Anomalies: Belle (II) status and prospects

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KEK

on behalf of the Belle and Belle II collaboration

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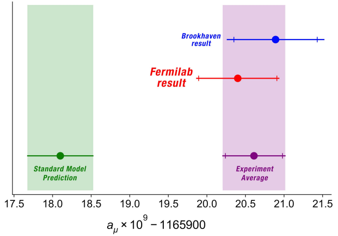
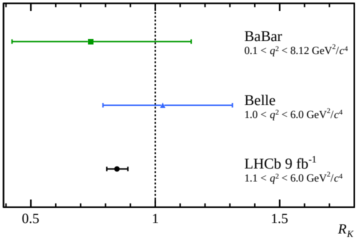
Anomalies 2021

The year of anomalies

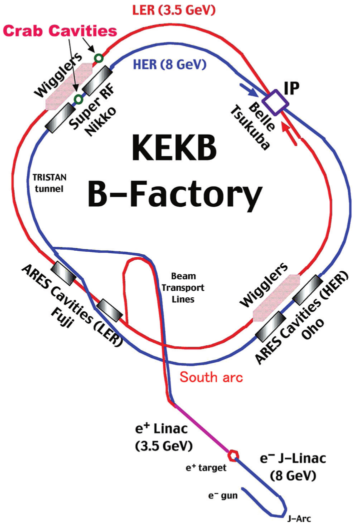
- Various impressive results appear within 2021
  - BNL + FNAL combined result of $(g-2)_\mu$
    - 4.2σ deviation from the SM
  - LHCb run 1+2 data results
    - Evidence (3.1σ) of $R(K^+)$ anomaly
    - $R(K^*)$ and $R(K_S^0)$ results
  - Belle full data results of $R(K^{(*)})$
- Also, angular analysis of $b \to s\ell^+\ell^-$,
- $R(D^{(*)})$ related studies from BaBar, Belle, and LHCb...

→ NOT ENOUGH YET! More studies are necessary for various channel based on larger data samples.

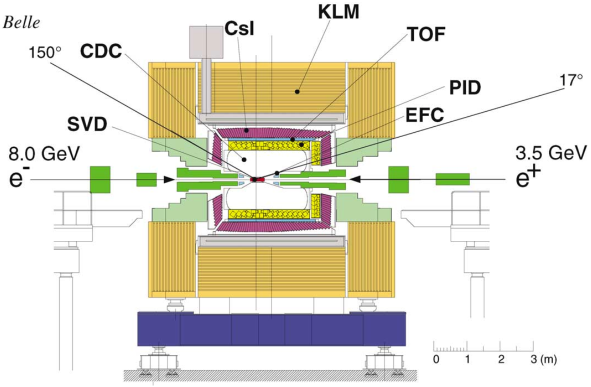




Belle experiment

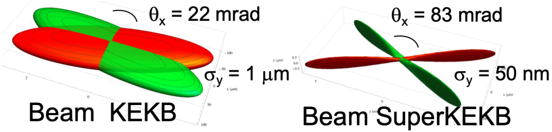


- $1040\ \mathrm{fb}^{-1}$ of data were collected by Belle (1999–2010)
  - $711\ \mathrm{fb}^{-1}$ of $\Upsilon(4S) = 772 \times 10^6 B\overline{B}$

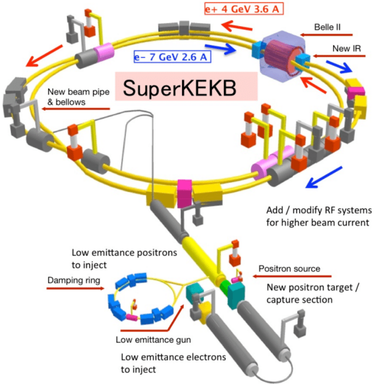


SuperKEKB

- **Upgrade of KEKB with same center-of-mass energy ($\Upsilon(nS)$, mainly $\Upsilon(4S)$)**
  - Less beam energy asymmetry ($8 \to 7$ GeV e^- and $3.5 \to 4$ GeV e^+)
- **Aiming to deliver $50\ \mathrm{ab}^{-1}$ ($= 50\times$ Belle) of data by 2031.**
- **Aiming to achieve $6.5 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($= 30\times$ KEKB)**
  - 1/20 of beam size (nanobeam scheme)
  - 150% of beam current

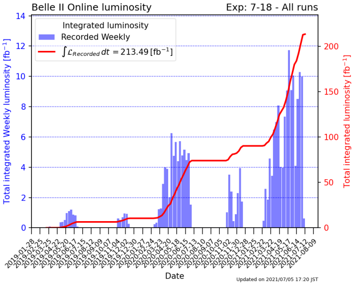


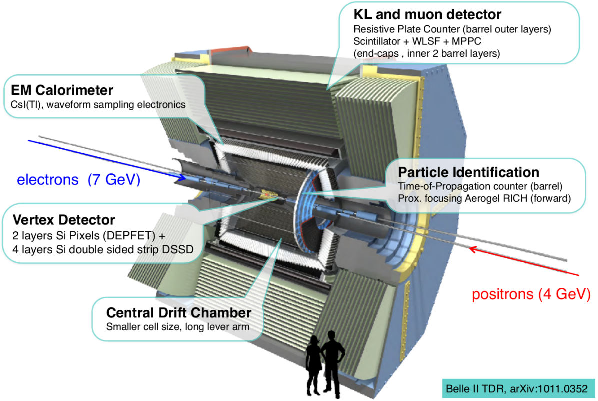
$$L = \frac{N_+ N_- n_b f_0}{4\pi \sigma^*_{x,\mathrm{eff}} \sqrt{\varepsilon_y \beta^*_y}}$$



Belle II detector

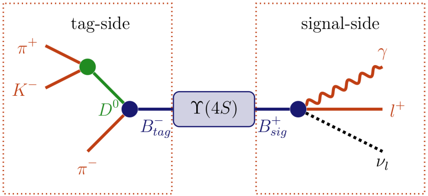
- **Almost new detector compared to Belle**
  - Except calorimeter crystal and superconducting magnet
- **Performance improvements**
  - Better vertexing resolution
  - New and improved trigger system
  - Better p_T resolution

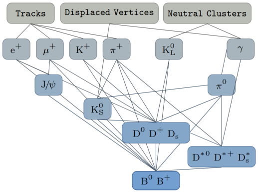


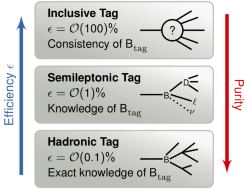


Belle II strengths

- Well known initial state kinematics
- $B\bar{B}$ production from $\Upsilon(4S)$ without extra energy
  - Allow B-tagging method to reconstruct a decay involving undetected particles
  - → Full event interpretation (FEI) method [Comput. Softw. Big Sci. 3, 6 (2019)] for Belle and Belle II
- High reconstruction efficiency and purity for neutral particles
- Low multiplicity processes including τ pair production
  - Single photon trigger is available on Belle II (not in Belle)



