Recent Belle II results related to flavor anomalies

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

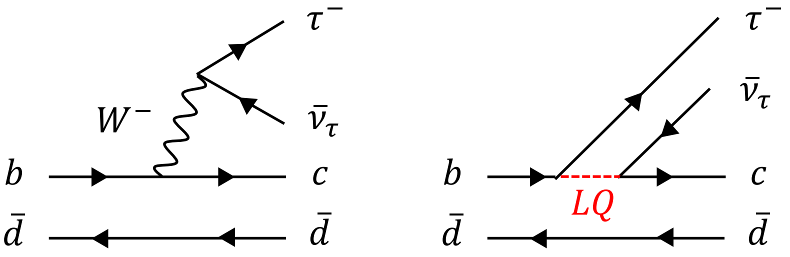
International Conference on the Physics of the Two Infinities

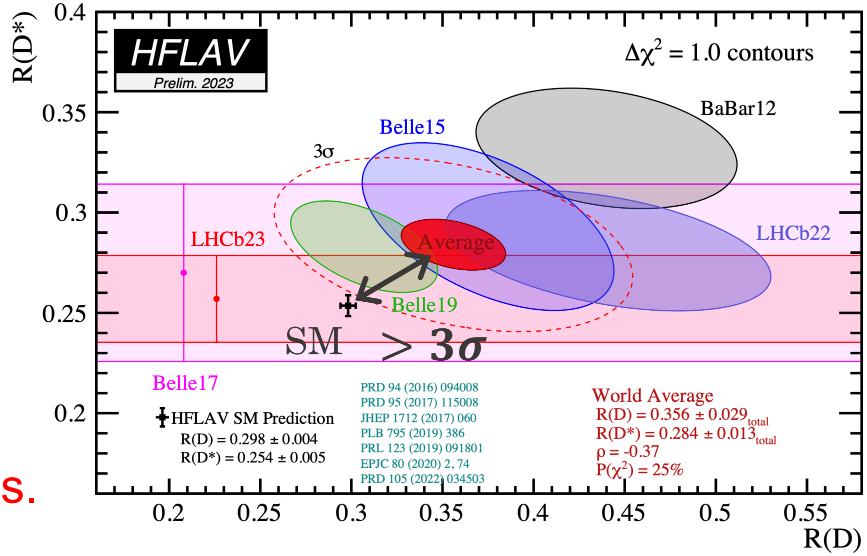
Mar. 29th, 2023

Anomalies in $b \to c$ 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.

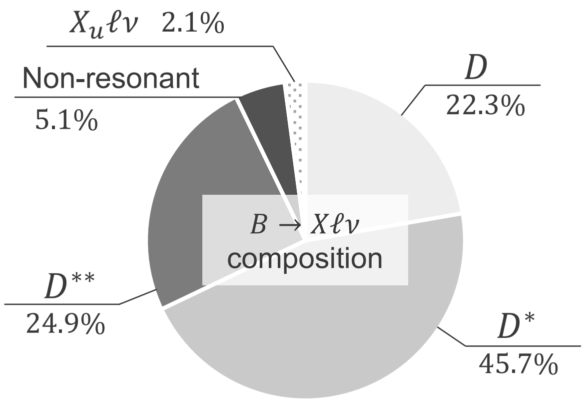
1. $$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}, \ (\ell = e \text{ or } \mu)$$

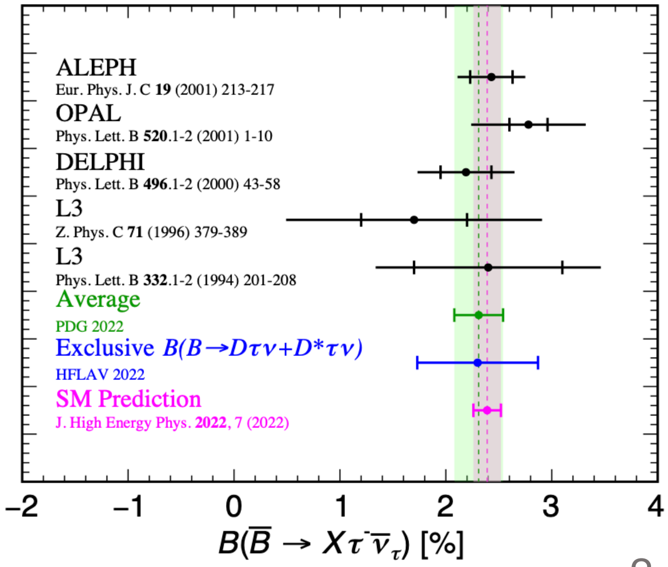




The tension with SM could be a sign of New Physics.

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





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

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

New Physics in $R\left(D^{(*)}\right)$ 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. $R\left(X_{e/\mu}\right) = \dfrac{\mathcal{B}(\bar{B} \to X e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B} \to X \mu^- \bar{\nu}_\mu)}$

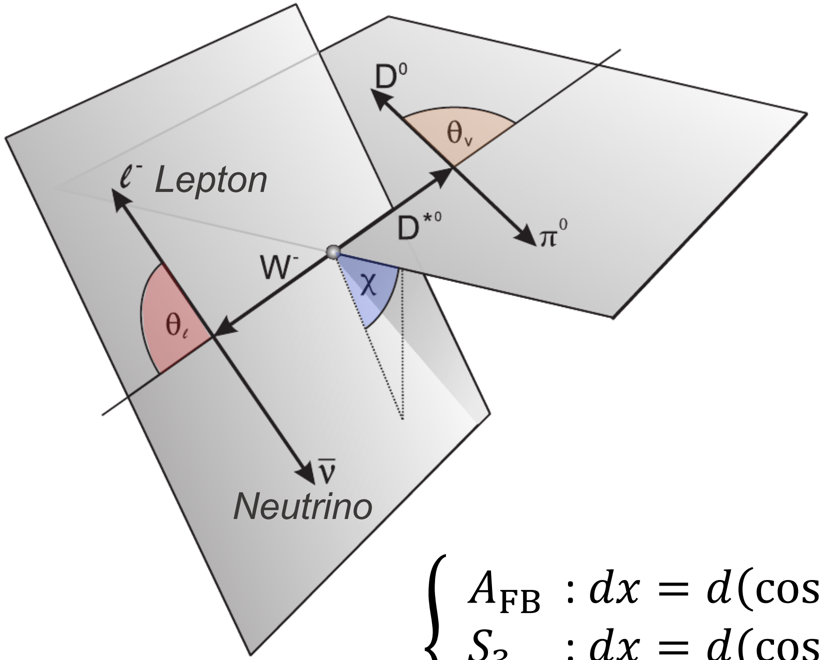
2. Angular asymmetries in $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$:

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

Angular observable

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

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



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

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

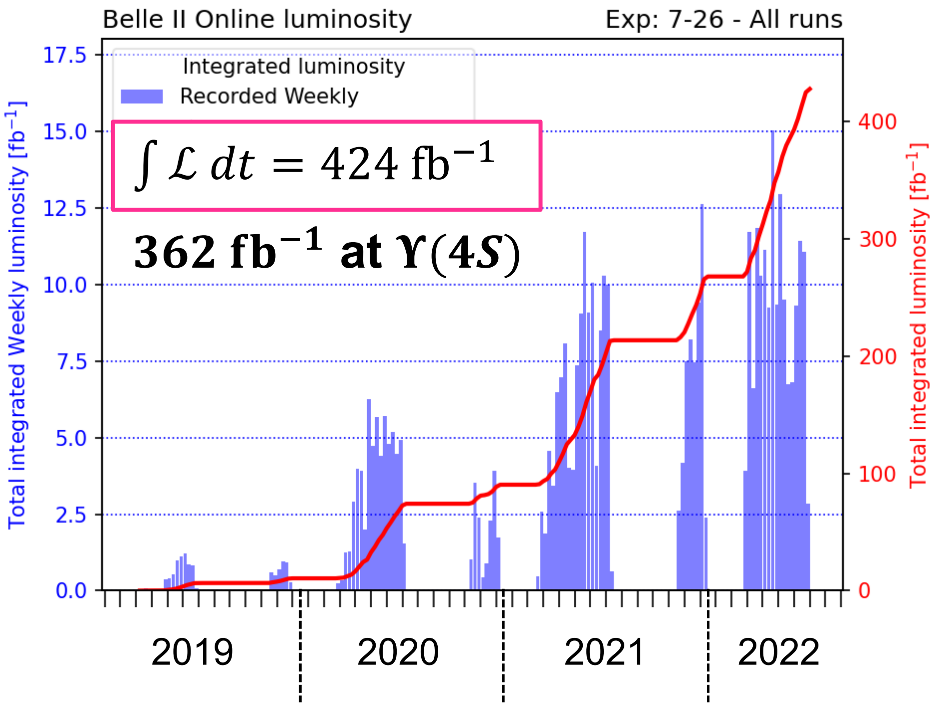
Major cancellation of theoretical and experimental uncertainties

