



名古屋大学
NAGOYA UNIVERSITY



Recent Belle II results related to flavor anomalies

Kazuki Kojima (Nagoya University)
on behalf of the Belle II Collaboration

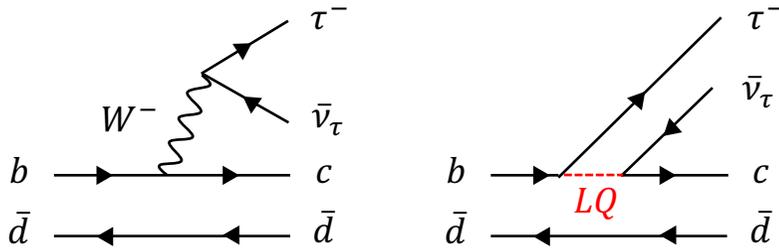
International Conference on the Physics of the Two Infinities

Mar. 29th, 2023

Anomalies in $b \rightarrow c$ Decays

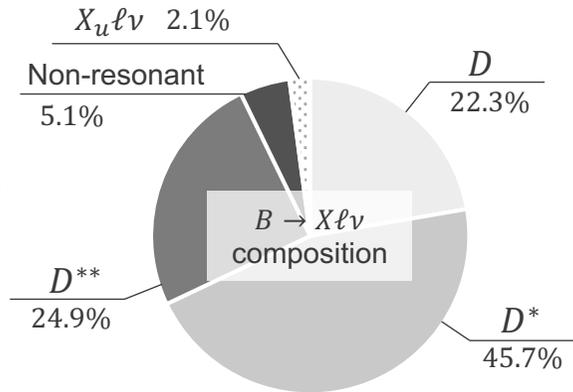
A fundamental axiom of the Standard Model (SM) is the universality of the lepton coupling, g_ℓ ($\ell = e, \mu, \tau$), to the electroweak gauge bosons.

$$1. R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)}, \quad (\ell = e \text{ or } \mu)$$

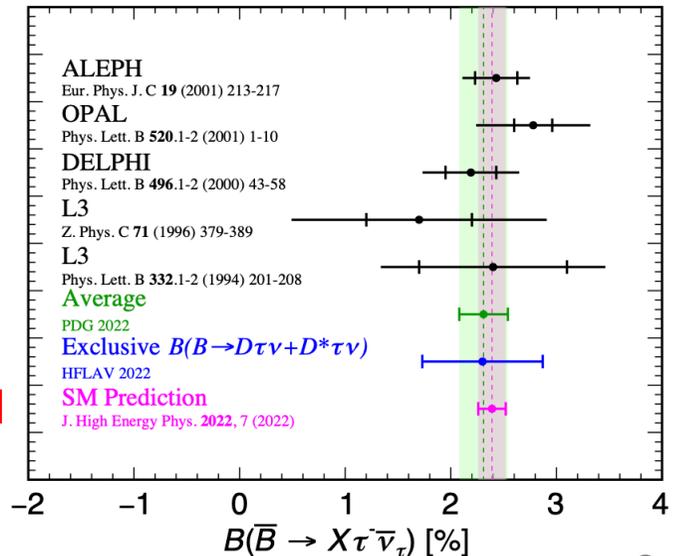
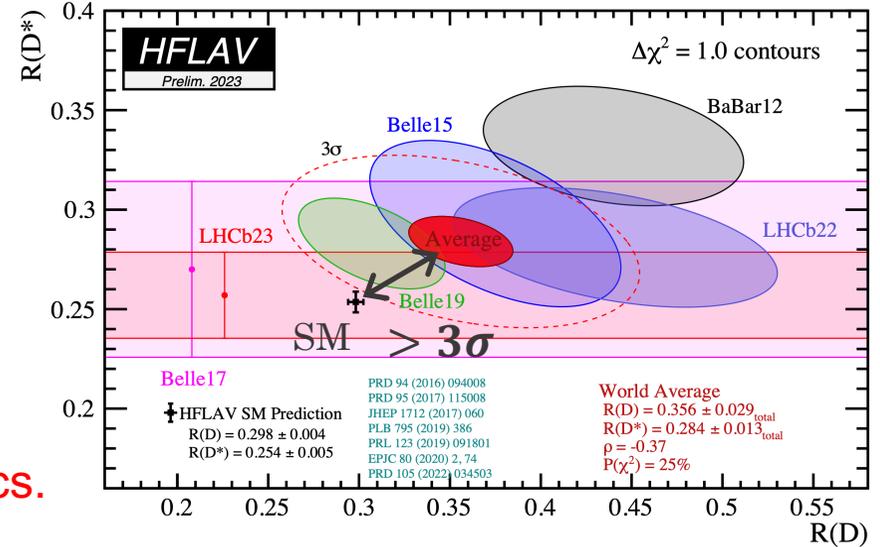


The tension with SM could be a sign of New Physics.

$$2. R(X) = \frac{\mathcal{B}(\bar{B} \rightarrow X \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow X \ell^- \bar{\nu}_\ell)}$$



Measurements of $\mathcal{B}(\bar{B} \rightarrow X \tau^- \bar{\nu}_\tau)$ are completely saturated by $\mathcal{B}(\bar{B} \rightarrow D \tau^- \bar{\nu}_\tau + D^* \tau^- \bar{\nu}_\tau)$ unlike $\mathcal{B}(\bar{B} \rightarrow X \ell^- \bar{\nu}_\ell)$.



Light-Lepton Universality Tests in $b \rightarrow c$ Decays

New Physics in $R(D^{(*)})$ and $R(X)$ could induce a violation of the lepton flavor universality in the following observables for the light-lepton side of e and μ .

$$1. R(X_{e/\mu}) = \frac{\mathcal{B}(\bar{B} \rightarrow X e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B} \rightarrow X \mu^- \bar{\nu}_\mu)}$$

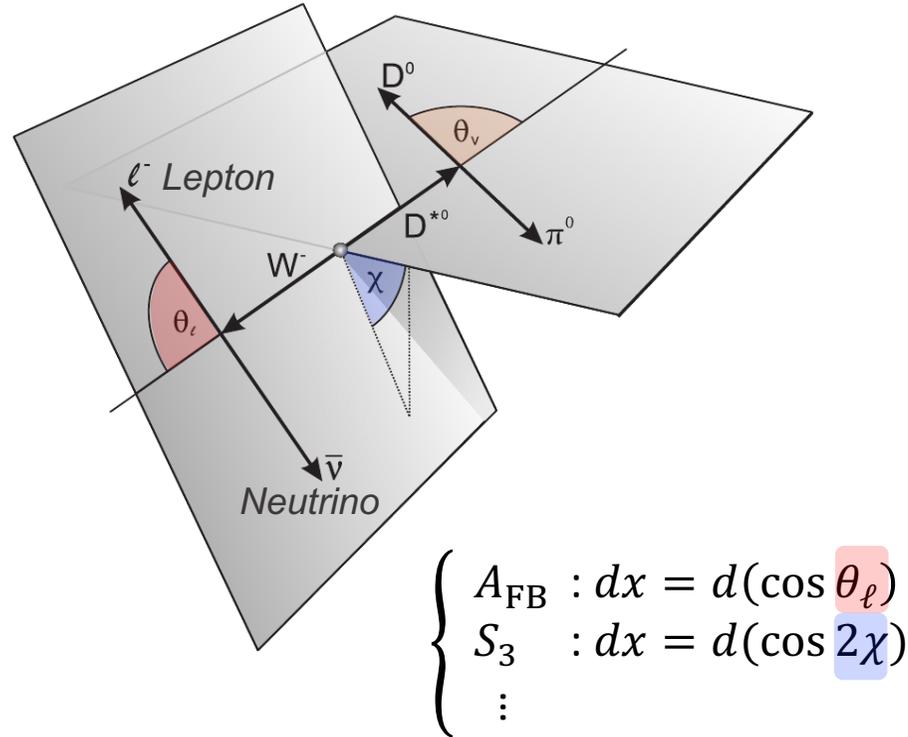
2. Angular asymmetries in $\bar{B} \rightarrow D^* \ell^- \bar{\nu}_\ell$:

$$\Delta \mathcal{A}_x(w) = \mathcal{A}_x^e(w) - \mathcal{A}_x^\mu(w)$$

Angular observable

$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw} \right)^{-1} \left[\int_0^1 - \int_{-1}^0 \right] dx \frac{d^2\Gamma}{dw dx}$$

$$w \equiv \frac{m_B^2 + m_D^2 - (p_B - p_{D^*})^2}{2m_B m_{D^*}} \quad : \text{recoil parameter}$$



$$\begin{cases} A_{\text{FB}} : dx = d(\cos \theta_\ell) \\ S_3 : dx = d(\cos 2\chi) \\ \vdots \end{cases}$$

$R(X_{e/\mu})$ and $\mathcal{A}_x(w)$ can provide
theoretically and experimentally clean probes of light-lepton universality.