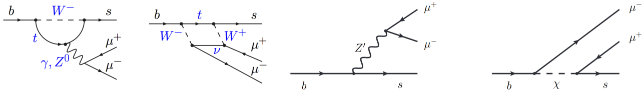




$b \to s\ell^+\ell^-$

$b \to s\ell^+\ell^-$ and $R(K^{(*)})$

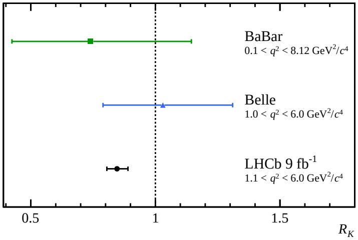
- **In the SM, both penguin and box amplitudes explain the $b \to s\ell^+\ell^-$ process.**

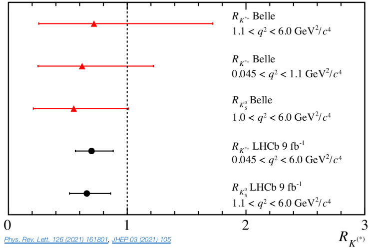


  - Highly suppressed, $\mathcal{O}(10^{-7})$ branching fraction
  - SM gauge bosons have no lepton flavor preference

$$\to R(K^{(*)}) = \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to K^{(*)}e^+e^-)} = 1 \pm 0.01$$ [EPJC 76, 440 (2016)]

- **However, LHCb 9 fb^{-1} data show some differences to the SM [arXiv:2103.11769, arXiv:2110.09501]**

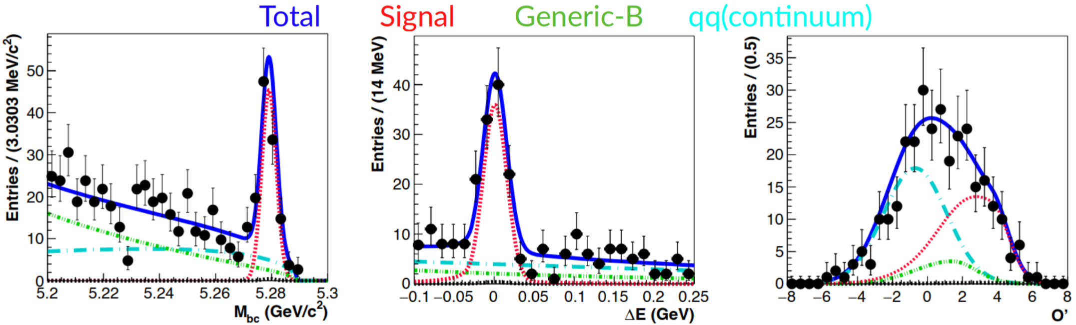




$R(K^+)$ and $R(K_S^0)$ at Belle [JHEP 03 (2021) 105]

Signal selection variables

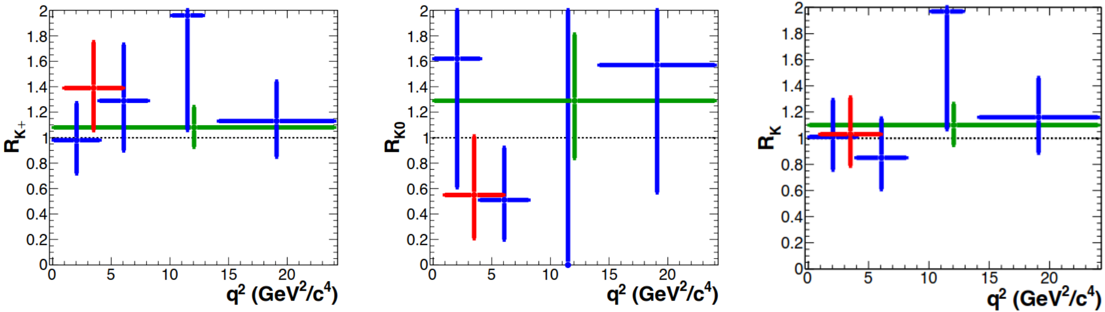
- $M_{bc} = \sqrt{(E_{CM}/2)^2 - |\vec{p}|^2}$: beam-energy constrand mass
- $\Delta E = E_B - E_{CM}/2$
- MVA training (neural network) output of signal and background MC



$B^+ \to K^+\mu^+\mu^-$ distributions (The other modes are in backup)

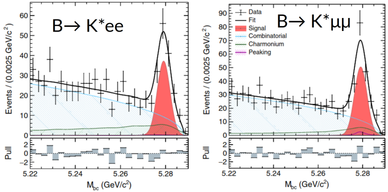
$R(K^+)$ and $R(K_S^0)$ at Belle [JHEP 03 (2021) 105]

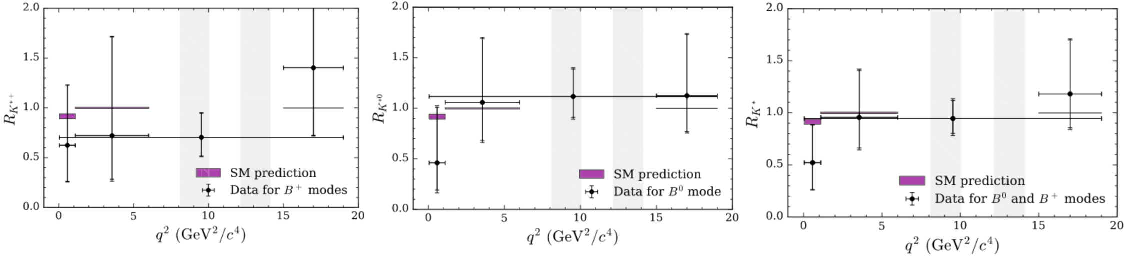
- Performing M_{bc}, ΔE, and neural network output 3D fit to extract signal
- $R(K)$ results with various bins
  - $q^2 \in$ [0.1, 4.0], [4.0, 8.12], [10.2, 12.8], 14.18 <, [1.0, 6.0], and 0.1 <
  - 1.6σ deviation from the LHCb $R(K^+)$ with $q^2 \in$ [1.0, 6.0] bin



$R(K^{*0})$ and $R(K^{*+})$ at Belle [PRL 126, 121801 (2021)]

