News from Belle II-2

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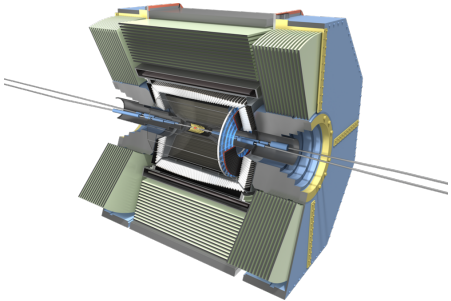
Belle II Physics Program

SuperKEKB and Belle II

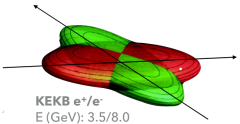


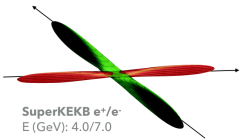
Belle II: general purpose detector situated at the interaction point of SuperKEKB.

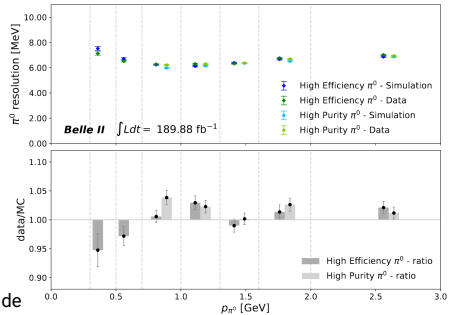
SuperKEKB: asymmetric $e^+ - e^-$ collider operating at $\Upsilon(4S)$ resonance.

Aim:

- $\mathcal{L}^{\text{peak}} = 6 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$ (30 $\times$ Belle)
- $\mathcal{L} = 50\ \text{ab}^{-1}$ (50 $\times$ Belle)

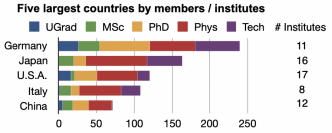






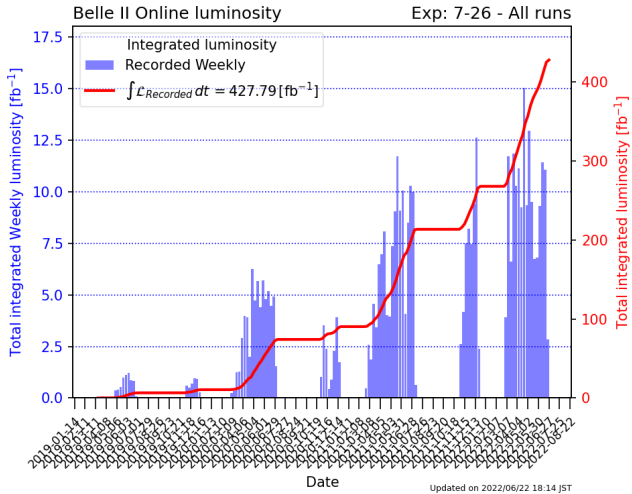
Belle II Collaboration

- 27 countries
- 123 institutions
- 1151 members



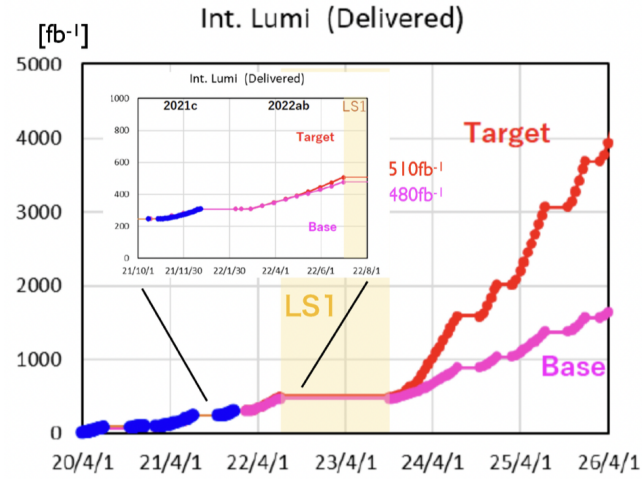
Data Taking Status

- Belle II continued operation throughout the pandemic
- Recorded $\approx$ 424 fb^{-1} (on-res $\approx$ 360 fb^{-1})
- Achieved world record: $\mathcal{L} = 4.7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (more than twice of KEKB/Belle)



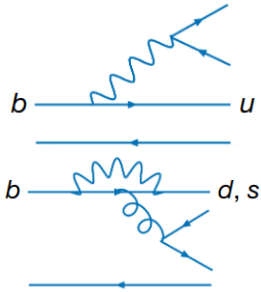
Data Taking Prospects

- Long shutdown (LS1) until Fall 2023
- Target scenario: Extrapolation including expected improvements
- Base scenario: Conservative extrapolation
- Time-frame of LS2: 2026-2027



Charmless B Decays

- Hadronic B decays, where $b \to u, d, s$ but not $b \to c$;
- Cabbibo-suppressed $b \to u$ trees;
- Non-negligible contribution from $b \to d, s$ penguins.
  - Highly sensitive to non-SM physics;
  - Probe non-SM dynamics in all three CKM angles.



