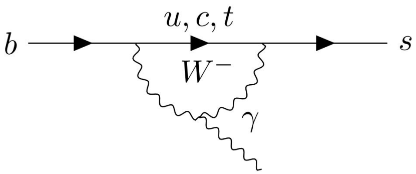
Probing radiative and electroweak penguins at Belle II

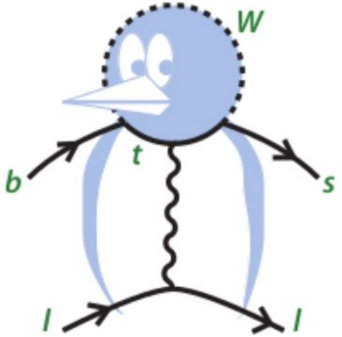
Soumen Halder
On behalf of TIFR Belle (II) group

BSM search via rare B decays

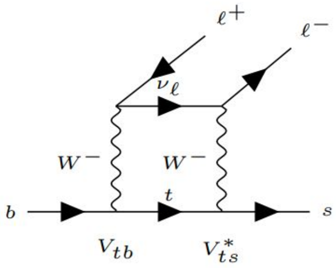
- b ↠ s (d) is an FCNC transition, which is not allowed at tree level in the standard model (SM)
  - both loop and CKM suppressed (BF ~ 10^{-6})
- BSM models allowing FCNC at tree level or new particles appearing in loop can change decay branching fractions and/or other observables



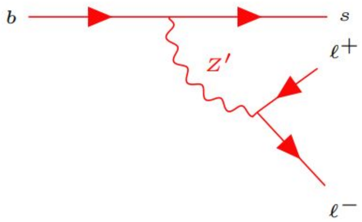
EW radiative penguin



$b \to s\ell\ell$ (EW penguin)



$b \to s\ell\ell$ (box diagram)

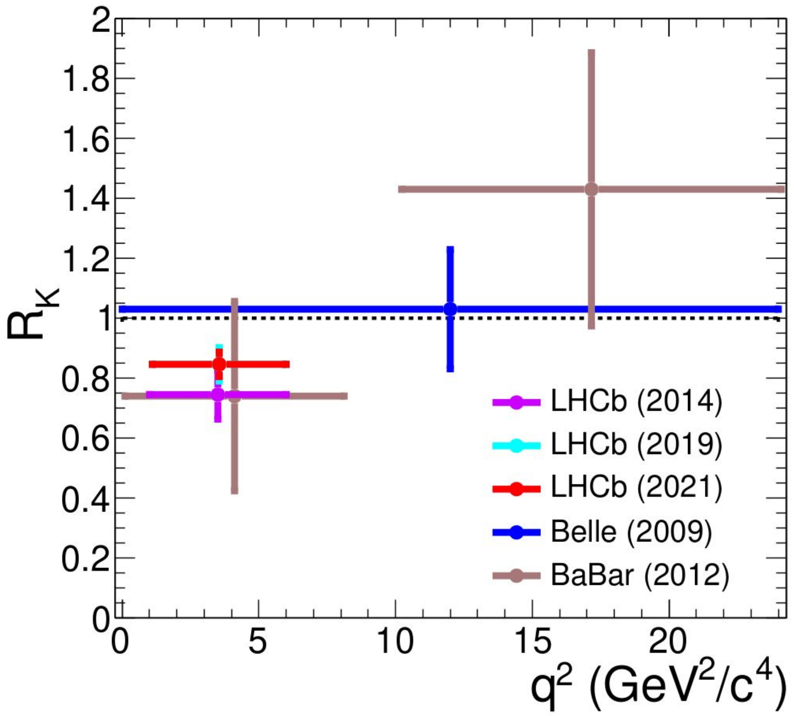


A possible BSM model diagram (Z' model)

Lepton family universality test

$$R_K[q_0^2, q_1^2] = \frac{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B\to K\mu^+\mu^-)}{dq^2}}{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B\to Ke^+e^-)}{dq^2}}$$

- In SM gauge bosons couple equally to different lepton flavours.
- Precise prediction of R_K ratios in SM (~1%).
- Results are mostly driven by LHCb
- Away from SM by 3.1 standard deviations at the low q^2 bin



- Angular observables like P_5' expected to be theoretically robust[1]
- Tension in this variable 2.9σ (LHCb measurement[2])
- Belle[3] has already measured for both electron and muon mode,
  - Bonus LFU observables : $Q_5 = P_5'^{\mu} - P_5'^{e}$

[1] JHEP 05 (2013) 137
[2] PRL 125, 011802 (2020)
[3] PRL 118, 111801 (2017)

Asymmetry measurement

$$A_{\mathrm{CP}} = \frac{\Gamma(\bar{B}\to\bar{K}^*\gamma)-\Gamma(B\to K^*\gamma)}{\Gamma(\bar{B}\to\bar{K}^*\gamma)+\Gamma(B\to K^*\gamma)}$$

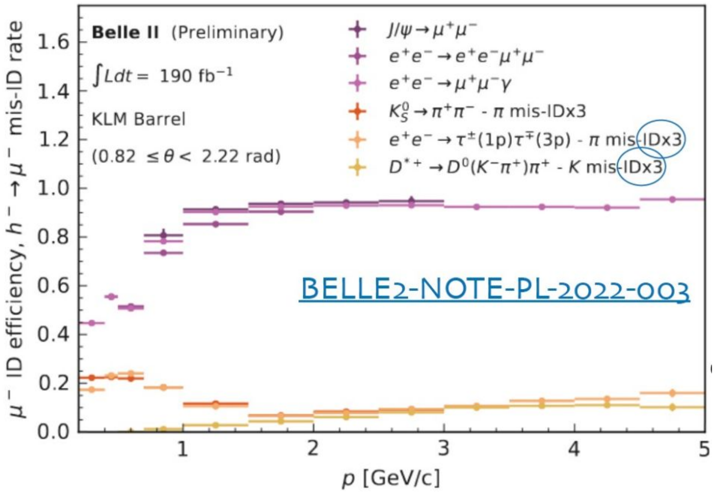
$$\Delta_{+0} = \frac{\Gamma(B^0\to K^{*0}\gamma)-\Gamma(B^+\to K^{*+}\gamma)}{\Gamma(B^0\to K^{*0}\gamma)+\Gamma(B^+\to K^{*+}\gamma)}$$