The SuperKEKB/Belle II Experiment

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

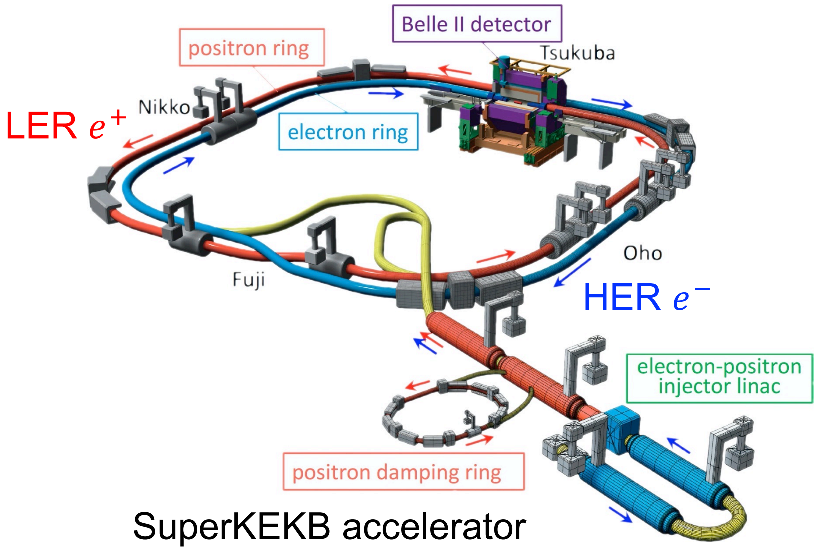
The world's highest instantaneous luminosity:
$\mathbf{4.7 \times 10^{34}\ cm^{-2}s^{-1}}$

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



$\int \mathcal{L}\, dt = 424\ \mathrm{fb^{-1}}$

$\mathbf{362\ fb^{-1}}$ **at** $\boldsymbol{\Upsilon(4S)}$



SuperKEKB accelerator

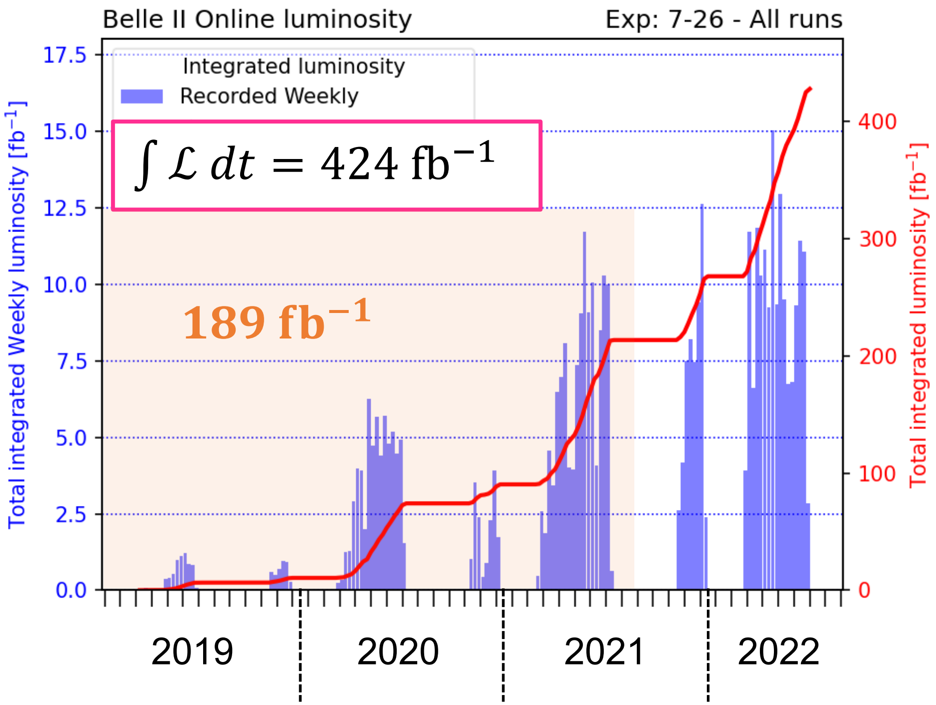
$\sigma(b\bar{b}) \sim 1.1\ \mathrm{nb},\ \sigma(q\bar{q}) \sim 3.7\ \mathrm{nb}\ (q = u, d, s, c)$
at $\sqrt{s} = 10.58\ \mathrm{GeV}$

The SuperKEKB/Belle II Experiment

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

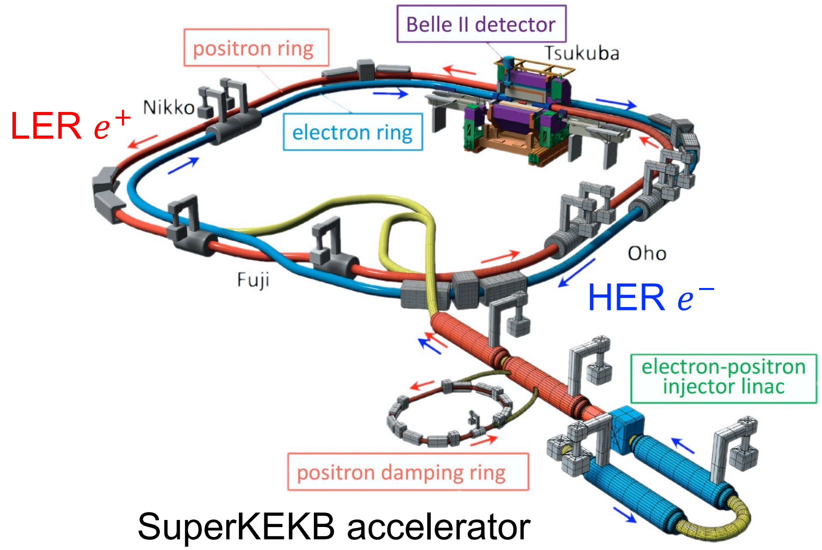
The world's highest instantaneous luminosity:
$\mathbf{4.7 \times 10^{34}\ cm^{-2}s^{-1}}$

