RESULTS AND PROSPECTS OF RADIATIVE AND ELECTROWEAK PENGUIN DECAYS AT BELLE II

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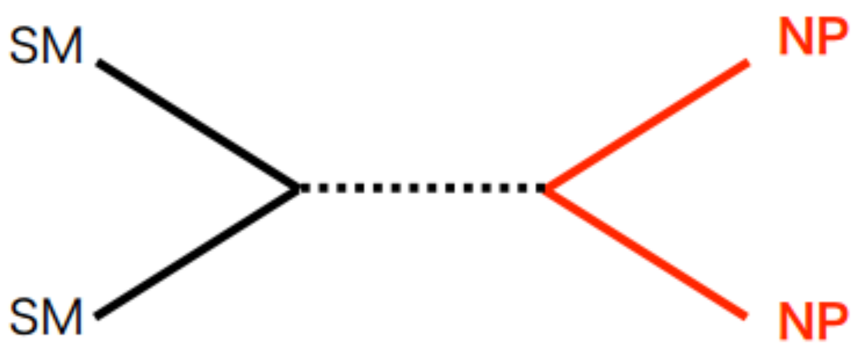
OVERVIEW

- New Physics Search
- Belle II data taking
- Radiative penguin B decay
    - Analysis strategy
    - Observables
- Semi-leptonic penguin B decay
    - Angular analysis
    - Lepton universality test
    - $B \to K^{(*)}\nu\bar{\nu}$ prospects
- Summary

NEW PHYSICS SEARCH

Energy frontier

~direct approach~

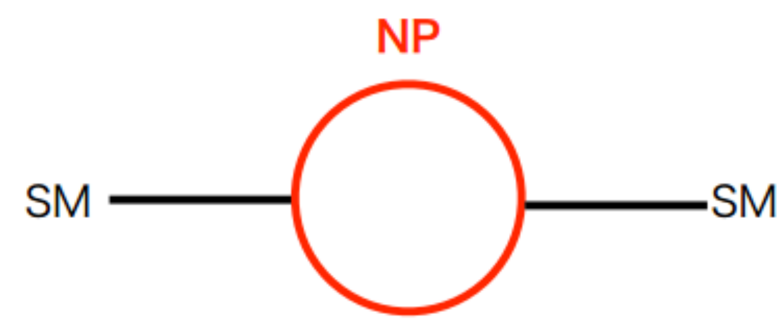


- Directly produce new physics particle using high energy collisions
- Sensitive to energy scale of new physics
- Limited by energy availability in CMS frame

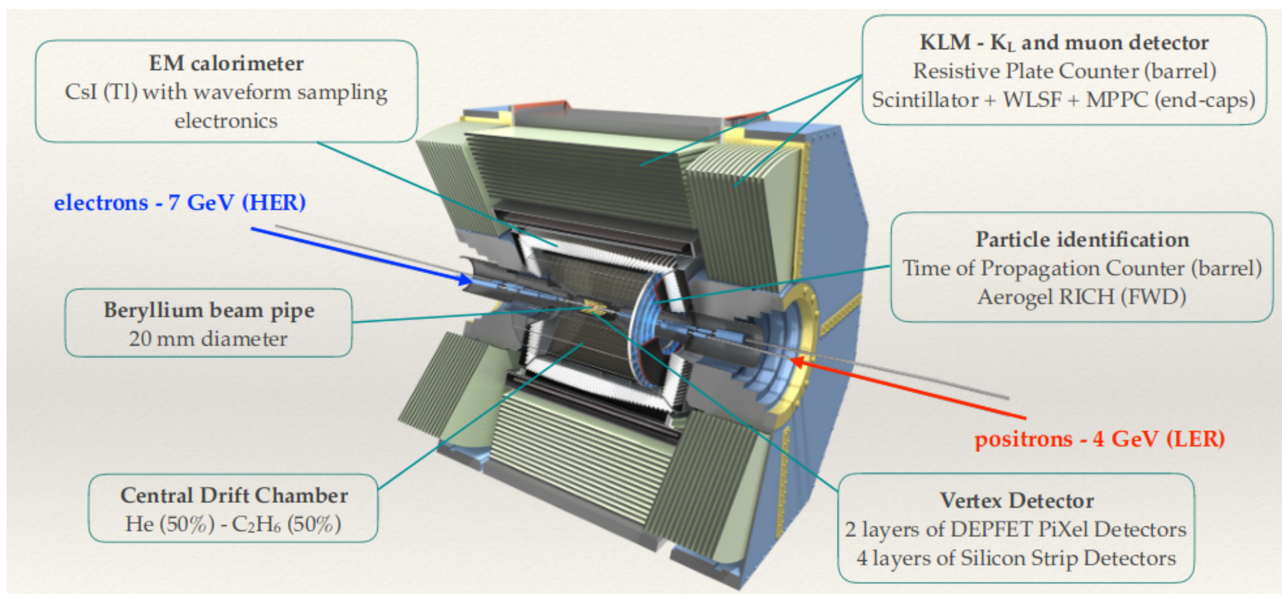
CMS is a energy frontier experiment

Luminosity frontier

~indirect approach~



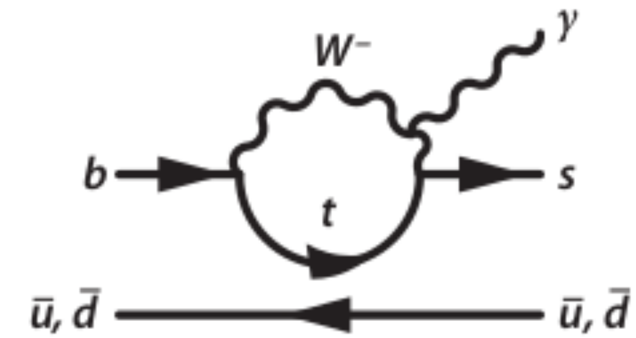
- Find `indirect' sign of NP particles in the quantum loop
- Sensitive to Flavour structure of new physics
- Limited by integrated luminosity in probing rarer process

