$B \to X_s\, \gamma$ and other beyond-SM search program at Belle II

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outline

- B factories in Japan – aparatus and physics analysis strategy

- Last Belle (II) results and potentials for beyond SM physics

  - Radiative pinguins

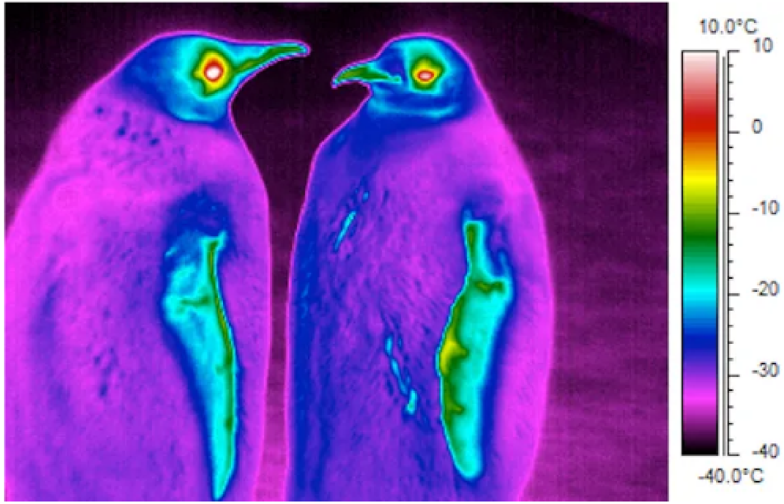
    $B \rightarrow X_s \gamma$

    $B \rightarrow K_s K_s \gamma$

  - Electroweek penguins

    $B \rightarrow K^{(*)} \ell\ell$

    $B \rightarrow K \nu\bar{\nu}$



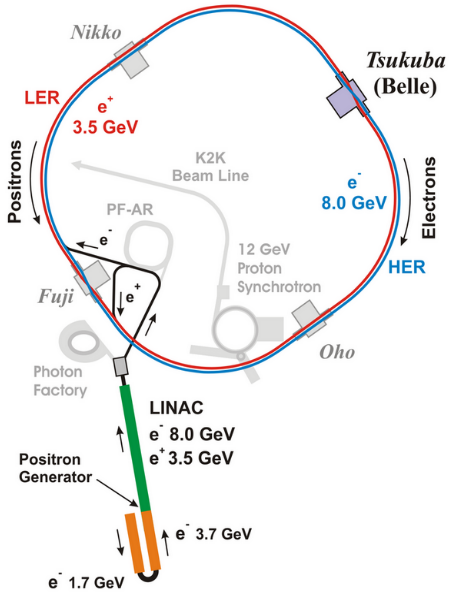
Biol. Lett.9:20121192

e^+ e^- colliders in Japan: KEKB → SuperKEKB

Asymmetric e^+e^- collider with center-of-mass (CM) energy at $B\bar{B}$ threshold, 10.58 GeV.

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

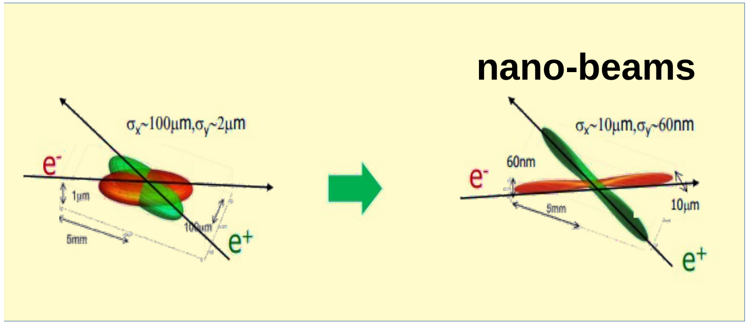
KEKB



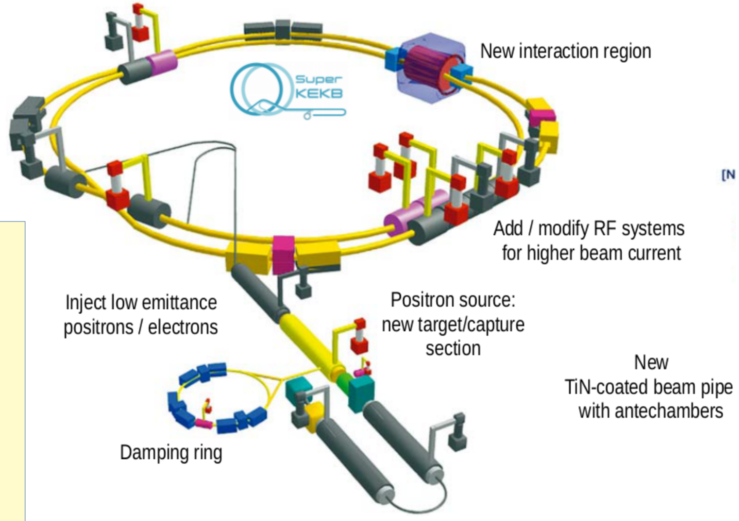
1999 - 2010

Max. instantaneous luminosity:

$2.1 \times 10^{34}\ \mathrm{cm}^{-2} s^{-1}$

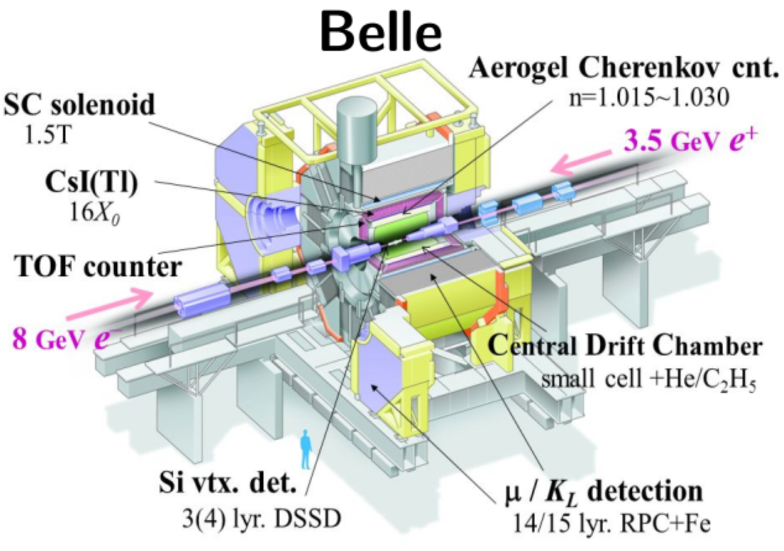


SuperKEKB



- Aims to collect 50 ab^{-1} (50 × Belle) of data sample.
- Plan to deliver collision at a peak luminosity of $6.5 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (30 times that of KEKB)
  Current record instantaneous luminosity:
  $4.7 \times 10^{34}\ \mathrm{cm}^{-2} s^{-1}$

Belle and Belle II detectors

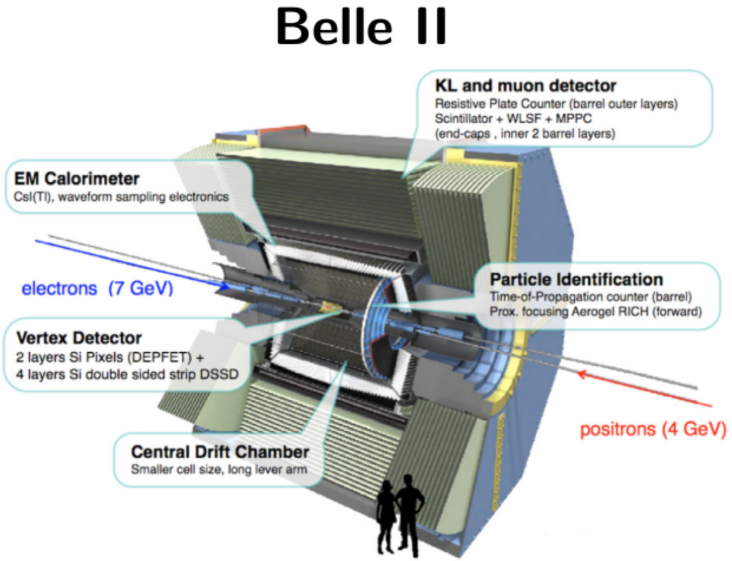


Largest integrated luminosity collected by a B factory:

- 711 fb^{-1} on $\Upsilon(4S)$ mass
- ≈ 100 fb^{-1} below $\Upsilon(4S)$ mass

- improved vertex resolution ($2\times$ Belle) and K^0_S reconstruction efficiency
- enhanced K/π separation
- new trigger lines for dark sector searches
- more efficient reconstruction and analysis tools

Can be also used to analyse Belle data (B2BII)



Goal: total integrated luminosity 50 ab^{-1}

- Currently in a 1 year operational pause
- 363 fb^{-1} on $\Upsilon(4S)$ mass
- 42 fb^{-1} below $\Upsilon(4S)$ mass

Measurement strategies at B factories

Two *B* mesons are produced via Y(4S) resonance without additional particles:

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ → large *B* samples available

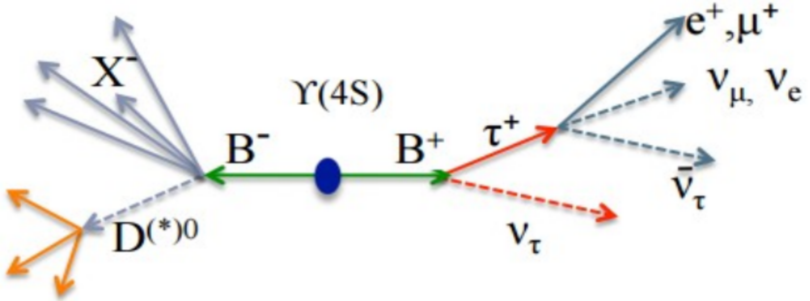
Many interesting analysis of *B* mesons include

- inclusive measurements
- neutrinos are present in the final state

} missing kinematic information!

