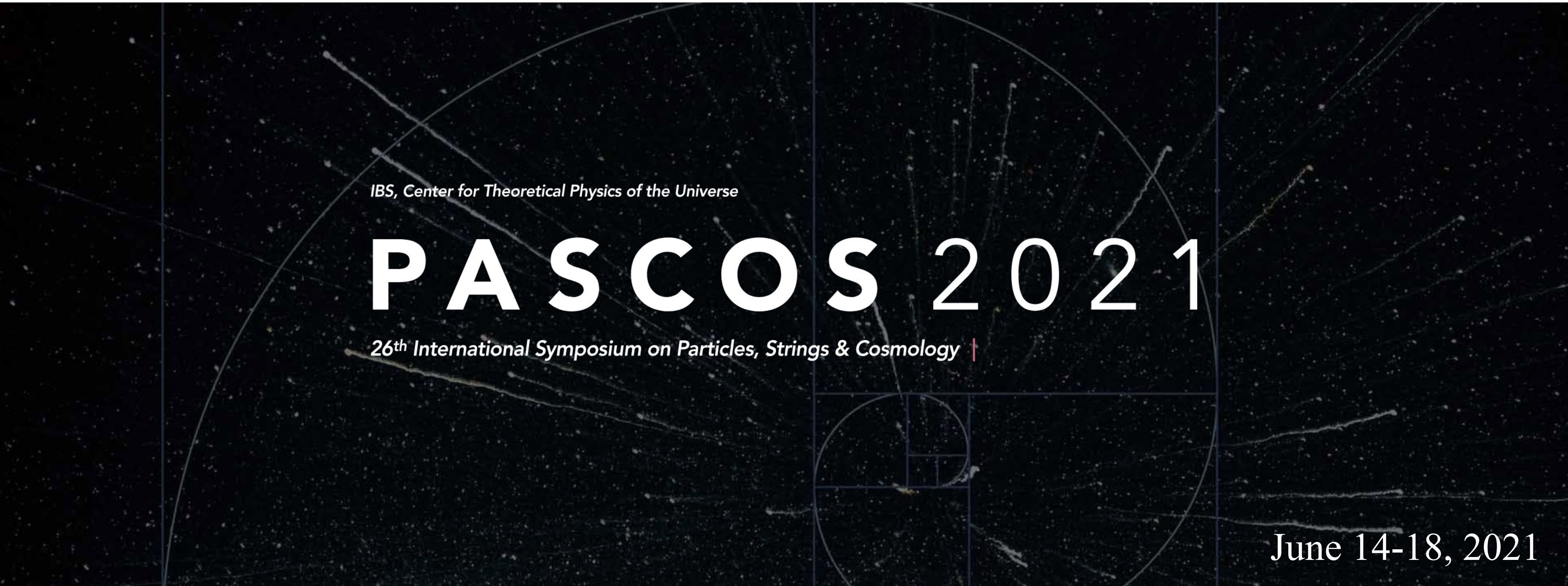
Latest results from Belle and Belle II

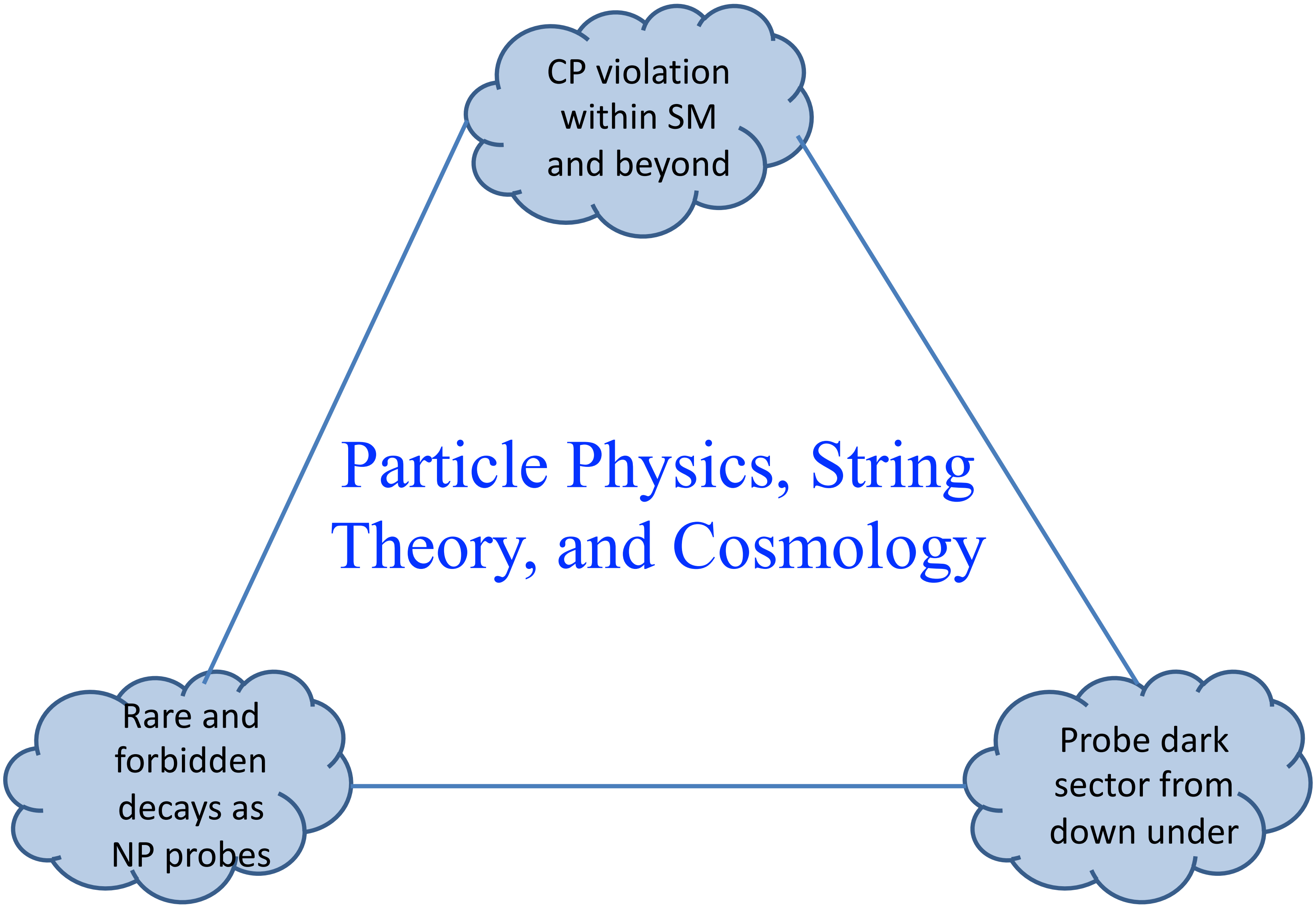
Gagan Mohanty
tifr

BELLE Belle II

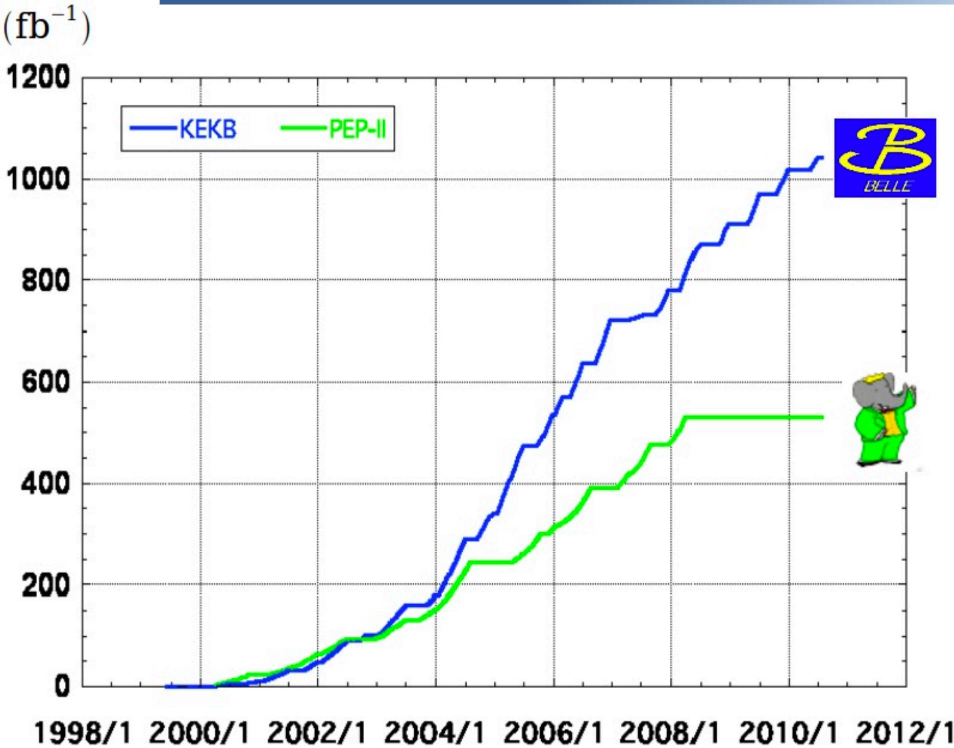


June 14-18, 2021

Ethos of the PASCOS series



1st-generation flavor factory experiments

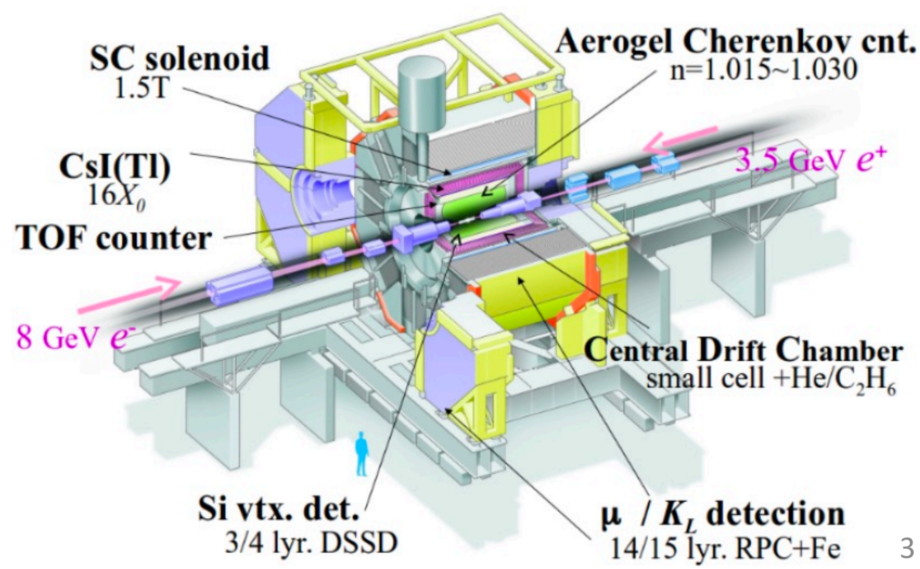


> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

- Belle stopped taking data more than 10 yr ago, though physics harvesting continues unabated
- Has published 2 PRL, 4 JHEP and 15 PRD papers since last yr

