Flavour Physics from non-LHC experiments

Justine Serrano
on behalf of Belle II collaboration

LHCP2021

7-11th of June

Disclaimer

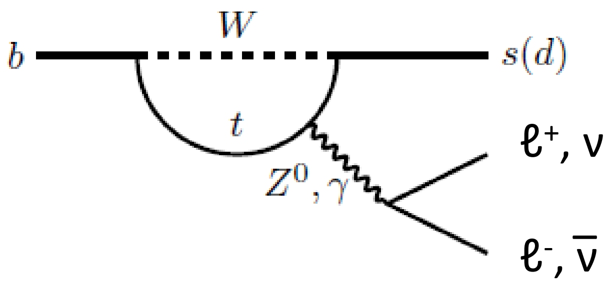
Too many interesting results to fit in this talk!
I will try to give an overview of the diversity of flavour results, focusing on a totally biased choice of recent measurements.

NP searches with leptons

Flavour changing neutral currents

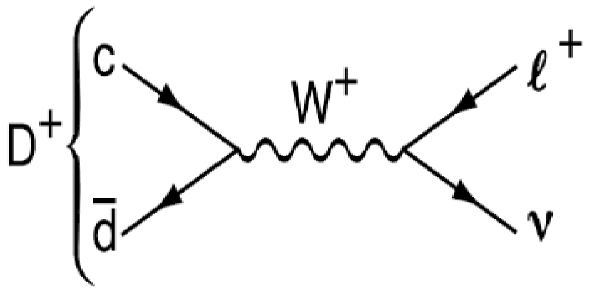
e.g: s → d$\nu\bar{\nu}$, b → sℓℓ

- Loop-level in SM, suppressed by GIM mechanism
- Rare decays, BR ~ $10^{-6} - 10^{-11}$
- Need to control theory errors



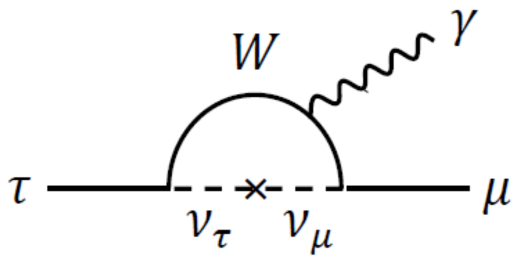
Tests of lepton flavor universality

- Ratios of BR with τ/μ, μ/e, τ/e in final state
- Can be tree-level or loop-level transition
- Almost free from theory uncertainties since lepton flavour is conserved in SM



Forbidden decays

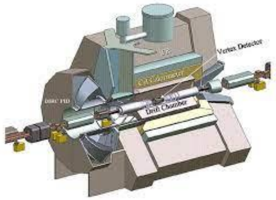
- Lepton flavour violating
- Lepton number violating
- Baryon number violating
- Forbidden or very suppressed in SM, BR~O(10^{-54})
- Observation is a clear sign of NP



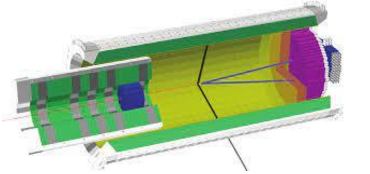
Can do these searches in different flavour sectors: strange, charm, beauty, tau, muon
Correlations between observables depends on NP type!

The main players

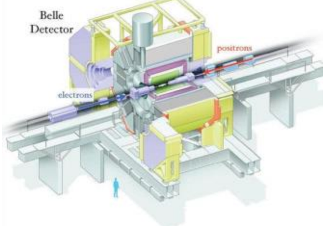
Babar at SLAC
2000-2008



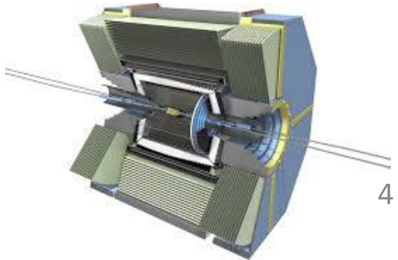
KOTO at JPARC
2015-…

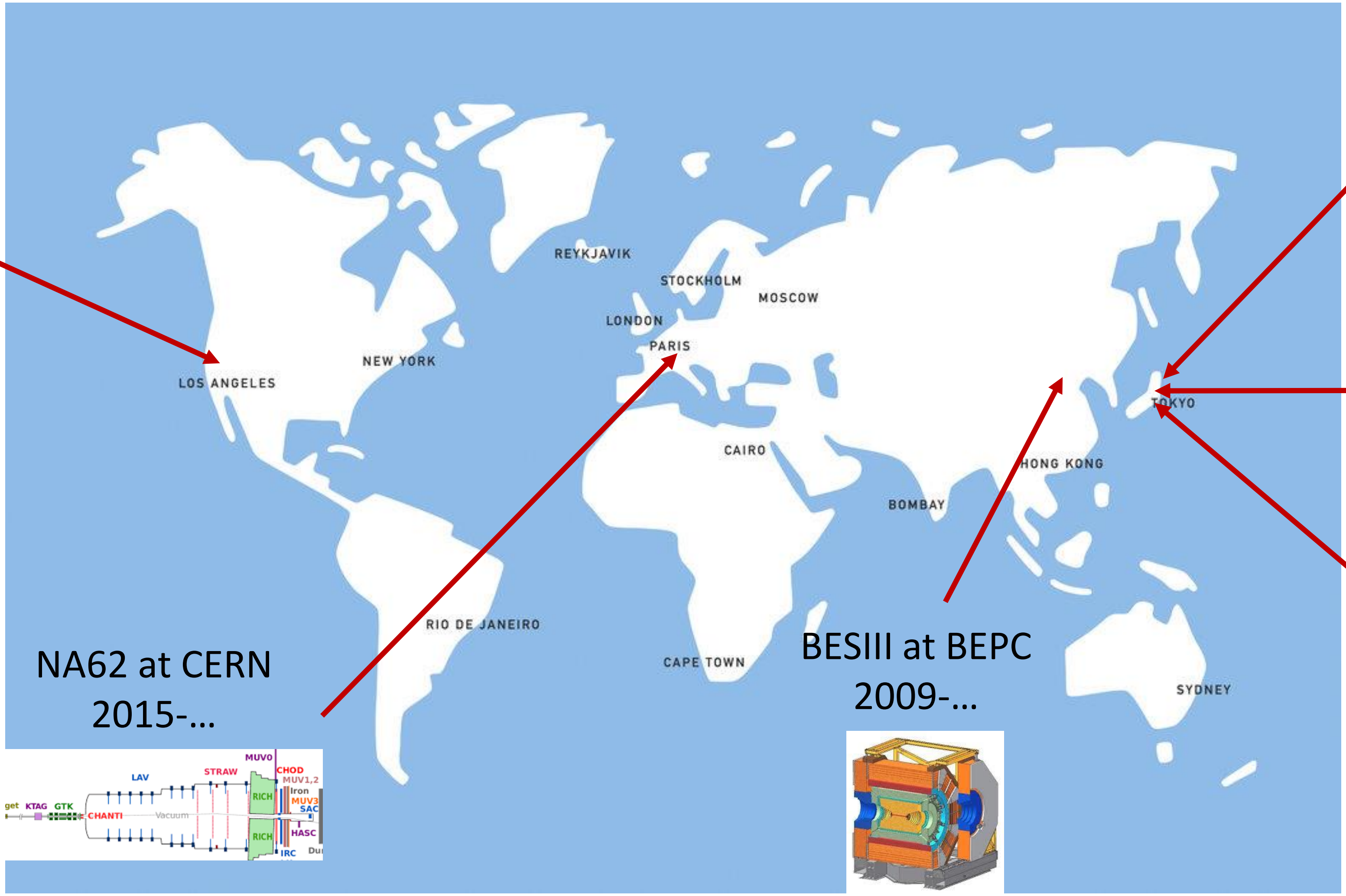


Belle at KEK
2000-2010



Belle II at KEK
2019- …





NA62 at CERN
2015-…

BESIII at BEPC
2009-…

+ nEDM, g-2,
μ→e, …

Interplay with LHC flavour physics

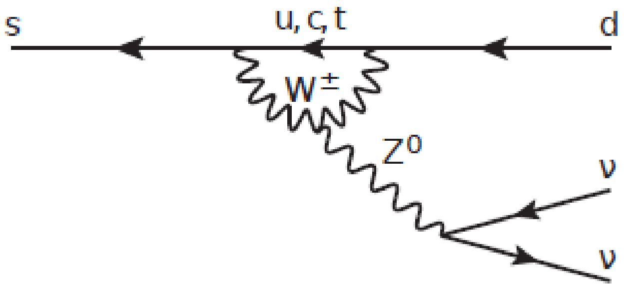
- LHC and non-LHC experiments are very complementary:

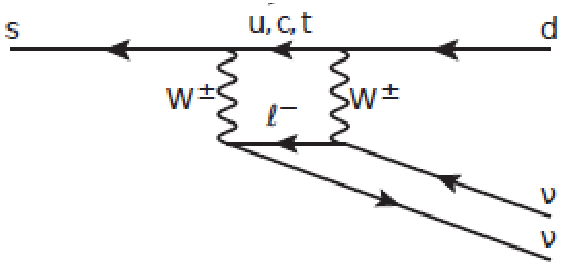
LHC	Non-LHC
Large background (pp)	Clean environment (e^+e^-)
Large cross section (σ_{bb}=284ub at LHCb)	Small cross section (σ_{bb}=1.1nb at B factories)
Poor tagging and neutral efficiency	High tagging and neutral efficiency
No hermeticity (LHCb)	Hermeticity
All species of b-hadron produced	Mainly B^0 and $B^\pm$
Complex triggers	Efficient and simple triggers
Initial state not well known	Constraints on kinematics

