Status & Outlook for $R_{D^{(*)}}$ & $R_{K^{(*)}}$ from Belle/Belle II

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December 15, 2021

Belle II at SuperKEKB

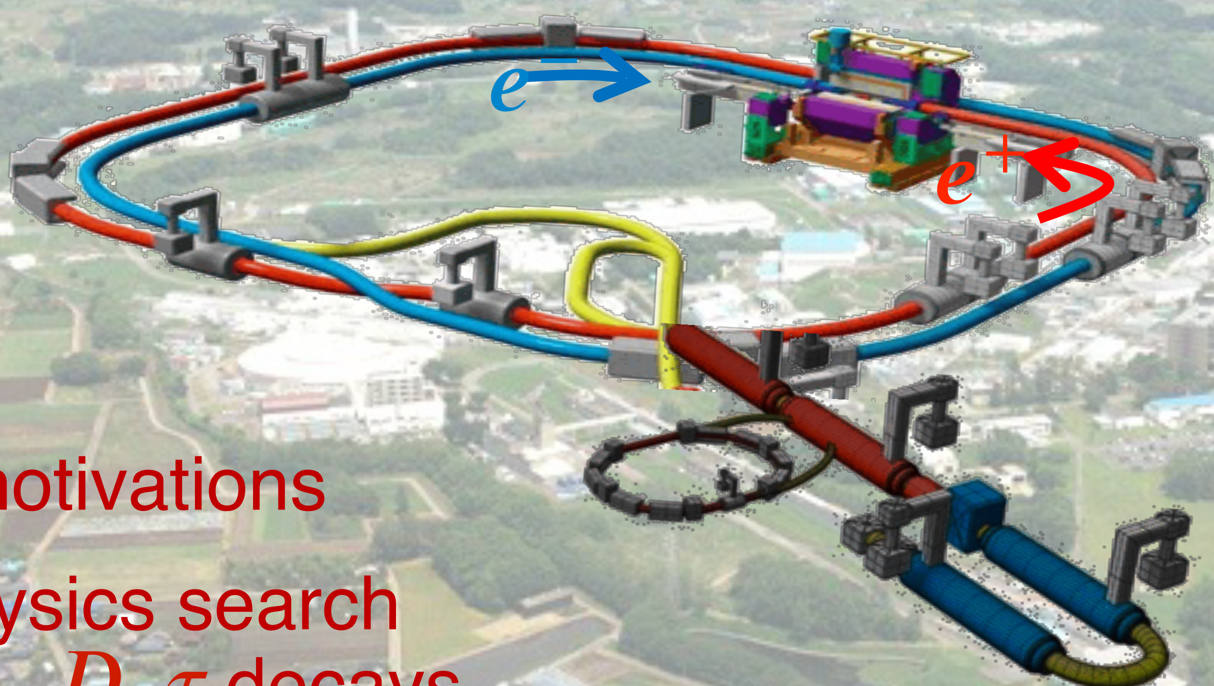
Plan to collect **50 ab⁻¹** of collisions at and near $\Upsilon(4S)$

Successor to Belle at KEKB (1.05 ab⁻¹)

At $\Upsilon(4S)$, $E_{CM} = 10.58$ GeV

7 GeV e^- (HER; High Energy Ring)

4 GeV e^+ (LER; Low Energy Ring)

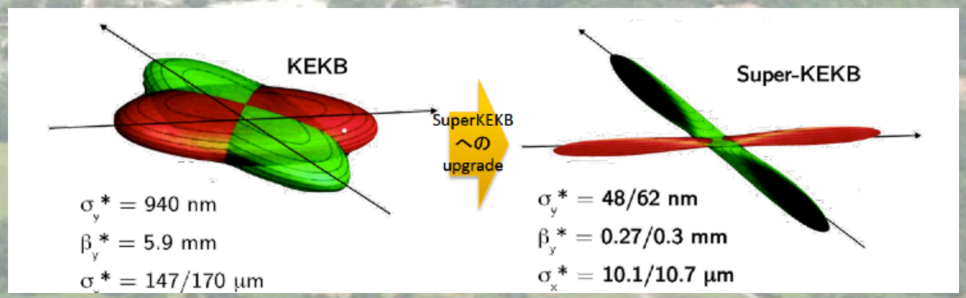


Nano beam scheme

$$\mathscr{L} = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

5.9 → 0.3 mm

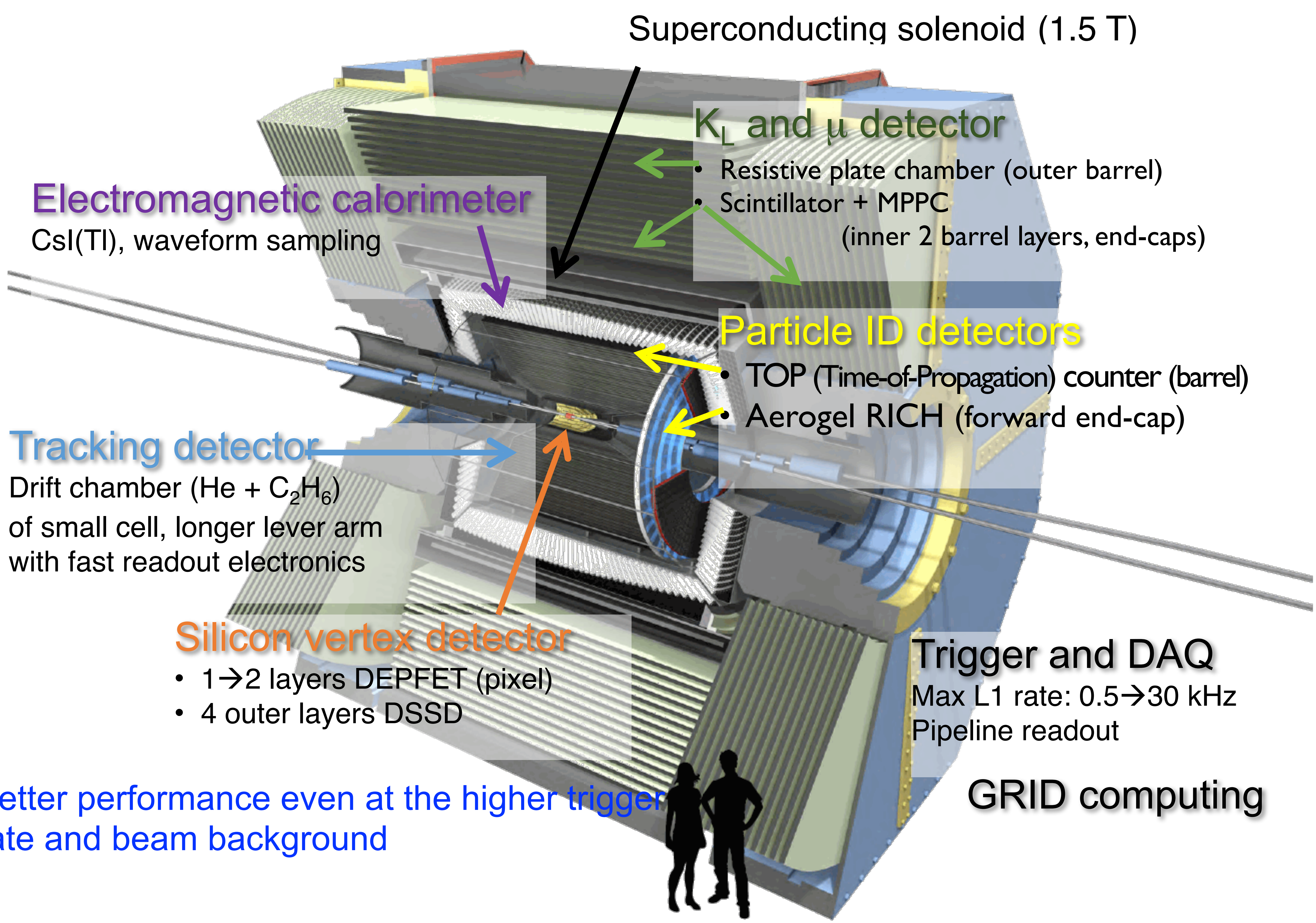
KEKB SuperKEKB



Physics motivations

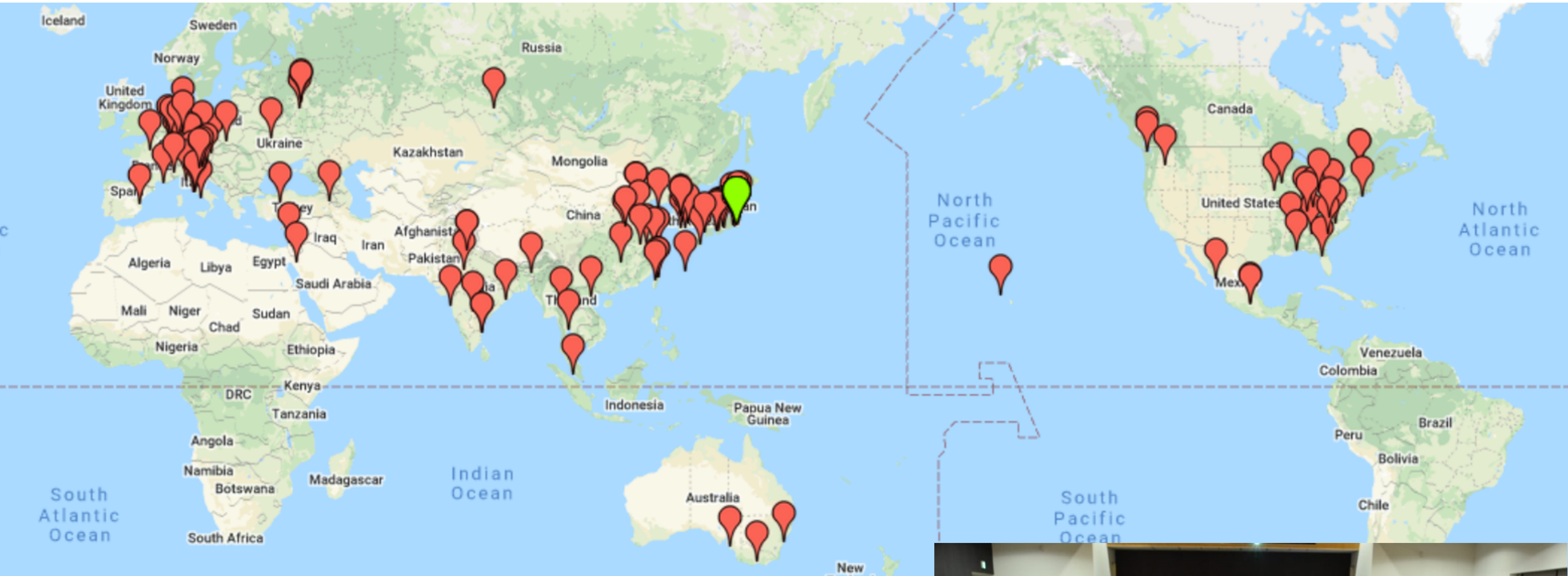
- New physics search in B, B_s, D, τ decays
- Direct search for light new particles
- Precise measurement of Standard Model
- Hadron physics

Belle II detector



Better performance even at the higher trigger rate and beam background

Belle II Collaboration



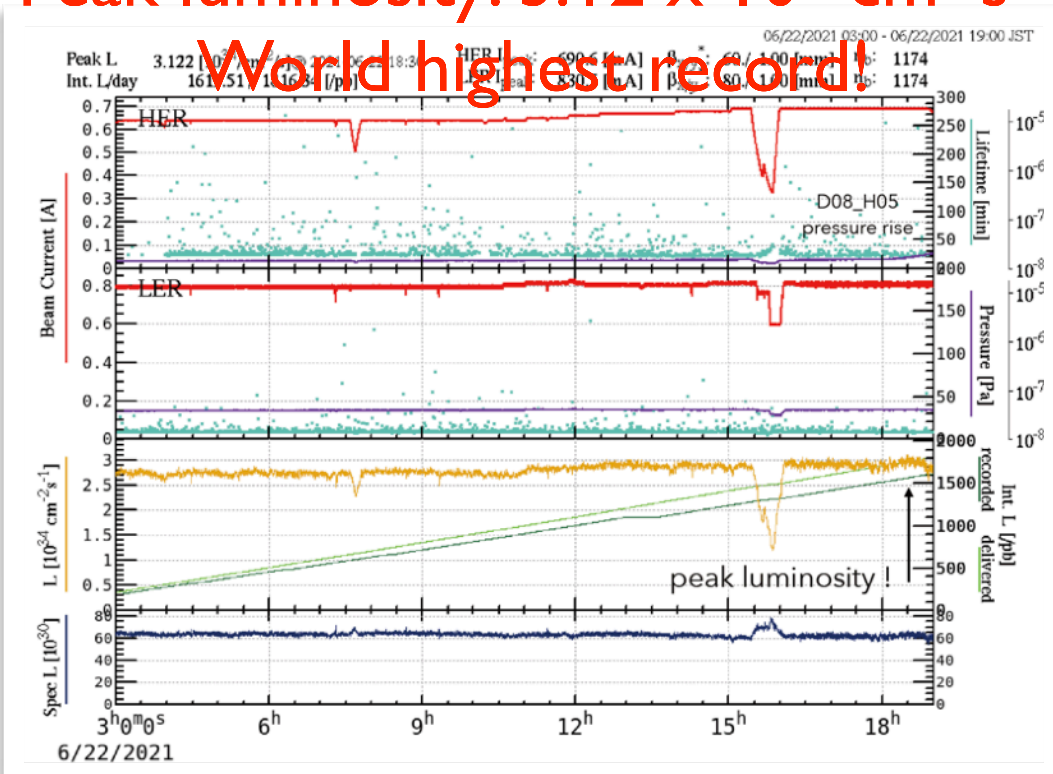
- ~1120 active members
  - ~240/~140/~70 (Ph.D/Msc/Undergrad.) students
- 123 institutes
- 26 countries/regions

