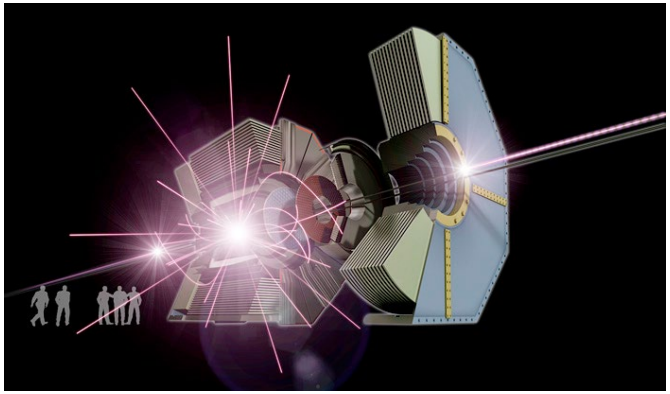
20. Božični simpozij fizikov Univerze v Mariboru
20th Christmas Symposium of Physicists of the University of Maribor



Precision Flavour Physics at Belle II

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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.

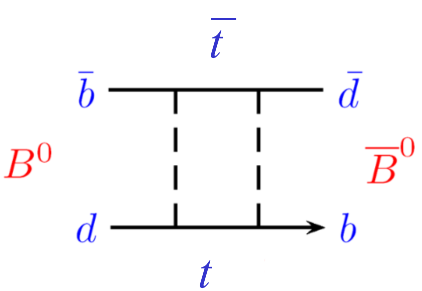
Flavour physics in searches for new particles – two historic examples

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

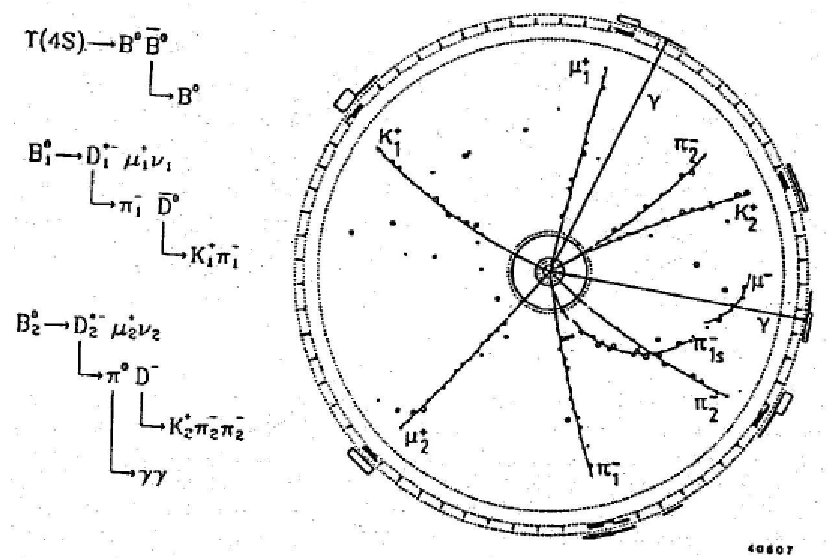
Large mixing rate → high top mass (in the Standard Model)

The top quark has only been discovered seven years later!



mixing frequency $\Delta m \propto$

$$|V_{tb}^* \, V_{td}|^2 m_t^2 \;\propto\; \lambda^6 m_t^2$$

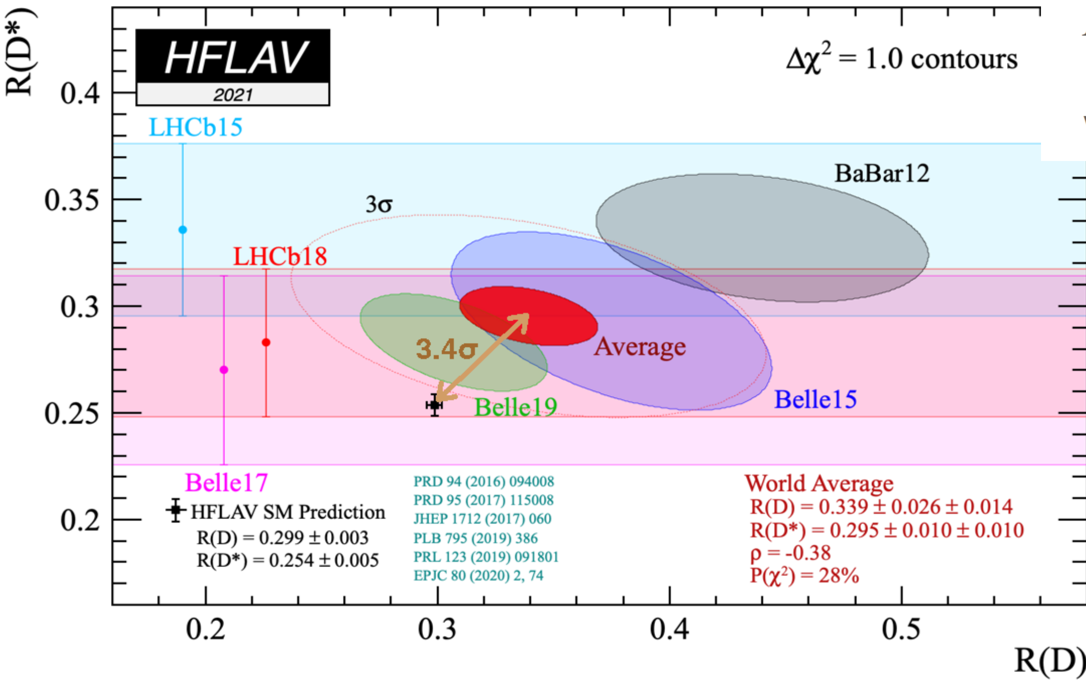


ARGUS: A fully reconstructed event where an anti-B^0 turns into a B^0

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 $B \to K(*)\mu^+\mu^-$ decays
- Anomaly in muon magnetic dipole moment $(g\text{-}2)_\mu$

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

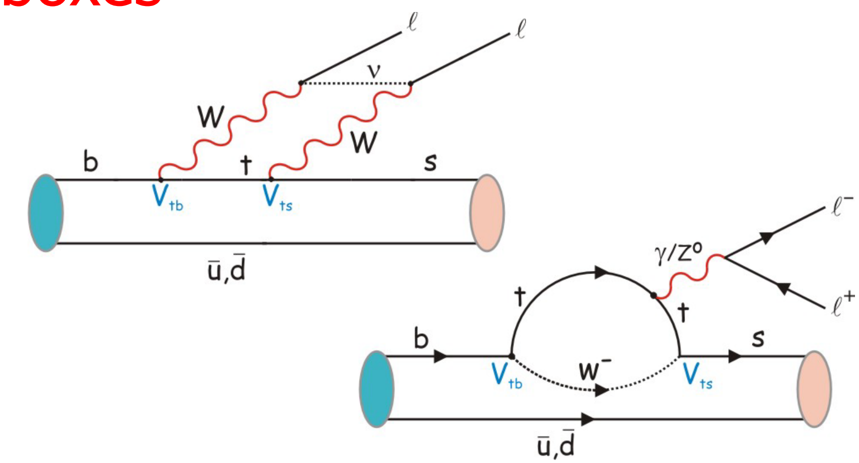
Measurements of R(D) and R(D*) compared to the SM predictions

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

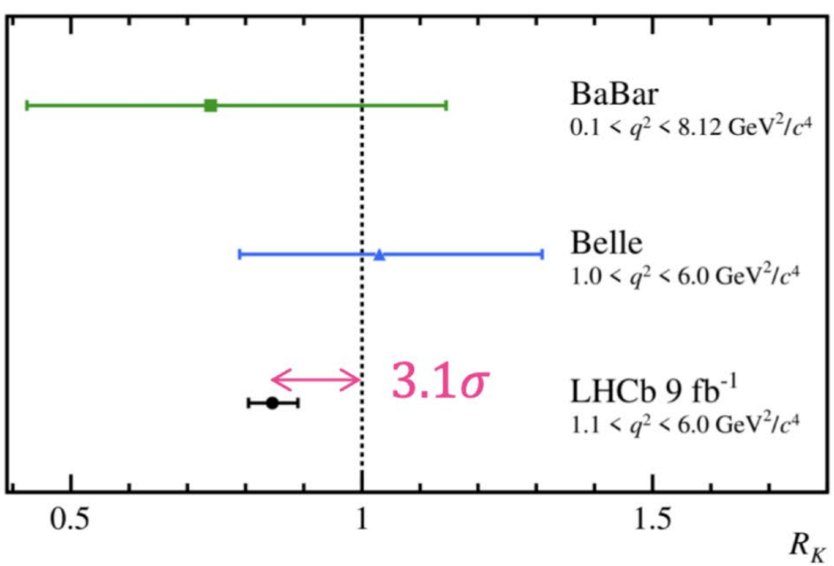


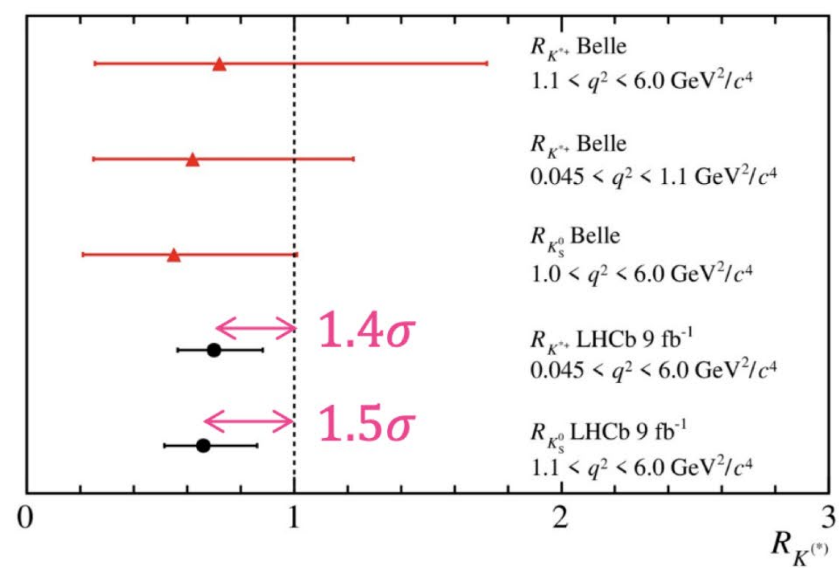
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

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

Experiment as of 2022: below 1

[arXiv:2103.11769], [arXiv:2110.09501]



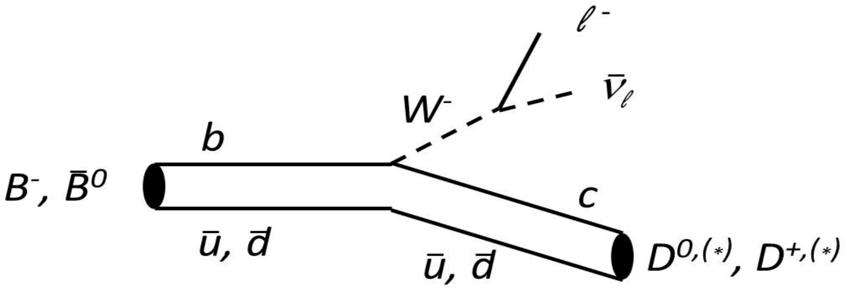


If this hints are confirmed on a larger data sample, what are possible interpretations?

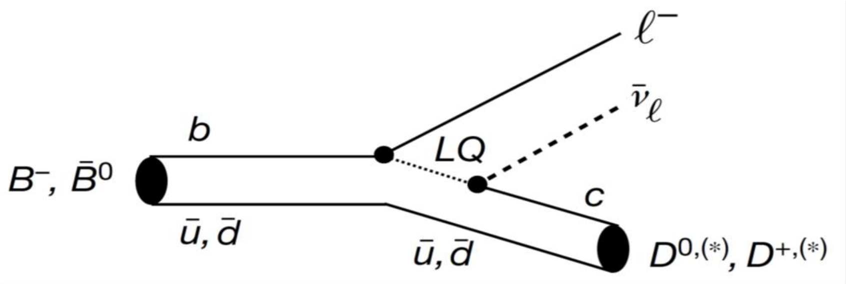
These anomalies challenge lepton flavour universality (LFU), one of the cornerstones of SM.

