Anomalies from R_K and R_{K^*} at Belle/Belle II

Kota Nakagiri
KEK

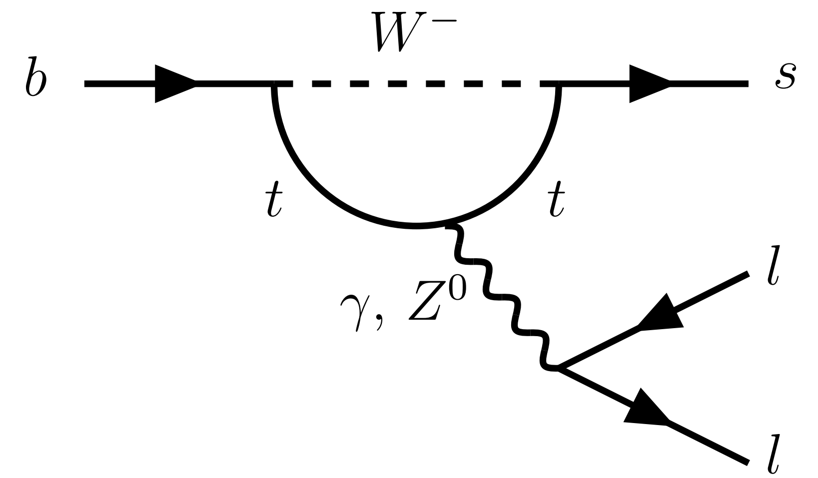
$b \to s\ell^+\ell^-$

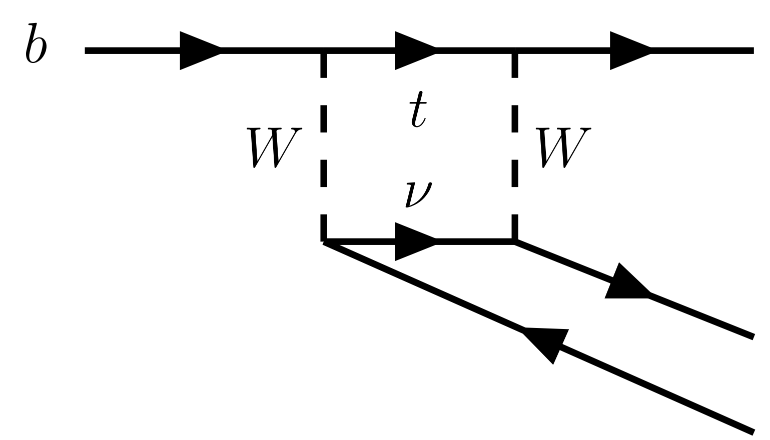
- Flavor Changing Neutral Current process
  - Penguin/Box diagrams are dominant
  - suppressed in the SM (Br ~ O(10^{-6}))

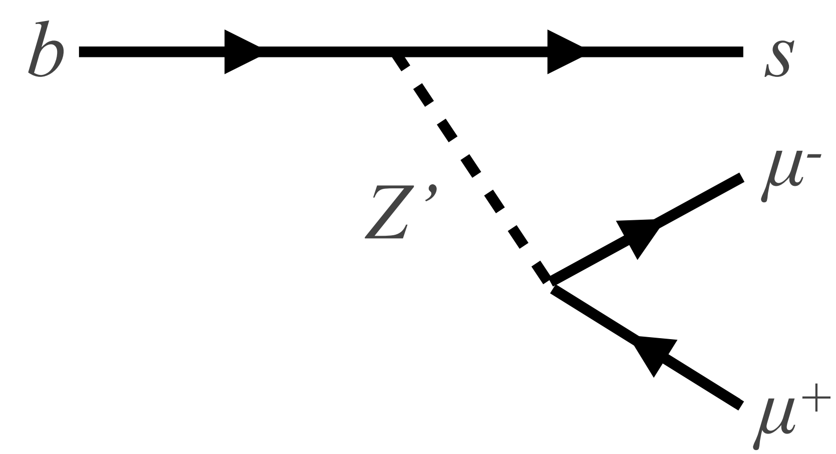
  ➡ sensitive to NP
    - loop or tree level NP contributions
      - SUSY, Leptoquark, flavorful Z', etc..

- various observables :
  - Branching fraction
  - Angular distribution (P'_5 , A_{FB}, etc..)
  - Lepton Flavor Universality test ($R_{K^{(*)}}$)

  ※ represented as a function of q^2 (=$m^2(\ell^+\ell^-)$)







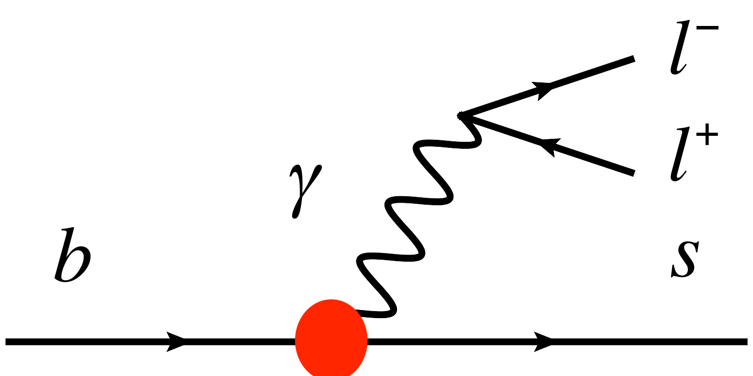
$b\to s\ell^+\ell^-$: Wilson Coefficients

- effective Hamiltonian :

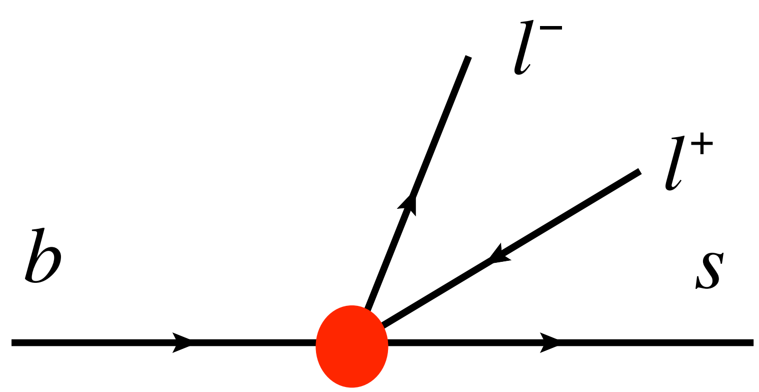
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

$$\begin{aligned}
\mathcal{O}_7 &= \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \\
\mathcal{O}_{7'} &= \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}, \\
\mathcal{O}_{9\ell} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \\
\mathcal{O}_{9'\ell} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell), \\
\mathcal{O}_{10\ell} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), \\
\mathcal{O}_{10'\ell} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),
\end{aligned}$$

  - in the SM, $b\to s\ell^+\ell^-$ is dominated by O_7, O_9, O_{10} operators



O_7
photon penguin

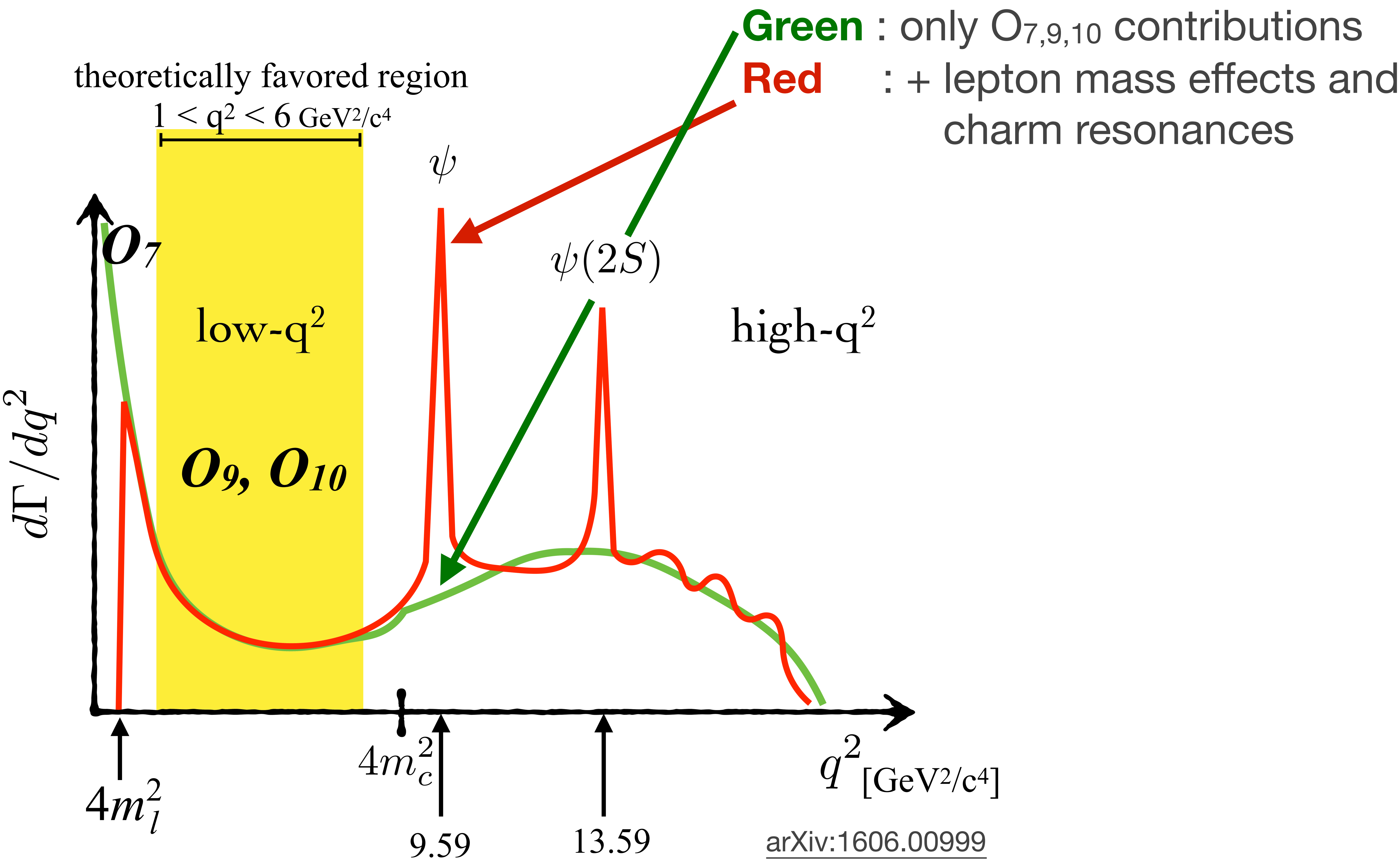


O_9, O_{10}
vector, axial-vector (EW penguin/box)

$$C_7^{\rm SM} \sim -0.3, \quad C_9^{\rm SM} \sim 4.1, \quad C_{10}^{\rm SM} \sim -4.2, \quad C_{7',9',10'}^{\rm SM} = 0$$

deviation from C^{SM} = NP contribution

$b \to s\ell^+\ell^-$: Wilson Coefficients



arXiv:1606.00999

$R_{K^{(*)}}$

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}, \qquad R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)}$$

- Lepton Flavor Universality test with $b \to s\ell^+\ell^-$
  - take a ratio of branching fractions
    →cancel out many of theoretical/experimental uncertainties
    →very clean observable

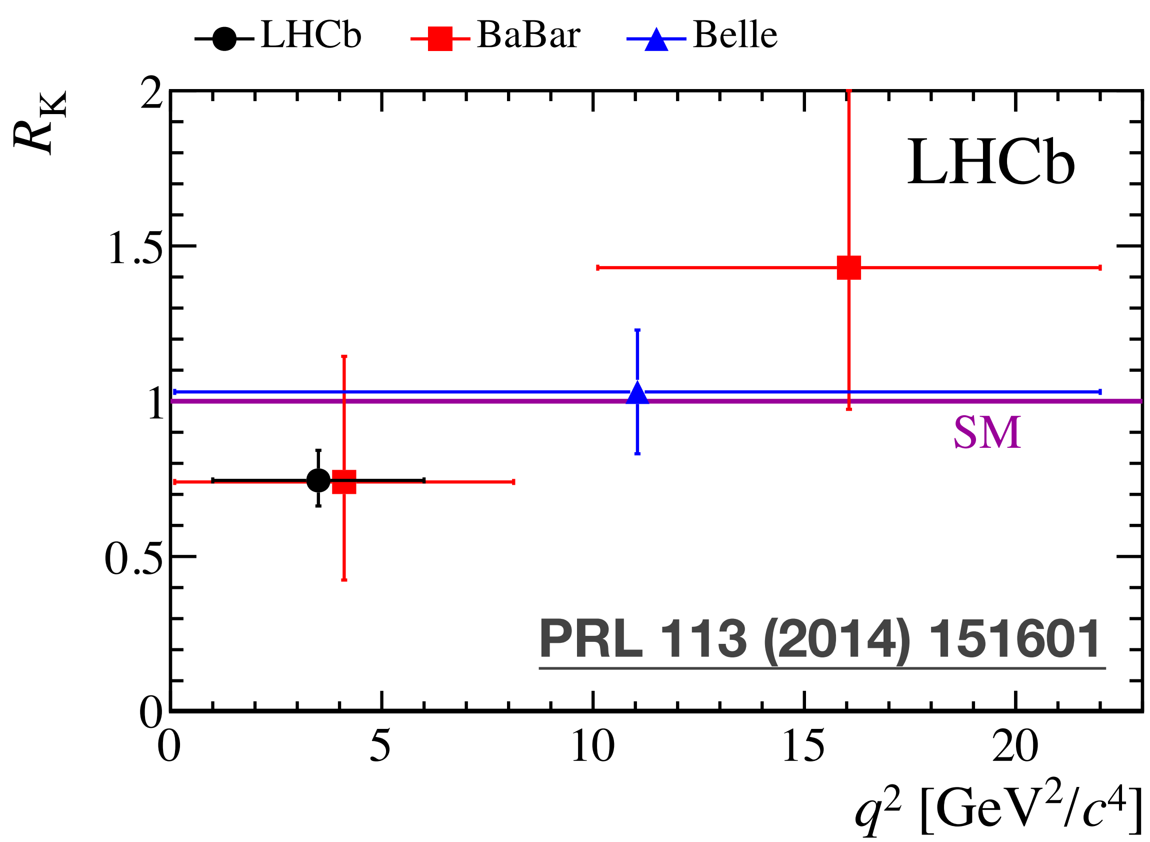
- if LFU holds (SM), $R_{K^{(*)}} \sim 1$
  - small deviation from unity in low q^2 region due to m_e/m_μ difference
  - other deviation from unity implies NP

