Measurements of b→sl+l- at Belle and Prospects at Belle II

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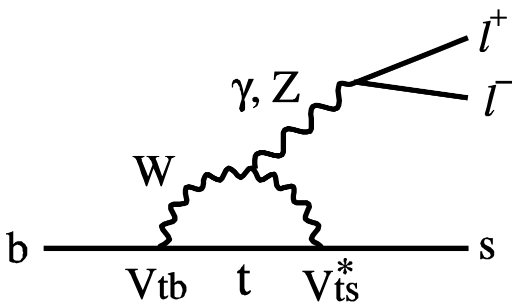
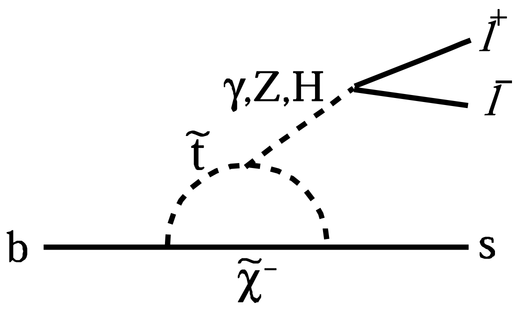
(Tohoku)





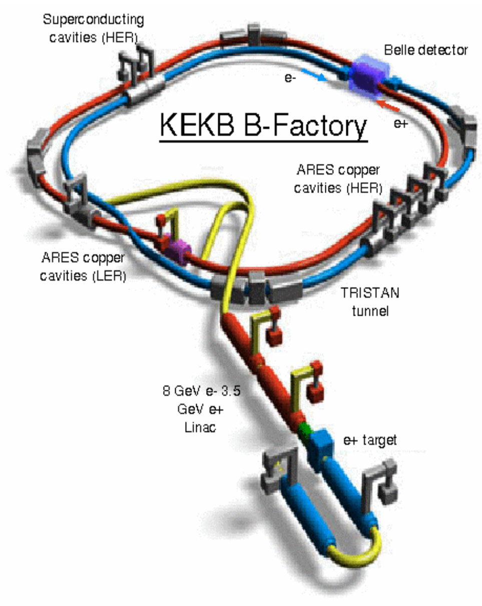
Observation of b→sl+l-

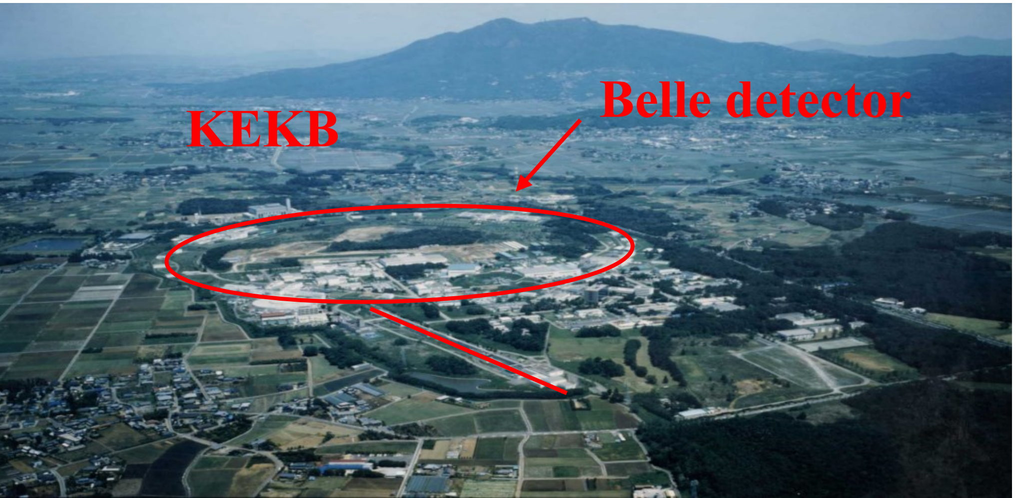
- Belle first observed b→sl+l- (new decay process) using exclusive B→Kl+l- with 30/fb in 2001 (published in 2002)
  - My PhD thesis.
  - B→K*l+l- with 140/fb in 2003.

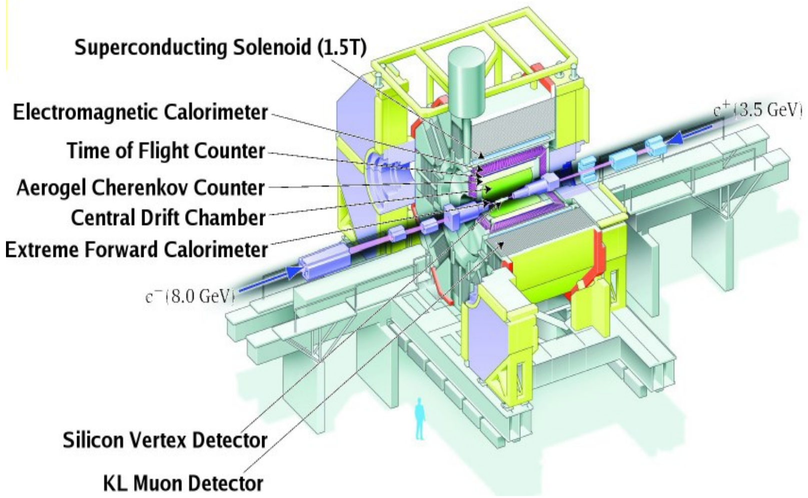
- As ATLAS and CMS observed the Higgs boson (new particle) which is an important tool to search for new physics with precision measurements, Belle also did the b→sl+l- (new decay process) which is a good probe for new physics.
  - Now LHCb, Babar, ATLAS and CMS also use the decay.

Belle and KEKB

- KEKB
  - e^+e^- collider
  - World highest luminosity machine
    - $L = 2.1 * 10^{34}$ /cm^2/sec
  - Asymmetric-energy to boost B meson
    - 8.0GeV e^- × 3.5GeV e^+
- Belle
  - Designed to measure time dependent CPV
    - But multi purpose 4π (x94%) detector
  - Accumulated 772×10^6 B meson pair events



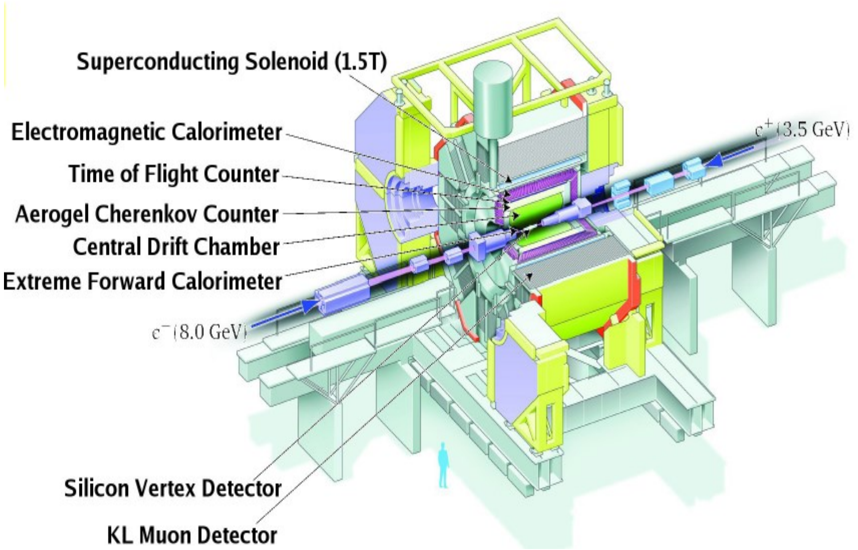




Basics of B-factory for Beginners (or ATLASians)

- Process at B-factory
  - $e^+e^- \rightarrow Y(4S) \rightarrow BB$
    - Cleaner environment
    - $<N_{charged}>$ ~ 11
    - $<N_{photon}>$ ~5
      - $0.94^{16} = 0.37$
    - Average difference of two B meson decay positions in z ~200um
    - width of z_{PV} ~ 6mm
- Trigger efficiency
  - ~100% for BB events
- Kaon ID
  - dE/dx in CDC, ToF, ACC
  - Effi ~ 90%, fake ~ 7%
- Lepton ID
  - Threshold
    - p~0.4GeV (0.7GeV) for e (mu)
  - Electron ID better than muon ID
    - Effi ~ 95% (88%) for e (mu)
    - Fake ~0.2% (1%) for e (mu)
      - Decay In flight pion/Kaon

