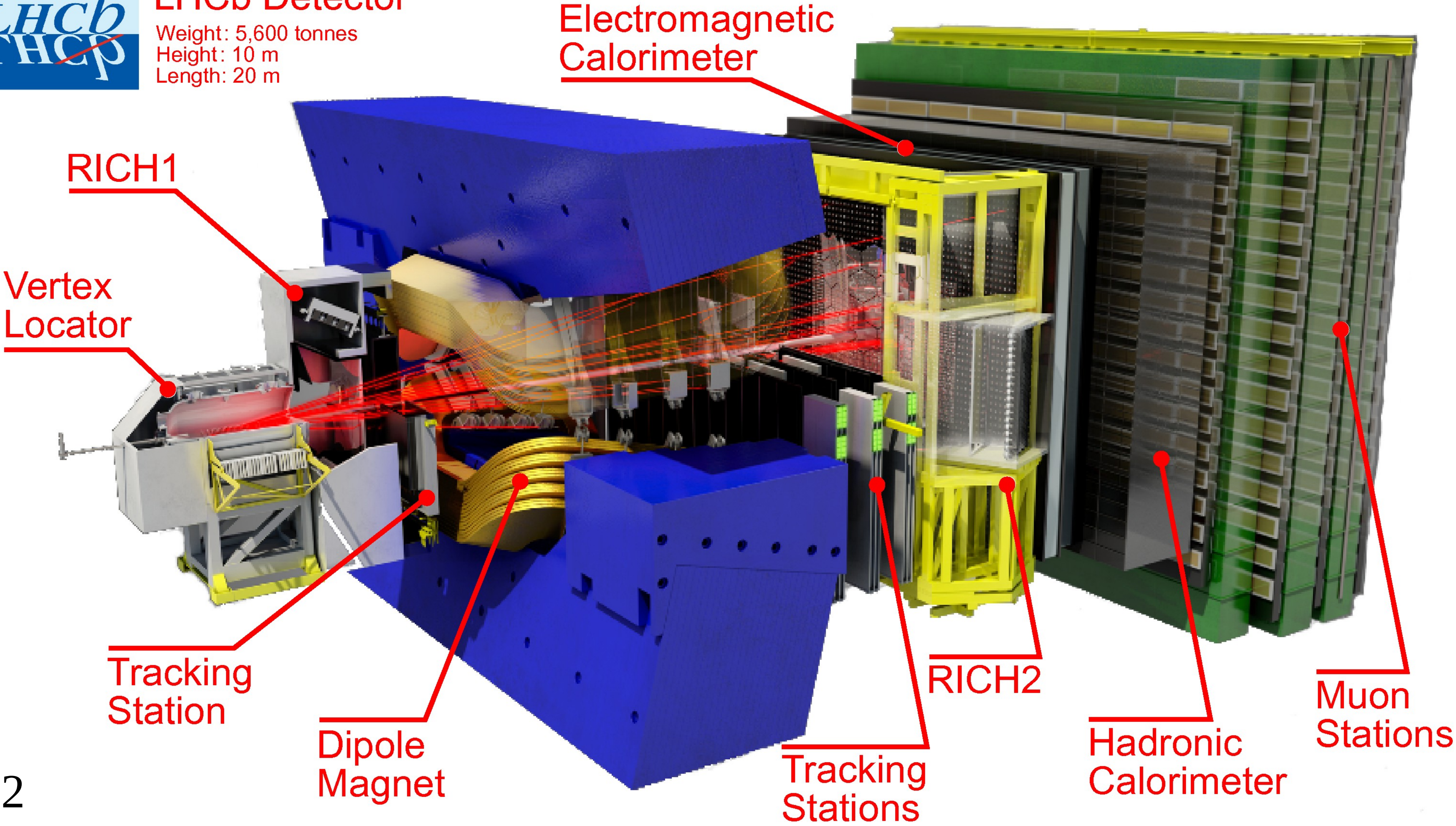
What additional LFU ratios will add

27/04/2022

Yasmine Amhis and Gianluca Inguglia

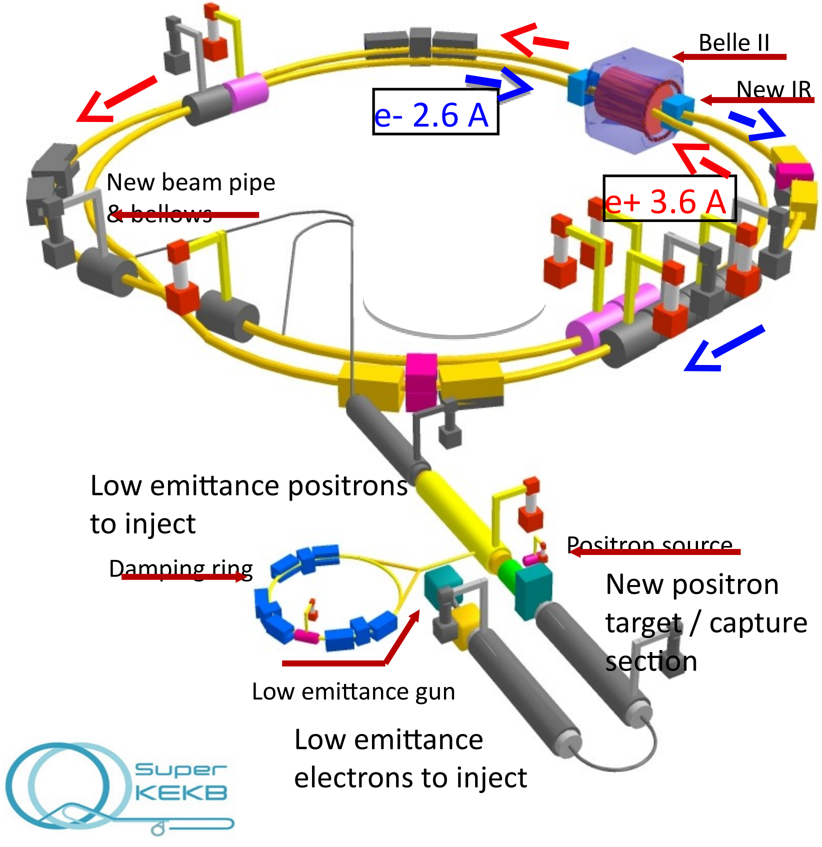
LHCb Detector

Weight: 5,600 tonnes
Height: 10 m
Length: 20 m

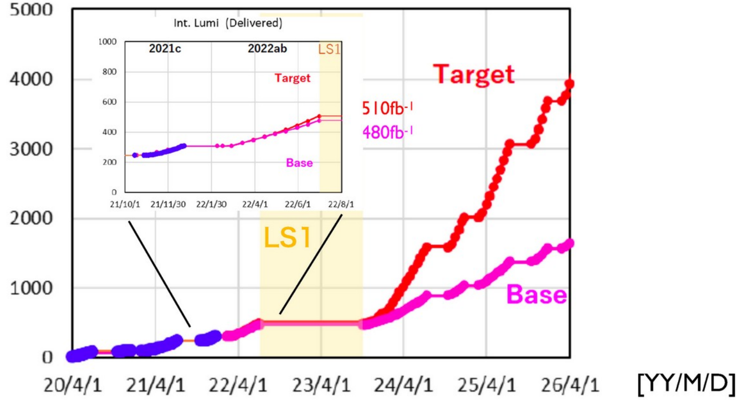


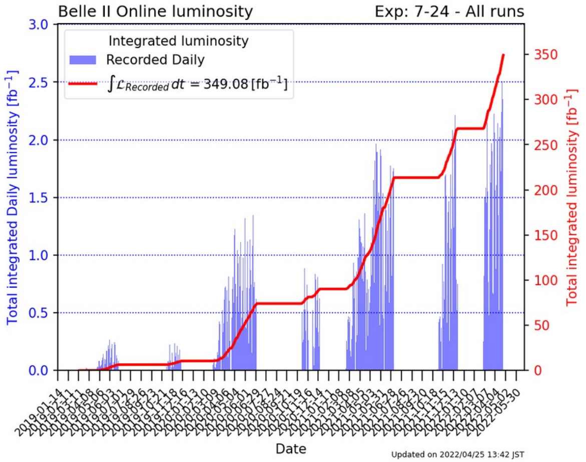
SuperKEKB

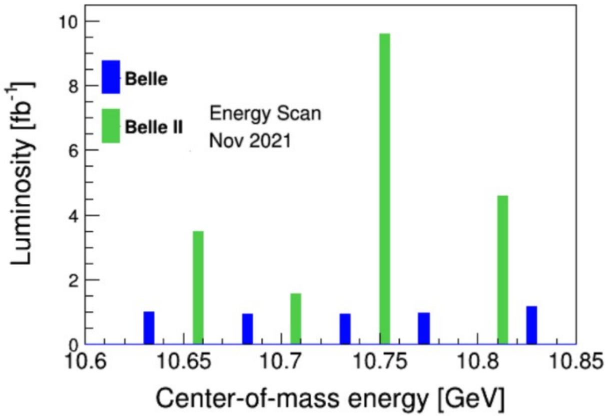
Peak luminosity world record 3.81 x 10^{34} ($cm^{-2}s^{-1}$), December 23, 2021.



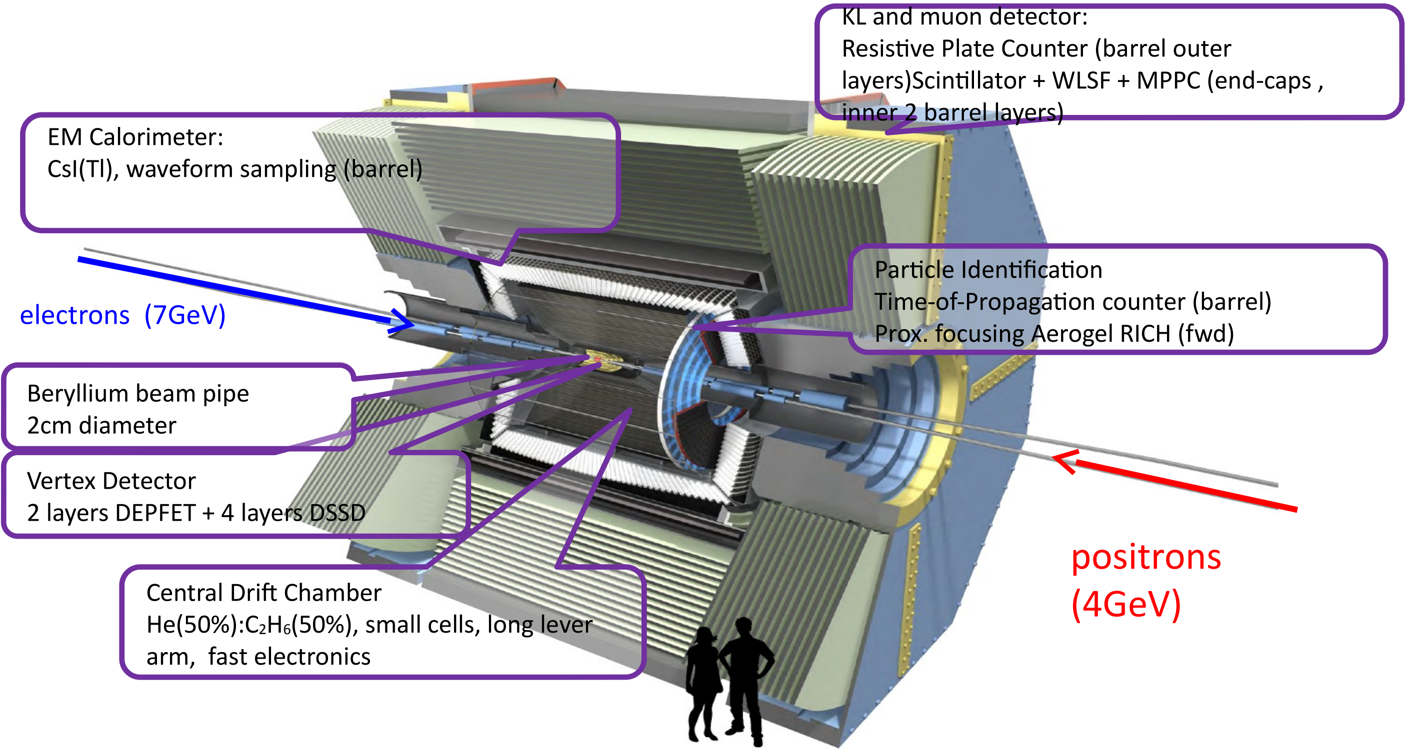
Mid-term luminosity profile



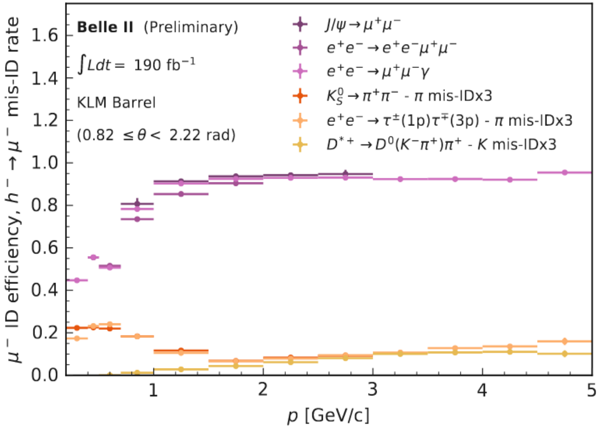


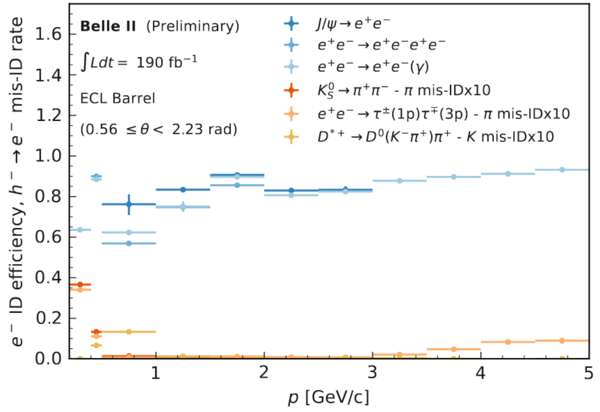


Belle II detector



→Belle 2 Lepton-ID pub. document





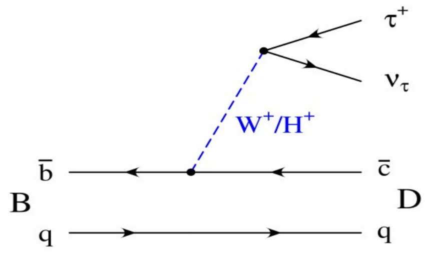
Belle II is a multipurpose detector with an almost 4π coverage perfectly suited and not limited to