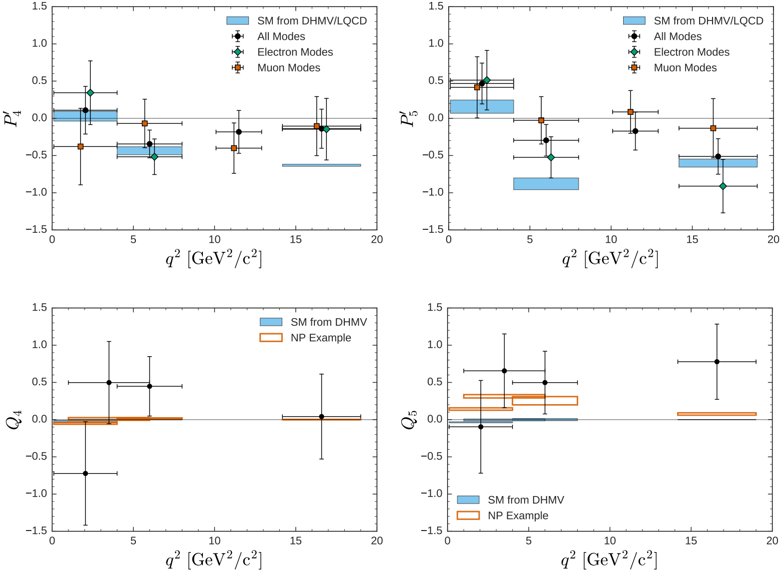
- **$K^{*}\ell^{+}\ell^{-}$ is reconstructed as B-candidates**
  - $K^{*+} \to K^{+}\pi^{0} / K_S^0\pi^{+}$ and $K^{*0} \to K^{+}\pi^{-}, K_S^0\pi^{0}$ (4-channel)
  - Background suppression via NN training and ΔE
  - $M_{\rm bc}$ fitting to extract signal





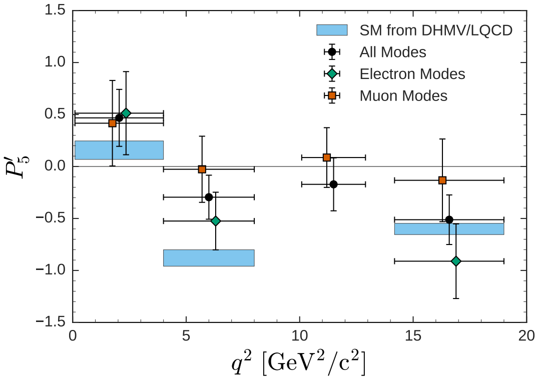
$R(K^{*+})$ (left), $R(K^{*0})$ (center), and combined $R(K^{*})$ (right)

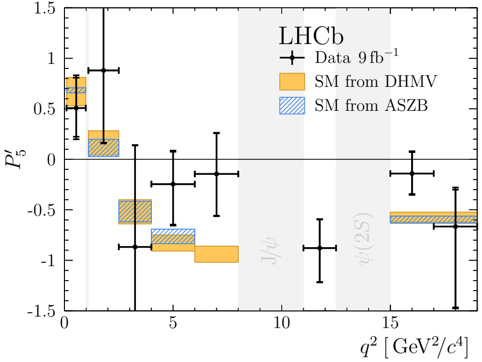
$B \to K^* \ell^+ \ell^-$ angular anaylsis at Belle [PRL 118 111801]



$B \to K^* \ell^+ \ell^-$ angular anaylsis at Belle [PRL 118 111801]

- P_5' comparison with the latest LHCb result (μ mode only) [PRL 126 161802]
  - Both data show good agreement with each other

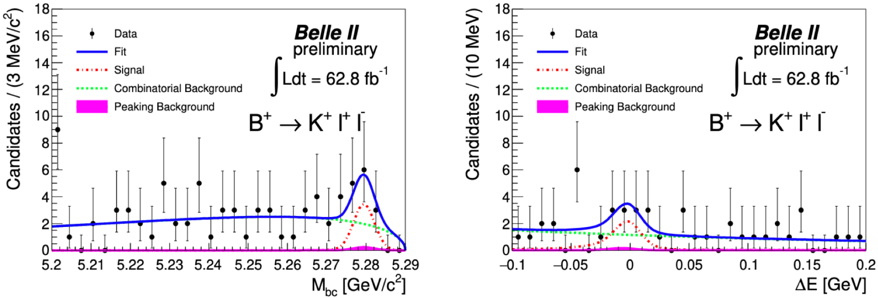




$B^+ \to K^+\ell^+\ell^-$: early benchmark of Belle II

- **Preliminary result with 2020 summer dataset of Belle II ($63\ \mathrm{fb}^{-1}$)**
  - FastBDT [Comput Softw Big Sci 1, 2 (2017)] algorithm for background suppression
  - Extract signal via M_{bc} and ΔE 2D fit

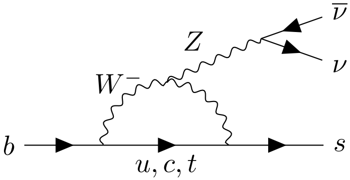
  → 2.7σ significance of signal yield

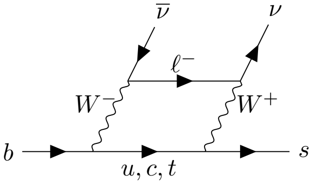


- **With $5-10\ \mathrm{ab}^{-1}$ may be decisive in proving the LHCb observation**
  - All $R(K)$, $R(K^*)$, and $R(X_s)$ in low and high q^2 region

$B^+ \to K^+ \nu\nu$ at Belle II: complementary analysis of $R(K^+)$ [PRL 127 181802]

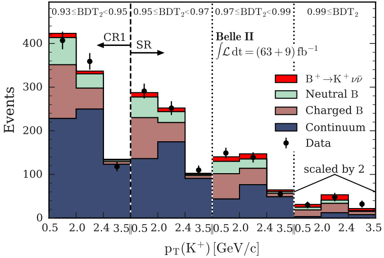
- **In the SM, $\mathcal{B}(B \to K\nu\nu) = (4.6 \pm 0.5) \times 10^{-6}$ [Prog. Part. Nucl. Phys. 92, 50 (2017)]**
  - No observation yet, the best upper limit is given by BaBar with hadronic + semi-leptonic combined result [PRD 87, 112005]
- **$B \to K\nu\nu$ experimental results will give access to the new phyics**
  - Leptoquarks [PRD **98** 055003], axions [PRD **102** 015023], dark matter particles [PRD **101** 095006]
  - Some of new physics scenarios to explain $R(K^{(*)})$ anomaly also can affect to the $B \to K\nu\nu$
- **$63\ \mathrm{fb}^{-1}$ of data are used for the analysis**
  - Inclusive tagging ← higher efficiency than the other tagging method
  - Signal classification via BDT (event shape, ROE kinematics, signal K^+ kinematics and vertex)

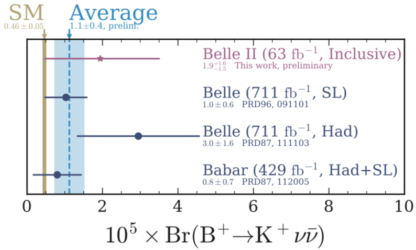




$B^+ \to K^+ \nu\nu$ at Belle II: complementary analysis of $R(K^+)$ [PRL 127 181802]