Major cancellation of theoretical and experimental uncertainties

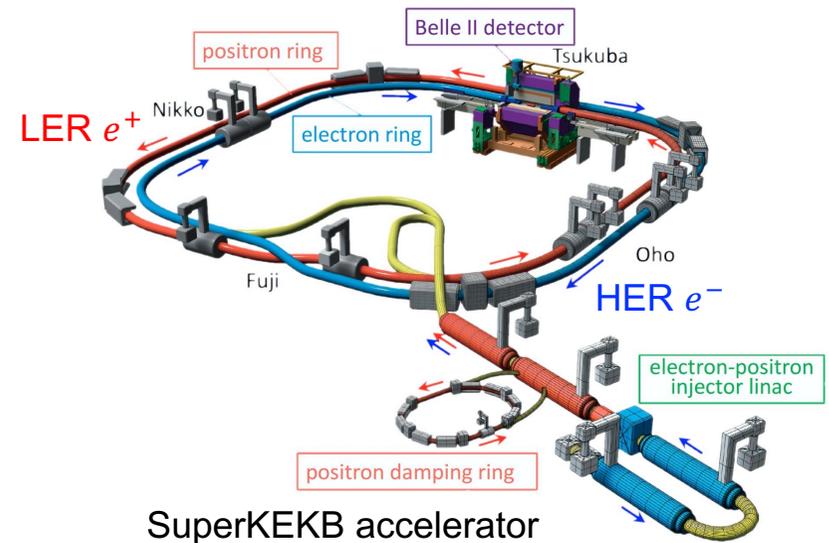
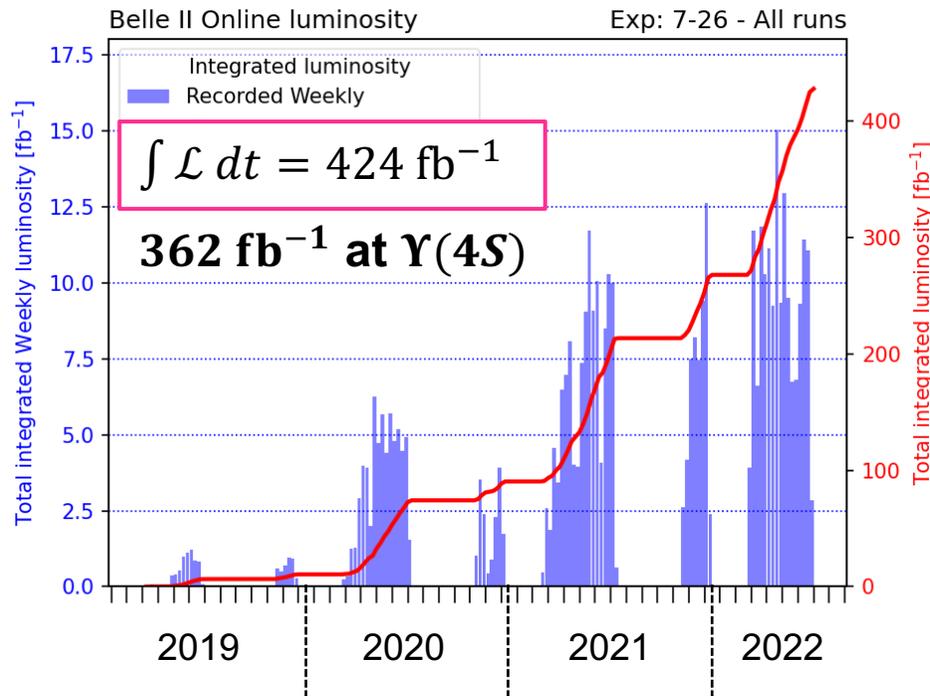
The SuperKEKB/Belle II Experiment

Electron-positron collider experiment at a center of mass energy of the $\Upsilon(4S)$ or around.

The world's highest instantaneous luminosity:

$$4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

(KEKB record: $2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)



$\sigma(b\bar{b}) \sim 1.1 \text{ nb}$, $\sigma(q\bar{q}) \sim 3.7 \text{ nb}$ ($q = u, d, s, c$)
at $\sqrt{s} = 10.58 \text{ GeV}$

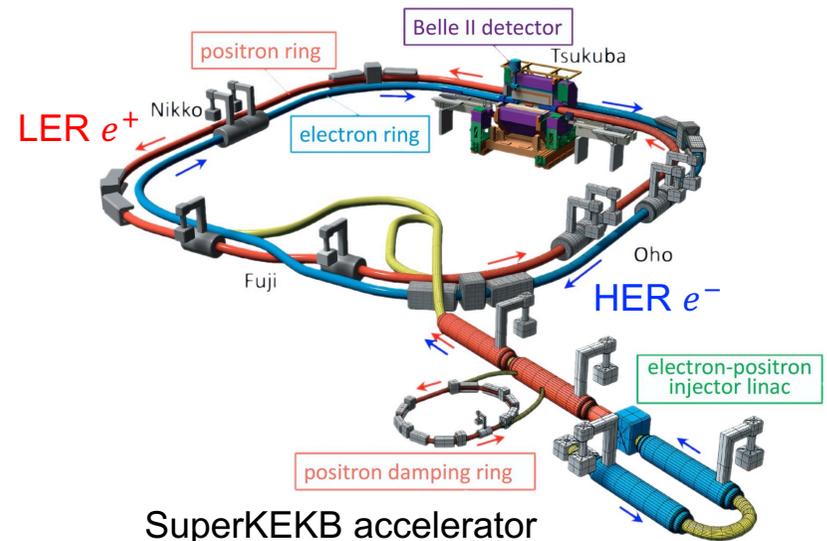
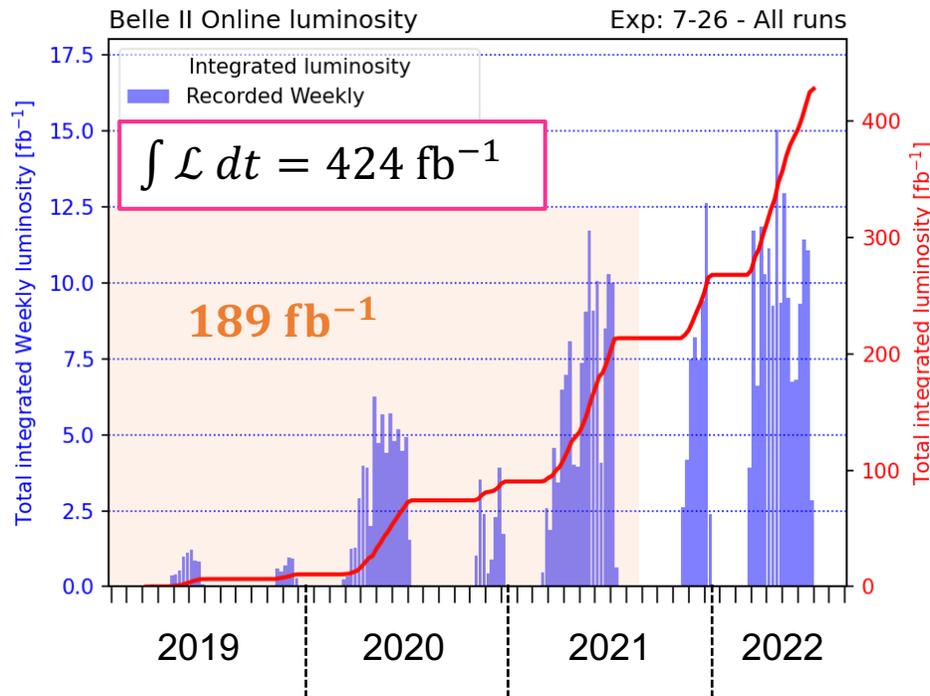
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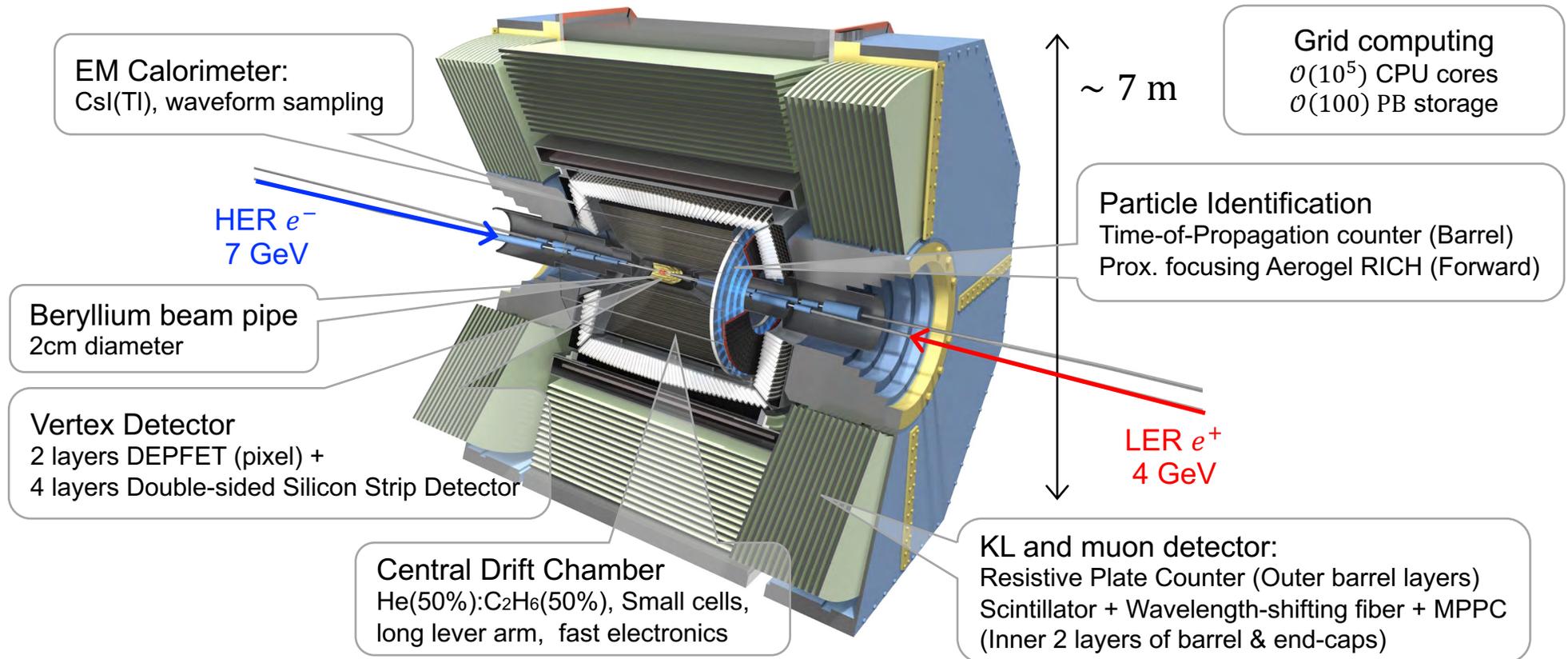
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at $\sqrt{s} = 10.58 \text{ GeV}$