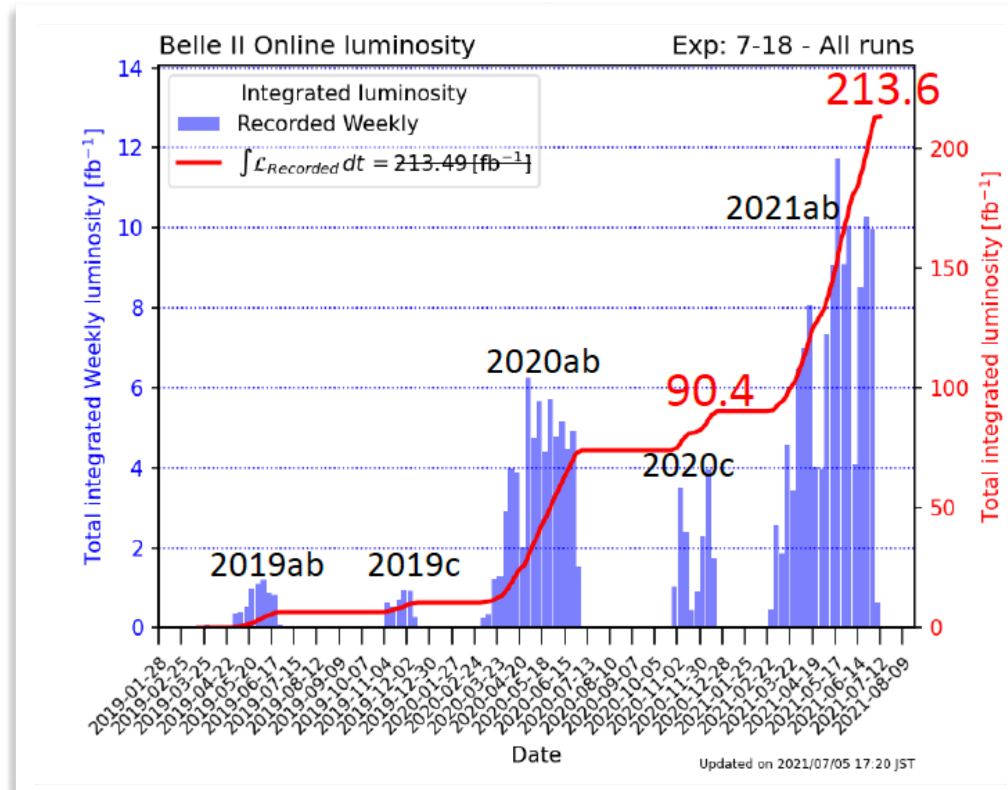
Status of the SuperKEKB/Belle II

highlight of the 2021run by summer

Peak luminosity: 3.12 x $10^{34}cm^{-2}s^{-1}$

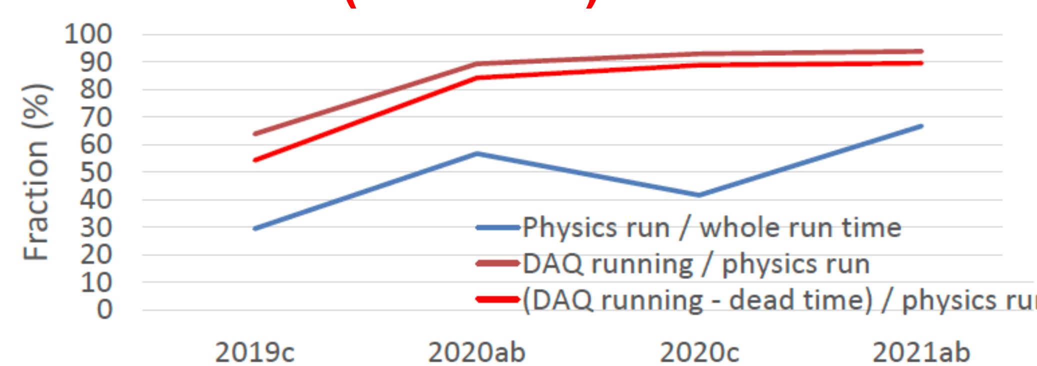
World highest record!





Data taking efficiency:

- 88.8 (2020c)
- 89.5% (2021ab)



Luminosity records (recorded/delivered):

- L_{shift} = 747.2 / 787.6 pb^{-1}
- L_{day} = 1.964 / 2.233 fb^{-1}
- L_{7days} = 12.141 / 13.482 fb^{-1}
- L_{30days} = 42.319 / 47.370 fb^{-1}

Luminosity record is updating!

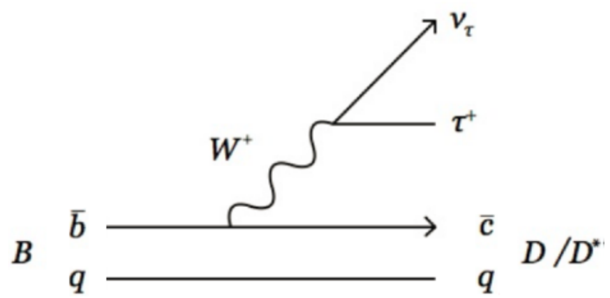
L_{peak} = 3.32 x $10^{34}cm^{-2}s^{-1}$, L_{day} = 2.15 fb^{-1}(delivered) on Dec.11

"B anomalies"

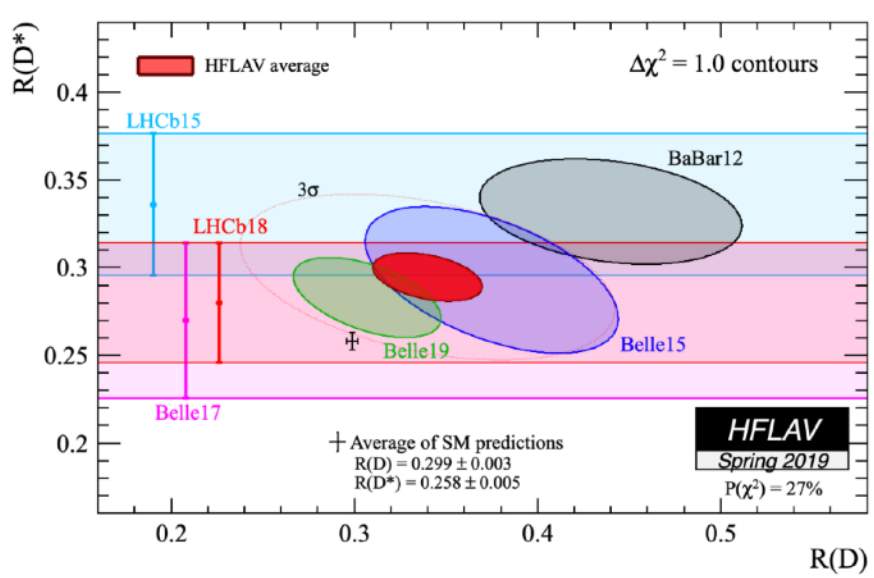
Indications for violation of lepton flavor universality have been claimed in the two types of B decays.

$b \to c \tau \nu$

Tree, BF ~ O(10^{-2})

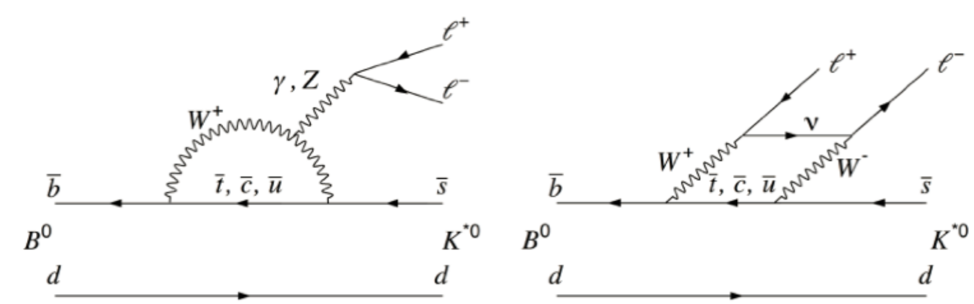


$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$

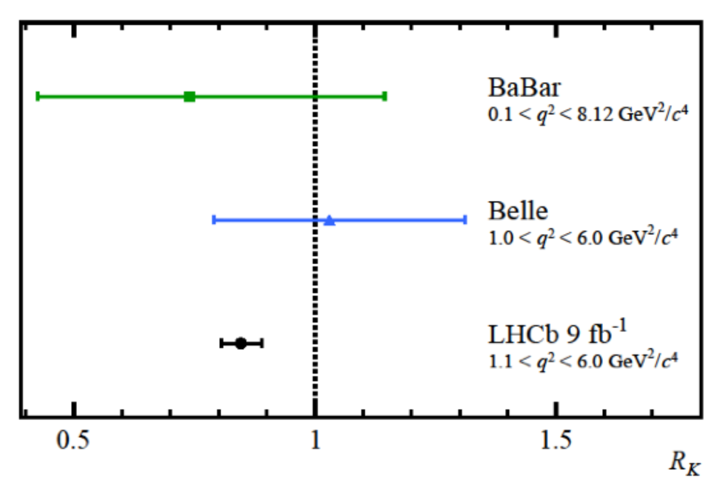


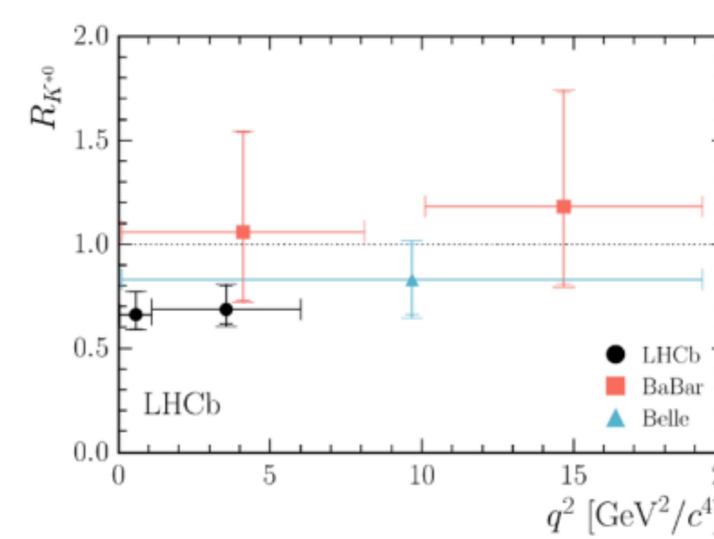
$b \to s l^+ l^-$

Loop, BF ~ O(10^{-6})



$$R_H = \frac{\mathcal{B}(B \to H \mu^+ \mu^-)}{B(B \to H e^+ e^-)} \qquad H = K, K^*, X_s, \ldots$$

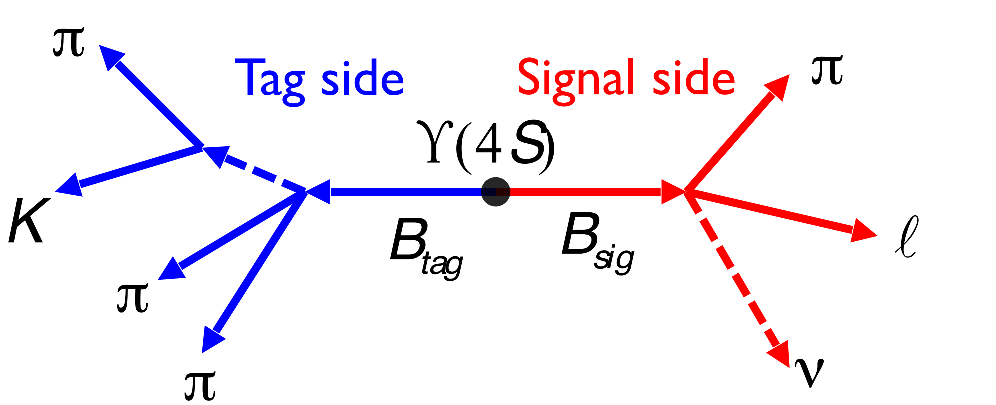




Are these clues for new physics?

