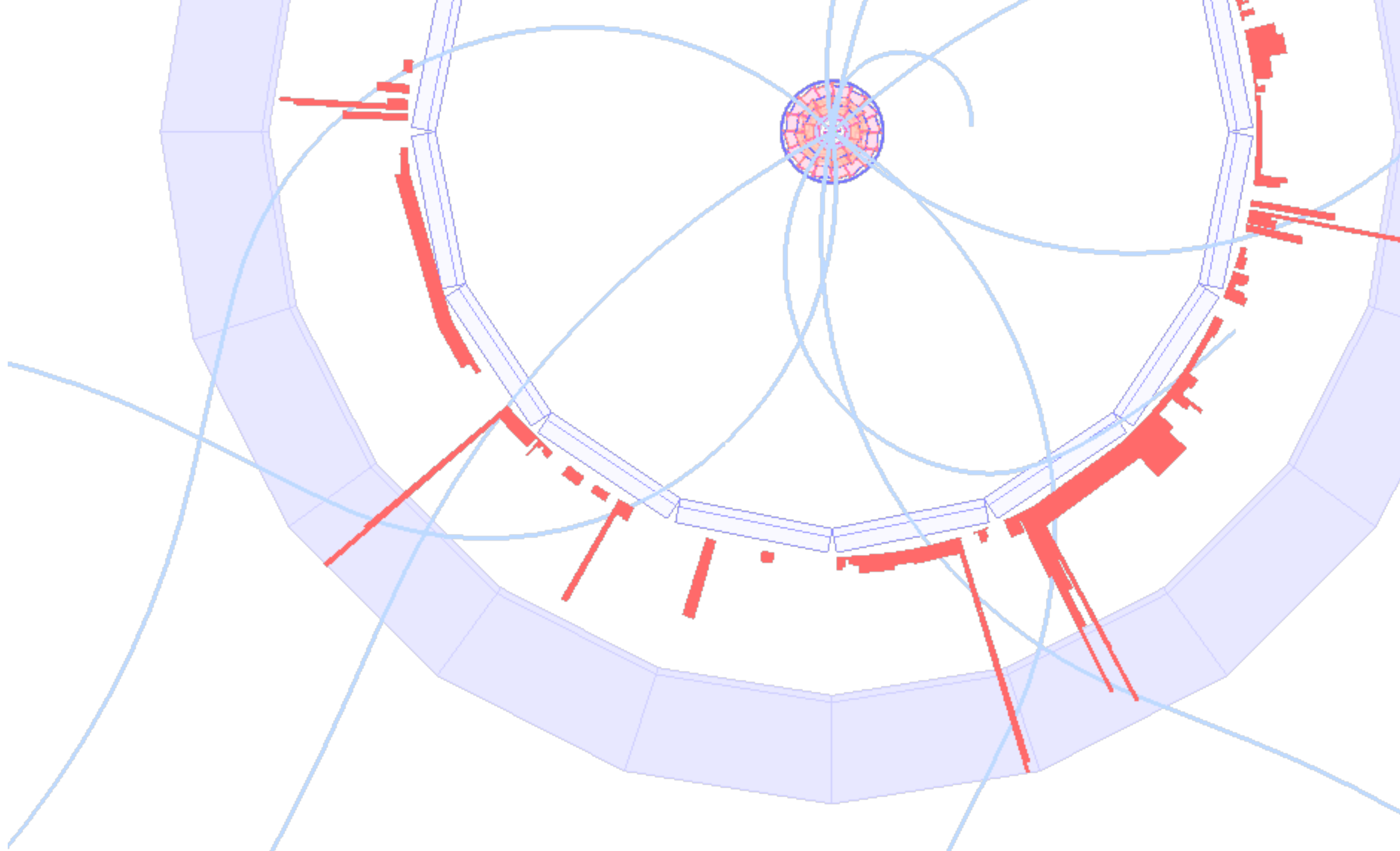


LFV $b\to s\ell\ell'$ transitions at Belle and Belle II

ANOMALIES AND PRECISION IN THE BELLE II ERA - WORKSHOP, 6-8.09.2021

Gaetano de Marino*

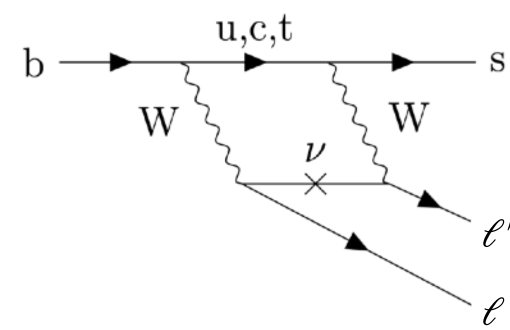
on behalf of the Belle and Belle II collaboration

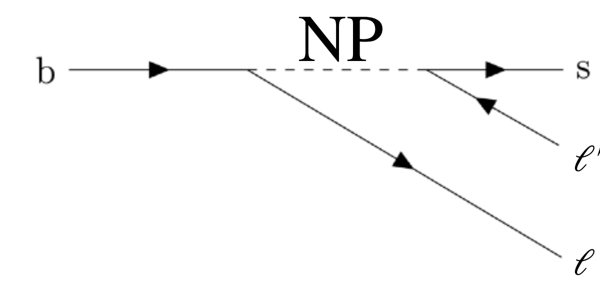
*demarino@ijclab.in2p3.fr - Université Paris-Saclay, CNRS/IN2P3, IJCLab

LFV AND B ANOMALIES

Lepton Flavor Violating (LFV) decays:

- Forbidden in the Standard Model w/o neutrino-oscillation
- Can occur via ν mixing but are highly suppressed ($\mathrm{m}_\nu^2/\mathrm{m}_W^2$) – well beyond any experimental sensitivity





Recent measurements of b-hadron decays have provided experimental indications of the lepton flavor universality violation (LFUV) - deviations from:

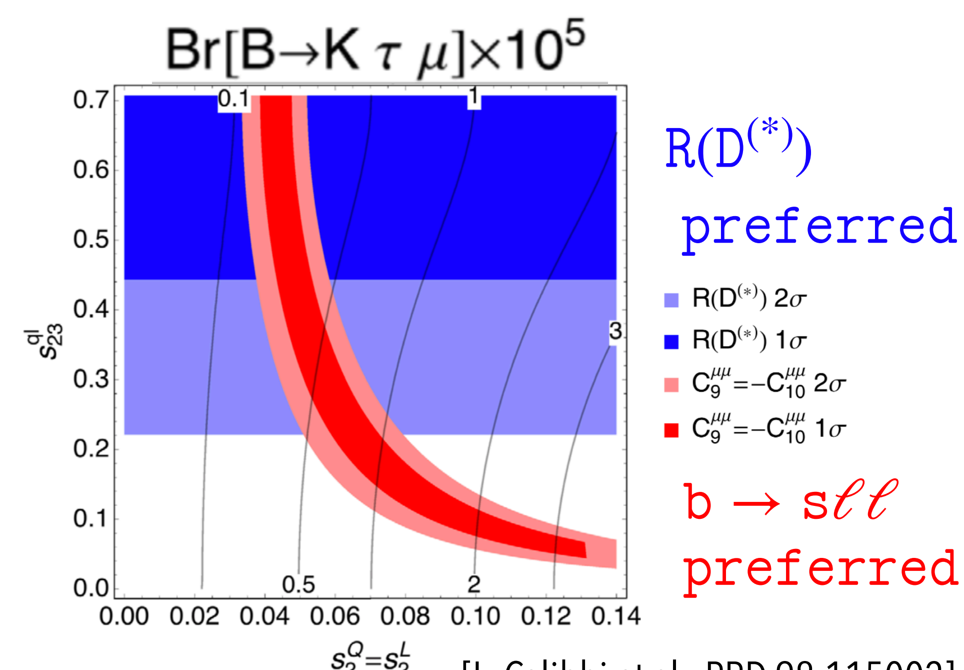
- μ/e universality in $\mathrm{b} \to \mathrm{s}\ell\ell$ neutral-current transitions
- τ/μ (and τ/e) universality in $\mathrm{b} \to \mathrm{c}\ell\nu$ charged-current transitions

Anomalies...

L~~F~~U $\xleftrightarrow{\text{BSM}}$ L~~F~~

Numerous extensions to the SM have been proposed* to connect the LFUV to the LFV, predicting significantly enhanced decay rates in $\mathrm{b} \to \mathrm{se}\mu$ or $\mathrm{b} \to \mathrm{s}\tau\mu$

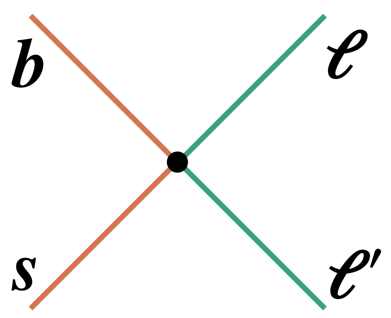
The observation of LFV in the charged sector would be a clear sign of physics beyond the Standard Model!



[L. Calibbi et al., PRD.98.115002]

*JHEP12(2016)027/ PRD92, 054013/ JHEP08(2021)050….

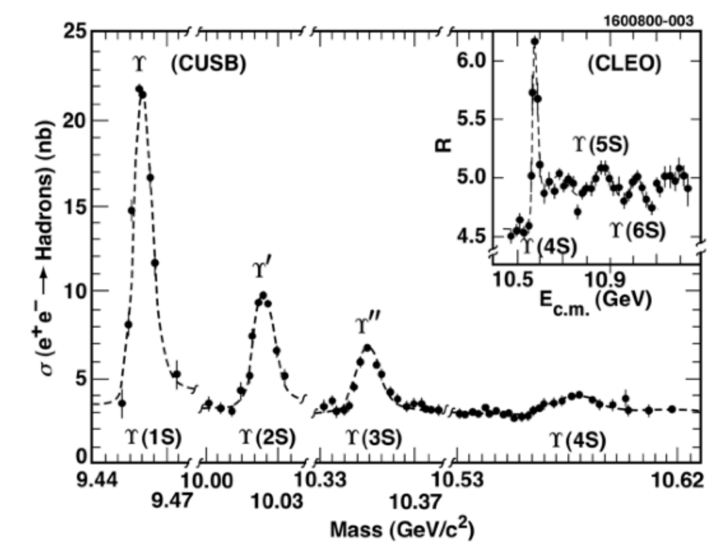
$b \to s\ell\ell'$ TRANSITIONS



$\ell, \ell' = \{e, \mu, \tau\}$

$B \to K^{(*)}\ell\ell'$ → Currently a very interesting topic in Belle (II) physics program (LFU and LFV in FCNC)

$B_s \to \ell\ell'$
$B_s \to \phi\ell\ell'$ → Only possible @$\Upsilon(5S)$ resonance
Belle: 121.4 fb^{-1}
Belle II: ~5 ab^{-1}* by 2031



$\Lambda_b \to \Lambda\ell\ell'$ → Beyond B-factories reach

$B \to \ell\ell'$ **2-body dynamics**
Leptons energy is monochromatic
ℓ has p* almost beyond endpoint of SL B decays

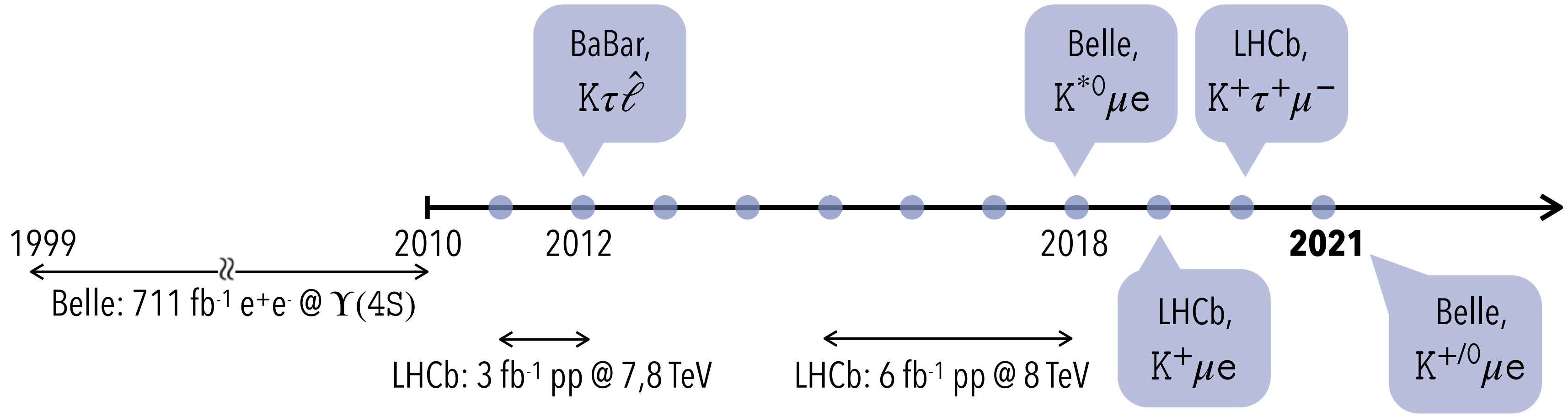
$B \to K\ell\ell'$ **3-body dynamics**
The final states topologically resemble
$b \to c\ell\nu$ modes (high-b.r.'s)
⇒ very large backgrounds

Will be focusing on $B \to K^{(*)}\ell\ell'$ searches at Belle and prospects at Belle II

With a mention to $B_d \to \tau\ell$ measurement

* $\sim 2.9 \times 10^8\ B_s^{(*)0}\overline{B}_s^{(*)0}$ pairs

EXPERIMENTAL STATUS



	Mode	**U.L. (90% CL)**	**Exp.**	
μ/e	$B^+\to K^+\mu^-e^+$	7.0×10^{-9}	LHCb	$3\,\mathrm{fb}^{-1}$
		3.0×10^{-8}	Belle	
	$B^+\to K^+\mu^+e^-$	6.4×10^{-9}	LHCb	
		8.5×10^{-8}	Belle	
	$B^0\to K^0\mu e$	3.8×10^{-8}	Belle	$711\,\mathrm{fb}^{-1}$
	$B^0\to K^{*0}\mu^+e^-$	1.2×10^{-7}	Belle	
	$B^0\to K^{*0}\mu^-e^+$	1.6×10^{-7}	Belle	
	$B^0\to K^{*0}\mu e$	1.8×10^{-7}	Belle	
τ/ℓ	$B^+\to K^+\tau\mu$	4.8×10^{-5}	BaBar	$433\,\mathrm{fb}^{-1}$
	$B^+\to K^+\tau e$	3.0×10^{-5}	BaBar	
	$B^+\to K^+\tau^+\mu^-$	3.9×10^{-5}	LHCb	$9\,\mathrm{fb}^{-1}$

- LFV searches containing 1st and 2nd generation leptons are often performed as ``incidental" studies along with related non-LFV modes
- Experimental limits on μ/e LFV modes ($\mathcal{O}(10^{-7})$) are more stringent than $\tau/\hat{\ell}$ ($\mathcal{O}(10^{-5})$)
- Models of LFV can produce signatures with different charge configurations ($\ell^+\ell'^-, \ell^-\ell'^+$) $\Rightarrow$ both limits are provided, in addition to the sum

$K^+\tau^-\ell^+$: **S**ame **S**ign
$K^+\tau^+\ell^-$: **O**pposite **S**ign

$B^0 \to K^{*0} e\mu$ AT BELLE

[Belle, PRD98, 0711001]

