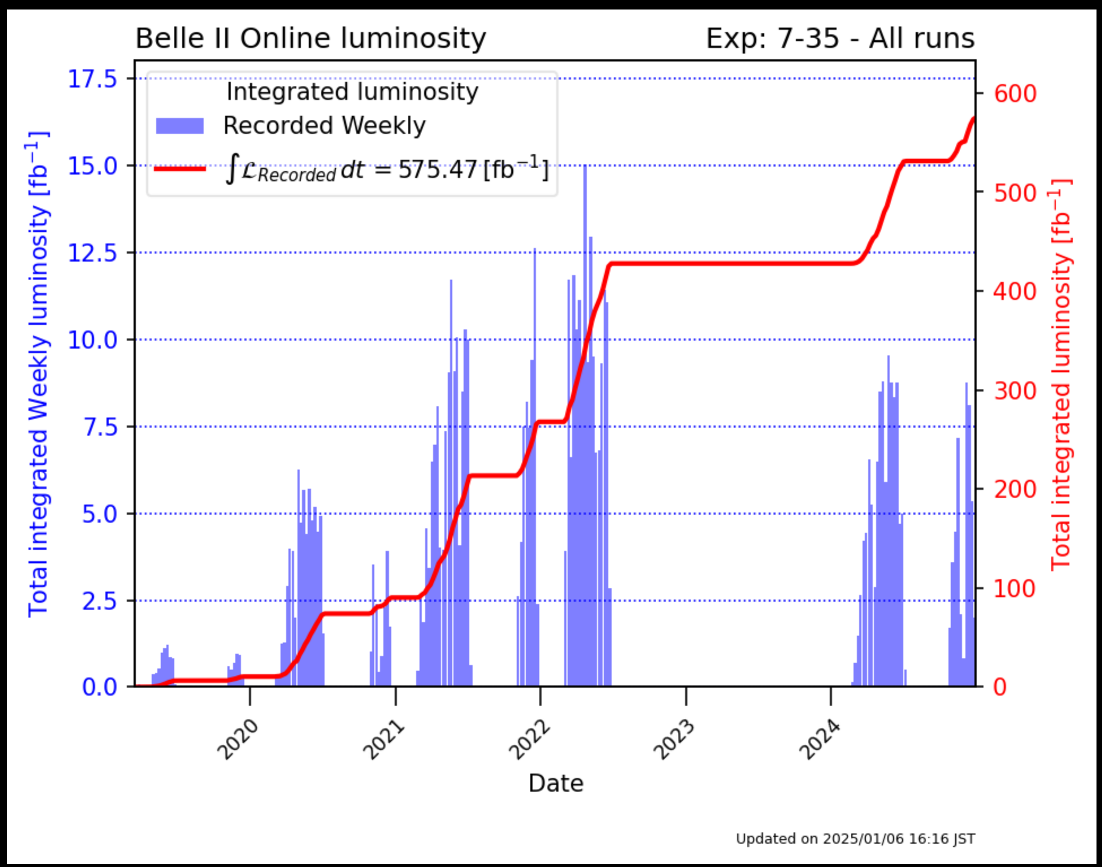
Current status and prospects of B-physics

Keisuke Yoshihara

University of Hawaii at Manoa

6th March 2025, KMI2025

Machine Operation Status



SuperKEKB luminosity is steadily increasing:

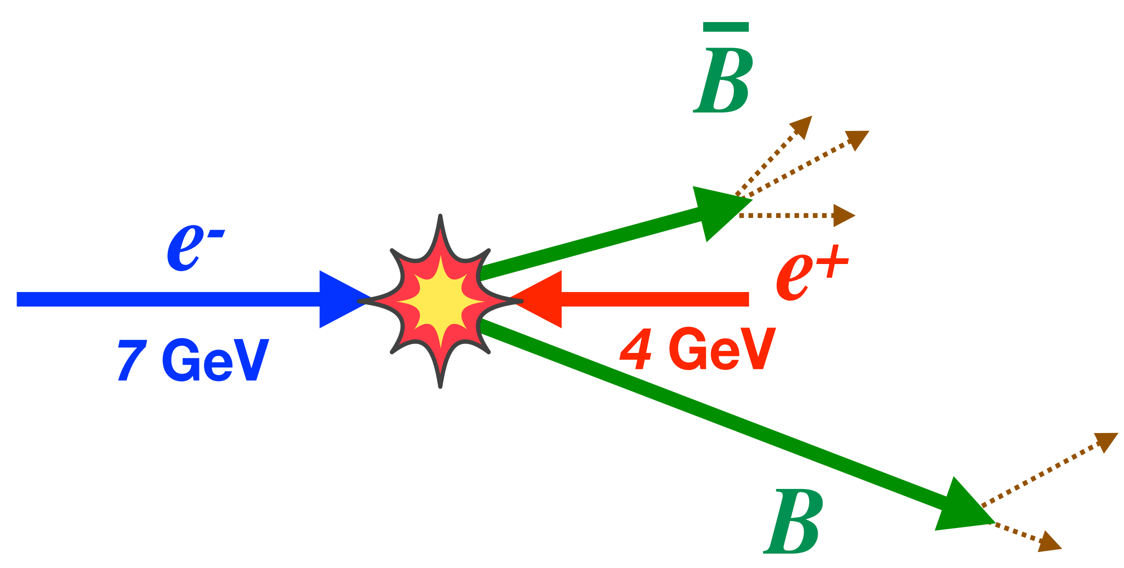
- **5.1 x 10^{34} $cm^{-2}s^{-1}$** achieved (World Record).
- **575 fb^{-1}** of data was collected, 495 fb^{-1} on Υ(4S) resonance.

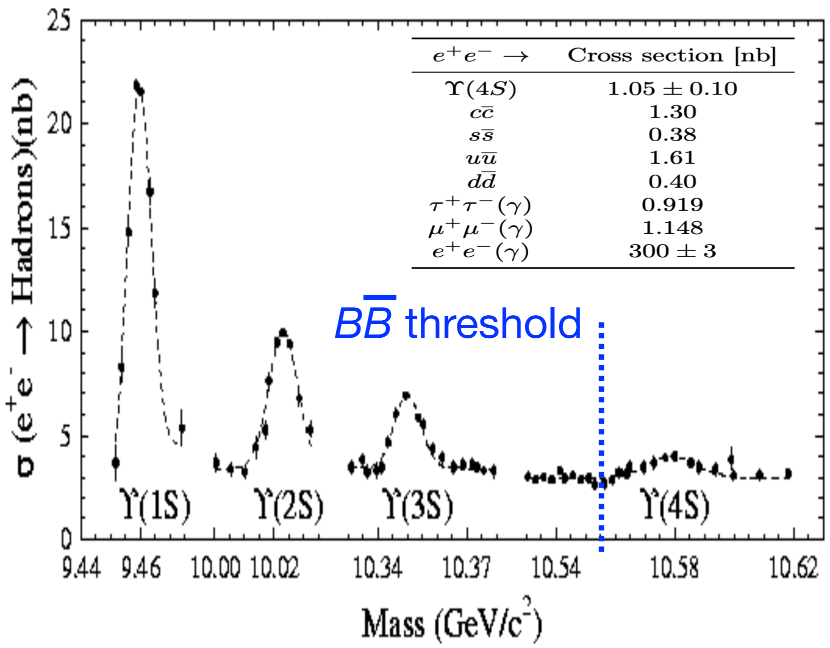
We are working on improving the luminosity (**Target: 6 x 10^{35} $cm^{-2}s^{-1}$**):

- "**Sudden Beam Loss**" is the main issue preventing us from increasing the beam current. It damaged 2% of PXD gates.

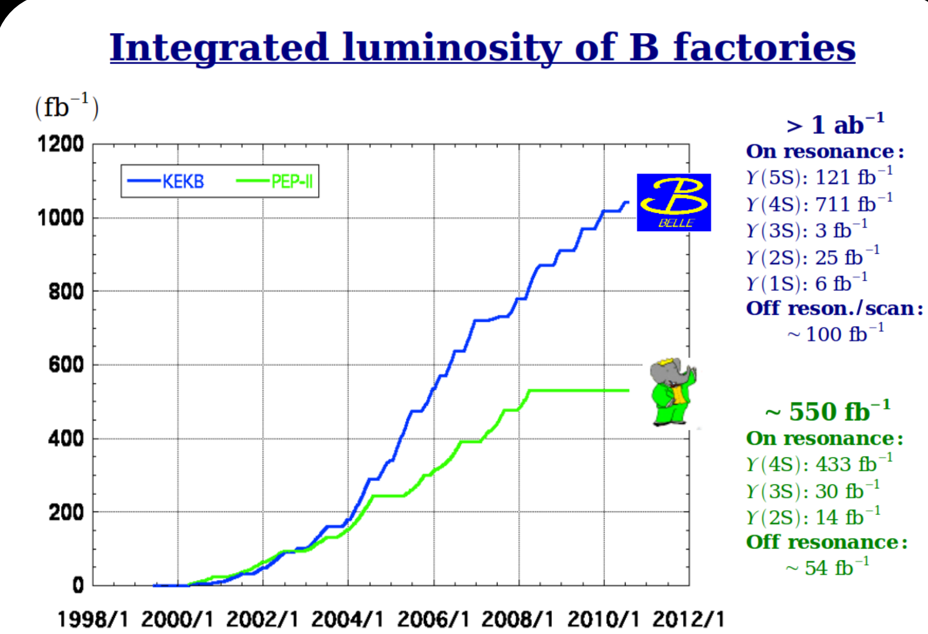
Introduction

At B-factories, electrons and positrons collide at the energy of the Υ(4S) resonance (10.58 GeV) to produce paris of B mesons.





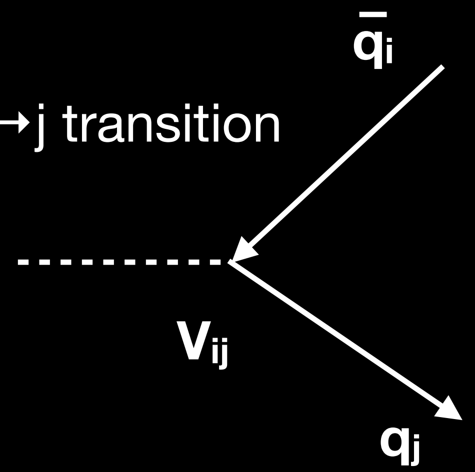
The KEKB/Belle (1ab^{-1}) and PEP-II/BaBar (550 fb^{-1}) discovered CP violation in the B meson system, enabling measurements of the CKM matrix elements.

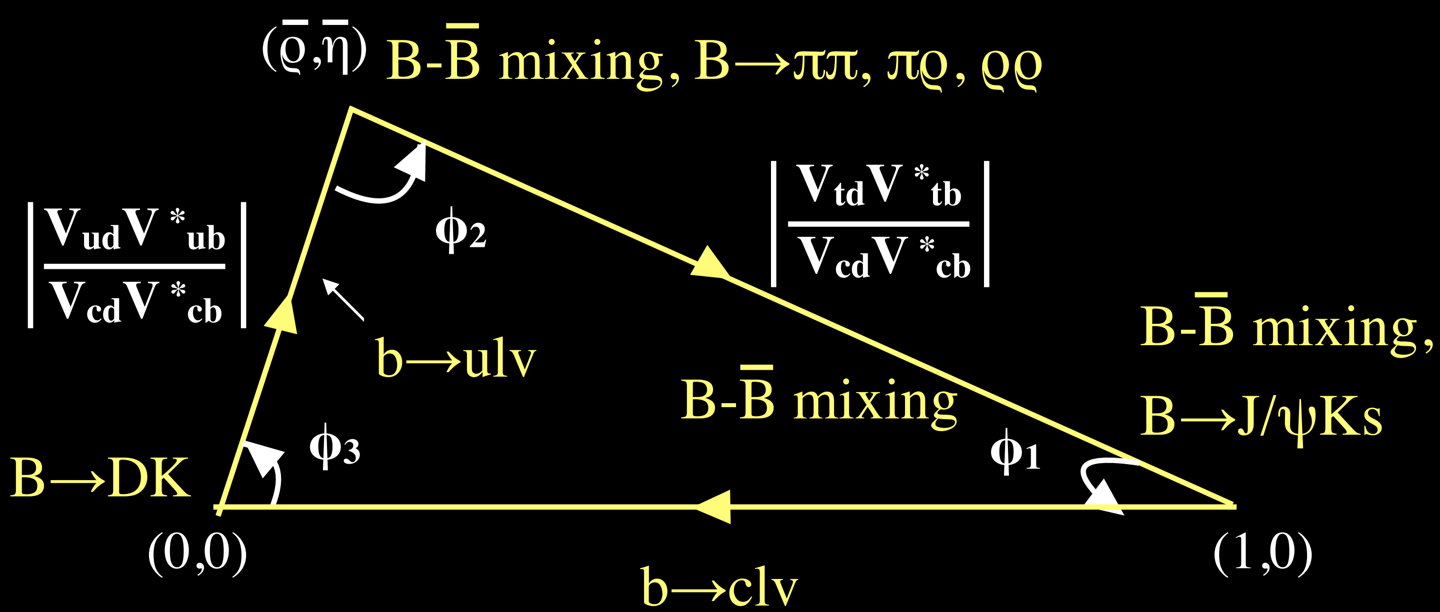


Unitarity triangle

CKM matrix

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



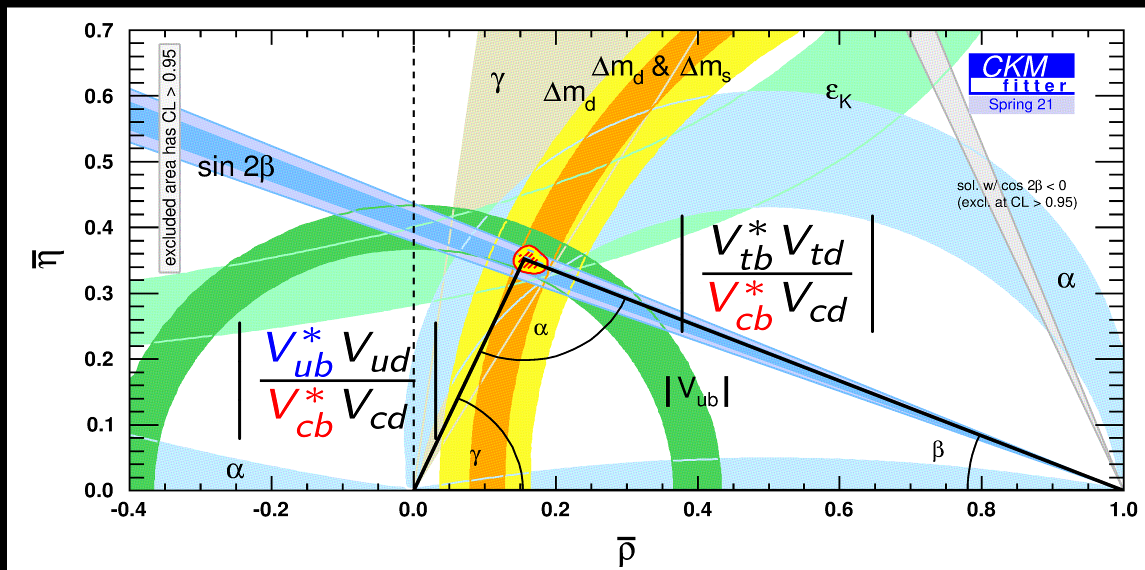


In B-factory, all parameters can be measured!!

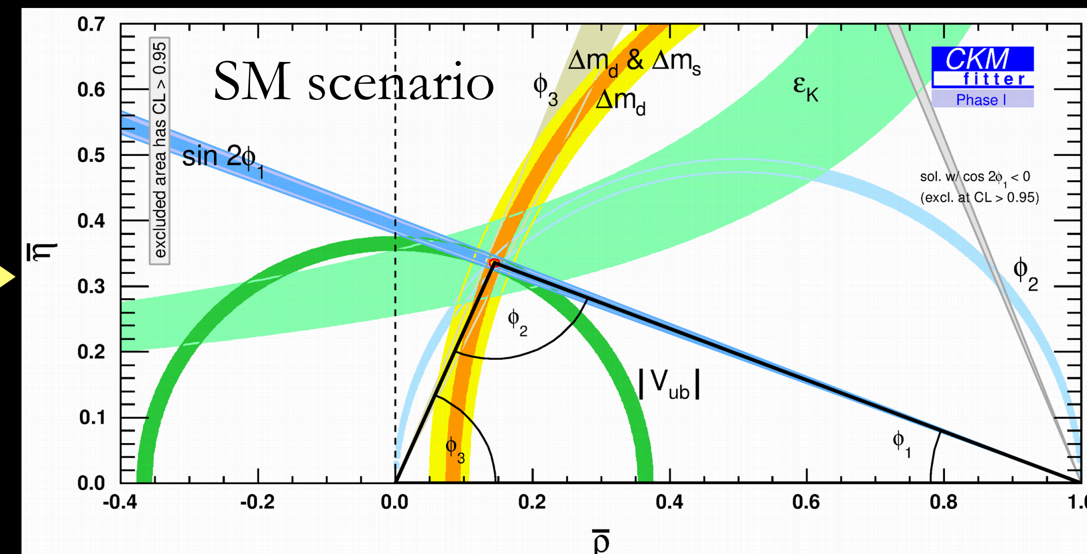
A triangle can be defined from CKM parameters by imposing a unitarity requirement. Each parameter can be determined by measurement of **semi-leptonic decay or B-$\bar{B}$ mixing**. Any distortion of the triangle could be a signature of new physics.