- Two kinematic variables to tag B meson
  - $M_{bc} \equiv \sqrt{E_{Beam}^2 - |\vec{p}_B|^2}$
    - Monochromatic B
    - peak at M_B
  - $\Delta E = E_B - E_{beam}$
    - Energy conservation
    - peak at zero
  - –

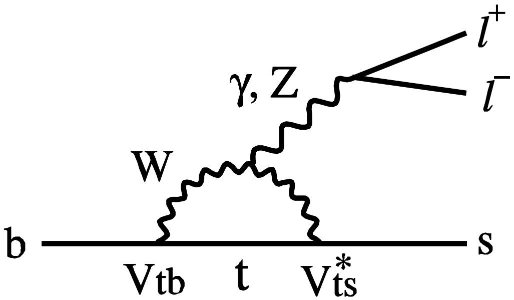


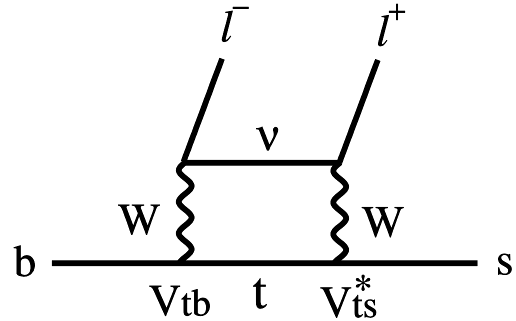
Contents for b→sl+l- at Belle

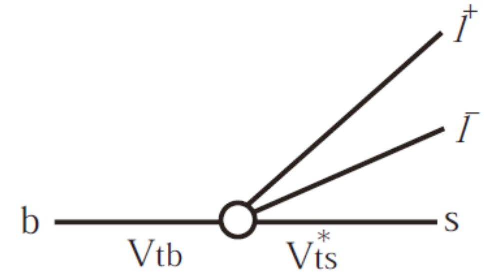
- $R_{K(*)}$ with $605 fb^{-1}$ — PRL 103, 171801 (2009)
- P_5' and Q_5' with $711 fb^{-1}$ — PRL 118, 111801 (2017 Mar 13)
  - BF(B→K*l+l-) ~ 10×10^{-7}
  - BF(B→Kl+l-) ~ 4×10^{-7}

- Inclusive Measurements are very important (especially at Belle II) but current constraints at Belle are not so great so let me skip
  - BF(B→Xsl+l-) ~ 40×10^{-7}

Wilson Coefficients in b→sl+l-







- In the SM, b→s ll can be written by real Wilson coefficients in Effective Hamiltoniam Approach
  - 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 $C_{9e} \neq C_{9\mu}$
  - Scalar and Tensor coefficients (C_S , C_P and C_T)
  - Right handed counter coefficients (C_i')
    - $P_{L(R)} \rightarrow P_{R(L)}$
  - Imaginary parts Im(Ci')

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

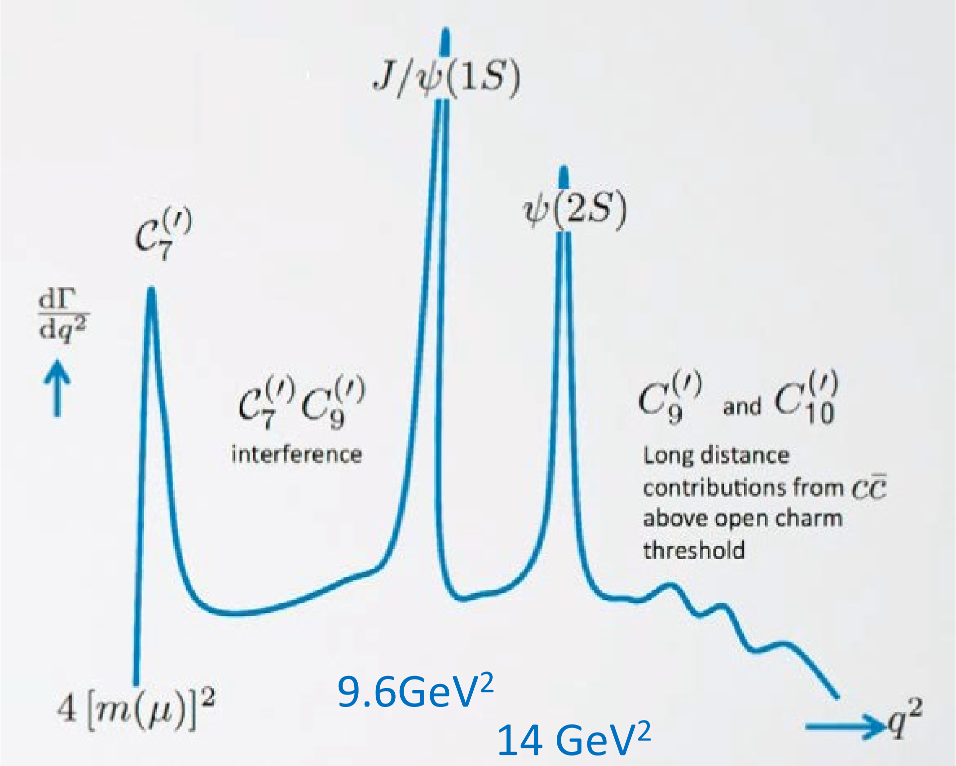
$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu},$$

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

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

q^2 distribution for B->K*l+l-

- Contribution from C_7 (dipole) is only for low q^2
  - photon pole $1/q^2$
- B→J/psi(l+l-) K* (tree level process) interferes with B→K*l+l-
  - Remove this q^2 region
- Contributions from C_9 (V) and C_{10} (A) are basically for whole q^2
- Interference btw Vector (C_7, C_9) and Axial vector (C_{10}) currents generates A_{FB}.



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$R_{K(*)}$

- In the SM, lepton flavor universality holds.
- R_K, and R_{K*} for not-very-low q2 are unity in the SM
  - Lepton mass effect for R_{K*} for very low q2 region

$$R_K = \Gamma(B \to K\mu\mu)/\Gamma(B \to Kee)$$
$$R_{K^*} = \Gamma(B \to K^*\mu\mu)/\Gamma(B \to K^*ee)$$

$$R_{K_{[\mathbf{1},\mathbf{6}]\mathrm{GeV}^2}} = 1.00 \pm 0.01$$

Marzia Bordone
1605.07633 in collaboration with G.Isidori and A.Pattori

	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
SM prediction	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01

