Rare B Decays at Belle II

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On Behalf of the Belle II Collaboration

Lake Louise Winter Institute 2020

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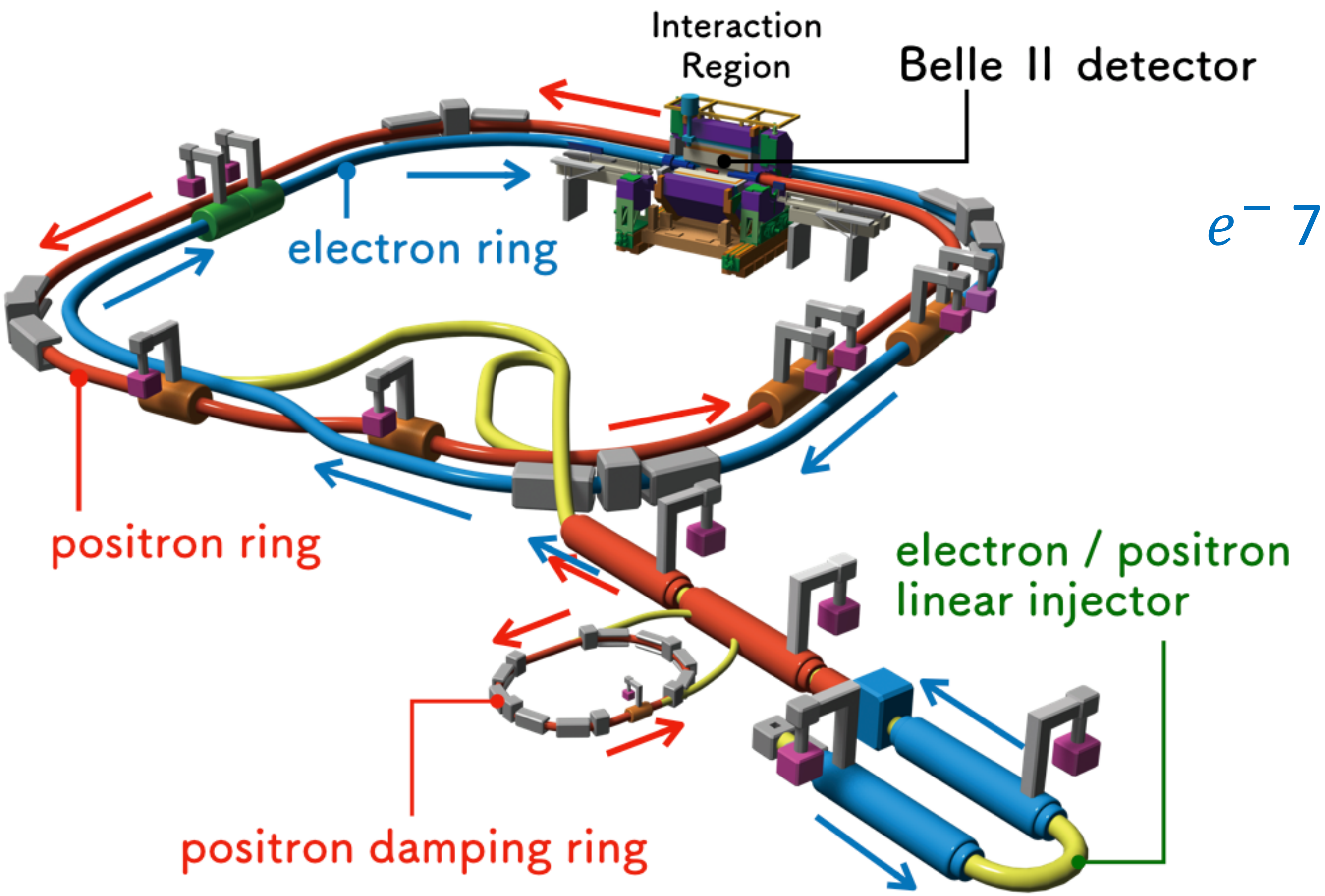
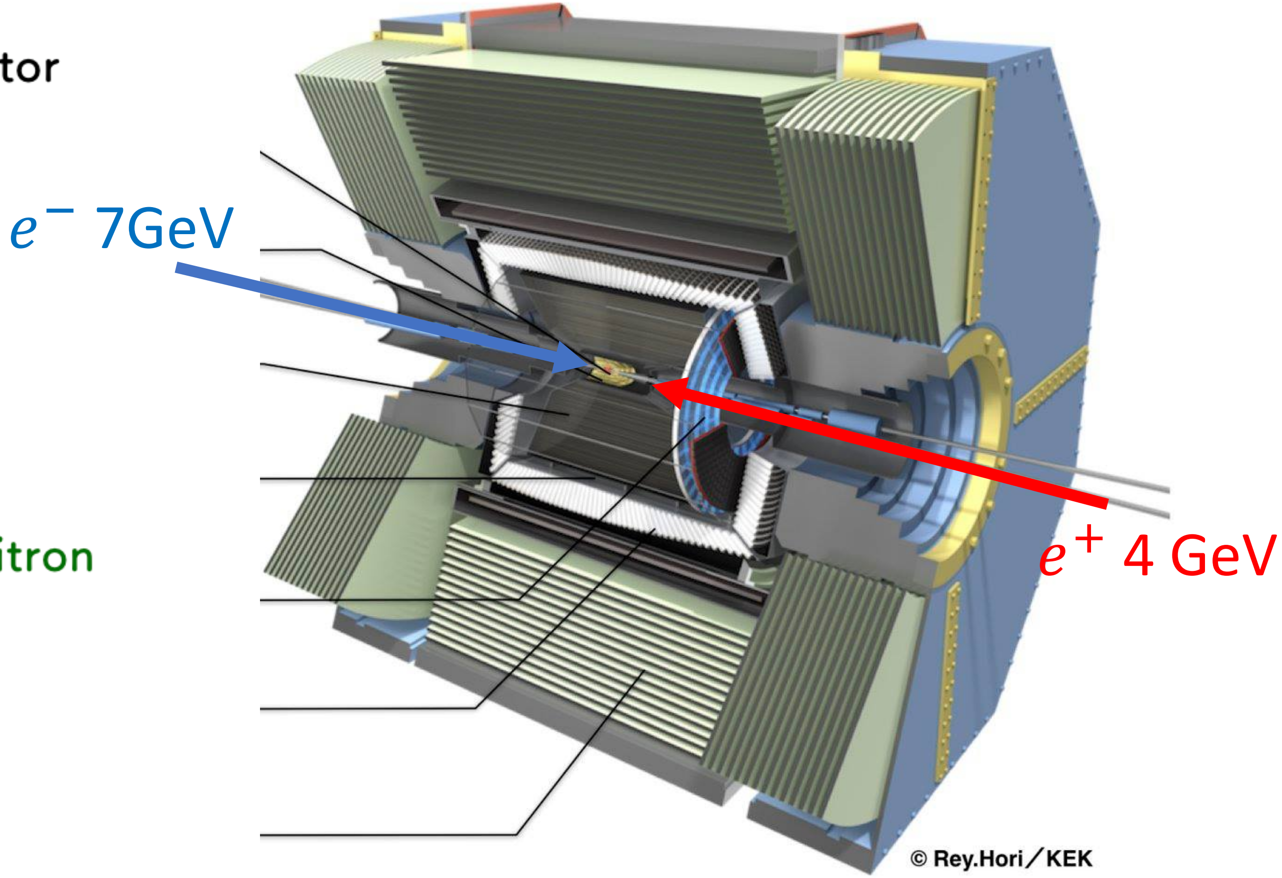
The 2nd-generation *B* factory: Belle II

SuperKEKB collider



Belle II detector

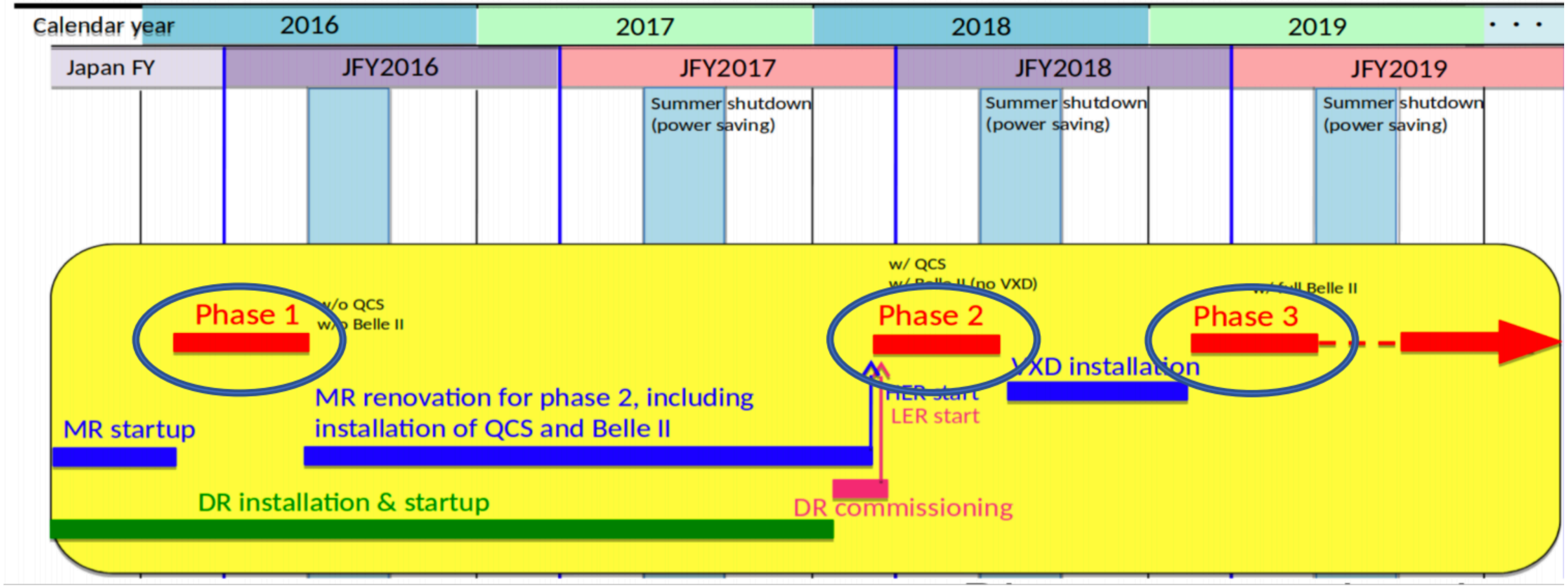


The 2nd-generation *B* factories: Belle II and LHCb

Property	LHCb	Belle II
$\sigma_{\bar{b}b}(nb)$	~150,000	~**1**
$\int Ldt\ (fb^{-1})\ by\ 2027$	~**25**	~50,000
Background level	**High**	Low
Typical efficiency	**Low**	High
π^0, K_s efficiency	**Low**	High
Initial state	**Not well known**	Well known
Decay-time resolution	Excellent	**Good**
Collision spot size	**Large**	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	**Partly B_s**
τ physics capability	**Limited**	Excellent
B-flavor tagging efficiency	**3.5-6%**	36%

Reference: Abi Soffer, Intensity Frontier in Particle Physics, October 2019, Taipei

Start-up schedule, phase 3 for physics data



- Phase 1: SuperKEKB commissioning w/o final focus w/o Belle II (2016-2018)
- Phase 2: collision w/ final focus w/ Belle II w/o VXD (2018)
- Phase 3: collision w/ full Belle II (2019-2027)

Detector performance and rediscovery of known physics

- Current integrated luminosity, ~**O(10 fb^{-1}) in 2019** is similar to that of CLEO in mid-90's.
- Used mostly for validating detector performance and commissioning

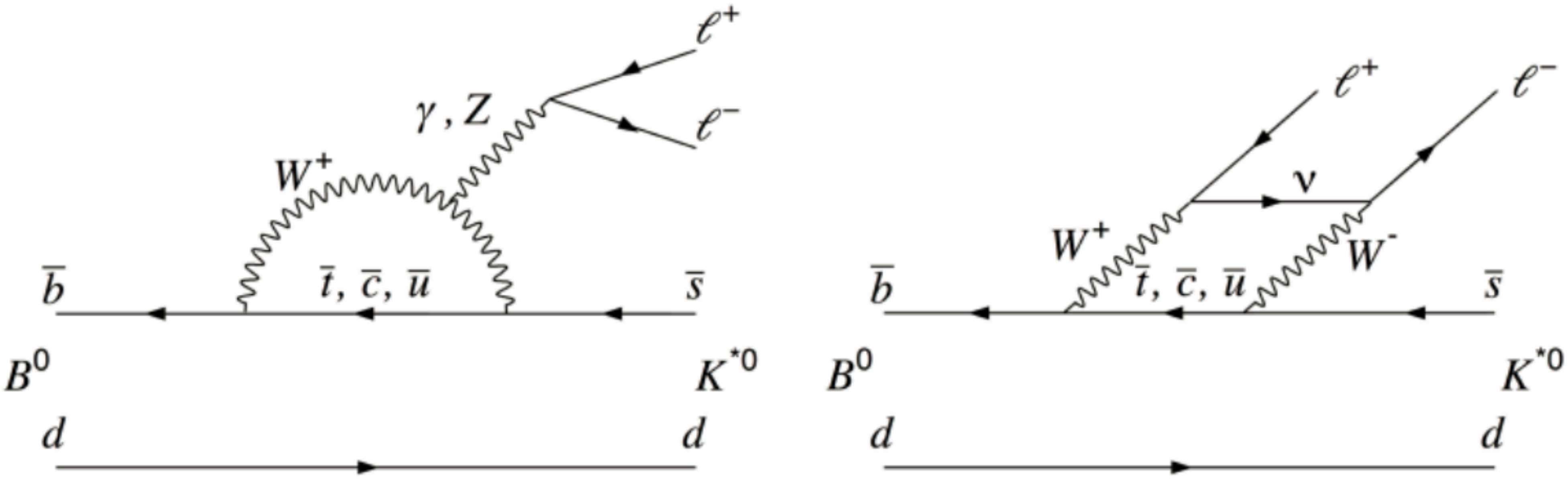
2020 summer	2021 spring	2022 spring	2027
~150 fb^{-1}	**~500 fb^{-1}**	**~1.5 ab^{-1}**	**50 ab^{-1}**