- Updated the BaBar result with ~3x larger statistics and provides the most stringent limits to date
- Vertex information of the four tracks $K\pi\mu e$
- 2 Multivariate analyzers constructed from NN
  1. Distinguish BB events from qq using event topology and flavor-tagging information of the non-signal B
  2. Reduce BB background

     Both B's decay SL

     $B \to D^{(*)}(\to X\ell\nu)X\ell\nu$

     Hadronic decay with mis-ID
- Peaking background

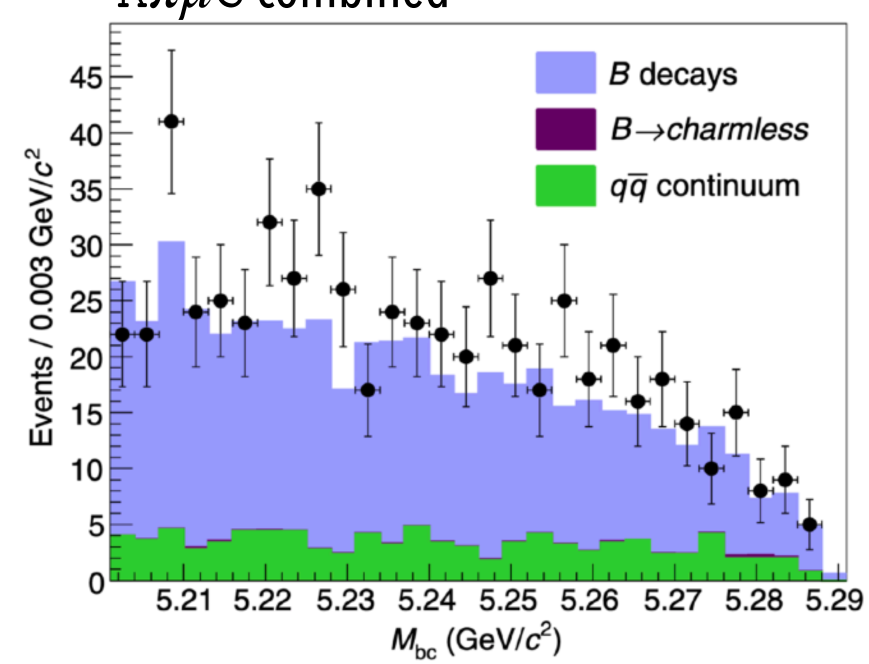
  $B^0 \to K^{*0}(\to K^+\pi^-)J/\psi(\to \ell^+\ell^-)$ (reduced with vetoes)
- **1-D** ML fit to the M_{bc} distribution

$$M_{bc} = \sqrt{(E_{beam}/c^2)^2 - (p_B^*/c)^2}$$

$$E_{beam} = \sqrt{s}/2$$

Mode	U.L. (90% CL)
$B^0 \to K^{*0}\mu^+e^-$	1.2×10^{-7}
$B^0 \to K^{*0}\mu^-e^+$	1.6×10^{-7}
$B^0 \to K^{*0}\mu e$	1.8×10^{-7}

$K\pi\mu e$ combined



$B \to Ke\mu$ AT BELLE

Mode	U.L. (90% CL)
$B^+ \to K^+\mu^+e^-$	8.5×10^{-8}
$B^+ \to K^+\mu^-e^+$	3.0×10^{-8}
$B^0 \to K^0\mu e$	3.8×10^{-8}

[Belle, 1908.01848]

- Come as a by-product of LFU tests and benefit from $R_{K^{(*)}}$ measurements updates/improvements
- Both neutral and charged B's $\Rightarrow K = K^+, K_S^0$
- Similar background as for $B \to K^*\mu e$, suppressed via a single NN with output $\mathcal{O}$
- D^0 and J/ψ vetoes applied
- **3-D** ML fit to the M_{bc}, ΔE, and $\mathcal{O}'$ distributions
- Use 89 fb^{-1} off-resonance data (60 MeV below $\Upsilon(4S)$) to constrain yields from continuum processes ($q\bar{q}, \tau^+\tau^-$)

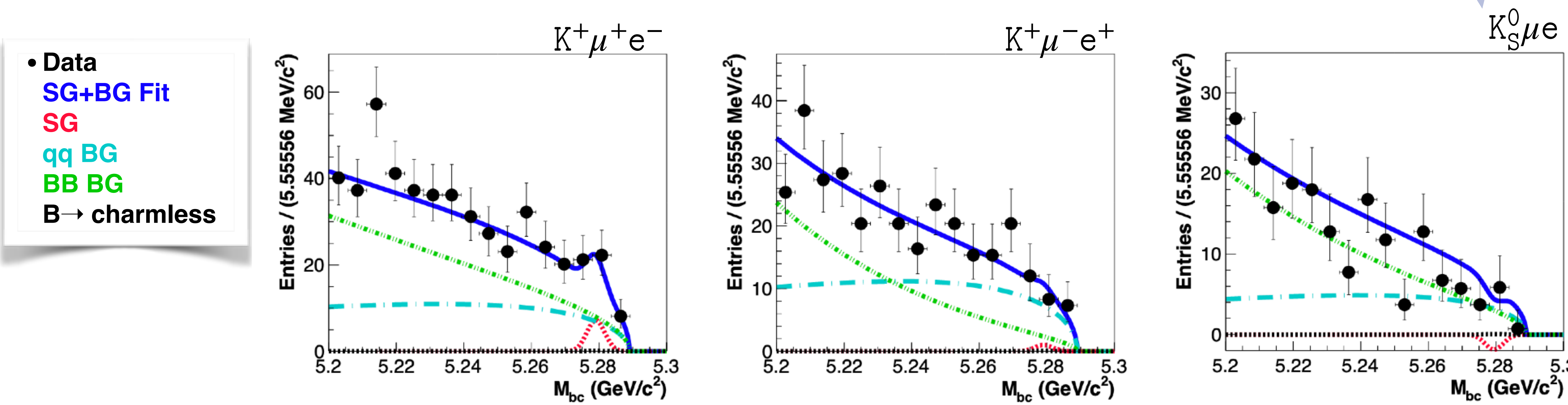
$$M_{bc} = \sqrt{(E_{beam}/c^2)^2 - (p_B^*/c)^2}$$

$$\Delta E = E^* - E_{beam}$$

$$E_{beam} = \sqrt{s}/2$$

$$\mathcal{O}' = \log\left[\frac{\mathcal{O} - \mathcal{O}_{min}}{\mathcal{O}_{max} - \mathcal{O}}\right]$$

Potential of neutral modes with K_S^0 - clean and strength of B-factories



$B \to K\tau\ell$ SEARCHES $\ell = \{e, \mu\}$

Mode	U.L. (90% CL)	Exp.
$B^+ \to K^+\tau\mu$	4.8×10^{-5}	BABAR
$B^+ \to K^+\tau e$	3.0×10^{-5}	BABAR
$B^+ \to K^+\tau^+\mu^-$	3.9×10^{-5}	LHCb

[BaBar, 1204.2852
LHCb, JHEP 06 (2020) 129]

- Experimentally, final states involving τ's generally require special techniques due to the presence of missing energy (neutrinos) and lack of a distinctive τ signature

- **To overcome these limitations, B-tagging is commonly used (full reconstruction of one B)**

Upper limits at w/ exclusive reco $\mathcal{O}(10^{-8,-7})$ → w/ B-tagging $\mathcal{O}(10^{-5})$

- Unlike SM processes like $B \to D^{(*)}\tau\nu$, $B \to \tau\nu$ etc. this channel has the unique property of having the only neutrino coming from the τ $\Rightarrow$ can compute τ recoil mass

The two B's are back to back in the CM frame ⇒

$$E^*_{B_{tag}} = E^*_{B_{sig}} = \sqrt{s}/2$$

$$\vec{p}^{\,*}_{B_{tag}} = -\vec{p}^{\,*}_{B_{sig}}$$

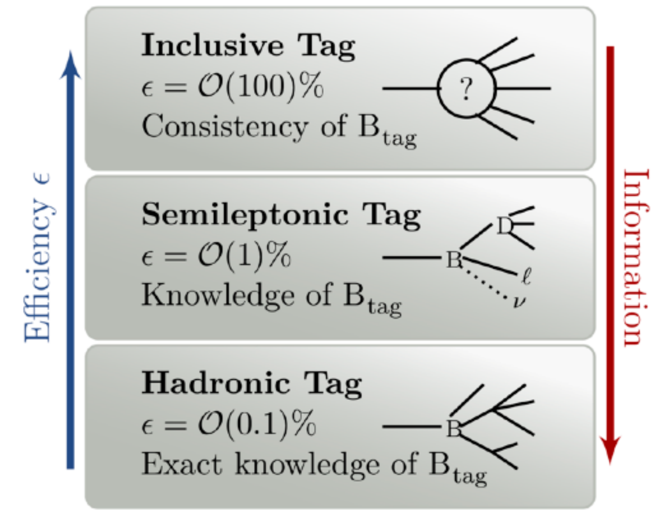
$$p_\tau = p_{e^+e^-} - p_K - p_\ell - p_{B_{tag}}$$

B-TAGGING ALGORITHMS

From FR to FEI and beyond…

FEI: Comput Softw Big Sci 3, 6 (2019)
FR: 1102.3876
SER: 1406.6311 , Sec. 7.4.1.1

- The **F**ull **E**vent **I**nterpretation is expected to improve previous algorithms (FR @ Belle, SER @ BaBar) with a higher tag-side efficiency
- Belle II Software framework allows to perform analyses on Belle dataset

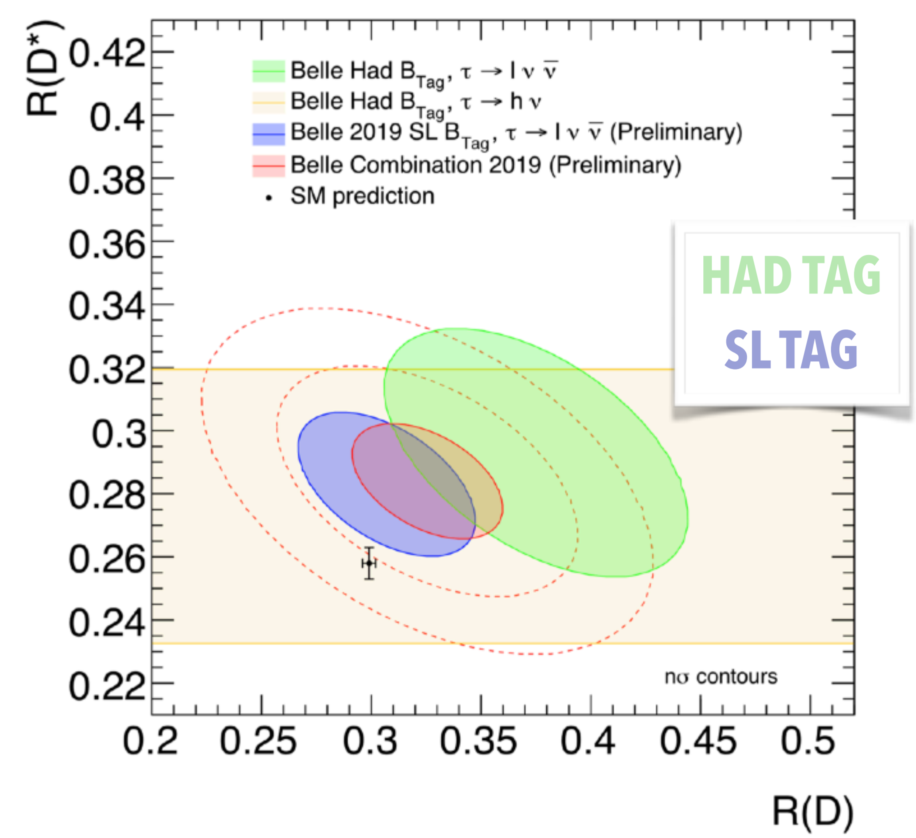


~10% purity ~5% purity

Tagging Algo.	Had B^+/B^0	SL B^+/B^0
FR (Belle MC)	$\mathcal{O}(0.3)/\mathcal{O}(0.2)$	$\mathcal{O}(0.3)/\mathcal{O}(0.3)$
FEI (Belle MC)	$\mathcal{O}(0.8)/\mathcal{O}(0.5)$	$\mathcal{O}(1.8)/\mathcal{O}(2.0)$

Comparable performance on Belle II MC

- SL tag *… beyond hadronic tagging!*
  - First R(D*) measurement with SL tag [Belle, 1607.07923] PRD94, 072007
  - R(D)−R(D*): SL FEI, Improved precision [Belle, 1910.05864] PRL124, 161803
- Inclusive tag *… beyond FEI!*
  - $B^+ \to K^+\nu\nu$ @ Belle II: Result with 63 fb^{-1} is already competitive with previous measurements @ Belle and BaBar [Belle II, 2104.12624]
  - $B^+ \to \mu\nu$ [Belle, 1911.03186] etc…



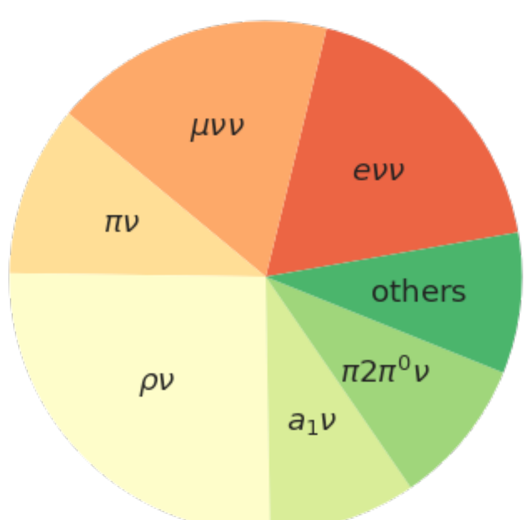
B-TAGGING APPROACHES FOR $B^+ \to K^+\tau\ell$

- Ongoing effort with Belle dataset and Belle II software
  - Hadronic FEI - well advanced status (Sensitivity $\mathcal{O}(10^{-5})$)

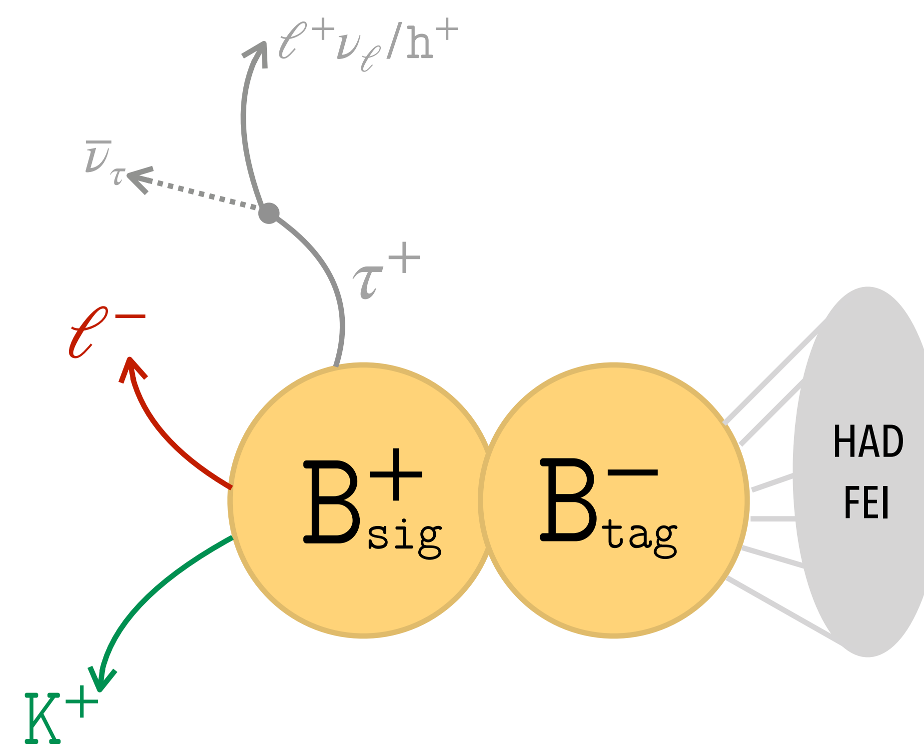
- Approach used also in BaBar's publication [BaBar, PRD86, 012004]
- One prong τ decays are considered
- Background depends on charge configuration
  - OS_μ: $B^+ \to \overline{D}^0(\to K^+\pi^-)X^+$
  - SS_ℓ: $B^+ \to \overline{D}^0(\to K^+X^-)\ell^+$
- MVA is adopted for background suppression
- Fit to m_τ distributions