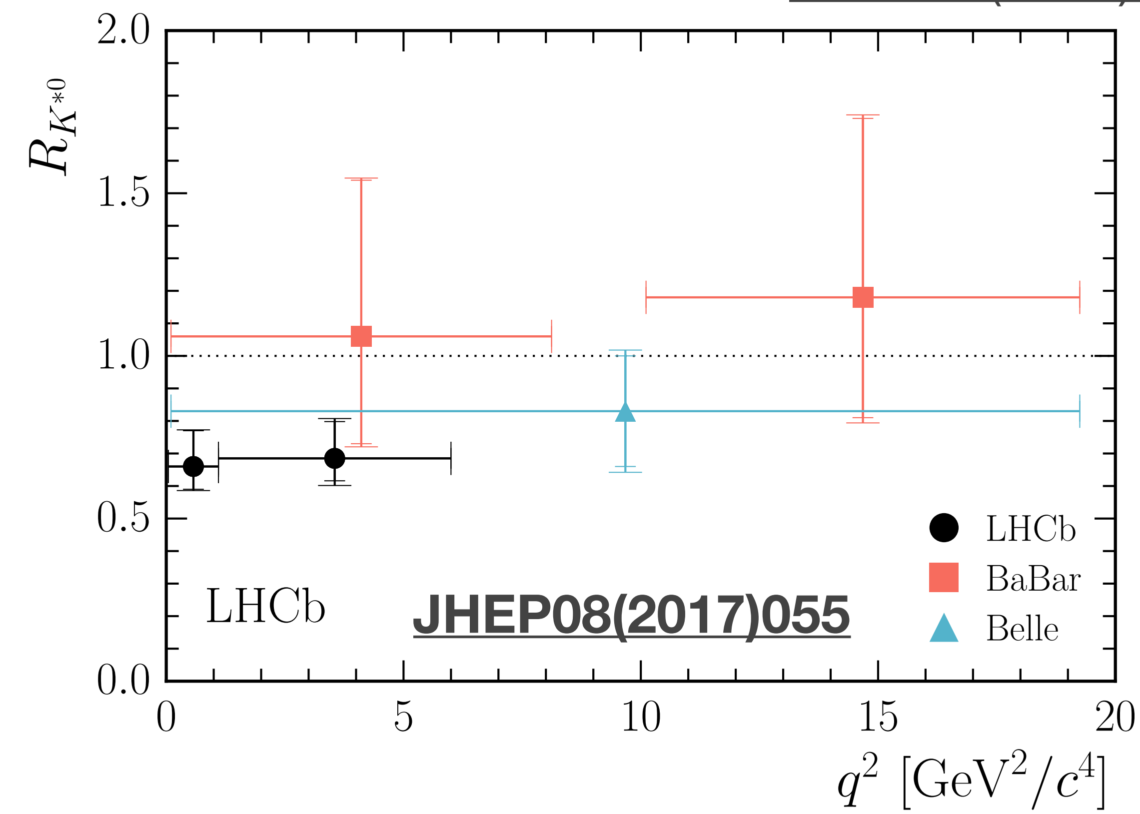
R_K and R_{K^*} anomalies

recent LHCb results (R_K in 2014, R_{K^*} in 2017) show deviations from SM

with LHC Run-1 data (3 fb^{-1})

Belle : PRL 103 (2009) 171801
BaBar : PRD 86 (2012) 032012





2.6σ deviation from SM

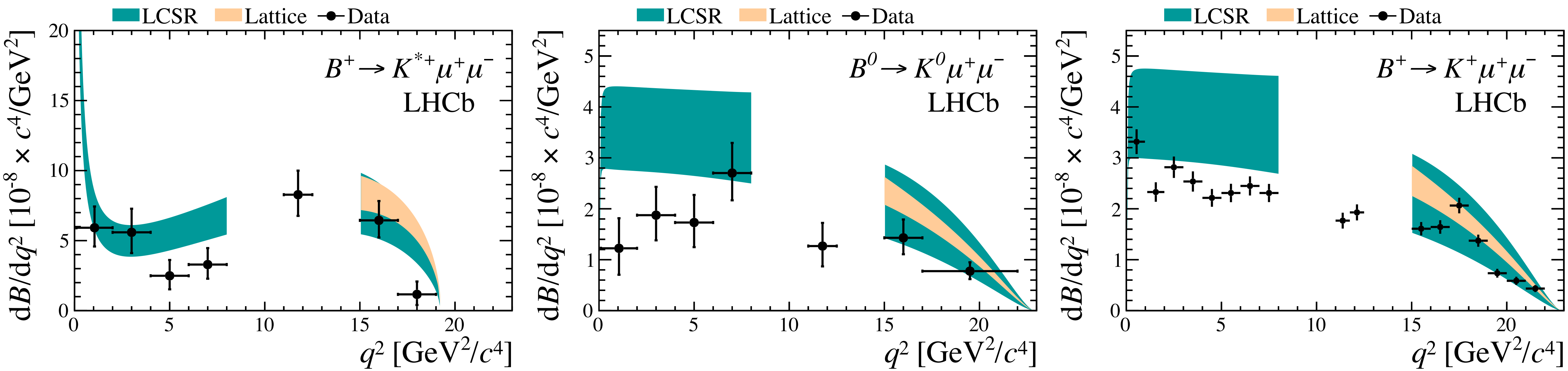
2.1-2.5σ deviation from SM

Belle & BaBar results are consistent with both SM and LHCb results

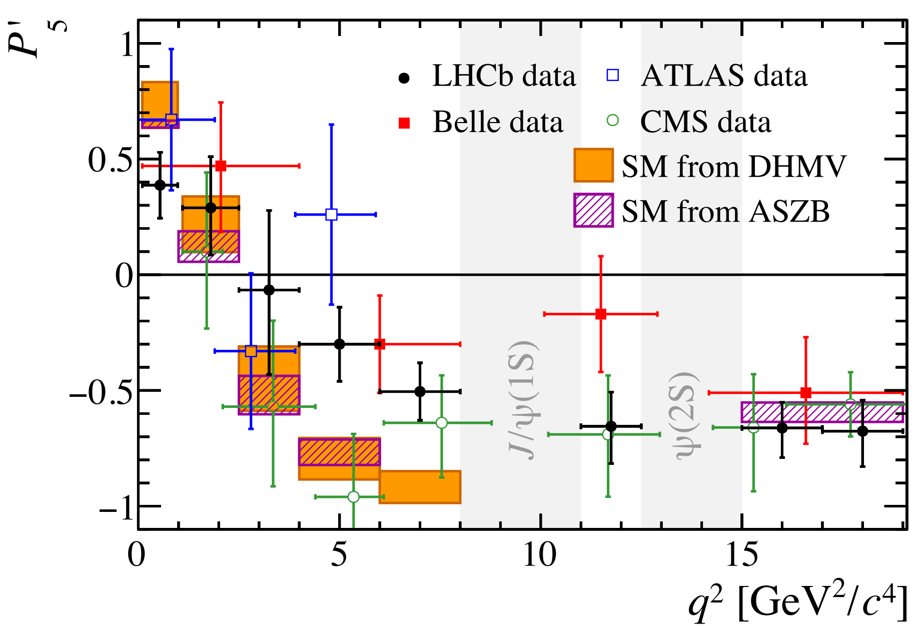
need more precise measurements ➡
- latest results from Belle(R_K, R_{K^*}) and LHCb(R_K) (← not mentioned today)
- prospect in Belle II

other b→sℓ⁺ℓ⁻ anomalies

LHCb : JHEP06(2014)133

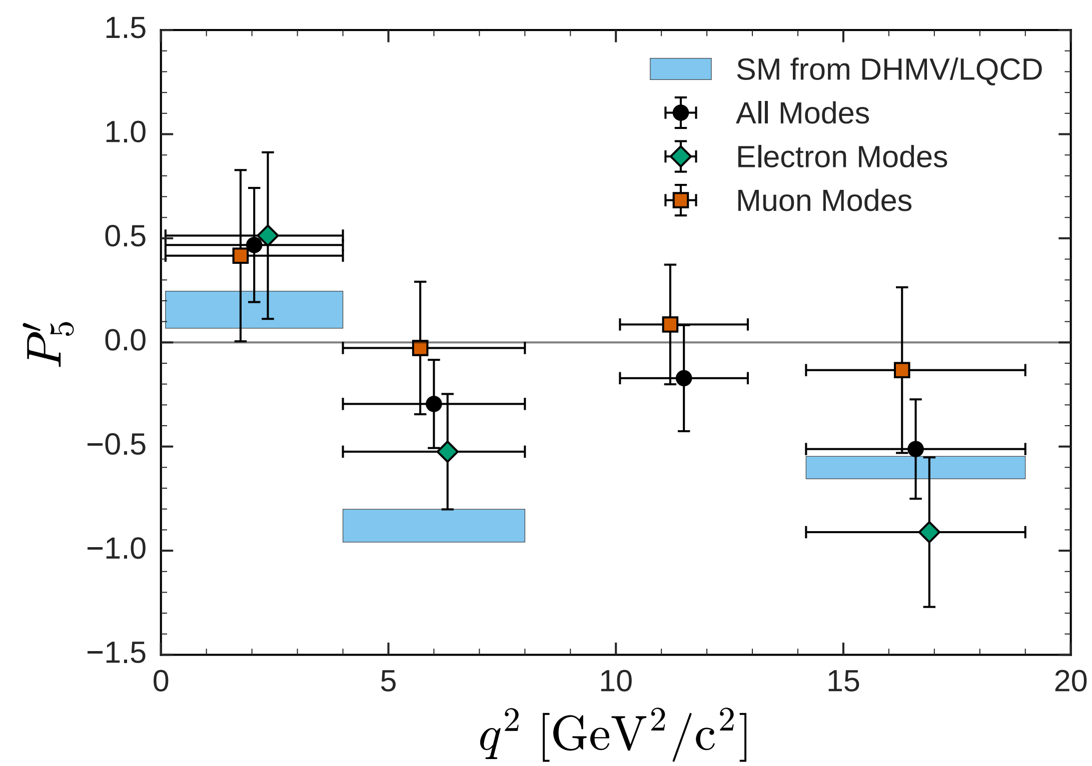


plot from arXiv:1606.00999



Belle : PRL 118 (2017) 111801 (av. of μ,e)
LHCb : JHEP02(2016)104 (μ)
ATLAS : JHEP10(2018)047 (μ)
CMS : Phys. Lett. B 781 (2018) 517 (μ)

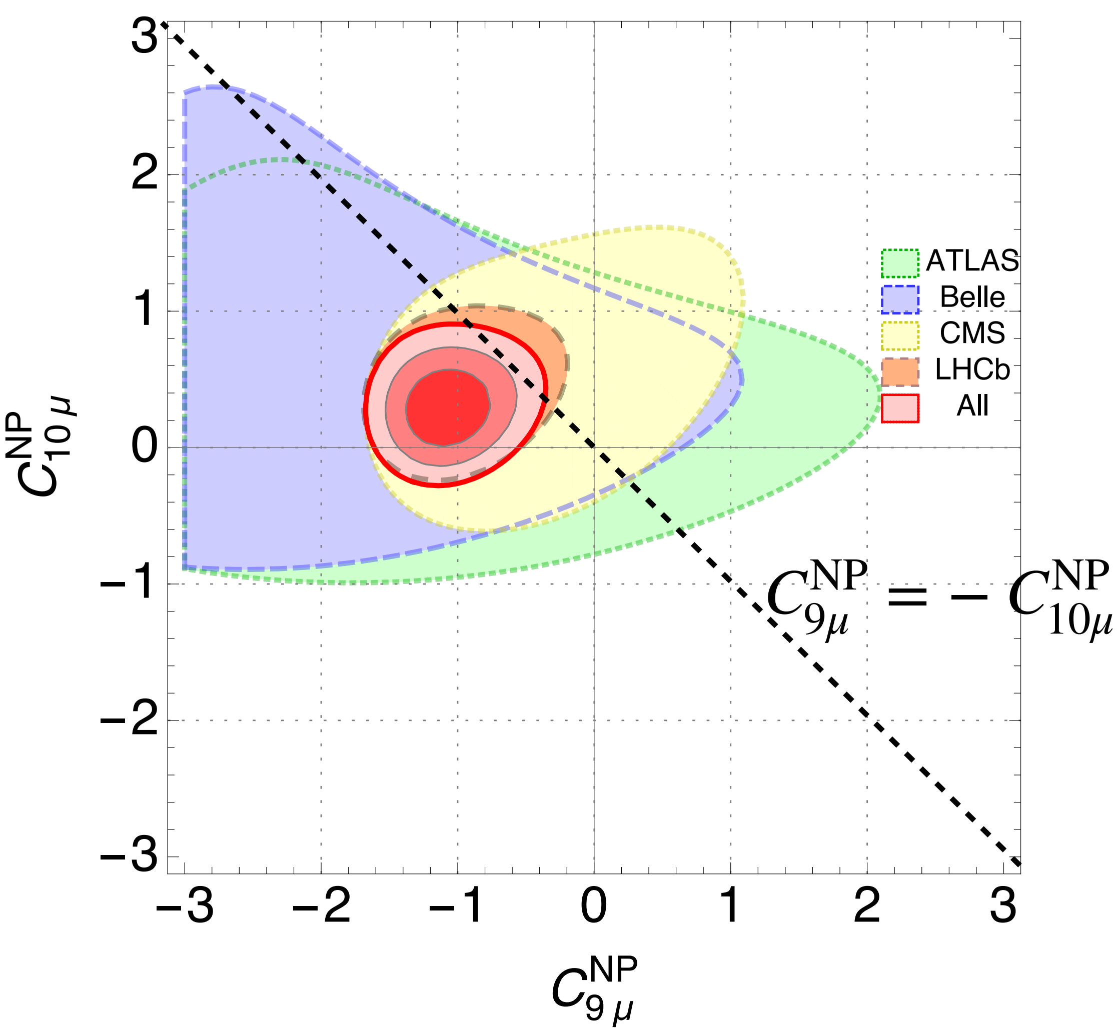
Belle :PRL 118 (2017) 111801



Global Fit

model-independent fit to Wilson coefficients using
$R_{K^{(*)}}$, $b \to s\ell\ell$ differential branching fractions, angular observables,
$b \to s\gamma$, $Br(B \to X_s \mu\mu)$, $Br(B_s \to \mu\mu)$

JHEP01(2018)093



$$C_{il} = C_{il}^{SM} + C_{il}^{NP}, \quad i = 7,9,10\ ,\ l = e, \mu$$

best fit : $C_{9\mu}^{NP} \sim -1$

- ~25% level of SM ($C_{9\mu}^{SM} \sim 4.1$)
- favor $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$ (V-A) scenario

LHCb results are dominant in the fit
➡ independent measurements from Belle / Belle II are important