- **Signal extraction with maximum likelihood fit to the binned data**
  - 4.1×10^{-5} at the 90% confidence interval
- **In future**
  - More channels (K^0 and K^*) with better particle identification (e.g. K_L ID)
  - Better signal selection and systematic study
  - More data
    - Expect SM sensitivity with $\sim 10\ \mathrm{ab}^{-1}$, 10% level of uncertainty with $\sim 50\ \mathrm{ab}^{-1}$ of data

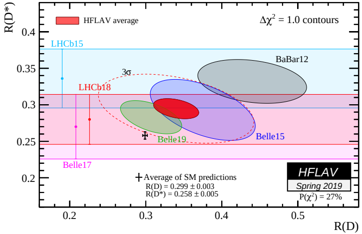


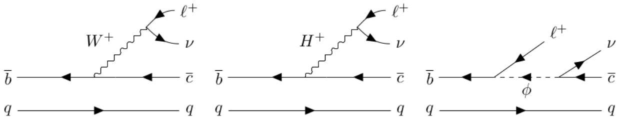


$b \to c\ell\nu$

$b \to c\ell\nu$ and $R(D^{(*)})$

- **$R(D^{(*)})$: Sensitive to the new physics scenarios**
  - $R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$ $(\ell = e, \mu)$
  - New physics can contribute at tree level
    - e.g. charged Higgs, leptoquark, ...
  - The SM expectation uncertainties $\sim 1-3\%$
    - Combined result of $R(D^{(*)}) \sim 3.1\sigma$ tension with the SM





- **Semi-leptonic B decay: large branching fractions**
  - Many missing neutrinos $\to$ challenging to reconstruct B-candidate

$\to$ e^+e^- collider approach: B-tagging

Latest $R(D^{(*)})$ at Belle [PRL 124, 161803 (2020)]

Two previous Belle analysis results

- 2015, hadronic tagging with $\tau \to \ell \nu \bar{\nu}$: $R(D) = 0.375 \pm 0.064 \pm 0.026$, $R(D^*) = 0.293 \pm 0.038 \pm 0.015$
- 2017, hadronic tagging with $\tau \to \pi/\rho\nu$: $R(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$

The latest Belle result: Semi-leptonic tagging with $\tau \to \ell \nu \bar{\nu}$

- Belle data analyzed in Belle II analysis software framework to use the FEI (see slide 6)
- Tag-side of B reconstruction based on hierarchical FastBDT algorithm
- 4 types of B signal final states: $D^+\ell^-$, $D^0\ell^-$, $D^{*+}\ell^-$, and $D^{*0}\ell^-$
  - $D^{*+} \to D^0\pi^+/D^+\pi^-$, $D^{*0} \to D^0\pi^0$ with 30% of D^0 and 22% of D^+
  - $B \to D^{(*)}\tau\nu$: signal mode, $B \to D^{(*)}\ell\nu$: normalization mode

Signal mode

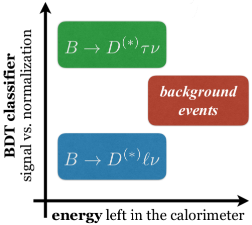
$$\frac{B \to D^{(*)}\tau(\to \ell\nu\nu)\nu}{B \to D^{(*)}\ell\nu} \longleftarrow \Upsilon(4S) \longrightarrow B \to D^{(*)}\ell\nu$$

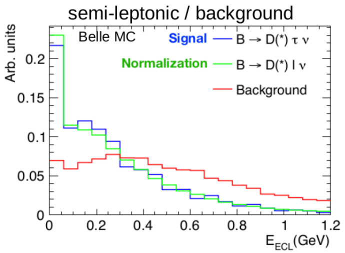
signal-side tag-side

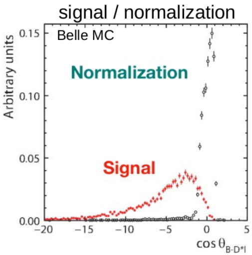
Normalization mode

Latest $R(D^{(*)})$ at Belle [PRL 124, 161803 (2020)]

- **Background vs. signal and normalization mode: E_{ECL}**
  - Energy in ECL without reconstructed particle association
  - Both signal and normalization make peak near the 0 of E_{ECL}
- **Signal vs. normalization mode: BDT based classification**
  - Visible energy, square of missing mass, and $\cos\theta_{B,D^{(*)}\ell} \rightarrow O_{\mathrm{cls}}$

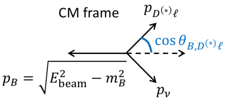






$$m^2_{miss} = (E_{beam} - E_{D^{(*)}} - E_\ell)^2 - (p_{D^{(*)}} + p_\ell)^2$$

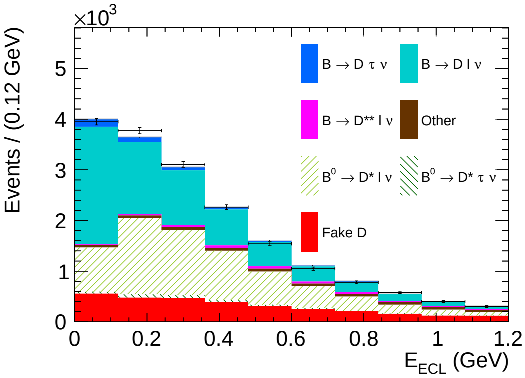
$$cos\theta_{B,D^{(*)}\ell} \equiv \frac{2E_{beam}E_{D^{(*)}\ell} - m_B^2 - m^2_{D^{(*)}\ell}}{2|p_B||p_{D^{(*)}\ell}|}$$

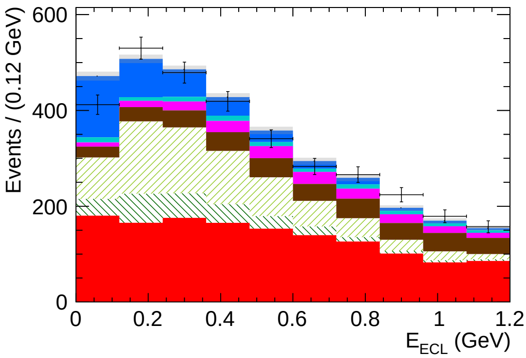


Latest $R(D^{(*)})$ at Belle [PRL 124, 161803 (2020)]

Signal extraction from simultaneous fit of extra energy in ECL (E_{ECL})

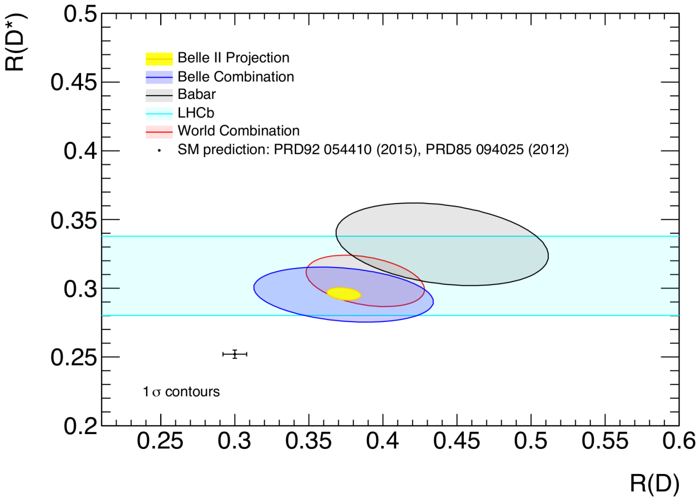
- $R(D) = 0.307 \pm 0.037 \pm 0.016$, $R(D^*) = 0.283 \pm 0.018 \pm 0.014$ → The most precise result





E_{ECL} distribution of $B^0 \to D^+ \ell^-$ for all O_{cls} (left) and > 0.9 region (right). The other modes are in backup slides.