Reminder

$K^{\oplus}\tau^-\ell^{\oplus}$: **S**ame **S**ign
$K^{\oplus}\tau^+\ell^{\ominus}$: **O**pposite **S**ign



$\tau \to$ lepton: 35 %
$\tau \to$ 1−prong: 85 %
$\tau \to 3\pi$: 9 %



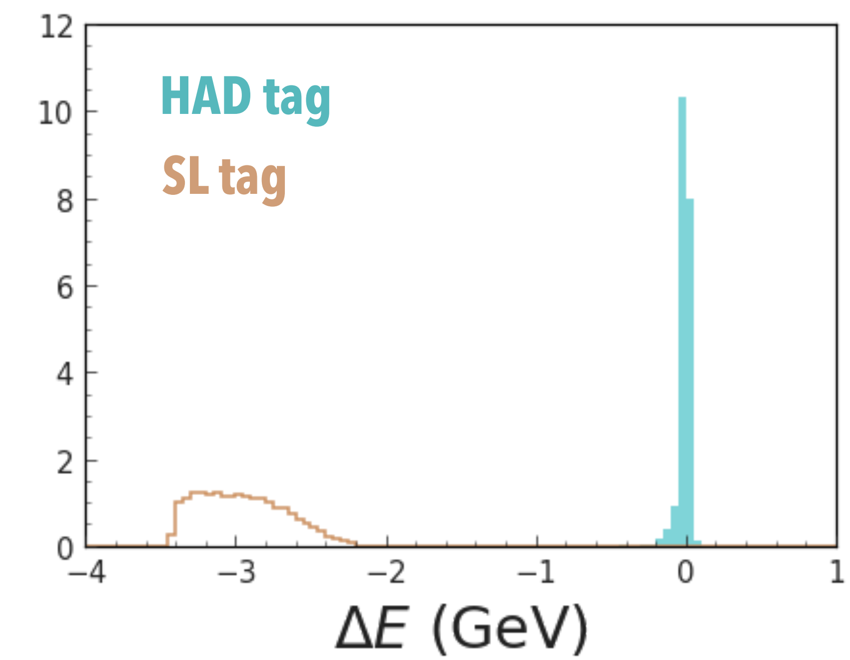
B-TAGGING APPROACHES FOR $B^+ \to K^+\tau\ell$

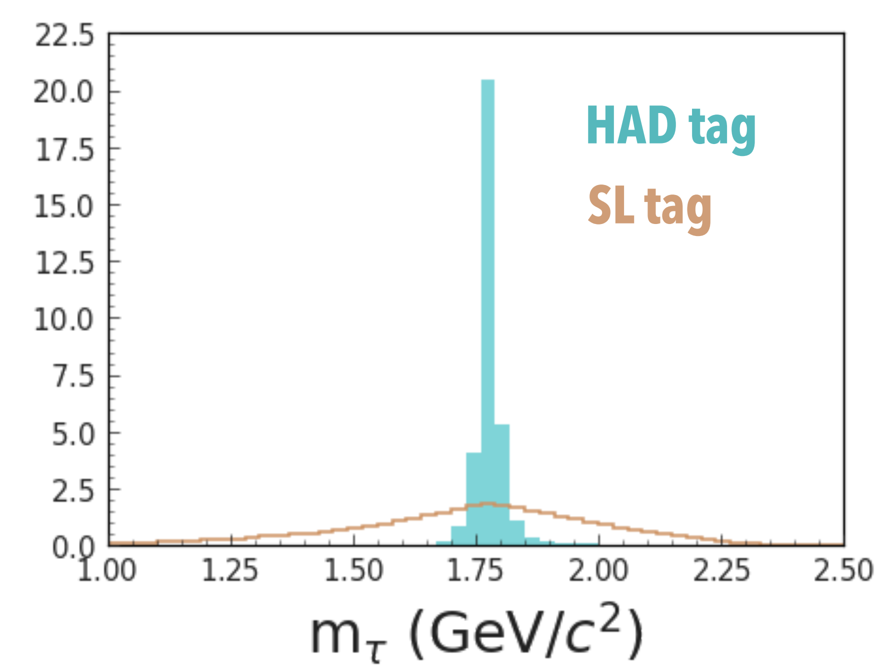
- Ongoing effort with Belle dataset and Belle II software
  - Hadronic FEI - well advanced status (Sensitivity $\mathcal{O}(10^{-5})$)
  - Hadronic vs. Semileptonic FEI

$B^+_{\rm tag}$ → **HADRONIC** ⟷ $\Delta E \sim 0$, $\varepsilon_{\rm TAG} \sim 0.5\,\%$ — **FEI Had***

$B^+_{\rm tag}$ → **SEMILEPTONIC** ⟷ $\Delta E < 0$, $\varepsilon_{\rm TAG} \sim 2\,\%$ — **FEI SL***

*Sum of exclusive modes

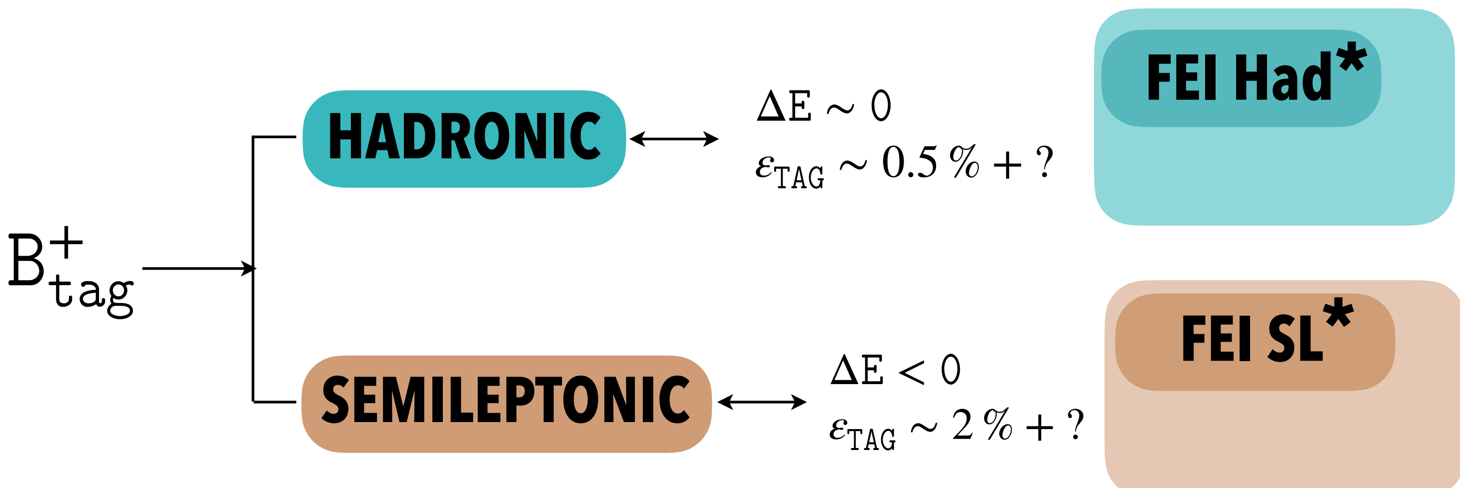




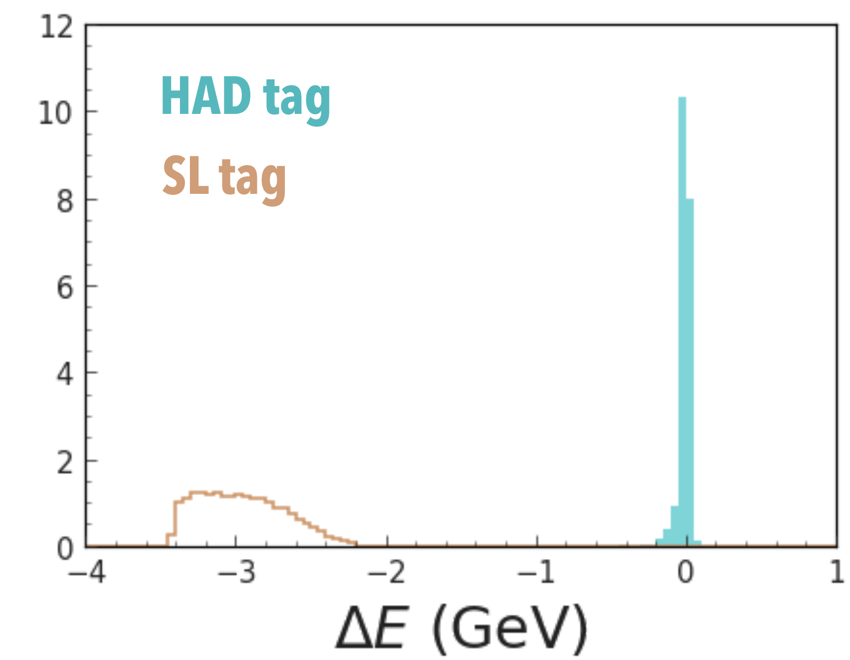
- Hadronic tag
  - Knowledge of the full $B_{\rm tag}$ 4-momentum ⇢ *better resolution on* m_τ
  - Very demanding in terms of efficiency ($\varepsilon^{\rm FEI}_{\rm had} \lesssim 1\%$)
- SL tag
  - $\vec{p}_{B_{\rm tag}}$ is unknown due to neutrino ⇢ *worse resolution on* m_τ *but still usable as long as signal side is well reconstructed*
  - Higher tagging efficiency ($\varepsilon^{\rm FEI}_{\rm sl} \sim 2\%$)

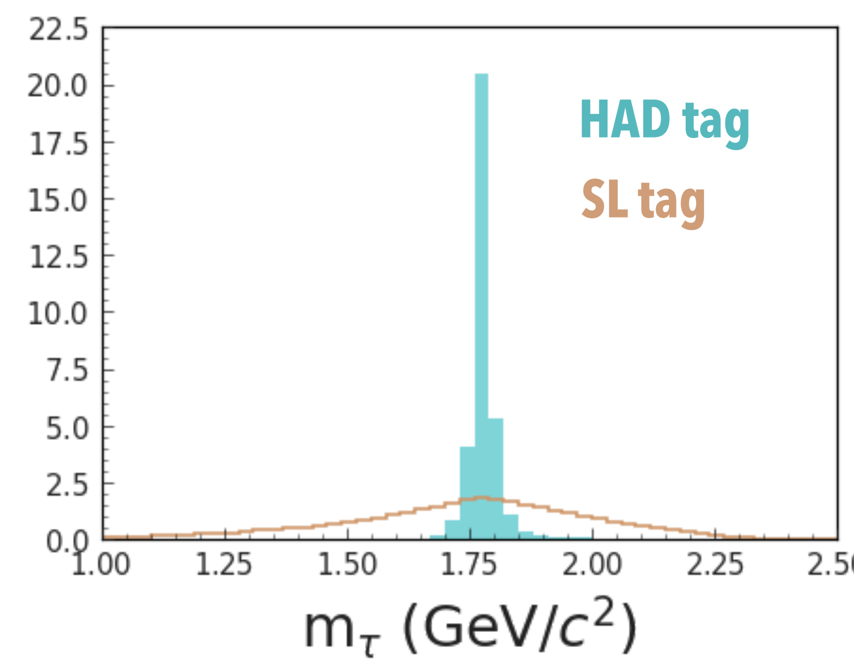
B-TAGGING APPROACHES FOR $B^+ \to K^+\tau\ell$

- Ongoing effort with Belle dataset and Belle II software
  - Hadronic FEI - well advanced status (Sensitivity $\mathcal{O}(10^{-5})$)
  - Hadronic vs. Semileptonic FEI
  - **More inclusive b-tagging approaches**



*Sum of exclusive modes

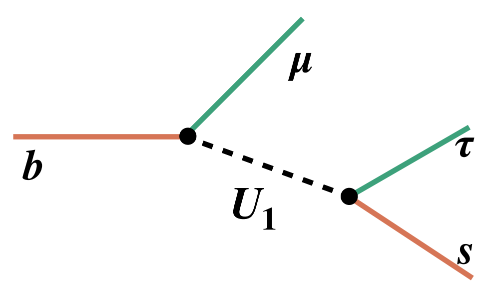




- A strategy to increase tagging efficiency while holding off the background
  - Enlarge the FEI-B^+_{tag} sample by adding D^0X candidates [c-tag⟷D^0-tag for charged B]
  - Treat separately HAD and SL tags
  - Good knowledge of BB simulation is necessary
- $B^0 \to K^0_S\tau\ell$ will be studied, although with variations due to different nature of neutral B decays

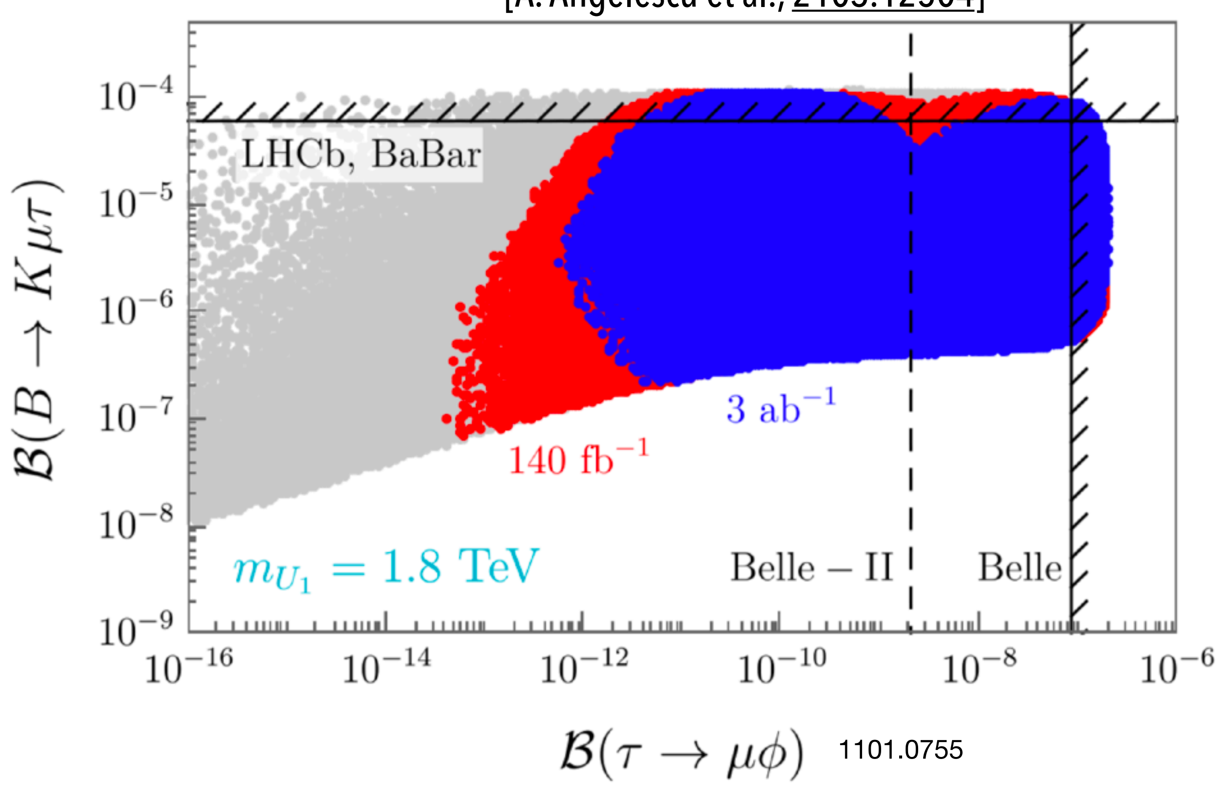
μ/τ LFV AND LEPTOQUARKS

A single LQ with $m_{LQ} \sim \mathcal{O}(1\text{ TeV})$ can satisfy both $R_{K^{(*)}} < R^{SM}_{K^{(*)}}$ and $R_{D^{(*)}} > R^{SM}_{D^{(*)}}$ and could enhance the rate of $b \to s\mu\tau$ processes