Belle Detector

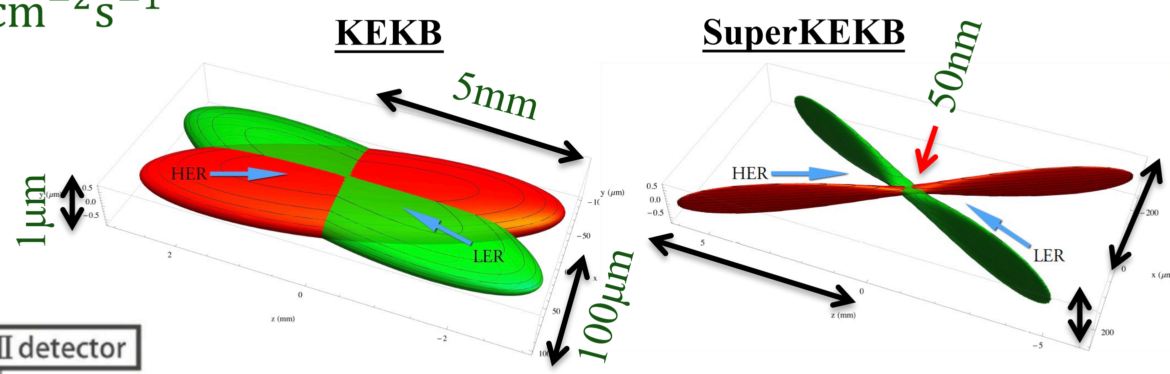


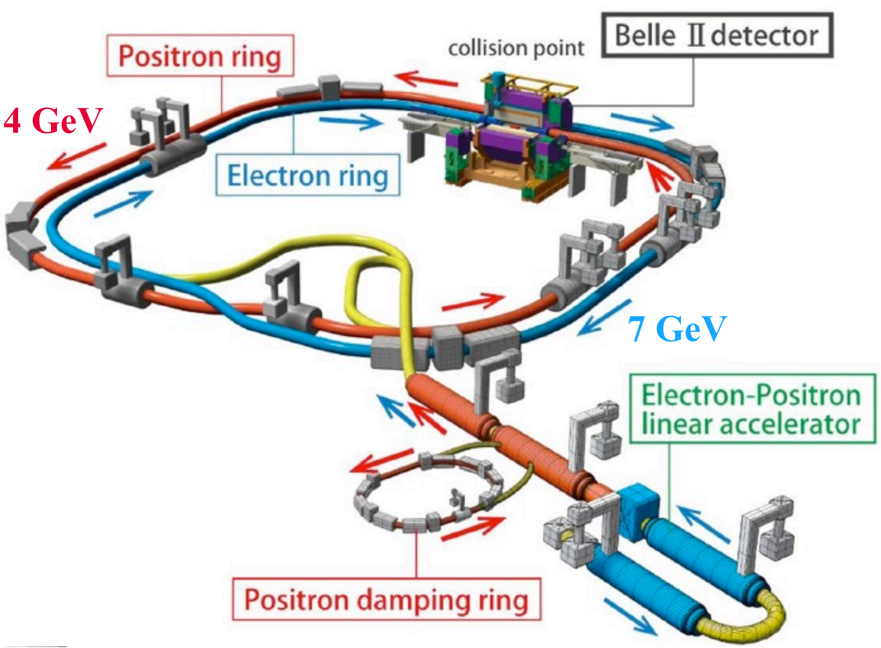
- Shall present a selected sample of results obtained with the full data sample, unless stated otherwise

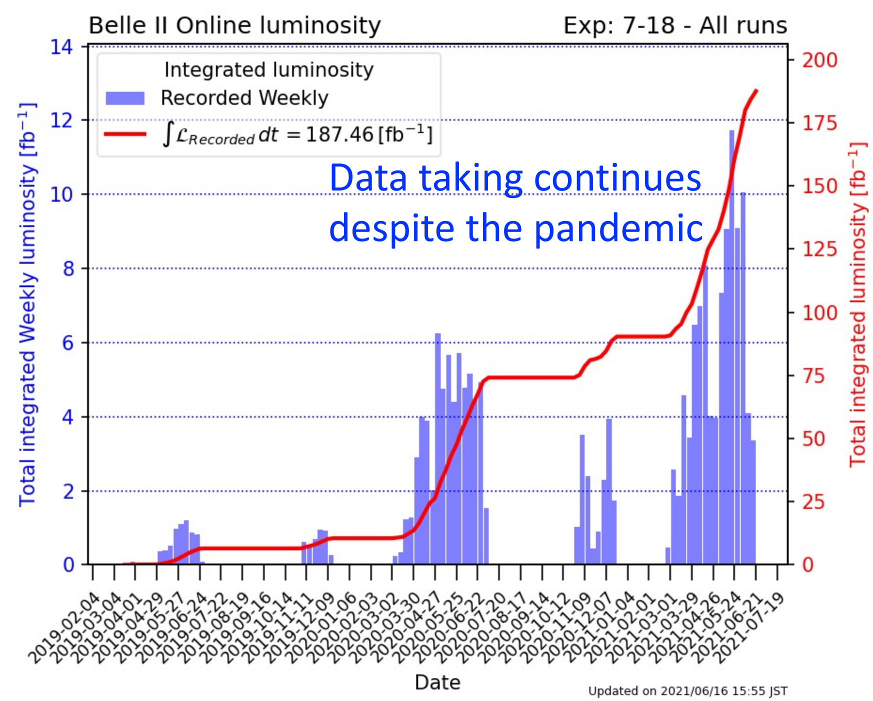
☞ For the complete list, refer to: https://belle.kek.jp/bdocs/b_journal.html

SuperKEKB: Next generation flavor factory

- Plan to deliver collisions at a peak luminosity of $6.5\times10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (30 times that of KEKB) by increasing beam current 1.5 times and reducing beam size by 20 times
- Reached already $2.96\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (May 17, 2021)



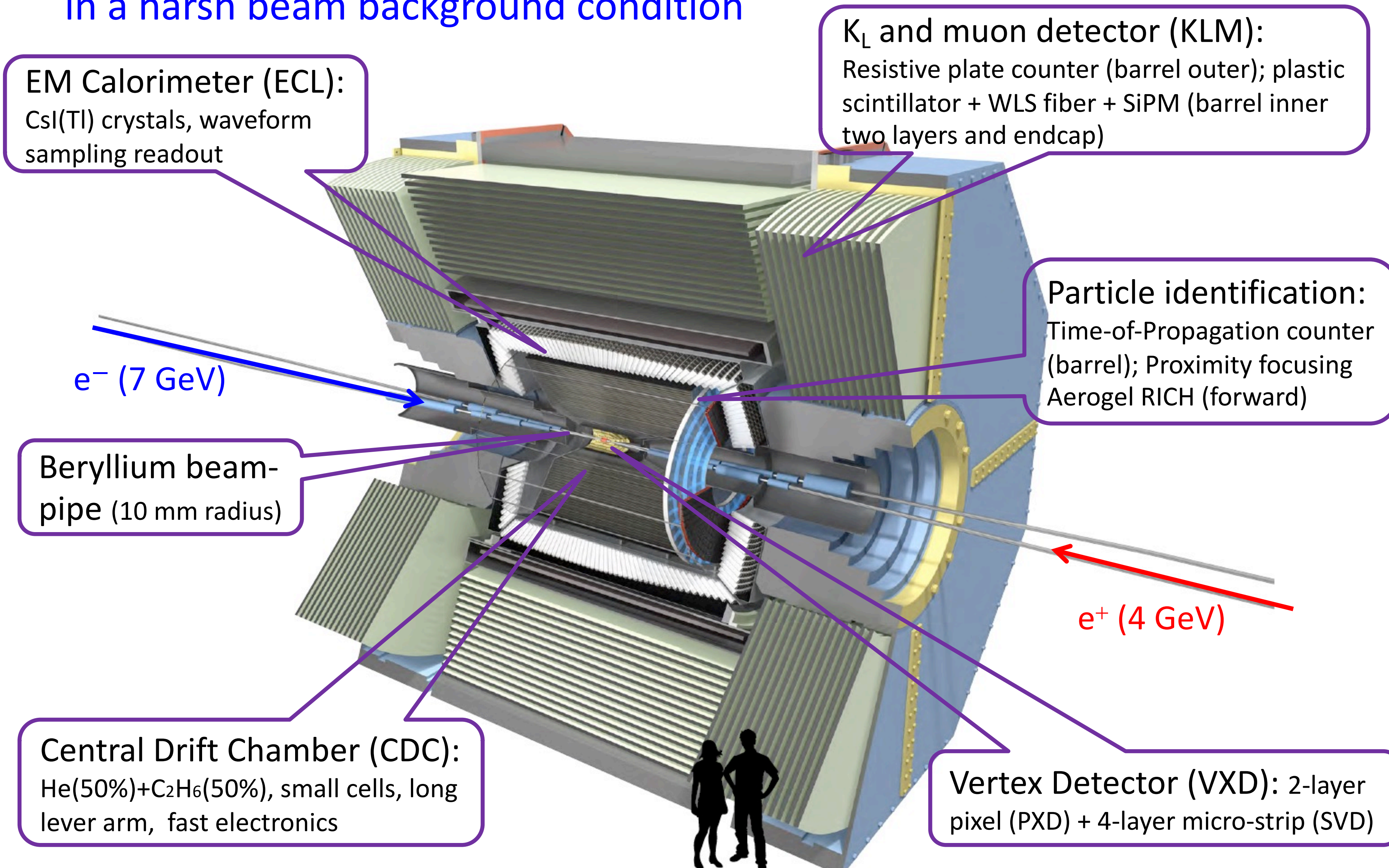




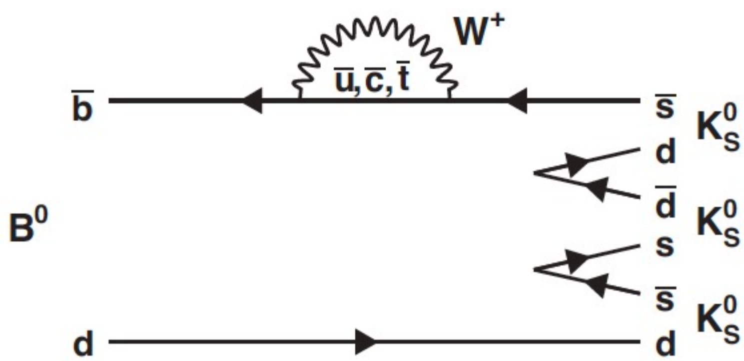
☞ Has recorded ~ 190 fb^{-1} so far, while latest published results based on ≤ 72 fb^{-1} data

Belle II: A 21^{st} century HEP experiment

☞ Designed to operate with a performance similar or better than Belle, but in a harsh beam background condition



Search for new CPV source in $B^0 \to K_S^0 K_S^0 K_S^0$

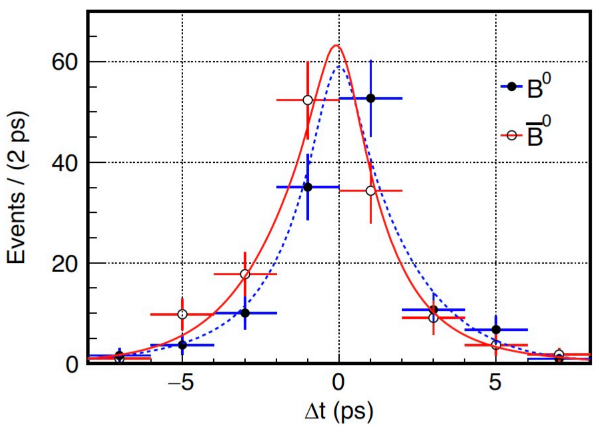


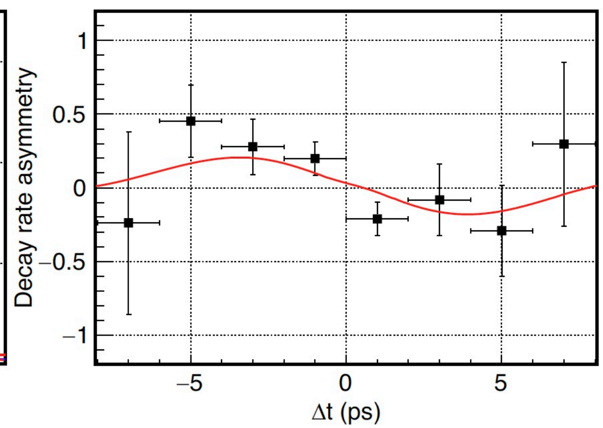
- Potential NP contributions in the $b \to s$ loop can affect the time-dependent decay rate

