Early results and prospects on B anomalies at Belle II

Brookhaven Forum 2021: Opening New Windows to the Universe

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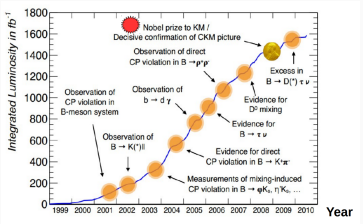
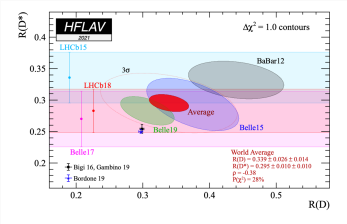
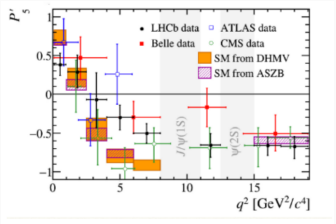
The Emergence of the B Anomalies

An impressive amount of discoveries and observations of rare decays has been made with increasing data samples in the past . . .

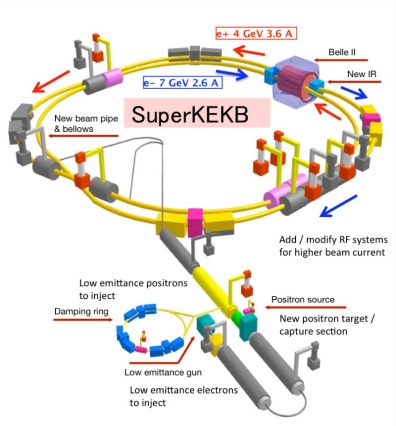






. . . and with our ever more increasing data sets, the B anomalies start to emerge

SuperKEKB

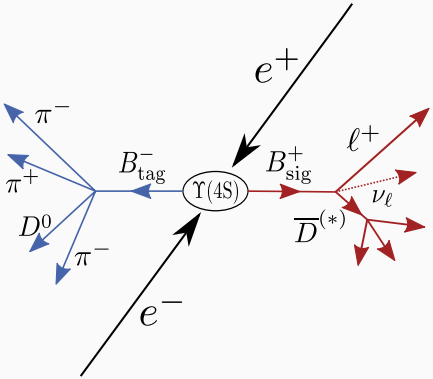


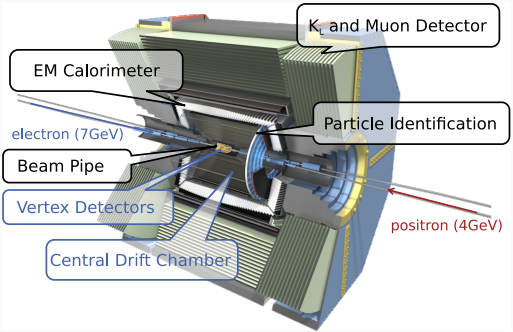
- Coherent and well defined initial state and no additional interactions
- Low (physics) backgrounds
- Excellent neutral reconstruction (γ, π^0, K_L^0)
- Absolute branching fractions can be measured.
- Systematics quite different from hadron machines. If NP is seen by one of the experiments, confirmation by the other would be important.

But: Small cross-section;