- precision measurements B/D
- large missing energy final states (i.e. dark matter, $b \rightarrow s\nu\nu$, etc.)
- precision τ physics

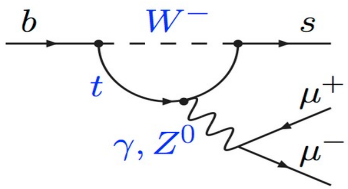
Anomalies in flavour

Anomalies have been reported in many processes involving both quarks and leptons

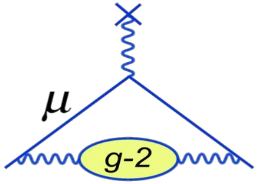
- In the **quark sector** anomalies have been observed for example
  - ***in $b \to c l \nu$***
    - $R(D)=BF[B \to D\tau^+\nu_\tau]/BF[B \to Dl^+\nu_l$ (l=e,μ)], ~1.4σ
    - $R(D^*)=BF[B \to D^*\tau^+\nu_\tau]/BF[B \to D^*l^+\nu_l$ (l=e,μ)], ~2.7σ
    - in the $R(D)$-$R(D^*)$ plane ~3.3σ



  in $b \to sll$
    - $R(K)=BF[B^+ \to K^+\mu^+\mu^-]/BF[B^+ \to K^+e^+e^-]$ ~3.1σ
    - $R(K^{*0})=BF[B^0 \to K^{*0}\mu^+\mu^-]/BF[B^0 \to K^{*0}e^+e^-]$ ~2.2-2.5σ
    - In the angular observables of $B \to K^*\mu^+\mu^-$ ~3.4σ
    - In the BR vs q^2 of $B_s \to \varphi\mu^+\mu^-$ ~3.6σ



- In the **lepton sector** anomalies have been observed for example
  - In the anomalous magnetic moment of the muon ***$(g\text{-}2)_\mu$*** ~4.2 σ
  - In the anomalous magnetic moment of the electron ~2.5σ



Our interpretation of the question asked

Which direction should we take ?

Additional LU branching fractions	**Additional LU with angular observables**

SM predictions

$$R_{K^*}[1.1,\ 6.0]^{\mathrm{SM}} = 1.00 \pm 0.01_{\mathrm{QED}} \qquad R_{K^+}[1.0,\ 6.0]^{\mathrm{SM}} = 1.00 \pm 0.01_{\mathrm{QED}}$$

Assuming V-A currents

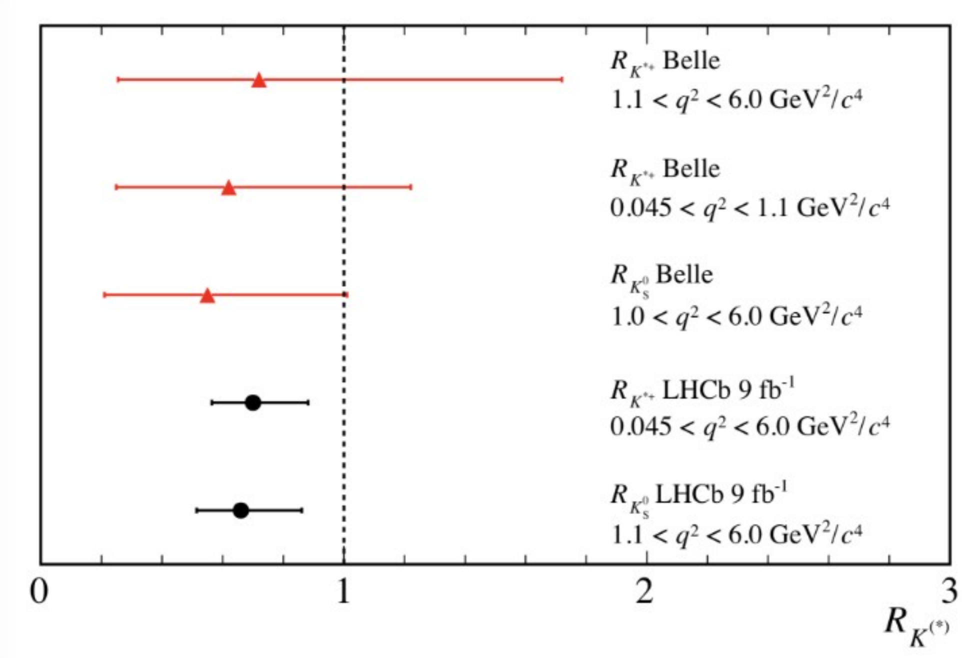
$$R_\phi(B_s) \approx R_{\pi K}(B) \approx R(\Lambda_b)_\Lambda \approx R(\Lambda_b)_{pK} \approx \ldots \approx R_K$$

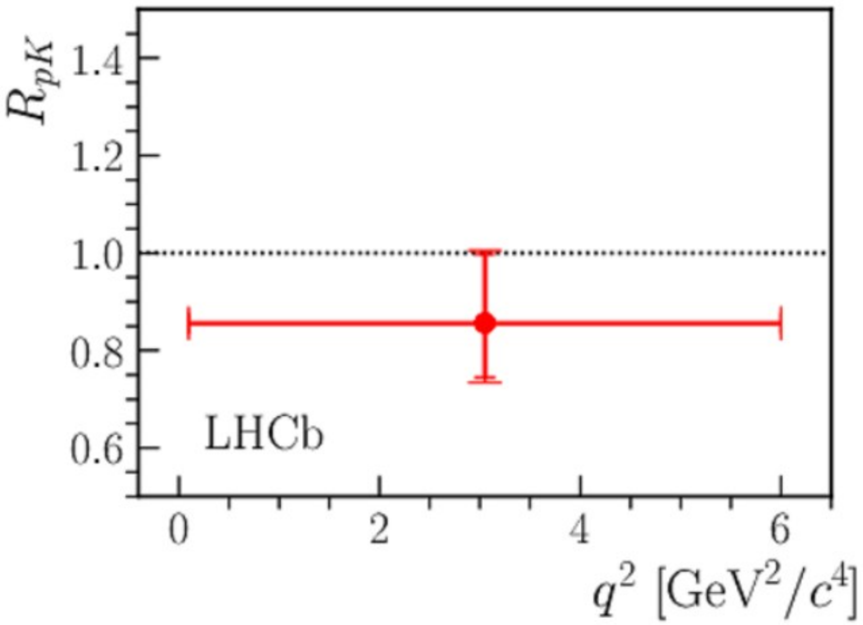
$R_{BD}^{(\mu/e)}$	$\frac{\mathcal{B}(B \to D\mu\bar{\nu})}{\mathcal{B}(B \to De\bar{\nu})}$	0.9960(2)
$R_{B_sD_s}^{(\mu/e)}$	$\frac{\mathcal{B}(B_s \to D_s\mu\bar{\nu})}{\mathcal{B}(B_s \to D_se\bar{\nu})}$	0.9960(2)
$R_{BD}^{(\tau/\mu)}$	$\frac{\mathcal{B}(B \to D\tau\bar{\nu})}{\mathcal{B}(B \to D\mu\bar{\nu})}$	0.295(6)
$R_{B_sD_s}^{(\tau/\mu)}$	$\frac{\mathcal{B}(B_s \to D_s\tau\bar{\nu})}{\mathcal{B}(B_s \to D_s\mu\bar{\nu})}$	0.295(6)

continuum model	1	2	3	4	Average	Ref. [7]	Ref. [8]	Ref. [16]
$R_{\Lambda_b}(SM)$	0.31	0.29	0.28	0.28	$0.29 \pm .02$	0.29	0.31	$0.34 \pm .01$

1909.02519 2012.09872 1605.07633 1502.07230

Lepton Universality in $b \to s$



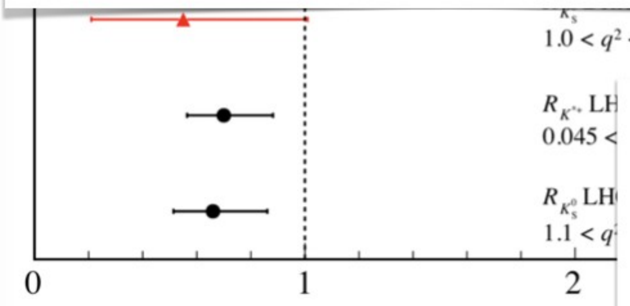


What we know so far

JHEP 05 (2020) 040 Nature Physics JHEP 08 (2017) 055 2110.09501.pdf

Lepton Universality in b → s

$$R_H \equiv \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2},$$

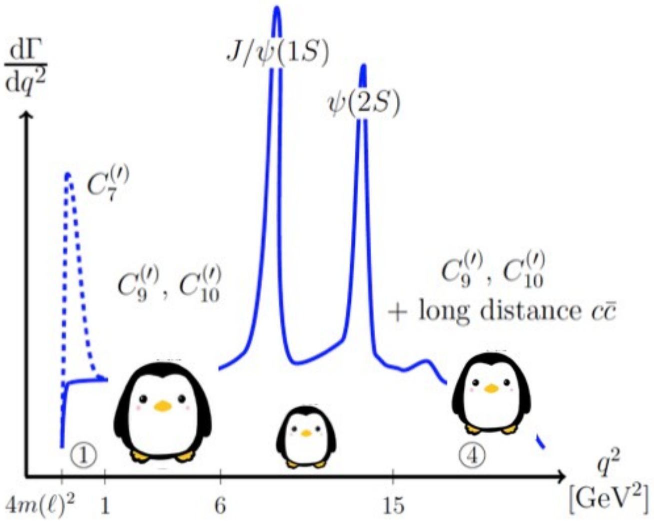


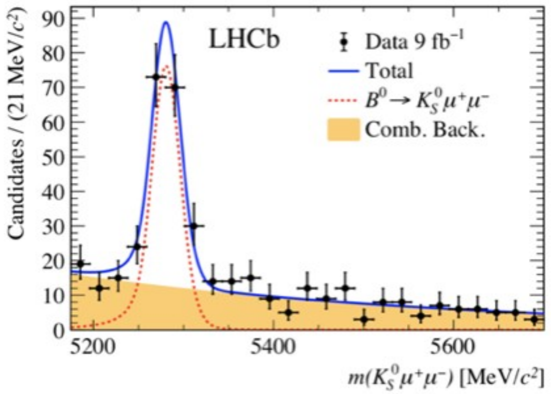
$$\begin{aligned} R^{-1}_{K^{(*)}} &= \frac{\mathcal{B}(B\to K^{(*)}e^+e^-)}{\mathcal{B}(B\to J/\psi\,(e^+e^-)\,K^{(*)})} \Big/ \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to J/\psi\,(\mu^+\mu^-)\,K^{(*)})} \\ &= \left(\frac{N^{ee}_{\rm sig}}{\epsilon^{ee}_{\rm sig}}\cdot\frac{\epsilon^{ee}_{\rm con}}{N^{ee}_{\rm con}}\right) \Big/ \left(\frac{N^{\mu\mu}_{\rm sig}}{\epsilon^{\mu\mu}_{\rm sig}}\cdot\frac{\epsilon^{\mu\mu}_{\rm con}}{N^{\mu\mu}_{\rm con}}\right), \end{aligned}$$

