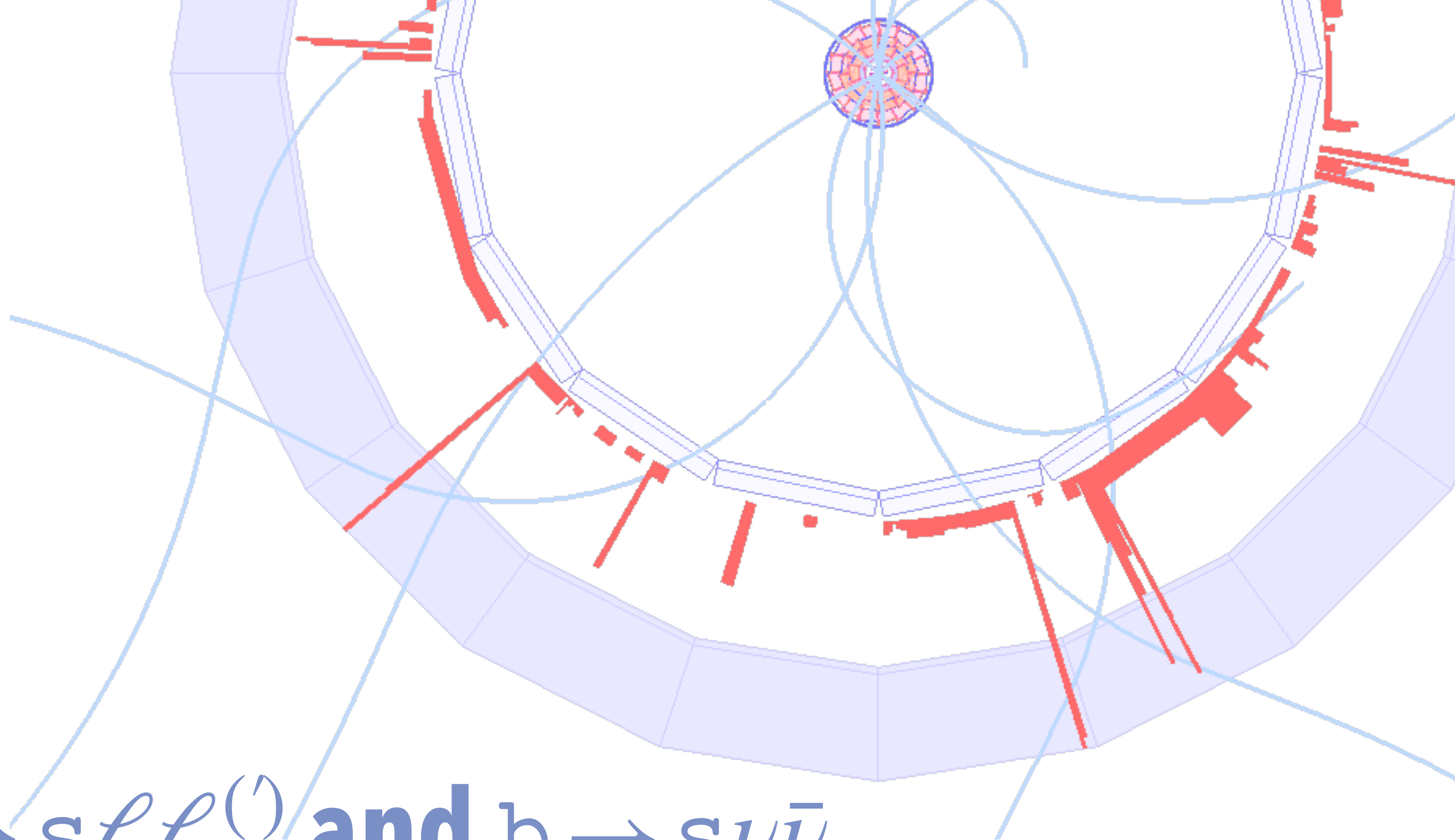
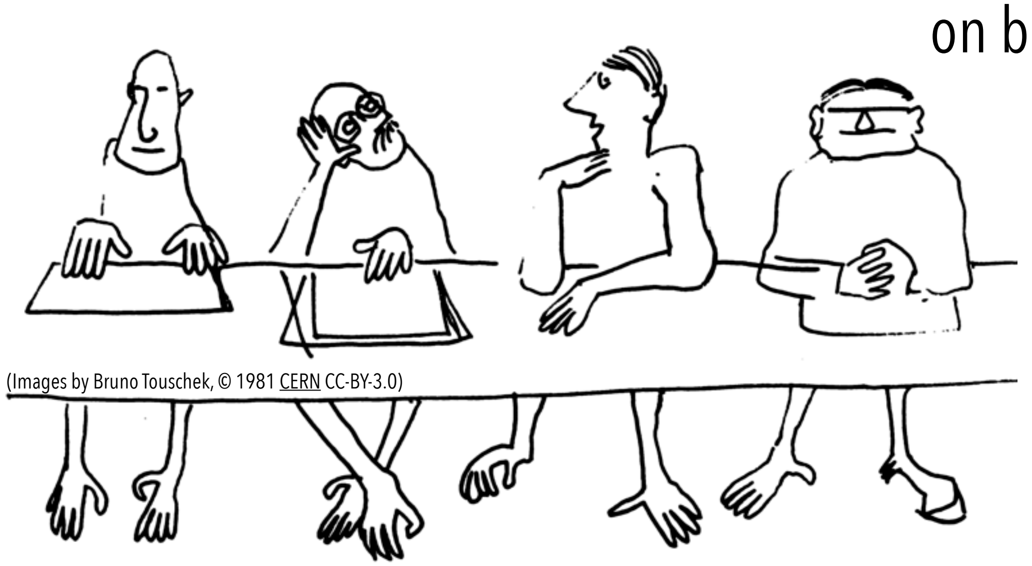


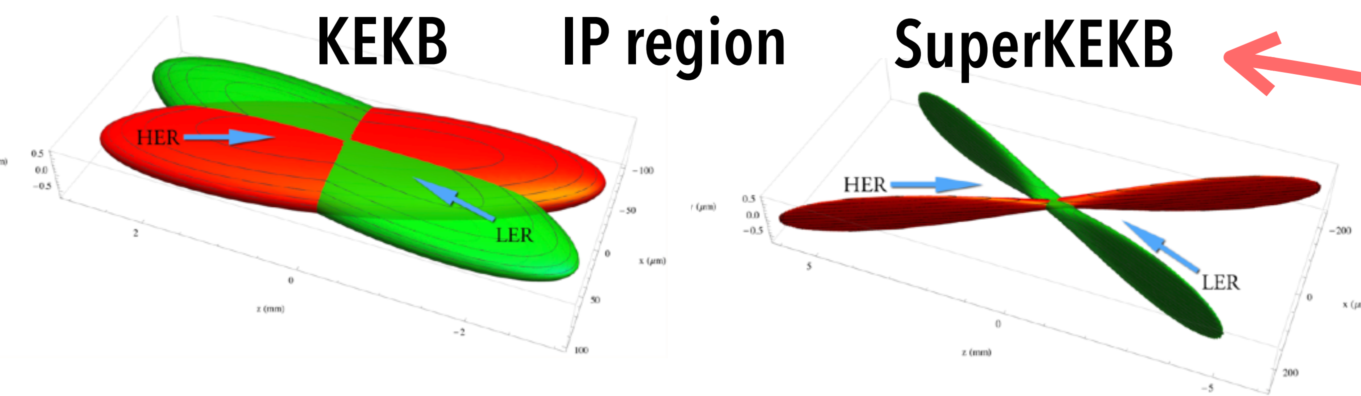
$b \to s\ell\ell^{(\prime)}$ and $b \to s\nu\bar{\nu}$ transitions at Belle II