→ **Tagging approach**

Reconstruction of one *B* meson (B_{tag}) constrains the 4-momentum and flavour of the other (B_{sig})



hadronic tagging: B_{tag} is fully reconstructed in numerous hadronic decays
semileptonic tagging: B_{tag} is partially reconstructed in semileptonic decays

→ **Higher signal purity but less efficiency**

Inclusive tagging: B_{tag} is identified inclusively from remaining signatures after signal reconstruction

Other B factory advanteges

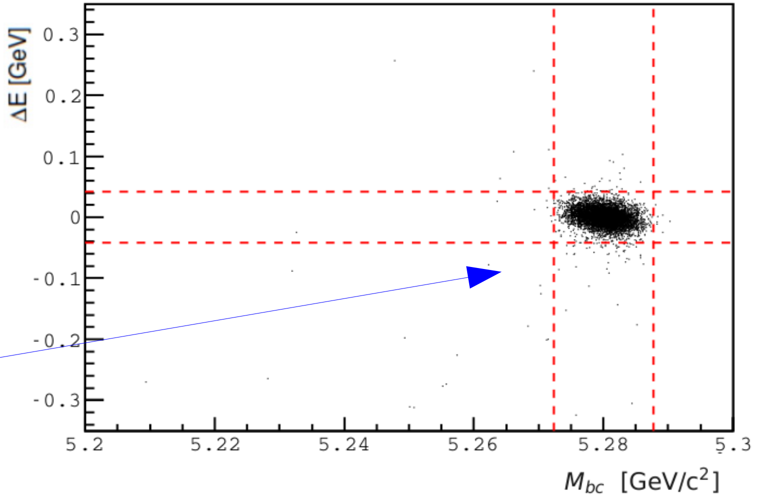
- Clear experimental environment – low background and thus easier reconstruction of decays with γ, π^0, ρ, η, η'.

- low track multiplicities and detector occupancy give:
  - high B, D, τ and quarkonia reconstruction efficiency
  - low trigger bias

  ↳ corrections and systematic uncertainties are substantially reduced in many types of measurements, e.g. Dalitz plot analyses, dark sector searches...

- known energy of the beams allows to use specific kinematic variables for *B* meson selection:

beam-constrained mass	energy difference
$M_{\rm bc} = \sqrt{(\frac{\sqrt{s}}{2})^2 - (p_B^*)^2}$	$\Delta E = E_B^* - \frac{\sqrt{s}}{2}$



$\sqrt{s}$ - beams' energy in CM frame

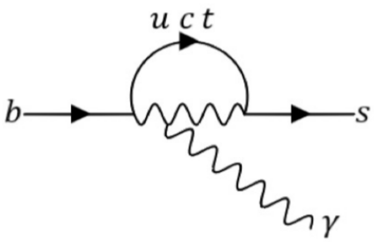
p_B^* / E_B^* - reconstructed momentum/energy of the *B*

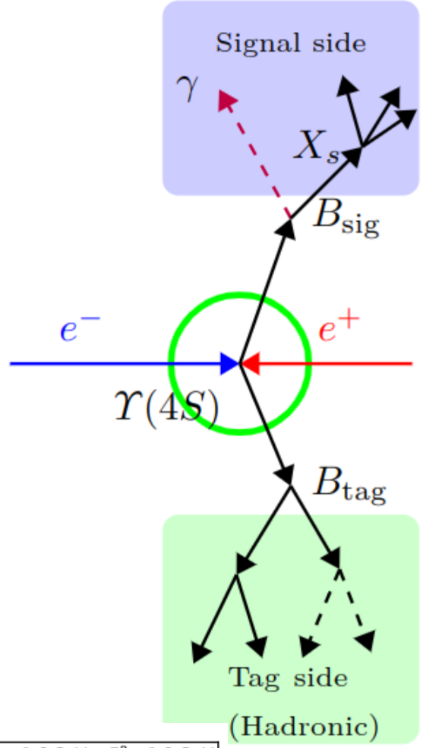
$B \to X_s \gamma$ with hadronic tagging

arXiv:2210.10220v1

FCNC $b \to s\gamma$ transition - Sensitivity for New Physics

→ The new charged Higgs boson (THDM model) would enter in the leading-order FCNC loop





- Insight into b-quark mass & its motion inside *B* meson by E_γ measurement

First radiative decay studied by Belle II

Tagging B meson reconstructed in **hadronic modes** (high purity)