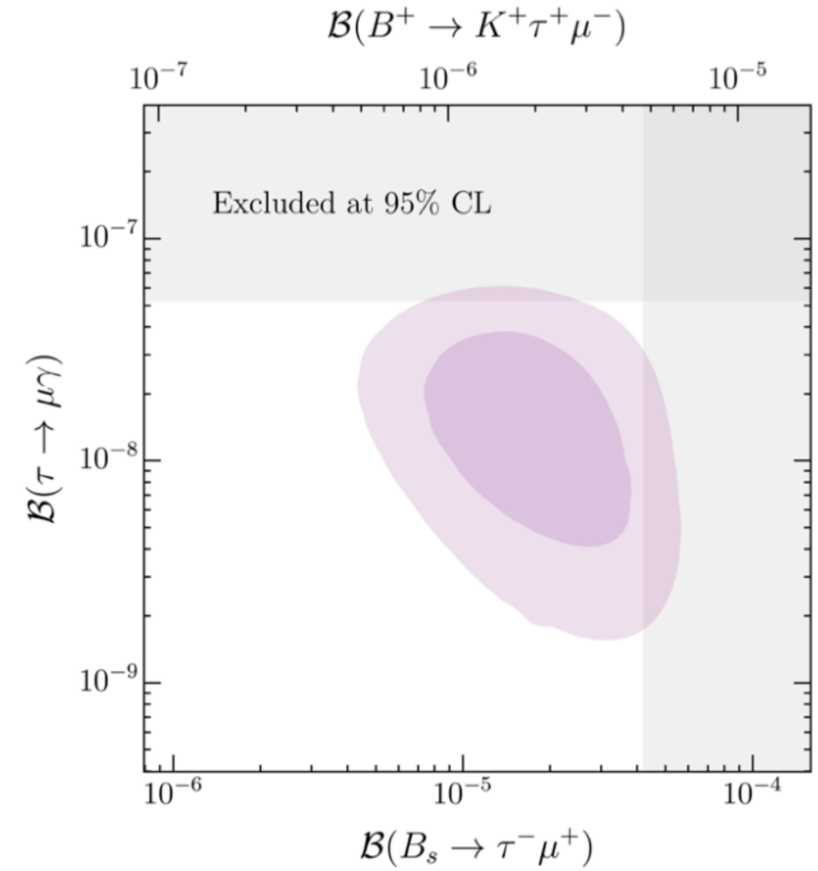


$U_1 \sim (\mathbf{3}, \mathbf{1})_{2/3}$

[A. Angelescu et al., 2103.12504]



1101.0755



[C. Cornella et al., 2103.16558]

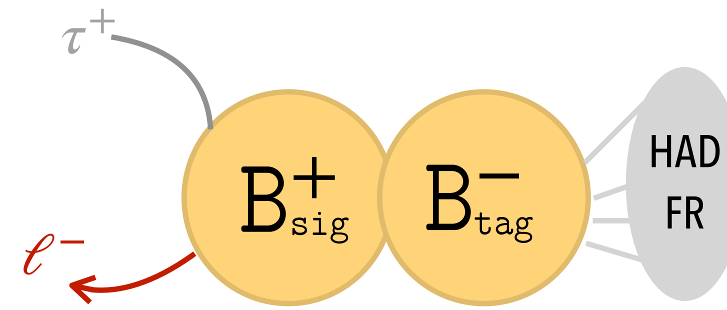
Predictions on $B \to K\tau\mu, B_s \to \tau\mu, \tau \to \mu\gamma$ b.r.'s using the results of a U_1 simplified model fit.

- Lower and upper bounds on the exclusive $b \to s\mu\tau$ processes as obtained from the **constraints** arising both **from the low-energy observables** and those coming from **the current direct searches at the LHC**

NEW

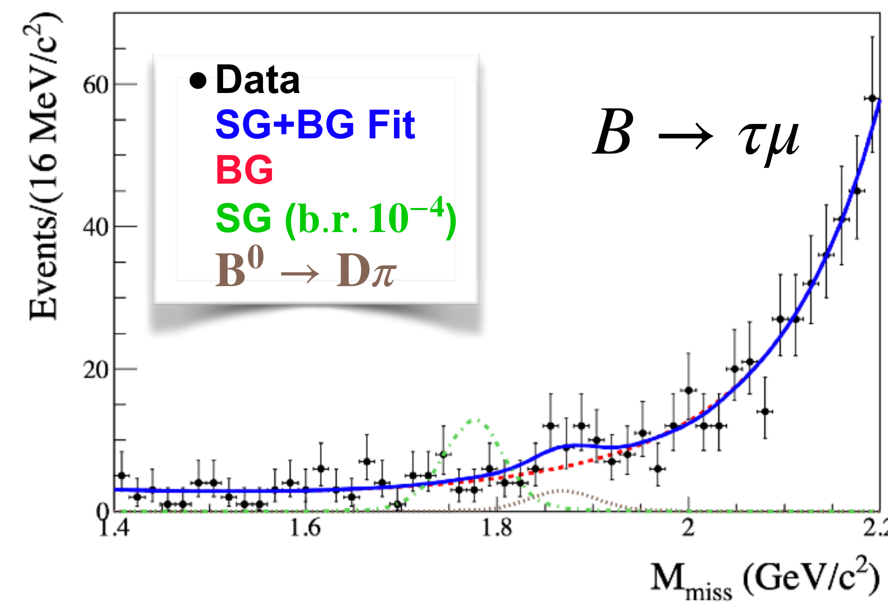
[Belle, 2108.11649]

$B^0 \to \tau\ell$ SEARCH AT BELLE



- $b \to d\ell\ell'$ - related mode!

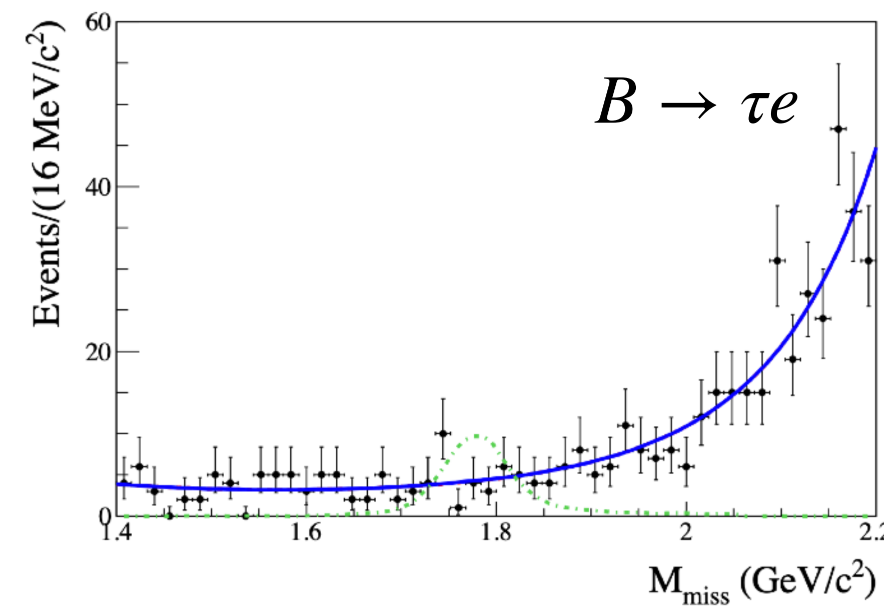
- Hadronic B-tagging (Belle algorithm - Full Reconstruction)
- $B_{tag}\ell$ with $M_{miss} \in [1.4, 2.2]\ \mathrm{GeV}/c^2$
- (Smooth) Background mainly from $b \to c(u)\ell\nu$
- Peaking background due to $B^0 \to D^{(*)-}\pi^+$ in $\tau\mu$ channel
- Unbinned extended ML fit to M_{miss} distribution



$$M^2_{miss} = [(\sqrt{s}, \mathbf{0}) - (E^*_B, \vec{\mathbf{p}}^*_B) - (E^*_\ell, \vec{\mathbf{p}}^*_\ell)]^2$$

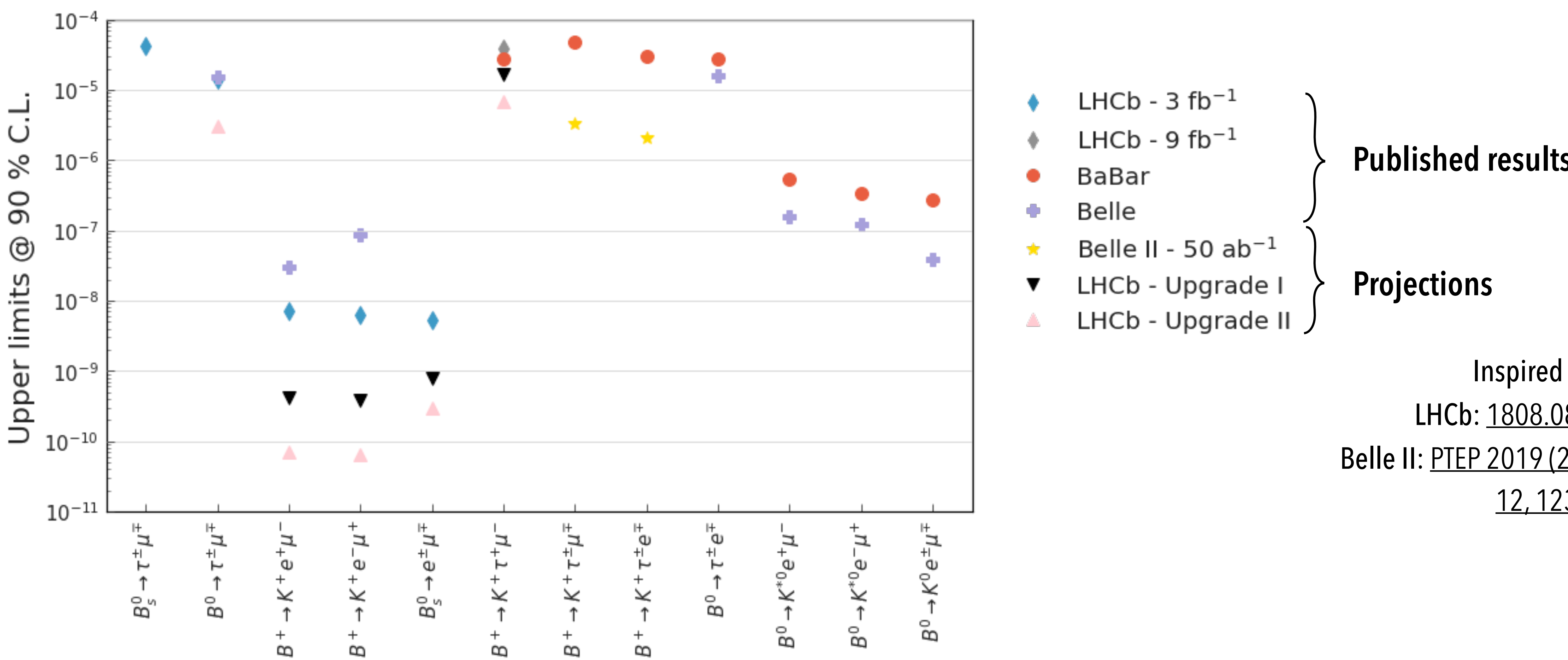
Reminder

$$E^*_{B_{tag}} = E^*_{B_{sig}} = \sqrt{s}/2$$
$$\vec{p}^*_{B_{tag}} = -\vec{p}^*_{B_{sig}}$$

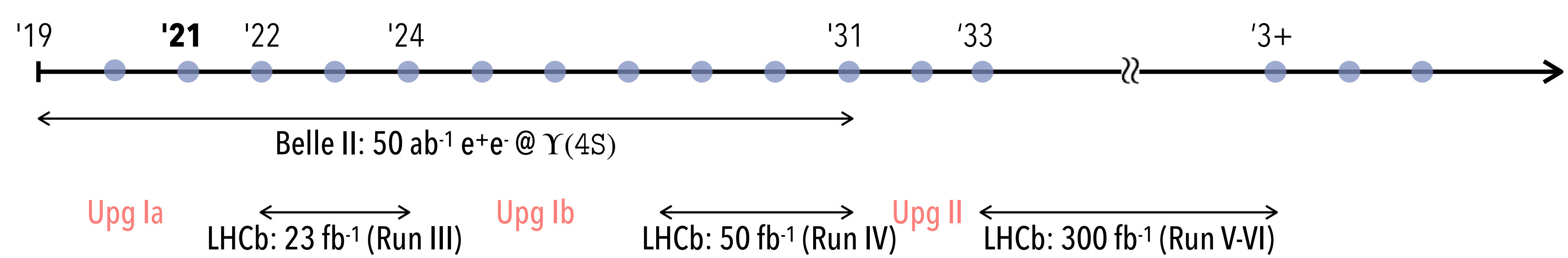


	Preliminary results @ 90 % C.L.	
Belle data	$\mathscr{B}(B \to \tau\mu) < 1.5 \times 10^{-5}$	Slightly worse than LHCb
711 fb^{-1}	$\mathscr{B}(B \to \tau e) < 1.6 \times 10^{-5}$	Most precise

SUMMARY (I) *and projections*



Inspired from
LHCb: 1808.08865
Belle II: PTEP 2019 (2019) 12, 123C01



SUMMARY (II)

Anomalies

- Hints of LFU
- LFV in FCNC processes enhanced for many NP scenarios (LQ?)