CCDMV, 1704.05340

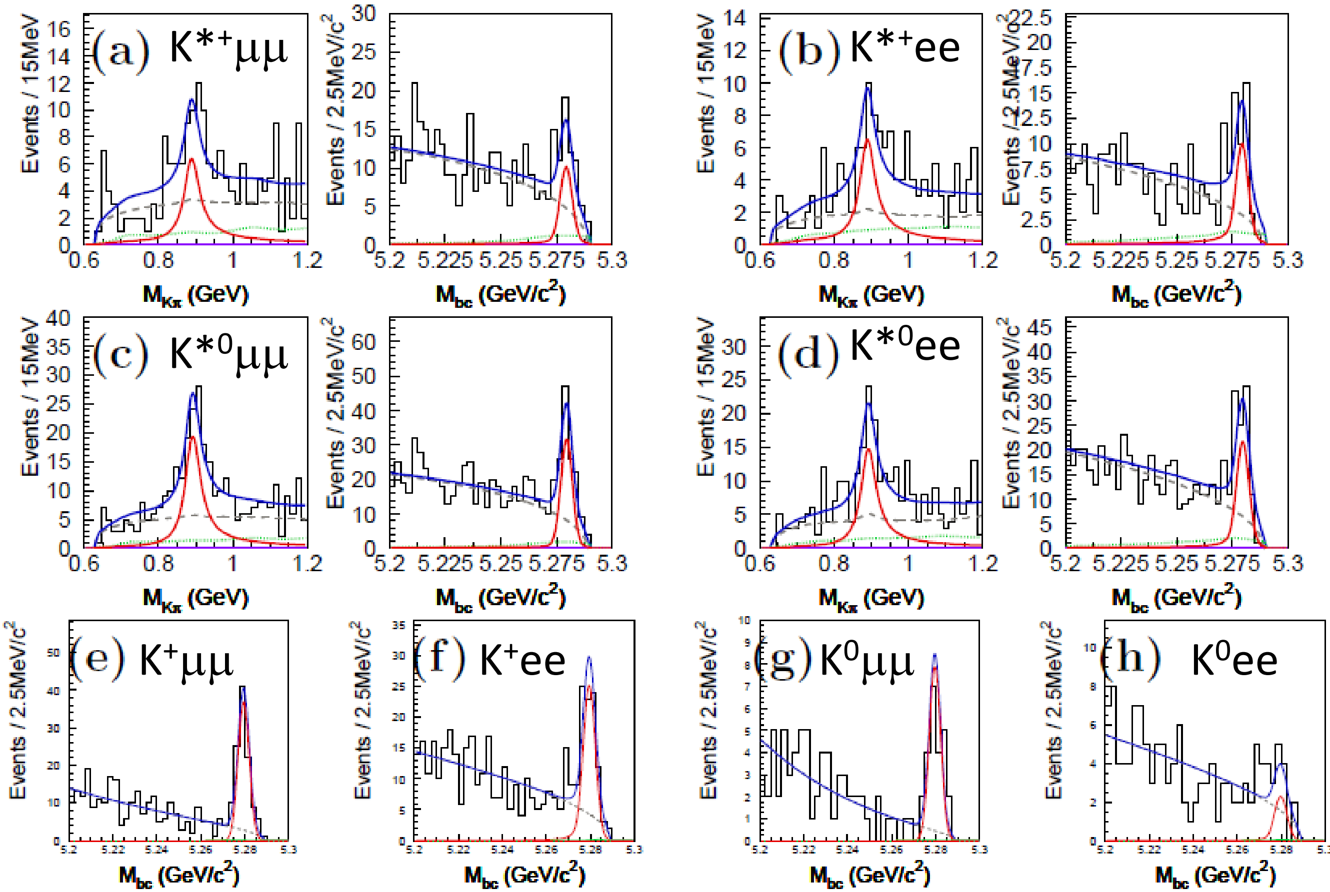
Analysis for $R_{K(*)}$

- Reconstruct $B \rightarrow K^{(*)}ee$ and $B \rightarrow K^{(*)}\mu\mu$
  - K+, Ks, K+π-, K+π0, Ksπ+
    - Ks$\rightarrow\pi+\pi$-, $\pi0\rightarrow\gamma\gamma$
  - For electron, bremsstrahlung recovery is performed.
    - 50mrad cone along electron direction
  - $q^2 > (2m_\mu)^2$
- Background suppression
  - Continuum (~3.5nb)
    - event shape
  - BB (1.08nb)
    - double semileptonic decays $\leftarrow$ missing energy
    - Veto B$\rightarrow$J/psi $K^{(*)}$

Results

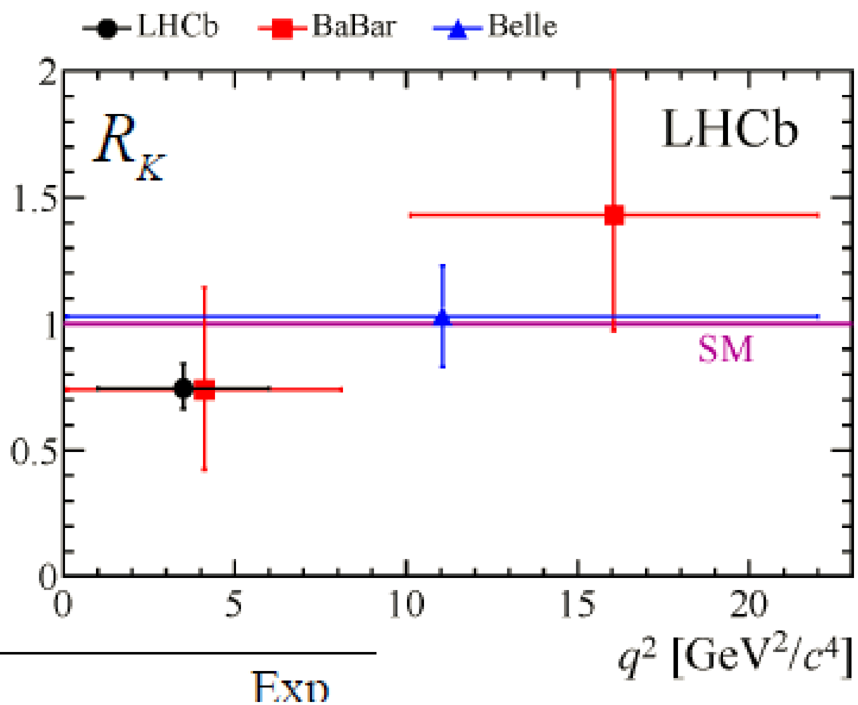
- Fit to M_{bc} (and M_{Kpi} for K*) to extract signal
- Since the statistics is low, whole q^2 region (>0.04GeV^2) is used to calculate $R_{K(*)}$
  - B→K*ll ~250 events
  - B→Kl+l- ~160 events
- Consistent with Unity

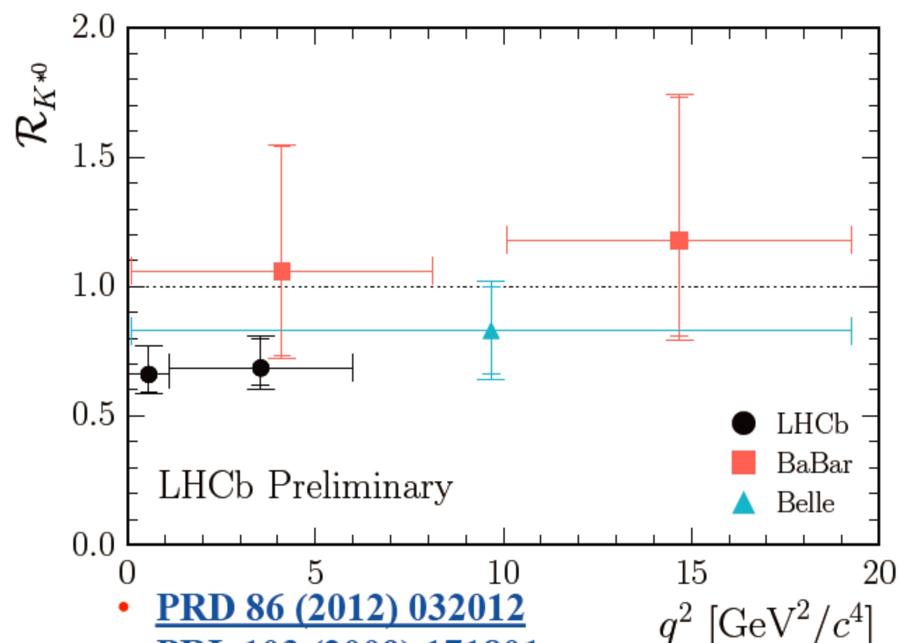
$$R_{K^*} = 0.83 \pm 0.17 \pm 0.08 \; ,$$
$$R_K = 1.03 \pm 0.19 \pm 0.06 \; .$$



Comparison

- Even full q^2 region is used, the uncertainties at **Belle** are larger than **LHCb**





- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

Prospects at Belle

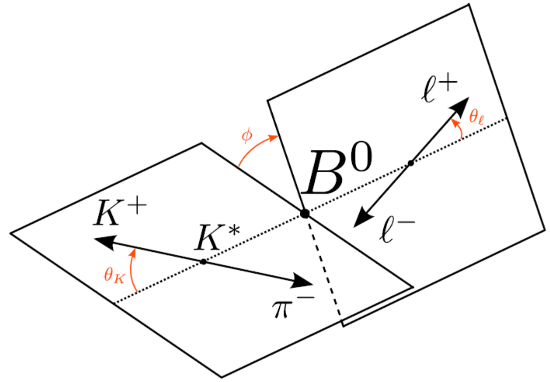
- The analysis technique is somewhat old and not optimal (performed in 2008).
  - Some improvements are foreseen.
    - Background suppression with neuralnet
    - Use of vertex information
    - Better Ks reconstruction