- Belle II research goals are summarized in "**The Belle II Physics Book**".
- https://arxiv.org/abs/1808.10567 and https://doi.org/10.1093/ptep/ptz106

- Please check the talks:
  - Belle II **Status and prospects**, Friday morning, Speaker: Tadeas Bilka
  - First results on **DM** searches at Belle II, Thursday morning, Speaker: Michael de Nuccio
  - **Semileptonic and leptonic B decays** at Belle II, Tuesday morning, Speaker: Andreas Warburton

b→ $s\ell^+\ell^-$

- **Angular analysis in B→ $K^{(*)}\ell^+\ell^-$**
- **B→ $X_s\ell^+\ell^-$**
- Lepton Flavour Universality (LFU) Violation



Please also check the details:
- Lepton Flavour Universality in b → sll Decays at LHCb, Tue morning, Speaker: Sam Maddrell-Mander
- Flavour Physics review, Tue morning, Speaker: G U Y W O R M S E R

Wilson Coefficients in b→ *s* prcoesses

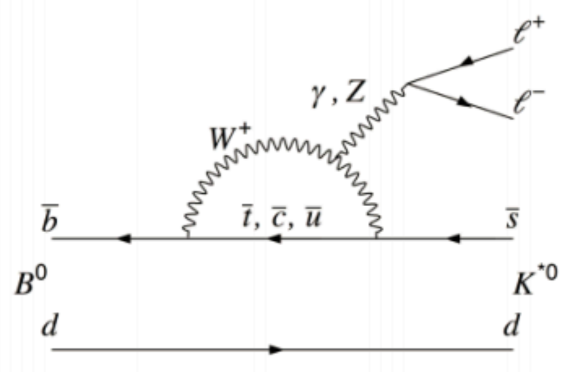
- In the SM
  - b→sγ : C_7
  - b→sll : C_7, C_9 and C_{10}
  - C_7 ~ -0.3, C_9 ~ 4, C_{10} ~ -4
- If NP contributes,
  - Deviation from the SM values
  - Lepton flavor dependent $C_{9e} \neq C_{9\mu}$
  - New coefficients appear
    - $Im(C_i)$, C_i', C_S , C_P , C_T and C_{T5}

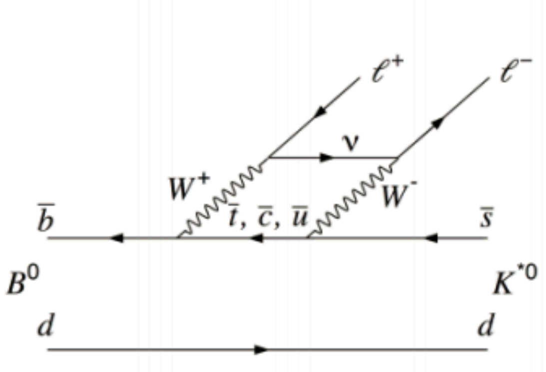
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

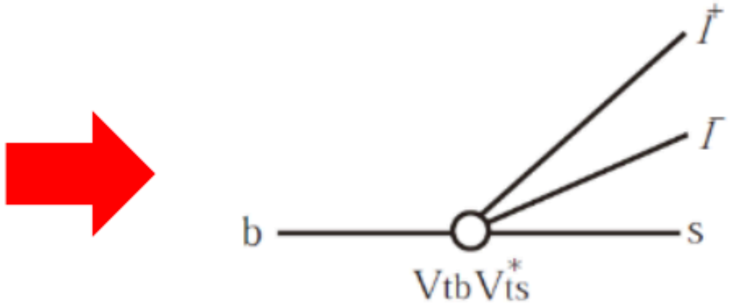
$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu},$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell),$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$





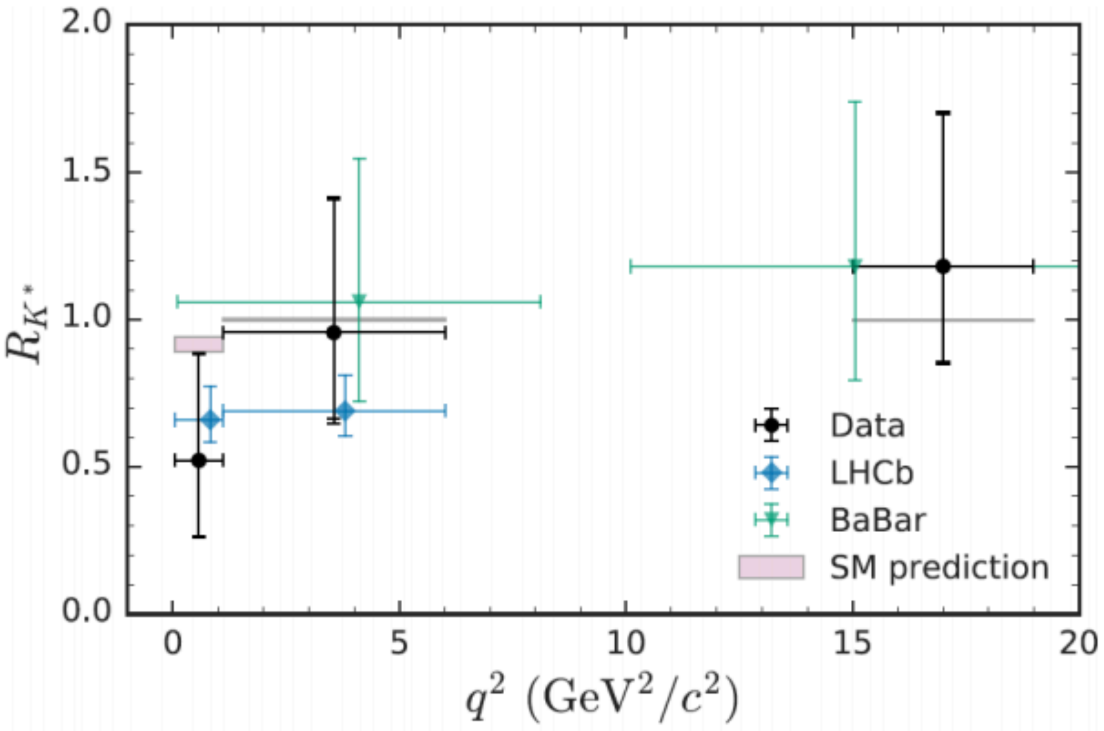


Anomalies in $\mathbf{b} \rightarrow s\ell^{+}\ell^{-}$

- Claimed by LHCb
  - LFU violation
    - Theoretically clean
    - Naïve combination of R_K and R_{K*} ~4σ
    - ~30% deviation from the SM

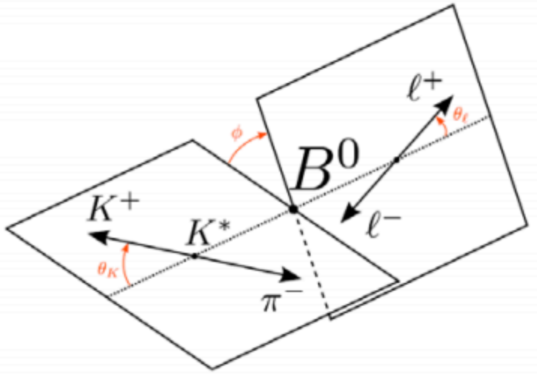
$$R_H = \frac{\mathcal{B}(B \to H\mu^+\mu^-)}{B(B \to He^+e^-)}$$

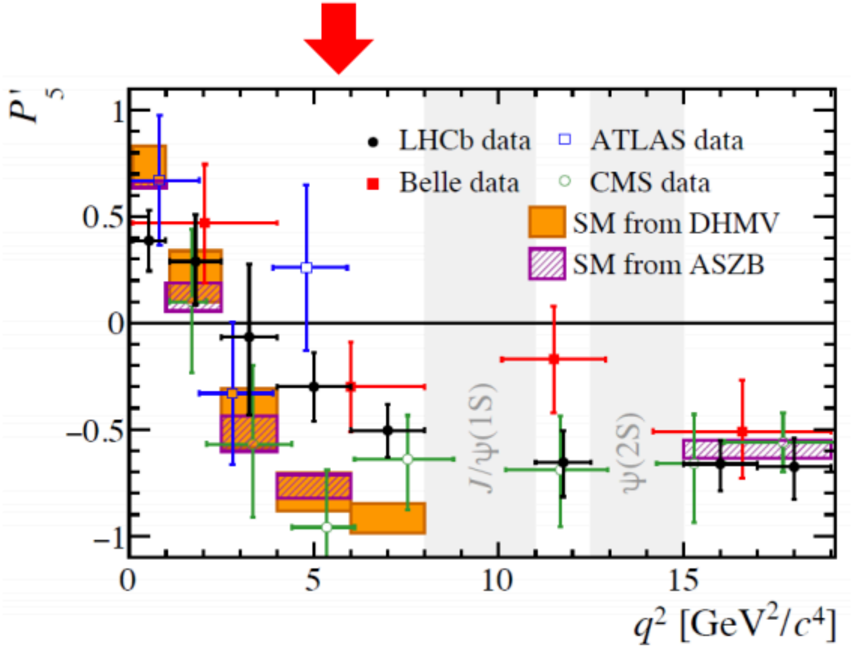
$$H = K, K^*, X_s, \ldots$$



Angular analysis in $b \to s\ell^+\ell^-$

- Claimed by LHCb
  - Angular Observable P_5'
    - Theoretically dirty (charm loop)
    - About ~4σ deviation q^2=[4,8]GeV2
    - ~50% deviation





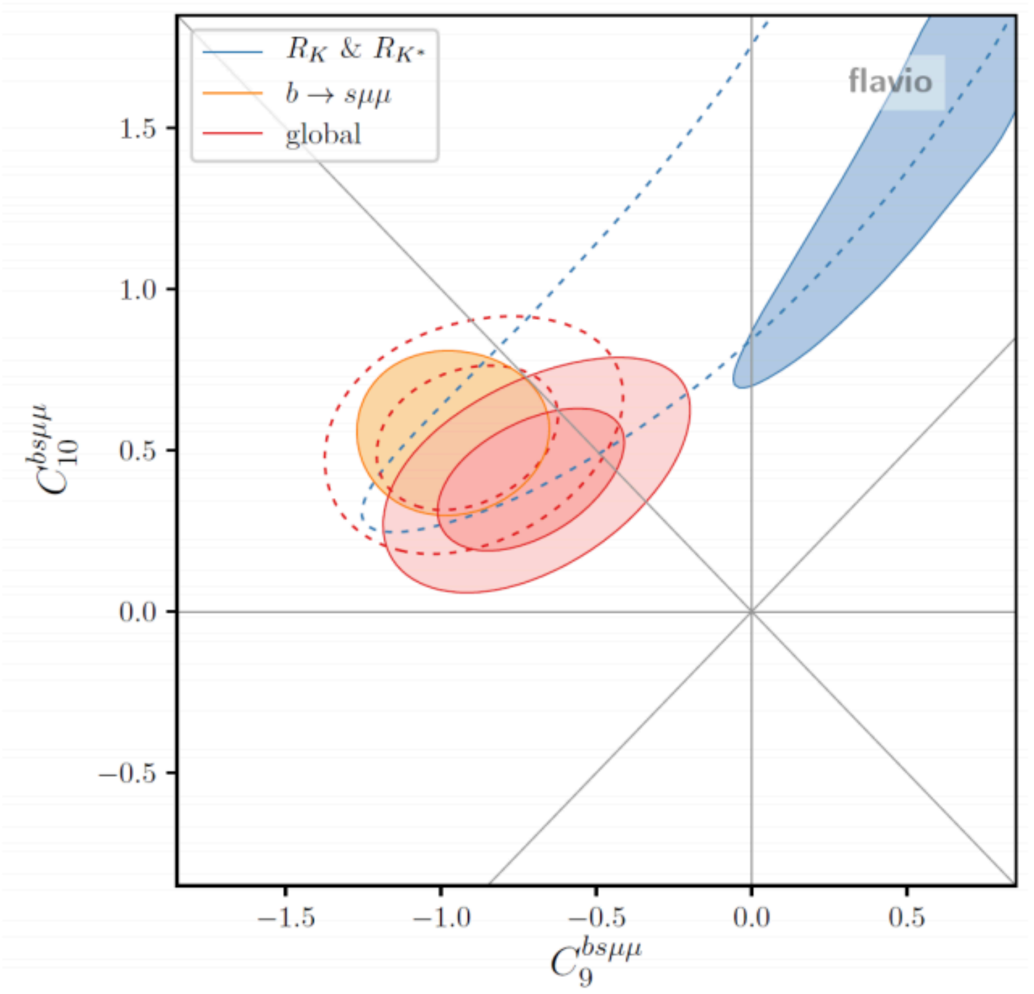
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos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