Exp. challenges: $\mathcal{B} \approx \mathcal{O}(10^{-5})$, large contribution from $e^+e^- \to q\bar{q}$ background

Belle II charmless program:

- Test Standard Model using isospin sum rules
- Improve precision on CKM angle ϕ_2 (α)
- Investigate localized CP asymmetries in Dalitz plot of three-body decays

$K\pi$ puzzle

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

Isospin sum rule provides null test of standard model:

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

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

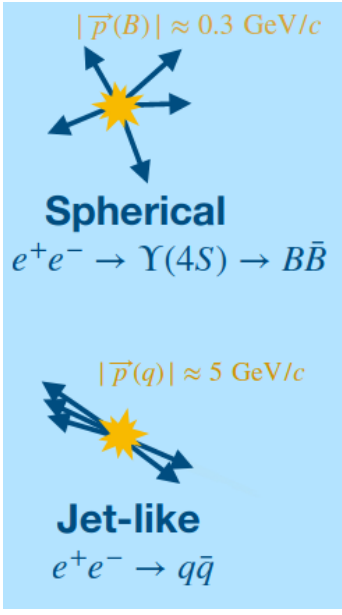
Previous tests of sum rule at Belle II:

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:2206.07453) and $B^+ \to K^+\pi^0$ (arXiv:2209.05154).

Today: Measurement of $\mathcal{B}$ and $\mathcal{A}^{CP}$ of $B^+ \to K^+\pi^0$ and $B^0 \to K^0_S\pi^0$

$B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$ Analysis

- Reconstruct $B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$ events using common selection
- Large background from $e^+e^- \to q\bar{q}$
  $\Rightarrow$ Reduced with multivariate algorithm
- Divide into pion- and kaon-enhanced sample
- All fit shapes but $B\overline{B}$ are controlled from data using off-resonance data and $B \to \overline{D}\pi$ decays



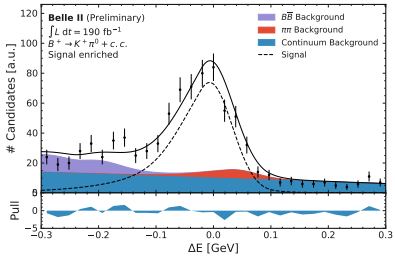
$B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$ Result

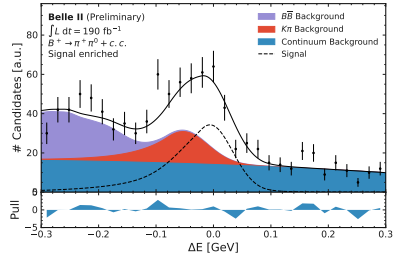
3D (ΔE, M_{bc}, BDT output) fit simultaneous to pion- and kaon-enhanced sample

$N(K^+\pi^0) = 887 \pm 43$, $N(\pi^+\pi^0) = 422 \pm 37$

$$\mathcal{A}^{CP}_{K^+\pi^0} = \ \ 0.014 \pm 0.047\ (\text{stat}) \pm 0.010\ (\text{syst})$$
$$\mathcal{B}_{K^+\pi^0} = (14.30 \pm 0.69\ \ (\text{stat}) \pm \ 0.79\ \ (\text{syst}))\cdot 10^{-6}$$
$$\mathcal{A}^{CP}_{\pi^+\pi^0} = -0.085 \pm 0.085\ (\text{stat}) \pm 0.019\ (\text{syst})$$
$$\mathcal{B}_{\pi^+\pi^0} = \ \ (6.12 \pm 0.53\ \ (\text{stat}) \pm \ 0.53\ \ (\text{syst}))\cdot 10^{-6}$$

WA: $\mathcal{A}^{CP}_{K^+\pi^0} = 0.030 \pm 0.013$, $\mathcal{A}^{CP}_{\pi^+\pi^0} = 0.03 \pm 0.04$