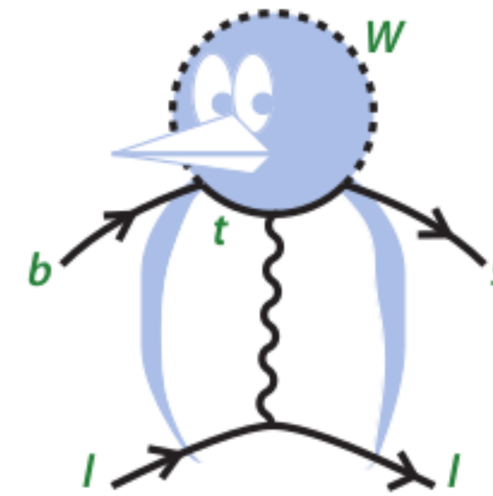


Belle II is a luminosity frontier experiment

NEW PHYSICS SEARCH THROUGH EWP B MESON DECAY

- $b \to s(d)$ is FCNC which is not allowed in Tree level in SM (Loop suppression and CKM suppression)
- Being rare nice probe to new physics
- NP can appear in loop, change BR or other observables



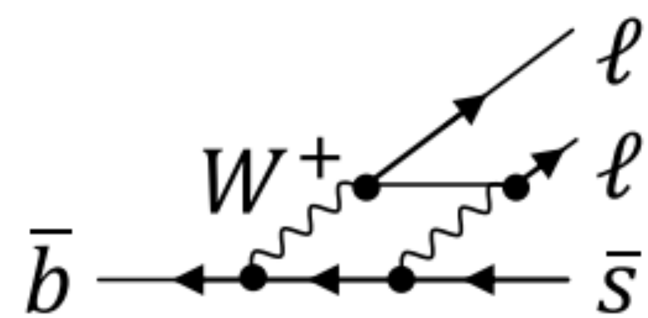


<u>Effect Field theory approach</u>

$$\mathcal{H}_{\text{eff}} = \sum_i \lambda^i_{CKM} C_i(\mu) Q_i(\mu) + \text{h.c}$$

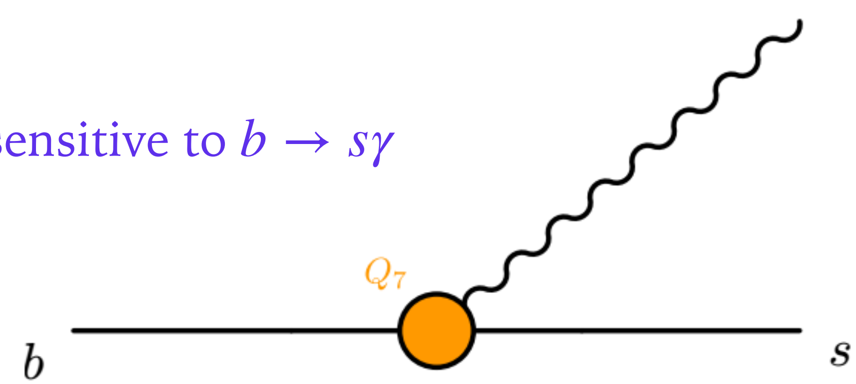
- $C_i(\mu)$: Short distance contribution (Physics above EW scale)
- $Q_i(\mu)$: Local operators constructed from field below EW scale, encode large distance contribution

- NP can contribution
  1. $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$
  2. Generate new operators not present in SM

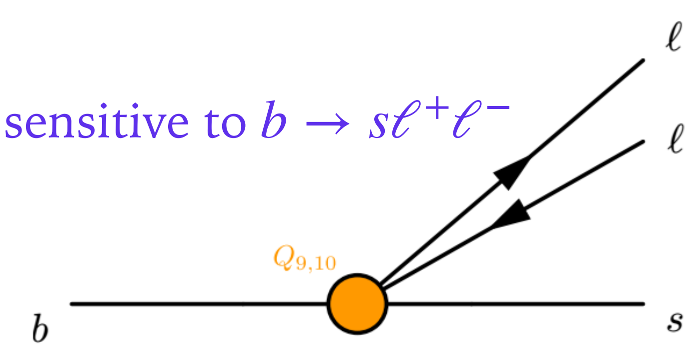


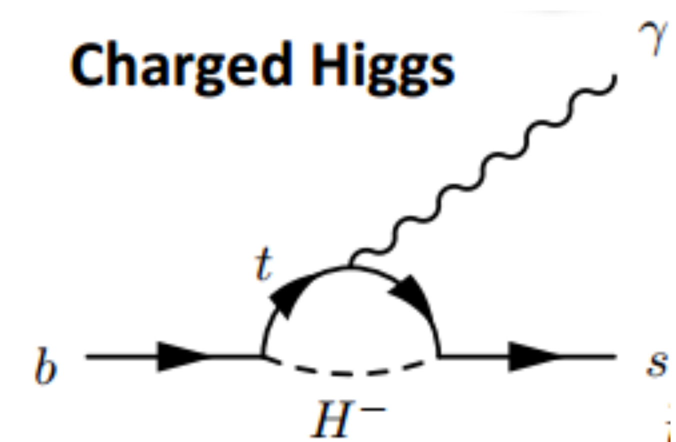
$\ell \leftrightarrow \nu$ to get $b \to s\nu\bar{\nu}$