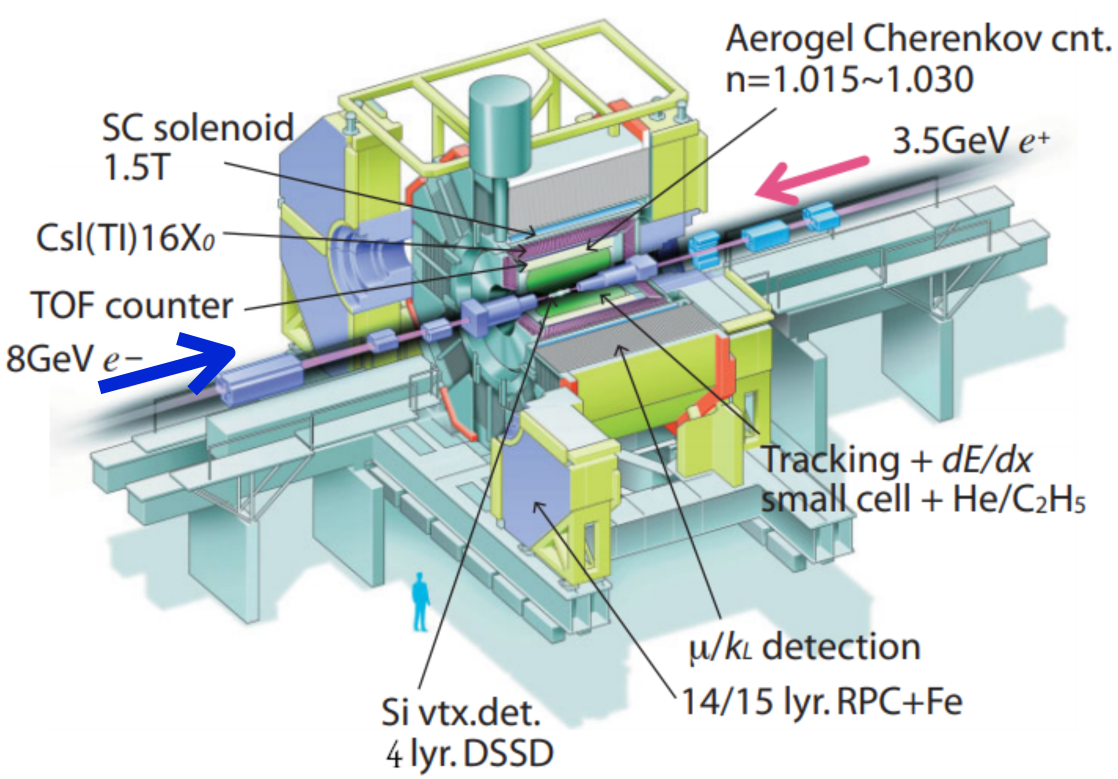
Belle / Belle II

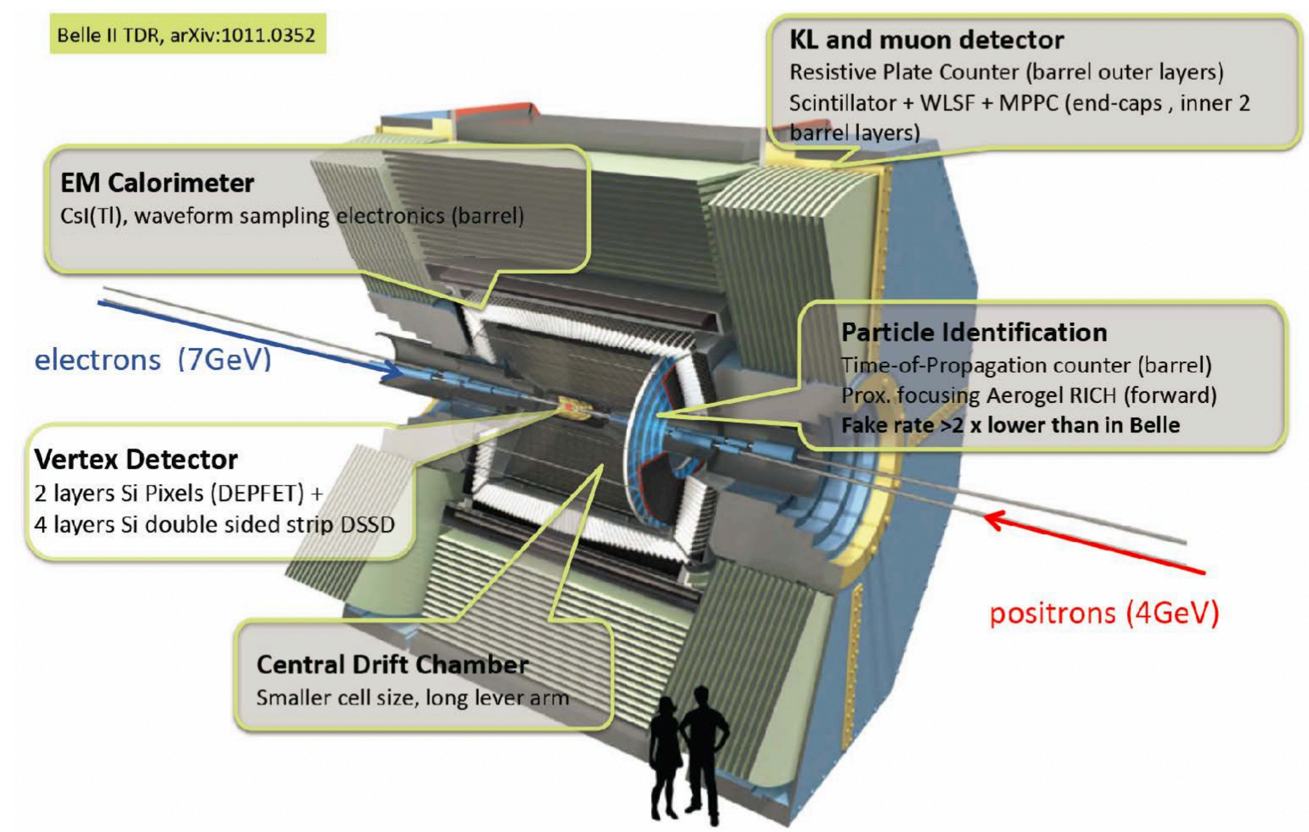
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

KEKB → **SuperKEKB** accelerator

Lumi. : 2.11×10^{34} cm^{-2}s^{-1} → 8×10^{35} cm^{-2}s^{-1}

Stat. : 1 ab^{-1} → 50 ab^{-1}



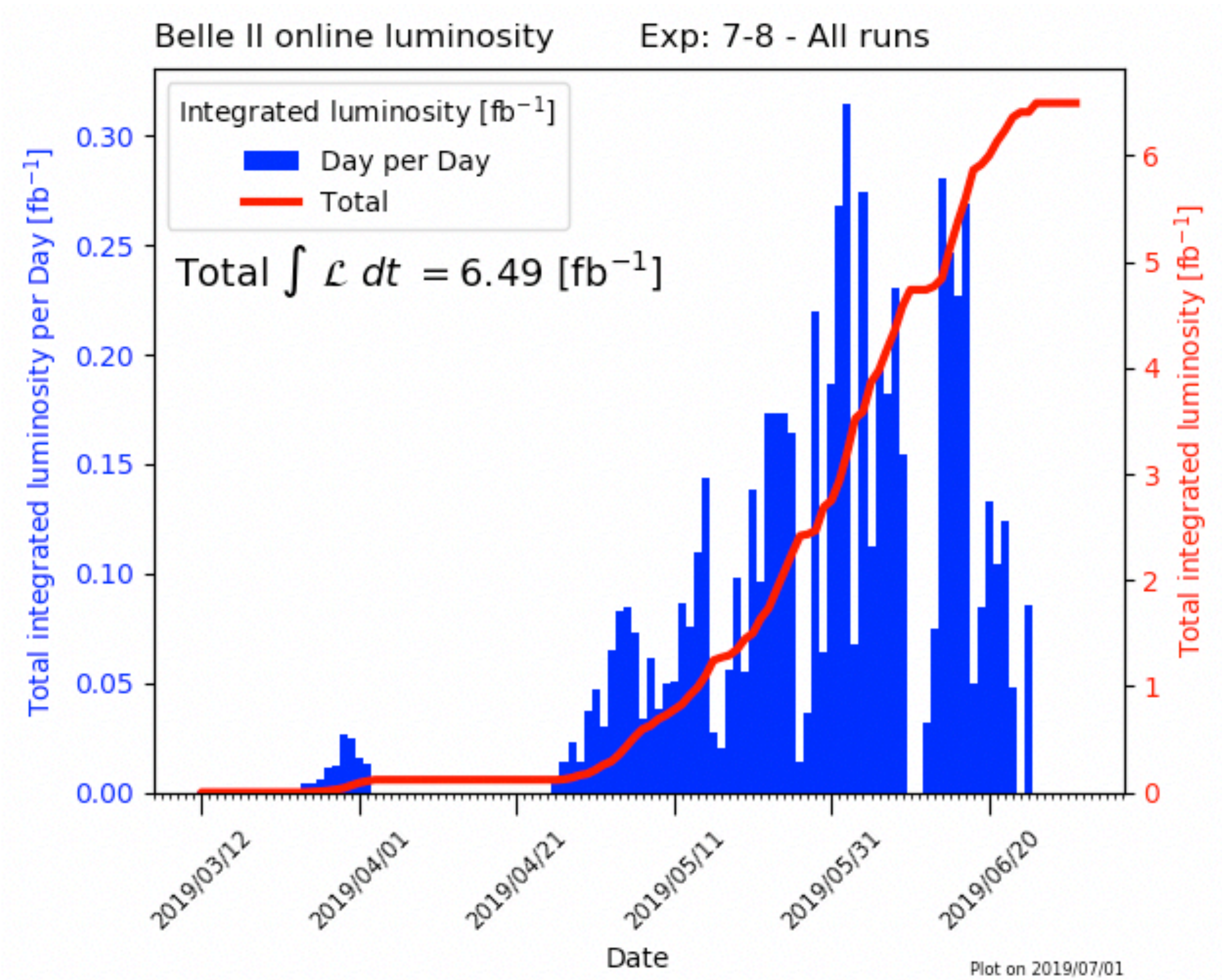


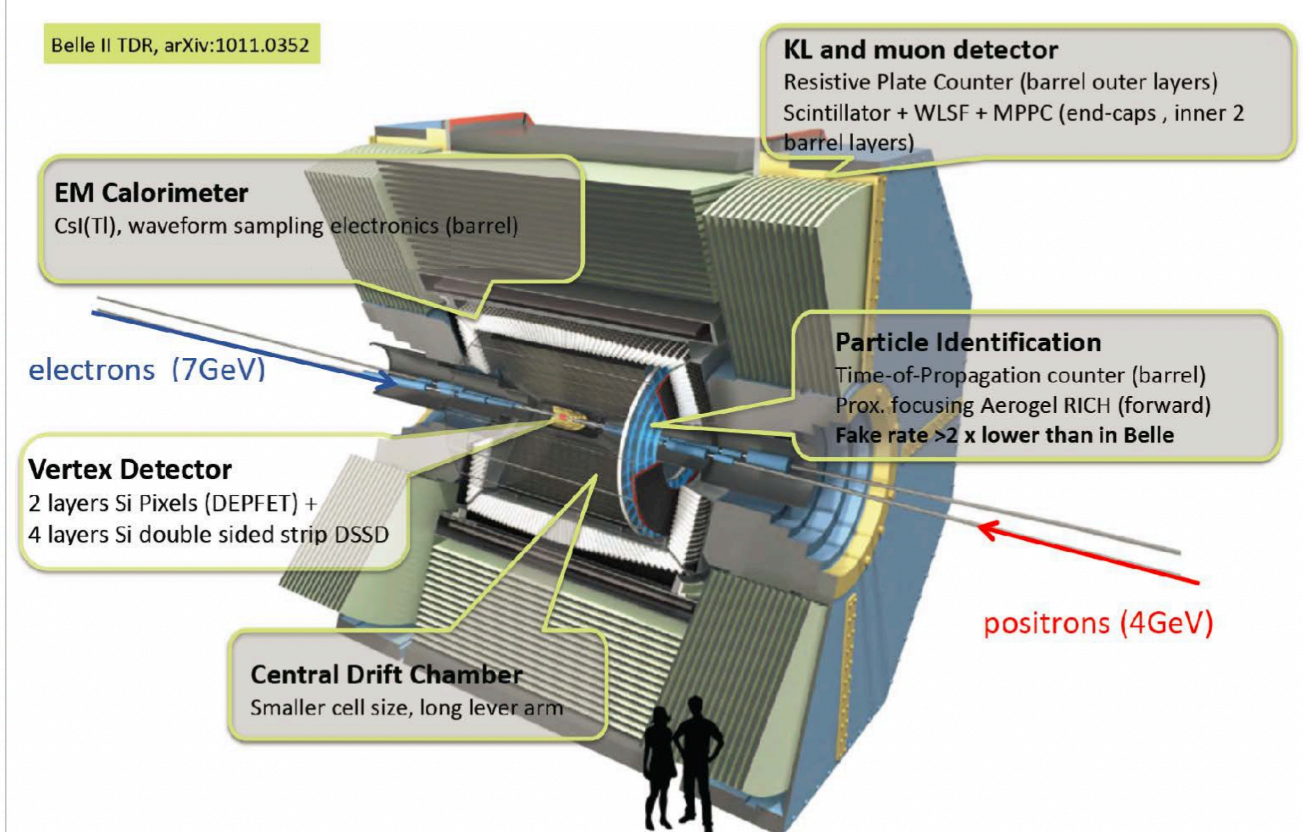
Detector upgrades

- better and larger vertex detectors (PXD+SVD)
- improved PID with TOP and ARICH

Belle / Belle II

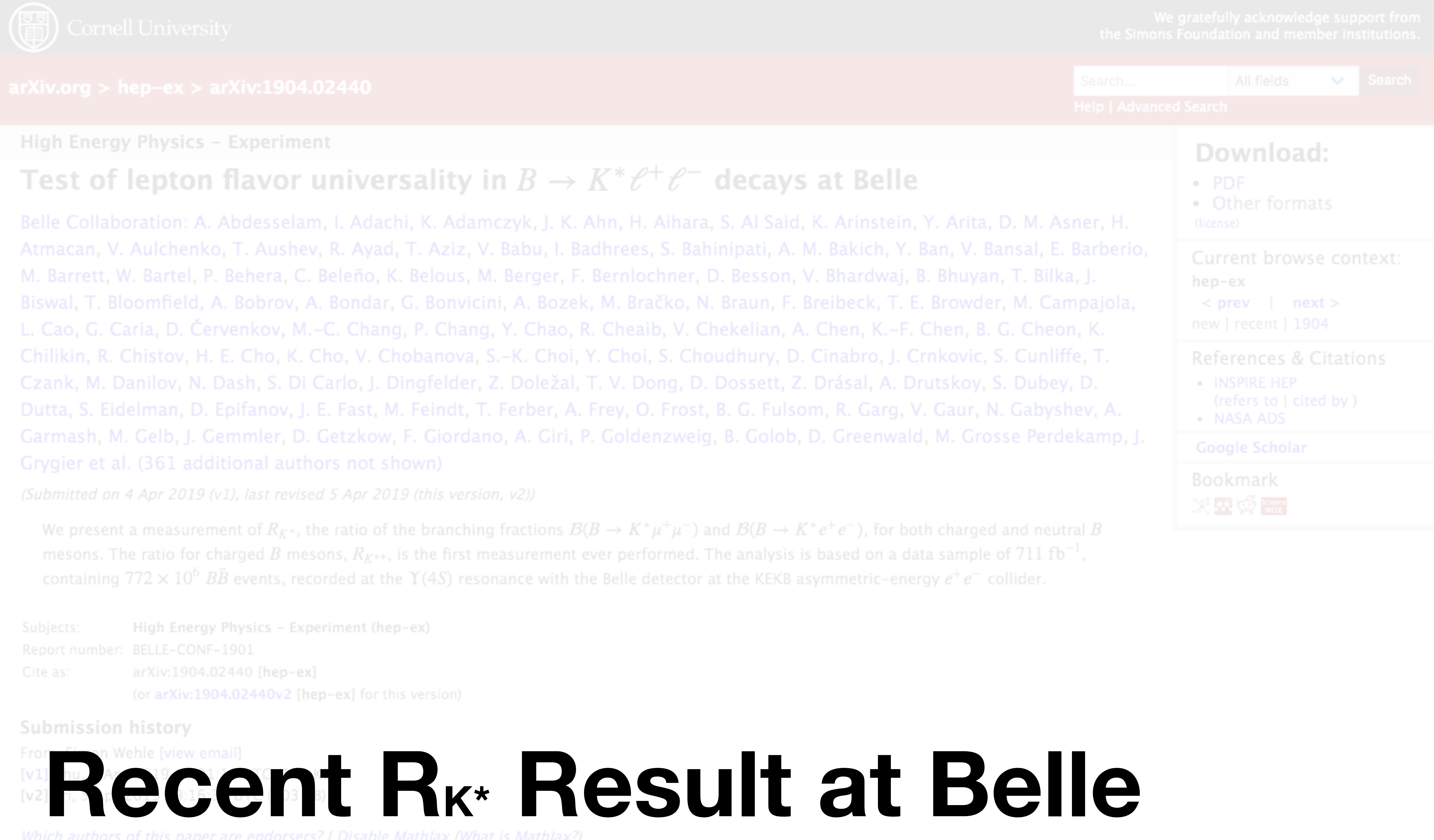
$e^+e^- \to Y(4S) \to BB$





Belle II started data taking

- achieved luminosity of 1.2×10^{34} cm^{-2}s^{-1}
- accumulated 6.5 fb^{-1} data by this summer


Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

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High Energy Physics – Experiment

Test of lepton flavor universality in $B \to K^* \ell^+ \ell^-$ decays at Belle

Belle Collaboration: A. Abdesselam, I. Adachi, K. Adamczyk, J. K. Ahn, H. Aihara, S. Al Said, K. Arinstein, Y. Arita, D. M. Asner, H. Atmacan, V. Aulchenko, T. Aushev, R. Ayad, T. Aziz, V. Babu, I. Badhrees, S. Bahinipati, A. M. Bakich, Y. Ban, V. Bansal, E. Barberio, M. Barrett, W. Bartel, P. Behera, C. Beleño, K. Belous, M. Berger, F. Bernlochner, D. Besson, V. Bhardwaj, B. Bhuyan, T. Bilka, J. Biswal, T. Bloomfield, A. Bobrov, A. Bondar, G. Bonvicini, A. Bozek, M. Bračko, N. Braun, F. Breibeck, T. E. Browder, M. Campajola, L. Cao, G. Caria, D. Červenkov, M.-C. Chang, P. Chang, Y. Chao, R. Cheaib, V. Chekelian, A. Chen, K.-F. Chen, B. G. Cheon, K. Chilikin, R. Chistov, H. E. Cho, K. Cho, V. Chobanova, S.-K. Choi, Y. Choi, S. Choudhury, D. Cinabro, J. Crnkovic, S. Cunliffe, T. Czank, M. Danilov, N. Dash, S. Di Carlo, J. Dingfelder, Z. Doležal, T. V. Dong, D. Dossett, Z. Drásal, A. Drutskoy, S. Dubey, D. Dutta, S. Eidelman, D. Epifanov, J. E. Fast, M. Feindt, T. Ferber, A. Frey, O. Frost, B. G. Fulsom, R. Garg, V. Gaur, N. Gabyshev, A. Garmash, M. Gelb, J. Gemmler, D. Getzkow, F. Giordano, A. Giri, P. Goldenzweig, B. Golob, D. Greenwald, M. Grosse Perdekamp, J. Grygier et al. (361 additional authors not shown)

(Submitted on 4 Apr 2019 (v1), last revised 5 Apr 2019 (this version, v2))

We present a measurement of R_{K^*}, the ratio of the branching fractions $\mathcal{B}(B \to K^* \mu^+ \mu^-)$ and $\mathcal{B}(B \to K^* e^+ e^-)$, for both charged and neutral B mesons. The ratio for charged B mesons, $R_{K^{*+}}$, is the first measurement ever performed. The analysis is based on a data sample of 711 fb^{-1}, containing 772×10^6 $B\bar{B}$ events, recorded at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

Subjects:	High Energy Physics – Experiment (hep-ex)
Report number:	BELLE-CONF-1901
Cite as:	arXiv:1904.02440 [hep-ex]
	(or arXiv:1904.02440v2 [hep-ex] for this version)

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Recent R_{K^*} Result at Belle

arXiv:1904.02440

R_{K^*} measurement at Belle

※ first measurement for $R_{K^{*+}}$

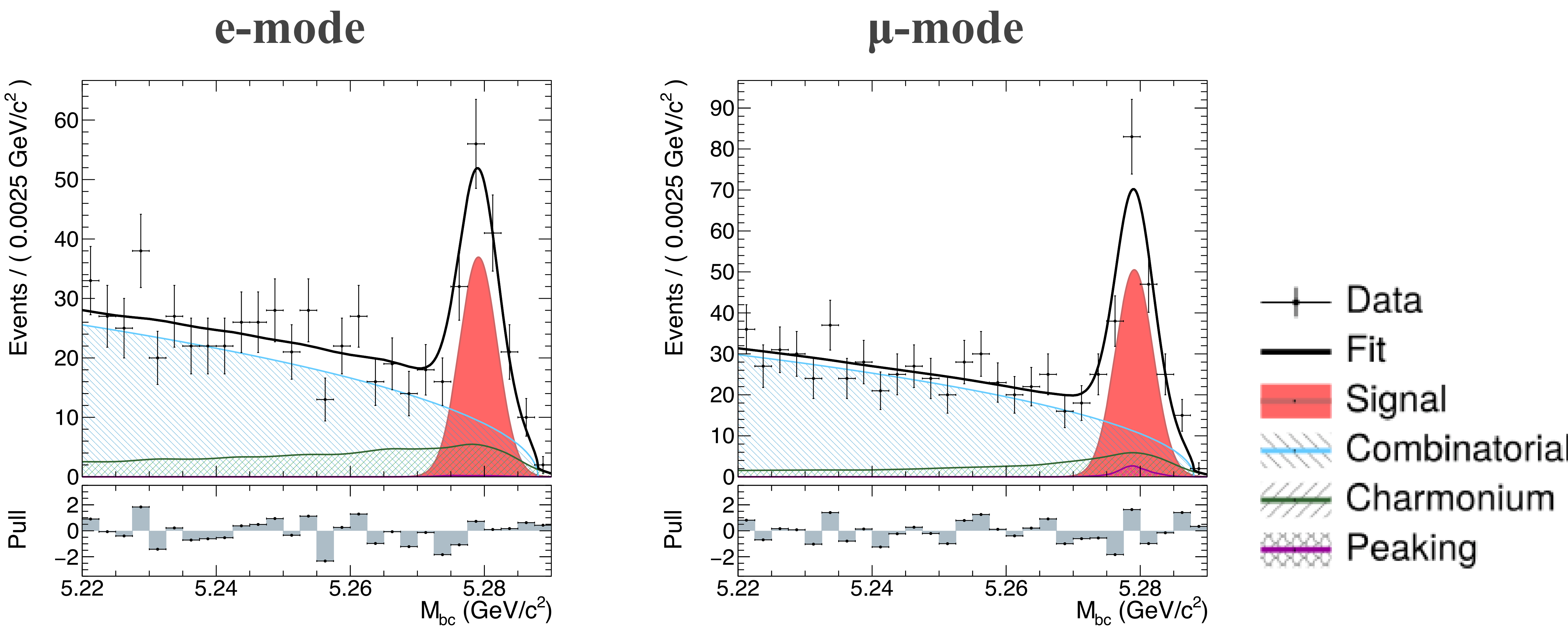
- with full data set of 711 fb^{-1}
- mode : $B^0 \to K^{*0}\ell^+\ell^-$, $B^+ \to K^{*+}\ell^+\ell^-$ +C.C. ($\ell^+\ell^- = e^+e^-$, $\mu^+\mu^-$)

  K^{*0} : $K^{*0} \to K^+\pi^-$
  K^{*+} : $K^{*+} \to K^+\pi^0$、$K^{*+} \to K_S\pi^+$

- main background sources:
  - **Combinatorial BG** :
    - require $M_{bc} = \mathrm{sqrt}(E_{beam}^2 - p_B^2) \sim m_B$, $\Delta E = E_B - E_{beam} \sim 0$
  - **Charmonium BG** : $B \to J/\psi K^*$, $B \to \psi(2S)K^*$
    - veto $m(\ell\ell) \sim m_{J/\psi}$, $m_{\psi(2S)}$
  - **Peaking BG** : $K\pi\pi\pi \to K\pi\mu\mu$ mis-PID
  - **Continuum BG** : $e^+e^- \to qq$ contribution
    - Event shape, MVA

- Fit M_{bc} distribution with Signal + Combinatorial / Charmonium / Peaking BG components in each q^2 region

Fit to M_{bc}

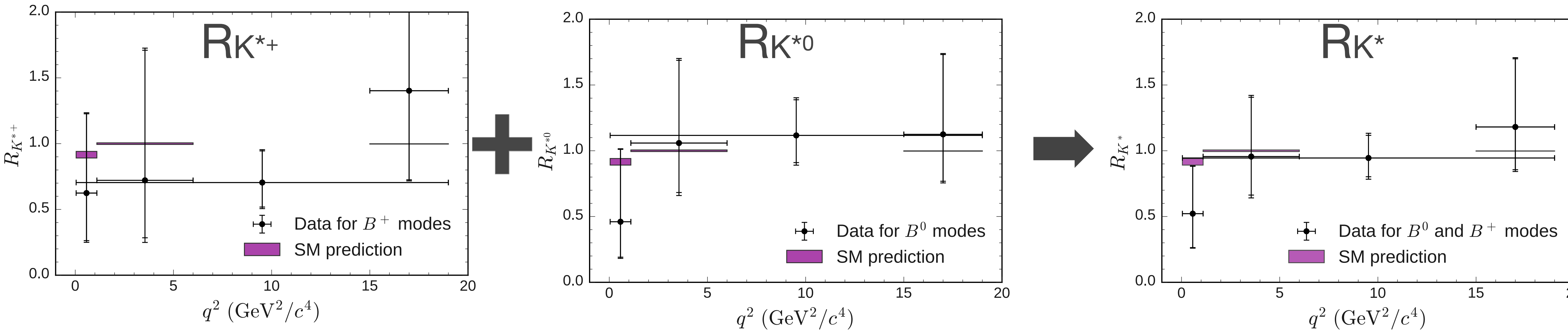


fit example : $q^2>0.045$ $(\mathrm{GeV}/c^2)^2$ (full q^2 region)

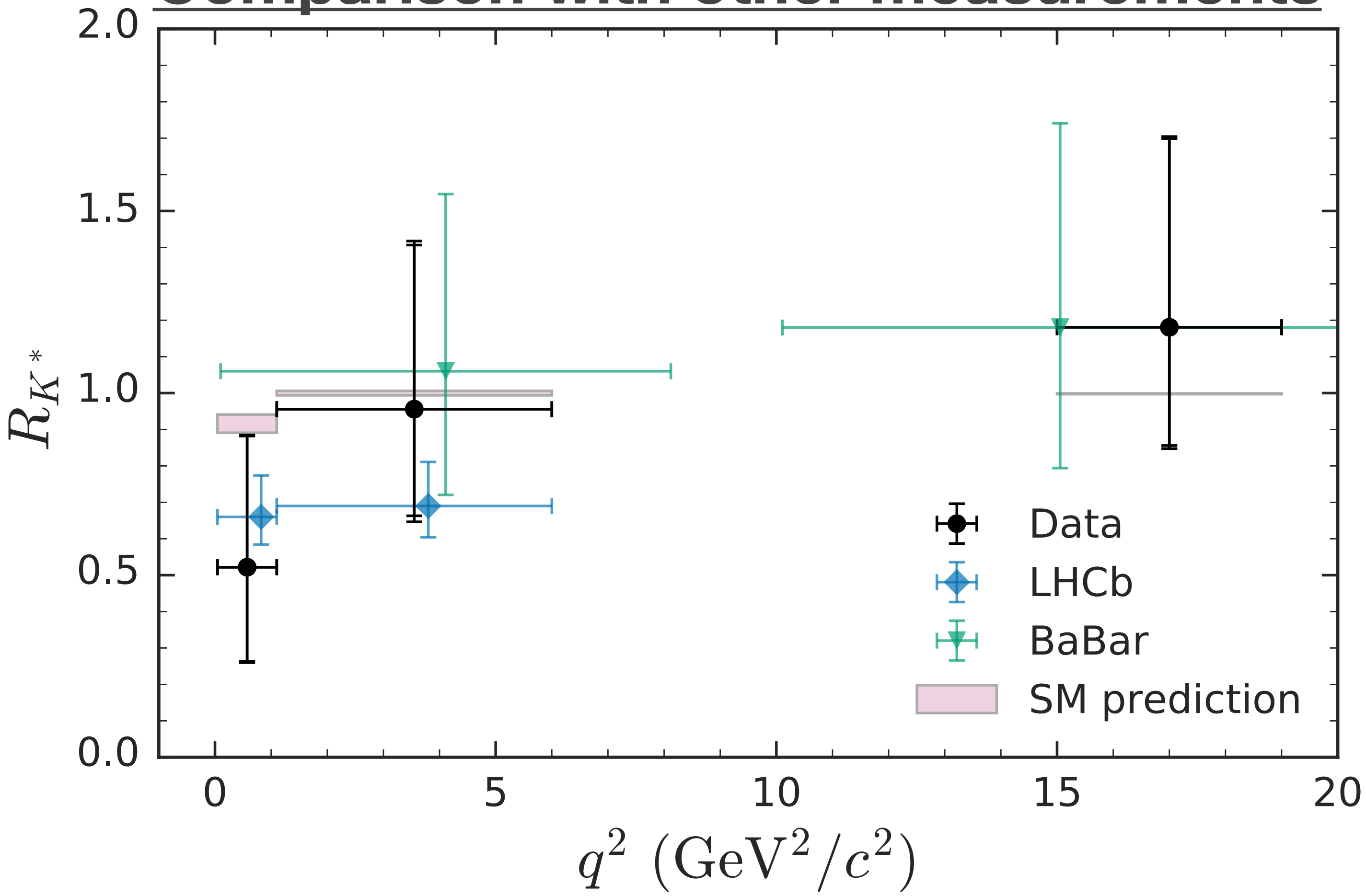
signal yield : e-mode : $103.0^{+13.4}_{-12.7}$, μ-mode : $139.9^{+16.0}_{-15.4}$

Results

Measurements vs. SM



Comparison with other measurements



q^2 in GeV$^2/c^4$	R_{K^*}
$[0.045, 1.1]$	$0.52^{+0.36}_{-0.26} \pm 0.05$
$[1.1, 6]$	$0.96^{+0.45}_{-0.29} \pm 0.11$
$[0.1, 8]$	$0.90^{+0.27}_{-0.21} \pm 0.10$
$[15, 19]$	$1.18^{+0.52}_{-0.32} \pm 0.10$
$[0.045,]$	$0.94^{+0.17}_{-0.14} \pm 0.08$

SM consistent.

Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

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High Energy Physics – Experiment

Test of lepton flavor universality in $B \to K\ell^+\ell^-$ decays

A. Abdesselam, I. Adachi, K. Adamczyk, J. K. Ahn, H. Aihara, S. Al Said, K. Arinstein, Y. Arita, D. M. Asner, H. Atmacan, V. Aulchenko, T. Aushev, R. Ayad, T. Aziz, V. Babu, I. Badhrees, S. Bahinipati, A. M. Bakich, Y. Ban, V. Bansal, E. Barberio, M. Barrett, W. Bartel, P. Behera, C. Beleño, K. Belous, J. Bennett, M. Berger, F. Bernlochner, D. Besson, V. Bhardwaj, B. Bhuyan, T. Bilka, J. Biswal, T. Bloomfield, A. Bobrov, A. Bondar, G. Bonvicini, A. Bozek, M. Bračko, N. Braun, F. Breibeck, T. E. Browder, M. Campajola, L. Cao, G. Caria, D. Červenkov, M.-C. Chang, P. Chang, Y. Chao, R. Cheaib, V. Chekelian, A. Chen, K.-F. Chen, Y. Chen, B. G. Cheon, K. Chilikin, R. Chistov, H. E. Cho, K. Cho, V. Chobanova, S.-K. Choi, Y. Choi, S. Choudhury, D. Cinabro, J. Crnkovic, S. Cunliffe, T. Czank, M. Danilov, N. Dash, G. De Nardo, S. Di Carlo, F. Di Capua, J. Dingfelder, Z. Doležal, T. V. Dong, D. Dossett, Z. Drásal, A. Drutskoy, S. Dubey, D. Dutta, S. Eidelman, D. Epifanov, J. E. Fast, M. Feindt, T. Ferber, A. Frey, O. Frost, B. G. Fulsom, R. Garg, V. Gaur, N. Gabyshev, A. Garmash, M. Gelb, J. Gemmler, D. Getzkow, F. Giordano, A. Giri, P. Goldenzweig, B. Golob et al. (356 additional authors not shown)

(Submitted on 5 Aug 2019)

We present measurements of the branching fractions for the decays $B \to K\mu^+\mu^-$ and $B \to Ke^+e^-$, and their ratio (R_K), using a data sample of 711 fb^{-1} that contains 772×10^6 $B\bar{B}$ events. The data were collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The ratio R_K is measured in four bins of dilepton invariant-mass squared, q^2; the results are

$$R_K = \{ 0.95^{+0.27}_{-0.24} \pm 0.06 \quad q^2 \in (0.1, 4.0)\ \mathrm{GeV}^2c^4\ , 0.81^{+0.28}_{-0.23} \pm 0.05 \quad q^2 \in (4.0, 8.12)\ \mathrm{GeV}^2c^4\ , 0.98^{+0.27}_{-0.23} \pm 0.06 \quad q^2 \in (1.0, 6.0)\ \mathrm{GeV}^2c^4\ , 1.11^{+0.29}_{-0.26} \pm 0.07 \quad q^2 > 14.18\ \mathrm{GeV}^2c^4\ .$$

The first uncertainties listed are statistical, and the second uncertainties are systematic. The R_K value in the whole q^2 range is found to be $1.06^{+0.15}_{-0.14} \pm 0.07$. We also measure CP−averaged isospin asymmetries in the same q^2 bins; the results are consistent with a null asymmetry with the largest difference of 2.7 standard deviations is found in the $q^2 \in (1.0, 6.0)$ GeV^2c^4 bin in the mode with muon final states. The measured branching fractions are $\mathcal{B}(B \to K\mu^+\mu^-) = (5.5 \pm 0.5 \pm 0.3) \times 10^{-7}$ and $\mathcal{B}(B \to Ke^+e^-) = (5.1 \pm 0.5 \pm 0.3) \times 10^{-7}$. These results are compatible w... dard model expectations.

Subj...: ... Exp... (he...ex)

Report number: BELLE-CONF-1904

Cite as: arXiv:1908.01848 [hep-ex]

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Recent R_K Result at Belle

arXiv:1908.01848

R_K measurement at Belle

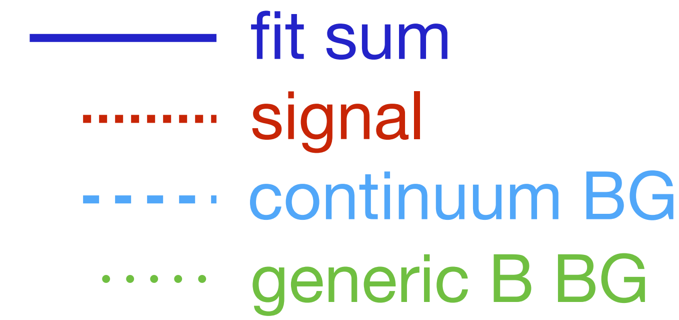
- with full data set of 711 fb^{-1}
- mode : $B^+ \to K^+\ell^+\ell^-$, $B^0 \to K_S\ell^+\ell^-$ +C.C. ($\ell^+\ell^-=e^+e^-$, $\mu^+\mu^-$)

- main background sources:
  - **Charmonium BG** : $B \to J/\psi K$, $B \to \psi(2S)K$
    - veto $m(\ell\ell) \sim m_{J/\psi}$, $m_{\psi(2S)}$
  - **Peaking BG** :
    - $B^+ \to D^0(\to K^+\pi^-)\pi^+$, ππ miss-ID as μμ → veto $m(K^+\mu^-) \sim m_D$
    - $B^+ \to K^+ J/\Psi(\to \mu\mu)$, Kμ miss-ID as μK → veto $m(K^+\mu^-) \sim m_{J/\Psi}$
  - **Continuum BG** : $e+e- \to qq$
  - **Generic B decay BG**
    - semileptonic decays of B-B pair, $B \to D^{(*)}(\to X\ell\nu)\ell\nu$, hadron miss-ID as lepton

- Neural Net for continuum and generic B backgrounds
  - use event shapes, vertex quality, kinematic variables
  - 1/4 background suppression with 4-5% signal acceptance loss

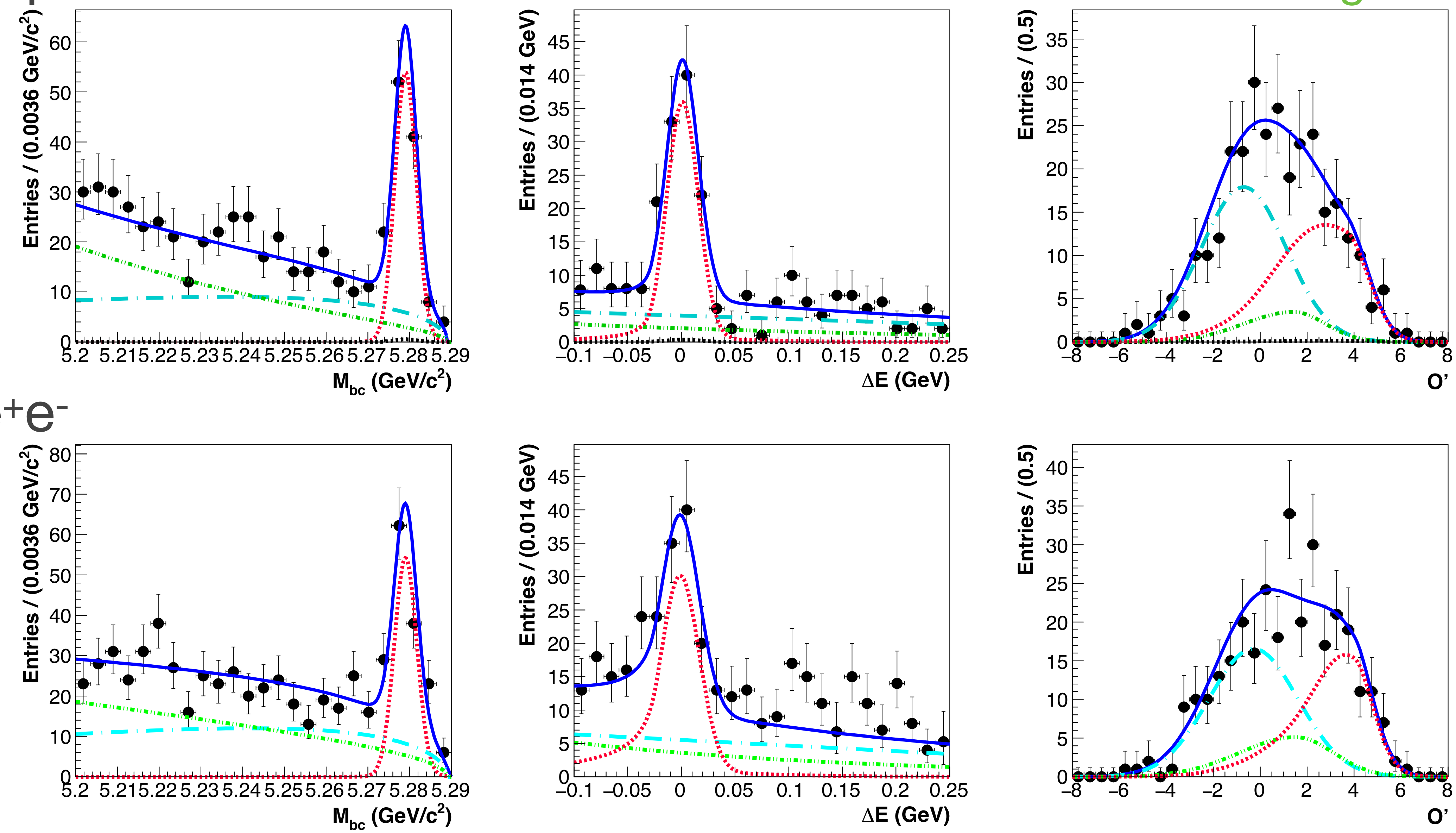
- 3D fit to M_{bc}, ΔE, NN output in each q^2 region

Fit Results



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

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

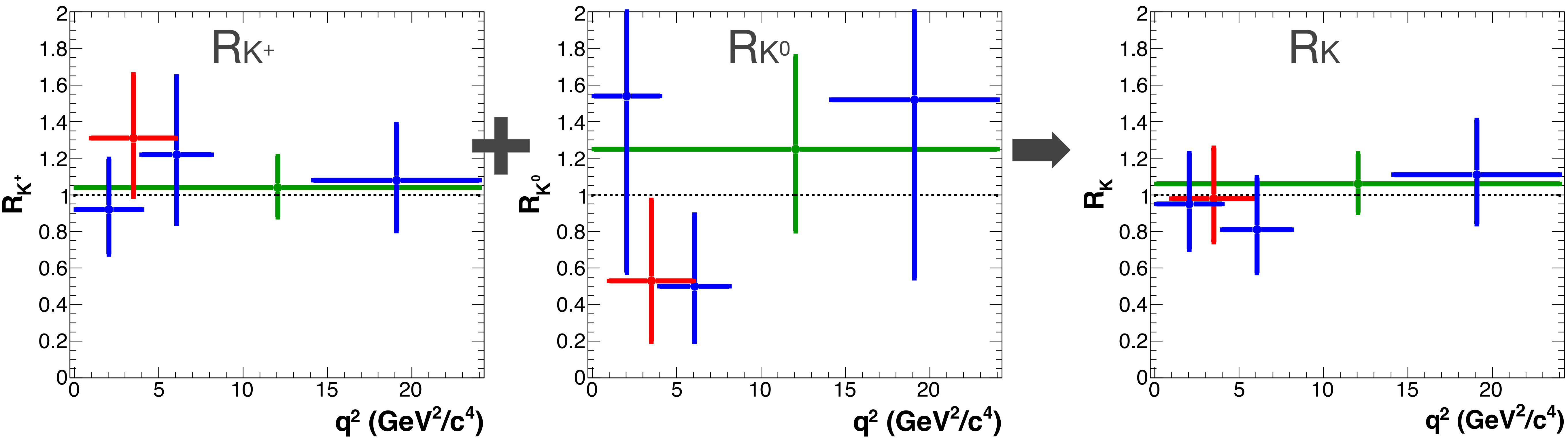


fit example: $q^2>0.1$ $(GeV/c^2)^2$ (whole q^2 region)

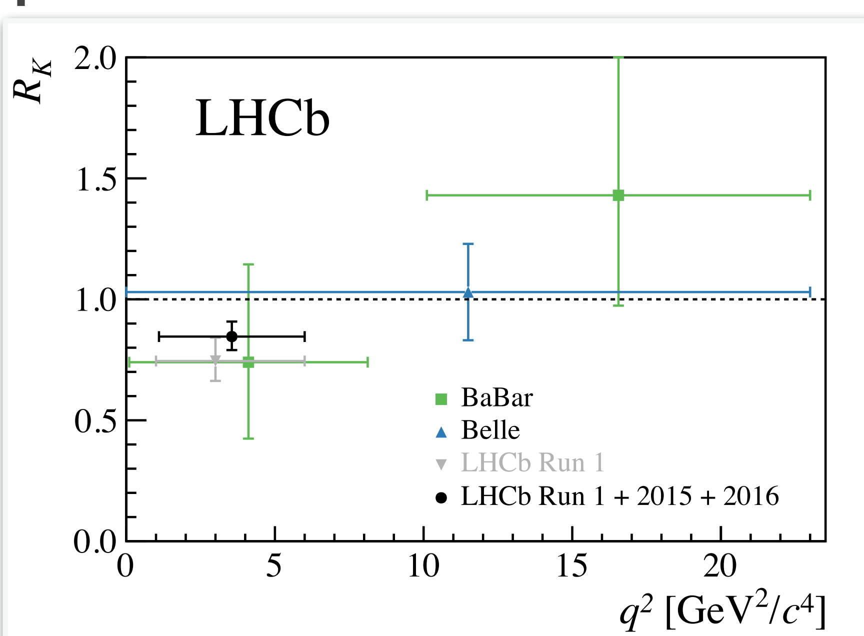
signal yield : μ-mode: $137.0^{+14.2}_{-13.5}$, e-mode: $138.0^{+15.5}_{-14.7}$

※ $B^0 \to K_S \ell^+\ell^-$ modes : μ-mode: $27.3^{+6.6}_{-5.9}$, e-mode: $21.8^{+7.0}_{-6.1}$