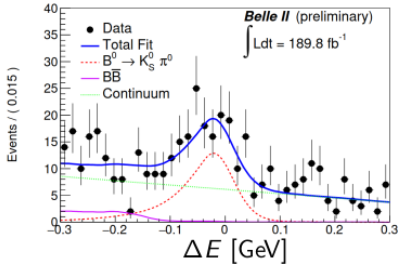


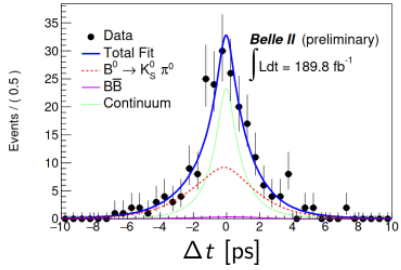
$B^0 \to K^0\pi^0$ Measurement

- Key challenge, reconstruction of $B^0 \to K^0_S\pi^0$ decay vertex
  $\Rightarrow$ Find intersection between K^0_S flight direction and IP
- 4D fit: (M_{bc}, ΔE, Δt, BDT output);
- τ^0_B, Δm_d and S_{CP} constrained to world average to maximize precision on A_{CP}.

Results:

- $\mathcal{B} = (11.0 \pm 1.2\ (\text{stat.}) \pm 1.0\ (\text{syst.})) \cdot 10^{-6}$
- $A_{CP} = -0.41^{+0.30}_{-0.32}\ (\text{stat.}) \pm 0.009\ (\text{syst.})$





Measurement of α

CKM angle α accessible in combination of sets of three decays:

$$B^0 \to \pi^+\pi^-,\ B^+ \to \pi^+\pi^0,\ B^0 \to \pi^0\pi^0$$

- Most challenging mode $B^0 \to \pi^0\pi^0$, very hard for LHCb
- Background from fake photons suppressed using dedicated multivariate algorithm
- Using Flavour Tagger to get direct CP asymmetry
- 3D fit simultaneous in 7 bins of the flavor tagger quality
- Extract data-simulation correction factors using $B^0 \to D^0(\to K^-\pi^+\pi^0)\pi^0$

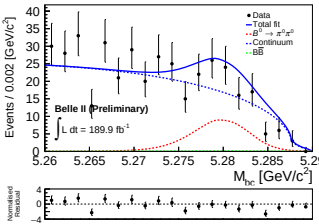
Similar determination of α using $B \to \rho\rho$ decays, see J.Skorupa @ ICHEP2022

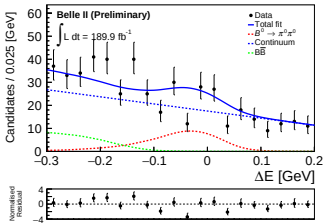
$B^0 \to \pi^0\pi^0$ Result

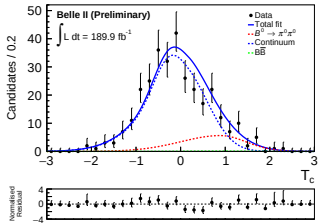
Results competitive with Belle with a data set of less than one third!

$$\mathcal{A}^{CP} = 0.14 \pm 0.46\ (stat) \pm 0.07\ (syst)$$
$$\mathcal{B} = (1.27 \pm 0.25\ (stat) \pm 0.17\ (syst)) \cdot 10^{-6}$$

WA: $\mathcal{A}^{CP} = 0.33 \pm 0.22$, $\mathcal{B} = (1.59 \pm 0.26) \cdot 10^{-6}$



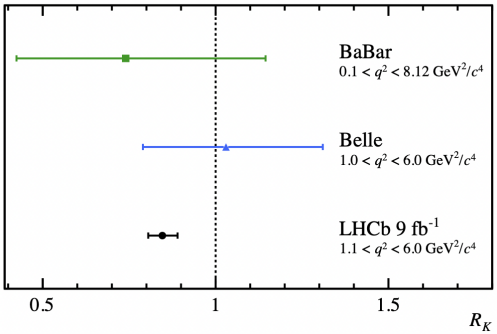


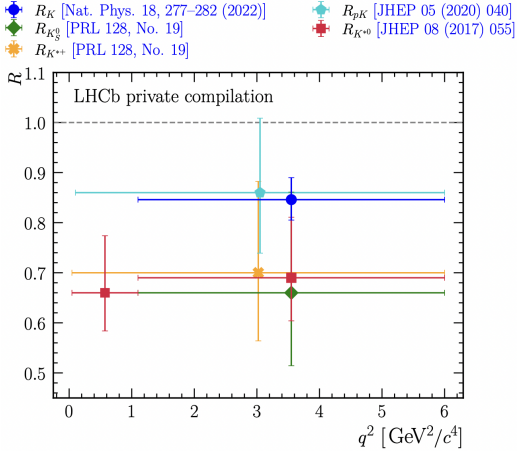


$N(\text{sig}) = 93 \pm 18$

R_K Status

$$R^{\mathrm{SM}}_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \approx 1$$