$$e^+e^- \to \Upsilon(4S) \to B\bar{B} \approx 1.1\text{nb}$$

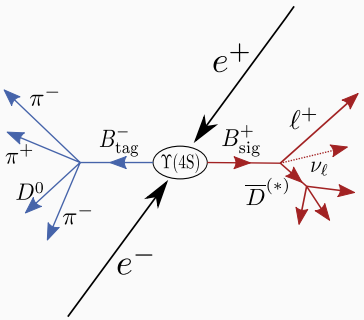
The Belle II Detector

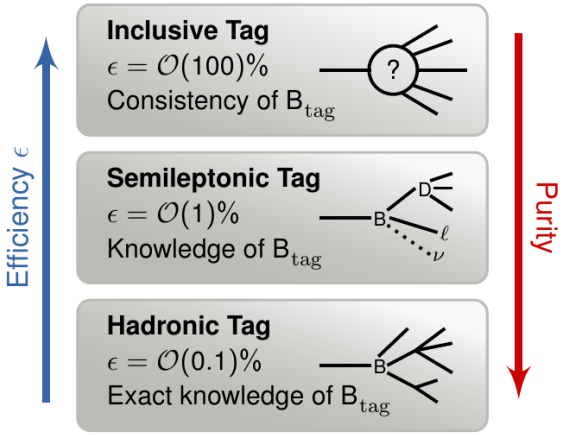




Belle II collected over $200\,\text{fb}^{-1}$ with world-record instantenous luminosity ($> 3 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$).

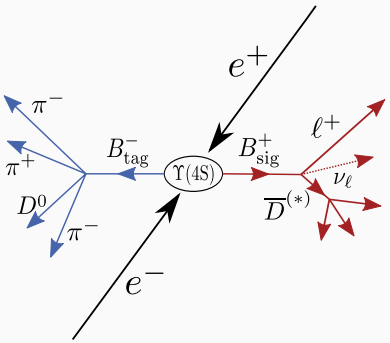
B-Tagging at Belle II





Tagging enables us to measure invisible final states.

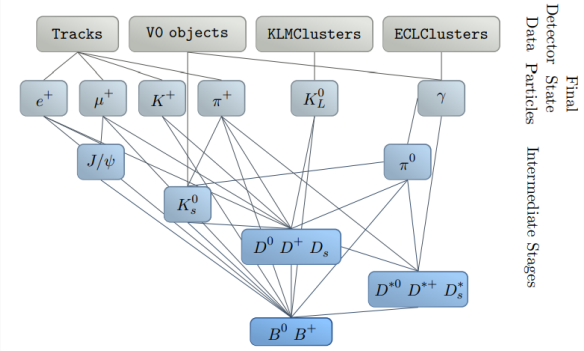
Exclusive B-Tagging at Belle II



- $\mathcal{O}(200)$ classifiers.
- $\mathcal{O}(10000)$ automatically reconstructed decay channels.

Exclusive Tagging:
The Full Event Interpretation (FEI)

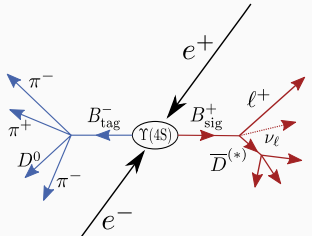
Comput.Softw.Big Sci. 3 (2019)

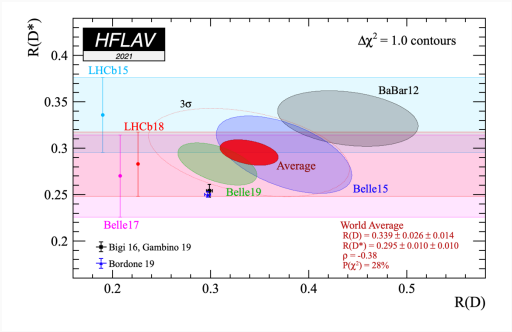


- Up to 50 % improvement over the previous algorithm.

$b \to c\tau\nu$ Transitions - $R(D^{(*)})$

- $R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$
- Not a rare decay, but challenging to reconstruct due to multiple neutrinos in the final state.
- Challenging $B \to D^{**}\ell\nu$ background.
- Multiple measurements available from LHCb, BaBar and Belle available.