Belle II measured light-lepton universalities at 189 fb^{-1}

The Belle II Detector

Substantially upgraded from the Belle detector
except for calorimeter crystal and superconducting magnet

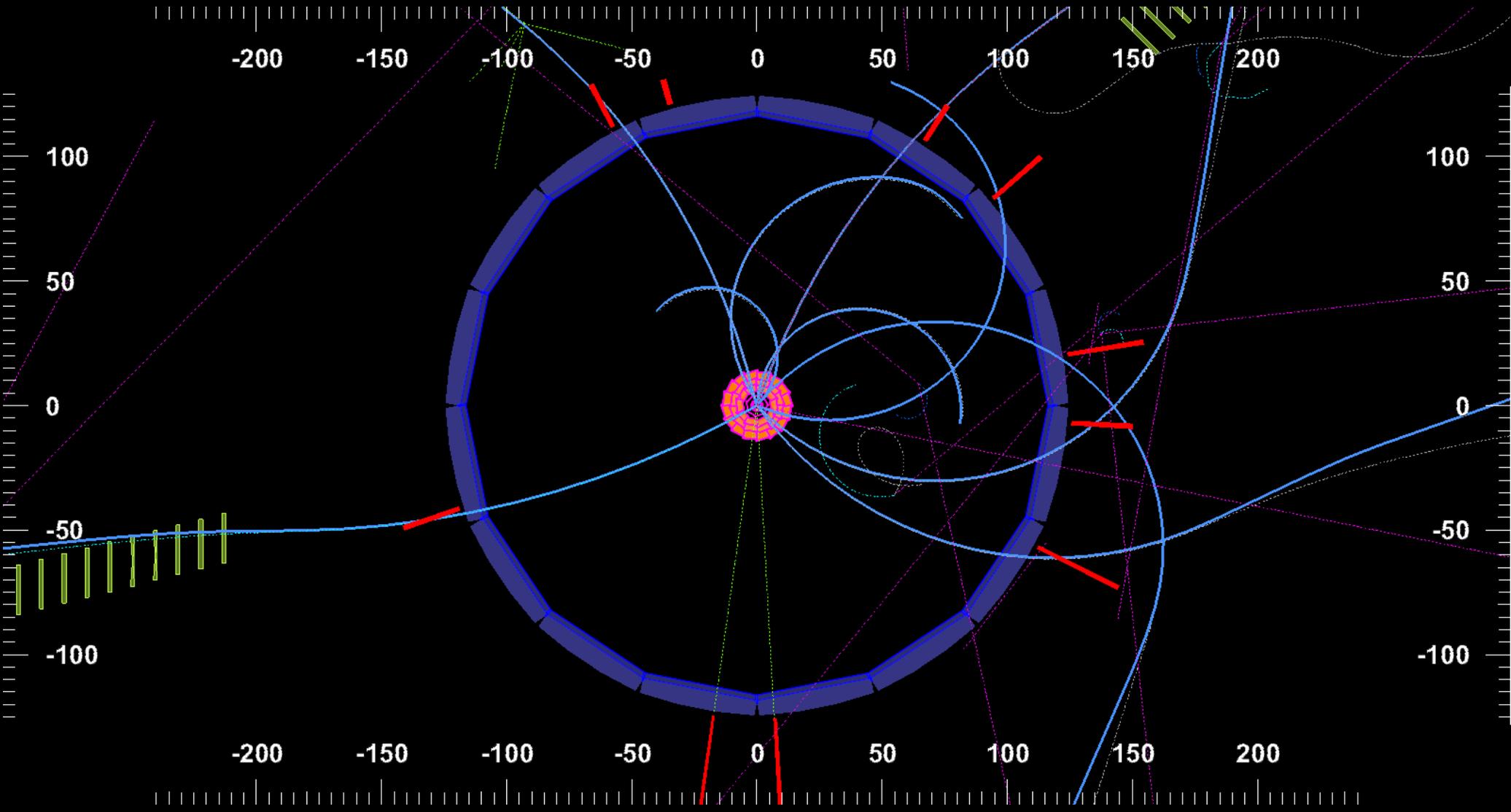
Equivalent or improved performances under higher beam background and event rate conditions.
e.g. vertex resolution, K_S^0 reconstruction, K/π identification, trigger system, ...