Right image: S. Schmitt @ ICHEP2022

R_K Prospects from Belle

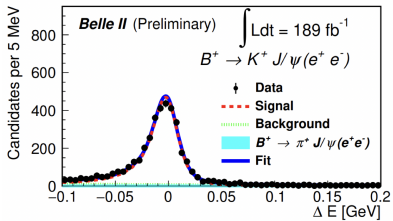
- Similar efficiency for muons and electrons
- Access to both the low-q^2 and high-q^2 regions
- Lepton identification is main systematic rel. uncert. $\approx 0.4\%$
- Stat. limited with 50 ab^{-1}
- Confirm R_K anomaly with 5σ with 20 ab^{-1}

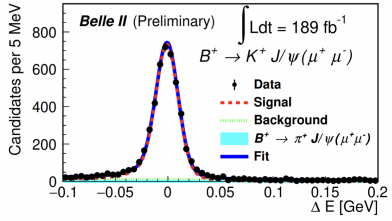
Belle II Physics Book

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%

Towards R_K: $B^+(B^0) \to J/\psi K^+(K_S^0)$

- Important control channel for R_K
- 2D fit in M_{bc} and ΔE





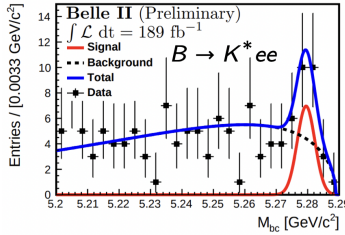
Observable	Belle II	Belle (2021)
$R_{K^+}(J/\psi)$	$1.009 \pm 0.022 \pm 0.008$	$0.994 \pm 0.011 \pm 0.010$
$R_{K^0_S}(J/\psi)$	$1.042 \pm 0.042 \pm 0.008$	$0.993 \pm 0.015 \pm 0.010$

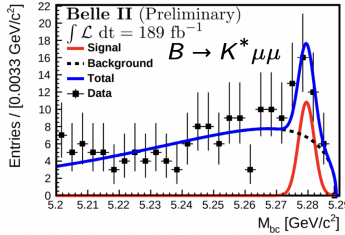
Lepton ID systematic $< 1\%$, improved compared to Belle

Towards R_{K^*}: $B \to K^* \ell^+ \ell^-$

- Discovery of $B \to K^* \ell^+ \ell^-$ first step towards R_{K^*}
- Here, K^* denotes $K^*(892)^0 (\to K^+ \pi^-)$ and $K^*(892)^+ (\to K^0_S \pi^+, K^+ \pi^0)$
- Dilepton mass vetoes to suppress charmonium resonances
- 2D fit in M_{bc} and ΔE

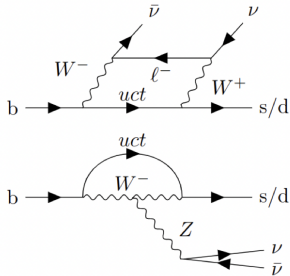
Mode	Observed events	Branching Fraction ($\times 10^{-6}$)	World Average ($\times 10^{-6}$)
$B \to K^* e^- e^-$	22 ± 6	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+ \mu^-$	18 ± 6	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09





$B^+ \to K^+ \nu\bar{\nu}$

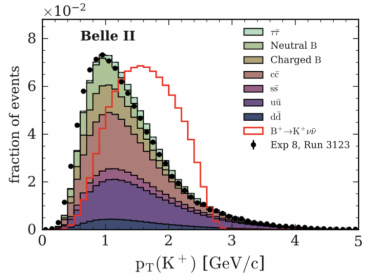
- Search for $b \to s\nu\bar{\nu}$ is complementary to $b \to s\ell\ell$
- Predicted $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) \approx 5 \times 10^6$
- Sensitive to new physics
  (leptoquarks, dark matter, axions)

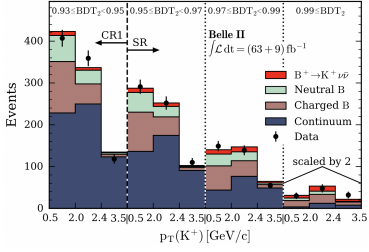


- Existing measurements relied on semileptonic or hadronic tagging
  $\Rightarrow$ Suppresses background
  $\Rightarrow$ Lower signal efficiency
- Use inclusive tagging **for the first time**