- Now the analysis with full data is on-going
  - 605/fb→711/fb

P_5' and Q_5

Decay Width of B→K*l+l-

- Functions of q^2 and three angles



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

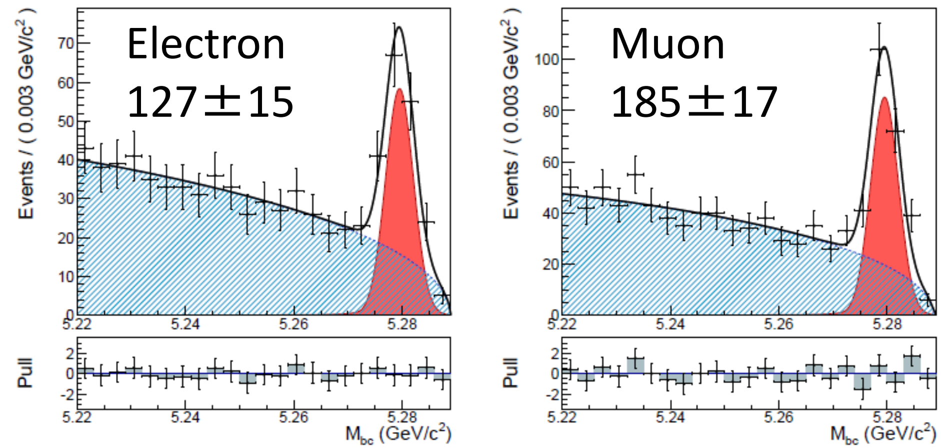
- Helicity amplitude bilinears. The coefficients S_i and F_L are functions of q^2 (and form factors)
  - P_i' is form factor insensitive observables and "clean"
  - P_i' is a function of Wilson coefficients

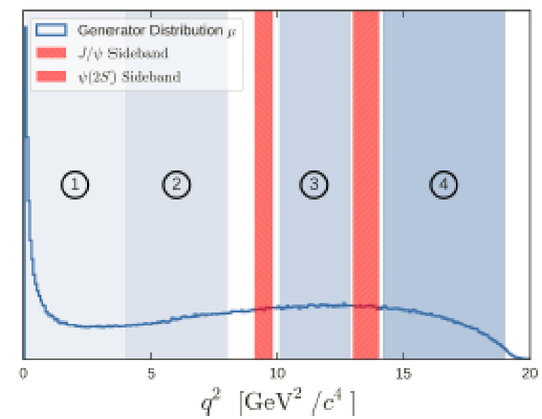
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

$$\langle F_L\rangle_{[1,6]} \simeq +0.77 + 0.25\,C_7^{\mathrm{NP}} + 0.05\,C_9^{\mathrm{NP}} - 0.04\,C_9' + 0.04\,C_{10}'\,,$$
$$\langle S_4\rangle_{[14.18,16]} \simeq +0.29 - 0.02\,C_9' + 0.03\,C_{10}'\,,$$
$$\langle S_5\rangle_{[1,6]} \simeq -0.14 - 0.59\,C_7^{\mathrm{NP}} - 0.49\,C_7' - 0.09\,C_9^{\mathrm{NP}} - 0.03\,C_9' + 0.10\,C_{10}'\,.$$

  - How "clean"? Discussion needed.

Reconstruction





- Decay modes
  - $B^0 \rightarrow K^{*0} l^+ l^-$, $K^{*0} \rightarrow$ K+pi-
  - $B^+ \rightarrow K^{*+} l^+ l^-$, $K^{*+} \rightarrow K_S \pi^+$, $K^+ \pi^0$
  - 312±23events (LHCb 2398±57)
- Signal fraction as a function of Mbc
- Separate electron and muon modes to test Lepton Flavor Universality, Q_i = 0 in the SM
  - $P_i'^e$, $P_i'^\mu$ and $Q_i = P_i'^e - P_i'^\mu$
- Only measured P_4', P_5' , Q_4', Q_5'
  - Since theoretically these two are important and publish to PRL before LHCb
  - Full paper to PRD including all the observables in progress

Folding

- Since statistics is small, we performed folding technique as LHCb did in 2013
  - LHCb did not use folding in 2015
  - Use symmetry of trigonometric function to eliminate coefficients other than F_L, S_3 and another one

$$P'_4, S_4 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases} \quad P'_5, S_5 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

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

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

Factorization

- Assuming factorization valids for background distribution

$$f_{\mathrm{bkg}}^{\mathrm{hist}}(q^2, \cos\theta_\ell, \cos\theta_K, \phi) = h_1(q^2, \cos\theta_\ell) \cdot h_2(q^2, \cos\theta_K) \cdot h_3(q^2, \phi)$$

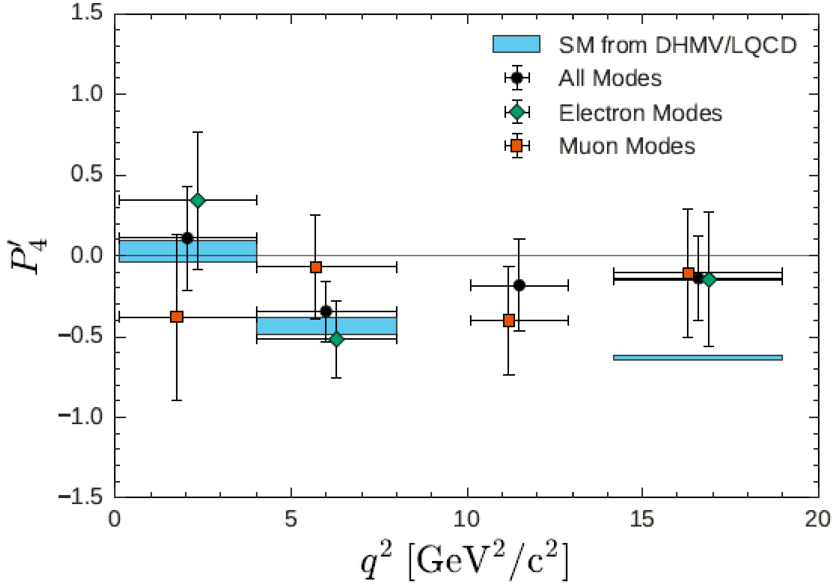
- Also for signal efficiency

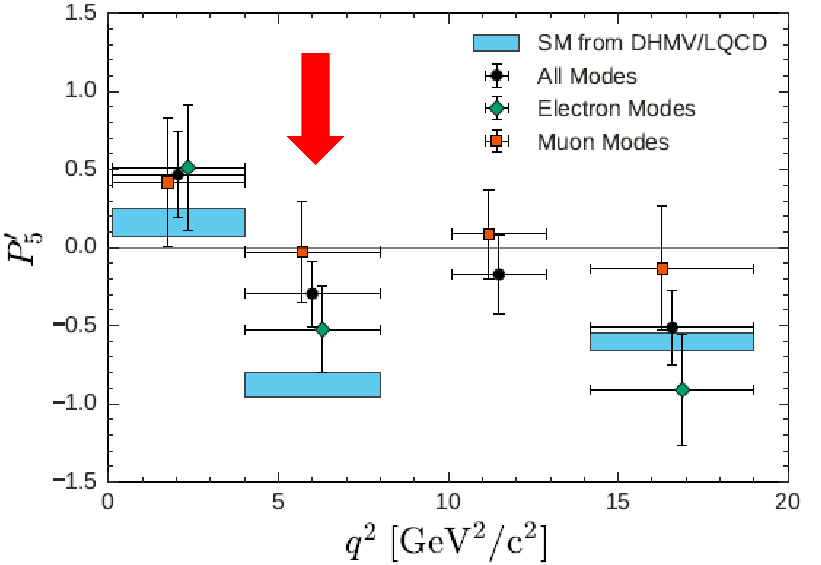
$$f_{\mathrm{eff}}^{\mathrm{bin}}(\cos\theta_\ell, \cos\theta_K, \phi, q^2) = \epsilon(\cos\theta_\ell) \otimes \epsilon(\cos\theta_K) \otimes \epsilon(\phi) \otimes \epsilon(q^2)$$

- These assumption are very good approximation but there are small correlation → systematic error (very small)

Results P_4' and P_5'

- Observed 2.6σ deviation from the SM prediction by DHMV
  - Systematic error small (taken very conservatively)