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



$\int \mathcal{L}\, dt = 424\ \mathrm{fb}^{-1}$

$\mathbf{189\ fb^{-1}}$



SuperKEKB accelerator

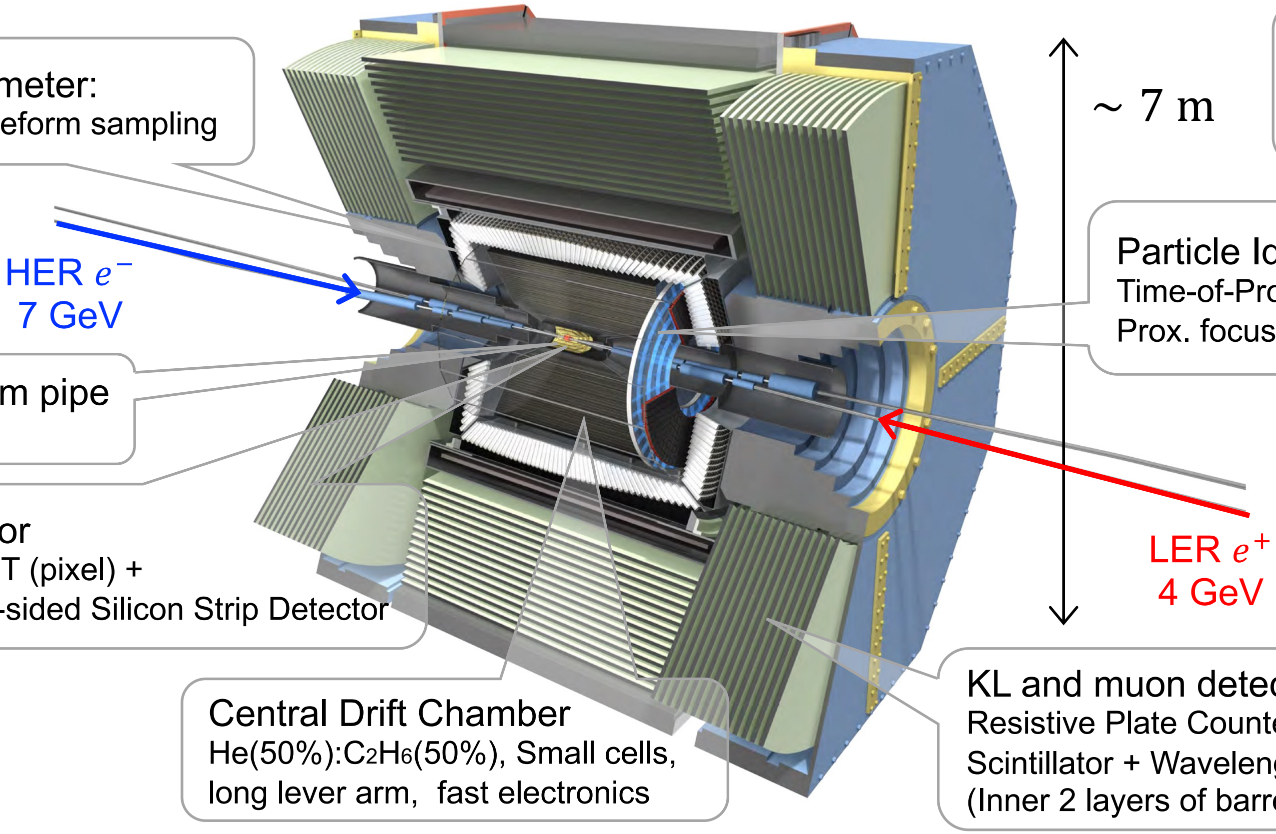
$\sigma(b\bar{b})\sim 1.1\ \mathrm{nb},\ \sigma(q\bar{q})\sim 3.7\ \mathrm{nb}\ (q = u, d, s, c)$
at $\sqrt{s} = 10.58\ \mathrm{GeV}$

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

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, …



EM Calorimeter:
CsI(Tl), waveform sampling

Grid computing
$\mathcal{O}(10^5)$ CPU cores
$\mathcal{O}(100)$ PB storage

Particle Identification
Time-of-Propagation counter (Barrel)
Prox. focusing Aerogel RICH (Forward)

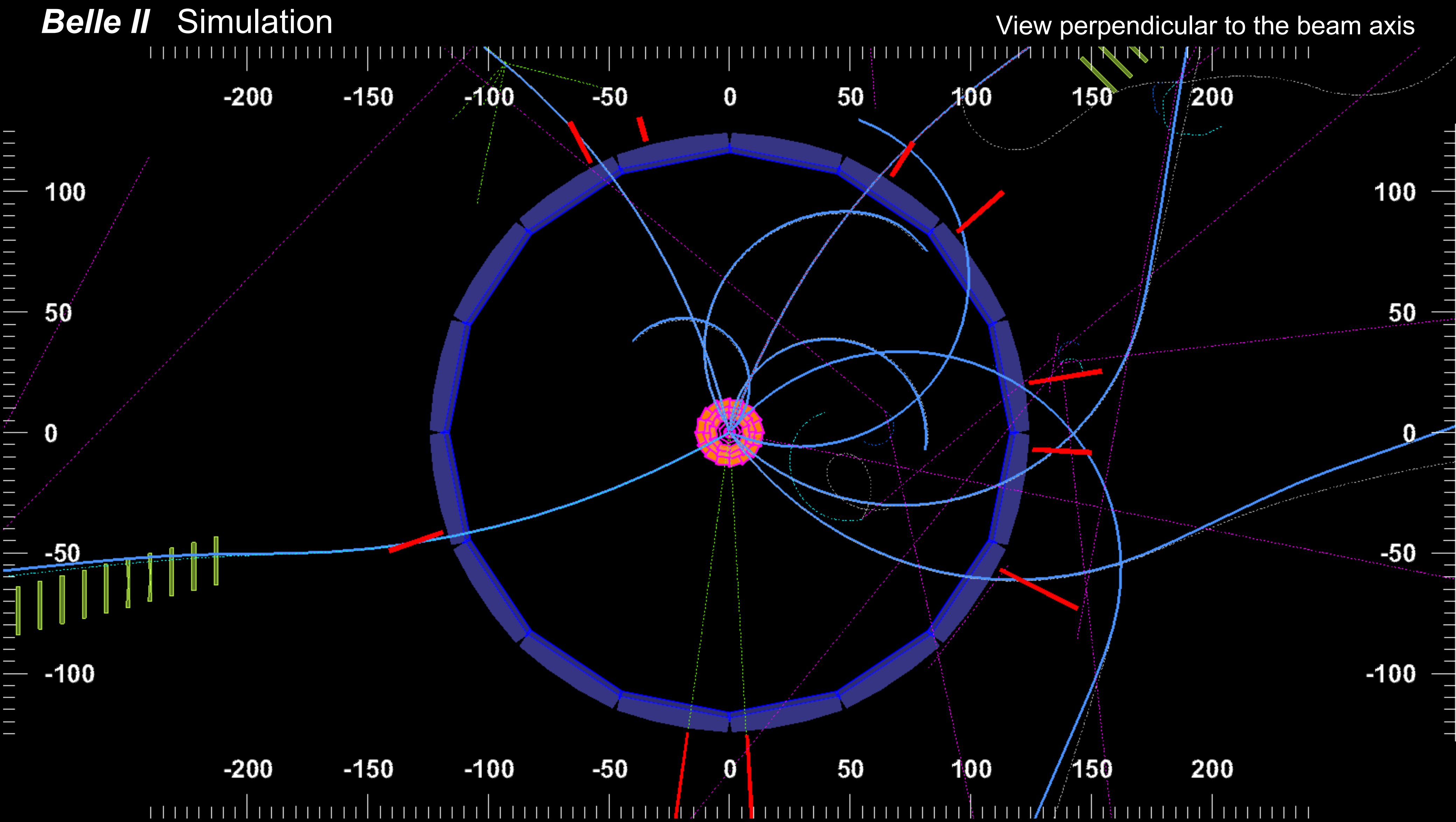
Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET (pixel) +
4 layers Double-sided Silicon Strip Detector