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}(1 + q[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)])$$

- Mixing-induced CPV term $\mathcal{S}$ will then differ from that measured in $b \to c\bar{c}s$ transitions ($\equiv -\sin 2\phi_1$), which acts as an SM candle

- Direct CP violation term $\mathcal{A}$ can also deviate from its SM value of zero





PRD 103, 032003 (2021)

$\mathcal{S} = -0.71 \pm 0.23(\text{stat}) \pm 0.05(\text{syst})$

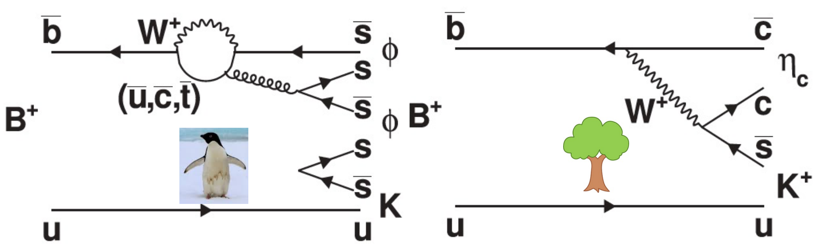
2.5σ significance

$\mathcal{A} = 0.12 \pm 0.16(\text{stat}) \pm 0.05(\text{syst})$

- Consistent with the WA of $-\sin 2\phi_1$ (-0.70) as well as with its inferred value
- Significantly more precise than the previous Belle result PRL 98, 031802 (2007) and consistent with BaBar PRD 85, 054023 (2012)

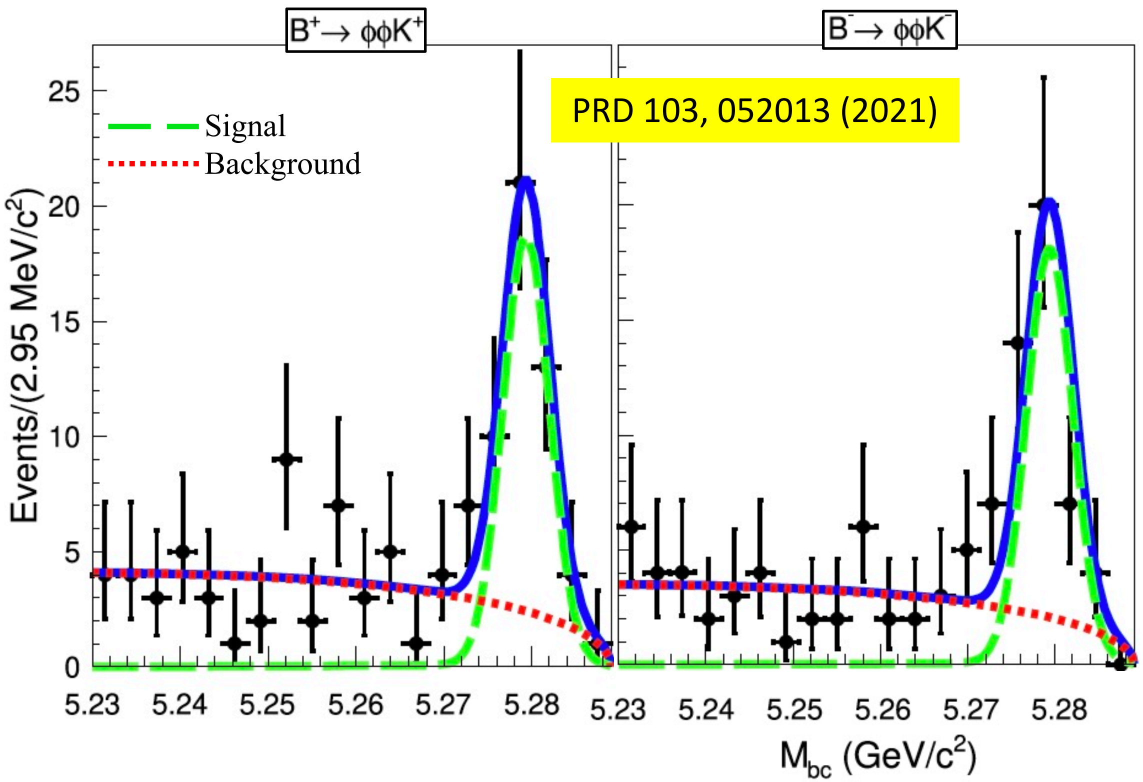
☞ Earlier there was a 1.6σ discrepancy between the two experiments

Story of another $b \to s\bar{s}s$ mediated decay



- Expect no CP violation from the interference btw penguin and tree ($\eta_c \to \phi\phi$) diagrams
- NP contributions in the loop can enhance CP asymmetry to the level of 40%

PLB 583, 285 (2004)



- BF and CP asymmetry measured below the η_c threshold ($m_{\phi\phi} < 2.85\ \mathrm{GeV}/c^2$):

$$\mathcal{B}(B^\pm \to \phi\phi K^\pm) = (3.43^{+0.48}_{-0.46} \pm 0.22)\times 10^{-6}$$
$$A_{CP}(B^\pm \to \phi\phi K^\pm) = -0.02 \pm 0.11 \pm 0.01$$

- CP asymmetry in the η_c region ($m_{\phi\phi} \in [2.94, 3.02]\ \mathrm{GeV}/c^2$):

$$A_{CP}(B^\pm \to \phi\phi K^\pm) = -0.12 \pm 0.12 \pm 0.01$$

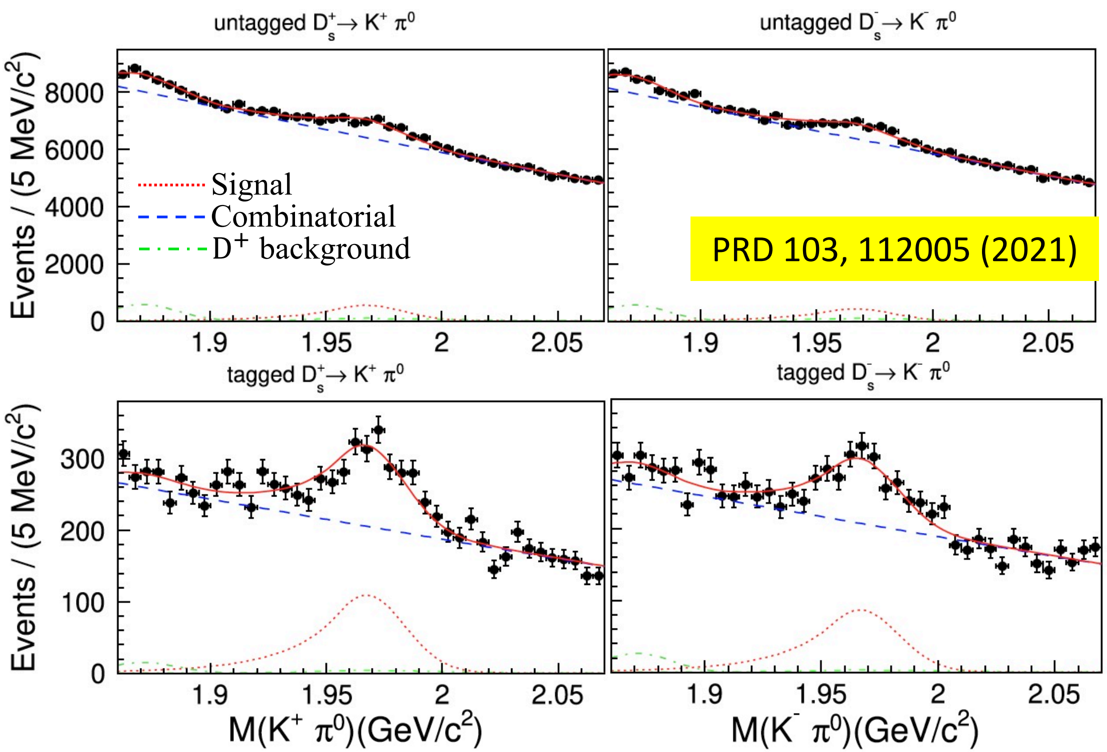
is consistent with no CP violation

- Measured BF for the $B^0 \to \phi\phi K^0$ decay is $\left(3.02^{+0.75}_{-0.66} \pm 0.20\right)\times 10^{-6}$
- Consistent with theory prediction that lies in the range $(1.3\text{–}4.3)\times 10^{-6}$

PRD 69, 114020 (2004) PRD 70, 054006 (2004)

Moving to CP violation in charm decays

- CP violation in the charm sector is expected to be $\mathcal{O}(10^{-3})$ or smaller PRD 86, 036012 (2012)
- Largest effect in singly Cabibbo-suppressed (SCS) decays, thanks to the contribution from penguin diagrams
- As Cabibbo-favored (CF) decays proceed via tree-level amplitudes, nonzero CPV asymmetry in these decays would be a smoking gun signal for NP



$$\mathcal{B}(D_s^+ \to K^+\pi^0) = (0.735 \pm 0.052 \pm 0.030 \pm 0.026) \times 10^{-3}$$
$$\mathcal{B}(D_s^+ \to K^+\eta) = (1.75 \pm 0.05 \pm 0.05 \pm 0.06) \times 10^{-3}$$
$$\mathcal{B}(D_s^+ \to \pi^+\eta) = (19.00 \pm 0.10 \pm 0.59 \pm 0.68) \times 10^{-3}$$

- Measured BF and CP asymmetry in the SCS decays $D_s^+ \to K^+(\pi^0, \eta)$ as well as in the CF decay $D_s^+ \to \pi^+\eta$
- We reconstruct D_s^+ either directly (untagged) or in the decay $D_s^{*+} \to D_s^+\gamma$ (tagged)
  - ☞ $D_s^+ \to \phi\pi^+$ is the reference channel

$$A_{CP}(D_s^+ \to K^+\pi^0) = 0.064 \pm 0.044 \pm 0.011$$
$$A_{CP}(D_s^+ \to K^+\eta) = 0.021 \pm 0.021 \pm 0.004$$
$$A_{CP}(D_s^+ \to \pi^+\eta) = 0.002 \pm 0.003 \pm 0.003$$

  - ☞ Most precise results, significantly improve over current WA values showing no hint for CP violation
- These BF and A_{CP} values can be used in sum rules to provide stringent predictions for CPV in charm PRL 115, 251802 (2015)

Rekindling the ΔA_{CP} saga

- Significant difference ($\Delta A_{CP} = 0.124 \pm 0.021$) between the direct CP asymmetry in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays
- As these decays suffer from large hadronic uncertainties, an isospin sum rule has been proposed in order to clear the air

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

- Constitutes a null test of SM in the limit of isospin symmetry and in absence of electroweak penguin contributions to $B \to K\pi$ decays