Advantage of e^+e^- B factories

- Clean environment
  - Efficient detection of neutrals (γ, π^0, η, …)
- Good hermeticity
  - acceptance close to 4π
- Full reconstruction tagging possible



$B \to \pi l \nu$
$B \to \tau \nu, D \tau \nu$
$B \to K \nu \nu$

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

Easier bremsstrahlung energy recovery for electrons,
eff(e) ~ eff(μ)

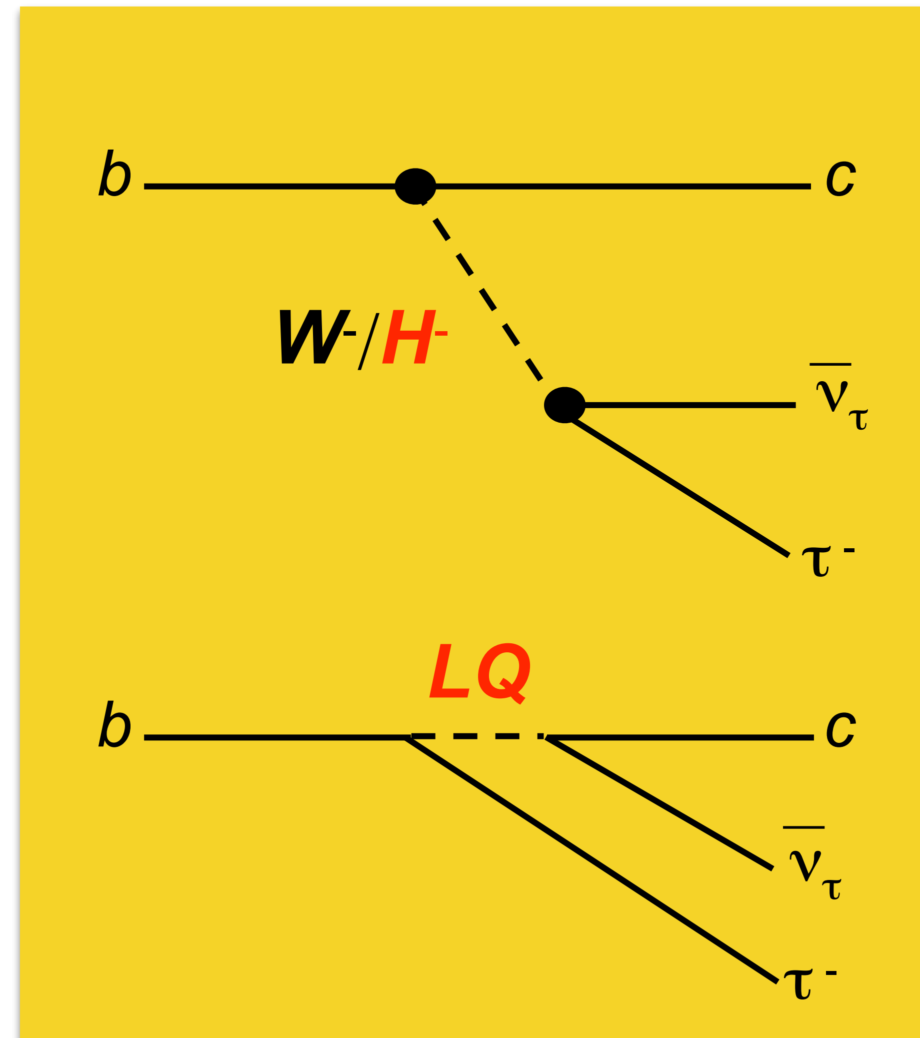
Measurements of
- $b \to u$ semileptonic decays
- decays with large missing energy

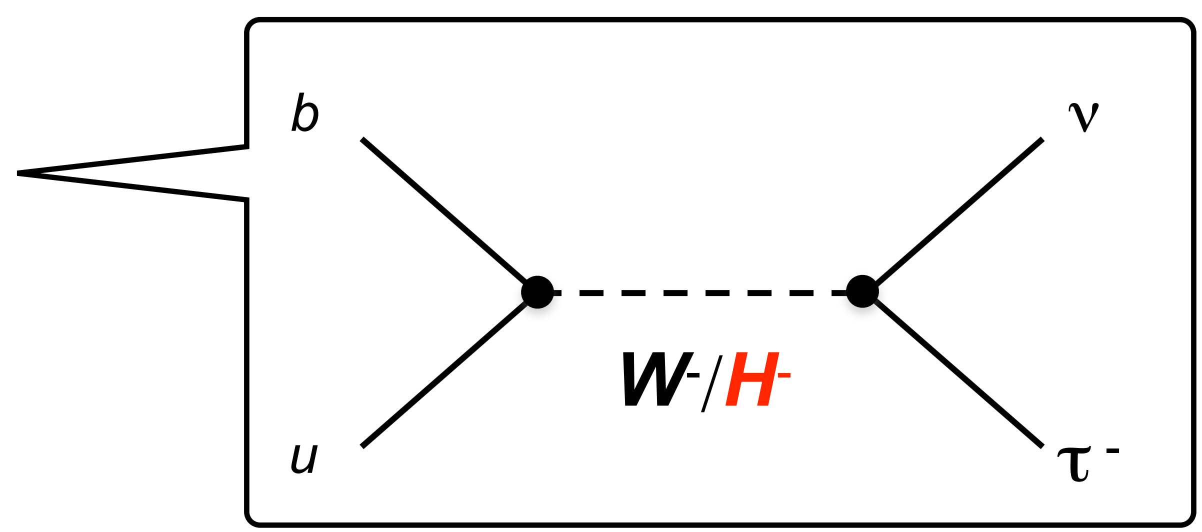
Measurement of the τ polarization

- Systematics different from experiments at hadron machines
  - Two experiments are required to establish NP

$B \to D^{(*)} \tau \nu$

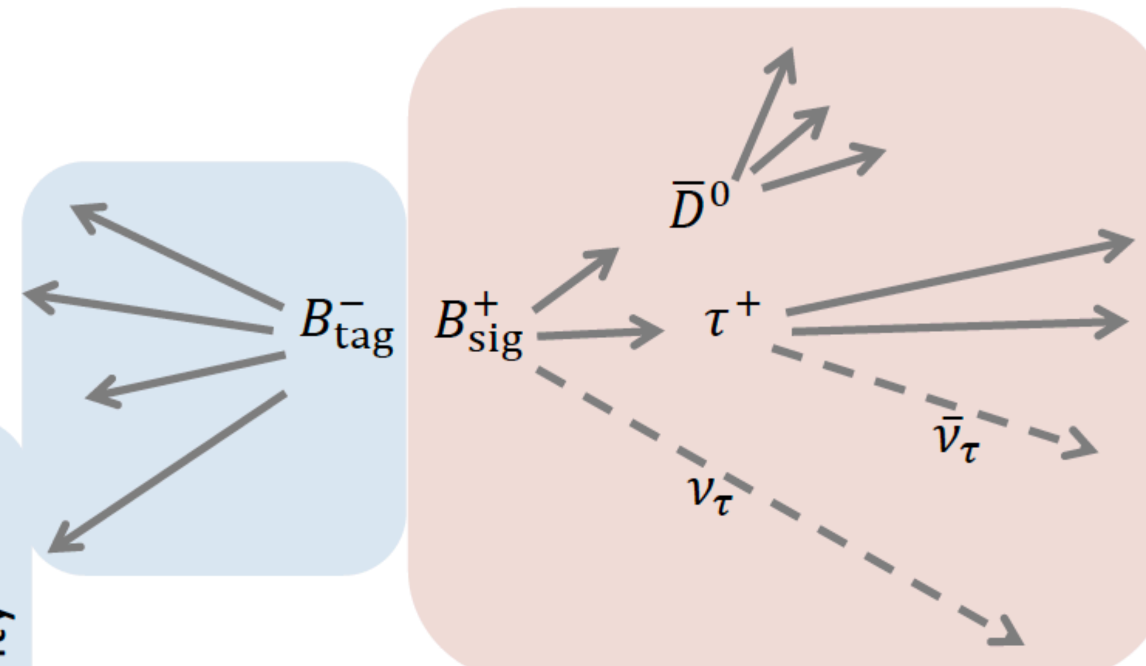
- New Physics may appear in tree level.
- 3rd generation quark (b) and lepton (τ) involved.
  - large masses → sensitivity to NP
  - Charged Higgs, Leptoquark, …
- Quantities of interest
  - Lepton Flavor Universality :
    - R(D), R(D*)
  - Polarization: P_τ, P_{D^*}
  - q^2 distribution etc.
- Complementary to $B \to \tau \nu$
  - Different sensitivity to NP models.





$B \to D^{(*)}\tau\nu$ reconstruction at Belle/Belle II

- Not a rare decay
  - In SM, $\mathcal{B}(B^+ \to \bar{D}^0\tau^+\nu_\tau)$ = 0.66% and $\mathcal{B}(B^+ \to \bar{D}^{*0}\tau^+\nu_\tau)$ = 1.23%
- but reconstruction of τ is challenging due to multiple neutrinos.
  - → Need full reconstruction of the event
    - Suppress non-$B\bar{B}$ bkgd. and misreconstructed events
  - → quite low efficiency
  - → need a high statistics



Reconstruct one of the B's decaying

1. Hadronically ($\varepsilon_{\rm sig} \approx$ 0.2%)
2. Semileptonically ($\varepsilon_{\rm sig} \approx$ 0.5%)
3. Inclusively ($\varepsilon_{\rm sig} \approx$ a few %)

Efficiency ↓ Purity ↑

Select the other B of the signal decay with

- a $D^{(*)}$
- a charged daughter of τ
  1. Leptonic τ decay
  2. Hadronic τ decay

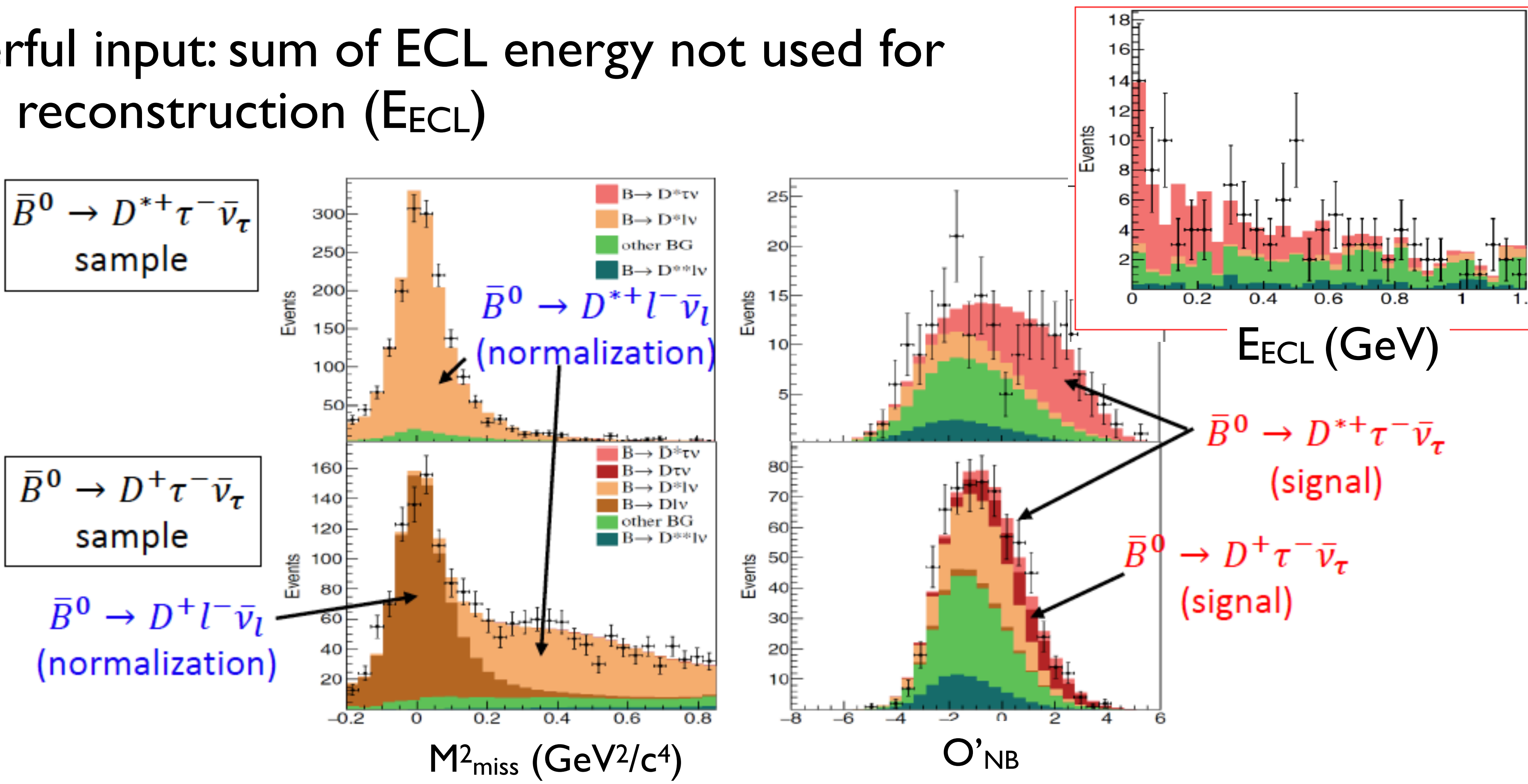
Background from B → D^{**} decays, where the D^{**} isn't identified as such and mimics a D^* (one of the major sources of the systematic errors)