Belle II projection of $R(D^{(*)})$ [PTEP 12, 123C01 (2019)]

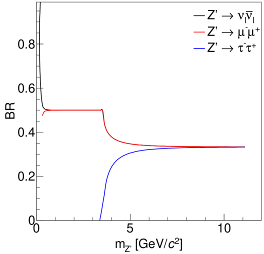


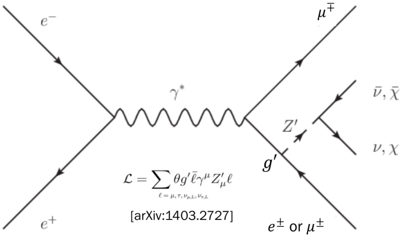
Belle II will be world-leading

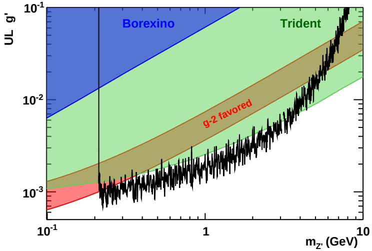
Z'

$e^+e^- \to \mu^+\mu^- Z'$: Introduction

- **$Z'_{L_\mu - L_\tau}$ can be a solution of $(g-2)_\mu$ and $b \to s\ell^+\ell^-$ LFU anomaly**
  - The branching fraction depends on the mass of Z'
- **B-factory results**
  - 90% C.L. limits of visible Z' coupling from BaBar (bottom-right figure) [PRD **94** 011102]
  - Belle preliminary result for $Z' \to \mu^+\mu^-$(visible) [arXiv:2109:08596]
  - The first Belle II physics paper is for $Z' \to \text{invisible}$ [PRL **124** 141801]
    - Two scenarios: $e^+e^- \to \mu^+\mu^- Z'$ and $e^+e^- \to e^\pm\mu^\mp Z'$ (LFV Z')







Visible Z' search at Belle [arXiv:2109:08596]

Event selection

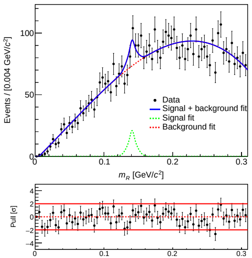
- Require four charged tracks (include 2 same-signed muon) and zero sum of charge
- ECL remaining without track association < 200 MeV
- 4-muon invarient mass within beam energy ± 500 MeV

Signal extraction

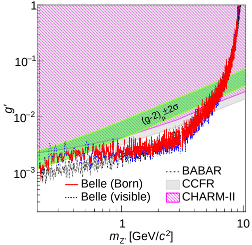
- The coupling constant g' is obtained by Born cross section

$$g'^2/g_0'^2 = \sigma_{\text{Born}}/\sigma_{\text{theory}}, \ \sigma_{\text{Born}} = N_{\text{obs}}/(\mathcal{L} \times \mathcal{B} \times \epsilon_{\text{rec}}) \quad (1)$$

where σ_{theory} is theoritical cross section by g_0', $\mathcal{L}$ is int. luminosity, $\mathcal{B}$ is branching ratio of $Z' \to \mu^+\mu^-$, and ϵ_{rec} is reconstruction efficiency. N_{obs} is extraced by $M_{Z'}$ fitting



$m_{Z'} = 0.256$ ($m_{\text{recoil}} = 0.145$) GeV fit result



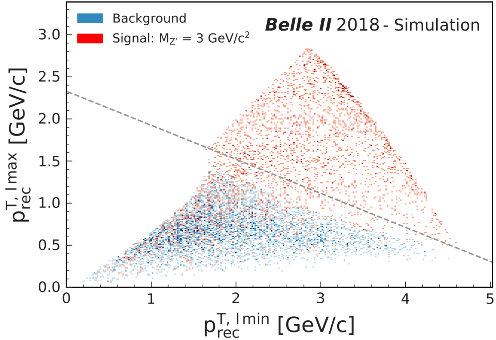
Invisible Z' search at Belle II [PRL 124 141801]

Signal event signature

- Events only with exactly two opposite charged tracks, $\mu^+\mu^-$ or $e^\pm\mu^\mp$ (LFV mode)
- Missing energy with no extra photon
- Recoil mass peak: $M^2_{\rm rec} = s + M^2_{\mu\mu/e\mu} - 2\sqrt{s}E^*_{\mu\mu/e\mu}$

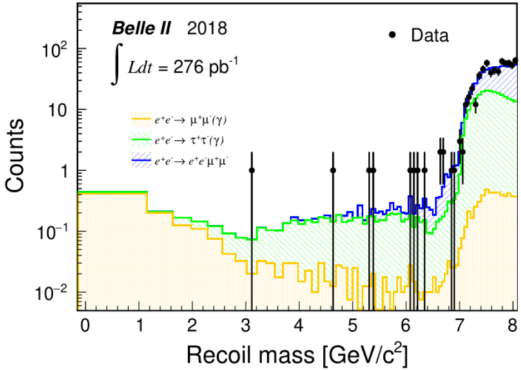
Background ($e^+e^- \to \tau^+\tau^-(\gamma)$) suppression

- After basic background rejection (backup), $e^+e^- \to \tau^+\tau^-(\gamma)$ is the dominant background
- $p_{\rm rec}^{T,min(max)}$: Transverse momentum of recoil momentum in the direction of low (high) momentum lepton
- Linear discriminant between two variables

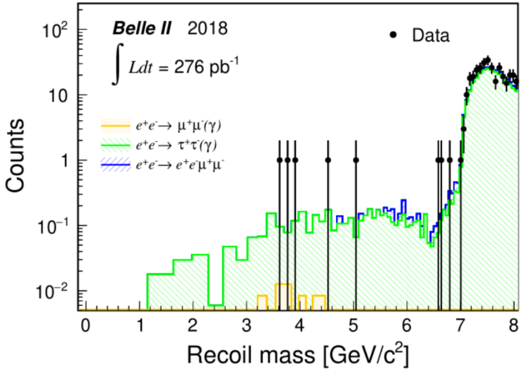


Invisible Z' search at Belle II [PRL 124 141801]