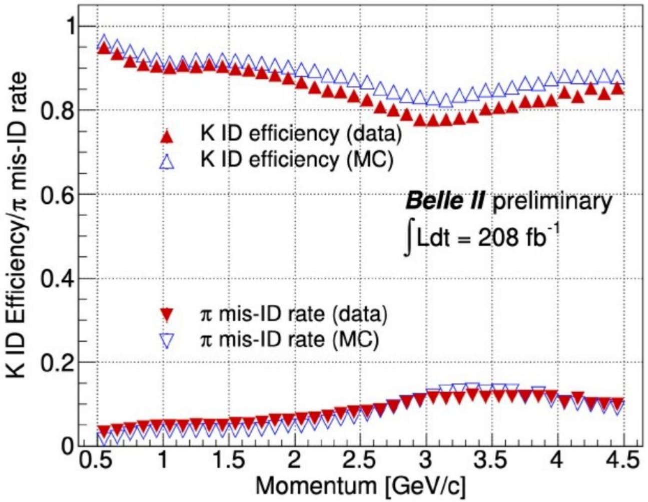
- SM prediction of branching fraction suffers from large uncertainties due to form factors.
- Observables like CP (A_{cp}) and isospin (Δ_{+o}) asymmetries are theoretically clean due to cancellation of these form factors.

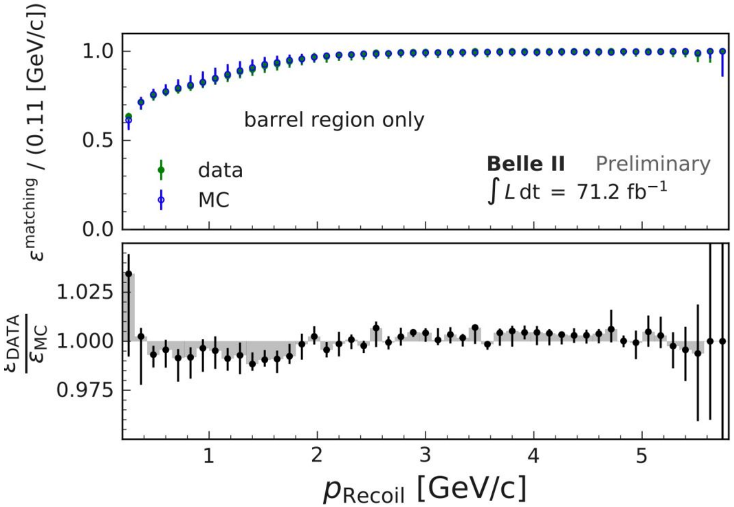
- The latest measurement by Belle[1] found evidence of isospin violation at a significance of 3.1 standard deviations.
- Inclusive measurements[2,3] of B → $X_s\gamma$ provide a strong constraint on the charged Higgs mass[4]
    - $M(H^+) > 580$ GeV at 95% CL

[1] T. Horiguchi et. al. Phys. Rev. Lett. 119 (2017) 19, 191802
[2] Phys. Rev. D 91 052004 (2015), [3] arXiv: 1608.02344
[4] O. Deschamps et al. Phys. Rev. D 82 073012 (2010)

Belle II performance



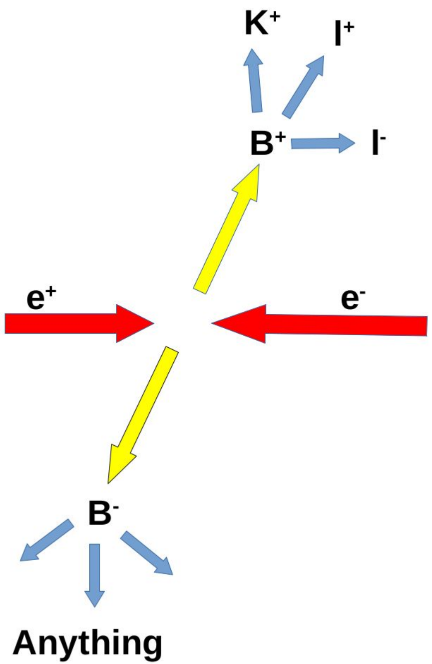




- Good performance for lepton and hadron ID, as well as for photon reconstruction
- Still room for improvement, to be achieved with larger dataset

B meson reconstruction

A schematic B → Kll event at Belle II



- Selecting final-state particles :
  - Charged track candidates are identified using the information from particle identification subdetectors
  - γ candidates are reconstructed from ECL clusters with several shower shape variables

- Composite particles:
  - K^*, Ks candidates are reconstructed by combining 4 momenta of their final-state decay products.
  - Further selection on the invariant mass, vertex fit quality variables etc. applied
  - For exclusive analysis, we use following two kinematic variables to select B candidates

$$\Delta E = E_B^* - E_{\text{beam}}^*$$

$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$$

Major backgrounds: a quick glance

Background event	Nature	Suppression strategy
Continuum ($e^+e^- \rightarrow q\bar{q}$)	Combinatorial	BDT based MVA

