Clues to a mysterious Universe - exploring the interface of particle, gravity and quantum physics
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Flavour Physics as a Window for New Physics Searches

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for the Belle II and Belle Collaborations,
with material from the LHCb collaboration

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Motivation

Decays of B, D, K mesons and tau leptons have been and continue being a very hot topic in searches for new physics.

Physics of these decays has contributed substantially to our present understanding of elementary particles and their interactions.

Intriguing phenomena that have been seen in recent years make this research area one of the most interesting in particle physics.

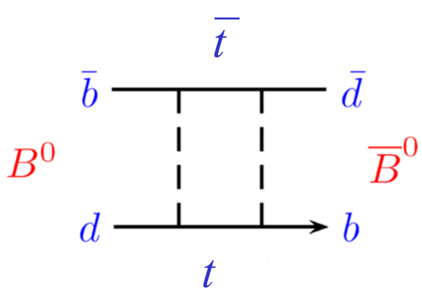
Flavour physics in searches for new particles – two historic examples

Possibly the most prominent example: the prediction of the charm quark based on the unexpectedly low rate of the rare kaon decay $K^0 \rightarrow \mu^+ \mu^-$

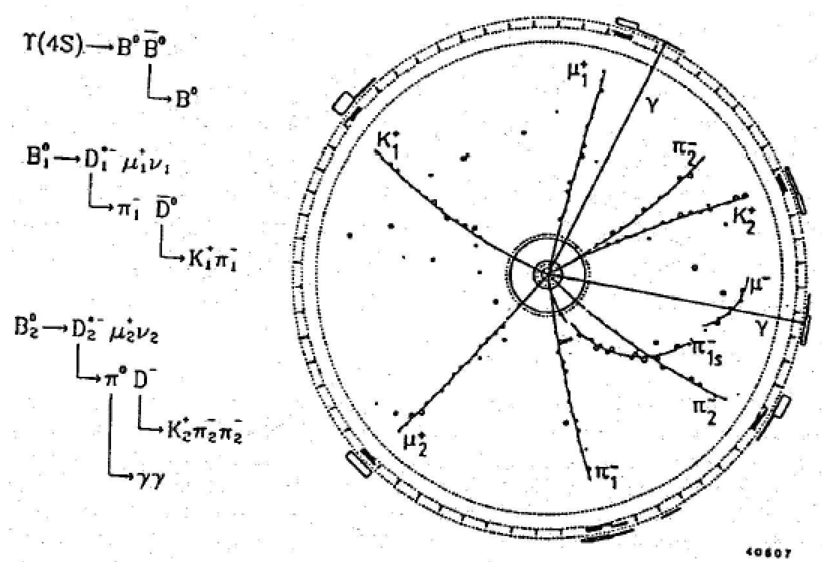
1987: ARGUS (and U1) discovered a large BB mixing: B^0 turns into anti-B^0

Large mixing rate → high top mass (in the Standard Model)

The top quark has only been discovered seven years later!



mixing frequency $\Delta m \propto |V_{tb}^* V_{td}|^2 m_t^2 \propto \lambda^6 m_t^2$

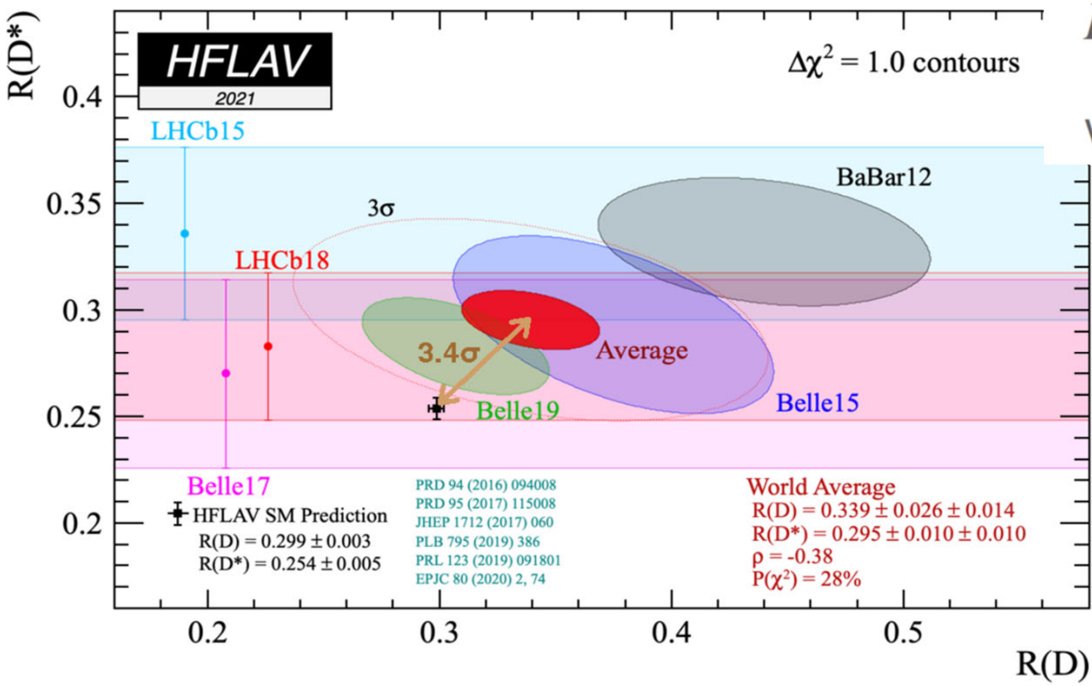


ARGUS: A fully reconstructed event where an anti-B^0 turns into a B^0

Are we now in a similar situation with present hints of anomalies?

- Anomalies in $B \to D(*)\tau^- \nu$ decays
- Anomalies in $B \to K(*)\, e^+e^-$ and $B \to K(*)\mu^+\mu^-$
- Anomaly in $(g\text{-}2)_\mu$

Anomalies in $B \to D(^*)\tau\nu$ decays



$$R(D, D^*, X) = \frac{\mathcal{B}(B \to D, D^*, X\tau\nu)}{\mathcal{B}(B \to D, D^*, X\ell\nu)}$$

with ℓ a light lepton

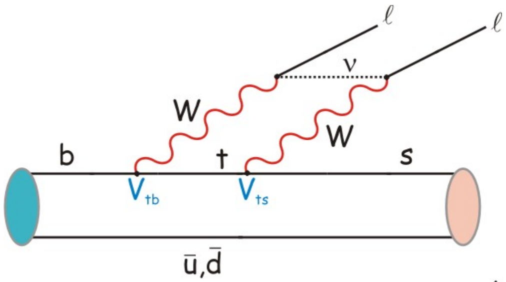
Measurements of R(D) and R(D*) compared to the SM predictions

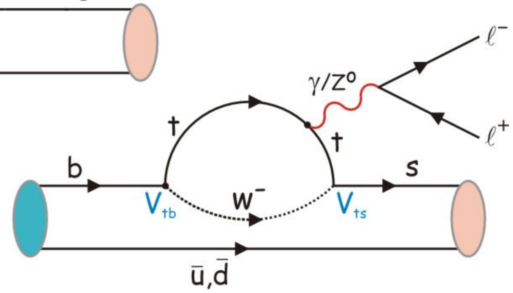
SM: R(D*) = 0.254±0.005 and R(D) = 0.299±0.003

Experiment: R(D*)= 0.295±0.010±0.010 and R(D)=0.339±0.026±0.014

Anomalies in $B \to K(*)e^+e^-$ and $B \to K(*)\mu^+\mu^-$

b → s transition, loops and boxes



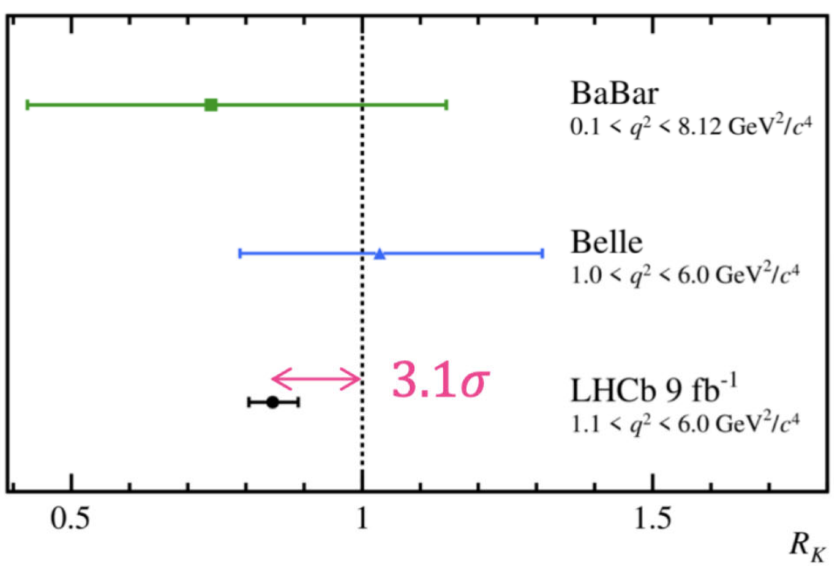


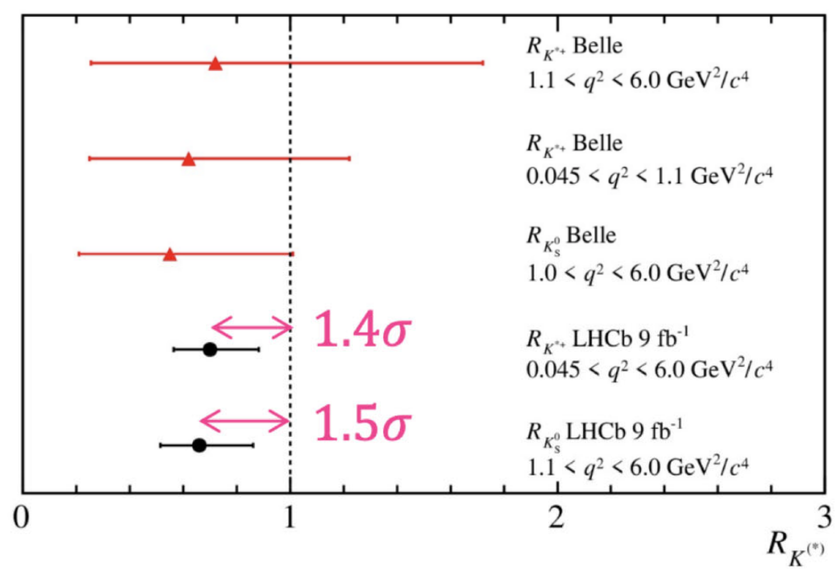
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

