

B Physics at Belle and Belle II

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on behalf of the Belle and Belle II collaborations

XXXIX^e Rencontres de
Physique de la Vallée d'Aoste

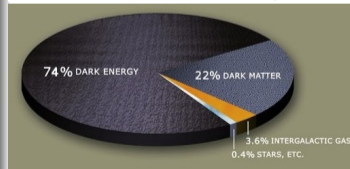


The big picture

- Standard Model successful yet incomplete
- Promising to search for New Physics at the **intensity frontier**: precise tests of the Standard Model can probe energy scales inaccessible to direct production
- Important to select modes sensitive to New Physics both theoretically clean and experimental accessible

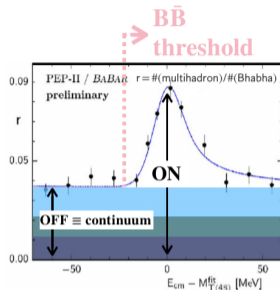
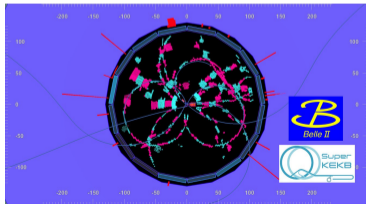
Main goals of *B*-physics

- Null tests of Standard Model
- Neutral meson mixing and flavour-changing neutral currents
- Tests of lepton flavour universality (LFU)
- Precise measurement of CKM elements



Advantages of an $e^+ e^-$ flavour factory

- Known initial kinematics and good hermeticity
 - possible to fully reconstruct events with invisible particles
- Clean environment (average 11 tracks per event)
 - efficient detection of neutrals (γ , π^0 , η , ...)
- Run at the $\Upsilon(4S)$ mass just above $B\bar{B}$ threshold
 - Relatively low background
 - Data off-resonance provide control sample without $B\bar{B}$

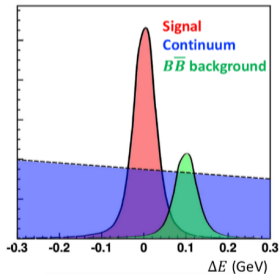


Hadronic cross-section
@ $\sqrt{s} = 10.58 \text{ GeV}$

Tools at an $e^+ e^-$ flavour factory

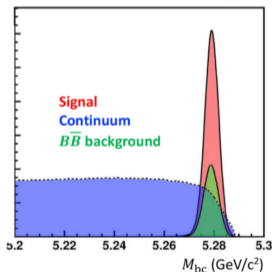
- Optimised variables to exploit information on initial kinematics
- Exploit different event shape to separate $B\bar{B}$ from continuum background

$$\Delta E = E_B^* - \sqrt{s}/2$$

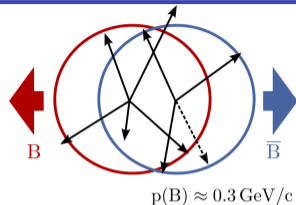


Expected $\Delta E \simeq 0$

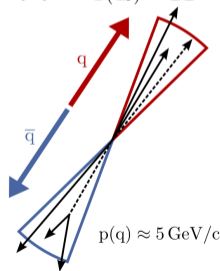
$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_B^*|^2}$$



Expected $M_{bc} \simeq m_B$



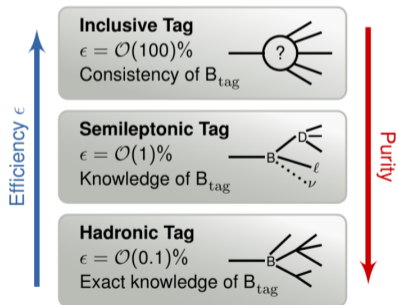
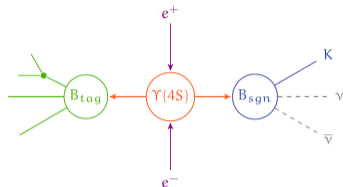
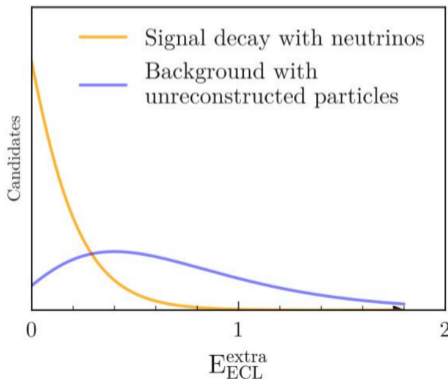
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$



