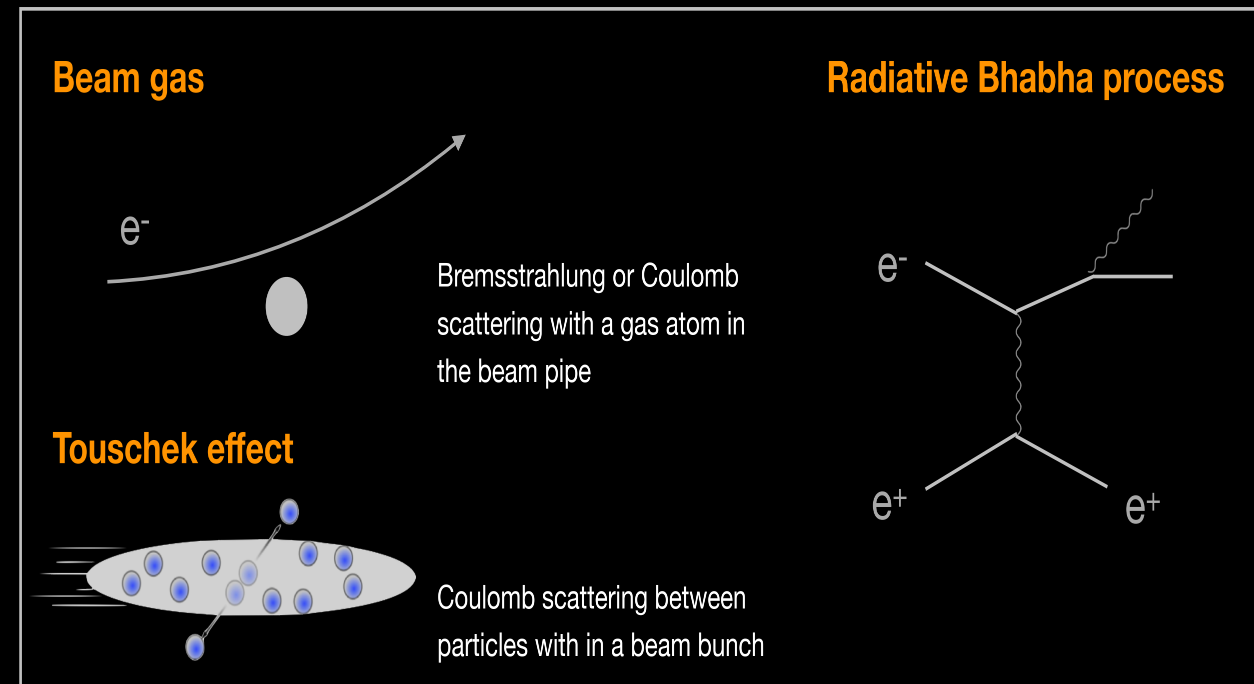
Belle II is a unique experiment for τLFV

Challenges and prospect

Beam Background

Beam background crucial to maintain Belle II detector performance

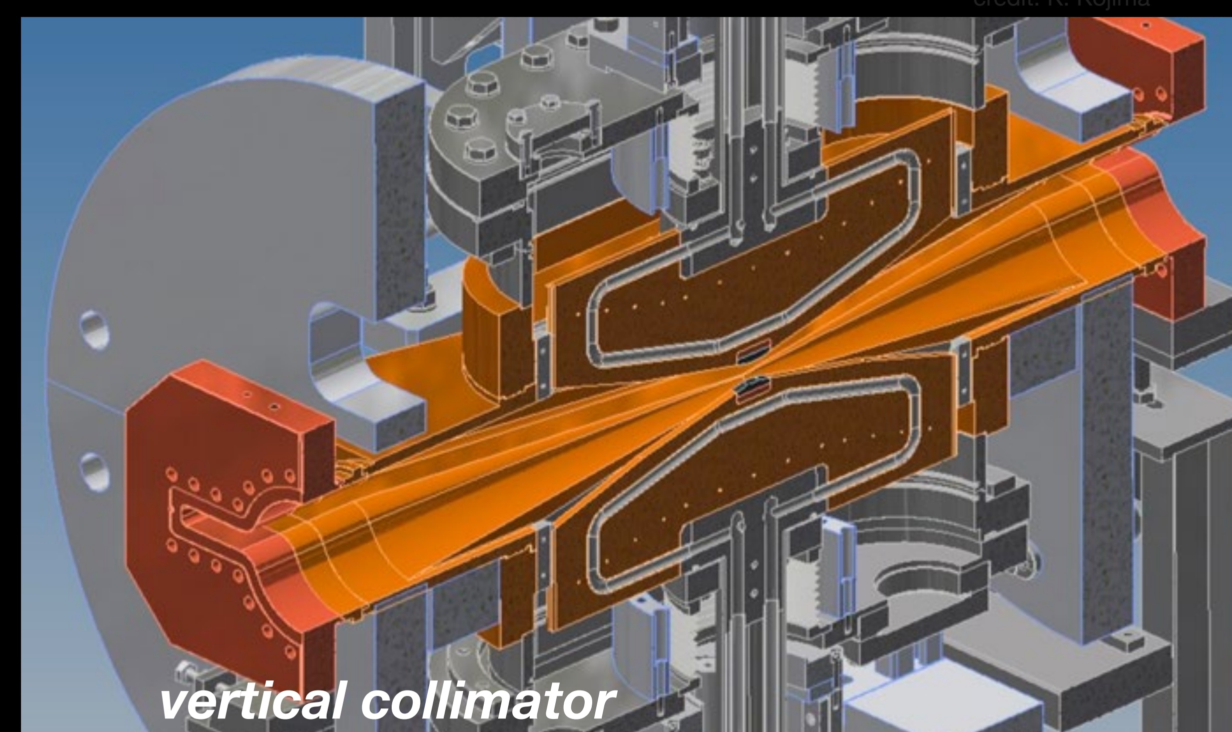
- Single-beam background
  - Touschek, beam-gas, synchrotron radiation, injection background
- Luminosity background
  - radiative Bhabha, two photon process