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

Global Fit to b→ $s\ell^+\ell^-$

- NP effect in C_9^μ

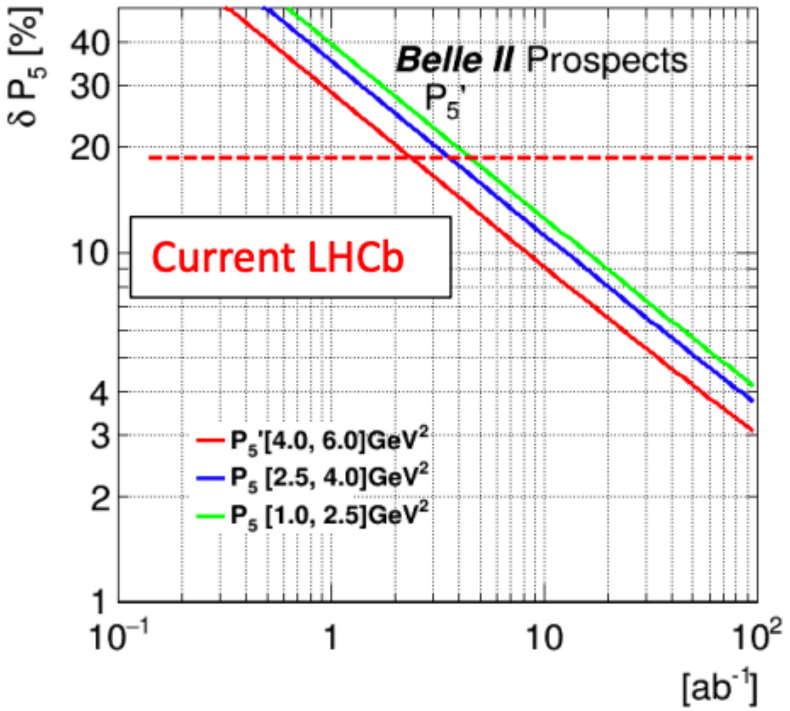
D. Straub@MoriondEW2019



Belle II Prospects of P_5' in B→ $K^* \ell^+ \ell^-$

- LHCb can observe the deviation with data already in hand.
- In 2022, Belle II can reach current LHCb sensitivity
  - Belle II can confirm or deny LHCb anomaly in P_5' with
- Statistically dominated even with 50ab^{-1}
  - With 50ab^{-1}, the sensitivity is competitive to LHCb with 50fb^{-1}

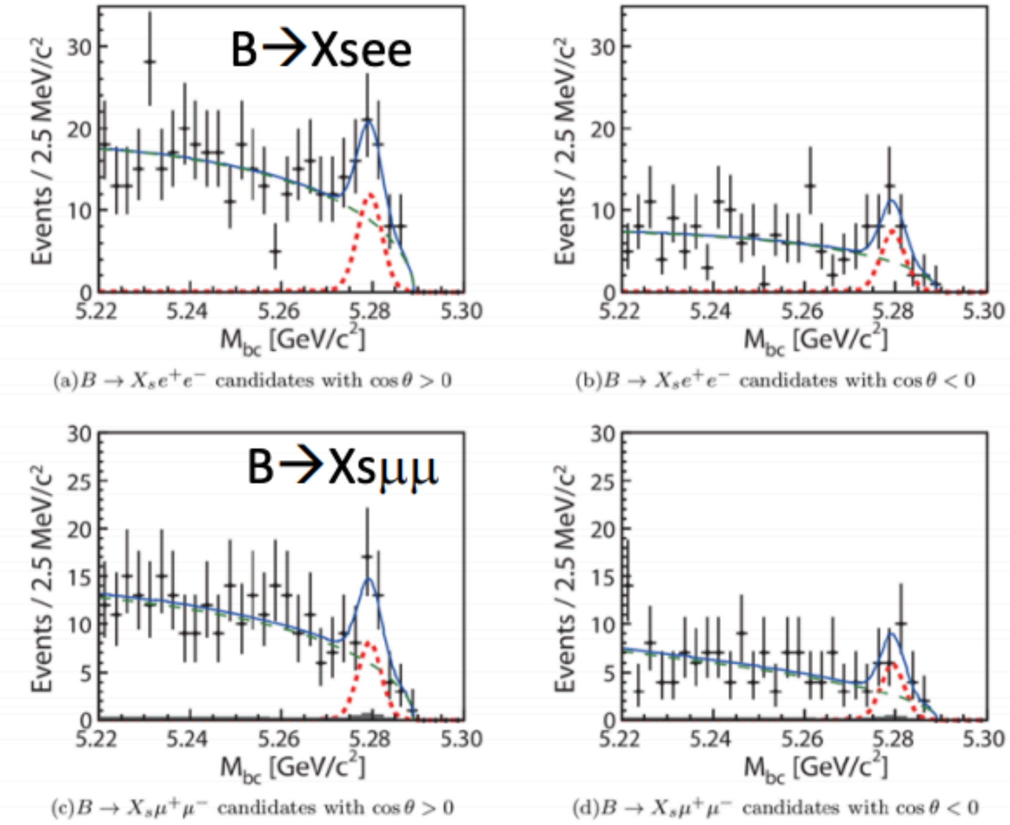
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
P_5' ([1.0, 2.5] GeV^2)	0.47	0.17	0.054
P_5' ([2.5, 4.0] GeV^2)	0.42	0.15	0.049
P_5' ([4.0, 6.0] GeV^2)	0.34	0.12	0.040
P_5' (> 14.2 GeV^2)	0.23	0.088	0.027



Reconstruction of $B \to X_s \ell^+ \ell^-$

- We will use sum-of-exclusive method
  - Xs is reconstructed from $K n\pi$ ($0 <= n <= 4$).
    - We can add three kaon modes and η modes (two pi0 modes?)
  - then combined with dilepton
- Reconstruction efficiencies for electron and muon modes are almost similar
  - Good for LFU test
- Backgrounds
  - Dominated by B→Xlν and B→Ylν
    - Can be suppressed with missing energy and vertex information.
  - Second largest is ee→cc
    - event shape information can suppress the background so much.
- We could also use fully inclusive dilepton but need dedicated simulation study.

Y. Sato (Belle Collaboration), Phys.Rev. D93 032008 (2016)



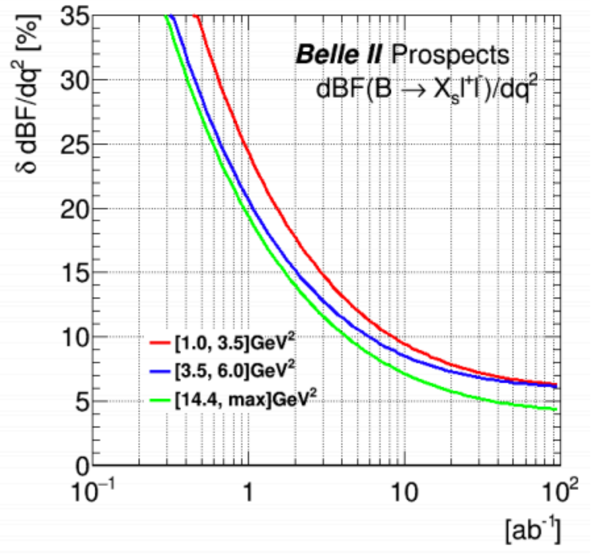
Forward event | backward event

$[1,6]\,\mathrm{GeV}^2$

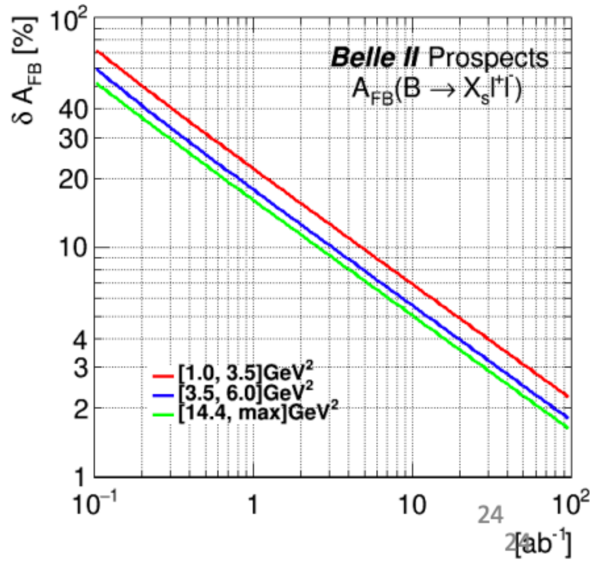
Prospects of BF and A_{FB} in $B \rightarrow X_s \ell^+ \ell^-$

BF and A_{FB} in B→Xsl+l-

- The uncertainty of BF is dominated by systematic one with ~15ab^{-1}.
  - Largest one is due to fragmentation modeling which could be improved by adding decay modes and data driven PYTHIA tuning.
  - We can use finner binning of 1GeV^2 with 50ab^{-1} or can go higher M_{Xs} cut of ~2.5GeV.
- A_{FB} is still statistically dominated thanks to the ratio observable.
  - We can also measure CP difference (or asymmetry) of Forward-backward asymmetry

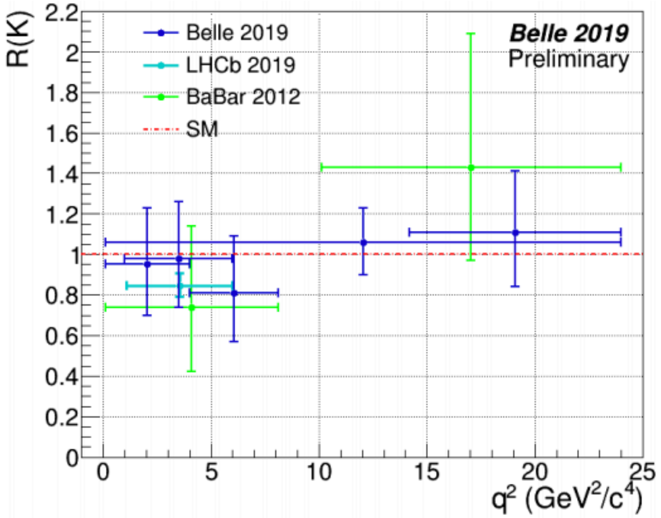


Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s \ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	29%	13%	6.6%
$\mathrm{Br}(B \to X_s \ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	24%	11%	6.4%
$\mathrm{Br}(B \to X_s \ell^+\ell^-)$ (> 14.4 GeV^2)	23%	10%	4.7%
$A_{\mathrm{CP}}(B \to X_s \ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	26%	9.7 %	3.1 %
$A_{\mathrm{CP}}(B \to X_s \ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	21%	7.9 %	2.6 %
$A_{\mathrm{CP}}(B \to X_s \ell^+\ell^-)$ (> 14.4 GeV^2)	21%	8.1 %	2.6 %
$A_{\mathrm{FB}}(B \to X_s \ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	26%	9.7%	3.1%
$A_{\mathrm{FB}}(B \to X_s \ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	21%	7.9%	2.6%
$A_{\mathrm{FB}}(B \to X_s \ell^+\ell^-)$ (> 14.4 GeV^2)	19%	7.3%	2.4%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ ([1.0, 3.5] GeV^2)	52%	19%	6.1%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ ([3.5, 6.0] GeV^2)	42%	16%	5.2%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ (> 14.4 GeV^2)	38%	15%	4.8%

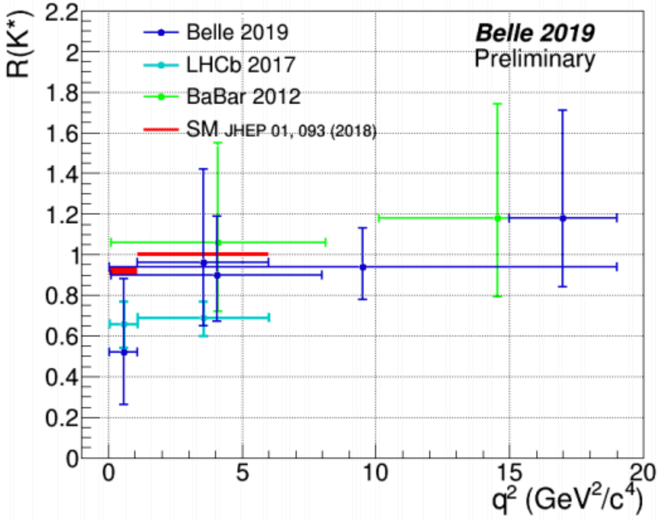


Belle II Prospects of R_K, R_{K^*}, R_{X_s} in $\mathbf{b} \to s\ell^+\ell^-$

arXiv:1908.01848 (Belle 2019)



arXiv:1904.02440 (Belle 2019)



Observables	Belle $0.71\,\text{ab}^{-1}$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
R_K ($[1.0, 6.0]\,\text{GeV}^2$)	28%	11%	3.6%
R_K ($> 14.4\,\text{GeV}^2$)	30%	12%	3.6%
R_{K^*} ($[1.0, 6.0]\,\text{GeV}^2$)	26%	10%	3.2%
R_{K^*} ($> 14.4\,\text{GeV}^2$)	24%	9.2%	2.8%
R_{X_s} ($[1.0, 6.0]\,\text{GeV}^2$)	32%	12%	4.0%
R_{X_s} ($> 14.4\,\text{GeV}^2$)	28%	11%	3.4%