$$e^+e^- \rightarrow q\bar{q} \quad (q \in \{u, d, s, c\})$$

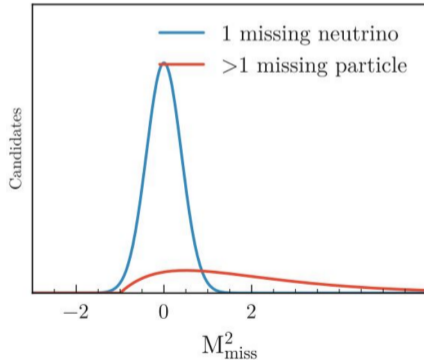
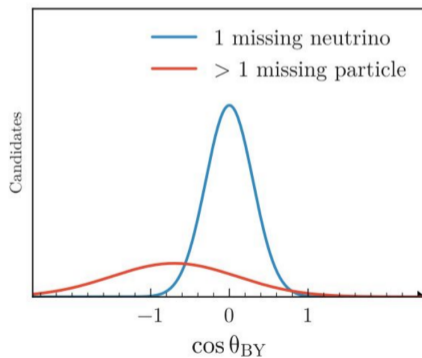
How to deal with missing particles

- Exploit the information from the **other B** of the event
- Possible to reduce background by requiring **no extra particle** in the event and low **Extra energy** in the calorimeter



Common variables for $B \rightarrow (X)l\nu$ decays (only one neutrino missing)



- Leptonic system mass squared $q^2 = (p_l + p_\nu)^2$
- Missing mass squared M_{miss}^2
- $\cos \vartheta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - M_Y^2}{2|p_B^*||p_Y^*|}$, $Y = Xl$ system



Selection of recent results

- Search for $B \rightarrow hX_{inv}$
- $R(D)$ and $R(D^*)$
- Search for $B^+ \rightarrow \mu^+ \nu$
- Search for time-dependent CP violation in $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$

Datasets used

	on-resonance	off-resonance
	711 fb ⁻¹	90 fb ⁻¹
	365 fb ⁻¹	42 fb ⁻¹

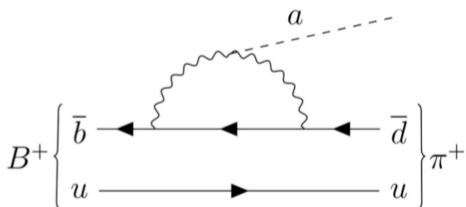




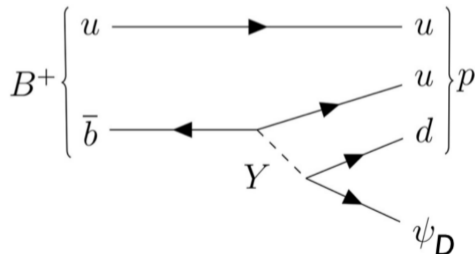
$$B \rightarrow hX_{inv}$$

arXiv:2601.07104

- First direct search for $B^\pm \rightarrow hX_{inv}$, $h = \pi^\pm, K^\pm, D_s^\pm, p$ and $B^0 \rightarrow \bar{D}^0 X_{inv}$
- Absence of new physics at the energy frontier motivates search for new feebly interacting particles
- Many candidates (axion-like particles, dark scalars and dark baryons, ...)
- Possible link with open problems (strong CPV, baryogenesis)

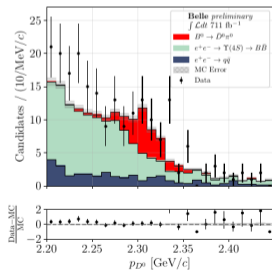
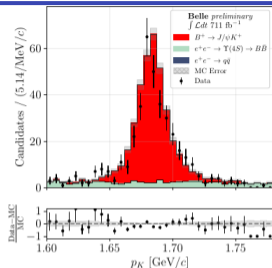