- To be **very** simplistic, LHC experiments are usually better on muonic final states, and heavy b-hadrons (B_s, Λ_b,…)
- Non-LHC experiments are better for final states with missing energy, electrons and neutrals
- There are many exceptions: e.g $B \rightarrow K^*ee$ by LHCb, $B_s \rightarrow \gamma\gamma$ at Belle,…

Strange sector

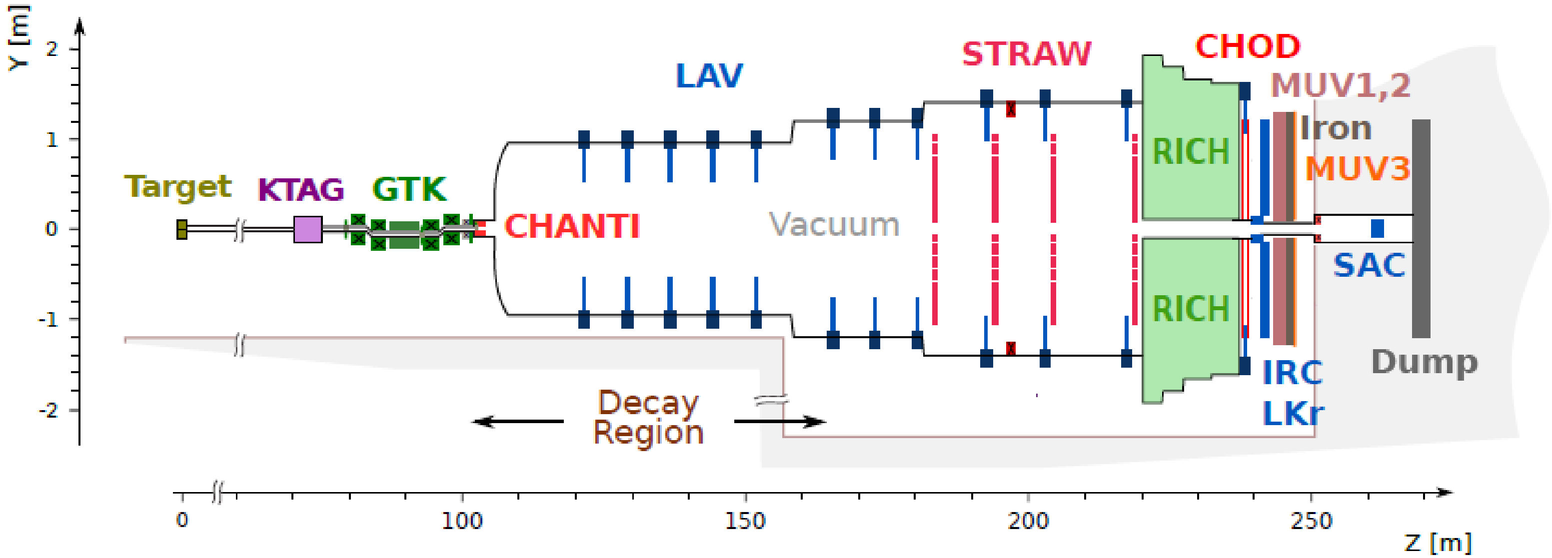
Search for FCNC $K \to \pi\nu\bar{\nu}$ decays

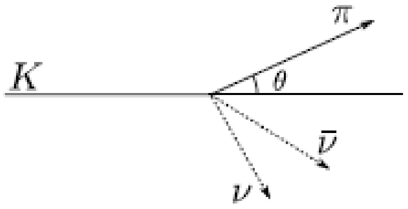




$K^+ \rightarrow \pi^+\nu\bar{\nu}$ at NA62

- SM prediction: BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$)=(8.4±1.0).10^{-11}
- NA62 uses secondary beam from SPS at CERN (75GeV, 6% of K^+)
- K^+ decay in flight in ~120m long region
- Detect a K^+ associated with a π^+ and missing energy
- Vetoes for γ and μ
- Data taken in 2016-2018





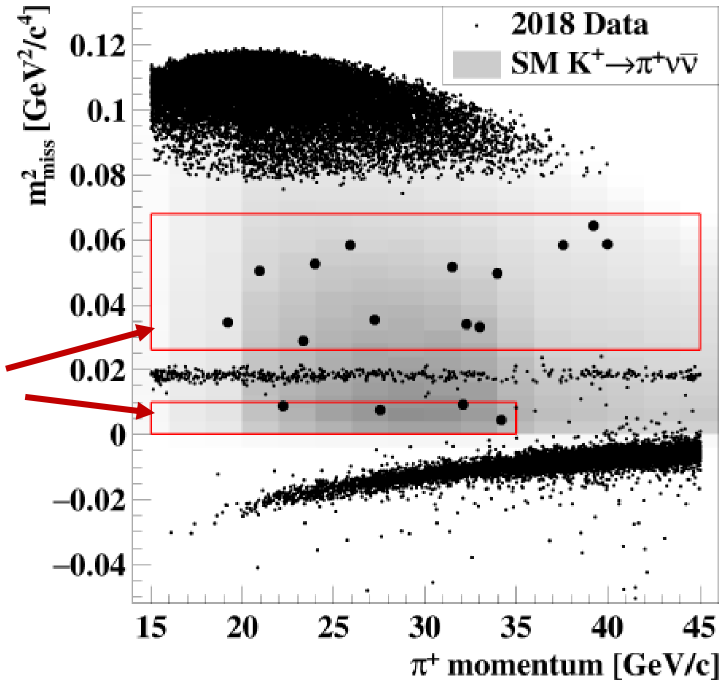
arXiv:2103.15389

$K^+ \to \pi^+\nu\bar{\nu}$ at NA62

	Expected signal	Expected background	Observed candidates
2016	$0.267 \pm 0.20_{syst.} \pm 0.32_{ext.}$	0.15 ± 0.093	1
2017	$2.16 \pm 0.13_{syst.} \pm 0.26_{ext.}$	1.46 ± 0.30	2
16' + 17' + 18'	$10.01 \pm 0.42_{syst.} \pm 1.19_{ext.}$	$7.03^{+1.05}_{-0.82}$	20

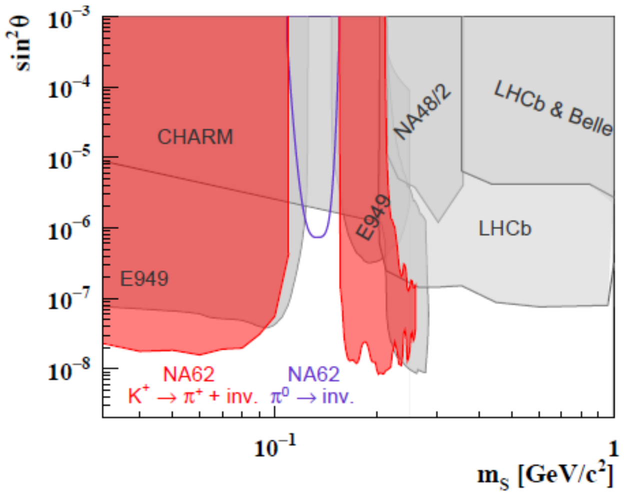
$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9).10^{-11}$$

Signal regions



$$m^2_{miss} = (P_K - P_\pi)^2$$

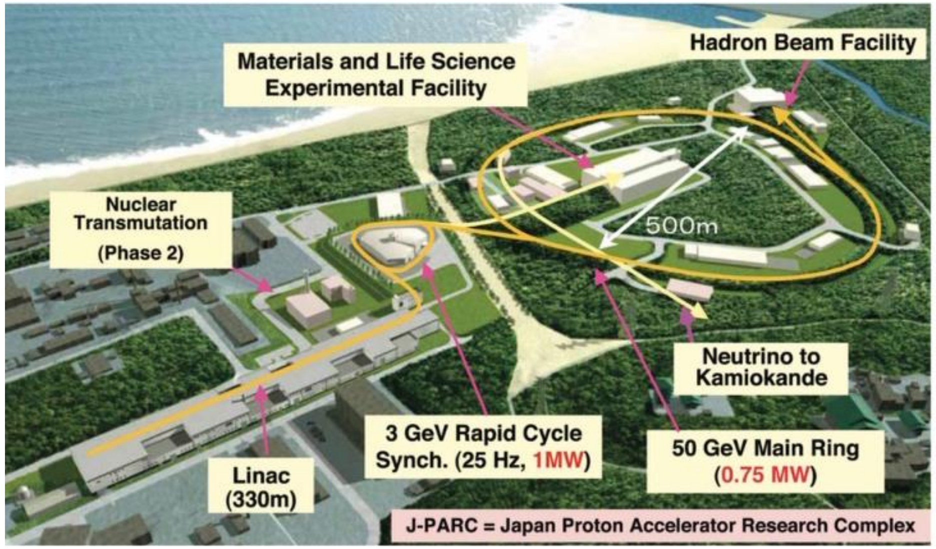
- Main bkg: upstream bkg, $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^- e^+\nu$
- 3.4 sigma evidence !
- BR in agreement with SM predictions
- Reinterpretation in term of $K^+ \to \pi^+ X$, where X is a feebly interacting particle
  See talk by C. Hearty at this conference!