B → D(*) τ ν w/ τ→lνν & had. tag

Belle 2015

PRD92, 072014 (2015)

- M^2_{miss} to measure B→D(*) l ν
  - M^2_{miss} = [p(e⁺e⁻) - p(B_{tag}) - p(D(*)) - p(l)]^2
- Transformed neural network output (O'_{NB}) to measure B→D(*) τ ν
  - Powerful input: sum of ECL energy not used for signal reconstruction (E_{ECL})



$$R(D) = 0.375 \pm 0.064(\text{stat.}) \pm 0.026(\text{syst.})$$
$$R(D^*) = 0.293 \pm 0.038(\text{stat.}) \pm 0.015(\text{syst.})$$

B → D* τ ν w/ τ→π/ρν & had. tag

Belle 2017

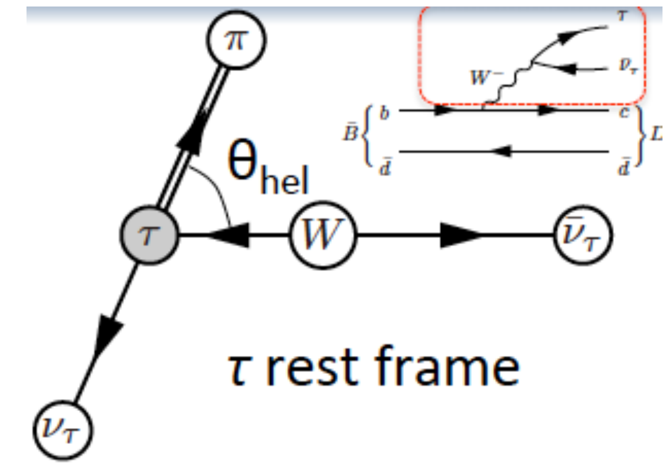
PRL118, 211801 (2017), PRD97, 012004 (2018)

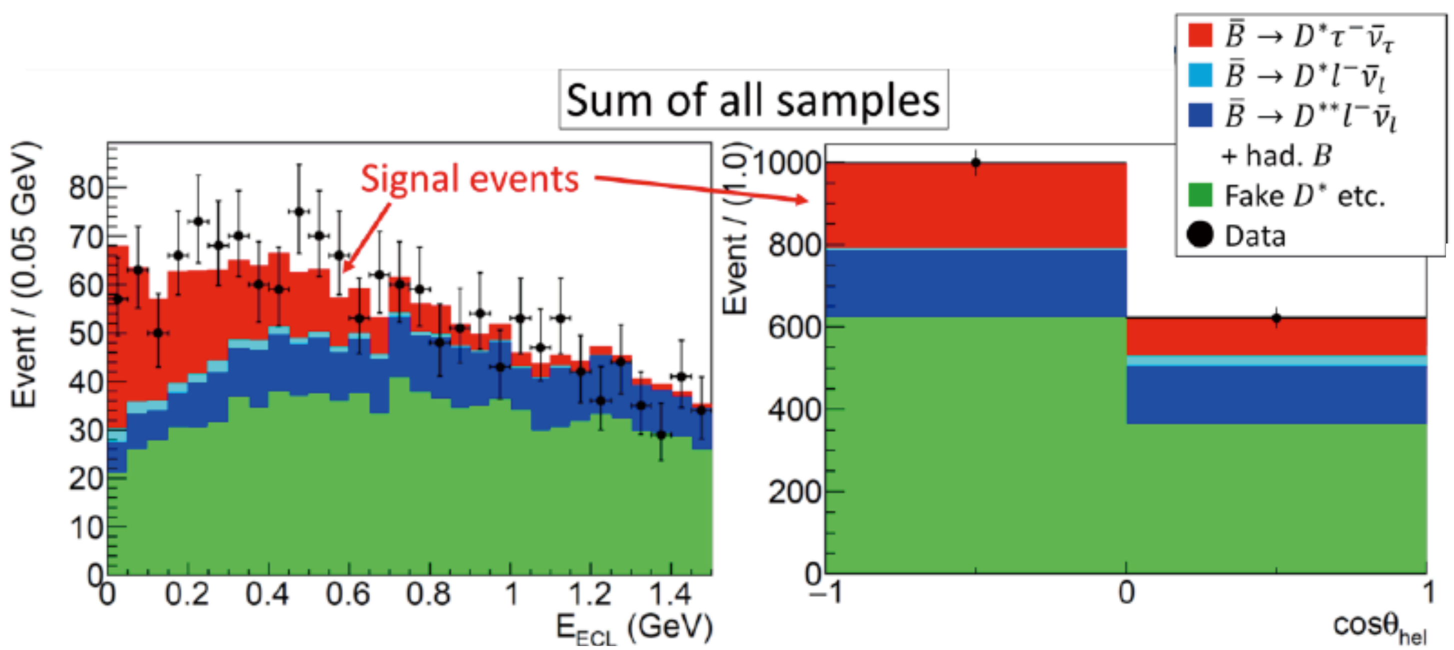
Analysis w/ τ hadronic decays
→ τ polarization

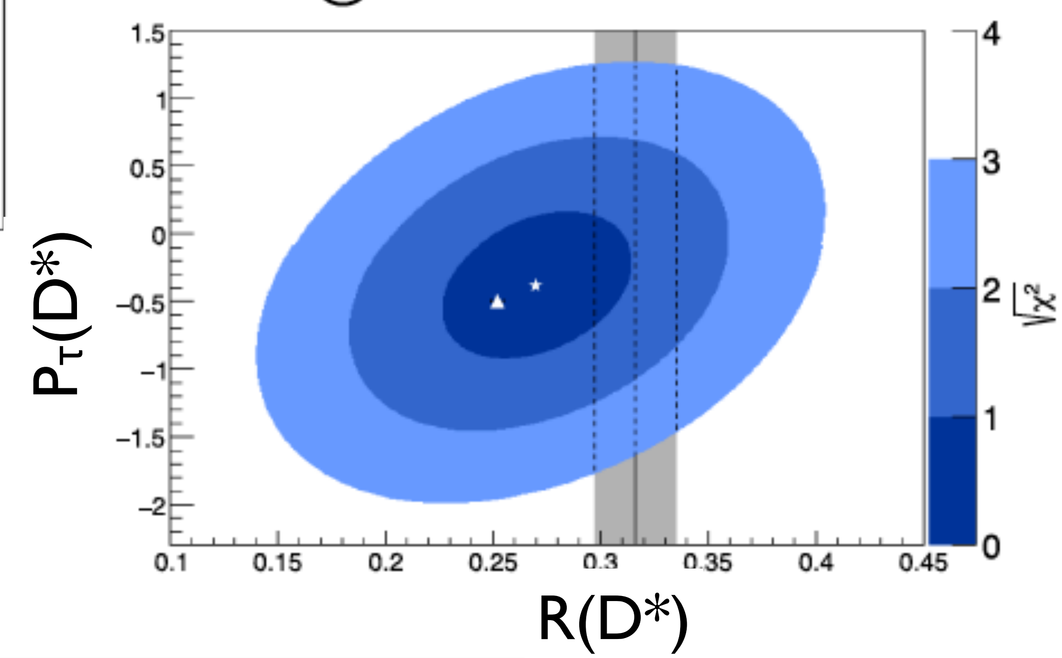
$$\frac{1}{\Gamma(D^{(*)})}\frac{d\Gamma(D^{(*)})}{d\cos\theta_{\rm hel}} = \frac{1}{2}\left[1+\alpha P_\tau(D^{(*)})\cos\theta_{\rm hel}\right]$$

τ→πν : α=1.0 , τ→ρν : α=0.449

$$P_\tau(D^*) = \frac{2}{\alpha}\frac{N_{\rm sig}(\cos\theta_{\rm hel}>0) - N_{\rm sig}(\cos\theta_{\rm hel}<0)}{N_{\rm sig}(\cos\theta_{\rm hel}>0) + N_{\rm sig}(\cos\theta_{\rm hel}<0)}$$







$$R(D^*) = 0.270 \pm 0.035(\text{stat.})\,^{+0.028}_{-0.025}(\text{syst.})$$
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat.})\,^{+0.21}_{-0.16}(\text{syst.})$$

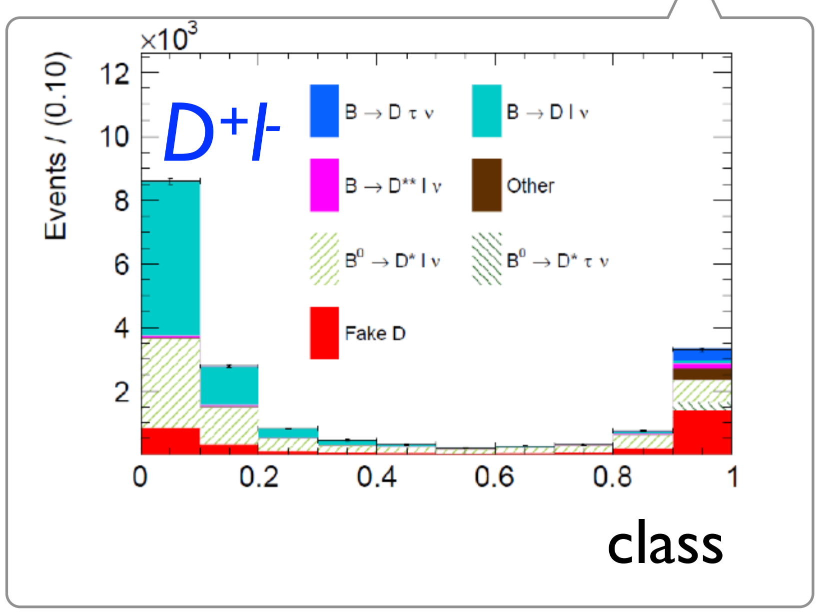
The first measurement of $P_\tau(D^*)$: < +0.5 (90% C.L.)

B → D(*) τ ν w/ τ→lνν & s.l. tag

- More background due to additional ν
  - Signal/normalization modes are separated by $\cos\theta_{B\text{-}D^{*}l}$
- Belle 2019 analysis is featured by;
  - Simultaneous extraction of R(D) and R(D*)
  - Both B^0 and B^+
  - Analysis with the Belle II framework with FEI (Full Event Interpretation, multivariate analysis with the BDT classifier) to improve the efficiency.