[Y. Zhang et al., arXiv:2306.03464]

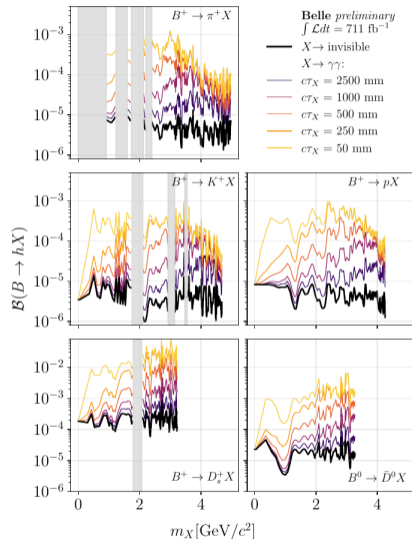
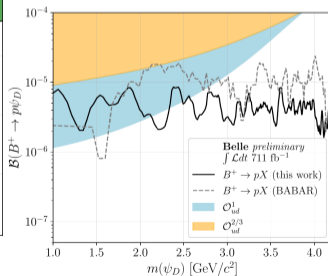
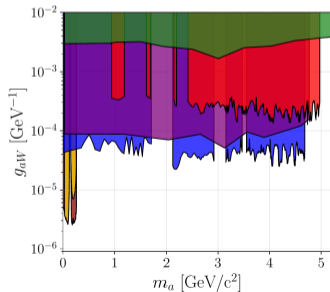


[G. Elor et al., PRD 99, 035031 (2019)]

- Optimised for two-body decay kinematics
- Hadronic tag \rightarrow momentum of B_{sgn} is known
- Require no extra tracks in the event and $E_{ECL}^{extra} < 1.5$ GeV
- Two consecutive BDTs to reject background based on event shape variables, M_{miss}^2 , E_{ECL}^{extra} and B_{tag} energy
- Momentum of the hadron in the B_{sgn} rest frame is monochromatic and depends on the mass of X_{inv}
- Bump-hunting on m_X distribution by fitting a two-Gaussian signal shape over Kernel density estimator for background
- Veto around SM resonances
- Validated with $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow \bar{D}^0 \pi^0$



- Look also for $X \rightarrow \gamma\gamma$ with different lifetime
 - analysis not optimised for this case
- No significant signal observed
- Set 90% confidence level upper limits ranging from 10^{-4} to 10^{-6} across all channels
- These limits can be applied to phenomenological models

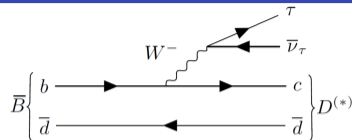




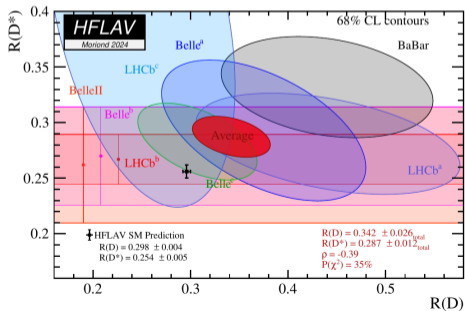
$$R(D^{(*)})$$

PRD 112, 032010 (2025), BELLE2-PUB-PH-2025-034

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} l \nu_l)}$$



- Test of lepton flavour universality involving third generation
- Longstanding tension with SM prediction



2024 status before Run 1 Belle II results:

3.2 σ tension with SM

Experiment	Channels	τ decay mode	Tagging / Notes
BaBar	$R(D), R(D^*)$	$\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$	Hadronic tag
Belle ^a	$R(D), R(D^*)$	$\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$	Hadronic tag
Belle ^b	$R(D^*), P_\tau(D^*)$	$\tau^- \rightarrow \pi^- (\pi^0) \nu_\tau$	Hadronic tag
Belle ^c	$R(D), R(D^*)$	$\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$	Semileptonic tag
LHCb ^a	$R(D), R(D^*)$	$\tau^- \rightarrow \mu^- \nu_\mu \nu_\tau$	
LHCb ^b	$R(D^*)$	$\tau^- \rightarrow 3\pi^- (\pi^0) \nu_\tau$	via $K(D^*)$ ratio
LHCb ^c	$R(D^+), R(D^{*+})$	$\tau^- \rightarrow \mu^- \nu_\mu \nu_\tau$	
Belle II	$R(D^*)$	$\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$	Hadronic tag