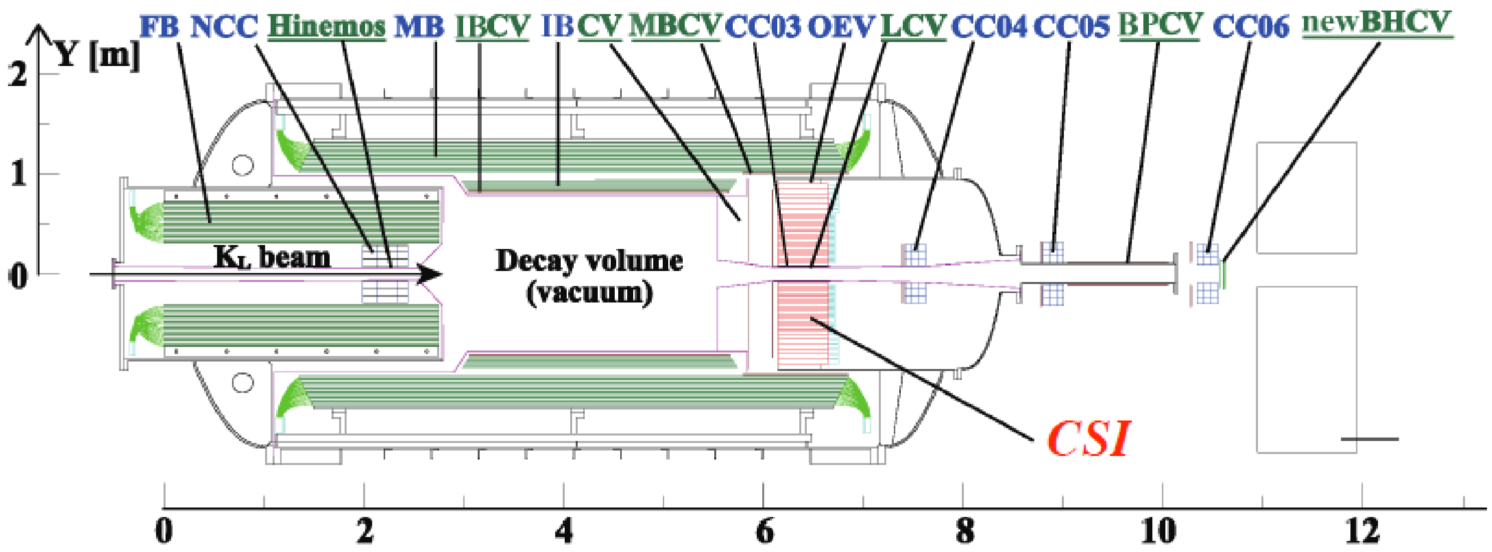


Data taking will resume in July 2021 with an upgraded beam line, limiting upstream backgrounds

$K^0 \to \pi^0 \nu\bar{\nu}$ at KOTO

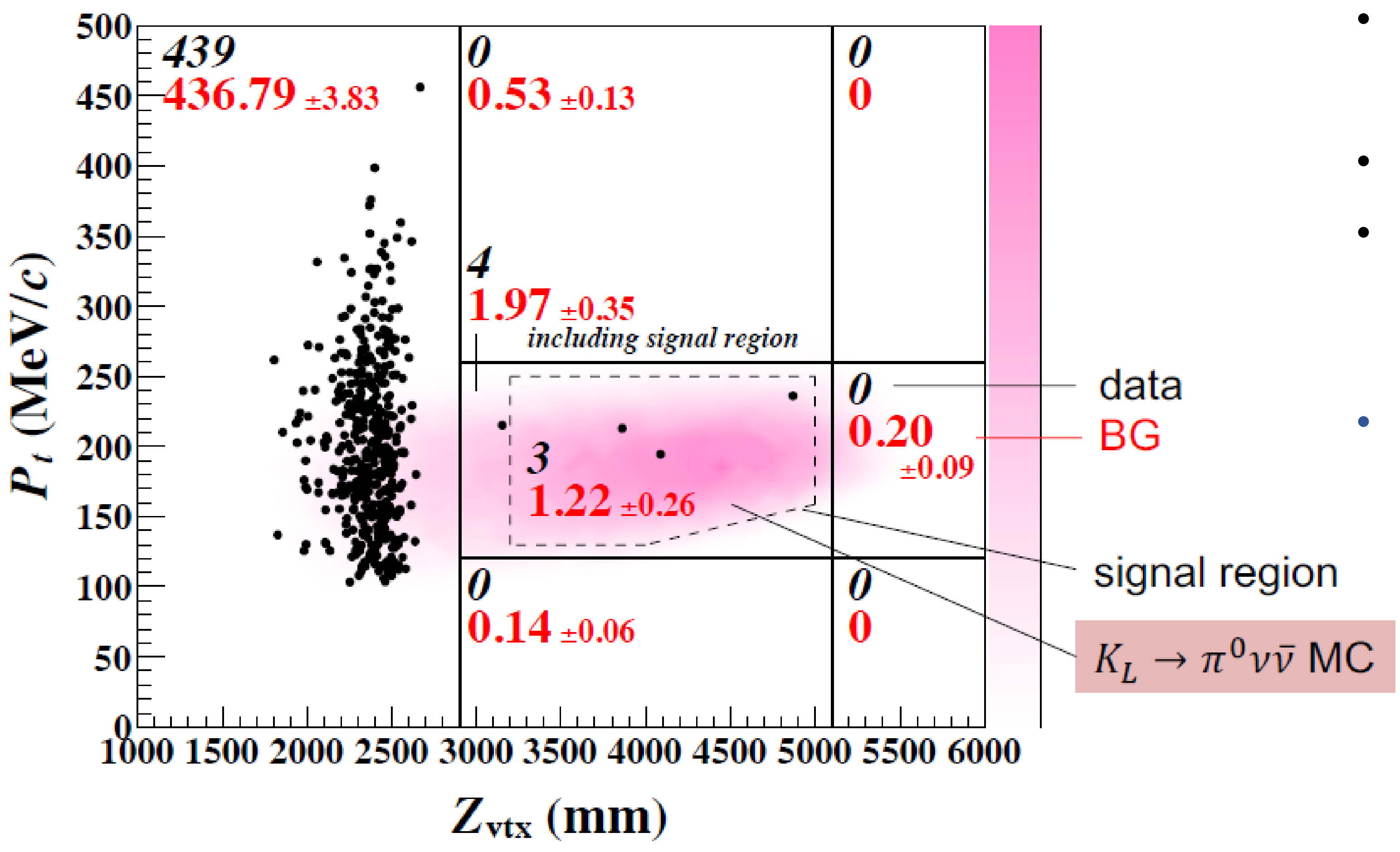
- SM prediction BR($K^0 \to \pi^0 \nu\bar{\nu}$)= (3.4±0.6).10^{-11}
- KOTO uses a 30 GeV proton beam from J-Parc main ring
- Detect only 2 γ from the π^0 decay in a CSI calorimeter
- Decay volume surrounded by charged and photon vetoes





PRL 126 (2021) 121801

$K^0 \to \pi^0\nu\bar{\nu}$ at KOTO



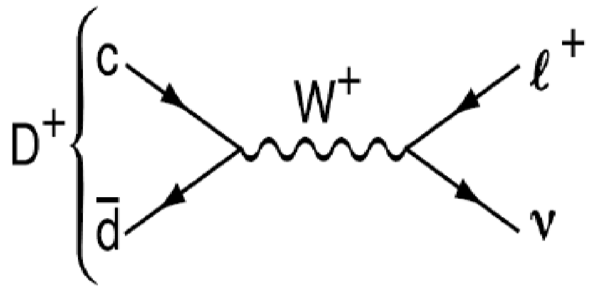
- New result from 2016-2018 data!
- No signal found:

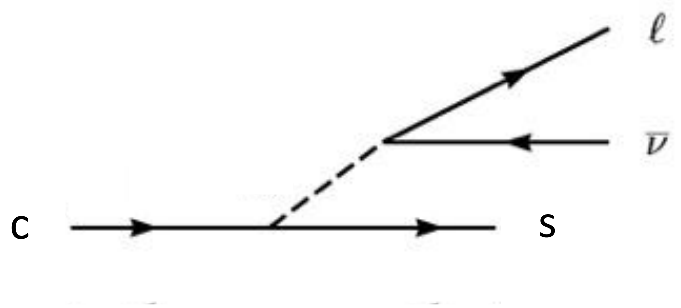
  BR($K^0 \to \pi^0\nu\bar{\nu}$) < 4.9 10^{-9} at 90%CL
- 2 orders of magnitudes higher than SM
- Main backgrounds: $K^+ \to e^+\pi^0\nu$ and beam halo $K^0 \to \gamma\gamma$

- Improvements foreseen to reach SM sensitivity:
  - New charged particle veto to be installed to suppress K^+ background
  - New software development to suppress $K^0 \to \gamma\gamma$ background

Charm sector

Test of LFU in (semi)leptonic decays



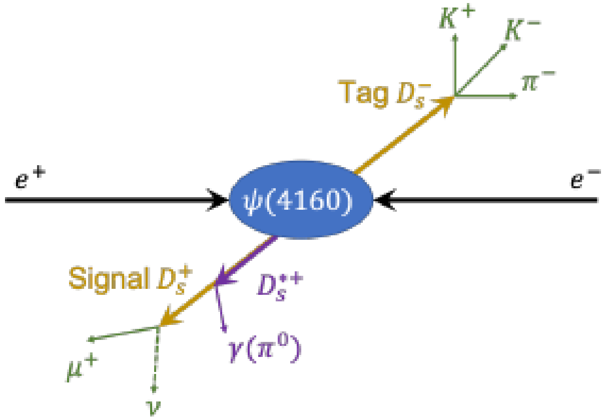


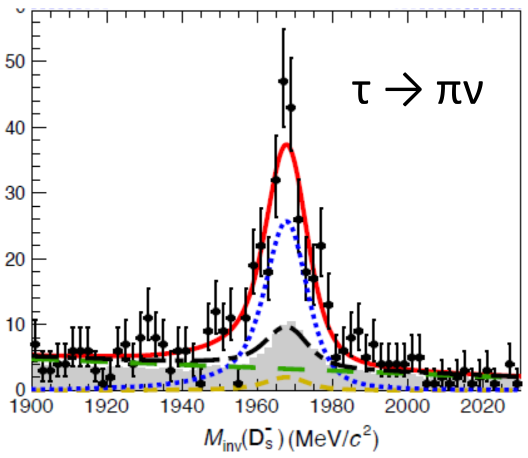
Charm sector: LFUV at BES III

- e^+e^- collider, √s from 2 to 5 GeV, large dataset recorded at $D_{(s)}D_{(s)}$ production threshold
- Full reconstruction of the opposite $D_{(s)}$: clean reconstruction of decay with missing energy ➡ Ideal place to test LFU in (semi)leptonic decays
- Example: $D_s \to \tau/\mu\ \nu$

$$\Gamma(D_s^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} f_{D_s^+}^2 m_\ell^2 m_{D_s^+} (1 - \frac{m_\ell^2}{m_{D_s^+}^2})^2 |V_{cs}|^2$$