Belle

- **Still delivering physics results which are sensitive to the BSM**
  - $B \to K^{(*)} \mu e$: go along LFU measurements, some of them the most stringent to date
  - $B^0 \to \tau \ell$: new result, $\mathcal{O}(10^{-5})$
  - $B^+ \to K^+ \tau \ell$: coming soon, $\mathcal{O}(10^{-5})$

Belle II

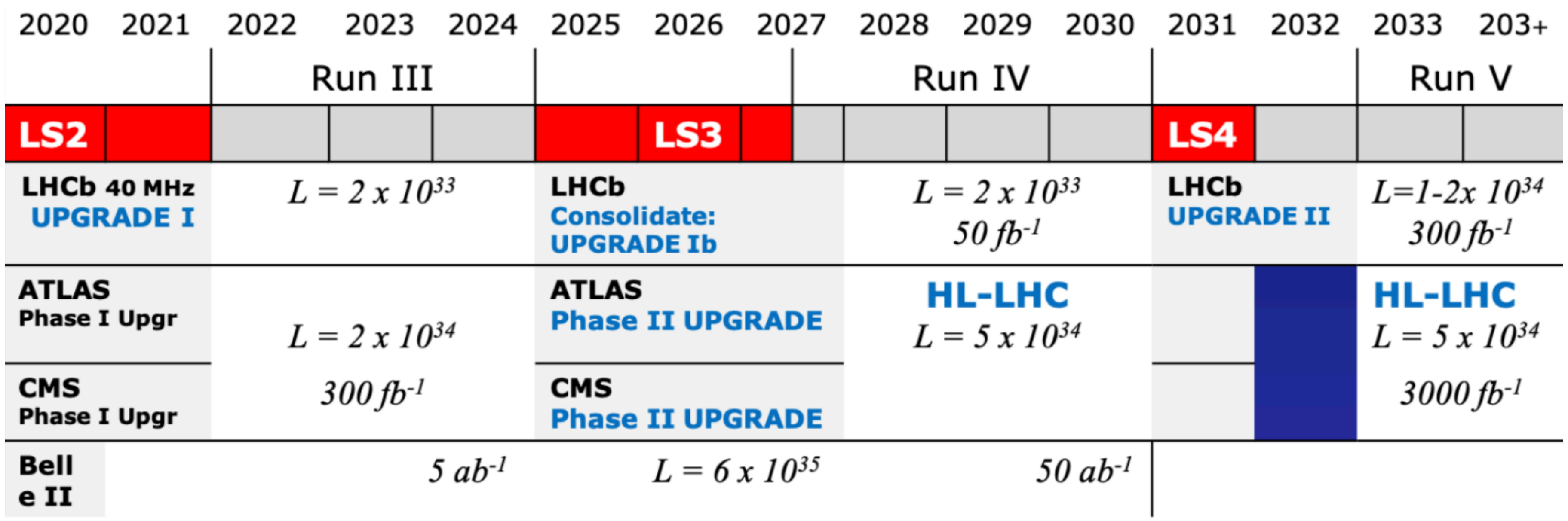
- First EWP decays show the **high capabilities of Belle II** — Seema Choudhury's talk!
- Not only larger statistics, but also improved software/tools (B-tagging with FEI and beyond!) — Filippo Dattola's talk!
- Will contribute to **further constrain NP models** with the help of
  - τ LFV searches — Alberto Martini's talk!
  - Direct searches at LHC
  - Complementary contribution of LHCb for many channels

THANK YOU FOR YOUR ATTENTION!

BACKUP →

LHC*b* UPGRADES

EPS-HEP Conference 2021
Franz Muheim - LHCb highlights



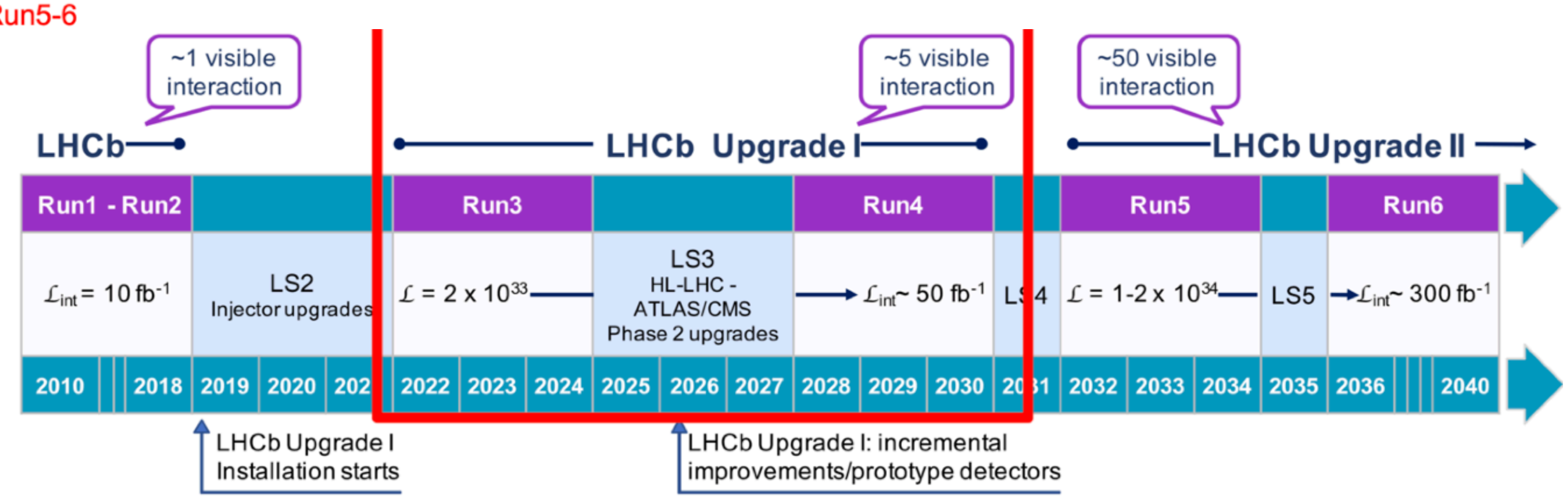
LHCb physics reach with the Phase-I and Phase-II upgrades

Aim at collecting 50 fb^{-1} in Run3-4 and 300 fb^{-1} in Run5-6

✓ Collected ~9 fb^{-1} of data in Run1-2

arXiv:1808.08865

ICHEP Conference 2021
F. Alessio - The LHCb upgrades for Run3 and Run4



SEMI-EXCLUSIVE RECONSTRUCTION AT BABAR

D^0 decays
- $K^-\pi^+$
- $K^-\pi^+\pi^0$
- $K^-3\pi$
- K^-K^+
- $K_s^0\pi^0$
- $K_s^0\pi^+\pi^-$
- $K_s^0\pi^+\pi^-\pi^0$
- $\pi^-\pi^+$
- $\pi^-\pi^+\pi^0$

D^+ decays
- $K^-\pi^+\pi^-$
- $K^-\pi^+\pi^-\pi^0$
- $K_s^0\pi^+$
- $K_s^0\pi^+\pi^0$
- $K_s^0\pi^+\pi^+\pi^-$
- $K^+K^-\pi^+$
- $K^+K^-\pi^+\pi^0$

D^{*+} decays
- $\overline{D}^0\pi^+$
- $D^+\pi^0$

D^{*0} decays
- $D^0\pi^0$
- $D^0\gamma$

D_s^+ decays
- $\phi\pi^0$
- $K_s^0K^+$

D_s^{*+} decays

J/ψ decays
- e^+e^-
- $\mu^+\mu^-$

π^0 decays
- $\gamma\gamma$

K_s^0 decays
- $\pi^+\pi^-$

$$B_{\text{tag}} \to D_{\text{seed}} Y^{\pm}$$

$$Y^{\pm} = n_1\pi^{\pm} + n_2K^{\pm} + n_3\pi^0 + n_4K_s^0$$

$n_1 \in [1,5]$

$n_2 \in [0,2]$

$n_3 \in [0,2]$

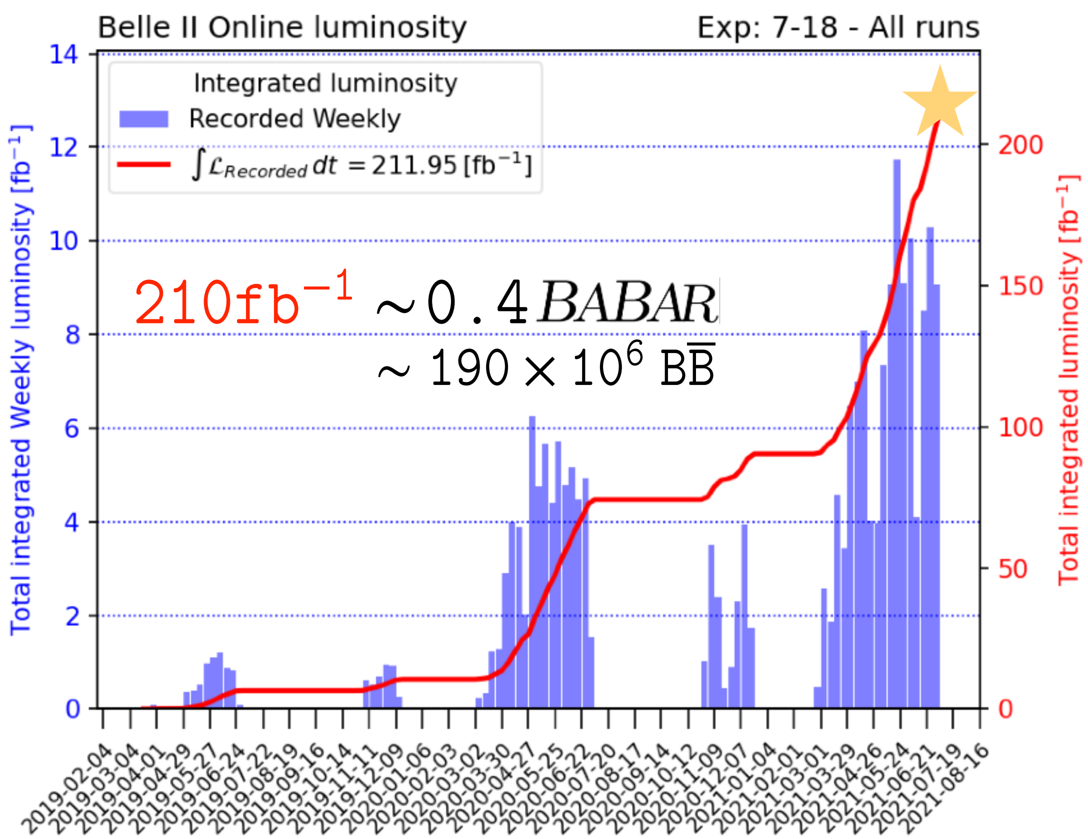
$n_4 \in [0,1]$

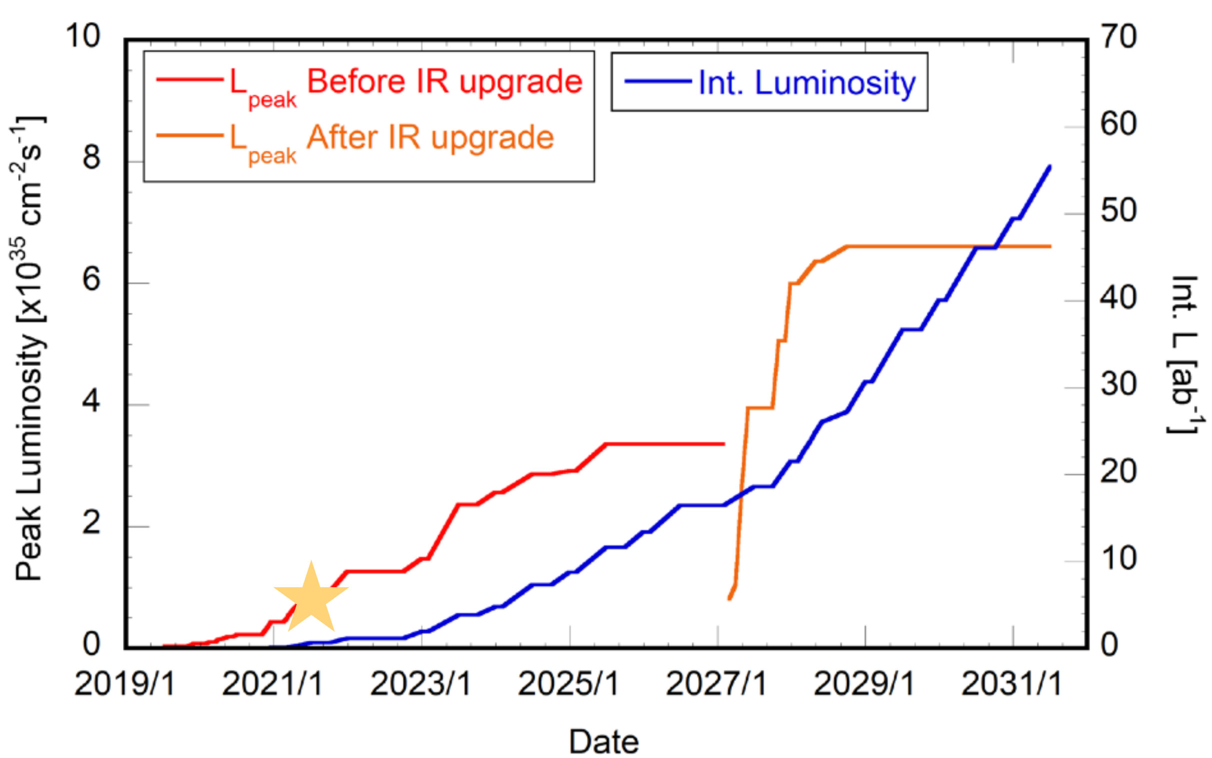
$\{0,1,0,0\}, \{1,0,1,0\}, \{2,0,0,0\}, \{0,0,2,0\}$ *

*Expansions for neutral Y

First results (IN2P3)
Lumi record (IJCLab)

BELLE II IS TAKING DATA NOW!





World Record Luminosity

$\mathscr{L}_{\mathrm{peak}} = 3.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ **(June 22th 2021)**

Currents ~0.8 A (LER)/0.7 A (HER)

Nano beam scheme

$$\mathscr{L} = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\ \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

5.9 mm (KEKB)→ 0.3 mm (SuperKEKB)

Many rediscoveries

2 papers (dark sector:

PRL 124, 141801 (2020)

PRL 125, 161806 (2020))

1st B physics result

arXiv:2104.12624

D lifetimes

A long journey ...