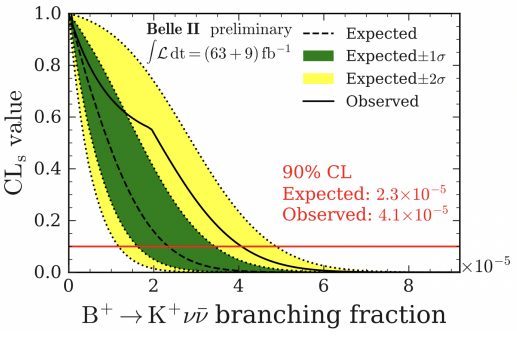
$B^+ \to K^+ \nu\bar{\nu}$ Inclusive Tagging

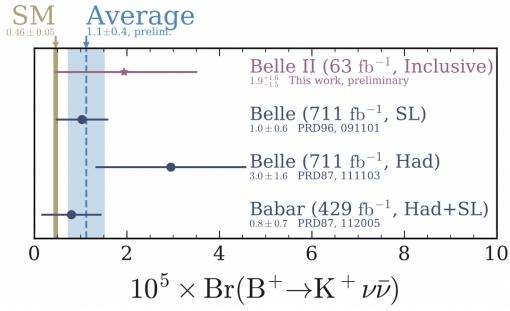
- Signal candidate: track with highest-p_T
- Combine remaining tracks and energy deposits to reconstruct accompanying B meson
- Train two sequential BDTs to remove backgrounds
- Test BDT performance using $B \to K^+ J/\psi$ as control channel
- 2D template fit in bins of p_T and BDT2





$B^+ \to K^+ \nu\bar{\nu}$ Result



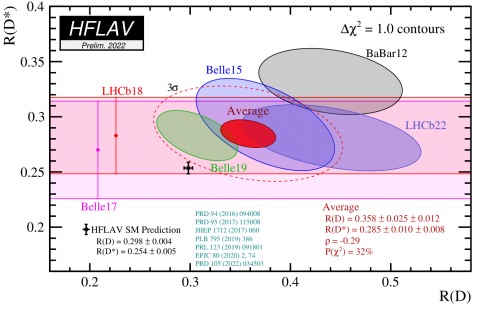


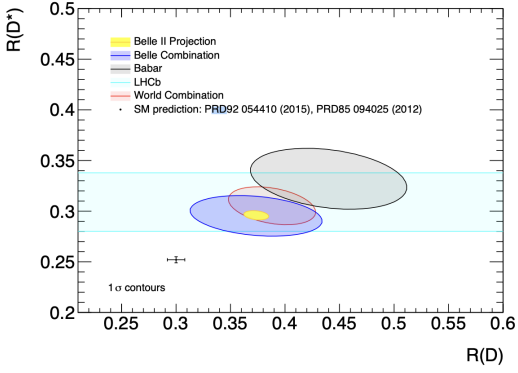
More sensitive per integrated luminosity compared to tagged methods:

→ 20% better than semileptonic tagged

→ 350% better than hadronic tagged

Prospects R_D, R_D^*

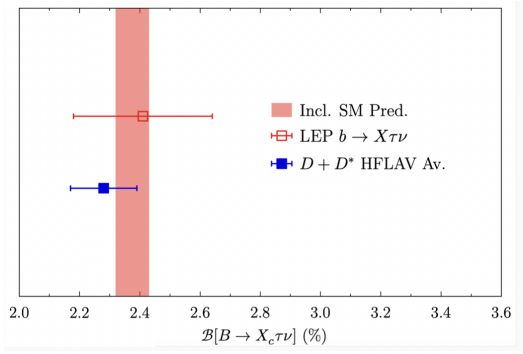




	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

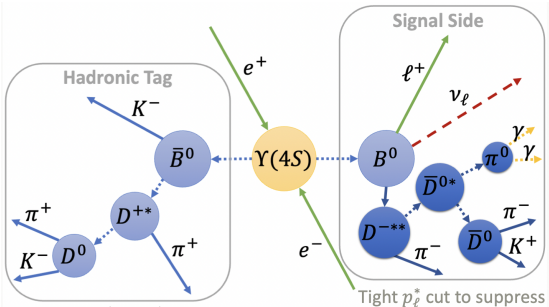
Torwards $B \to X\ell\nu$

- LFU test via inclusive decays complementary to exclusive studies:
  $R(X\tau/\ell) = \frac{\mathcal{B}(B\to X\tau\nu)}{\mathcal{B}(B\to X\ell\nu)}$
- Unique and high profile goal of Belle
- Last measured by LEP
- Large background from less constrained X system
- Precise modeling of $B \to X\ell\nu$ is critical
- Today: $R(Xe/\mu) = \frac{\mathcal{B}(B\to Xe\nu)}{\mathcal{B}(B\to X\mu\nu)}$