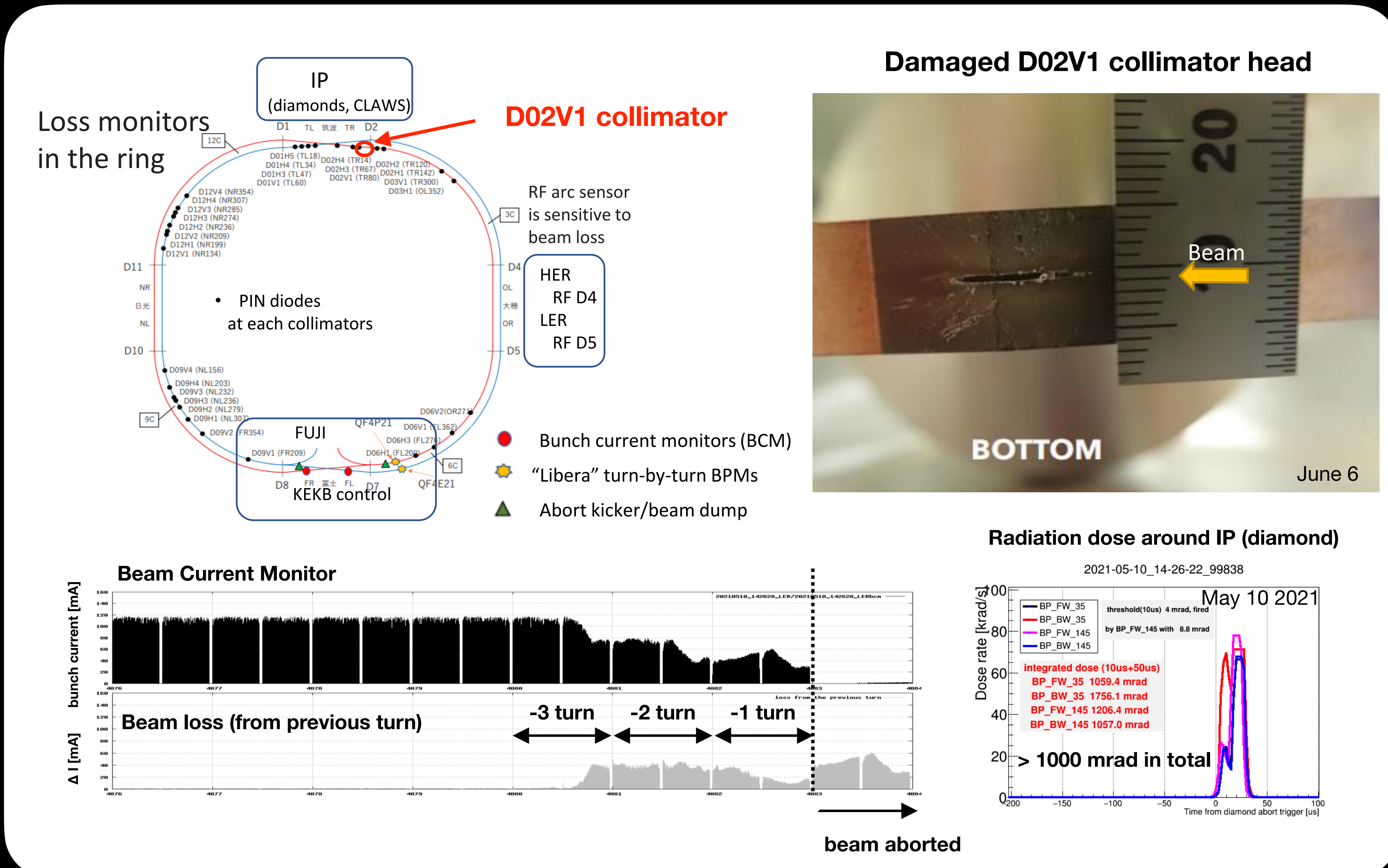
credit: K. Kojima

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

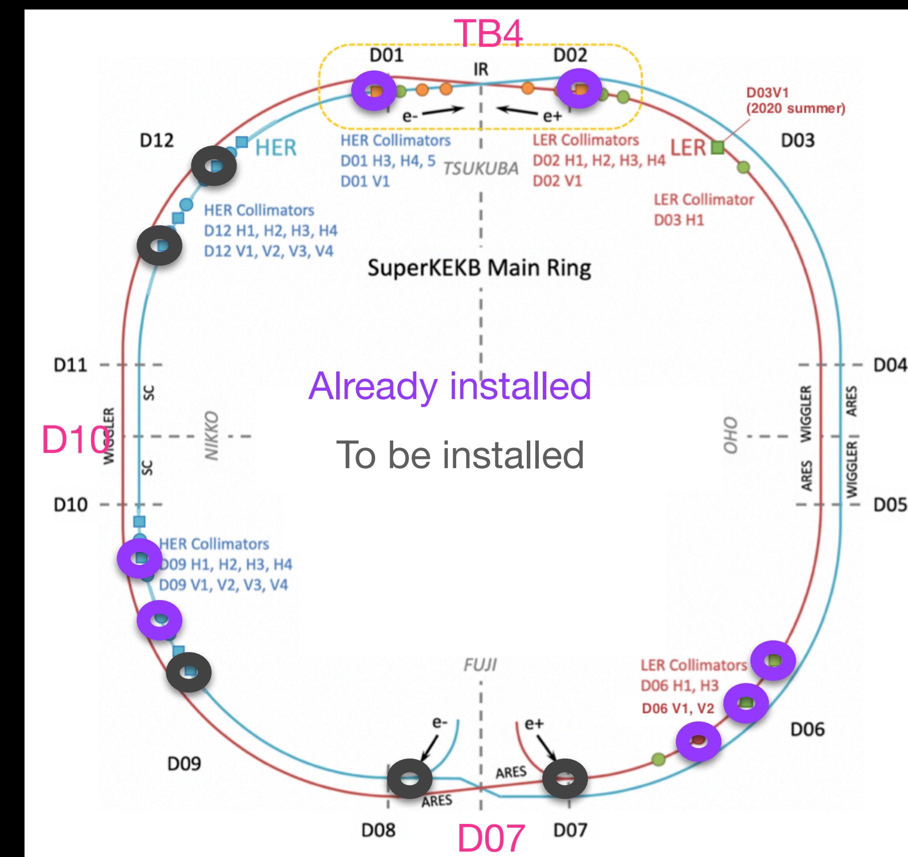


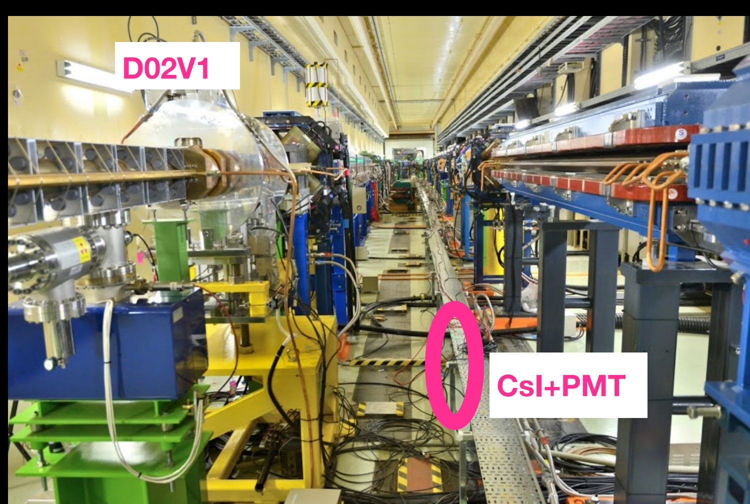
A significant beam loss at high beam current operation resulted in severe damage on a collimator or the vertex detector. Our abort system is not fast enough to protect such a sudden beam loss. → **A limitation toward higher beam current**

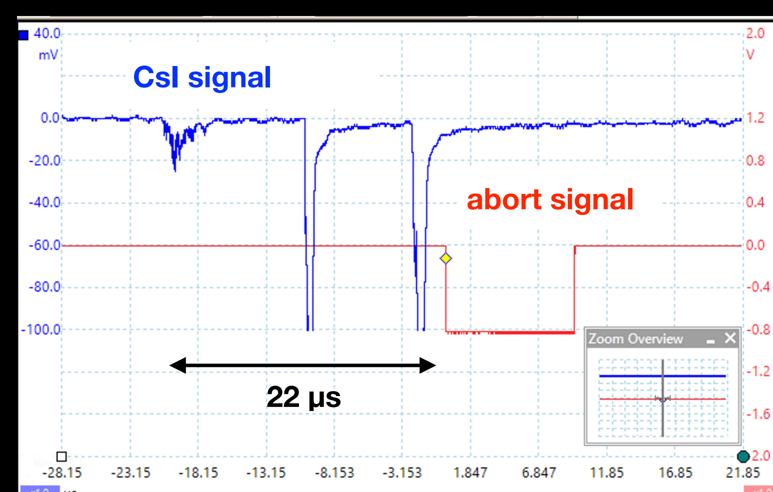
Beam diagnosis system

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

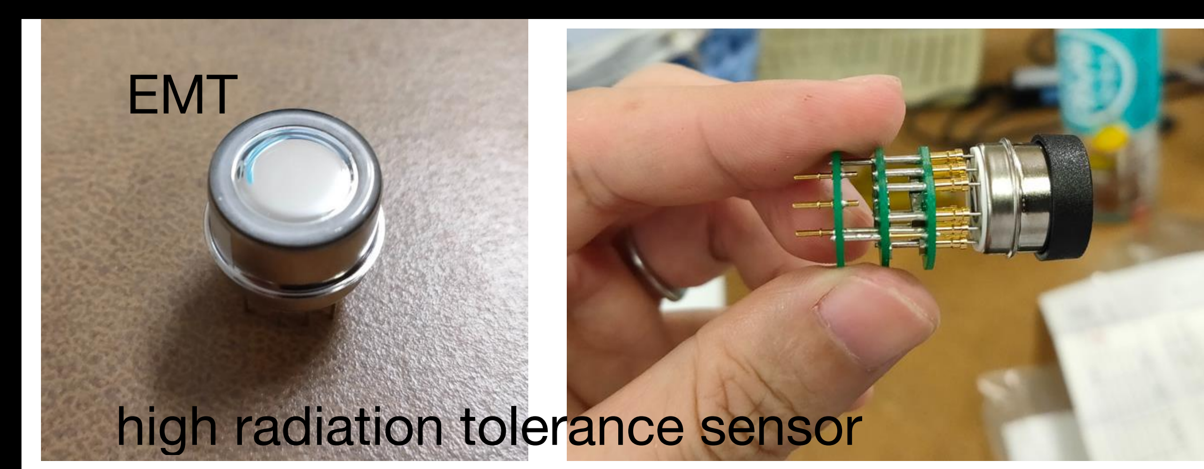
- A new beam diagnosis system is developed to identify the location of the loss w/ accuracy of 20 m in the MR (corresponding to ~100 ns)



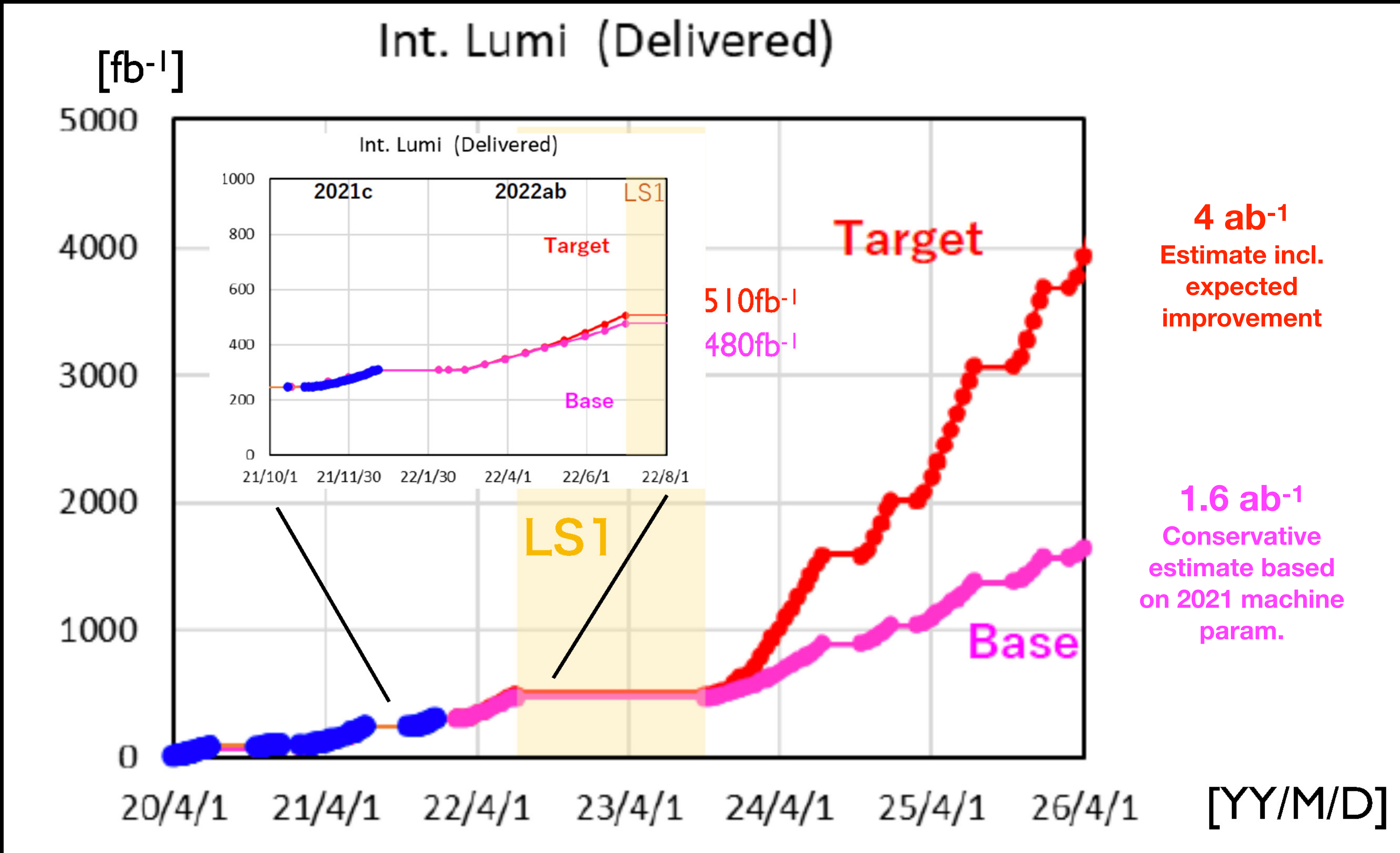




- At present, 7 loss monitors (CsI+PMT or EMT) have been newly installed in the main ring. White Rabbit (CERN) is used for time synchronization.



Luminosity projection



4 ab^{-1}
Estimate incl. expected improvement

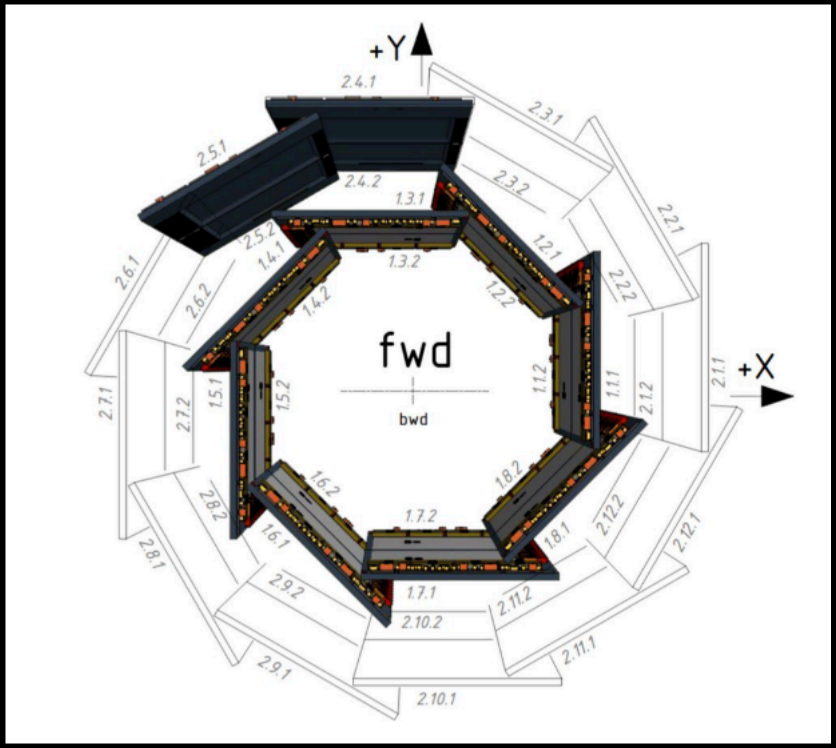
1.6 ab^{-1}
Conservative estimate based on 2021 machine param.