Measurement of the CKM Parameters

Current Status



Belle II: 50 ab^{-1} and LHCb: 23 fb^{-1}



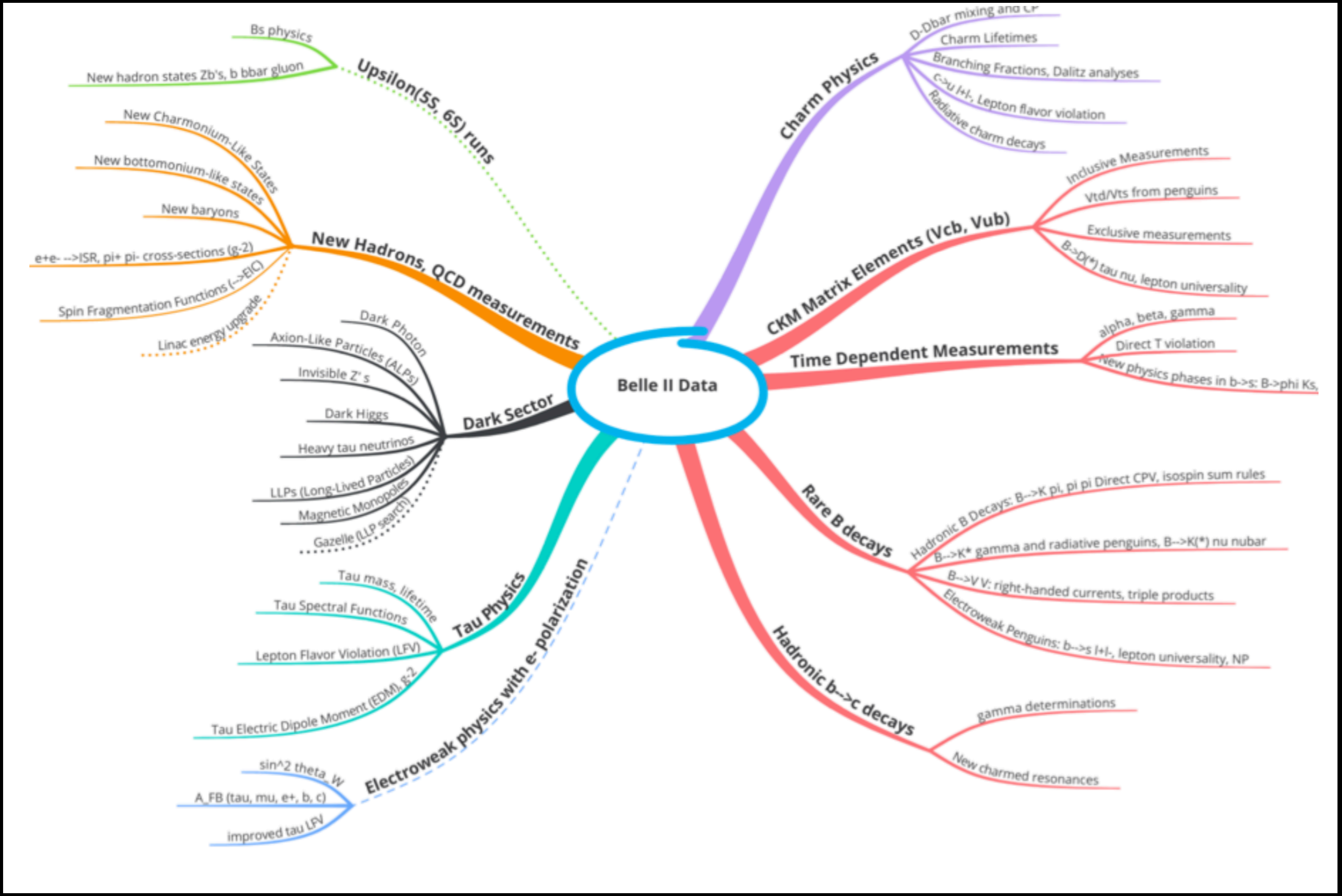
Measurement Precision at Belle II

arXiv:1808.10567

Observable	Belle	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
$\lvert V_{cb}\rvert$ incl.	1.8%	1.2%	1.2%
$\lvert V_{cb}\rvert$ excl.	$3.0_{ex} \pm 1.4_{th}$%	1.8%	1.4%
$\lvert V_{ub}\rvert$ incl.	$6.0_{ex} \pm 2.5_{th}$%	3.4%	3.0%
$\lvert V_{ub}\rvert$ excl.	$2.5_{ex} \pm 3.0_{th}$%	2.4%	1.2%
sin2ϕ_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

With 50 ab^{-1} of data, not only the precision of ϕ_1, but also **$|V_{ub}|$, ϕ_2, ϕ_3** will be significantly improved. On the other hand, the precision of $|V_{cb}|$ and $|V_{td}|$ is tied to theoretical models and the accuracy of Lattice QCD calculations.

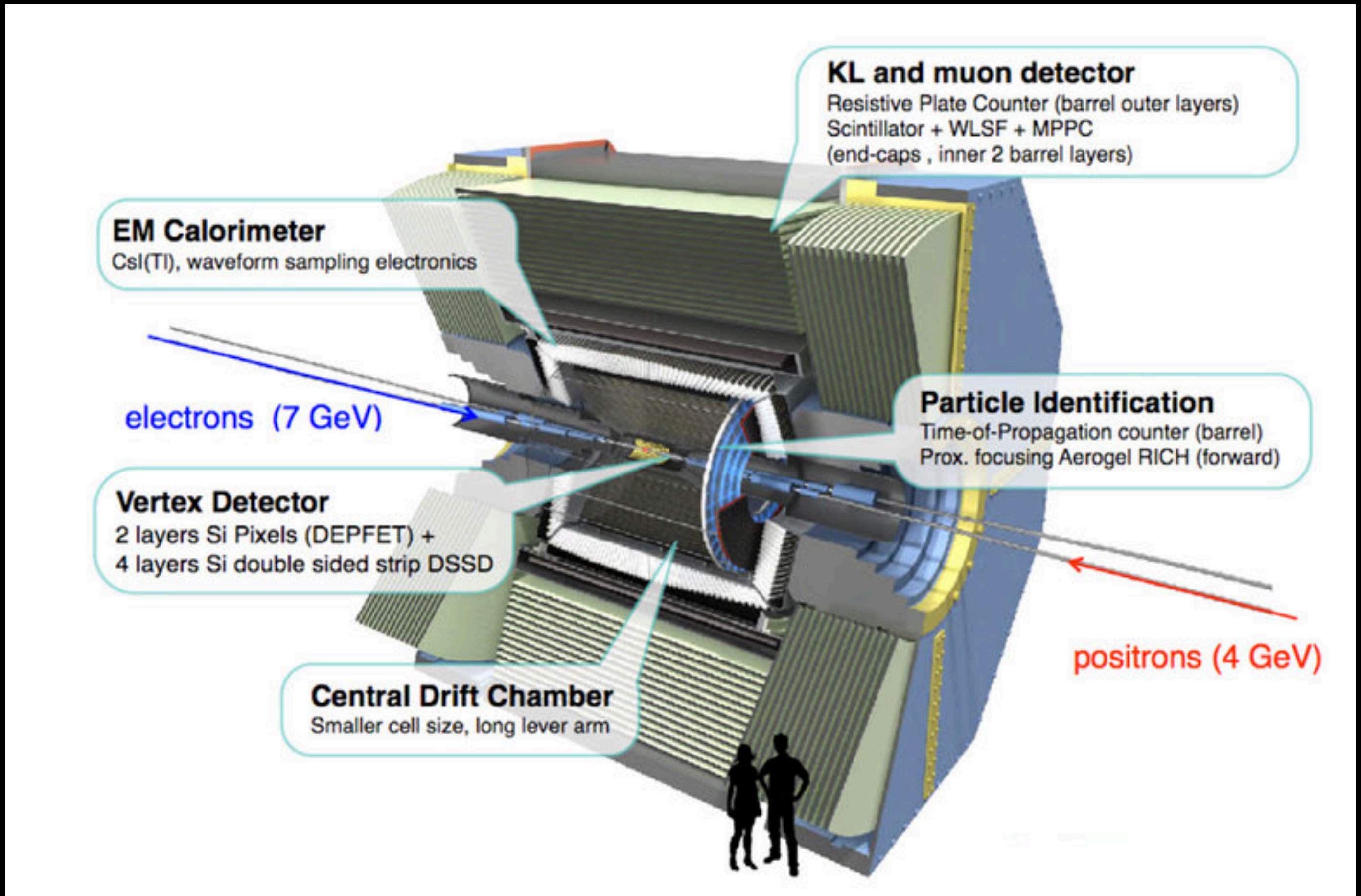
Physics Program



SuperKEKB/Belle II Experiment

Physics objectives

- Precise CKM measurements, rare decay studies,
- GeV-scale dark matter searches (e.g., axion-like particles and dark photons),
- Tau physics and hadron physics.



Belle II TDR, arXiv:1011.0352

- A large tracking volume, providing high vertex resolution against high-background environment.
- Improved π/K separation (~4σ)
- Trigger rate up to **30 kHz**
  - ~100% eff. for B meson events
  - Dedicated triggers for dark sector searches
- Grid computing technology for data analysis

Vertexing performance — charm lifetime

The lifetime meas. nicely demonstrates performance of vertex reconstruction.

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

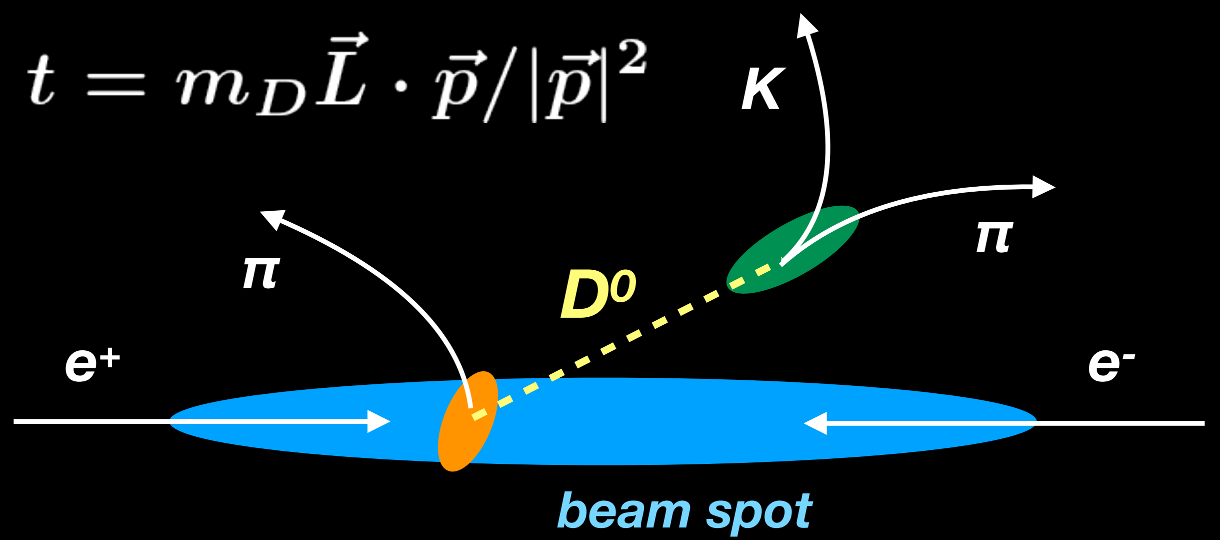
$$\begin{cases} D^{*+} \to D^0(\to K^-\pi^+)\pi^+ \\ D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0 \end{cases}$$
$$\begin{cases} D_s^+ \to \phi\pi^+ \\ \Lambda_c^+ \to pK^-\pi^+ \end{cases}$$

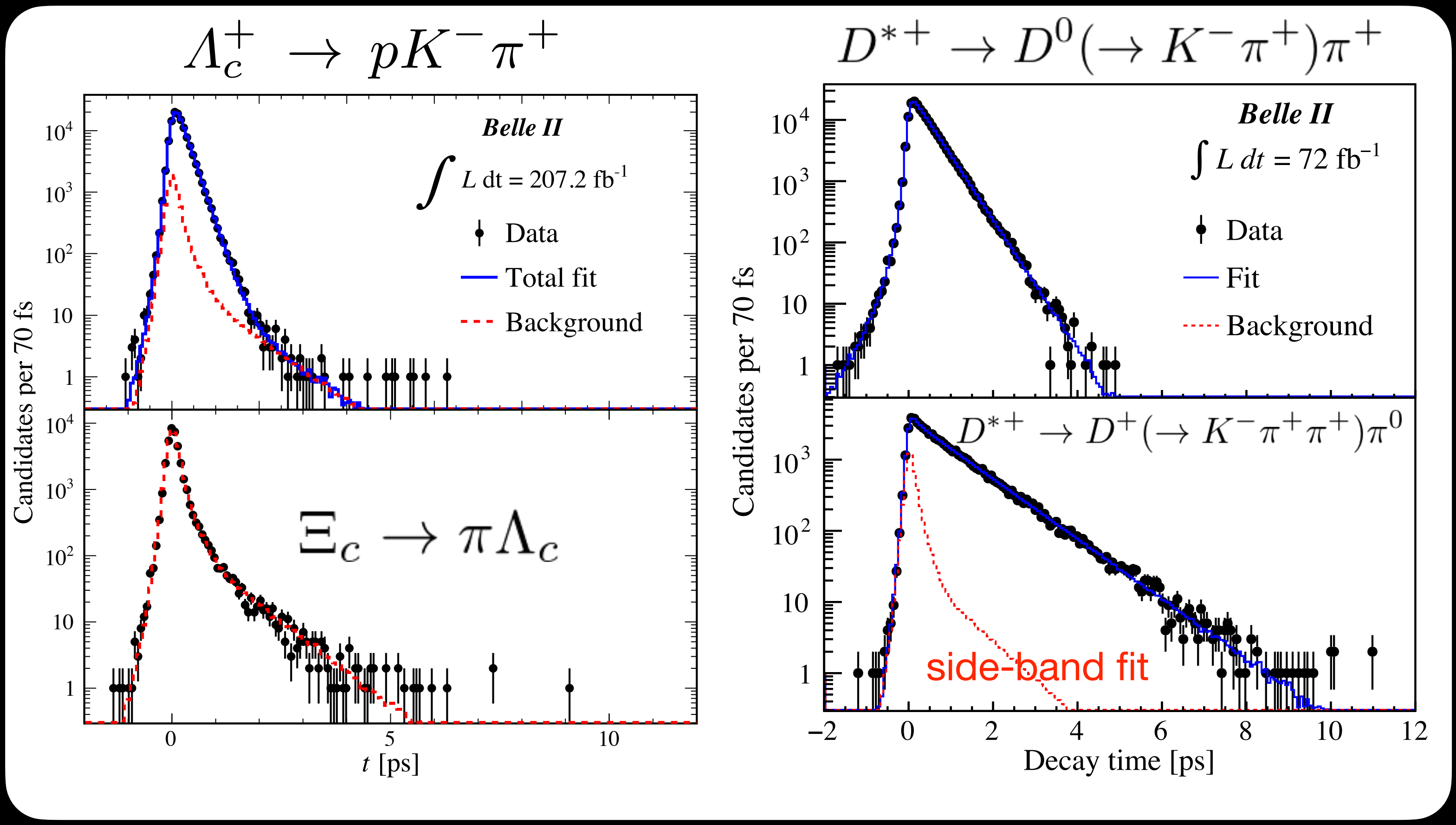
Backgrounds are estimated from the side-band or simulation.

$$\begin{cases} \tau(D^0) = (410.5 \pm 2)\text{fs} \\ \tau(D^+) = (1030.4 \pm 5.6)\text{fs} \end{cases}$$
$$\begin{cases} \tau(D_s^+) = (499.5 \pm 1.9)fs \\ \tau(\Lambda_c^+) = (203.2 \pm 1.1)\text{fs} \end{cases}$$

World best meas. achieved thanks to new PXD layers.

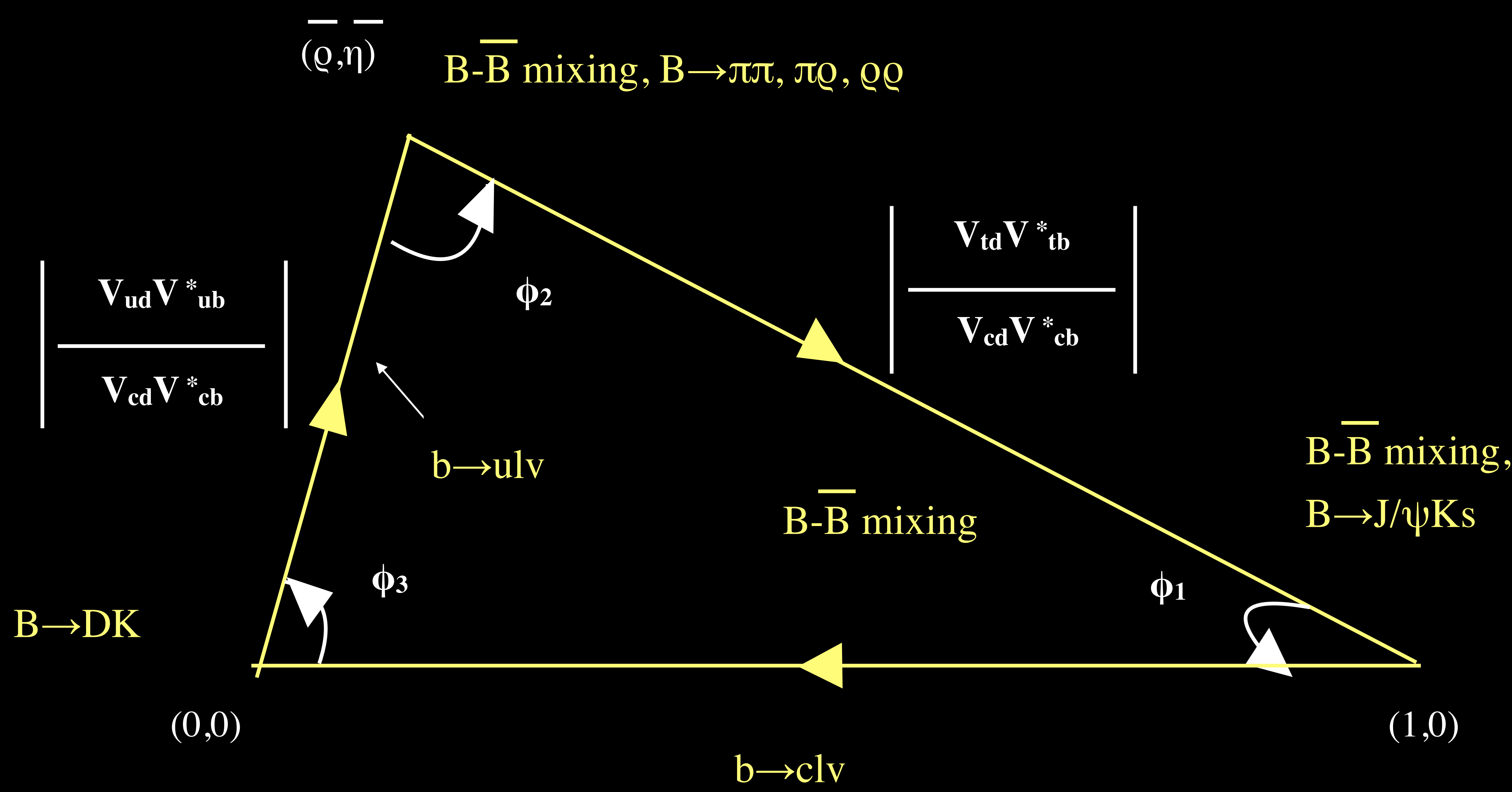
$$t = m_D \vec{L} \cdot \vec{p}/|\vec{p}|^2$$