SM: the ratio R_K should be equal to 1
(most systematic uncertainties in the hadronic corrections are canceled)

Experiment: below 1

[arXiv:2103.11769], [arXiv:2110.09501]

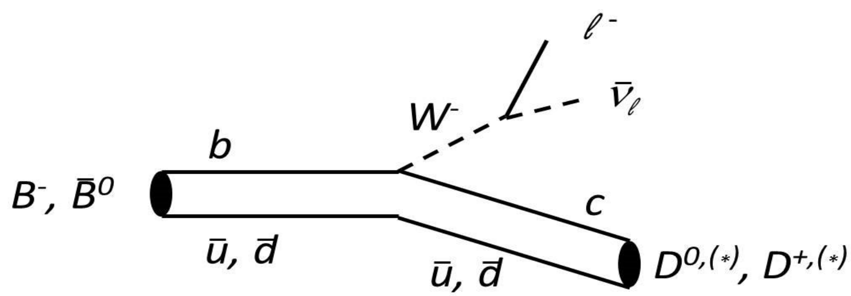




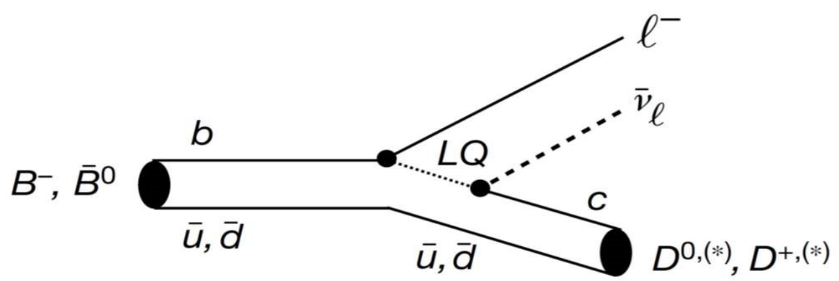
If this hints are confirmed on a larger data sample, what are possible interpretations?

These anomalies challenge lepton flavour universality (LFU), one of the cornerstones of SM.

Diagrams for the $B \to D(^*)\tau\nu$ transition:



mediated by the charged SM weak interaction

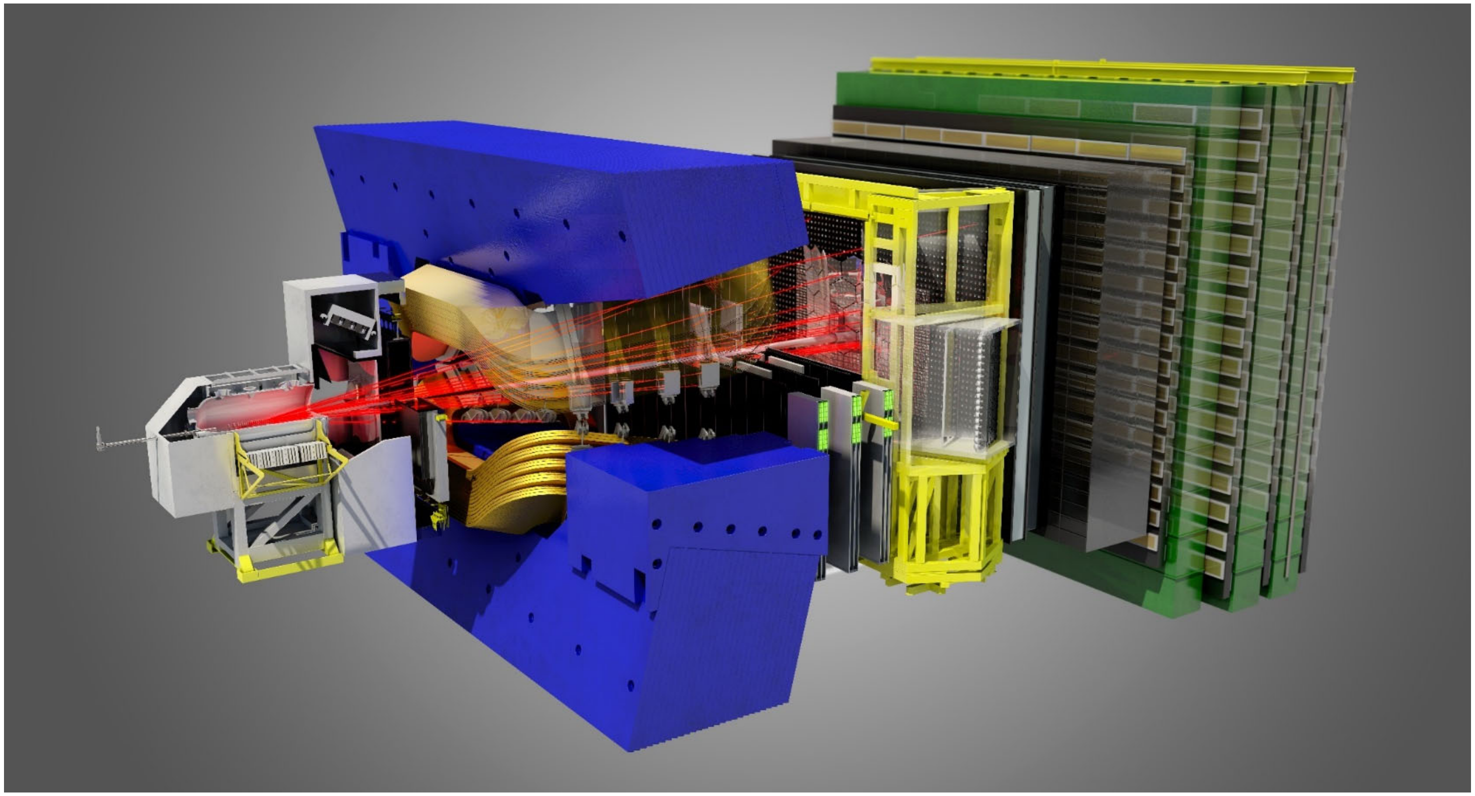


example of a non-SM decay process involving leptoquarks

Other possibilities: models with a Z´ boson, and others

See, e.g., Altmanshofer&Zupan, arXiv:2203.07726v3

Facilities: LHCb @ LHC



pp collisions in the forward region: huge production rates of b hadrons.

Large boost + excellent vtx resolution: background rejection and decay-length resolution.

Excellent momentum and mass resolution.

Outstanding PID (K-π) and μ reconstruction.

Dedicated trigger system for beauty and charmed hadrons.