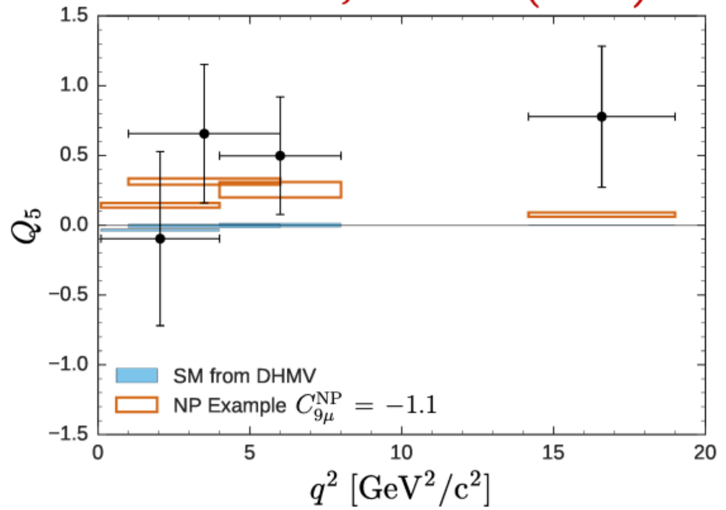
Belle II projections

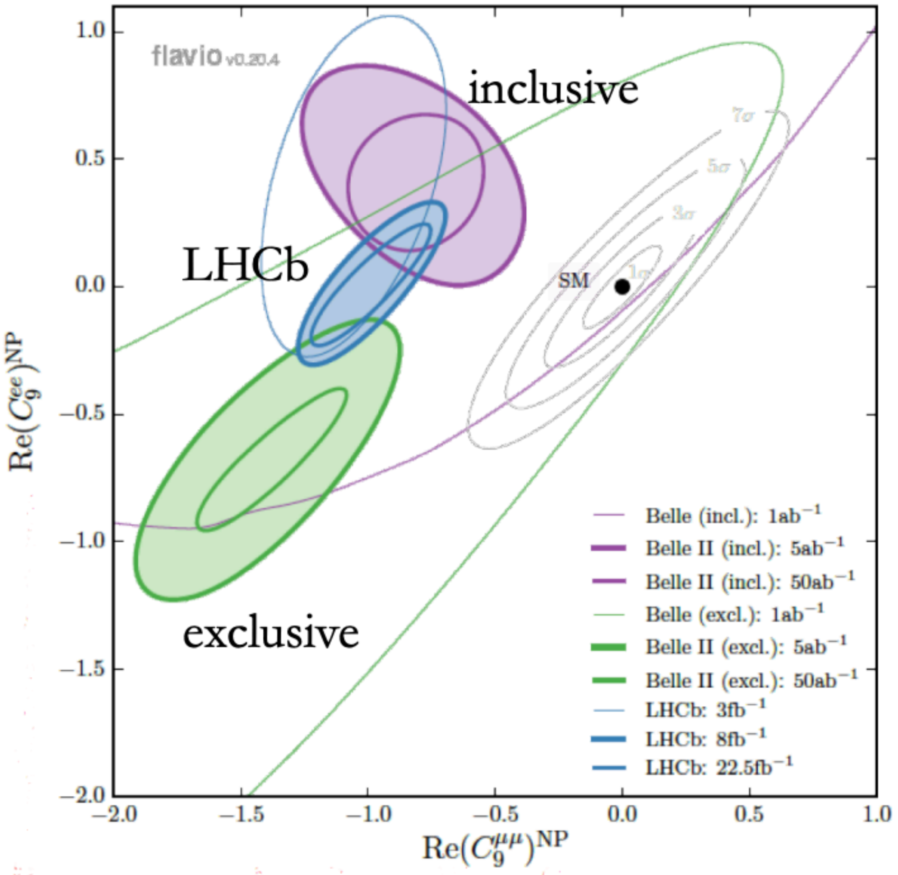
- Differential distributions in q^2 (dilepton invariant mass squared)
- Latest Belle result closer to the SM expectation (~1)
- Measurements still dominated by statistical uncertainty
- Inclusive studies of $B \to X_s\ell\ell$ possible: reduce hadronic uncertainties

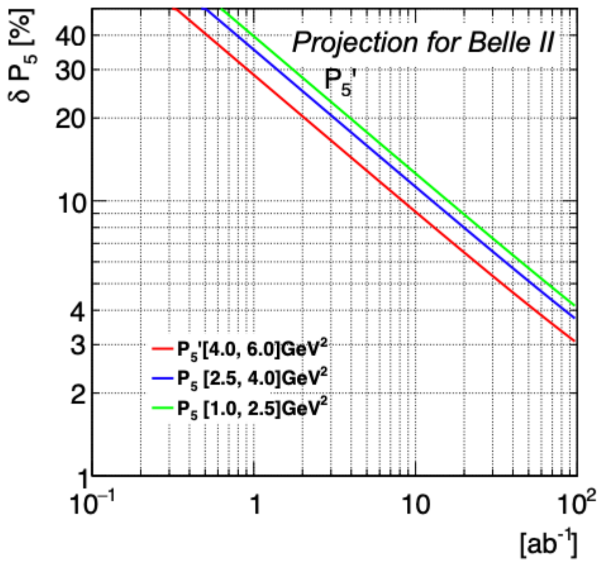
Belle II Prospects of NP in C_9 and P_5'

- Angular variables sensitive to NP
- LHCb measurement dominated by systematics
- Exploit Full Event Interpretation to perform fully inclusive searches

PRL118, 111801 (2017)



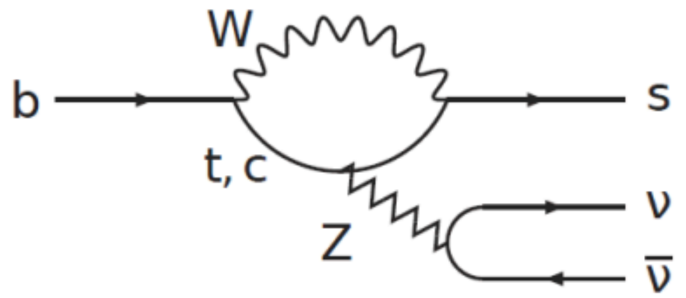




5σ confirmation of NP possible with 20 ab^{-1} at Belle II

$\mathbf{B \to K^*\nu\bar{\nu}}$

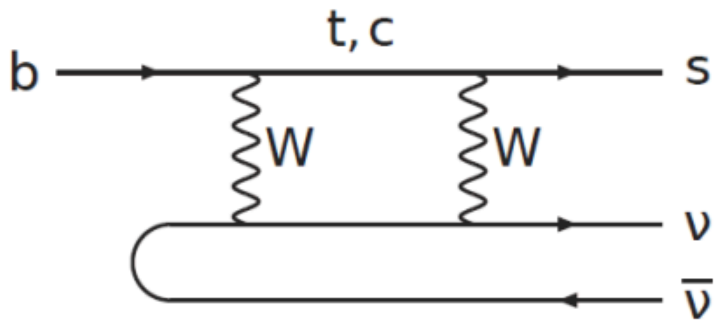
- If C_9 is deviated from the SM value, vector current in b→sνν might be also affected in some BSM models?
- If so, at Belle II, we can test the deviation with B→K(*)νν
- The BF is cleanly predicted in the SM.
  - F_L also



Buras, Girrbach-Noe, Niehoff and Straub, JHEP 02 184 (2015)

Mode	$\mathcal{B}\ [10^{-6}]$
$B^+ \to K^+\nu\bar{\nu}$	$3.98 \pm 0.43 \pm 0.19$
$B^0 \to K^0_S\nu\bar{\nu}$	$1.85 \pm 0.20 \pm 0.09$
$B^+ \to K^{*+}\nu\bar{\nu}$	$9.91 \pm 0.93 \pm 0.54$
$B^0 \to K^{*0}\nu\bar{\nu}$	$9.19 \pm 0.86 \pm 0.50$

$$F_L^{\rm SM} = 0.47 \pm 0.03$$



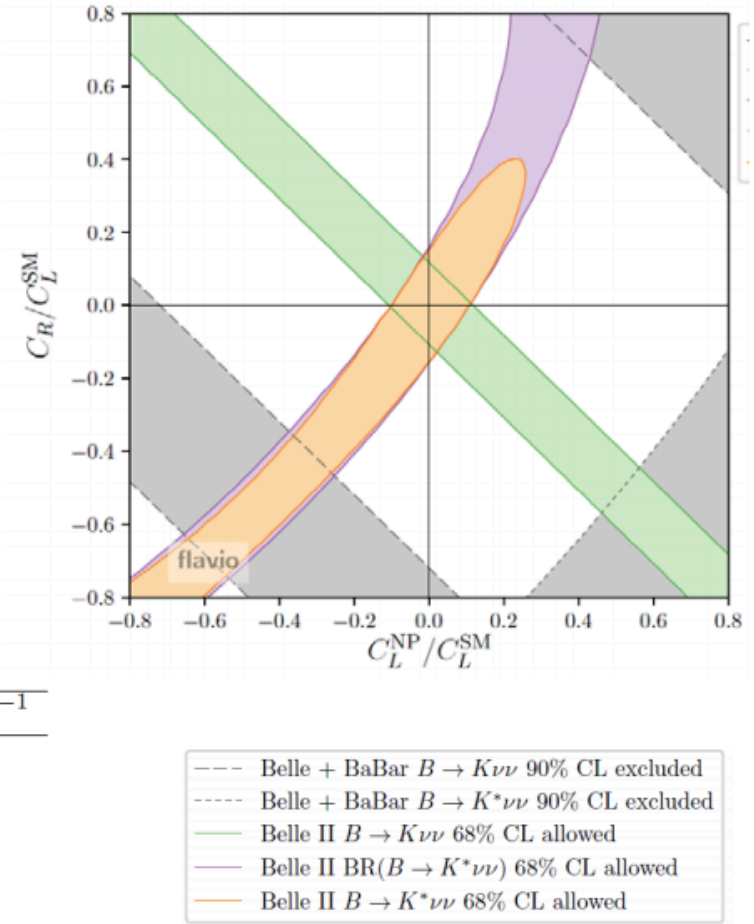
Belle II Prospects of $\mathbf{B \to K^{*}\nu\bar{\nu}}$

- We can observe the B→K(*)νν at early stage (several ab^{-1}) of Belle II, and the sensitivity of the BF is 10% level with 50ab^{-1}.
- We can measure the $F_L(K^*)$, which is less sensitive to form factor uncertainties than BF, with 20% precision with 50ab^{-1}

$$\mathcal{O}_L = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

$$\mathcal{O}_R = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

D. Straub, Belle II Physics Book
Inputs from AI and E. Manoni

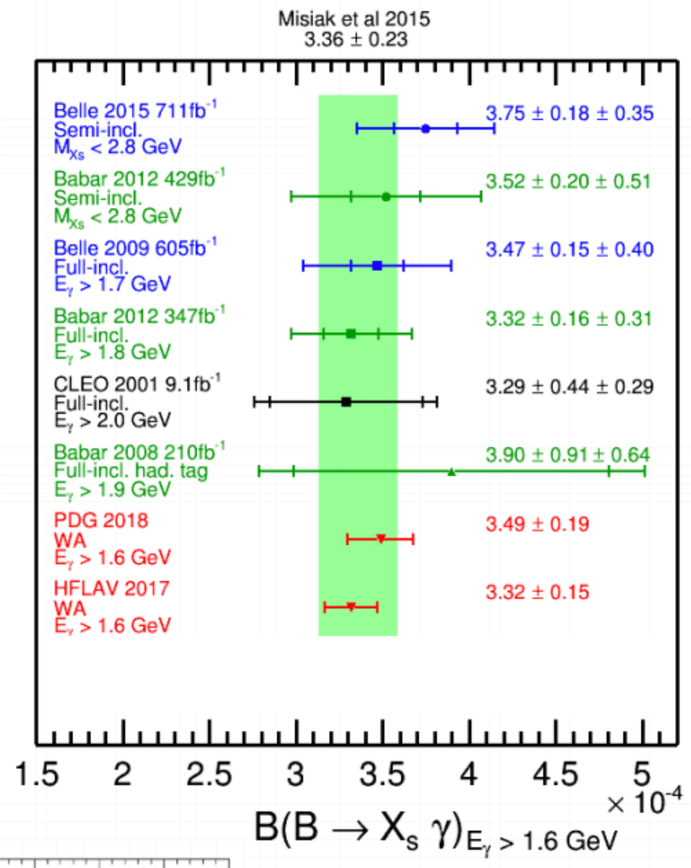


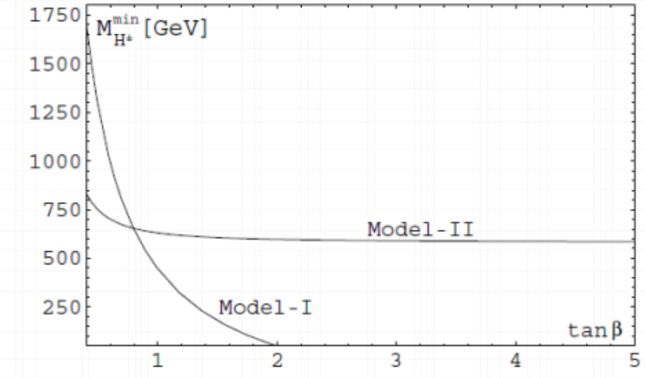
Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077
$\mathrm{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$\mathrm{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–