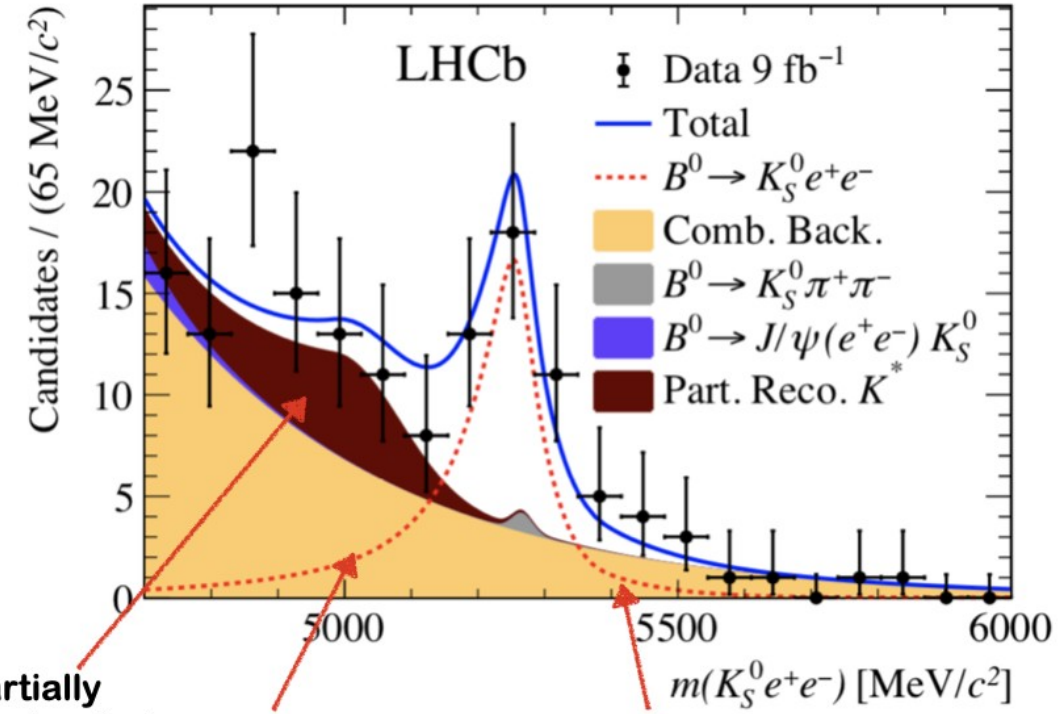
What we know so far

JHEP 05 (2020) 040 | Nature Physics | JHEP 08 (2017) 055 | 2110.09501

Decay anatomy







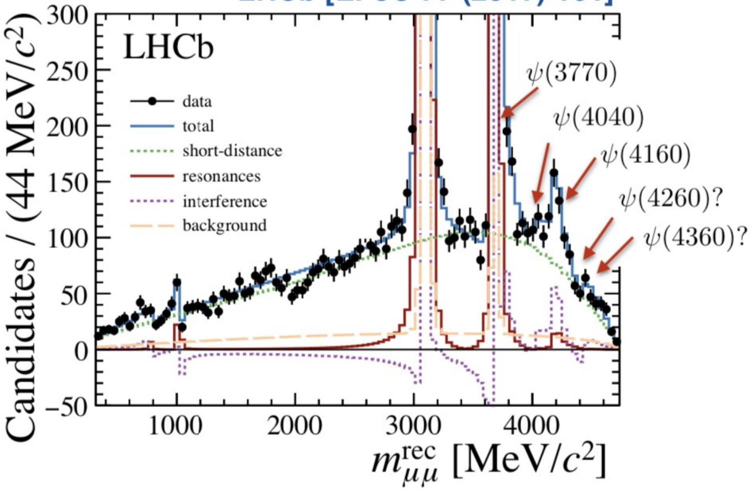
Partially reconstructed backgrounds

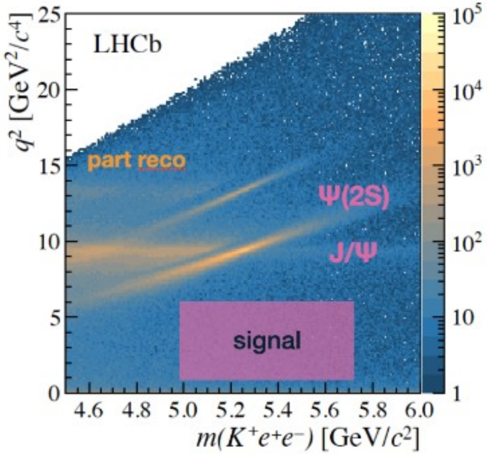
Non trivial shape from simulation

When brem photons are added

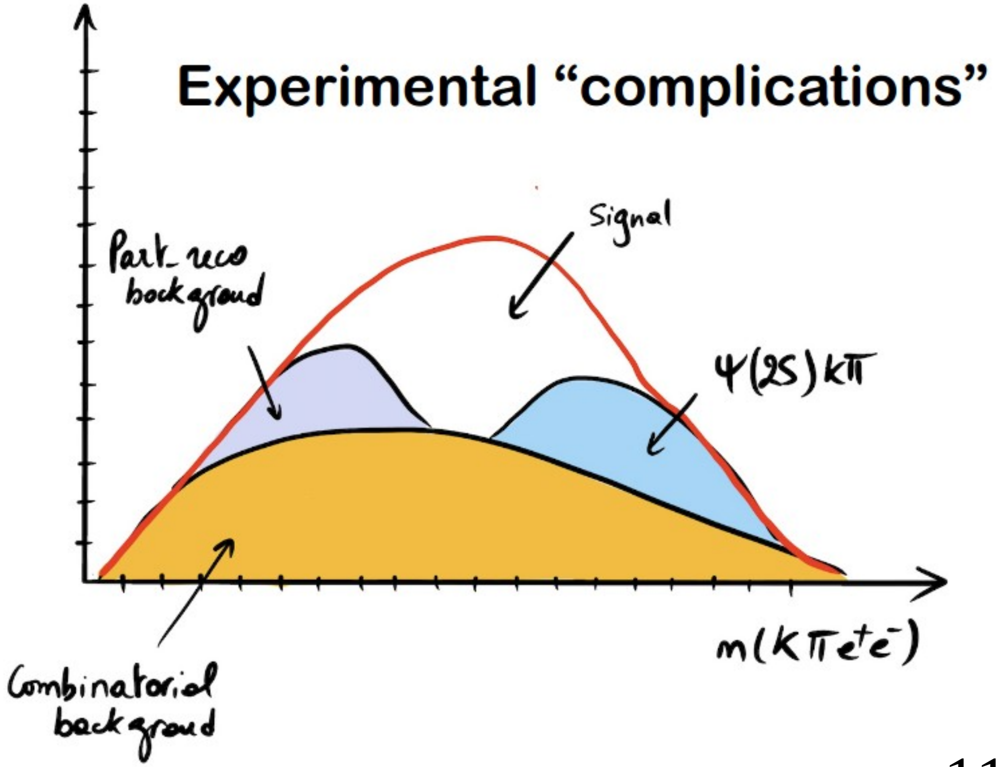
LU in b → s - high q^2

LHCb [EPJC 77 (2017) 161]



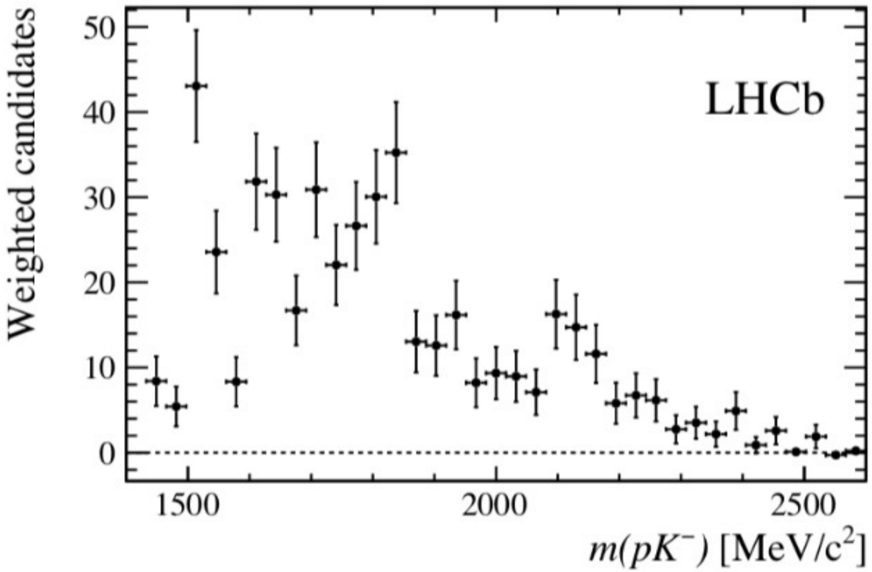


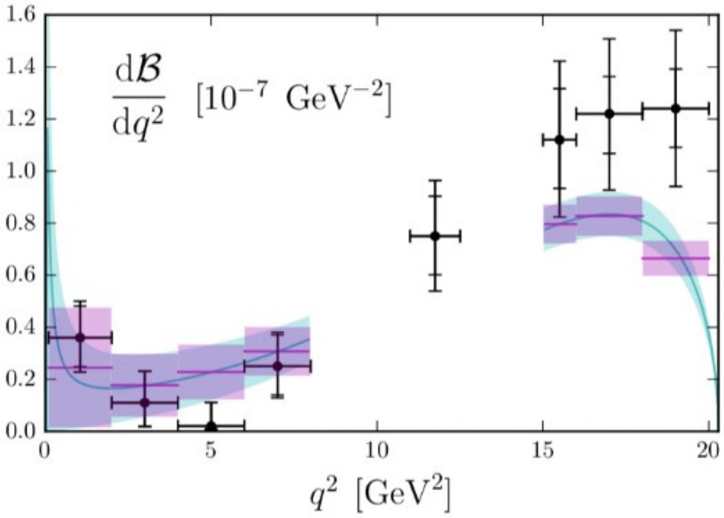
What about the electrons ?



LU in b → s with b-baryons

$m(pK) < 2.6\ \mathrm{GeV/c^2}$ $\quad q^2 \in [0.1, 6]\mathrm{GeV}/c^2$



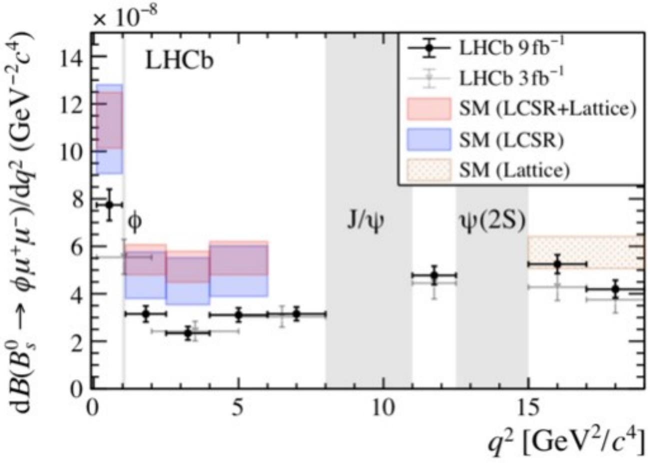


Possibility of isolating the Λ(1520) and/or split the bin in two.

First thing will be to observe the electron mode

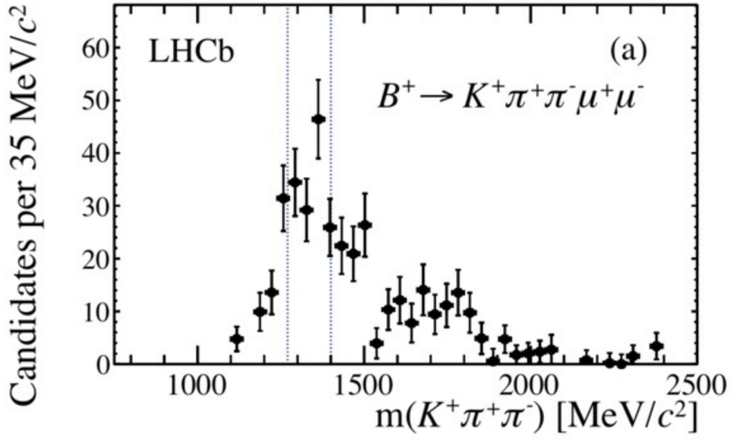
LU in $b \to s$ - others $B_{(s)}$ decays

Lower yields, but experimentally clean



R(ϕ)

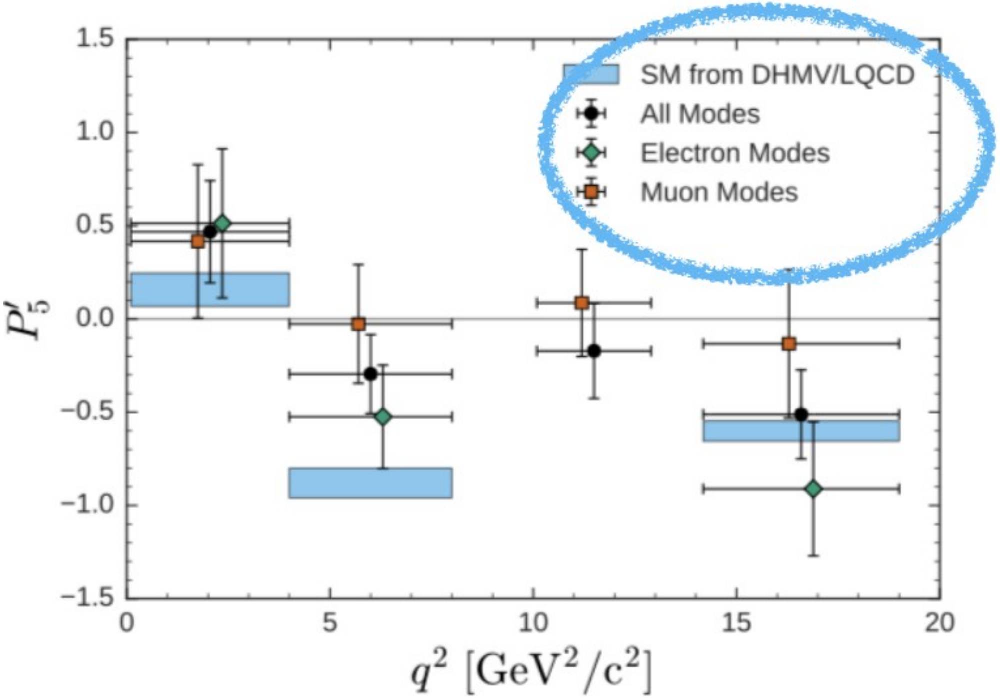
R(Kππ)