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

mediated by the charged SM weak interaction



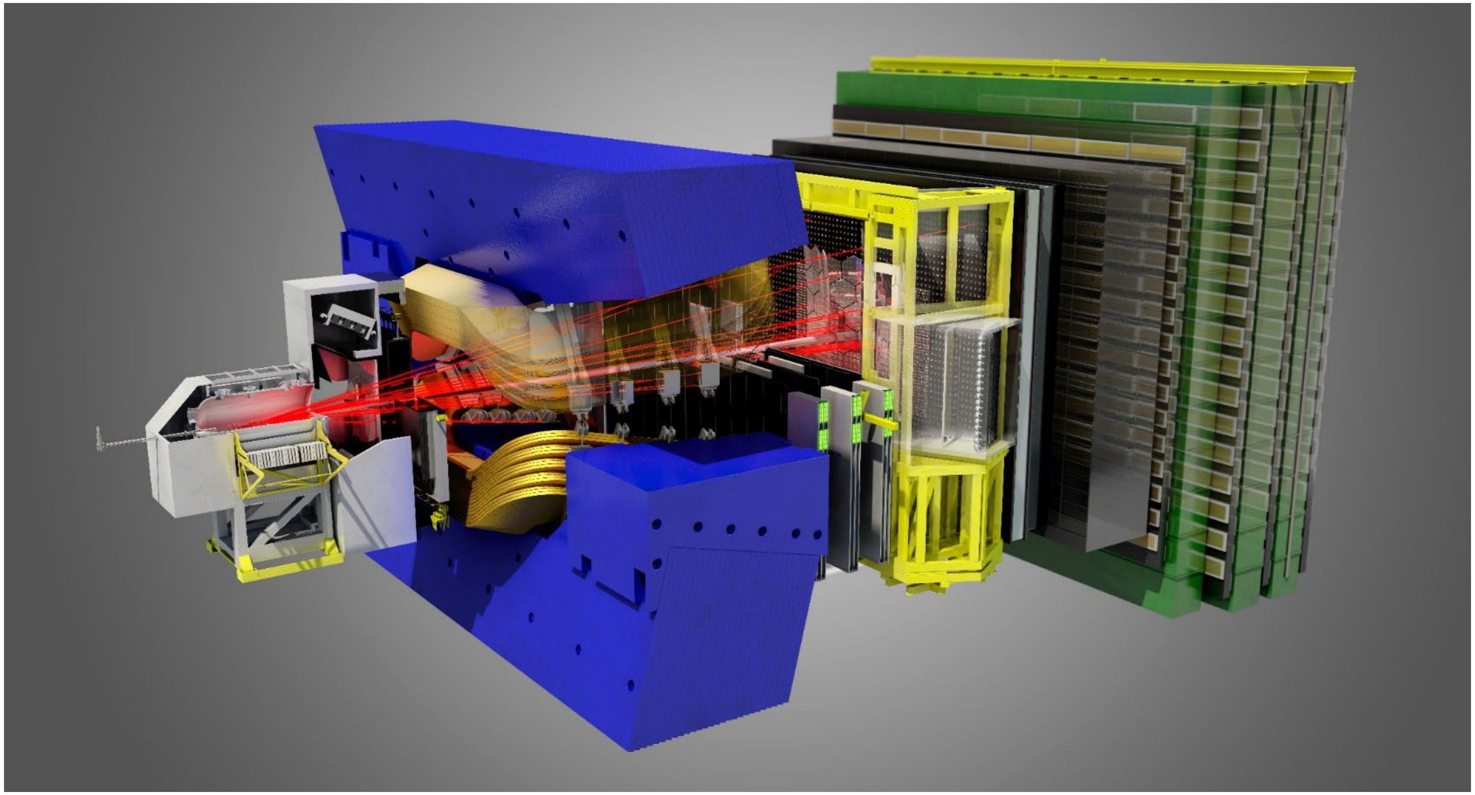
example of a non-SM decay process involving leptoquarks



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.

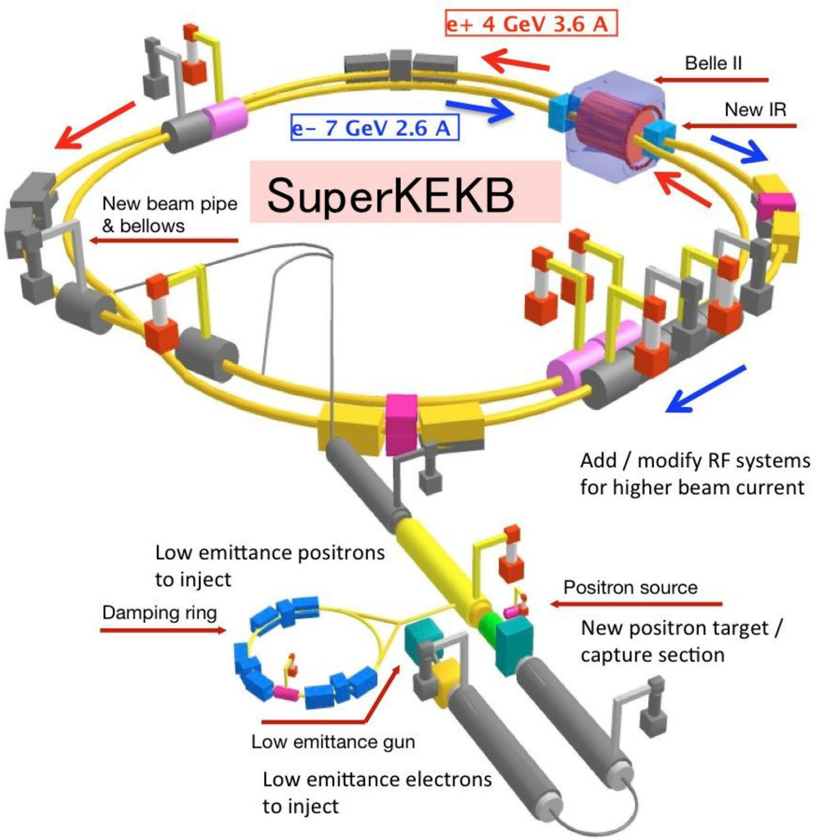
Facilities: Belle II @ SuperKEKB

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**

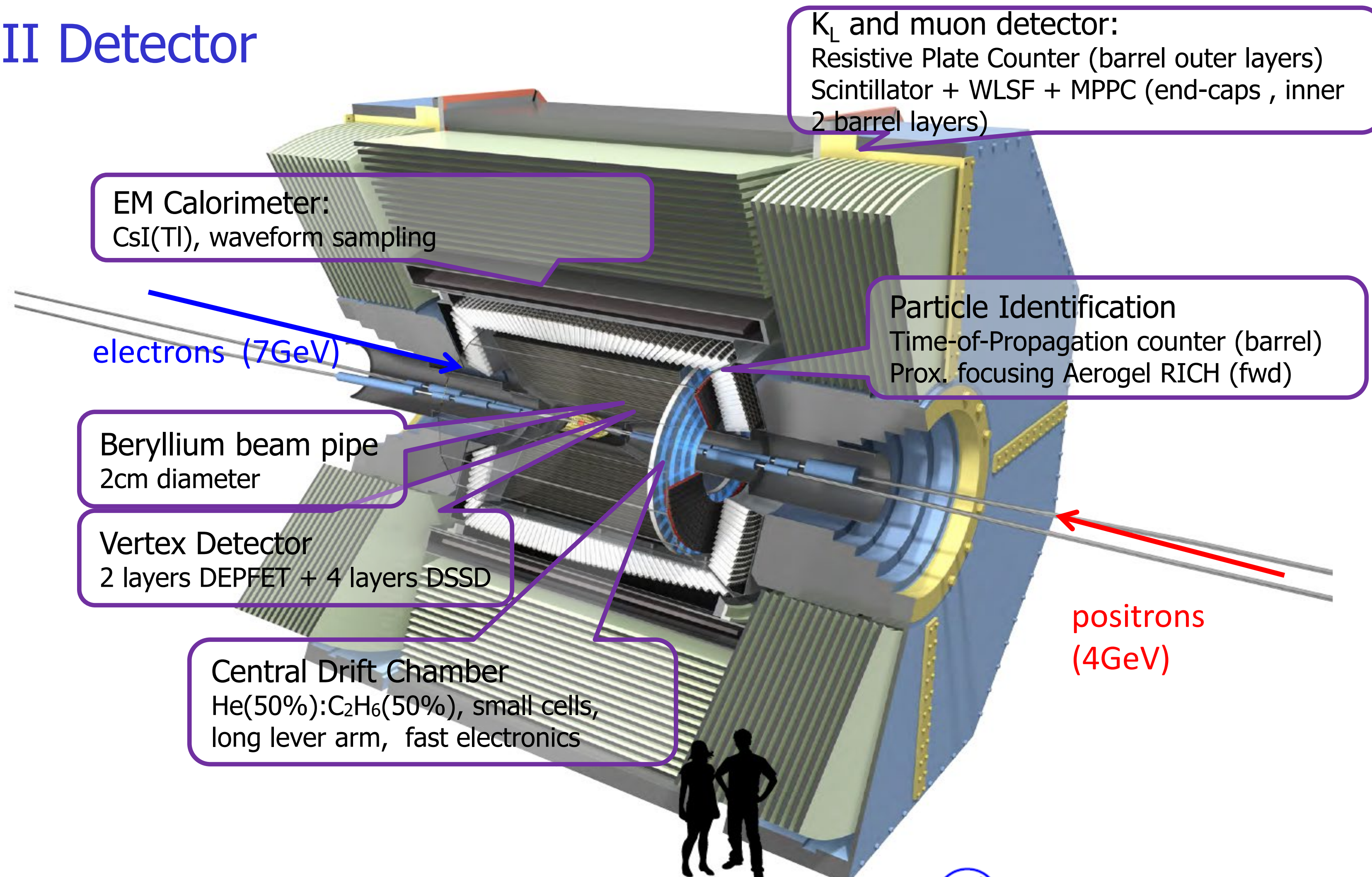


Idea: to increase the luminosity of KEKB by a factor of 30, employ Nano-Beam scheme (P. Raimondi): squeeze beta function at the IP (βx*,βy*) and minimize longitudinal size of overlap region

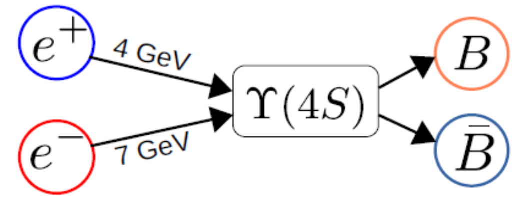
- Modestly increase the beam currents from 1.64A + 1.19A to 2.8A+2.0A (e-,e+)
- Dramatically decrease the beam cross section: β_y^* from 5.9mm/5.9mm to 0.27mm/0.30mm
- Increase the crossing angle to 83mrad

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

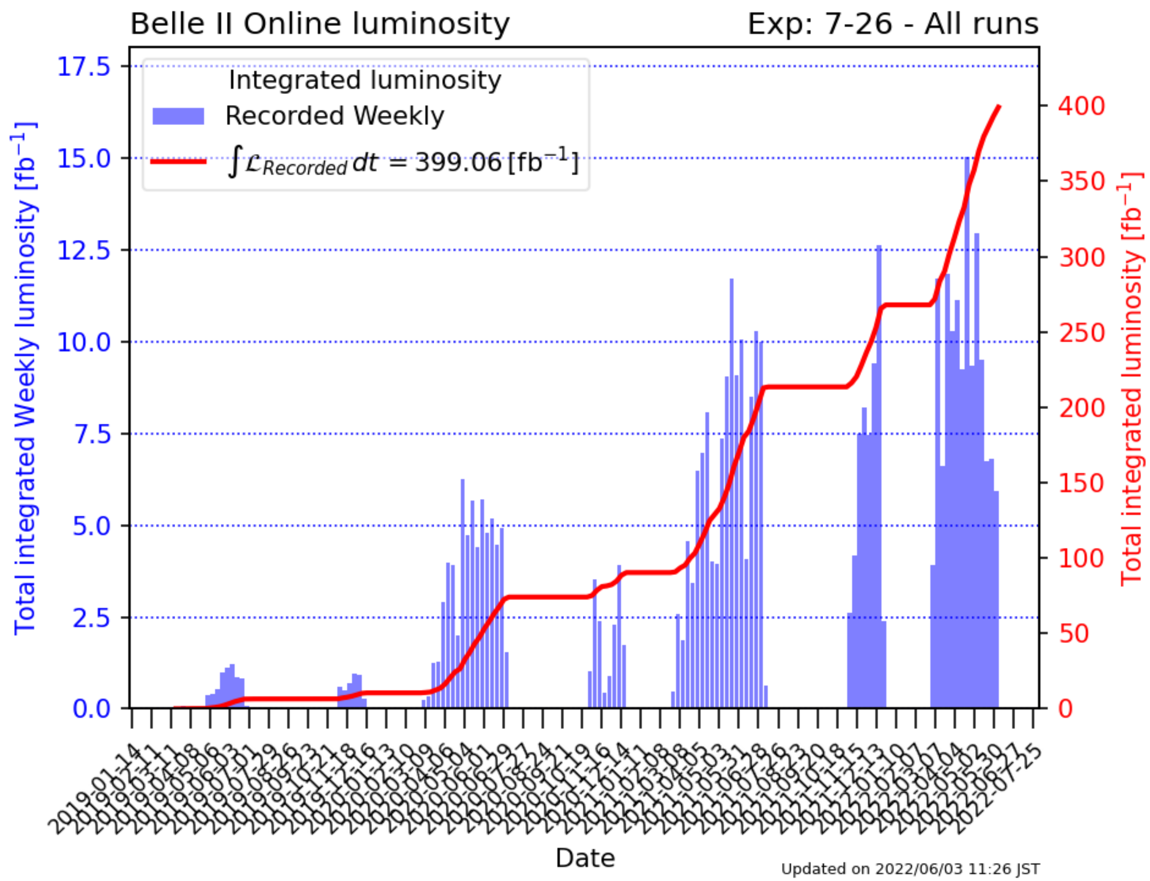
Belle II Detector



- Exactly two B mesons produced (at $\Upsilon(4S)$)
- 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})