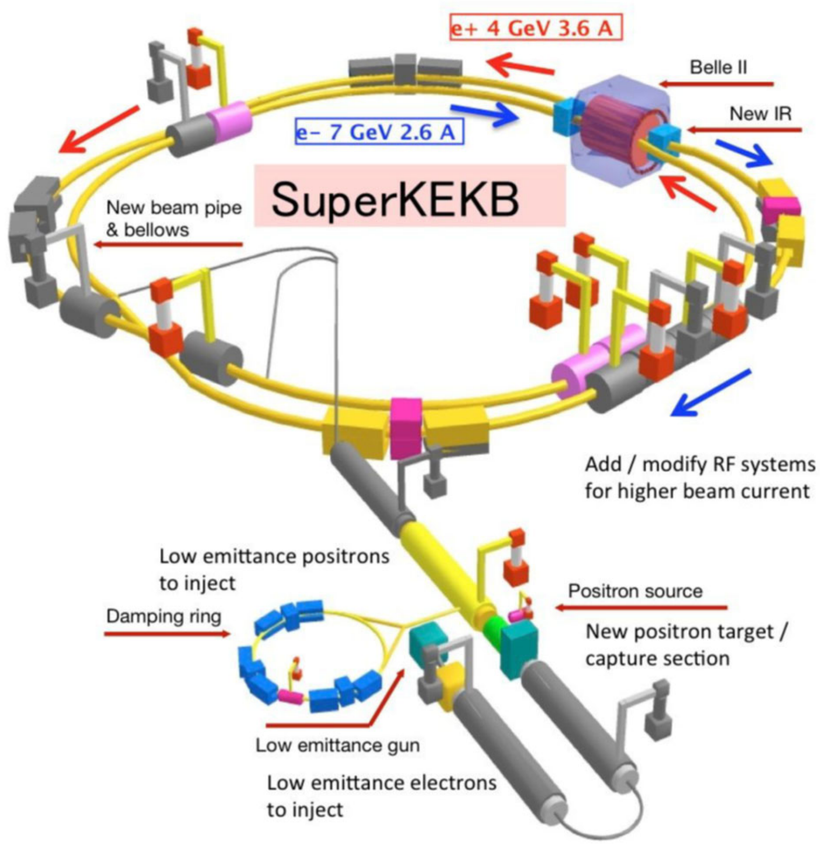
Facilities: Belle II @ SuperKEKB

beam current x1.5

beam-beam param. x1

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

vertical beta function x 1/20

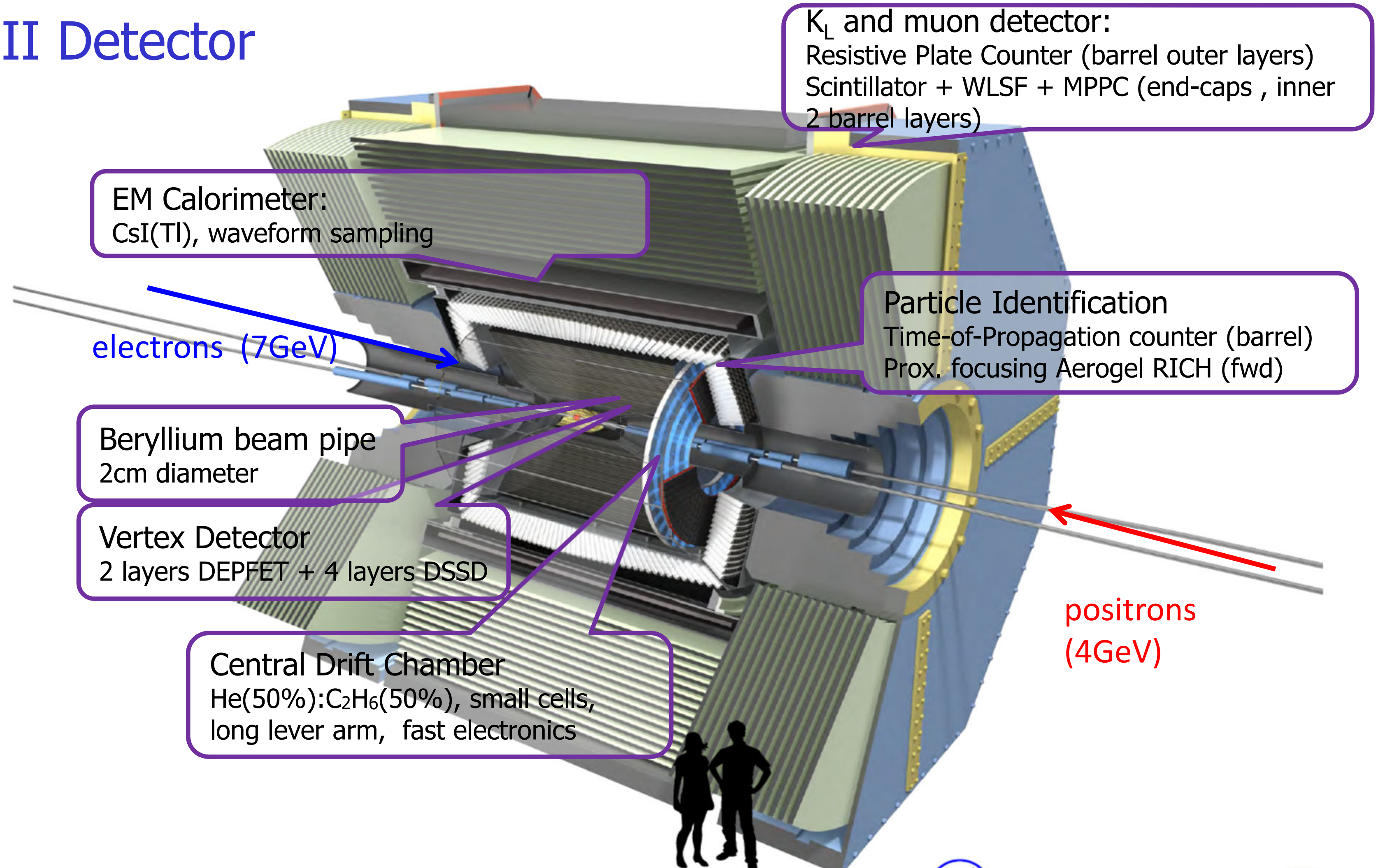


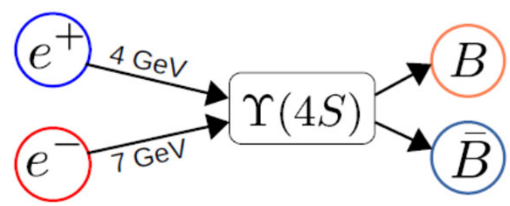
Idea: to increase the luminosity of KEKB by a factor of 30, employ Nano-Beam scheme (P. Raimondi): squeeze beta function at the IP (βx*,βy*) and minimize longitudinal size of overlap region

- Modestly increase the beam currents from 1.64A + 1.19A to 2.8A+2.0A (e-,e+)
- Dramatically decrease the beam cross section: β_y^* from 5.9mm/5.9mm to 0.27mm/0.30mm
- Increase the crossing angle to 83mrad

Strong focusing of beams down to vertical beam size of ~50 nm requires very low emittance beams and a powerful sophisticated final focus

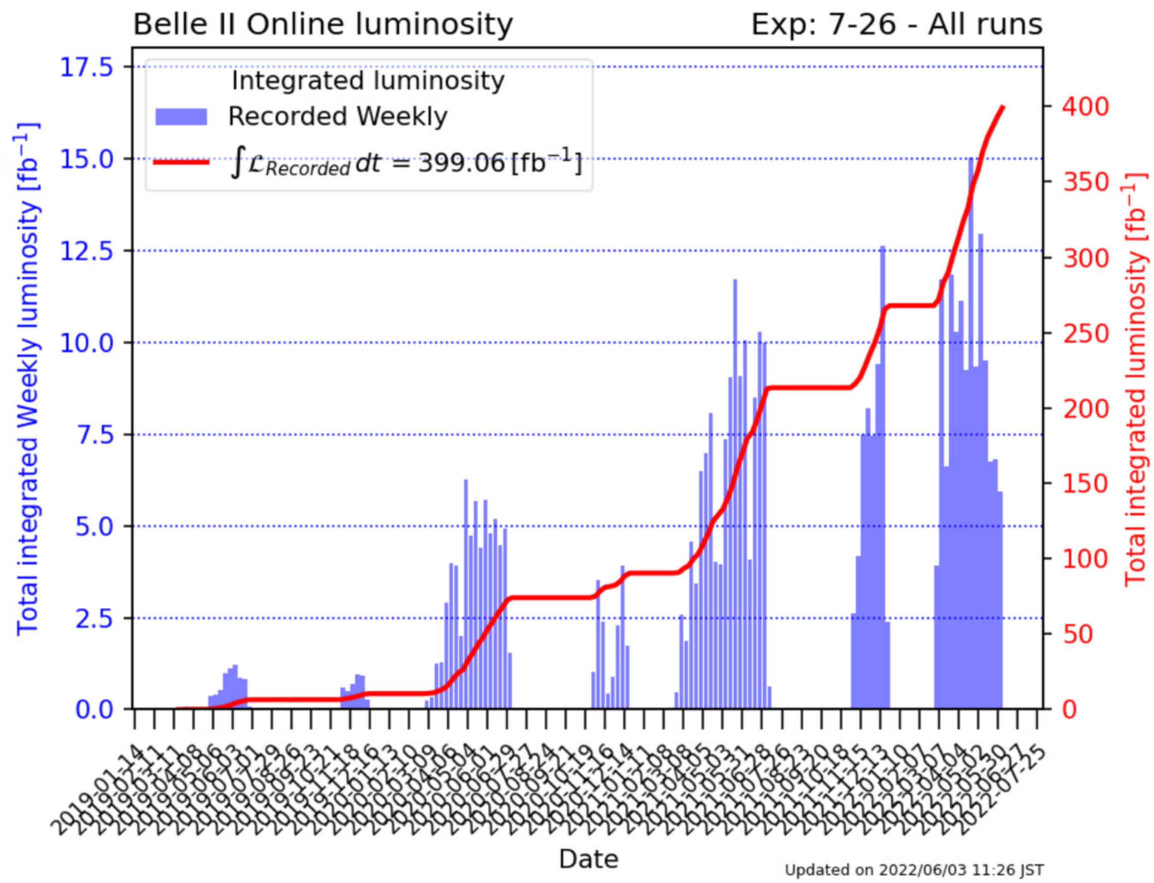
Belle II Detector





- Exactly two B mesons produced (at Υ(4S))
- Hermetic detector
- High flavour tagging efficiency (~30%)
- Detection of gammas, π^0s, K_Ls
- Very clean detector environment (can observe decays with several neutrinos in the final state!)

Facilities: Belle II



Very successful data taking throughout the pandemic

-overall data taking efficiency of 89.5%

-reached world record instantaneous luminosity: 4.65×10^{34} cm^{-2} s^{-1} , collected up to 15 fb^{-1} per week: Super-B factory mode

-recorded luminosity at Belle II: 428 fb^{-1} (Belle 988 fb^{-1}, BaBar 513 fb^{-1})

This talk: results with 63 fb^{-1} and 128 fb^{-1}

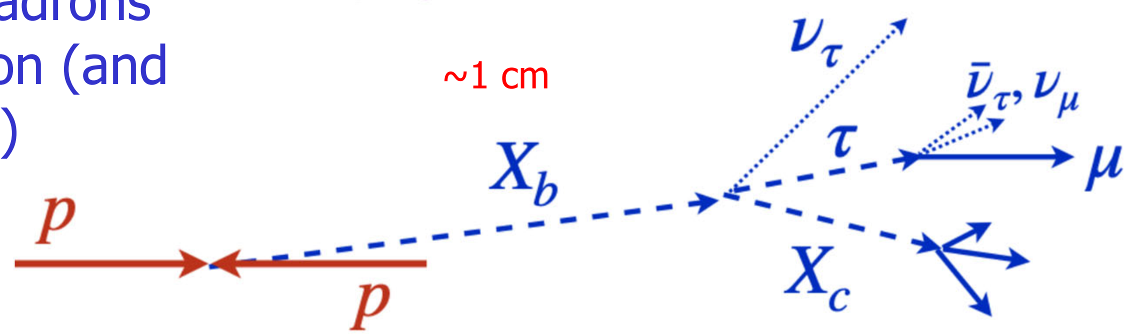
Ultimate goal: reach 50 ab^{-1} by operating at the instantaneous luminosity of 6×10^{35} cm^{-2} s^{-1}

Understanding the anomalies – need:

- Larger statistics
- Search for possible missed systematic effects
- More channels
- Different final states (e.g., $b \rightarrow u$ instead of $b \rightarrow c$ transitions)
- More experiments

R(D*) at LHCb

Exploit the large boost of b hadrons and the large vertex separation (and an excellent vertex resolution)