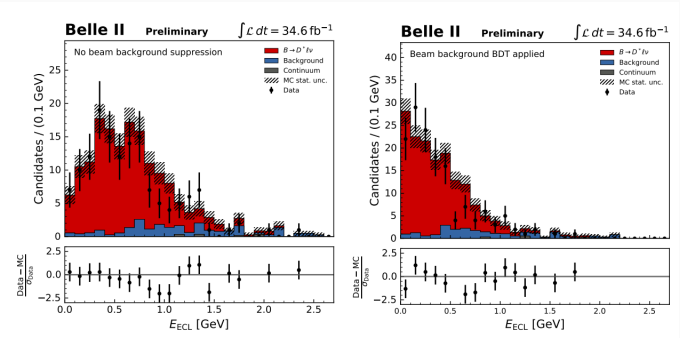


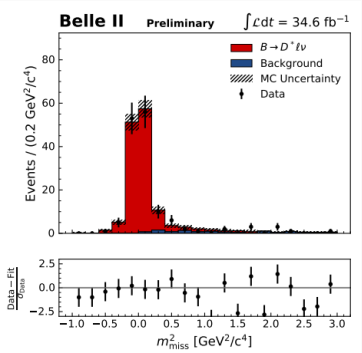
Current tension with the SM:

- $R(D)$: 1.4σ
- $R(D^*)$: 2.9σ
- Combined: 3.4σ

$b \to c\tau\nu$ Transitions - The Normalization Channel - Preliminary

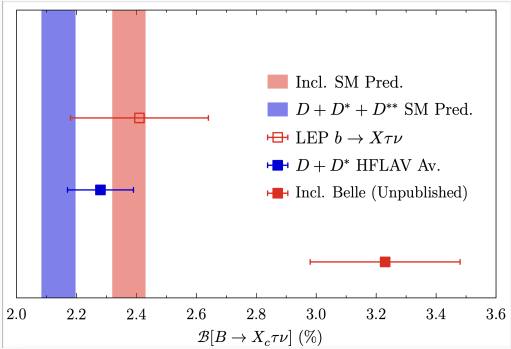
- Measurement of normalisation channel with $34.6\,\text{fb}^{-1}$ using hadronic tagging.
- $\mathcal{B}(B^0 \to D^*\ell\nu) = (4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{sys}} \pm 0.45_{\pi_s})\%$.
- Dedicated studies to improve the E_{ECL} reconstruction.

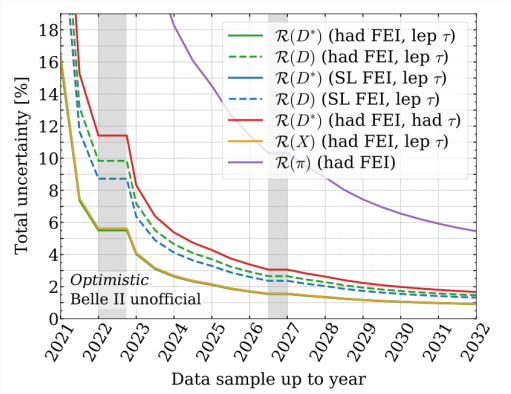




$b \to c\tau\nu$ - Prospect for Belle II

- Inclusive $B \to X_c \tau\nu$ measurement complementary to exclusive measurements.
- Long time no update.
- Work in progress, stay tuned!