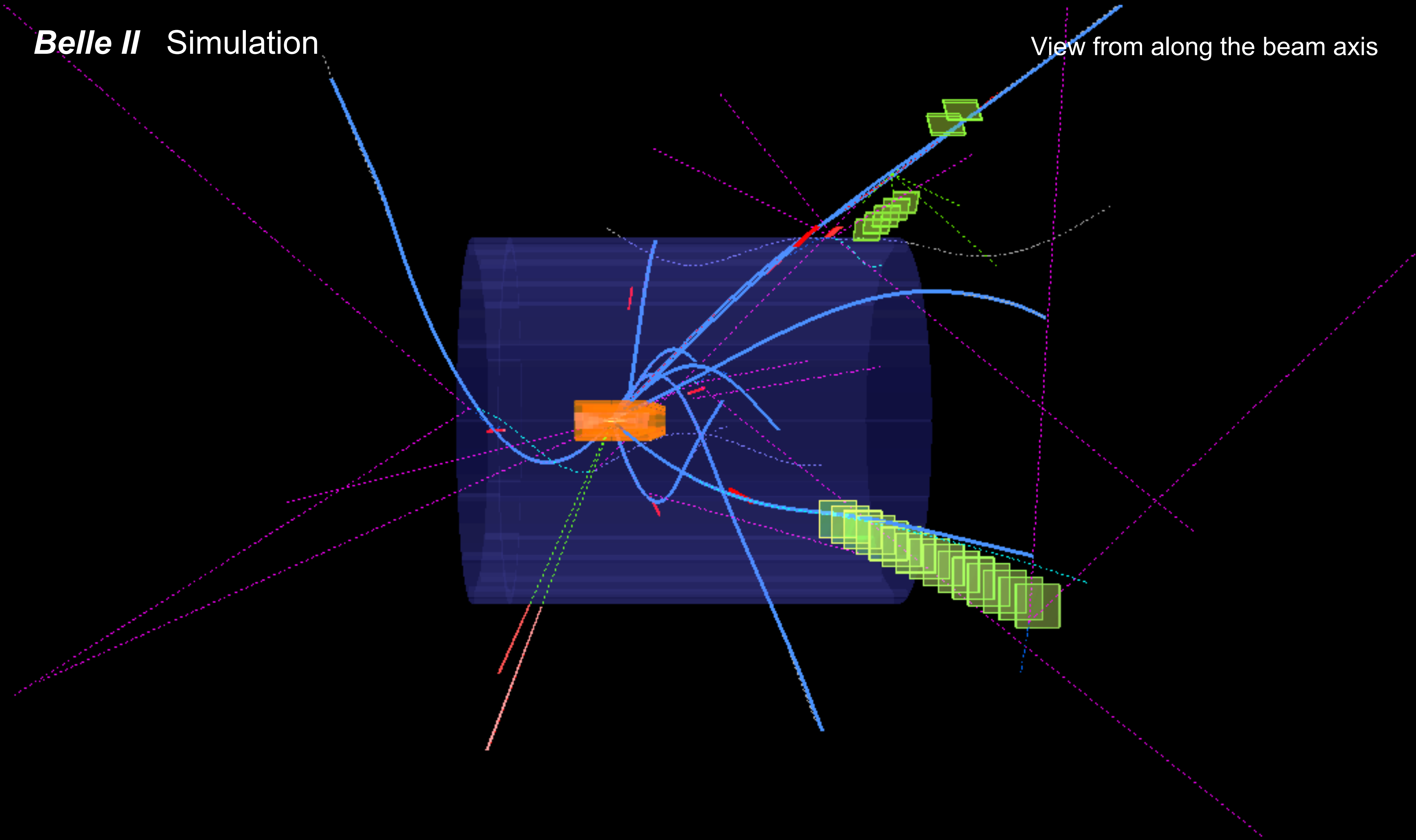
Central Drift Chamber
He(50%):C_2H_6(50%), Small cells,
long lever arm, fast electronics

KL and muon detector:
Resistive Plate Counter (Outer barrel layers)
Scintillator + Wavelength-shifting fiber + MPPC
(Inner 2 layers of barrel & end-caps)

The Belle II Detector: Event Display

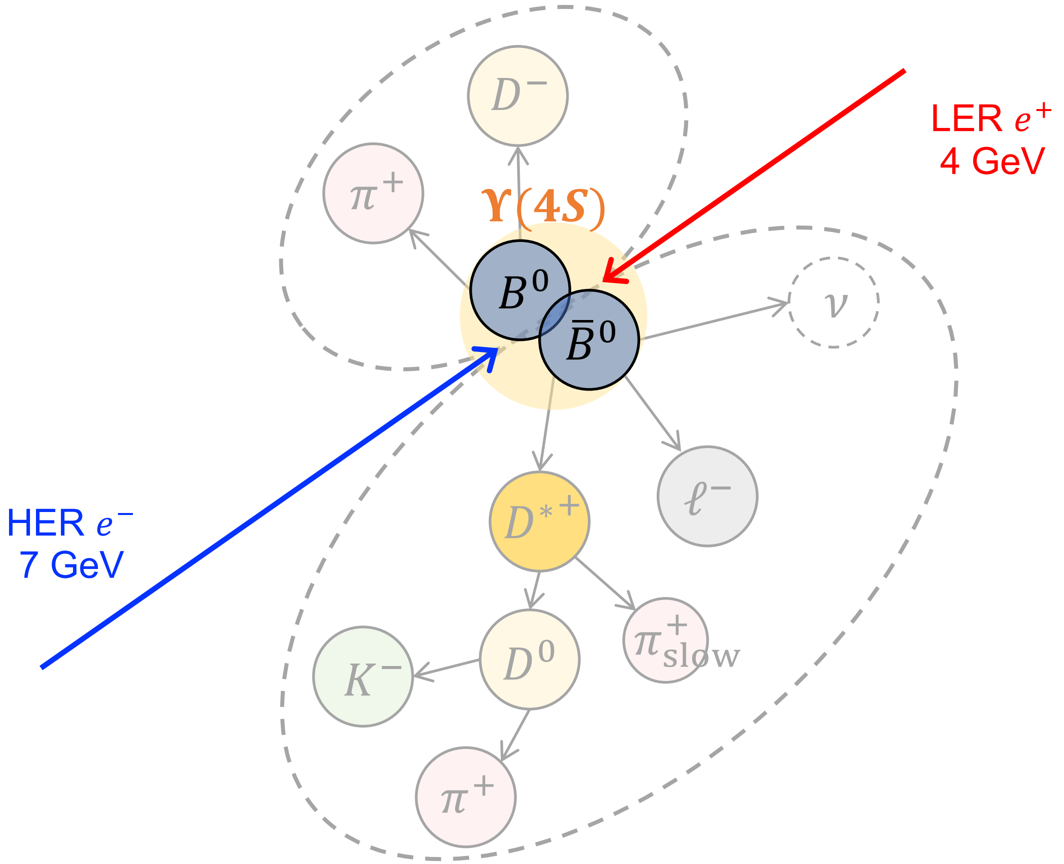


The Belle II Detector: Event Display



Reconstruction

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



Reconstruction: B Tagging

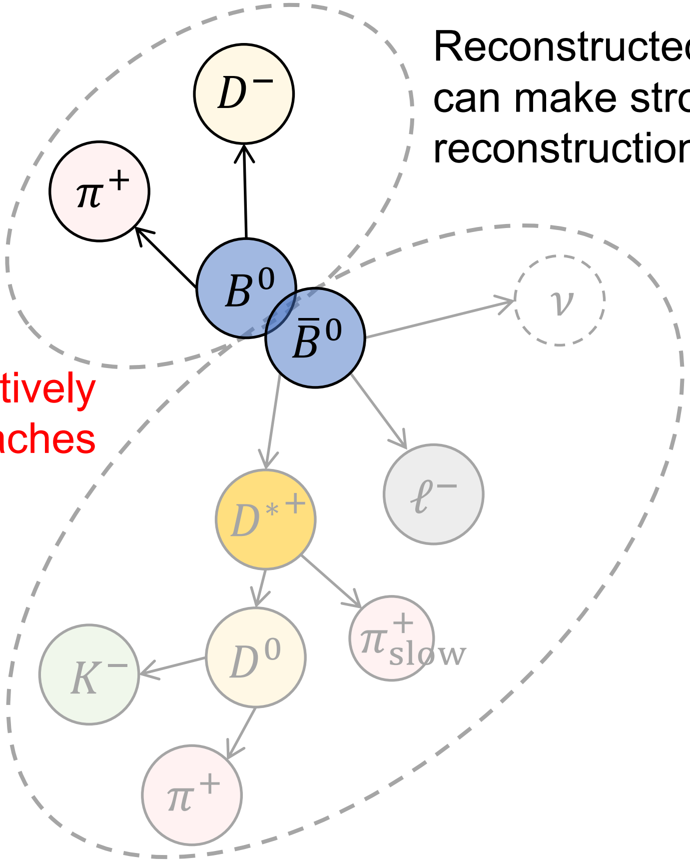
B mesons are generated in pairs from a $\Upsilon(4S)$ ($b\bar{b}$ resonance) decay.