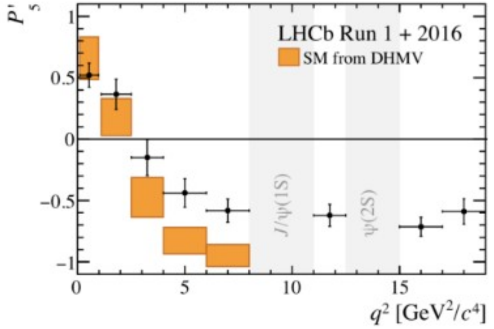


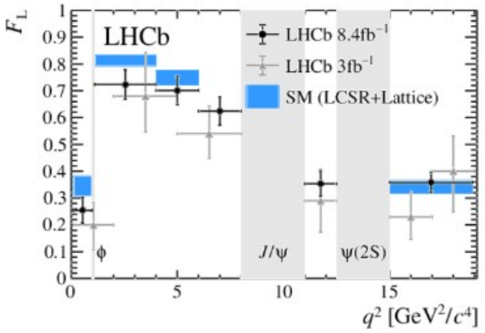
Rich overlapping resonant structure

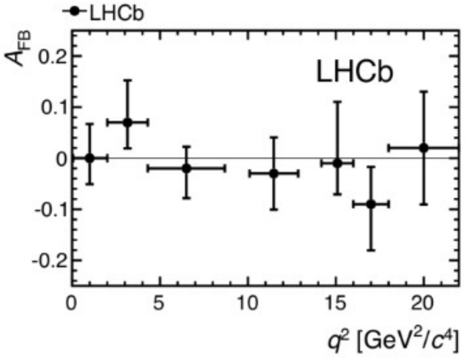
b→ s angular analyses

"Easiest way to by pass the charm loops contaminations"









PRL 118 (2017) 111801

R_K and R_{K^*} at Belle and prospects for Belle II

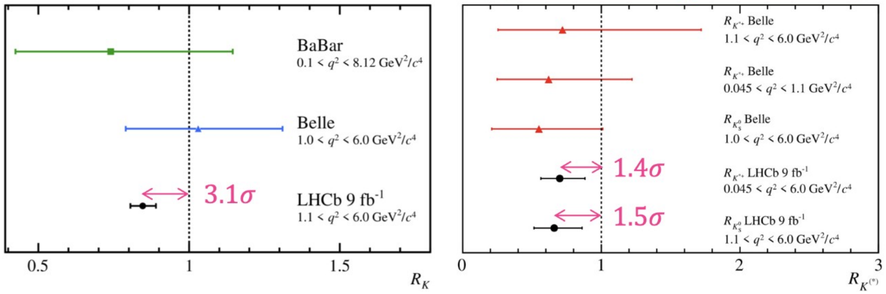
SM

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

$q^2 \in [1(1.1), 6]$ for $R(K^{(*)})$

JHEP 2018, 93 (2018)

arXiv:2103.11769, arXiv:2110.09501



From the Belle II physics book, 1808.10567

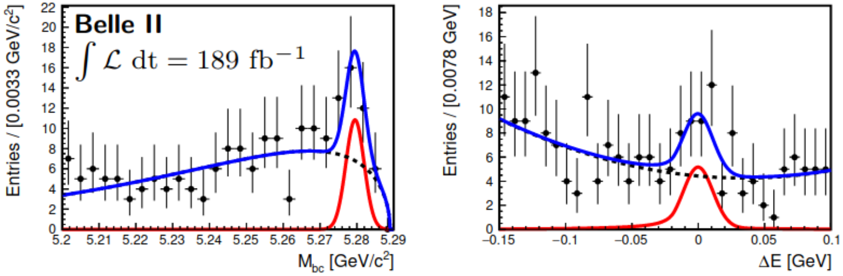
Table 67: The Belle II sensitivities to $B \to K^{(*)}\ell^+\ell^-$ observables that allow to test lepton flavour universality. Some numbers at Belle are extrapolated to $0.71\,\mathrm{ab}^{-1}$.

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

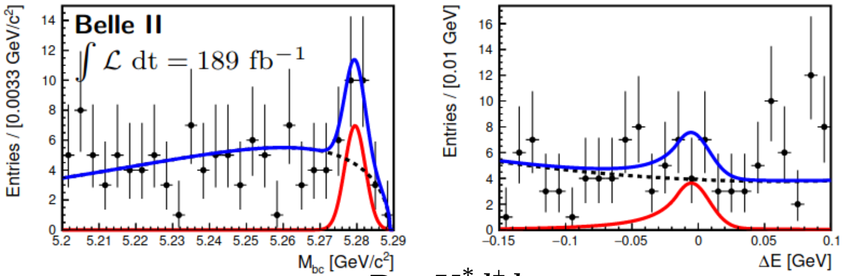
Belle II will provide an independent measurement to confirm (or not) a tension with few ab^{-1} of data.

$B \to K^{(*)}ll$ at Belle II

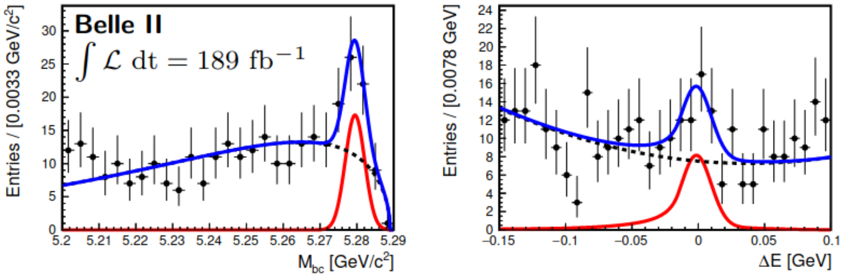
$B \to K^* \mu^+ \mu^-$



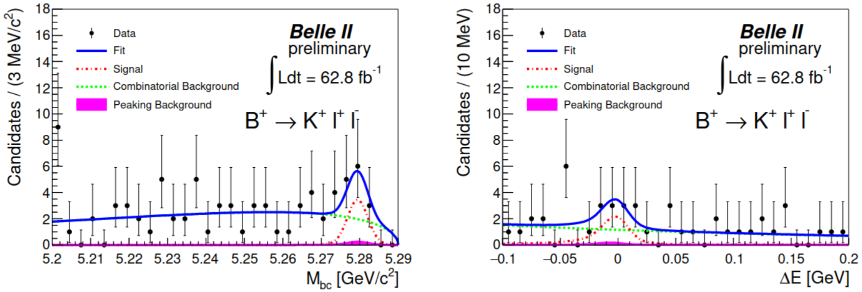
$B \to K^* e^+ e^-$



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



$B^+ \to K^+ l^+ l^-$



$N[B^+ \to K^+ l^+ l^-] = 8.6\ ^{+4.3}_{-3.9} \pm 0.4$

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

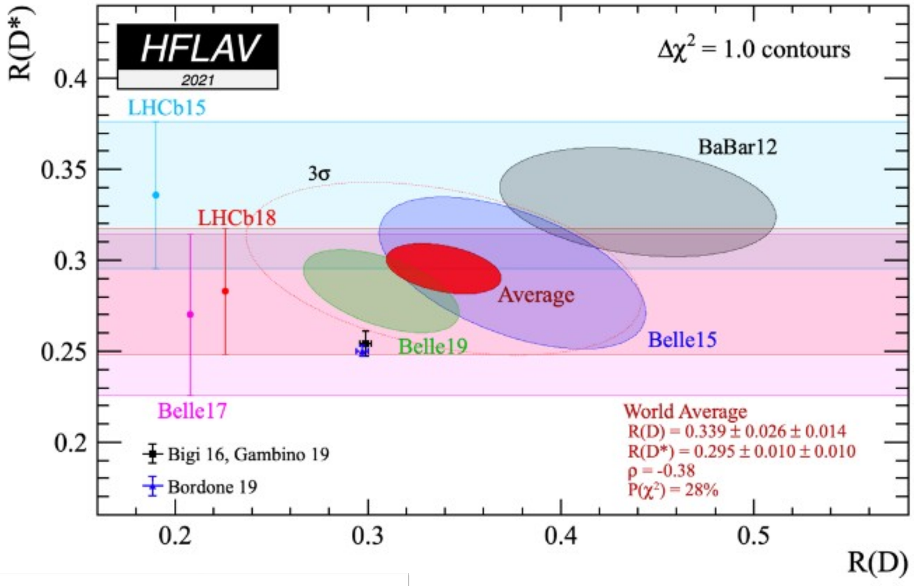
$$M_{bc} \equiv \sqrt{E_{beam}^2 - |\vec{p}_B|^2}$$
$$\Delta E \equiv E_B - E_{beam}$$

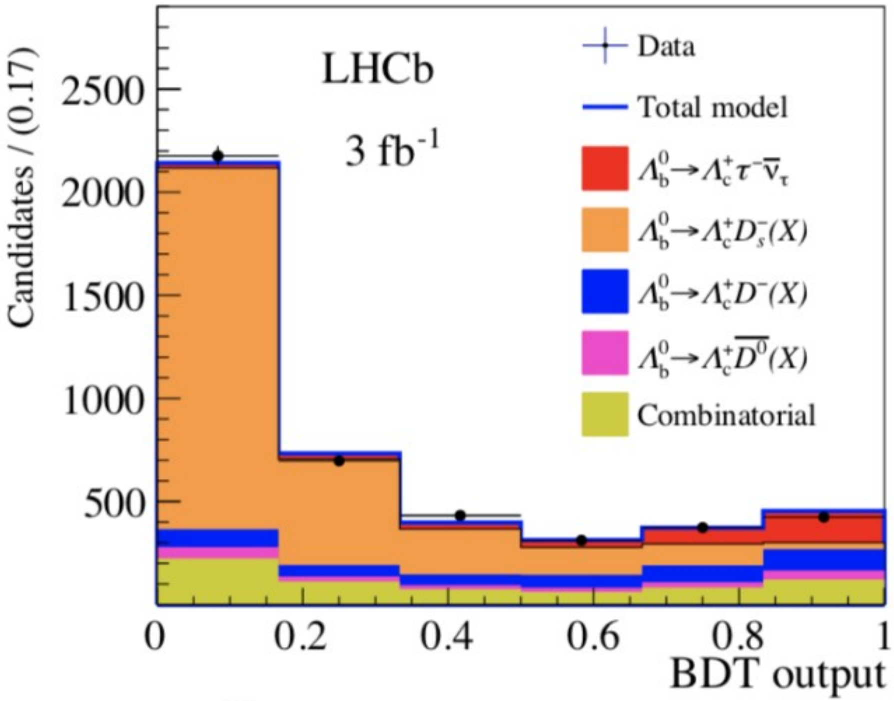
$$\mathcal{B}(B \to K^* \mu\mu) = (1.28 \pm 0.29 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\boxed{\mathcal{B}(B \to K^* ee) = (1.04 \pm 0.48 \pm 0.09) \times 10^{-6}},$$
$$\mathcal{B}(B \to K^* \ell\ell) = (1.22 \pm 0.28 \pm^{+0.08}_{-0.07}) \times 10^{-6}.$$

- Yields extracted from a 2D fit to M_{bc} and ΔE
- All final states currently limited by the sample size
- Similar precision for electrons ()and muons

► Already close to PDG precision!

Lepton Universality in $b \to c$





$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

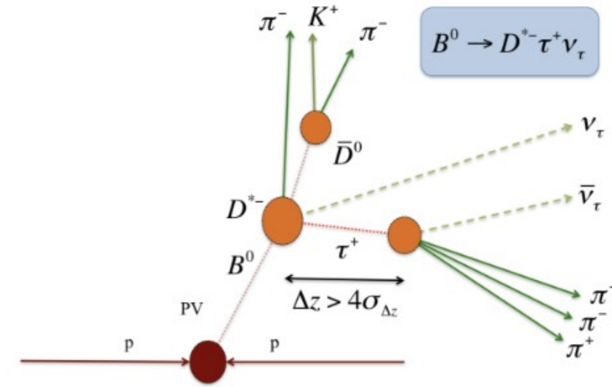
$$\mathcal{R}(\Lambda_c) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)}$$