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

Upgrade work in LS1

- PXD2 installation
  - PXD will be fully re-installed (→PXD2).
  - New IP chamber also in production
    - synchrotron radiation shielding
- TOP MCP-PMT replacement
  - Some PMTs will be replaced with life-extended ALD type PMTs
- Additional shields for BG mitigation
  - Concrete shield, PE shield, QCS bellows shield
- Collimator system upgrade
  - Non linear collimator installation (LER)
  - Robust collimator head (LER)
- Beam pipe upgrade at injection point (HER)

PXD1 configuration

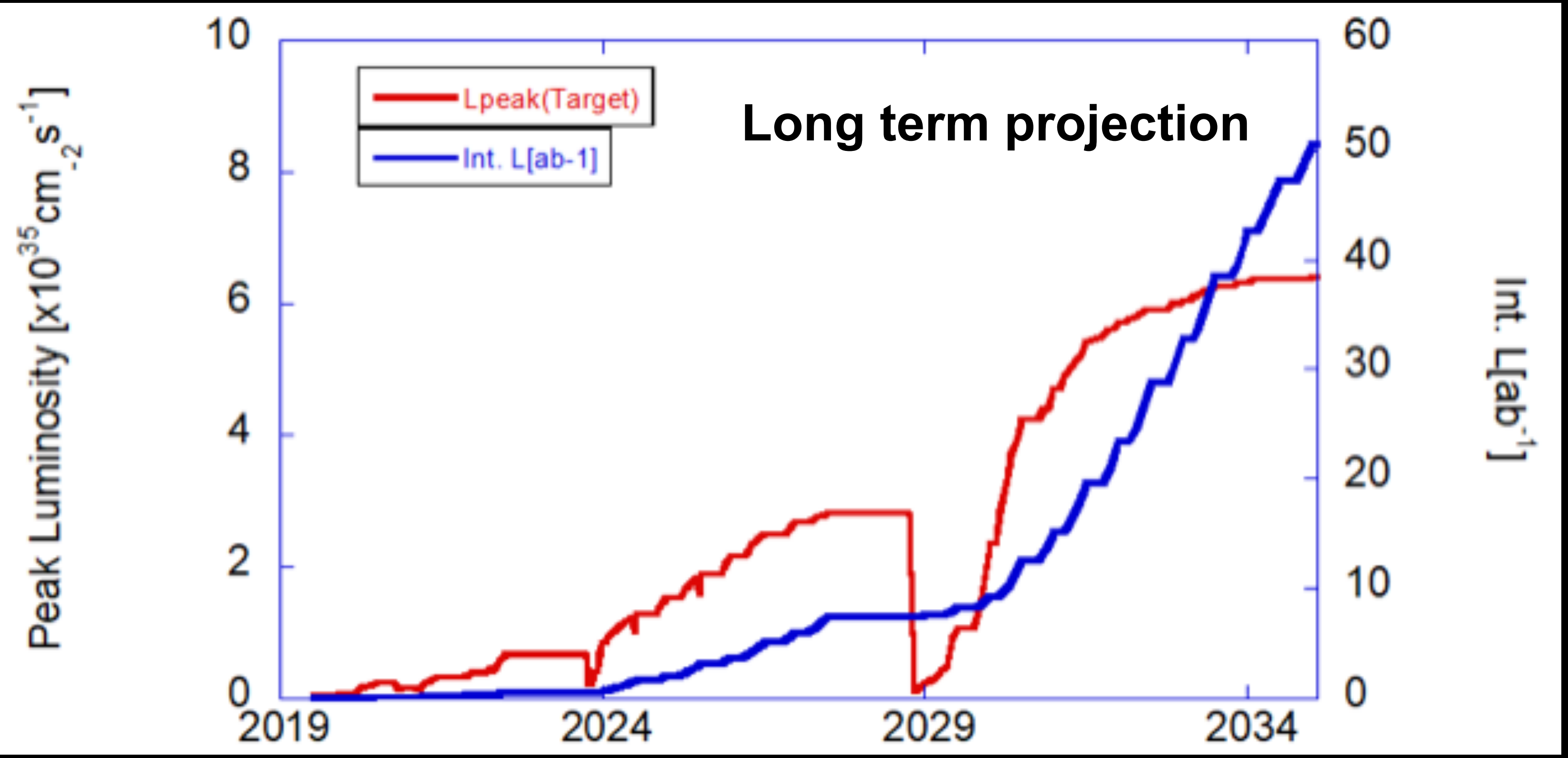


Due to problems in ladder gluing, only half of designed PXD (full L1+ 2 L2 ladders) was installed in 2018/2019.

Summary

- SuperKEKB/Belle II is a new generation B-factory having unique capabilities for new physics search.
- Machine operation going well so far and 424 fb^{-1} has been collected.
  - LER/HER: 1460/1260 mA
  - n. bunch: 2346 bunches (2-bucket spacing)
  - Peak luminosity: 4.65 x 10^{34} $cm^{-2}s^{-1}$
- During the LS1, detector and machine upgrade going on to aim for designed luminosity

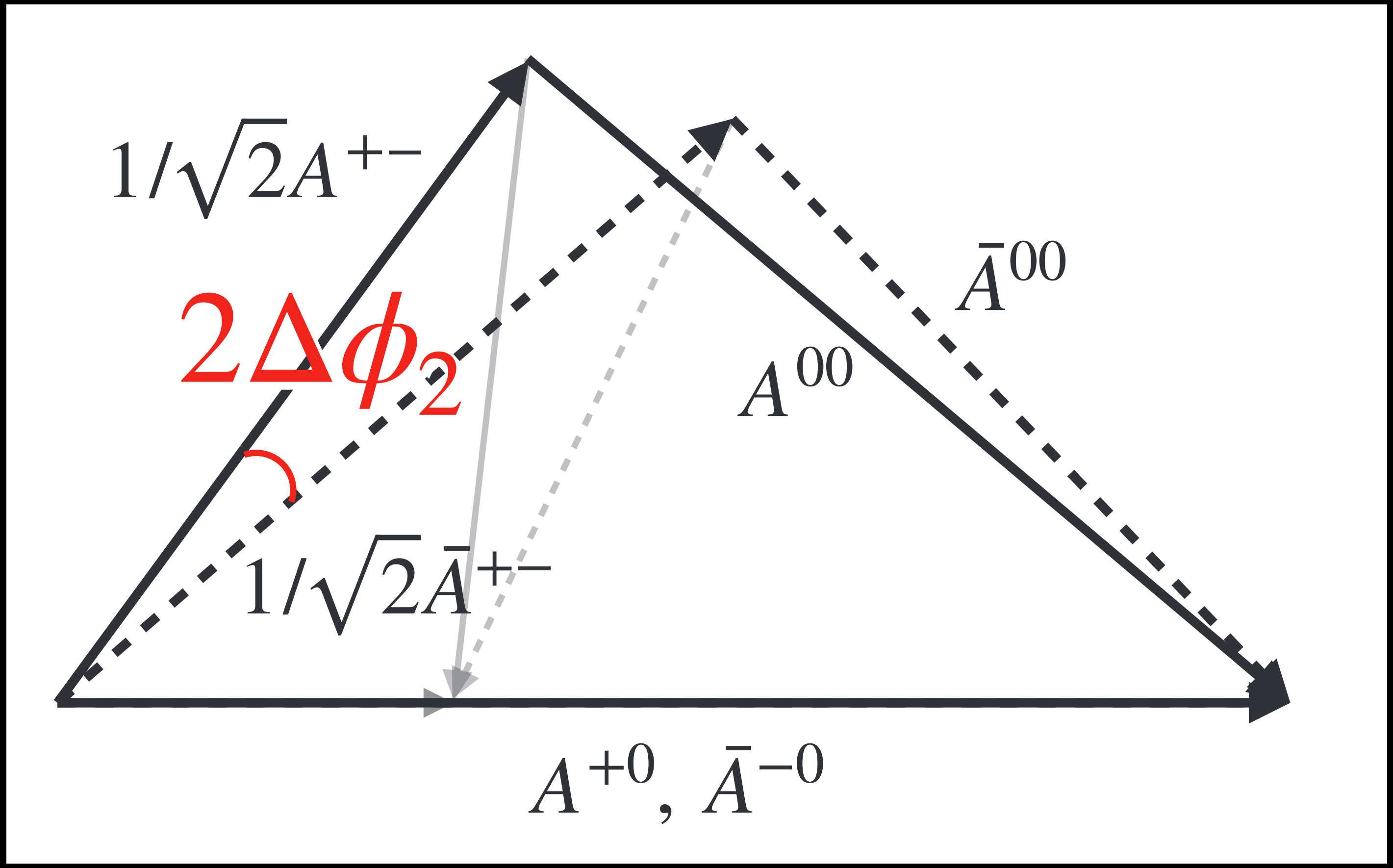
Stay tuned.



Thank you!