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 effiiciency up to 50% relatively with respect to conventional approaches

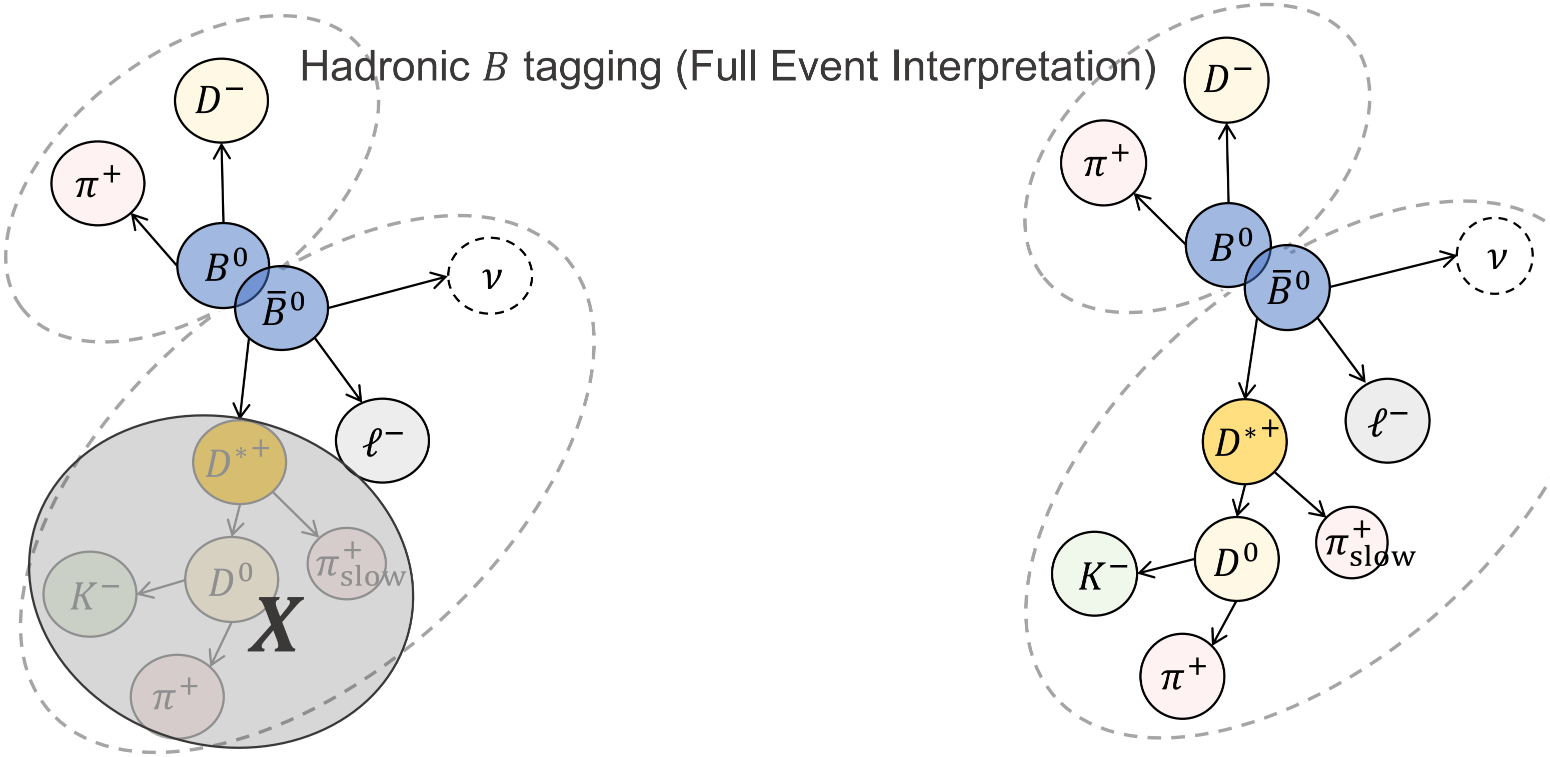


Reconstructed momentum of the partner B can make strong kinematic constraints in reconstruction for the signal side with neutrinos.

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.

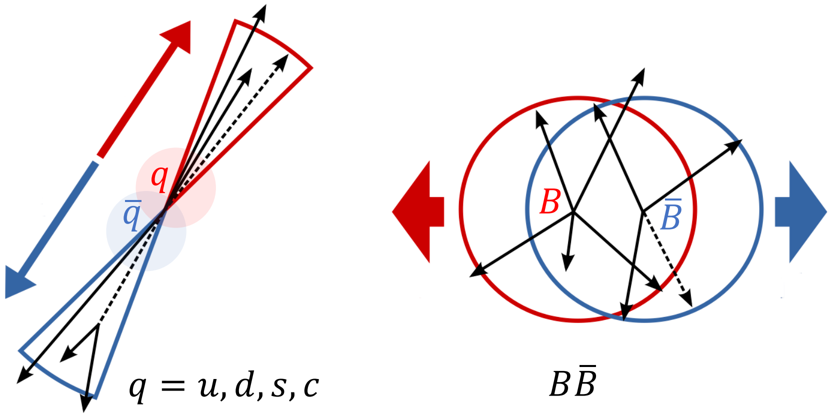
Light-Lepton Universality Test: $R(X_{e/\mu})$ Measurement

arXiv:2301.08266

We tested light-lepton universality by $R(X_{e/\mu}) = \dfrac{\mathcal{B}(\bar{B} \to X e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B} \to X \mu^- \bar{\nu}_\mu)}$ 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^0B^0/B^+B^+) channels.

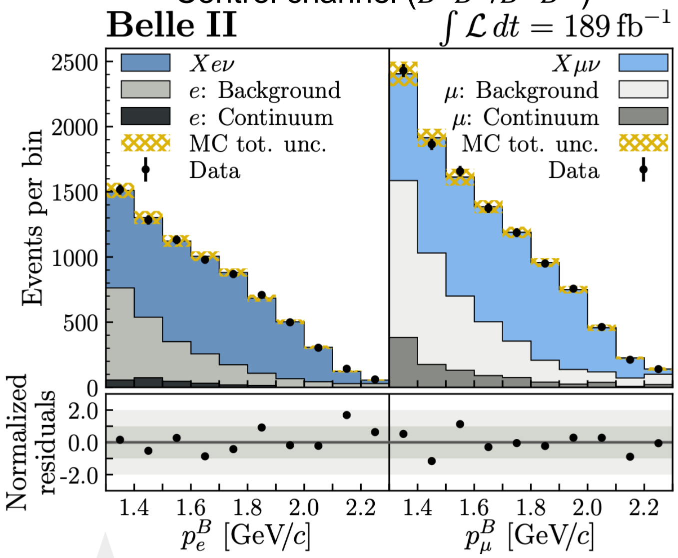
Background from $q\bar{q}$ events (continuum background)



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

Control channel (B^0B^0/B^+B^+)