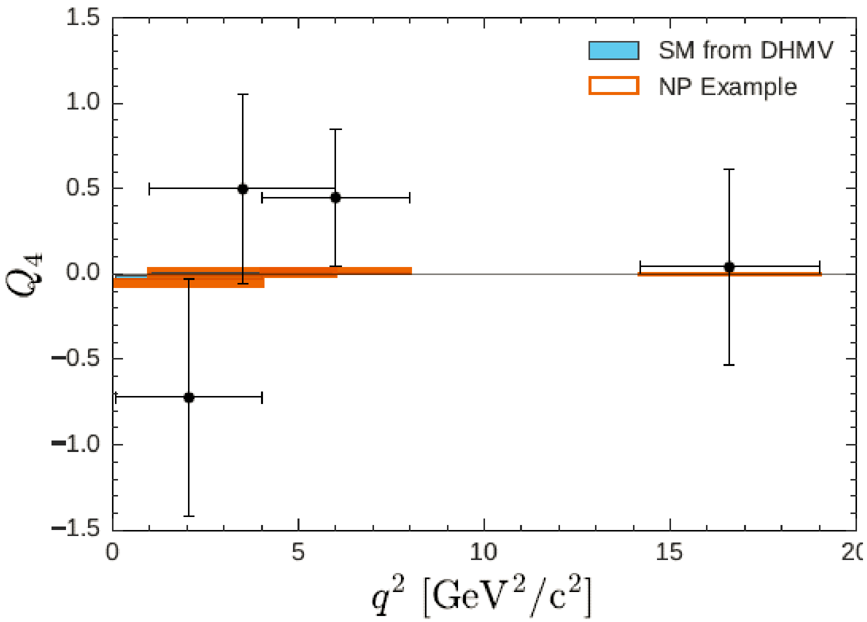


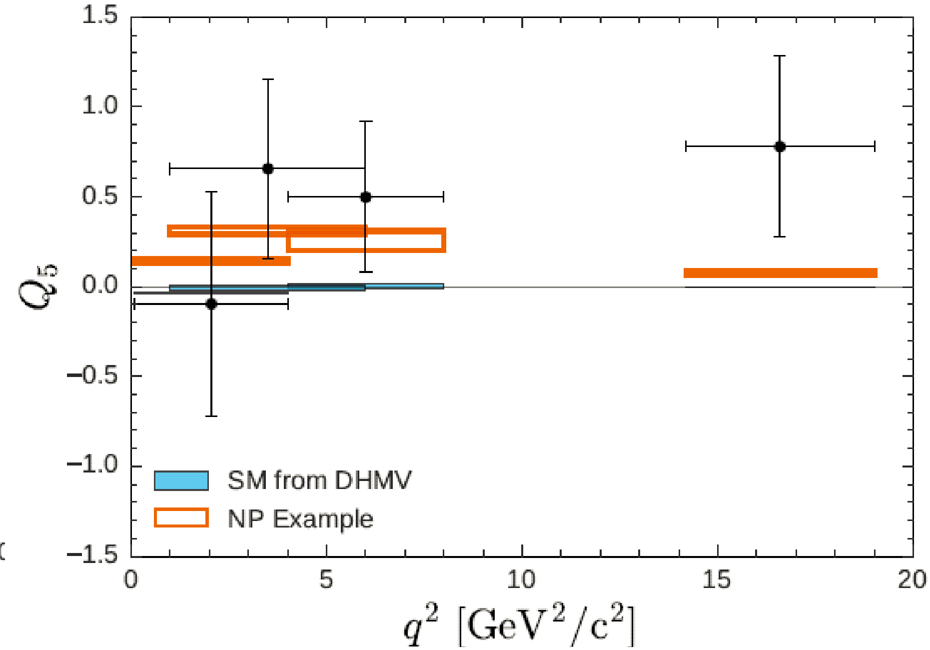


q^2 in GeV^2/c^2	P_4'	P_5'
$[1.00, 6.00]$	$-0.45^{+0.23}_{-0.22} \pm 0.09$	$0.23^{+0.21}_{-0.22} \pm 0.07$
$[0.10, 4.00]$	$0.11^{+0.32}_{-0.31} \pm 0.05$	$0.47^{+0.27}_{-0.28} \pm 0.05$
$[4.00, 8.00]$	$-0.34^{+0.18}_{-0.17} \pm 0.05$	$-0.30^{+0.19}_{-0.19} \pm 0.09$
$[10.09, 12.90]$	$-0.18^{+0.28}_{-0.27} \pm 0.06$	$-0.17^{+0.25}_{-0.25} \pm 0.01$
$[14.18, 19.00]$	$-0.14^{+0.26}_{-0.26} \pm 0.05$	$-0.51^{+0.24}_{-0.22} \pm 0.01$

Results Q_4 and Q_5

- Consistent with both SM and NP with $C_9{}^{\mu}{}_{NP} = -1$
  - Systematic error small (taken very conservatively)