PLB 627, 82 (2005)

☞ A violation of the sum rule would be evidence for NP

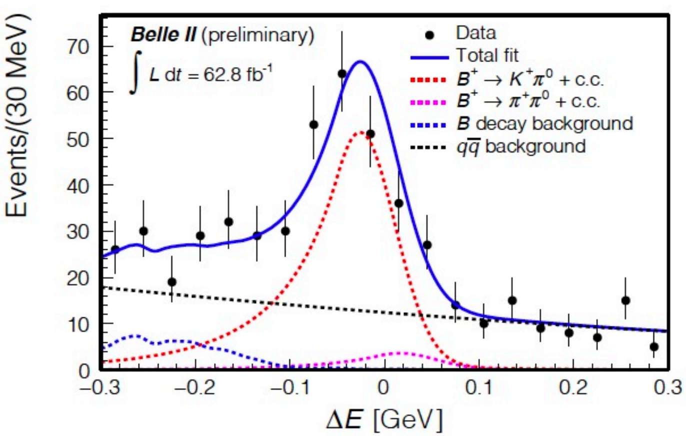
- Performed measurements of $\mathcal{B}$ and A_{CP} of $B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$

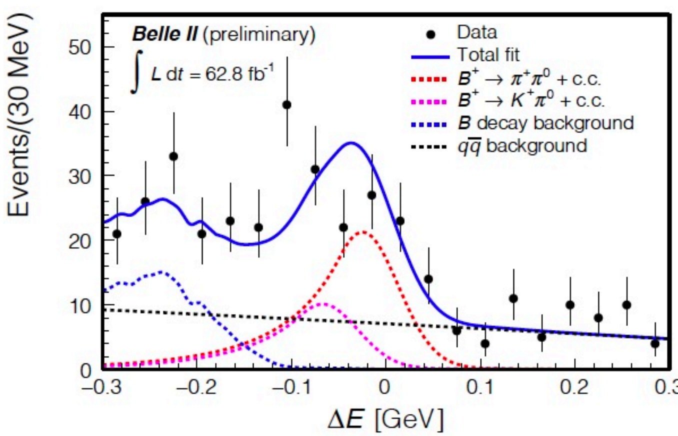
$$\mathcal{B}(B^+ \to K^+\pi^0) = [11.9^{+1.1}_{-1.0}(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-6}$$
$$\mathcal{B}(B^+ \to \pi^+\pi^0) = [5.5^{+1.0}_{-0.9}(\text{stat}) \pm 0.7(\text{syst})] \times 10^{-6}$$

$$\mathcal{A}_{CP}(B^+ \to K^+\pi^0) = -0.09 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$$
$$\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})$$

arXiv:2105.04111

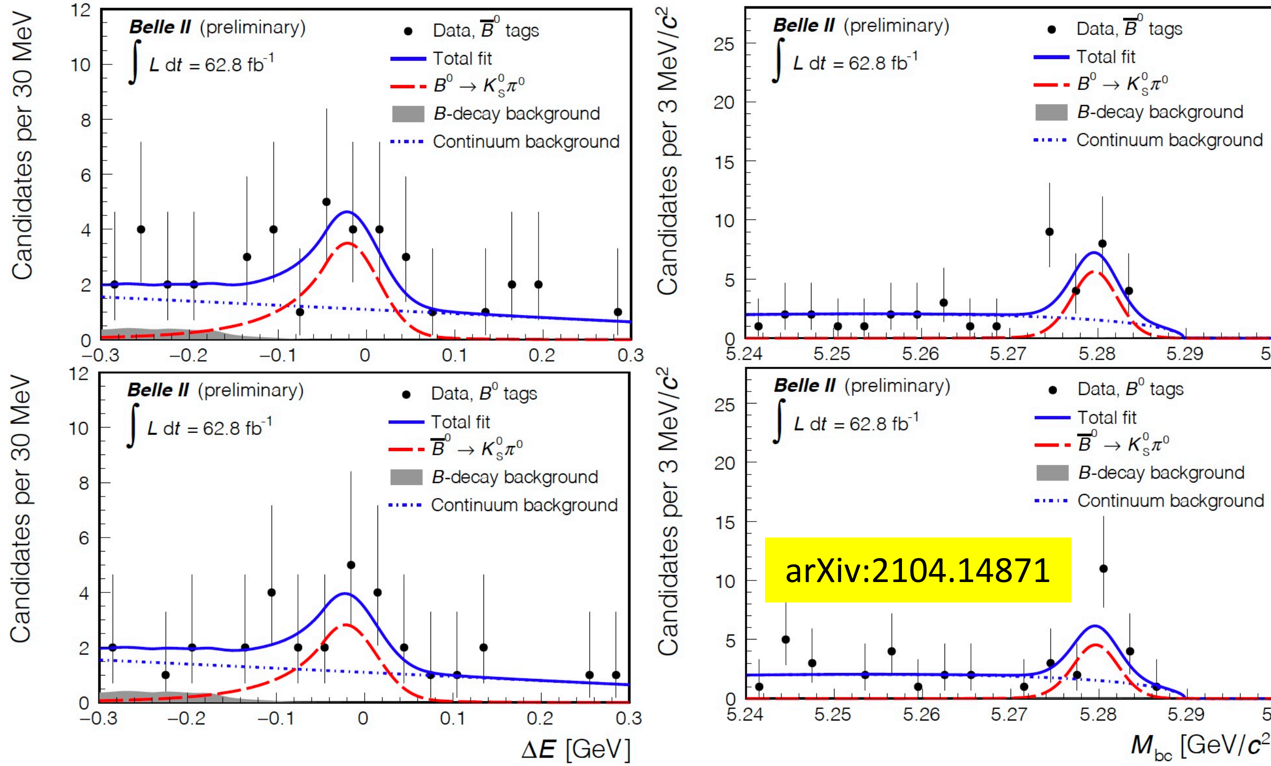
- Consistent with previous results & show detector performance to be comparable with early Belle





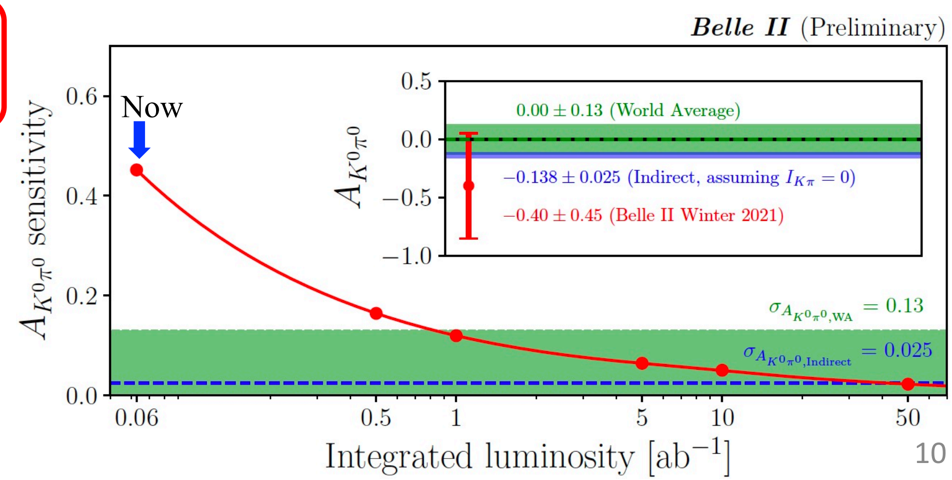
The most challenging one: $B^0 \to K_S^0 \pi^0$

- Precision on $A_{K^0\pi^0}$ is the most limiting input for testing the sum rule
- Experimental challenges:
  - π^0 final state $\Rightarrow$ tail in ΔE distributions
  - CP eigenstate $\Rightarrow$ need flavor tagging
  - K_S^0 flies before decay $\Rightarrow$ has own challenge for time-dependent CP violation study
- Found ~ 50 $B^0 \to K_S^0 \pi^0$ candidates and measured:



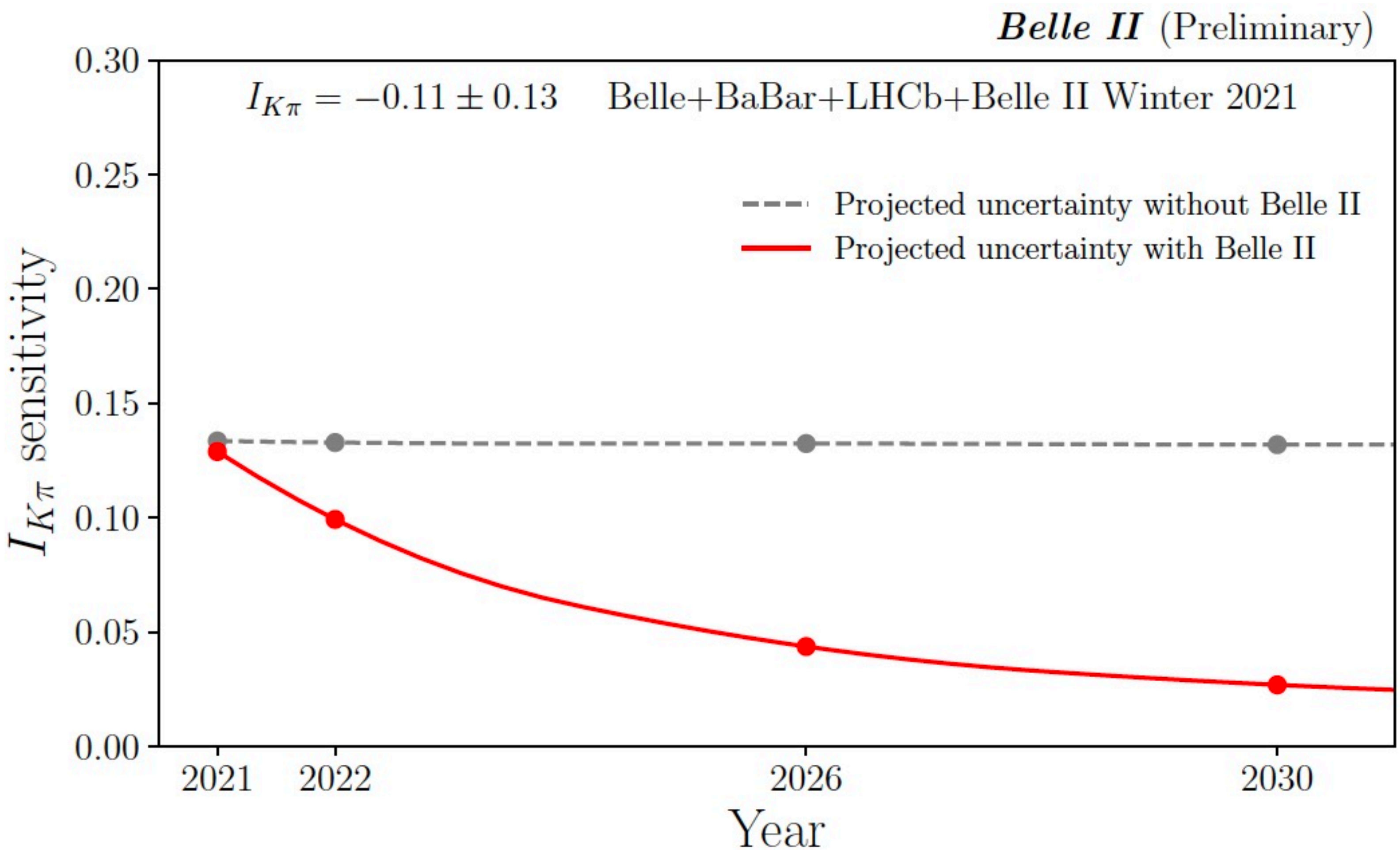
$$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\mathrm{stat}) \pm 1.2(\mathrm{syst})] \times 10^{-6}$$
$$\mathcal{A}_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(\mathrm{stat}) \pm 0.04(\mathrm{syst})$$