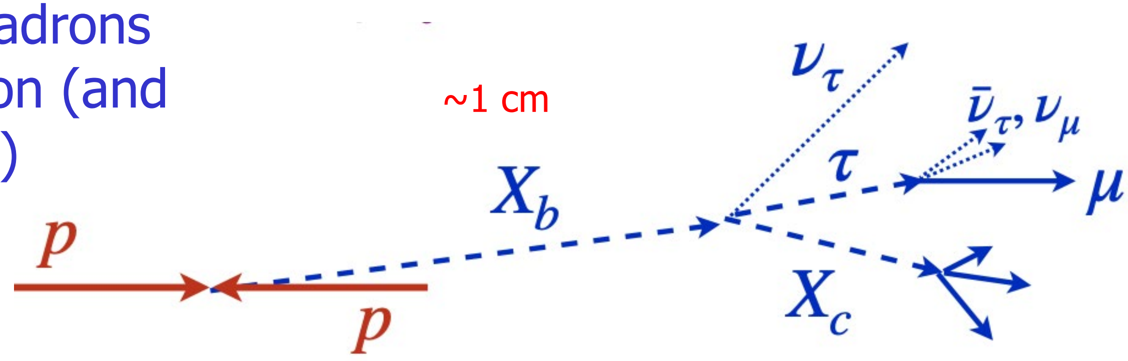
Ultimate goal: reach 50 ab^{-1} by operating at the instantaneous luminosity of 6×10^{35} cm^{-2} s^{-1}

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

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

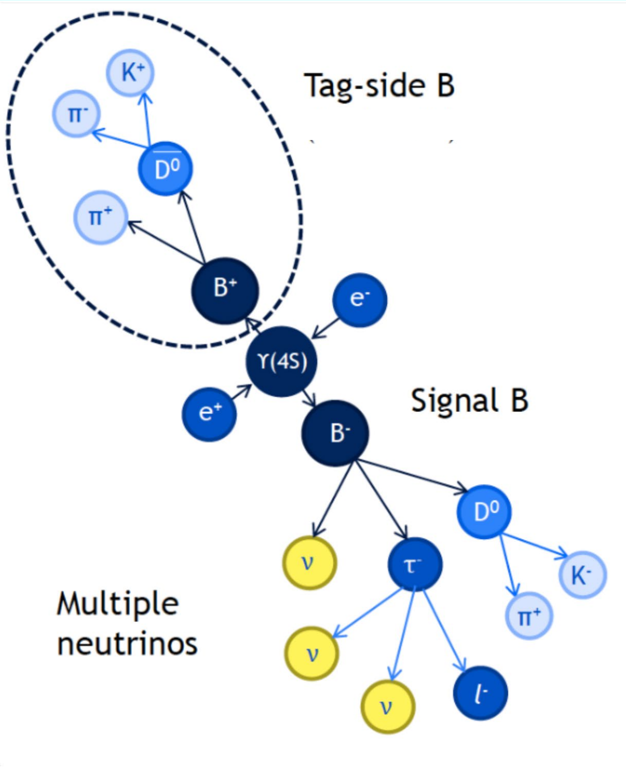
$$\downarrow$$

$$\mathscr{R}(D^{(*)}, D_s^{(*)}, X, \pi, \dots)$$

Full Event Interpretation (FEI) - tagging of the B meson decay

At Belle II (just like previously at Belle and BaBar) exactly two B mesons are produced in the e^+e^- collision.

Idea: fully (or partially) reconstruct one of the B's to tag B flavor/charge, determine its momentum, and exclude decay products of this B from further analysis



Offline B meson beam!

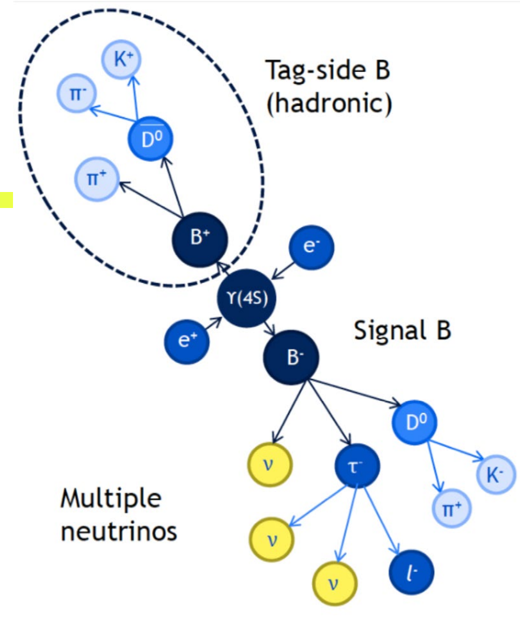
full reconstruction:
- hadronic tagging, $B \rightarrow D\pi$ etc.

partial reconstruction:
- semileptonic tagging

Decays of interest
- $B \rightarrow X_u\, l\, \nu$,
- $B \rightarrow K\, \nu\, \nu$
- $B \rightarrow D\tau\nu$, $\tau\nu$

Powerful tool for B decays with neutrinos →unique feature at B factories

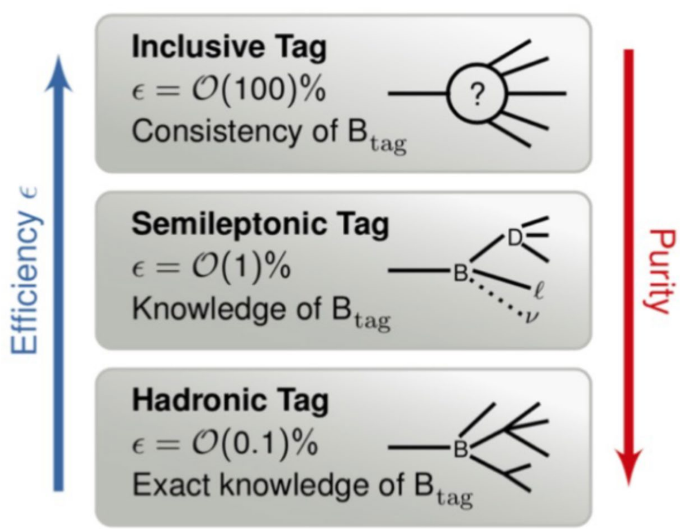
Hadronic tagging at Belle II

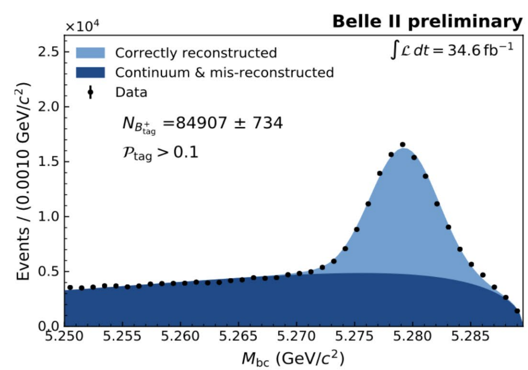


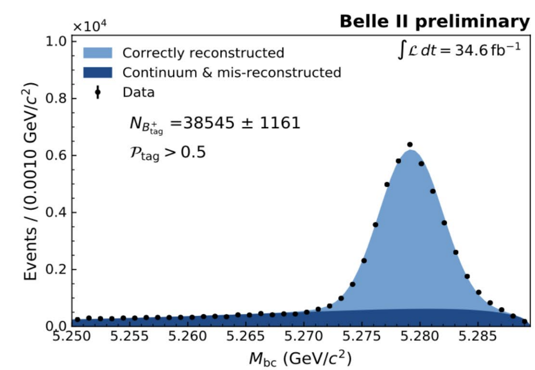
Profit from the fact that exactly two B mesons are produced in e^+e^- collisions

→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



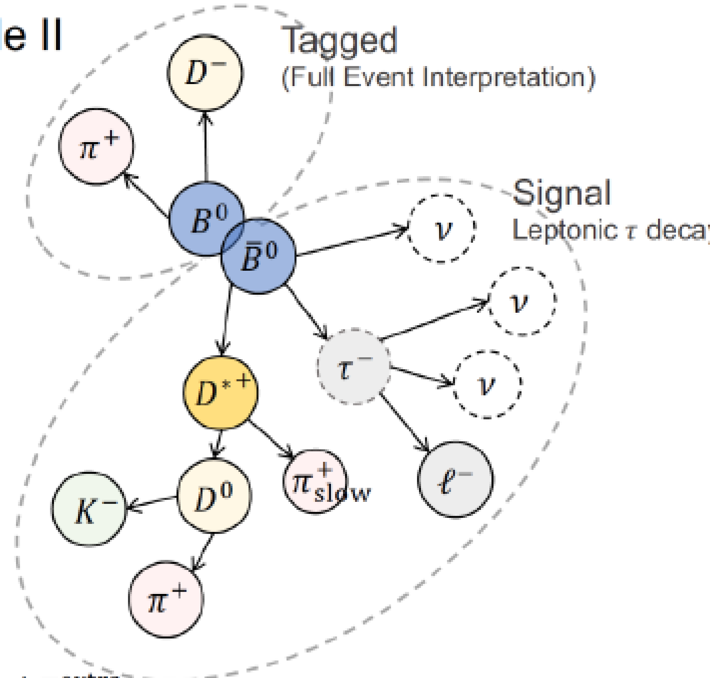




$$M_{bc} = \sqrt{s/4 - p_{cm}^2 c^2}$$

The first R(D*) measurement at Belle II

The first measurement of $R(D^*) = \dfrac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)}$ at Belle II



- Reconstruct $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^*\ell^-\bar{\nu}_\ell$ $(\ell = e, \mu)$ with the same selections.
  - Hadronic B-tagging
  - Leptonic τ decays: $\tau \to e\bar{\nu}_e\nu_\tau / \mu\bar{\nu}_\mu\nu_\tau$
  - Three D^* decay channels: $D^{*+} \to D^0\pi^+ / D^+\pi^0$, $D^{*0} \to D^0\pi^0$

- Extract yields of both signal $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ and normalization $\bar{B} \to D^*\ell^-\bar{\nu}_\ell$ modes

  with two discriminating variables unique to a tagged analysis, $M^2_{\rm miss}$ and $E^{\rm extra}_{\rm ECL}$, through a simultaneous fit among three D^* decay channels.