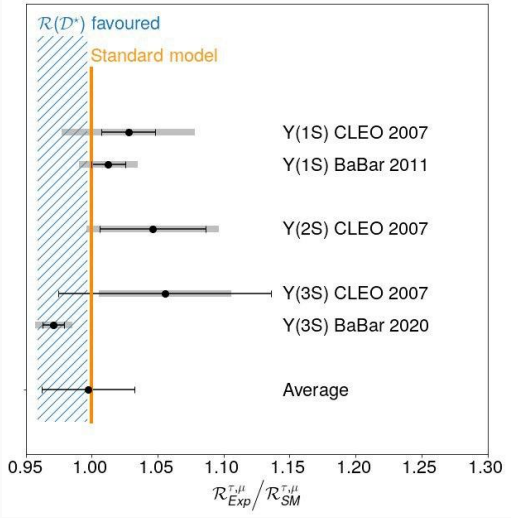
2101.08326

Υ Decays to Tackle the $R(D^{(*)})$ Puzzle

- When Belle II will collect data at the lower Υ resonances, the ratio

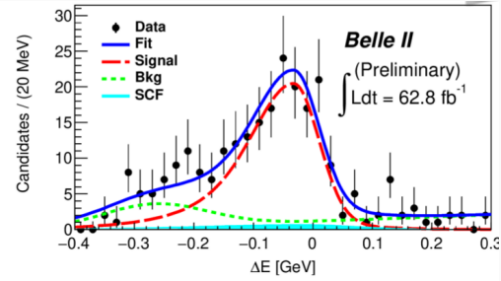
$$R^{\Upsilon}_{\tau/\ell} = \frac{\Gamma(\Upsilon \to \tau\tau)}{\Gamma(\Upsilon \to \ell\ell)}, (\ell = e, \mu)$$

  can be measured.
- Orthogonal probe to the operators governing $R(D^{(*)})$ decays.
- $< 0.5\%$ precision on $R(\Upsilon)$ helps to shed light on the $R(D^{(*)})$ anomaly J. High Energ. Phys. 2017, 19 (2017)



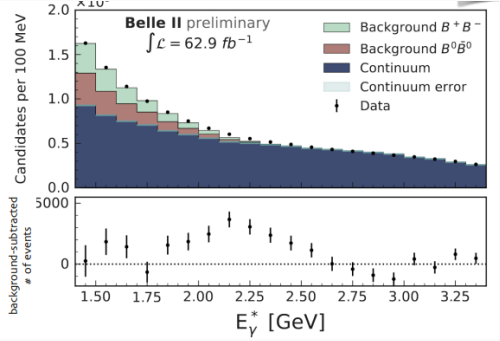
$b \to s\gamma$ Transitions - First Results

- Excellent probe for new physics.
- Large uncertainty in the exclusive measurements (e.g. $B \to K^*\gamma$) due to form factors.



$B^+ \to K^{*+}[\to K^+\pi^0]\gamma$

- Belle (II) can measure the inclusive decay $B \to X_s\gamma$.
- Untagged analysis, where we look for the high-energetic monochromatic γ.

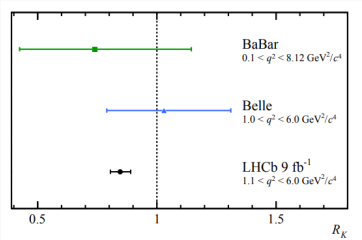


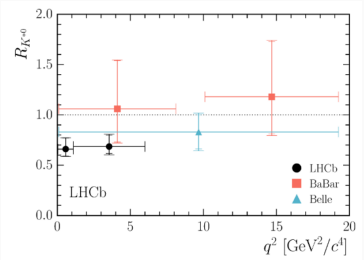
$b \to s\ell\ell$ Transitions - $R(K)$ and $R(K^*)$

SM is lepton flavor universal, and predicts this with high accuracy $R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = (1 \pm \mathcal{O}(10^{-2}))_{\text{SM}}$. LHCb observes tensions in both

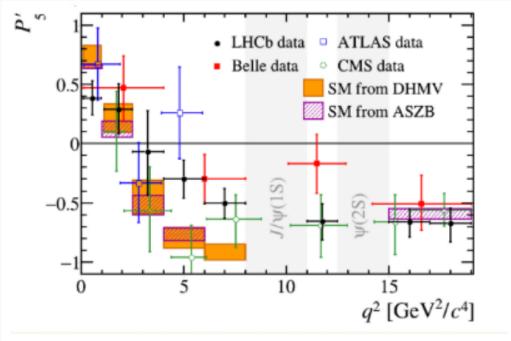
- R_K : 3.1σ in $q^2 \in [1.1, 6]\text{GeV}^2/c^4$. 2103.11769
- R_{K^*} : $2.1 - 2.3\sigma$ in $q^2 \in [0.045, 1.1]\text{GeV}^2/c^4$ and $2.4 - 2.5\sigma \in [1.1, 6.0]\text{GeV}^2/c^4$.

  J. High Energ. Phys. 2017, 55 (2017)
- Belle II needs a substantial fraction of its final target luminosity to contribute significantly.