$D_s^+\ N_{\mathrm{Tag}} \sim 6.2 \times 10^5$





$$R = \frac{\Gamma(D_s^+ \to \tau^+\nu_\tau)}{\Gamma(D_s^+ \to \mu^+\nu_\mu)} = \frac{m_\tau^2 (1 - \frac{m_\tau^2}{m_{D_s}^2})^2}{m_\mu^2 (1 - \frac{m_\mu^2}{m_{D_s}^2})^2}$$

R=9.75±0.01 in SM

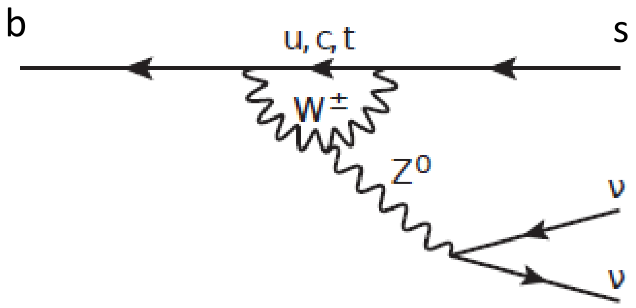
Charm sector: LFUV at BES III

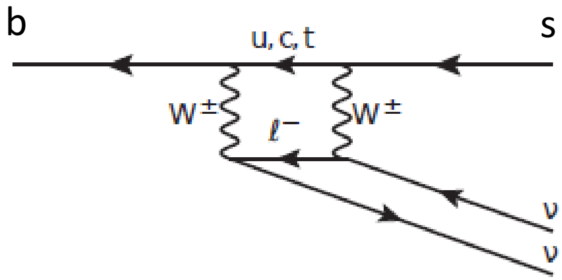
Mode	Measured ratio	SM prediction	Ref
$D^+ \to \tau/\mu\ \nu$	3.21±0.77	2.66	PRL 123(2019)211802
$D_s \to \tau/\mu\ \nu$	9.58±0.44	9.75	arXiv:2106.02218, arXiv:2102.11734, arXiv:2105.071078
$D^+ \to \eta\ \mu/e\ \nu$	0.91± 0.13	0.97-1.00	PRL 124 (2020) 231801
$D^+ \to \omega\ \mu/e\ \nu$	1.05±0.14	0.93-0.99	PRD 101 (2020) 072005
$D^+ \to \pi^0\ \mu/e\ \nu$	0.964±0.045	~0.985	PRL 121 (2018) 171803
$D^0 \to \pi^+\ \mu/e\ \nu$	0.922±0.037	~0.985	"
$D^0 \to K^+\ \mu/e\ \nu$	0974±0.014	~0.970	PRL 122 (2019) 011804
$\Lambda_c^+ \to \Lambda\ \mu/e\ \nu$	0.96±0.16	~1	PRL115(2015)221805 PLB767(2017)42

- No evidence of LFUV in charm (semi)leptonic decays with BES III data
- Individual BR measurements also provide test of Lattice QCD and CKM parameters extraction
- More data and results are expected in the coming years, see BES III white paper in Chin. Phys. C 44, 040001 (2020)

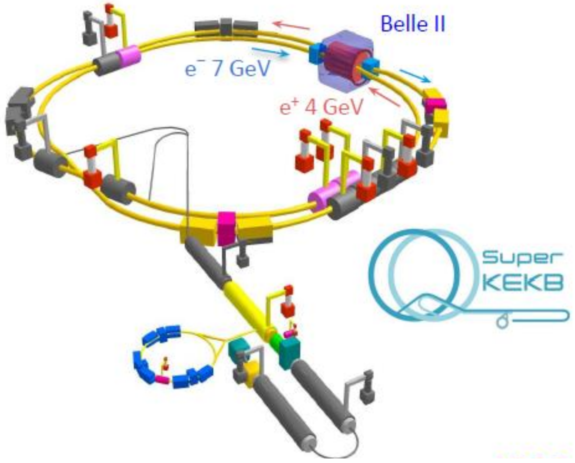
B sector

FCNC decays

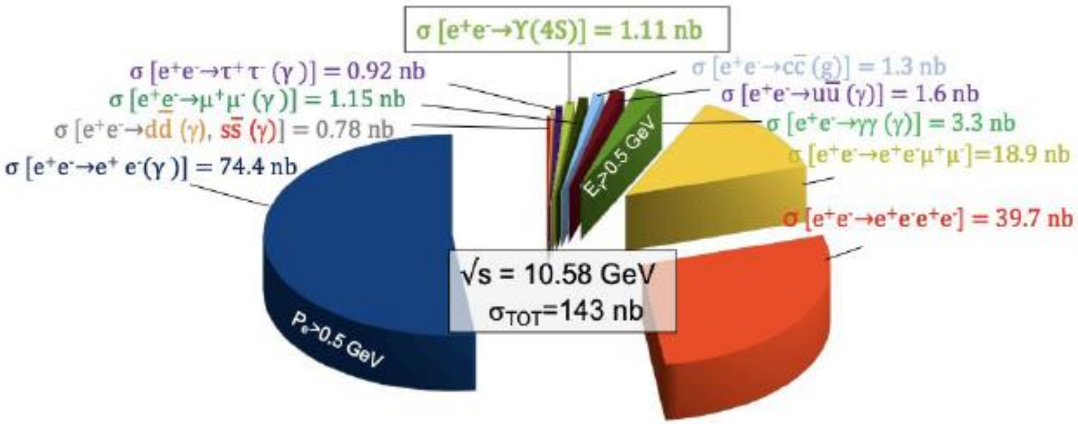




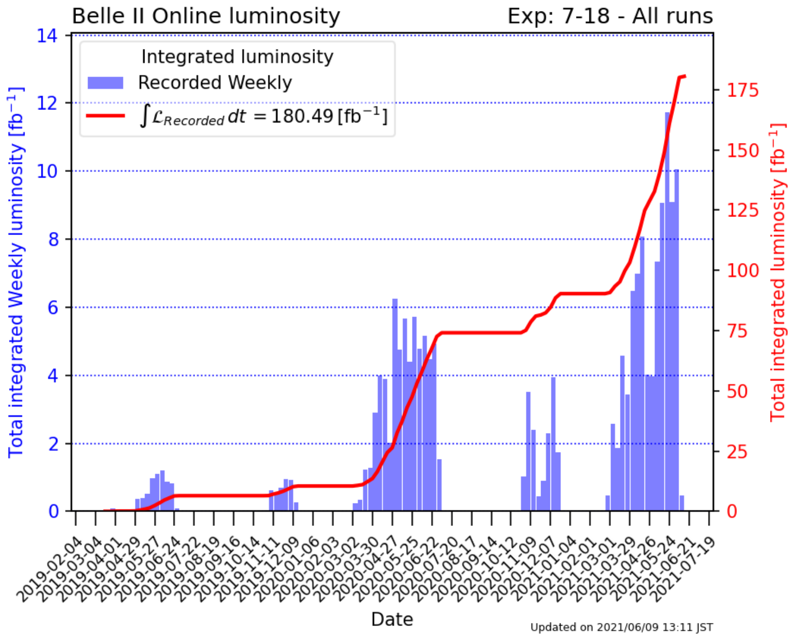
B sector: $B^+ \to K^+\nu\bar{\nu}$ at Belle II



- SuperKEKB is an e^+e^- asymmetric collider, located in Tsukuba, Japan
- $\sqrt{s} = M_{\psi(4s)}$ =10.58 GeV : B factory, but also charm, and tau!



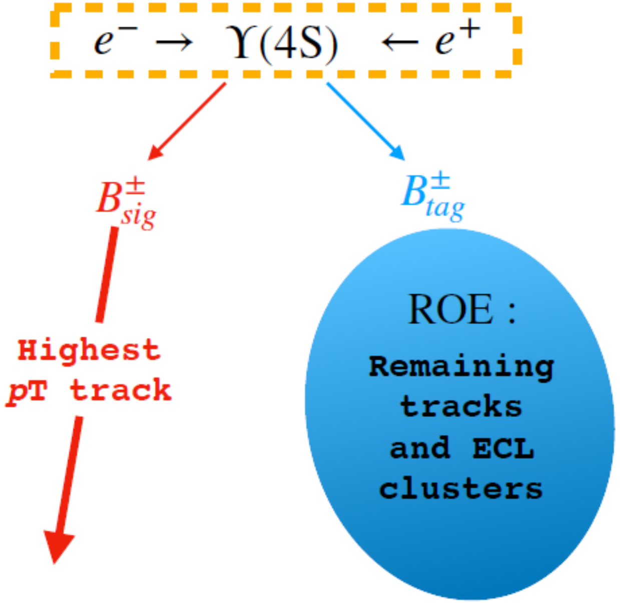
- Machine target:
  - Instantaneous lumi $6x10^{35}$ $cm^{-2}s^{-1}$ (30 x KEKB)
  - Integrated lumi 50 ab^{-1} (50 x Belle)
  - Thanks to the nano beam scheme (vertical beam size 50nm at IP)
- Achieved:
  - World record of instantaneous lumi at $2.9x10^{34}$ $cm^{-2}s^{-1}$
  - Recorded 180 fb^{-1} since 2019
  - Continuous data taking even with COVID crisis