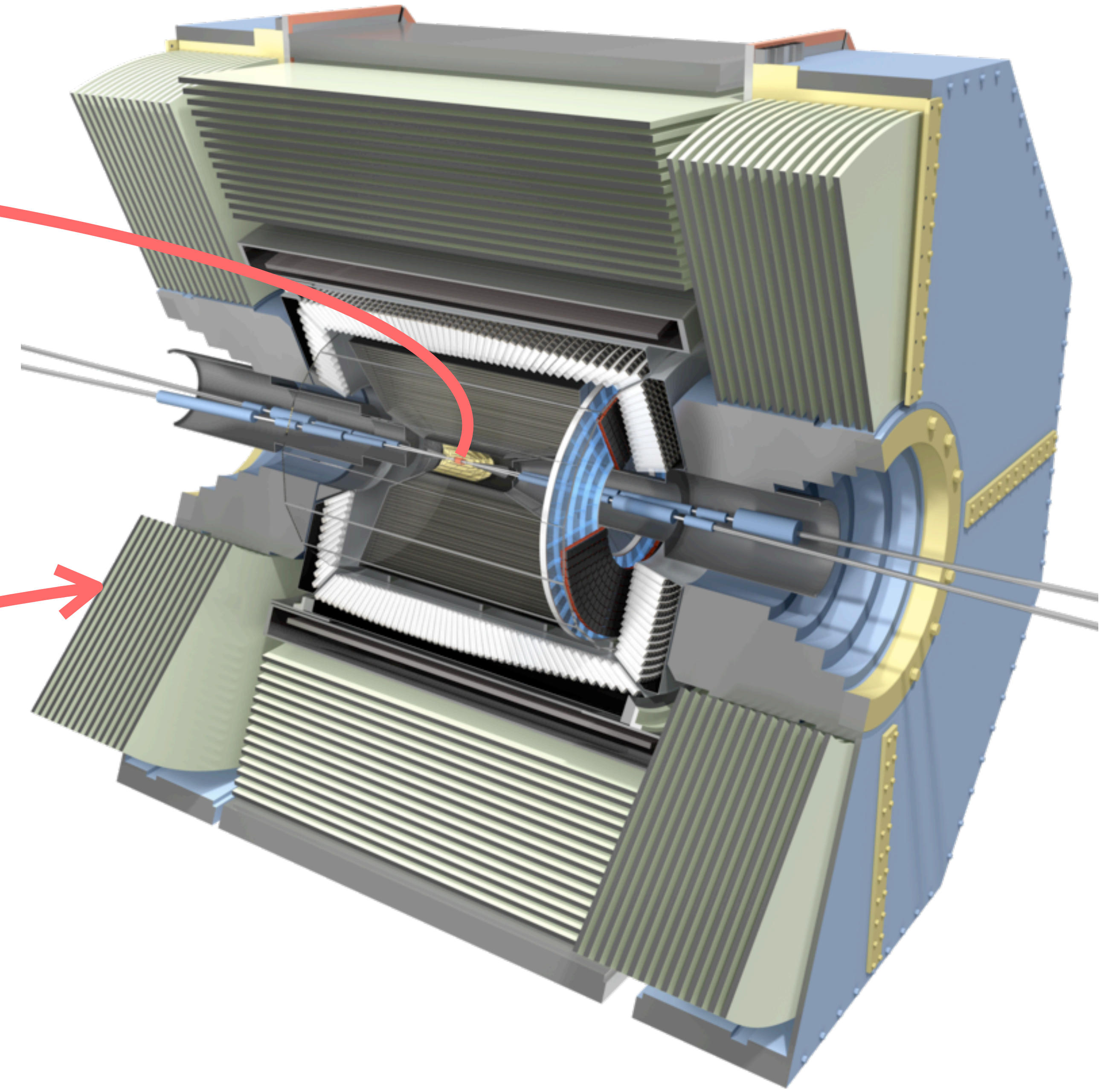
WORKSHOP ON STATUS AND PERSPECTIVES OF PHYSICS AT HIGH INTENSITY, INFN-LNF

Gaetano de Marino
on behalf of the Belle II collaboration

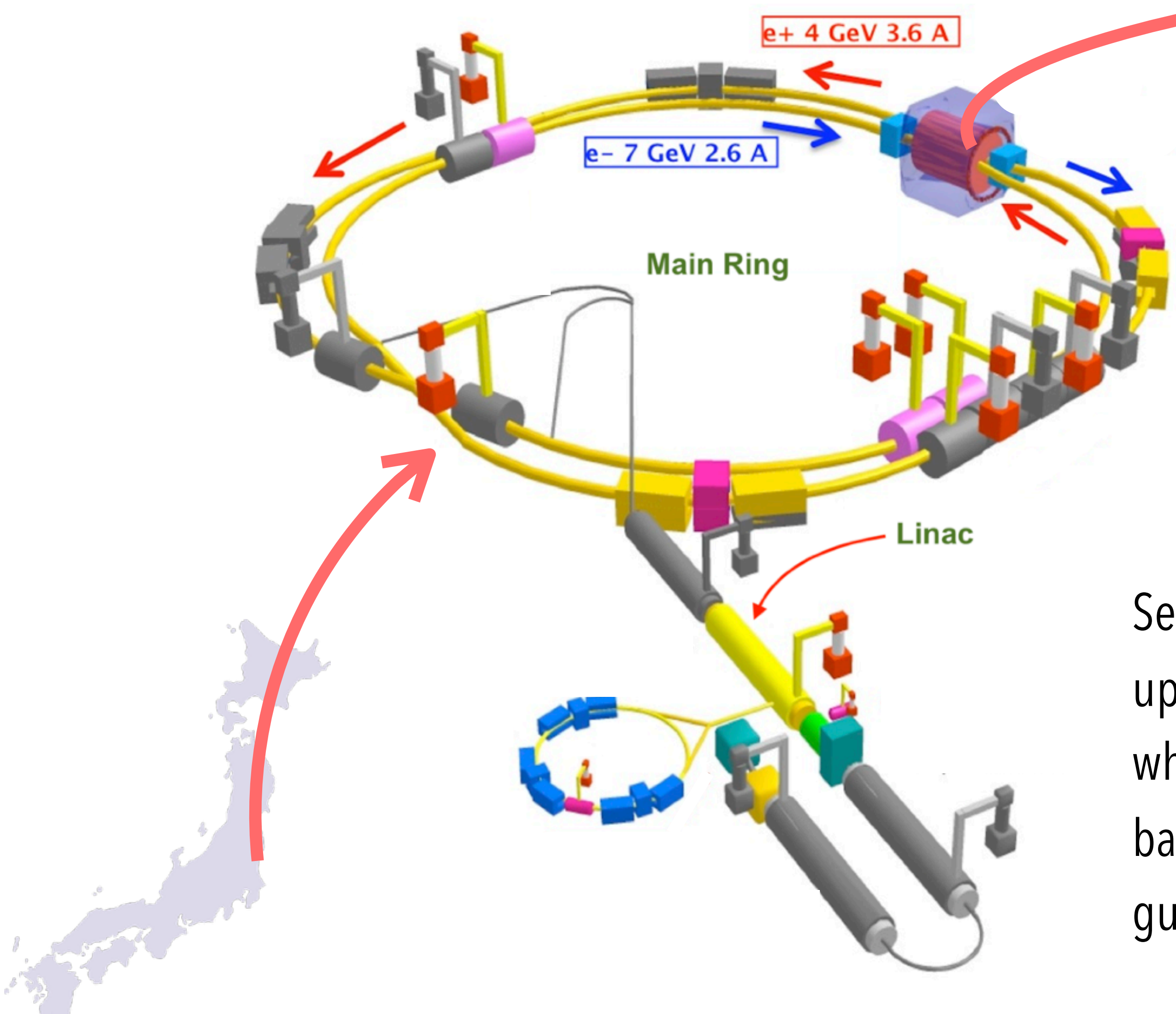


BELLE II EXPERIMENT





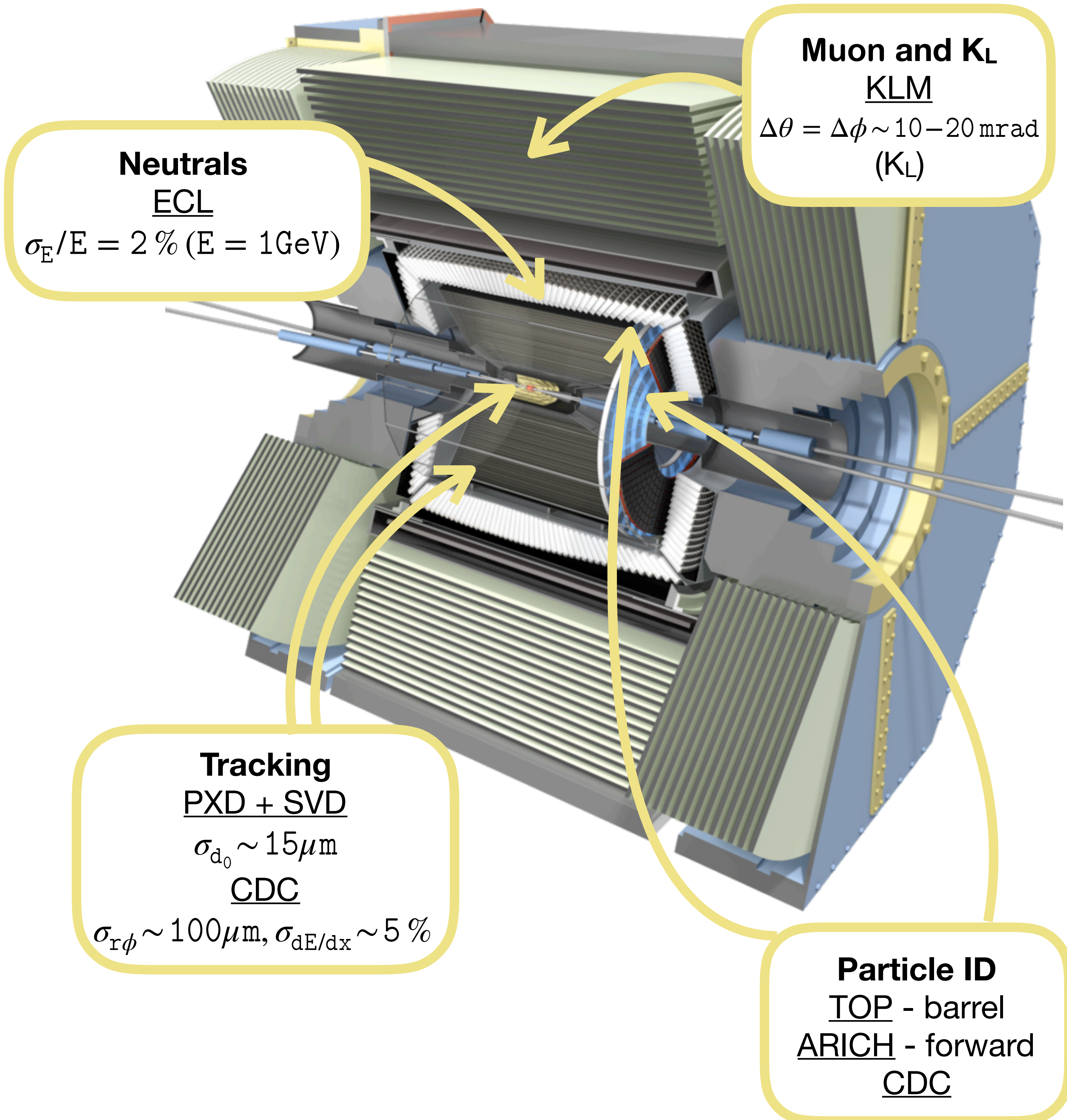
Asymmetric-energy e^+e^- collider:



Second generation B-factory based on the **nanobeam scheme**. The upgrade required a substantial redesign of the Belle II detector, whose performance is challenged by radiation damage and higher background (**design luminosity is x40 higher**). The aim is to guarantee **equal or better performance than Belle** @ KEKB.

BELLE II EXPERIMENT

- Good momentum and vertex resolution
- Well-known initial state and large acceptance
- Excellent calorimetry
- Sophisticated particle ID



BELLE II EXPERIMENT

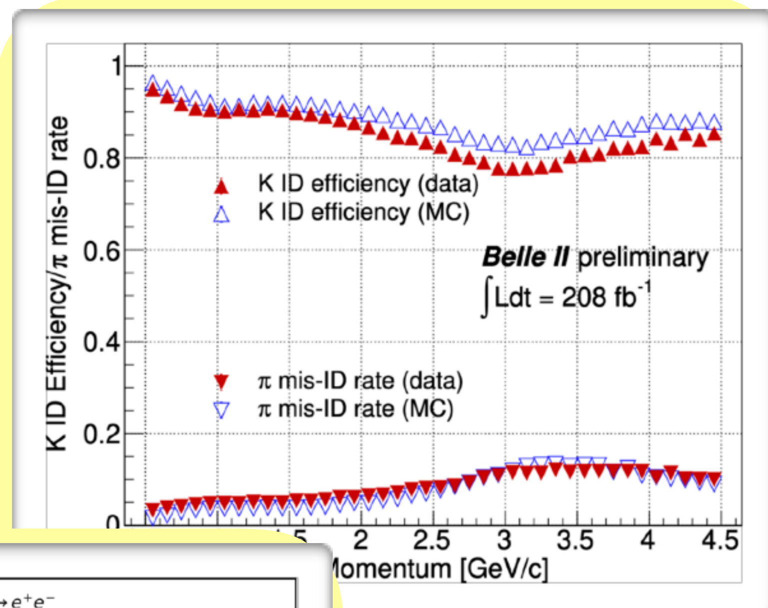
- Good momentum and vertex resolution
- Well-known initial state and large acceptance
- Excellent calorimetry
- Sophisticated particle ID

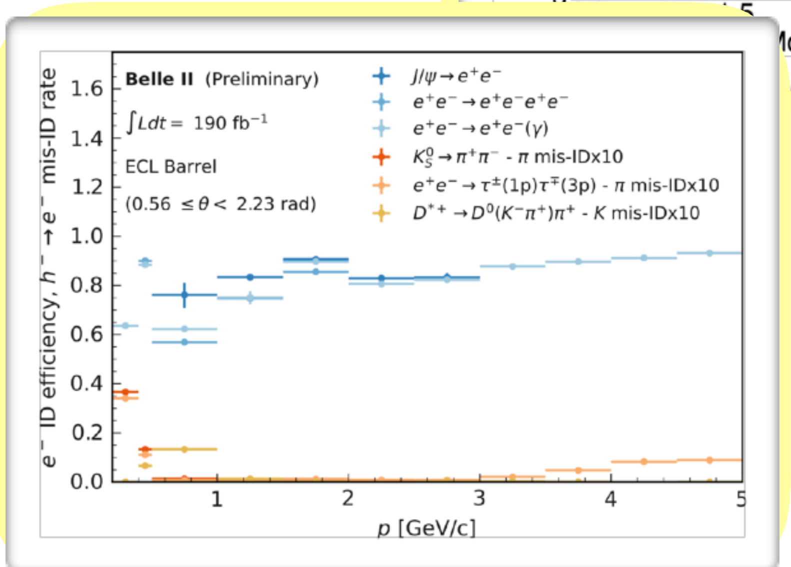
  K/π separation (ε~90% @ 5-10% fake)

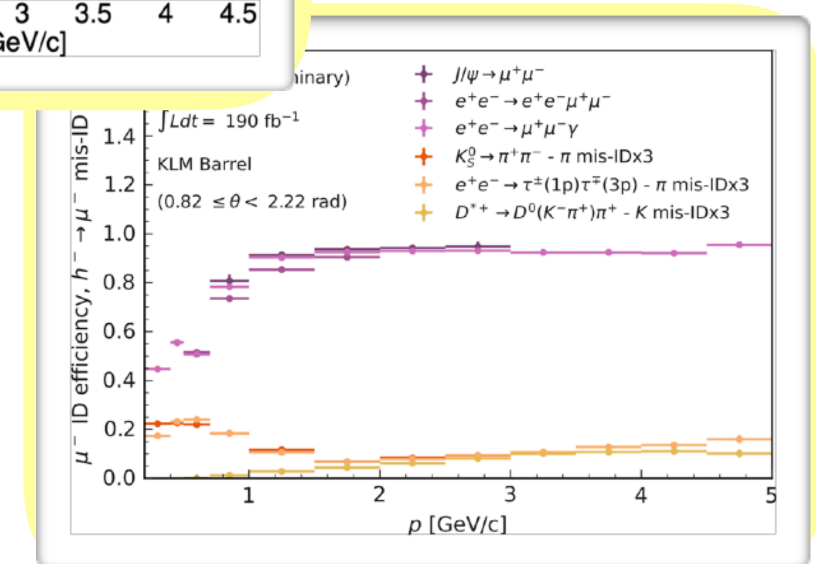
  Lepton identification

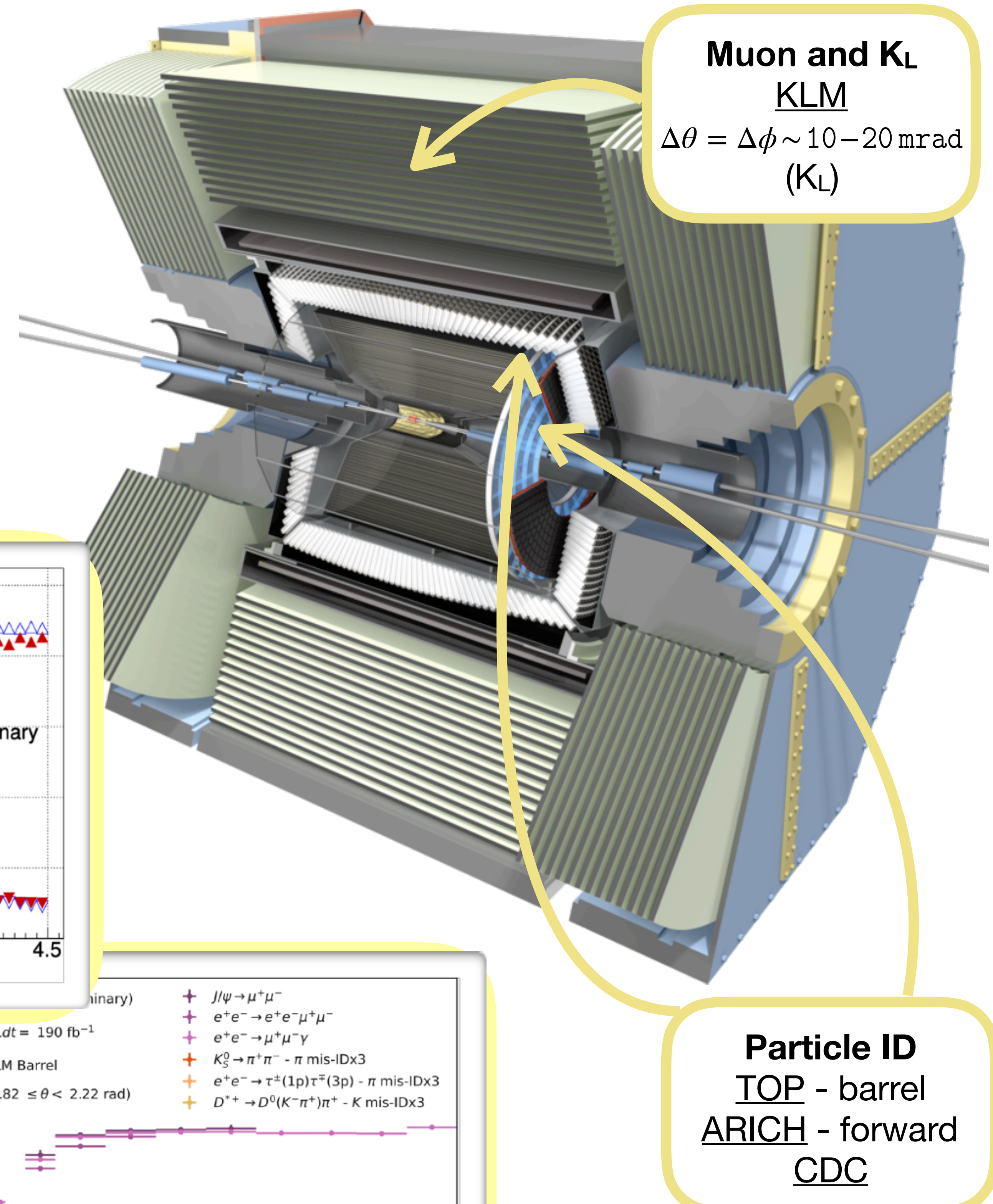
  μ/π (ε~90% @ 7% fake)

  e/π (ε~86% @ <1% fake)