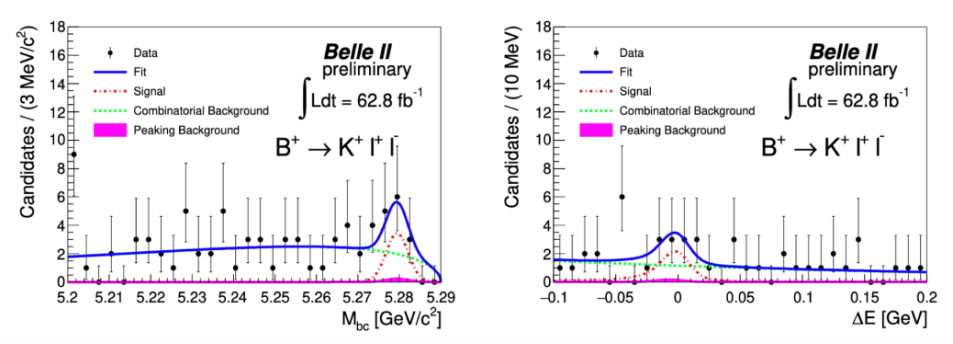
- P_i' observables are free from form factor uncertainties.
- Both Belle and LHCb ($\ell = \mu$) report P_5' tensions.
  - LHCb 2.5σ in $q^2 \in [4, 6]\text{GeV}^2/c^4$
  - LHCb 2.9σ in $q^2 \in [6, 8]\text{GeV}^2/c^4$
  - Belle 2.6σ in $q^2 \in [4, 8]\text{GeV}^2/c^4$
- Belle (II) has access to $Q_i = P_i'^{\mu} - P_i'^{e}$



Observables	Belle (0.71 ab^{-1})	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
P_5' ([1.0, 2.5] GeV$^2/c^4$)	0.47	0.17	0.054
P_5' ([2.5, 4.0] GeV$^2/c^4$)	0.42	0.15	0.049
P_5' ([4.0, 6.0] GeV$^2/c^4$)	0.34	0.12	0.040
P_5' (>14.2 GeV$^2/c^4$)	0.23	0.088	0.027

$b \to s\ell\ell$ Transitions - $B^+ \to K^+\ell^+\ell^-$ Preliminary measurement

- $9.6^{+4.3}_{-3.9} \pm 0.4$ signal events (2.7σ significance) with 62.8fb^{-1}.
- Not sufficient to extract key observables.

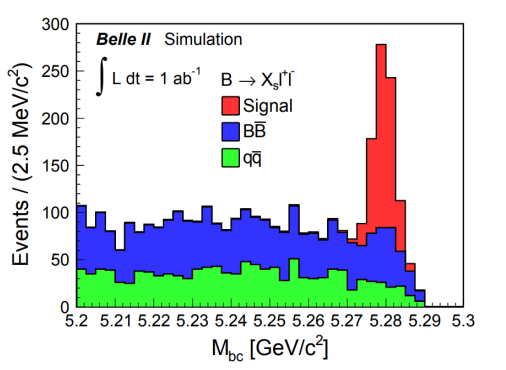


- $M_{\text{bc}} = \sqrt{E^2_{\text{beam}}/c^4 - |p_B|^2/c^2}, \quad \Delta E = E_B - E_{\text{beam}}$

$b \to s\ell\ell$ Transitions - $B \to X_s \ell^+ \ell^-$ Simulation

- Complementary information with different hadronic uncertainties.
- Two methods:
  - Sum-of-exclusive modes (right).
  - Fully inclusive using tagging.
- Sensitivity on forward-backward asymmetry and branching fraction few percent with $\mathcal{L} = 50\text{ab}^{-1}$.