See [\[HFLAV\]](#)

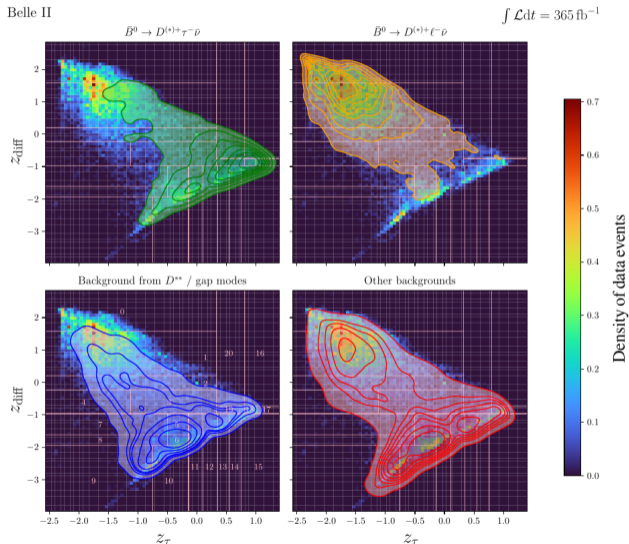
PRD 112, 032010 (2025)

- **Semileptonic tag** (higher tag-side efficiency but lower purity)
- First $R(D^{(*)})$ with full run 1 dataset and first combined $R(D)$ and $R(D^{*})$ analysis at Belle II
- Restricted to B^0 modes
 - $D^{(*)+}$ in 13 final states
 - $\tau \rightarrow l\nu\bar{\nu}$

BELLE2-PUB-PH-2025-034

- Hadronic tag
- Supersedes previous $R(D^{*})$ measurement with hadronic tag
- Reconstruct both B^0 and B^+ models
 - Both $D^{*\pm} \rightarrow D^{0/\pm}\pi^{\pm/0}$ and $D^{*0} \rightarrow D^0\pi^0$
 - D reconstructed in 11 decay modes
 - $\tau \rightarrow l\nu\bar{\nu}$

- 3-classes BDT to separate between
 - $B \rightarrow D^{(*)} \tau \nu_\tau$
 - $B \rightarrow D^{(*)} l \nu_l$
 - Background events
- 5 variables (main ones are $\cos \vartheta_{BY}$ and E_{ECL}^{extra})
- Each event is assigned BDT scores z_τ , z_l , z_{bkg}
- 2-D binned fit of z_τ and $z_{diff} = z_l - z_{bkg}$
- Fit performed over 4 separate channels: $D^+ e^-$, $D^+ \mu^-$, $D^{*+} e^-$ and $D^{*+} \mu^-$



Measurement is statistically limited

$$R(D^+) = 0.418^{+0.075}_{-0.073}(\text{stat})^{+0.049}_{-0.056}(\text{syst})$$

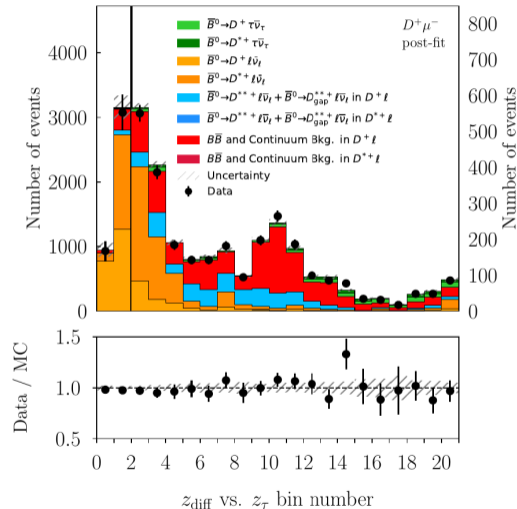
$$R(D^{*+}) = 0.306^{+0.035}_{-0.033}(\text{stat})^{+0.016}_{-0.018}(\text{syst})$$