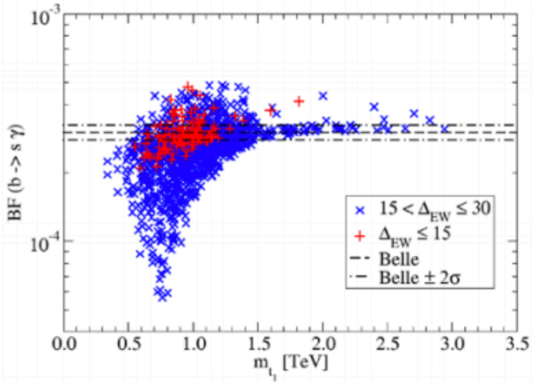
Branching Fraction of $\mathbf{B \to X_s \gamma}$

- Exp and theory are in a good agreement
  - The uncertainties are almost comparable
  - Exp WA ~5% : already systematic dominant
  - Theory ~7%
- Strong constraint on new physics
  - Constraint on $|C_7|^2 + |C_7'|^2$
  - Charged Higgs in 2HDM type-II
    - > 580GeV Misiak and Steinhauser (2018)
  - stop in natural SUSY

Baer, Bager, Nagata and Savoy (2017)







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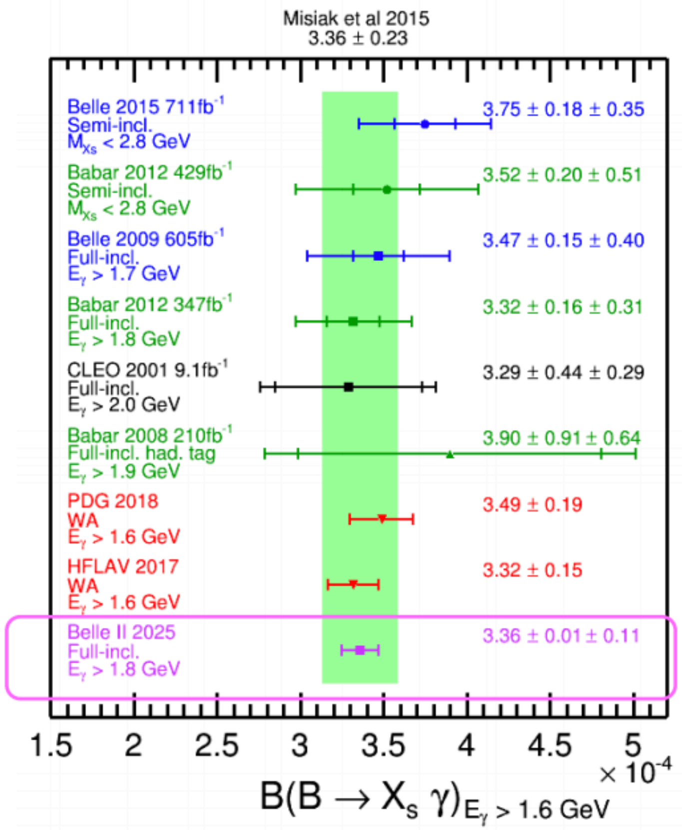
Belle II Prospects the BF of $\mathbf{B \to X_s\gamma}$

- Exp : Already systematic dominant
  - But large Belle II data can reduce the uncertainty to ~3% (WA ~2.6%)
    - Photon detection etc.
- Theory
  - Part of Non-perturbative uncertainties (5%) : data driven reduction possible
    - Isospin asymmetry

      Watanuki, Ishikawa et al (Belle), PRD 99, 032012 (2019)
      Gunawardana and Paz 1908.02812
    - Photon energy spectrum
    - HQE parameters from b→clν and b→sγ moments
  - Other uncertainties also reducible
  - 3.5% in 2025 Private communication with M. Misiak

Some people say that BF(B→Xsγ) is already uncertainty limited at B-factories but it is not true!



Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s\gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.9%	3.2%
$\mathrm{Br}(B \to X_s\gamma)^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$\mathrm{Br}(B \to X_s\gamma)_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.4%	0.94%	0.69%
$\Delta_{0+}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	9.0%	2.6%	0.85%

Belle II Physics book 1808.10567

CP asymmetry study of $\mathbf{B} \rightarrow X_s\gamma$

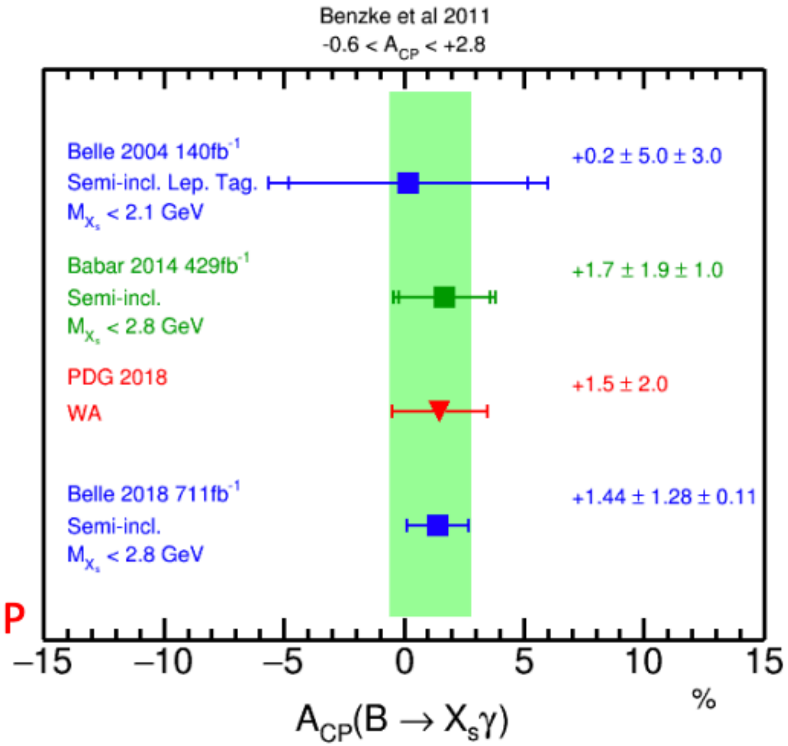
- $A_{CP}(B \rightarrow X_s\gamma)$ is sensitive to CPV in NP but theoretical uncertainty already dominant

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{X}_s\gamma) - \Gamma(B \to X_s\gamma)}{\Gamma(\bar{B} \to \bar{X}_s\gamma) + \Gamma(B \to X_s\gamma)}$$

- New observable ΔA_{CP} is null in SM and sensitive to NP

$$\begin{aligned}\Delta A_{CP} &= A_{CP}(B^+ \to X_s^+\gamma) - A_{CP}(B^0 \to X_s^0\gamma) \\ &= 4\pi^2\alpha_s \frac{\tilde{\Lambda}_{78}}{m_b} \mathrm{Im}\left(\frac{C_8}{C_7}\right), \\ &\approx 0.12 \left(\frac{\tilde{\Lambda}_{78}}{100\ \mathrm{MeV}}\right) \mathrm{Im}\left(\frac{C_8}{C_7}\right),\end{aligned}$$

M. Benzke, S. J. Lee, M. Neubert, G. Paz, JHEP 08 (2010) 099



Recent estimation gives larger uncertainty
Gunawardana and Paz 1908.02812

- Belle measured the observable in 2018

$$\Delta A_{CP} = [+3.69 \pm 2.65(\mathrm{stat.}) \pm 0.76(\mathrm{syst.})]\%$$

Watanuki, Ishikawa et al (Belle), PRD 99, 032012 (2019)

Belle II Prospects CP asymmetry study of $\mathbf{B \to X_s \gamma}$

- The latest Belle result

$$\Delta A_{CP} = [+3.69 \pm 2.65(\text{stat.}) \pm 0.76(\text{syst.})]\%$$

  - We found the systematic uncertainty is much smaller then statistical one
  - And also most of the systematic uncertainties are reducible
- At Belle II, we can reduce the uncertainty to 0.3% level
  - If current central value holds, the deviation is about 12σ from zero
  - If consistent with zero, strong constraints on $\mathrm{Im}(C_8/C_7)$
    - Theoretical improvement on ~Λ_{78} is desirable.

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\Delta A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.7%	0.98%	0.30%

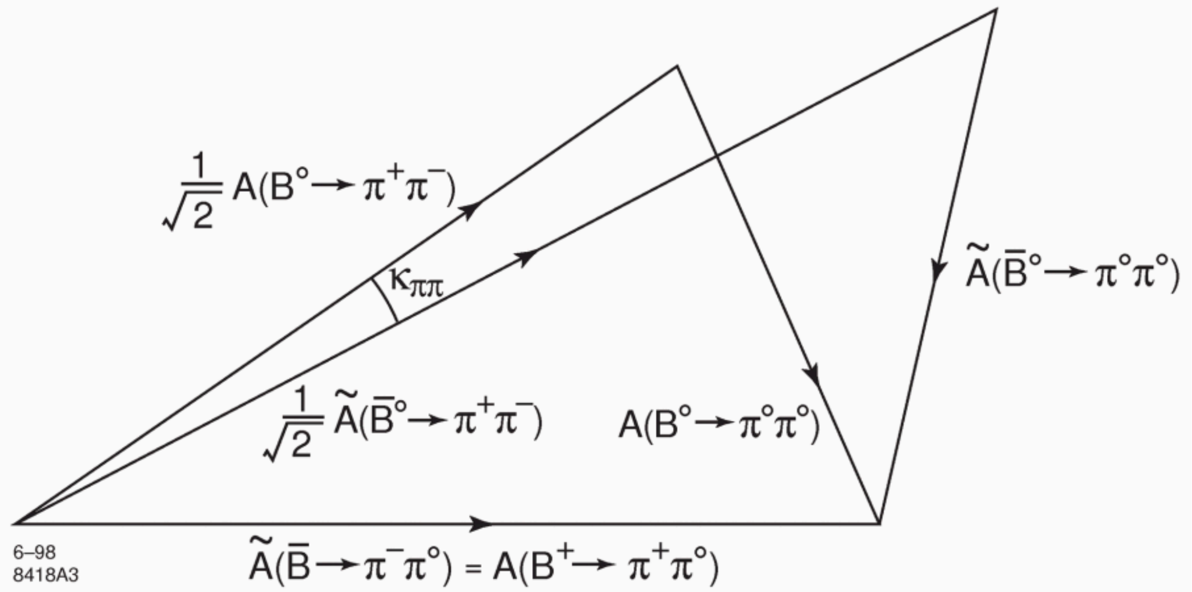
- If deviation found
  - EW Baryogenesis in G2HDM — Modak and Senaha Phys.Rev. D99, 11, 115022 (2019)
  - SUSY with FV trilinear coupling — Endo, Goto, Kitahara, Mishima, Ueda and Yamamoto, JHEP 04 (2018) 019.

Measurement of ϕ_2

- The measurement of ϕ_2 from $B \to \pi\pi$ (or $B \to \rho\rho$) final states comes from an isospin analysis:

The following equalities hold:

$$\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$$
$$\frac{1}{\sqrt{2}} \tilde{A}^{+-} + \tilde{A}^{00} = \tilde{A}^{+0}$$
$$A^{+0} = \tilde{A}^{+0}$$



see e.g. Eur. Phys. J. C77 (2017) no. 8, 574

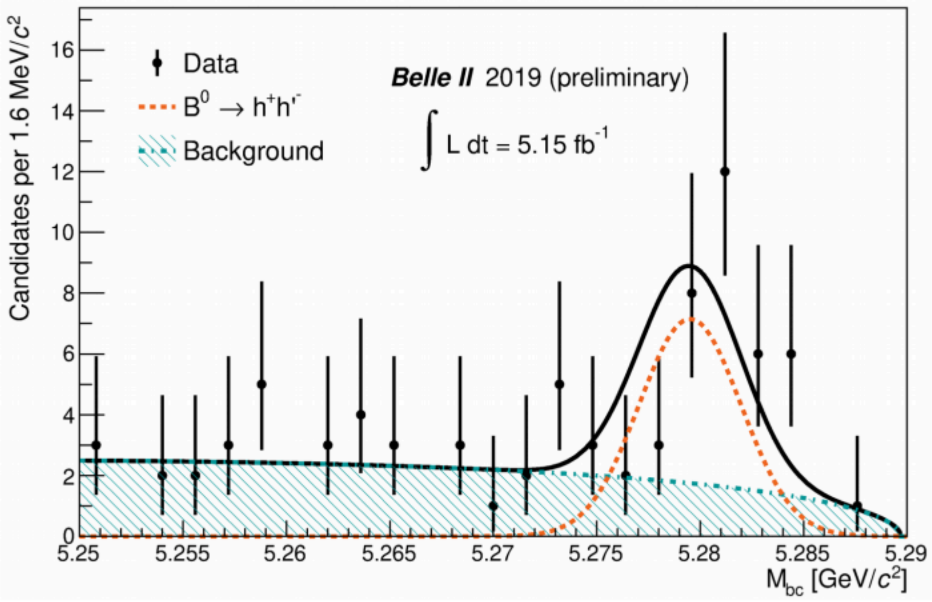
- Observables (for e.g. $B \to \pi\pi$):
  - branching fractions of: $B^\circ \to \pi^+\pi^\circ, \pi^+\pi^-, \pi^\circ\pi^\circ$;
  - direct (time independent) CP asymmetries: C^{+-}, $C^{\circ\circ}$;
  - time dependent CP asymmetries: S^{+-}, $S^{\circ\circ}$.