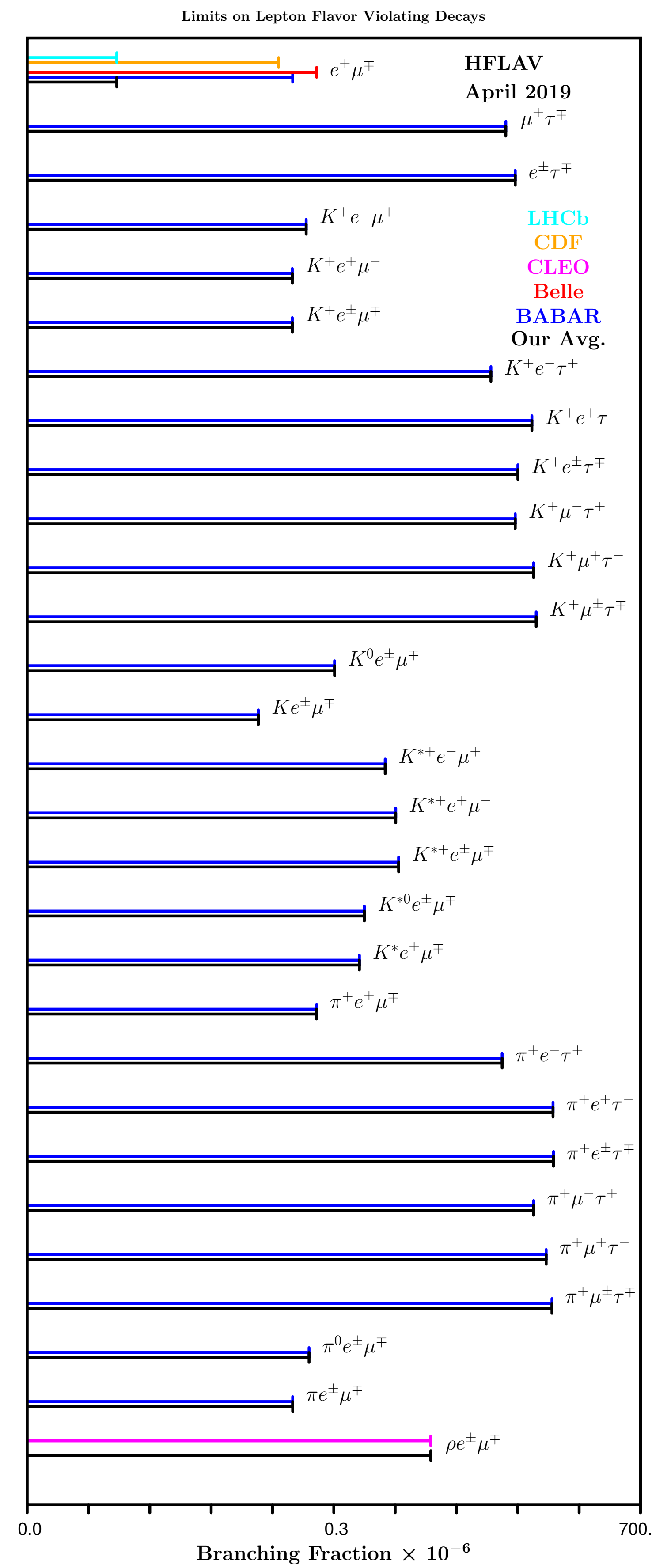
- 1st Long shutdown in 2022 (PXD, TOP)
- 2nd Long shutdown in ~2026 (QCS, RF)
- The target integrated luminosity is **50 ab^{-1} by ~2031**

Stay tuned!

TABLES

Decay Mode	$N_{B\overline{B}}$ (10^6)	$\mathcal{B}$ upper limit (90% C.L.)
Lepton flavor violating modes (light flavors):		
$B^0 \to \mu^\pm e^\mp$	85	17×10^{-8}
$B^0 \to \mu^\pm e^\mp$	384	9.2×10^{-8}
$B^+ \to \pi^+ \mu^\pm e^\mp$	230	17×10^{-8}
$B^0 \to \pi^0 \mu^\pm e^\mp$		14×10^{-8}
$B \to \pi \mu^\pm e^\mp$		9.2×10^{-8}
$B^+ \to K^+ \mu^- e^+$	229	9.1×10^{-8}
$B^+ \to K^+ \mu^+ e^-$		13×10^{-8}
$B^+ \to K^+ \mu^\mp e^\pm$		9.1×10^{-8}
$B^0 \to K^0 \mu^\mp e^\pm$		27×10^{-8}
$B \to K \mu^\mp e^\pm$		3.8×10^{-8}
$B^+ \to K^{*0} \mu^- e^+$		53×10^{-8}
$B^+ \to K^{*0} \mu^+ e^-$		34×10^{-8}
$B^+ \to K^{*0} \mu^\mp e^\pm$		58×10^{-8}
$B^+ \to K^{*+} \mu^- e^+$		130×10^{-8}
$B^+ \to K^{*+} \mu^+ e^-$		99×10^{-8}
$B^+ \to K^{*+} \mu^\mp e^\pm$		140×10^{-8}
$B \to K^* \mu^\mp e^\pm$		51×10^{-8}

Decay Mode	$N_{B\overline{B}}$ (10^6)	$\mathcal{B}$ upper limit (90% C.L.)
Lepton flavor violating modes (including τ):		
$B^0 \to \tau^\pm e^\mp$	378	2.8×10^{-5}
$B^0 \to \tau^\pm \mu^\mp$		2.2×10^{-5}
$B^+ \to K^+ \tau^- \mu^+$	472	4.5×10^{-5}
$B^+ \to K^+ \tau^+ \mu^-$		2.8×10^{-5}
$B^+ \to K^+ \tau^\mp \mu^\pm$		4.8×10^{-5}
$B^+ \to K^+ \tau^- e^+$		4.3×10^{-5}
$B^+ \to K^+ \tau^+ e^-$		1.5×10^{-5}
$B^+ \to K^+ \tau^\mp e^\pm$		3.0×10^{-5}
$B^+ \to \pi^+ \tau^- \mu^+$		6.2×10^{-5}
$B^+ \to \pi^+ \tau^+ \mu^-$		4.5×10^{-5}
$B^+ \to \pi^+ \tau^\mp \mu^\pm$		7.2×10^{-5}
$B^+ \to \pi^+ \tau^- e^+$		7.4×10^{-5}
$B^+ \to \pi^+ \tau^+ e^-$		2.0×10^{-5}
$B^+ \to \pi^+ \tau^\mp e^\pm$		7.5×10^{-5}

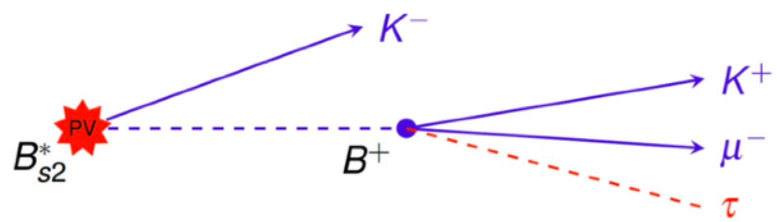


LHC*b* MEASUREMENT

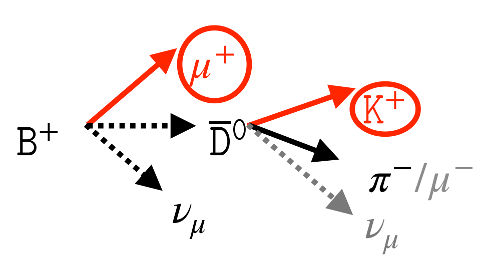
$B^+ \to K^+\mu^-\tau^+$ *(using* B^{*0}_{s2}*)*

JHEP 06 (2020) 129
S. Weber - ICHEP 2020

- 9 fb^{-1} @ 7, 8 and 13 TeV (Run1 & Run2)
- Use $B^{*0}_{s2} \to B^+K^-$ decay: about 1% of B^+ production
- $K^+\mu^-$ pair from secondary vertex plus additional track t^+

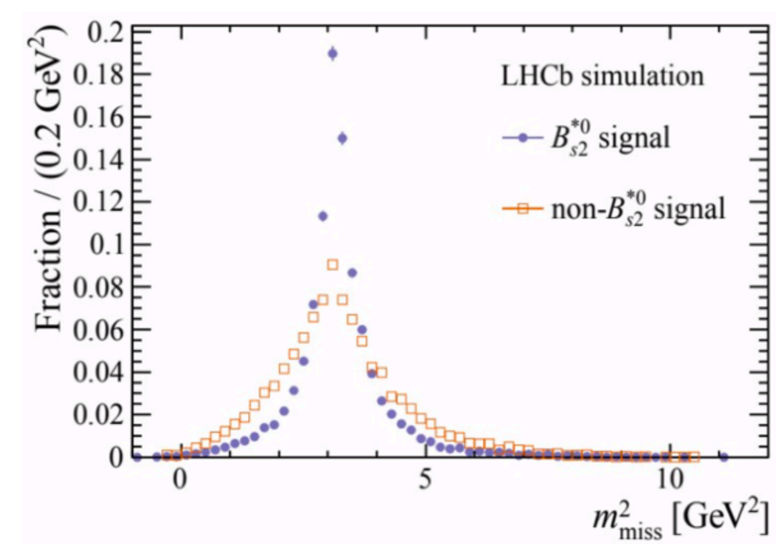


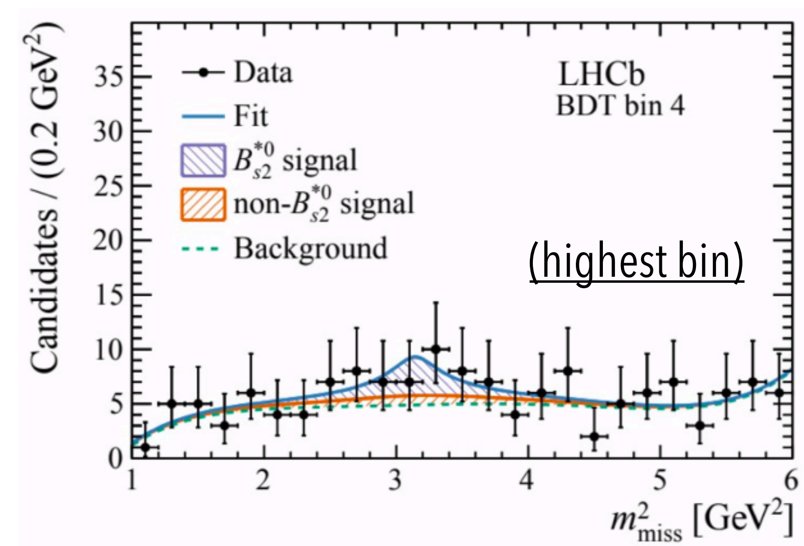
- Expect peak at τ mass also for B not from B^{*0}_{s2} decay, but wider distribution
- $K^+\mu^-\tau^+$ experimentally preferred over $K^+\mu^+\tau^-$ as it has a lower background from sSL B decays, because CF decays of the D mesons are likely to lead to K's of the same charge as the muon



- Remaining backgrounds produce smooth m^2_{miss} distributions
- Search performed in bins of final BDT output with increasing signal sensitivity

Mode	U.L. (90% CL)	Exp.
$B^+ \to K^+\tau\mu$	4.8×10^{-5}	BaBar
$B^+ \to K^+\tau e$	3.0×10^{-5}	BaBar
$B^+ \to K^+\tau^+\mu^-$	3.9×10^{-5}	LHCb





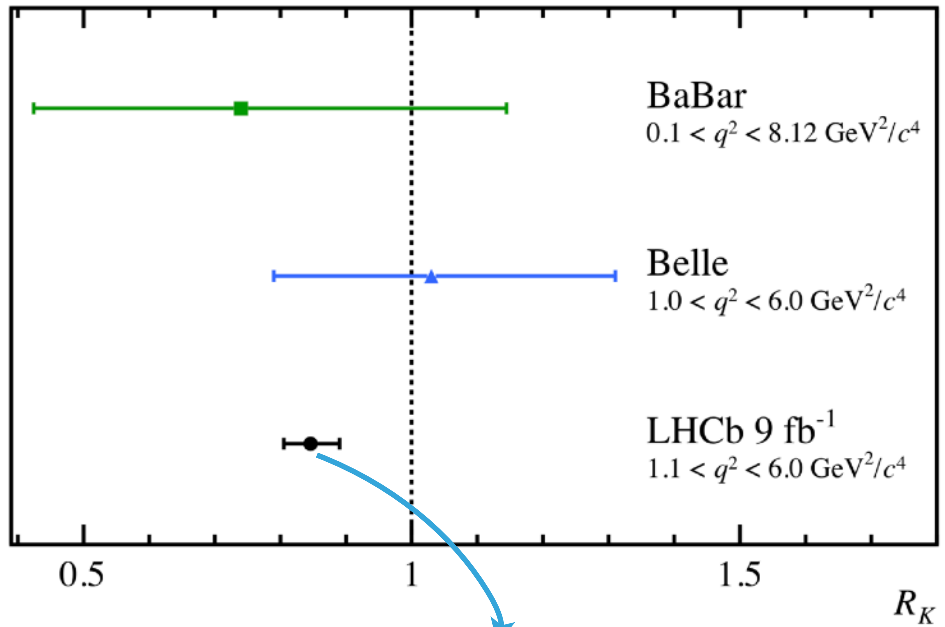
STATUS OF R_K AND PROSPECTS

Semi-leptonic B decays are showing tensions with the SM predictions that are connected to a possible violation of the Lepton Flavor Universality (LFU).
Different behaviour of lepton generations in the process:

$b \to s l^+ l^-$ (neutral current): **μ vs. e**

$$R_K = \left.\frac{\Gamma\left(B \to K\mu^+\mu^-\right)}{\Gamma\left(B \to K e^+ e^-\right)}\right|_{q^2 \in (q^2_{\min}, q^2_{\max})}$$

$$R_K^{\mathrm{exp}} < R_K^{\mathrm{SM}} \sim 1$$



3.1 σ deviation

Belle 2021

$$R_K = 1.03^{+0.28}_{-0.24} \pm 0.01$$
$q^2 \in (1.0, 6.0)$ GeV$^2/c^4$ (0.7 ab^{-1})

[JHEP 03 (2021) 105]

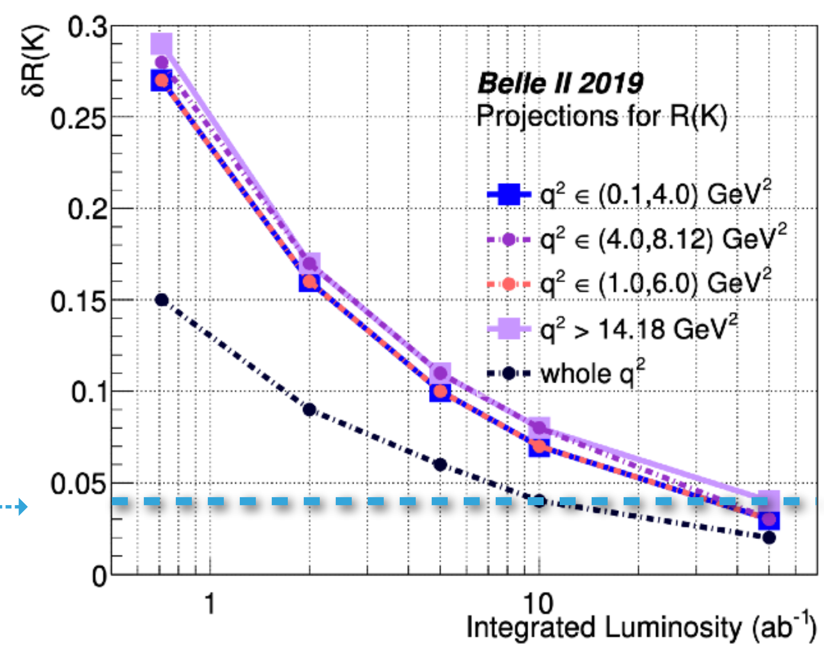
LHCb 2021

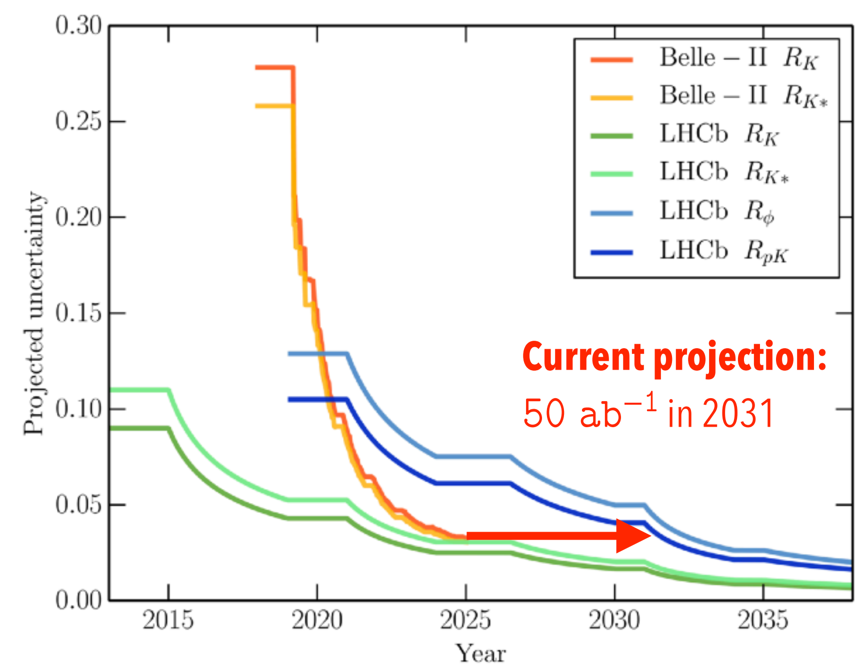
$$R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$$
for $q^2 \in [1.1, 6.0]$ GeV$^2/c^4$ (9 fb^{-1})

[arXiv:2103.11769v1]

Belle II will provide new, independent tests of the anomalies in the $b \to s l^+ l^-$ family!