Main systematic uncertainties

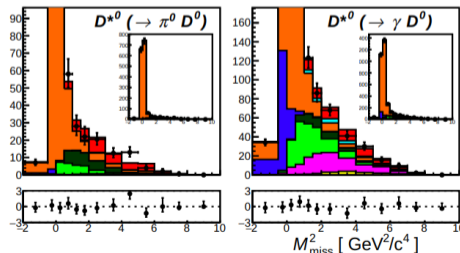
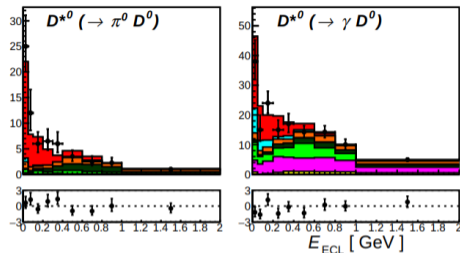
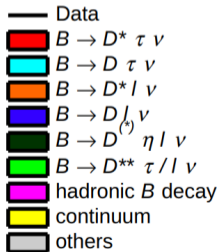
- Finite size of the simulated samples
- Lepton identification efficiency and fake rate corrections

Belle II

$\int \mathcal{L} dt = 365 \text{fb}^{-1}$



- Ask no remaining tracks in the event
- $q^2 > 4 \text{ GeV}^2$ to increase $B \rightarrow D^{(*)} \tau \nu$ contribution
- 2-D binned fit of E_{ECL}^{extra} and M_{miss}^2
- Main backgrounds validated using $B \rightarrow D^* \pi^0 l \nu$ events



$$R(D) = 0.439 \pm 0.055(\text{stat}) \pm 0.045(\text{syst})$$

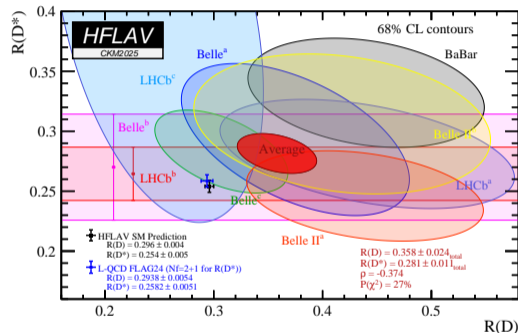
$$R(D^*) = 0.242 \pm 0.019(\text{stat}) \pm 0.016(\text{syst})$$

Most precise determination of $R(D^{(*)})$ with hadronic tagging

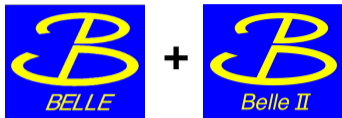
Main systematic uncertainties

- Finite size of the simulated samples
- Background branching fractions

Belle II^a = Hadronic tag
 Belle II^b = Semileptonic tag



Does not include preliminary BaBar result with semileptonic tag



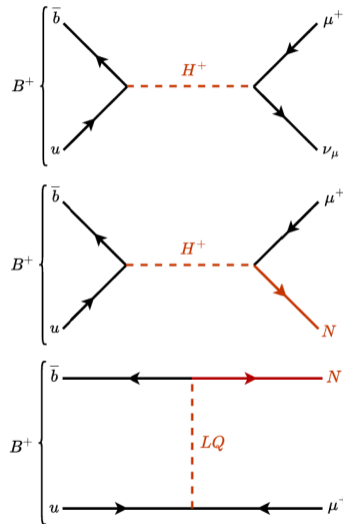
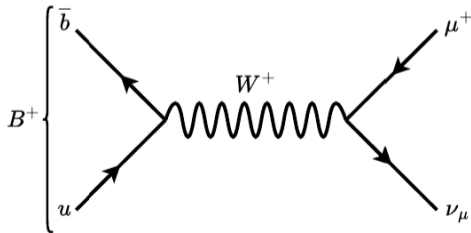
$$B^+ \rightarrow \mu^+ \nu$$