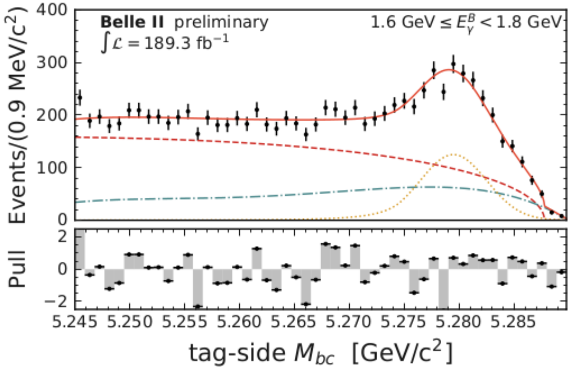
From **signal B meson** only photon is reconstructed

→ photon energy in *B* rest frame (E_γ^B) is measured

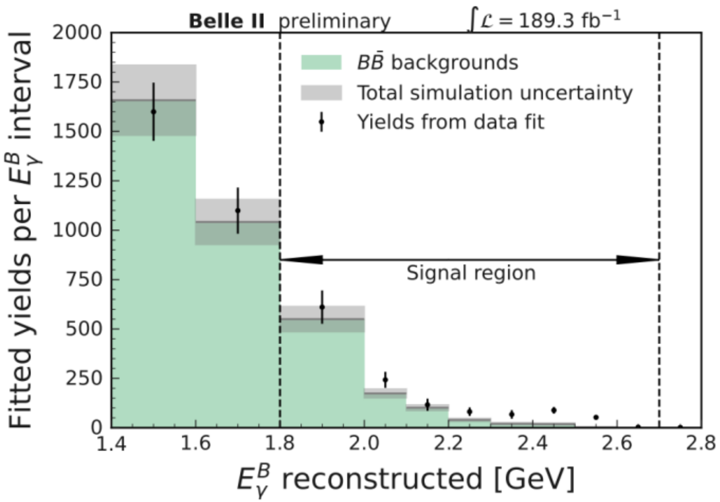
→ signal photon: highest-E photon with E_γ^B > 1.4 GeV

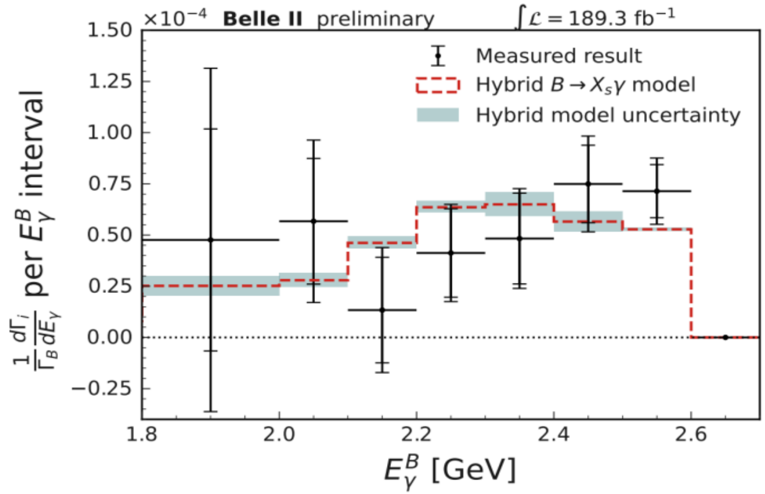
- challenging background suppression to keep "inclusiveness"

- Tag-side background suppression → M_{bc} fits in bins of E_γ^B to extract correctly tagged event counts



$B \to X_s \gamma$ with hadronic tagging





E_γ^B threshold, GeV	Branching fraction (10^{-4})
1.8	$3.54 \pm 0.78\,(\text{stat.}) \pm 0.83\,(\text{syst.})$
2.0	$3.06 \pm 0.56\,(\text{stat.}) \pm 0.47\,(\text{syst.})$

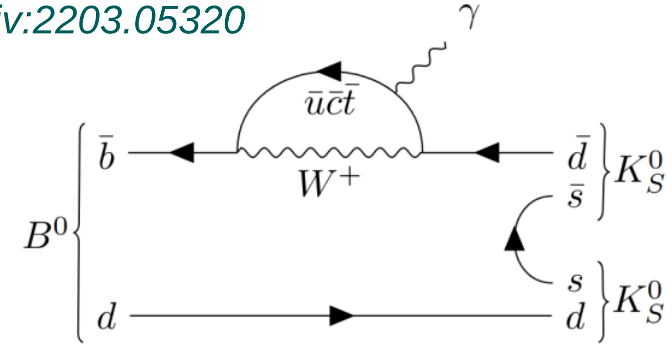
Largest systematic effects due to:
- simulation mismodelings
- bkg normalization data-simulation discrepancy

❖ **Consistent with world average**: $(3.49 \pm 0.19) \times 10^{-4}$ @ 1.8 GeV [PDG]