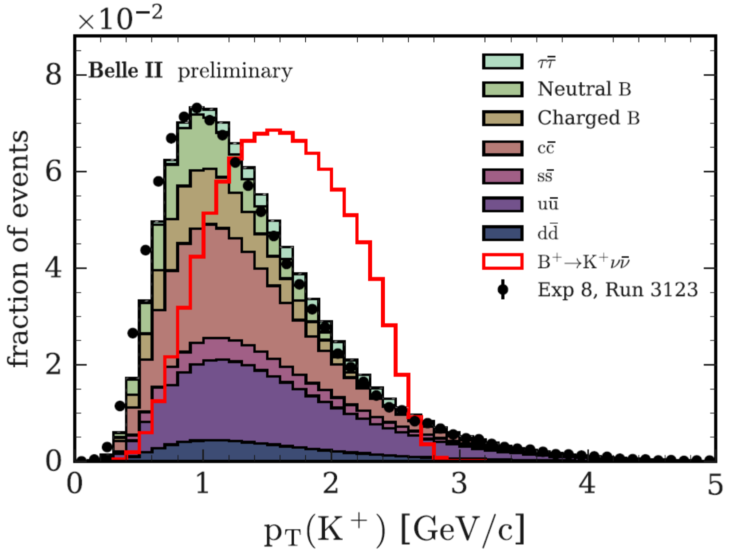


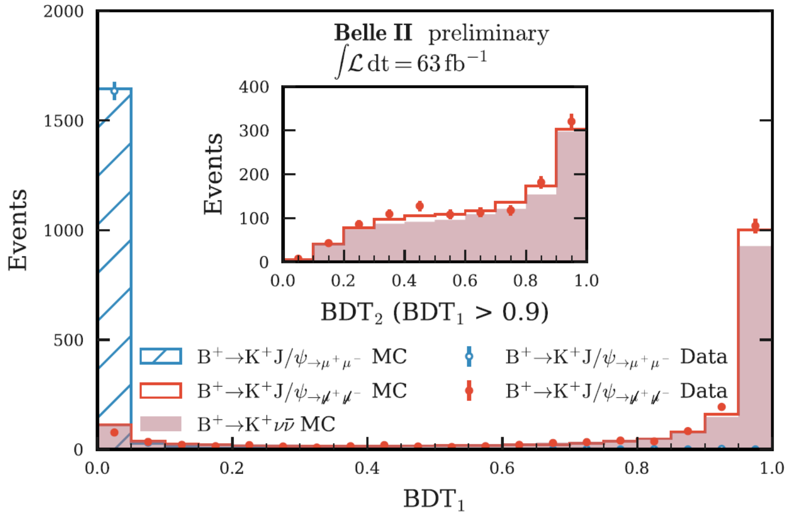
B sector: $B^+ \to K^+ \nu\bar{\nu}$ at Belle II

- SM prediction: $BR(B^+ \to K^+\nu\nu) = (4.6\pm0.5).10^{-6}$
- Experimentally very challenging !
- New method using an inclusive tagging
  - Identify the signal K^+ as the highest p_T track
  - Remaining tracks and cluster constitutes the Rest of the Event (ROE)

  ⟹ High signal efficiency but large background
- Two consecutive BDTs (51 variables) used to separate signal from background





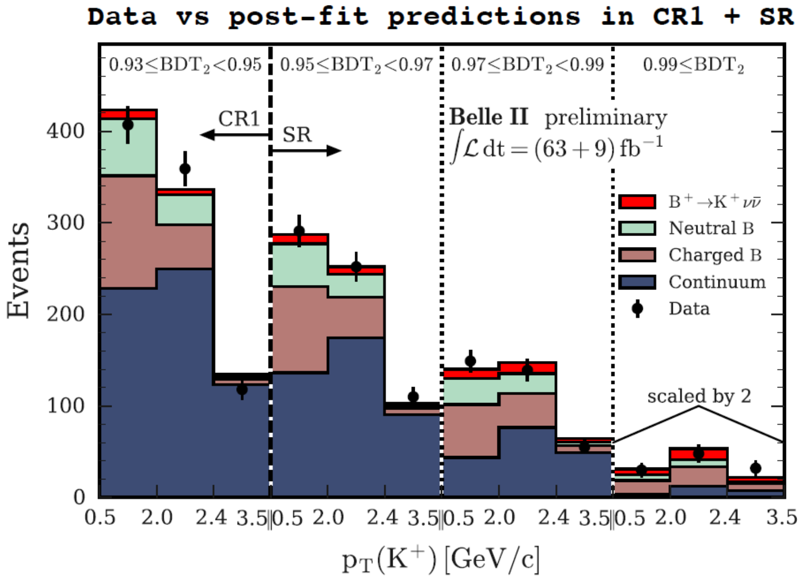


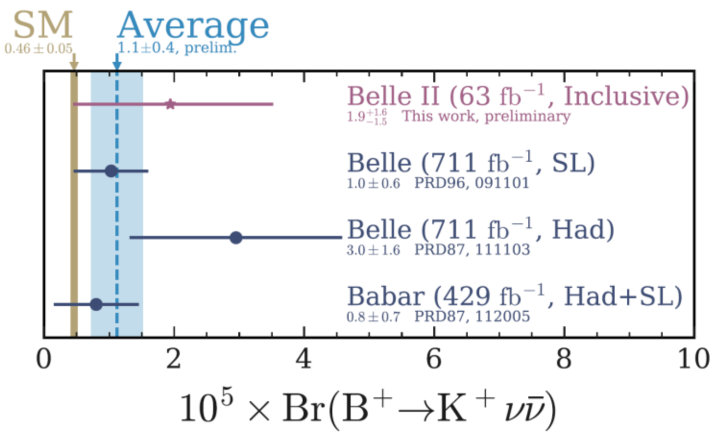
Control mode:
$B^+ \to J/\psi (\to\mu\mu) K^+$

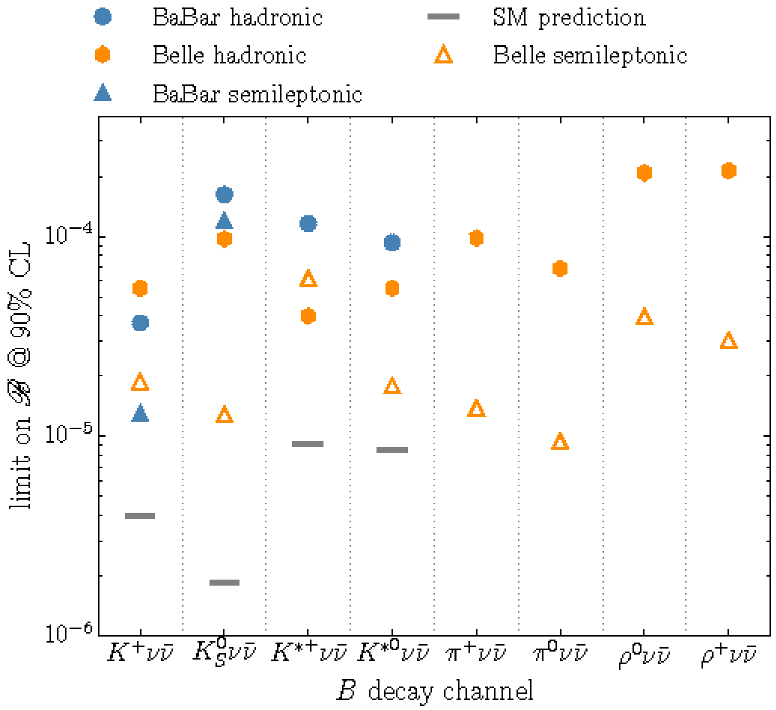
B sector: $B^+ \to K^+ \nu\bar{\nu}$ at Belle II

[arXiv:2104.12624](https://arxiv.org/abs/2104.12624)

- Signal is obtained with a maximum likelihood fit in bins on BDT2 and $p_T(K)$
- No signal found but result obtained with 63 fb^{-1} is already competitive with previous measurements!



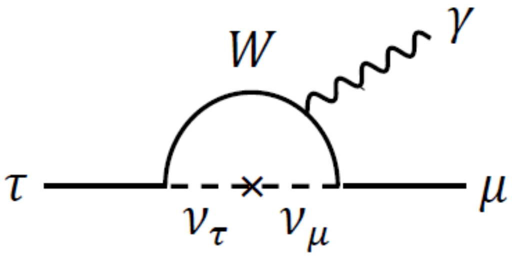




- Many more channels were done by Belle and Babar, expect new Belle II results soon

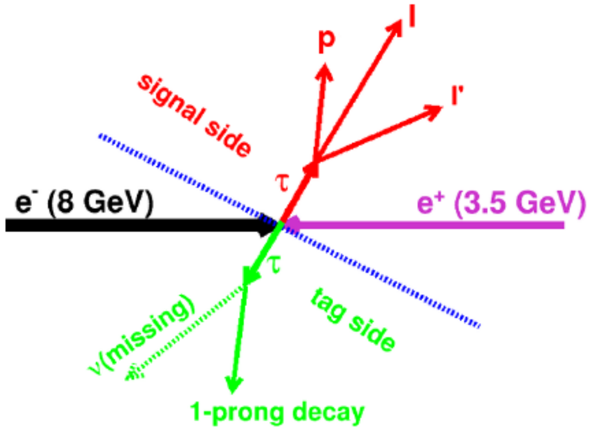
τ sector

LFV decays



τ sector : LFV decays at Belle

- τ LFV decays have been searched for by Babar, Belle, ATLAS and LHCb



- At B-factories, tau pair events are jet-like. Analysis strategy:
  - Selection based on the topology
  - Signal is searched in 2D plane: M_{sig} and $\Delta E = E_{sig} - E_{beam}$
  - Background is evaluated from sidebands