Recoil mass spectrums



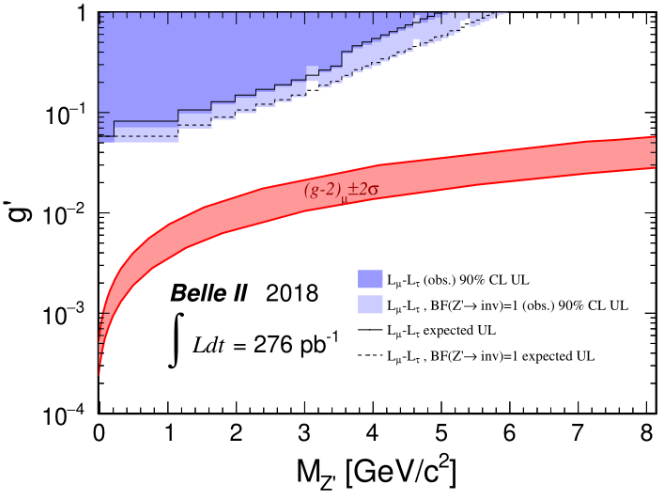
$ee \to \mu\mu Z'$



$ee \to e\mu Z'$

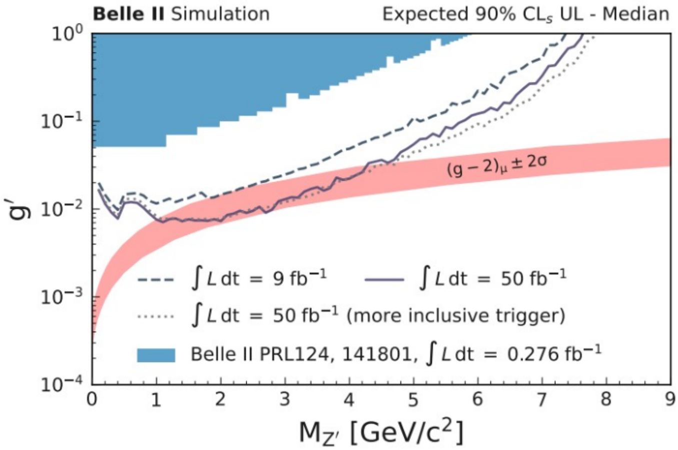
Invisible Z' search at Belle II [PRL 124 141801]

- g' upper limits of 90% C.L.



Invisible Z' search at Belle II [PRL 124 141801]

- **Short-term projection**
  - With more data, KLM based μID, new triggers, ...



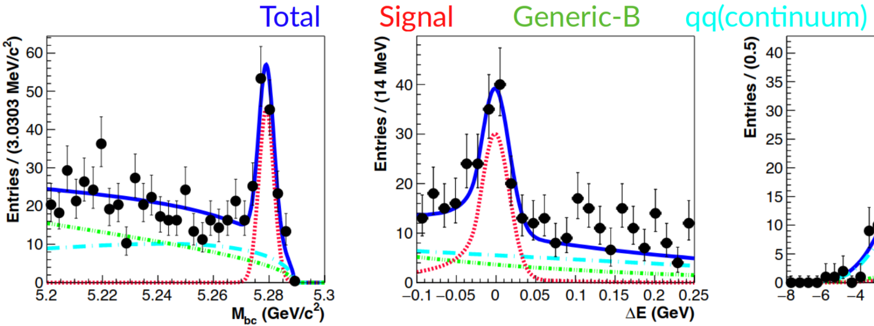
Summary

- **Belle II started taking data from 2019 and is succefully running**
- **In 2021, many anomalies are announced including $b \to s\ell^+\ell^-$ studies from Belle**
  - Belle published $R(K^+)$, $R(K_S)$, $R(K^*)$, angular analysis results which are consistent with the SM
  - With $5-10\ \mathrm{ab}^{-1}$ may be decisive in proving the LHCb observation for all $R(K)$, $R(K^*)$, $R(X_s)$ in low and high q^2 region
  - $B^+ \to K^+\nu\nu$ result was published and set the 4.1×10^{-5} 90% C.L. of upper limit
    - Belle II can observe the process with $10\ \mathrm{ab}^{-1}$, and has 10% level of uncertainties with $50\ \mathrm{ab}^{-1}$ of data
- **Recent $R(D^{(*)})$ result with semi-leptonic from Belle is the best result in the world**
  - With $50\ \mathrm{ab}^{-1}$ of data, both uncertainties will be around $3-4\%$
- **Z' can be a solution of $(g-2)_\mu$ and $b \to s\ell^+\ell^-$ anomaly**
  - Belle visible preliminary result, 90% upper limits, covers the $(g-2)_\mu$ favored region
  - Belle II invisible result has not enoutgh statistics yet, but with $50\ \mathrm{fb}^{-1}$ of data, $1-3$ GeV of Z' can cover the $(g-2)_\mu$ favored region

Backup

$R(K^+)$ and $R(K_S^0)$ at Belle [JHEP 03 (2021) 105]

- **Signal selection variables**
  - $M_{bc} = \sqrt{(E_{CM}/2)^2 - |\vec{p}|^2}$: beam-energy constrand mass
  - $\Delta E = E_B - E_{CM}/2$
  - MVA training (neural network) output of signal and background MC

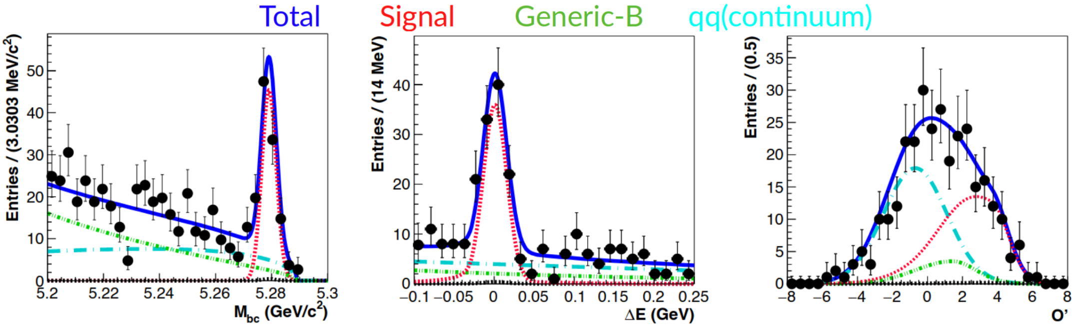


$B^+ \to K^+ e^+ e^-$ distributions

$R(K^+)$ and $R(K_S^0)$ at Belle [JHEP 03 (2021) 105]

Signal selection variables

- $M_{bc} = \sqrt{(E_{CM}/2)^2 - |\vec{p}|^2}$: beam-energy constrand mass
- $\Delta E = E_B - E_{CM}/2$
- MVA training (neural network) output of signal and background MC