❖ Comparable precision to BaBar hadronic-tag measurement with 210 fb^{-1}

$B^0 \to K_S^0 K_S^0 \gamma$

arXiv:2203.05320

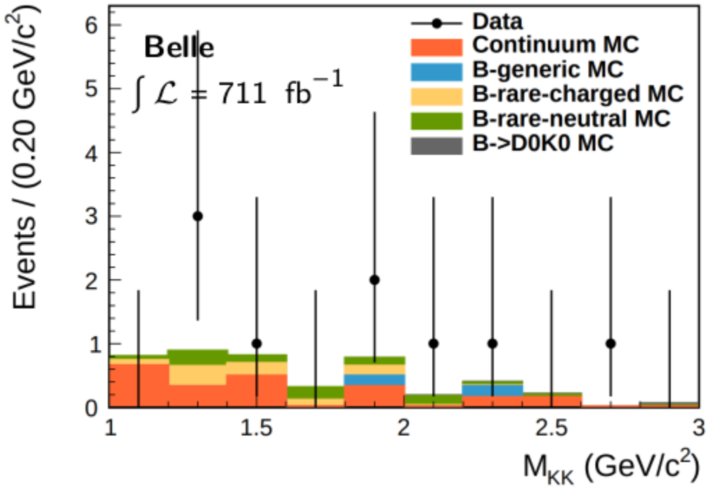


- Radiative **b** → **dγ** transition, with additional $s\bar{s}$ pair creation
  → senstitive to New Physics (e.g. 2HDM)
  → challenging mode, not measured before!
- $K_S K_S$ system must have an even spin (Bose Einstein statistic), J≠0, J=2 allowed
  → can occur via intermediate **tensor** states
- K_S selection and suppression of dominant $e^+ e \to q\bar{q}$ background
  → utilization of **neural network**

Signal efficiency estimated in 10 bins of $M_{KK} \in (1.0, 3.0)$ GeV/c² by performing M_{bc} fits to signal MC sample

→ average efficiency of all bins: (2.5 ± 0.4)%

number of events observed in the full data sample and the estimated background events in each M_{KK} bin



$B^0 \to K_S^0 K_S^0 \gamma$

arXiv:2203.05320

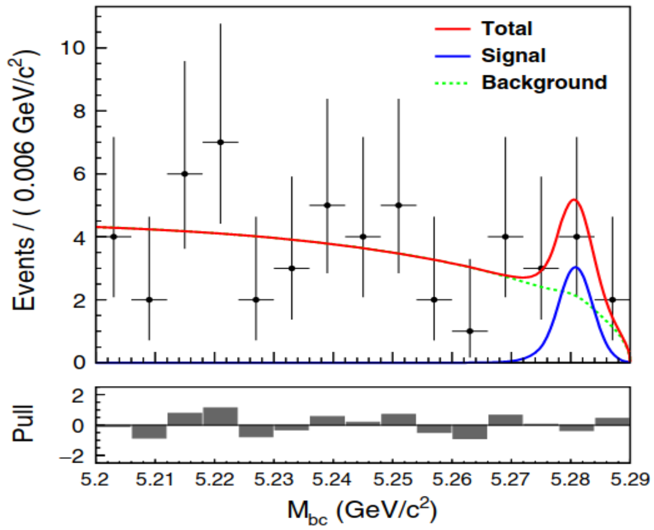
Calculated partial branching fractions in M_{KK} bins

M_{KK} GeV/c^2	Partial BF upper limit at 90% CL (10^{-7})
1.0 − 1.2	0.7
1.2 − 1.4	2.8
1.4 − 1.6	1.7
1.6 − 1.8	1.1
1.8 − 2.0	2.9
2.0 − 2.2	2.5
2.2 − 2.4	2.4
2.4 − 2.6	1.3
2.6 − 2.8	2.3
2.8 − 3.0	1.2

Extended unbinned ML fit to M_{bc} distribution in ΔE signal region
→ no statisticly significant signal found!

Nsig = 3.8 ± 3.0

Nbgk = 5.6 ± 0.8



Upper limits at the 90% C.L. are set:

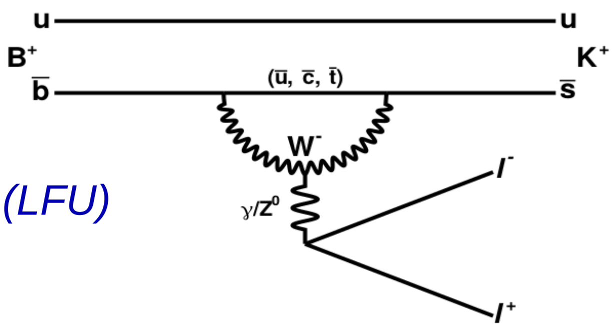
$$\mathcal{B}(B \to K_S^0 K_S^0 \gamma) < 5.8 \times 10^{-7}$$

Branching fraction product	U.L.(10^{-7})
$B^0 \to f_2(1270)(\to K_S^0 K_S^0)\gamma$	3.1
$B^0 \to f_2'(1525)(\to K_S^0 K_S^0)\gamma$	2.1