Challenges:

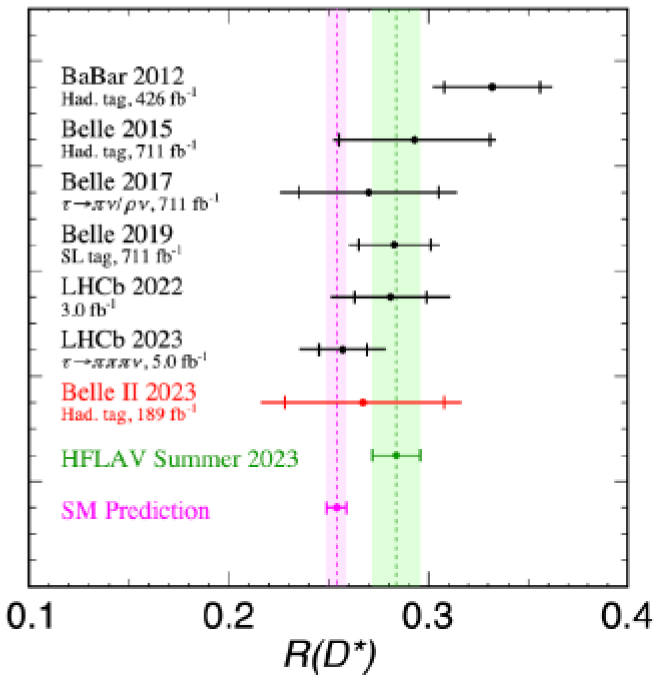
- Multiple missing neutrinos in the final state of $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$

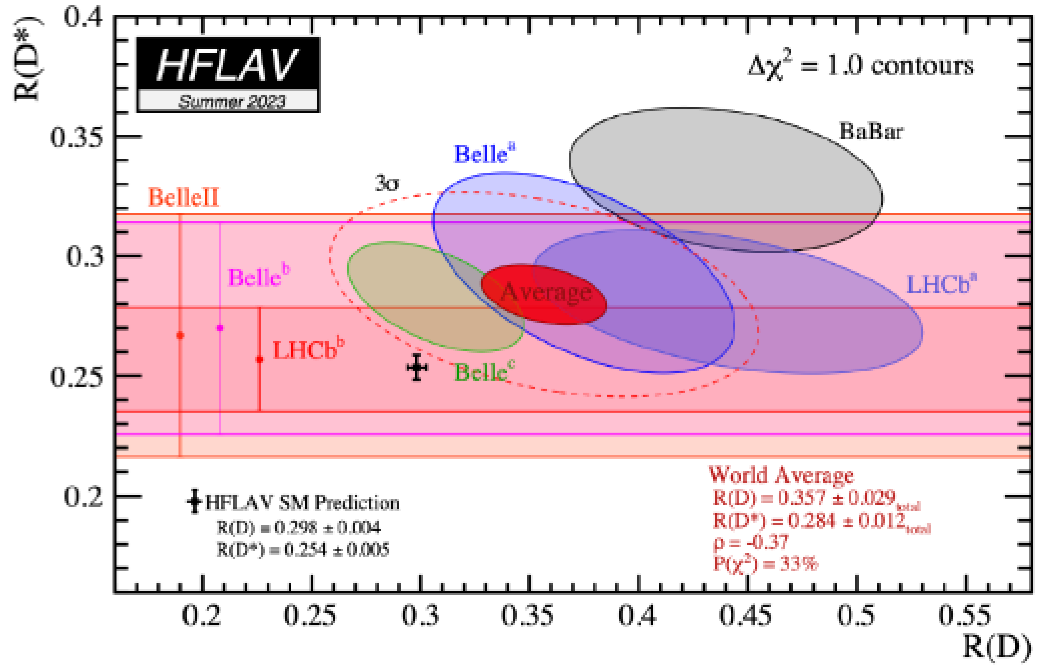
  → No clear peak in observables
- Background control from $\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$

Summary of R(D*) Measurements

Belle II result $R(D^*) = 0.267\,^{+0.041}_{-0.039}(\text{stat.})\,^{+0.028}_{-0.033}(\text{syst.})$

40% improvement in statistical precision over Belle at the same sample size





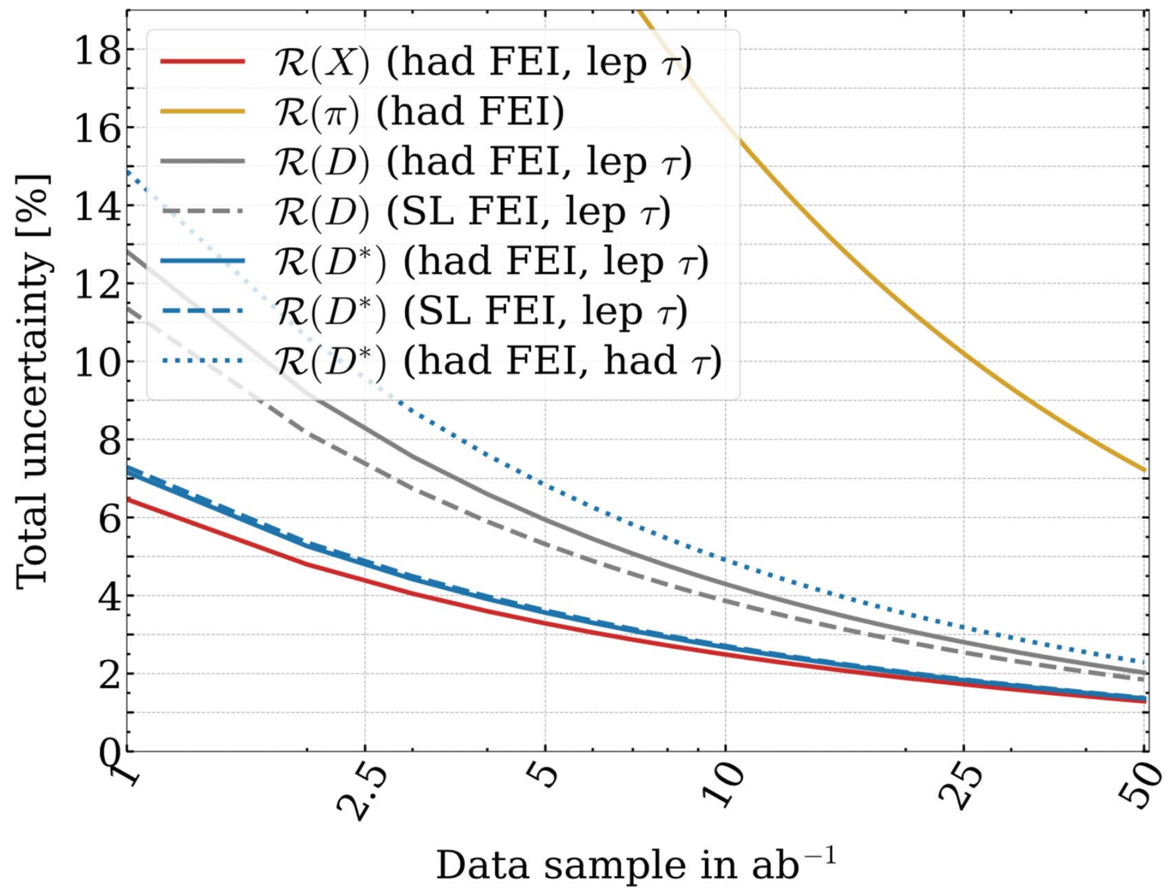
Our result is consistent with both the SM prediction and the HFLAV average.

The new HFLAV average increases the tension with the SM from 3.2σ to 3.3σ.

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

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

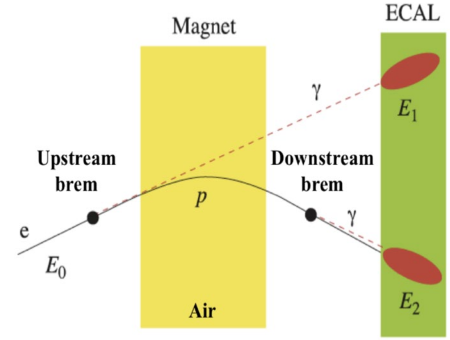
with ℓ a light lepton



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

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

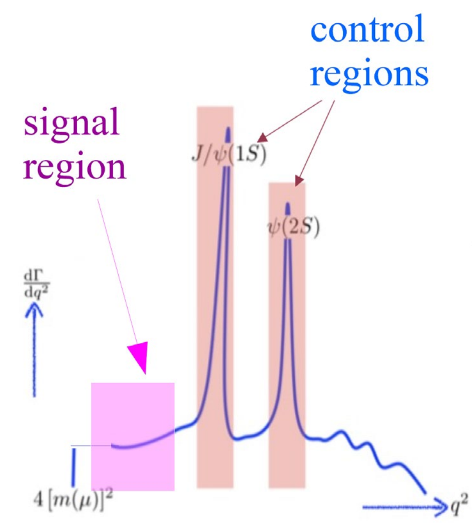


Lepton reconstruction is not universal at LHCb: electrons affected by large bremsstrahlung emission

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

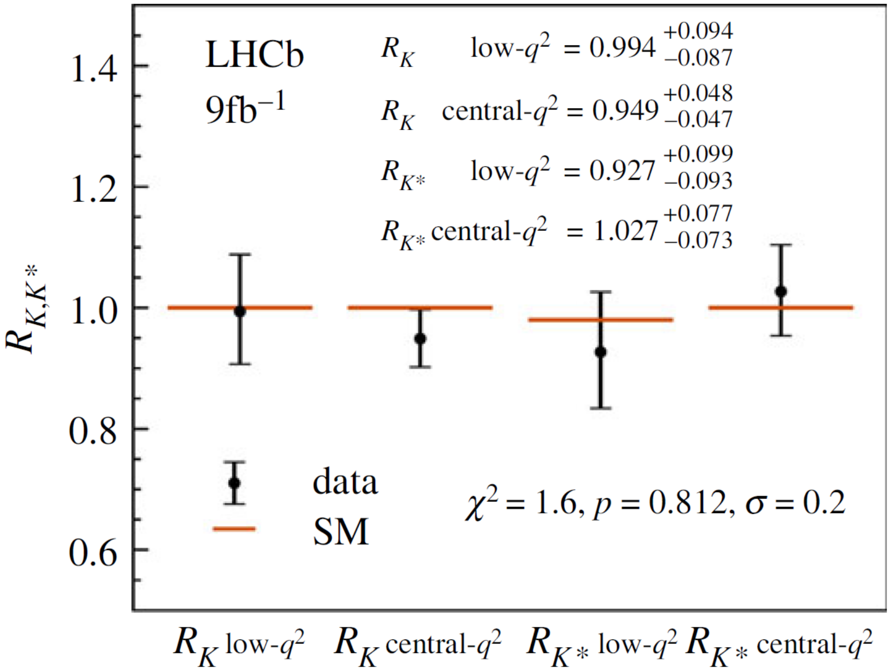
Measurement of the double ratio with J/ψ control mode allows better control of efficiency

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



Different q^2 regions → Contributions from different processes.

R_K at LHCb – updated



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

With more data available and refined analysis, the ratio RK as measured by LHCb is now consistent with 1 – no deviation from the Standard Model.

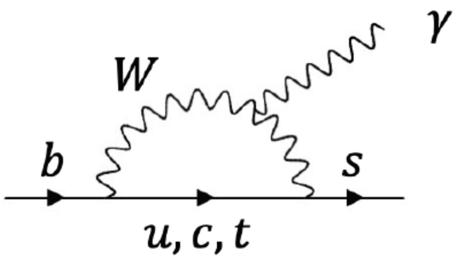
Rare decays of the type $b \to s$ still remain, however, a hot topic in particle physics. Among others, searches for new physics are carried out in differential decay rates in $B \to K^*\mu\mu$ and and $B_s \to \varphi\mu\mu$ decays (by LHCb) where further hints for anomalies were seen, searches for rare $B^\pm \to K^\pm \nu\nu$ decays (at Belle II), as well for SM-forbidden lepton-flavour violating decays B$\to K^{(*)}\tau l$ with $l=e,\mu$.