Results



previous results and latest LHCb result



from Phys. Rev. Lett. 122, 191801

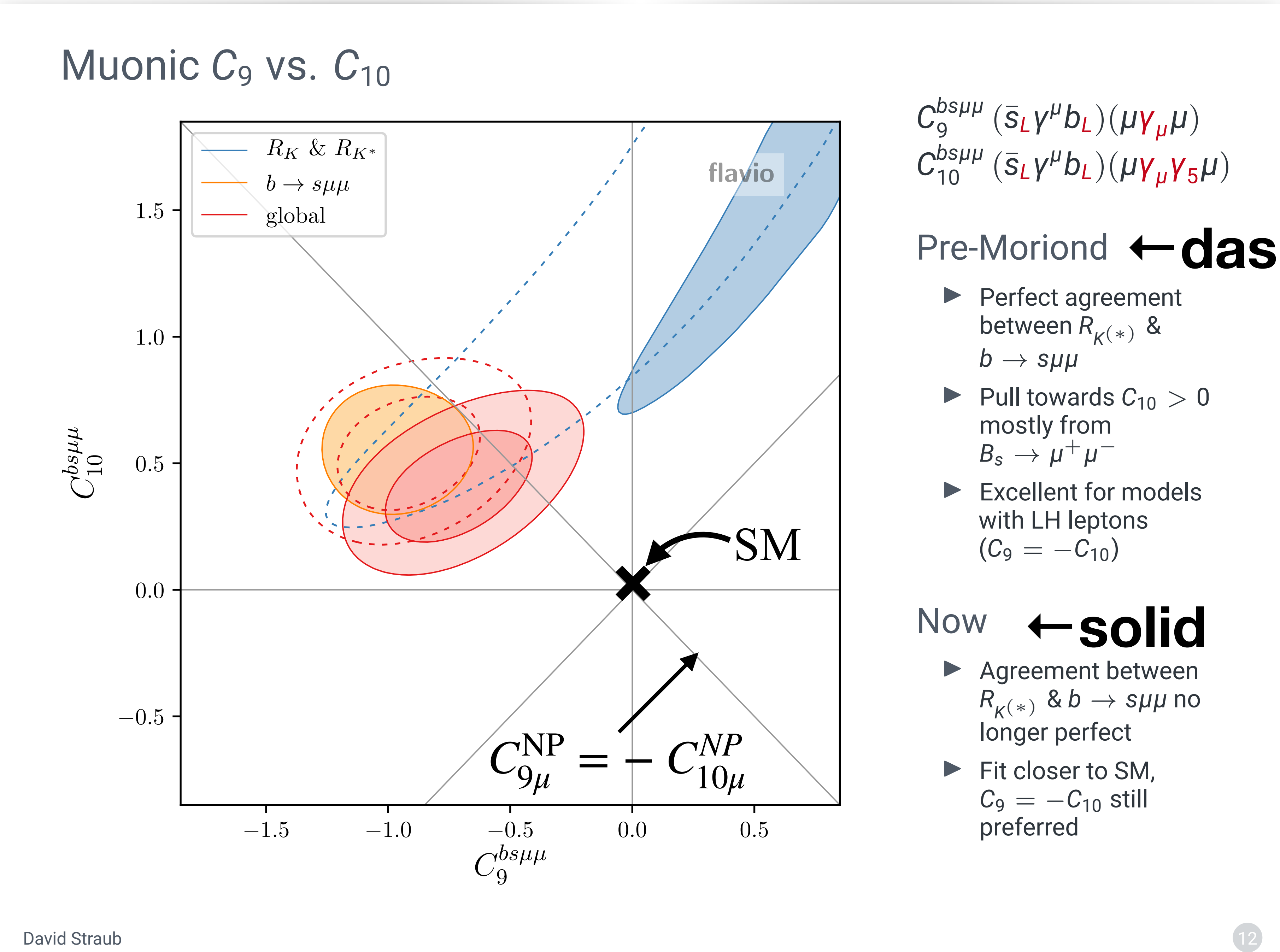
q^2 in GeV^2/c^4	R_K
$[0.1, 4.0]$	$0.95^{+0.27}_{-0.24} \pm 0.06$
$[4.0, 8.12]$	$0.81^{+0.28}_{-0.23} \pm 0.05$
$[1.0, 6.0]$	$0.98^{+0.27}_{-0.23} \pm 0.06$
> 14.18	$1.11^{+0.29}_{-0.26} \pm 0.07$
$[0.1,]$	$1.06^{+0.15}_{-0.14} \pm 0.07$

SM consistent.

Global Fit

(latest Belle R_K result is not included)

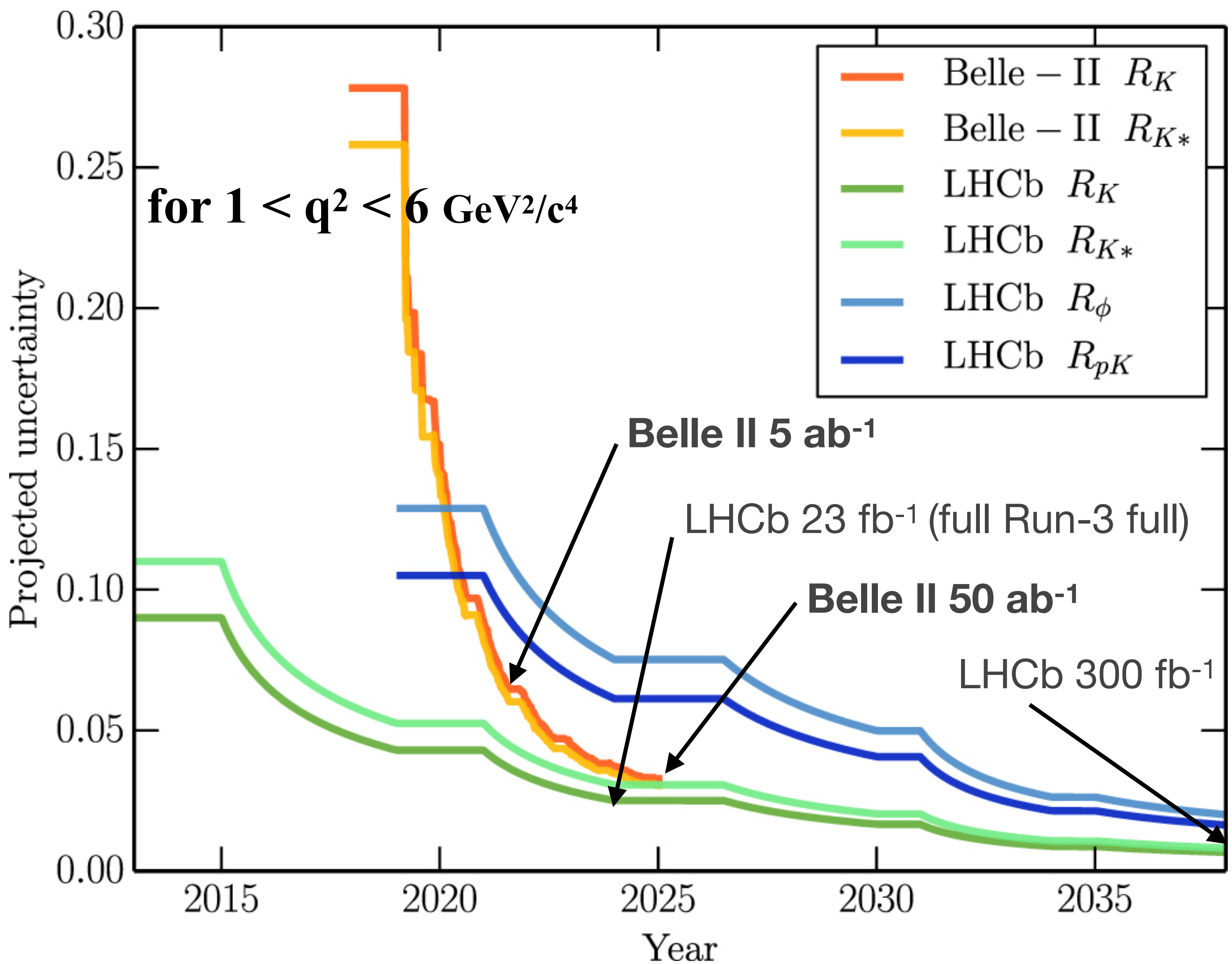
D. Straub, Moriond EW 2019



- tension is mitigated
- not so agree with other $b \to s\mu\mu$ anomaries
- $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$ senario is preferred

$R_{K^{(*)}}$ Prospects in Belle II

J. Phys. G: Nucl. Part. Phys. 46 (2019) 023001



- O(3%) precision measurements with 50 ab^{-1} data
- comparable sensitivity to LHCb for low-q^2 region
- advantage in high-q^2 region, R_{X_s}

Summary

- $b \to s \ell^+ \ell^-$ is a rich field of NP search
- Latest Belle results of $R_{K^{(*)}}$ are consistent with SM
- Belle II will measure $R_{K^{(*)}}$ with O(3%) precision

Stay tuned !!

P'_5

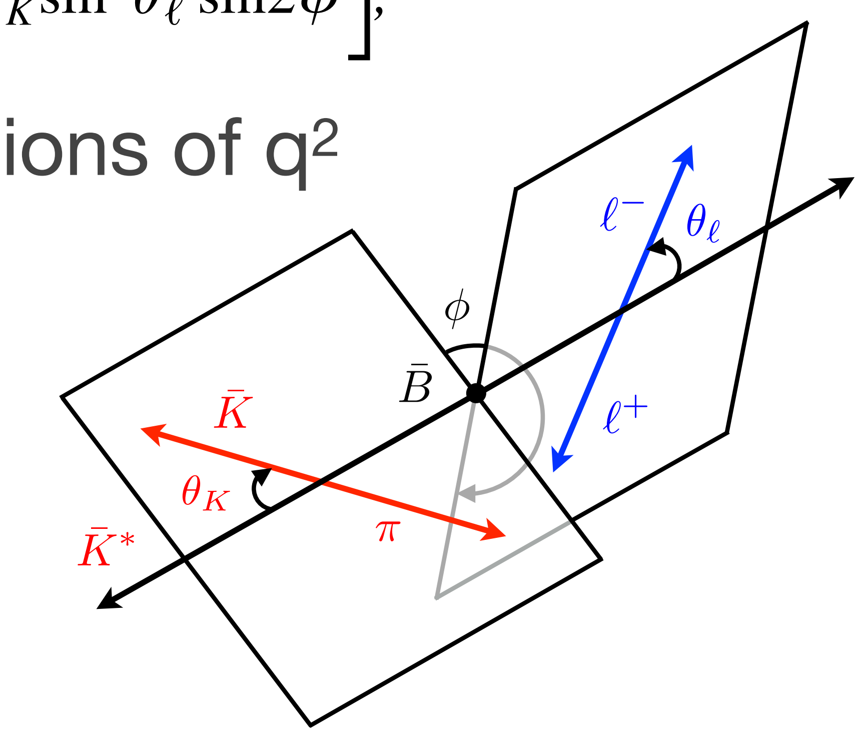
one of the angular obserbables in B→K*(→Kπ)μμ (JHEP01(2013)048)
reducing form factor uncertaiinty

angular distribution can be represented as a function of three angles and q^2:

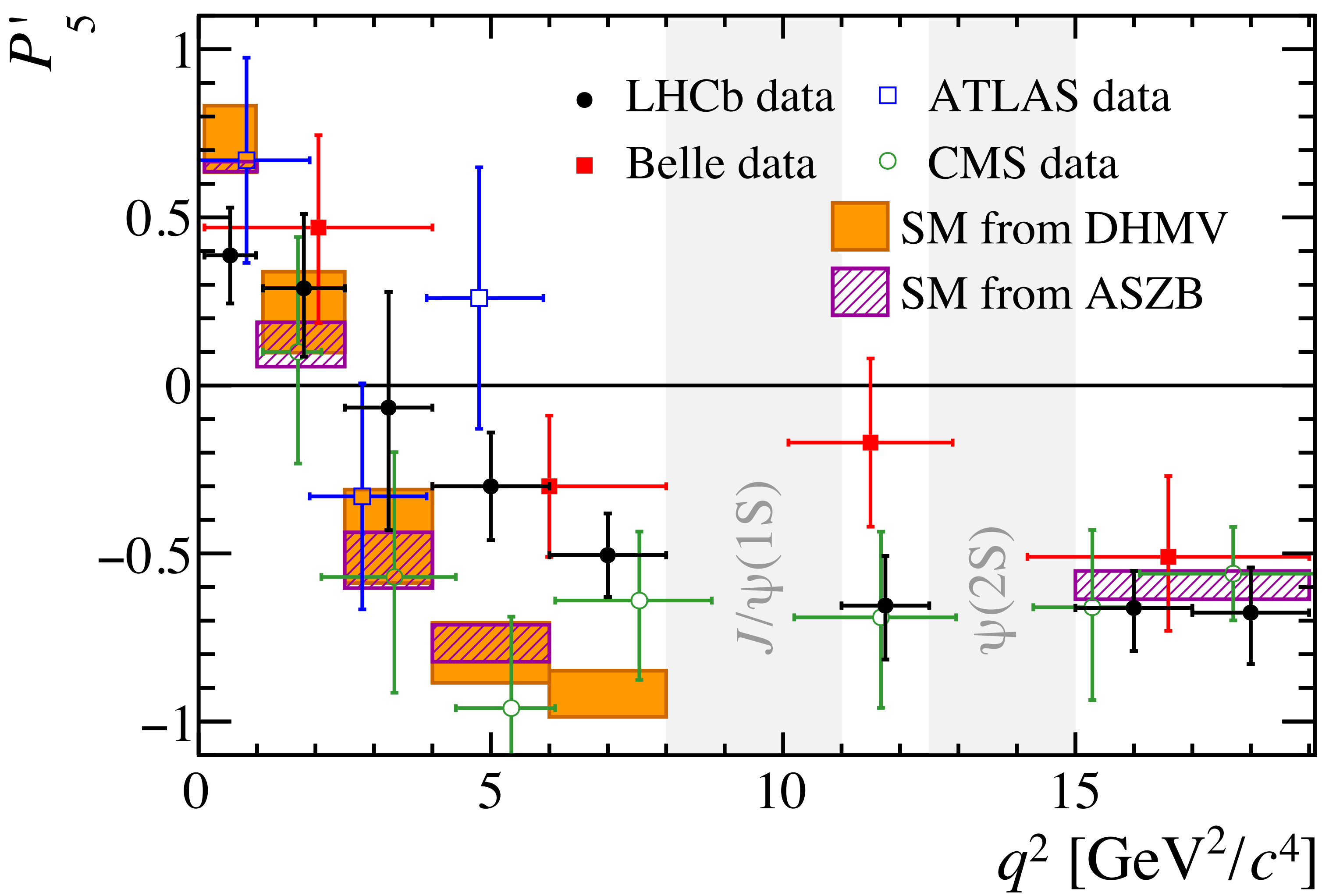
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+ S_5\sin2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin2\theta_K\sin2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big],$$

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

※ S_i, F_L are functions of q^2



P'$_5$



plot from arXiv:1606.00999 (original ?)

Belle : PRL 118 (2017) 111801 (μ,eの平均)
LHCb : JHEP02(2016)104 (μ)
ATLAS : JHEP10(2018)047 (μ)
CMS : Phys. Lett. B 781 (2018) 517 (μ)

SM (DHMV) : JHEP12(2014)125 (?)
SM (ASZB) : JHEP08(2016)098 (?)
Eur.Phys,J,C 75 (2015) 382 (?)