Backup

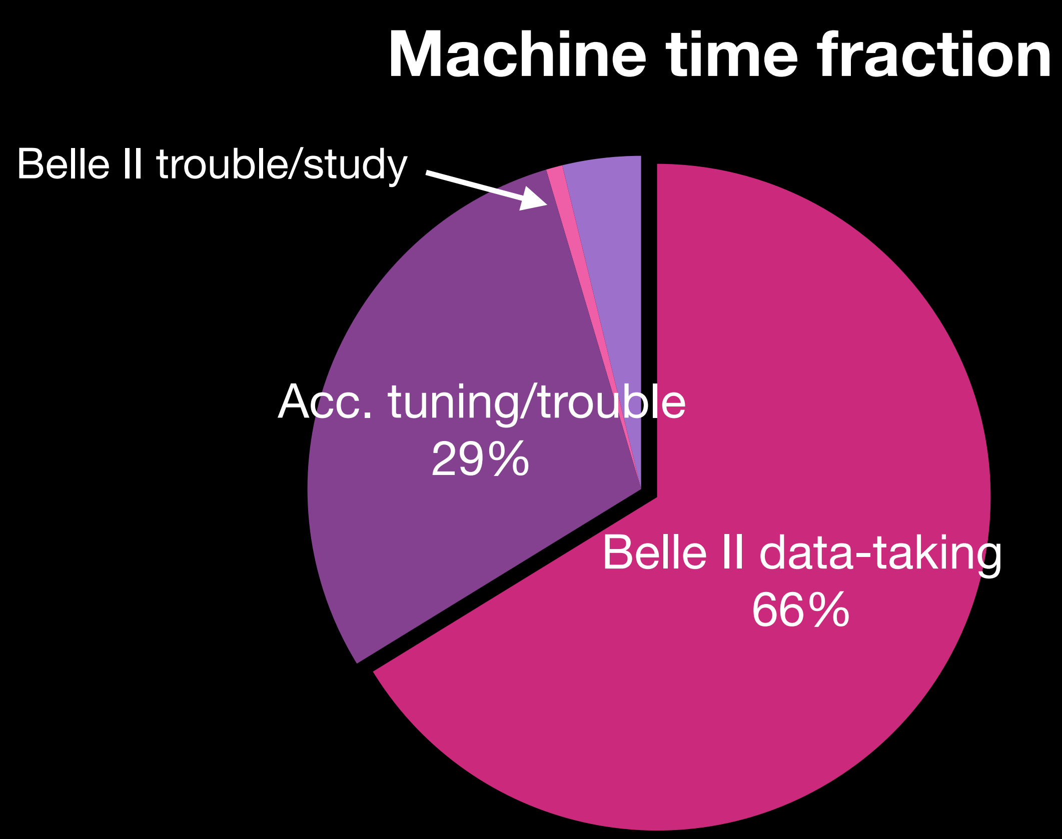
isospin triangle

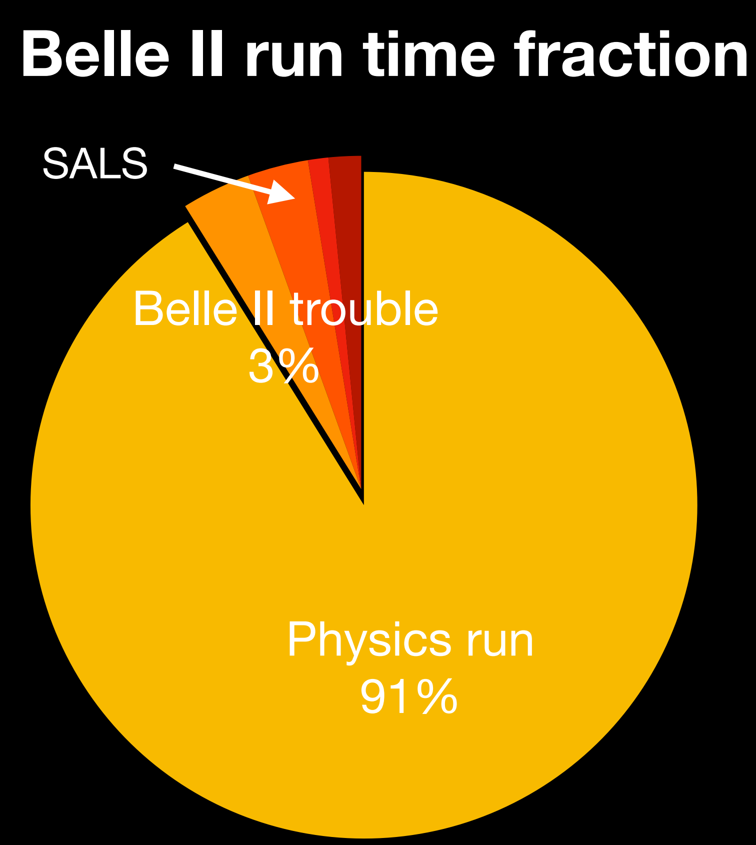


$$\left.\begin{aligned} \pi^+\pi^- &: 1/\sqrt{2}A^{+-} = A_2 - A_0 \\ \pi^0\pi^0 &: A^{00} = 2A_2 + A_0 \\ \pi^+\pi^0 &: A^{+-} = 3A_2 - A_0 \end{aligned}\right\} \quad 1/\sqrt{2}A^{+-} = A^{00} + A^{+-}$$

A_2: tree only, A_0: tree + penguin

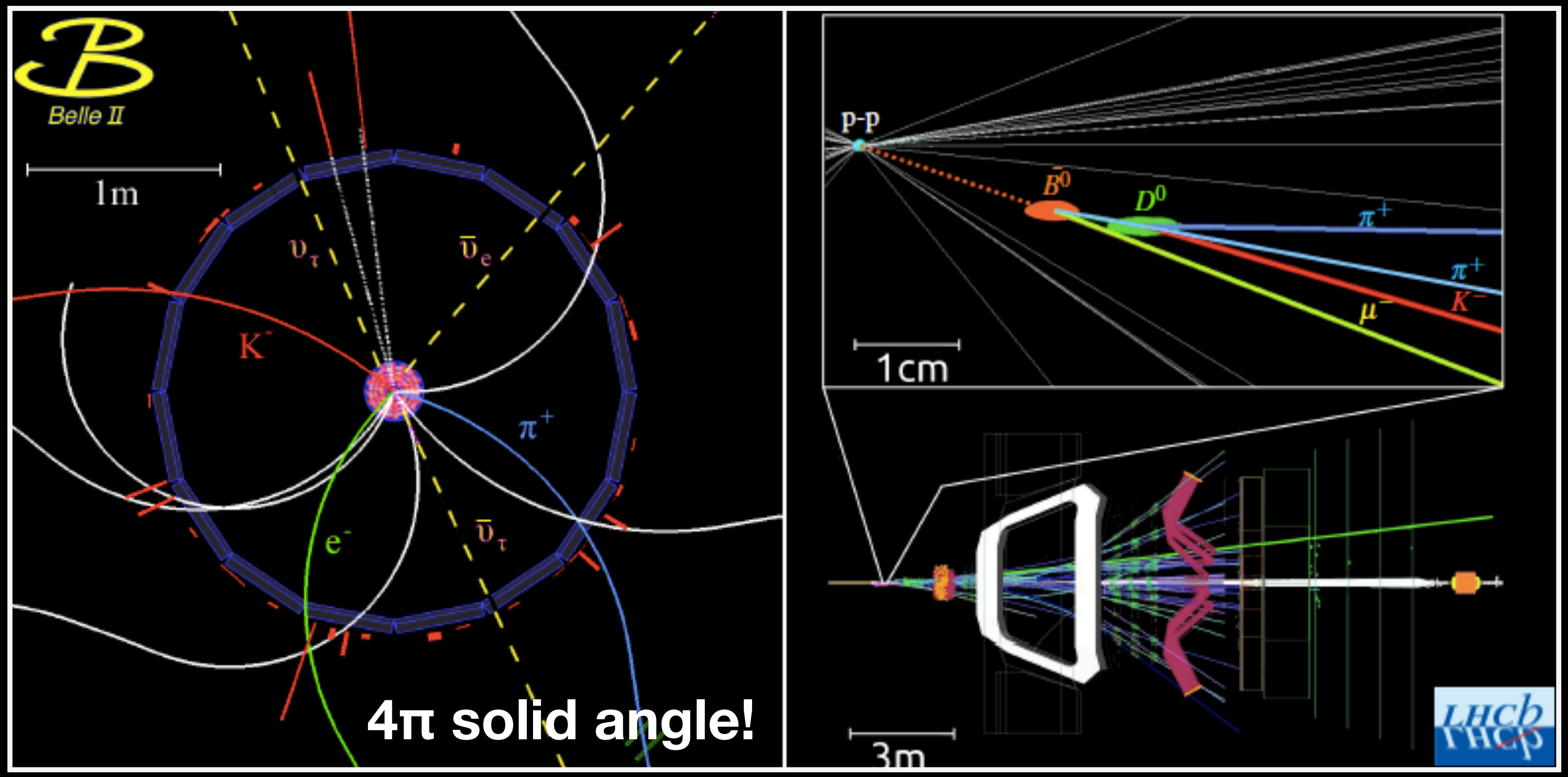
Belle II operation summary (2022ab)





- (Basically) stable operation at β_y^* = 1mm optics with CW.
- **A new luminosity world record (4.65 x 10^{34} cm^{-2} s^{-1}) achieved**
- Belle II DAQ stable (DAQ eff ~87%) — it was ~90%
    - Dead time (5.8%) dominated by **injection veto (~5.2%)**
    - DAQ trouble
        - Frequent HLT error at high L1 rate
        - Single Event Upset (iTOP and CDC)