Current LHCb precision ⇢

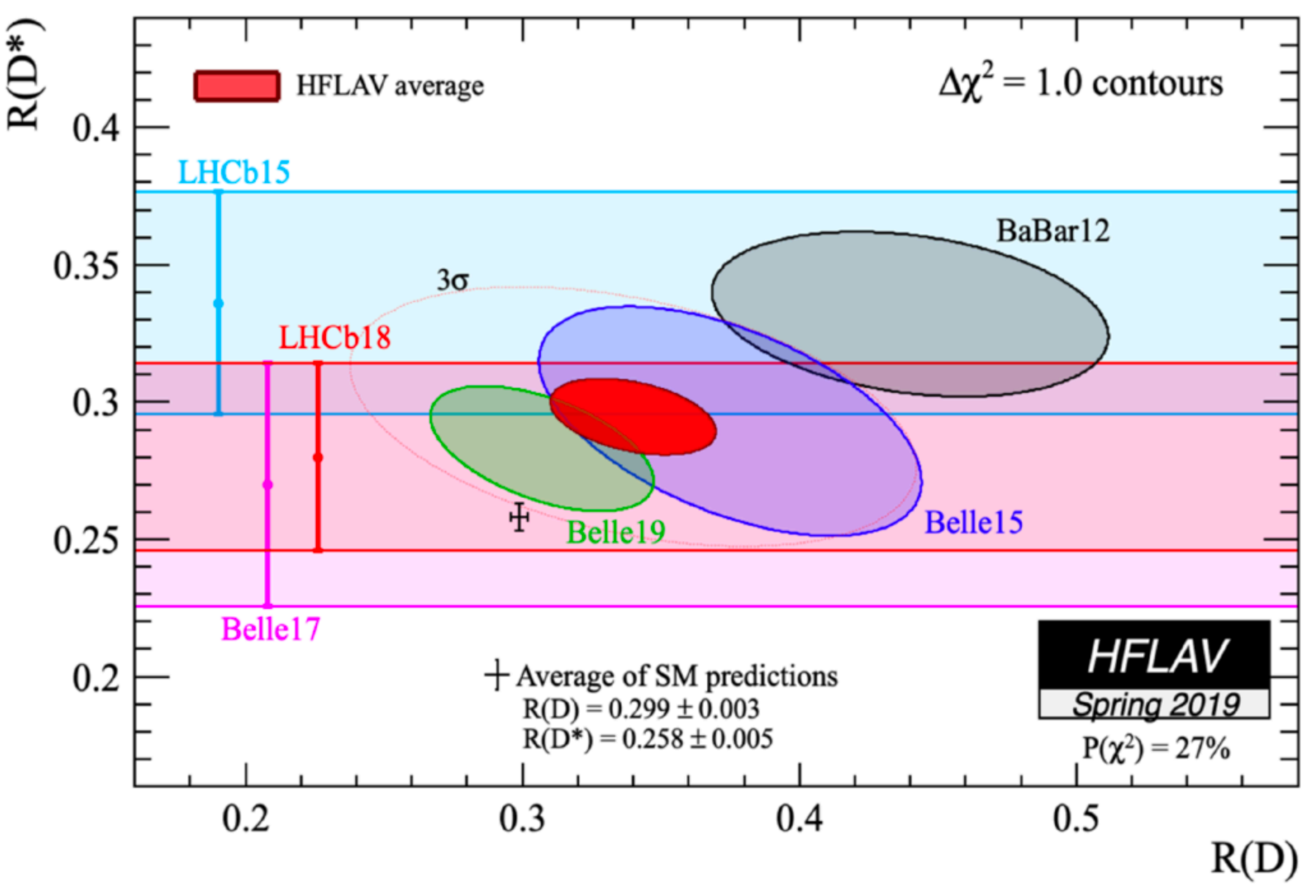




Current projection:
50 ab^{-1} in 2031

CURRENT STATUS OF R(D$^{(*)}$)

$$R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)}\tau\nu_\tau\right)}{\Gamma\left(B \to D^{(*)}l\nu_l\right)} \qquad l \in \{e, \mu\}$$



Belle15

$R(D) = 0.375 \pm 0.064 \pm 0.026$	(Had tag)
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$	

Belle19

$R(D) = 0.307 \pm 0.037 \pm 0.016$	(SL tag)
$R(D^*) = 0.283 \pm 0.018 \pm 0.014$	

LHCb

$R(D) = 0.336 \pm 0.027 \pm 0.030$	2015
$R(D) = 0.280 \pm 0.018 \pm 0.029$	2018

BaBar12

$R(D) = 0.440 \pm 0.058 \pm 0.042$

$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Average

$R(D) = 0.340 \pm 0.027 \pm 0.013$

$R(D^*) = 0.295 \pm 0.011 \pm 0.008$

R(D) and R(D*) exceed the SM predictions given in the last row of the table above, by 1.4σ and 2.5σ respectively. Considering the R(D)-R(D*)) correlation of -0.38, the resulting combined χ^2 is 12.33 for 2 degree of freedom, corresponding to a p-value of 2.07 x 10^{-3}. The difference with the SM predictions reported above, corresponds to about 3.08σ **HFLAV**

SHAPE VARIABLES FOR CONTINUUM SUPPRESSION

Variables related to the B meson direction: the spin-1 $\Upsilon(4S)$ decaying into two spin-0 B mesons results in a $\sin^2\theta_B$ angular distribution with respect to the beam axis; in contrast for $e^+e^- \to f\bar{f}$ events, the spin-1/2 fermions f, and its two resulting jets, are distributed following a $1 + \cos^2\theta_B$ distribution. Using the angle θ_B between the reconstructed momentum of the B candidate (computed in the $\Upsilon(4S)$ reference frame) and the beam axis, the variable **$|\cos\theta_B|$** allows one to discriminate between signal B decays and the B candidates from continuum background.

The **Fox-Wolfram moments**: for a collection of N particles with momenta p_i, the k-th order Fox-Wolfram moment H_k is defined as

$$H_k = \sum_{i,j}^{n} |\vec{p}_i||\vec{p}_j| P_k(\cos\theta_{ij})$$

where θ_{ij} is the angle between p_i and p_j, and P_k is the k-th order Legendre polynomial. Notice that in the limit of vanishing particle masses, $H_0 = 1$; that is why the normalized ratio $R_k = H_k/H_0$ is often used, so that for events with two strongly collimated jets, R_k takes values close to zero (one) for odd (even) values of k. These sharp signatures provide a convenient discrimination between events with different topologies.

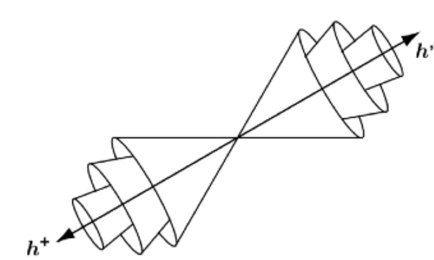
$$R_n = \frac{H_n}{H_0}$$

Thrust: for a collection of N momenta p_i ($i = 1,\cdots N$), the thrust axis T is defined as the unit vector along which their total projection is maximal; the thrust scalar T (or thrust) is a derived quantity defined as

$$T = \frac{\sum_{i=1}^{N} |\vec{T}\cdot\vec{p}_i|}{\sum_{i=1}^{N} |\vec{p}_i|}$$

For a BB event, both B mesons are produced almost at rest in the $\Upsilon(4S)$ rest frame, so their decay particles are isotropically distributed, their thrust axes are randomly distributed, and thus $|\cos\theta_T|$ follows a uniform distribution in the range [0,1]. In contrast for $q\bar{q}$ events, the momenta of particles follow the direction of the jets in the event, and as a consequence the thrusts of both the B candidate and the ROE are strongly directional and collimated, yielding a $|\cos\theta_T|$ distribution strongly peaked at large values.

Cleo Cones: Set of nine variables corresponding to the momentum flow around the thrust axis of the B candidate, binned in nine cones of 10° around the thrust axis as illustrated



SUPERKEKB ACCELERATOR

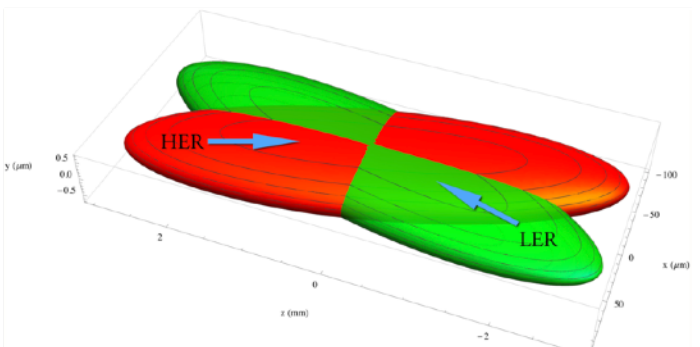
$$\mathscr{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\,\xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

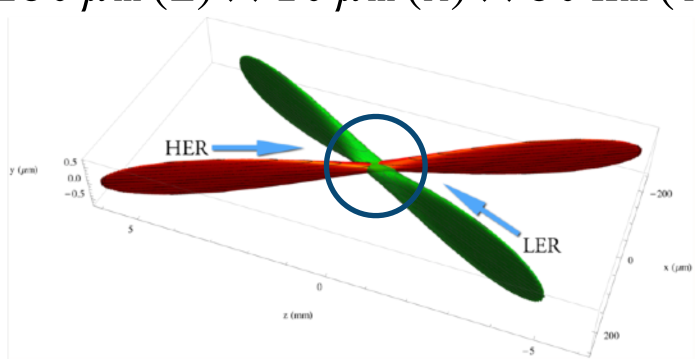
- **"Nano-beam"** scheme and higher currents
- Larger crossing angle Φ
- Lower βγ by 40%

Wrt to 1st generation B factories

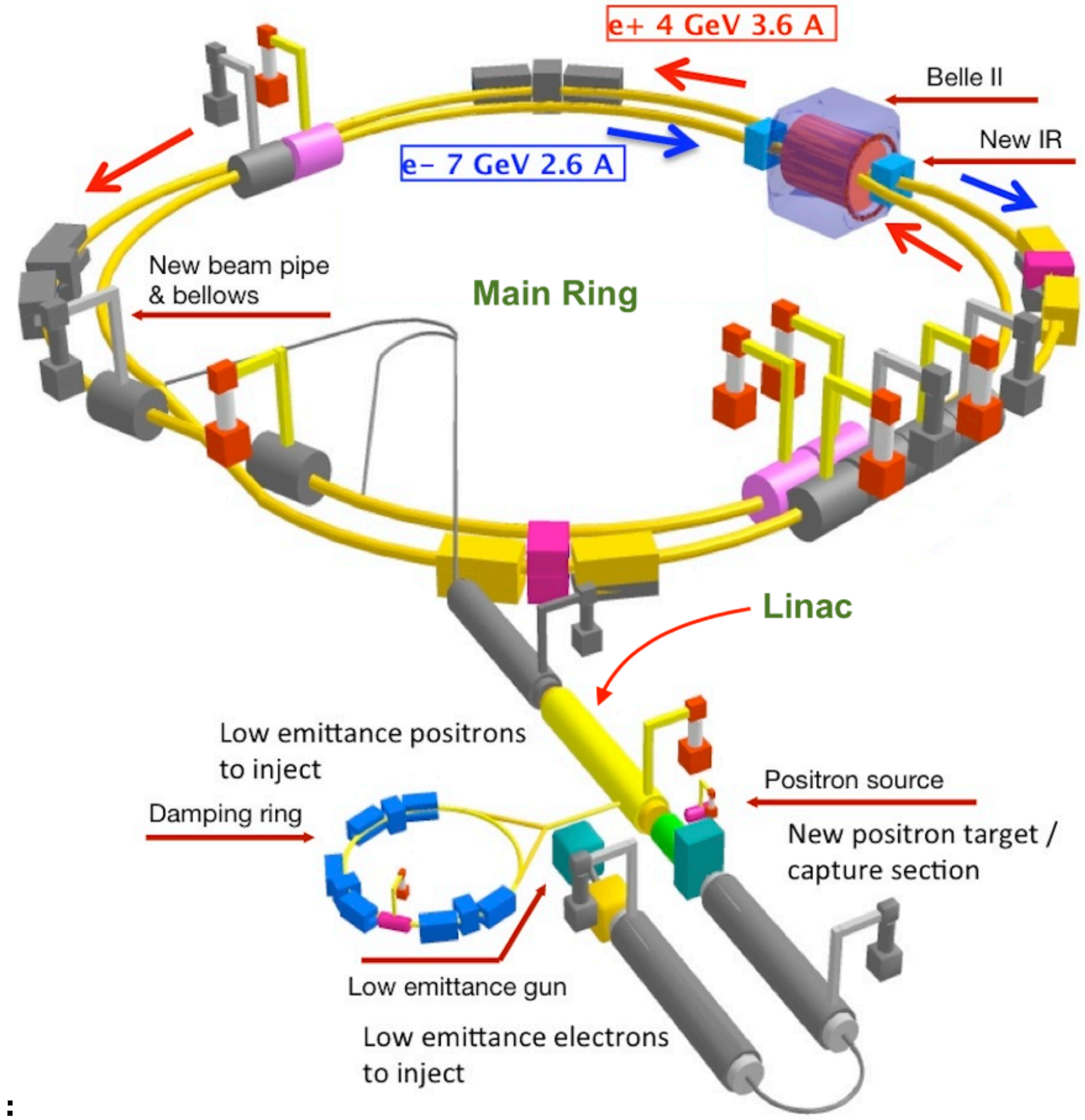
Beamspot

$250\,\mu\mathrm{m}\,(Z) \times 10\,\mu\mathrm{m}\,(X) \times 50\,\mathrm{nm}\,(Y)$