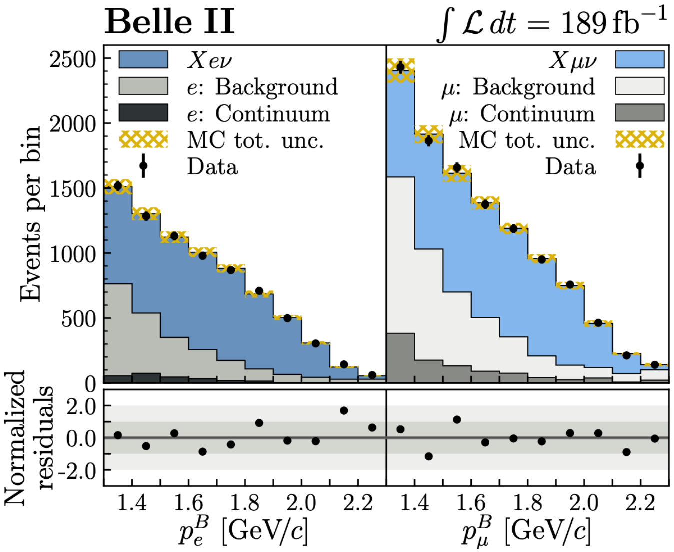
Background from $B\bar{B}$ events are constrained using the background-enriched control sample through the simultaneous fit.

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

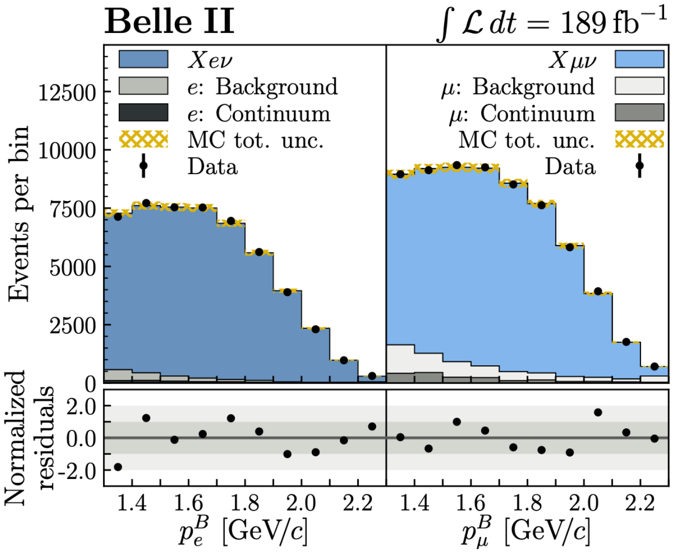
arXiv:2301.08266

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

Control channel ($B^0 B^0 / B^+ B^+$)



Signal channel ($B^0 \bar{B}^0 / B^+ B^-$)



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

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 $R(X_{e/\mu})_{\mathrm{SM}}$[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

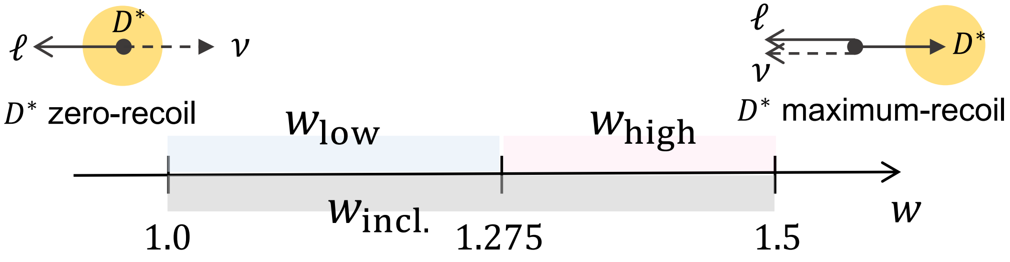
Light-Lepton Universality Test: Angular Asymmetry

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 $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays.

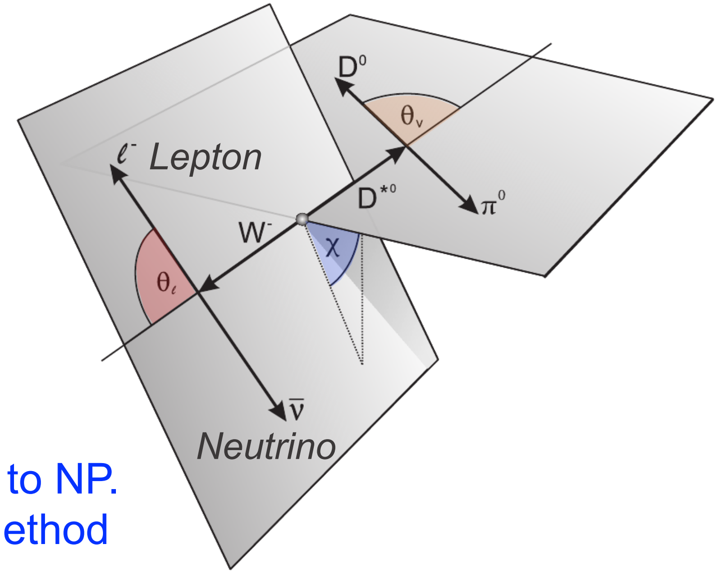
Angular observable

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

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



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



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

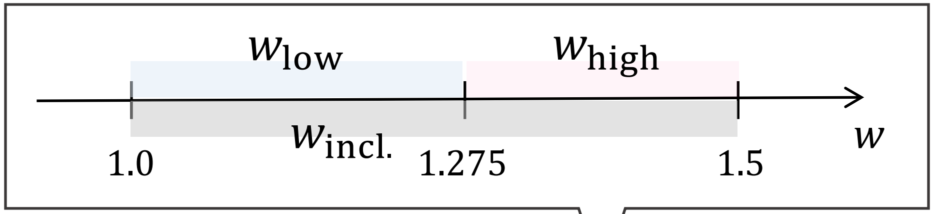
Light-Lepton Universality Test: Angular Asymmetry

New

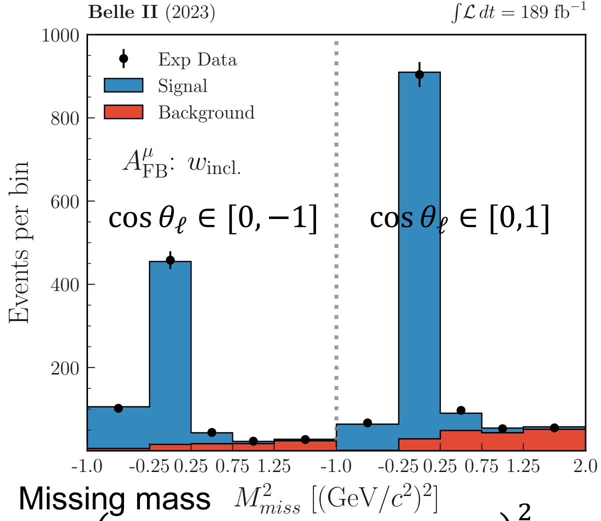
We tested lepton universality by comparing five angular asymmetries of e and μ, $\Delta\mathcal{A}_x(w) = \mathcal{A}_x^{\mu}(w) - \mathcal{A}_x^{e}(w)$ using exclusive $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays.