$B \rightarrow K^*\gamma$

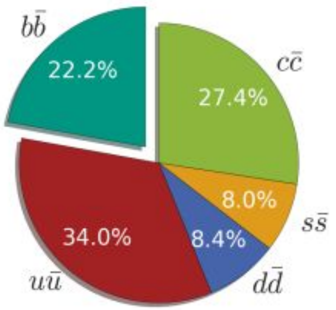
π^0/η faking γ candidate	Peaking	BDT based MVA
$B \rightarrow X_{s+d}\gamma$	Peaking	Irreducible background
$B \rightarrow K^{*n}\gamma$	Peaking	Irreducible background

$B \rightarrow Kll$

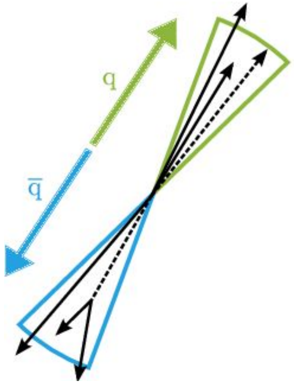
$B \rightarrow J/\psi K$	Peaking	Mass veto
Semi-leptonic B decays	Combinatorial	BDT based MVA
$\pi^0 \rightarrow e^+e^-\gamma$ and $\gamma^* \rightarrow e^+e^-$	Combinatorial	Mass veto
$B \rightarrow D(K\pi)\pi$	Peaking	Mass veto
$B \rightarrow K^*\pi$ and $B \rightarrow K\rho$	Peaking	Irreducible background

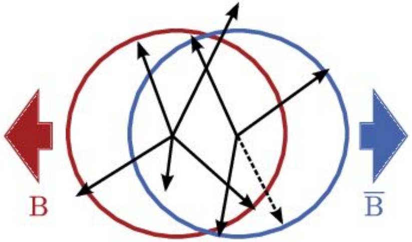
Continuum ($q\bar{q}$) background and its suppression

Event shape variables as the discriminator

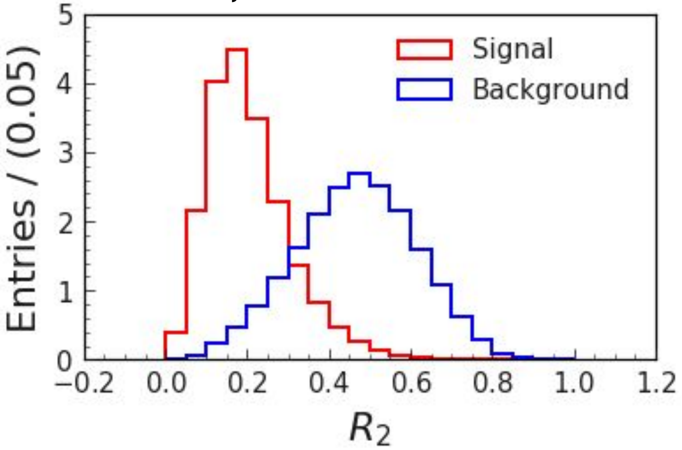


- Boosted decision tree (BDT) to suppress background from light quark (u, d, s and c) events, denoted as qq
- The BDT was trained using variables exploiting the topological differences between signal and background events.

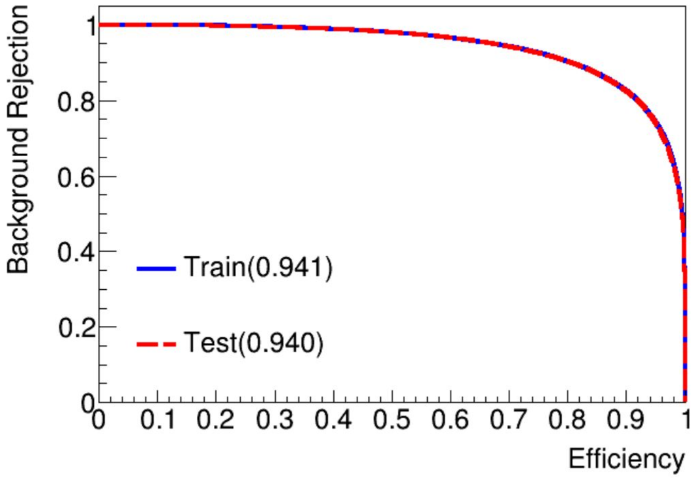


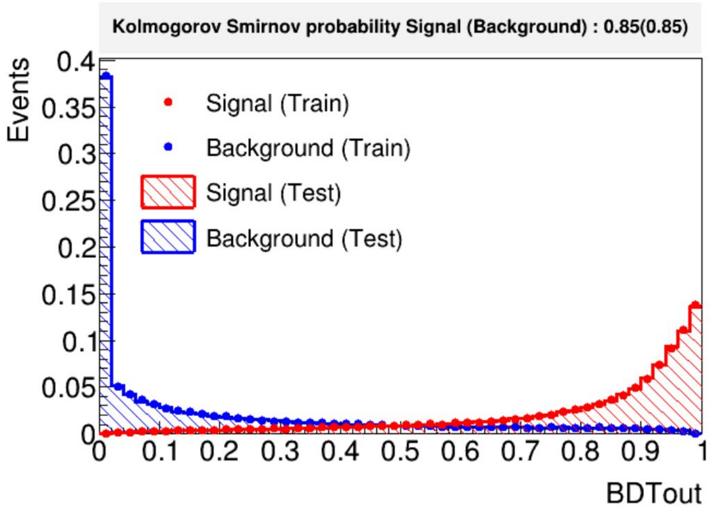


Example of a discriminating variable R_2 (Ratio of second to zeroth order Fox-Wolfram moments)