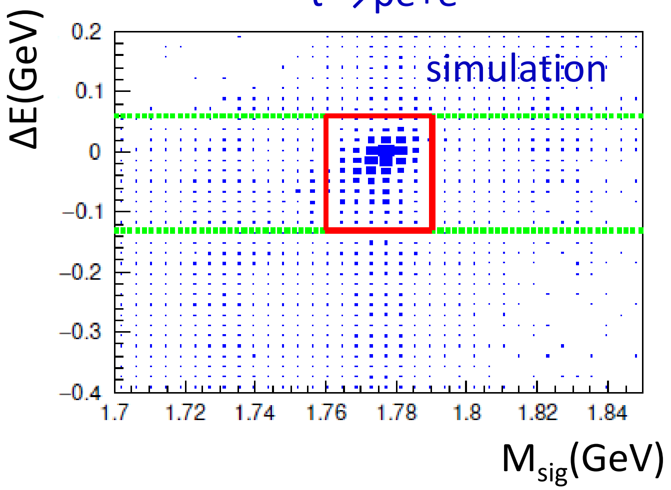
- New results from Belle (PRD 102 (2020) 111101) :

Channel	ϵ (%)	N_{bkg}	N_{obs}	N_{sig}^{UL}	$\mathcal{B}$ ($\times 10^{-8}$)
$\tau^- \to \bar{p}e^+e^-$	7.8	0.50 ± 0.35	1	3.9	< 3.0
$\tau^- \to pe^-e^-$	8.0	0.23 ± 0.07	1	4.1	< 3.0
$\tau^- \to \bar{p}e^+\mu^-$	6.5	0.22 ± 0.06	0	2.2	< 2.0
$\tau^- \to \bar{p}e^-\mu^+$	6.9	0.40 ± 0.28	0	2.1	< 1.8
$\tau^- \to p\mu^-\mu^-$	4.6	1.30 ± 0.46	1	3.1	< 4.0
$\tau^- \to \bar{p}\mu^-\mu^+$	5.0	1.14 ± 0.43	0	1.5	< 1.8

First limits

Improve LHCb results by one order of magnitude

τ →pe+e-



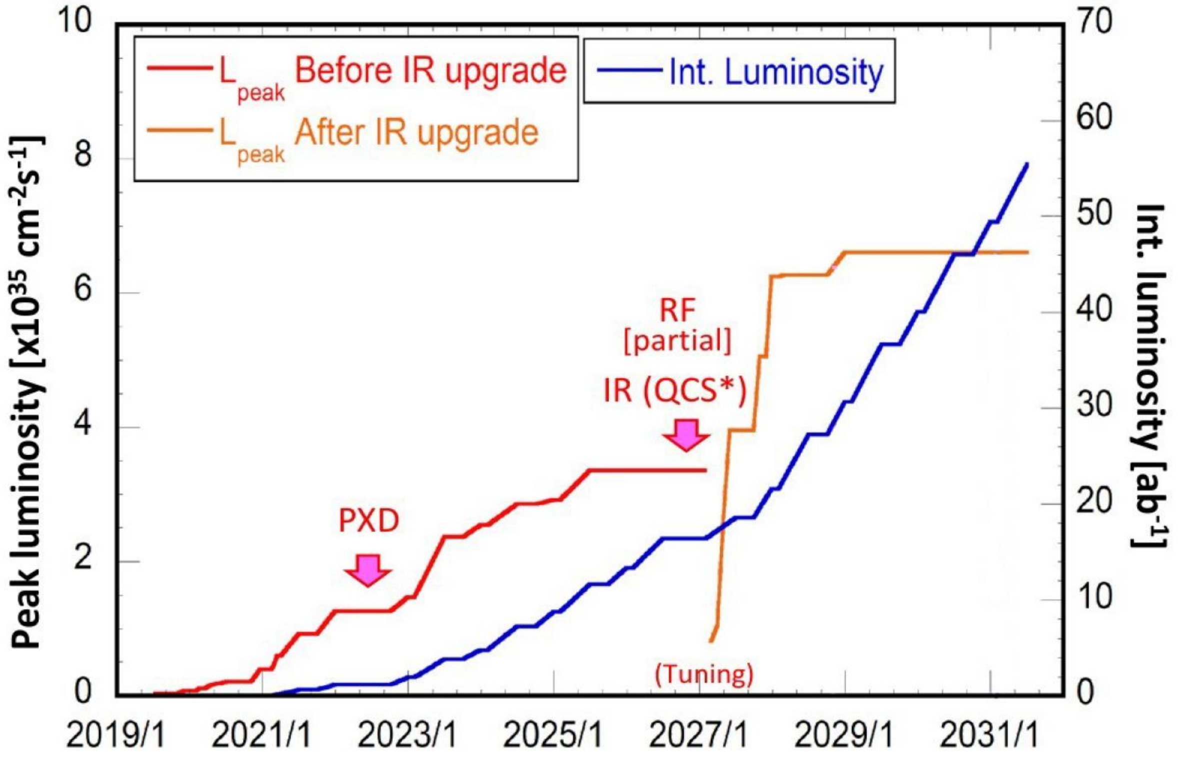
- New results from Belle (arXiv:2103.12994) on τ→ ℓγ:
  BR(τ→ eγ) < 5.6 10^{-8} and BR (τ→ μγ) < 4.2 10^{-8}

Prospects for Belle II

- We are just at the beginning!
- Belle II is uniquely sensitive to
  - Inclusive final states such as B → Xℓℓ, D → Xℓℓ
  - Final states with neutrinos or taus (e.g B → Xτμ)
  - As nearly equal μ and e efficiency for LFU test
  - B tagging efficiency improved by a factor 2 wrt Belle thanks to the *Full Event Interpretation*

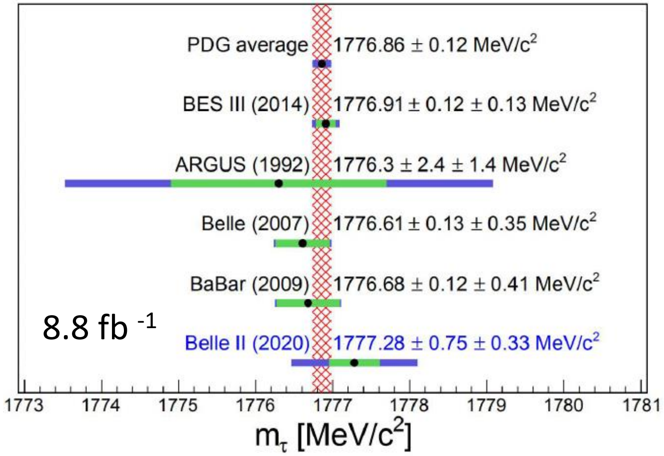
Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$	$< 19 \times 10^{-6}$	30%	11%
$A_{CP}(B \to X_{s+d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$	1.5	0.5
$S(B \to K^0_S\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(1 < q^2 < 3.5\ \mathrm{GeV}^2/c^4)$	26%	10%	3%
$Br(B \to K^+\mu^+\mu^-)/Br(B \to K^+e^+e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	28%	11%	4%
$Br(B \to K^{*+}(892)\mu^+\mu^-)/Br(B \to K^{*+}(892)e^+e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	24%	9%	3%
$\mathcal{B}(B_s \to \gamma\gamma)$	$< 8.7 \times 10^{-6}$	23%	–
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–	< 0.8	–

Belle II Physics Book



Prospects for Belle II

- Many τ physics results to come:
  - Improve τ LFV limits by ~2 orders of magnitude
  - Mass (BELLE2-CONF-PH-2020-010) and lifetime



  - CPV
  - Electric and magnetic dipole moments
  - Michel parameters
  - …

- But also CKM and CPV measurements:
  - Rediscovery of B →η'K (BELLE2-CONF-PH-2021-009)

    TDCPV sensitive to new physics in the loop
  - First B →$\pi^0\pi^0$ decays reconstructed (BELLE2-CONF-PH-2021-009), used for ϕ_2 measurements
  - Many more rediscoveries are being done, *see talk by F. Meier today!*

Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\sin 2\phi_1(B \to J/\psi K^0)$	$0.667 \pm 0.023 \pm 0.012$	0.012	0.005
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	0.048	0.020
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	0.032	0.015
$S(B \to J/\psi \pi^0)$	$-0.65 \pm 0.21 \pm 0.05$	0.079	0.025
ϕ_2 [°]	85 ± 4 (Belle+BaBar)	2	0.6
$S(B \to \pi^+\pi^-)$	$-0.64 \pm 0.08 \pm 0.03$	0.04	0.01
$Br.(B \to \pi^0\pi^0)$	$(5.04 \pm 0.21 \pm 0.18) \times 10^{-6}$	0.13	0.04
$S(B \to K^0\pi^0)$	-0.11 ± 0.17	0.09	0.03

- And spectroscopy, exotics, dark sectors,..