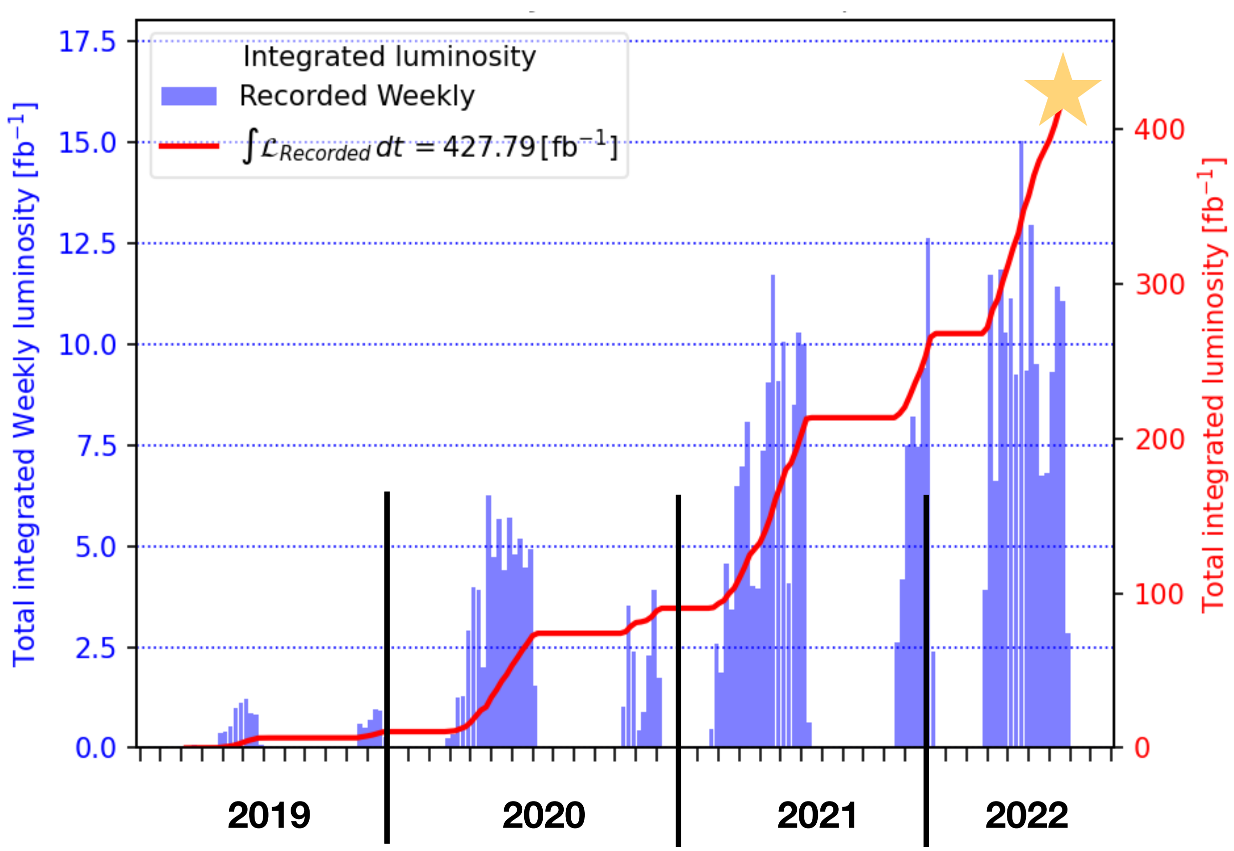








DATA TAKING



World Record Luminosity

$\mathscr{L}_{\text{peak}} = 4.71 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (June 22, 2022)

Currents ~1460 mA (LER) / 1143 mA (HER)

ON-resonance data $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

OFF-resonance data $e^+e^- \to \gamma^* \to q\bar{q}$

(60 MeV below the resonance)

Integrated lumi ON-resonance

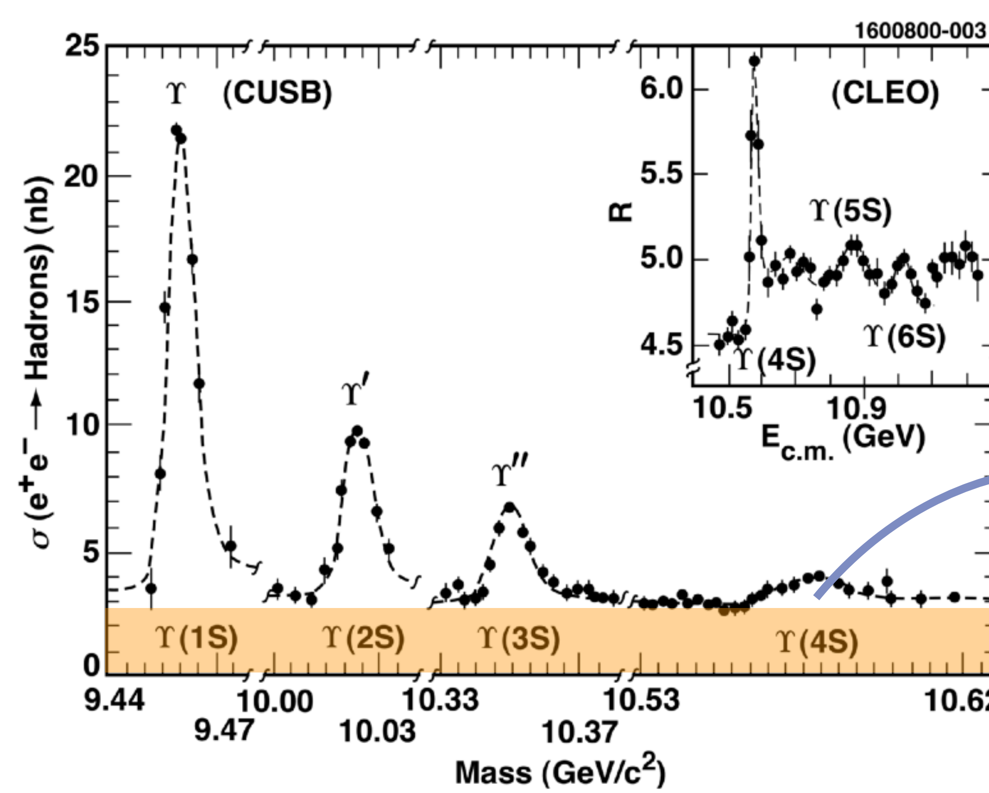
$365\ \mathrm{fb}^{-1} \sim 0.9\ BABAR$

$\sim 400 \times 10^6\ B\bar{B}$

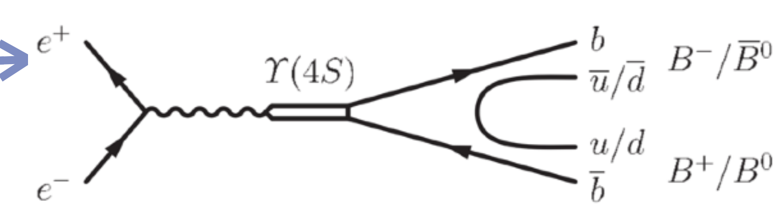
`Continuum'

$q\bar{q},\ q \in \{u, d, s, c\}$

$\tau^+\tau^- \ldots$



ON-resonance

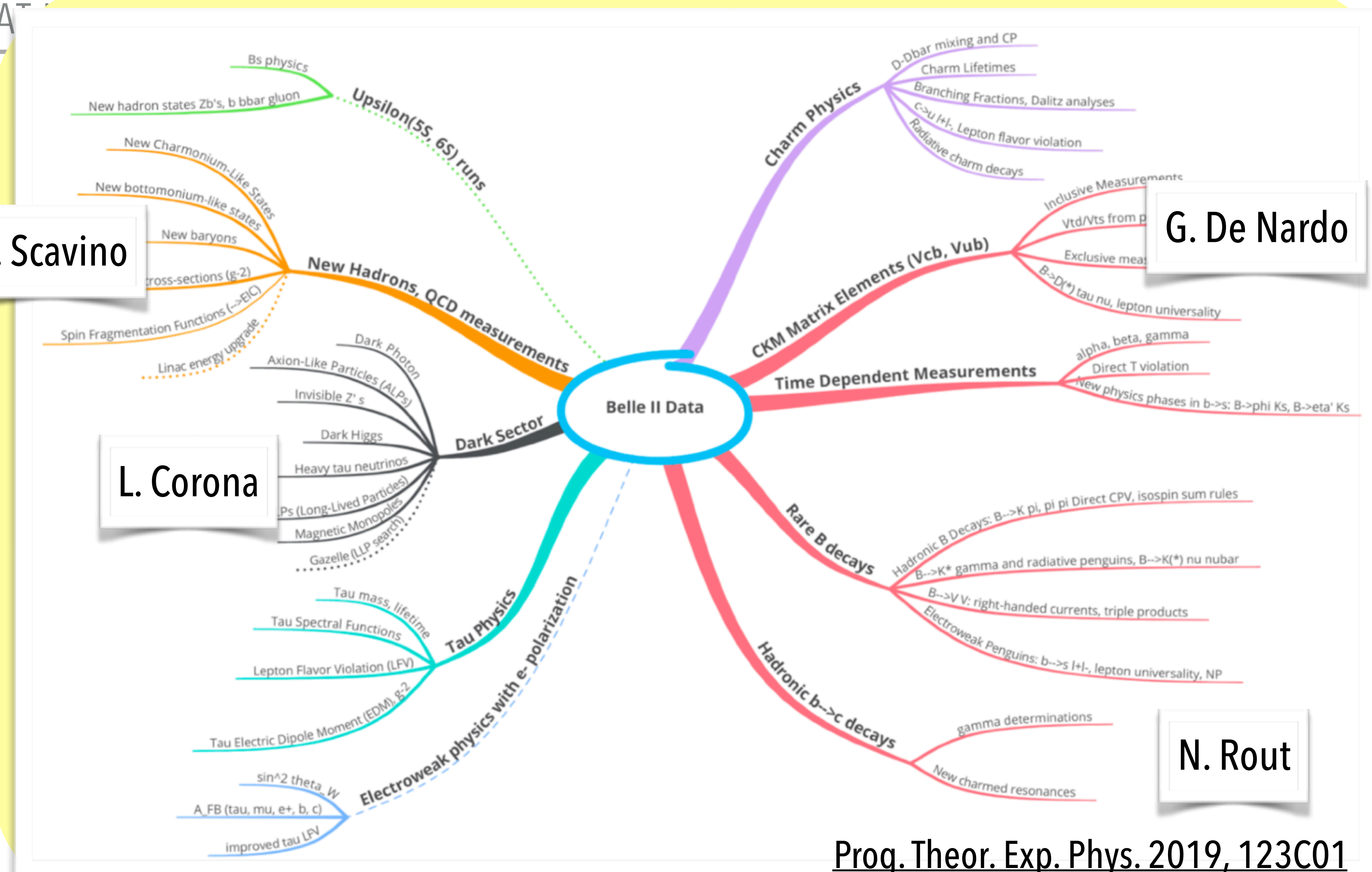


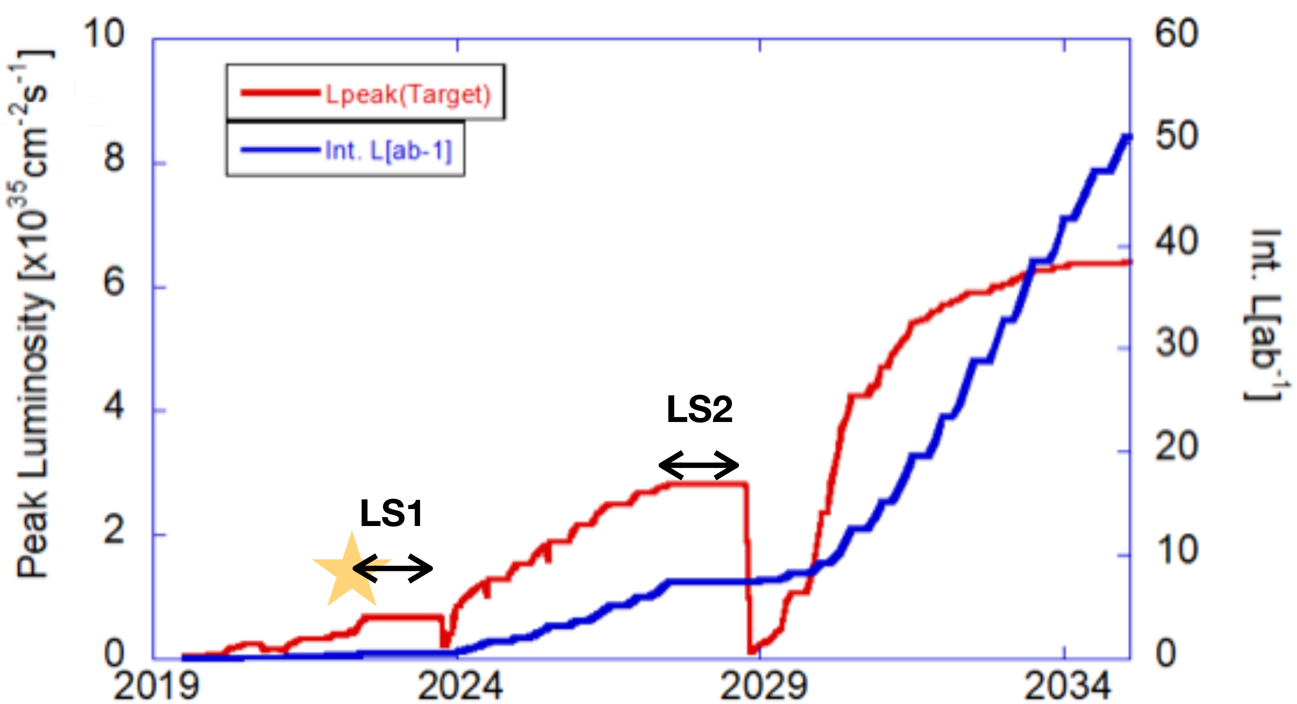
DATA TAKING

Belle II has a broad physics program, covering not only B-mesons but also

- Tau-leptons
- Charmed mesons/baryons
- Dark sector
- Etc.

Many topics will be presented during this workshop

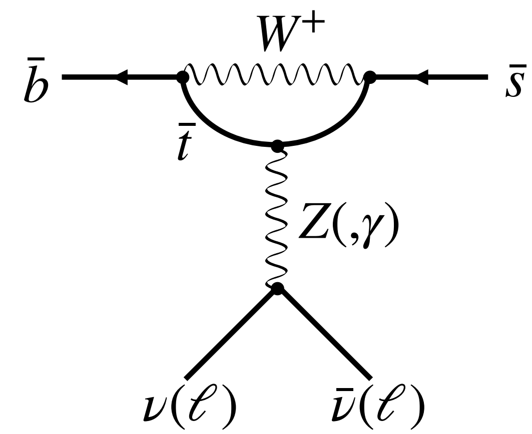


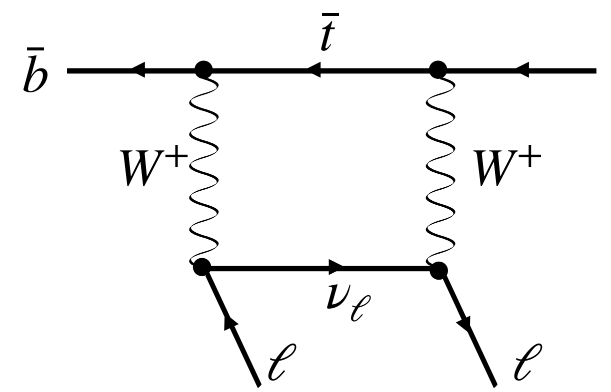


A long journey …

- 1st Long shutdown (LS1) in 2022-2023 (PXD, beam pipe, TOP)
- 2nd Long shutdown (LS2) in ~2028 (QCS, RF)
- The target integrated luminosity is **50 ab^{-1} by ~2034**

MOTIVATION FOR THE b → s SEARCHES





- FCNC transitions: Loop and box diagrams
- The b.r.'s are $\mathcal{O}(10^{-5\div7})$ level

  E.g. $\mathcal{B}_{SM}(B^+ \to K^+\nu\bar{\nu}) = (5.67 \pm 0.38) \times 10^{-6}$[1]