sensitive to $b \to s\gamma$



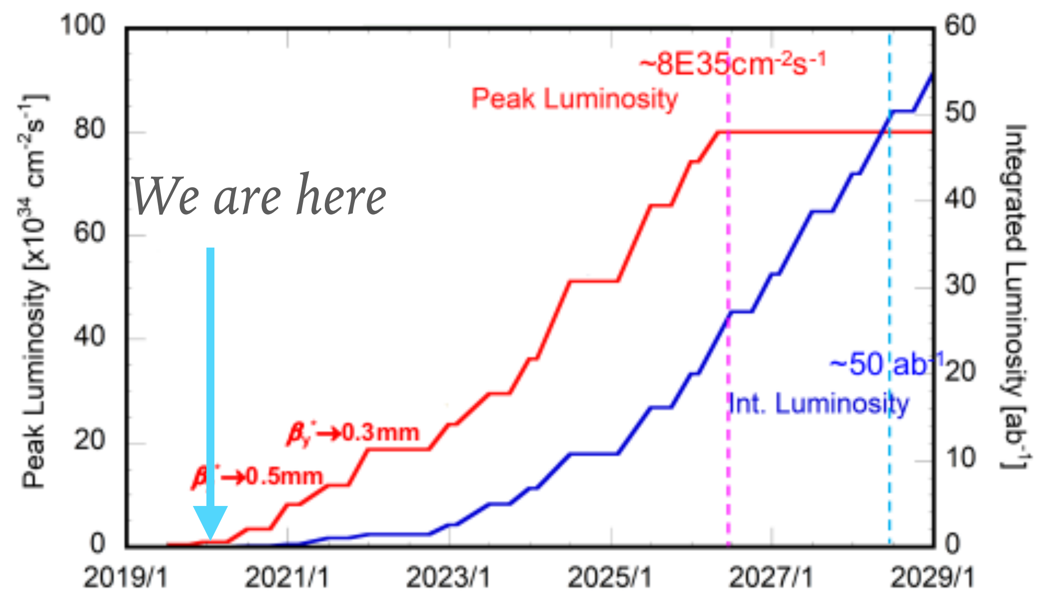
sensitive to $b \to s\ell^+\ell^-$

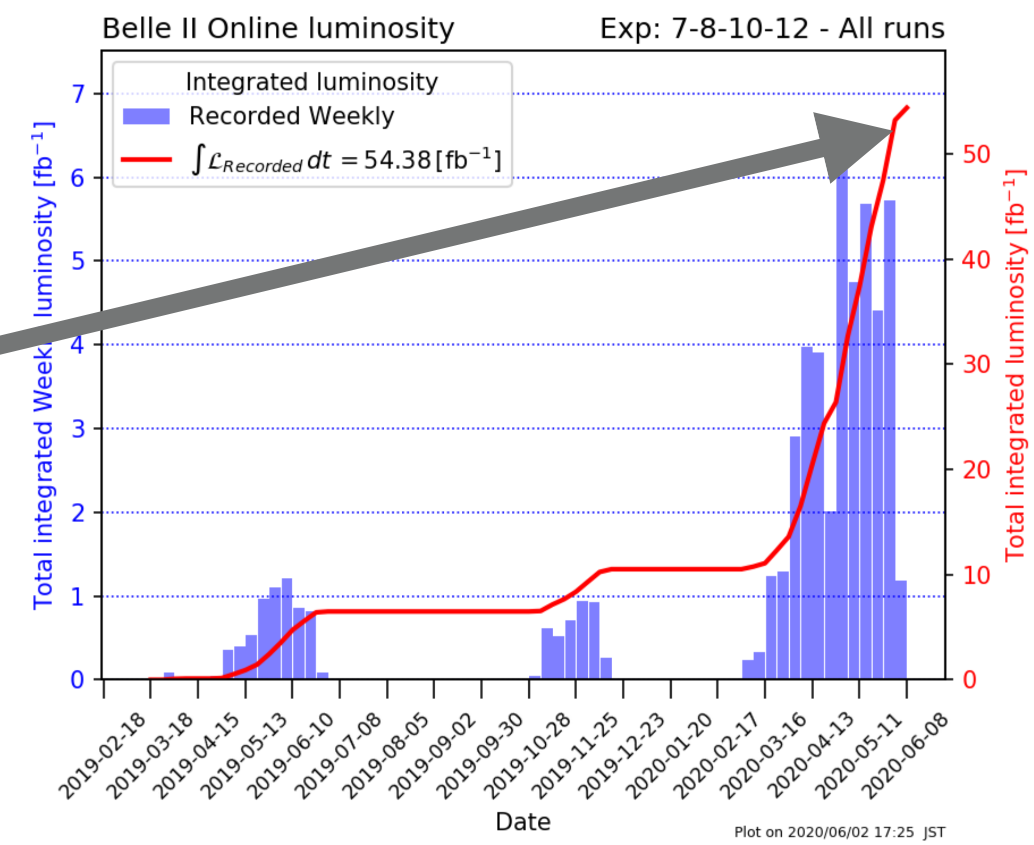




SUPERKEKB AND BELLE II OPERATION

First collisions: 26th April 2018



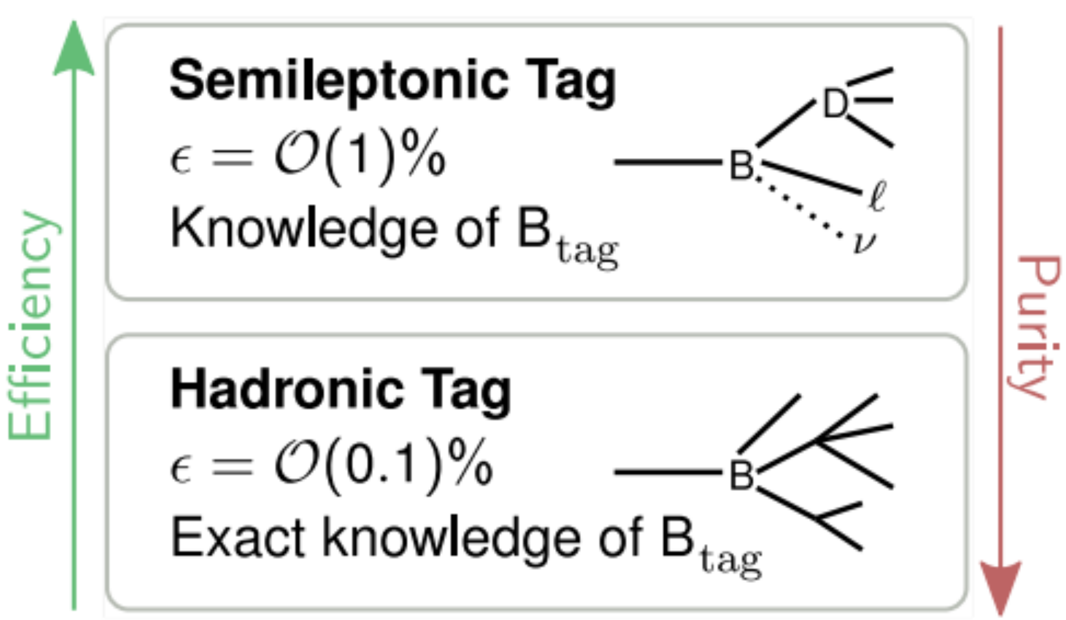


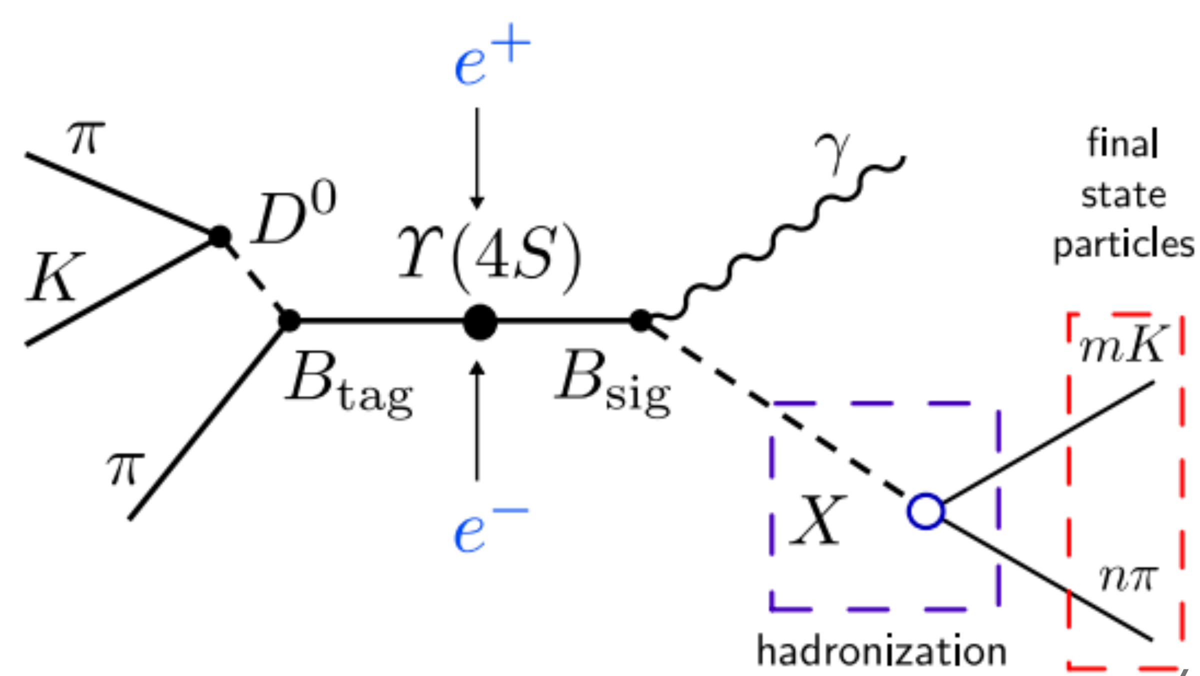
- Collected 0.5 fb^{-1} in 2018
- Collected about 55 fb^{-1} since 2019

Goal: integrate upto 50ab^{-1} by 2029

RADIATIVE PENGUIN: ANALYSIS STRATEGY

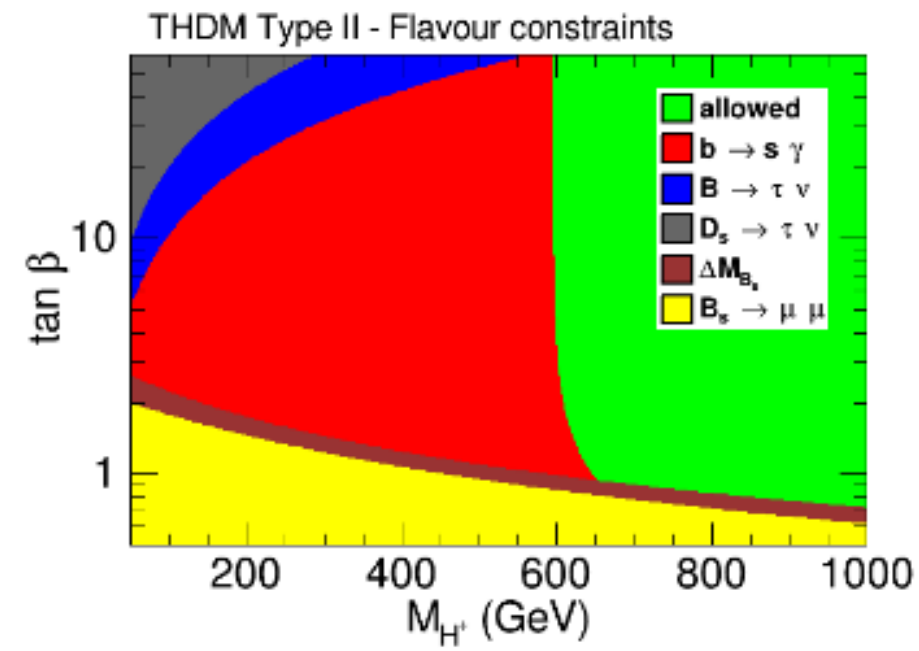
- Exclusive: Reconstruct specific decay channel say, $B \to K^*\gamma$. Theory uncertainty is relatively larger.
- Inclusive: Reconstruct $B \to X_s\gamma$, as example
  - Fully inclusive: Info about X_s (not reconstructed explicitly) provided by tag side B. Thanks to the clean $e^+ - e^-$ collider.
    - Hadronic tag: Fully reconstruct tag B from hadronic final state. Statistically limited, Hope on Belle II.
    - Semi-leptonic tag: Fully reconstruct tag B from semi-leptonic decay
  - Sum-of-exclusive: Reconstruction of X_s from as many final states as possible. Tag info not needed to determine flavour or charge.