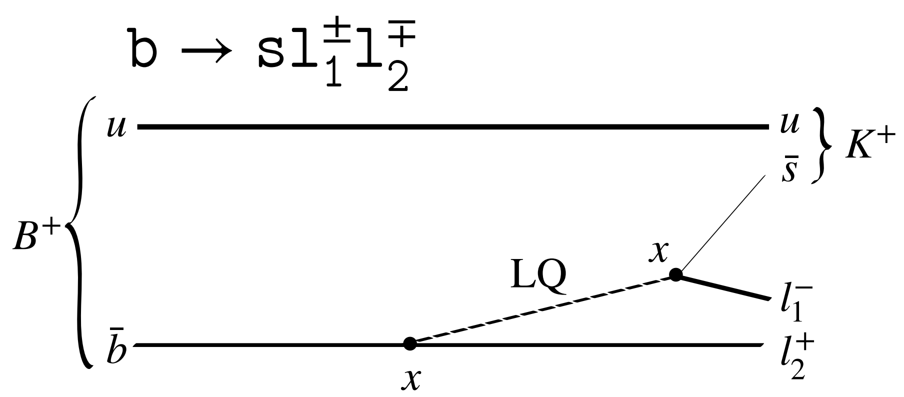
KEKB **SuperKEKB**



	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (mm) LER/HER	Φ (mrad)	I (A)	L (cm⁻²s⁻¹) x10³⁵
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	0.2
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	8

Factor 20 Factor 2-3

THEORY - U_1 MODEL



Weak singlet vector LQ that can simultaneously explain R_K and R_D - Absence of the tree level constraint coming from $\mathscr{B}(B \to K^{(*)}\nu\bar{\nu})$. Such NP extension is non-renormalizable at loop level: additional assumptions must be specified (e.g. completions involving Z' and a color-octet of vector bosons).

$$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$$
$$Q = Y + T_3 = 0 + 2/3 = 2/3$$

"Simplified models with LQ states seem to be favored. Among them, the U_1 case stands for simplicity & phenomenological success." G. Isidori (FCPC)

$$\mathcal{L} \supset + x_{1\,ij}^{LL} \bar{Q}_L^{i,a} \gamma^\mu U_{1,\mu} L_L^{j,a} + x_{1\,ij}^{RR} \bar{d}_R^i \gamma^\mu U_{1,\mu} e_R^j + x_{1\,ij}^{\overline{RR}} \bar{u}_R^i \gamma^\mu U_{1,\mu} \nu_R^j + \text{h.c.}.$$

'Genuine' LQ: does not possess "diquark" couplings due to the SM quantum number assignment.

x denotes the coupling matrices of scalar (vector) leptoquarks with the quark–lepton pairs **arXiv:1603.04993v3 [hep-ph]**

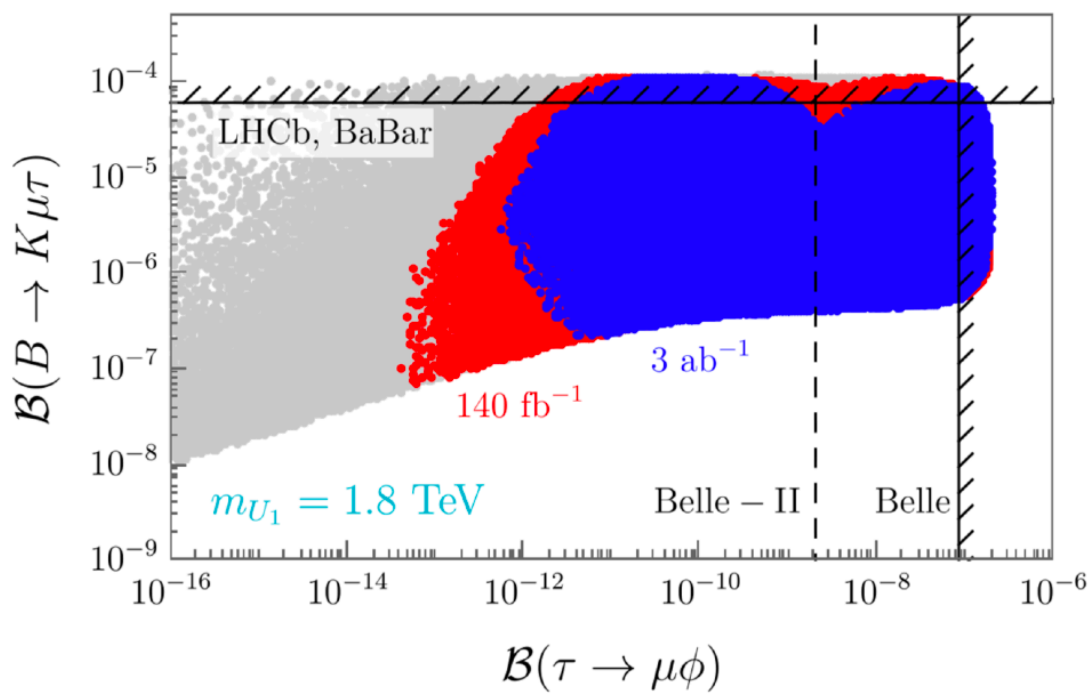
arXiv:2103.12504v1 [hep-ph]

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

TABLE III. *Summary of the LQ models which can accommodate $R_{K^{(*)}}$ (first column), $R_{D^{(*)}}$ (second column), and both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ (third column), without being in conflict with existing constraints. See text for details.*

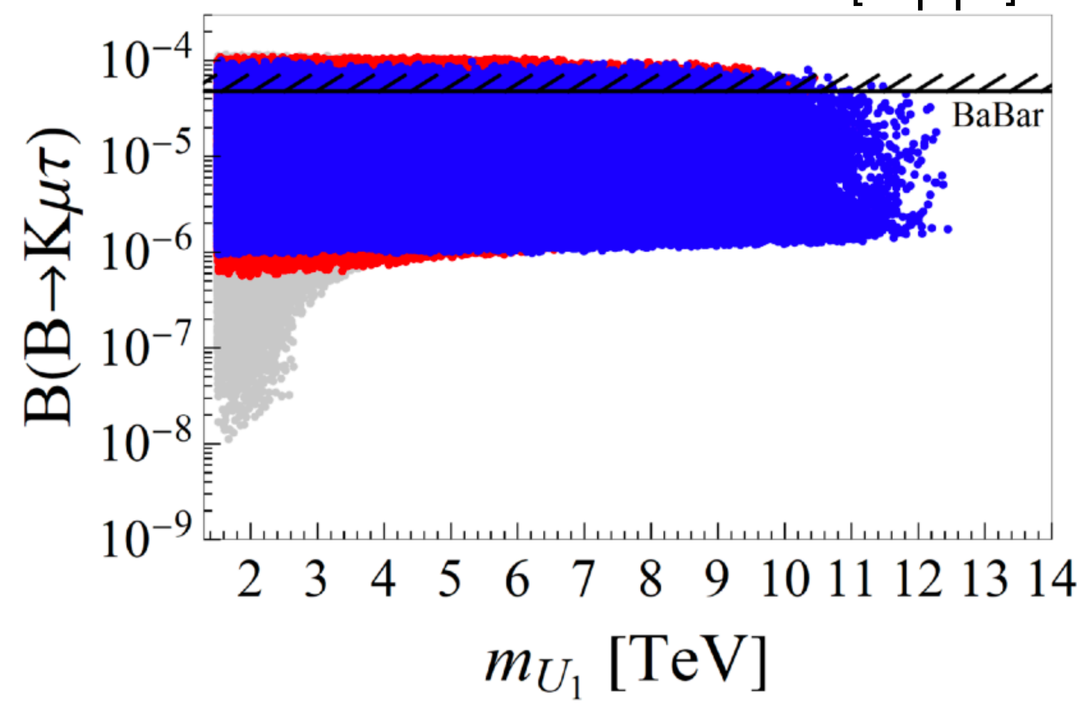
THEORY - PREDICTION ON BR

arXiv:2103.12504 [hep-ph]



Lower and upper bounds on the exclusive $b \to s\mu\tau$ processes as obtained in the minimal U_1 scenario from the constraints arising both from the low-energy observables (gray points) and those coming from the current direct searches at the LHC (red points), the subset of which (blue points) correspond to the projected integrated luminosity of 3 ab^{-1}

arXiv:1808.08179v3 [hep-ph]



[…] In particular we find the lower bound on the LFV mode B(B → K$\mu\tau$) few×10^{-7} for any mass of m_{U1} in which Yukawa couplings are kept within the perturbativity limits and in the minimal U1 scenario in which only left-handed couplings are allowed to take values different from zero. The upper bound is superseded by the current experimental bound B(B → K$\mu\tau$)^{exp} < 4.8×10^{-5}, which can be improved both at LHCb and Belle II. Improving that bound by two orders of magnitude can therefore either exclude or, if observed, corroborate the validity of the minimal U1 scenario.

BABAR RESULTS ON $B \to h\tau\ell$

TABLE IV: Results for the observed sideband events $N_{sb,i}$, signal-to-sideband ratio $R_{b,i}$, expected background events b_i, number of observed events n_i, signal efficiency $\epsilon_{h\tau\ell,i}$ (assuming uniform three-body phase space decays) for each τ channel i and $B \to h\tau\ell$ [9] branching fraction central value and 90% C.L. upper limits (UL). All uncertainties include statistical and systematic sources.

Mode	τ channel	$N_{sb,i}$	$R_{b,i}$	b_i	n_i	$\epsilon_{h\tau\ell,i}$	$\mathcal{B}(B \to h\tau\ell)$ $(\times 10^{-5})$ central value	$\mathcal{B}(B \to h\tau\ell)$ $(\times 10^{-5})$ 90% C.L. UL
	e	22	0.02 ± 0.01	0.4 ± 0.2	2	$(2.6 \pm 0.2)\%$		
$B^+ \to K^+\tau^-\mu^+$	μ	4	0.08 ± 0.05	0.3 ± 0.2	0	$(3.2 \pm 0.4)\%$	$0.8\ ^{+1.9}_{-1.4}$	< 4.5
	π	39	0.045 ± 0.020	1.8 ± 0.8	1	$(4.1 \pm 0.4)\%$		
	e	5	0.03 ± 0.01	0.2 ± 0.1	0	$(3.7 \pm 0.3)\%$		
$B^+ \to K^+\tau^+\mu^-$	μ	3	0.06 ± 0.03	0.2 ± 0.1	0	$(3.6 \pm 0.7)\%$	$-0.4\ ^{+1.4}_{-0.9}$	< 2.8
	π	153	0.045 ± 0.010	6.9 ± 1.5	11	$(9.1 \pm 0.5)\%$		
	e	6	0.095 ± 0.020	0.6 ± 0.1	2	$(2.2 \pm 0.2)\%$		
$B^+ \to K^+\tau^-e^+$	μ	4	0.025 ± 0.010	0.1 ± 0.1	0	$(2.7 \pm 0.6)\%$	$0.2\ ^{+2.1}_{-1.0}$	< 4.3
	π	33	0.045 ± 0.015	1.5 ± 0.5	1	$(4.8 \pm 0.6)\%$		
	e	8	0.10 ± 0.06	0.8 ± 0.5	0	$(2.8 \pm 1.1)\%$		
$B^+ \to K^+\tau^+e^-$	μ	3	0.045 ± 0.020	0.1 ± 0.1	0	$(3.2 \pm 0.7)\%$	$-1.3\ ^{+1.5}_{-1.8}$	< 1.5
	π	132	0.035 ± 0.010	4.6 ± 1.3	4	$(8.7 \pm 1.2)\%$		
	e	55	0.017 ± 0.010	0.9 ± 0.6	0	$(2.3 \pm 0.2)\%$		
$B^+ \to \pi^+\tau^-\mu^+$	μ	10	0.11 ± 0.04	1.1 ± 0.4	2	$(2.9 \pm 0.4)\%$	$0.4\ ^{+3.1}_{-2.2}$	< 6.2
	π	93	0.035 ± 0.010	3.3 ± 0.9	4	$(2.8 \pm 0.2)\%$		
	e	171	0.012 ± 0.003	2.1 ± 0.5	2	$(3.8 \pm 0.3)\%$		
$B^+ \to \pi^+\tau^+\mu^-$	μ	89	0.04 ± 0.01	3.6 ± 0.9	4	$(4.8 \pm 0.3)\%$	$0.0\ ^{+2.6}_{-2.0}$	< 4.5
	π	512	0.050 ± 0.005	25 ± 3	23	$(9.1 \pm 0.6)\%$		
	e	1	0.050 ± 0.025	0.1 ± 0.1	1	$(2.0 \pm 0.8)\%$		
$B^+ \to \pi^+\tau^-e^+$	μ	16	0.025 ± 0.010	0.4 ± 0.2	1	$(2.8 \pm 0.3)\%$	$2.8\ ^{+2.4}_{-1.9}$	< 7.4
	π	172	0.035 ± 0.008	6.0 ± 1.4	7	$(5.8 \pm 0.3)\%$		
	e	31	0.033 ± 0.013	1.0 ± 0.4	0	$(2.9 \pm 0.3)\%$		
$B^+ \to \pi^+\tau^+e^-$	μ	247	0.012 ± 0.005	3.0 ± 1.2	2	$(4.6 \pm 0.4)\%$	$-3.1\ ^{+2.4}_{-2.1}$	< 2.0
	π	82	0.07 ± 0.03	5.7 ± 2.5	3	$(3.7 \pm 1.0)\%$		

FEI PERFORMANCE

Tagging efficiency: the fraction of ϒ(4S) events which can be tagged
Tag-side efficiency: the fraction of ϒ(4S) events with a correct tag
Tag-side purity: the fraction of the tagged ϒ(4S) events with a correct tag

BELLE2-NOTE-PL-2020-002

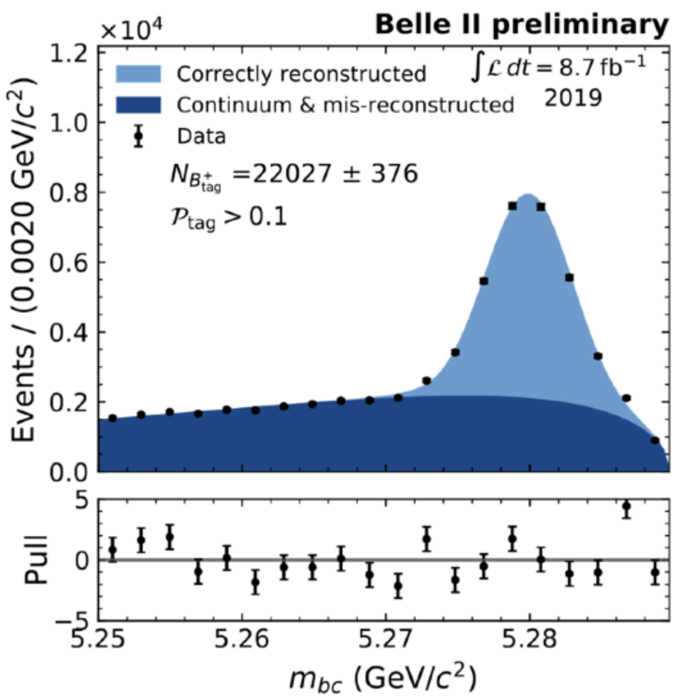


Table 1: Summary of the maximum tag-side efficiency of the Full Event Interpretation and for the previously used exclusive tagging algorithms. For the FEI simulated data from the last official Monte Carlo campaign of the Belle experiment were used. The maximum tag-side efficiency on recorded data is lower (see Section 4.1). The numbers for the older algorithms (see Section 3), are not directly comparable due to different selection criteria, like best-candidate selections and selections to suppress non-ϒ(4S) events.

	$B^\pm$	B^0
Hadronic		
FEI with FR channels	0.53 %	0.33 %
FEI	0.76 %	0.46 %
FR	0.28 %	0.18 %
SER	0.4 %	0.2 %
Semileptonic		
FEI	1.80 %	2.04 %
FR	0.31 %	0.34 %
SER	0.3 %	0.6 %

arXiv:hep-ex/1807.08680v4