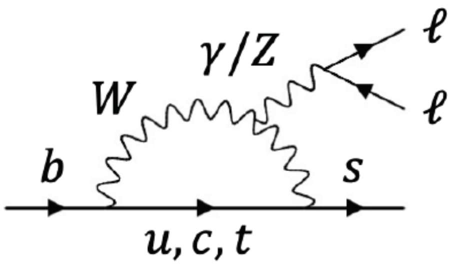
More on rare decays with b→s transitions

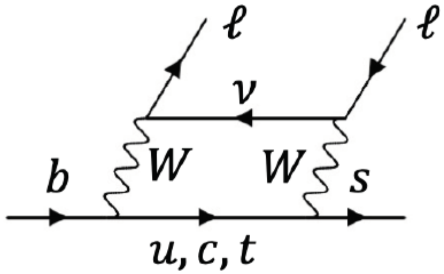
→ More searches for new physics in rare decays of the type b → s

- 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

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



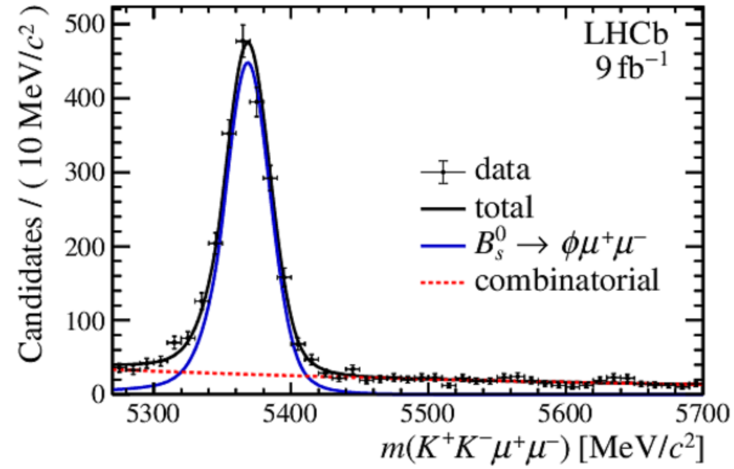




$b \to s \ell^+\ell^-$ branching fractions

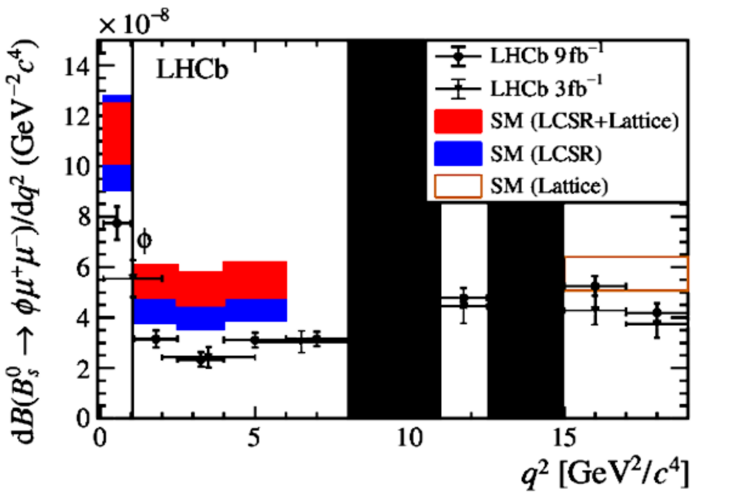
$B_s^0 \to \varphi \mu^+ \mu^-$
$dB/dq^2 = (2.88 \pm 0.22) \times 10^{-8}/(GeV^2/c^4)$
for $q^2 \in [1.1, 6.0]$ GeV^2/c^4
– In agreement with Run 1 result
– 3.6σ deviation tension with SM

arXiv:2105.14007



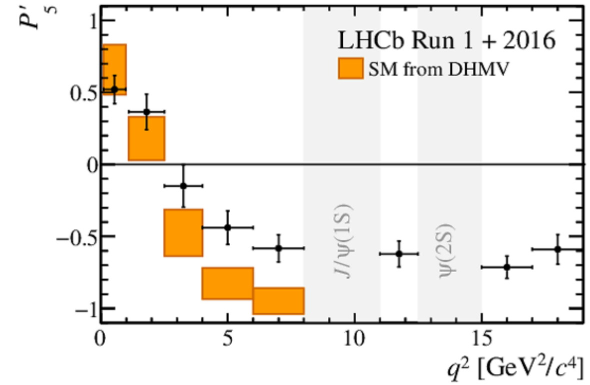
$B_s^0 \to \varphi\mu^+\mu^-$
– Observables F_L, ACPi asymmetries, coefficients Si
– Compatible with SM, tension in F_L

arXiv:2107.13428



b → s $\ell^+\ell^-$ angular analysis

Angular observables: polarisation, asymmetries vs q^2

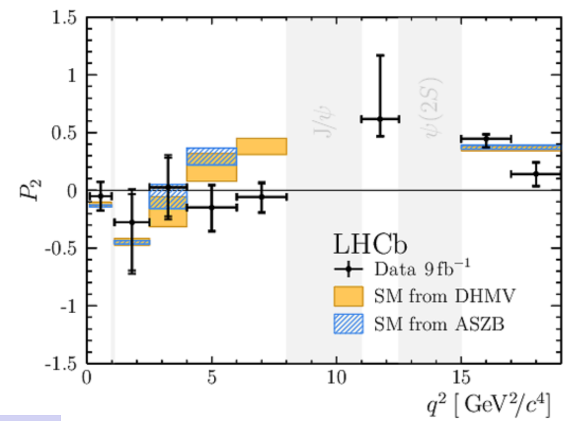


$B^0 \to K^{*0}\mu^+\mu^-$ PRL 125 (2020) 011802

– 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

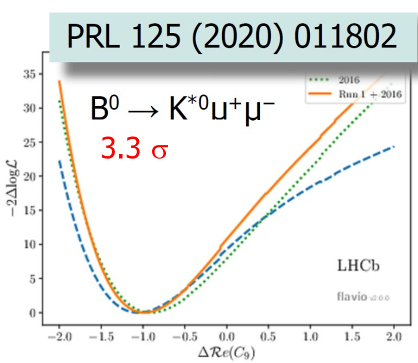


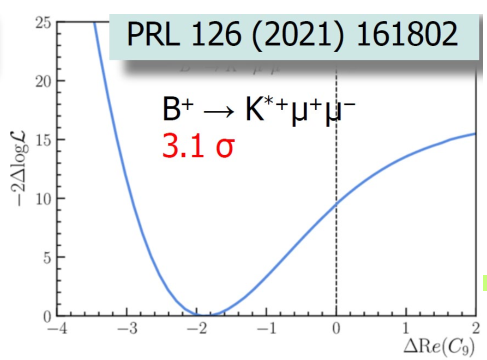
$B^+ \to K^{*+}\mu^+\mu^-$ PRL 126 (2021) 161802

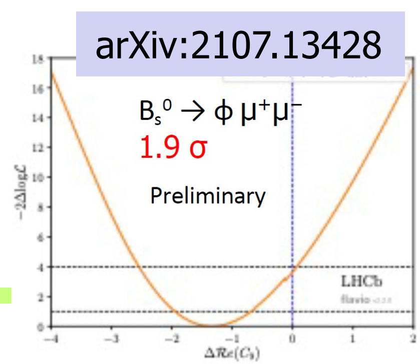
– First LHCb measurement

– 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)







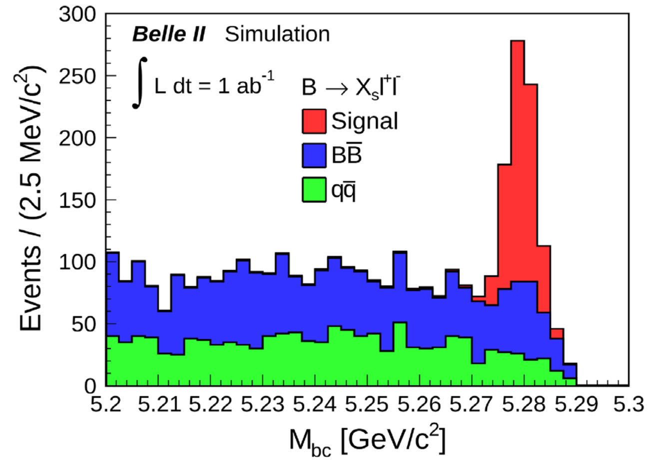
Negative shift of ΔRe(C_9) from SM preferred value by a 2 to 3σ level

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

Measurement of

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

[arXiv:2012.15394], [arXiv:1709.10308]

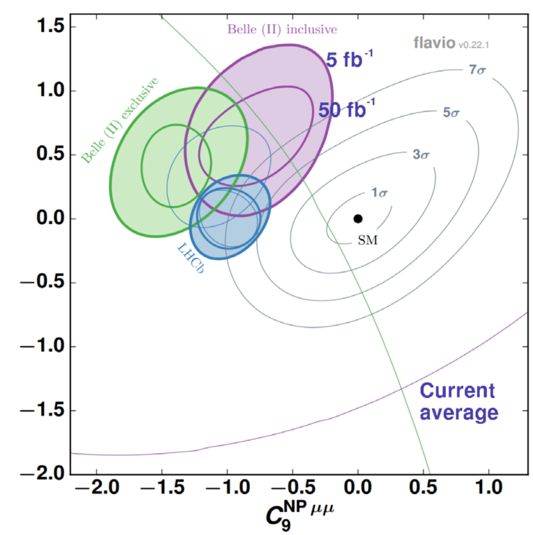


Two methods available:

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

Expected sensitivity:

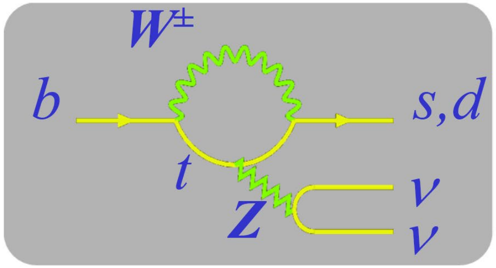
Observables	Belle (0.71 ab^{-1})	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
R_{X_s} ([1.0, 6.0] GeV^2/c^4)	32%	12%	4.0%
R_{X_s} ([> 14.4] GeV^2/c^4)	28%	11%	3.4%

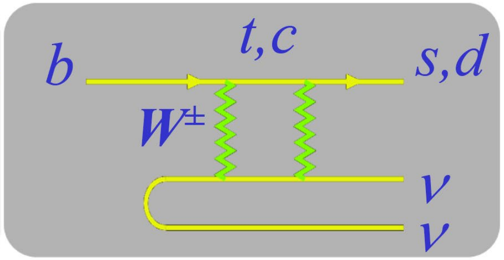


Angular analysis of $B \to X_s \ell\ell$ will improve constraints on Wilson coefficients C_9 and C_{10}

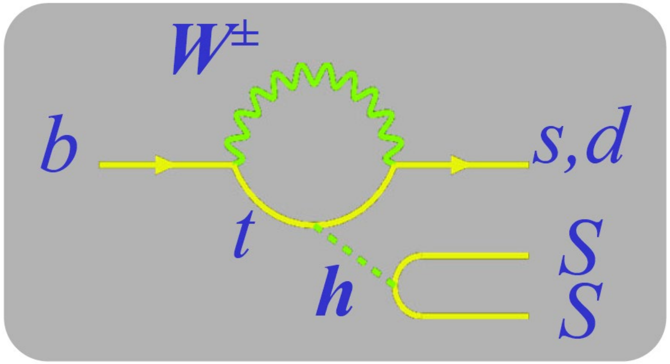
Search for $B^\pm \to K^\pm \nu\bar{\nu}$

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 been observed before

-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

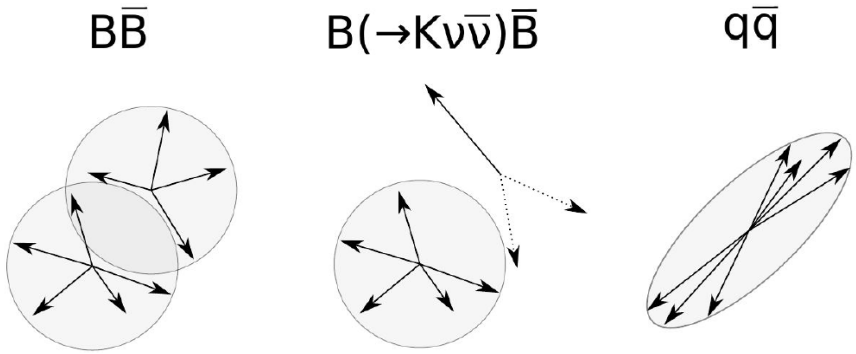
-semi-leptonic tag: $\varepsilon_{sig} \sim 0.2\%$ (Belle)

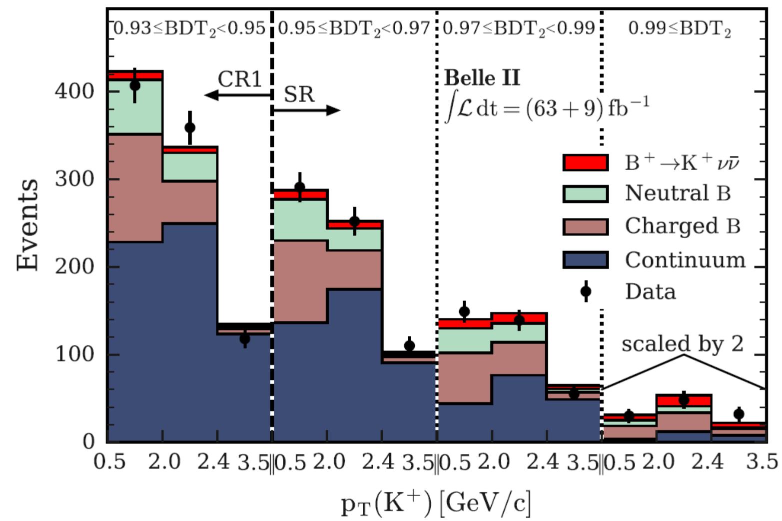
-hadronic tag: $\varepsilon_{sig} \sim 0.04\%$ (BaBar)