The Belle II Detector: Event Display

Belle II Simulation

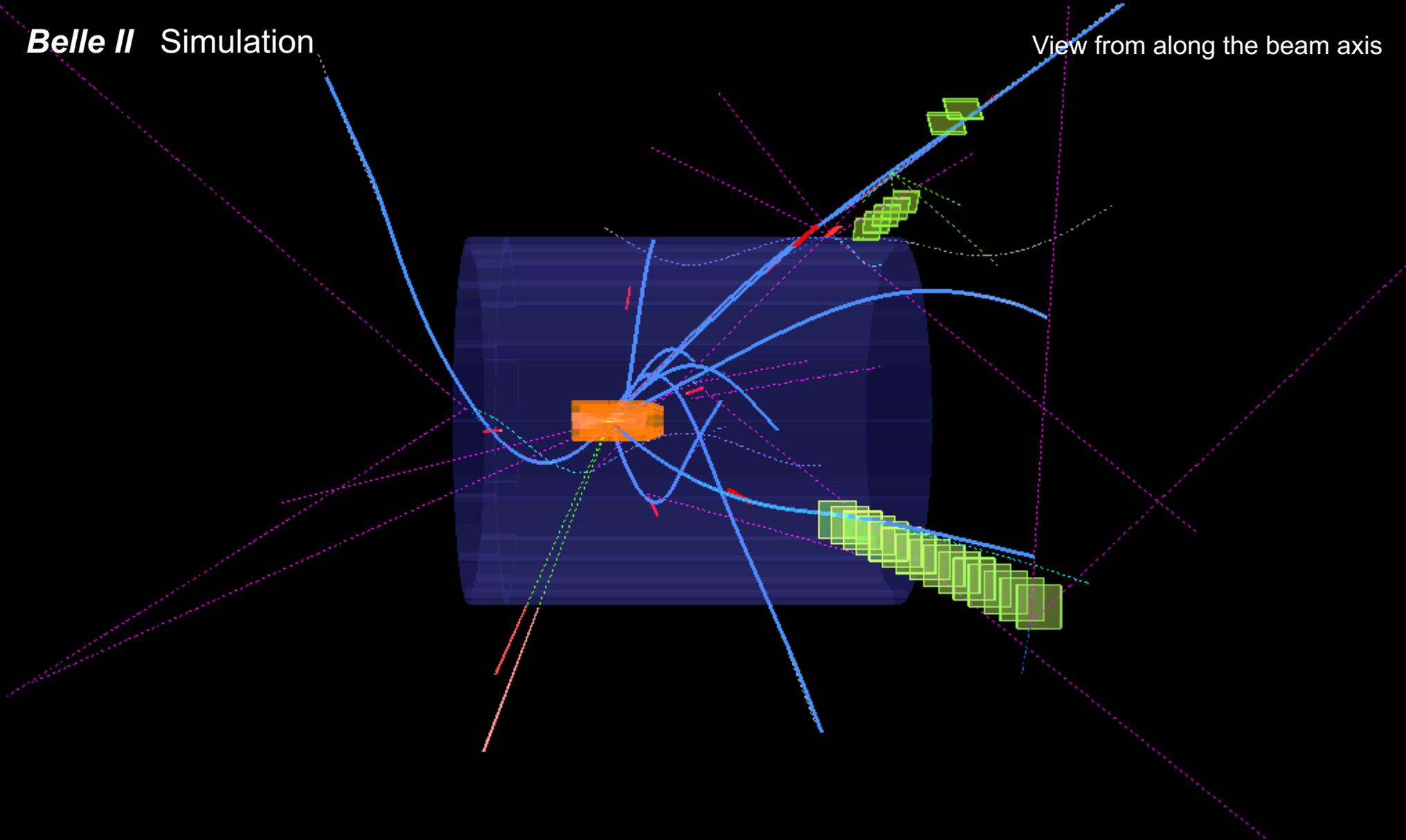
View perpendicular to the beam axis



The Belle II Detector: Event Display

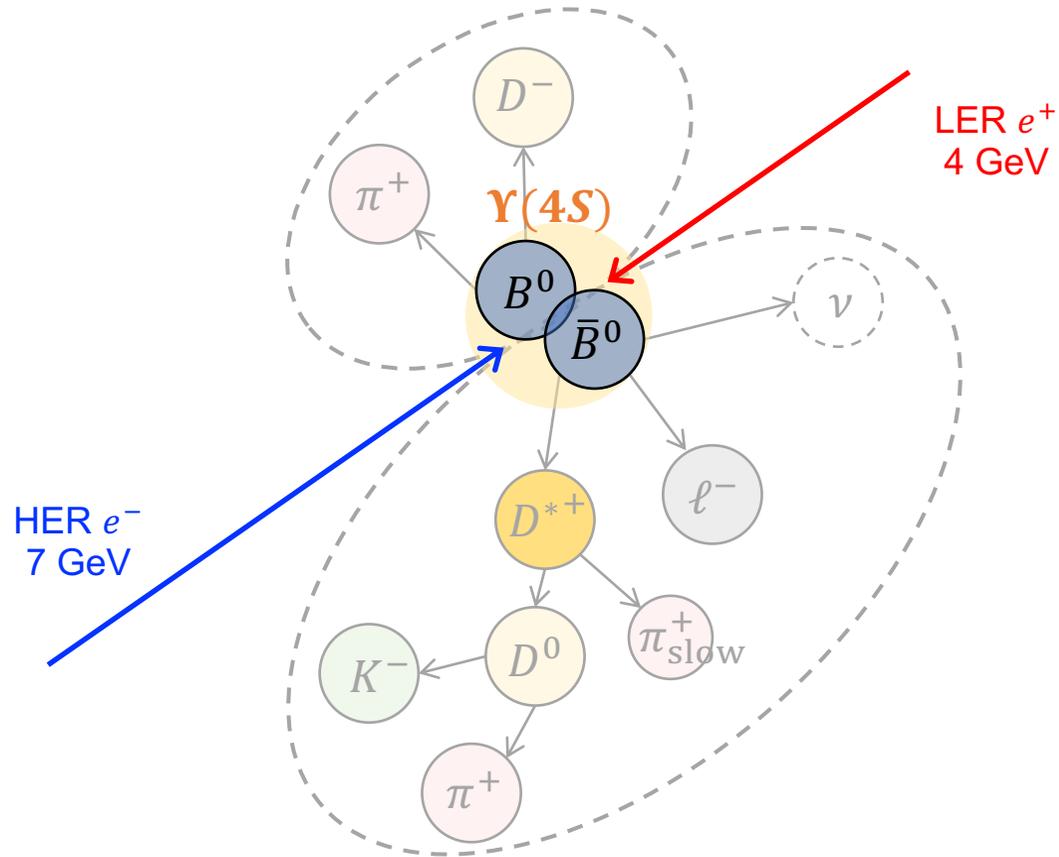
Belle II Simulation

View from along the beam axis



Reconstruction

B mesons are generated in pairs from a $\Upsilon(4S)$ ($b\bar{b}$ resonance) decay.



Reconstruction: B Tagging

B mesons are generated in pairs from a $\Upsilon(4S)$ ($b\bar{b}$ resonance) decay.

One B meson from $\Upsilon(4S)$ decay is fully reconstructed with hadronic decays to tag $B\bar{B}$ events.

Hadronic B tagging
(Full Event Interpretation)

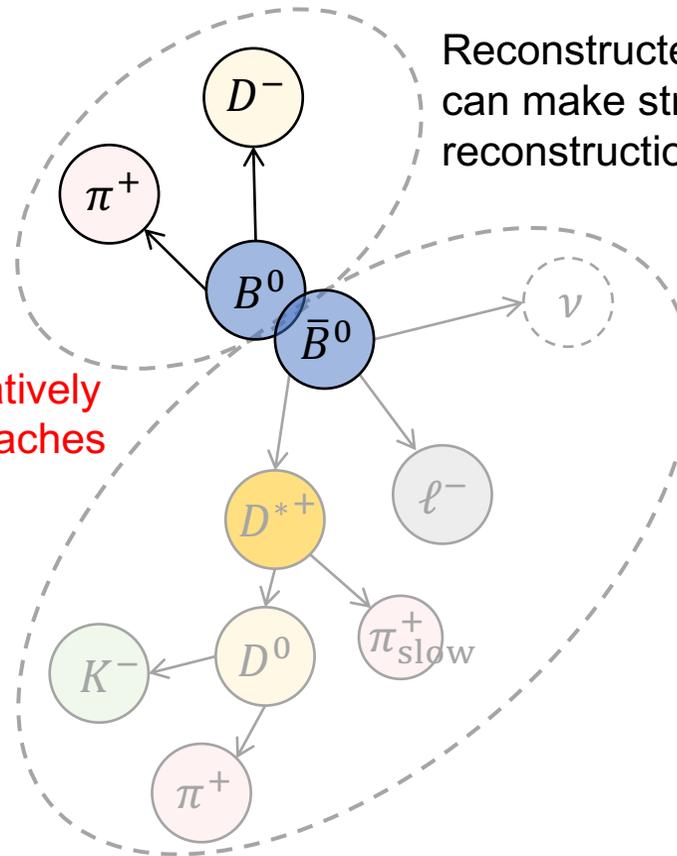
[Comp. and Soft. For Big Sci. 3, 6 \(2019\)](#)

Efficiency

B^0 : 0.27%, B^+ : 0.35%

[arXiv:2008.06096](#)

Improved efficiency up to 50% relatively
with respect to conventional approaches

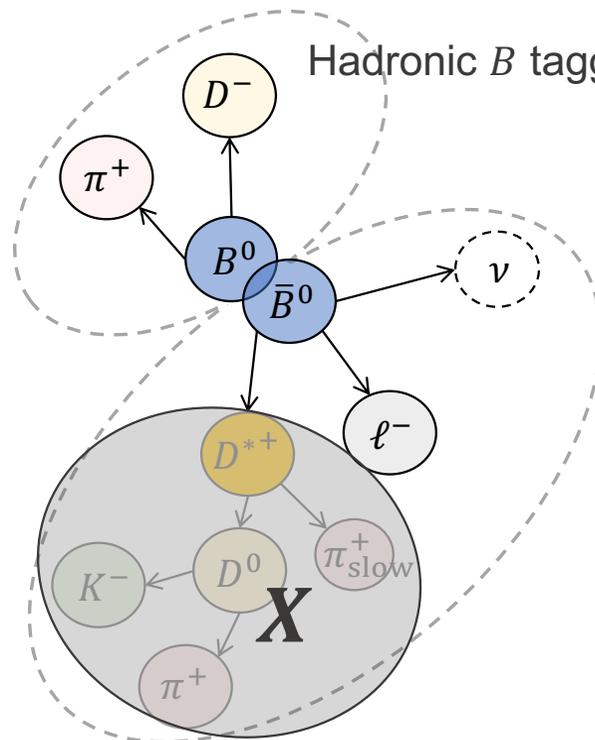


Reconstructed momentum of the partner B can make strong kinematic constraints in reconstruction for the signal side with neutrinos.