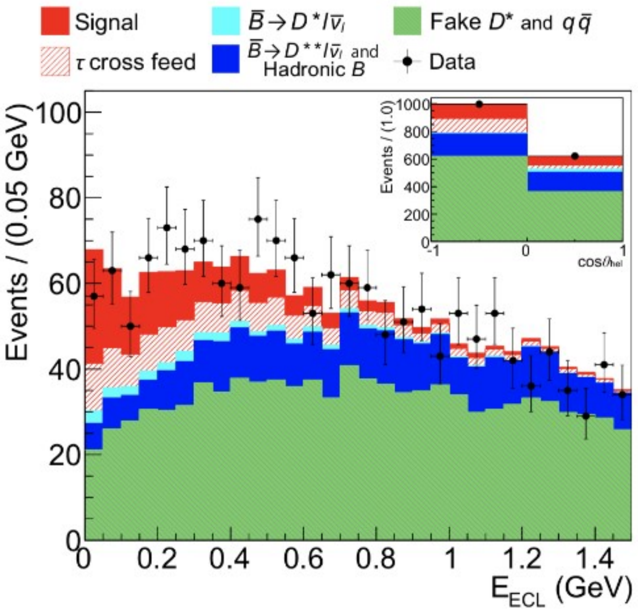
HFLAV

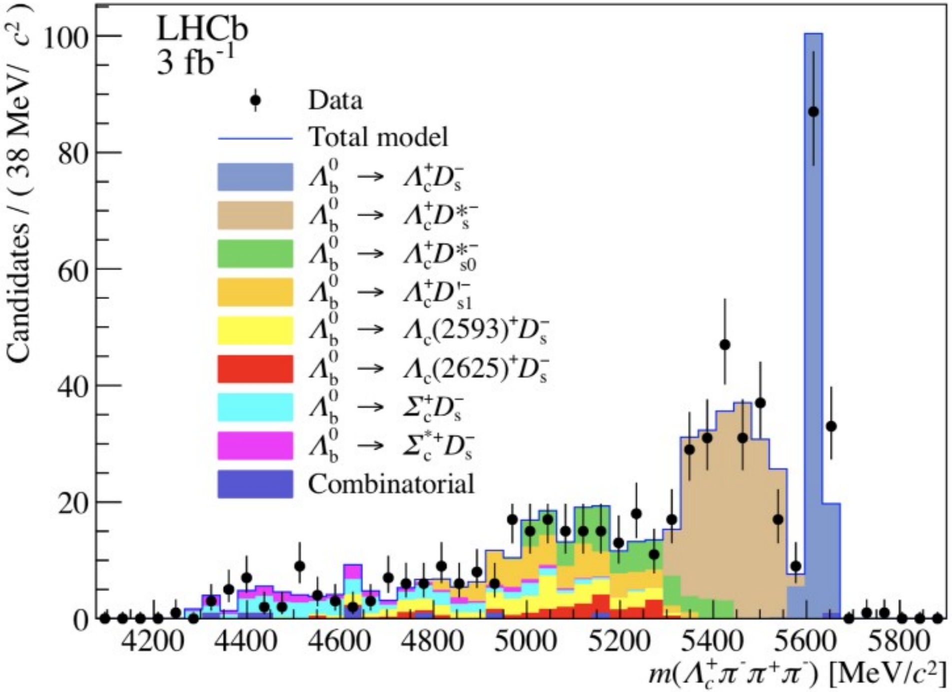
What we know so far

2201.03497

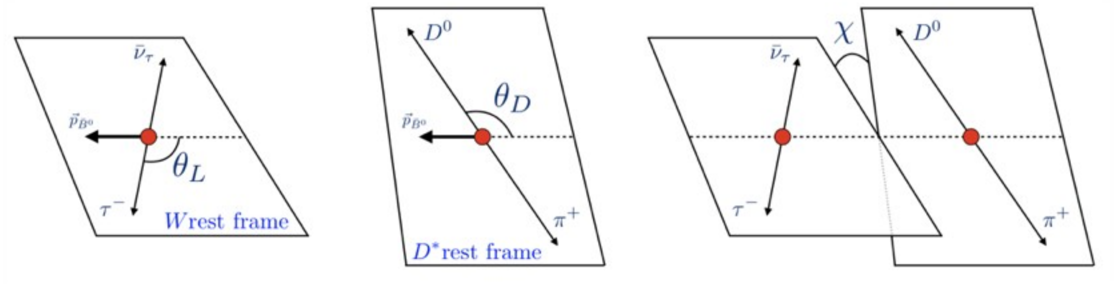
Decay anatomy

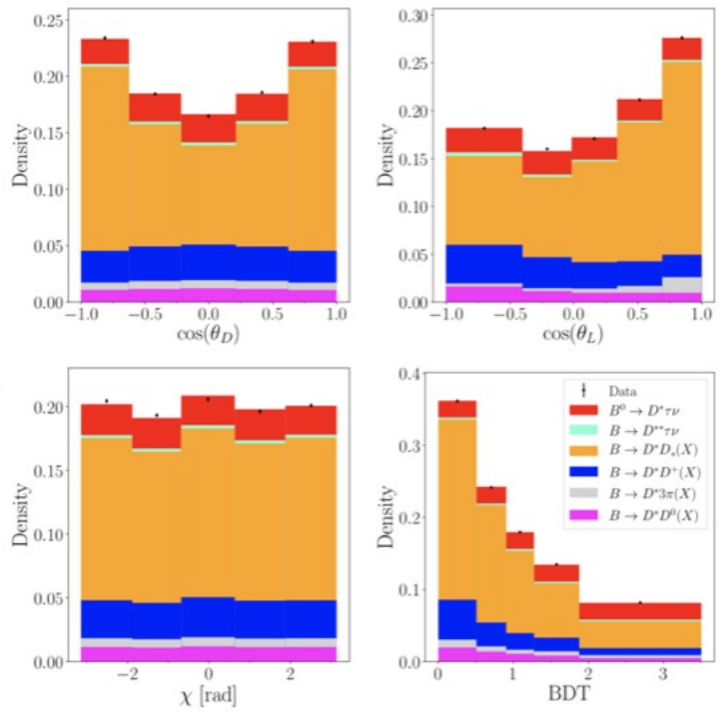






b→ c angular analyses



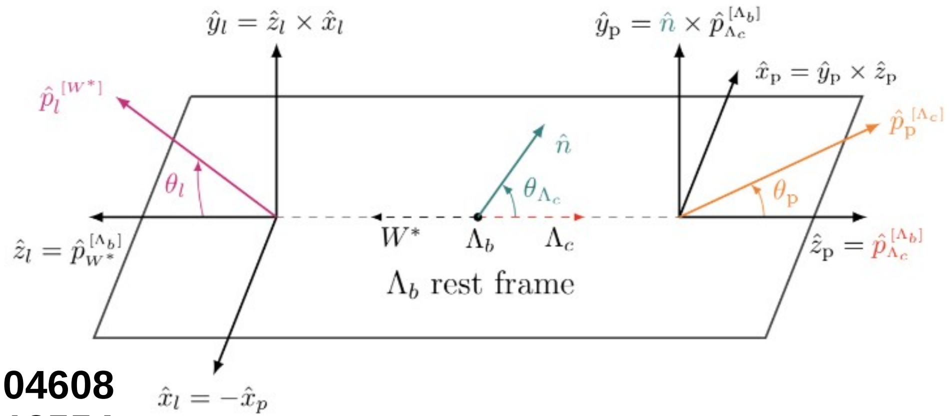


Use τ → 3πν$_\tau$ decays and kinematic reconstruction to measure the three decay angles

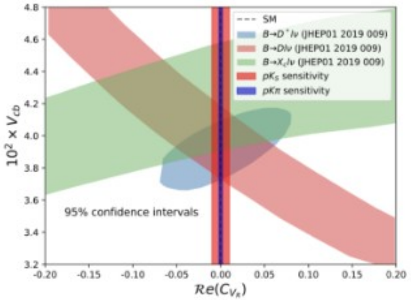
Possible extensions here using ratios of tauonic mode and muon/electrons modes

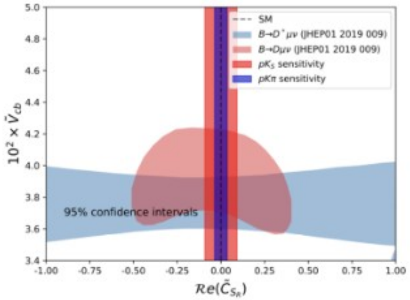
1908.04643

b→ c angular analyses



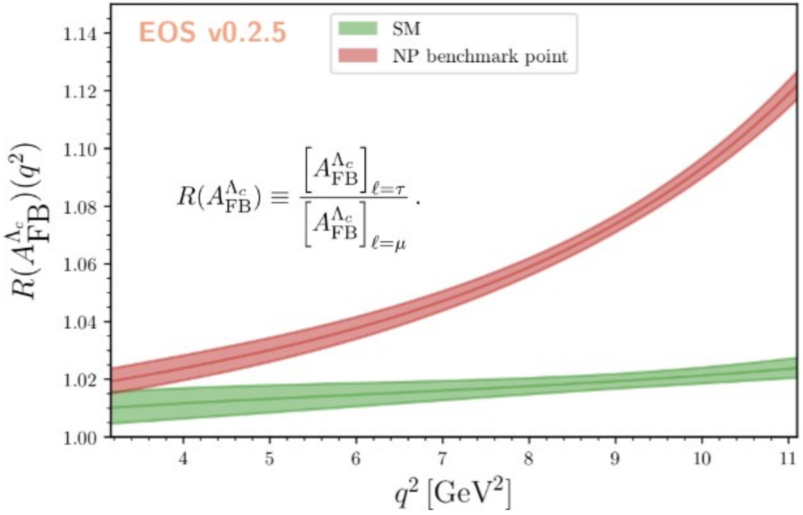
1909.04608
1907.12554
2012.09872



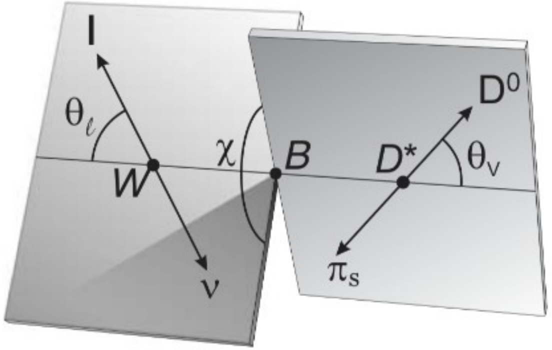


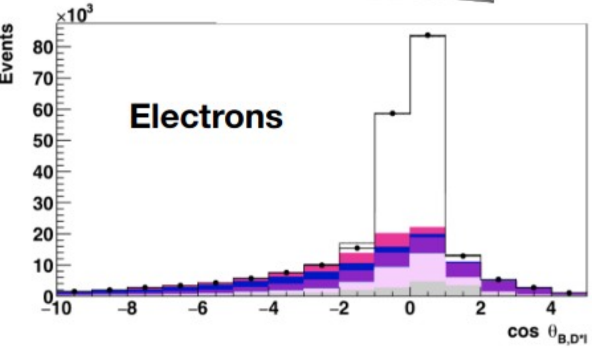
We could explore baryons as well

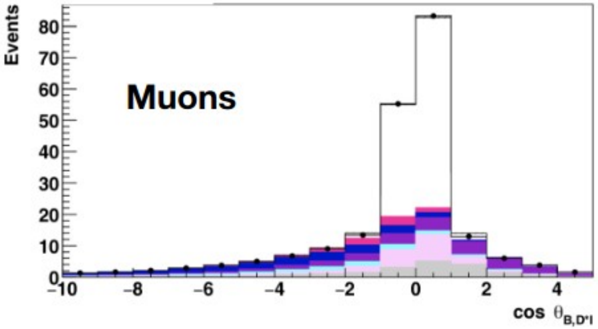
$\Lambda_b \to \Lambda_c \ell \nu$
$\hookrightarrow \Lambda \pi$
$\hookrightarrow K_S p$

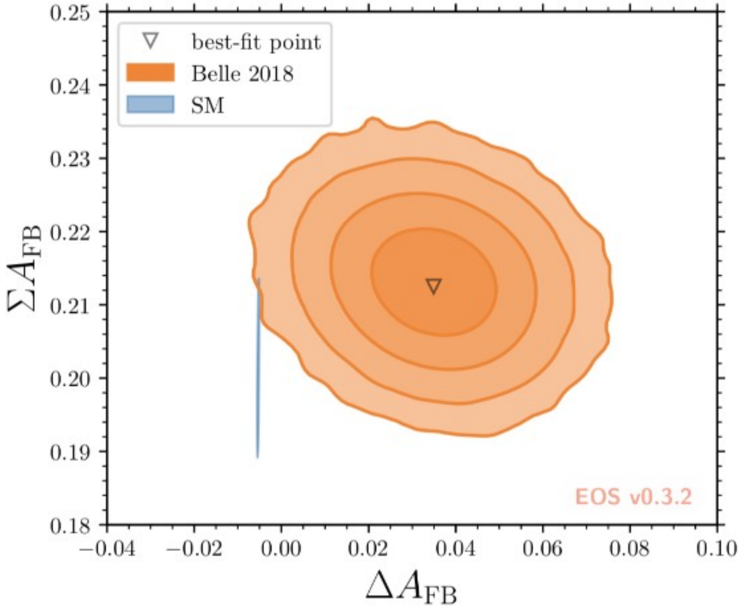


b→ c angular analyses









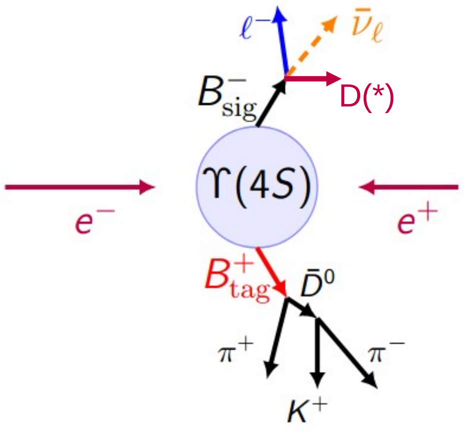
$$\Sigma A_{\mathrm{FB}} = (A_{\mathrm{FB}}^{(\mu)} + A_{\mathrm{FB}}^{(e)})/2$$

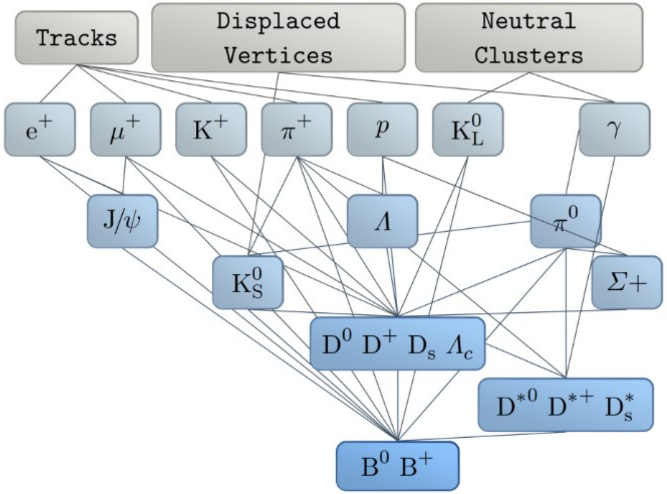
$$\Delta A_{\mathrm{FB}} = A_{\mathrm{FB}}^{(\mu)} - A_{\mathrm{FB}}^{(e)}$$

1809.03290
2104.02094

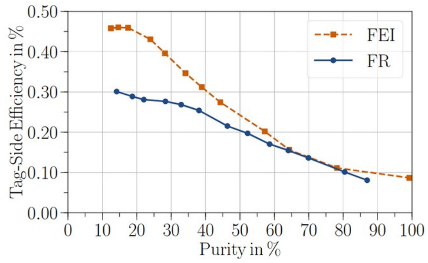
R_D and R_{D^*} prospect for Belle II

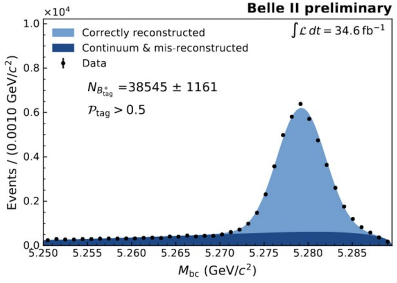
New hierarchical algorithm, the Full Event Interpretation (FEI, Comput Softw Big Sci 3, 6 (2019)) to improve the full reconstruction of decay chains with tagging.