  $\mathcal{B}_{SM}(B \to K\tau\bar{\tau}) = \mathcal{O}(10^{-7})$[2]
- Powerful probes of the SM consistency

b→sγ

Covered by H. Svidras (next talk)

b→sℓℓ LFU tests

$$R_H = \frac{\Gamma(B \to H\mu^+\mu^-)}{\Gamma(B \to He^+e^-)}\Bigg|_{q^2 \in (q^2_{min}, q^2_{max})} \qquad H \in \{K^+, K^{*0/+}, K^0_S\}$$

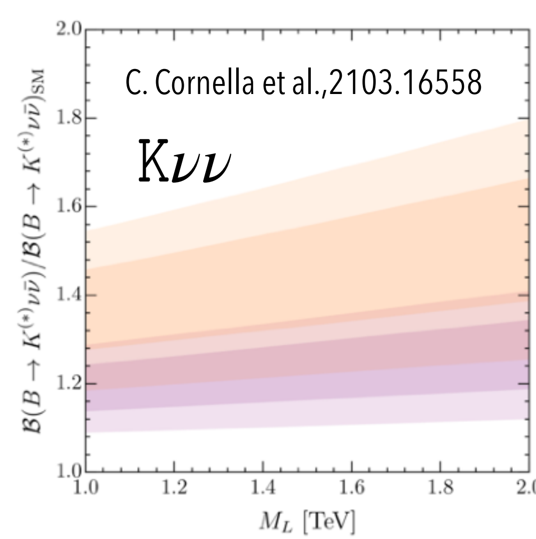
Missing-energy modes

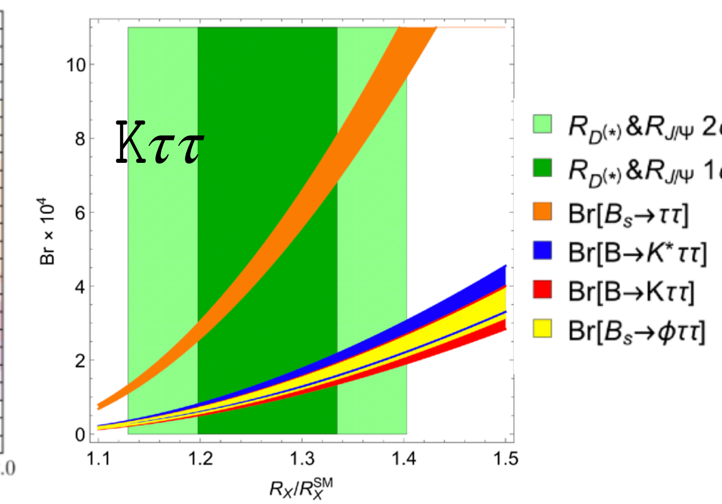
b→sνν

b→sττ

b → sνν is theoretically cleaner (no diagrams with γ)

New-physics particles may enter the loop diagrams or even mediate FCNCs at tree level, enhancing the BRs and/or modifying the angular distributions etc.





Capdevila et. al, PRL 120, 181802

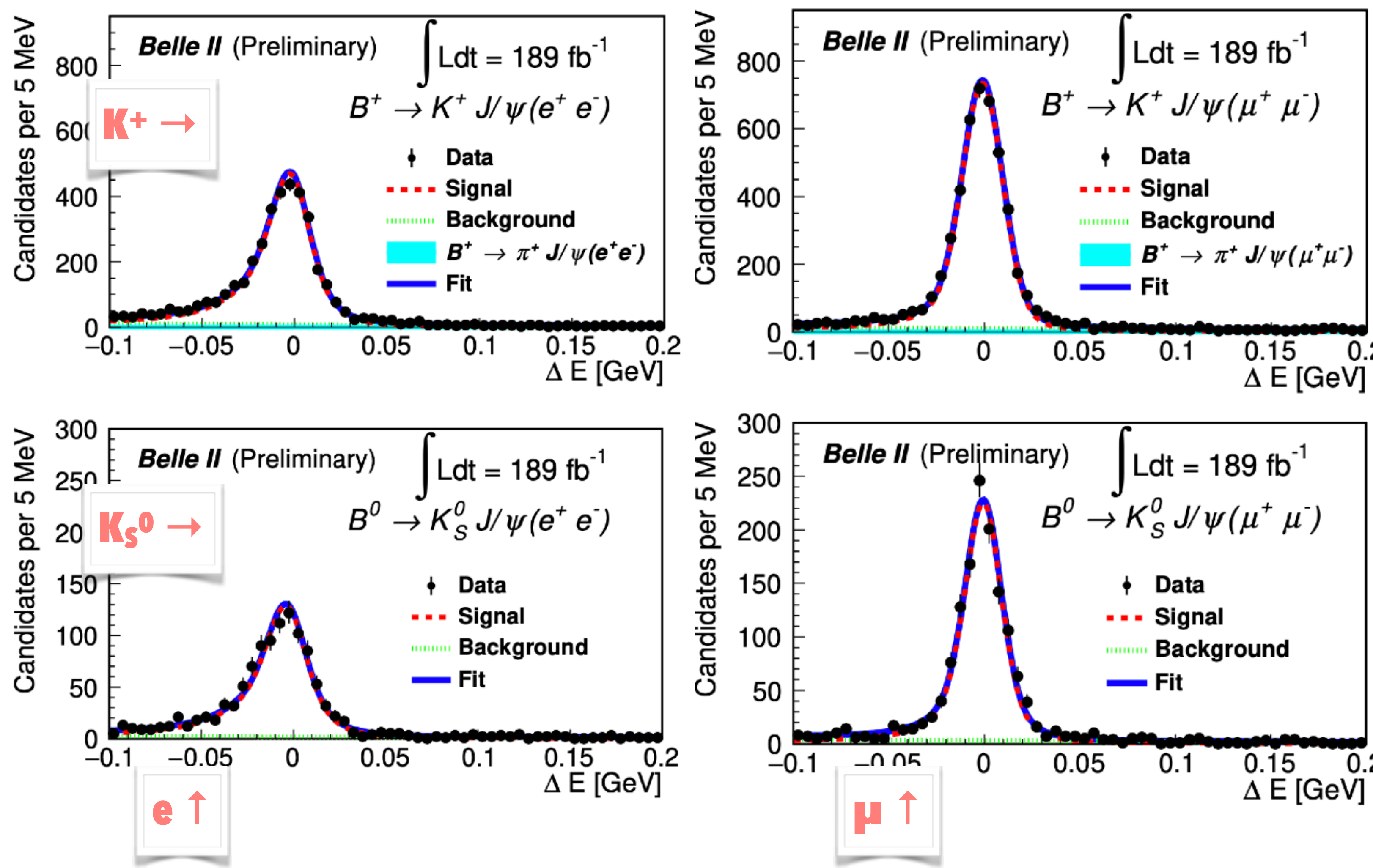
[1] 2207.13371, [2] 1712.01919, [3] 2103.11769, [4] 1512.04442, [5] HFLAV

$b \to s\ell^+\ell^-$ TOWARDS $R_{K^{(*)}}$

- Measurement of the tree-level $B \to KJ/\psi$ in preparation for the penguin $B \to K\ell\ell$
- Result with 189 fb^{-1} data
- Signal extracted from a 2-D fit to (M_{bc}, ΔE)

$$R_K(J/\psi) = \frac{\Gamma\left(B \to KJ/\psi(\mu^+\mu^-)\right)}{\Gamma\left(B \to KJ/\psi(e^+e^-)\right)}$$

ΔE fit projections



$R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$

$R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$

Belle (2021) JHEP 03 (2021) 105

$R_{K^+}(J/\psi) = 0.994 \pm 0.011 \pm 0.010$

$R_{K^0}(J/\psi) = 0.993 \pm 0.015 \pm 0.010$

Improved syst uncertainty related to lepton-ID

Reminder

$M_{bc} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$

$\Delta E = E^*_B - E^*_{beam}$

$E^*_{beam} = \sqrt{s}/2$

Analysis for $B \to K\ell\ell$ BF measurement on pre-LS1 dataset ongoing!

$b \to s\ell^+\ell^-$ TOWARDS $R_{K^{(*)}}$

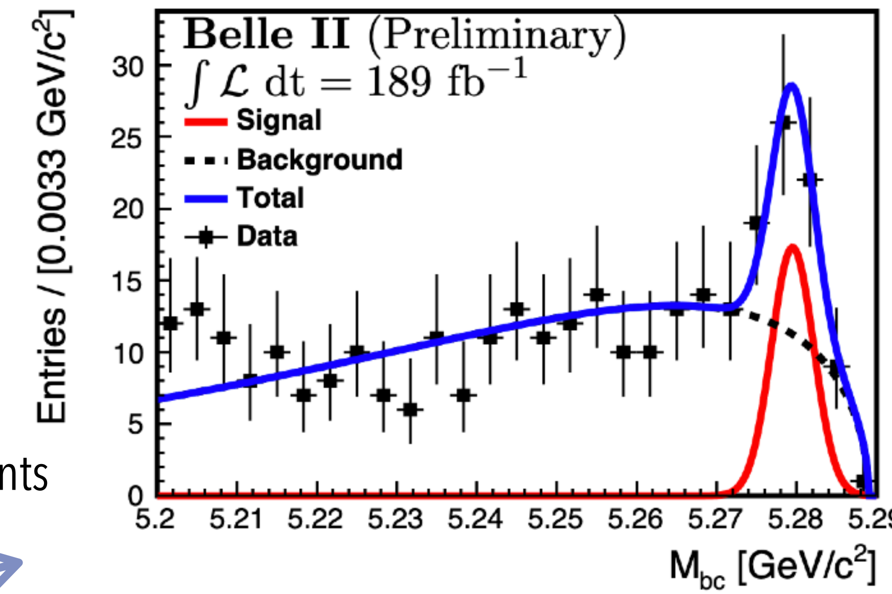
- Measurement of the BF of $B \to K^*\ell\ell, \ell = \{e, \mu\}$ in preparation for the LFU tests
- The dataset corresponds to 189 fb^{-1} and the studied channels are:

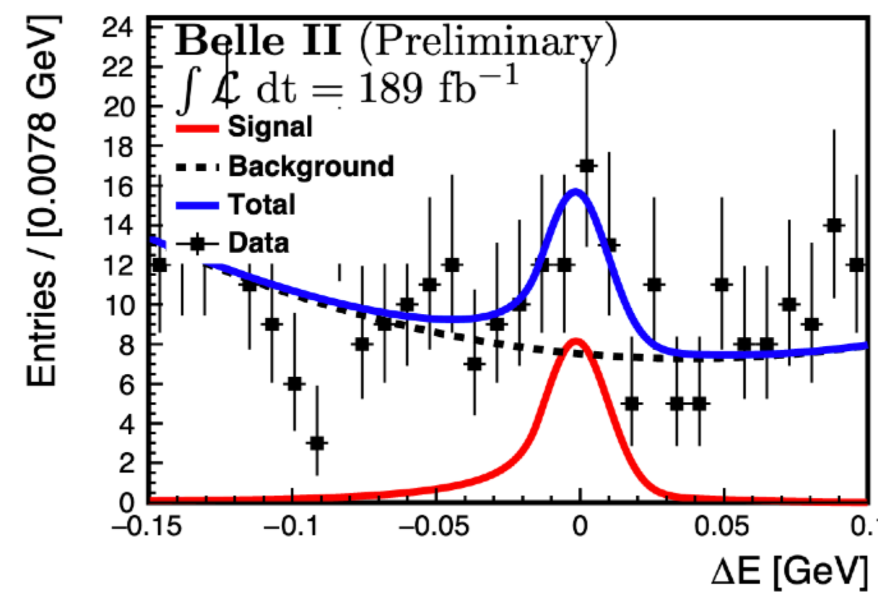
$$B^0 \to K^{*0}(892)(K^+\pi^-)\ell^+\ell^-$$
$$B^+ \to K^{*+}(892)(K^0_S\pi^+, K^+\pi^0)\ell^+\ell^-$$

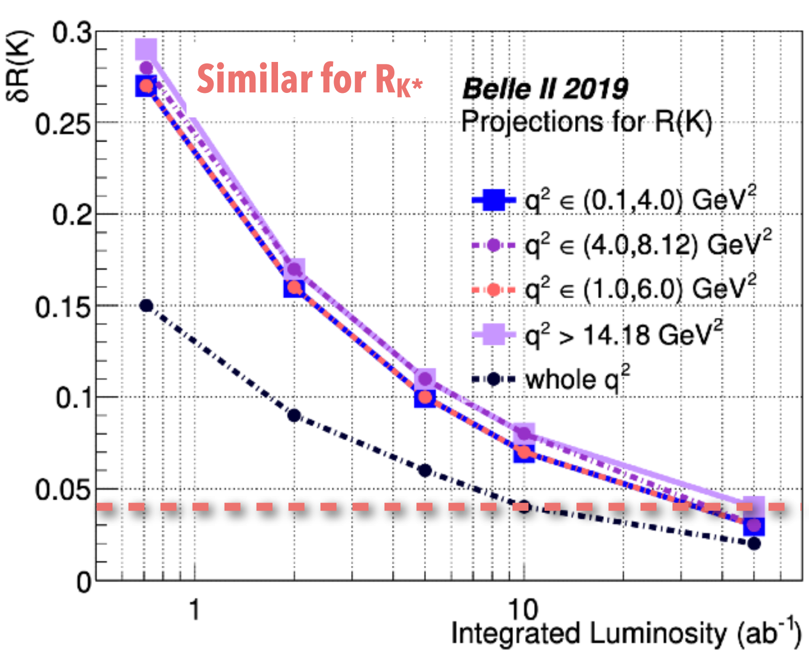
- Background sources are suppressed with charm vetoes and BDT for $q\bar{q}$ and $B\bar{B}$ events
- **Similar efficiency/precision for e and μ channels**

Mode	Yield	Sign.
$B \to K^*\mu\mu$	22 ± 6	4.8σ
$B \to K^*ee$	18 ± 6	3.6σ
$B \to K^*\ell\ell$	38 ± 9	5.9σ

Fit projections







Current LHCb precision (9fb^{-1})

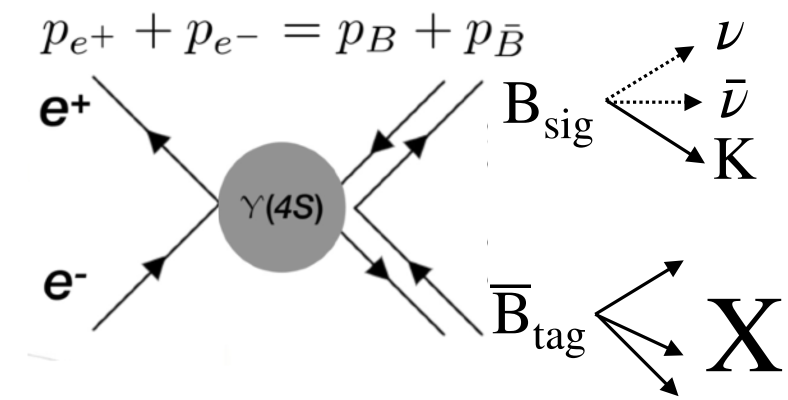
Independent measurement of $R_{K^{(*)}}$ at Belle II with 5-10 ab^{-1} will probe the existence of the anomaly