Reconstruction: Signal B Reconstruction

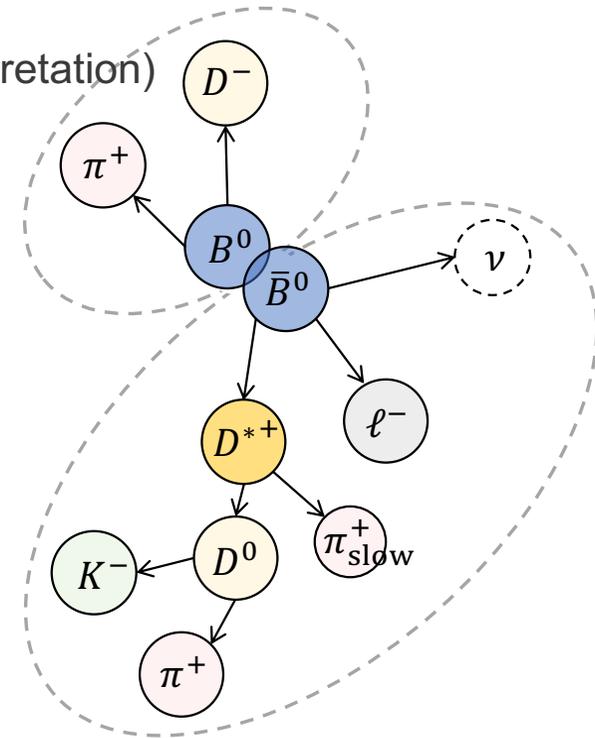
B mesons are generated in pairs from a $\Upsilon(4S)$ ($b\bar{b}$ resonance) decay.

One B meson from $\Upsilon(4S)$ decay is fully reconstructed with hadronic decays to tag $B\bar{B}$ events. The signal semi-leptonic B decays are reconstructed via inclusive or exclusive modes.



1. Inclusive signal B modes

Reconstruct other particles than a lepton inclusively as X .



2. Exclusive signal B modes

Reconstruct all B daughters through specific decay channels.

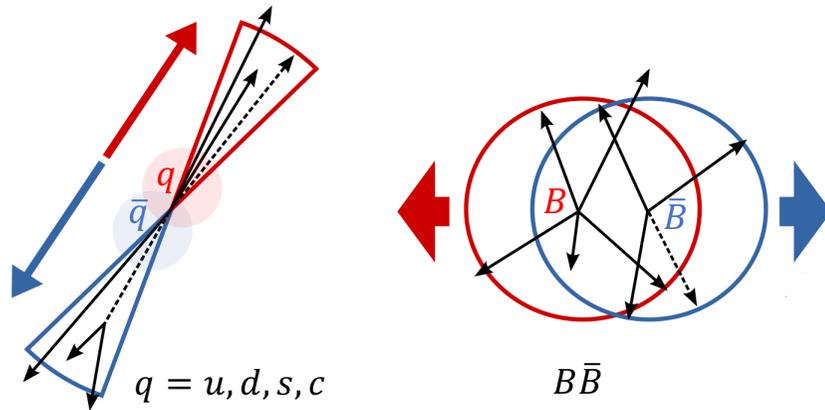
Light-Lepton Universality Test: $R(X_{e/\mu})$ Measurement

[arXiv:2301.08266](https://arxiv.org/abs/2301.08266)

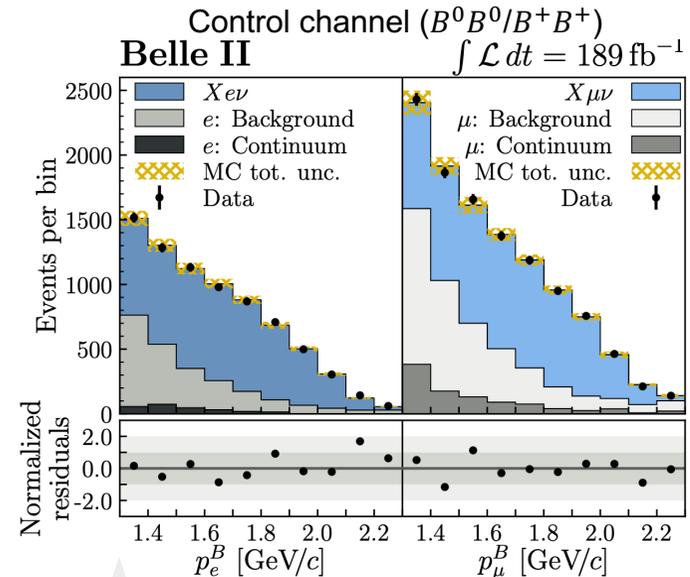
We tested light-lepton universality by $R(X_{e/\mu}) = \frac{\mathcal{B}(\bar{B} \rightarrow X e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B} \rightarrow X \mu^- \bar{\nu}_\mu)}$ of the inclusive signal B modes.

The signal yields are extracted through a binned maximum-likelihood simultaneous fit to lepton momentum of the signal B rest frame, p_ℓ^B , among the signal ($B^0 \bar{B}^0 / B^+ B^-$) and control ($B^0 B^0 / B^+ B^+$) channels.

Background from $q\bar{q}$ events
(continuum background)



Background from $B\bar{B}$ events



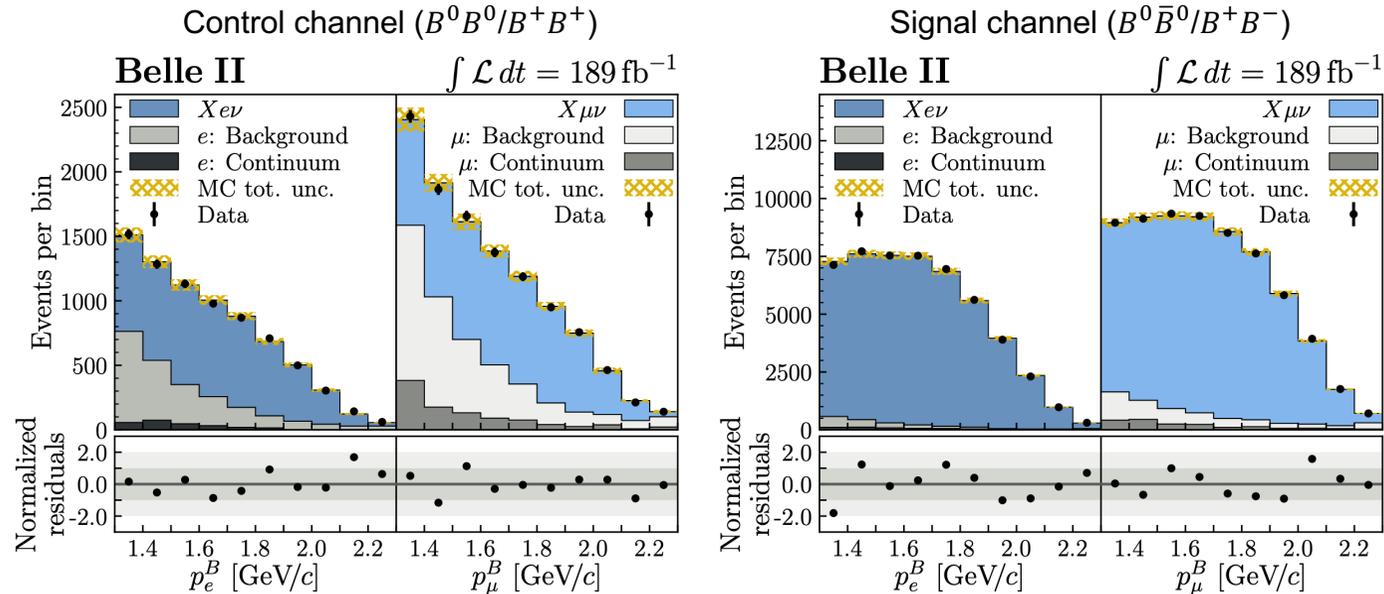
MVA with 21 event-topology variables:
55% rejection of the continuum background at
97% retention of the $B\bar{B}$ candidates.

Background from $B\bar{B}$ events are constrained
using the background-enriched control sample
through the simultaneous fit.