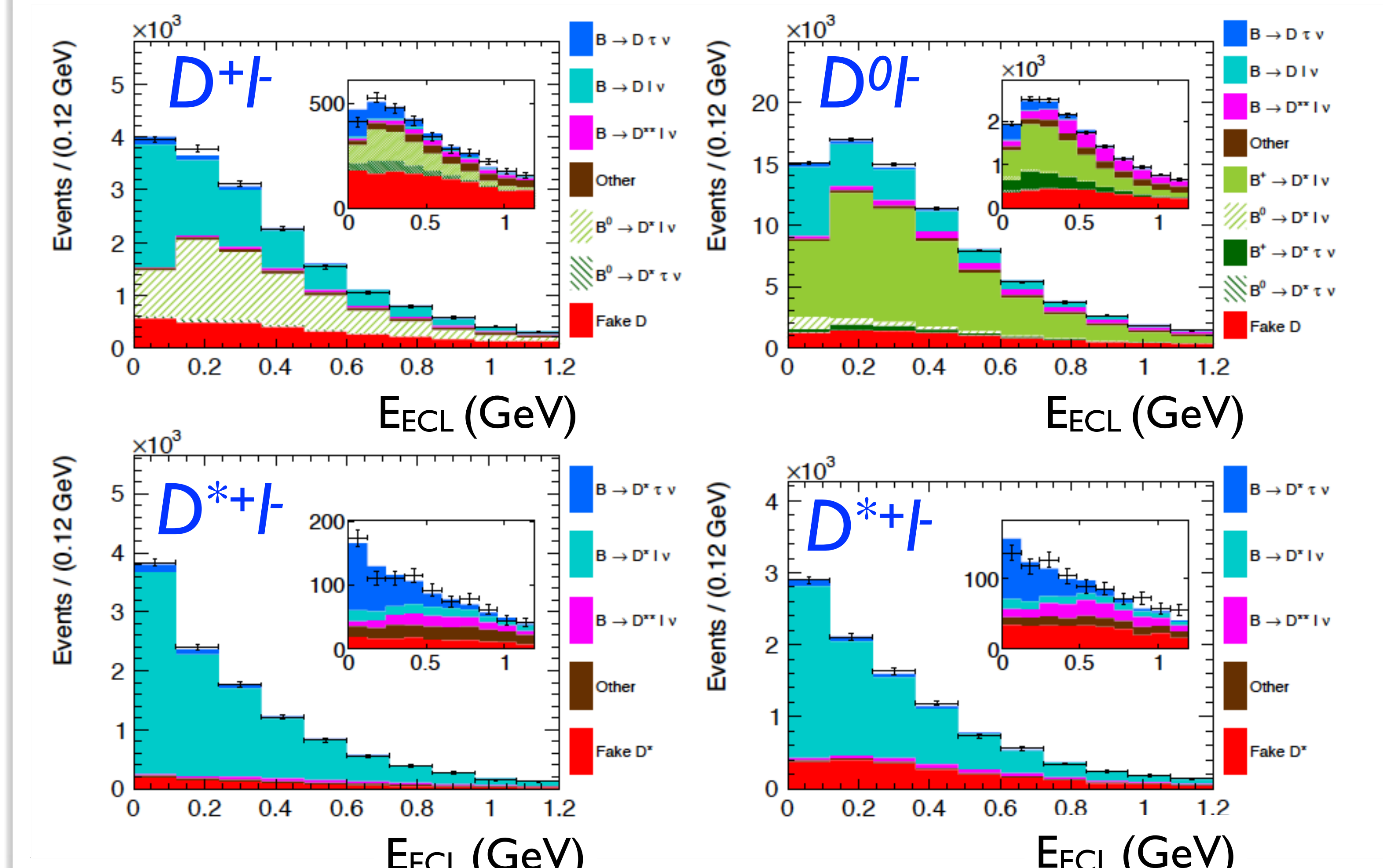
Belle 2019
PRL124, 161803 (2020)
arXiv: 1910.058642

$$\cos\theta_{B,D^{(*)}\ell} \equiv \frac{2E_{\rm beam}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|p_B||p_{D^{(*)}\ell}|}$$

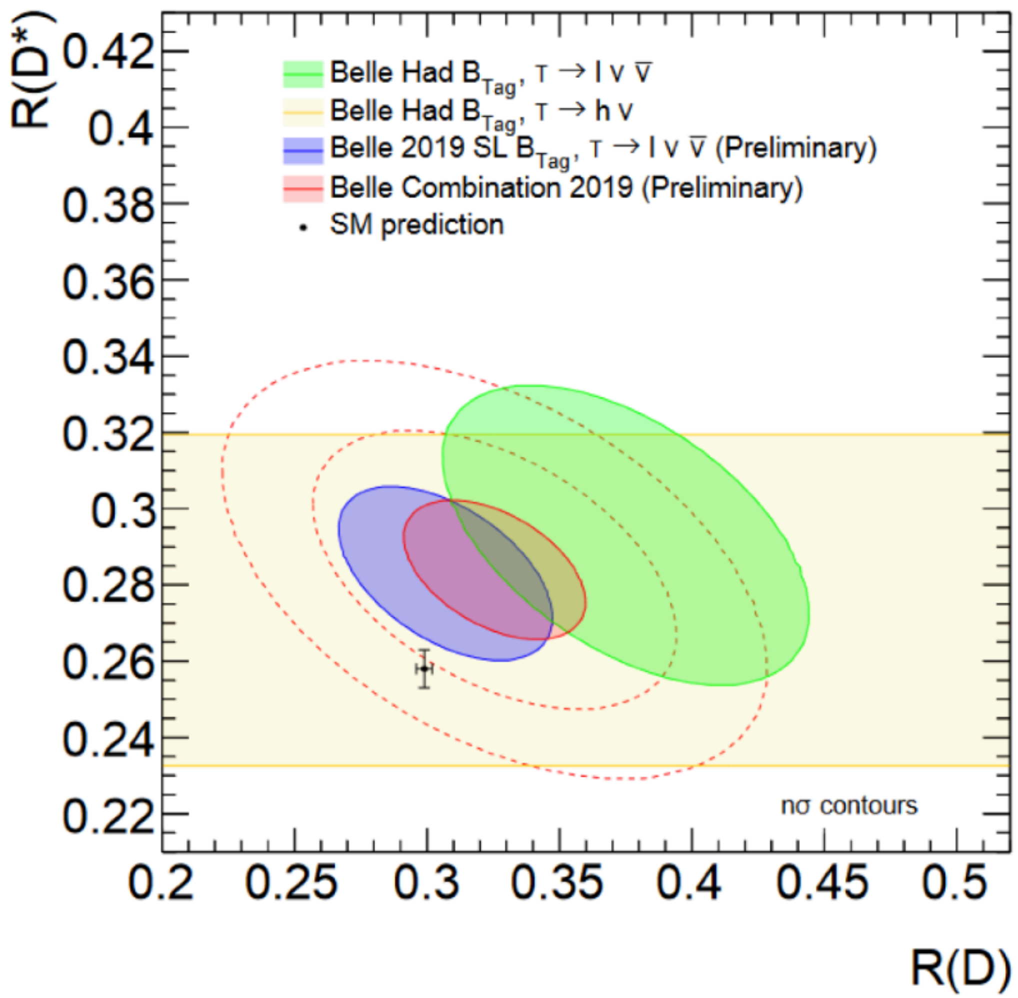


$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

insets: distributions for class>0.9



$B \to D^{(*)} \tau \nu$ by Belle



R(D) = 0.325 ± 0.034

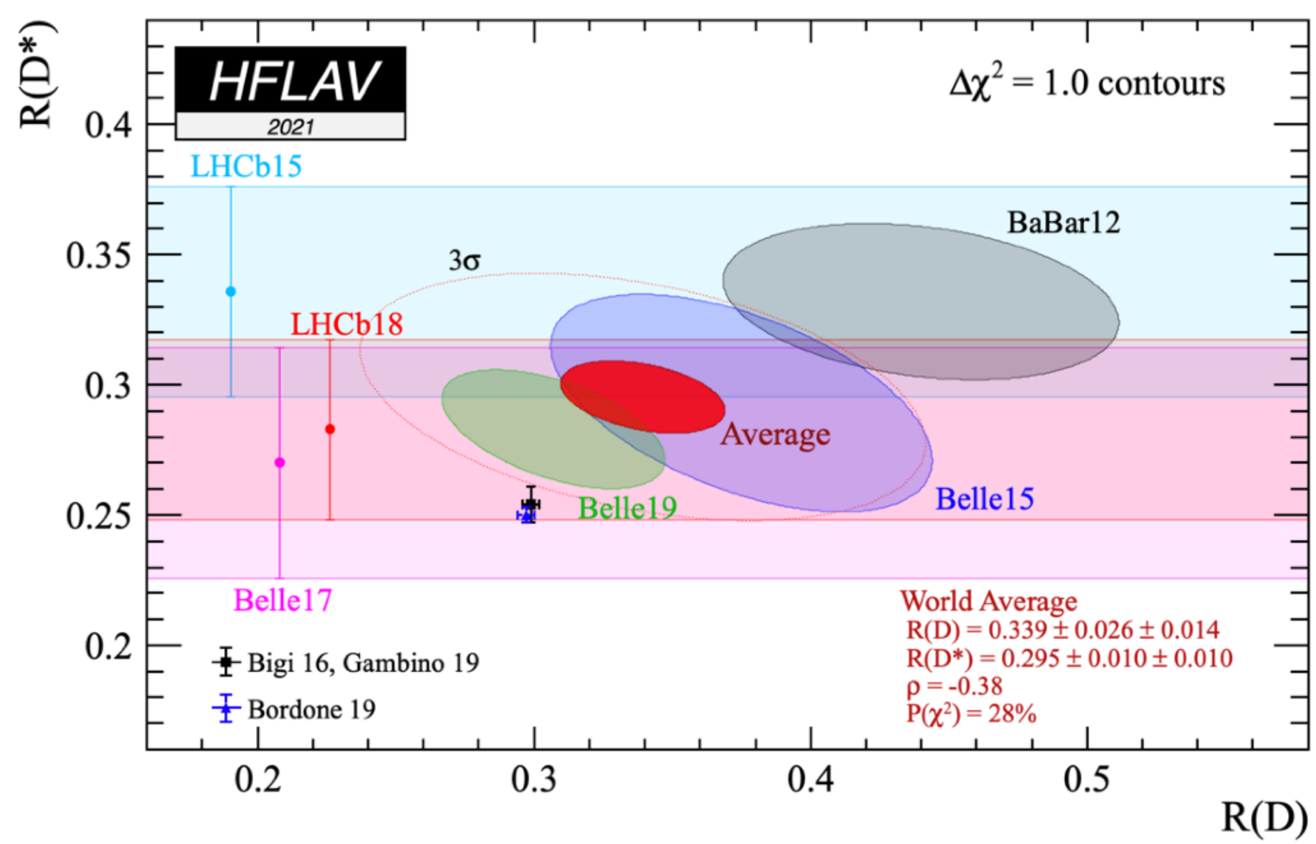
R(D) = 0.283 ± 0.018*

Consistent with SM within 1.6σ

World average (HFLAV)

R(D) = 0.339 ± 0.026 ± 0.014

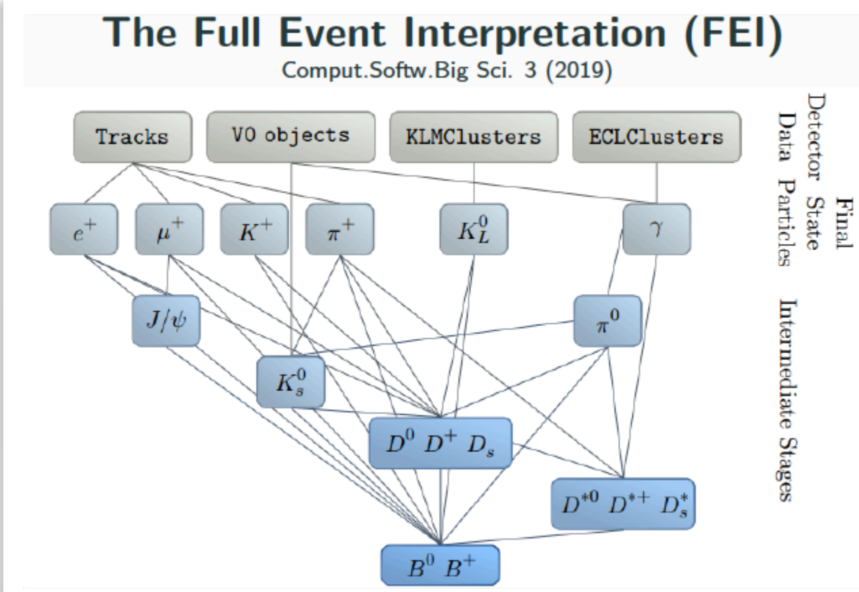
R(D) = 0.295 ± 0.010 ± 0.010*



Prospects for $B \to D^{(*)} \tau \nu$ at Belle II

- Statistical error will be further reduced by luminosity and also by improved tagging with the FEI (Full Event Interpretation) algorithm with Fast BDT and more decay modes.

- Reduction of systematic errors become more important.