Belle II can provide $R(X_s)$ measurement with similar precision Prog. Theor. Exp. Phys. 2019, 123C01

Rules of 👍

- ab^{-1}@ Belle II ~1 fb^{-1} @ LHCb
- Belle II: 1 fb^{-1} ⇔ 10^6 $B\bar{B}$

B-TAGGING ALGORITHMS *For modes with missing energy*

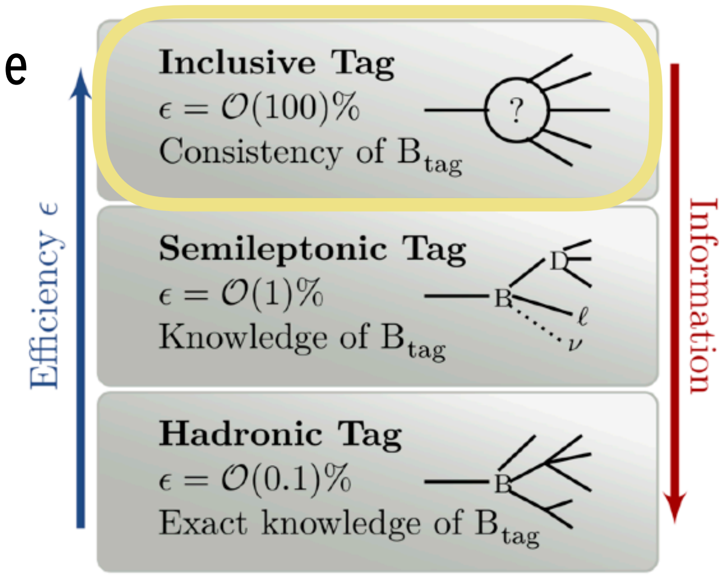


@ B-factories we exploit the knowledge of the initial 4-momentum

Beam energy transferred to $B\bar{B}$ pair: $e^+e^- \to \Upsilon(4S) \to B_{sig}\bar{B}_{tag}$

The reconstruction of the tag-side allows to infer the properties of the signal-side with missing energy – (semi-)leptonic/penguin decays – and to have a handle on backgrounds

Different B-tagging strategies are possible



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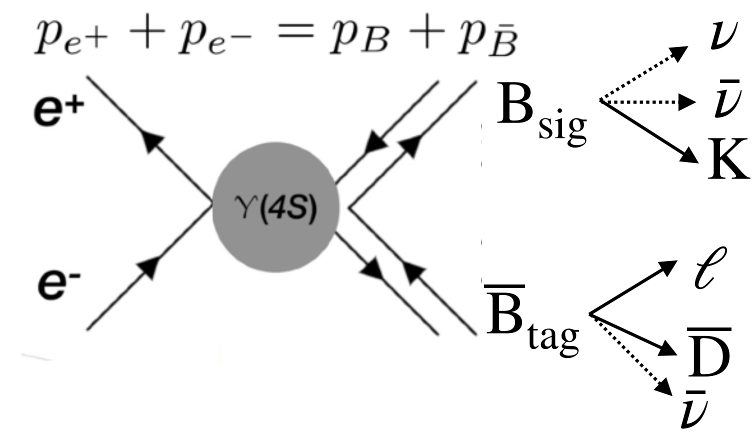

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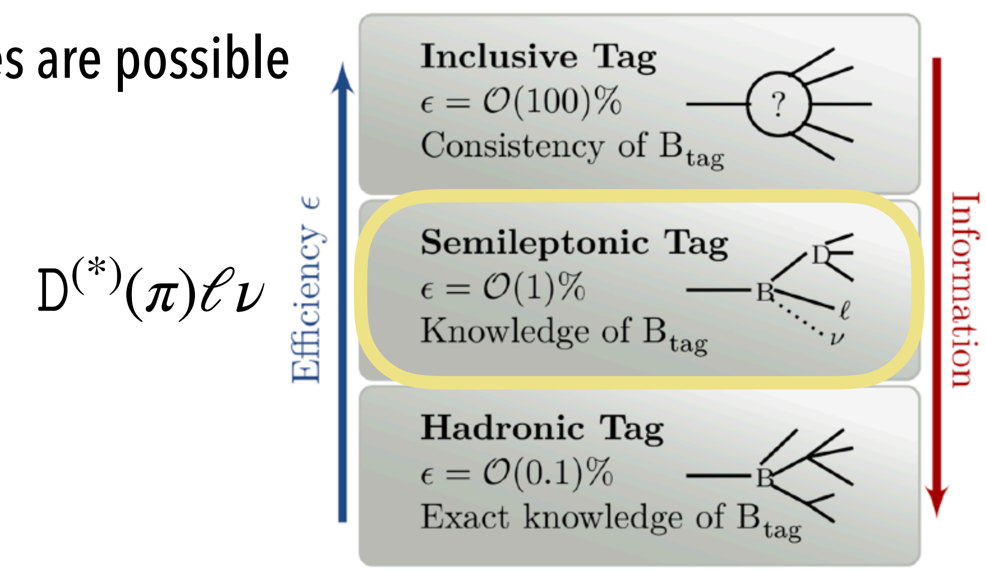
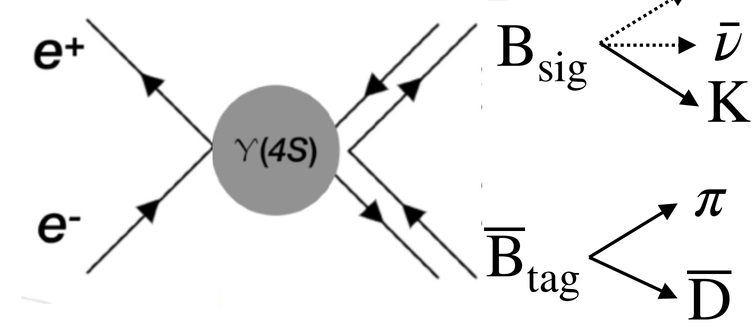


B-TAGGING ALGORITHMS *For modes with missing energy*

$$p_{e^+} + p_{e^-} = p_B + p_{\bar{B}}$$



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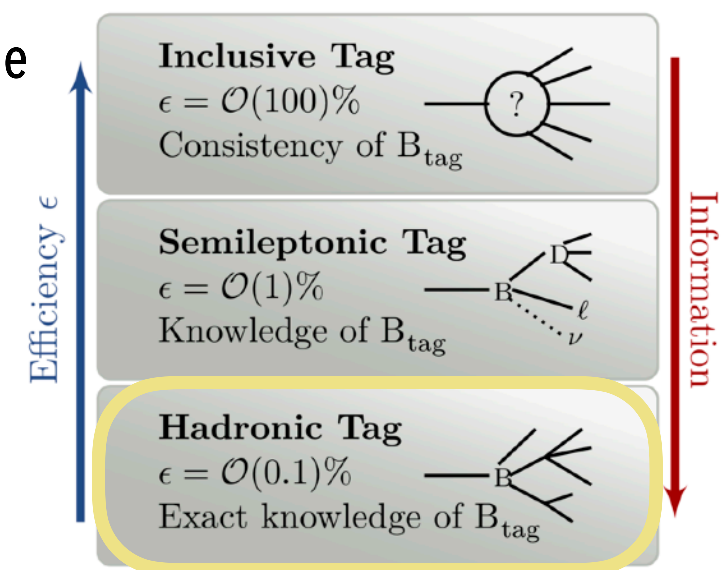
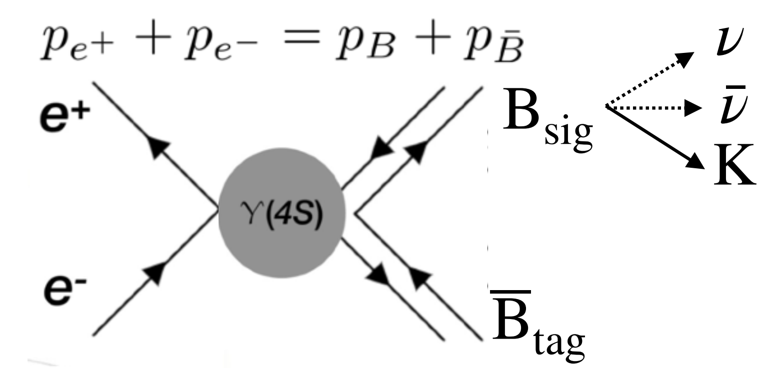


$D^{(*)}n\pi$, $J/\psi(n\pi)K^{(*)}$

$D^{(*)}D_s^{(*)}$, DDK . . .

B-TAGGING ALGORITHMS *For modes with missing energy*



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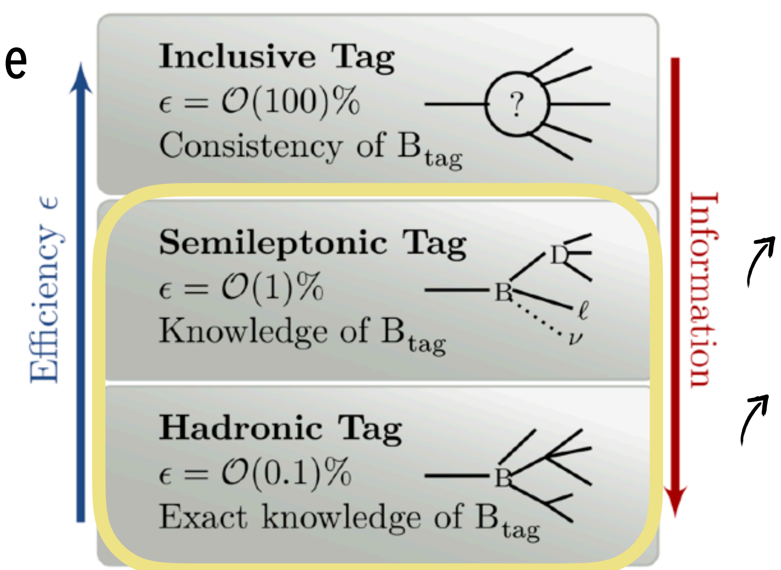
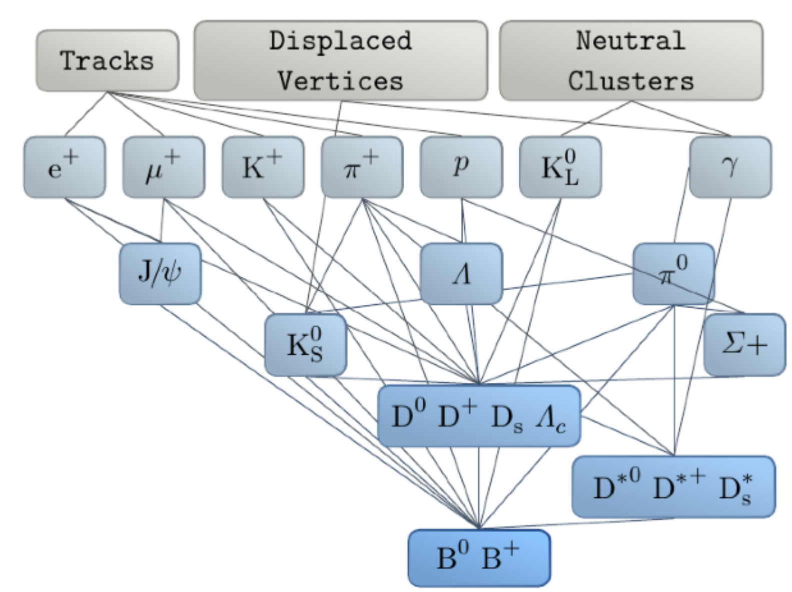


$\mathcal{O}(1.8\%)/\mathcal{O}(2.0\%)$ at ~5% purity or B^+/B^0

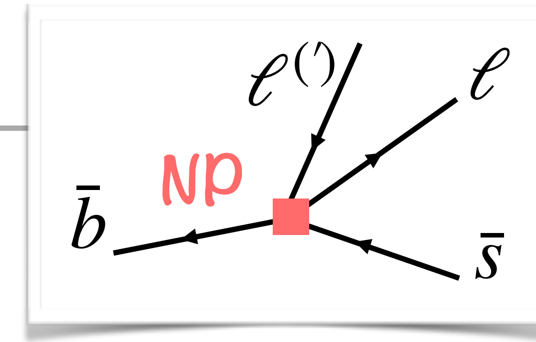
$\mathcal{O}(0.8\%)/\mathcal{O}(0.5\%)$ at ~10% purity or B^+/B^0

~2x higher efficiency wrt previous algorithms

- The **F**ull **E**vent **I**nterpretation (FEI) is the algorithm for hadronic/semileptonic tag-side reconstruction at Belle II Comput Softw Big Sci 3, 6 (2019)
- Hierarchical approach. employs over 200 BDTs trained on simulated $\Upsilon(4S) \to B\bar{B}$ events to reconstruct $\mathcal{O}(10k)$ *B*-decay chains
- The FEI efficiency is calibrated with high-stat samples like $X\ell\nu$, where the signal B is reconstructed in $X\ell\nu$ final states: $\varepsilon_{calib} = N^{X\ell\nu}_{DATA}/N^{X\ell\nu}_{MC}$