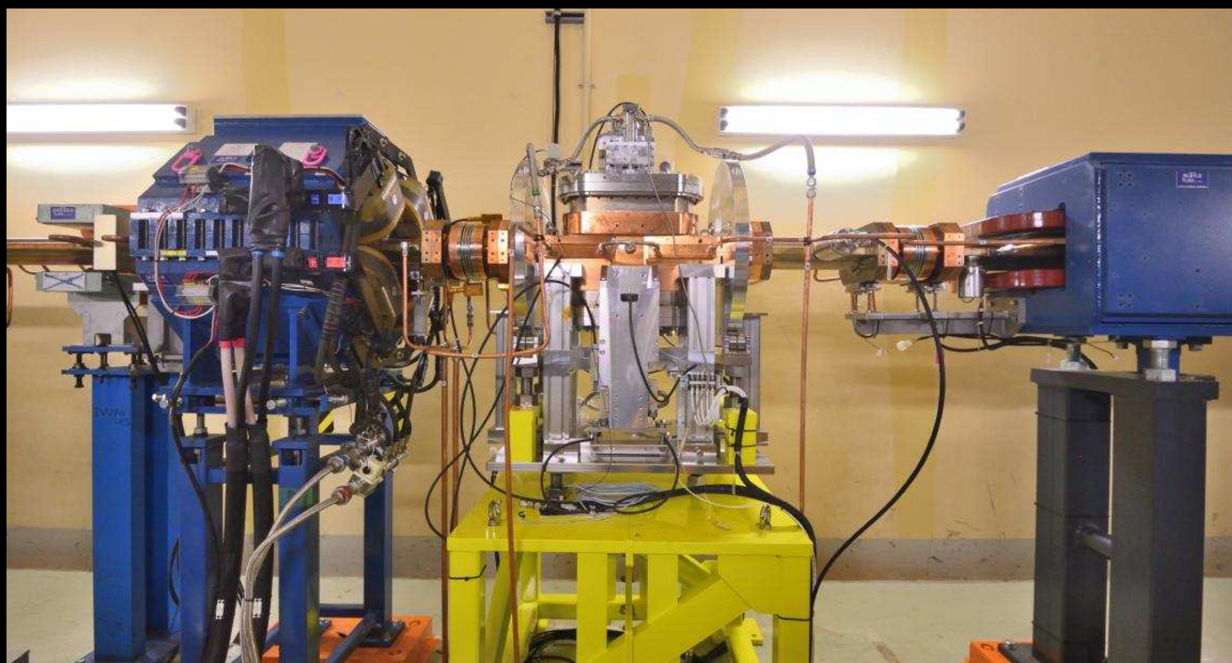
LHCb vs Belle II

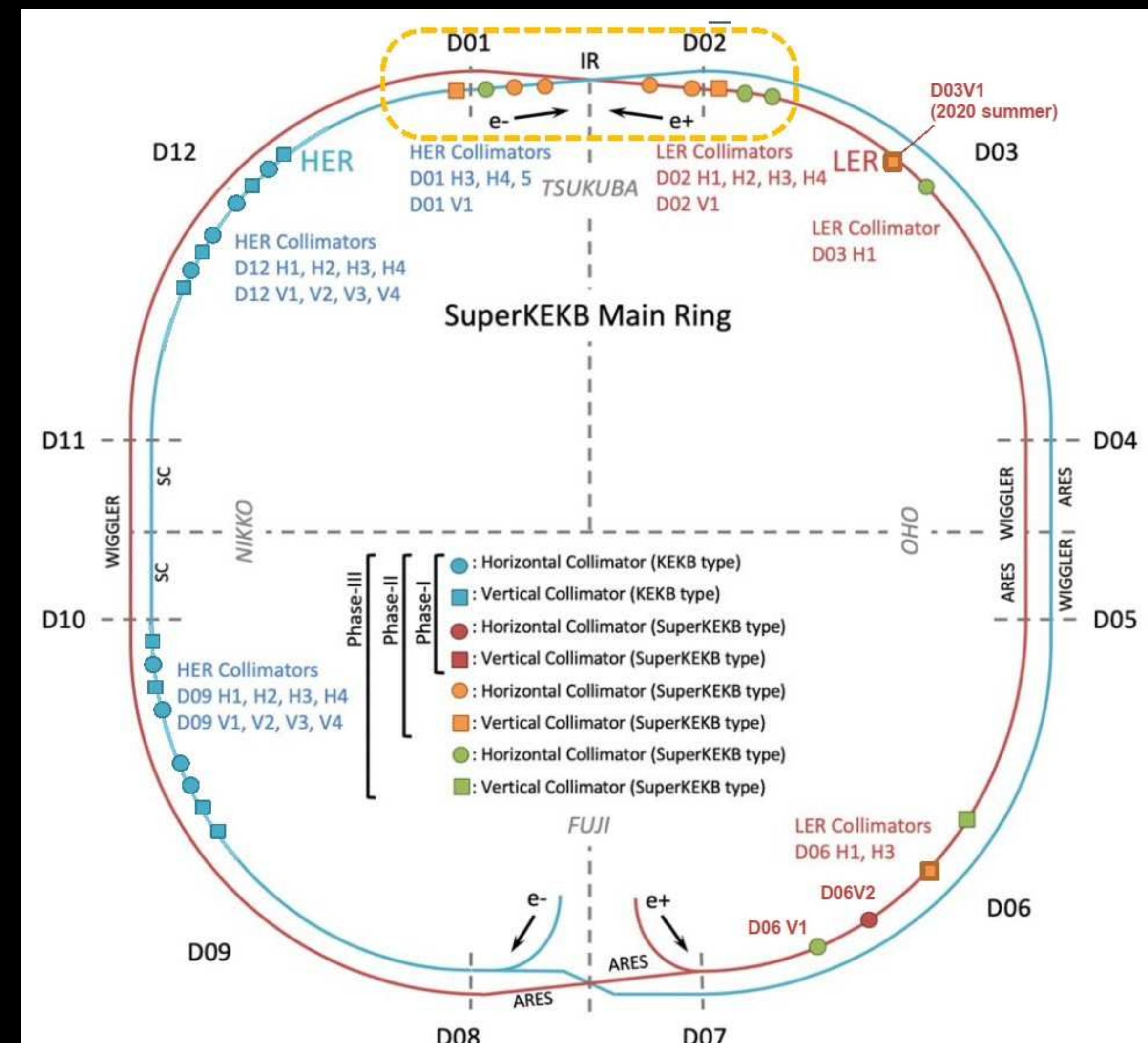


Credit: G. Ciezarak et al, Nature 546, 227 (2017)

- 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***

Collimator system



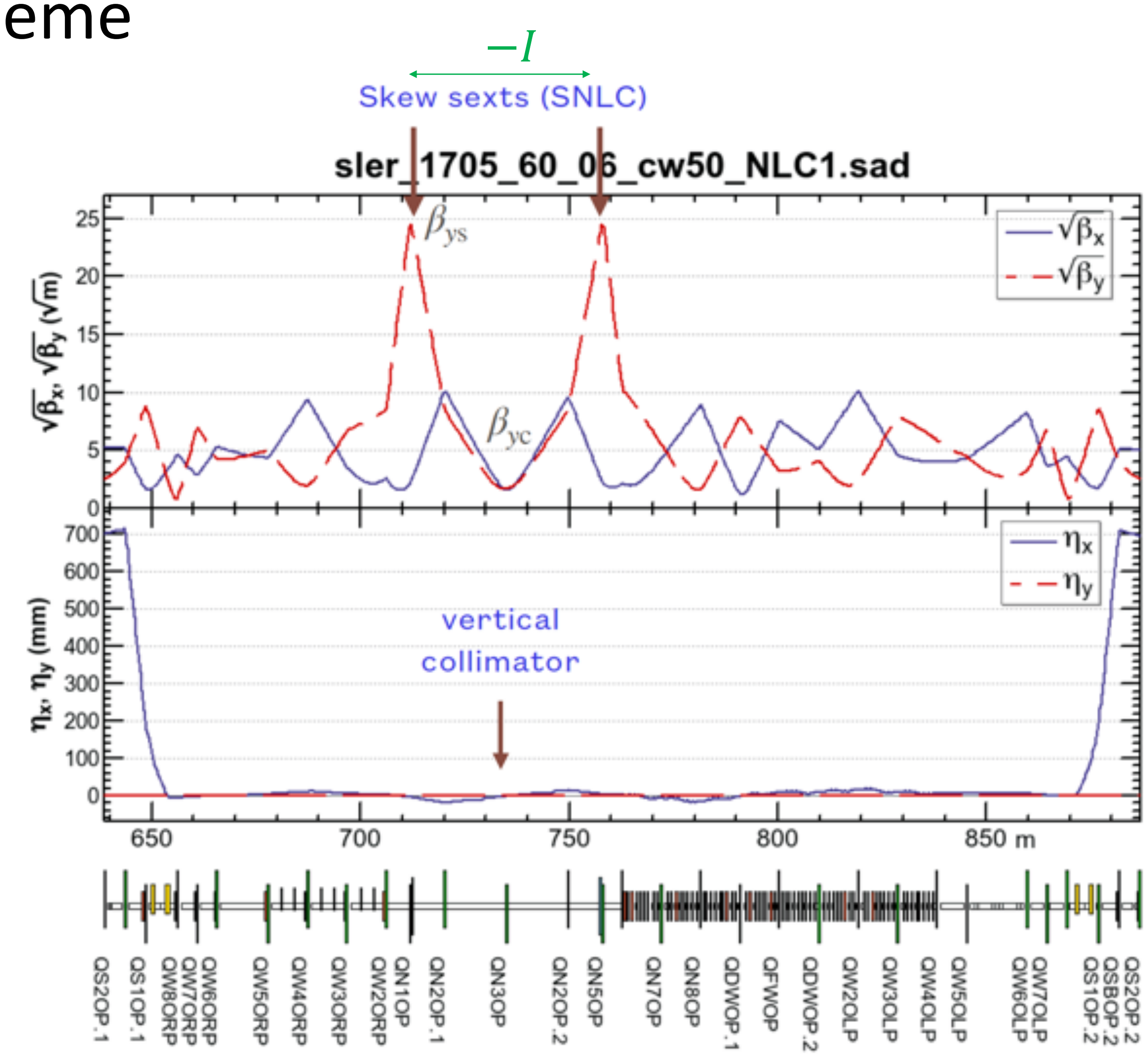


- **31 collimators** (18 horizontal and 13 vertical ones) are installed in the ring to protect the Belle II and the accelerator components from the beam background.

Non linear collimator

- Scheme

[K. Oide]



Requirements for the NLC optics:

- Large $\beta_y = \beta_{ys}$ at the (skew) sextupole.
  - $\beta_y = \beta_{yc}$ at the collimator: $\sqrt{\beta_{yc}\beta_{ys}} \approx 1.7 \times L_{sc}$
- A (skew) sextupole pair connected by a $-I$ transformation.
- No dispersion at the sextupoles and the collimator.
- ≈ 0.25 vertical phase advance between the sexts and the IP.

Five sections of wigglers are removed!

L_{sc}

$\Delta\mu_y = \frac{\pi}{2}$

Here the collimator is placed right before the center quad (QN3OP).
If the quad is split into two pieces, the collimator can be placed in the middle of them.

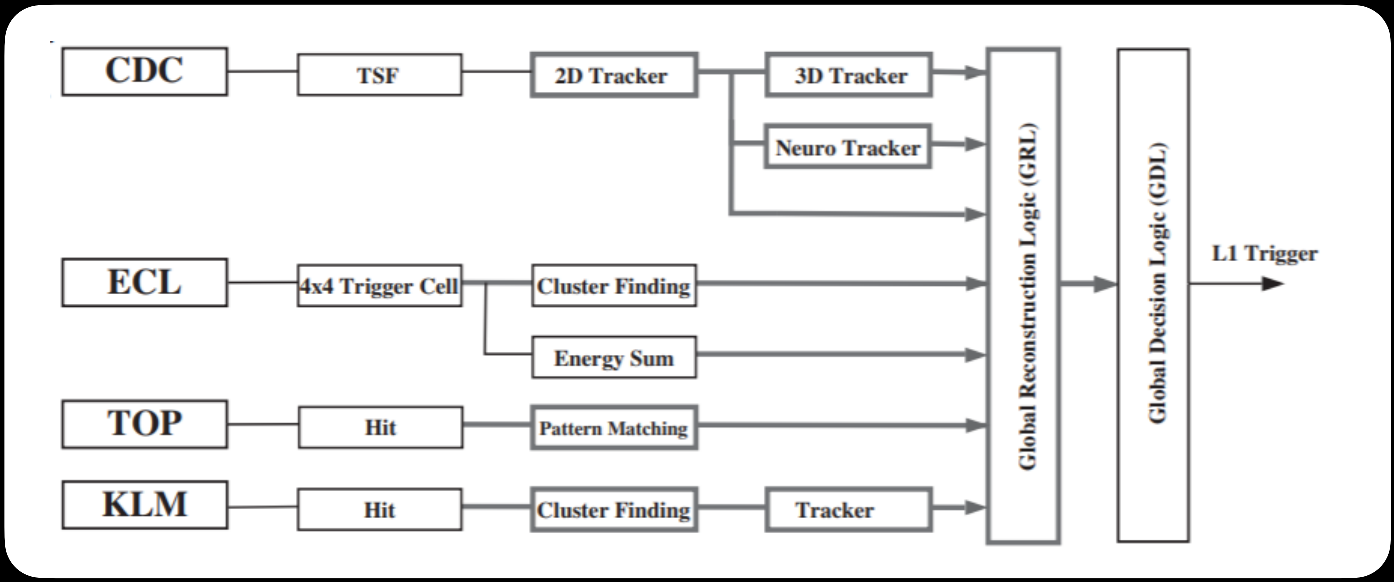
June 17, 2021 K. Oide

17

Skew sextuple magnets are used for collimation. No additional impedance budget. Robust against the damage. Installation during LS1 at OHO wiggler section.

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}.

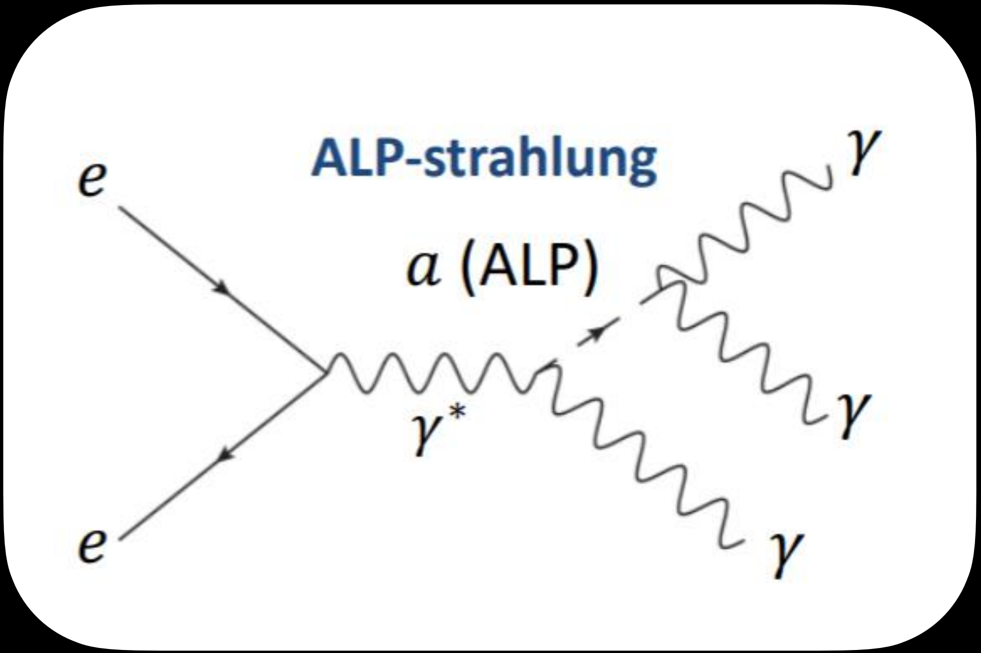


process	σ [nb]	Rate [Hz] @ L= 8 x 10^{35} cm^{-2} s^{-1}
Υ(4S)	1.2	960
Continuum	2.8	2200
μμ	0.8	640
ττ	0.8	640
Bhabha (*)	44.0	350
γ-γ (*)	2.4	19
Two photon (**)	13.0	10,000
Total	67	~15,000