Composition of the systematic uncertainties in each Belle analysis

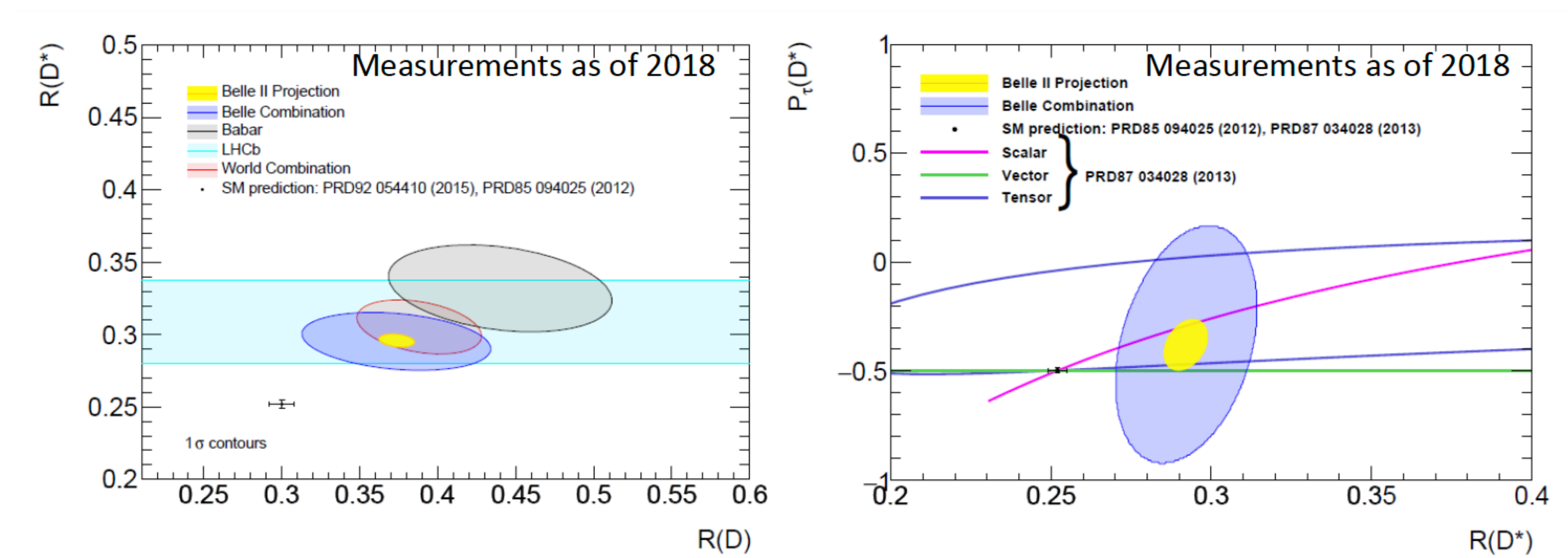
Source	Belle (Had, ℓ^-) R_D	Belle (Had, ℓ^-) R_{D^*}	Belle (SL, ℓ^-) R_{D^*}	Belle (Had, h^-) R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}$%
$B \to D^{**} \ell \nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}$%	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}$%
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}$%	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

"The Belle II Physics Book", arXiv:1808.10567

Prog. Theor. Exp. Phys. 2019, 123C01

- The uncertainty due to the MC statistics is reducible.
  - MC stat affects the estimation of the reconstruction efficiency, understanding of small cross-feed components and PDFs for the fit.
- The uncertainties from Br(B→D**lv) decays and hadronic B decays have to be reduced by dedicated measurements of the background decays.

Prospects for B → $D^{(*)}$ τ ν at Belle II



Expected precision (stat and syst)

	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

In addition, q^2 and other distributions of kinematic observables to discriminate the new physics scenarios.

"The Belle II Physics Book", arXiv:1808.10567
Prog. Theor. Exp. Phys. 2019, 123C01

Belle II will lead the exploration of $R(D^{(*)})$ in the next decade

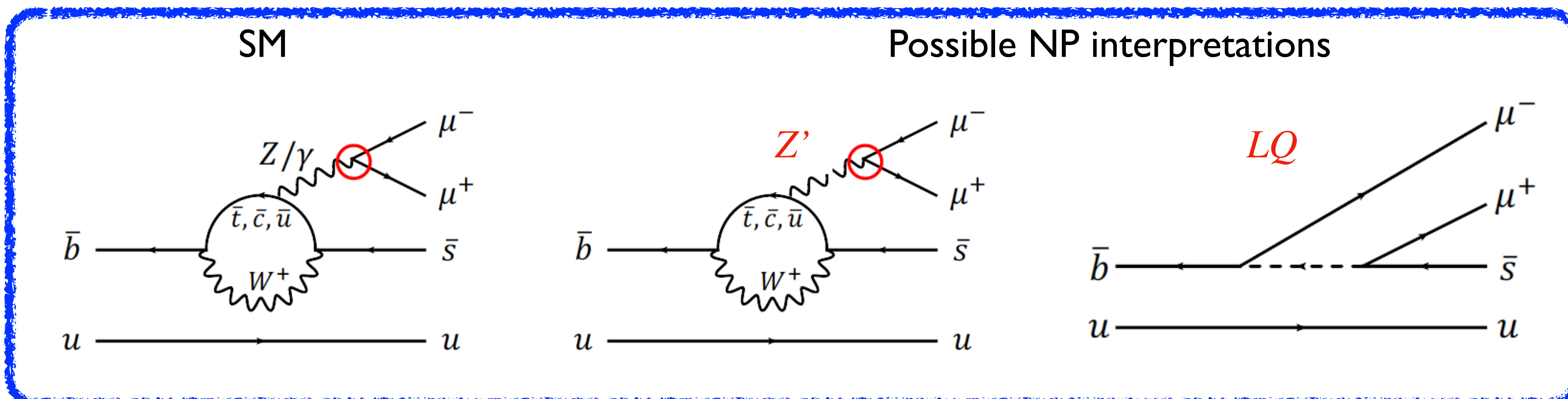
LFUV in $b \to s\, l^+ l^-$

- In SM, the coupling constants of each generation leptons with Z/γ are identical (Lepton Flavor Universality). i.e.,

$$\to R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \approx 1(SM)$$

with very high accuracy

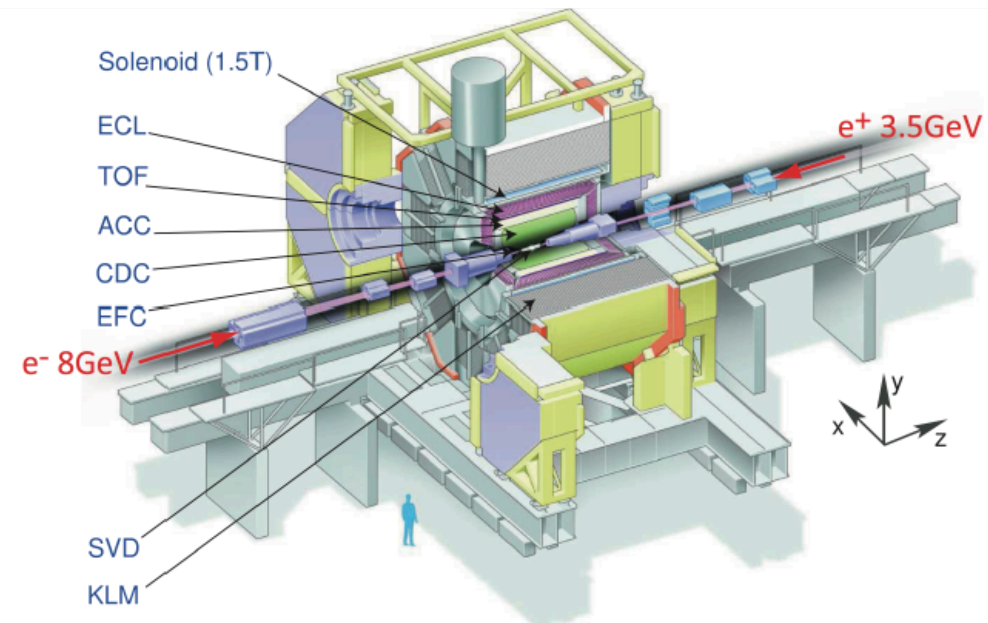
- LHCb has reported anomalies in $B^+ \to K^+ l^+ l^-$, $B^0 \to K^{*0} l^+ l^-$, and more recently $B^0 \to K_S^0 l^+ l^-$, $B^+ \to K^{*+} l^+ l^-$, all indicating R<1.
    - Also in $\Lambda_b \to pK l^+ l^-$
    - Angular observables (P5') in $K^* l^+ l^-$ also deviates from SM, although it suffers from hadronic uncertainties.



R_{K^*} measurements at Belle

PRL126, 161801 (2021)
arXiv:1904.02440

- 711fb^{-1} (772x10^6 $B\bar{B}$) collected by Belle detector.
- Reconstruct 4 decay modes:
  - $B^+ \to K^{*+}(\to K^+\pi^0, K_S^0\pi^+)\ell^+\ell^-$
  - $B^0 \to K^{*0}(\to K^+\pi^-, K_S^0\pi^0)\ell^+\ell^-$
- Results in several q^2 bin options, including high q^2 region (up to 19 GeV^2/c^4).

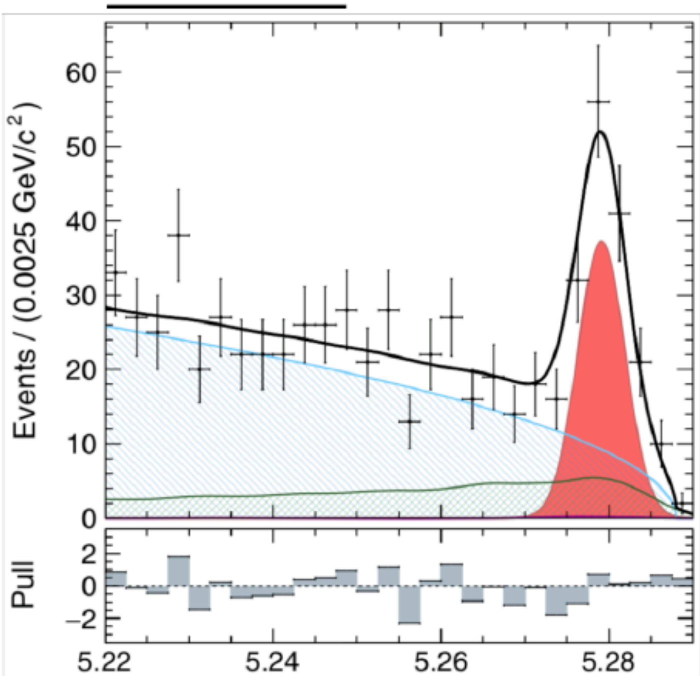


B factory observables

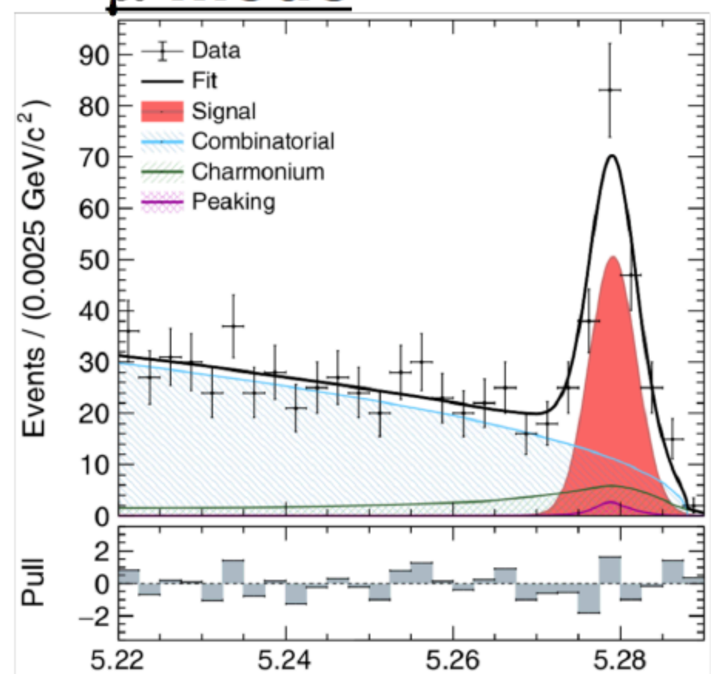
- $M_{bc} \equiv \sqrt{E_{beam}^2 - \left|\vec{p}_B\right|^2}$
- $\Delta E \equiv E_B - E_{beam}$

e mode can be measured as clean as μ mode.