~200 boosted decision trees (BDTs) are used to reconstruct ~10000 B decay chains reaching an overall reconstruction efficiency of up to 0.5%



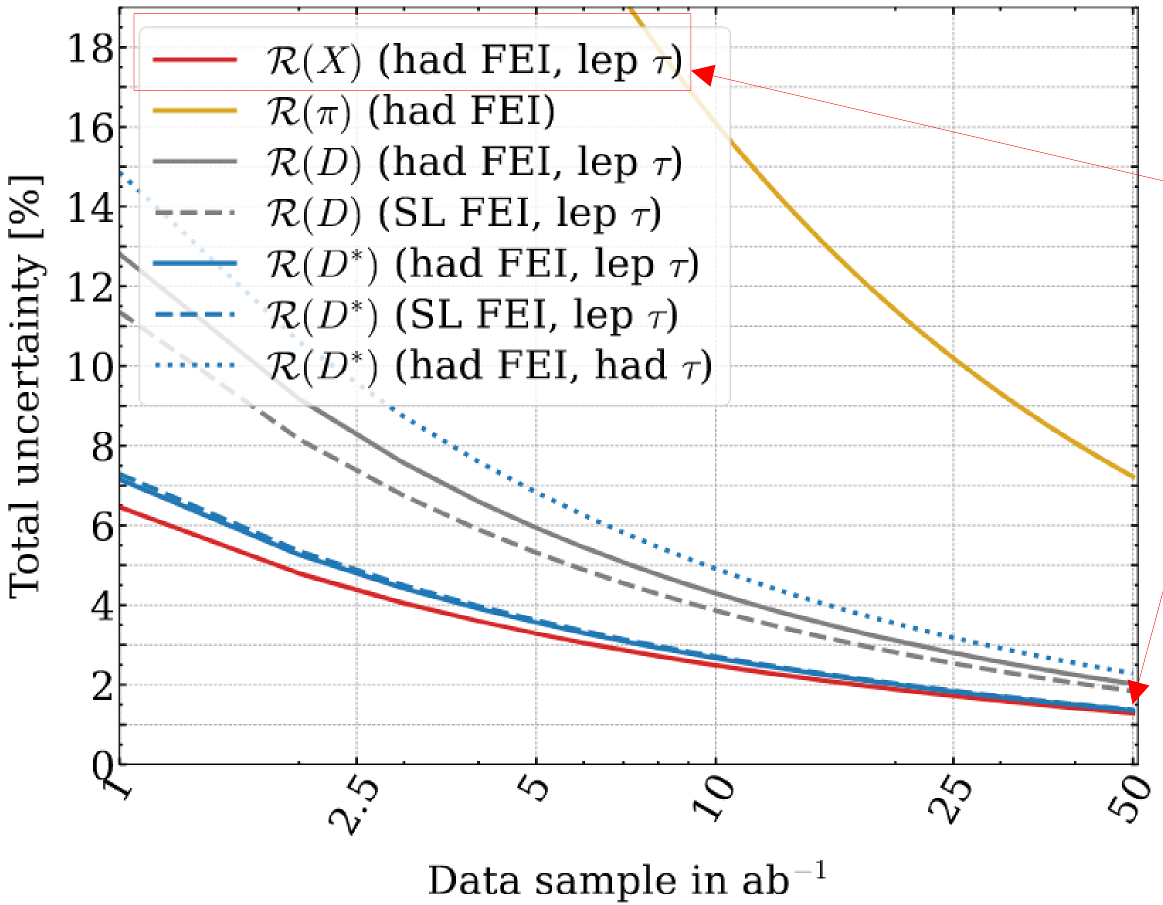


Essential observable at B factories:

$$M_{bc} \equiv \sqrt{E^2_{beam} - \left|\vec{p}_B\right|^2}$$

For correctly reconstructed *B* mesons M_{bc} (beam-constrained mass) peaks at M_B

R_D and R_{D*} prospect for Belle II



R(X) [and in general inclusive processes] is unique at Belle II, although it is a very difficult measurement to be achieved for the first time.

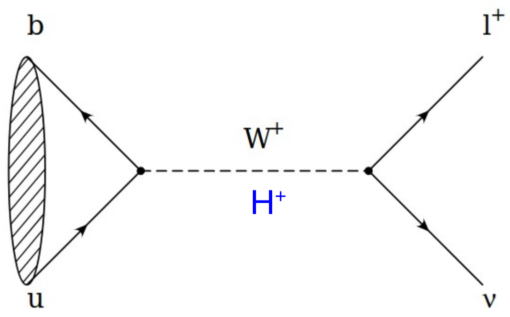
Few ab^{-1} of data will suffice to clarify whether the anomaly on R_D-R_{D*} has a statistical (fluctuation) or systematic origin.

Dedicated measurements at Belle II to reduce/evaluate D** pollution possible.

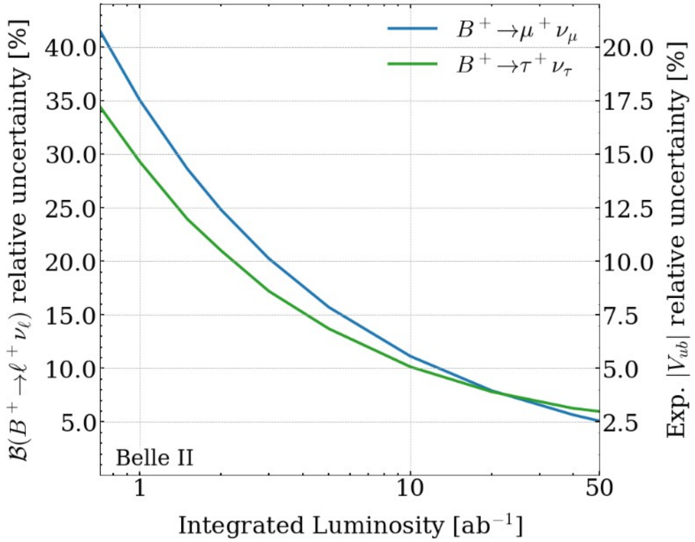
Other channels with missing energy

Belle II experiment well suited and equipped for studies with missing energy

- precision studies of channels such as $B \to l\nu$ (l= e, μ, τ) are exclusive to Belle II



- Channel sensitive to new charged fields, for example a charged Higgs, H^+.
- Provide complementary approach to measure the CKM matrix element $|V_{ub}|$.
- Challenging measurements: few tracks and missing energy from neutrinos.



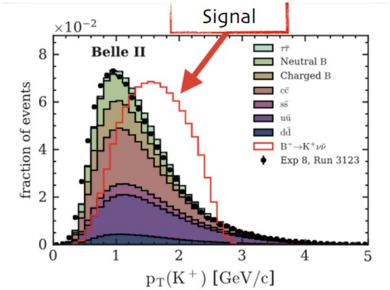
- Belle II will also offer unprecedented precision to $B \to K^*\tau\tau$ (or LFV modes $B \to X\tau l$)

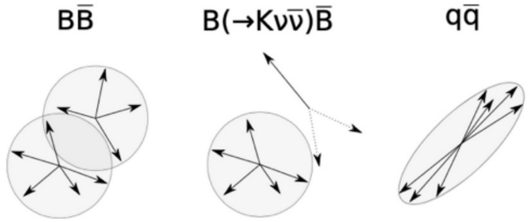
- Many models predict LFU violation in the third generation (PhysRevLett.120.181802, JHEP10(2015)184).
- SM prediction at the level of 10^{-7}, while experimental upper bound $2\text{x}10^{-3}$ (ArXiv: 2110.03871 , PhysRevLett.118.031802).
- Belle II is well suited for this measurement.

	$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)	
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

$B^+ \to K^+\nu\nu$

- Channel connected to flavour anomalies and with unique access to Belle II
- Small SM expectation (see Buras et al. 1409.4557) ~4.6x10^{-6}
- Previous measurements at Belle and Babar used hadronic and/or semileptonic tag
  - In Phys.Rev.Lett. 127 (2021) 18, 181802 we introduced a novel inclusive approach
    - The signal is reconstructed via the “signal Kaon”, the track with highest p_T

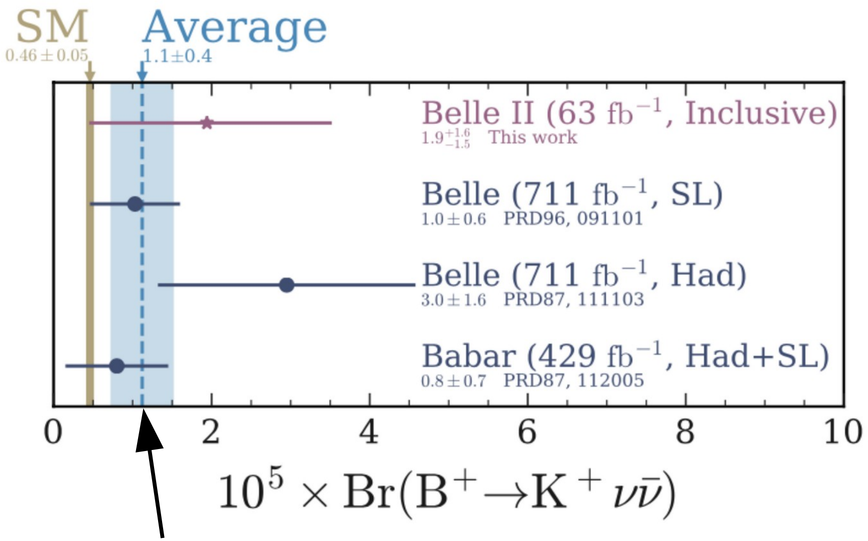




    - All other tracks and clusters associated to the other B and use BDT (2 in cascade) with kinematics, event shape, vertexing, to suppress background
    - Final signal reconstruction efficiency ~4.5% (~10x Had/SL tag)

$B^+ \to K^+ \nu\nu$

- Extract signal from simultaneous maximum likelihood fit to on-resonance + off- resonance data in bins of $p_T(K^+)$ and second BDT
- Results:
  - signal strength: $\mu = 4.2^{+2.9}_{-2.8} \pm^{+1.8}_{-1.6}$
  - Upper Limit @ 90% CL:
    $\mathscr{B}(B \to K\nu\bar{\nu}) < 4.1 \times 10^{-5}$
  - corresponding BF:
    $\mathscr{B}(B \to K\nu\bar{\nu}) = (1.9^{+1.6}_{-1.5}) \times 10^{-5}$



Is this going to be another anomaly?

- Comparing theory and experiments:
  - Inclusive method offers 20%—350% sensitivity improvement over previous approaches

See E. Manoni, Moriond EW presentation

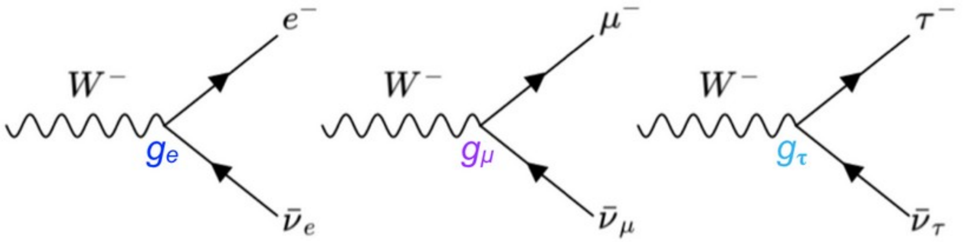
Expected sensitivity at higher luminosities

Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

After the BF is measured, can open the way to new LFU ratios: $R^{\nu/l} = \dfrac{B(B \to K^{(*)}\nu\nu)}{B(B \to K^{(*)}ll)}$

LFU in leptonic τ decays

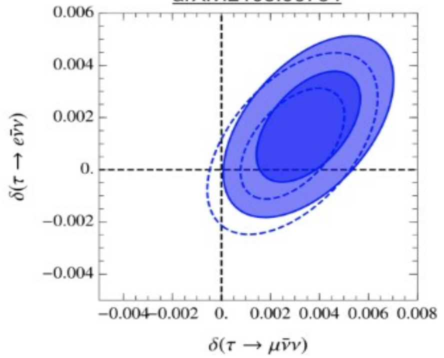
LFU ⇒ couplings of leptons to W bosons is flavour independent $g_e = g_\mu = g$



Hints of a new fundamental interaction that violates LFU?

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} = R_\mu$$

arXiv:2105.06734



- Global fits to $\tau \to e\nu\bar{\nu}$ and $\tau \to \mu\nu\bar{\nu}$ ratios → 2σ tension with SM
- New Physics could enter in a variety of ways: LFU violating Z', singly charged scalar, W' + many more
- Will this tension become more significant with better precision on R_μ?