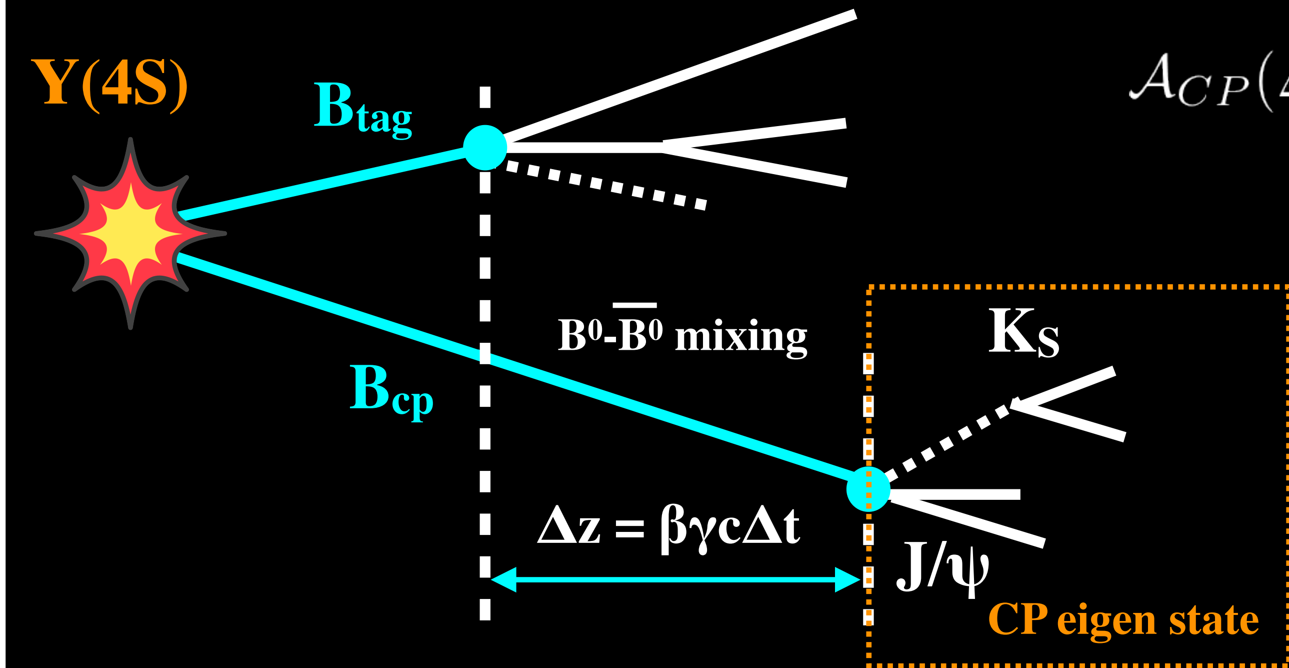


Phys. Rev. Lett. 127, 211801 (2021) Phys. Rev. Lett. 130, 071802 (2023)
Phys. Rev. Lett. 131, 171803 (2023)

CKM Parameter Measurements



Time dependent CP asymmetry



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

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

mixing induced CPV

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

B → $J/\psi K_S$

B → $\bar{B}$ → $J/\psi K_S$

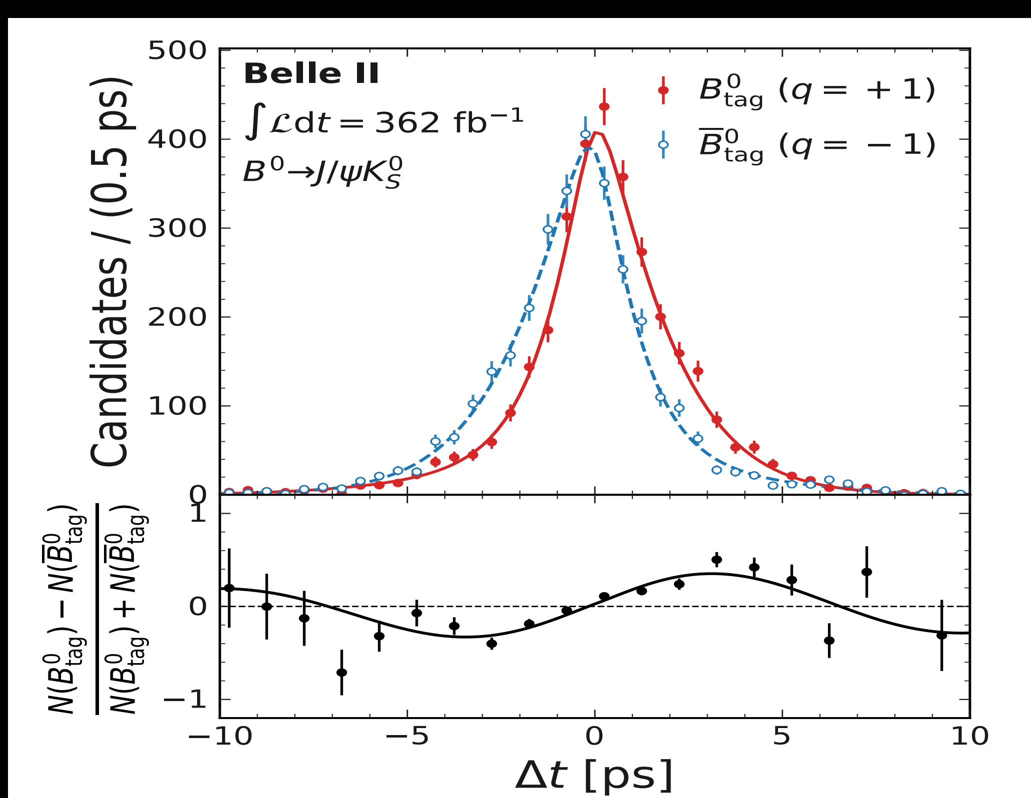
Direct CPV

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

|B> → | f>
≠
|$\bar{B}$> → | f>

A_{CP} = 0 (tree level)

∗ **S, A: defined by final state**



[Phys. Rev. D 110, 012001 (2024)]

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

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

→ golden mode for ϕ_1

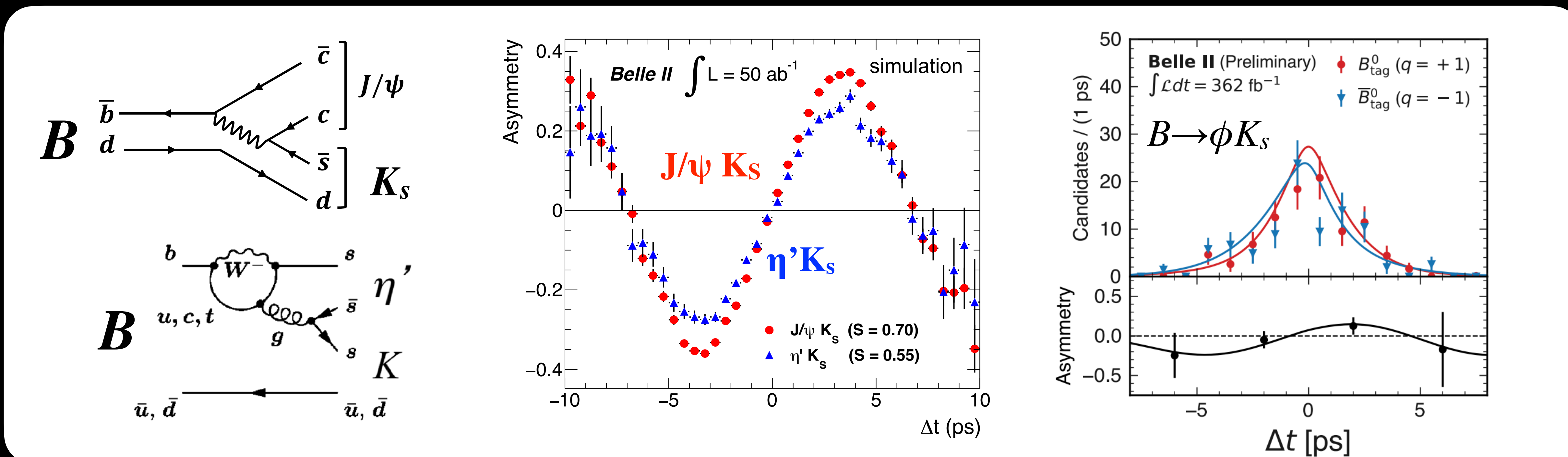
<u>*B→J/ψ K_S* (362 fb^{-1}) at Belle II (GFlaT)</u>

S_{CP} = 0.724 ± 0.035 (stat.) ± 0.009 (syst.)

(S_{PDG} = 0.701 ± 0.017)

ϕ_1/β Measurement: Tree vs Penguin

- $b\to sq\bar{q}$ transitions with quantum loops, CP asymmetry should be similar to that of tree-level $b\to c\bar{c}s$ (e.g $J/\psi\ K_S$) in the SM. However, if new particles contribute, the CP asymmetry can be modified. ($\phi_1^{eff} = \phi_1 + \delta\phi_1^{NP}$)



- ***$B\to\phi K_s, \eta' K_s, K_sK_sK_s$*** are golden channels (small theoretical uncertainty).
  - ϕK_s (362 fb^{-1}) : **S_{CP} = 0.54 ± 0.26 (stat.) $^{+0.06}_{-0.08}$ (syst.)** [Phys. Rev. D 108, 072012 (2023)]
  - $\eta' K_s$ (362 fb^{-1}) : **S_{CP} = 0.67 ± 0.10 (stat.) ± 0.03 (syst.)** [Phys. Rev. D 110, 112002 (2024)]
  - $K_sK_sK_s$ (362 fb^{-1}) : **S_{CP} = -1.37 $^{+0.35}_{-0.45}$ (stat.) ± 0.03 (syst.)** [Phys. Rev. D 109, 112020 (2024)]

→ All consistent with HFLAV values.

ϕ_2/α measurement: $B\to\pi\pi$ (365 fb^{-1})

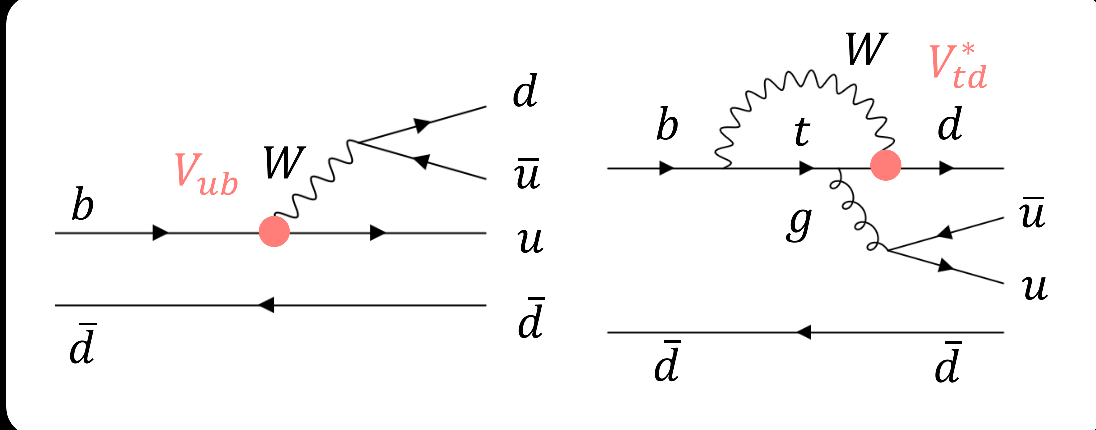
NEW $\pi^0\pi^0$ (365 fb^{-1}) arXiv:2412.14260
$\pi^0\pi^+$ (362 fb^{-1}) Phys. Rev. D 109, 012001 (2024)

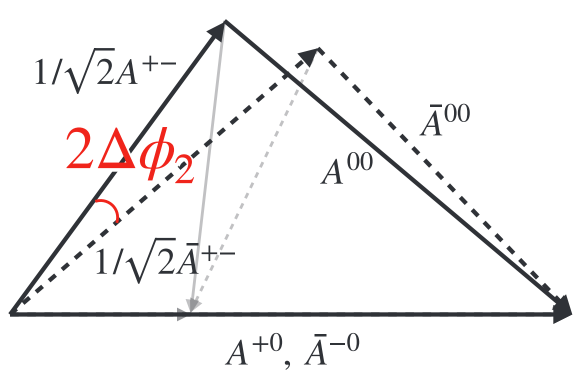
- $B \to \pi\pi$ and $B \to \rho\rho$ are the most sensitive channels for ϕ_2.
- Tree and Penguin contributions must be disentangled to determine ϕ_2.
- **Isospin analysis ($\pi^+\pi^0, \pi^+\pi^-, \pi^0\pi^0$)** is effective

  → All isospin modes of $B\to\pi\pi$ can be analyzed at Belle II.

- **Sensitive to direct CP asymmetry as well**

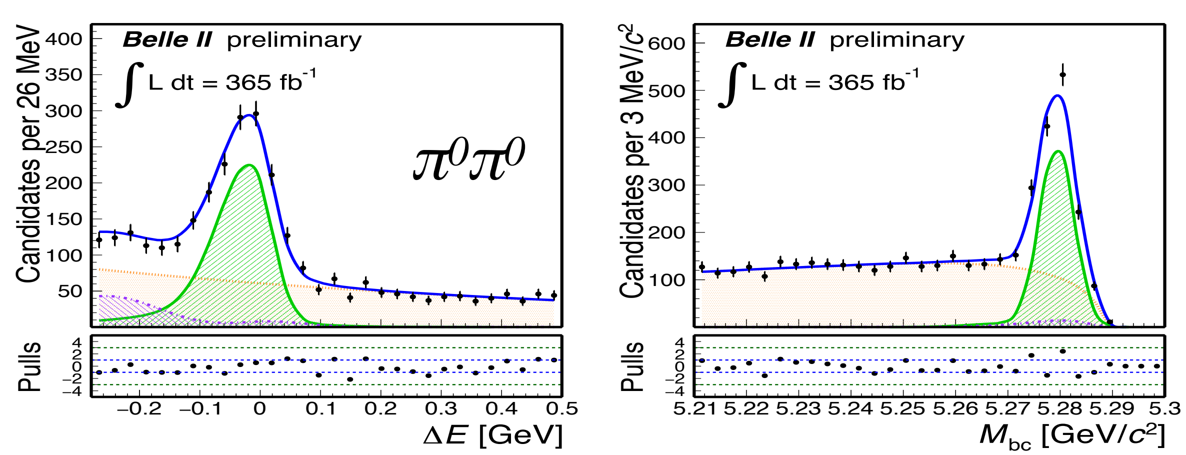
$$S_{CP} = \sqrt{1 - A_{CP}^2}\sin(2\phi_2 - 2\Delta\phi_2), A_{CP} \neq 0$$





A$_2$: tree only,
A$_0$: tree + penguin

$$\pi^+\pi^- : 1/\sqrt{2}A^{+-} = A_2 - A_0$$
$$\pi^0\pi^0 : A^{00} = 2A_2 + A_0$$
$$\pi^+\pi^0 : A^{+-} = 3A_2 - A_0$$
$$1/\sqrt{2}A^{+-} = A^{00} + A^{+-}$$

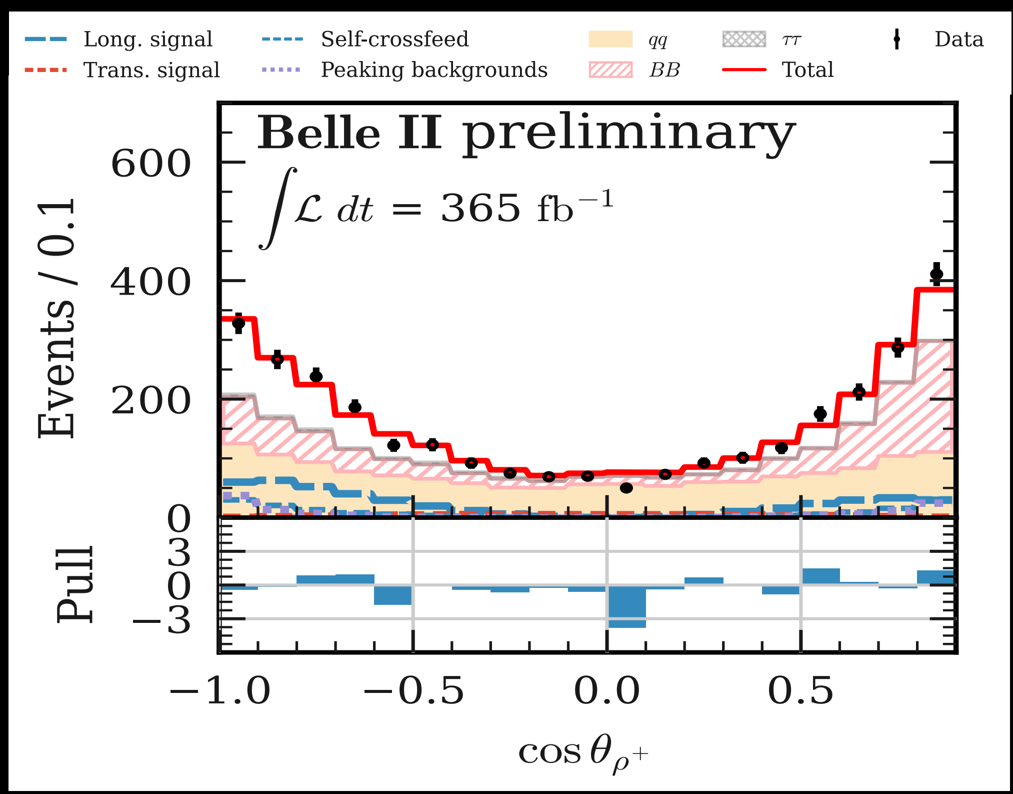


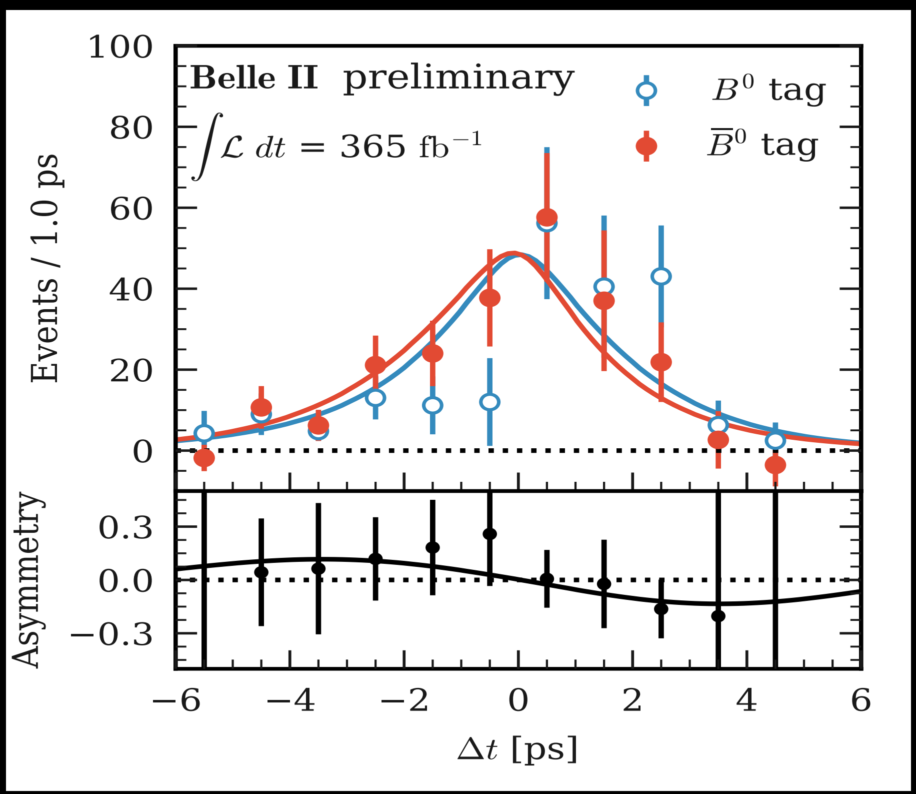
360 fb^{-1}	$B(x10^{-6})$	A_{cp}
$\pi^+\pi^-$	5.83 ± 0.22 ± 0.17	—
$\pi^+\pi^0$	5.02 ± 0.28 ± 0.31	-0.082 ± 0.054 ± 0.008
$\pi^0\pi^0$	1.25 ± 0.20 ± 0.11	0.03 ± 0.30 ± 0.04