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

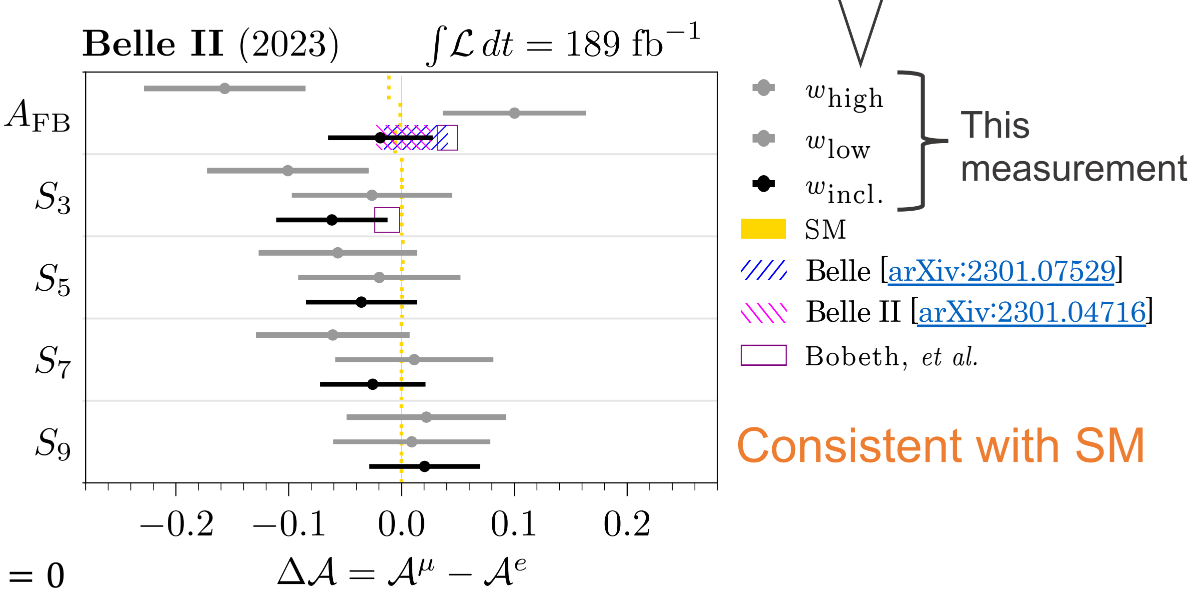
$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx\,\frac{d^2\Gamma}{dw\,dx}$$



A_{FB}: $dx = d(\cos\theta_\ell)$



$$M_{\text{miss}}^2 \equiv \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell\right)^2 \sim M_\nu^2 = 0$$



Consistent with SM

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 $b \to c$ transitions.
New Physics could contribute to the lepton universality violations.

The Belle II performed two light-lepton universality tests.

1. $R\left(X_{e/\mu}\right) = 1.033 \pm 0.010\ (\mathrm{stat}) \pm 0.019\ (\mathrm{syst})$
2. $\Delta A_{\mathrm{FB}}(w)$, $\Delta S_3(w)$, $\Delta S_5(w)$, $\Delta S_7(w)$, $\Delta S_9(w)$

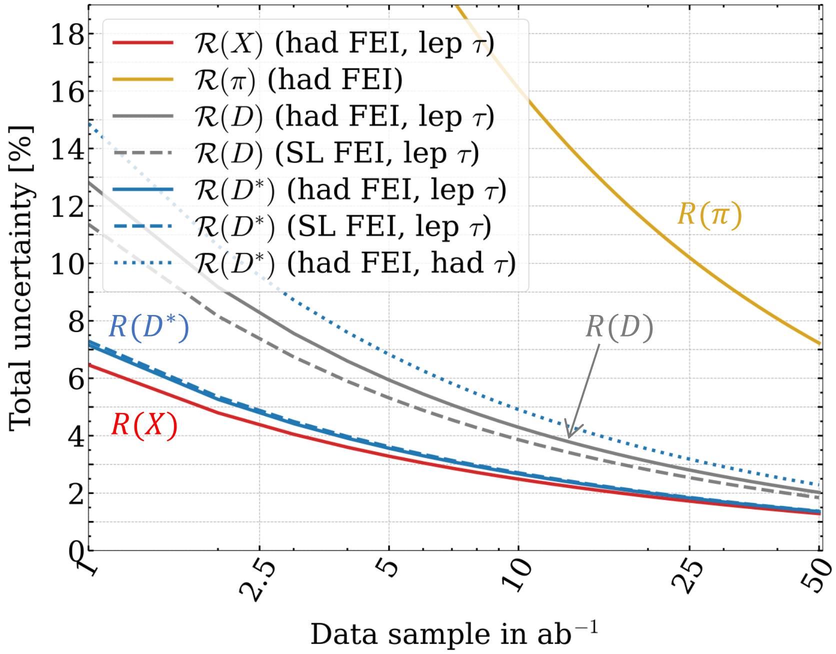
Both tests are world-leading/first results and are consistent with the SM expectation.

Long-Term Prospects for τ-ℓ Universality Tests

Lepton universality tests including τ leptons by measurements of $R(X) = \frac{\mathcal{B}(\bar{B}\to X\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to X\ell^-\bar{\nu}_\ell)}$ and $R(D^*) = \frac{\mathcal{B}(\bar{B}\to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^*\ell^-\bar{\nu}_\ell)}$ with Belle II data are in progress.

SuperKEKB/Belle II luminosity projection

arXiv:2207.06307



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 $R\left(D^{(*)}\right) = \frac{\mathcal{B}\left(\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathcal{B}\left(\bar{B}\to D^{(*)}\ell^-\bar{\nu}_\ell\right)}$ and $R(X) = \frac{\mathcal{B}(\bar{B}\to X\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to X\ell^-\bar{\nu}_\ell)}$.

Appendix

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

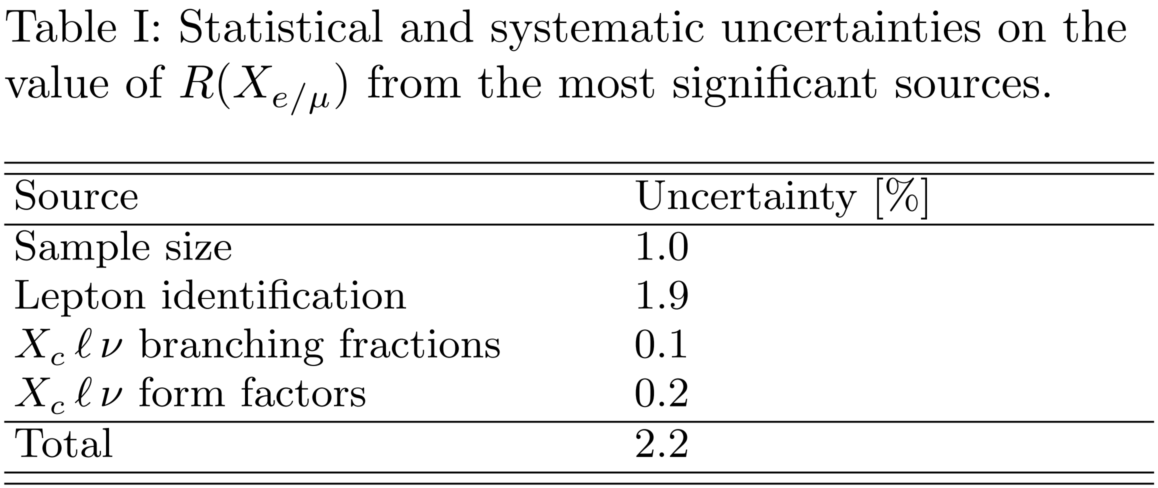


Table I: Statistical and systematic uncertainties on the value of $R(X_{e/\mu})$ from the most significant sources.