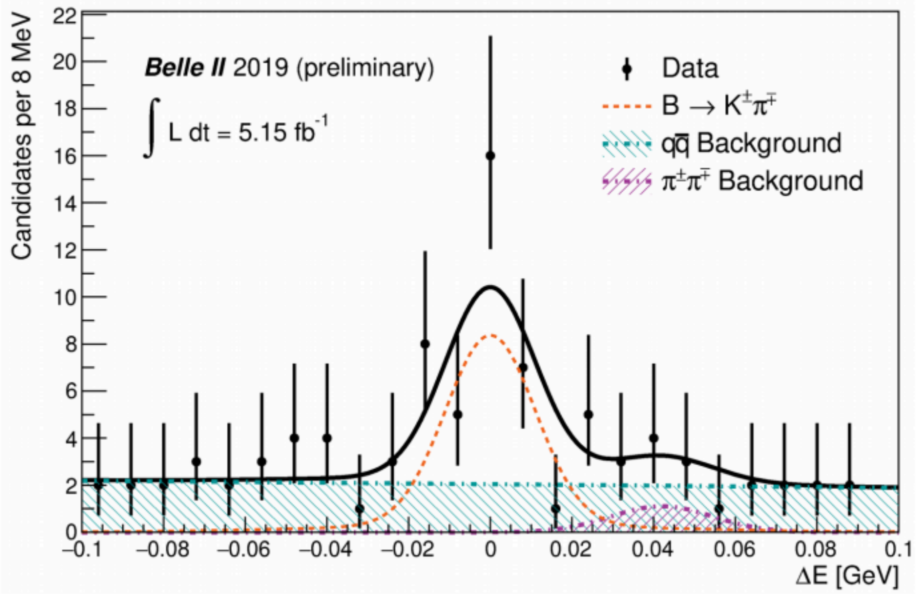
This will be measured for the first time at Belle II

- LHCb will make precise measurements of $B^\circ \to \pi^+\pi^-$ and $B^\circ \to \rho^\circ\rho^\circ$, but won't be able to make a full isospin analysis.

Rediscovery of $B \to h^+ h'^-$

- First milestone for the measurement of ϕ_2: rediscovery of the charmless $B \to h^+ h'^-$ decays;
- Continuum background is suppressed using a BDT classifier utilizing variables sensitive to the event topology;
- Only very loose PID requirements on the final state particles;
- A clear signal (~25 events) is observed for the $K^+\pi^-$ mode;
- More statistics will be needed to observe the more elusive $\pi^+\pi^-$ signal.





Summary

- Belle II began taking physics data in 2019
- Integrated luminosity ~O(10 fb^{-1}) used for commissioning and some unique measurements
- Will reach Belle's integrated luminosity in 2022
- Belle II will be competitive/complementary to LHCb on many other areas soon

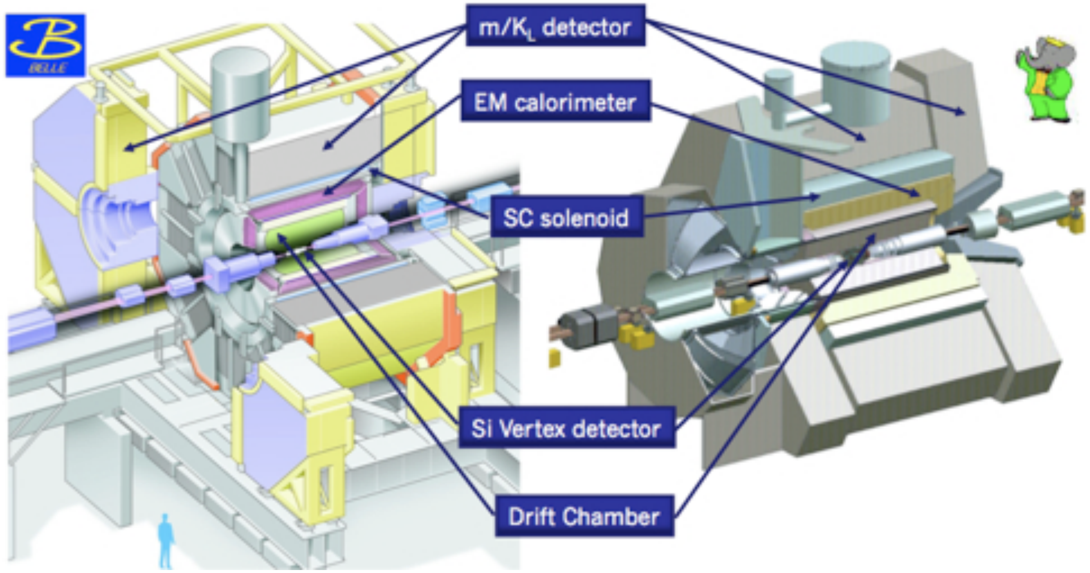
Backup

Outline

- The **SuperKEKB** collider and **Belle II** detector
- The **Prospects** of **rare B decays at Belle II**
  - Flavour Changing Neutral Currents (FCNC) B decays
    - b $\rightarrow s\ell^{+}\ell^{-}$
  - B decays with missing energy
    - $\mathrm{B} \rightarrow K^{(*)}\nu\bar{\nu},$
  - B decays with γ
    - $\mathrm{B} \rightarrow K^{(*)}\gamma, X_s\gamma$
  - Direct CP violation
    - $B \rightarrow hh\ (h = K\ or\ \pi)$

The 1st-generation *B* factories

"*B* factory": High-luminosity, asymmetric-energy e^+e^- collider operating at $\sqrt{s} = 10.58$ GeV to produce $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



https://www2.kek.jp/proffice/archives/feature/2010/BelleBaBarBook.html

Belle in Japan
1999-2010
~1000 fb^{-1}= 1 ab^{-1}

BaBar in the US
1999-2008
~500 fb^{-1}= 0.5 ab^{-1}

Initial goal: test the CP-violation mechanism of the SM

Expected Luminosity in the Near Term

	Until 2020/7/1				Until 2021/3/31			
	Int. L [fb^{-1}]	L_p [E34]	I_{max} [A]	β_y^* [mm]	Int. L [fb^{-1}]	L_p [E34]	I_{max} [A]	β_y^* [mm]
Base (conservative) plan	100	2.2	0.8	1				
Possible (expected) plan	150	3.5	0.9	1				
Case N1: 6.5 months operation	150	3.5	0.9	1	500	9.5	1.1	0.5
Case N2: 5.4 months operation	150	3.5	0.9	1	320	8.1	1	0.5

Reference: Y. Suetsugu, B2GM, 2020.Feb.03

The Int. L will be **100 - 150 fb^{-1}** until 2020/7/1, and **320 – 500 fb^{-1}** until 2021/3/31.

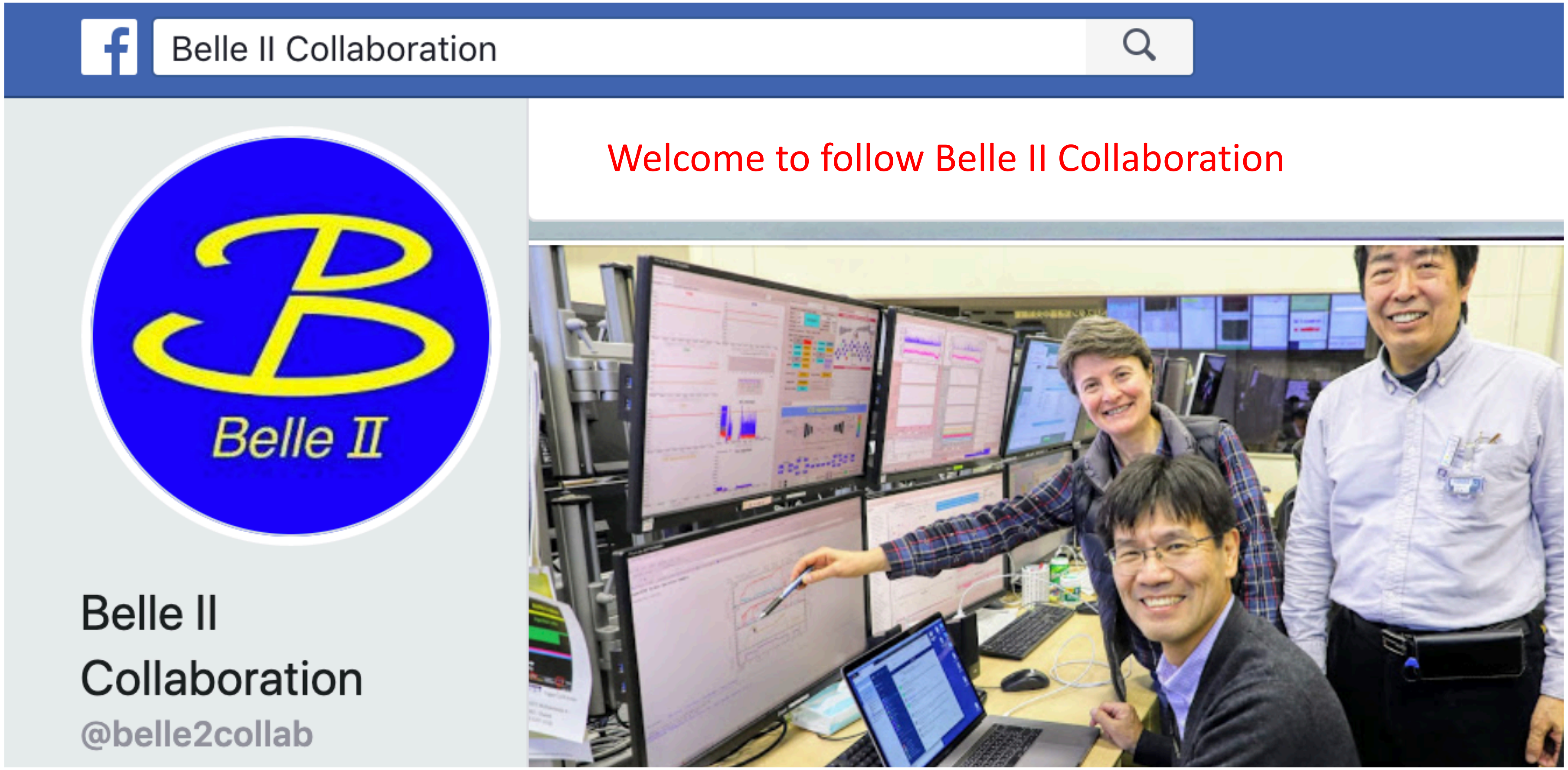
Expected Luminosity in the Middle Term

	Until 2022/3/1				Until 2023/3/31			
	Int. L [ab^{-1}]	L_p [E34]	I_{max} [A]	β_y^* [mm]	Int. L [ab^{-1}]	L_p [E34]	I_{max} [A]	β_y^* [mm]
Case M1: FY2020 6.5 months PXD exc. 2022	1.5	19	1.3	0.3	3.4	26	1.7	0.3
Case M2: FY2020 5.4 months PXD exc. 2021	0.6	16	1.1	0.3	3.4	25	1.6	0.3
Case M3: FY2020 5.4 months PXD exc. 2022	1.2	17	1.2	0.3	2.7	24	1.6	0.3

Reference: Y. Suetsugu, B2GM, 2020.Feb.03

The Int. L will be **0.6 – 1.5 ab^{-1}** until 2022/3/1, and **2.7 – 3.4 ab^{-1}** until 2023/3/31.

The new record of the peak luminosity



The photograph indicates the peak luminosity of Belle II experiment reached $\mathbf{105.43\times 10^{32}/cm^{2}/sec}$ in the evening of December 3, 2019. Credit: KEK Outreach Committee.