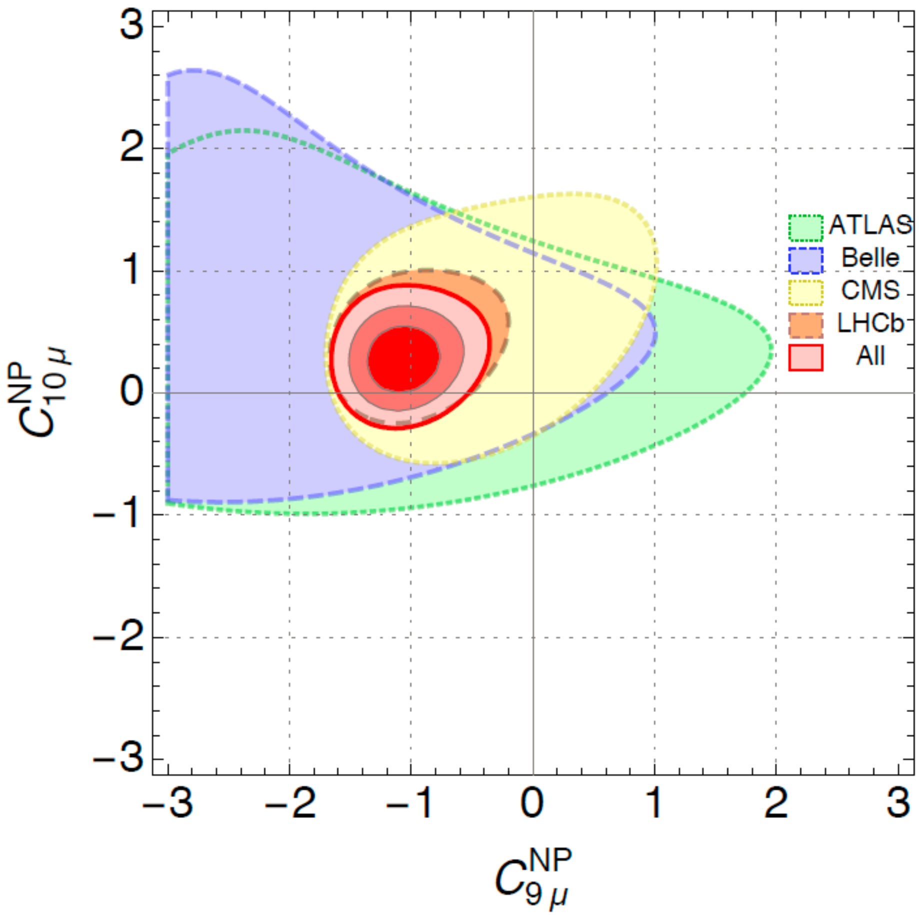


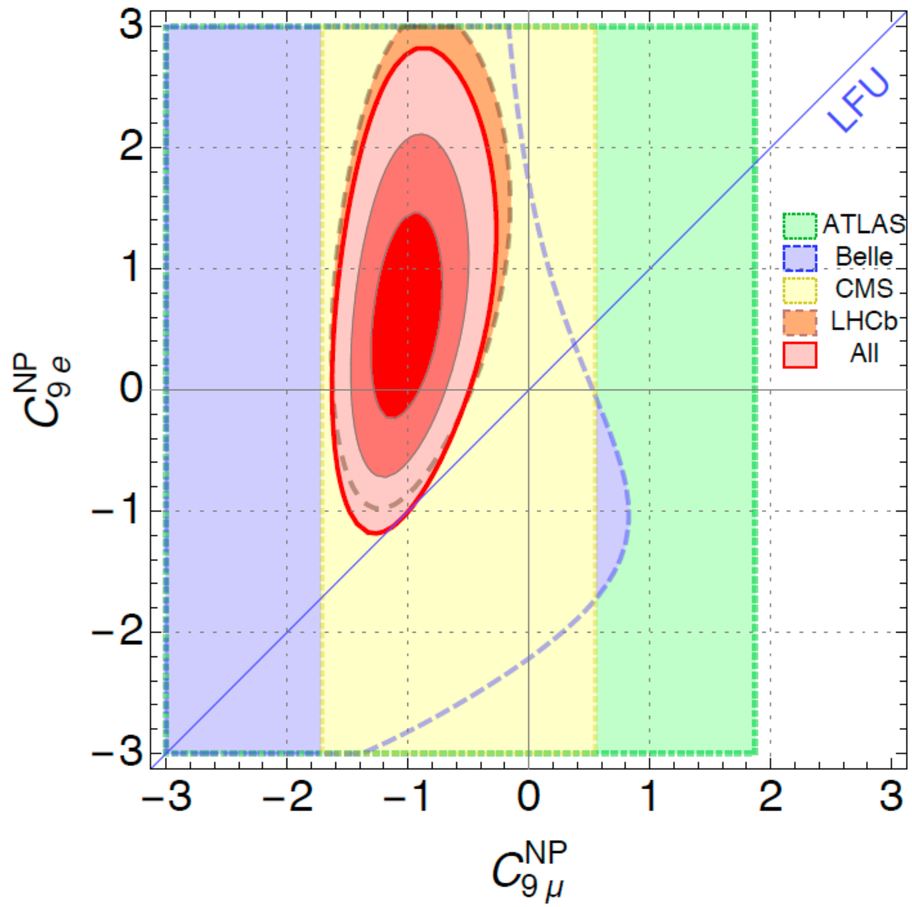
q^2 in GeV$^2/c^2$	Q_4	Q_5
[1.00, 6.00]	$0.498 \pm 0.527 \pm 0.166$	$0.656 \pm 0.485 \pm 0.103$
[0.10, 4.00]	$-0.723 \pm 0.676 \pm 0.163$	$-0.097 \pm 0.601 \pm 0.164$
[4.00, 8.00]	$0.448 \pm 0.392 \pm 0.076$	$0.498 \pm 0.410 \pm 0.095$
[14.18, 19.00]	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

Global Fit to b→s

1704.05340

- b→sl+l- including $R_{K(*)}$, Bs→μμ, b→sγ
  - Suggest $C_{9\mu}^{NP} \sim -1$

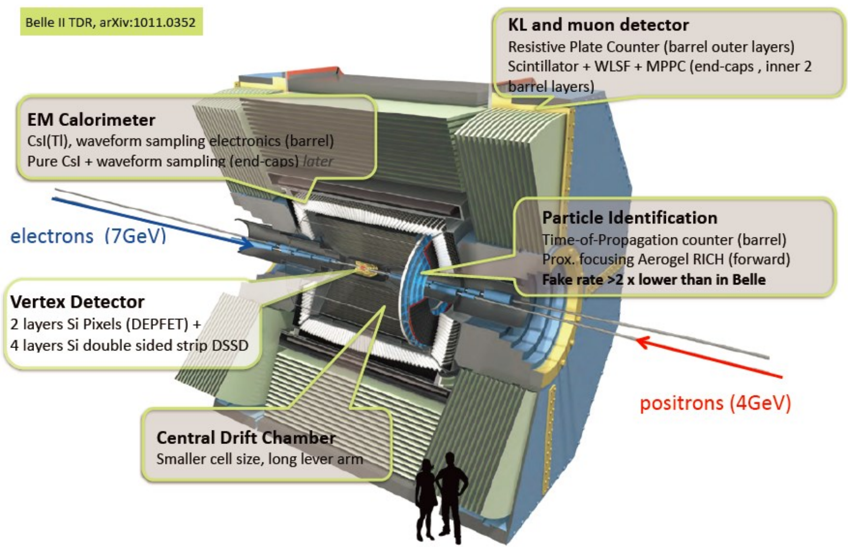




Prospects at Belle II

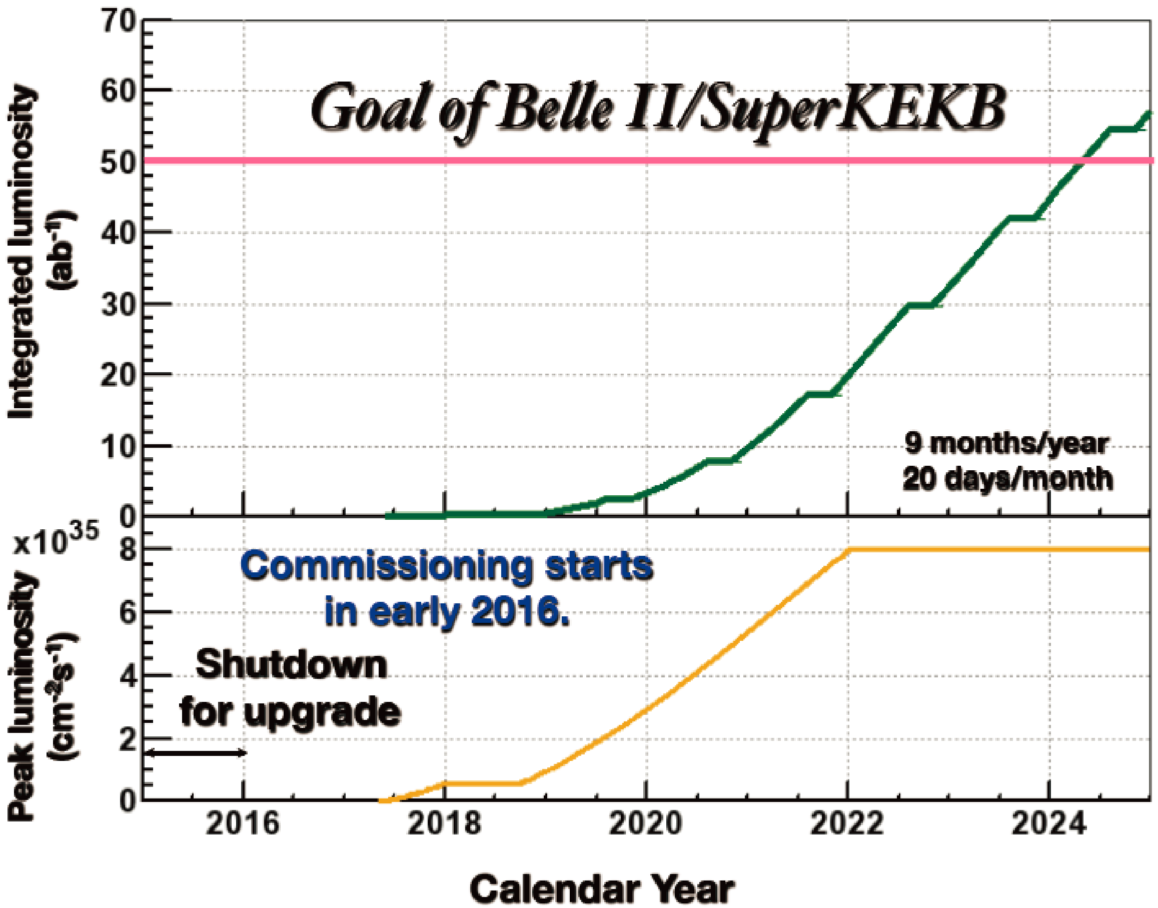
Belle II Detector

- Same or better performace even under 10-20 times larger background than Belle
  - Much better Kaon ID for Barrel/Forward Endcap
    - B→K*γ VS B→$\rho\gamma$
  - Inner layer of VXD smaller and outer layer larger
    - Improved vertex resolution、vertexing with long lived Ks 30% better
  - π^0, K_s can be reconstructed, electron ID of course.
- （Almost) All B decays are recorded
  - Even B^0→ nothing can be searched for
  - Effective flavor tagging efficiency >30% (LHCb ~3%)