- $R(X_{c,\tau/\ell})_{SM} = 0.223 \pm 0.004$
  Phys. Rev. D 92, 054018 (2015)
- $R(X_{e/\mu})_{SM} = 1.006 \pm 0.001$
  K. Vos, M. Rahimi, in progress

$R(X\tau/\ell)$ Reconstruction



- Reconstruct $\Upsilon(4S) \to B^-_{\text{tag}} \ell^+ X$ $\Upsilon(4S) \to \bar{B}^0_{\text{tag}} \ell^+ X$
- $p^*_\ell > 1.3$ GeV
- Only basic quality cuts on tracks and calorimeter signals
- Tight constraints on tag quality

$\epsilon = \mathcal{O}(0.1\%)$

Precise knowledge of B_{tag} kinematics

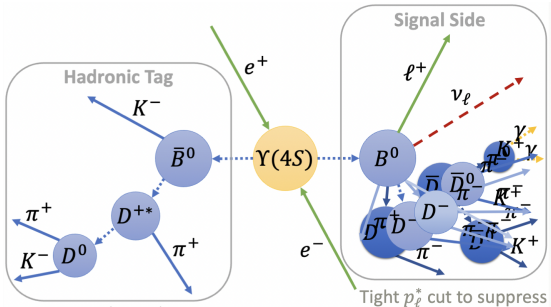
Tight p^*_ℓ cut to suppress

- hadrons faking leptons (“**fakes**”)
- secondary leptons from $b \to c \to (\ell, s)$ cascades (“**secondaries**”)
- $B \to X\tau\nu$

[53% (e) / 66% (μ) of selected B $\to X\ell\nu$ is retained]

Slide from H. Junkerkalefeld @ ICHEP2022

$R(X\tau/\ell)$ Reconstruction



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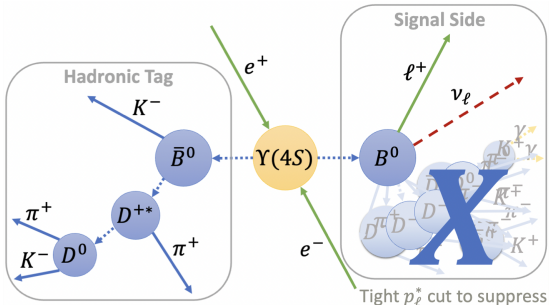
$R(X\tau/\ell)$ Reconstruction



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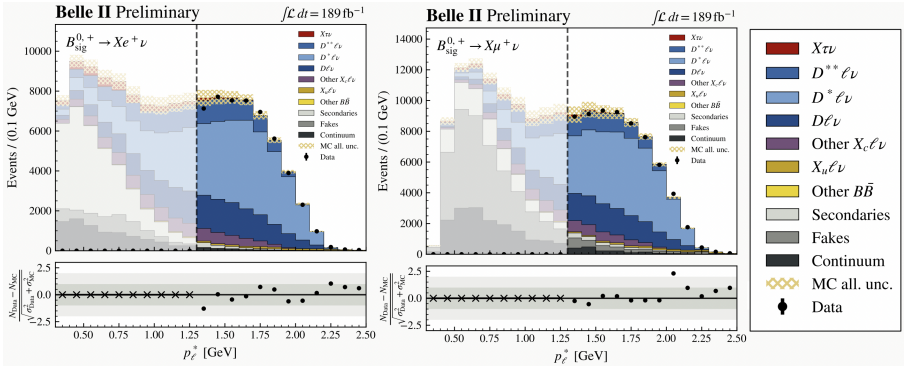
Slide from H. Junkerkalefeld @ ICHEP2022

$R(X\tau/\ell)$ Sample Composition



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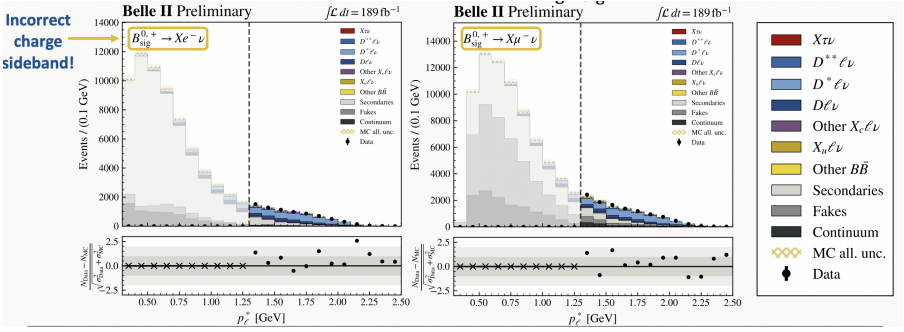
$R(X\tau/\ell)$ Background