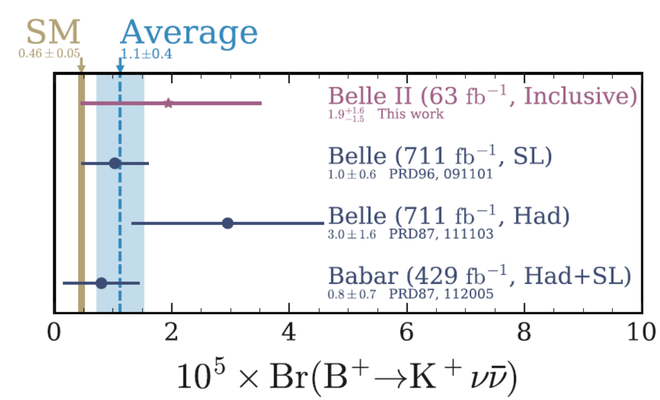
New approach by Belle II based on an inclusive tag

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

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

-much higher efficiency of ε_{sig} ~ 4.3% resulting in increased sensitivity per luminosity

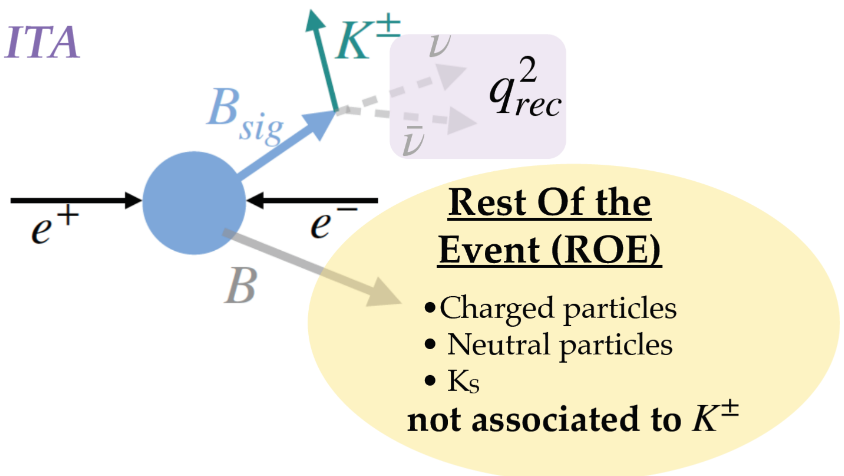
Further improvements possible

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

Search for $B^\pm \to K^\pm \nu\nu$

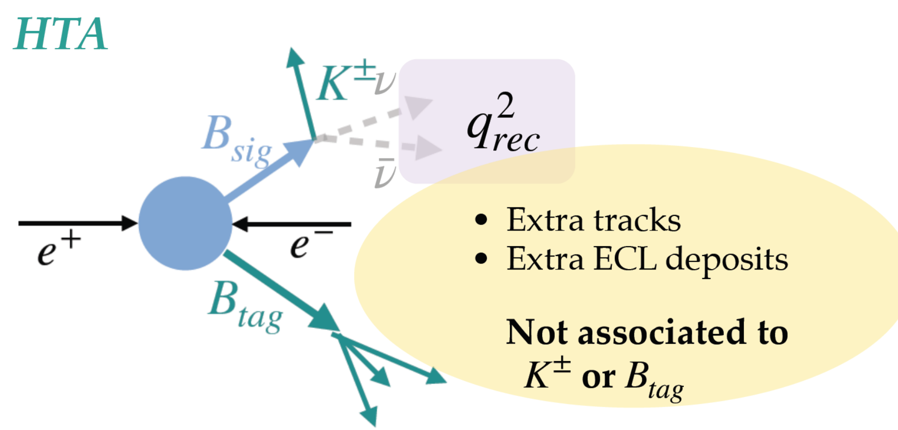
New measurement on the full available data sample (6x larger than the first try)

Employ the inclusive (ITA) and hadronic (HTA) tagging methods



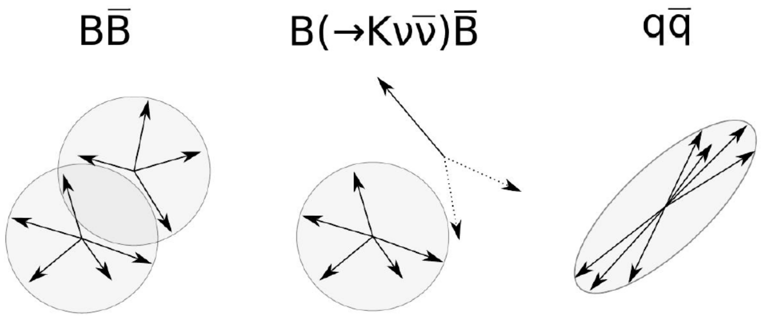
$q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^*$

In case of multiple signal candidates => pick lowest q^2_{rec} one



- Reconstruct the B_{tag} in one of the 35 hadronic final states with the full-event interpretation algorithm [springer41781-019-0021-8]
- $q^2_{rec} = \frac{s}{4} + m_K^2 - \sqrt{s}E_K^* - 2\mathbf{p}_{tag} \cdot \mathbf{p}_K$

Search for B$^\pm \to$ K$^\pm\nu\nu$



New measurement on the full available data sample (6x larger than the first try)

Employ the inclusive (ITA) and hadronic (HTA) tagging methods

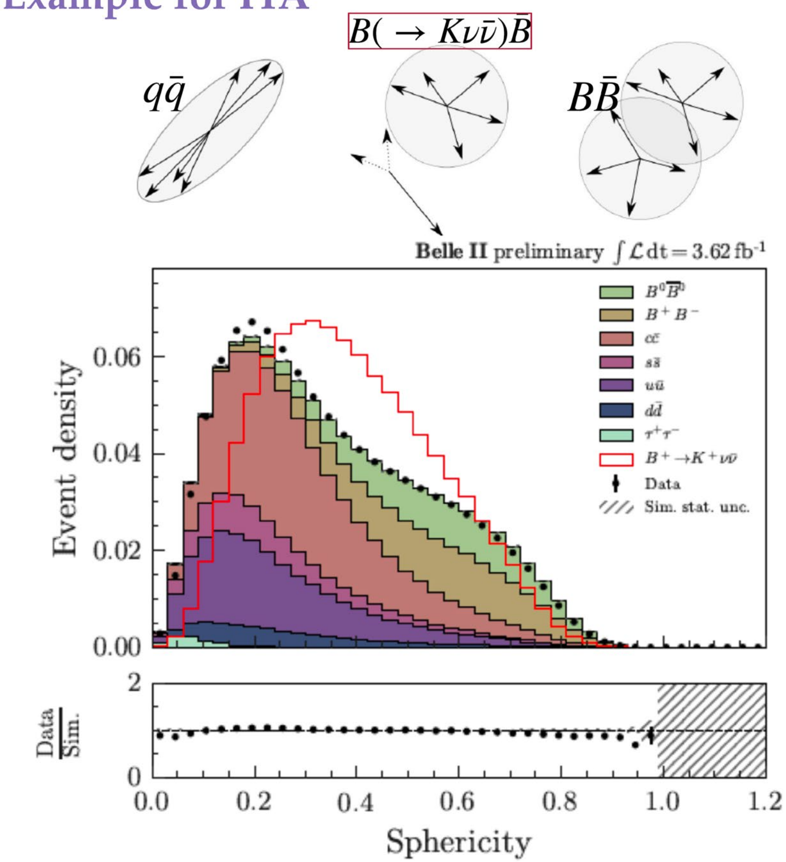
ITA background suppression:

- Build BDT1 and use it as a first filter: $BDT1$>**0.9**
- Build BDT2, define $\eta(BDT2)$ variable (BDT2 w/ flat signal efficiency) and require $\eta(BDT2)$>**0.92**

HTA background suppression:

- Build $BDTh$, define $\eta(BDTh)$ and require $\eta(BDTh)$>**0.4**

Example for ITA

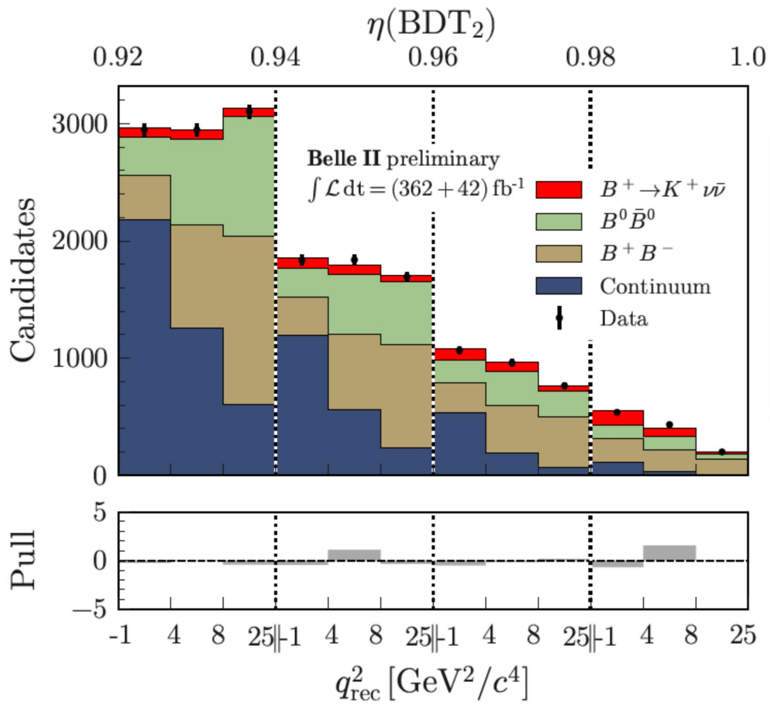


Search for $B^{\pm} \to K^{\pm}\nu\nu$

Signal extraction for the inclusive (ITA) and hadronic (HTA) tagging methods on the full available data sample (6x larger than the first try)

ITA

$$\mu = 5.4 \pm 1.0\ (\text{stat}) \pm 1.1\ (\text{syst})$$



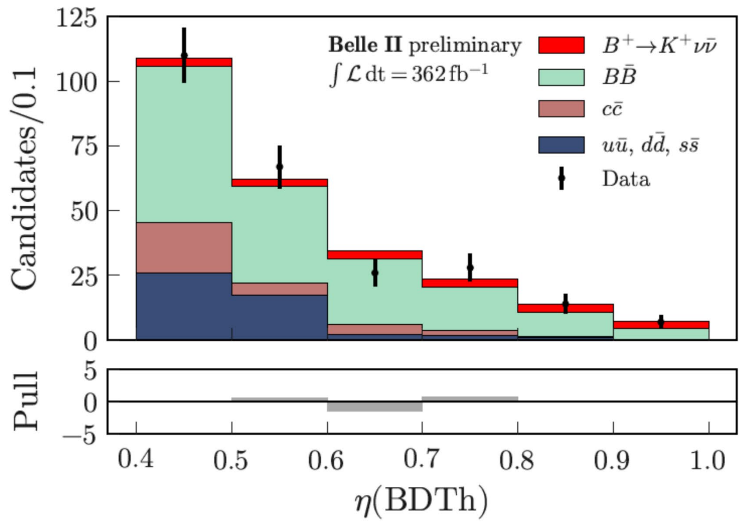
3.5 σ significance wrt bkg-only hypothesis

2.9 σ deviation from SM

HTA

$$\mu = 2.2^{+1.8}_{-1.7}\ (\text{stat})^{+1.6}_{-1.1}(\text{syst})$$

- Compatible with the Background-only hypothesis at the level of **1.1 σ**
- Compatible with the SM at the level of **0.6 σ**



$B^{\pm} \rightarrow K^{\pm}\nu\nu$: combining the measurements wit the two methods

• ITA and HTA results are consistent at 1.2σ level

• Overlap between the two data samples: the ITA sample contains 2% of HTA events. Remove common events from ITA sample and combine results taking into account common correlated uncertainties.