  See Belle II Physics Book

Conclusion

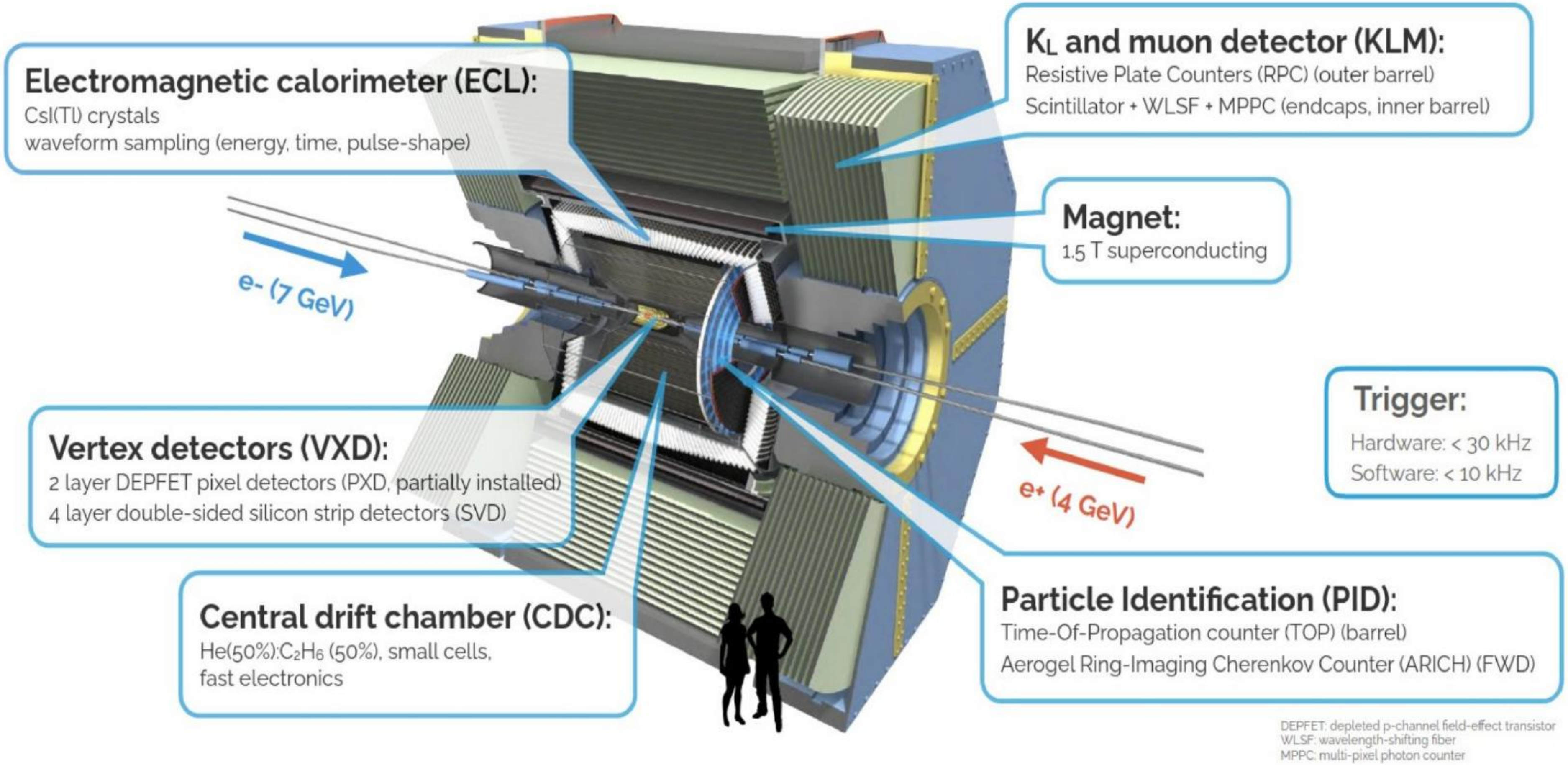
- Flavour physics is a very active field at LHC and non-LHC experiments
  - This talk aimed to provide an insight of this variety

- Beautiful program for the coming years
  - Data taking will restart at NA62 and KOTO, BES III and Belle II will continue data taking
  - Several upgrades are being discussed (KLEVER at CERN, polarized beams at Belle II,…)

- Many key results are awaited in the coming years!

Back up

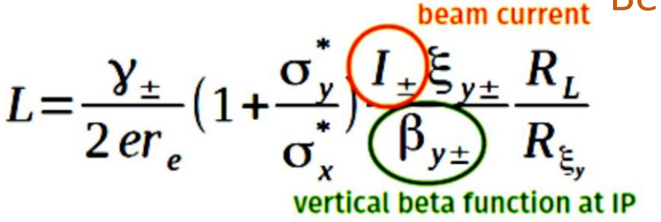
Belle II



Similar or better performances than Belle even with 10x more background!

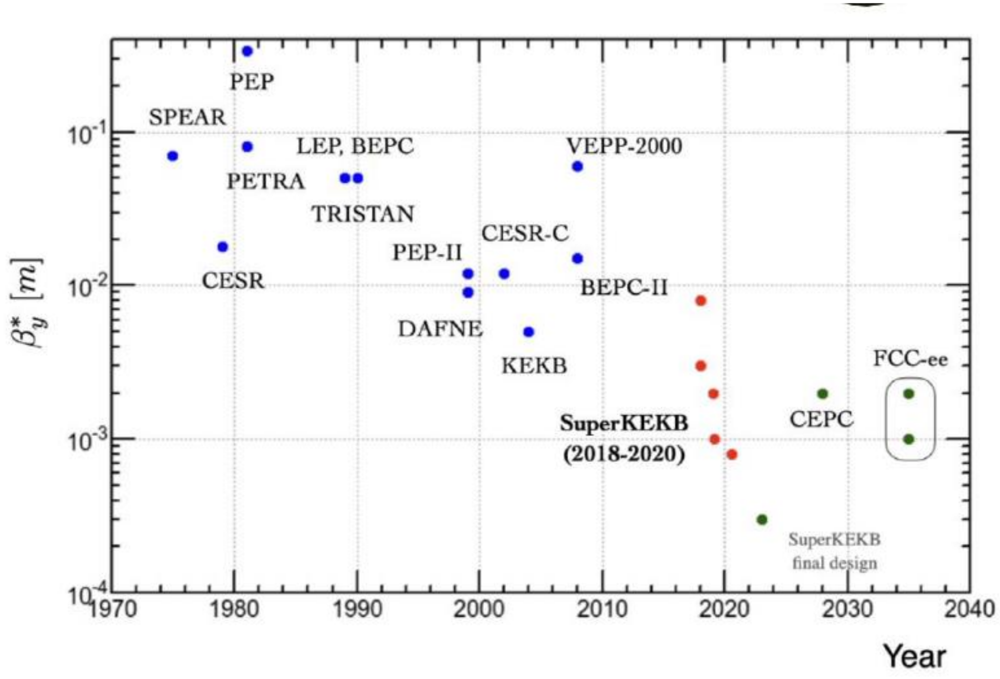
Belle II luminosity

Four steps: *Intermediate luminosity* (1-2 x 10^{35} /cm^2/sec, 5-10 ab^{-1});
High Luminosity (6.5 x 10^{35}/cm^2/sec, 50 ab^{-1}) with a detector upgrade
Polarization Upgrade, Advanced R&D
Ultra high luminosity (4 x 10^{36}/cm^2/sec, 250 ab^{-1}), R&D Project

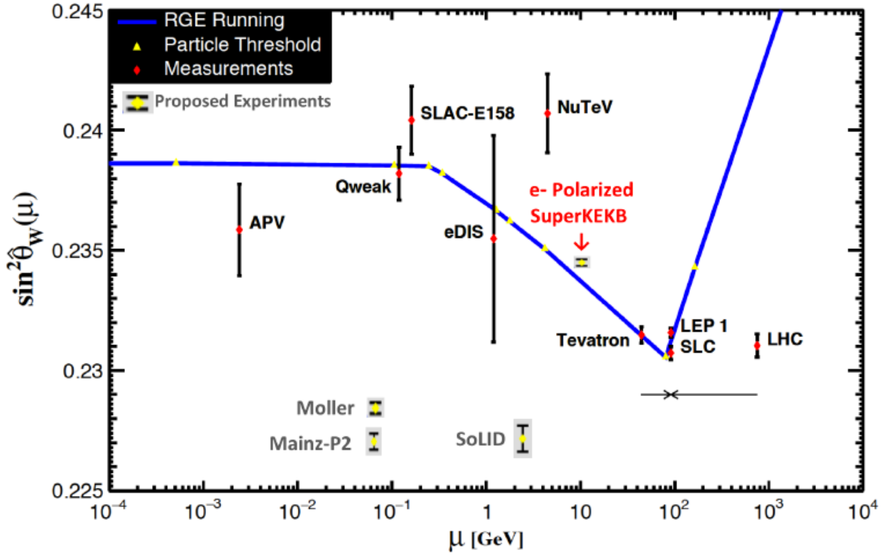


Bellex1.5

Belle/20



arXiv:1907.03503



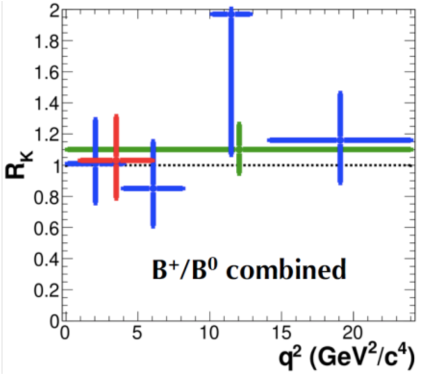
Belle II submitted 9 LOI to the Snowmass 2021 process (here)

Example of physics reach with 40ab^{-1} with polarized beam:

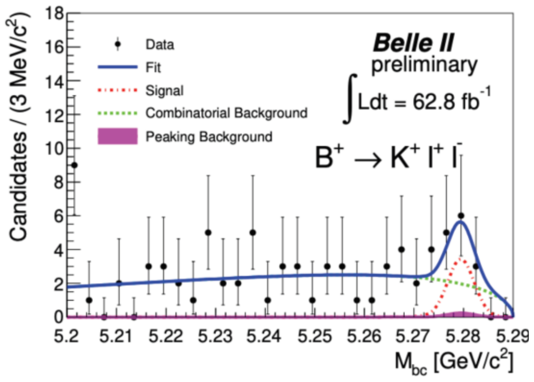
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle P \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

Prospect for $RK^{(*)}$ at Belle II

- Belle results on RK and RK* statistically limited
  JHEP03(2021)105



- About 20fb^{-1} needed to confirm RK anomaly at 5 sigma
- $B^+ \to K^+\ell\ell$ already seen with 63 fb-1
- Belle II can also do inclusive final state analysis