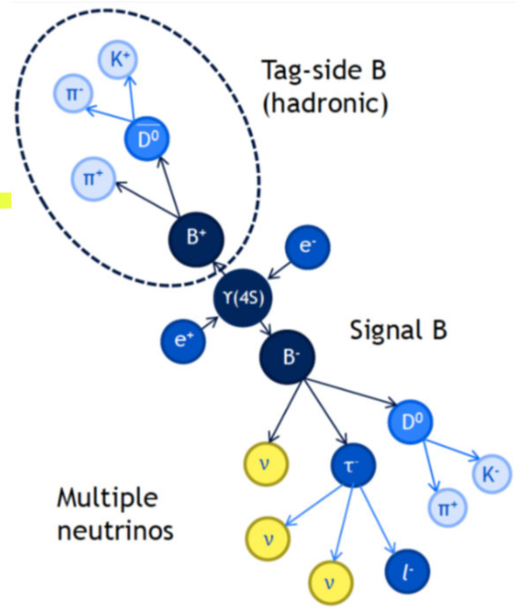
- Many ongoing analyses, different b-hadrons and final states
- Extension to angular observables are planned

$$\mathcal{R} = \frac{b \to q\,\tau\,\bar{\nu}_\tau}{b \to q\,\ell\,\bar{\nu}_\ell} \quad \ell = e, \mu$$

$$\downarrow$$

$$\mathcal{R}(D^{(*)}, D_s^{(*)}, X, \pi, \ldots)$$

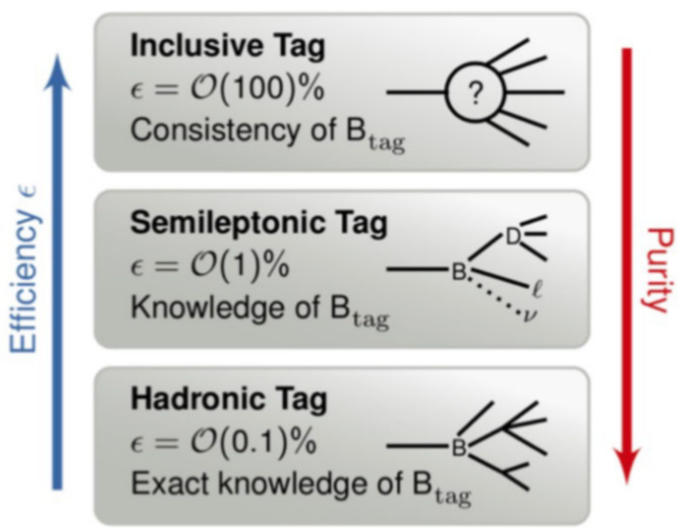
Hadronic taging at Belle II

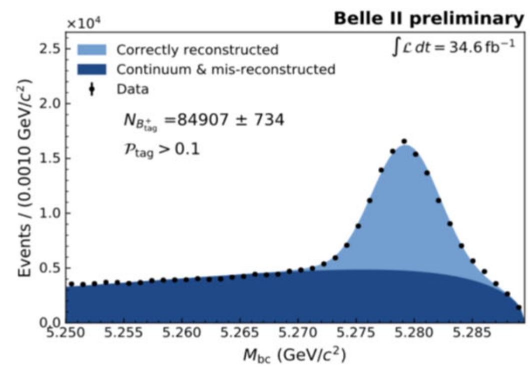


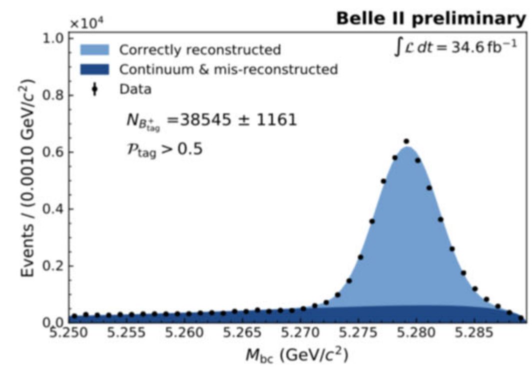
Profit from the fact that exactly two B mesons are produced in e^+e^- collisions

→Full Event Interpretation

- hierarchical multivariate technique (>200 BDTs) to reconstruct the B-tag side (semi-leptonic or hadronic) through $O(10^3)$ different decay modes
- results in a significantly increased tagging efficiency compared to Belle



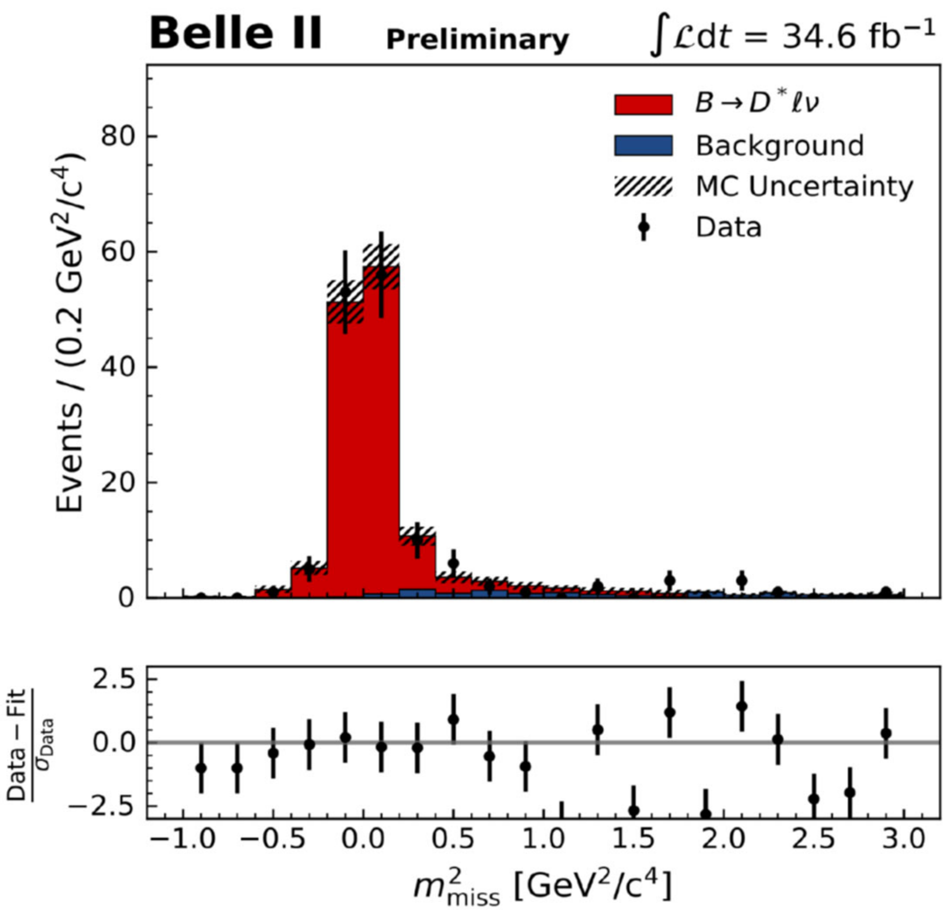




$$M_{bc} = \sqrt{s/4 - p_{cm}^2 c^2}$$

Belle II: preparation for the R(D*) measurement

[arXiv:2008-10299]



→ Measure $B(B^0 \to D^{*+} \ell^- \nu_\ell)$

Multiple neutrinos in final state

- Hadronic tagging

Feed down from D** poorly understood

- Tagged measurement of $B \to D^{**} \ell \nu_\ell$ planned

First tagged Belle II results of $B(B^0 \to D^{*+} \ell^- \nu_\ell)$:

- 34 fb^{-1} Belle II data
- Signal: Fit of missing mass spectrum

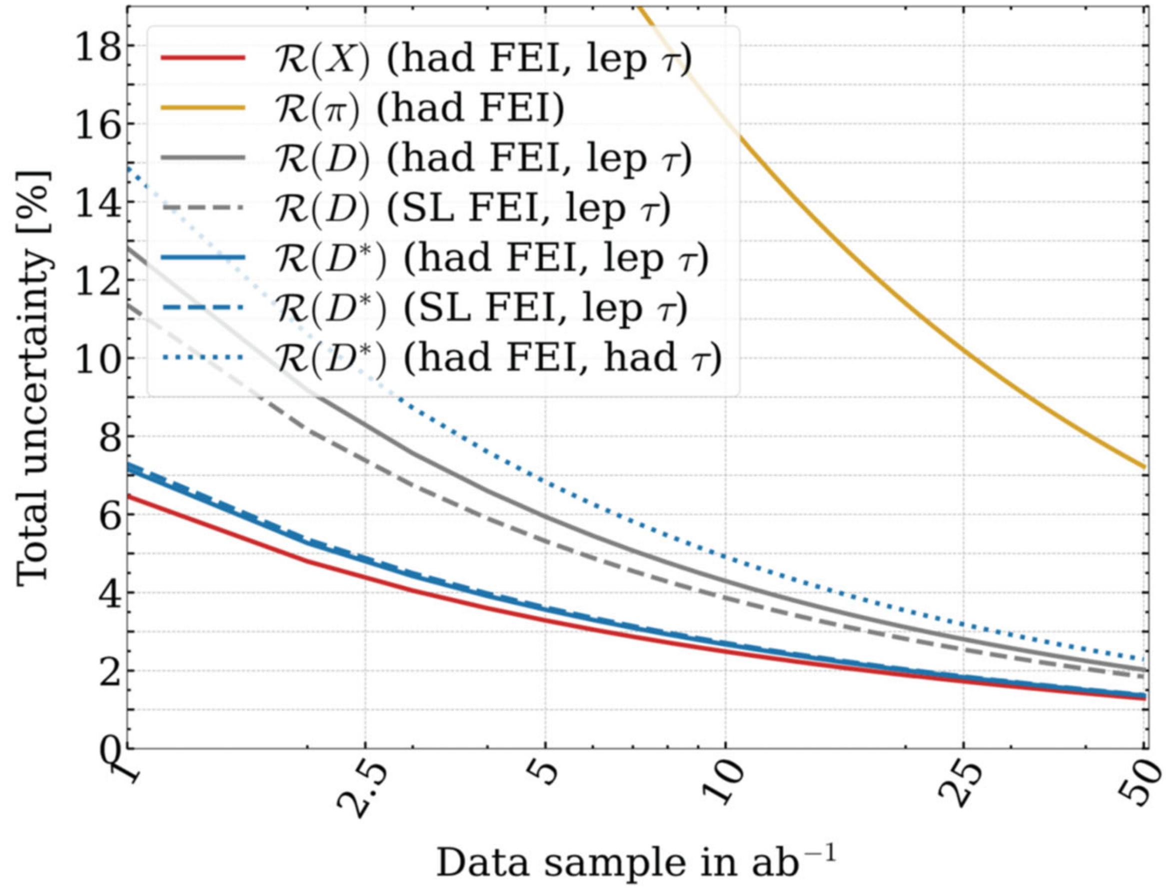
Note that Belle II measures the absolute branching fractions of both decays in the R(D*) ratio.