ϕ_2/α measurement: $B\to\rho\rho$ (365 fb^{-1}) NEW

arXiv:2412.19624

- $B\to\rho\rho$ 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.
- Simultaneous fit in kinematic variables to extract branching fraction, longitudinal polarization fraction (f_L), charge asymmetry (A_{cp})



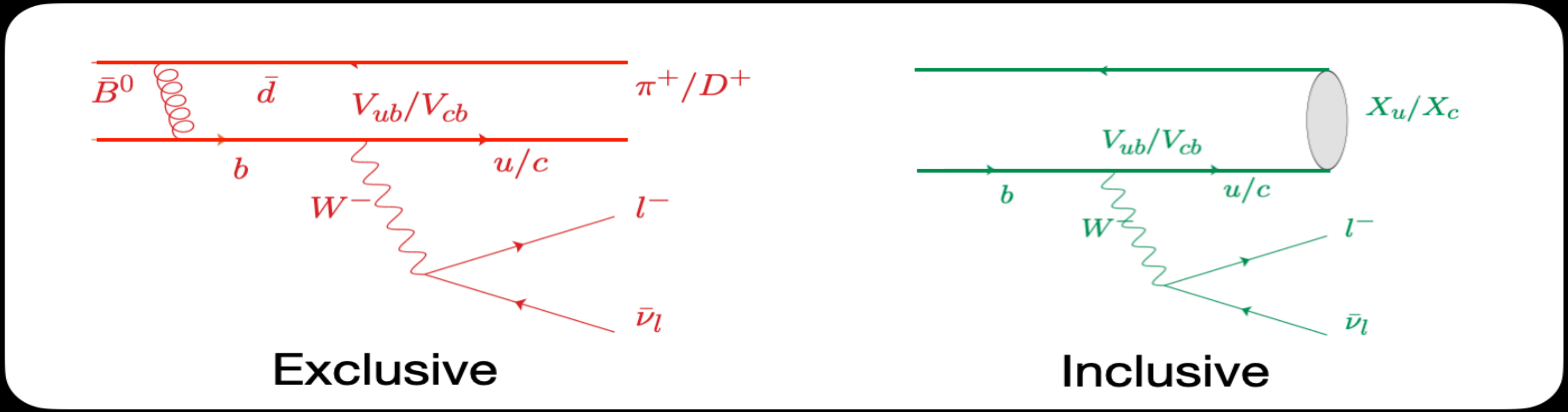


- Suppress continuum with NNet and tag the flavor to measure the CP asymmetry:
  - **A_{CP} = -0.26 ± 0.21, S_{CP} = -0.02 ± 0.13**
- Obtain a 10% improvement on WA for ϕ_2 when including this new result:
  - **$\phi_2 = (92.6^{+4.5}_{-4.8})$**

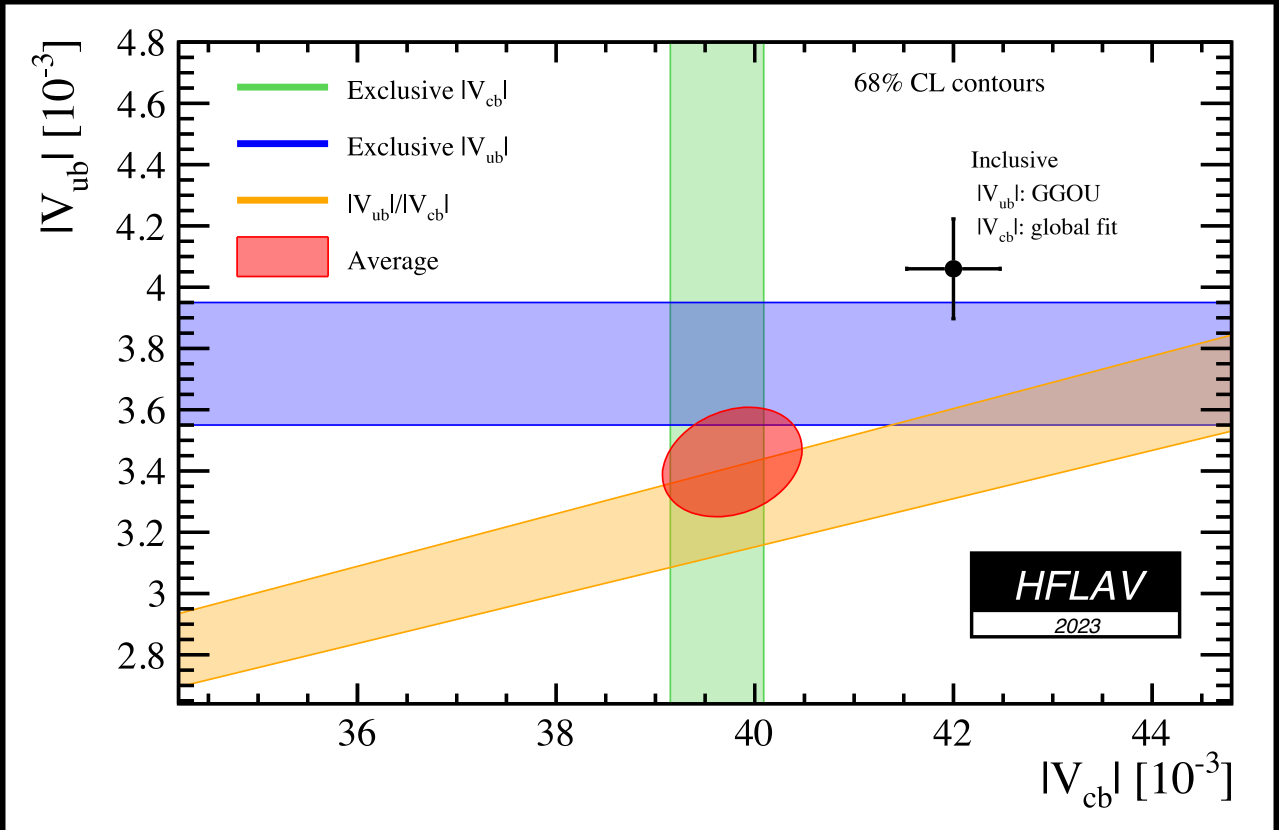
$|V_{ub}|$ and $|V_{cb}|$ measurement

arXiv: 2411.18639

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



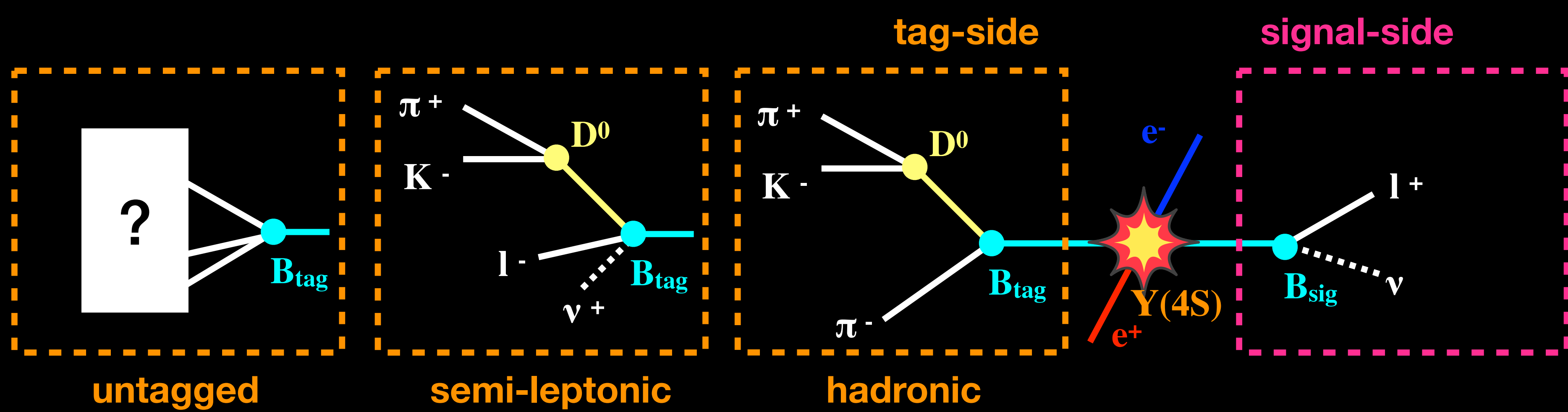
- $B \to \pi\ell\nu$ and $B \to D\ell\nu$ are golden modes for $|V_{ub}|$ and $|V_{cb}|$ measurements.
- There exists a longstanding discrepancy (**~3.3σ**) between exclusive and inclusive measurements.
- Belle II can precisely measure both modes.



B Meson Tagging

Reconstruct Opposite-Side B Meson (B_{tag})

(Since B mesons are produced in paris, they can be identified with high efficiency)



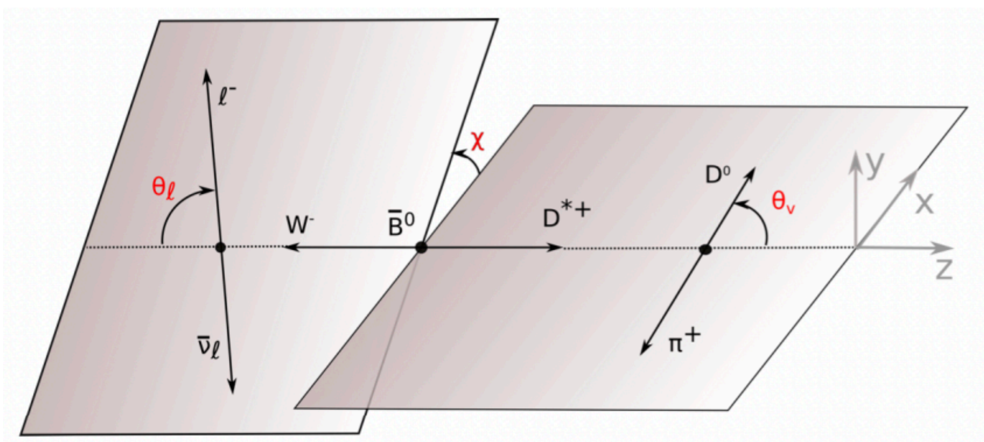
Signal-Side B Meson (B_{sig}) depends on the analysis mode.

- Presence of B_{tag} allows analysis in three modes:
  - Hadronic, semi-leptonic, and untagged
  - Reconstructing B_{tag} requires a lot of data (low efficiency)
  - B_{tag} is crucial when neutrinos are present on the signal side.
- **AI/ML approach** significantly improves reconstruction efficiency compared to the Belle era.

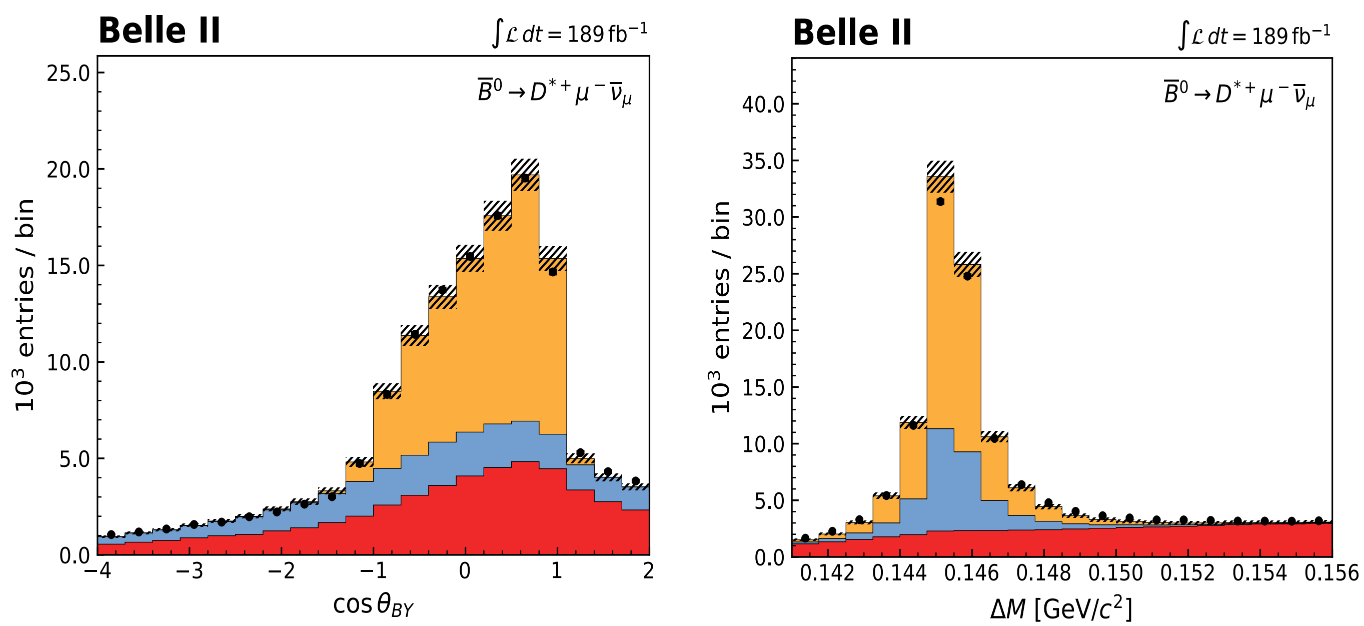
$|V_{cb}|$ measurement : $B \to D^{(*)}\ell\nu$ (190 fb^{-1})

Phys. Rev. D 108, 092013 (2023)

- Untagged analysis was performed at Belle II
- Reconstructing low momentum π from D* is challenging in $D^* \to D^0(\to K\pi)\pi$
- Simultaneous fit using the angle $\cos\theta$ and mass difference ΔM $(= M(D^*) - M(D))$ in the B and $D^*\ell(=Y)$ system.



$$\cos\theta_{BY} = \frac{2E_B^{\rm CM}E_Y^{\rm CM} - m_B^2c^4 - m_Y^2c^4}{2|\vec{p}_B^{\,\rm CM}||\vec{p}_Y^{\,\rm CM}|c^2},$$