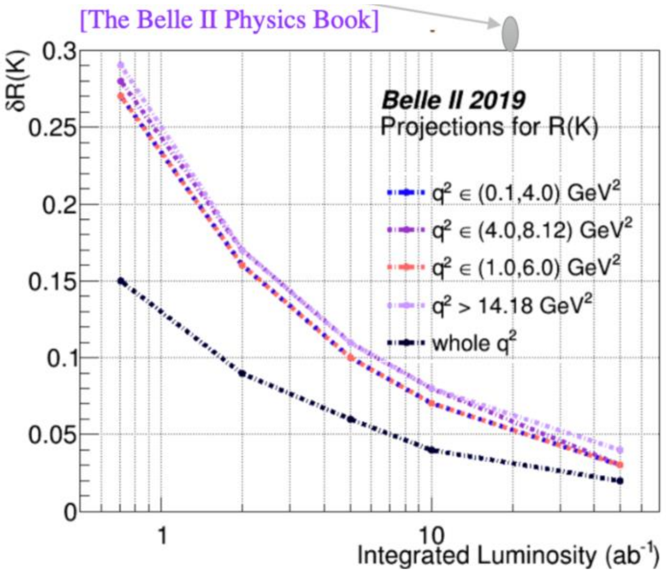


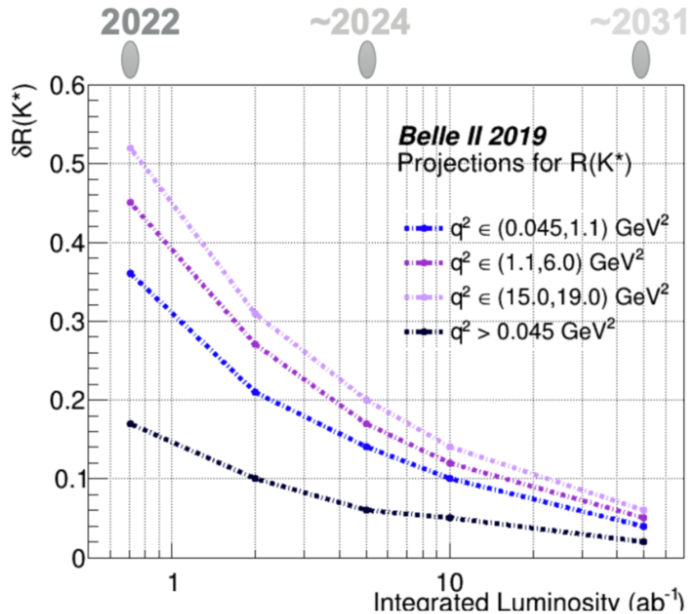
BELLE2-NOTE-PL-2021-005

$$M_{bc} = \sqrt{E_{beam}^2 - |\overrightarrow{p_B}|^2}$$

In comparison to LHCb, 3 different aspects to consider: efficiency, statistics and resolution

	Belle II	LHCb
Signal	K^+, K_S	K^+
Same K e e Statistics	1 ab^{-1}	1 fb^{-1}
B->K mu mu Efficiency	30 %	~5 %
B->K e e Efficiency	30 %	<5% Lower due to tracking and trigger
B->K e e Resolution	Better thanks to M_{bc}	Worse because of Brems
High q² bin	Accessible	Hard

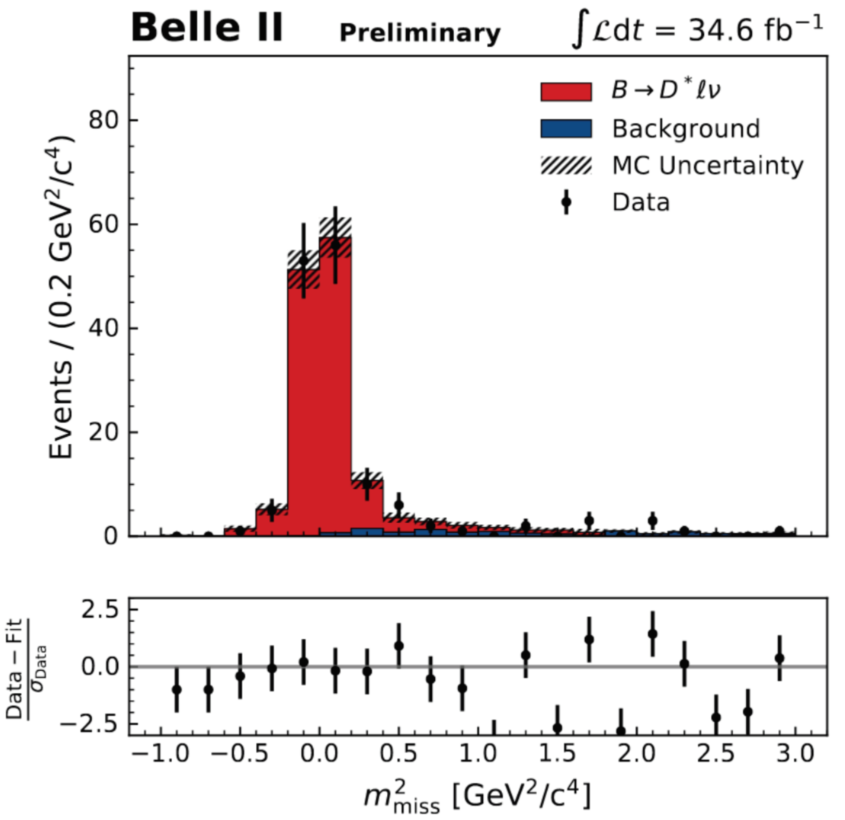




Prospects for RD(*)

- Rediscovery of $B \to D^{+*}\ell\nu$

Belle coll.,BELLE2-CONF-PH-2020-009



Bernlochner et al, arXiv:2101.08326

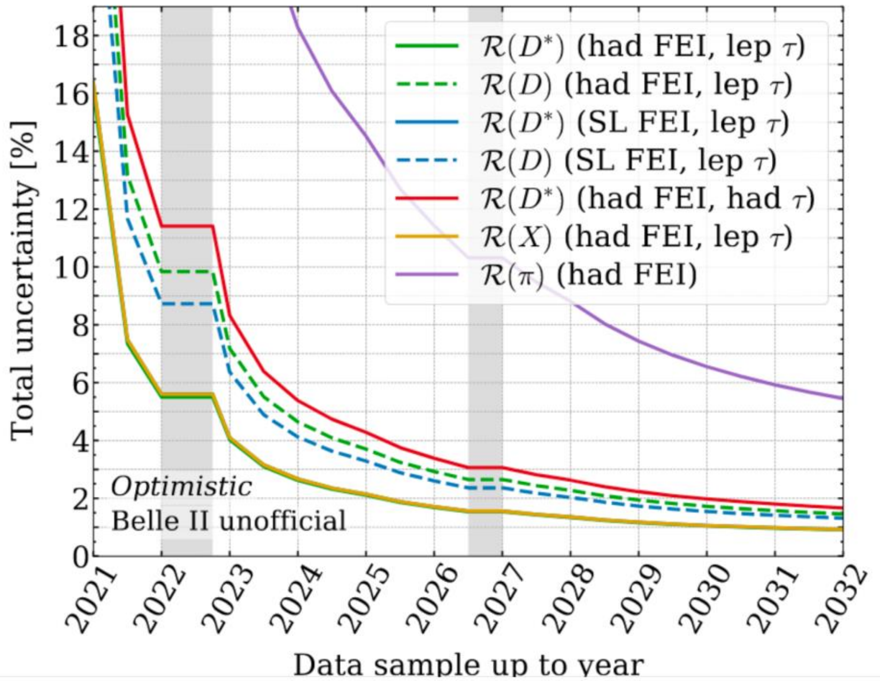


Table 49: Composition of the systematic uncertainty in each Belle analysis. Relative uncertainties in percent are shown. The analysis method and the τ decay mode are indicated in the parentheses; their meaning is explained in the caption of Table 48.

	Belle (Had, ℓ^-)	Belle (Had, ℓ^-)	Belle (SL, ℓ^-)	Belle (Had, h^-)
Source	R_D	R_{D^*}	R_{D^*}	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%	$^{+3.4}_{-3.5}\%$	$^{+10.0}_{-9.0}\%$

More Prospects on LFV modes

Mode	BR U.L. (90% CL)
$B^0 \to K^{*0}\mu^+e^-$	$<1.2\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu^-e^+$	$<1.6\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu e$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\mu^-e^+$	$<7.0\times10^{-9}$ (**LHCb**) $<3.0\times10^{-8}$ (**Belle**)
$B^+ \to K^+\mu^+e^-$	$<6.4\times10^{-9}$ (**LHCb**) $<8.5\times10^{-8}$ (**Belle**)
$B^0 \to K_s^0\mu^\pm e^\mp$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\tau\mu$	$<4.8\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau e$	$<3.0\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau^+\mu^-$	$<3.9\times10^{-5}$ (**LHCb**)

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-)\cdot 10^5$	< 32	< 6.5	< 2.0
$\mathrm{Br}(B^0 \to \tau^+\tau^-)\cdot 10^5$	< 140	< 30	< 9.6
$\mathrm{Br}(B_s^0 \to \tau^+\tau^-)\cdot 10^4$	< 70	< 8.1	–
$\mathrm{Br}(B^+ \to K^+\tau^\pm e^\mp)\cdot 10^6$	–	–	< 2.1
$\mathrm{Br}(B^+ \to K^+\tau^\pm \mu^\mp)\cdot 10^6$	–	–	< 3.3
$\mathrm{Br}(B^0 \to \tau^\pm e^\mp)\cdot 10^5$	–	–	< 1.6
$\mathrm{Br}(B^0 \to \tau^\pm \mu^\mp)\cdot 10^5$	–	–	< 1.3