Performance of the MVA

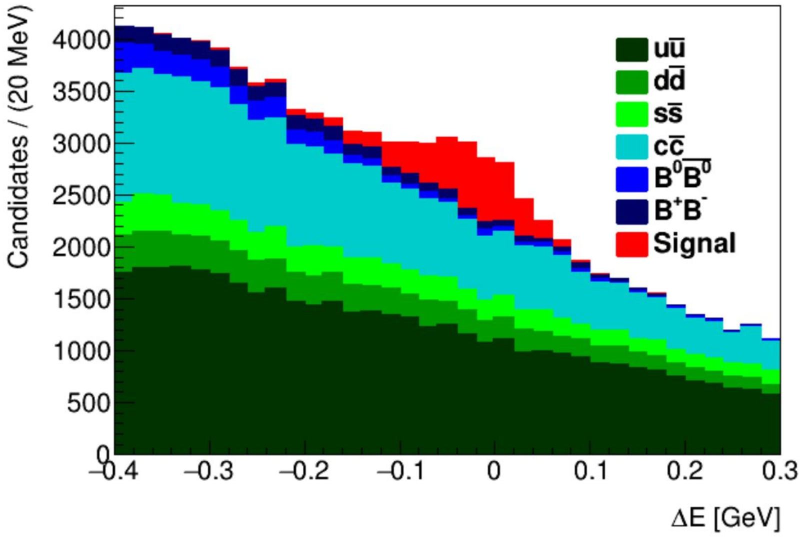




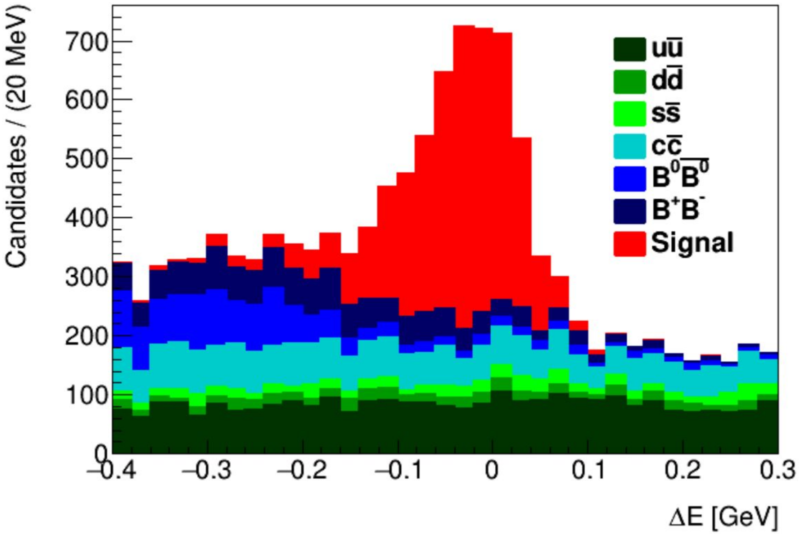
- Independent classifiers are used to train each mode separately
- ROC integral for both signal and background are almost same (no overtraining)

Optimization of BDT cut to suppress background

Before BDT cut



After BDT cut



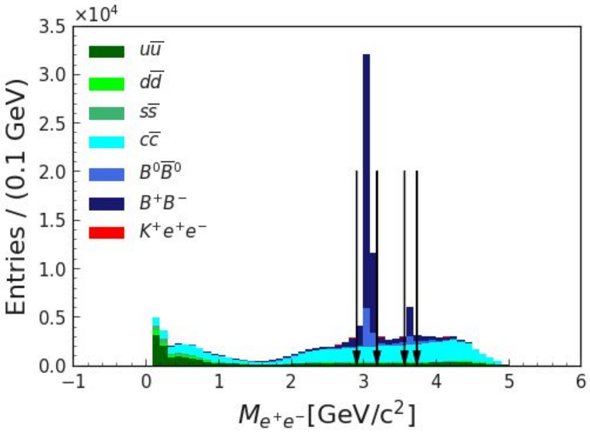
- Optimize the FOM = S/ √(S+B) in signal region
- More than 90% background suppressed at the cost of 7-15% signal.

Other background suppression

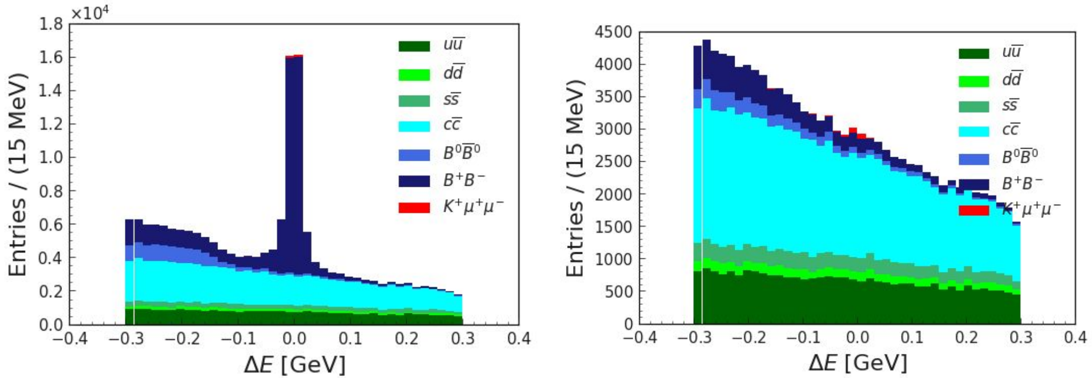
Backgrounds suppression for B → Kll

- ΔE and M_{bc} help to distinguishing various combinatorial backgrounds
- Typically ΔE ϵ [-0.3, 0.3] GeV and M_{bc}ϵ[5.2,5.29] GeV/c² applied
- Further cuts are applied depending on the mode and signal extraction procedure.