LFV: $b \to s\ell\ell'$

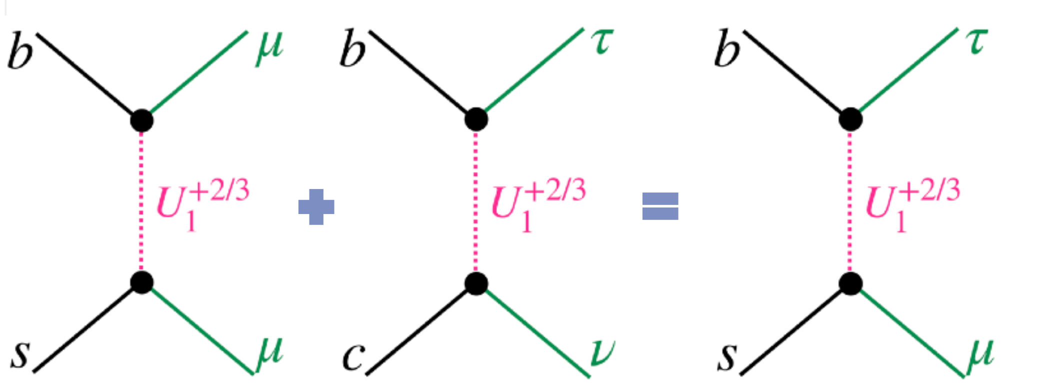


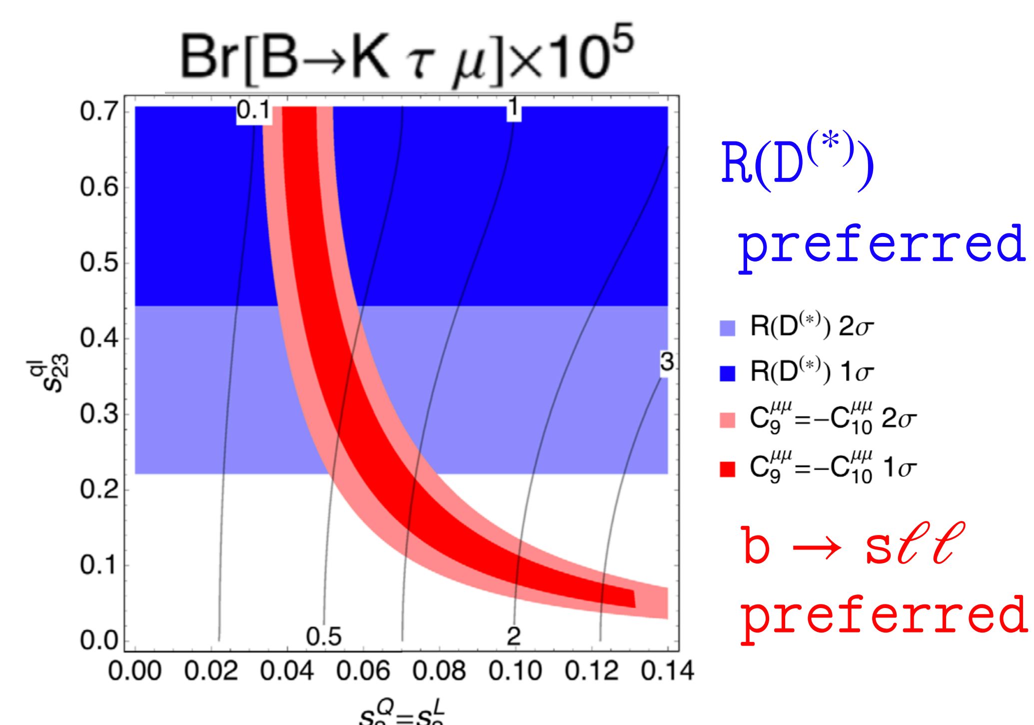
- Neutrino mass and neutrino oscillations → the accidental lepton family symmetry in the SM is broken → family lepton number can be violated
- Charged LFV can occur through oscillations in loops but it is very suppressed
- Hints for LFU violation in $b \to sll$ and $b \to cl\nu$[1-3]
- If **LFU** is violated, some BSM extensions predict that rates for **LFV** decays are close to current experimental sensitivity
- **Some BSM extensions:** Leptoquarks, Z'… [JHEP12(2016)027/ PRD92, 054013/ JHEP08(2021)050]

Experimental limits

$b \to s e \mu$	$B^{+/0} \to K^+/K^{*0}/K^0_S e\mu$:	$\mathcal{O}(10^{-8\div-9})$	Belle, LHCb
$b \to s \tau \ell$	$B^{+(0)} \to K^{+(*0)}\tau\ell(\mu)$:	$\mathcal{O}(10^{-5\div-6})$	BaBar, LHCb

The $U_1 \sim (\mathbf{3}, 1)_{2/3}$ LQ can simultaneously explain the charged and neutral anomalies





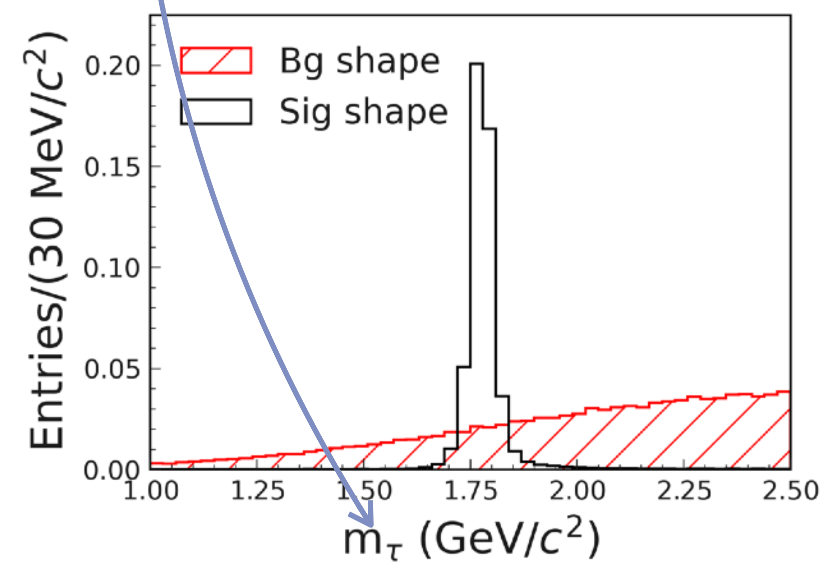
Calibbi et al., PRD.98.115002

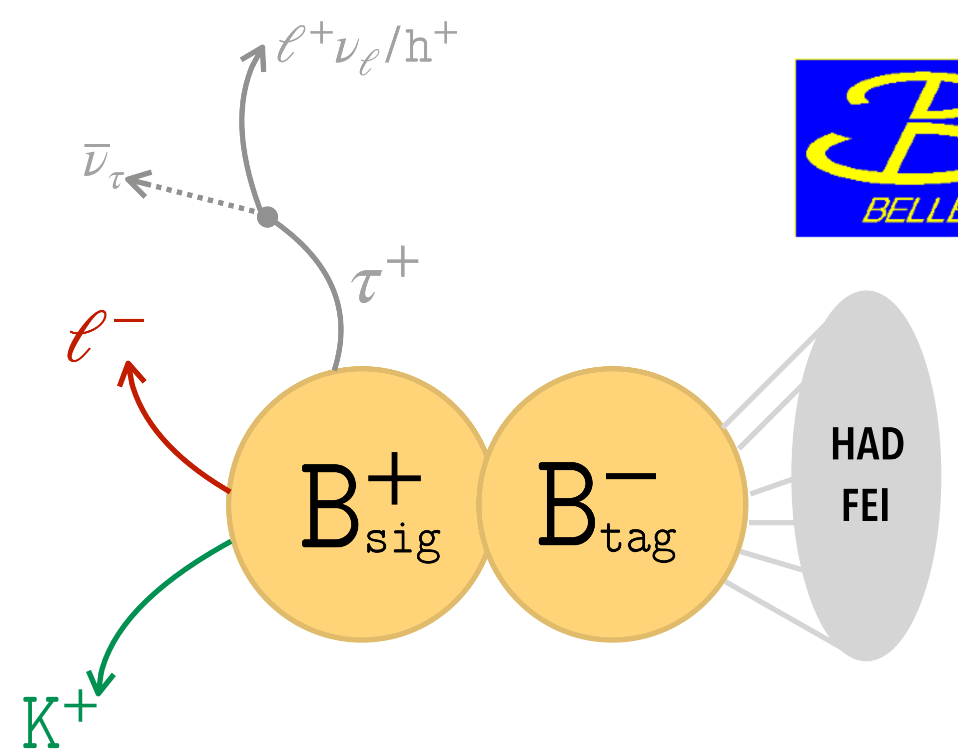
[1] 2103.11769, [2] 1512.04442, [3] HFLAV

$b \to s\tau\ell$ SEARCHES $\ell = \{e, \mu\}$

$$M^2_{\mathrm{recoil}} = m^2_\tau = (p_{e^+e^-} - p_K - p_\ell - p_{B_{\mathrm{tag}}})^2$$

- Unlike tree-level, 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 m_τ
  - Belle dataset (711 fb^{-1}) + hadronic B-tagging (FEI)
  - One prong τ decays are considered: $\tau^+ \to \ell^+\nu\bar{\nu}, \pi^+(n\pi^0)\bar{\nu}$
  - Background depends on charge configuration
    $K^+\tau^+\ell^-$: $B^+ \to \bar{D}^0(\to K^+\ell^-)X^+$
    $K^+\tau^-\ell^+$: $B^+ \to \bar{D}^0(\to K^+X^-)\ell^+$
  - MVA is adopted for background suppression
  - Fit to m_τ distributions





$b \to s\tau\ell$ SEARCHES $\ell = \{e, \mu\}$

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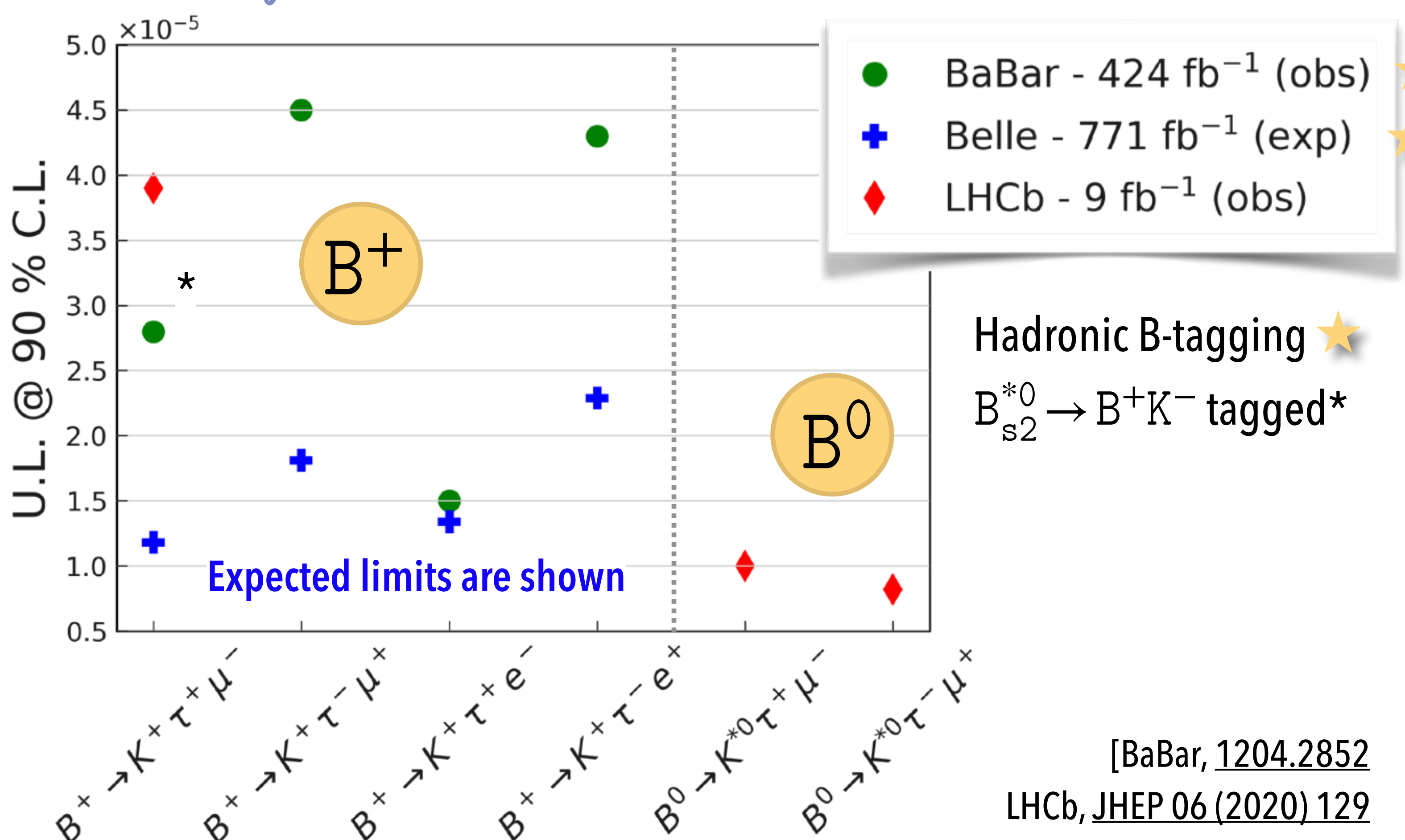
    $K^+\tau^-\ell^+$: $B^+ \to \bar{D}^0(\to K^+X^-)\ell^+$
  - MVA is adopted for background suppression
  - Fit to m_τ distributions
- Belle benefits from higher statistics than BaBar
  Belle II will provide updates with improved methods (e.g. different tagging strategy) and additional modes like $B^0 \to K^0_S/K^{*0}\tau\ell$

Limits for B→Kτℓ modes



Hadronic B-tagging ★

$B^{*0}_{s2} \to B^+K^-$ tagged*

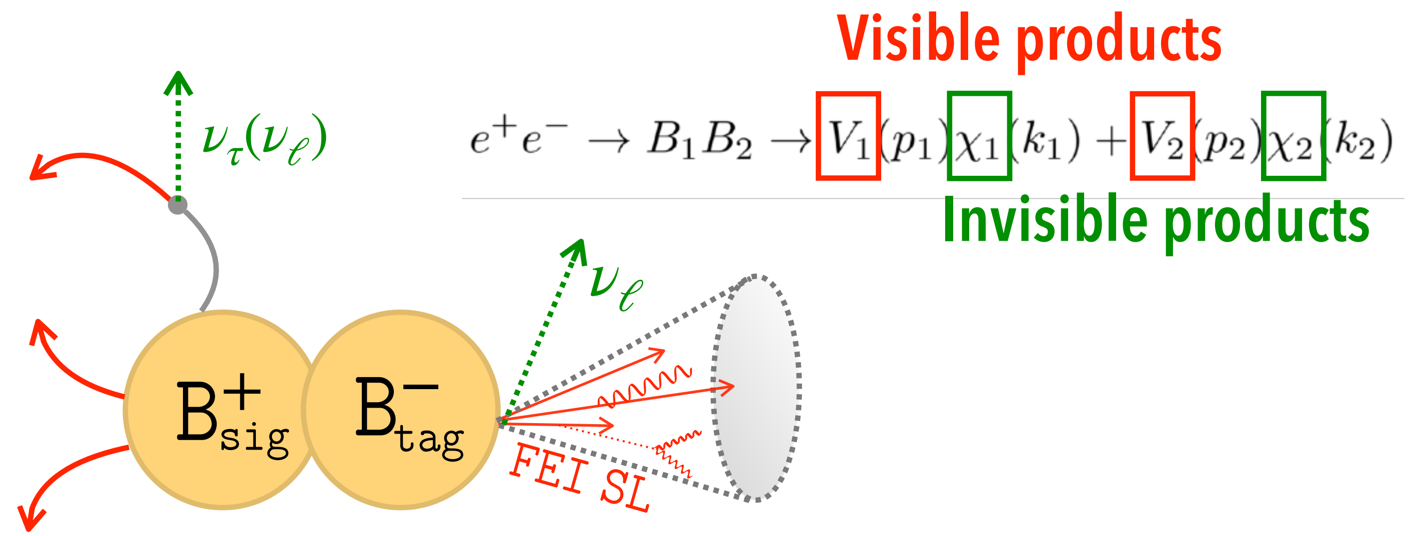
[BaBar, 1204.2852
LHCb, JHEP 06 (2020) 129
arXiv:2209.09846]

$B^+ \to K^+\tau\ell$ WITH SEMILEPTONIC B-TAGGING

At Belle the semileptonic tagging is also tried

The main differences wrt the hadronic approach are:

1. Higher efficiency efficiency BUT
2. Different background nature
3. Worse resolution on M_{recoil}



$$M_{recoil} = [m_B^2 + m_{K\ell}^2 - 2(E_B^* E_{K\ell}^* + |\vec{p}_B^*||\vec{p}_{K\ell}^*|\cos\theta)]^{\frac{1}{2}}$$

E^*_{beam}

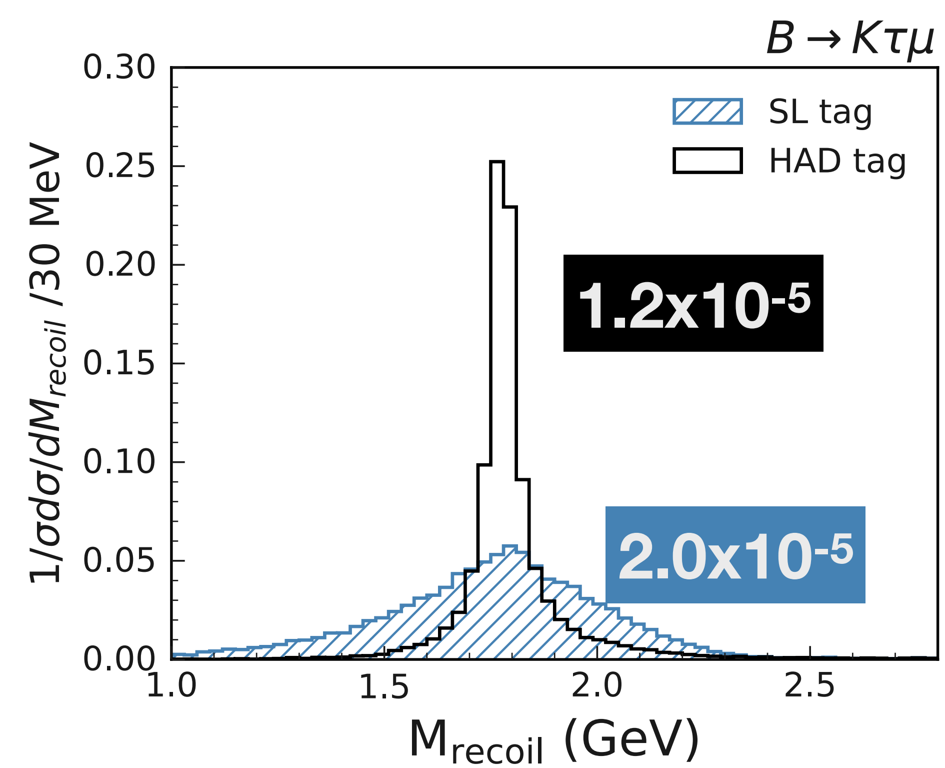
$p^*_{B_{tag}}$

$\sqrt{(E^*_{beam})^2 - m_B^2}$

The direction of the B_{tag} is lost!

θ: $\angle(\vec{p}^*_{B_{tag}}, \vec{p}^*_{K\mu})$

Random $\cos\theta$



Despite the degraded resolution, the background level is under control, which combined to the higher signal efficiency, provide a **sensitivity in the same ballpark of the hadronic-tag** analysis

$B^+ \to K^+ \tau \ell$ WITH SEMILEPTONIC B-TAGGING

At Belle the semileptonic tagging is also tried
The main differences wrt the hadronic approach are:

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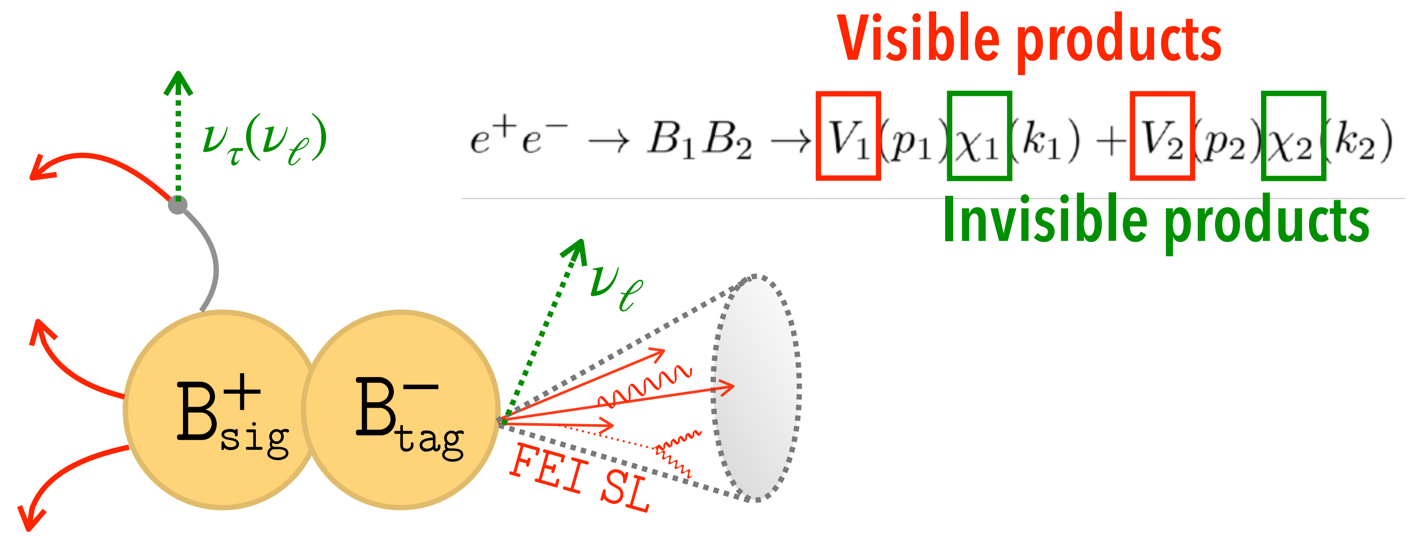
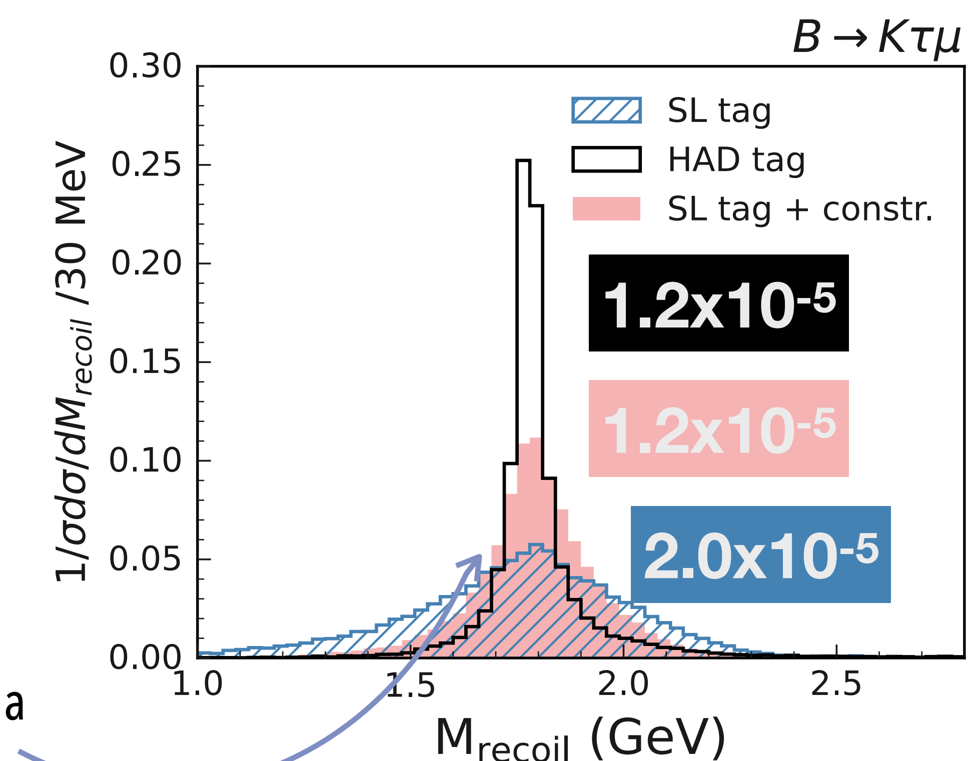
2. Different background nature
3. Worse resolution on M_{recoil}



Can we do better?

MC study presented in arXiv:2209.03387 (de Marino, Guadagnoli, Park, Trabelsi)
Obtain M_{recoil} as a solution of a constrained minimisation, the constraints being:

- Kinematic information → Initial state knowledge + 2-body τ (hadronic) decays
- Vertexing information → Not very constraining at B-factories



This information only brings improvement in resolution (~2x)
The semileptonic tagged-sample is orthogonal to the hadronic one; reaching a similar sensitivity is crucial to confirm an observation at any level of significance

$b \to s\tau^+\tau^-$ SEARCHES

Belle II projections from the Snowmass White Paper

$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (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	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

Results at *B*-factories

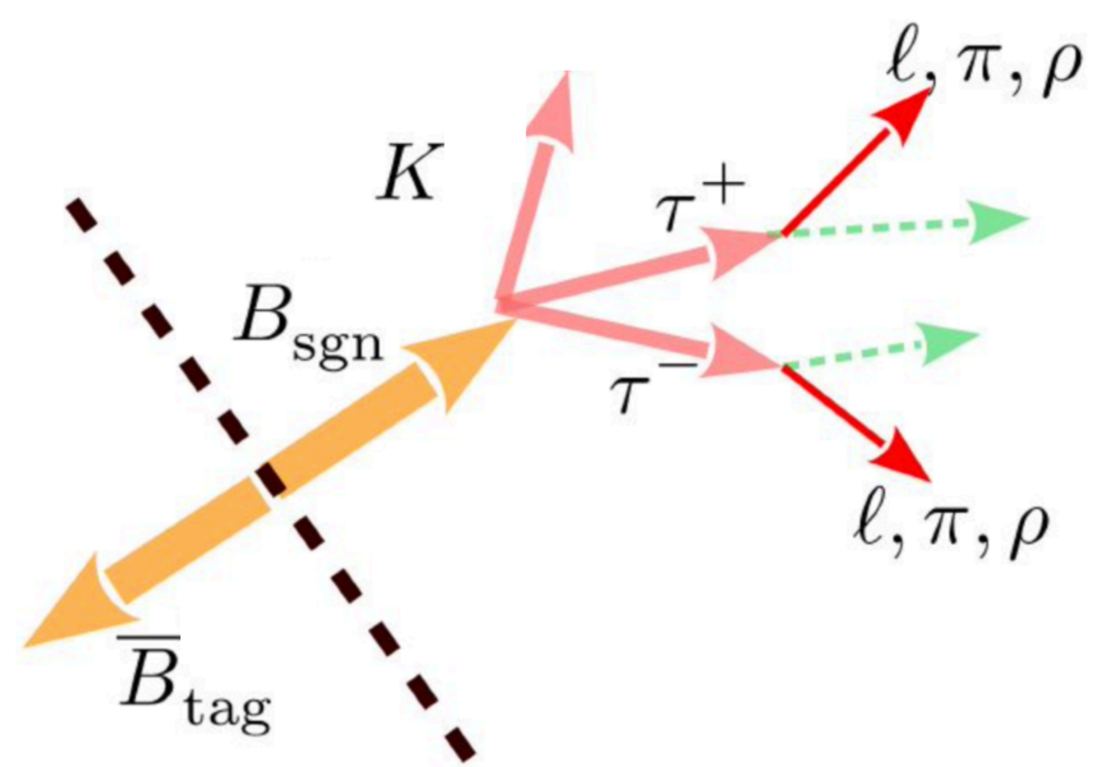
BR($B^+ \to K^+\tau\tau$) < 2.0 × 10^{-3} (90%CL) BaBar

BR($B^0 \to K^{*0}\tau\tau$) < 2.25 × 10^{-3} (90%CL) Belle - sub. to PRD

Obtained with full Belle stat (711 fb^{-1})
Hadronic B-tagging Belle algorithm (Neurobayes FR)
$\tau \to \ell\nu\bar{\nu}, \pi\nu$ modes considered
Cut&count analysis

"baseline": no further improvements other than higher stats

"Improved": 50% increase in signal efficiency for the same background level



Handles for improvement with respect to Belle

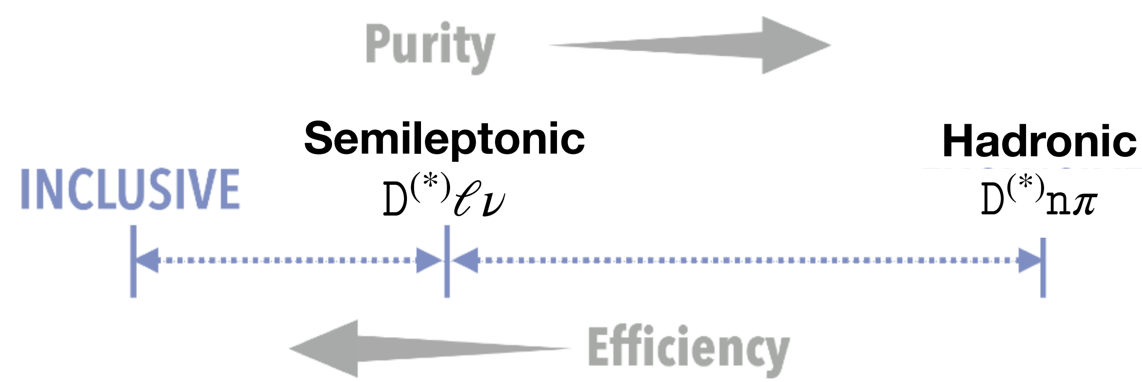
- ~2x hadronic B-tagging efficiency: FR → FEI
- Multivariate analysis
- Additional τ modes

$B^+ \to K^+ \nu\bar{\nu}$ - RECONSTRUCTION AND SELECTION

- Two neutrinos in the final state leaving no signature in the detector; the BF **can be measured at *B*-factories** because of the clean event environment and the well-defined initial state

- Previous analyses at Belle/BaBar utilised the full reconstruction of the B_{tag} followed by the signal reconstruction. Low efficiencies (**~0.04% for hadronic tag and ~0.2% for semileptonic tag**) are obtained