e mode



μ mode

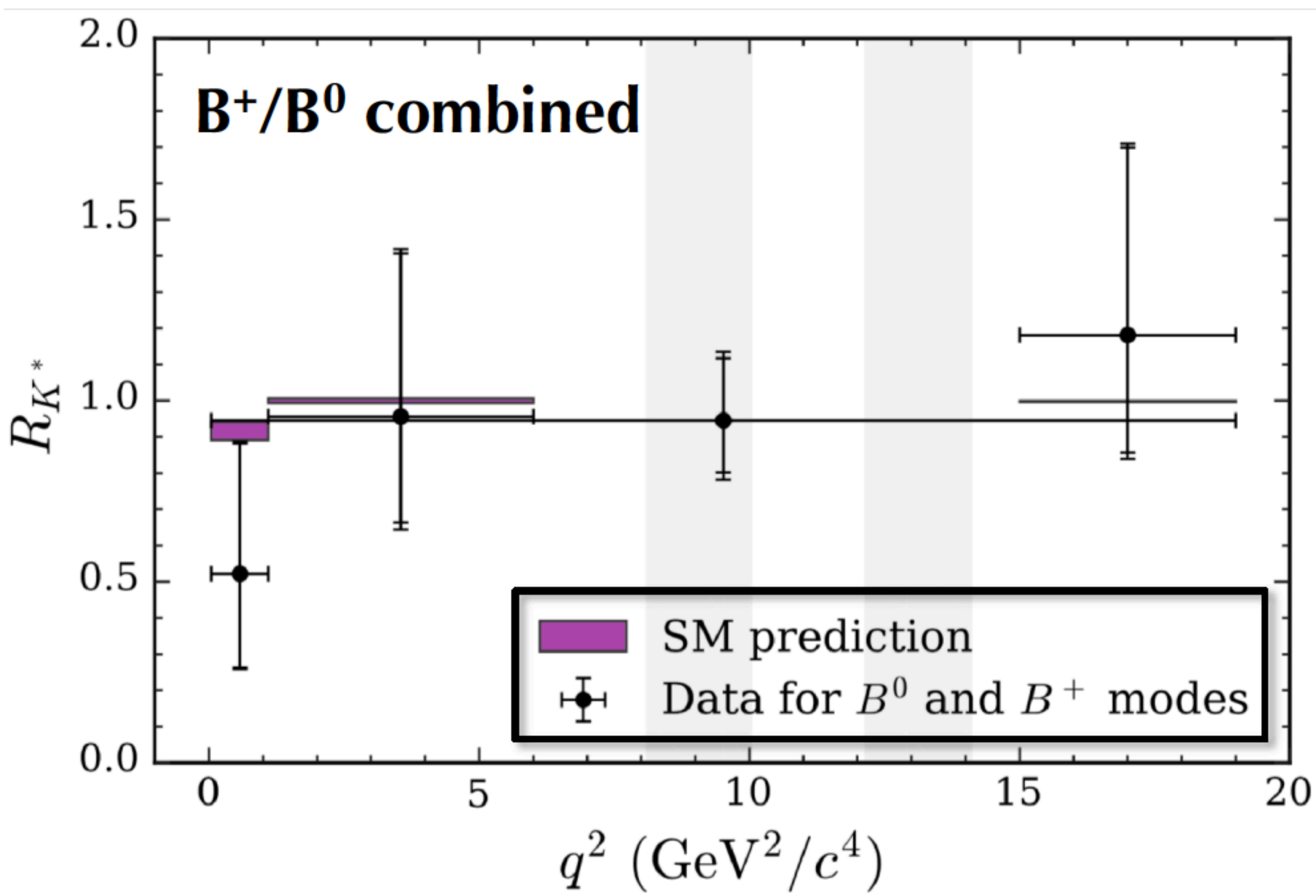


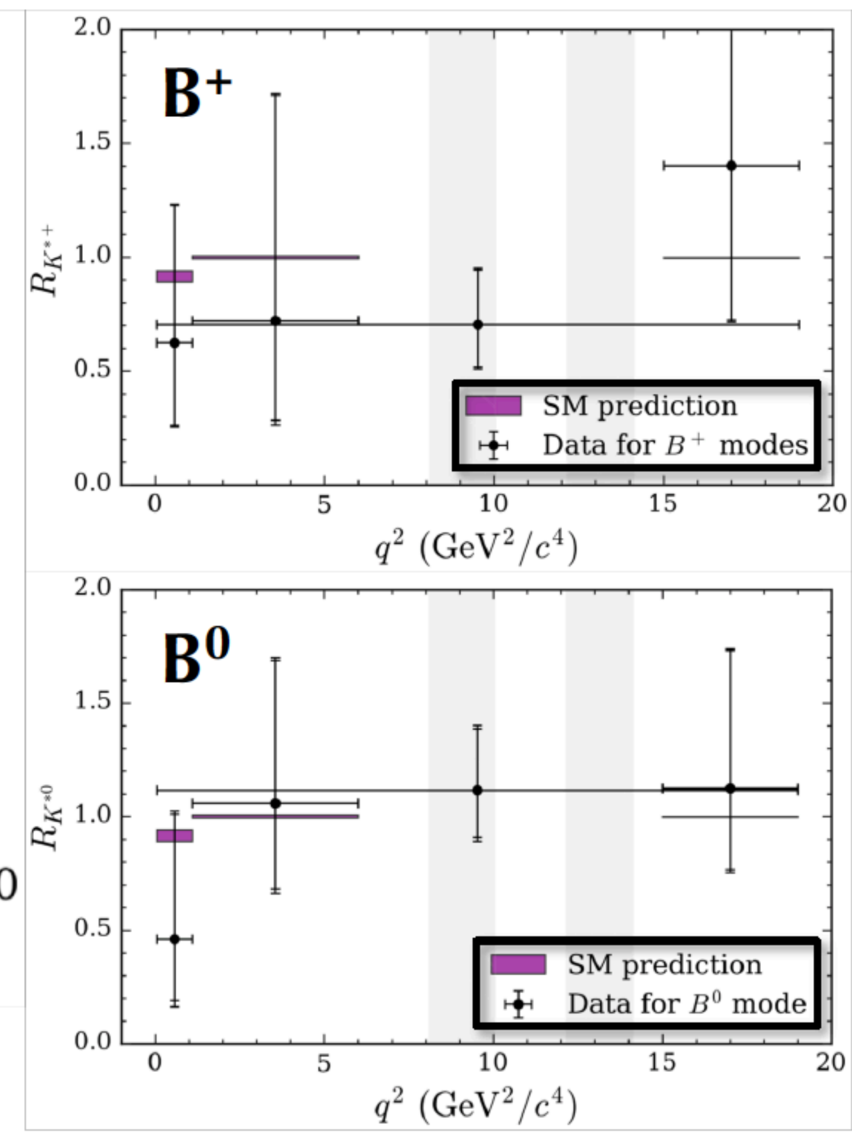
M_{bc} (GeV/c^2) M_{bc} (GeV/c^2)

B$^+$/B^0 combined

$R_K{}^*$ results from Belle

PRL126, 161801 (2021)
arXiv:1904.02440



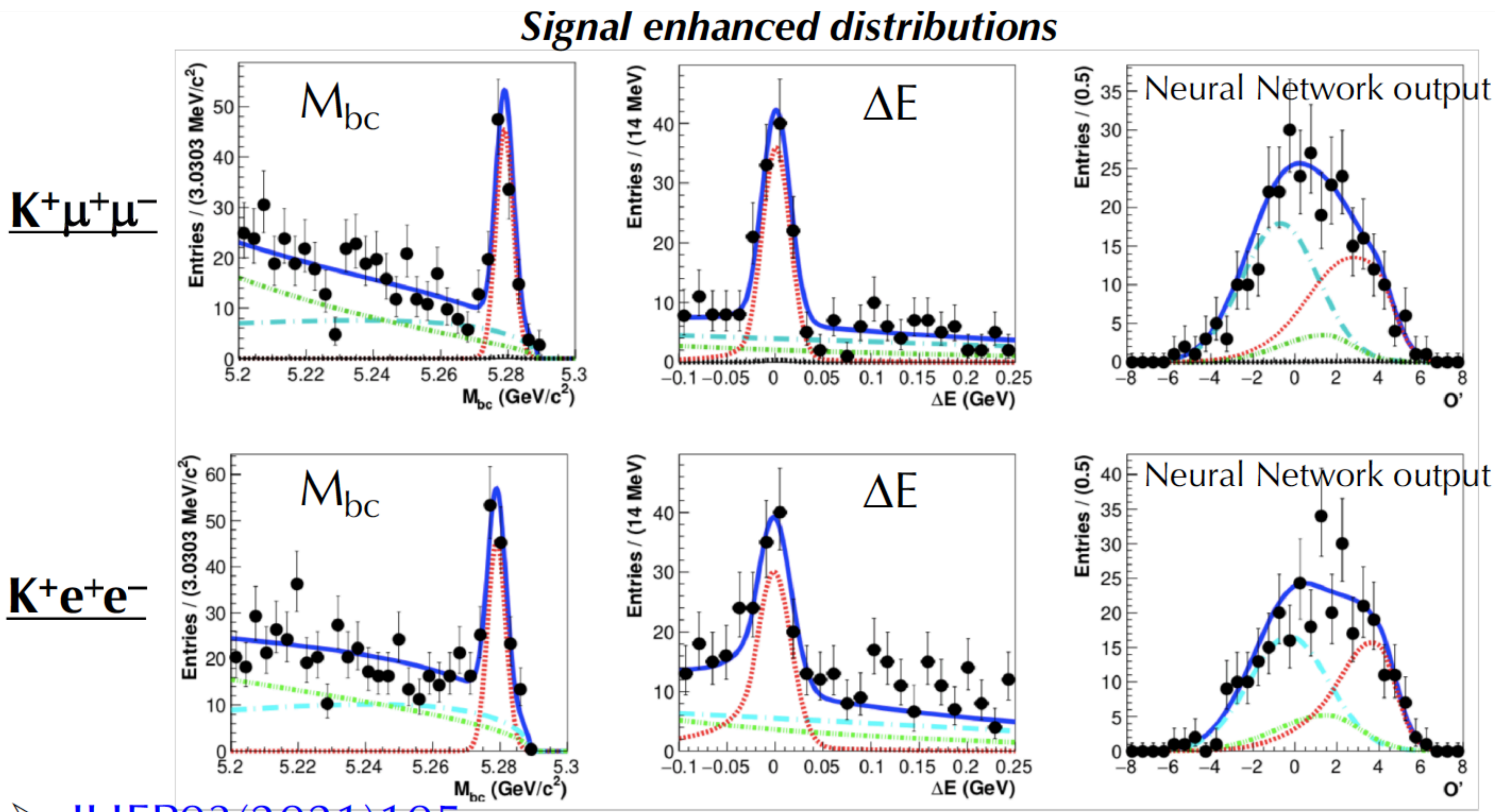


q^2 (GeV^2/c^4)	Comb. (B^0/B^+)
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$
[0.045, 19]	$\mathbf{0.94}^{+0.17}_{-0.14} \pm 0.08$

- R_{K^*} measured in Belle is **all consistent with SM**.
  - The largest deviation is in the lowest q^2 bin. (same as LHCb)
- This is the first result for $R_{K^{*+}}$ measurement.