B → J/ψK bkg can be removed by veto on M_{ll} around ψ (1S/2S) nominal mass

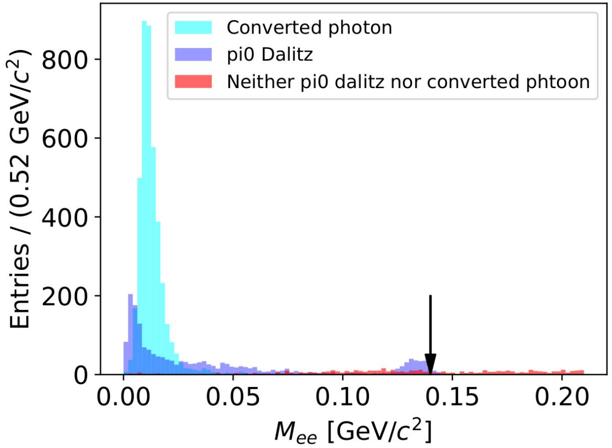


Distribution of ΔE before (left) and after (right) ψ(1S/2S) veto

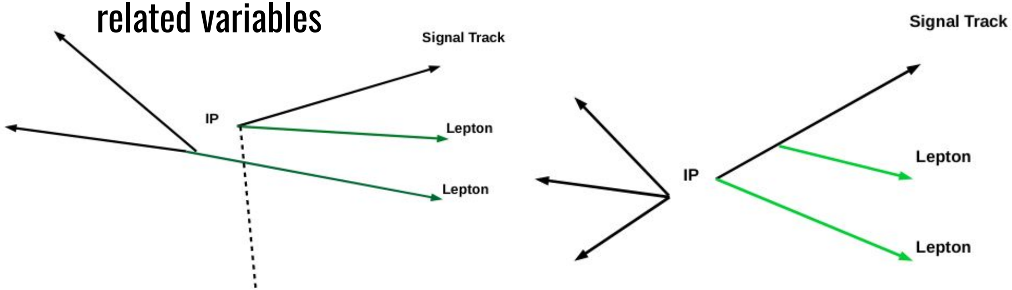


Backgrounds suppression for B $\rightarrow$ Kll: contd..

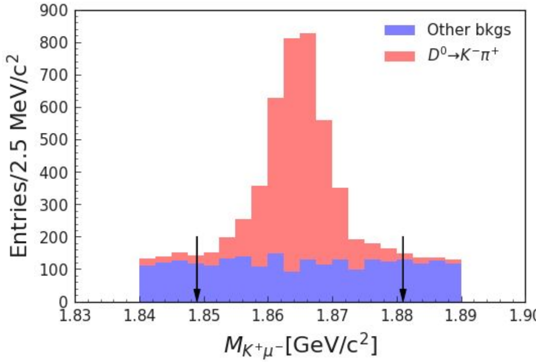
M_{ee} > 0.14 GeV/c^2 is applied to suppress $\pi^0 \rightarrow e^+e^-\gamma$ Dalitz decay and photon conversion events.



Event topology for semileptonic $B \rightarrow D^{(*)} l \nu$ background. They are suppressed by MVA with the help of vertex related variables



$B^- \rightarrow D^0\, [K^- \pi^+]\pi^-$ where π^+ (π^-) misidentified as μ^+(μ^-).



- $B \rightarrow KJ/\psi(\mu\mu)$ where μ^+ (μ^-) misdentified as K^+ (K^-) and vice versa $\Rightarrow$ double misID
- Reduce contamination from $B \rightarrow K^*\ell\ell$ events by requiring $\Delta E > -0.1$ GeV

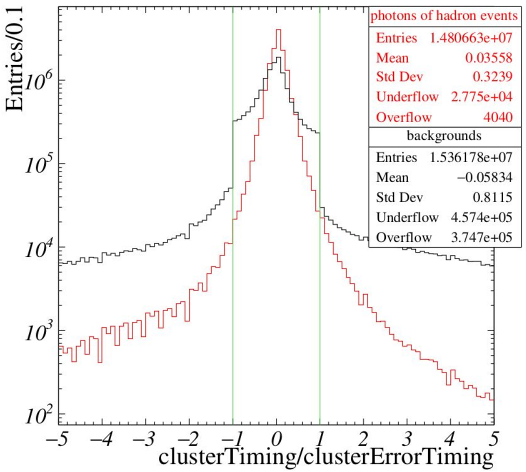
Background suppression for $B \to K^*\gamma$

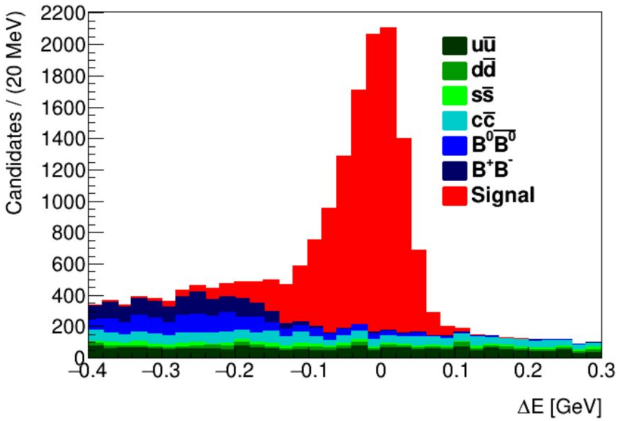
Asymmetric decays of $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ where the hard gamma fakes signal candidate.