Prospect for Belle II

$B \to K^* \ell^+ \ell^-$

arXiv:2206.05946



Rare ***b*** → ***s*** loop-level transition – probe to test *Lepton Flavour Universality (LFU)* – hot topic in fundamental physics due to several puzzles

LFU ratio of respective branching fractions:

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

2.1-2.5σ tension with SM on $R_{K^{*0}}$ meausured by LHCb *JHEP 08, 055 (2017)*

Recent, more precise measurement (LHCb):

$R_K = 0.846\,^{+0.044}_{-0.041}$ (3.1σ of deviation from SM) *arXiv:2103.11769*

According to SM this ratio should be 1 [EPJC **76**, 440 (2016)], as the coupling of lepton to gauge boson is independent of flavor.

Belle II provides better electron identification – lower systematics!

First steps to determine R_{K^*} in Belle II:

$B^+ \to J/\psi(\ell\ell)K^+$ and $B^0 \to J/\psi(\ell\ell)K^0$ can be used as as control channels to check the ratio = 1

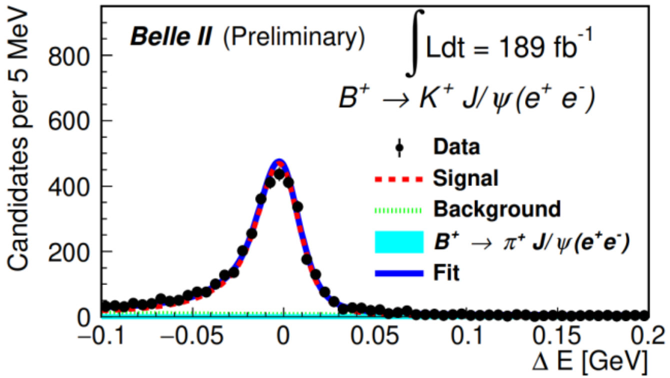
forward by measurement of:

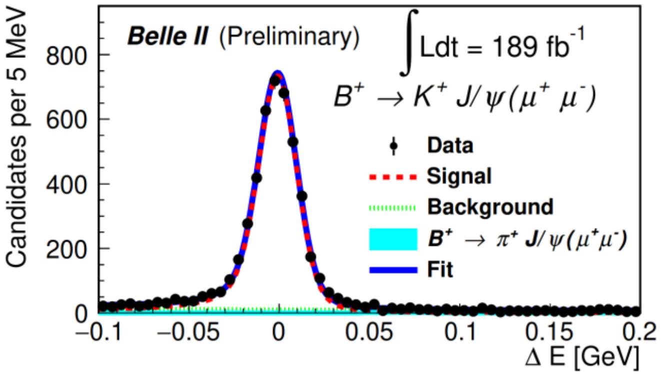
$B^0 \to K^{*0}(K^+\pi^-)\ell\ell$ and $B^+ \to K^{*+}(K^+\pi^0, K^0_S\pi^+)\ell\ell$

$B^+(B^0) \to J/\psi K^+(K_S^0)$ results

arXiv:2206.05946

Extract signal by fitting M_{bc} and ΔE





Mode	$n_{J/\psi \to e^+e^-}$	$n_{J/\psi \to \mu^+\mu^-}$	$R_K(J/\psi)$
$B \to K^+ J/\psi$	3706 ± 62	4578 ± 62	$1.009 \pm 0.022 \pm 0.008$
$B \to K_S^0 J/\psi$	1052 ± 33	1343 ± 37	$1.042 \pm 0.042 \pm 0.008$

Belle results:

$$R_{K^+}(J/\psi) = 0.994 \pm 0.011 \pm 0.010$$
$$R_{K^0}(J/\psi) = 0.993 \pm 0.015 \pm 0.010$$

- Results are statistically dominated and in agreement with results from Belle and LHCb.
- Systematics uncertainties have been reduced compared to most precise measurements from Belle [JHEP **03**, 105 (2021)].