arXiv:2602.09800 submitted to PRD

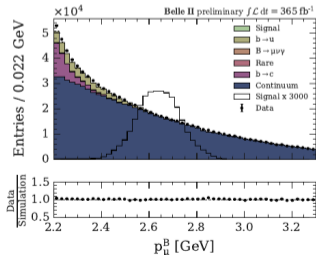
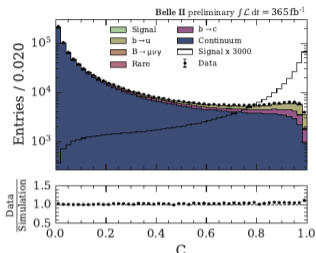
- $B^+ \rightarrow \mu^+ \nu$ highly suppressed in SM (helicity + CKM)

$$\mathcal{B}_{SM} = (4.18 \pm 0.44) \times 10^{-7}$$

- Sensitive to many new physics models (e.g., charged Higgs, leptoquarks, sterile neutrinos)
- Allow independent determination of $|V_{ub}|$



- New Belle II analysis combined with published Belle result updated with improved simulation (bkg \mathcal{B} , form factors) [Phys.Rev.D 101 (2020) 3, 032007]
- Use including tagging (strong need to reduce background)
 - ▶ Ask high momentum ($p_{\mu}^* > 2.1$ GeV) muon with tight PID selection
 - ▶ M_{bc} and ΔE of rest of the event compatible with B
 - ▶ Further BDT based on event shape and B_{tag} properties
- Boost the muon into the B signal rest frame where it is monochromatic for the signal
 - ▶ Deduce 4-momentum of B signal from the rest of the event
 - ▶ Use MC to calibrate bias in p_{μ}^B
- Combined binned fit of p_{μ}^B in 4 (Belle)+ 4 (Belle II) categories based on BDT output
- Validate with $B^+ \rightarrow \bar{D}^0 \pi^+$ decay



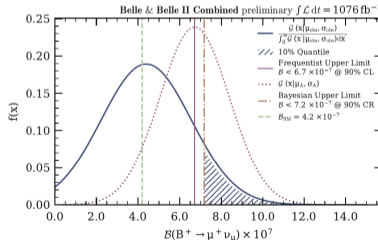
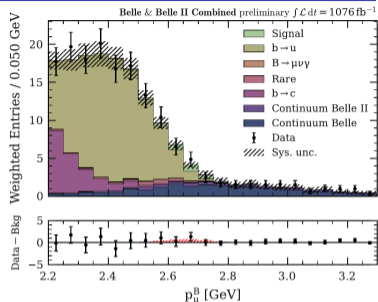
Most precise determination to date

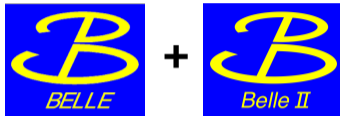
$$\mathcal{B}(B^+ \rightarrow \mu^+ \nu_\mu) = (4.4 \pm 1.9 \pm 1.0) \times 10^{-7}$$

- 150 ± 73 signal events
- 2.35σ over bkg-only hypothesis
- $|V_{ub}| = 3.92_{-0.96}^{+0.77}(\text{stat})_{-0.49}^{+0.44}(\text{syst}) \pm 0.03(\text{theo})$
compatible with both inclusive and exclusive determination

Main systematic uncertainties

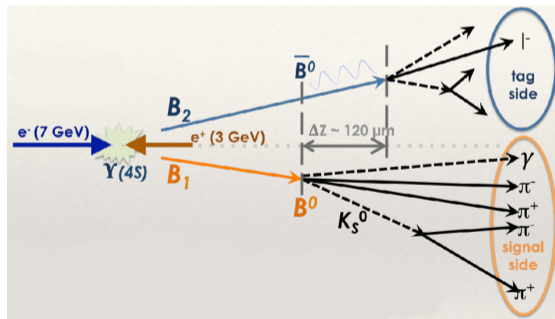
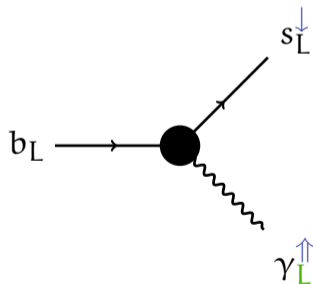
- $b \rightarrow u$ modeling
- Continuum modeling