- π^0 reconstruction efficiency is dominant systematic source for branching fraction
- Need to substantially improve the $A_{K^0\pi^0}$ precision as we accumulate more data
  - Time-dependent CP study is underway

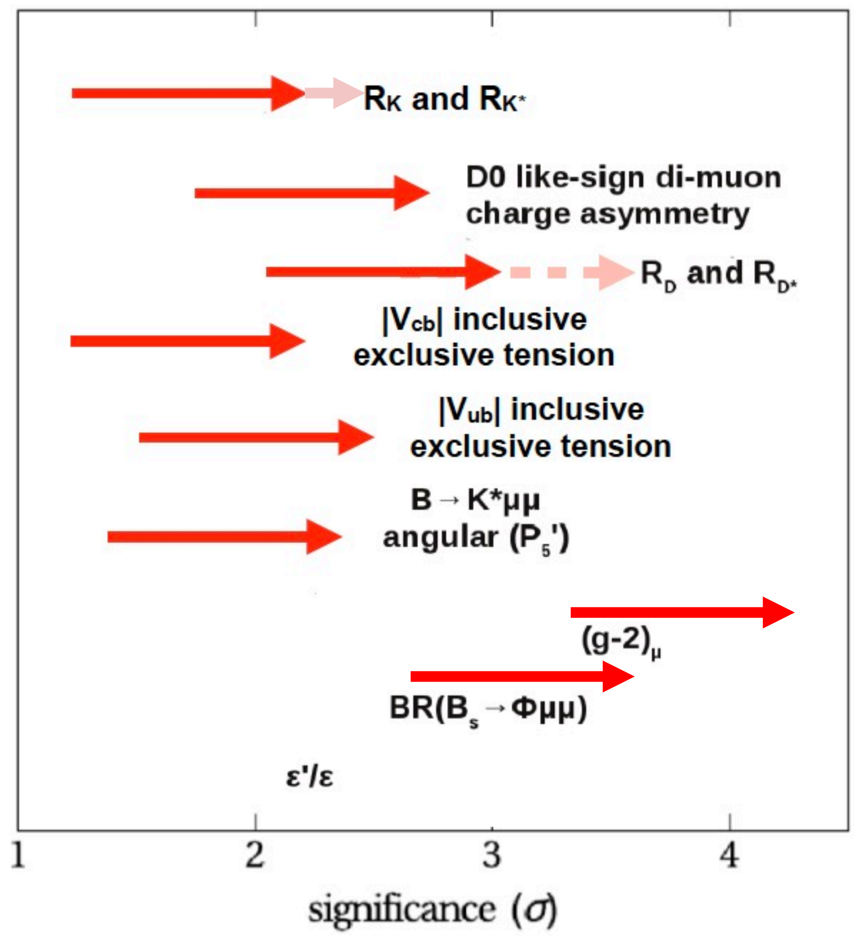


Sum rule test: present and future

- Expect Belle II to be a crucial player in resolving the Kπ puzzle
- Direct CP asymmetry in the $B^0 \to K_S^0\pi^0$ channel will be the key



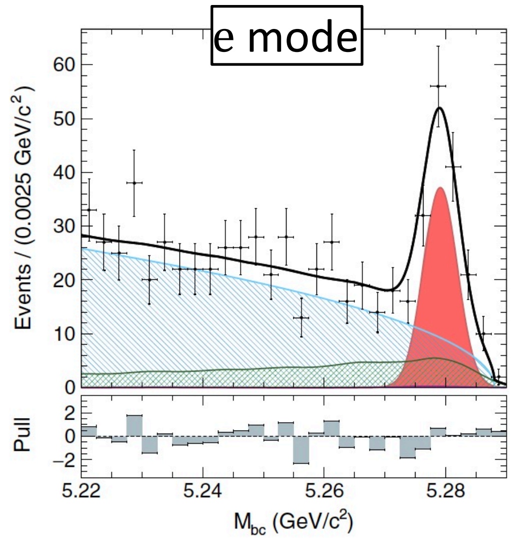
Nature's hint or teasing?

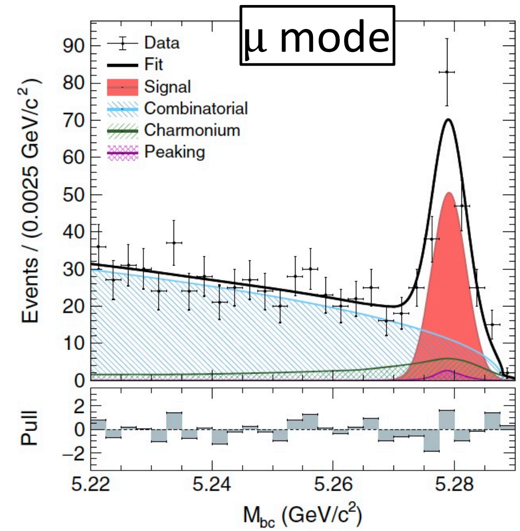


☞ At present we are faced with a number of flavor anomalies, mostly related to muons, that needed to be tested with more data and taken in a complementary setup

Measurement of R_{K^*} at Belle

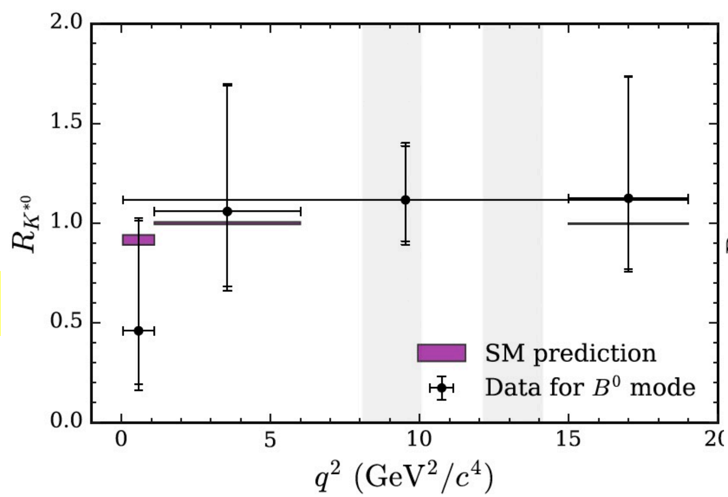
- Test the lepton-flavor universality (LFU) by measuring the ratio of $\mathcal{B}(B \to K^* \mu^+ \mu^-)$ and $\mathcal{B}(B \to K^* e^+ e^-)$, with K^{*+} reconstructed in the final states of $K^+\pi^0$ and $K^0_S\pi^+$ and K^{*0} in $K^+\pi^-$ and $K^0_S\pi^0$
- The R_{K^*} ratio is theoretically robust as FF related uncertainties cancel
- Measured R_{K^*} in a number of q^2 bins including the one up to 19 GeV^2/c^4
- Similar performance for electron and muon mode (103 vs. 140 signal evt)
- $R_{K^{*+}}$ is measured for the first time



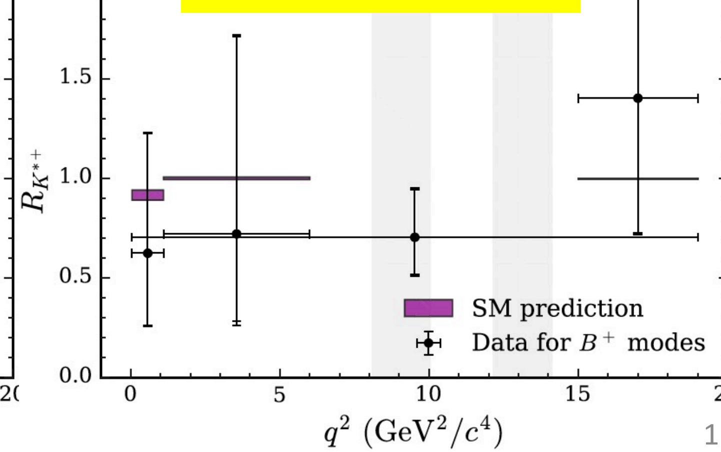


☞ Results consistent with SM predictions with largest deviation found in the lowest q^2 bin, where LHCb reports an $R_{K^{*0}}$ value differing from the SM expectation

JHEP 08 (2017) 055

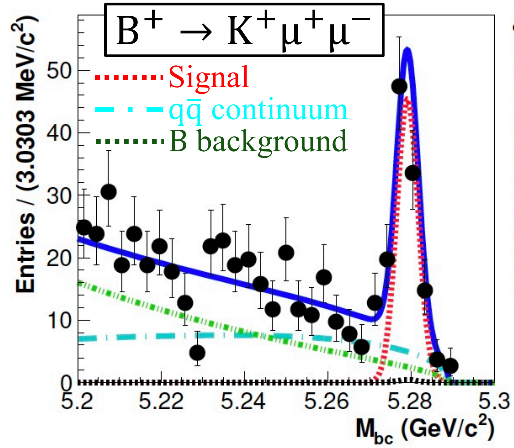


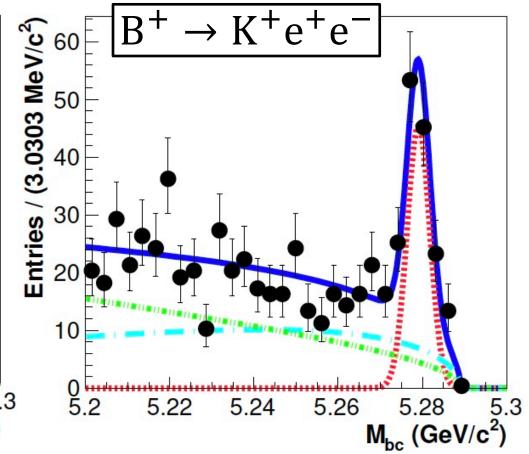
PRL 126, 161801 (2021)



Measurement of R_K at Belle

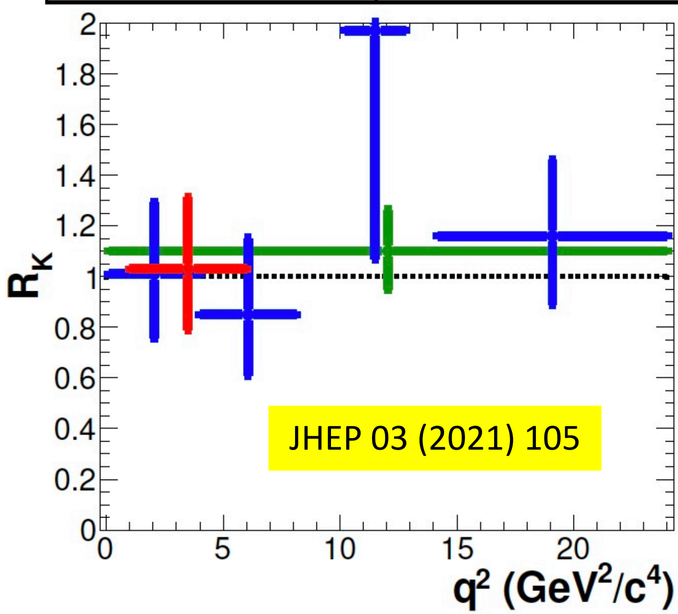
- Similar to R_{K^*}, tested LFU in the ratio $\mathcal{B}(B \to K\mu^+\mu^-)/\mathcal{B}(B \to Ke^+e^-)$ in a number of q^2 bins
- Also, measured CP-averaged isospin asymmetries (A_I) in the electron and muon mode
- M_{bc} projections of a multidim. fit for B^+ case are shown in right two plots