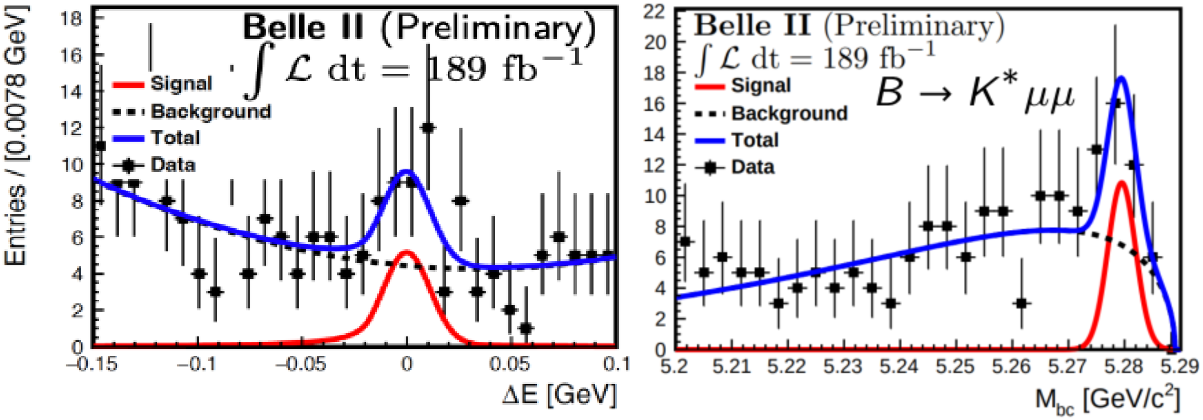
$B \to K^* \ell^+ \ell^-$ results

arXiv:2206.05946

Background suppression:

- **Dilepton mass vetoes:**
  $\Rightarrow B \to J/\psi(\to \ell\ell)K^*$
  $\Rightarrow B \to \psi(2S)(\to \ell\ell)K^*$
  $\Rightarrow B \to K^*\gamma$ photon conversion
- $e^+e^- \to q\bar{q}$: **boosted decision tree** (BDT)

2D unbinned fit in M_{bc} and ΔE



Mode	Observed events	Branching Fraction ($\times 10^{-6}$)	World Average ($\times 10^{-6}$)
$B \to K^* e^+ e^-$	22 ± 6	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+ \mu^-$	18 ± 6	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

Belle: *JHEP 03, 105 (2021)*

$R_K = 1.03^{+0.28}_{-0.24} \pm 0.01$ for $q^2 \in (1.0, 6.0)\ \mathrm{GeV}^2/c^4$

$B^0 \to K^{*0}\tau^+\tau^-$

arXiv:2110.03871

3rd generation version of $B \to K^* \ell^+ \ell^-$

Highly suppressed FCNC decay - $\mathcal{B} \sim \mathcal{O}(10^{-7})$ in SM

BUT: The branching fraction can be enhanced up to 1-5 × 10^{-4} , if NP effects contribute

PRL 120, 181802 (2018), JHEP 10, 184 (2015), JHEP 09, 40 (2017)

So far – only Upper Limit at 90% CL on the charged channel by BABAR [PRL 118, 031802]:

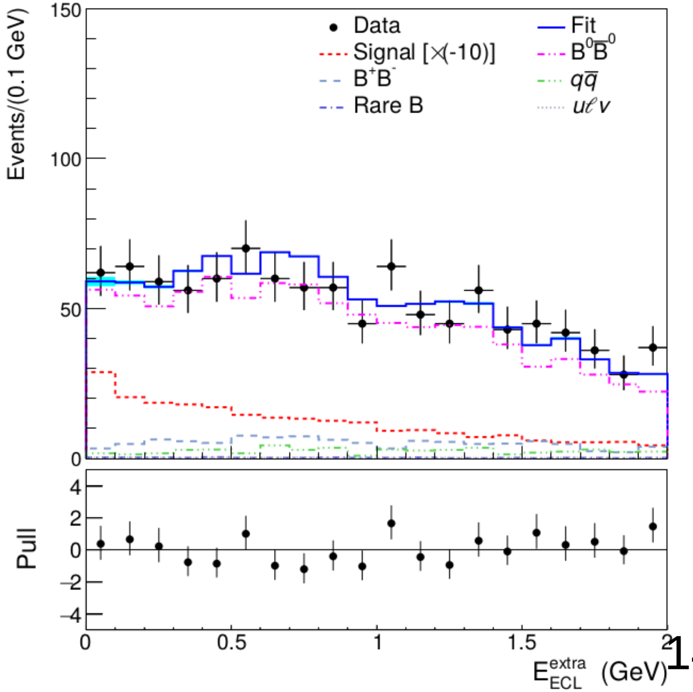
$$\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$$

The first search for the *neutral channel* using **hadronic tagging**

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

$\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ or $\tau^- \to \pi^- \nu_\tau$

Four track required from the signal B meson



Signal region, $E_{ECL}^{extra} < 0.2$ GeV

→ The total energy of the neutral clusters detected in the ECL not associated with either tag *B* meson or signal *B* meson.

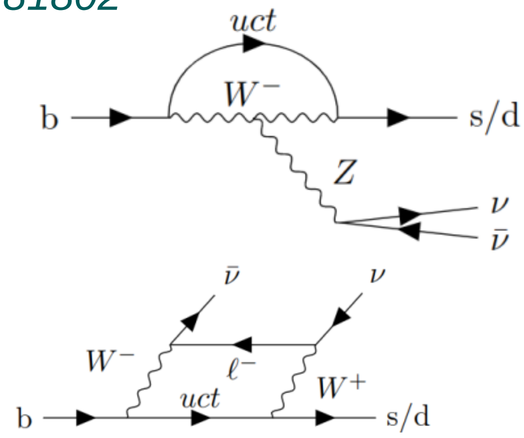
Binned maximum likelihood fit to E_{ECL}^{extra} :

$N_{sig} = -4.9 \pm 6.0$ → ***no significant signal found***

$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3}$ at 90% CL

$B^+ \to K^+ \nu\bar{\nu}$

PRL 127, 181802



$b \to s\nu\bar{\nu}$ are a complementary to $b \to s\ell\ell$ studies

SM prediction on BF: $(4.0 \pm 0.5) \times 10^{-6}$ [JHEP. 2015, 184 (2015)]

→ **but** can be enhanced by NP and Dark Matter contribution!