$B(B^0 \to D^{*+} \ell^- \nu_\ell) = (4.51 \pm 0.41\text{stat} \pm 0.27\text{syst} \pm 0.45_{\pi\ \text{slow}})\%$

Belle II: prospects for the R(D*), R(D), R(X), R(π) measurements

$$R(D, D^*, X) = \frac{\mathscr{B}(B \to D, D^*, X\tau\nu)}{\mathscr{B}(B \to D, D^*, X\ell\nu)}$$

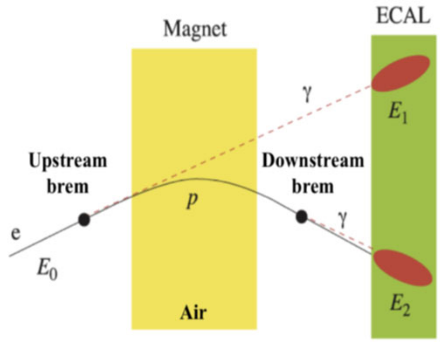
with ℓ a light lepton



From: Snowmass white paper "Belle II physics reach and plans for the next decade and beyond" https://www.slac.stanford.edu/~mpeskin/ Snowmass2021/ BelleIIPhysicsforSnowmass.pdf

R_K at LHCb

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

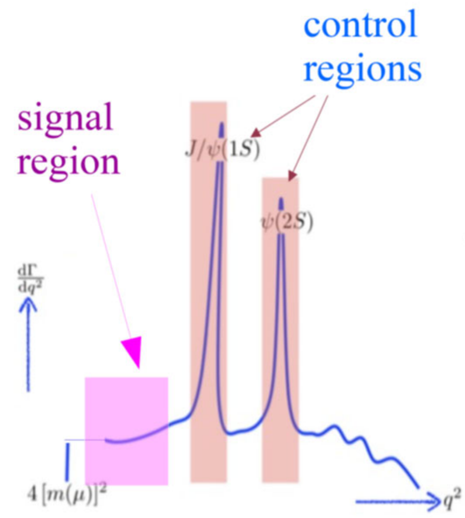


Lepton reconstruction is not universal at LHCb: electrons affected by large bremsstrahlung emission

- Partially recovered → affects mass resolutions with electrons
- Low trigger and reconstruction efficiency

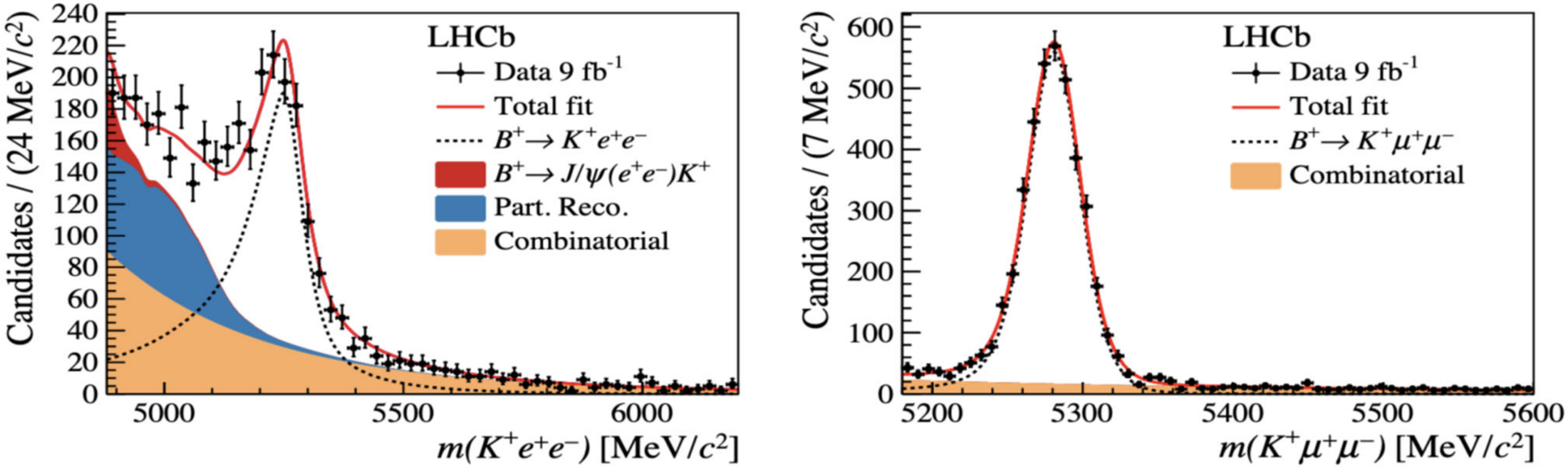
Measurement of the double ratio with J/ψ control mode allows better control of efficiency

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \Big/ \frac{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$



Different q^2 regions → Contributions from different processes.

R_K at LHCb



$$R_K(1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,(\mathrm{stat.})\,^{+0.013}_{-0.012}\,(\mathrm{syst.})$$

3.1 σ from SM

- Ratio measured around $q^2 \approx m(J/\psi)^2$ resonance: R_K=0.981 ± 0.020
- Analogous LHCb study using Λ_b gives $R_{pK}|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 0.86\,^{+0.14}_{-0.11} \pm 0.05$

The BR for the electron mode is consistent with the SM prediction

- The muon mode seems systematically smaller (muon anomaly?) in the q^2 range 1.1 – 6.0 GeV^2

R(K) and R(K*) with Belle

Using the full Belle dataset (711/fb at $\Upsilon(4S)$)

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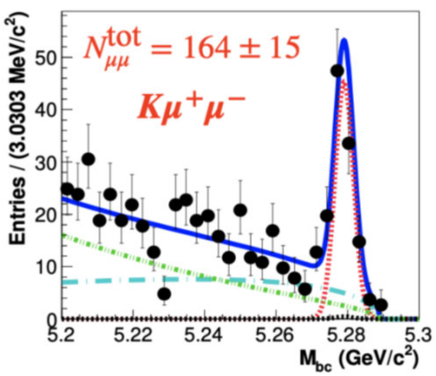
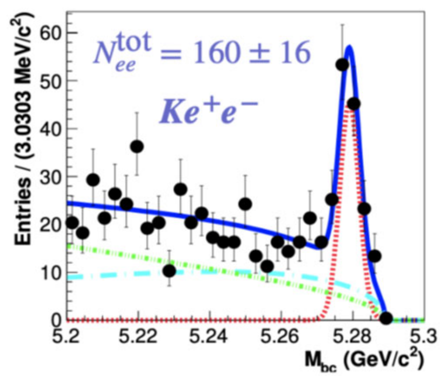
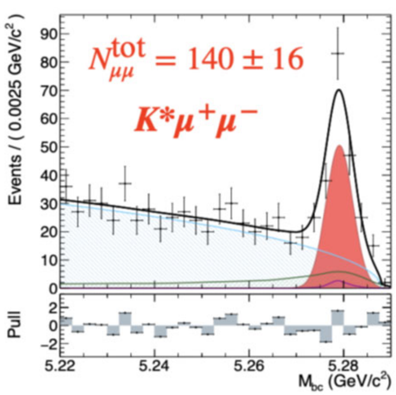
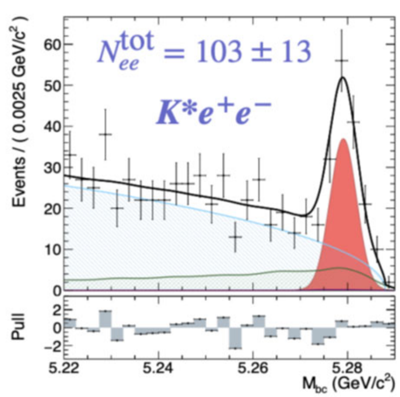




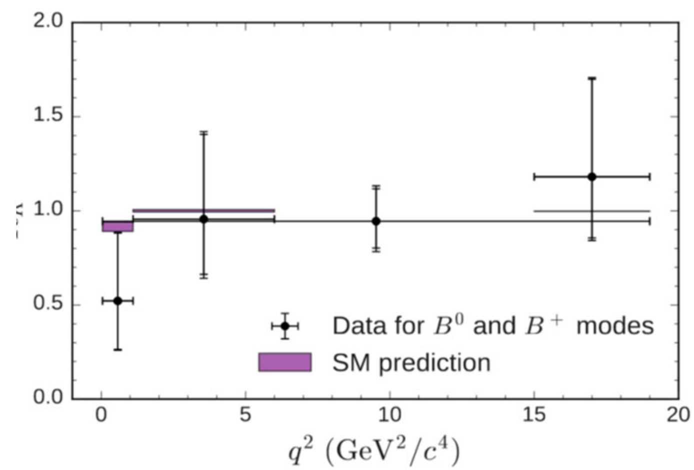
PRL 126, 161801 (2021)





Results consistent with SM expectation but statistically limited

Compared to LHCb, at B-factories muons and electrons have about the same efficiency!



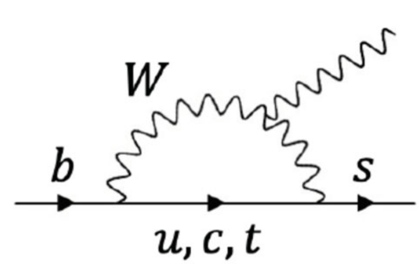
Expected considerable improvements from Belle II

More on rare decays with b→s transitions

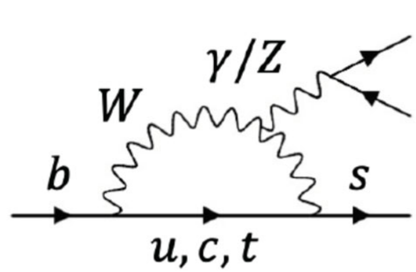
$B \to K(*)e^+e^-$ and $B \to K(*)\mu^+\mu^-$ involve a b→s transition.