Light-Lepton Universality Test: $R(X_{e/\mu})$ Measurement

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We tested light-lepton universality by $R(X_{e/\mu}) = \frac{\mathcal{B}(\bar{B} \rightarrow X e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B} \rightarrow X \mu^- \bar{\nu}_\mu)}$ of the inclusive signal B modes.



$$R(X_{e/\mu}) = 1.033 \pm 0.010 \text{ (stat)} \pm 0.019 \text{ (syst)}$$

First e - μ universality test using inclusive semi-leptonic B decays

The most precise test of branching-fraction based e - μ universality of semi-leptonic B decays

Consistent with SM $R(X_{e/\mu})_{\text{SM}}^{[1]}$ by 1.2σ and the exclusive Belle $R(D^*_{e/\mu})^{[2],[3]}$.

[1] [J. High Energy Phys. 11, 007 \(2022\)](#), [2] [Phys. Rev. D 100, 052007 \(2019\)](#), [3] [arXiv:2301.07529](#)

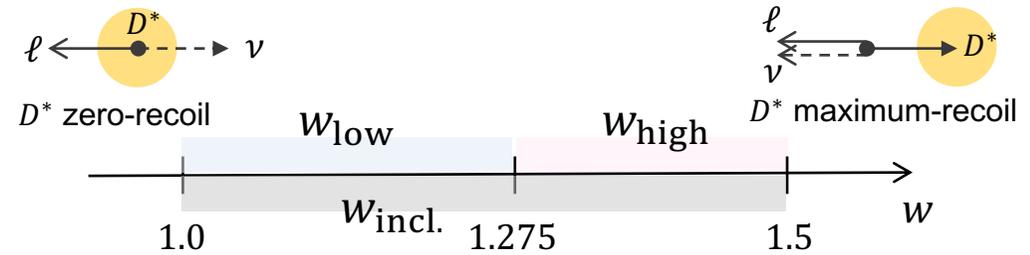
Light-Lepton Universality Test: Angular Asymmetry

We tested lepton universality by comparing five angular asymmetries of e and μ , $\Delta\mathcal{A}_x(w) = \mathcal{A}_x^\mu(w) - \mathcal{A}_x^e(w)$ using exclusive $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$ decays.

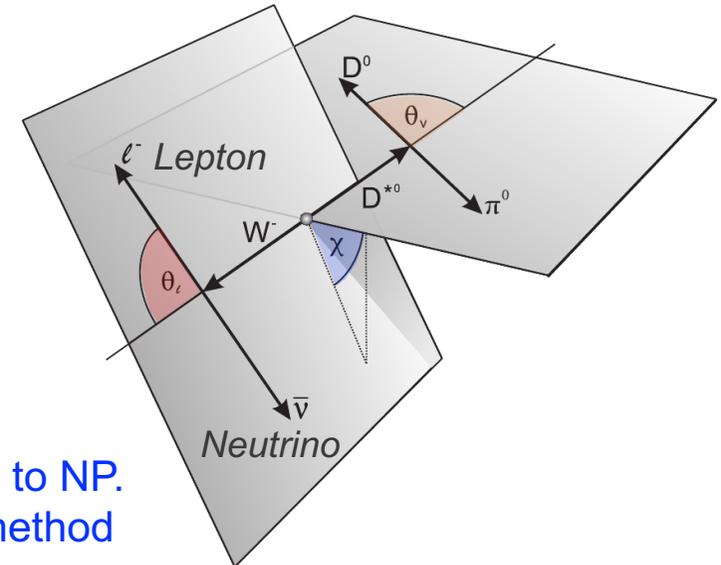
Angular observable

$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1} \left[\int_0^1 - \int_{-1}^0 \right] dx \frac{d^2\Gamma}{dw dx}$$

$$w \equiv \frac{m_B^2 + m_D^2 - (p_B - p_{D^*})^2}{2m_B m_{D^*}} : \text{recoil parameter}$$



$\mathcal{A}_x(w)$	dx	
$A_{FB}(w)$	$d(\cos \theta_\ell)$	Highly sensitive to lepton universality violation
$S_3(w)$	$d(\cos 2\chi)$	
$S_5(w)$	$d(\cos \chi \cos \theta_V)$	
$S_7(w)$	$d(\sin \chi \cos \theta_V)$	Less sensitive or insensitive to NP. For control of the analysis method
$S_9(w)$	$d(\sin 2\chi)$	



The simultaneous determination of all asymmetries in different w ranges is performed.

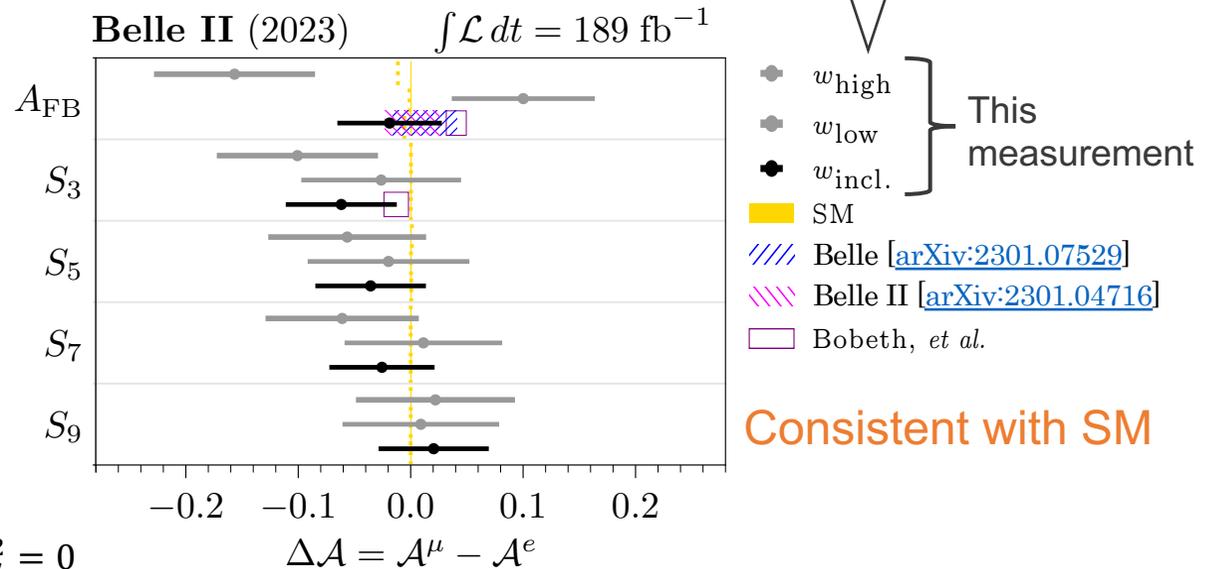
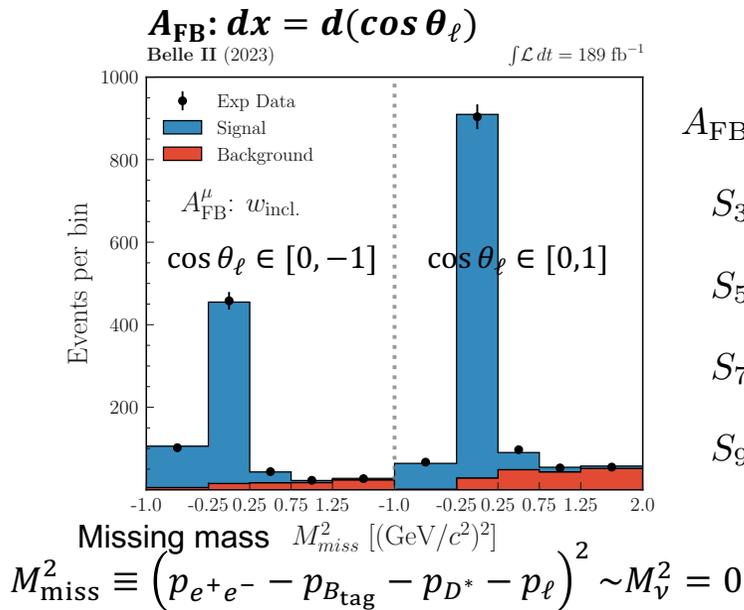
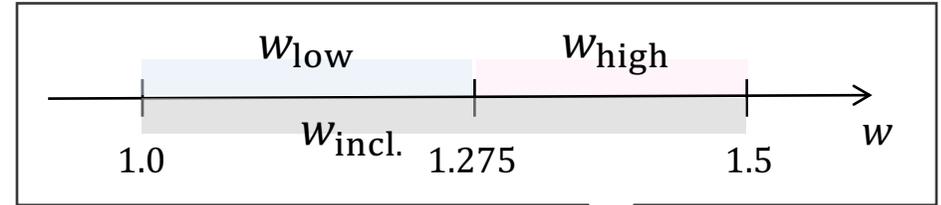
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The signal yields are extracted through a binned maximum-likelihood fit to M_{miss}^2 distributions.