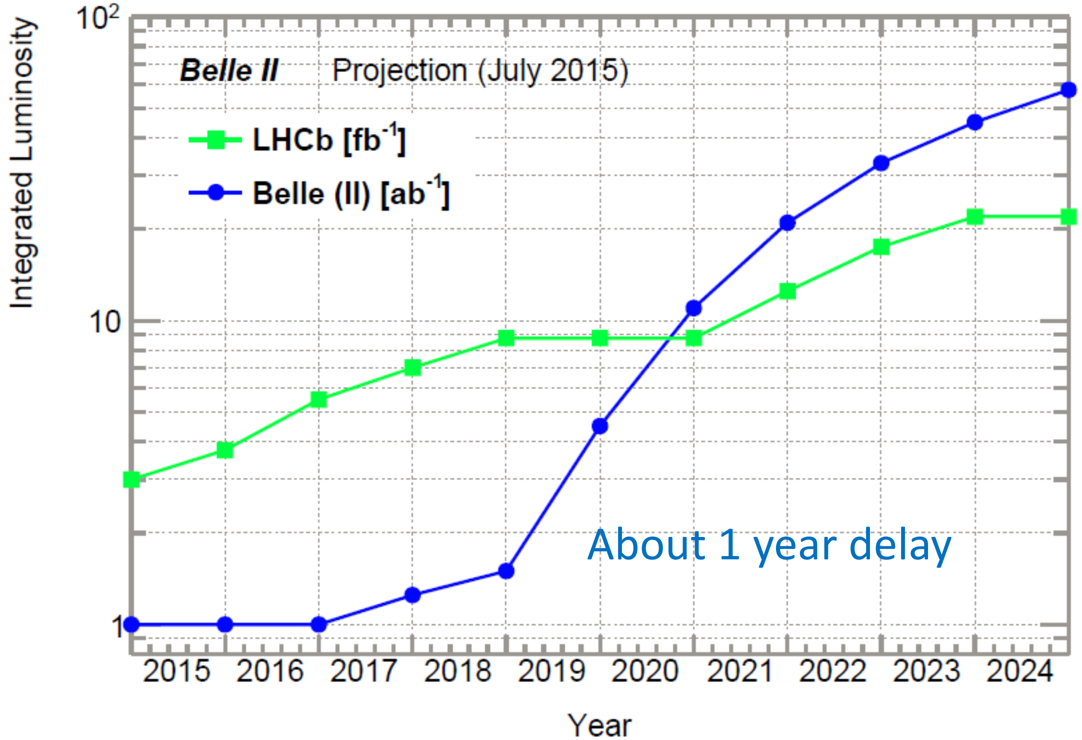
Integrated Luminosity

- $50ab^{-1}$ in 2024 (50 times larger than Belle)
  - $5x10^{10}$ BB pairs, $4.5x10^{10}$ $\tau^{+}\tau^{-}$ pairs



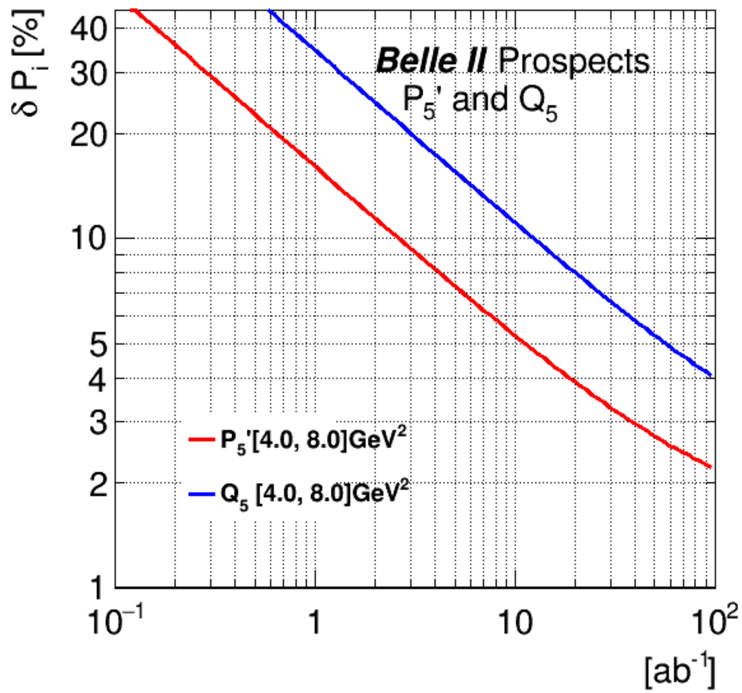
Belle II VS LHCb in 2024

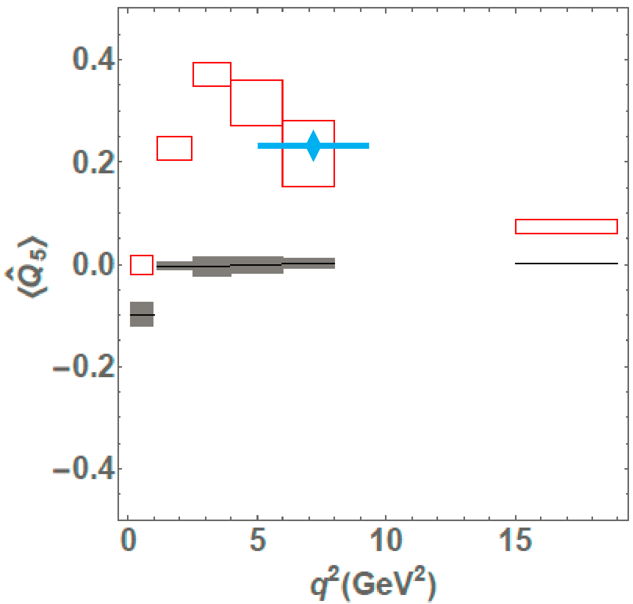
- Belle II 50ab^{-1}
- LHCb 22fb^{-1}



P_5' and Q_5 In 2024

- P_5'
  - 2.4% for [4,8]GeV^2 with 50/ab (e and μ combined)
  - Better than LHCb with 22/fb (3.7%, only μ)
    - Just 20% worse than LHCb with $50fb^{-1}$ 1.6%
- Q_5
  - 5.3% with 50/ab
    - LHCb might be difficult to perform angular analysis with electron.
  - Can resolve the $C_{9\mu}^{NP}$