MVA trained to discriminate photons coming from hadronic B decays vs. π^0/η

Mbc peaking backgrounds

- Quark fragmentation channels $B^+ \to X_{su}^+\gamma$ and $B^0 \to X_{sd}^0\gamma$
- Self-crossfeed signal events
- Decays of higher resonances like $K_n^*\gamma$
- Events evading the π^0/η veto (MVA classifier)



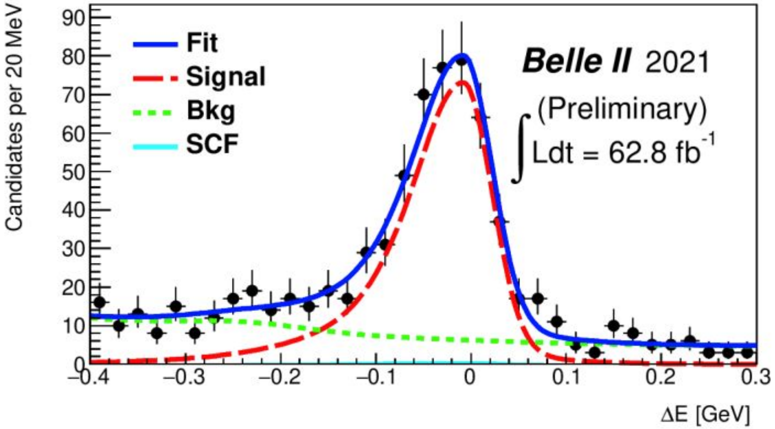


Distribution of ΔE after applying all the cut for $B^0 \to K^{*0}(K^+\pi^-)\gamma$

Signal extraction

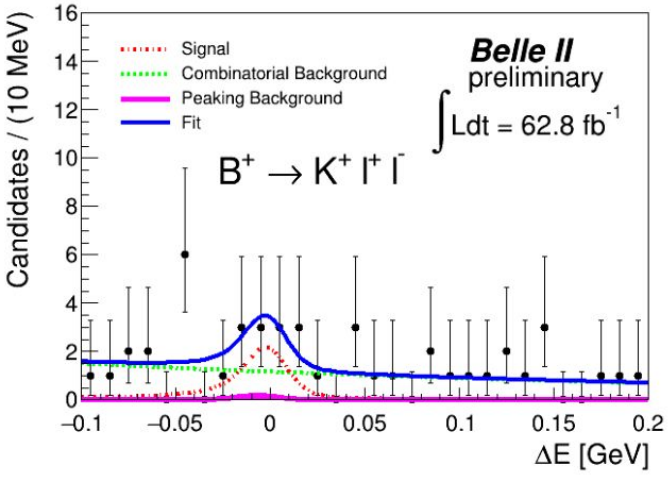
Signal extraction for $B \to K^*\gamma$

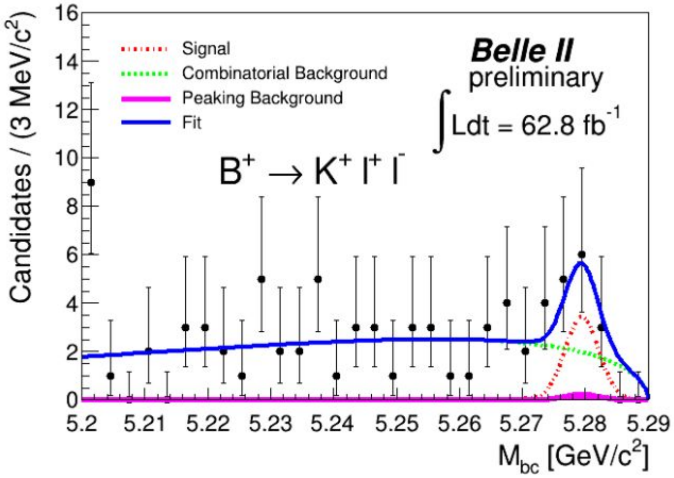
- Signals are extracted using an unbinned maximum likelihood fit to ΔE–M_{bc} 2D distribution (**Kll** and **K^*ll**)or to the ΔE distribution with signal-region criteria applied on M_{bc} (**$K^*\gamma$**)
- Signal, background and peaking (SCF) are three components in likelihood fit



Fit to data ΔE distribution for $B^0 \to K^{*0}(K^+\pi^-)\gamma$. This result is approved by Belle II and published in arxiv-2110.08219

Signal extraction for B → Kll



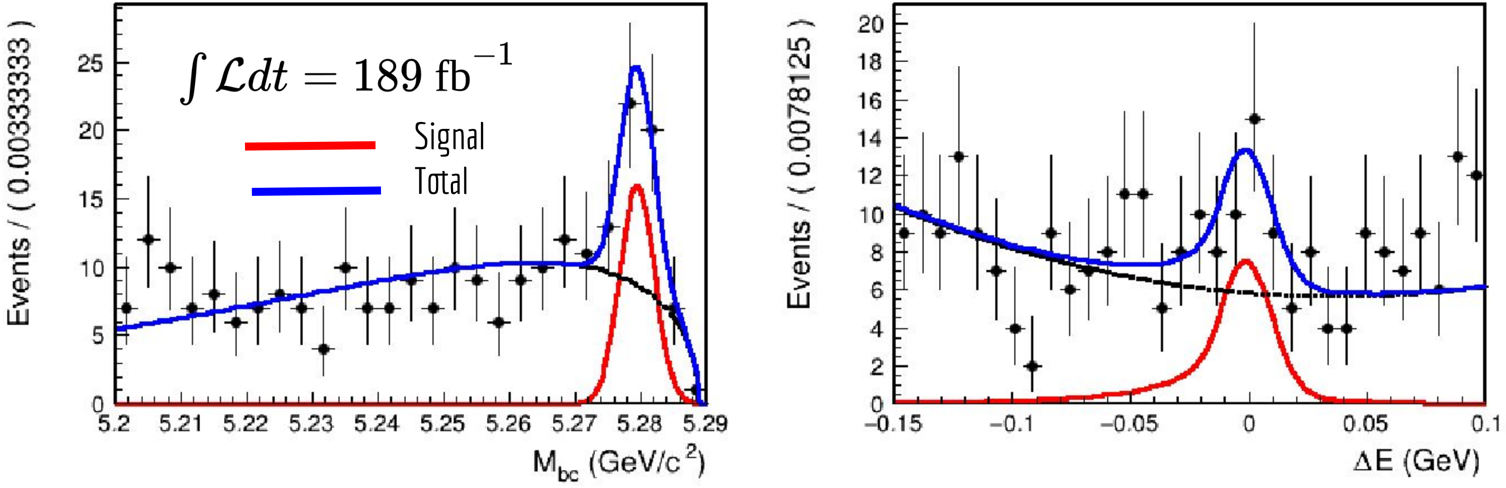


Signal enhanced projection of 2D fit along ΔE (left) and M_{bc} (right). $\Delta E \in [-60, 40]$ MeV applied while plotting M_{bc}, and $M_{bc} \in [5.27, 5.29]$ GeV/c² applied while plotting ΔE