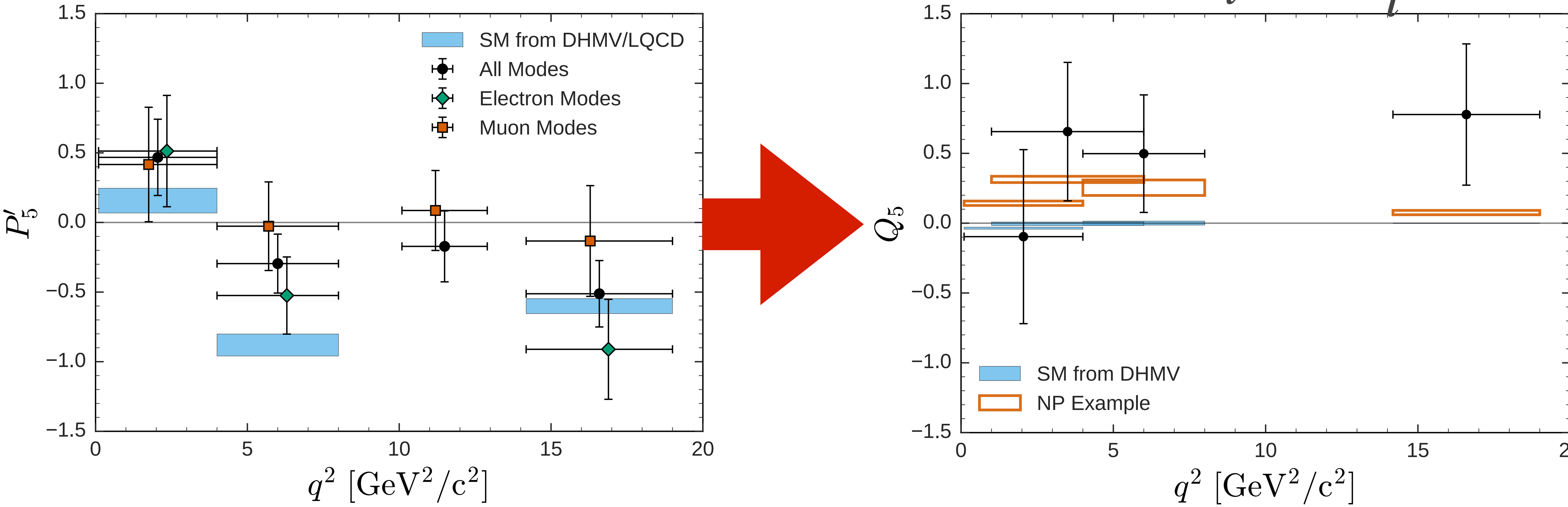
hadronic partの取扱いが違う

Belle, LHCb, ATLAS measurements show deviations from SM prediction

Q_5 : LFU observable

Belle : PRL 118 (2017) 111801

$$Q_i = P_i^{\prime\mu} - P_i^{\prime e}$$



- larger deviation from SM in μ-mode
- Q_5 is a LFU observable
    - hadronic uncertainties cancel to a large extent
    - more reliable SM prediction

R_{K^*}, Belle(2019) : arXiv:1904.02440

PID:

Likelihood using CDC, TOF, ACC, ECL, KLM information:
$P_e = L_e / (L_e + L_\pi) > 0.9$

$P_\mu = L_\mu / (L_\mu + L_\pi) > 0.9$

kinematic selection :
e : $p > 0.4$ GeV/c → >86% efficiency w/ >99% π rejection
μ : $p > 0.7$ GeV/c → >92% efficiency w/ >99% π rejection

Brems. recovery for electrons
add energy within 0.05 rad of the initial direction of electron track

charged-K
$P_K = L_K / (L_K + L_\pi) > 0.1$ → >99% eff. w/ 94% π rejection

R_{K^*}, Belle(2019) : arXiv:1904.02440

Reconstruction:

Ks : vertex fit with π+π- → 74% efficiency

π0 : Eγ>30 MeV & 115 < M(γγ) < 153 MeV/c2 (±4σ)

K^* : K^{*0} : $K^{*0} \to K^+\pi^-$
K^{*+} : $K^{*+} \to K^+\pi^0$, $K^{*+} \to K_S\pi^+$

require 0.6 < M(Kπ) < 1.4 GeV/c2 & vertex fit quality

➡
B reconstruction with K* candidate and two oppositely charged leptons

R_{K^*}, Belle(2019) : arXiv:1904.02440

Background:

- **Combinatorial background** ← dominant background

  incorrect combinations of tracks
  ➡Mbc, ΔE cut
  $5.22 < M_{bc} < 5.30$ GeV/c^2
  $-0.10\ (-0.05) < \Delta E < 0.05$ GeV for electron (muon)

- **Charmonium background**

  $B \to J/\psi\ (\to l^+l^-)K^*$, $B \to \psi(2S)\ (\to l^+l^-)K^*$ contribution (irreducible background)
  ➡veto for $M(l^+l^-)$
  $-0.25\ (-0.15) < M(l^+l^-) - M_{J/\psi} < 0.08$ GeV/c^2 for electron (muon)
  $-0.20\ (-0.10) < M(l^+l^-) - M_{\psi(2S)} < 0.08$ GeV/c^2 for electron (muon)
  in electron mode, both w/ and w/o Brems. recovery

- **Peaking background**

  double flavor misidentification ($K\pi\pi\pi \to K\pi\mu\mu$) →peak in Mbc
  only for muon mode.
  better PID for electron (E/p~1 with ECL) makes this BG negligible small for e-mode.

- **Continuum background**

  $ee \to qq$ contribution. suppress using MVA.

R_{K^*}, Belle(2019)： arXiv:1904.02440

MVA Classifier:

Continuum BG 含め、さらにBGを減らすためのMVA : hierarchal neural net

Decay chainの中で出てくる全粒子($e^{\pm}$, $\mu^{\pm}$, K^{+},π^{+}, K^{*}, K_S, π^{0})それぞれに対して、

particle dedicated NN identifier

BのDecay mode毎($B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^{*+}e^-e^+$ など)にtop-level classifier を用意して

Signal - BGを判別

インプットは、particle dedicated NN identifier, Event shape variables (modified FW moments), vertex fit 結果, reconstructed mass や momentum angleなどのkinematics

top-level classifier のoutputでカット。

cut pointは FoM = n_s / sqrt(n_s + n_b)を定義し、これが最大となるように決めた。

FoMはMbc>5.27 GeV/c2 のMC sampleを用いて評価

R_{K^*}, Belle(2019) : arXiv:1904.02440

Fit:

Fit to Mbc with four components (in each q^2 region):

- Signal : Crystal Ball function
    - $B \to J/\psi K^*$ → calibrate shape parameters
- Combinatorial BG : ARGUS function
- Charmonium BG : Kernel Density Estimation (KDE) w/ x100 stat. MC
- Peaking BG : KDE w/ MC

yields of Charmonium BG and Peaking BG are evaluated by MC and fixed in the fit.

(systematic uncertainty of the yields are evaluated by varying the fixed yields by ± 50%(peaking) / ±25%(charmonium). Resulting signal yield deviations are included as part of the systematics.)

R_{K^*}, Belle(2019)： arXiv:1904.02440

Systematic Uncertainty:

- Crystal-Ball functionのshape parameterをそのuncertainty範囲で振って、その最大変化幅を計上
- Charmonium BG とPeaking BGのnormalizationによるsignal yield のsystematicsは、BG yieldを50%(peaking) / 25%(charmonium) 振って評価
- Lepton ID eff. のData-MC differenceによるsystematicsはee→eeee(μμ)から補正
  - Signal eff. は Br(B→J/ψK*)を求めること(world average consistent)でvalidate
  - この補正を使って

    $Br(B\to J/\psi(\to\mu\mu)K^*) / Br(B\to J/\psi(\to ee)K^*) = 1.015 \pm 0.025_{stat.} \pm 0.038_{corr.}$
    を求めて validate →OK
- MVA Classifier response についてはclassifier output bin毎にBr(B→J/ψK*)を求めてnominal resultと評価→違いをweightとしてDataに当てたうえでMbc Fit
  → signal yieldの変化をsystematicsに計上

R_{K^*}, Belle(2019) : arXiv:1904.02440

Systematic Uncertainty:

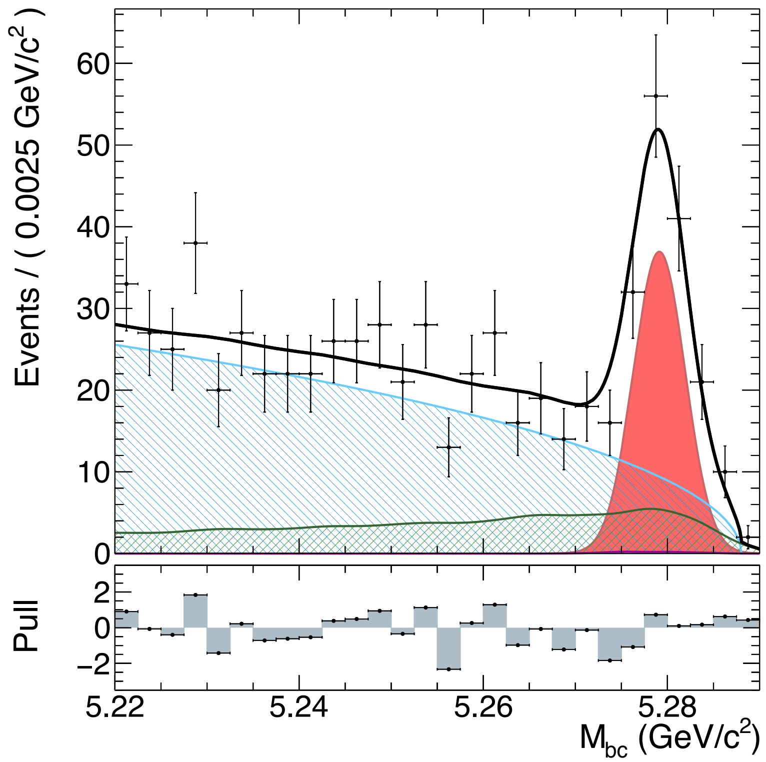
TABLE I. Systematic uncertainties on R_{K^*} for different q^2 regions.

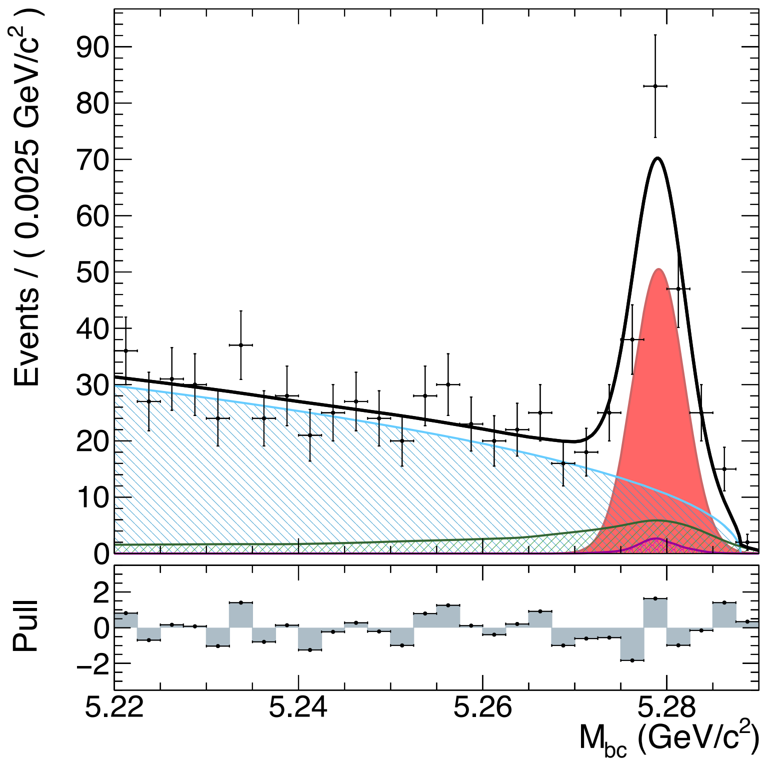
q^2 in GeV$^2/c^4$	e, μ eff.	MC size	Classifier	Sig. shape	Tracking	Peaking bkg.	Charmonia bkg.	Total
All modes								
[0.045, None]	0.061	0.004	0.013	0.008	0.016	0.031	0.023	0.075
$[0.1, 8]$	0.058	0.005	0.029	0.002	0.016	0.054	0.051	0.100
$[15, 19]$	0.090	0.012	0.012	0.014	0.020	0.003	0.003	0.095
$[0.045, 1.1]$	0.027	0.006	0.008	0.025	0.009	0.026	0.001	0.047
$[1.1, 6]$	0.065	0.008	0.048	0.033	0.017	0.070	0.013	0.114
B^0 modes								
[0.045, None]	0.073	0.006	0.030	0.018	0.022	0.031	0.021	0.092
$[0.1, 8]$	0.058	0.006	0.040	0.019	0.017	0.033	0.018	0.084
$[15, 19]$	0.091	0.013	0.007	0.012	0.022	0.007	0.001	0.096
$[0.045, 1.1]$	0.024	0.007	0.044	0.005	0.009	0.049	0.001	0.071
$[1.1, 6]$	0.082	0.010	0.040	0.062	0.021	0.070	0.012	0.133
B^+ modes								
[0.045, None]	0.044	0.005	0.032	0.018	0.010	0.025	0.023	0.068
$[0.1, 8]$	0.060	0.010	0.039	0.040	0.014	0.048	0.107	0.144
$[15, 19]$	0.089	0.028	0.016	0.041	0.021	0.008	0.002	0.106
$[0.045, 1.1]$	0.033	0.013	0.067	0.060	0.009	0.006	0.000	0.097
$[1.1, 6]$	0.045	0.010	0.137	0.060	0.011	0.086	0.009	0.179