- Non-perturbative form factor models: BGL, CLN

$|V_{cb}|_{BGL}$ = (40.6 ± 0.3(stat) ± 1.0(syst) ± 0.6(tho)) x 10^{-3}

$|V_{cb}|_{CLN}$ = (40.1 ± 0.3(stat) ± 0.9(syst) ± 0.6(tho)) x 10^{-3}

Latest Status: $|V_{ub}|$ and $|V_{cb}|$

arXiv2301.07529

arXiv:2407.17403

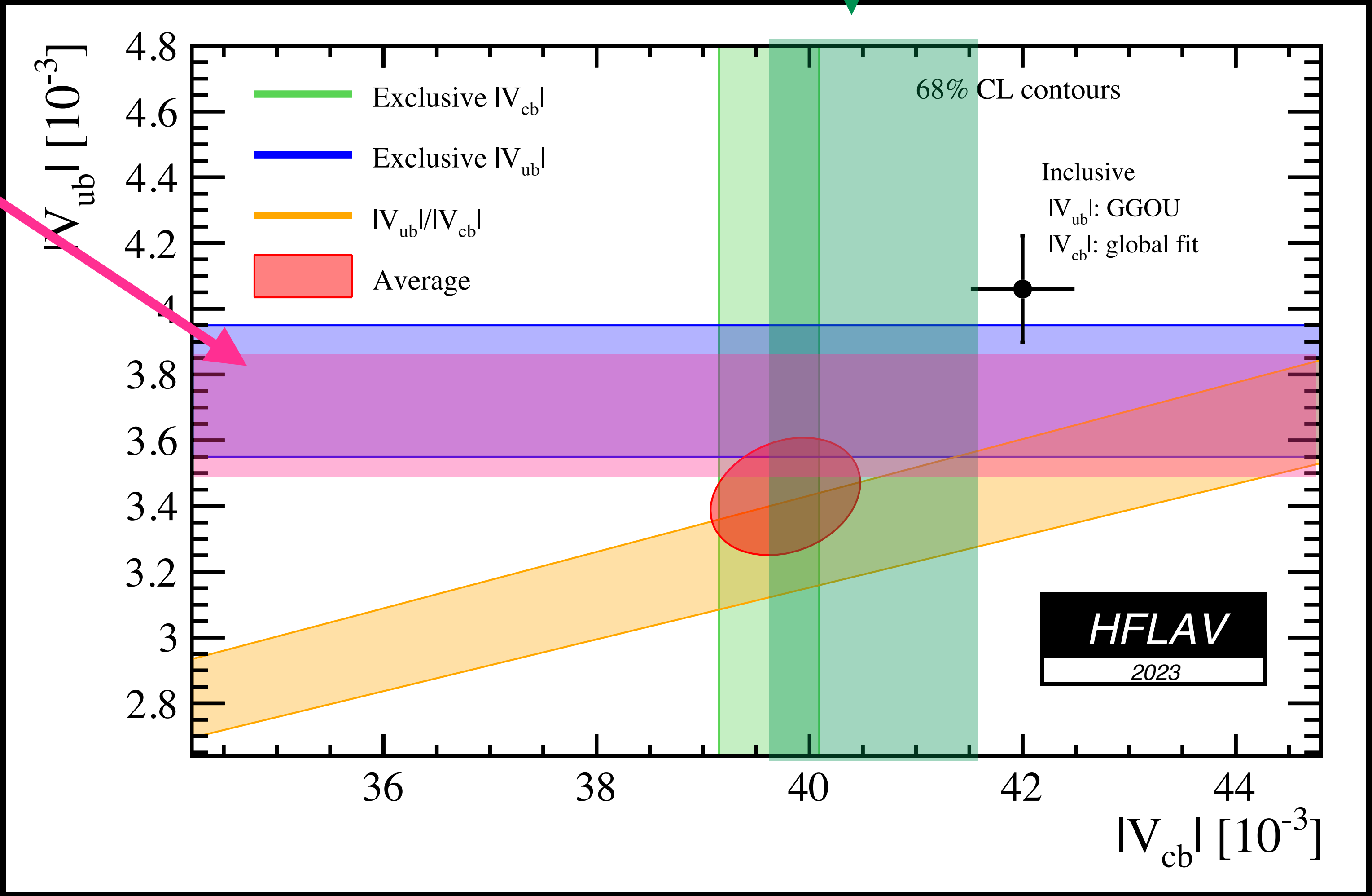
New exclusive measurement (tagged) from Belle (711 fb^{-1}) exploiting full differential information from $B\to D^*l\nu$ decays for the first time: **$|V_{cb}| = (40.6 \pm 0.9) \times 10^{-3}$**

New exclusive results from Belle II (untagged)

- $B\to \pi l\nu$ (362 fb^{-1}):

  $|V_{ub}| = (3.73 \pm 0.16) \times 10^{-3}$
- $B\to \rho l\nu$ (362 fb^{-1}):

  $|V_{ub}| = (3.19 \pm 0.33) \times 10^{-3}$

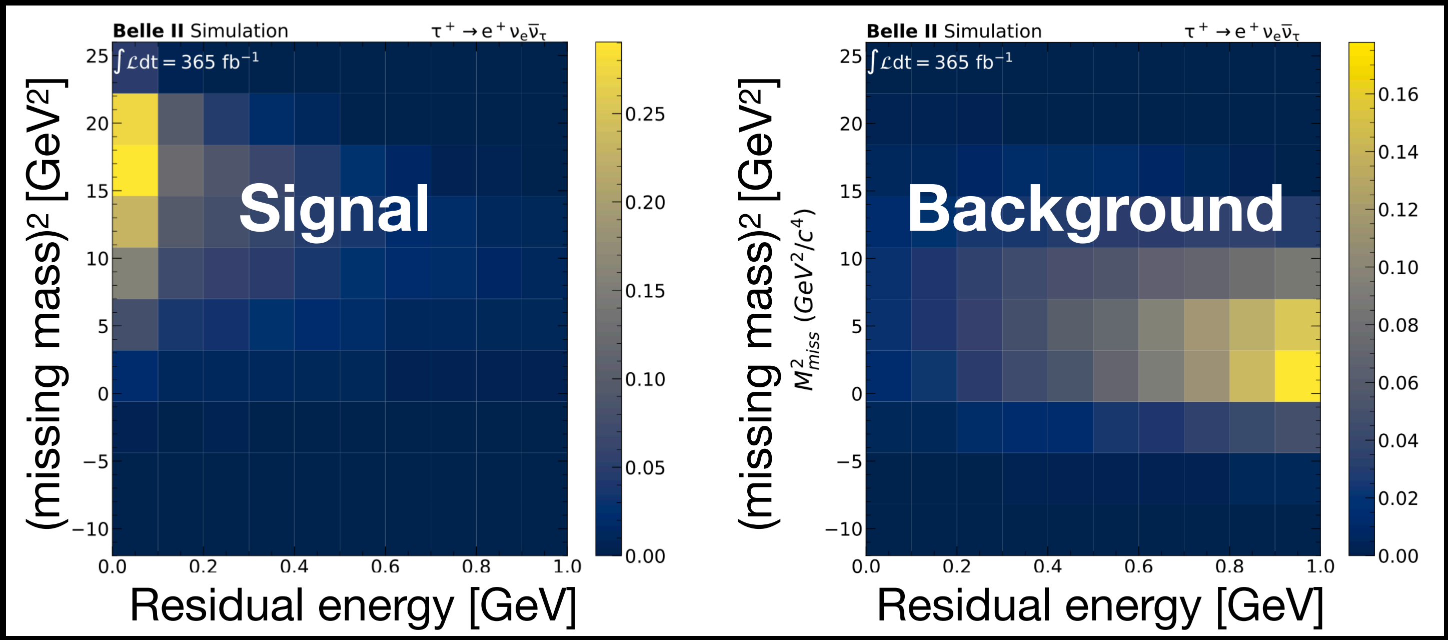


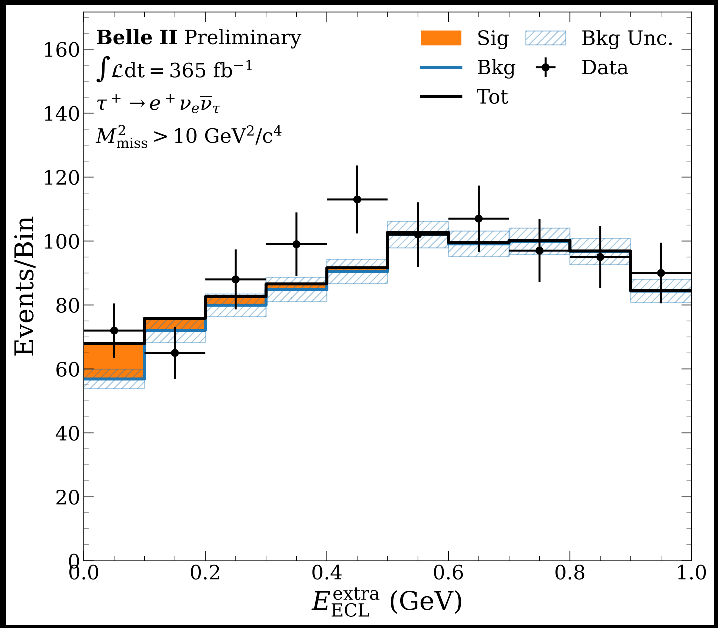
Pion modes reduce the tension, while large uncertainty with ρ. Theory inputs are key.

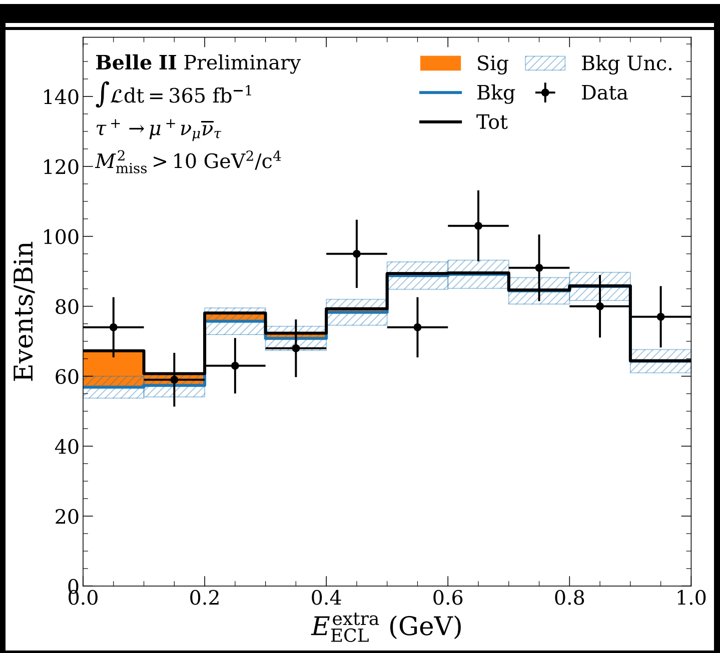
Evidence for $B \to \tau\nu$ (365 fb^{-1}) NEW

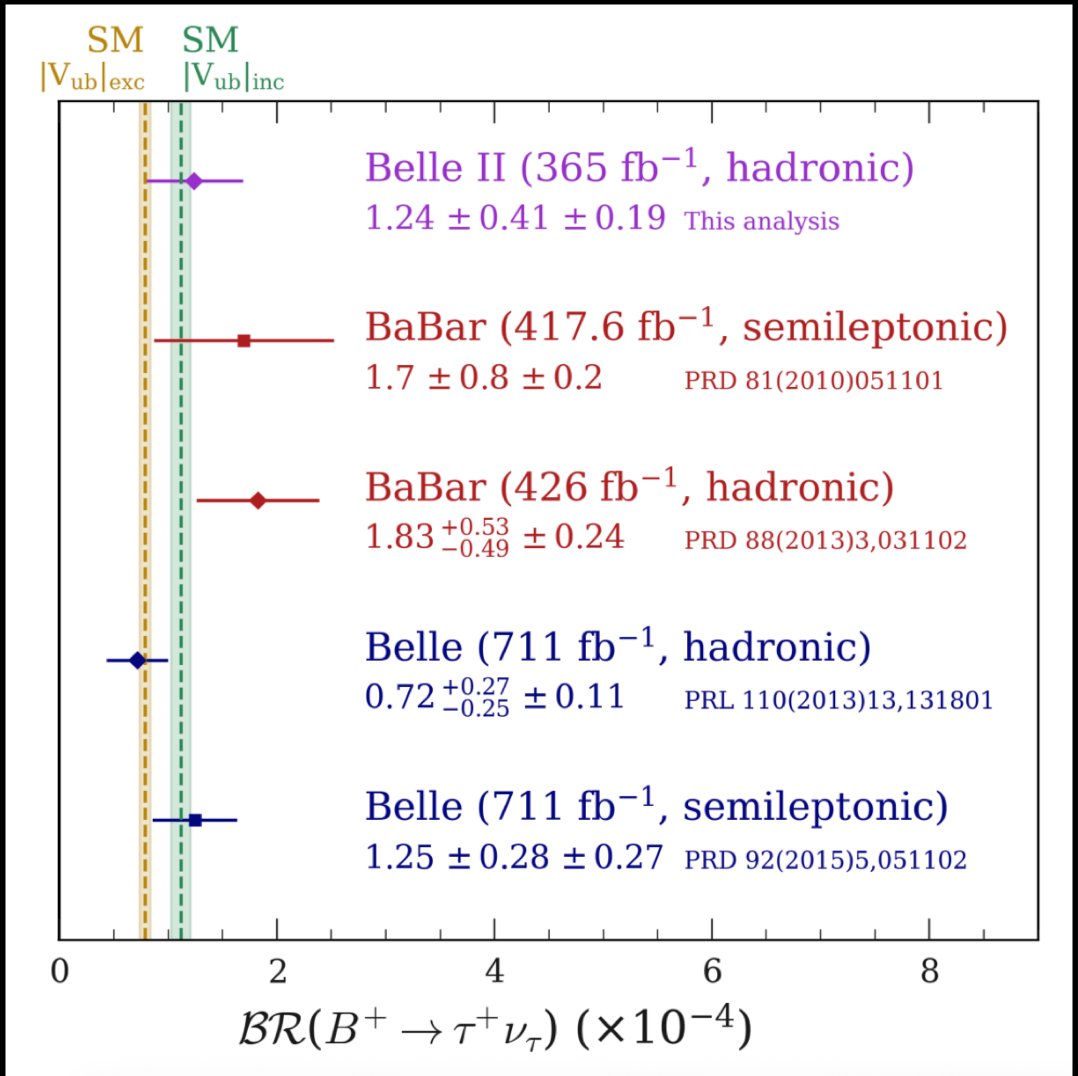
arXiv:2502.04885

- Ideal probe for $|V_{ub}|$, but helicity suppressed. Not yet observed.
- Use Hadronic tag. Reconstruct the tau decays into leptons, a pion, or a ρ.
- At least 2 neutrinos, large missing mass and no residual energy in the calorimeter.







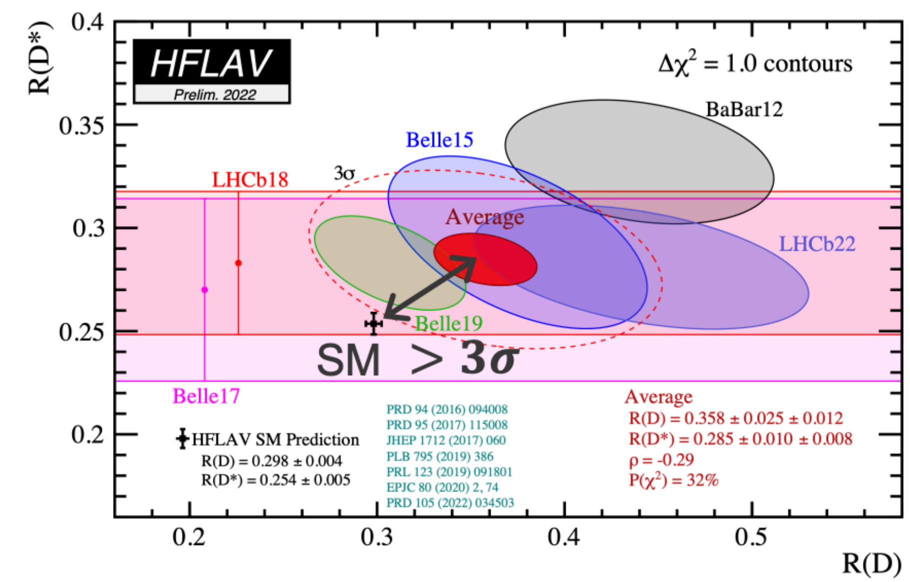


$$|V_{ub}|_{B^+ \to \tau^+ \nu_\tau} = [4.41^{+0.74}_{-0.89}] \times 10^{-3}.$$

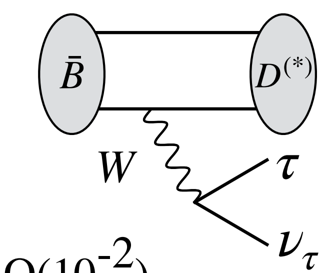
Lepton Flavor Universality (LFU)

- In the SM, the coupling constants for weak interactions should be independent of the charged lepton flavor (e, μ, τ).
- Measurement of $R(D^{(*)})$ in $b \to c\ell\nu$ transitions show deviations from the SM.
- Such anomalies are crucial for determining new physics directions, requiring further validation.
- **Belle II will perform independent and complementary tests of LFU in various final states.**

$b \to c\tau\nu$

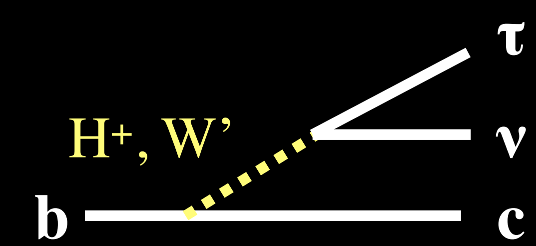


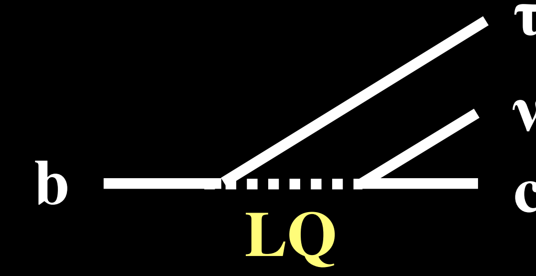
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$



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

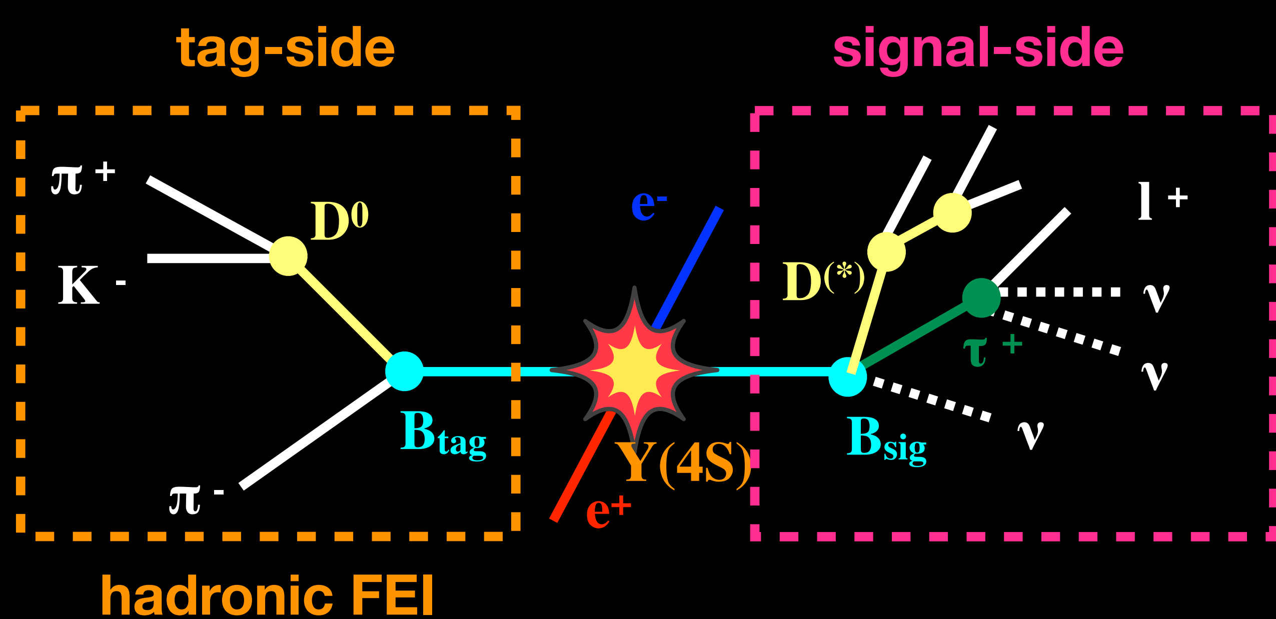
$B \to D^{(*)}\tau\nu$ (190 fb^{-1})