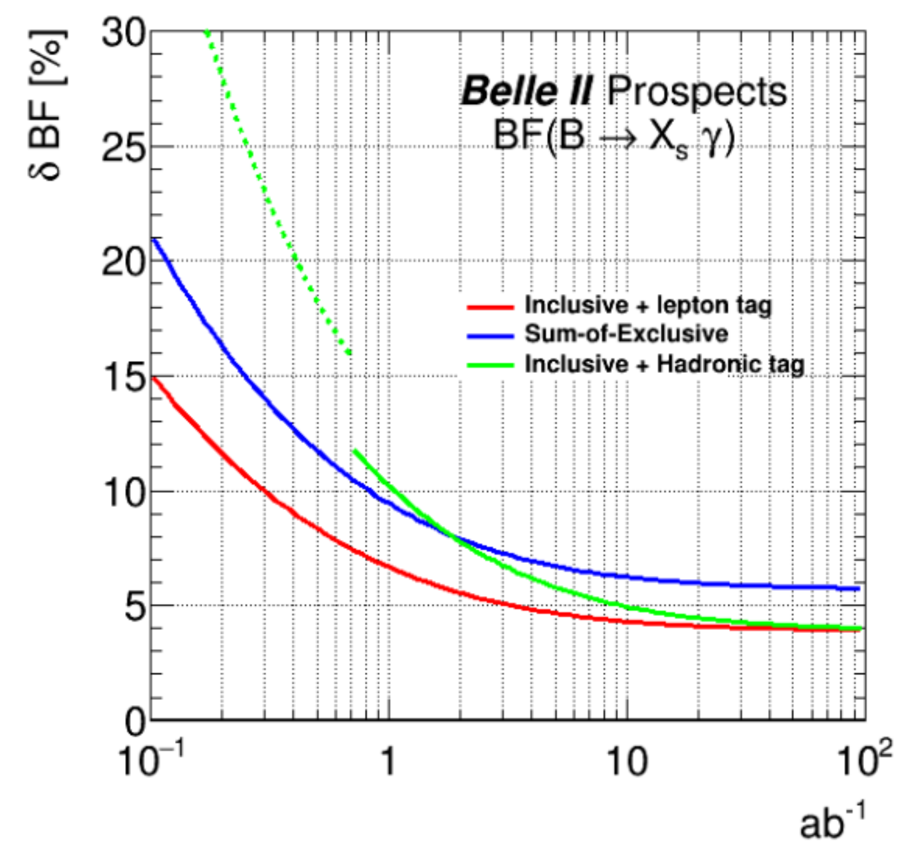




OBSERVABLES OF RADIATIVE PENGUIN DECAY

- $\mathscr{B}(B \to X_s\gamma)$
  - Both theoretically and experimentally clean.
  - Newest Belle measurement $\mathscr{B}(B \to X_s\gamma) = 3.12 \pm 0.10 \pm 0.21$ with $E_\gamma > 1.6GeV$(arxiv:1608.02344) is systematically dominant (Only 7.3% uncertainty)
  - Consistent with SM prediction
  - Constrain Charged Higgs mass (2HDM type-II) > 580 GeV in 95% CL (Eur. Phys. J. C. 78 (2018) 3)
  - **Goal in Belle II to reduce systematic uncertainty and measure BR with $E_\gamma > 1.6GeV$ w/o extrapolation**
- $\mathscr{B}(B \to X_d\gamma)$
  - Extra CKM suppression factor $|\frac{V_{td}}{V_{ts}}|^2 \approx \mathscr{O}(\lambda^2)$
  - Rely on Sum-of-exclusive analysis, as fully inclusive analysis not possible (large $B \to X_s\gamma$ background)



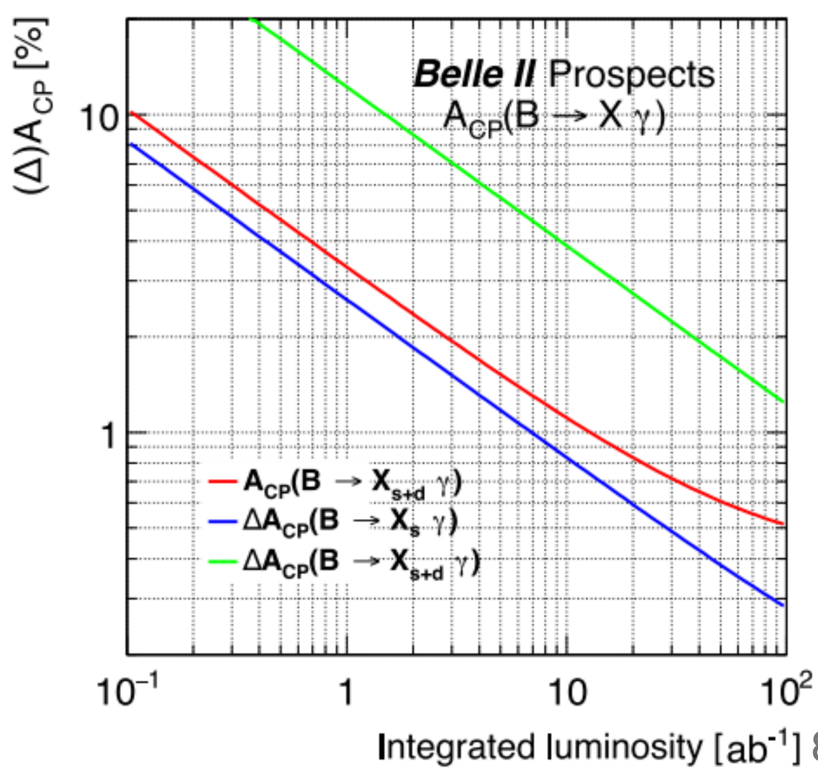


OBSERVABLES OF RADIATIVE PENGUIN DECAY

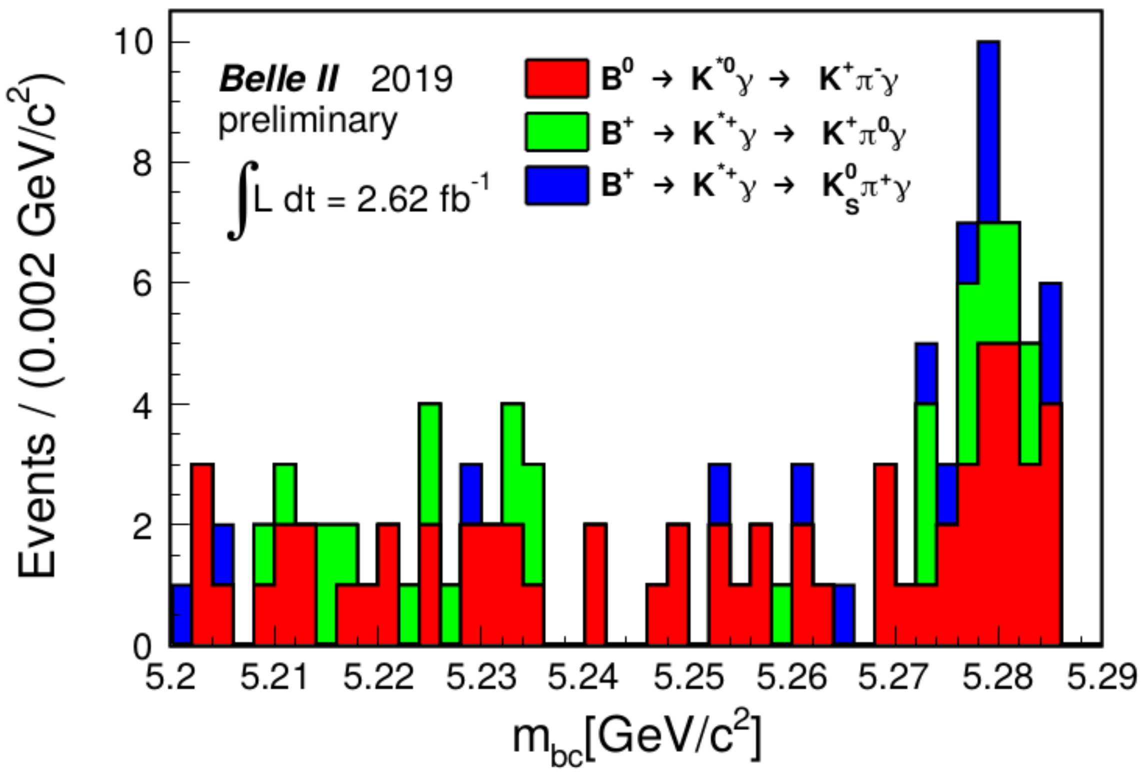
- Direct CP asymmetry: $A_{CP} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}$
  - Has large uncertainty in SM for both $B \to X_s\gamma$ and $B \to X_d\gamma$
- $\mathscr{A}^{X_{s+d}\gamma}_{\text{CP}} \sim \mathcal{O}(\Lambda_{QCD}/m_b)$ in SM, and any deviation from zero indicates NP
  - Belle full dataset measurement (PRL 114 (2015) 15) result ($\mathscr{A}^{X_{s+d}\gamma}_{\text{CP}} = (2.2 \pm 3.9 \pm 0.9)\%$) is statistically limited
- $\Delta\mathscr{A}_{\text{CP}}(B \to X_s\gamma) = \mathscr{A}_{\text{CP}}(B^+ \to X_s^+\gamma) - \mathscr{A}_{\text{CP}}(B^0 \to X_s^0\gamma) \propto Im(C_{8g}/c_{7\gamma})$ (zero in SM)
  - Belle measured (PRD 99 (2019) 3) is $\Delta\mathscr{A}_{\text{CP}}(B \to X_s\gamma) = (3.69 \pm 2.65 \pm 0.76)\%$, statistically limited
- $\Delta_{0+} = \frac{\Gamma(B^0 \to X_s\gamma) - \Gamma(B^+ \to X_s\gamma)}{\Gamma(B^0 \to X_s\gamma) + \Gamma(B^+ \to X_s\gamma)}$
  - Belle measured (PRD 99 (2019) 3) $\Delta_{0-} = -0.48 \pm 1.49(\text{stat.}) \pm 0.97\text{syst.} \pm 1.15(f_{+-}/f_{00})$