Belle II can provide answers, however LID systematics needs to be kept under control: this is the most delicate part of such a precision measurement

With a cross-section σ=0.9 nb (compare to ~1nb for B-pair production), pairs of τ are copiously produced at Belle II
→Ongoing work to test LFU, will match and possibly exceed BaBar precision

Conclusions

- Additional LFU tests, whether branching ratios or angular analyses will
  - Probe topologies with different backgrounds
  - Test the consistency of measurements.
  - Cancel hadronic uncertainties

- Belle II and LHCb have complementary approaches and very different physics reach and potential(s). Both experiments will provide the needed inputs for the field of flavour physics (and beyond) to progress

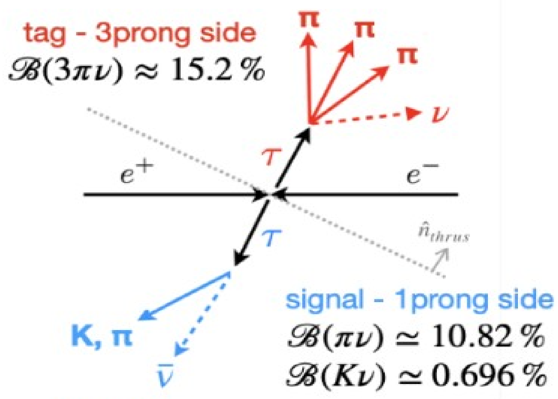
Thanks for your attention!

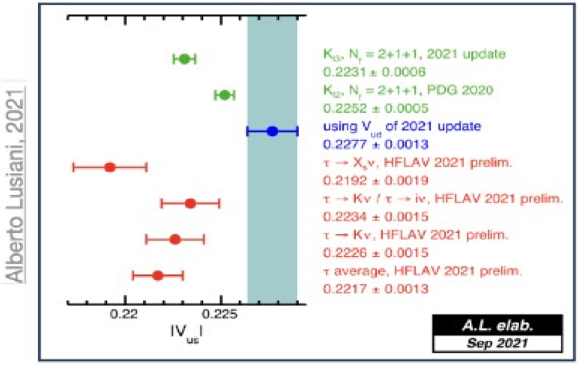
LFU in hadronic τ decays and Vus extraction

- Methods for the V_{us} parameter extraction:
  1. **τ exclusive**

$$R_{K/\pi} = \frac{\mathscr{B}\left(\tau^- \to K^-\nu_\tau\right)}{\mathscr{B}\left(\tau^- \to \pi^-\nu_\tau\right)} = \frac{f_K^2 \left|V_{us}\right|^2}{f_\pi^2 \left|V_{ud}\right|^2} \left(\frac{1 - m_K^2/m_\tau^2}{1 - m_\pi^2/m_\tau^2}\right)^2 (1 + \delta_{LD})$$

  2. τ inclusive (strange vs. non-strange)
  3. CKM matrix unitarity
  4. K^0 decays, e.g. $K_L^0 \to \pi^- e^+ \nu$
- Tension between different approaches is observed





- BaBar measurements from 2010:
ArXiv 0912.0242

	π	K
N^D	369091	25123
Purity	78.7%	76.6%
Total Efficiency	0.324%	0.330%
Particle ID Efficiency	74.6%	84.6%

Phys. Rev. Lett. 105, 051602 (2010)

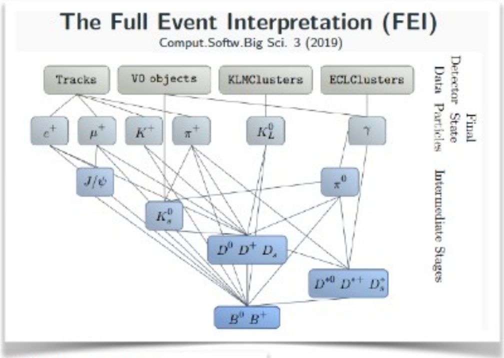
- Aim at surpassing their purity and efficiency

$$|V_{ud}|^2 + \boxed{|V_{us}|^2} + |V_{ub}|^2 = 0.9985 \pm 0.0005$$

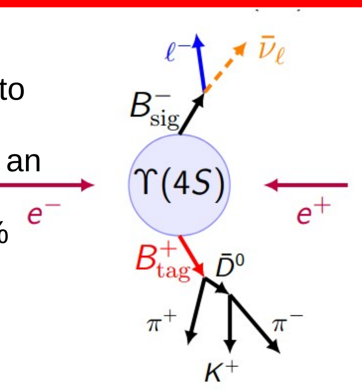
This is the Cabibbo anomaly (CAA), a 3 sigma tension with the SM..

R_D and R_{D^*} at Belle and prospect for Belle II

- Statistical error will be further reduced by luminosity and also by improved tagging with the FEI (Full Event Interpretation) algorithm with Fast BDT and more decay modes.
- Reduction of systematic errors become more important.



~200 boosted decision trees (BDTs) are used to reconstruct ~10000 B decay chains reaching an overall reconstruction efficiency of up to 0.5%



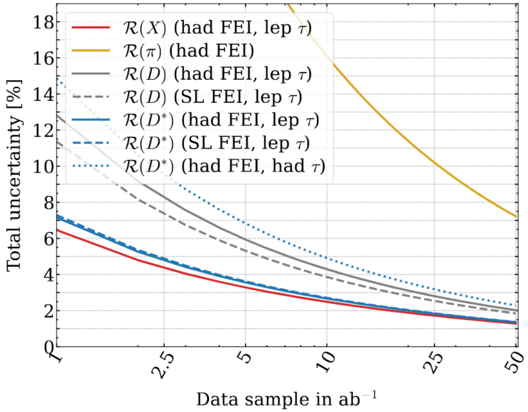
Composition of the systematic uncertainties in each Belle analysis

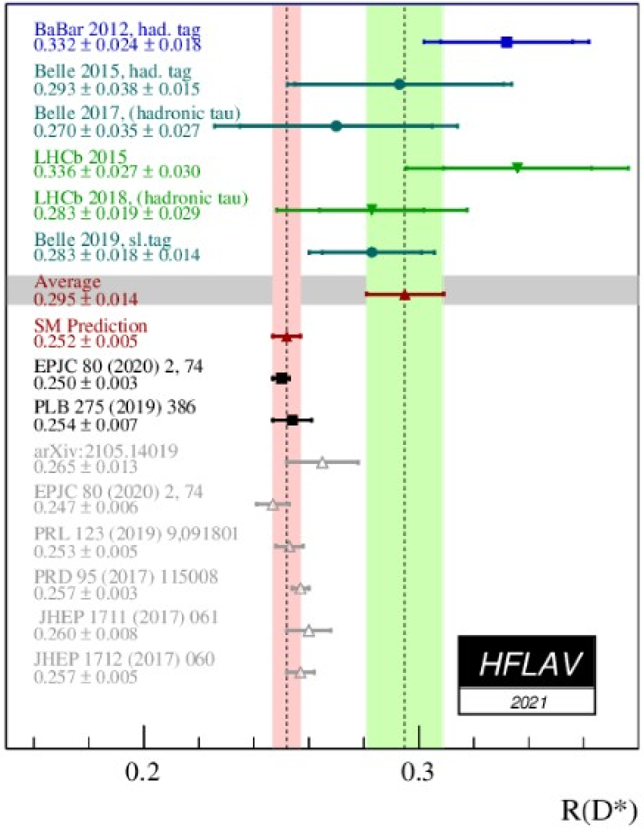
Source	Belle (Had, ℓ^-) R_D	Belle (Had, ℓ^-) R_{D^*}	Belle (SL, ℓ^-) R_{D^*}	Belle (Had, h^-) R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}$%
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}$%	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}$%
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}$%	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

"The Belle II Physics Book", arXiv:1808.10567

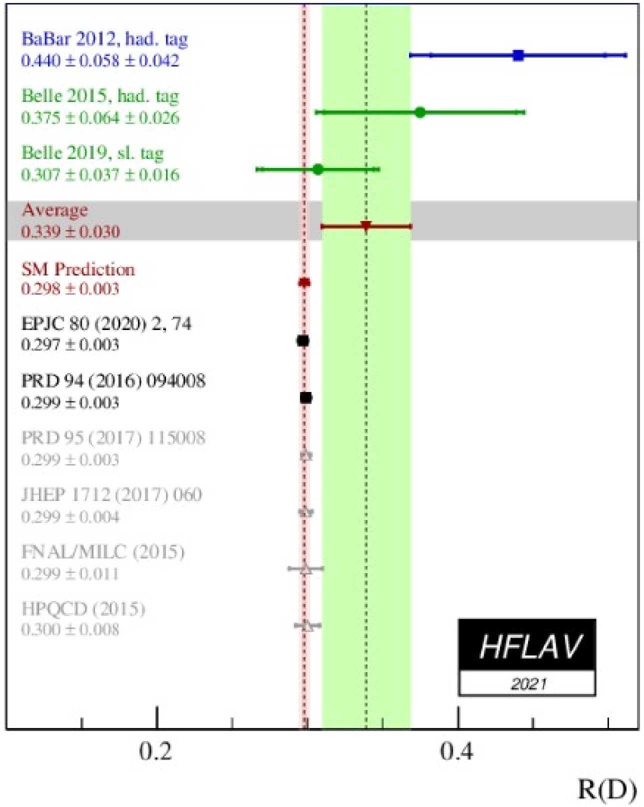
Prog. Theor. Exp. Phys. 2019, 123C01

- The uncertainty due to the MC statistics is reducible.
  - MC stat affects the estimation of the reconstruction efficiency, understanding of small cross-feed components and PDFs for the fit.
- The uncertainties from Br(B→D**lv) decays and hadronic B decays have to be reduced by dedicated measurements of the background decays.





BaBar 2012, had. tag
0.332 ± 0.024 ± 0.018
Belle 2015, had. tag
0.293 ± 0.038 ± 0.015
Belle 2017, (hadronic tau)
0.270 ± 0.035 ± 0.027
LHCb 2015
0.336 ± 0.027 ± 0.030
LHCb 2018, (hadronic tau)
0.283 ± 0.019 ± 0.029
Belle 2019, sl.tag
0.283 ± 0.018 ± 0.014
Average
0.295 ± 0.014
SM Prediction
0.252 ± 0.005
EPJC 80 (2020) 2, 74
0.250 ± 0.003
PLB 275 (2019) 386
0.254 ± 0.007
arXiv:2105.14019
0.265 ± 0.013
EPJC 80 (2020) 2, 74
0.247 ± 0.006
PRL 123 (2019) 9,091801
0.253 ± 0.005
PRD 95 (2017) 115008
0.257 ± 0.003
JHEP 1711 (2017) 061
0.260 ± 0.008
JHEP 1712 (2017) 060
0.257 ± 0.005
HFLAV
2021
0.2
0.3
R(D*)



BaBar 2012, had. tag
0.440 ± 0.058 ± 0.042
Belle 2015, had. tag
0.375 ± 0.064 ± 0.026
Belle 2019, sl. tag
0.307 ± 0.037 ± 0.016
Average
0.339 ± 0.030
SM Prediction
0.298 ± 0.003
EPJC 80 (2020) 2, 74
0.297 ± 0.003
PRD 94 (2016) 094008
0.299 ± 0.003
PRD 95 (2017) 115008
0.299 ± 0.003
JHEP 1712 (2017) 060
0.299 ± 0.004
FNAL/MILC (2015)
0.299 ± 0.011
HPQCD (2015)
0.300 ± 0.008
HFLAV
2021
0.2
0.4
R(D)

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|\boldsymbol{k}|\beta\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta^2\left|\mathcal{C}_{10}f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2-m_K^2)^2}{q^2m_B^2}\left|\mathcal{C}_{10}f_0(q^2)\right|^2\right.$$

$$\left. + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|\mathcal{C}_9f_+(q^2)+2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\},$$

arXiv:2104.02094v1 [hep-ph] 5 Apr 2021

EOS-2021-03, TUM-HEP 1305/20, P3H-21-021, SI-HEP-2021-12

Lepton-flavour non-universality of $\bar{B} \to D^* \ell \bar{\nu}$ angular distributions in and beyond the Standard Model

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Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät,
Universität Siegen, Walter-Flex-Straße 3, D-57068 Siegen, Germany

We analyze in detail the angular distributions in $\bar{B} \to D^* \ell \bar{\nu}$ decays, with a focus on lepton-flavour non-universality. We investigate the minimal number of angular observables that fully describes current and upcoming datasets, and explore their sensitivity to physics beyond the Standard Model (BSM) in the most general weak effective theory. We apply our findings to the current datasets, extract the non-redundant set of angular observables from the data, and compare to precise SM predictions that include lepton-flavour universality violating mass effects. Our analysis shows that the current presentation of the experimental data is not ideal and prohibits the extraction of the full set of relevant BSM parameters, since the number of independent angular observables that can be inferred from data is limited to only four. We uncover a $\sim 4\sigma$ tension between data and predictions that is hidden in the redundant presentation of the Belle 2018 data on $\bar{B} \to D^* \ell \bar{\nu}$ decays. This tension specifically involves observables that probe $e - \mu$ lepton-flavour universality. However, we find inconsistencies in these data, which renders results based on it suspicious. Nevertheless, we discuss which generic BSM scenarios could explain the tension, in the case that the inconsistencies do not affect the data materially. Our findings highlight that $e - \mu$ non-universality in the SM, introduced by the finite muon mass, is already significant in a subset of angular observables with respect to the experimental precision.

I. INTRODUCTION

Exclusive $\bar{B} \to D^{(*)} \ell \bar{\nu}$ decays have become precision probes of the semileptonic parton-level transitions $b \to c \ell \bar{\nu}$. As such, they provide excellent means for the determination of the corresponding Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{cb}|$ of the Standard Model (SM). The combination of good experimental and theoretical control renders them also sensitive probes of beyond-the-SM (BSM) physics that potentially modifies both the normalization and the angular distribution of these modes. In the SM, the lepton-flavour universal (LFU) nature of the underlying $W^{\pm}$-boson exchange allows for precision predictions of LFU ratios that are almost free of hadronic uncertainties. Measurements of the three different lepton modes $\ell = e, \mu, \tau$ then allow to test SM paradigms such as CKM unitarity and LFU. Improved LFU tests are especially important in light of the recent indications for LFU violation in the so-called *B anomalies*, concerning $b \to c \tau \bar{\nu}$ and $b \to s \ell^+ \ell^-$ ($\ell = e, \mu$) transitions. Further motivation for precision analyses of $\bar{B} \to D^* \ell \bar{\nu}$ decays is provided by the persisting V_{cb} puzzle, *i.e.* a tension between the inclusive and exclusive determinations of this CKM element.