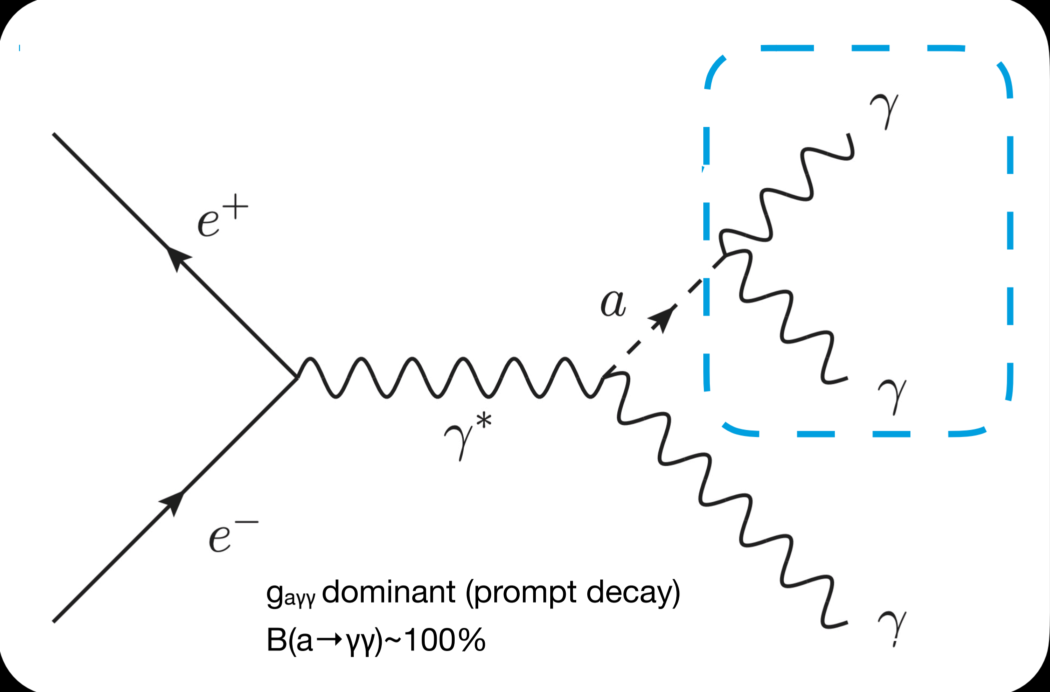
(*) Rate of Bhabha and γ-γ are pre-scaled by a factor of 100
(**) Rate are estimated by the luminosity component in Belle L1 rate

- 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

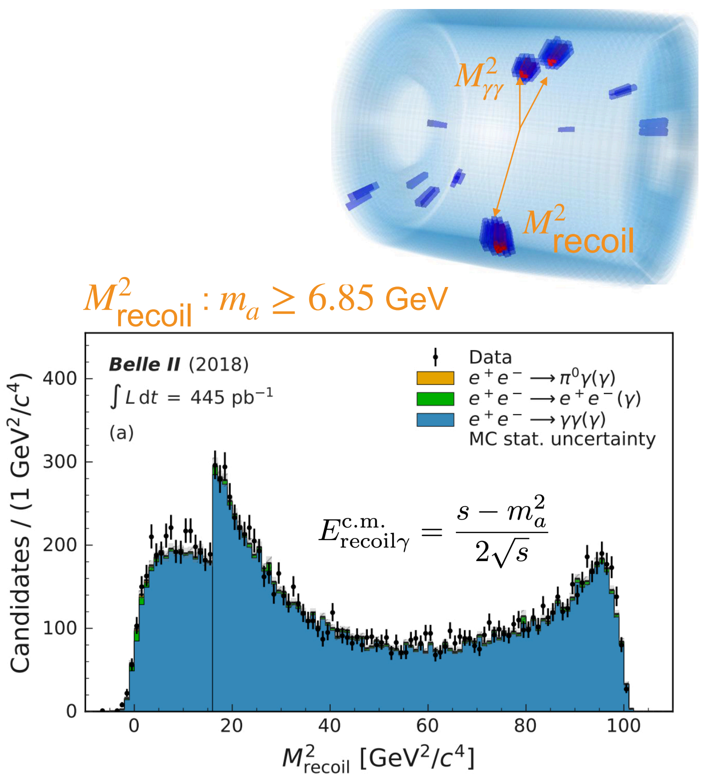


ALP search

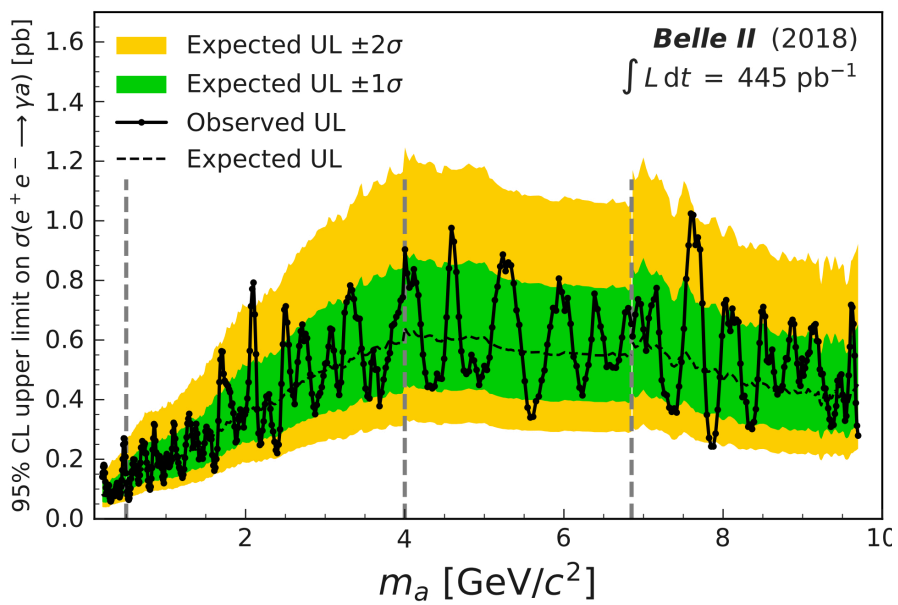


- GeV scale ALP (a) as a pseudo portal mediator btw Dark Sector and SM
- Peak hunting by selecting events with three photons with invariant mass consistent with √s.
- Background dominated by (irreducible) ee →3γ
- Set upper limits on σ(ee→γa)
  — no excess in $0.2 < m_a < 9.7$ GeV/c^2

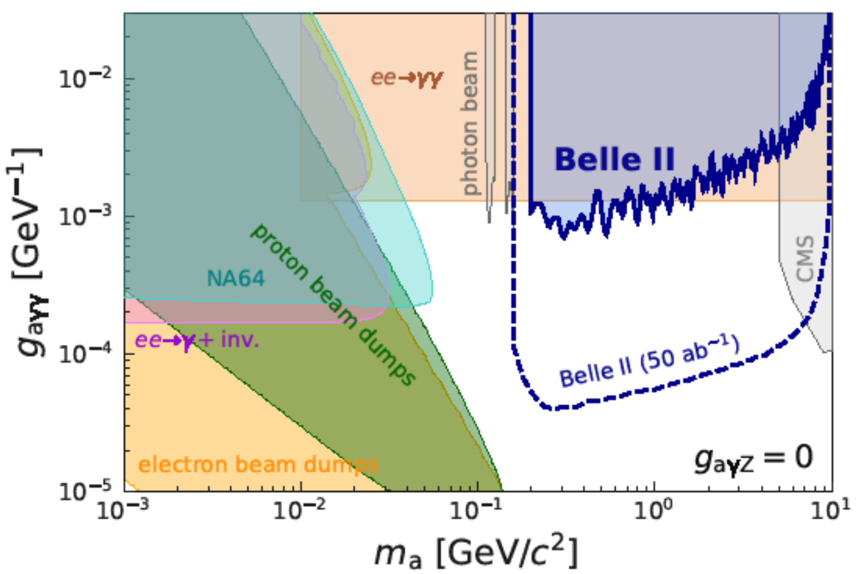
Phys. Rev. Lett. 125, 161806 (2020)



Upper limit on σ(ee → γa)

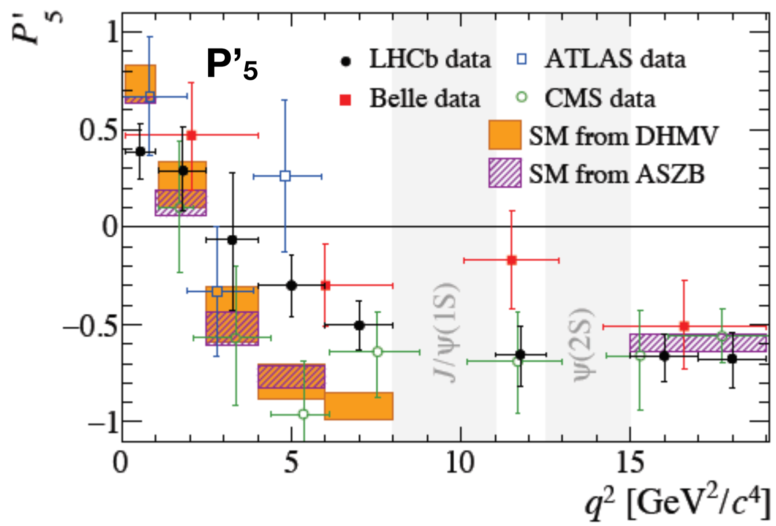


Upper limit on m_a vs $g_{a\gamma\gamma}$

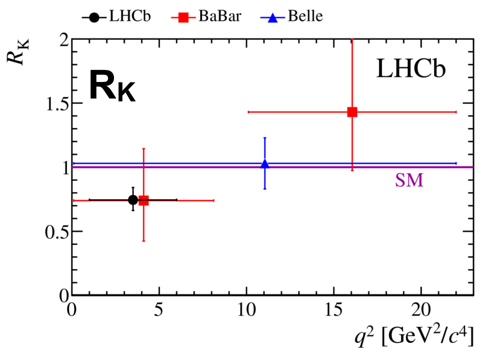


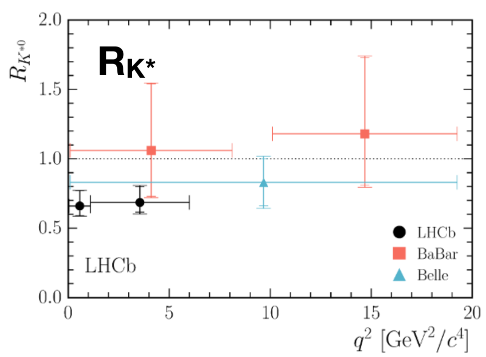
Projection to anomalies

Belle II will provide important cross-check to the anomalies in $B \to K^*\mu^+\mu^-$ and $R_{K^{(*)}}$



Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 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





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

- In the area of EWK Penguin, sensitivity of ~5 ab^{-1} Belle II data (~2024) will be comparable to 4.7 fb^{-1} of LHCb
- Other important physics results will be also coming up in the similar timeline.