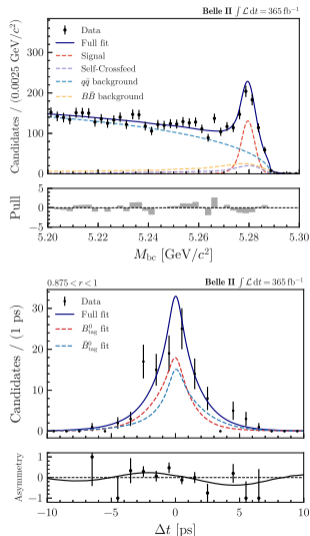


$$B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$$

- In SM photon from $b \rightarrow s \gamma$ transitions has mainly left polarisation (right polarisation helicity-suppressed by m_s/m_b)
 - Suppressed interference as $B^0 \rightarrow K_S^0 (\rho^0 \rightarrow \pi^+ \pi^-) \gamma_R$ and $\bar{B}^0 \rightarrow K_S^0 (\rho^0 \rightarrow \pi^+ \pi^-) \gamma_L$
- Expect negligible time dependent CP violation from SM but can be enhanced in NP
- Constraint on Wilson coefficient $C_7^{(r)}$



- Separate Belle and Belle II analyses combined at the end
- Ask for $E_\gamma > 4(3.5)$ GeV for Belle (II) to suppress photons from beam background
- BDT with event shape variables against continuum background
- Time-dependent CP fit to extract CP parameters S and C from 3-D fit to M_{bc} , ΔE and Δt
- Cross check with control mode $B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$



- Most precise determination of time dependent CP parameters for this mode (improvement by more than a factor two previous results)

$$C = -0.17 \pm 0.09 \pm 0.04$$

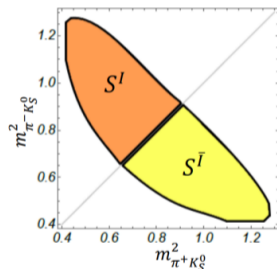
$$S = -0.29 \pm 0.11 \pm 0.05$$

- First measurements of S^+ and S^- introduced in [S. Akar, E. Ben-Haim, J. Hebing, E. Kou, F.S. Yu, arXiv:1802.09433] that allows for complementary constraints on real and imaginary parts of $C_7^{(\prime)}$

$$S^+ = S^I + S^{\bar{I}} = -0.57 \pm 0.23 \pm 0.10$$

$$S^- = S^I - S^{\bar{I}} = 0.31 \pm 0.24 \pm 0.05$$

- All results compatible with SM expectations
- Interpretation in term of $B^0 \rightarrow K_S^0 (\rho^0 \rightarrow \pi^+ \pi^-) \gamma$ will require amplitude model from amplitude analysis of isospin partner $B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$



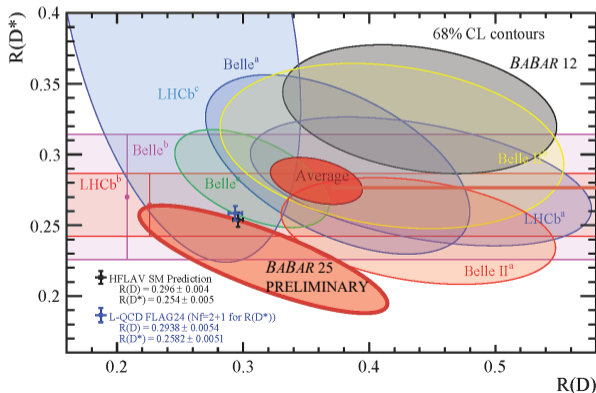
Conclusion

- B decays are a promising place to look for New Physics
- Belle II offer unique features to excel in this search
- Presented five recent results
 - Search for $B \rightarrow hX_{inv}$
 - $R(D)$ and $R(D^*)$ with hadronic and semileptonic tag
 - Search for $B^+ \rightarrow \mu^+ \nu$
 - Search for time-dependent CP violation in $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$
- Results statistically limited; Belle II Run 2 data taking ongoing, stay tuned for updates