- Signal yield: $8.6\ ^{+4.3}_{-3.9} \pm 0.4$ (statistical and systematic uncertainty).
- Significance: 2.7 standard deviations

This result was shown in Moriond QCD (2021)

Signal extraction for B → K*ll



$$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6}$$
$$\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6}$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$$

- Measurement is limited by sample size
- N_{BB} and π^0 identification are the most dominant systematic uncertainty (~3%)

This result was shown in Moriond EW (2022)

Observable calculation

Branching Fraction

For calculating the branching fraction in data, we use the following relation:

$$\mathcal{B} = \frac{\text{Yield}}{N_{B\overline{B}} \times 2 \times f^{+-/00}\,(f^{00/+-}) \times \epsilon}$$

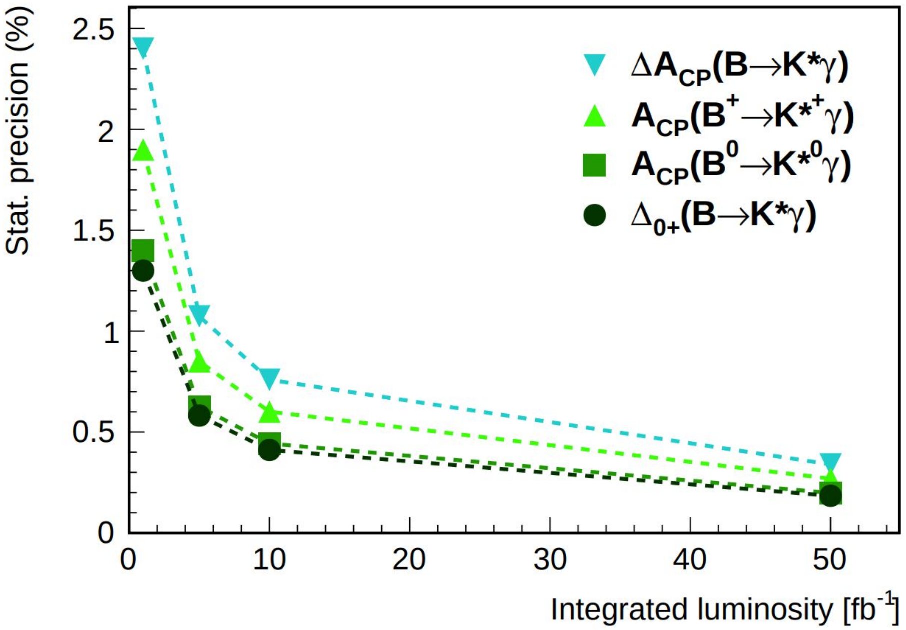
- N_{BB} : Number of BB pairs, for the current dataset
- ϵ: $\epsilon_{MC} \times f_{data/MC}$,
  - ϵ_{MC} is selection efficiency in MC
  - $f_{data/MC}$ is correction between data and MC through particle ID, MVA classifier efficiency etc.

Mode	Signal yield	Signal efficiency (%)	B.F (Fit) $\times 10^{-5}$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	454 ± 28	15.2	$4.5 \pm 0.3 \pm 0.2$
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$	50 ± 10	1.7	$4.4 \pm 0.9 \pm 0.6$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	169 ± 18	4.8	$5.0 \pm 0.5 \pm 0.4$
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$	160 ± 17	4.2	$5.4 \pm 0.6 \pm 0.4$

MVA selection, π^0/η selection are the dominant source of systematics (~4%)

Results are consistent with PDG within uncertainty

Future prospects (radiative B decays)