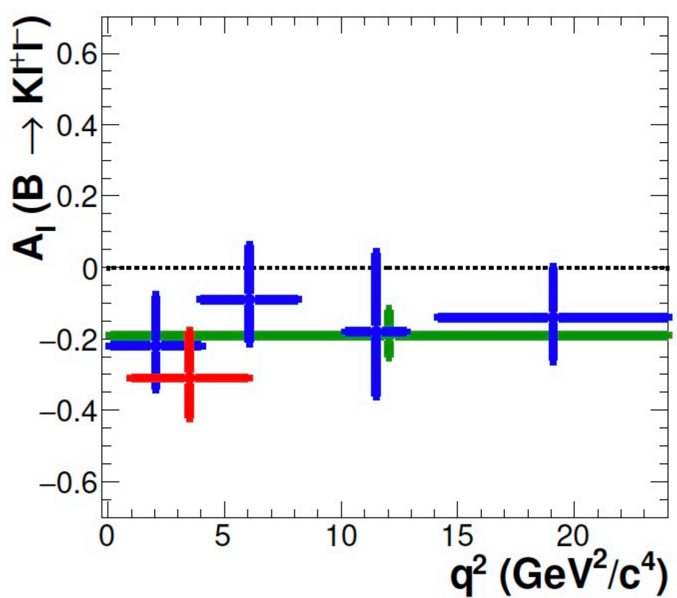




q^2 (GeV^2/c^4)	Comb. (B^0/B^+)
[1.0, 6.0]	$1.03^{+0.28}_{-0.24} \pm 0.01$
whole q^2	$\mathbf{1.10}^{+0.16}_{-0.15} \pm 0.02$

- ☞ R_K values for various q^2 bins agree with SM predictions
- ☞ Our result for the bin of interest (red marker in lower left) is higher than LHCb by 1.6σ





- ☞ A_I results are consistent with null asymmetry with the largest difference of 2σ found in q^2 bin: $[1,6]\ GeV^2/c^4$

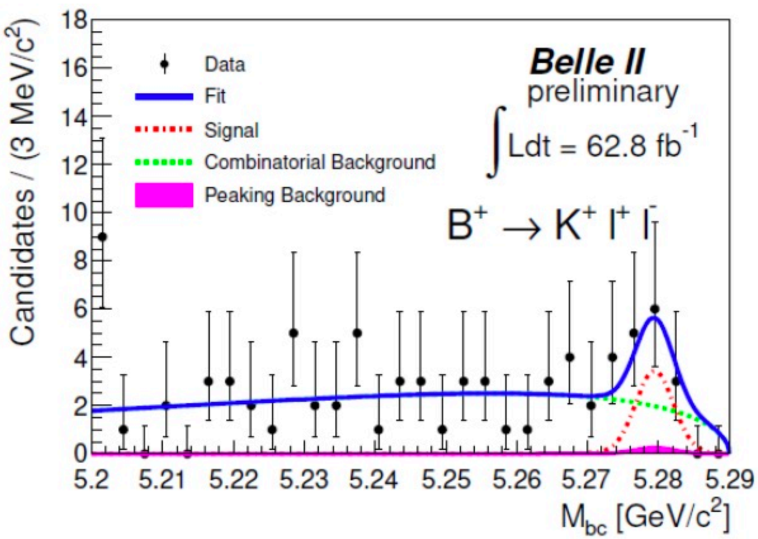
What does future hold for LFU test?

PTEP 2019 (2019) 12, 123C01

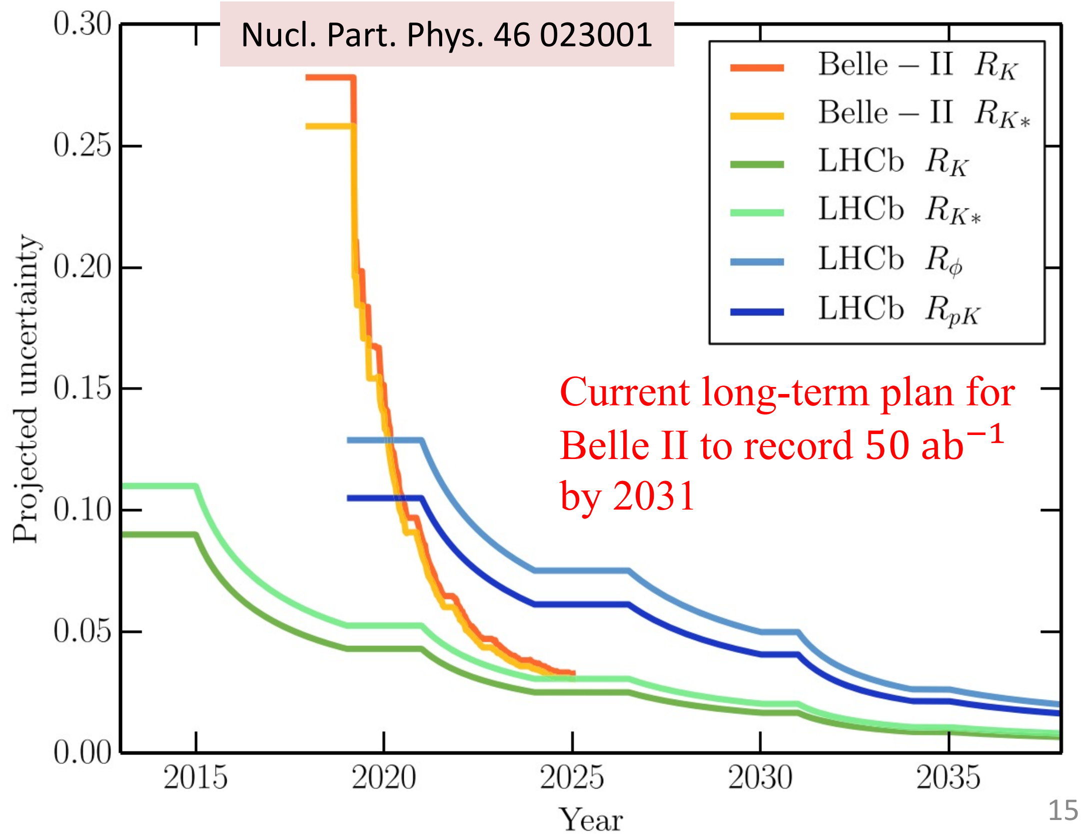
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (>14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (>14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (>14.4 GeV^2)	28%	11%	3.4%

- Using more data, we can reduce both stat and syst uncertainties
- Belle II offers a complementary setup with respect to LHCb
  - Similar performance for muon and electron channels
  - Upper hand in inclusive modes

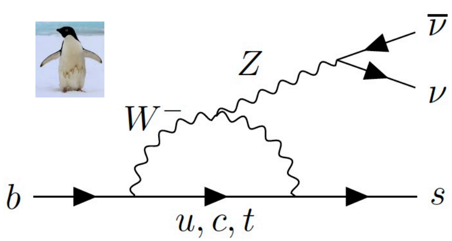
- While we have a long way to go, a beginning has been made with the rediscovery of one related channel

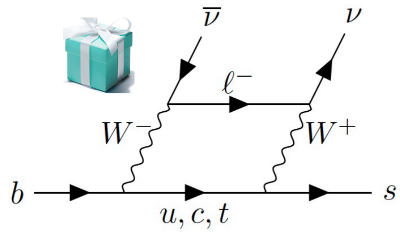


Nucl. Part. Phys. 46 023001



Search for $B^+ \to K^+ \nu\bar{\nu}$ decays

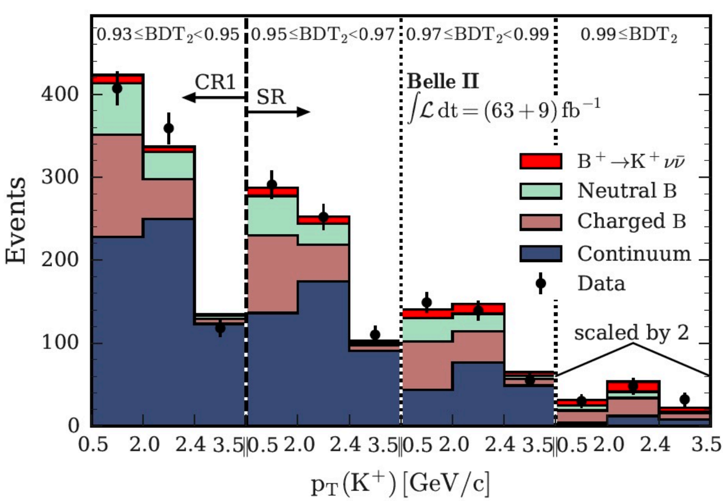




- This suppressed FCNC decay offers a complementary probe of NP scenarios proposed to explain flavor anomalies

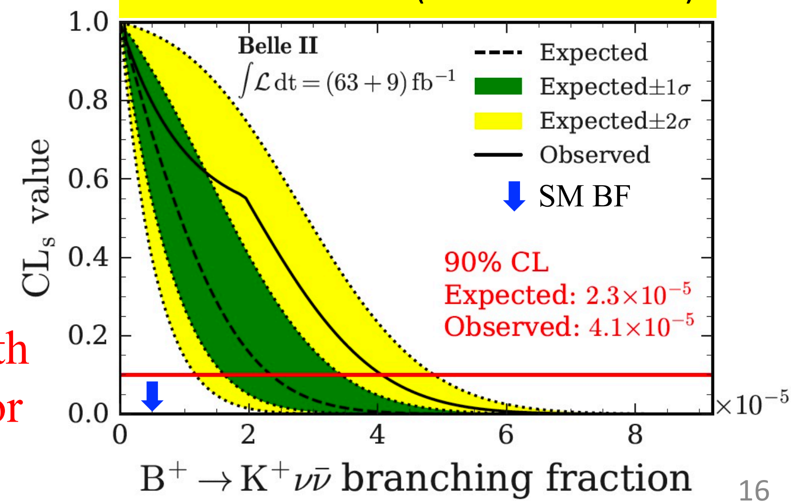
PRD 98, 055003 (2018); 102, 015023 (2020); 101, 095006 (2020)

- It could help constrain models with leptoquarks, axions, or DM particles
- Experimentally very challenging with two (escaping) neutrinos ⇒ information of the other B meson in the process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ is required
- Deployed a novel inclusive tagging method
  - Substantially larger signal efficiency of ~ 4% compared to ≪ 1% of the earlier approaches at the cost of higher background levels
- Two boosted decision tree classifiers, of which the 2nd one is nested, to fight against various backgrounds



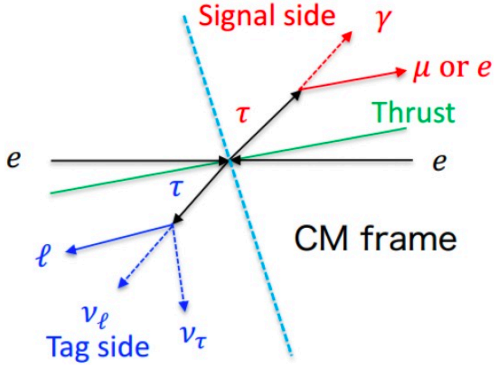
☞ Competitive with earlier results for similar data

arXiv:2104.12624 (submitted to PRL)