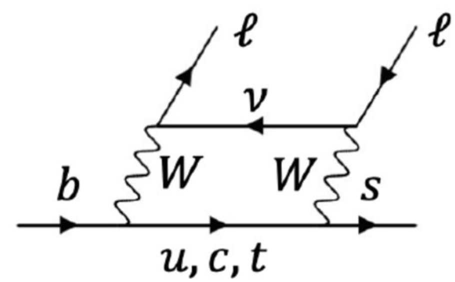
→ More searches for new physics in rare decays of the type b → s

- Differential decay rates in $B \to K^*\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$ – LHCb
- $B \to X_s\ell\ell$ – Belle II
- $B^\pm \to K^\pm\nu\nu$ – Belle II with the inclusive tag
- $b \to s\gamma$ - Belle II
- $K\pi$ puzzle – Belle II



b → s - loop and box diagrams in SM, new physics could be leptoquarks, new particles in loops/boxes, new particles in the final state instead of neutrino pairs





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

Differential branching fractions

– Decay rate of $b \to s \ell^+\ell^-$ sensitive to BSM

– Branching fractions low for muons (B^+, B^0, B_s^0 and Λ_b^0)

$B_s^0 \to \varphi \mu^+ \mu^-$ arXiv:2105.14007

$dB/dq^2 = (2.88 +- 0.22) \times 10^{-8}/(\mathrm{GeV}^2/c^4)$

for $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$

– In agreement with Run 1 result

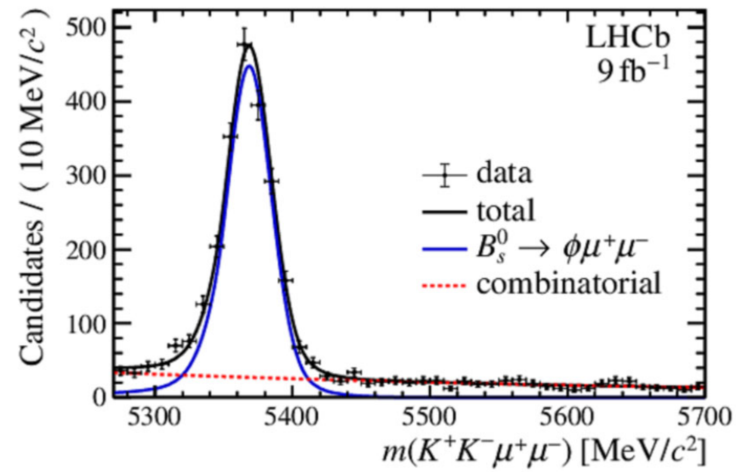
– 3.6σ deviation tension with SM

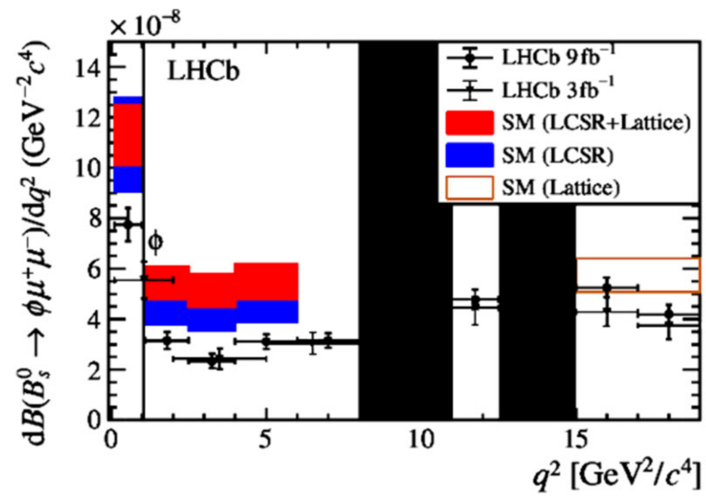
$B_s^0 \to \varphi\mu^+\mu^-$

– Observables F_L, ACPi asymmetries, coefficients Si

– Compatible with SM, tension in F_L

arXiv:2107.13428





$b \to s\, \ell^+\ell^-$ angular analysis

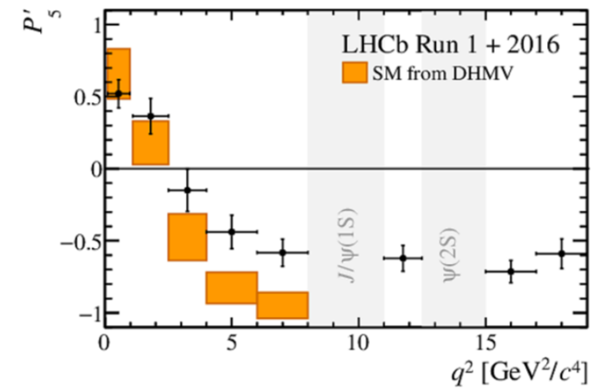
Angular observables: polarisation, asymmetries vs q^2

$B^0 \to K^{*0}\mu^+\mu^-$ PRL 125 (2020) 011802

– Local tensions 2.5σ and 2.9σ in asymmetry P_5' with SM in q^2 bins [4,6] and [6,8] GeV^2/c^4

– Global analysis finds a tension of 3.3σ

– Consistent with ATLAS, Belle, CMS results

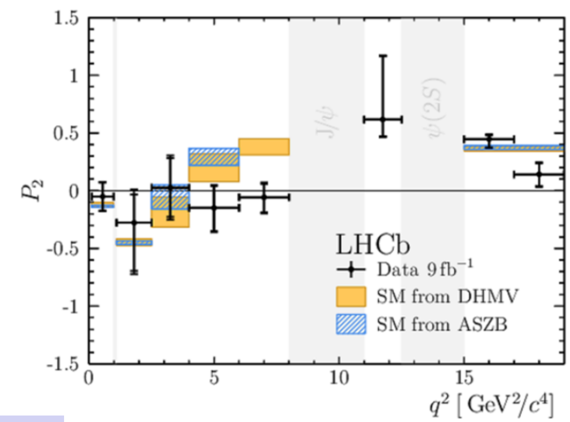


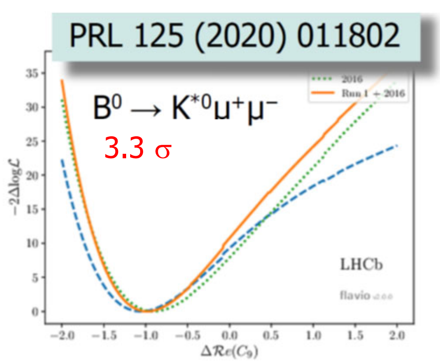
$B^+ \to K^{*+}\mu^+\mu^-$ PRL 126 (2021) 161802

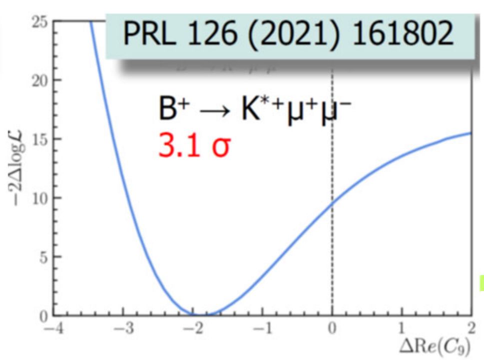
– First LHCb measurement

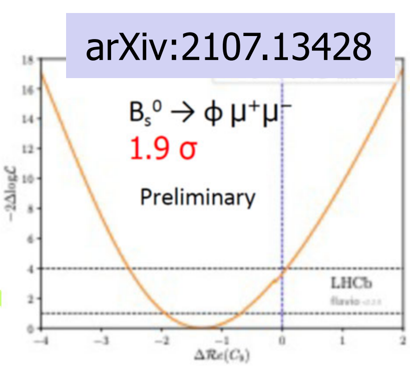
– Local tension with SM up to 3.0σ in P_2(~ A_{FB}) in q^2 bin [6,8] GeV^2/c^4

– Global tension 3.1σ determined in a fit to the effective field theory Wilson coefficient Re(C_9)





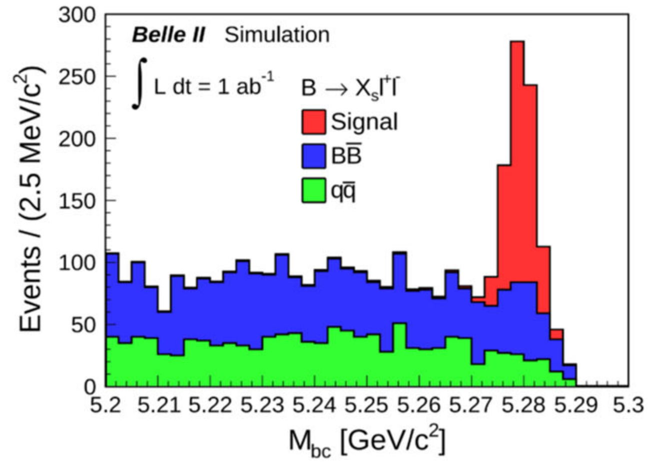




Negative shift of $\Delta\mathrm{Re}(C_9)$ from SM preferred value by a 2 to 3σ level

Belle II: $B \to X_s \ell\ell$

[arXiv:2012.15394], [arXiv:1709.10308]



Measurement of

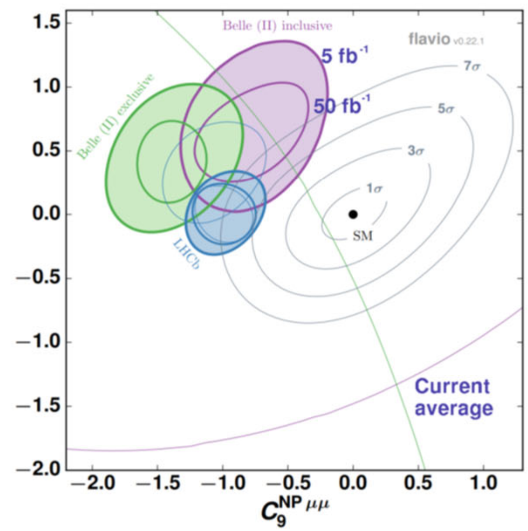
$R(X_s) = B(B \to X_s \mu^+\mu^-)/(B \to X_s e^+e^-)$ in progress

Two methods available:

- Sum-of-exclusive modes
- Fully inclusive using tagging

Expected sensitivity:

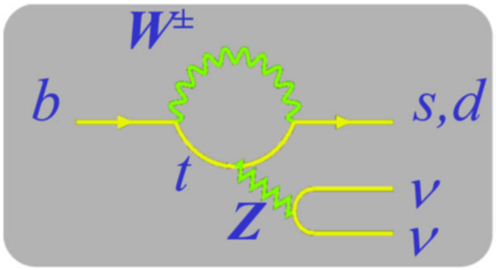
Observables	Belle (0.71 ab^{-1})	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
R_{X_s} ([1.0, 6.0] GeV^2/c^4)	32%	12%	4.0%
R_{X_s} ([> 14.4] GeV^2/c^4)	28%	11%	3.4%

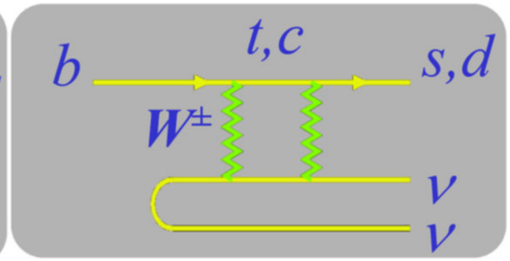


Angular analysis of $B \to X_s \ell\ell$ will improve constraints on Wilson coefficients C_9 and C_{10}

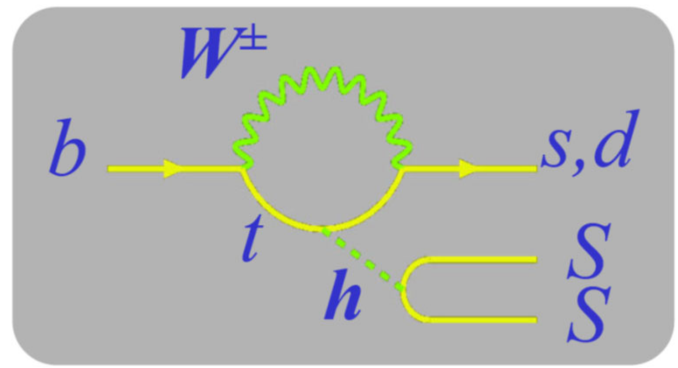
Search for $B^\pm \to K^\pm \nu\bar{\nu}$

SM: penguin + box diagrams





Look for deviations from the expected values → information on anomalous couplings C^{ν}_{L} and C^{ν}_{R} compared to the SM value $(C^{\nu}_{L})^{SM}$, coming from the loop or from processes like



Flavour-Changing Neutral Current process that has not yet been observed

-no photon contribution/much cleaner theoretical prediction

$\mathcal{B}(B^\pm \to K^\pm \nu\nu) = (4.6 \pm 0.5) \times 10^{-6}$

Previous searches based on tagged analyses

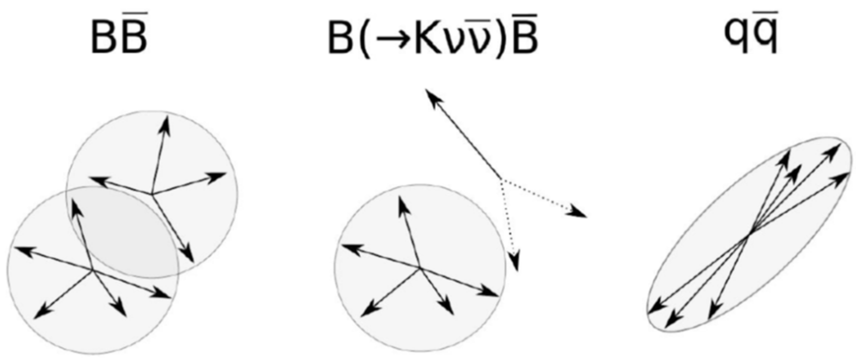
-semi-leptonic tag: $\varepsilon_{sig} \sim 0.2\%$ (Belle)

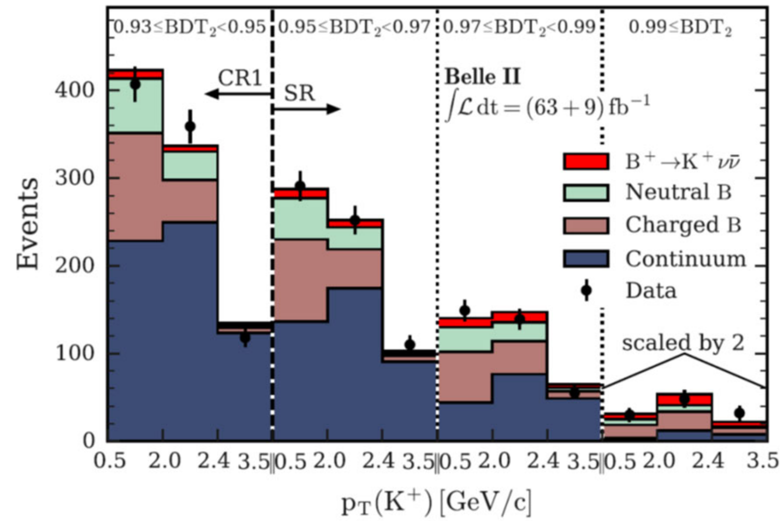
-hadronic tag: $\varepsilon_{sig} \sim 0.04\%$ (BaBar)

New approach by Belle II based on an inclusive tag

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

PRL 127 (2921)18, 121202



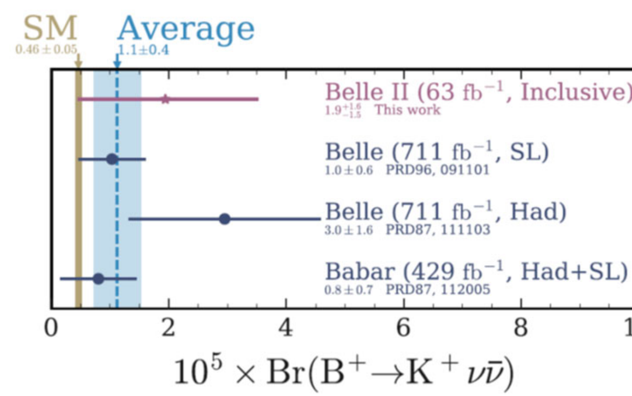


New approach by Belle II based on an inclusive tag

-no explicit reconstruction of the second B-meson

-use BDTs to exploit distinctive topological features of $B^\pm \to K^\pm \nu\bar{\nu}$

-much higher efficiency of $\varepsilon_{sig} \sim 4.3\%$ resulting in increased sensitivity per luminosity



Further improvements are underway

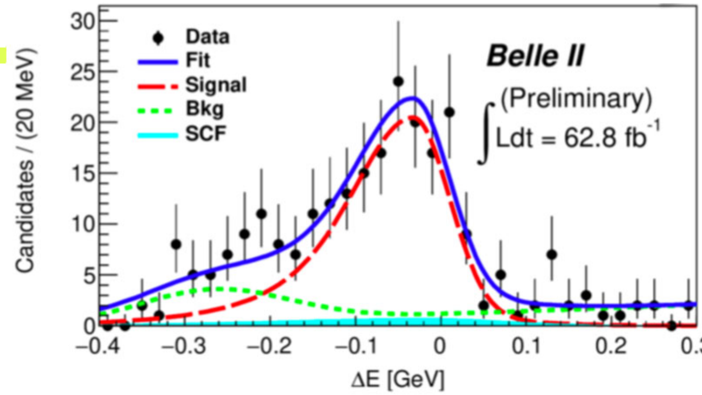
- more data (already have 6x more on tape)
- additional channels ($B^0 \to K^{*0}\nu\bar{\nu}$, $B^0 \to K_S^0\nu\bar{\nu}$...)
- improved/extended classifiers (neural networks)

Events of different tagging methods are to a large degree statistically independent and can be combined, details are under study.

b→sγ: first results at Belle II

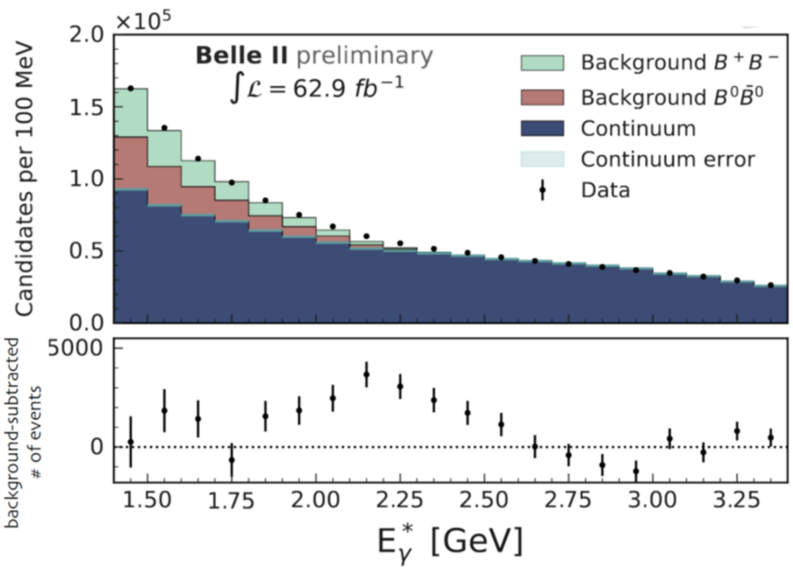
hep-ex:2110.08219

- $B \to K^* \gamma$ branching fraction measurement, with 63 fb^{-1}
- full reconstruction of the decay chain: charged and neutral K^* + high energy photon
- Measured BR consistent with world average values at 1-2 σ
- CP and isospin asymmetry measurement foreseen in the next iterations of the analysis



(c) $B^+ \to K^{*+}[K^+\pi^0]\gamma$

Mode	$\mathcal{B}_{\text{meas}}$ $[10^{-5}]$	$\mathcal{B}_{\text{PDG}}$ $[10^{-5}]$
$B^0 \to K^{*0}\gamma$	$4.5 \pm 0.3 \pm 0.2$	4.18 ± 0.25
$B^+ \to K^{*+}\gamma$	$5.2 \pm 0.4 \pm 0.3$	3.92 ± 0.22



- $B \to X_s \gamma$ with untagged method, 63 fb^{-1}
- Reconstruct only high energy γ from signal side
- Extract signal from photon energy spectrum
- Excess visible in the expected signal region