$$\mu = 4.6 \pm 1.0\,(\text{stat}) \pm 0.9\,(\text{syst})$$

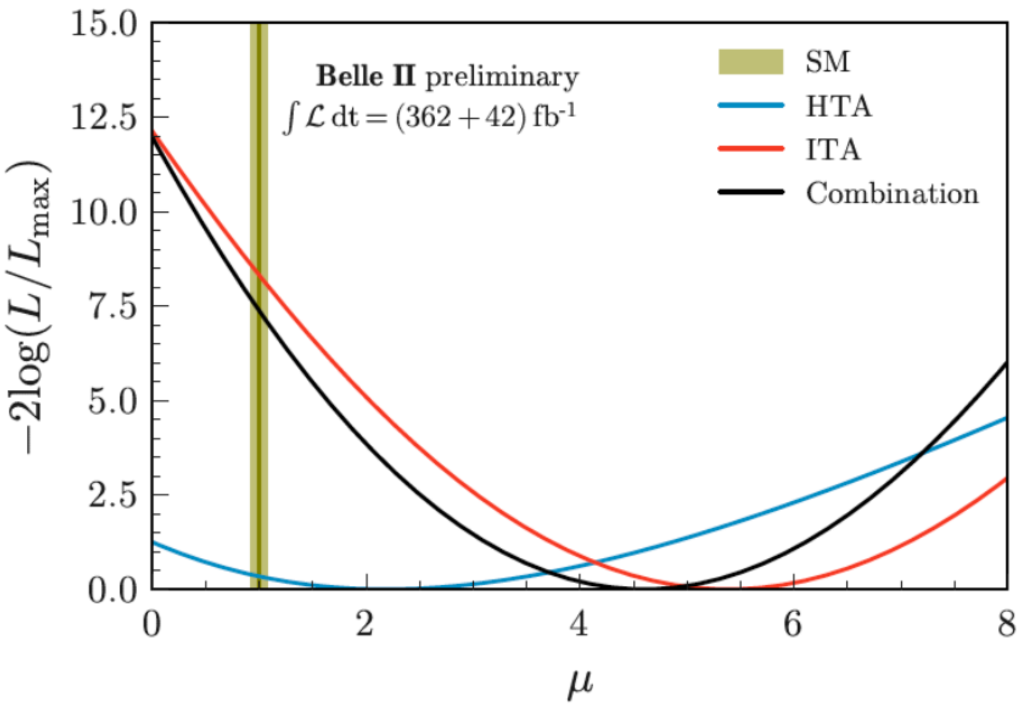
$$\mathscr{B}(B^+ \rightarrow K^+\nu\bar{\nu}) = [2.3 \pm 0.5\,(\text{stat})^{+0.5}_{-0.4}\,(\text{syst})] \times 10^{-5}$$

μ = BR(measured)/BR(SM)

3.5 significance wrt the background-only hypothesis

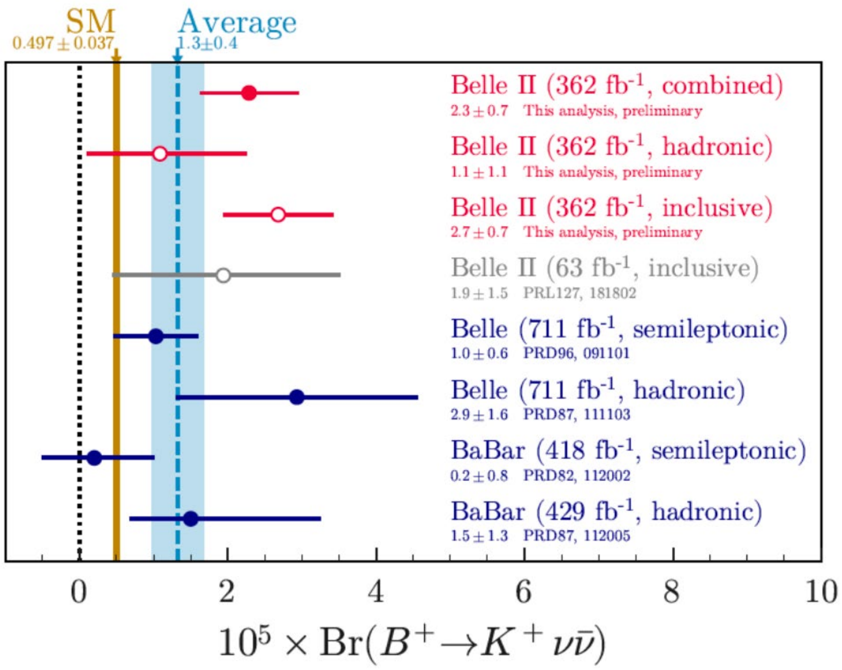
2.7 deviation from the SM signal

First evidence of the $B^+ \rightarrow K^+\nu\nu$ process



All the details in arXiv:2311.14647

$B^\pm \rightarrow K^\pm\nu\nu$: the big picture



Inclusive tagging method, result:

- in agreement with previous hadronic-tag and inclusive measurements
- 2.3 σ tension with BaBar semileptonic-tag analysis
- comparable precision wrt previous best measurements

Hadronic tagging method, result:

- In agreement with all the previous measurements
- Most precise result with hadronic tag strategy

Overall good compatibility:
p-value 35%

Outlook

Outlook: LHCb

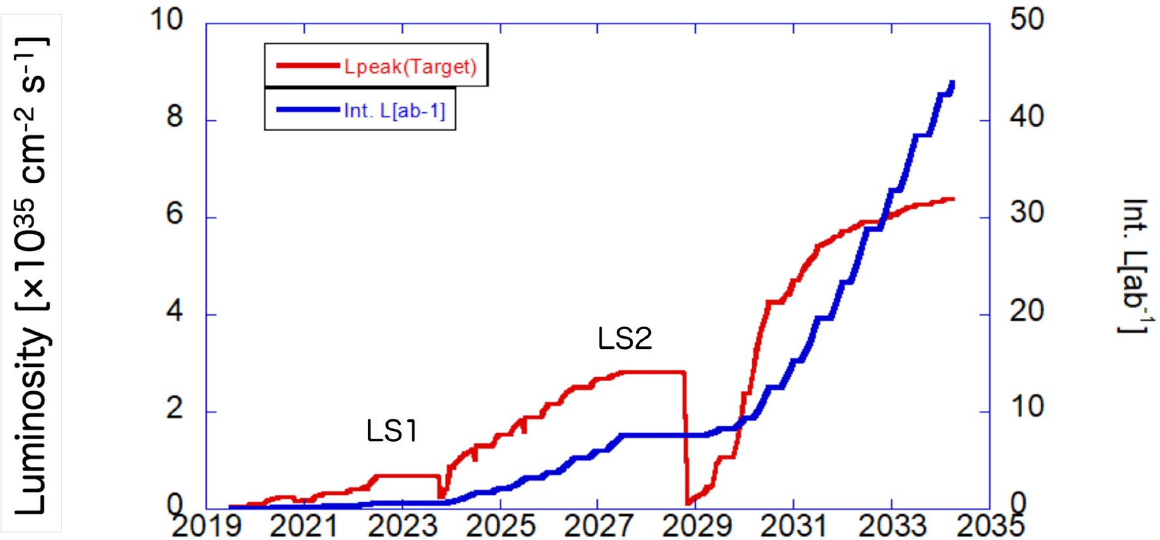
Upgrade I: Major upgrade for operation in Run 3

- 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

Outlook: Belle II



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

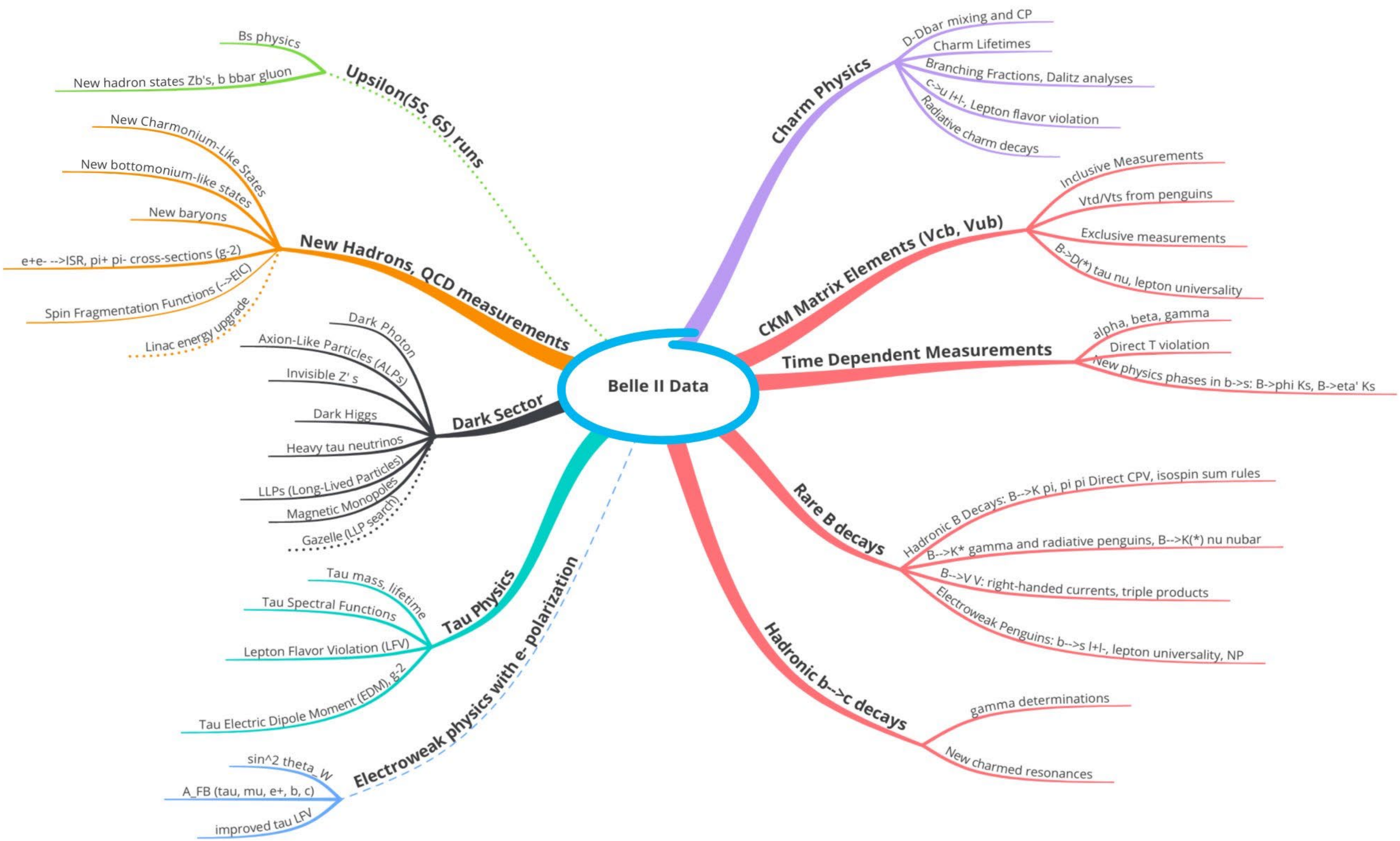
Current working plan follows the KEK Roadmap2020

- 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

Belle II Physics



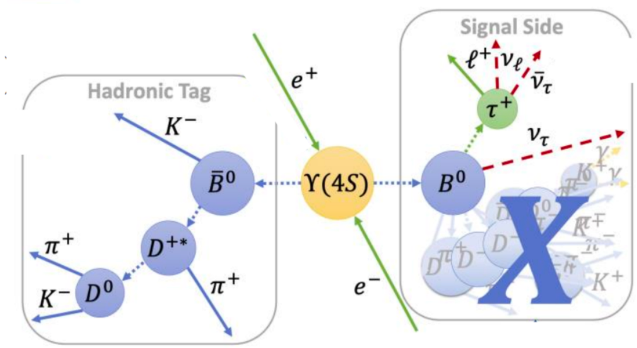
Summary

- 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

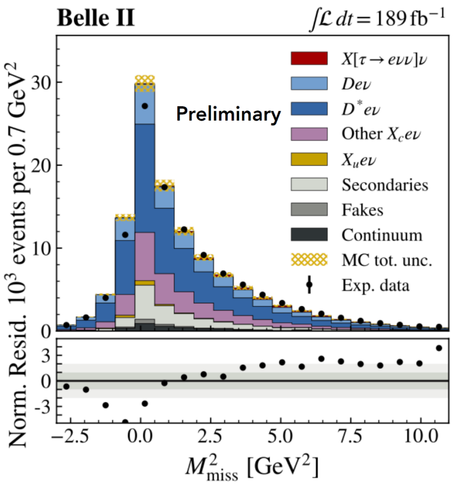
$R(X_{\tau/\ell})$ measurement: overview