Fakes + Secondaries background constrained by wrong-sign lepton charge samples

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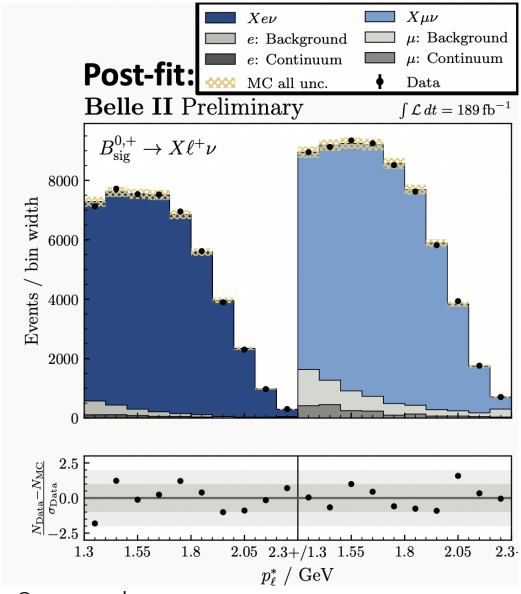
$R(X\tau/\ell)$ Result

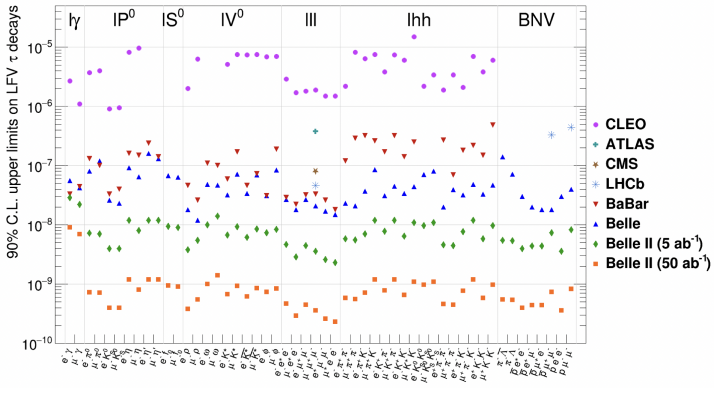
- $R(Xe/\mu) == 1.033 \pm 0.010 \pm 0.020$
- In agreement with SM: 1.006 ± 0.001

Source of uncertainty	Lepton ID	$X_c\ell\nu$ BFs	$X_c\ell\nu$ FFs	Statistical	Total
Rel. unc. of $R(X_{e/\mu})$	1.8%	0.1%	0.2%	1.0%	2.2%



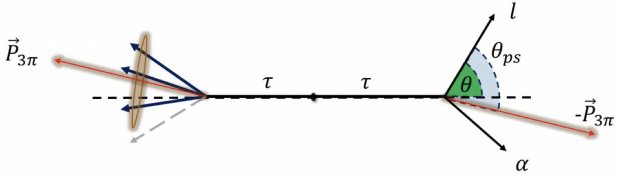
LFV τ Decay Searches at B Factories

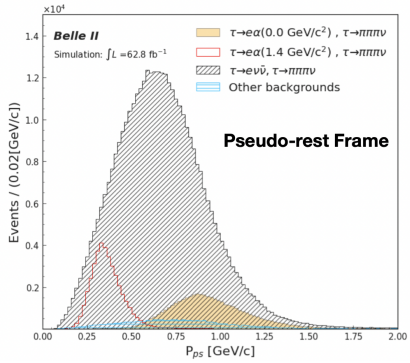
- B Factories are also τ factories $\Rightarrow \sigma(ee \to \tau\tau) \approx \sigma(ee \to b\bar{b})$
- Neutrinos $\Rightarrow$ missing energy
- Low background
- High resolution



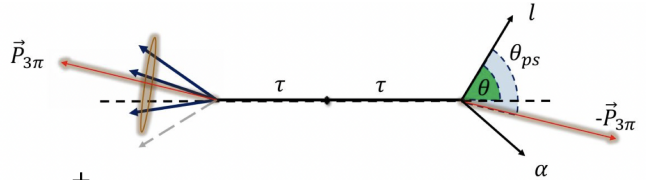
$\tau \to \ell\alpha$

- For α any non-SM invisible particle
- Best upper limit from ARGUS (1995)
- 3×1 prong event topology
- Construct τ pseudo restframe:
  $p_\tau \approx -\frac{p_{\text{tag}}}{|p_{\text{tag}}|}, E_\tau \approx \sqrt{s}, x_\ell = E^*_\tau / m_\tau$
- Template fit of x_ℓ