Lepton flavor violation in tau decays

- Conducted a search for LFV decays $\tau^{\pm} \to \ell^{\pm}\gamma$ ($\ell = e, \mu$) using twice the data size used in the earlier Belle result PLB 666, 16 (2008)
- Significant improvement in search sensitivities
  a) Introduced two new variables: energy asymmetry and $\xi^{CM}_{\tau(tag),track(tag)} \equiv \hat{p}^{CM}_{\tau(tag)} \cdot \hat{p}^{CM}_{track(tag)}$
  b) Performed optimization for the tag-side events
  c) Calibrated photon energy resolution using $\mu^+\mu^-(\gamma)$ events



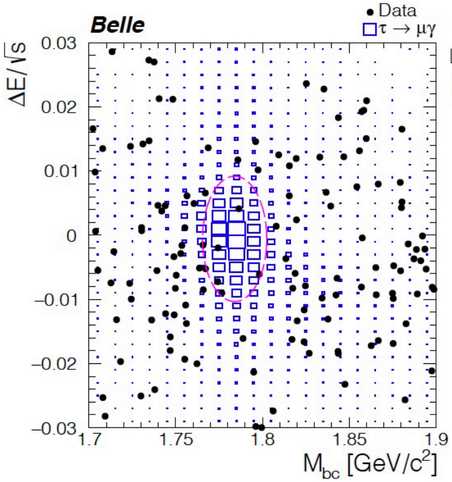
- Unbinned maximum-likelihood fit to:

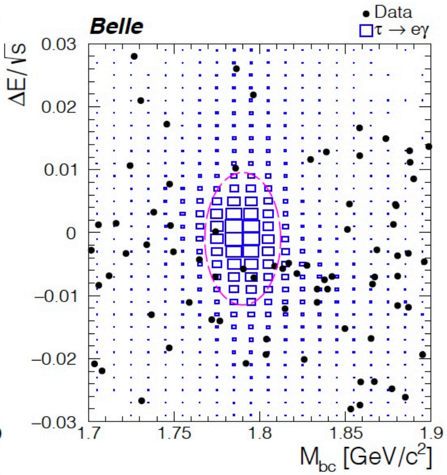
arXiv:2103.012994 (submitted to JHEP)

$$M_{bc} = \sqrt{(E^{CM}_{beam})^2 - (\vec{p}^{CM}_{\ell\gamma})^2}$$

$$\Delta E/\sqrt{s} = (E^{CM}_{\ell\gamma} - \sqrt{s}/2)/\sqrt{s}$$

Channel	$\tau \to \mu\gamma$	$\tau \to e\gamma$
Signal efficiency	3.7%	2.9 %
Exp. # bkgs.	5.8 ± 0.4	5.1 ± 0.4
Obs. event	5	5
N^{UL}_{sig}	2.8	3.0





➢ Expected 90% confidence-level upper limits, $\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\gamma) < 4.9\times 10^{-8}$ and $\mathcal{B}(\tau^{\pm} \to e^{\pm}\gamma) < 6.4\times 10^{-8}$, are 1.5–1.7 times more stringent than BaBar PRL 104, 021802 (2010)

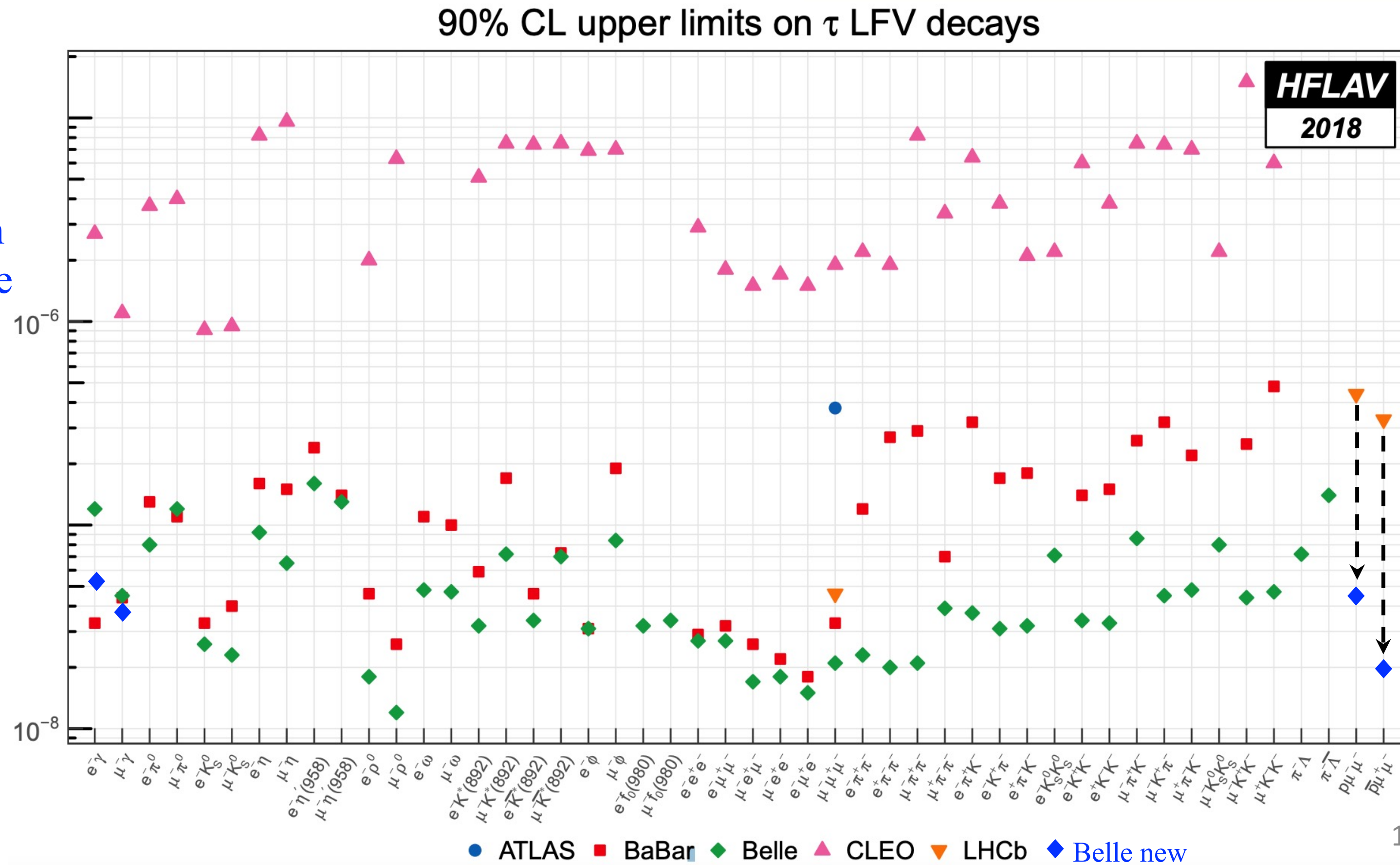
☞ Observed limits are $\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\gamma) < 4.2\times 10^{-8}$ and $\mathcal{B}(\tau^{\pm} \to e^{\pm}\gamma) < 5.6\times 10^{-8}$, of which the muon one is the most stringent to date

What about baryon number violation?

PRD 102, 111101(R) (2020)

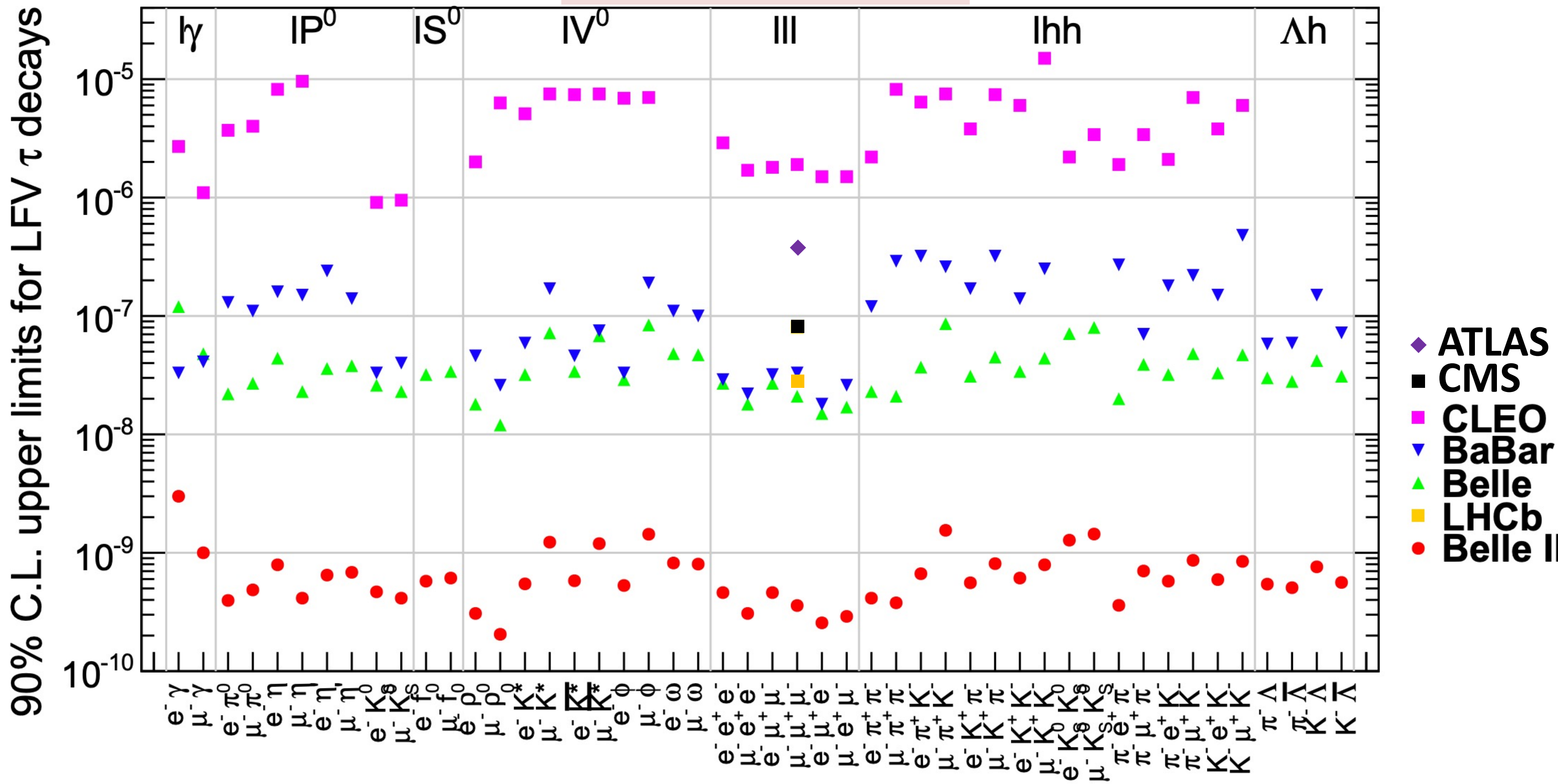
- Tau is the only lepton that can decay to hadrons
- Can potentially give rise to baryon number violating decays $\tau \to p\ell\ell'$ [$\ell^{(\prime)} = e, \mu$]; such processes will be a signature for NP e.g., supersymmetry, GUT and models with black holes
- Performed a search for $\tau \to p\ell\ell'$ decays
  - No evidence for a signal is found
  - Set 90% CL upper limits, improving LHCb limits by an order of magnitude in two channels
  - Brand new limits set for four other decay channels

All channels	$\epsilon(\%)$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}\,(\times 10^{-8})$
$\tau^- \to \bar{p}e^+e^-$	7.8	3.9	< 3.0
$\tau^- \to pe^-e^-$	8.0	4.1	< 3.0
$\tau^- \to \bar{p}e^+\mu^-$	6.5	2.2	< 2.0
$\tau^- \to \bar{p}e^-\mu^+$	6.9	2.1	< 1.8
$\tau^- \to p\mu^-\mu^-$	4.6	3.1	< 4.0
$\tau^- \to \bar{p}\mu^-\mu^+$	5.0	1.5	< 1.8



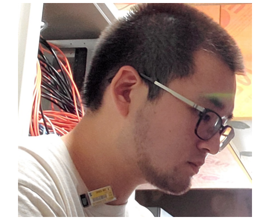
What can Belle II do?