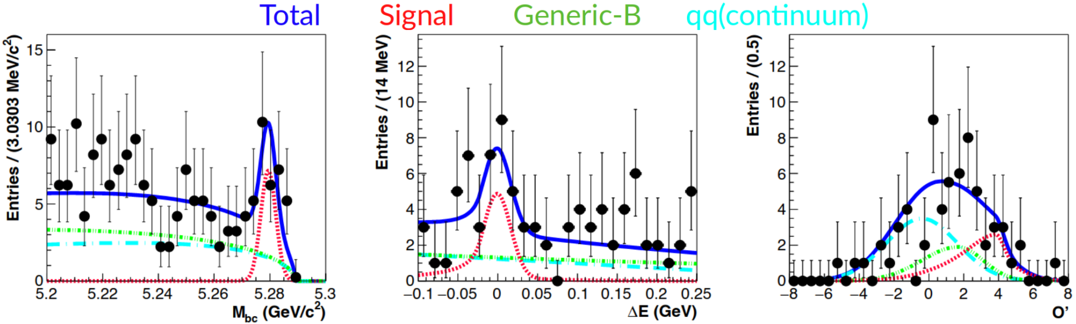


$B^+ \to K^+\mu^+\mu^-$ distributions

$R(K^+)$ and $R(K_S^0)$ at Belle [JHEP 03 (2021) 105]

Signal selection variables

- $M_{\rm bc} = \sqrt{(E_{\rm CM}/2)^2 - |\vec{p}|^2}$: beam-energy constrand mass
- $\Delta E = E_B - E_{\rm CM}/2$
- MVA training (neural network) output of signal and background MC

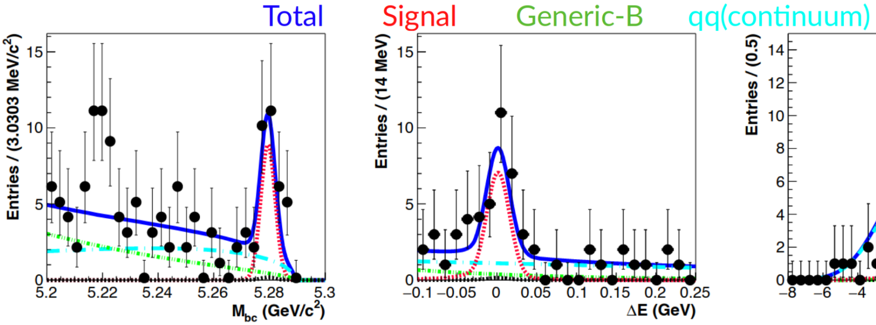


$B^0 \to K_S^0 e^+ e^-$ distributions

$R(K^+)$ and $R(K^0_S)$ at Belle [JHEP 03 (2021) 105]

Signal selection variables

- $M_{bc} = \sqrt{(E_{CM}/2)^2 - |\vec{p}|^2}$: beam-energy constraind mass
- $\Delta E = E_B - E_{CM}/2$
- MVA training (neural network) output of signal and background MC



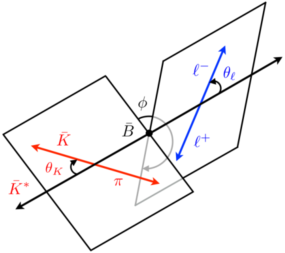
$B^0 \to K^0_S \mu^+ \mu^-$ distributions

$B \to K^* \ell^+ \ell^-$ angular anaylsis at Belle [PRL 118 111801]

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

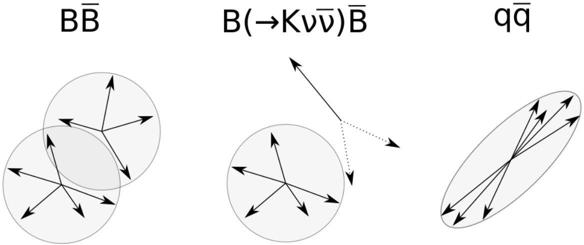
F_L (longitudinal polarization of K^*) and S_i are functions of q^2 only

- **Important cross-check to the $R(K^*)$ anomaly**
- **Two observable P_i' and Q_i**
  - $P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$ [JHEP 05 (2013) 137]
    - Free of form-factor uncertainties
  - $Q_i = P_i'^{\mu} - P_i'^{e}$ [JHEP 10 (2016) 075]
    - Lepton-flavor universality test



$B^+ \to K^+ \nu\nu$ at Belle II: complementary analysis of $R(K^+)$ [PRL 127 181802]

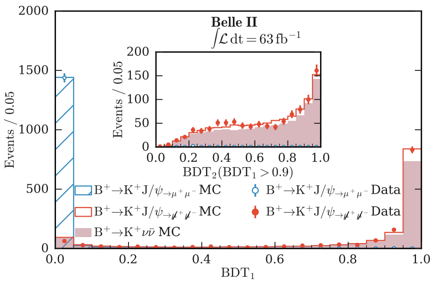
- **Analysis approach: inclusive tagging ← higher efficiency than the other tagging method**
  - Signal side: select the highest p_T track with at least 1 pixel vertex detector hit
  - Tag side: reconstruct rest-of-event (ROE) from all remaining tracks and clusters
  - Prepare BDT traning input variables
    - event shape variables, ROE kinematics, signal B track kinematics, vertexing information

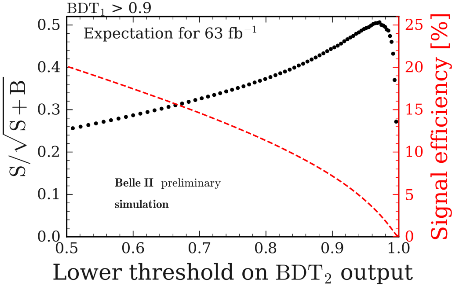


$B^+ \to K^+ \nu\nu$ at Belle II: complementary analysis of $R(K^+)$ [PRL 127 181802]

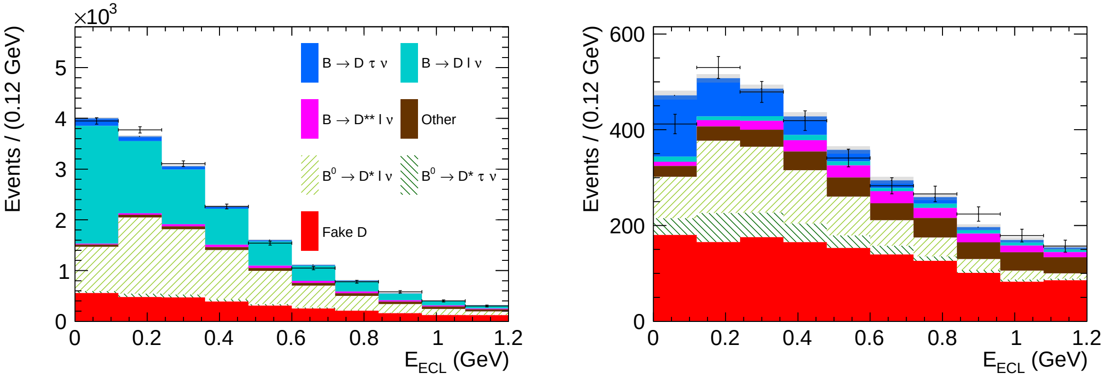
Analysis approach

- Two sequential machine-learning-based selections
  - narrow down the second BDT region from the first one
- Validate BDT output with $B^+ \to J/\psi(\mu^+\mu^-)K^+$ data
  - Background-like channel: just $B^+ \to J/\psi(\mu^+\mu^-)K^+$
  - Signal-like channel: $B^+ \to J/\psi(\mu^+\mu^-)K^+$ ignoring dimuon from J/ψ to mimic missing energy, 3-body like kinematics of K^+