This work is triggered by three recent developments:

Availability of experimental data: Starting with the 2015 analysis of $\bar{B} \to D \ell \bar{\nu}$ decays by Belle [1], experimental collaborations made their data on $b \to c \ell \bar{\nu}$ transitions available in a model-independent way [1–5], thereby making phenomenological analyses possible that vary the form-factor parametrizations and BSM scenarios. In particular, a recent Belle analysis [3] presents for the first time four single-differential distributions of $\bar{B} \to D^* \ell \bar{\nu}$ decays for both $\ell = e, \mu$ including their full correlation matrices.

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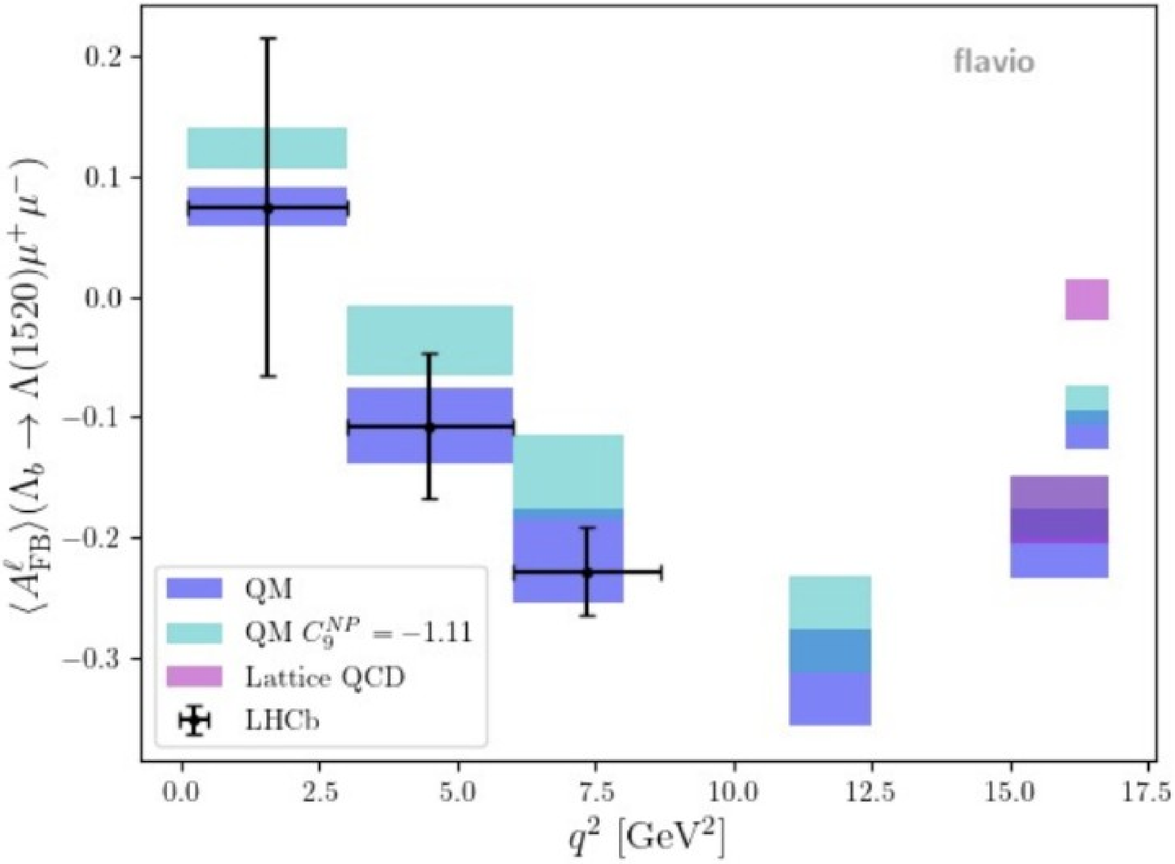
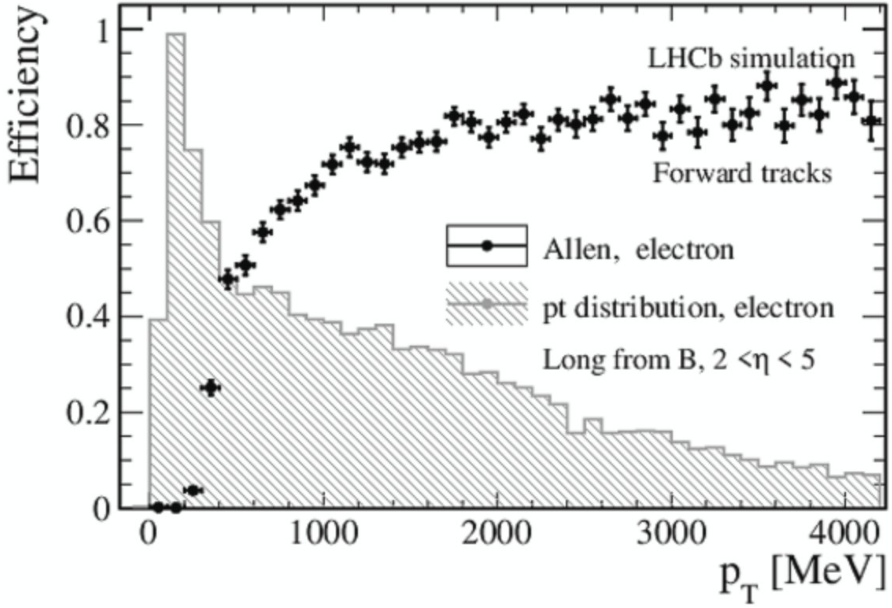
https://arxiv.org/pdf/2104.02094.pdf

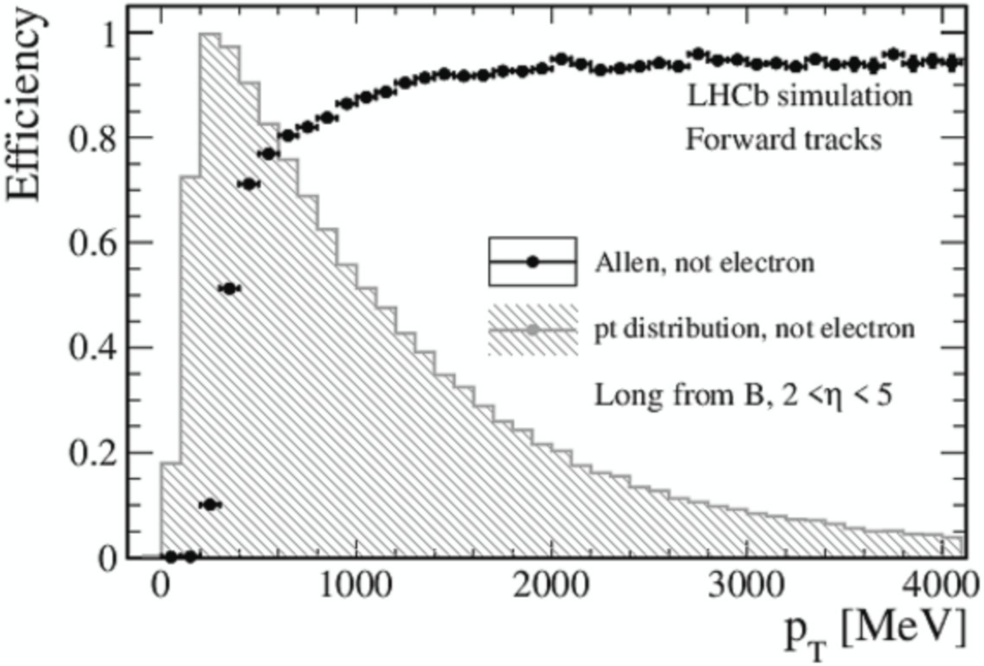


flavio
QM
QM $C_9^{NP} = -1.11$
Lattice QCD
LHCb
$\langle A_{\mathrm{FB}}^{\ell} \rangle (\Lambda_b \to \Lambda(1520)\mu^+\mu^-)$
q^2 [GeV^2]
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5

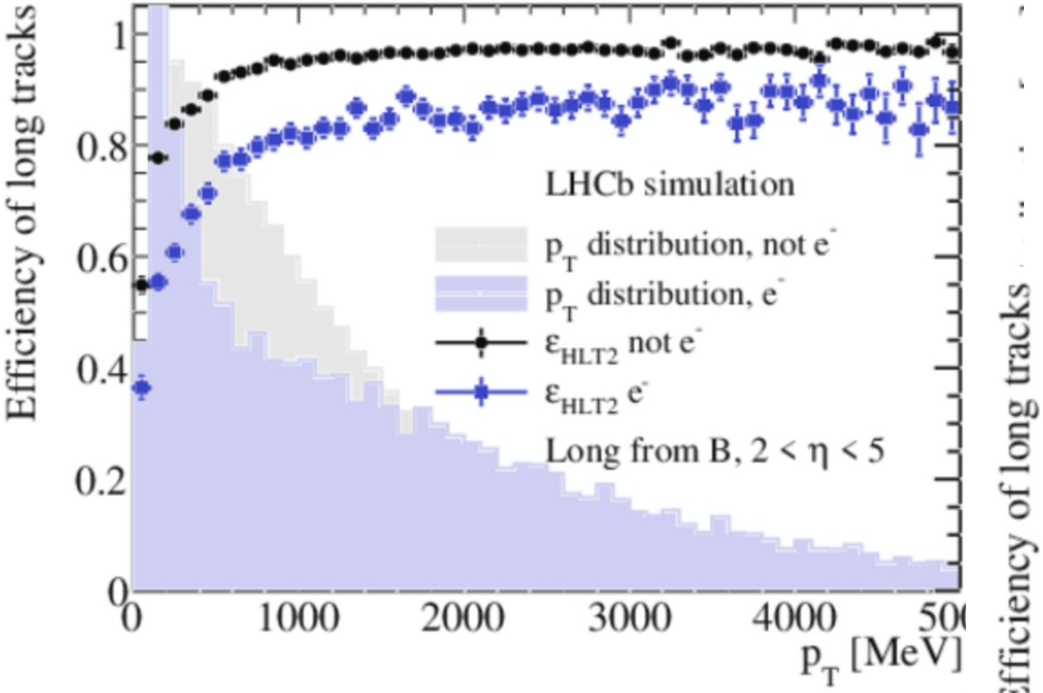
$$K(q^2, \cos\theta_\ell, \cos\theta_{\Lambda_c}, \phi) \equiv \frac{8\pi}{3} \frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2} \frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_{\Lambda_c}\,\mathrm{d}\phi}\,.$$

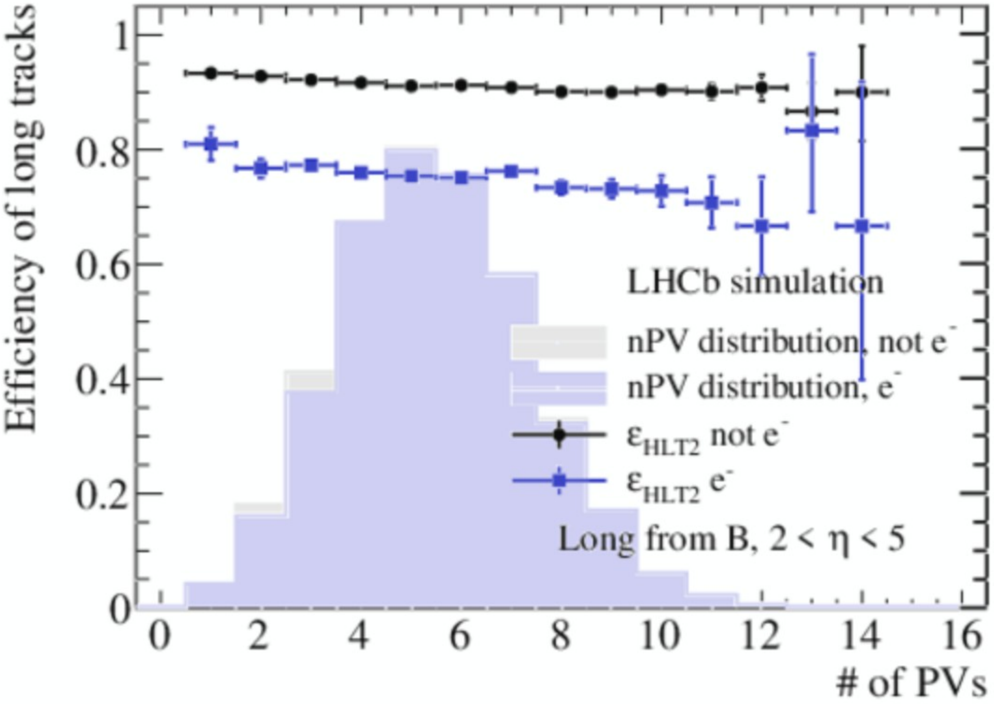
$$\begin{aligned}
K(q^2, \cos\theta_\ell, \cos\theta_{\Lambda_c}, \phi) = &\left(K_{1ss}\sin^2\theta_\ell + \; K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right) \\
&+ \left(K_{2ss}\sin^2\theta_\ell + \; K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_{\Lambda_c} \\
&+ \left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_{\Lambda_c}\sin\phi \\
&+ \left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_{\Lambda_c}\cos\phi\,,
\end{aligned}$$





Run 3 – public plots





Run 3 – public plots