PTEP 2019 (2019) 12, 123C01

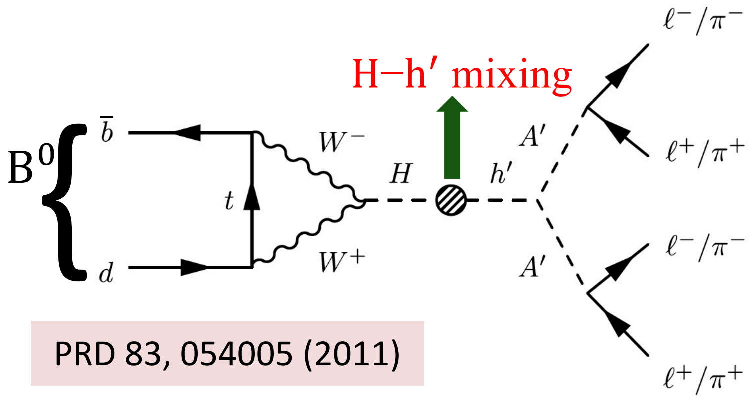


☞ Should be able to push upper limits for LFV and BNV decays by two orders of magnitude, in some cases hitting the 10^{-10} mark

Probing the dark sector



- A vector mediator of hypothetical $U'(1)$ gauge interaction of the dark sector, *aka* dark photon, may interact with matter via various portals

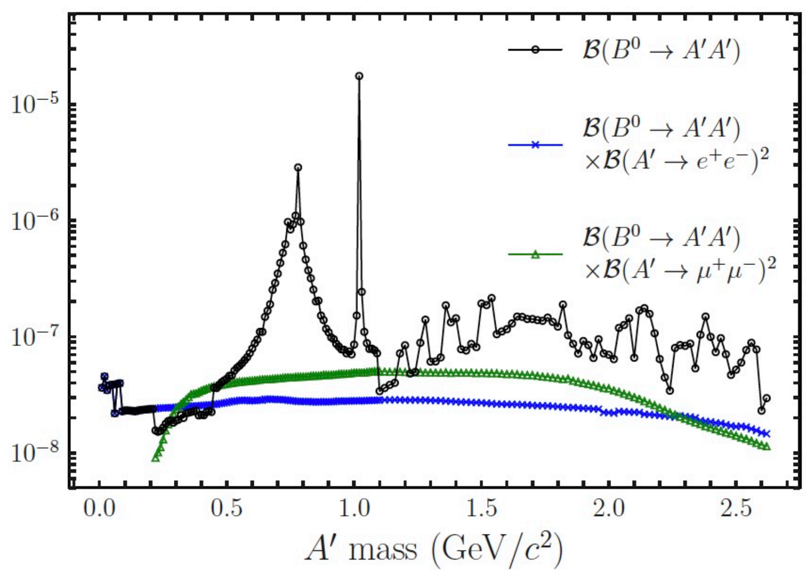


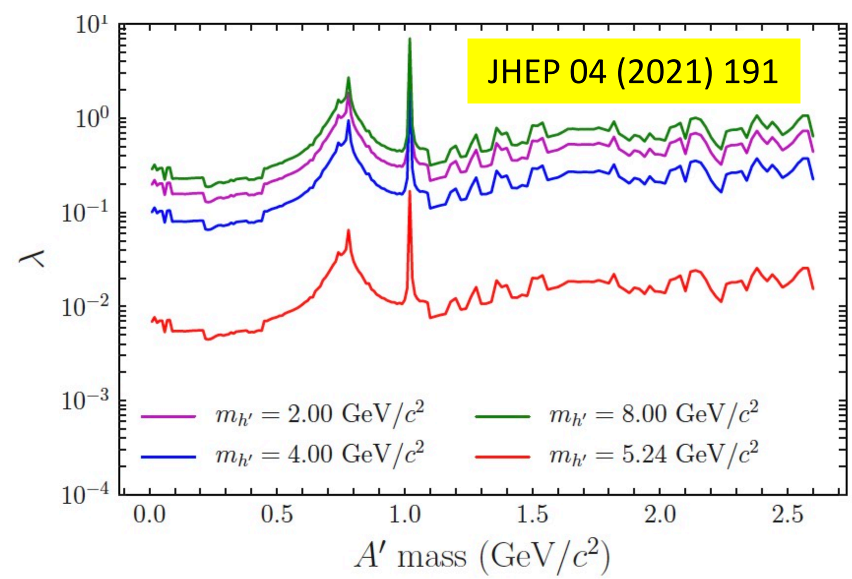
PRD 83, 054005 (2011)

- Search for a pair of dark photons A', mediated by an off-shell dark Higgs boson h', in decays of B^0 mesons
- These DM particles decay promptly each to a pair of leptons ($\ell = e, \mu$) or pions

➢ No signal found in the A' mass range $[0.01, 2.62]$ GeV/c^2 ⇒ 90% CL upper limits set on the product branching fractions

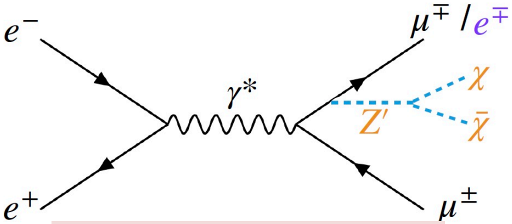
➢ From these limits, calculate the Higgs portal coupling λ for each assumed A' or h' mass





What about Belle II?

For more details refer to Savino's talk on Tuesday



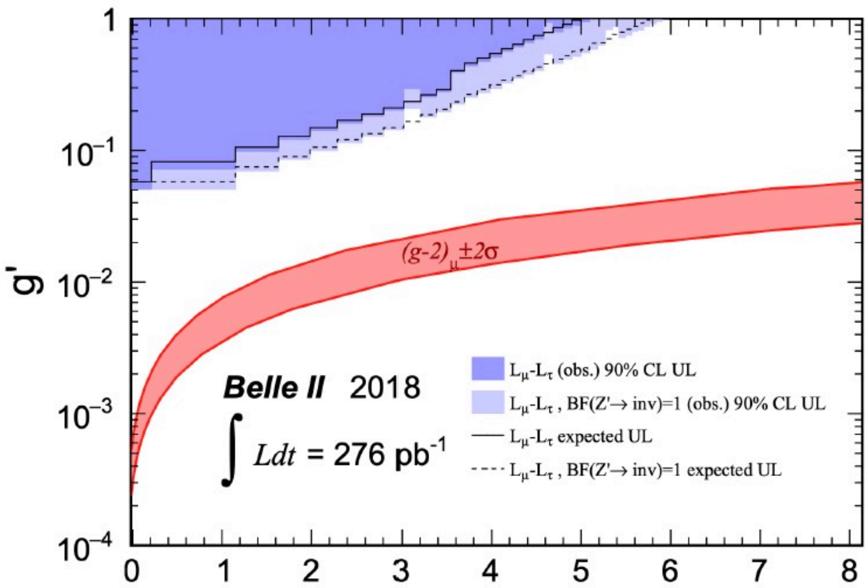
PRD 89, 113004 (2014)

JHEP 02 (2015) 157

JHEP 12 (2016) 106

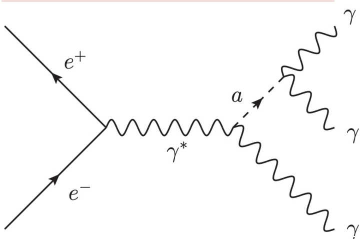
Look for the vector boson Z′ that only couples to 2nd & 3rd generation leptons and mostly decays to DM particles

- ❑ Expect a narrow peak in the recoil mass spectrum of $\mu^\pm\mu^\mp$ ($\mu^\pm e^\mp$ for LFV case)
- ❑ Found no large excess ⇒ turned to limit



PRL 124, 141801 (2020)

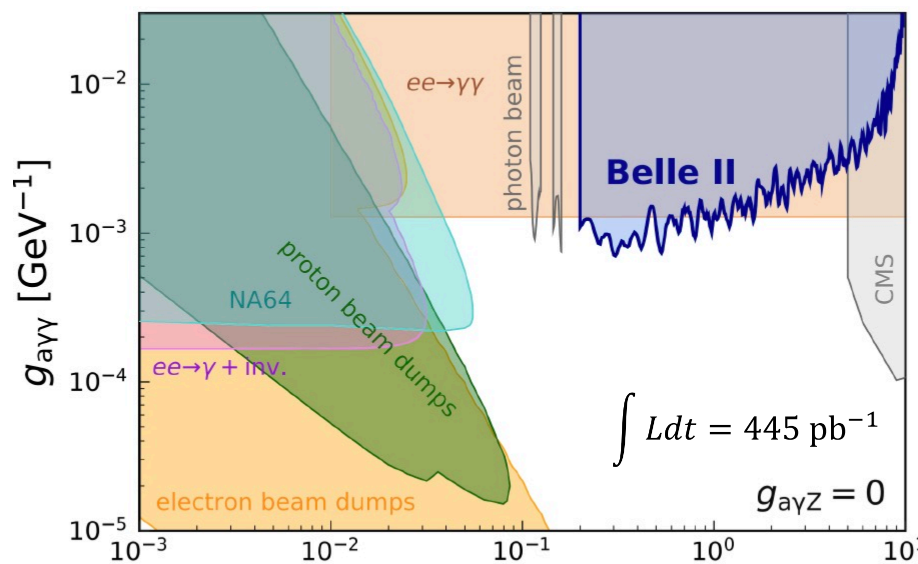
JHEP 12 (2017) 094



Look for an axion-like particle which decays to a pair of photons

$$\boxed{\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\rm QED}}{24}\left(1 - \frac{m_a^2}{s}\right)^3}$$

- ❑ Expect a narrow peak in the recoil- and invariant-mass spectrum of $\gamma\gamma$ system
- ❑ No significant excess is found



PRL 125, 161806 (2020)

Closing words

- Despite passing on the baton of frontier e^+e^- flavor-factory experiments to Belle II, Belle continues to produce exciting physics results and will do so for few more years
- Agenda for the day has been on how to probe new physics beyond the SM at the intensity frontier ➔complementary to high-p_T programs of ATLAS and CMS at the LHC
- Belle II has already integrated 190 fb^{-1} data ➔ expect to record a data size similar to Belle by the long shutdown next year
- As for LHCb, there is healthy competition and complementarity between the two experiments… need more and more data