$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1} \left[\int_0^1 - \int_{-1}^0 \right] dx \frac{d^2\Gamma}{dwdx}$$



First e - μ universality test of differential angular observables in w
No evidence of lepton universality violation with at least a p -value of 0.12

Summary

The test of lepton universality violation attracts attention by deviations of experimental results from the Standard Model by $> 3\sigma$ in $b \rightarrow c$ transitions.

New Physics could contribute to the lepton universality violations.

The Belle II performed two light-lepton universality tests.

1. $R(X_{e/\mu}) = 1.033 \pm 0.010 \text{ (stat)} \pm 0.019 \text{ (syst)}$

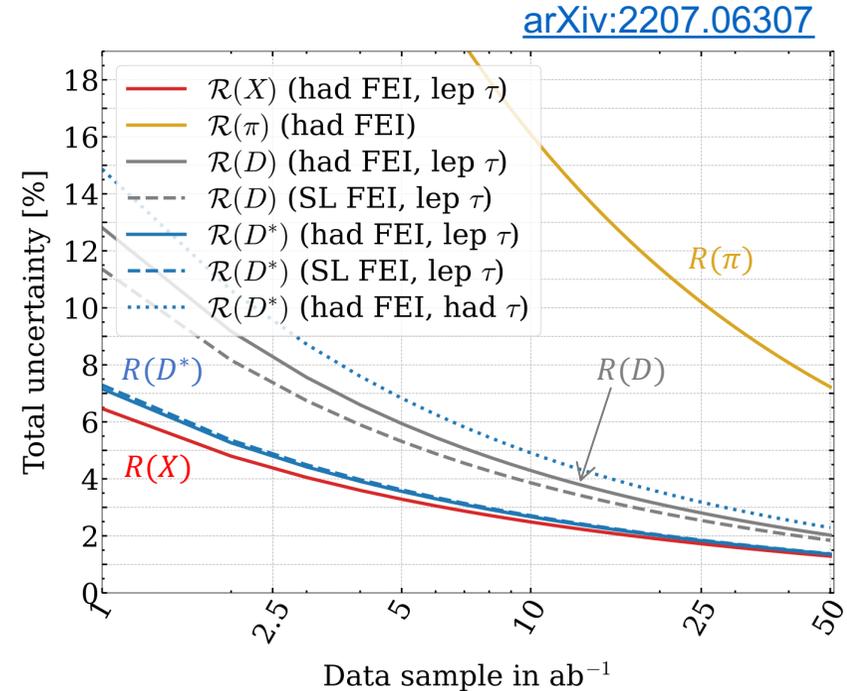
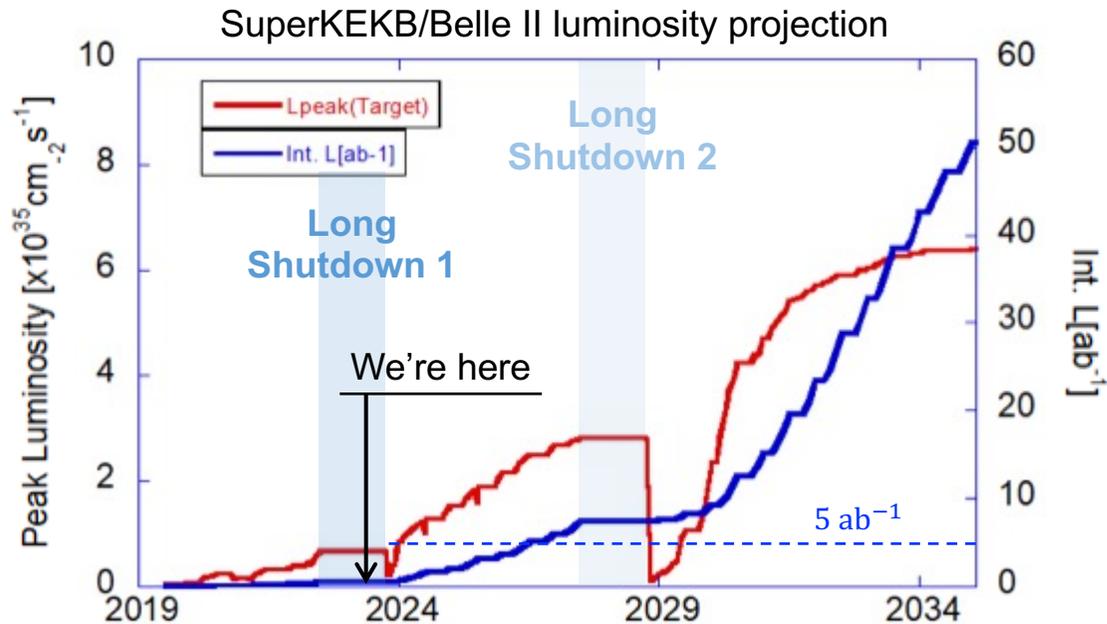
2. $\Delta A_{\text{FB}}(w), \Delta S_3(w), \Delta S_5(w), \Delta S_7(w), \Delta S_9(w)$

Both tests are world-leading/first results and are consistent with the SM expectation.

Long-Term Prospects for τ - ℓ Universality Tests

Lepton universality tests including τ leptons by measurements of $R(X) = \frac{B(\bar{B} \rightarrow X \tau^- \bar{\nu}_\tau)}{B(\bar{B} \rightarrow X \ell^- \bar{\nu}_\ell)}$ and

$R(D^*) = \frac{B(\bar{B} \rightarrow D^* \tau^- \bar{\nu}_\tau)}{B(\bar{B} \rightarrow D^* \ell^- \bar{\nu}_\ell)}$ with Belle II data are in progress.



The SuperKEKB/Belle II will resume operation in the winter of 2023.

Belle II will achieve $\mathcal{O}(10^{-2})$ sensitivities at 1-5 ab^{-1} for

$$R(D^{(*)}) = \frac{B(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau)}{B(\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu}_\ell)} \text{ and } R(X) = \frac{B(\bar{B} \rightarrow X \tau^- \bar{\nu}_\tau)}{B(\bar{B} \rightarrow X \ell^- \bar{\nu}_\ell)}$$

Appendix

Systematic Uncertainties on $R(X_{e/\mu})$

Table I: Statistical and systematic uncertainties on the value of $R(X_{e/\mu})$ from the most significant sources.

Source	Uncertainty [%]
Sample size	1.0
Lepton identification	1.9
$X_c \ell \nu$ branching fractions	0.1
$X_c \ell \nu$ form factors	0.2
Total	2.2

The modeling of charmed D meson decays by varying the branching ratio of each decay $D \rightarrow K^+$ anything within its uncertainty while fixing the total event normalization. The effect is negligible.

χ^2 Tests of Angular Asymmetries

In the full w region, $w_{incl.}$:

Angular observables	χ^2/N_{dof}	p -value
\mathcal{A}	15.0/10	0.13
$\Delta A_{FB}(w), \Delta S_3(w), \Delta S_5(w)$	2.1/3	0.56
$\Delta S_7(w), \Delta S_9(w)$	0.6/2	0.32

In the sub- w region, w_{high} & w_{low} :

Angular observables	χ^2/N_{dof}	p -value
\mathcal{A}	27.7/20	0.12
$\Delta A_{FB}(w), \Delta S_3(w), \Delta S_5(w)$	10.2/6	0.12
$\Delta S_7(w), \Delta S_9(w)$	1.1/4	0.89

Uncertainties on Angular Asymmetries

The systematic uncertainties are dominated by the sample size of MC statistics.