Fast beam abort

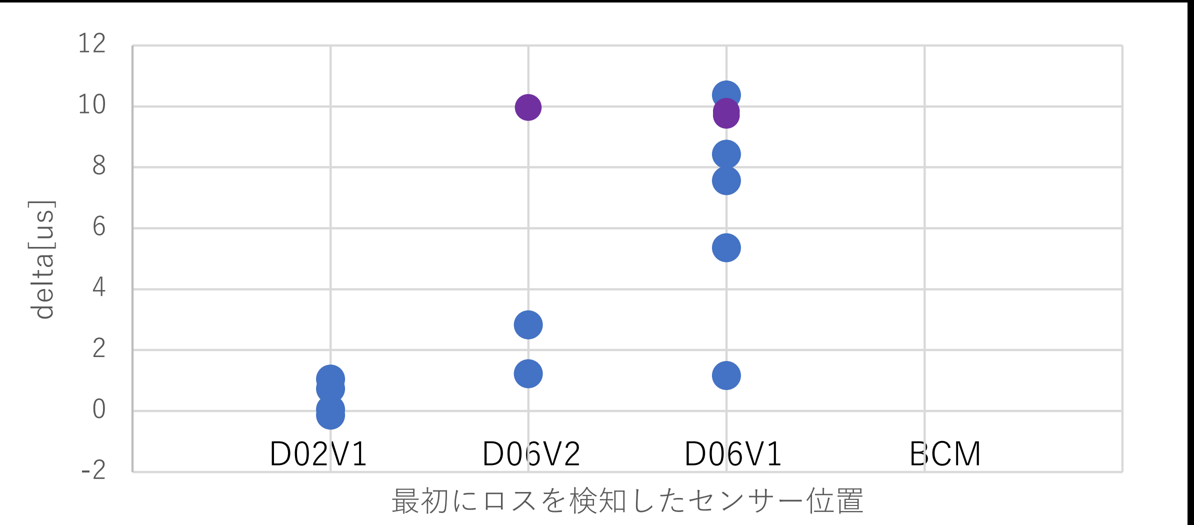
- According to the abort analysis, the first beam loss tends to be detected by D06 sensors (except for QCS quench events).

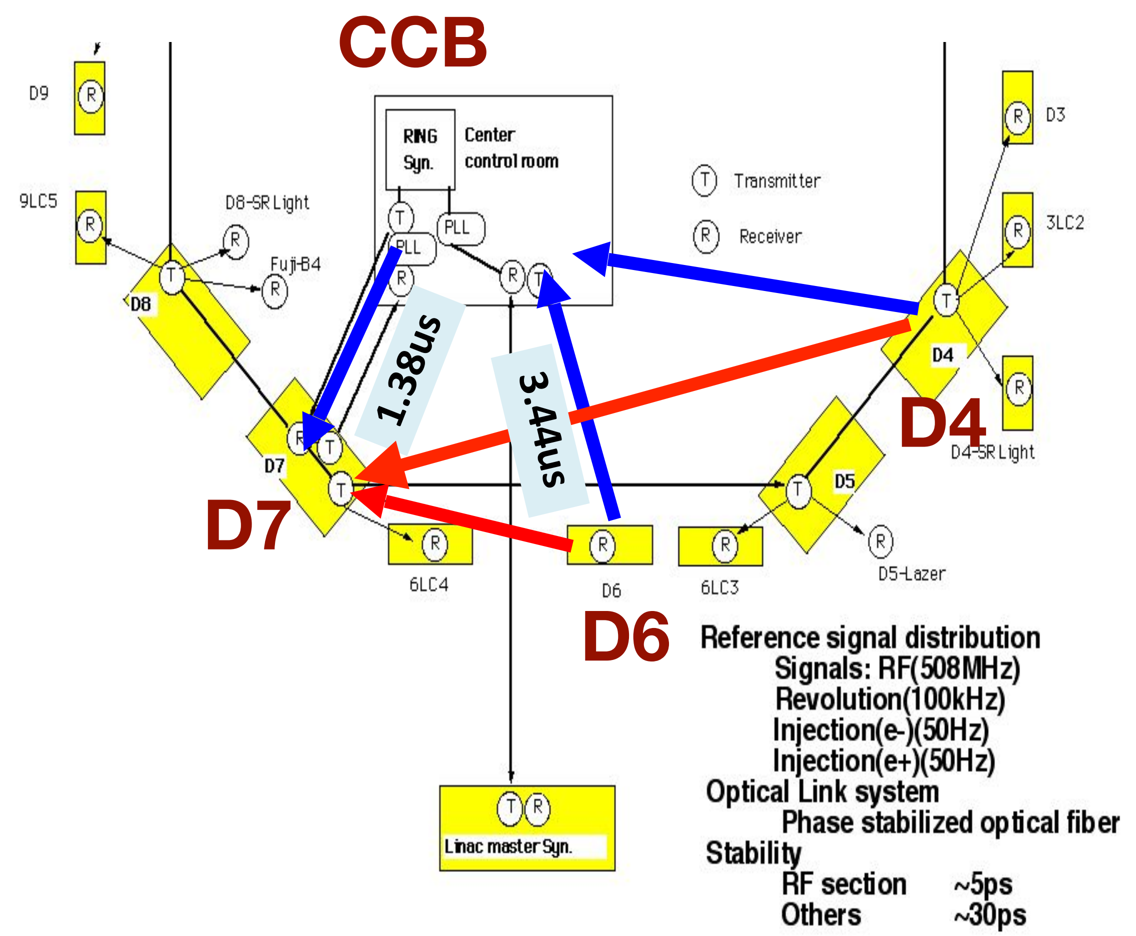
- The faster abort can be achieved by:

  ① having a sensor at better location

  ② faster sensor (**Ivan's talk**)

  ③ shorter transmission path





A transmission path changes from → to →

Machine parameters (at design)

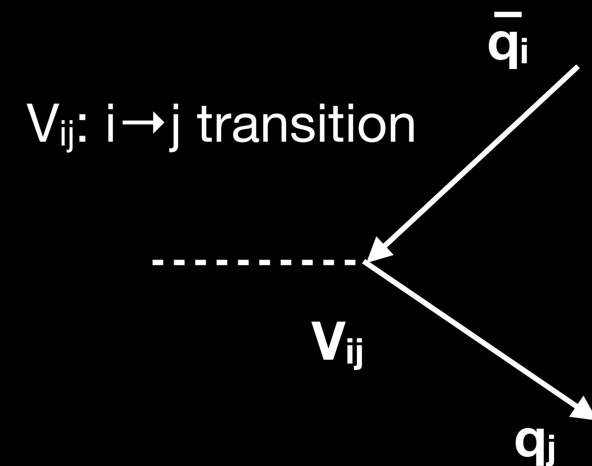
parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	**3.5**	**8**	**4**	**7.007**	GeV
Half crossing angle	ϕ	11		41.5		mrad
# of Bunches	N	1584		2500		
Horizontal emittance	ε_x	18	24	3.2	5.3	nm
Emittance ratio	κ	0.88	0.66	0.27	0.24	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		3.2/0.27	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}**		**$cm^{-2}s^{-1}$**

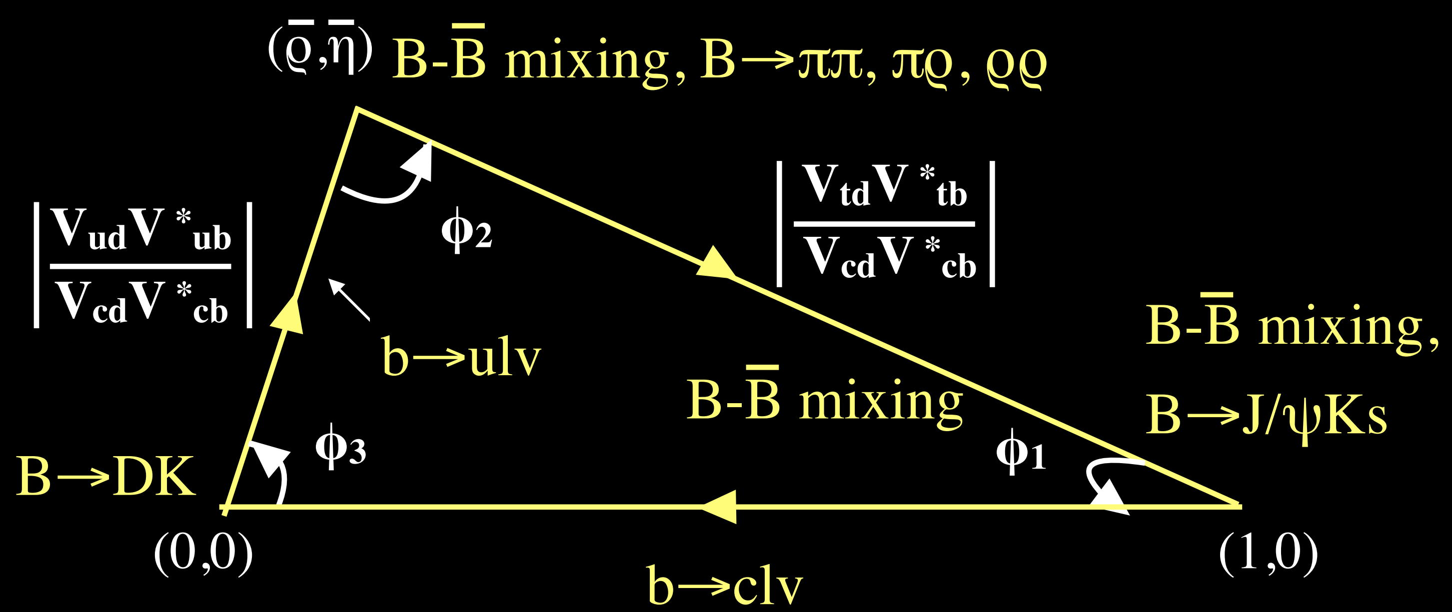
Note: beam energy changed because positron beam (Touschek) lifetime is too short while accepting smaller boost ($\beta\gamma$ = **0.42 → 0.28**) of decayed particles.

Unitarity triangle

CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^2(1-\varrho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$





In B-factory, all parameters can be measured!!

A triangle can be defined from CKM parameters by imposing a unitarity requirement. Each parameter can be determined by measurement of semi-leptonic decay or B-$\bar{B}$ mixing. Any distortion of the triangle could be a signature of new physics.

Kπ puzzle

https://arxiv.org/pdf/2206.07453.pdf

$K\pi$ puzzle

$K\pi$ puzzle: unexpected large difference between $\mathcal{A}^{\mathrm{CP}}_{K^+\pi^-}$ and $\mathcal{A}^{\mathrm{CP}}_{K^+\pi^0}$.

Isospin sum rule provides null test of standard model:

$$I_{K\pi} = \mathcal{A}^{\mathrm{CP}}_{K^+\pi^-} + \mathcal{A}^{\mathrm{CP}}_{K^0\pi^+}\frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^+\pi^0}\frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^0\pi^0}\frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}} \approx 0$$

Belle II is a unique place to measure all involved decays!

Previous tests of sum rule at Belle II using 62.8 fb^{-1}:
Measurements of $B^0 \to K^+\pi^-$, $B^+ \to K^0_S\pi^+$ (arXiv:2106.03766), $B^0 \to K^0_S\pi^0$ (arXiv:2104.14871) and $B^+ \to K^+\pi^0$ (arXiv:2105.04111).

Today: New measurement of $\mathcal{B}$ and $\mathcal{A}^{\mathrm{CP}}$ of $B^+ \to K^+\pi^0$ based on 190 fb^{-1}.

Update on $B^0 \to K^0_S\pi^0$ in Chiara La Licata's talk later today.