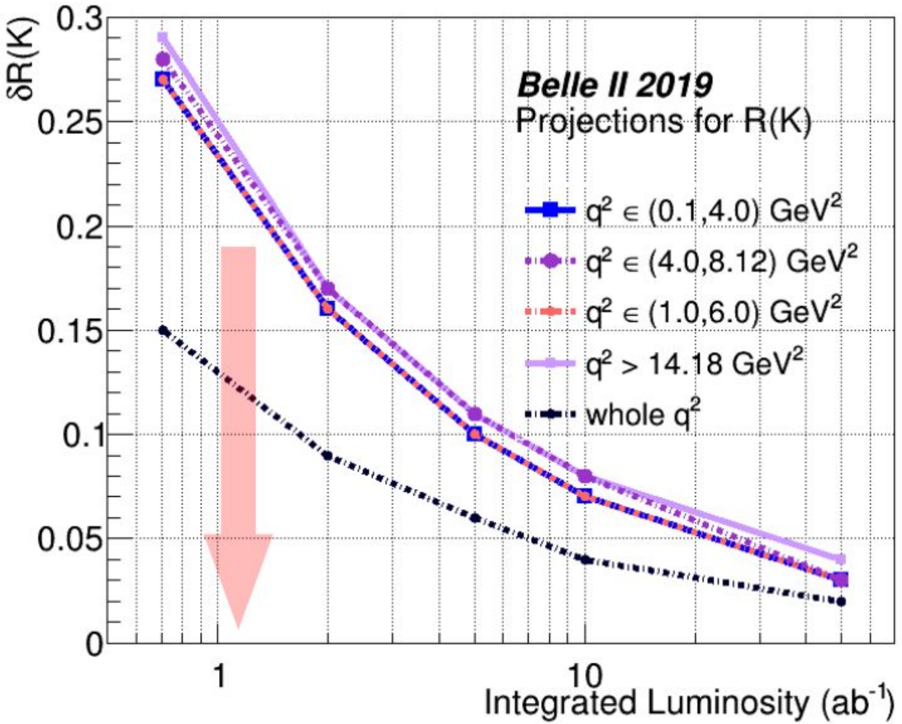


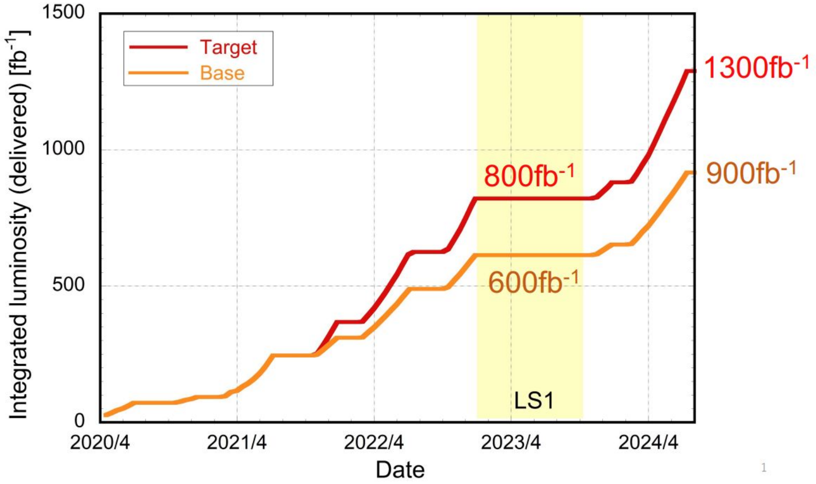
Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

Observable	Belle II (50 ab^{-1}) Stat.	Belle II (50 ab^{-1}) Syst.
$\Delta_{0+}(B \to K^*\gamma)$	0.20%	0.30%
$A_{cp}(B^+ \to K^{*+}\gamma)$	0.20%	0.20%
$A_{cp}(B^0 \to K^{*0}\gamma)$	0.30%	0.15%
$\Delta A_{cp}(B \to K^*\gamma)$	0.30%	0.25%

- Major source of improvement in systematics uncertainty at Belle II: photon reconstruction (2% → <1%)

Future prospects (R_K)





- Belle has collected 712 fb^{-1} data during its lifetime
- By the long shutdown (June 2022), Belle II will collect roughly similar dataset.
- Combining both the data samples, we expect to provide a competitive result for R_K

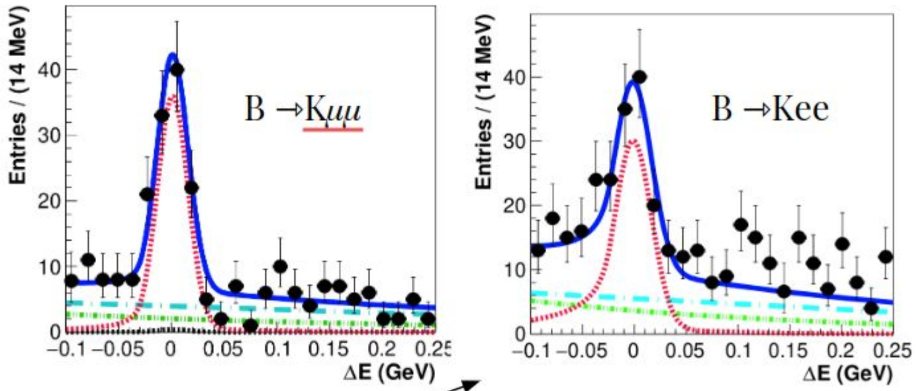
Summary

- Focused on some recent Belle II EWP studies where our group has directly contributed
- Clean environment at Belle II grants us access to unique observables in rare B decays
- Belle II has continued to record data during Covid-19 pandemic
- Stay tuned for interesting results from Belle II

Thank you for attention

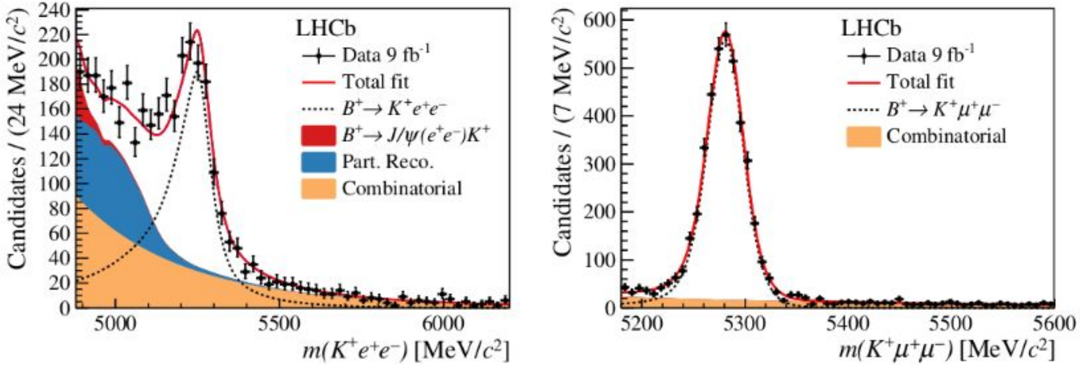
Backup

Advantages of LFV analyses @e^+e^- collider



- Electron and muon has almost similar efficiency
- All R_{K*} and R_{Xs} are possible to measure at Belle II

Belle result
JHEP 03 (2021) 105



LHCb result
Nature Phys. 18 (2022) 3