Technically challenging – 2 neutrinos in the final state

Previous analyses (CLEO, Belle, BABAR): Hadronic/semileptonic tagging approach
→ very low efficiency

Current experimental upper limit (PDG):

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) < 1.6 \times 10^{-5}$$

Bele II: inclusive tagging technique for this study for the 1st time

Study on 63 fb^{-1}

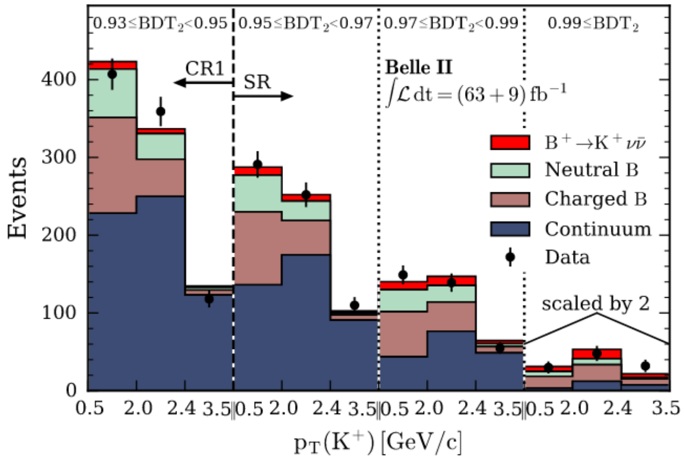
Signal candidate: single kaon track of the highest p_T

Rest-of-event: remaining tracks and energy deposits

Background rejection: training of two sequential BDTs that combine event topology, signal kaon and rest-of-event properties, vertexing information, etc.

$B^+ \to K^+ \nu\bar{\nu}$

PRL 127, 181802



- Validation channel used to test BDT performance: $B \to K^+ J/\psi\,(\to \mu^+\mu^-)$

- Simultaneous binned maximum likelihood fit is performed in bins of kaon-p_T × BDT 2

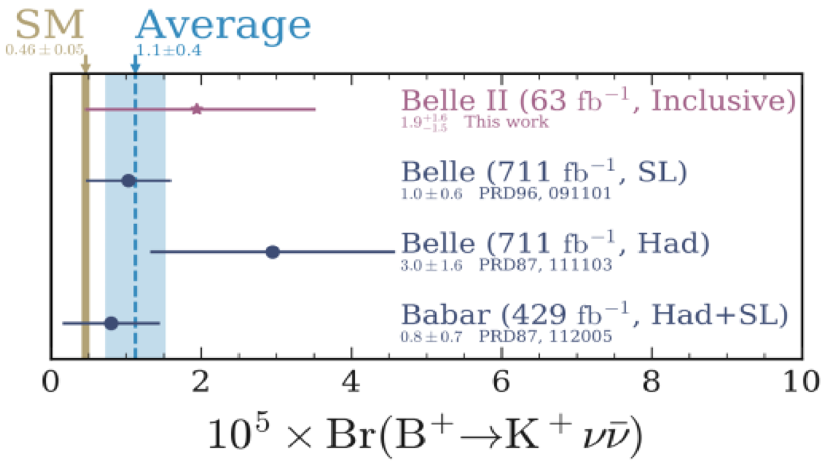
- Obtained BF: $[1.9^{+1.6}_{-1.5}] \times 10^{-5}$ - statistically compatible with other results

- Upper limit set (assuming SM signal):

  4.1×10^{-5} at the 90% C.L.

- 350% better sesitivity than for hadronic tagging approach

Great potential for Belle II to provide world-leading measurements in the future!



Summary

- **Belle II**, on current statistics, can be already competitive with old-generation B-factories in many precise measurement

  $B \to X_s\, \gamma$

  $B^+(B^0) \to J/\psi K^+(K_S^0)$

  $B^+ \to K^+\nu\bar{\nu}$

- **Belle** data still provide an excelent source of valuable physics studies

  $B^0 \to K_S^0 K_S^0 \gamma$

  $B^0 \to K^{*0}\tau^+\tau^-$

- In addition, **Belle** still delivers the most sensitive result on $B \to D^{(*)} \tau\, \nu$ (LFU)

- Great potential of **Belle II** for precise BSM physics measurement on full data sample!

- Analyses on combined **Belle** and **Belle II** data is a strategy for the improved results in the near future.