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)

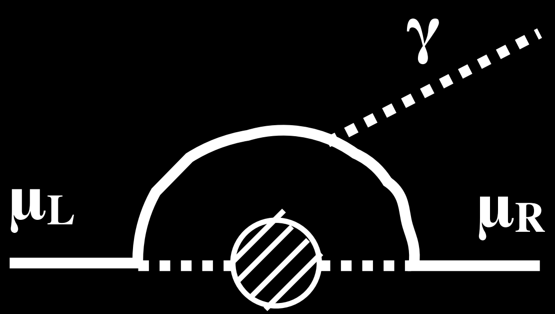
HVP： **H**adronic **V**acuum **P**olarization

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

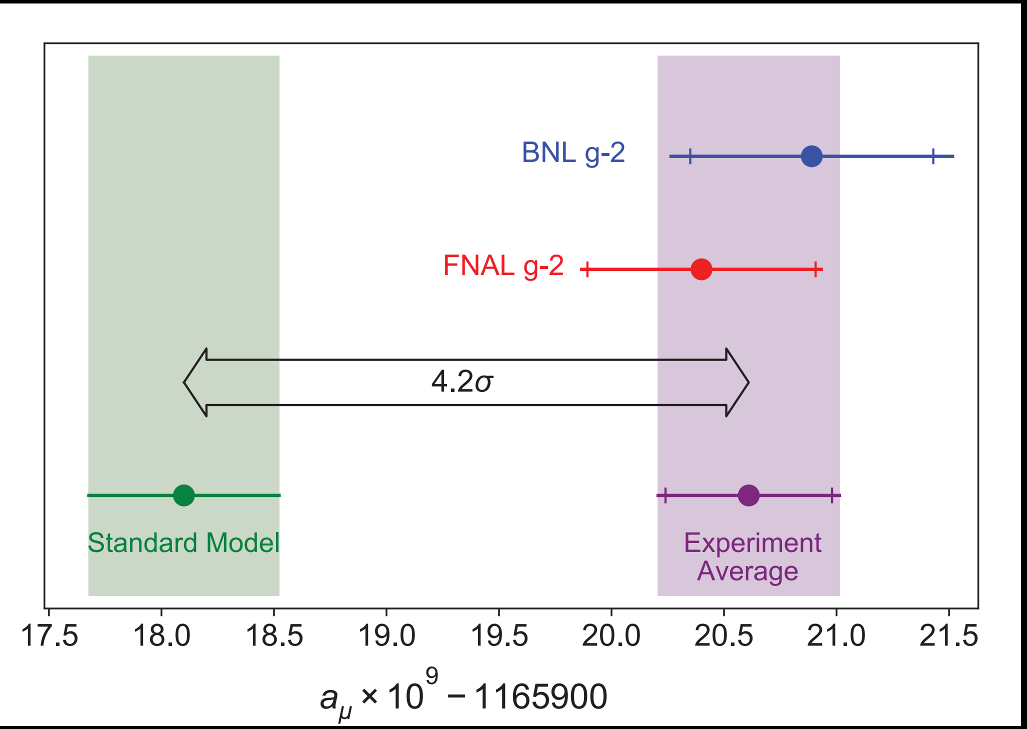
$$a_\mu^{QCD} = a_\mu^{HVP} + a_\mu^{HLbL}$$

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

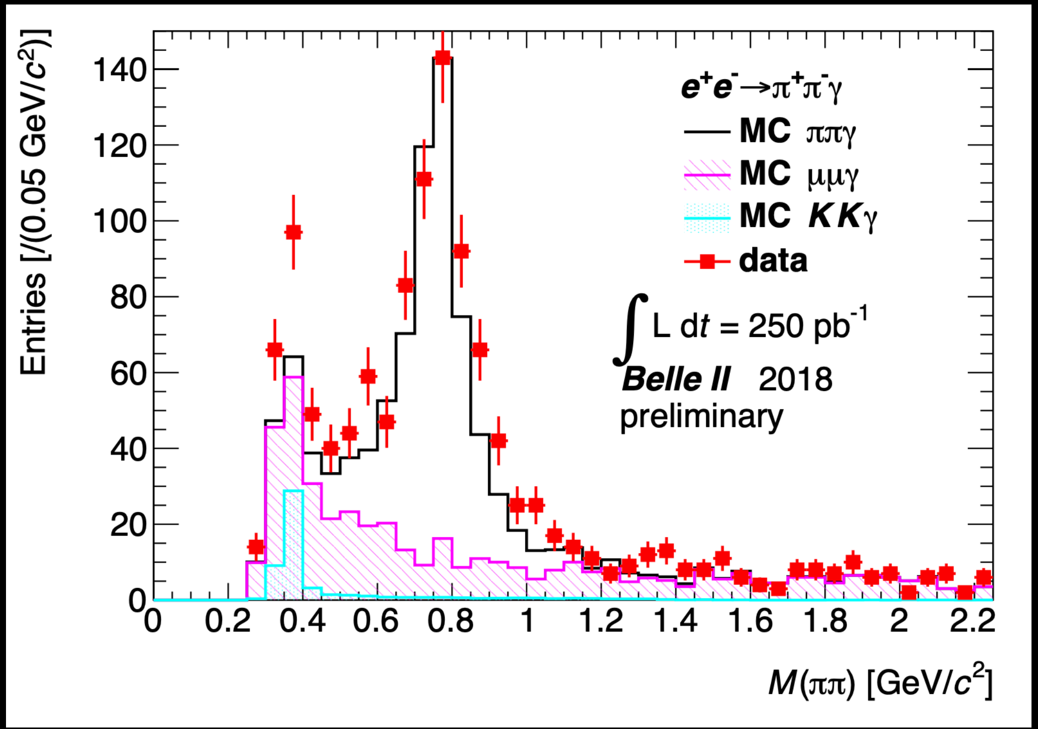
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



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?



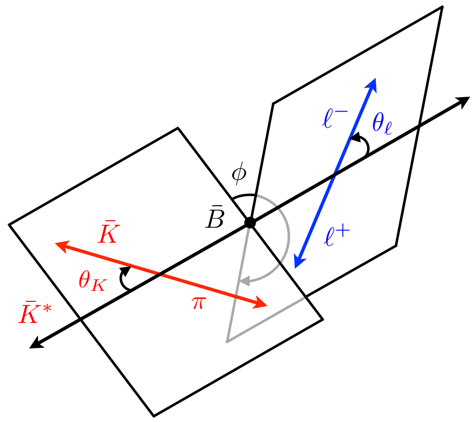
BELLE2-NOTE-PL-2018-023

Angular analysis

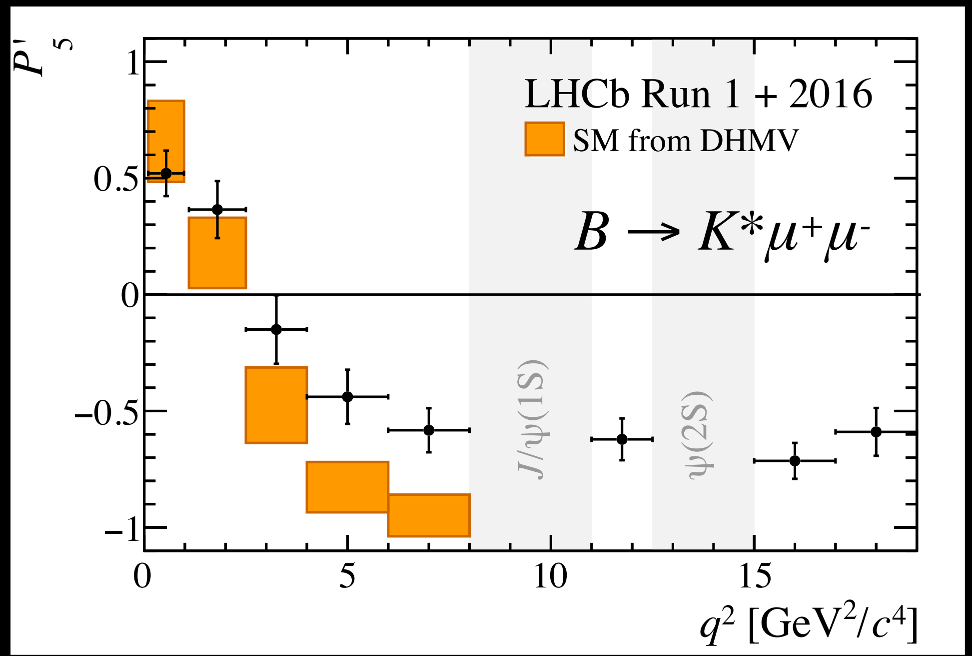
Measurement of $B \to K^* \ell^+ \ell^-$ at Belle II is an important cross check for $B \to K^* \mu^+\mu^-$ anomaly

angular variables $P'_{i=4,5,6,8}$ are sensitive to ***C_7, C_9 and C_{10}***

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



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



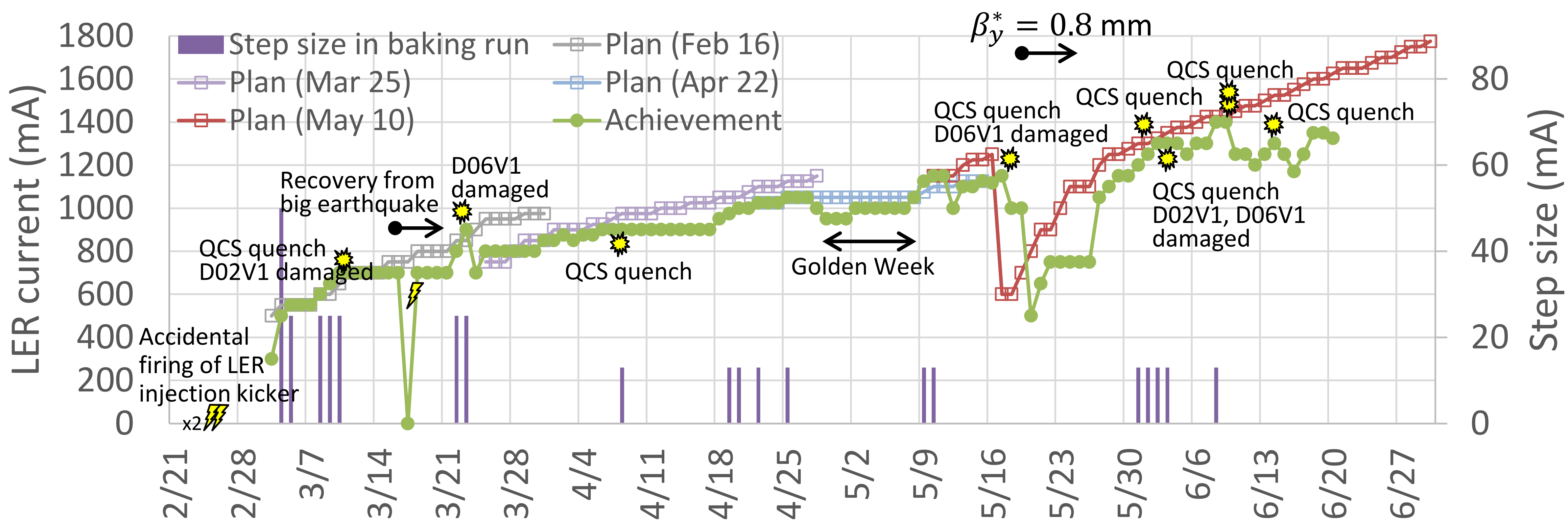
PRL125.011802(2020)

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}

Recent (2022ab) 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)

IR upgrade (long term)

- IR upgrade (QCS and its beam pipes) is essential to achieve 50 ab^{-1} (and peak luminosity of > 6×10^{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