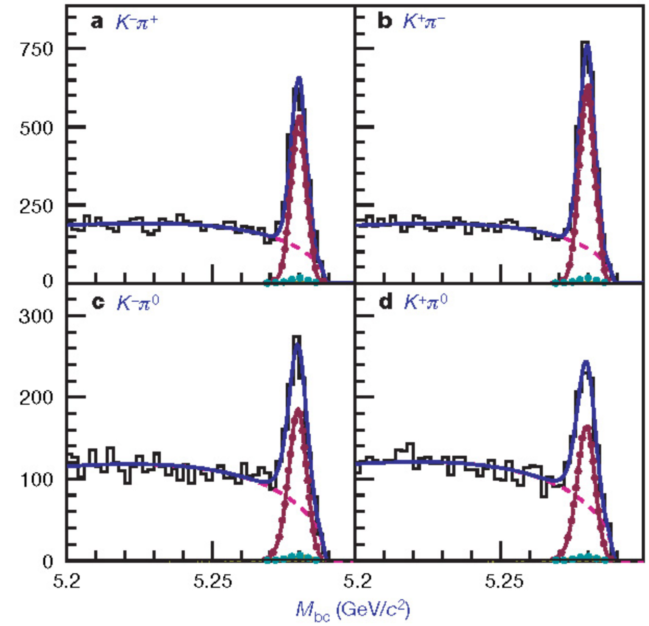
In the pipeline: hadronic-tag analysis

Expected impact of Belle II on the longstanding Kπ puzzle (another b → s transition)

Belle, Nature 452, 332 (2008)

A significant difference is seen between direct CP asymmetry in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays:
$\Delta A_{CP} = 0.124 \pm 0.021$

An Isospin sum rule has been proposed as a sensitive null-test: PLB 627 (2005) 82



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

- a violation of the sum rule would be evidence for New Physics
- precision on $A_{CP}^{K^0\pi^0}$ is the most limiting input for the test of the sum rule

Expected impact of Belle II on the longstanding Kπ puzzle (another b → s transition)

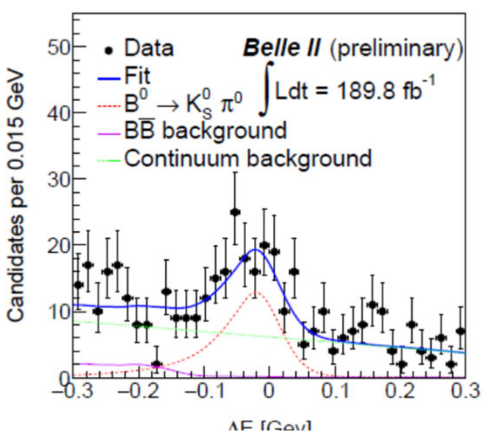
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+} \frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0} \frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0} \frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

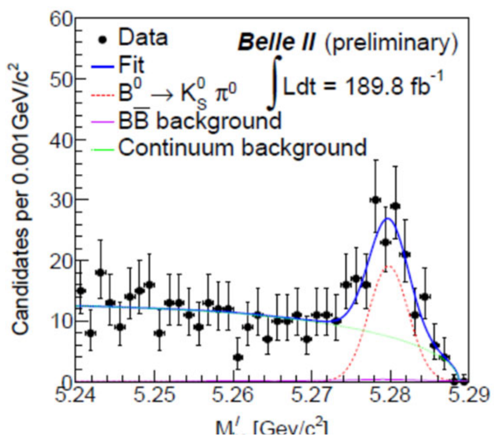
- precision on $A_{CP}^{K^0\pi^0}$ is the most limiting input for the test of the sum rule

$$\mathcal{B}(B^0 \to K^0\pi^0) = [11.0 \pm 1.2(\mathrm{stat}) \pm 1.0(\mathrm{syst})] \times 10^{-6}$$

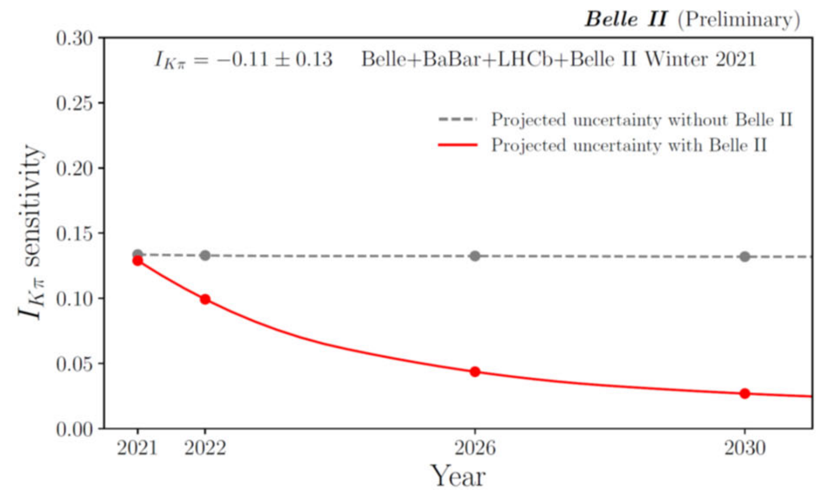
$$\mathcal{A}_{CP}(B^0 \to K^0\pi^0) = -0.41^{+0.30}_{-0.32}(\mathrm{stat}) \pm 0.09(\mathrm{syst})$$

arxiv.org/abs/2206.07453





Belle II: expected precision on $I_{K\pi}$



Belle II impact on the measurement of $(g\text{-}2)_\mu$

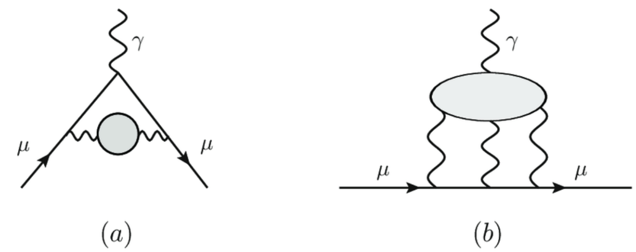
$(g\text{-}2)_\mu$ measurement among the most sensitive to New Physics

BUT: needs experimental input from the e^+e^- experiments to reduce theory uncertainty to the same level as the expected experimental uncertainties.

Needed:

- hadronic vacuum polarization (HVP) contribution

from $e^+e^- \to \pi\pi$



- hadronic light-by-light (HLbL) scattering contribution form factors and $\gamma\gamma \to$hadrons

Belle II with its detector optimized for precision physics with identified hadrons could reduce systematics by resolving the current experimental tension in HVP (BaBar vs KLOE)

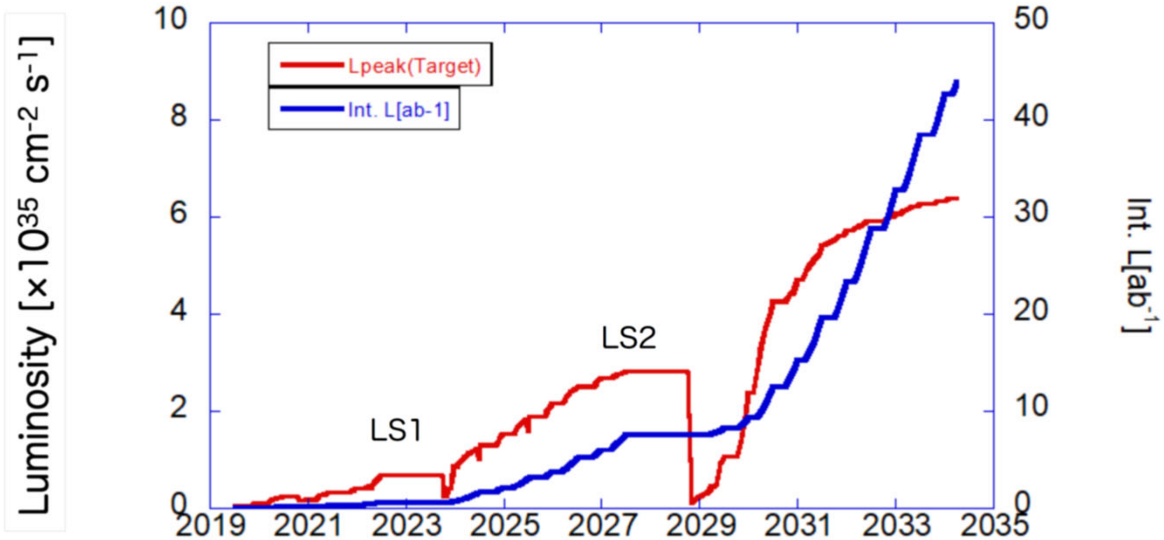
Excellent opportunity to reduce systematics to the level of the expected experimental precision of $(g\text{-}2)_\mu$

Must-do experiment to validate theory calculations for HVP and HLbL

2204.02280 [hep-ex]

Outlook

Outlook: Belle II



Ultimate goal: reach 50/ab by operating at the design luminosity of 6 x 10^{35} cm^{-2} s^{-1}

Current working plan follows the KEK Roadmap2020
- LS1 in 2022-23 for the full pixel vertex detector (PXD) installation & partial replacement of MCP-PMTs in TOP
- options for an interaction region upgrade (LS2) ≳2026 under study

→https://arxiv.org/abs/2203.11349

Beyond: discussions of physics and detector options with an upgraded accelerator to reach an even larger data sample of ~250/ab

Outlook: LHCb

Upgrade I: Major upgrade for operation in Run 3

- All sub-detectors read out at 40 MHz for a fully software trigger with the new data centre
- Pixel detector VELO with silicon microchannel cooling 5mm from LHC beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker: UT detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

Upgrade II

- Fully exploit LHC facility for flavour physics & beyond, for LS4
  - Expression of interest (2017), Physics Case (2018)
  - Strong support in European Strategy (2020)
- Framework Technical Design Report (autumn 2021)
  - Options to achieve the physics programme

Summary

- Physics of b and c hadrons and τ leptons has contributed substantially to our present understanding of elementary particles and their interactions
- B decays have been and continue being a very hot topic in searches for new physics. Intriguing phenomena that have been seen in recent years make this research area one of the most interesting in particle physics.
- LHCb finished its Upgrade I, and Belle II has entered the super-B-factory regime.
- Expect a new, exciting era of discoveries, and a friendly competition and complementarity of LHCb and Belle II, as well ATLAS and CMS

Additional slides

Belle II Physics