Obs.	w bin	Total	Stat.	MC stat.	LID	π_{slow}							
A_{FB}^e	w_{low}	0.047	0.044	0.015	0.004	0.001							
	w_{high}	0.052	0.049	0.017	0.004	0.001							
	$w_{\text{incl.}}$	0.034	0.032	0.011	0.004	0.001							
A_{FB}^μ	w_{low}	0.043	0.041	0.013	0.001	0.001							
	w_{high}	0.050	0.047	0.016	0.002	0.001							
	$w_{\text{incl.}}$	0.032	0.030	0.010	0.001	0.001							
ΔA_{FB}	w_{low}	0.064	0.060	0.020	0.004	0.001							
	w_{high}	0.072	0.067	0.024	0.004	0.001							
	$w_{\text{incl.}}$	0.046	0.044	0.015	0.004	0.001							
S_3^e	w_{low}	0.053	0.050	0.018	0.000	0.001	S_7^e	w_{low}	0.052	0.049	0.018	0.001	0.000
	w_{high}	0.051	0.048	0.018	0.000	0.000		w_{high}	0.049	0.046	0.017	0.000	0.000
	$w_{\text{incl.}}$	0.036	0.034	0.012	0.000	0.000		$w_{\text{incl.}}$	0.034	0.032	0.012	0.000	0.000
S_3^μ	w_{low}	0.048	0.045	0.016	0.001	0.000	S_7^μ	w_{low}	0.047	0.044	0.015	0.000	0.000
	w_{high}	0.050	0.047	0.016	0.000	0.000		w_{high}	0.047	0.045	0.015	0.000	0.000
	$w_{\text{incl.}}$	0.034	0.032	0.011	0.001	0.000		$w_{\text{incl.}}$	0.032	0.031	0.011	0.000	0.000
ΔS_3	w_{low}	0.071	0.067	0.024	0.001	0.000	ΔS_7	w_{low}	0.070	0.066	0.023	0.001	0.001
	w_{high}	0.072	0.067	0.025	0.001	0.000		w_{high}	0.068	0.064	0.022	0.000	0.000
	$w_{\text{incl.}}$	0.049	0.046	0.017	0.001	0.000		$w_{\text{incl.}}$	0.047	0.044	0.016	0.000	0.000
S_5^e	w_{low}	0.053	0.050	0.018	0.001	0.000	S_9^e	w_{low}	0.052	0.048	0.018	0.000	0.000
	w_{high}	0.051	0.048	0.017	0.001	0.000		w_{high}	0.051	0.048	0.018	0.000	0.000
	$w_{\text{incl.}}$	0.036	0.034	0.012	0.001	0.000		$w_{\text{incl.}}$	0.036	0.034	0.012	0.000	0.000
S_5^μ	w_{low}	0.048	0.045	0.016	0.001	0.000	S_9^μ	w_{low}	0.047	0.044	0.016	0.000	0.000
	w_{high}	0.049	0.046	0.016	0.000	0.000		w_{high}	0.049	0.047	0.016	0.000	0.001
	$w_{\text{incl.}}$	0.034	0.032	0.011	0.000	0.000		$w_{\text{incl.}}$	0.033	0.032	0.011	0.000	0.000
ΔS_5	w_{low}	0.072	0.068	0.024	0.001	0.000	ΔS_9	w_{low}	0.070	0.065	0.024	0.000	0.000
	w_{high}	0.070	0.066	0.023	0.001	0.000		w_{high}	0.071	0.067	0.024	0.001	0.001
	$w_{\text{incl.}}$	0.049	0.046	0.016	0.001	0.000		$w_{\text{incl.}}$	0.049	0.046	0.017	0.000	0.000

Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ with an Inclusive Tagging Method

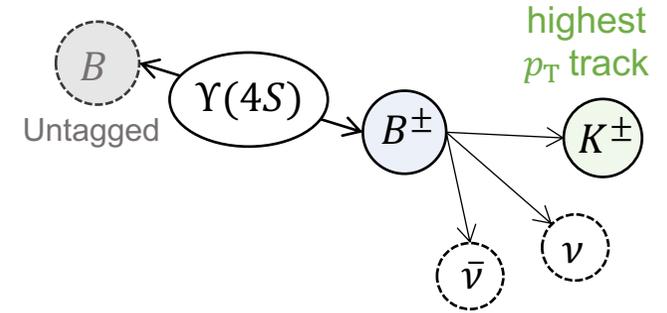
$b \rightarrow s \nu \bar{\nu}$ offers a complementary probe of new physics in $b \rightarrow s \ell \ell$.

$b \rightarrow s \nu \bar{\nu}$ decays are not observed yet.

Upper limit^[1] $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) < 1.6 \times 10^{-5}$

SM^[2] $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = (5.67 \pm 0.38) \times 10^{-6}$

[1] [Prog. Theor. Exp. Phys. 2020, 083C01 \(2020\)](#), [2] [arXiv:2207.13371](#)



Belle II performed the search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ with an inclusive tagging method for the first time.

[Phys. Rev. Lett. 127, 181802 \(2021\)](#)

Train two BDTs in cascade to suppress backgrounds using event shape and rest-of-event information.

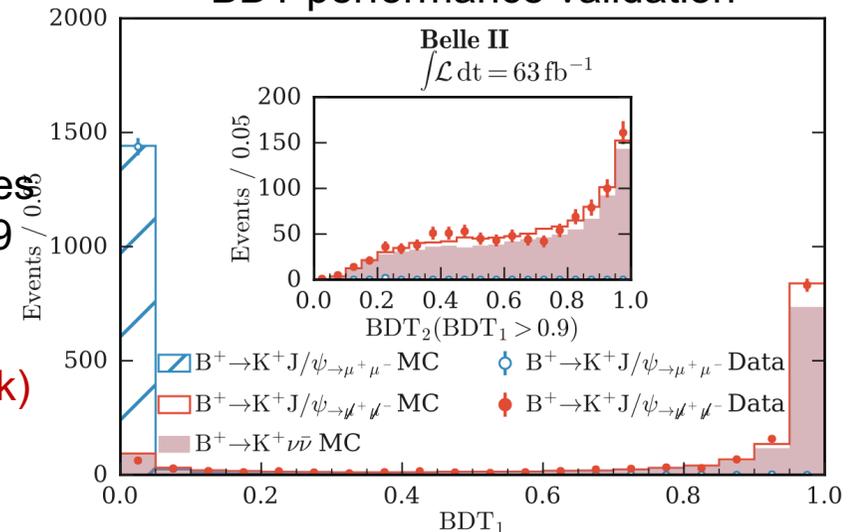
BDT₁ ... Discriminate signals mainly by topological features

BDT₂ ... Improve purity of signals in events with BDT₁ > 0.9
 → 35% increase at 4% signal efficiency

$B^+ \rightarrow K^+ J/\psi \rightarrow K^+ \mu^+ \mu^-$: Signal-like events (with dimuon mask)

$B^+ \rightarrow K^+ J/\psi \rightarrow K^+ \mu^+ \mu^-$: Background-like events

BDT performance validation

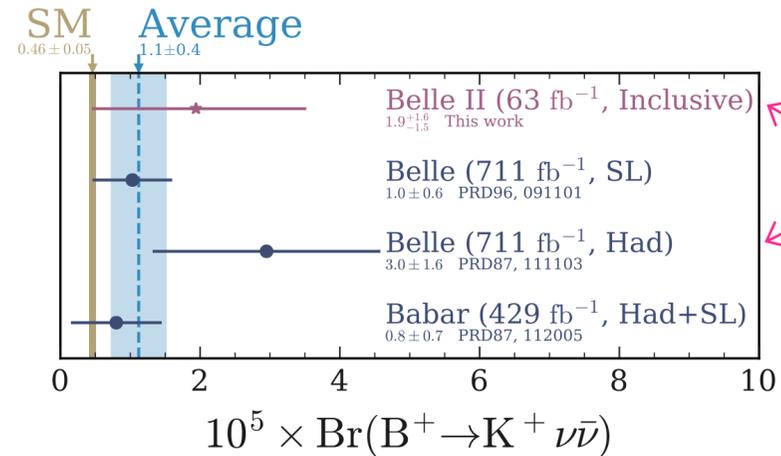
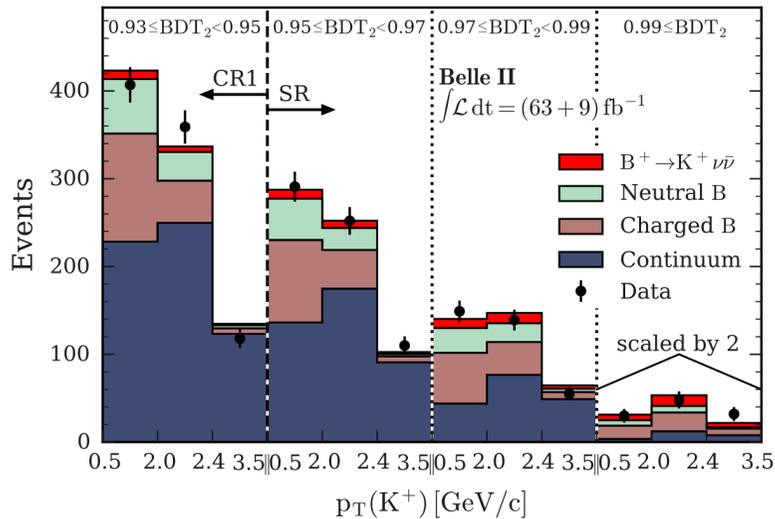


Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ with an Inclusive Tagging Method

Phys. Rev. Lett. 127, 181802 (2021)

Observed branching fraction:

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = \left(1.9^{+1.3}_{-1.3}{}_{\text{stat}} \quad {}^{+0.8}_{-0.7}{}_{\text{syst}} \right) \times 10^{-5}$$



Observed (expected) upper limit on the branching fraction:

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) < 4.1 \text{ (2.3)} \times 10^{-5} \text{ (90\% CL)}$$

Competitive as a new method!

20% and 350% improvement from the semi-leptonic and hadronic tagging methods at 711 fb⁻¹, respectively