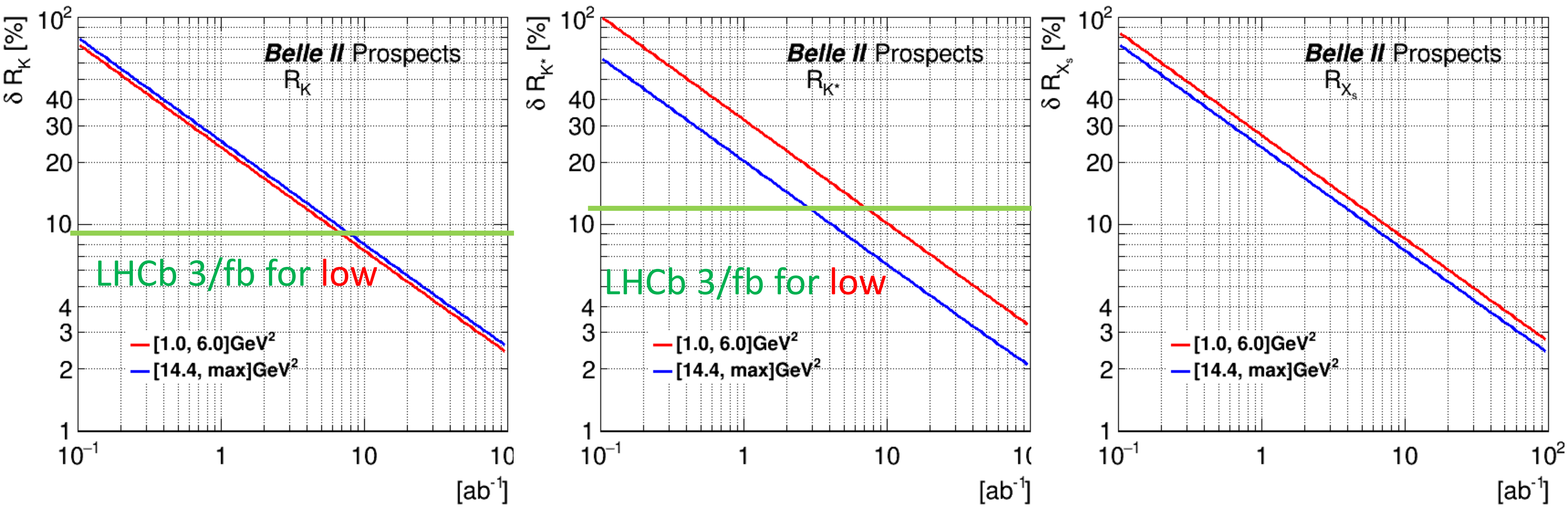
SM : gray

NP : red

$$C_{9\mu}^{\rm NP} = -1.11$$

R_K, R_{K*} and R_{Xs}

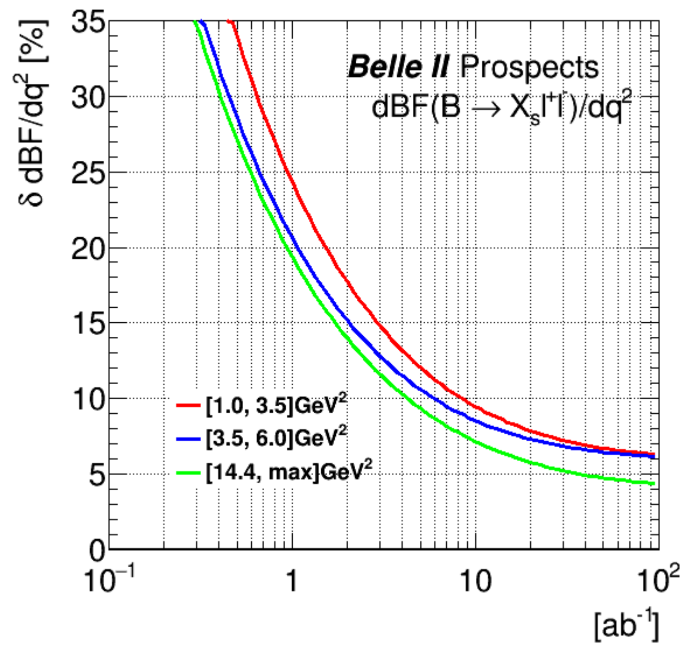
- Ideal measurements at e+e- B-factory
  - Dominant systematic error is from lepton ID ~0.4%.
  - Statistically dominated even with 50/ab
- About 10/ab (2021) is needed to observe the NP in $R_{K(*)}$ if central values unchange
- ~3% level for both high and low q^2 regions with 50/ab
  - Assuming the SM
  - High q^2 region is very hard at the LHCb
  - eID improvement with TOP and ARICH not included



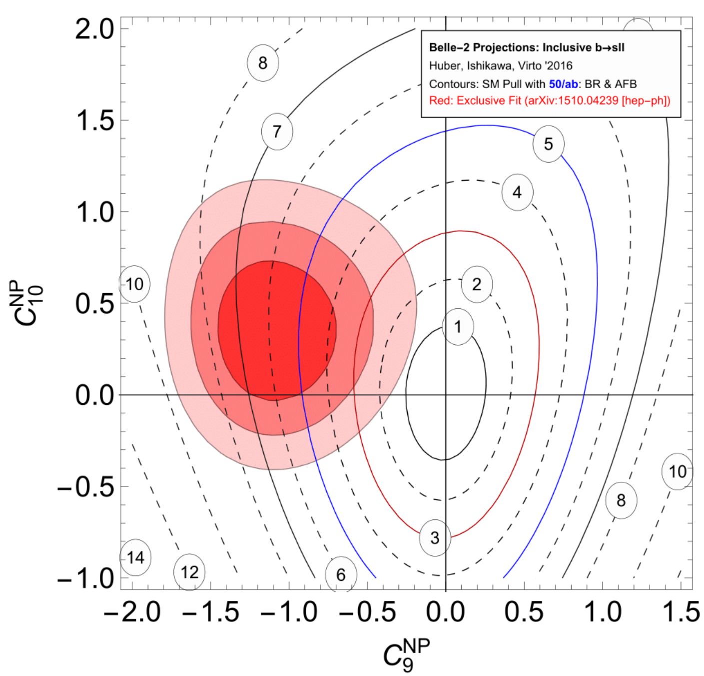
Inclusive $B \to X_s l^+ l^-$

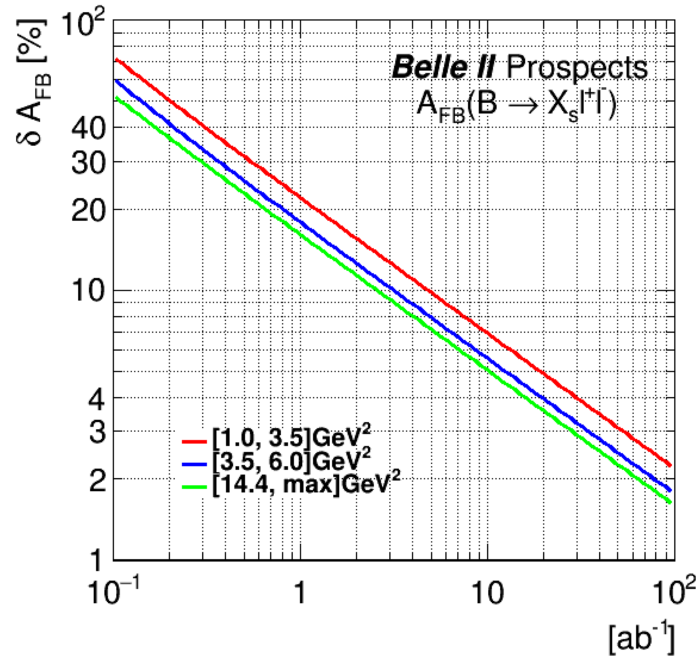
$$\frac{d\Gamma(b \to s \ell^+ \ell^-)}{d\hat{s}} = \left(\frac{\alpha_{em}}{4\pi}\right)^2 \frac{G_F^2 m_b^5 |V_{ts}^* V_{tb}|^2}{48\pi^3} (1-\hat{s})^2 \times \left[(1+2\hat{s})\left(|C_9^{\text{eff}}|^2 + |C_{10}^{\text{eff}}|^2\right) + 4\left(1+\frac{2}{\hat{s}}\right)|C_7^{\text{eff}}|^2 + 12\,\mathrm{Re}\left(C_7^{\text{eff}} C_9^{\text{eff}*}\right) \right]$$

- Theoretically clean.
  - No form factor uncertainty (~30% for exclusive).
  - Charm loop calculable more precisely
- A_{FB} and BF sensitive to Wilson coefficients.



Huber, Ishikawa, Virto





Tau modes

- If NP also contributes to tau, important to search for modes involving taus, $b \to s\tau\tau$, $B \to \tau\tau$
  - Gauged L_μ-L_τ
- Need to tag the other B meson since multiple neutrinos in the final states so sensitivities are above the SM predictions.
  - Tagging efficiency is expected to be ~0.8% at Belle II

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$B(B^+ \to K^+\tau^+\tau^-) \times 10^5$	< 32	< 6.5	< 2.0
$B(B^0 \to \tau^+\tau^-) \times 10^5$	< 140	< 30	< 9.6

Observables	Belle 0.12 ab^{-1}	Belle II 1.5 ab^{-1}	Belle II 15 ab^{-1}
$B(B_s \to \gamma\gamma)$	<250%	42%	13%
$B(B_s \to \tau^+\tau^-) \times 10^4$	< 70	< 14	< 4.7
$B(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 2.6	< 0.84

Summary

- Belle first measured Q5' which is sensitive to $C_{9\mu}^{NP}$
  - Current C_9 deviation driven by LHCb
- In near future, Belle II will perform similar or better analysis for b→see.

- Lepton Flavor Universality Violating in B decays?
- The New Physics only couples to muon (and tau?) with vector current?

backup

Lepton Flavor Violation in B Decays?

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Bilinears and Trigonometric Functions

i	I_i	f_i
$1s$	$\frac{3}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K$
$1c$	$\lvert\mathcal{A}_0^{\rm L}\rvert^2 + \lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K$
$2s$	$\frac{1}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K \cos 2\theta_l$
$2c$	$-\lvert\mathcal{A}_0^{\rm L}\rvert^2 - \lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K \cos 2\theta_l$
3	$\frac{1}{2}\left[\lvert\mathcal{A}_\perp^{\rm L}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2\right]$	$\sin^2\theta_K \sin^2\theta_l \cos 2\phi$
4	$\sqrt{\frac{1}{2}}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_l \cos\phi$
5	$\sqrt{2}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K \sin\theta_l \cos\phi$
$6s$	$2{\rm Re}(\mathcal{A}_\parallel^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_\parallel^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin^2\theta_K \cos\theta_l$
7	$\sqrt{2}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K \sin\theta_l \sin\phi$
8	$\sqrt{\frac{1}{2}}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_l \sin\phi$
9	${\rm Im}(\mathcal{A}_\parallel^{\rm L*}\mathcal{A}_\perp^{\rm L} + \mathcal{A}_\parallel^{\rm R*}\mathcal{A}_\perp^{\rm R})$	$\sin^2\theta_K \sin^2\theta_l \sin 2\phi$