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
$\Delta A_{\mathrm{FB}}(w)$, $\Delta S_3(w)$, $\Delta S_5(w)$	$2.1/3$	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
$\Delta A_{\mathrm{FB}}(w)$, $\Delta S_3(w)$, $\Delta S_5(w)$	$10.2/6$	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
	w_{high}	0.051	0.048	0.018	0.000	0.000
	$w_{\text{incl.}}$	0.036	0.034	0.012	0.000	0.000
S_3^{μ}	w_{low}	0.048	0.045	0.016	0.001	0.000
	w_{high}	0.050	0.047	0.016	0.000	0.000
	$w_{\text{incl.}}$	0.034	0.032	0.011	0.001	0.000
ΔS_3	w_{low}	0.071	0.067	0.024	0.001	0.000
	w_{high}	0.072	0.067	0.025	0.001	0.000
	$w_{\text{incl.}}$	0.049	0.046	0.017	0.001	0.000
S_5^{e}	w_{low}	0.053	0.050	0.018	0.001	0.000
	w_{high}	0.051	0.048	0.017	0.001	0.000
	$w_{\text{incl.}}$	0.036	0.034	0.012	0.001	0.000
S_5^{μ}	w_{low}	0.048	0.045	0.016	0.001	0.000
	w_{high}	0.049	0.046	0.016	0.000	0.000
	$w_{\text{incl.}}$	0.034	0.032	0.011	0.000	0.000
ΔS_5	w_{low}	0.072	0.068	0.024	0.001	0.000
	w_{high}	0.070	0.066	0.023	0.001	0.000
	$w_{\text{incl.}}$	0.049	0.046	0.016	0.001	0.000
S_7^{e}	w_{low}	0.052	0.049	0.018	0.001	0.000
	w_{high}	0.049	0.046	0.017	0.000	0.000
	$w_{\text{incl.}}$	0.034	0.032	0.012	0.000	0.000
S_7^{μ}	w_{low}	0.047	0.044	0.015	0.000	0.000
	w_{high}	0.047	0.045	0.015	0.000	0.000
	$w_{\text{incl.}}$	0.032	0.031	0.011	0.000	0.000
ΔS_7	w_{low}	0.070	0.066	0.023	0.001	0.001
	w_{high}	0.068	0.064	0.022	0.000	0.000
	$w_{\text{incl.}}$	0.047	0.044	0.016	0.000	0.000
S_9^{e}	w_{low}	0.052	0.048	0.018	0.000	0.000
	w_{high}	0.051	0.048	0.018	0.000	0.000
	$w_{\text{incl.}}$	0.036	0.034	0.012	0.000	0.000
S_9^{μ}	w_{low}	0.047	0.044	0.016	0.000	0.000
	w_{high}	0.049	0.047	0.016	0.000	0.001
	$w_{\text{incl.}}$	0.033	0.032	0.011	0.000	0.000
ΔS_9	w_{low}	0.070	0.065	0.024	0.000	0.000
	w_{high}	0.071	0.067	0.024	0.001	0.001
	$w_{\text{incl.}}$	0.049	0.046	0.017	0.000	0.000

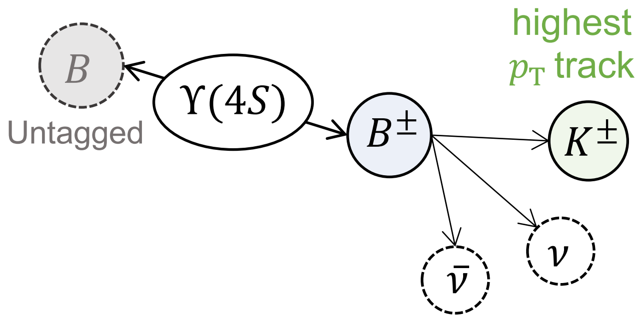
Search for $B^+ \to K^+\nu\bar{\nu}$ with an Inclusive Tagging Method

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

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

Upper limit[1]	$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 1.6\times10^{-5}$
SM[2]	$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (5.67 \pm 0.38)\times10^{-6}$

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



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

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

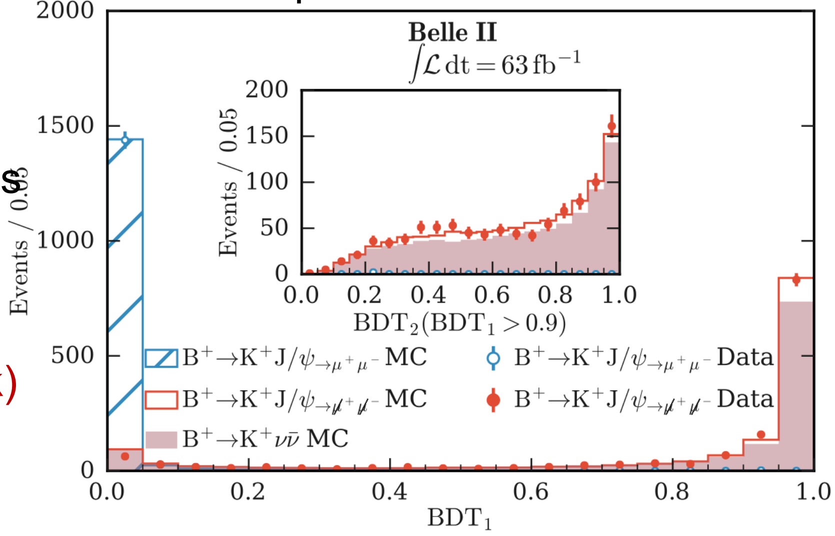
Train two BDTs in cascade to suppress backgrounds using event shape and rest-of-event information.

> BDT_1 … Discriminate signals mainly by topological features
> BDT_2 … Improve purity of signals in events with BDT_1>0.9
> → 35% increase at 4% signal efficiency

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

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

BDT performance validation

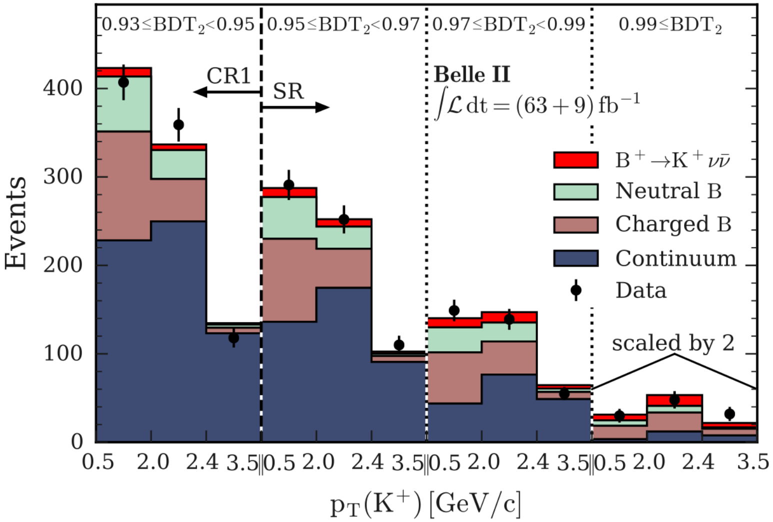


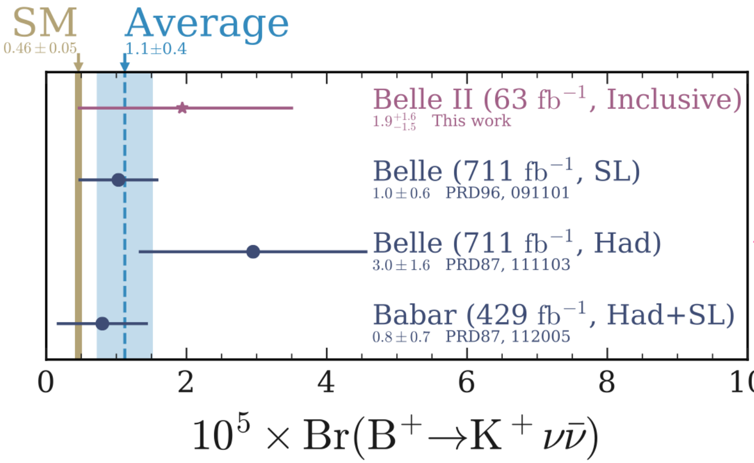
Search for $B^+ \to K^+ \nu\bar{\nu}$ with an Inclusive Tagging Method

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

Observed branching fraction:

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





Comparable accuracy

Observed (expected) upper limit on the branching fraction:

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

Competitive as a new method!

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