The Belle II Physics Book

- The "Belle II Physics Book" has been recently accepted for publication by PTEP;
- This is the results of several years of collaboration between Belle II and the Theory Community;
- Sensitivity estimates on the golden (and silver) channels are given

arXiv: 1808.10567
DOI: 10.1093/ptep/ptz106

200+ citations

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

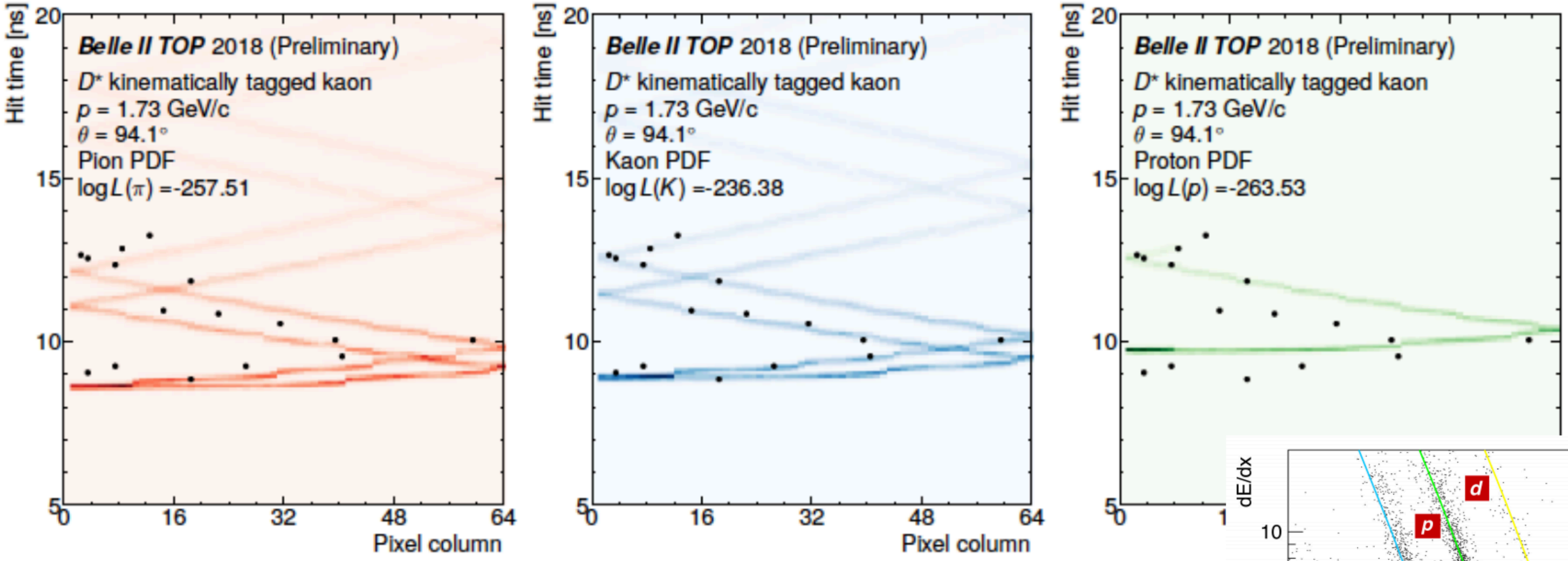
E. Kou[74,¶,†], P. Urquijo[143,§,†], W. Altmannshofer[133,¶], F. Beaujean[78,¶], G. Bell[120,¶], M. Beneke[112,¶], I. I. Bigi[146,¶], F. Bishara[148,16,¶], M. Blanke[49,50,¶], C. Bobeth[111,112,¶], M. Bona[150,¶], N. Brambilla[112,¶], V. M. Braun[43,¶], J. Brod[110,133,¶], A. J. Buras[113,¶], H. Y. Cheng[44,¶], C. W. Chiang[91,¶], M. Ciuchini[58,¶], G. Colangelo[126,¶], H. Czyz[154,29,¶], A. Datta[144,¶], F. De Fazio[52,¶], T. Deppisch[50,¶], M. J. Dolan[143,¶], J. Evans[133,¶], S. Fajfer[107,139,¶], T. Feldmann[120,¶], S. Godfrey[7,¶], M. Gronau[61,¶], Y. Grossman[15,¶], F. K. Guo[41,132,¶], U. Haisch[148,11,¶], C. Hanhart[21,¶], S. Hashimoto[30,26,¶], S. Hirose[88,¶], J. Hisano[88,89,¶], L. Hofer[125,¶], M. Hoferichter[166,¶], W. S. Hou[91,¶], T. Huber[120,¶], S. Jaeger[157,¶], S. Jahn[82,¶], M. Jamin[124,¶], J. Jones[102,¶], M. Jung[111,¶], A. L. Kagan[133,¶], F. Kahlhoefer[1,¶], J. F. Kamenik[107,139,¶], T. Kaneko[30,26,¶], Y. Kiyo[63,¶], A. Kokulu[112,138,¶], N. Kosnik[107,139,¶], A. S. Kronfeld[20,¶], Z. Ligeti[19,¶], H. Logan[7,¶], C. D. Lu[41,¶], V. Lubicz[151,¶], F. Mahmoudi[140,¶], K. Maltman[171,¶], S. Mishima[30,¶], M. Misiak[164,¶],

Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to \pi \ell \nu_\ell$	$\|V_{ub}\|$	★★★	10-20	★★★	★★★	★★	★
$B \to X_u \ell \nu_\ell$	$\|V_{ub}\|$	★★	2-10	★★★	★★	★★★	★
$B \to \tau \nu$	$Br.$	★★★	>50 (2)	★★★	★★★	★	★★★
$B \to \mu \nu$	$Br.$	★★★	>50 (5)	★★★	★★★	★	★★★
$B \to D^{(*)} \ell \nu_\ell$	$\|V_{cb}\|$	★★★	1-10	★★★	★★	★★	★
$B \to X_c \ell \nu_\ell$	$\|V_{cb}\|$	★★★	1-5	★★★	★★	★★	★★
$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	★★★	5-10	★★	★★★	★★★	★★★
$B \to D^{(*)} \tau \nu_\tau$	P_τ	★★★	15-20	★★★	★★★	★★	★★★
$B \to D^{**} \ell \nu_\ell$	$Br.$	★	-	★★	★★★	★★	-

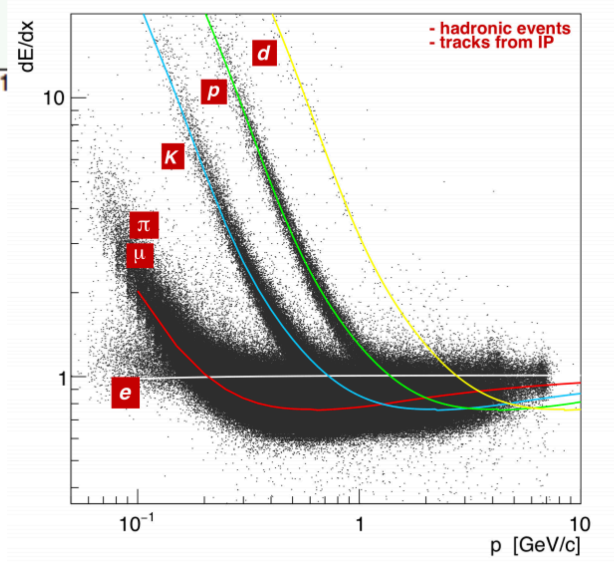
Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to J/\psi K^0_S$	ϕ_1	★★★	5-10	★★	★★	★	★
$B \to \phi K^0_S$	ϕ_1	★★	>50	★★	★★★	★	★★★
$B \to \eta' K^0_S$	ϕ_1	★★	>50	★★	★★★	★	★★★
$B \to \rho^\pm \rho^0$	ϕ_2	★★★	>50	★	★★★	★	★
$B \to J/\psi \pi^0$	ϕ_1	★★★	>50	★	★★★	-	-
$B \to \pi^0 \pi^0$	ϕ_2	★★	>50	★★★	★★★	★★	★★
$B \to \pi^0 K^0_S$	S_{CP}	★★	>50	★★★	★★★	★★	★★

Hadron-ID performance

ToP signature of kaon identified kinematically via $D^{*+} \to \pi^+ D^0 (\to K^- \pi^+)$
is visibly more consistent with being a kaon than a pion or proton



dE/dx in the drift chamber:



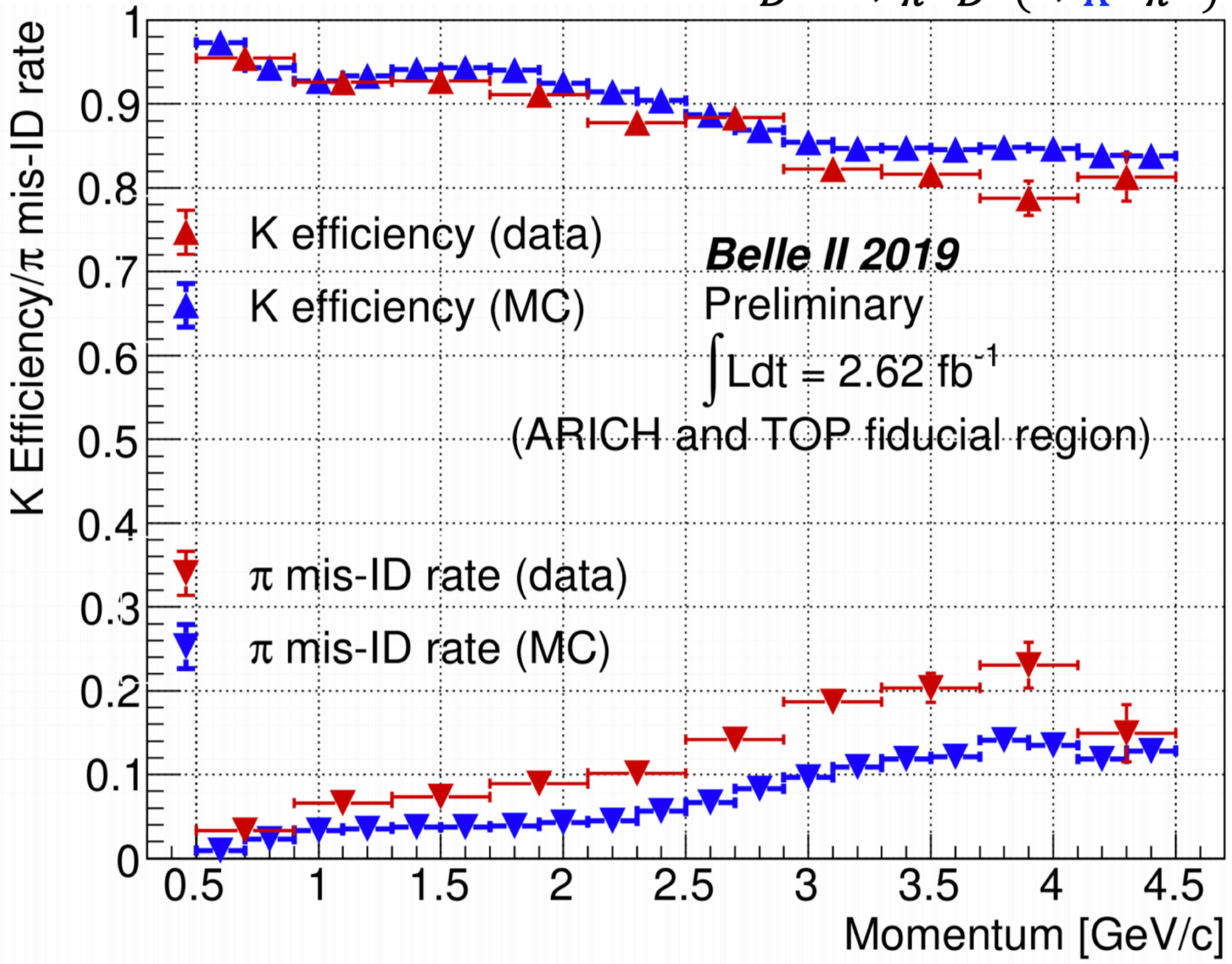
Hadron-ID performance

BELLE2-NOTE-PL-2019-022

Kaon candidate selection:

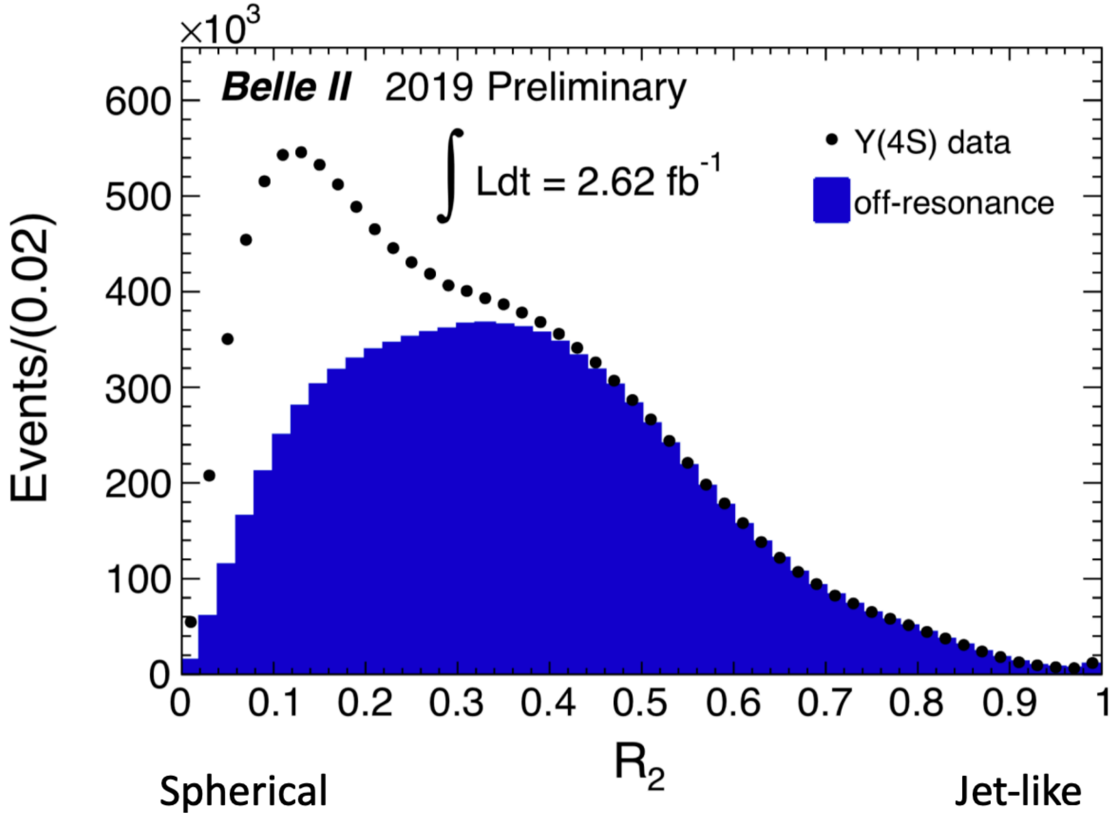
$$\frac{L_K}{L_K + L_\pi} > 0.5$$

$D^{*+} \to \pi^+ D^0(\to K^- \pi^+)$

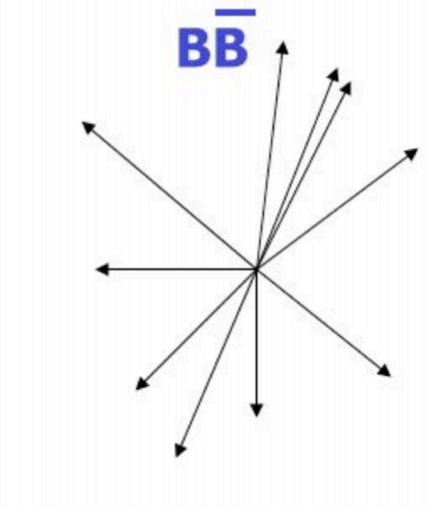


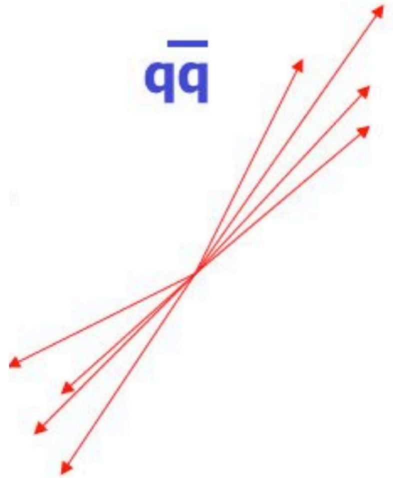
Event Topology tells us we are producing B's