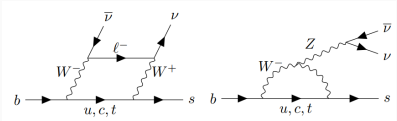
- $B \to X_s \ell\ell$ with $X_s \to Kn\pi, n \leq 4$ and $X_s \to 3K$



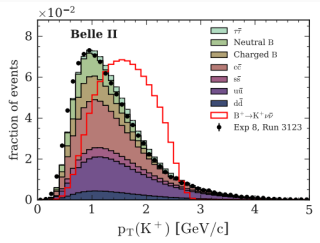
2012.15394 ↑, Prog Theor Exp Phys (2019) ↓

Observables	Belle (0.71 ab^{-1})	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
R_{X_s} ($[1.0, 6.0]$ GeV$^2/c^4$)	32%	12%	4.0%
R_{X_s} ($[> 14.4]$ GeV$^2/c^4$)	28%	11%	3.4%

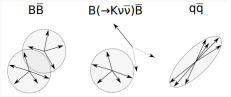
$b \to s\nu\nu$ Transitions - $B^+ \to K^+\nu\bar{\nu}$ with inclusive tagging Phys. Rev. Lett. 127, 181802



- Small theoretical uncertainty due to absence of charged leptons in the final state. Prog.Part.Nucl.Phys. 92 (2017)
- Not observed yet, theory predicts SM branching ratios of:
  - $\mathcal{B}(B \to K\nu\nu)_{\mathrm{SM}} = (4.6 \pm 0.5) \times 10^{-6}$,
  - $\mathcal{B}(B \to K^*\nu\nu)_{\mathrm{SM}} = (8.4 \pm 1.5) \times 10^{-6}$,
- which can be enhanced by NP connected to the anomalies. e.g. see Phys. Rev. Lett. 127, 181802

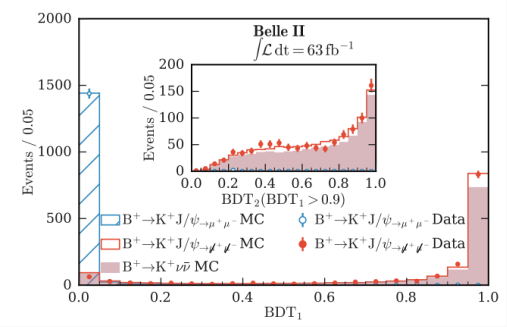


- Events tagged by identifying signal track, and reconstrucing the rest-of-event.
- Signal selection utilizing event topology $\to$ mva method.

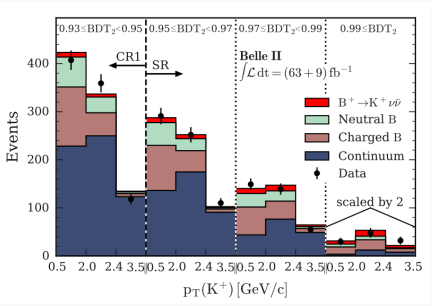


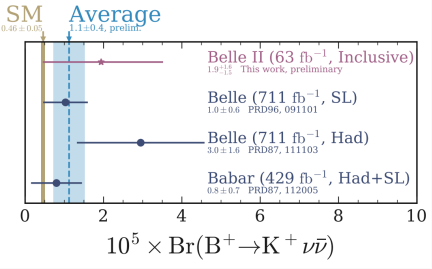
$b \to s\nu\nu$ Transitions - $B^+ \to K^+\nu\bar{\nu}$ with inclusive tagging Phys. Rev. Lett. 127, 181802

- Validation with $B^+ \to K^+ J/\Psi(\to \mu\mu)$ sample.



- *Belle II result*:
  $\mathcal{B}(B^+ \to K^+\nu\nu) < 4.1 \times 10^{-5}$ @ 90% CL





Summary

- SuperKEKB is providing data with world record instantenous luminosity and Belle II plans to collect 50ab^{-1} over the coming years.
- Belle II will provide complementary and unique measurements for semileptonic and electroweak penguin decays.
- The work on analyses has started, developing *new* techniques and delivering (preliminary) results with small data samples, and ready to scale with more data.

Belle II is getting ready to shed some light on the anomalies!