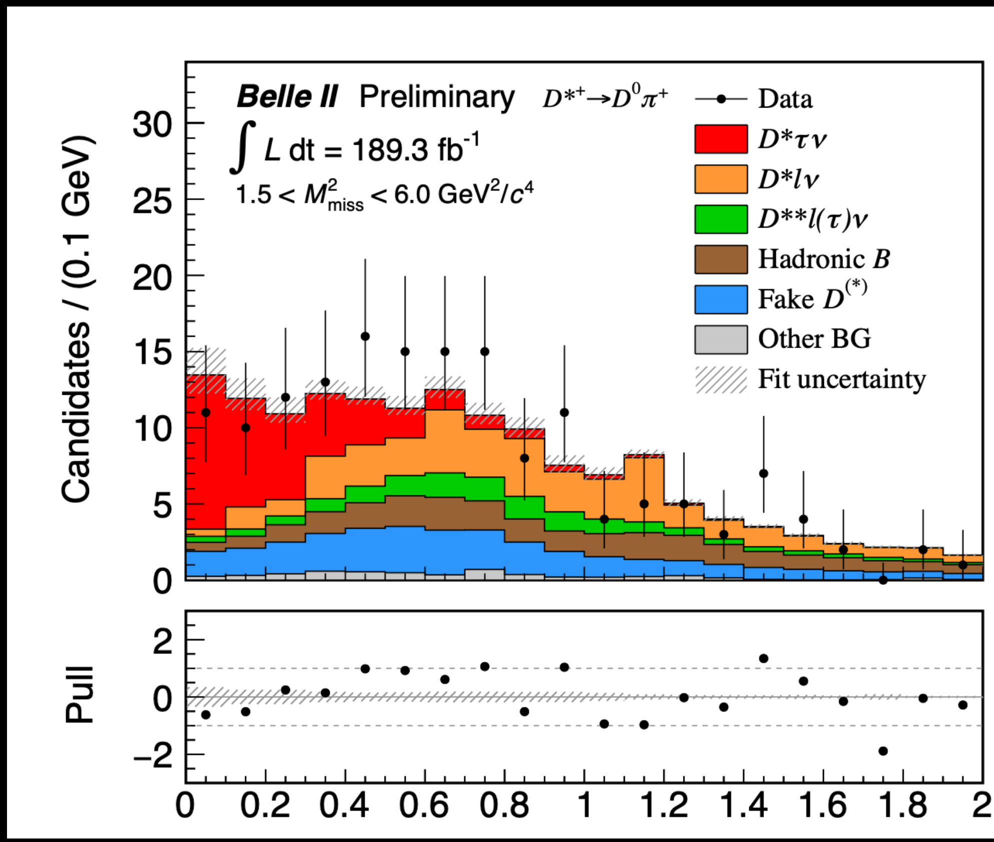




- Since B meson decays via W in the SM, the BF is large *O* (1) %
- This is a decay of 3rd gen. quark to 3rd gen. lepton
  - Large coupling to heavy particle（e.g. charged Higgs)
  - Large coupling to 3rd gen. particles (e.g. LQ or Z’ model)
- At least 3 neutrino in the final state → **Flavor tagging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

Phys. Rev. D 110, 072020 (2024)





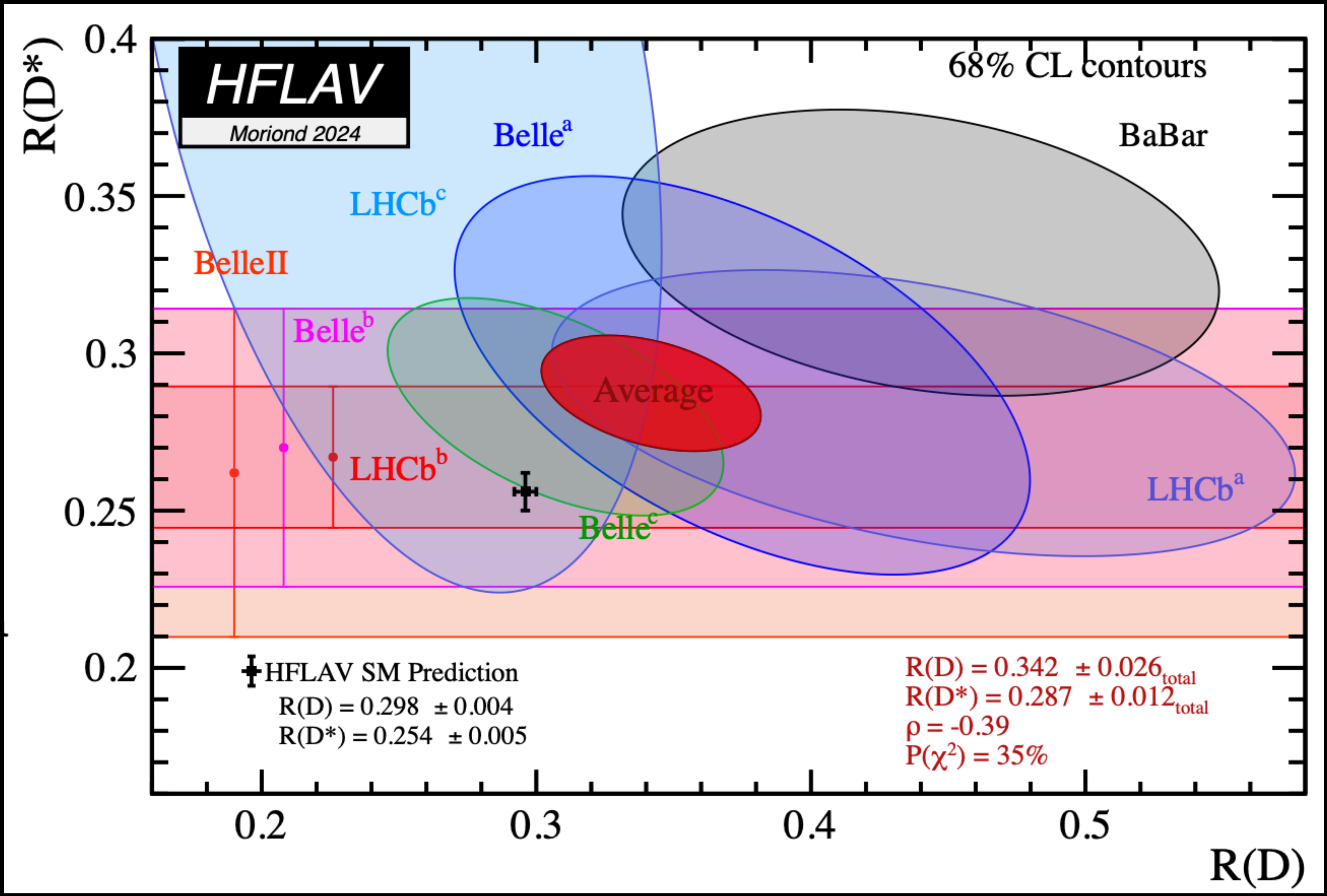
Residual energy in the calorimeter [GeV]

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

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

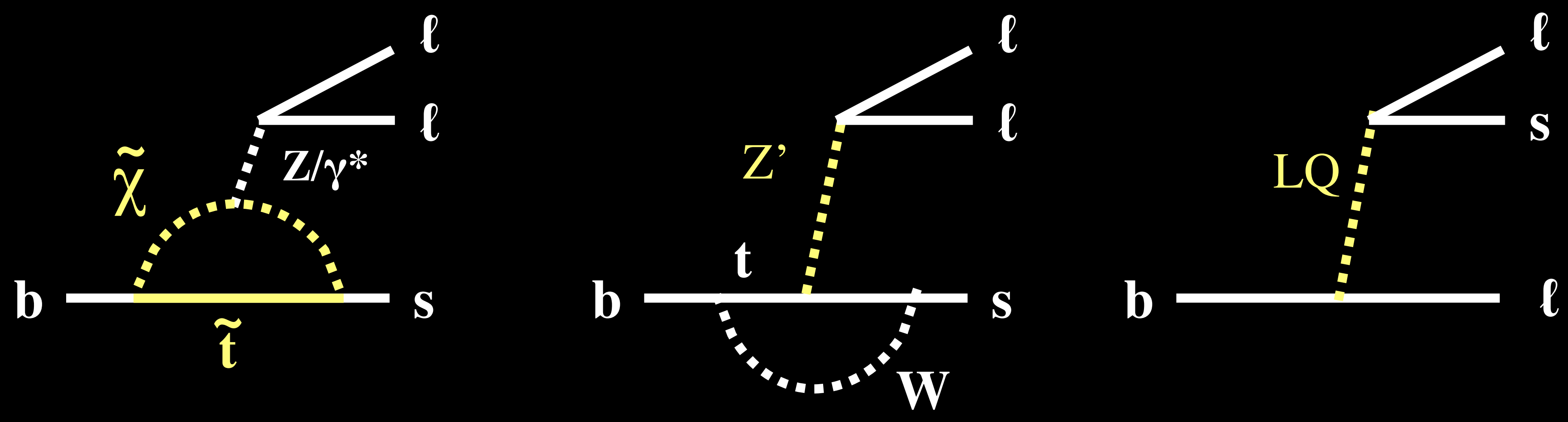
***R(D$^{(*)}$)* = 0.26 ± 0.04 (stat.) $^{+0.04}_{-0.03}$ (syst.).**

Latest Status: R(D*) vs R(D)



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

- Flavor changing neutral current (FCNC) $b \to s$ (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)



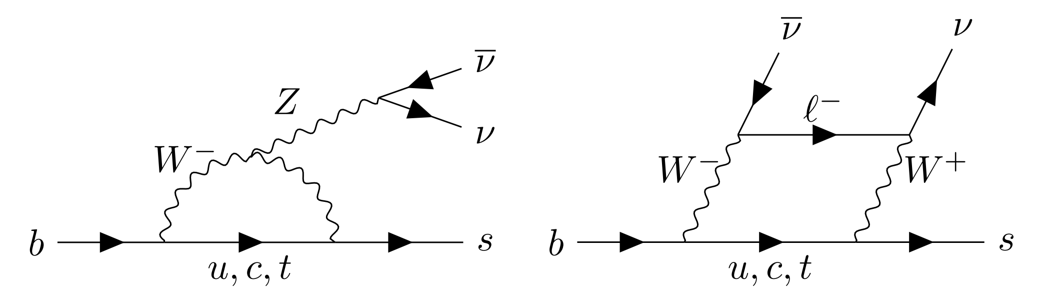
- $b \to s\ell^+\ell^-$ is experimentally a clean signature.
- Unc. can be suppressed by taking a ratio:

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

- In Belle II, in addition to R(K*), an **inclusive measurement** of R(Xs) is also possible. **Flat sensitivity over q^2**.

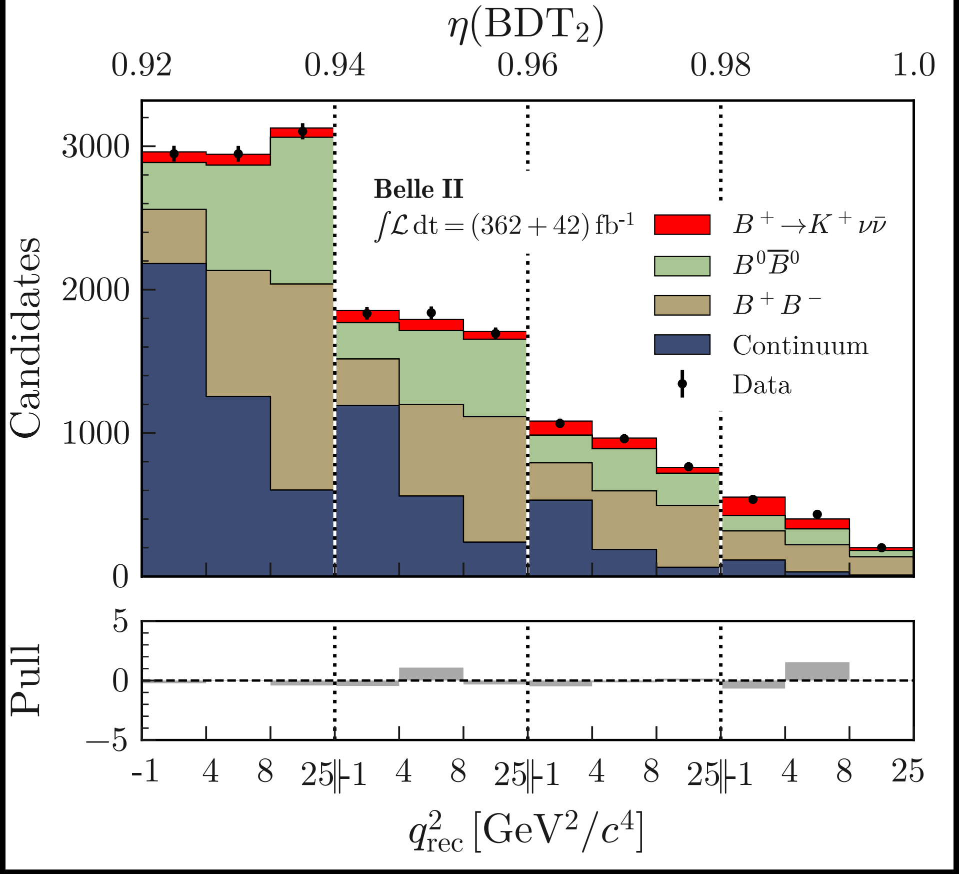
Evidence for B→K+νν (362 fb^{-1})

- FCNC *b→s (d)* process
- Independent probe against *b→sℓ⁺ℓ⁻*
- B_{tag} is a key since two neutrinos are in the final state. BDT analysis is employed to further improve the Belle II sensitivity.

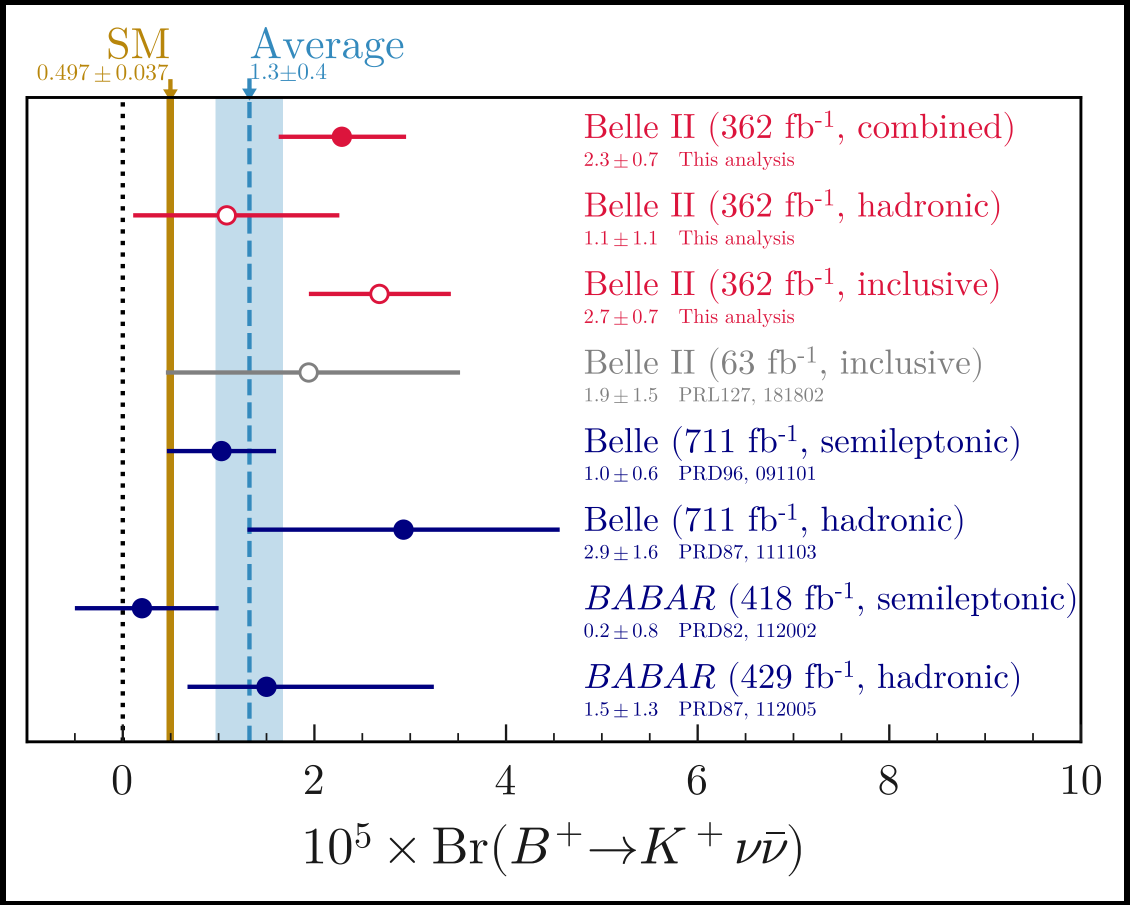


$$\mathcal{B}\left[B^+ \to K^+\nu\bar{\nu}\right] = (4.7 \pm 0.6) \times 10^{-6}$$
$$\mathcal{B}\left[B^0 \to K^{*0}\nu\bar{\nu}\right] = (9.5 \pm 1.1) \times 10^{-6}$$

[JHEP02 (2015)184]

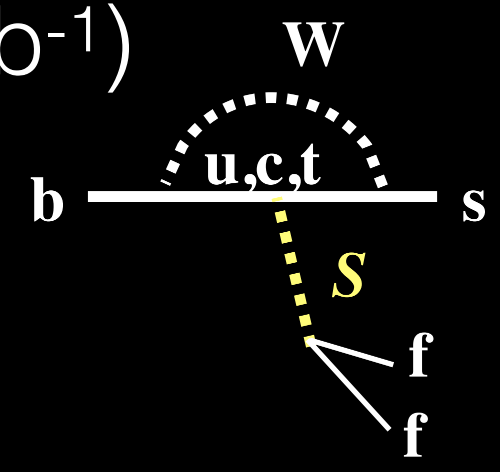


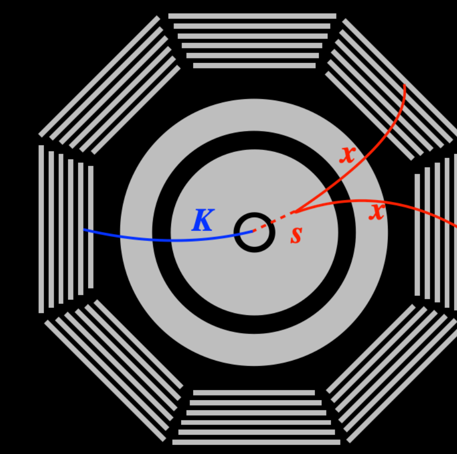
Phys. Rev. D 109, 112006 (2024)



- Continuum BG is estimated by off-resonance data with another BDT.