BELLE2-NOTE-PL-2019-017



Spherical Jet-like



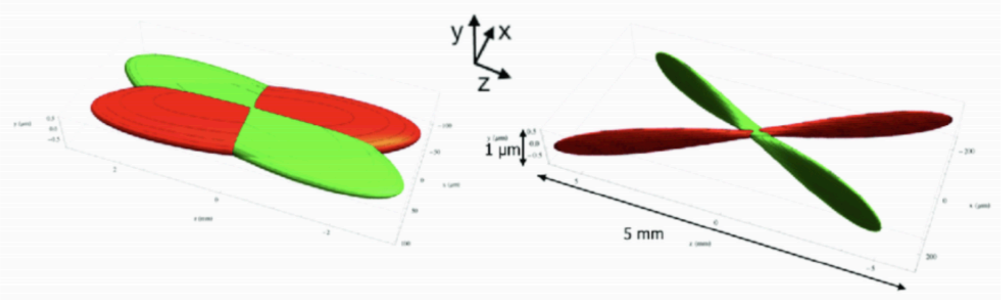


→We are running on the $\Upsilon(4S)$ resonance

$\mathbf{B} \rightarrow \boldsymbol{K^{*}\nu\bar{\nu}}$

Beam-constrained vertexing

- In time-dependent analyses, the key ingredient is the difference between the time of decay of two B mesons. Determining B decay vertex positions correctly is necessary
- In BaBar, B^0 and B^+ average flight distance ~20 μm in transverse plane and ~260 μm in Z direction
- The beamspot size was ~(120 x 5 x 8000 μm^3), similar in Belle
- To obtain the B decay vertex position correctly, a vertex fit with interaction point(ip) constraint was sufficient
- In Belle II, the beamspot is smaller ~(6 x 0.06 x 150μm^3): thanks to nanobeam scheme. In addition, the tracking resolution is ~twice as good as at BaBar/Belle



- In Belle II, an ip-constrained fit is not sufficient anymore. We need a better constraint

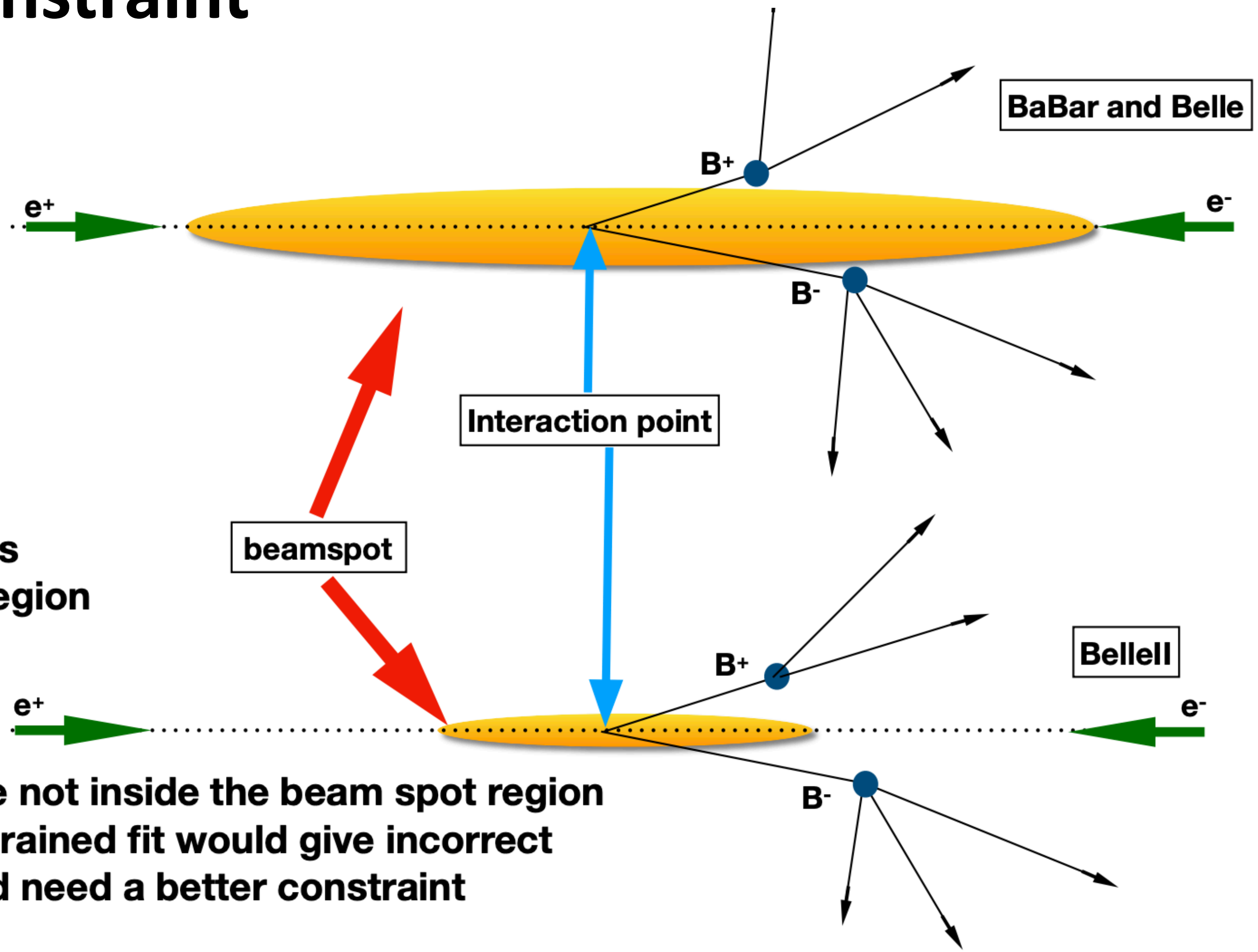
Reference: Sourav Dey@FHEP2019

$\mathbf{B} \rightarrow K^{*}\nu\bar{\nu}$

Need a better constraint

In Babar and Belle, The B decay vertices resided inside the beamspot region : an ip-constrained fit used to give good result

In Belle II, beamspot is much smaller : The B decay vertices come out of the beamspot region



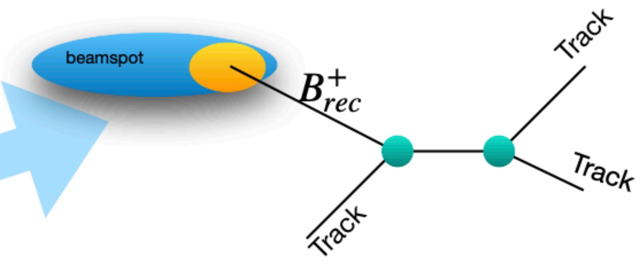
The B decay vertices are not inside the beam spot region anymore. An ip-constrained fit would give incorrect result. We indeed need a better constraint

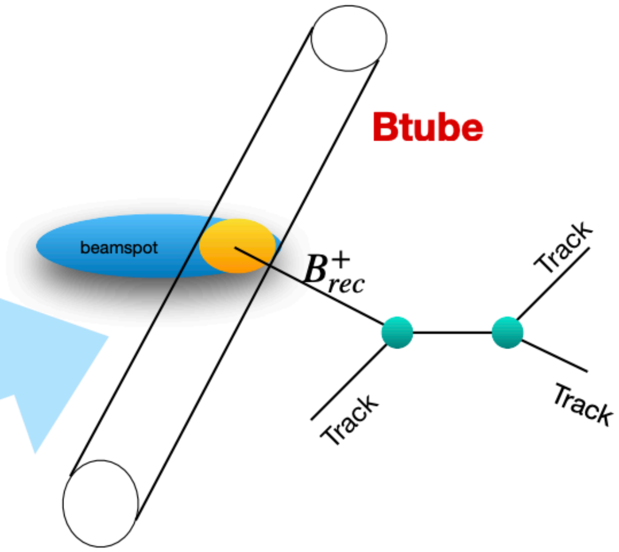
Reference: Sourav Dey@FHEP2019

$\mathbf{B} \rightarrow K^{*}\nu\bar{\nu}$

A new constraint: Btube

- Among two B mesons, we fully reconstruct one B (B_{rec})
- We propagate the B_{rec} track to the beamspot and apply a vertex fit. Result of this fit is a vertex which is the origin of both the B mesons.
- From four momentum conservation, we obtain the flight direction the other B .
- We then stretch the covariance matrix of the fully reconstructed B_{rec} vertex so that it has ~infinite size in the direction of the flight of the other B and use this tube-like object as the constraint of future other-B fits.



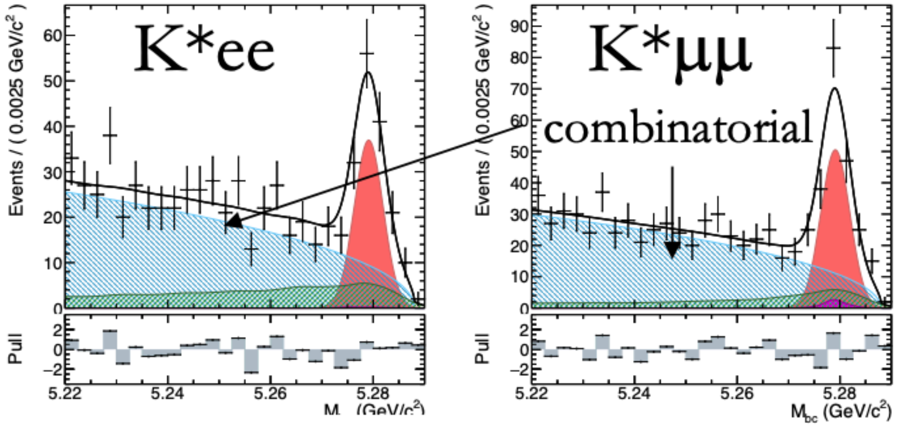


Reference: Sourav Dey@FHEP2019

Reconstruction of B→ $K^{(*)}\ell^{+}\ell^{-}$

- B → $K^{*}\ell\ell$

arXiv:1904.02440 (Belle 2019)

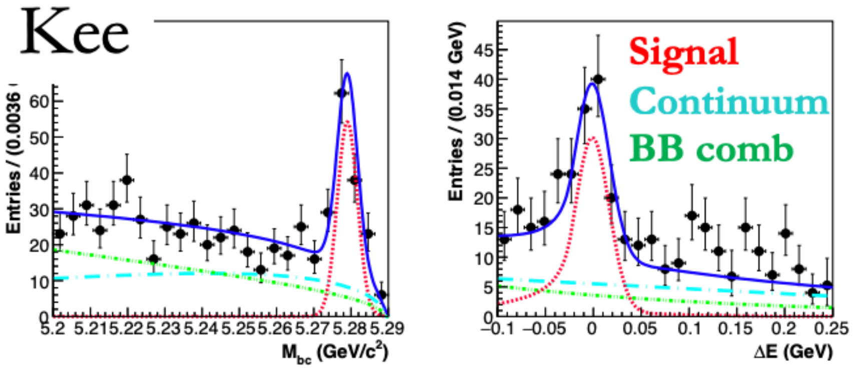


- Signal extraction with fit to M_{bc} distributions
- Dominant background: combinatorial
- Peaking background: charmonium $J/\psi K^{*}$
- Main systematics: lepton efficiency and peaking background

$$M_{bc} \equiv \sqrt{\frac{s}{4} - {p_B^{*}}^{2}}$$

arXiv:1908.01848 (Belle 2019)

- B → $K\ell\ell$



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

- Signal extraction with 3D fit to M_{bc}, ΔE, NN discriminant
- NN discriminant built using kinematic and angular variables
- Main systematics: lepton identification, B counting, NN discriminant