- Inclusive ratio: $R(X_{\tau/\ell}) = \dfrac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}, \quad \ell = e, \mu$
- B_{tag} to hadronic final states
  - 66 hadronic B decays, machine-learning based reconstruction algorithm [Comp.Soft.BigSci. 3, 6 (2019)], $\varepsilon_{tag} \sim O(1\%)$

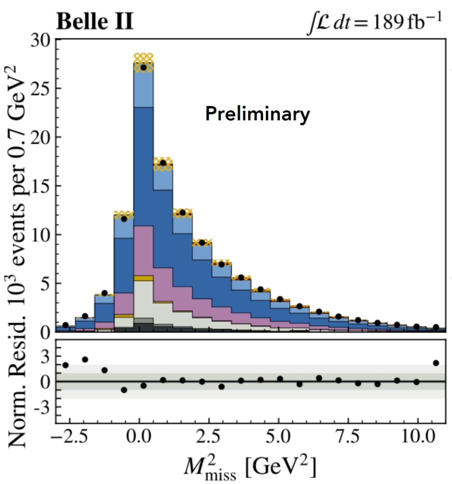


- Signal side τ to leptons
- Variables for yield extraction:
  - missing mass of undetected neutrinos (M^2_{miss})
  - lepton momentum in B rest frame (p^B_ℓ)
- Extensive use of control samples to derive correction for fit templates
  - example: correction to M_X from p^B_ℓ sideband

w/o M_X correction



with M_X correction



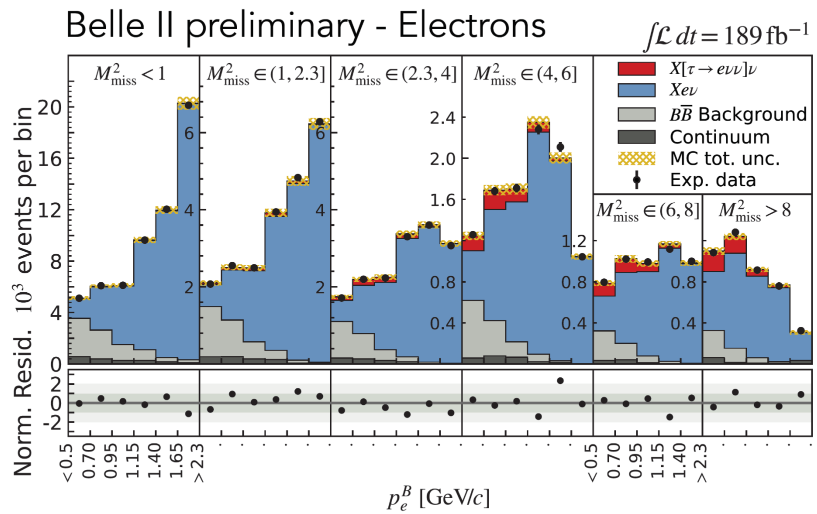
$R(X_{\tau/\ell})$ measurement: result

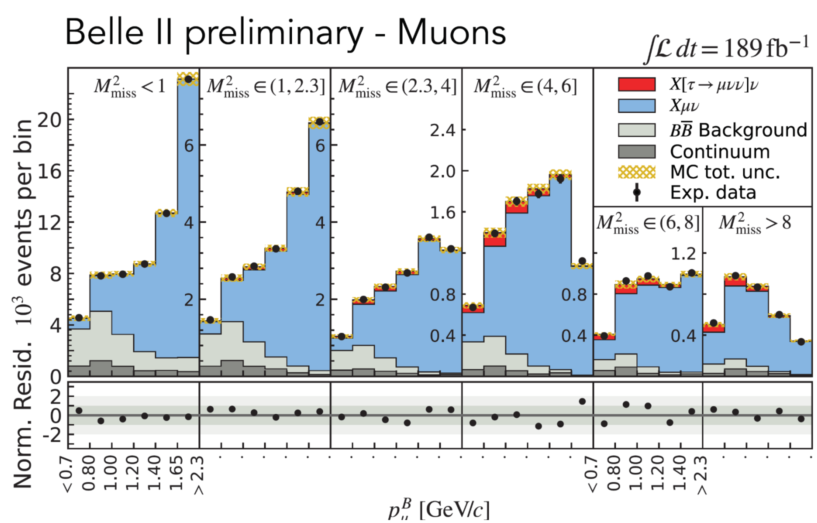
- Result:

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016\ (\text{stat}) \pm 0.036\ (\text{syst})$$

- Main systematic uncertainties from $B \to X_c \ell \nu$ BF and form factors, M_X correction
  - several major systematics are statistical in nature and will decrease with more data
- In agreement with SM prediction and $R(D^{(*)})$ measurements

First measurement of its kind at B factories





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

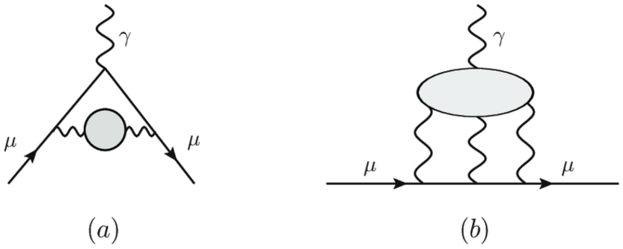
(g-2)$_\mu$ measurement among the most sensitive to New Physics

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-2)*$_\mu$

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

2204.02280 [hep-ex]

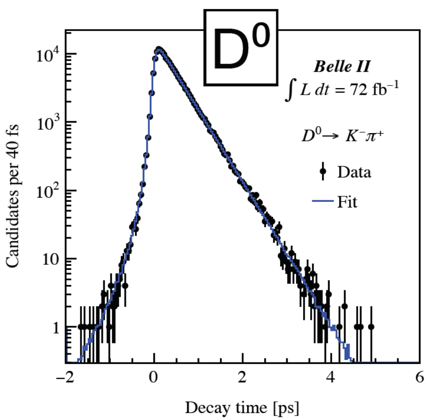
Belle II performance

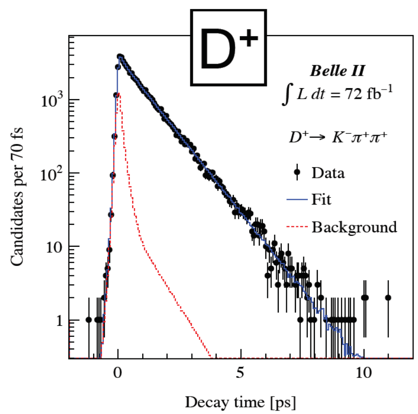
Charm Lifetime @Belle II

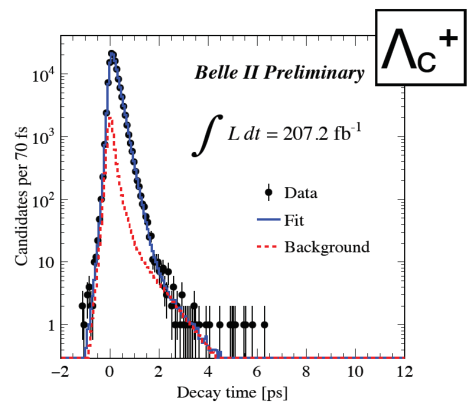
	Belle II	World average
$\tau(D^0)$ =	(410.5 ± 1.1 ± 0.8) fs	(410.1 ± 1.5) fs
$\tau(D^+)$ =	(1030.4 ± 4.7 ± 3.1) fs	(1040 ± 7) fs
$\tau(\Lambda_c^+)$ =	(204.1 ± 0.8 ± 0.7 - 1.4) fs	(202.4 ± 3.1) fs

extra syst from $\Xi_c \rightarrow \Lambda_c \pi$

- 2D fit of unbinned decay time distributions.
- Background from simultaneous fit of sidebands.
- Dominant uncertainties: physics background and detector alignment.
- **World's best** result, establishes the potential of the Belle II detector.







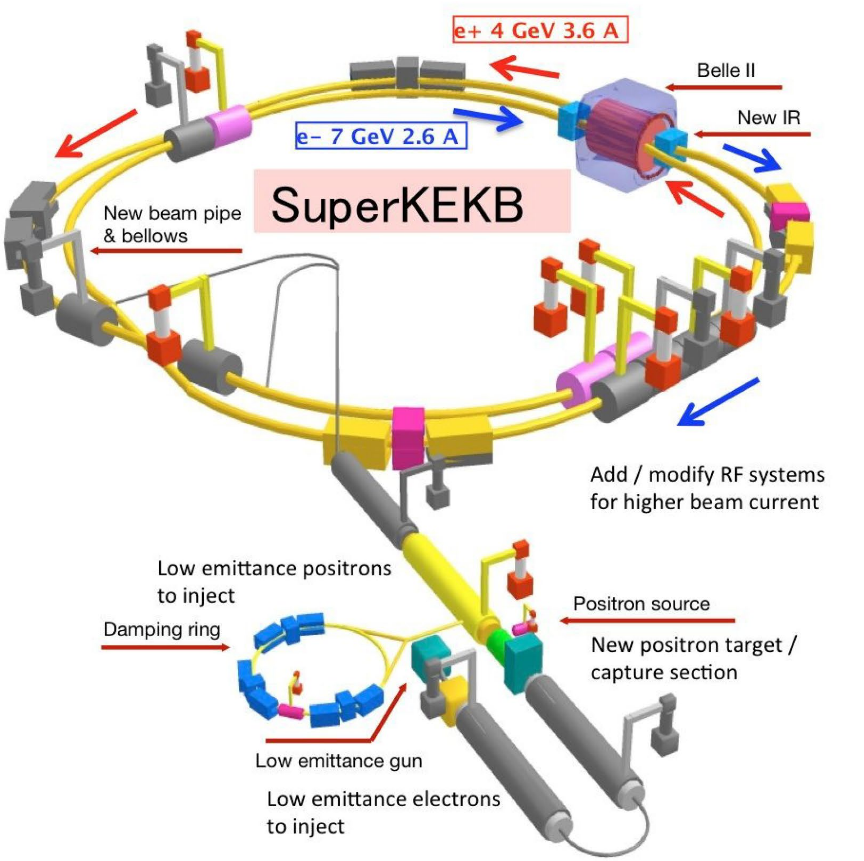
Facilities: Belle II @ SuperKEKB

beam current **x1.5** beam-beam param. **x1**

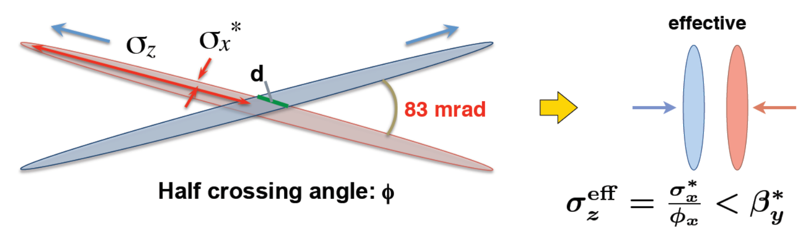
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{R_L}{R_\xi}\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}$$

vertical beta function **x 1/20**

LER / HER	KEKB	SuperKEKB	Effect
Energy [GeV]	3.5 / 8	4.0 / 7.0	**boost x 2/3**
Crossing angle $2\phi_x$ [mrad]	22	**83**	
β_y^* [mm]	5.9 / 5.9	**0.27 / 0.30**	**L x 20**
$I_\pm$ [A]	1.64 / 1.19	**2.8 / 2.0**	**L x ~1.5**
$\varepsilon_y = \sigma_y \times \sigma_{y'}$ [pm]	140 / 140	**13 / 16**	
$\xi_y \sim (\beta_y^*/\varepsilon_y)^{1/2}/\sigma_x^*$	0.129 / 0.09	**0.09 / 0.09**	**L x 1**
Luminosity [10^{34} cm^{-2} s^{-1}]	2.1	**60**	**L x 30**



Nano-Beam scheme (P. Raimondi): squeeze beta function at the IP (βx*,βy*) and minimize longitudinal size of overlap region to avoid hourglass effect



Strong focusing of beams down to vertical size of ~50 nm requires very low emittance beams and large crossing angle (83 mrad). Need powerful and sophisticated final focus system.