BACKUP

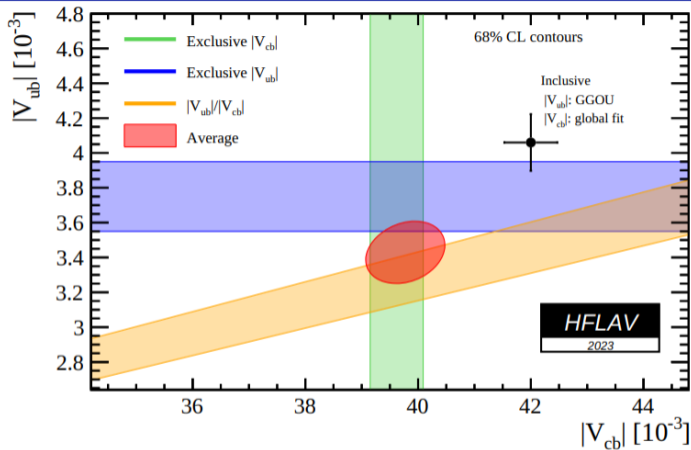
Experiment	$R(D)$	$R(D^*)$	Correlation
<i>BABAR</i> 12 (hadronic tag)	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$	-0.27
HFLAV (CKM 2025 average)	0.281 ± 0.011	0.358 ± 0.024	-0.374
<i>BABAR</i> 25 (leptonic tag) PRELIMINARY	$0.316 \pm 0.062 \pm 0.019$	$0.226 \pm 0.022 \pm 0.012$	-0.82



This average does not include the *BABAR* 25 preliminary result



V_{ub} inclusive vs exclusive

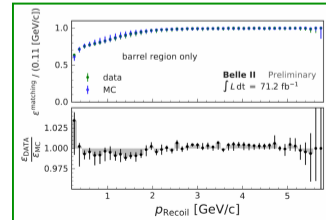
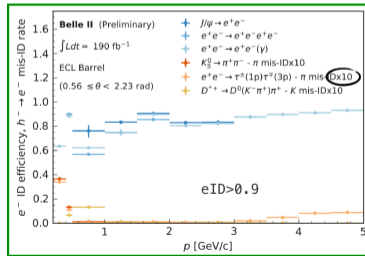
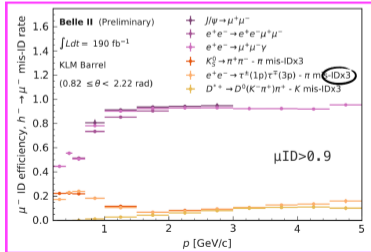
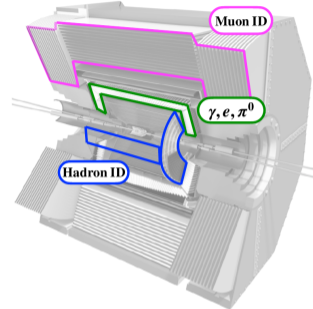
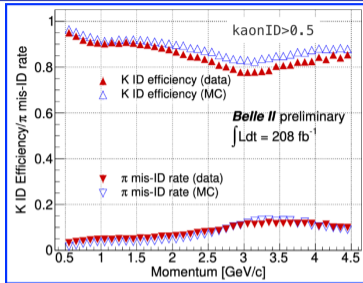


$$|V_{ub}| = (4.06 \pm 0.11 \pm 0.13 \pm 0.18) \times 10^{-3} \quad (\text{inclusive}),$$

$$|V_{ub}| = (3.75 \pm 0.06 \pm 0.19) \times 10^{-3} \quad (\text{exclusive}),$$

Key Belle II performance

- Good kaon identification in full momentum range
 - ▶ $\varepsilon(K) \sim 90\%$, $\pi \rightarrow K \sim 6\%$
- High photon efficiency
 - ▶ $\varepsilon(\gamma) \sim 90\%$ ($p > 1.5$ GeV)
- Good lepton ID performance
 - ▶ $\varepsilon(\mu) \sim 90\%$, $\pi \rightarrow \mu \sim 7\%$
 - ▶ $\varepsilon(e) \sim 86\%$, $\pi \rightarrow e \sim 0.4\%$



Cross sections at the $\Upsilon(4S)$