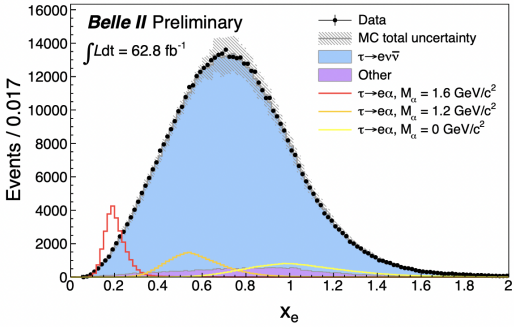


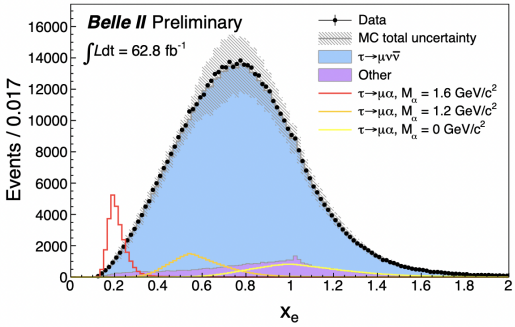


$\tau \to \ell\alpha$ Data-MC Comparison



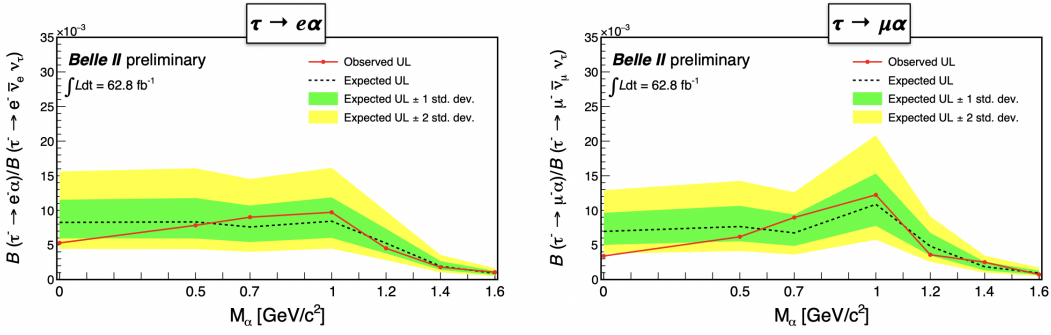
$\tau \to e^+\alpha$ $\tau \to \mu^+\alpha$



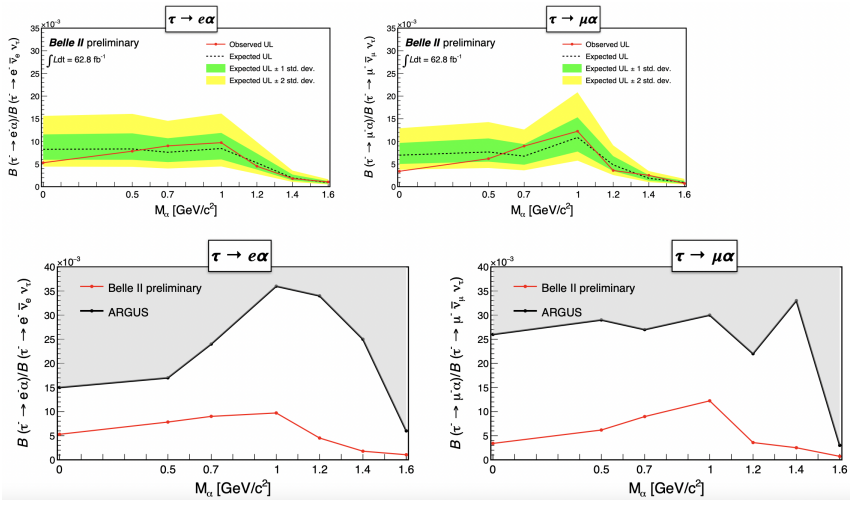


$\tau \to \ell\alpha$ Result

- No signal excess $\Rightarrow$ set 95% CL upper limits on $\mathcal{B}(\tau \text{ß} \ell\alpha)/\mathcal{B}(\tau \text{ß} \ell\nu\bar{\nu})$
- Most stringent limits in these channels to date



$\tau \to \ell\alpha$ Result



- More details: F. Tenchini @ ICHEP2022

Thank you