Sensitivity at Belle II (PTEP 2019(2019) 12)

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B \to X_s\gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.9%	3.2%
$Br(B \to X_s\gamma)^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$Br(B \to X_s\gamma)_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.1%	0.81%	0.63%
$\Delta_{0+}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	9.0%	2.6%	0.85%
$A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	1.3%	0.52%	0.19%
$A_{CP}(B^0 \to X_s^0\gamma)_{\text{sum-of-ex}}$	1.8%	0.72%	0.26%
$A_{CP}(B^+ \to X_s^+\gamma)_{\text{sum-of-ex}}$	1.8%	0.69%	0.25%
$A_{CP}(B \to X_{s+d}\gamma)^{\text{lep-tag}}_{\text{inc}}$	4.0%	1.5%	0.48%
$A_{CP}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	8.0%	2.2%	0.70%
$\Delta A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.5%	0.98%	0.30%
$\Delta A_{CP}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	16%	4.3%	1.3%

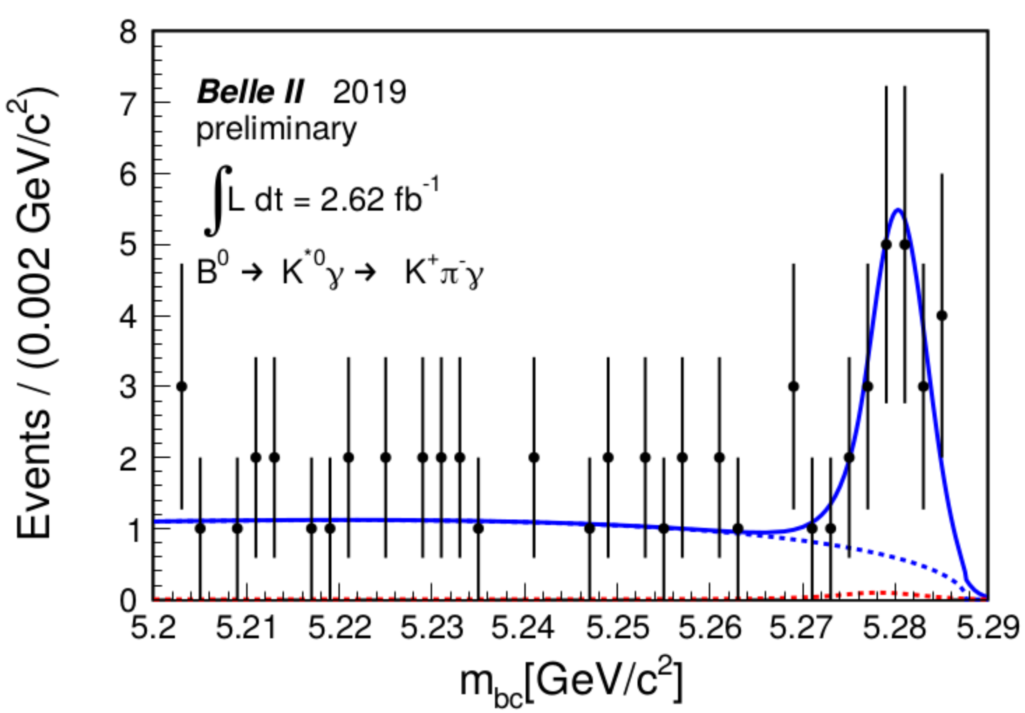


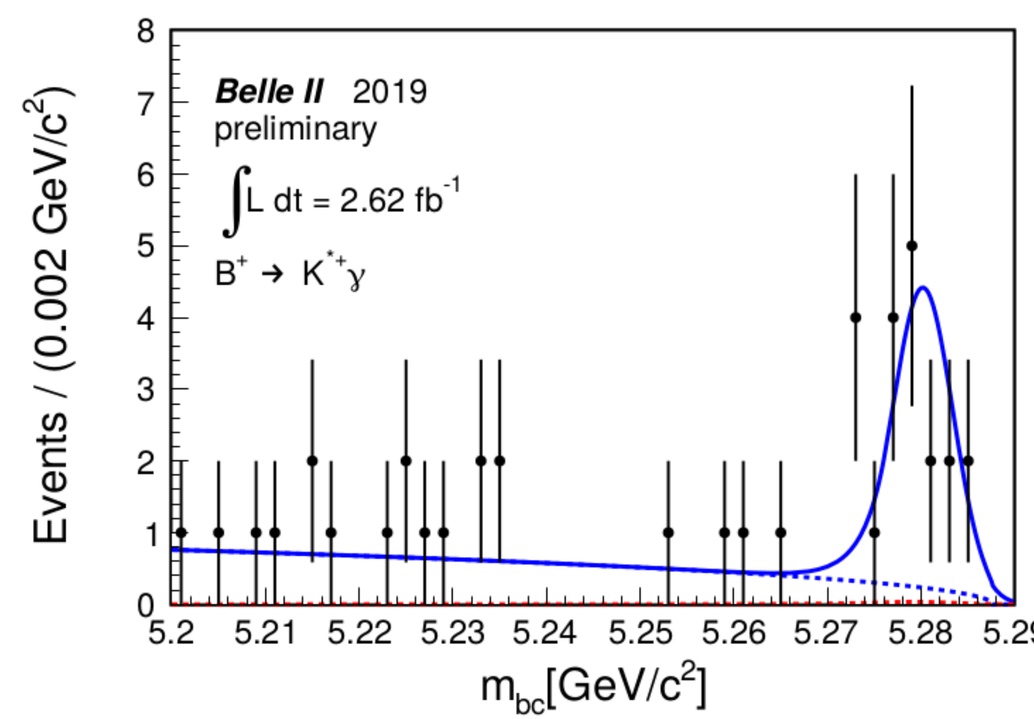
FIRST OBSERVED PENGUIN DECAY ($B \to K^*\gamma$)



	Signal Yield	Significance
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	19.1 ± 5.2	4.4σ
$B^+ \to K^{*+}[K^0_s\pi^+]\gamma$	6.6 ± 3.1	2.1σ
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	9.8 ± 3.4	3.7σ

- Combined significance exceeds 5σ
- Yield agree with PDG branching Fraction



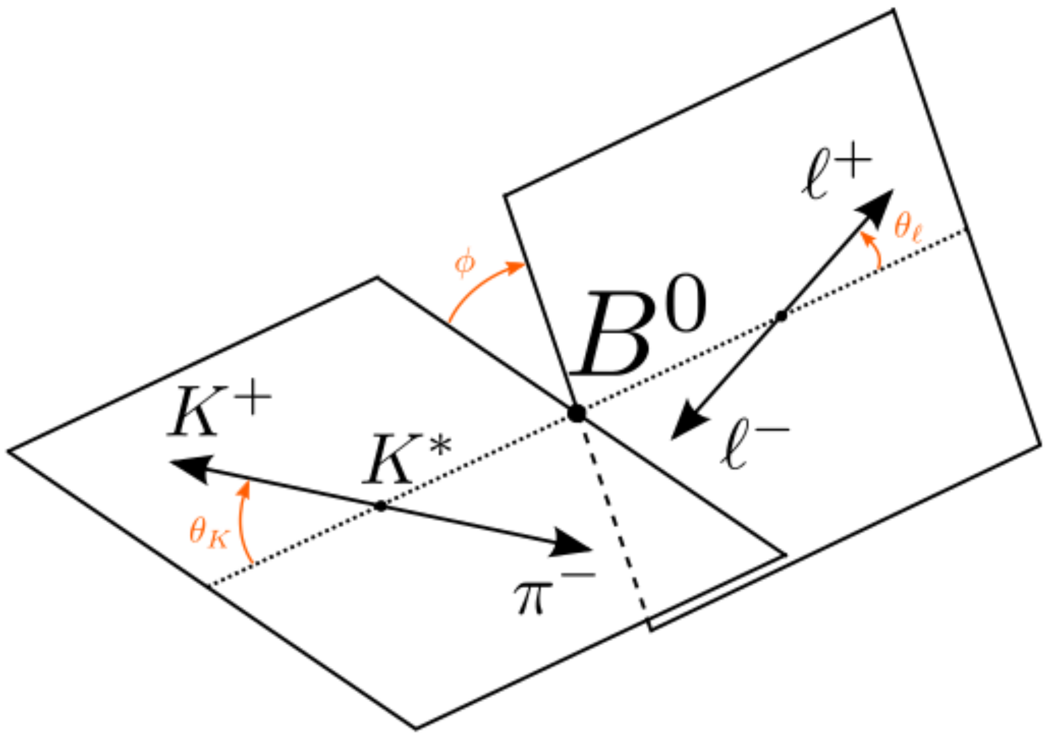


$B \to K^*\ell\ell$: ANGULAR ANALYSIS

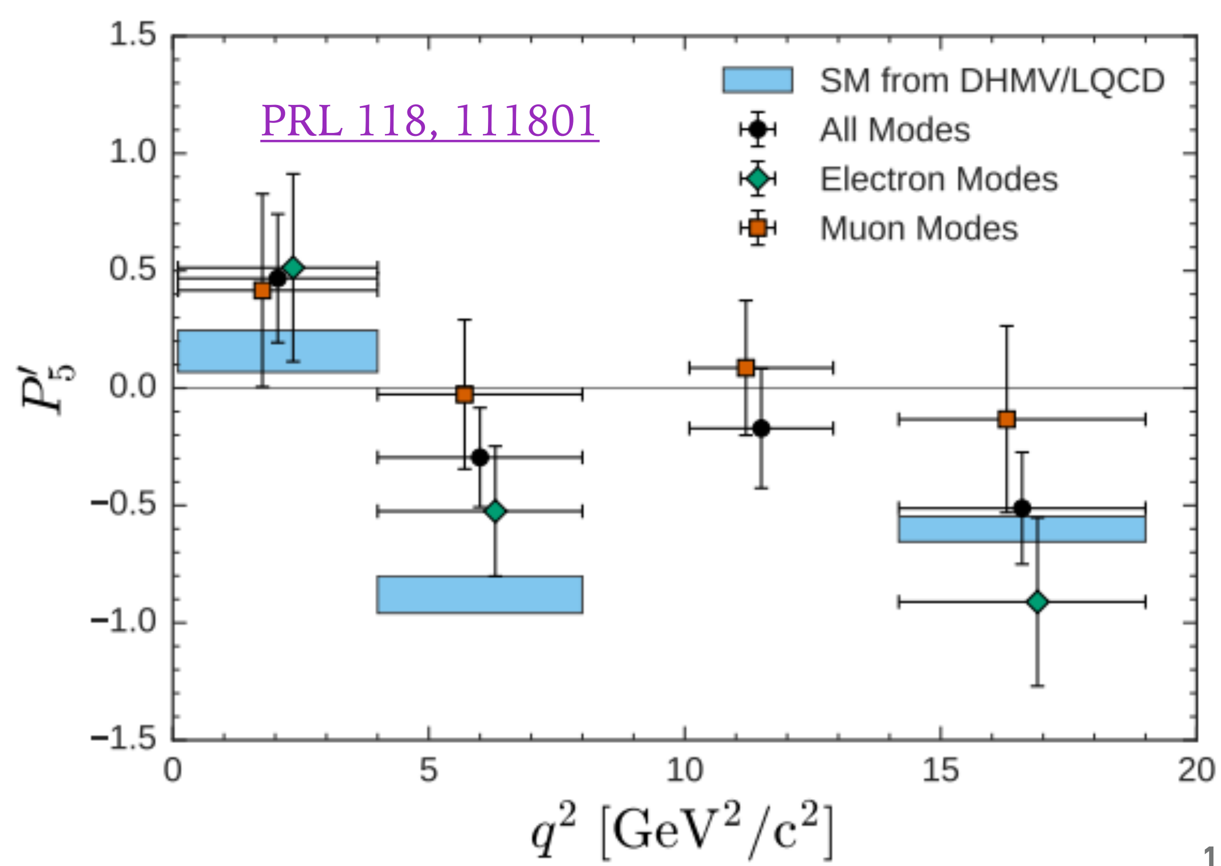
$$\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\sum_{i=1}^{i=9} I_i f_i(\theta_\ell, \theta_K, \phi)$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,6,8}}{\sqrt{F_L(1-F_L)}}$$