Long-Lived Particle Search (190 fb^{-1})

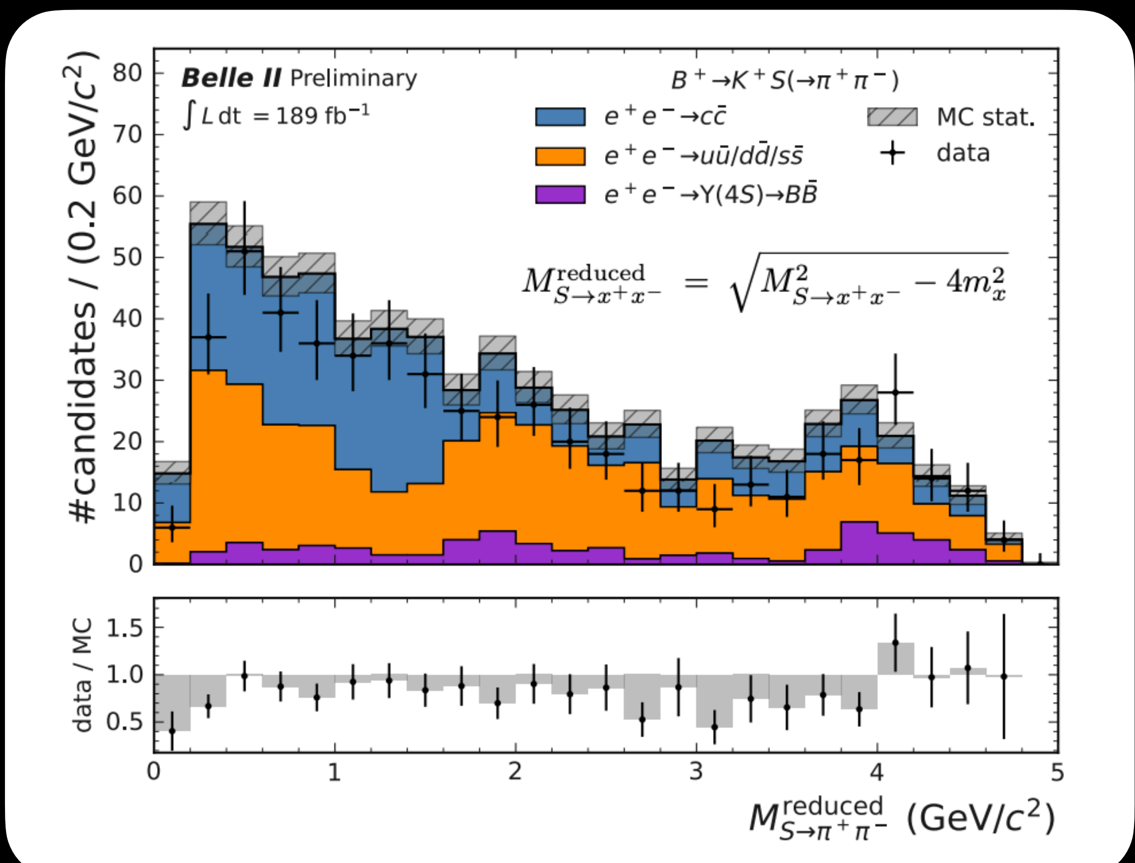


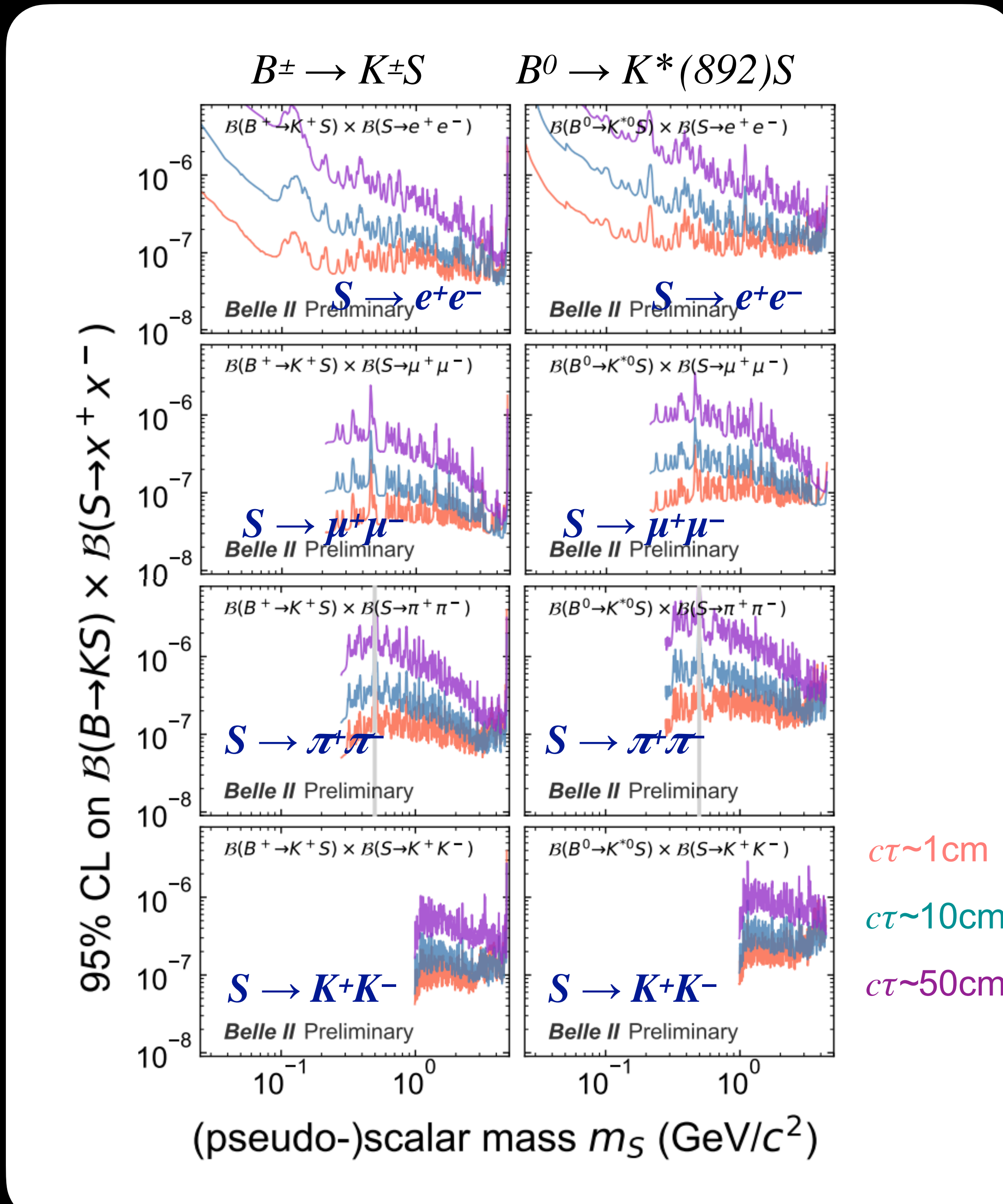


- First LLP Search at Belle II
  - In FCNC $b \to s$, some models predict the production of long-lived (pseudo) scalar S
  - $B^{\pm} \to K^{\pm} S$ or, $B^0 \to K^*(892) S$

    where $K^*(892) \to K^+\pi^-$,

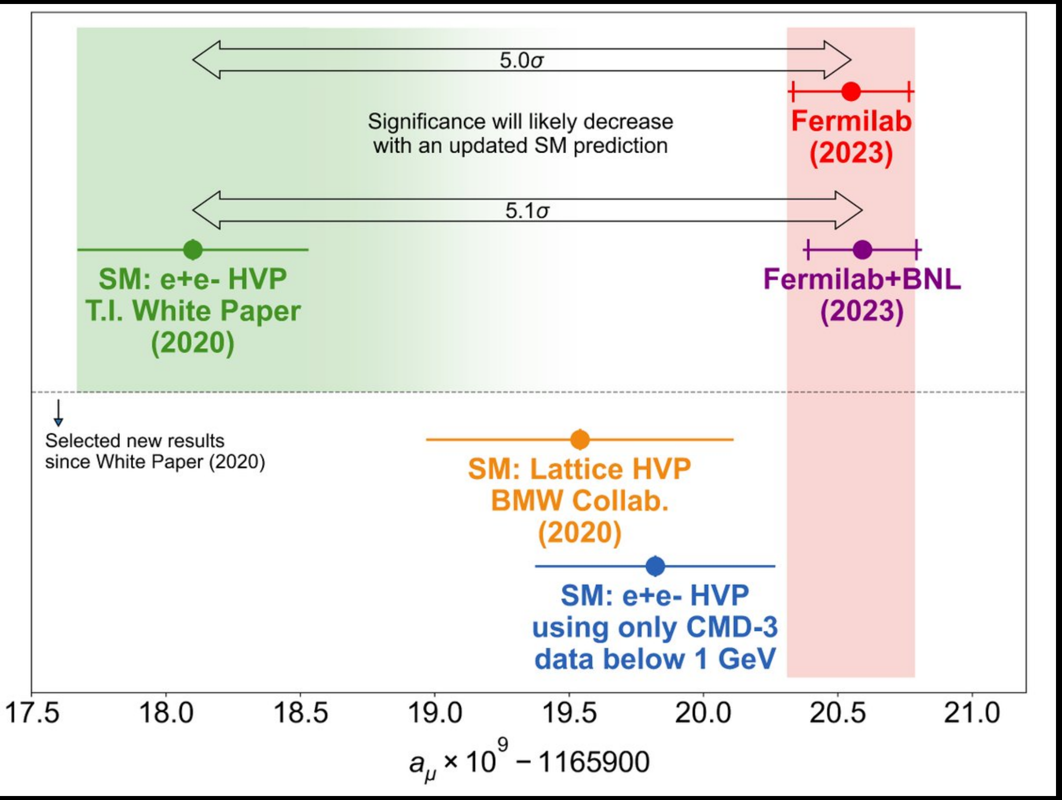
    $S \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$
- Peak search in the mass distribution of S





Hadronic Vacuum Polarization

- **5.1σ** 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)



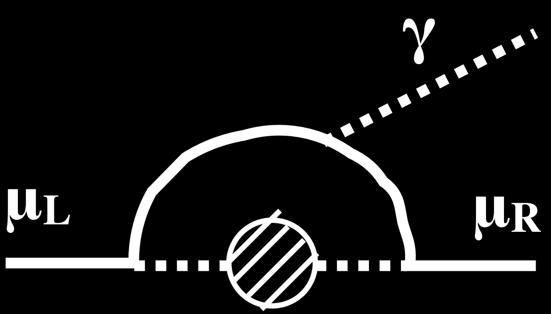
HVP： **H**adronic **V**acuum **P**olarization

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

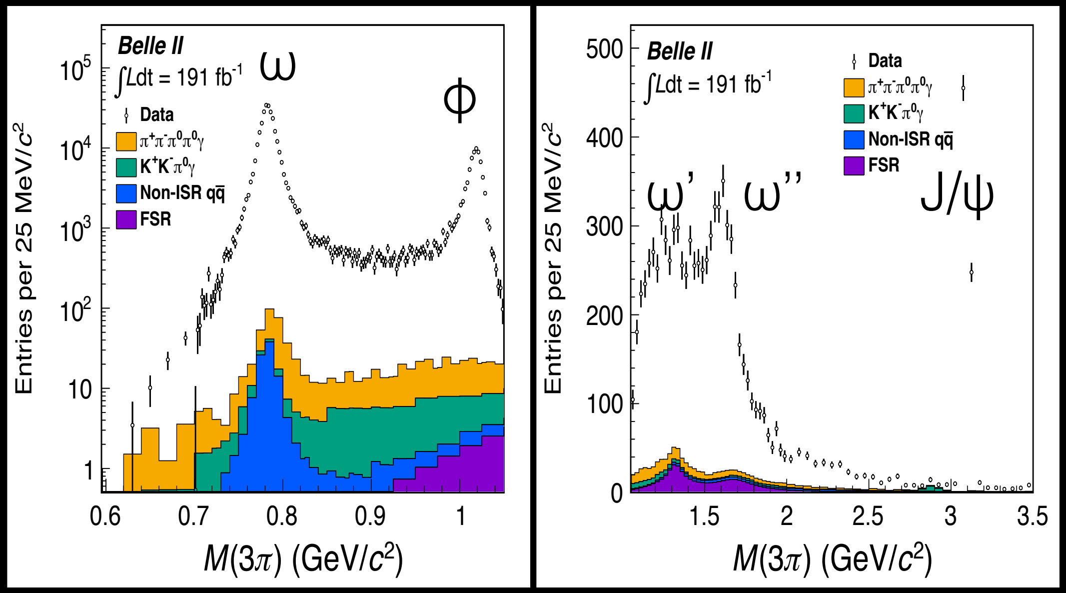
$$a_\mu^{QCD} = a_\mu^{HVP} + a_\mu^{HLbL}$$

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

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



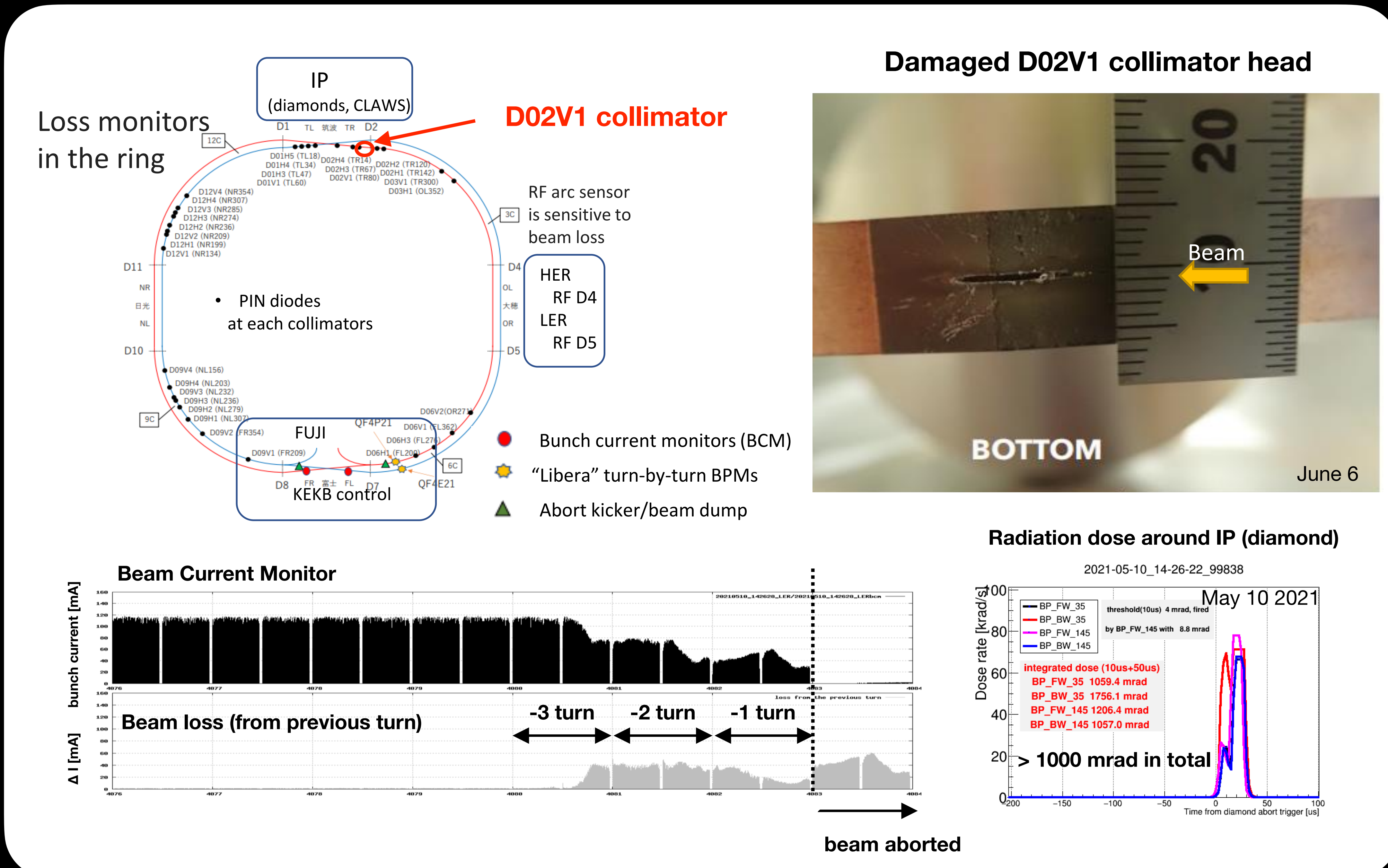
- Large diff. in measured xsec btw BaBar and KLOE
- **$e^+e^- \to \pi^+\pi^-\pi^0$ cross section at Belle II**
  - Energy of hadrons scales with ISR γ recoil energy
  - Measured xsec is 6.5% higher than BABAR, pushing **3.0×10^{-3}** higher in a_μ



Phys. Rev. D 110, 112005 (2024)