R_K measurements at Belle

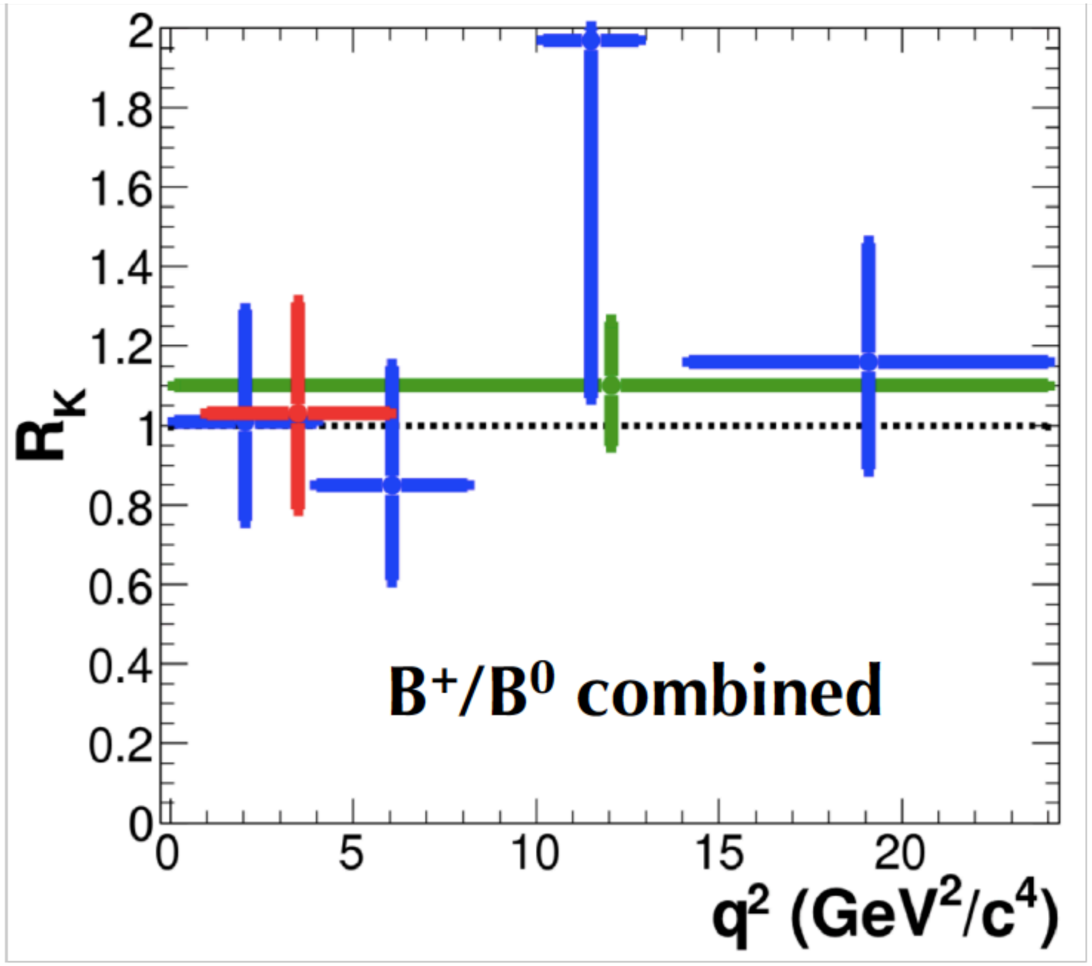
JHEP 2103, 105 (2021)
arXiv:1908.01848

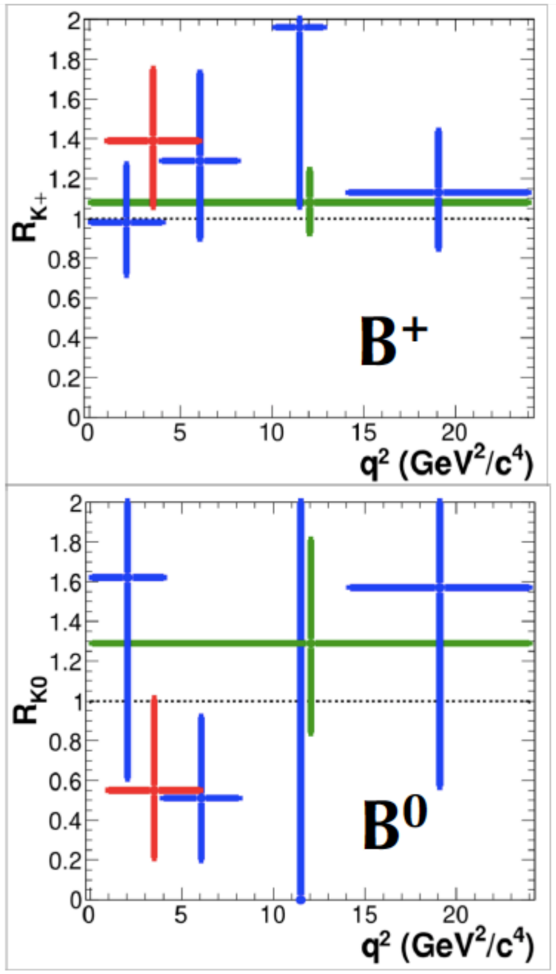


- JHEP03(2021)105
- 711fb^{-1} (772x10^6 $B\bar{B}$) collected by Belle detector.
- Both R_{K^+} and $R_{K_S^0}$ are measured.
- 3D fitting with M_{bc}, ΔE, and modified Neural Net output.

R_K results from Belle

JHEP 2103, 105 (2021)
arXiv:1908.01848



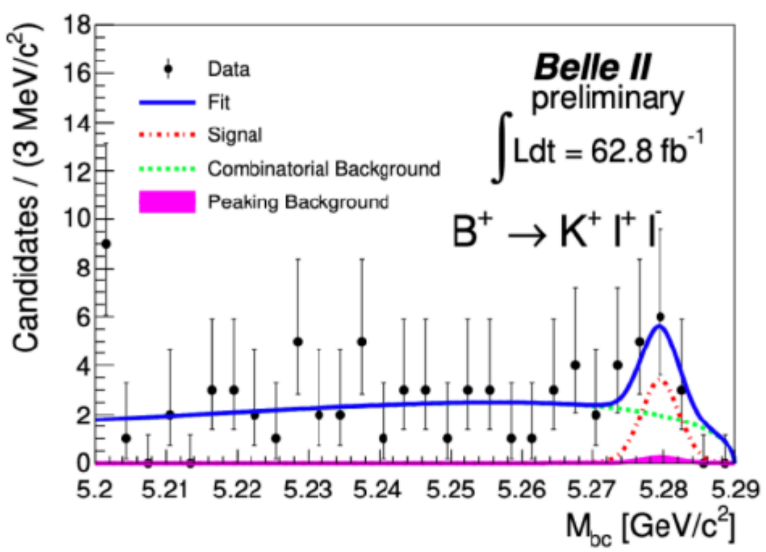


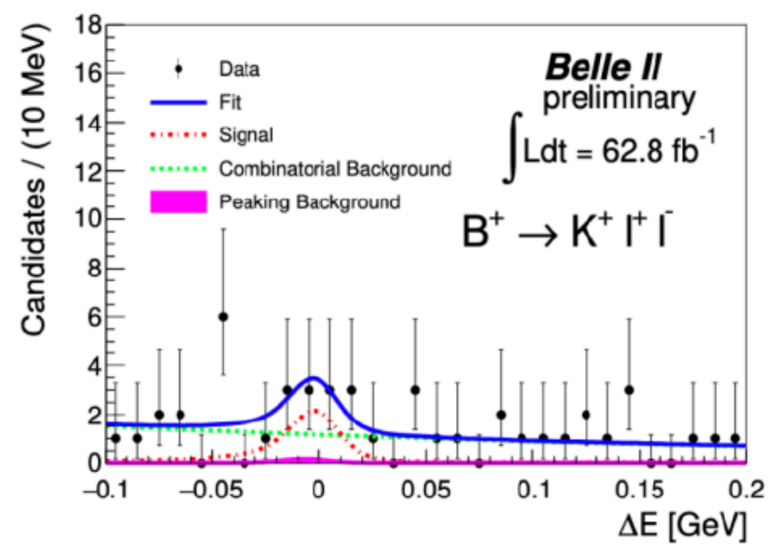
q^2 (GeV^2/c^4)	Comb. (B^0/B^+)
[1.0, 6.0]	$1.03^{+0.28}_{-0.24} \pm 0.01$
whole q^2	$1.10^{+0.16}_{-0.15} \pm 0.02$

- R_K measured in Belle is **all consistent with SM**.
- The red bin is corresponding to the same range as the study at LHCb.

Progress in Belle II

- Exclusive: preliminary measurements using Belle II early data (62.8 fb^{-1})





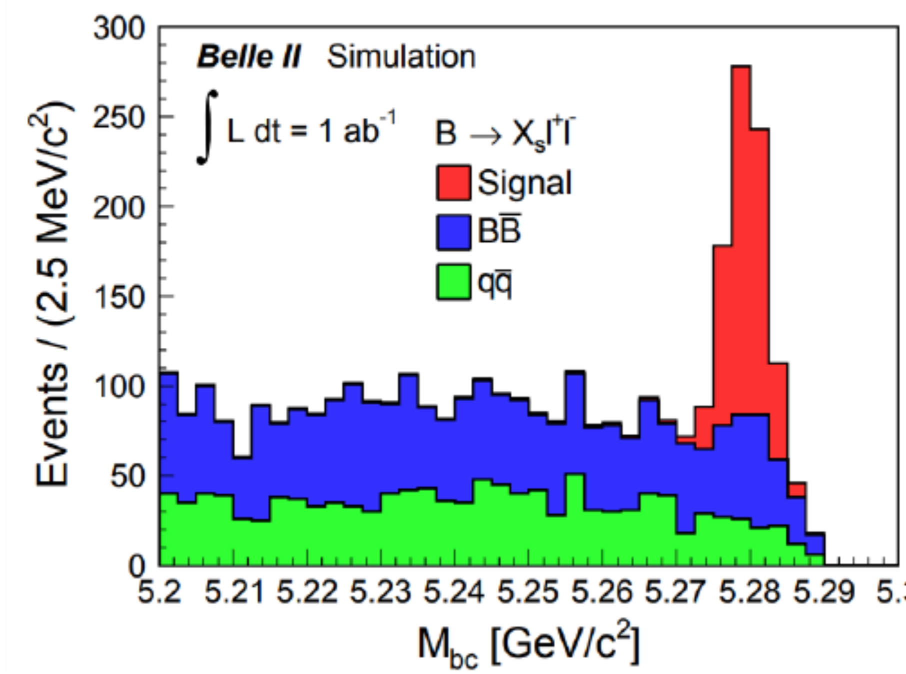
$Ns = 9.6^{+4.3}_{-3.9} \pm 0.4$

(2.7σ significance)

Not sufficient to extract key observables

- Inclusive: $B \to X_s l^+ l^-$ simulation
  - Complementary to B→K(*)l+l- with different hadronic uncertainties
  - Two methods explored:
    - Sum of exclusive modes
    - Fully inclusive using tagging

$X_s \to K n\pi$, $n \leq 4$ and $X_s \to 3K$



arXiv: 2012.15394

Prospects for R_{K,K^*,X_s} at Belle II

- Clean e^+e^- environment make easier;
  - Bremsstrahlung energy recovery for electrons
  - Measurements in the high q^2 region
  - Inclusive measurements (R_{X_s})
- Still statistics limited at $50ab^{-1}$
  - Primary systematic error comes from lepton ID (~0.4%)

Belle II data with >5/ab will be complementary and essential to check the presence of the effect claimed by LHCb

- Discovery sensitivity
  - ~$10ab^{-1}$ for $R_K + R_{K^*}$ combined
  - ~$20ab^{-1}$ for RXs
  - Then correlation between R_{K,K^*,X_s} as well as other observables (angular distributions etc.)

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

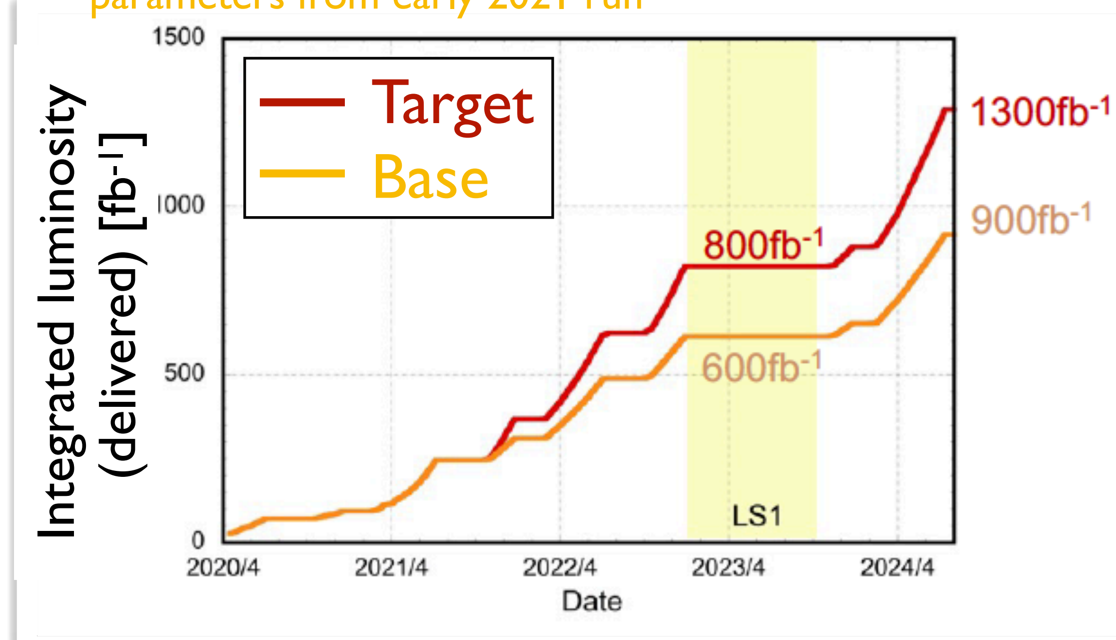
Prog. Theor. Exp. Phys. 2019, 123C01

Summary

- The deviations found in the LFU observables, R_{D, D^*}, R_{K,K^*}, need be clarified with higher accuracy. If confirmed, they could be clues for New Physics.
- The results for R_{D, D^*}, R_{K, K^*} from Belle are consistent with SM within the present errors.
- Belle II will be able to provide results with higher accuracies
  - Systematics different from measurements at LHC.
  - More information from other observables, distributions, also in inclusive measurements.
- Plan/prospect of the SuperKEKB/Belle II
  - L ~ Belle by long shutdown 1 (LS1), currently scheduled from January 2023, → many world-leading physics results.
  - Reach 50ab^{-1} goal by ~2031 after modification of SuperKEKB/Belle II components in LS2 (around 2026).

Target scenario: extrapolation from early 2021 run including expected improvements

Base scenario: conservative extrapolation of SuperKEKB parameters from early 2021 run



If SuperKEKB performance indicates that insufficient integrated luminosity will be collected before LS1 or COVID-19 travel restrictions persist, the option exists to postpone the start of LS1 to July 2023

Stay Tuned !

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