Cancel out uncertainties from form-factor at leading order (JHEP 05 (2013) 137)



- P'_5 is a sensitive probe of C_7,C_9 and C_{10}
- LFU test using $Q_i = P_i^\mu - P_i^e$



- Largest deviation from SM: 2.5σ for the muon mode in $q^2 \in [4,8]\text{GeV}^2/c^2$
- Electron mode deviates from the SM by 1.3σ
- The sensitivity at 50 /ab Belle II data in this bin will be around 0.04 (PTEP 2019(2019) 12)

LEPTON UNIVERSALITY TEST

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

- In SM guage bosons couple equally to the different flavours of lepton
- Precise prediction of R-ratios in $q^2 \in [1,6]\mathrm{GeV}^2/c^4$ and $q^2 > 14.4\ \mathrm{GeV}^2/c^4$ in SM
- Say for eg. $R_{K*} = 1.000 \pm 0.001$ (JHEP 12 (2007))

Advantage at Belle II

- Electron and muon modes have similar efficiency
- Both low and high q^2 regions possible
- All R_K, R_{K*} and R_{X_s} Is possible at Belle II

Result

- LHCb reported $R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$ for $q^2 \in [1.1,6]\mathrm{GeV}^2/c^4$, which is compatible with SM at 2.5σ (PRL 122 (2019)19)
- LHCb reported $R_{K^{*0}}$ for $q^2 \in [0.045,1.1]\mathrm{GeV}^2/c^4$ and $q^2 \in [1.1,6.0]\mathrm{GeV}^2/c^4$ which are compatible with SM at $2.1 - 2.3\sigma$ and $2.4 - 2.5\sigma$ respectively (JHEP 08 (2017) 055)

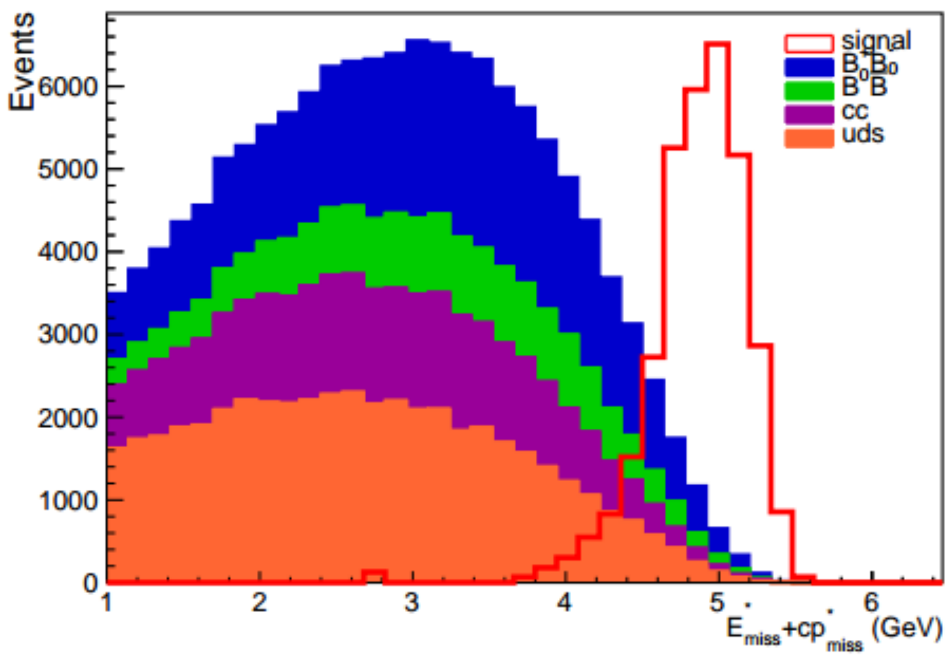
Belle II Sensitivity (PTEP 2019(2019) 12)

Observables	Belle 0.71/ab	Belle II 5/ab	Belle II 50/ab
$R_K[1,6]GeV^2$	28%	11%	3.6%
$R_{K*}[1,6]GeV^2$	26%	10%	3.2%
$R_{X_s}[1,6]GeV^2$	32%	12%	4.0%

$B \to K^{(*)}\nu\bar{\nu}$

- Probe dark matter coupling to $b \to s$ transition
- Allow to extract $B \to K^{(*)}$ form factors to high accuracy
- K^* longitudinal polarisation F_L is sensitive to right handed currents ($F_L^{SM} = 0.47 \pm 0.03$)
- NP can appear as new operator (eg. Q_R^{ℓ}), and wilson coeff can be constrained

Belle measurement (PRD 87, 111103(R)) provide an UL to the BR



Identify signal peak in missing 4 momentum in CM frame $E^*_{\text{miss}} + cp^*_{\text{miss}}$ with hadronic tag using FEI algorithm

- $\Gamma(B \to K^{(*)}\nu\bar{\nu})$ can be observed in Belle II even if at SM rate

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\text{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\text{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\text{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077

SUMMARY

- Belle II is collecting data and by now 55/fb data has been collected.
- Clean environment at Belle II grants access to unique observables (eg. R_{X_s})
- Model independent constrains on NP (C_7, C_9 and C_{10})with large data sample