SBL Investigation

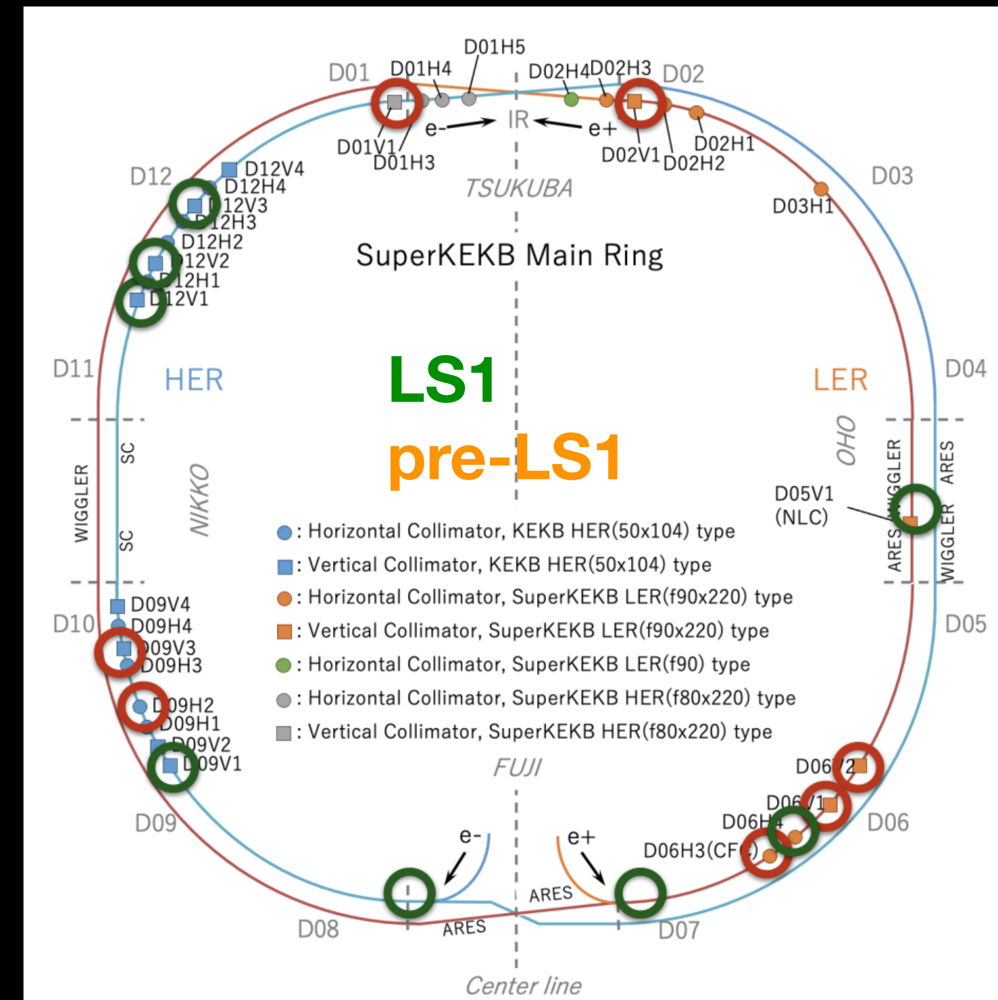
Sudden Beam Loss (SBL)



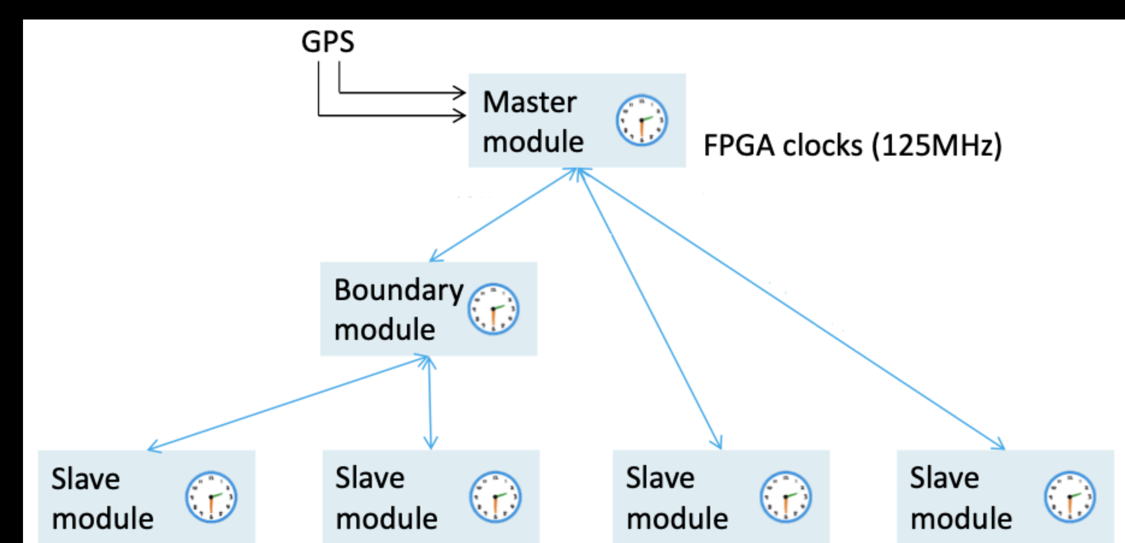
A significant beam loss at high beam current operation resulted in severe damage on a collimator or the vertex detector. Our abort system is not fast enough to protect such a sudden beam loss. → **A limitation toward higher beam current**

Fast LM system for beam diagnostic

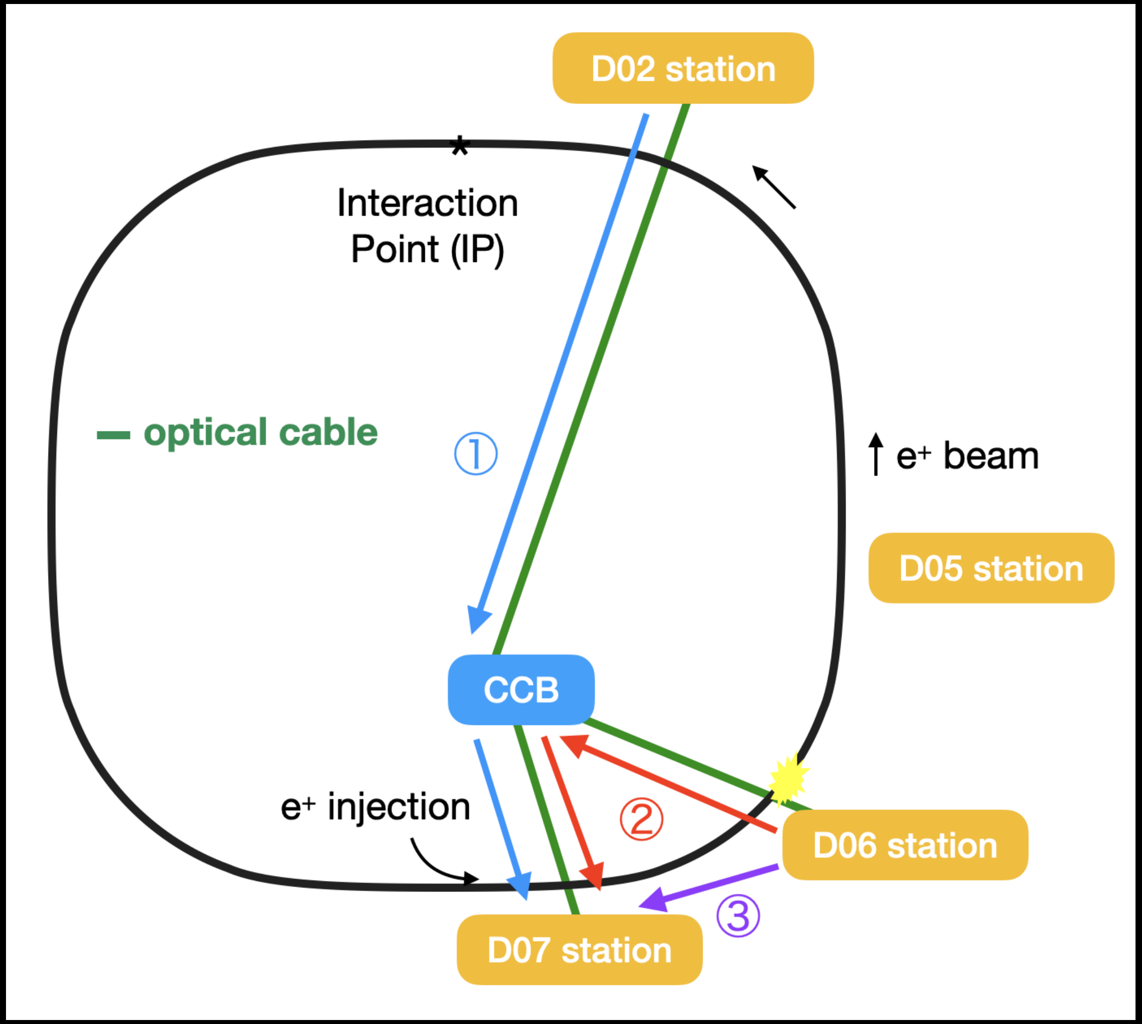
- To pinpoint the location of the initial beam loss, 15 loss monitors (CsI+PMT, EMT) have been installed around collimator locations (i.e. smallest aperture in the ring) since the summer of 2021.

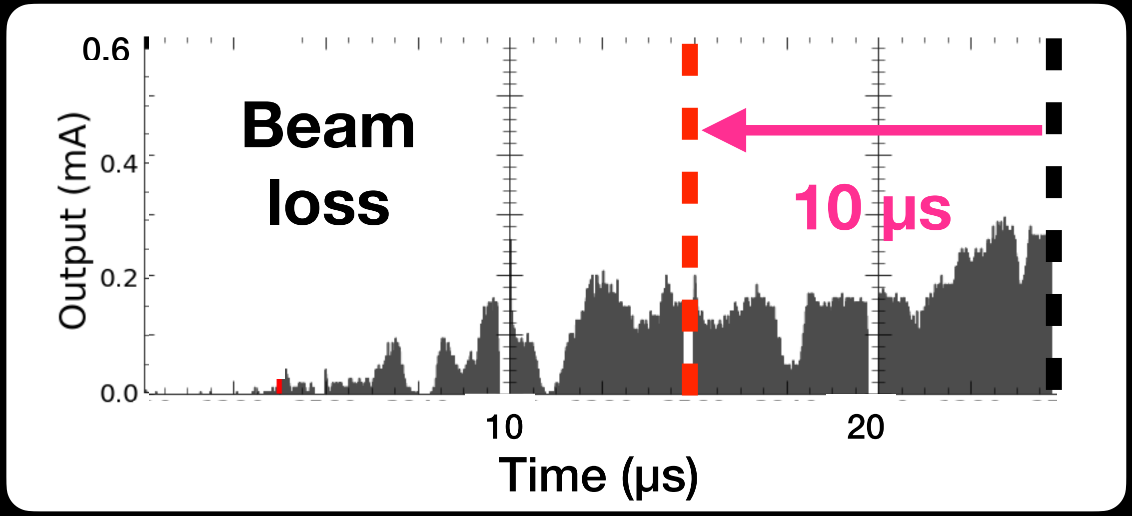


- White Rabbit (WR) time synchronization system, developed by CERN, has been employed.



Advanced Beam Abort System





In 2022, most SBL events triggered abort requests from CLAWS (IR). The timing of these aborts can be improved by:

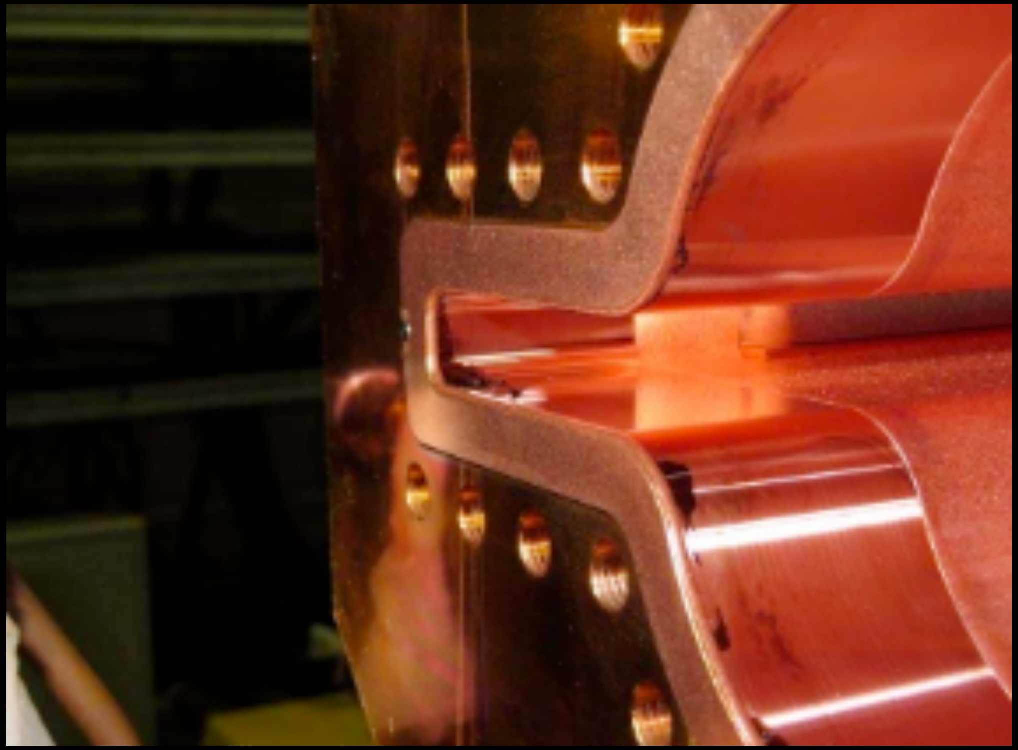
1. **Optimizing sensor placement**
2. **Reducing transmission path length (bypassing CCB)**

In 2022, we demonstrated that optimizing sensor placement at D06V1 allowed the abort signal to be issued 1-2 abort gaps earlier.

SBL Investigation (After Summer 2024)

- Upon opening the beam pipe in the D10 L02/L03 sections, **black stains** were discovered.
- These stains were identified as burnt silicon, most likely originating from the degradation of **vacuum sealants (VACSEAL)**.

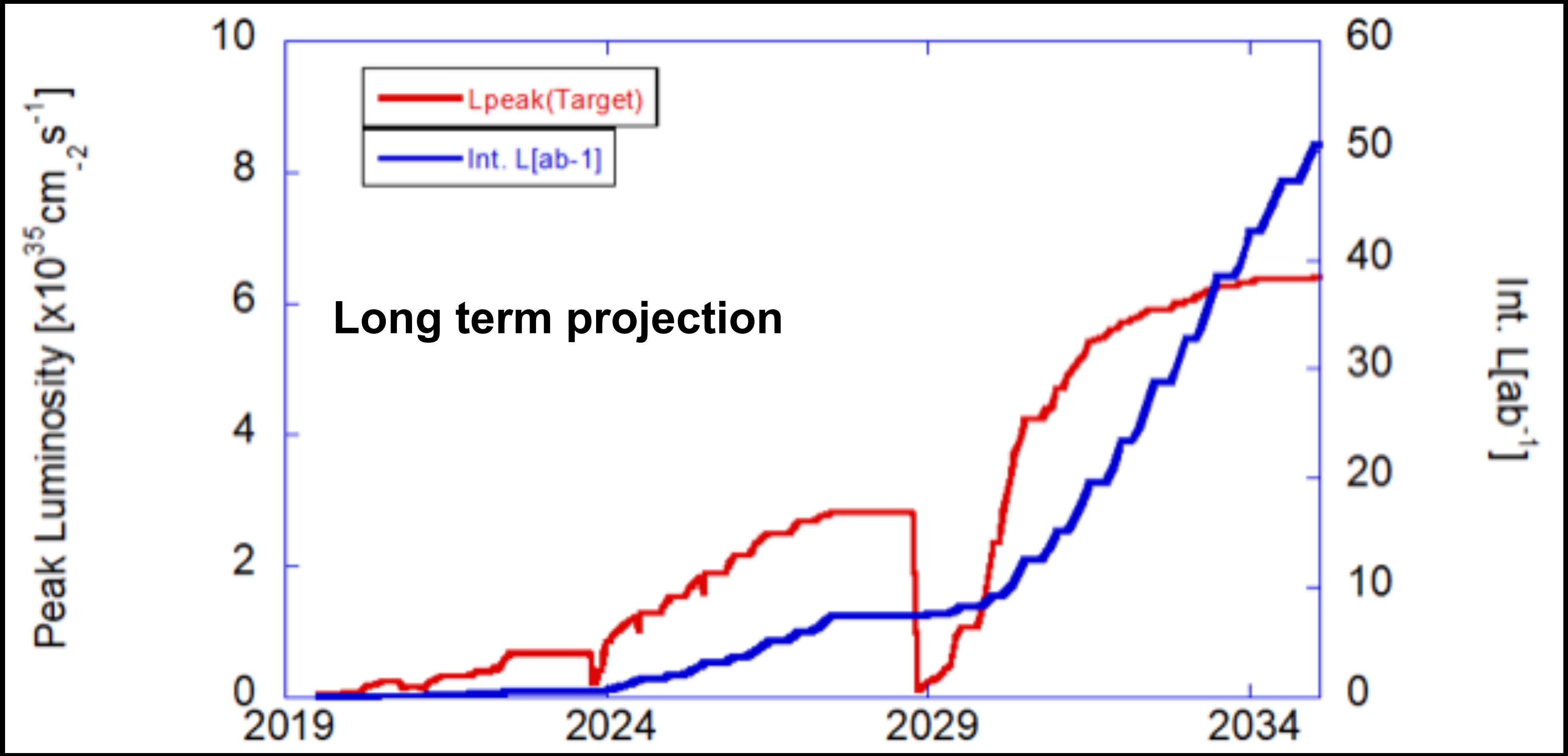
- After cleaning the affected piples (D10 L02/L03), SBL was completely eliminated in that section.
- **However SBL continues to occur in the D04 section, necessitating further clearning/monitoring.**



Summary

- SuperKEKB/Belle II is a new generation B-factory having unique capabilities for new physics search.

- Machine operation going well so far and 575 fb^{-1} has been collected.
  - LER/HER: 1632/1259 mA
  - n. bunch: 2346 bunches (2-bucket spacing)
  - Peak luminosity: 5.1 x 10^{34} $cm^{-2}s^{-1}$



Thank you!