R_{K^*}, Belle(2019)： arXiv:1904.02440

Fit Results:

e-mode　　　　　　　　μ-mode





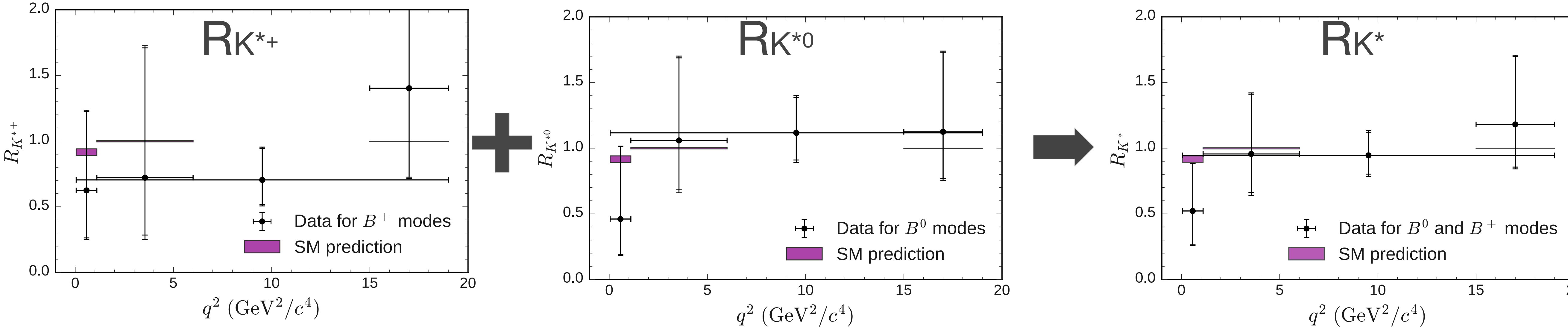
$q^2 > 0.045$ (GeV/c^2)^2 の全領域。

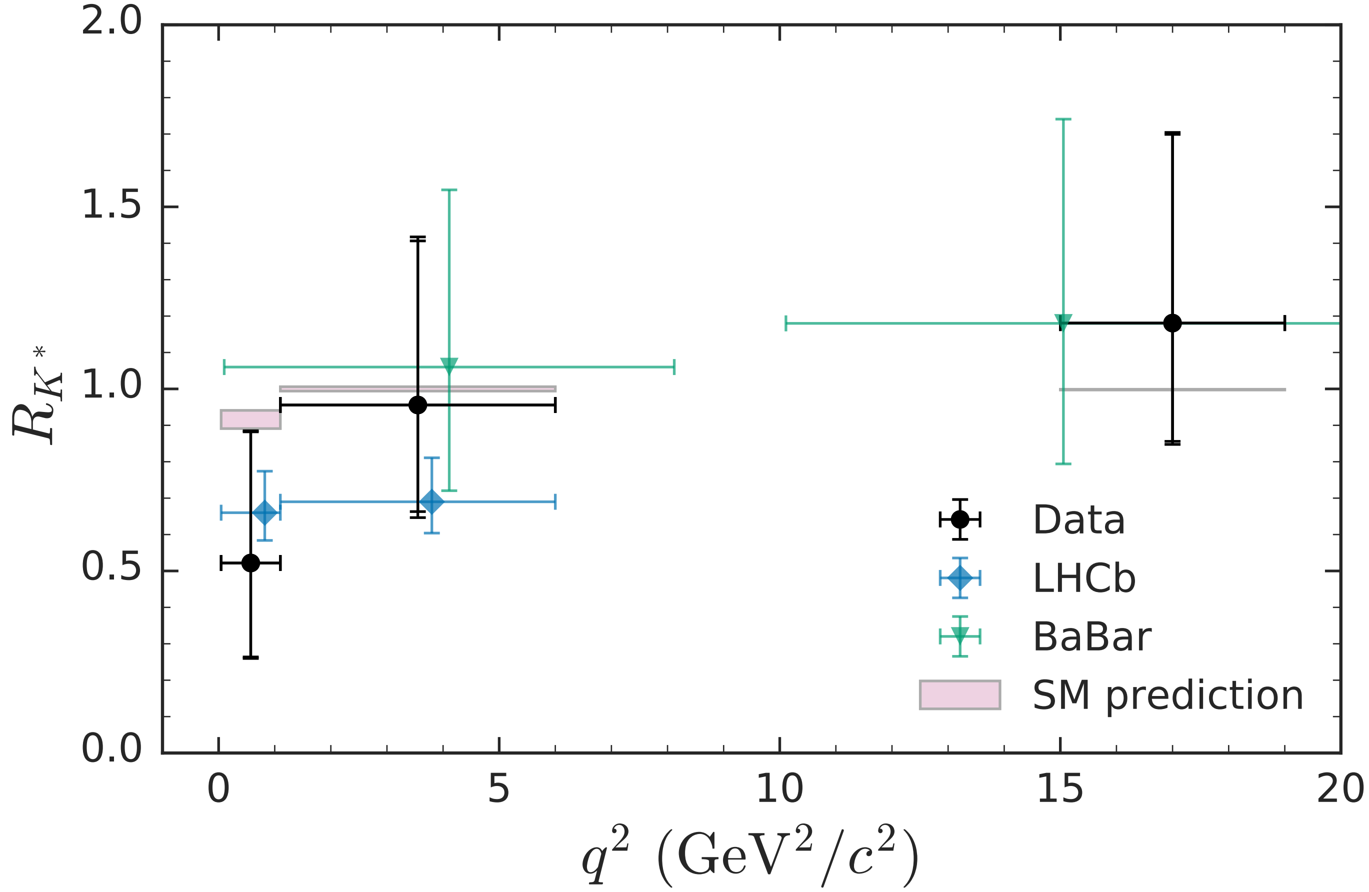
赤がシグナルで、yieldは、e: $103.0^{+13.4}_{-12.7}$，μ: $139.9^{+16.0}_{-15.4}$

青がCombinatorial BG、緑がcharmonium BG, 紫がpeaking BG.

R_{K^*}, Belle(2019) : arXiv:1904.02440

Results:





Consistent with both SM and other measurements

R_{K^*}, Belle(2019) : arXiv:1904.02440

Results:

TABLE II. Result for R_{K^*}, $R_{K^{*0}}$ and $R_{K^{*+}}$. The first uncertainty is statistical and the second is systematic.

q^2 in GeV$^2/c^4$	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045,]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$

R_K, Belle(2019) : arXiv:1908.01848

Pre-selection:

- impact parameter : |d| < 1 cm, |z| < 4 cm except for Ks daughters
- pt > 100 MeV/c for all tracks

Particle selection:

- K± : Likelihood ratio using CDC, TOF, ACC
  PK = LK / (LK + Lπ) ＞0.6 → >92% eff. w/ 93% π rejection
- Ks :
  487 < m(π+π-) < 508 MeV/c2 (3σ window)
  Neural Net based selector
- μ: KLM based PID
  p > 0.8 GeV/c,
  Rμ > 0.9 : 89% eff. w/ 1.5% π miss-PID
- e: CDC/ECL based PID
  p > 0.4 GeV
  Re > 0.9 : 92% eff. w/ <1% π miss-PID
  Brems. recovery for electrons

R_K, Belle(2019) : arXiv:1908.01848

Reconstruction:

B reconstruction with K±/Ks candidate and two oppositely charged leptons

- require ΔE and Abc cut :
  - $-0.1 < \Delta E < 0.25$ GeV
  - Mbc > 5.25 GeV/c2

R_K, Belle(2019) : arXiv:1908.01848

Background:

- **Charmonium background**

  $B \to J/\psi\ (\to l^+l^-)K$, $B \to \psi(2S)\ (\to l^+l^-)K$ contribution (irreducible background)
  ➡veto for $M(l^+l^-)$
  8.5 (8.75) < $M^2(l^+l^-)$ < 10.2 GeV^2/c^4 for electron (muon)
  12.8 (13.0) < $M^2(l^+l^-)$ < 14.0 GeV^2/c^4 for electron (muon)
  ##? in electron mode, both w/ and w/o Brems. recovery
- **$\gamma^* \to e^+e^-$ / $\pi^0 \to \gamma e^+e^-$ contamination**
  veto low q2 region : < 0.05 GeV^2/c^4
- **Continuum background :** $ee \to qq$ contribution
  two back-to-back jets of π/K
  suppress based on event topology
- **Generic B decay background: three categories**
  (a) bath B B-bar decay semileptonically
  (b) $B \to D(^*)\ (\to Xl\nu)\ Xl\nu$
  (c) hadronic B decays where one or more daughters are misidentified as leptons

➡ NN to suppress continuum and generic B decay backgrounds
using event shapes, vertex quality, kinematic variables
➡1/4 background suppression with 4-5% signal acceptance loss

R_K, Belle(2019) : arXiv:1908.01848

Background:

•

R_K, Belle(2019) : arXiv:1908.01848

Fit:

3D fit to Mbc, ΔE, NN output with four components (in each q^2 region):

- Signal :
  - Mbc : sum of a Gaussian and a Crystal Ball function
  - ΔE : single Gaussian
  - O’ : sum of asymmetric Gaus. and a regular Gaus. with common mean
    - all shape parameters from MC, with calibration using B→JpsiK
- B decay BG, Continuum BG
  - Mbc : ARGUS
  - ΔE : exponential
  - O’ : Gaussian

    yield of continuum BG is estimated with off-resonance data

R_K, Belle(2019) : arXiv:1908.01848

Systematic Uncertainty:

TABLE I: Results from the fits. The columns correspond to the q^2 bin size, decay modes, reconstruction efficiency, signal yield, branching fraction, lepton-flavor-separated and combined A_I and R_K.

q^2 (GeV^2/c^4)	Mode	ε (%)	N_{sig}	$\mathcal{B}$ (10^{-7})	A_I (individual)	A_I (combined)	R_K (individual)	R_K (combined)
(0.1,4.0)	$B^+ \to K^+\mu^+\mu^-$	20.8	$28.4^{+6.6}_{-5.9}$	$1.72^{+0.4}_{-0.4} \pm 0.08$	$A_I(\mu\mu) =$	$-0.22^{+0.14}_{-0.12} \pm 0.01$	$R_{K^+} =$	$0.95^{+0.27}_{-0.24} \pm 0.06$
	$B^0 \to K^0_S\mu^+\mu^-$	14.7	$6.8^{+3.3}_{-2.6}$	$0.62^{+0.30}_{-0.23} \pm 0.03$	$-0.10^{+0.20}_{-0.17} \pm 0.01$		$0.92^{+0.27}_{-0.24} \pm 0.05$	
	$B^+ \to K^+e^+e^-$	27.8	$41.5^{+7.7}_{-7.0}$	$1.88^{+0.35}_{-0.31} \pm 0.08$	$A_I(ee) =$		$R_{K^0_S} =$	
	$B^0 \to K^0_Se^+e^-$	18.4	$5.5^{+3.6}_{-2.7}$	$0.40^{+0.26}_{-0.21} \pm 0.02$	$-0.35^{+0.21}_{-0.17} \pm 0.01$		$1.5^{+1.2}_{-1.0} \pm 0.1$	
(4.0,8.12)	$B^+ \to K^+\mu^+\mu^-$	29.2	$28.4^{+6.4}_{-5.7}$	$1.2^{+0.3}_{-0.2} \pm 0.06$	$A_I(\mu\mu) =$	$-0.08^{+0.15}_{-0.12} \pm 0.01$	$R_{K^+} =$	$0.81^{+0.28}_{-0.23} \pm 0.05$
	$B^0 \to K^0_S\mu^+\mu^-$	20.8	$4.2^{+4.2}_{-3.5}$	$0.27^{+0.18}_{-0.13} \pm 0.02$	$-0.33^{+0.23}_{-0.19} \pm 0.01$		$1.22^{+0.42}_{-0.37} \pm 0.07$	
	$B^+ \to K^+e^+e^-$	33.9	$26.9^{+6.9}_{-6.1}$	$1.00^{+0.26}_{-0.23} \pm 0.04$	$A_I(ee) =$		$R_{K^0_S} =$	
	$B^0 \to K^0_Se^+e^-$	22.8	$9.3^{+3.7}_{-3.0}$	$0.54^{+0.22}_{-0.18} \pm 0.03$	$0.11^{+0.19}_{-0.16} \pm 0.01$		$0.50^{+0.39}_{-0.30} \pm 0.03$	
(1.0,6.0)	$B^+ \to K^+\mu^+\mu^-$	23.5	$42.3^{+7.6}_{-6.9}$	$2.3^{+0.4}_{-0.4} \pm 0.1$	$A_I(\mu\mu) =$	$-0.30^{+0.13}_{-0.11} \pm 0.01$	$R_{K^+} =$	$0.98^{+0.27}_{-0.23} \pm 0.06$
	$B^0 \to K^0_S\mu^+\mu^-$	16.7	$3.9^{+2.7}_{-2.0}$	$0.31^{+0.22}_{-0.16} \pm 0.02$	$-0.52^{+0.20}_{-0.17} \pm 0.02$		$1.31^{+0.34}_{-0.31} \pm 0.07$	
	$B^+ \to K^+e^+e^-$	30.4	$41.7^{+8.0}_{-7.2}$	$1.74^{+0.33}_{-0.30} \pm 0.08$	$A_I(ee) =$		$R_{K^0_S} =$	
	$B^0 \to K^0_Se^+e^-$	20.1	$8.9^{+4.0}_{-3.2}$	$0.59^{+0.27}_{-0.21} \pm 0.03$	$-0.12^{+0.18}_{-0.15} \pm 0.01$		$0.53^{+0.44}_{-0.33} \pm 0.03$	
> 14.18	$B^+ \to K^+\mu^+\mu^-$	45.3	$47.9^{+8.6}_{-7.8}$	$1.34^{+0.24}_{-0.22} \pm 0.06$	$A_I(\mu\mu) =$	$-0.13^{+0.14}_{-0.12} \pm 0.01$	$R_{K^+} =$	$1.11^{+0.29}_{-0.26} \pm 0.07$
	$B^0 \to K^0_S\mu^+\mu^-$	25.3	$9.6^{+4.2}_{-3.5}$	$0.51^{+0.22}_{-0.18} \pm 0.03$	$-0.07^{+0.17}_{-0.15} \pm 0.01$		$1.08^{+0.30}_{-0.27} \pm 0.06$	
	$B^+ \to K^+e^+e^-$	44.2	$43.2^{+9.1}_{-8.3}$	$1.24^{+0.26}_{-0.24} \pm 0.05$	$A_I(ee) =$		$R_{K^0_S} =$	
	$B^0 \to K^0_Se^+e^-$	23.6	$5.9^{+4.0}_{-3.1}$	$0.33^{+0.23}_{-0.18} \pm 0.02$	$-0.24^{+0.23}_{-0.19} \pm 0.01$		$1.52^{+1.23}_{-0.97} \pm 0.10$	
whole q^2	$B^+ \to K^+\mu^+\mu^-$	27.8	$137.0^{+14.2}_{-13.5}$	$6.24^{+0.65}_{-0.61} \pm 0.31$	$A_I(\mu\mu) =$	$-0.19^{+0.07}_{-0.06} \pm 0.01$	$R_{K^+} =$	$1.06^{+0.15}_{-0.14} \pm 0.07$
	$B^0 \to K^0_S\mu^+\mu^-$	18.2	$27.3^{+6.6}_{-5.9}$	$2.0^{+0.5}_{-0.4} \pm 0.1$	$-0.15^{+0.09}_{-0.08} \pm 0.01$		$1.04^{+0.16}_{-0.15} \pm 0.06$	
	$B^+ \to K^+e^+e^-$	29.1	$138.0^{+15.5}_{-14.7}$	$6.00^{+0.7}_{-0.6} \pm 0.3$	$A_I(ee) =$		$R_{K^0_S} =$	
	$B^0 \to K^0_Se^+e^-$	18.2	$21.8^{+7.0}_{-6.1}$	$1.60^{+0.52}_{-0.45} \pm 0.08$	$-0.24 \pm 0.11 \pm 0.01$		$1.25^{+0.50}_{-0.44} \pm 0.08$	

- lepton ID systematics : 2% for muon, 1.6 % for electron
- hadron ID systematics : 0.8% for K± and 1.6% for Ks
- O' systematics : 1.5%