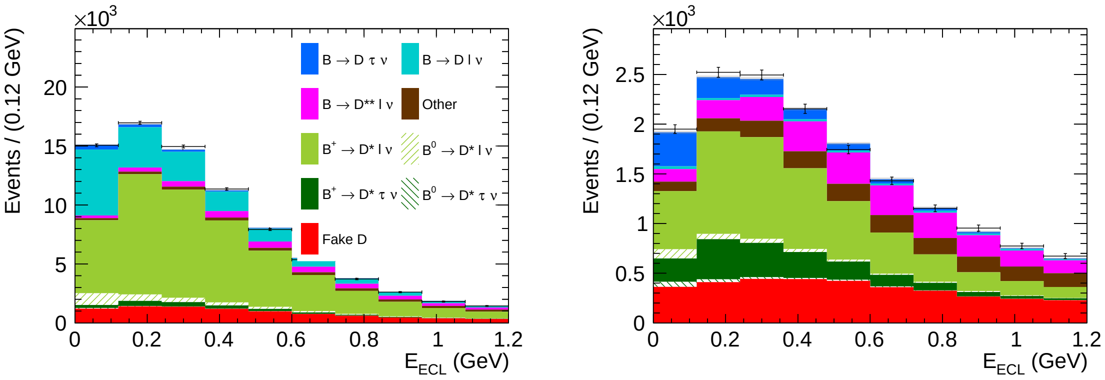


Latest $R(D^{(*)})$ at Belle [PRL 124, 161803 (2020)]



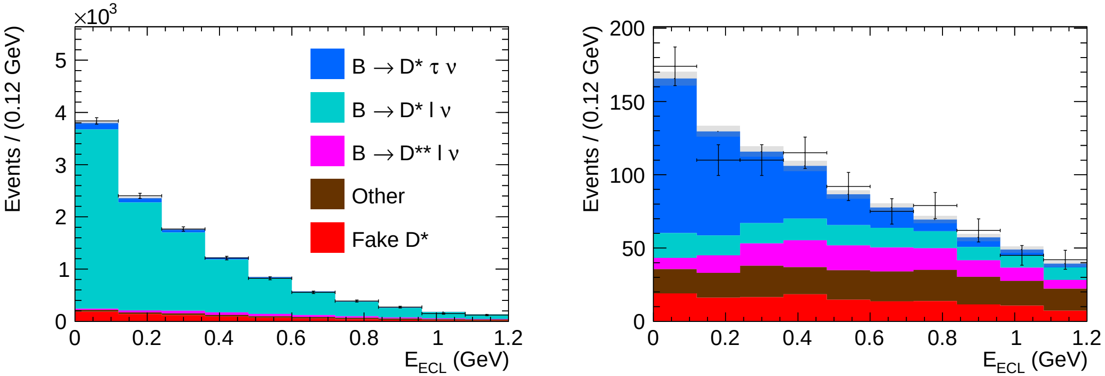
E_{ECL} disbribution of $B^0 \to D^+ \ell^-$ for all O_{cls} (left) and > 0.9 region (right).

Latest $R(D^{(*)})$ at Belle [PRL 124, 161803 (2020)]



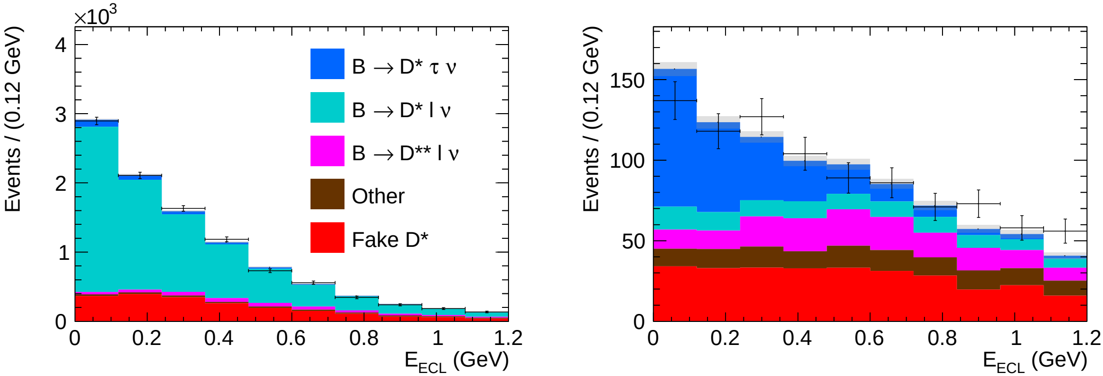
E_{ECL} disbribution of $B^- \to D^0 \ell^-$ for all O_{cls} (left) and > 0.9 region (right).

Latest $R(D^{(*)})$ at Belle [PRL 124, 161803 (2020)]



$E_{\rm ECL}$ disbribution of $B^0 \to D^{*+}\ell^-$ for all $O_{\rm cls}$ (left) and > 0.9 region (right).

Latest $R(D^{(*)})$ at Belle [PRL 124, 161803 (2020)]



E_{ECL} disbribution of $B^- \to D^{*0}\ell^-$ for all O_{cls} (left) and > 0.9 region (right).

Invisible Z' search at Belle II [PRL 124 141801]

- **Background suppression: $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^-\mu^+\mu^-$ (e^+e^-: out of acceptance), $\tau^+\tau^-(\gamma)$**
  - Central drift chamber two-track trigger (including azimuthal opening angle $> 90°$)
    - With Bhaha scattering rejection
  - Recoil momentum only with EM calorimeter barrel direction
  - EM calorimeter based PID (no K_L/μ detector at the time)
    - $\mu^{\pm}$: $0.15 < E < 0.4$ GeV, $E/p < 0.4$
    - $e^{\pm}$: $E > E1.5$ GeV, $0.8 < E/p < 1.2$
    - E: measued by EM calorimeter, p: measured by drift chamber
  - No photon around recoil momentum dirrection
  - No π^0 candidate
  - Total photon energy < 400 MeV
  - Transverse momentum (recoil and lepton pair) based selection (see main slide)