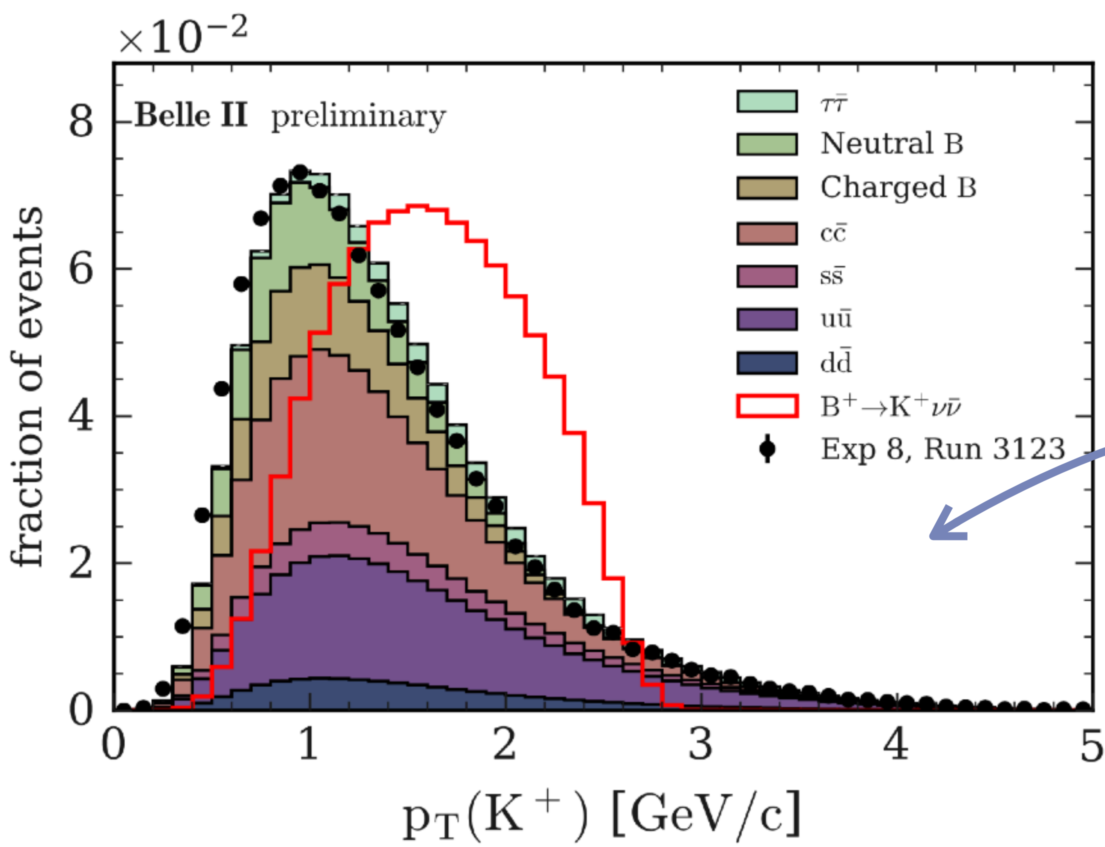
Exp	**U.L. (90% CL)**	**Tag Method**	**Stat (fb^{-1})**
BaBar	1.6 x 10^{-5}	SL+HAD	429
Belle	5.5 x 10^{-5}	HAD	711
Belle	1.9 x 10^{-5}	SL	711

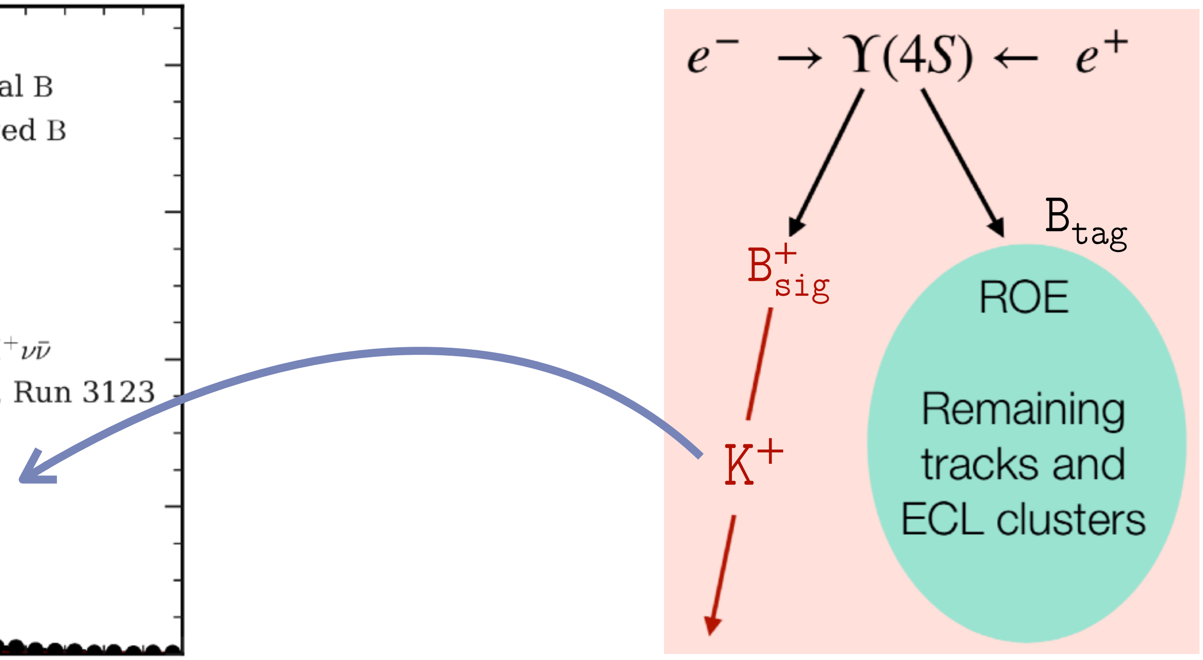


$B^+ \to K^+\nu\bar{\nu}$ - RECONSTRUCTION AND SELECTION

- Two neutrinos in the final state leaving no signature in the detector; the BF **can be measured at *B*-factories** because of the clean event environment and the well-defined initial state.

- **Idea at Belle II:** The signal is reconstructed as the highest p_T track with at least 1 PXD hit (correct match ~80 %) followed by **inclusive reconstruction** of the *Rest Of the Event* (ROE) → **higher signal efficiency (~4%) but larger backgrounds from generic B decays and continuum production!**

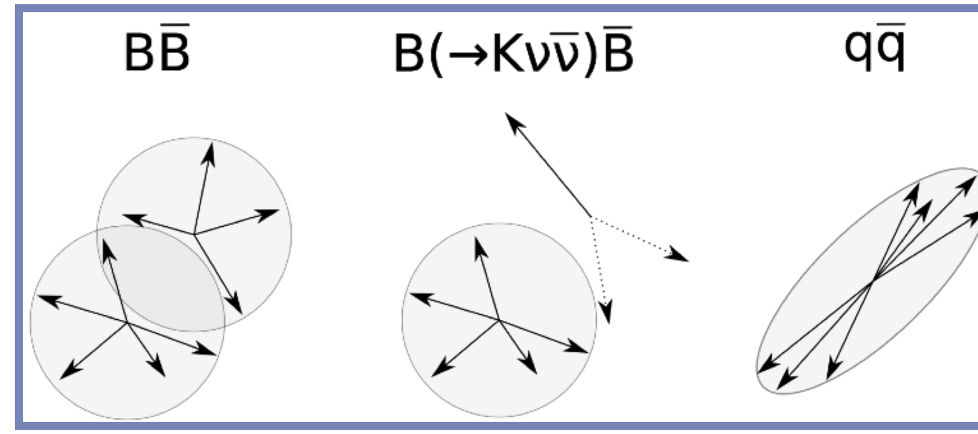




$B^+ \to K^+ \nu\bar{\nu}$ - BACKGROUND SUPPRESSION

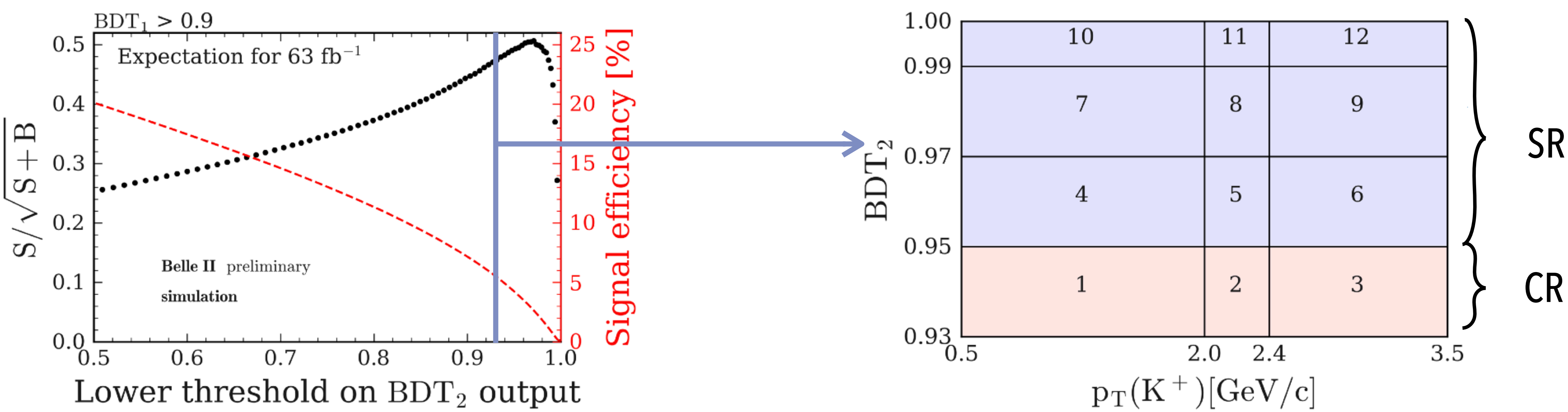
51 features are used to train 2 consecutive binary classifiers (FastBDT) called BDT_1 and BDT_2:

– Event shape
– Kinematics of the K^+ candidate
– variables related to the ROE
– variables related to the $D^{0/+}$ suppression



The BDT_2 is trained with the same features on the events with $\mathrm{BDT}_1 > 0.9$

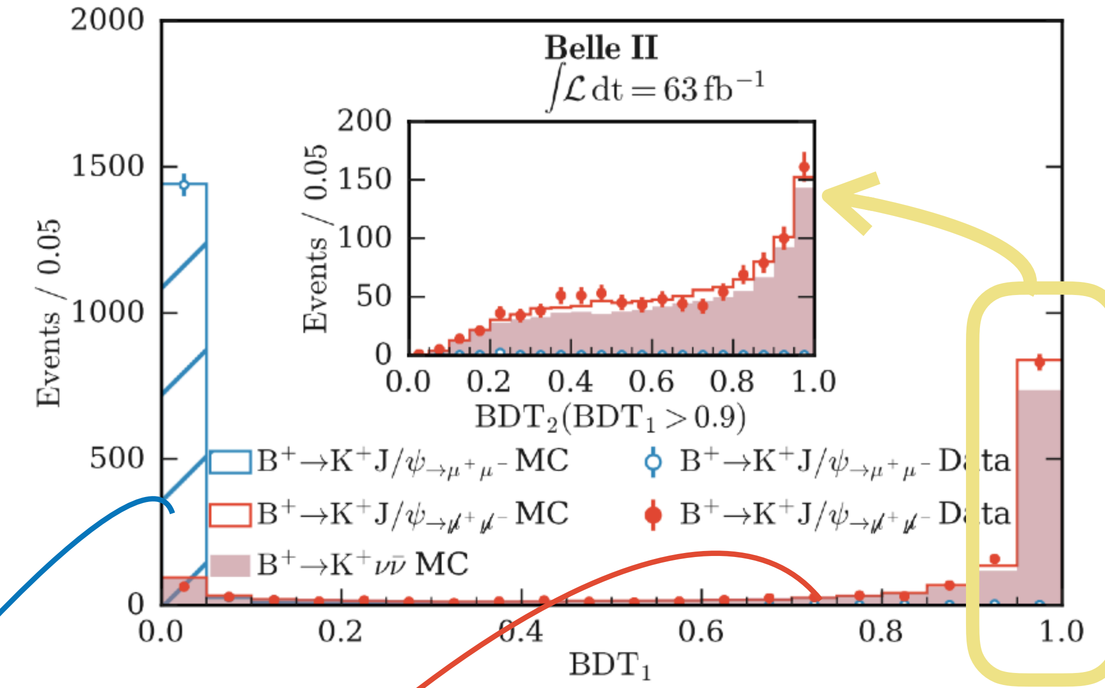
Signal region and control regions (used for background estimation) are defined in the $\mathrm{BDT}_2 \times p_T(K^+)$ space



$B^+ \to K^+ \nu \bar{\nu}$ - VALIDATION

The analysis procedure is validated using $B^+ \to K^+ J/\psi(\mu^+\mu^-)$ events. The momentum of the signal kaon (2-body) is corrected to match the spectrum of 3-body $B^+ \to K^+ \nu\bar{\nu}$ events

$\mu\mu$'s from the selected J/ψ decays are ignored and the modified events are reconstructed with the inclusive tagging



An excellent Data-MC agreement for the $\mathbf{BDT_{1,2}}$ outputs is observed

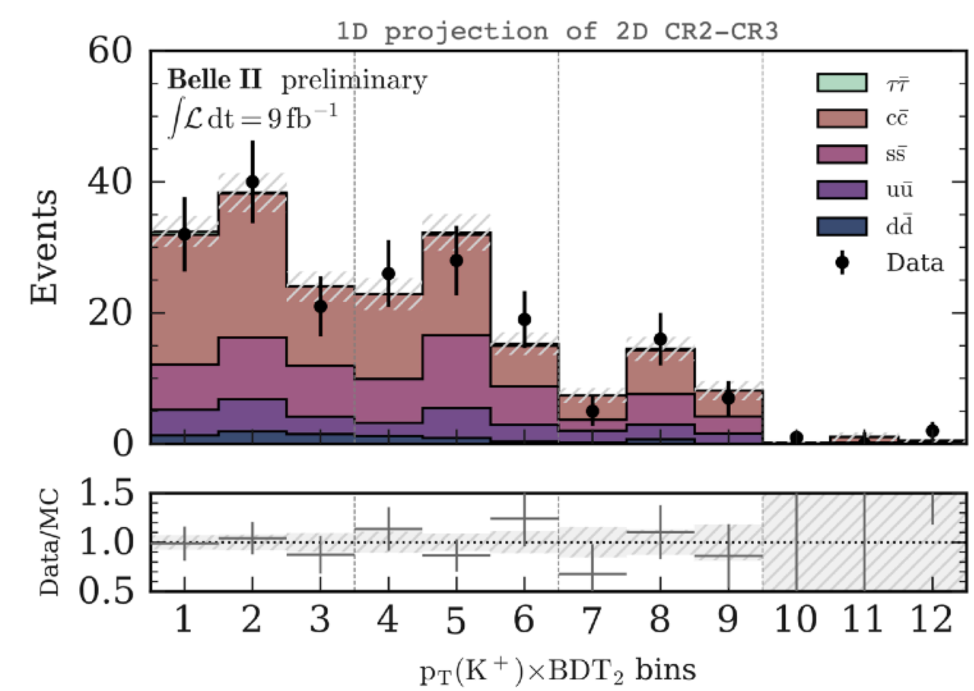
$B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ events

$B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ events where $\mu\mu$ are ignored and K^+ kinematics updated.

The Data-MC agreement is also checked with off-resonance data (9 fb^{-1})

A very good Data-MC shape agreement is found but with discrepancy in yields (factor 1.4 ± 0.1)

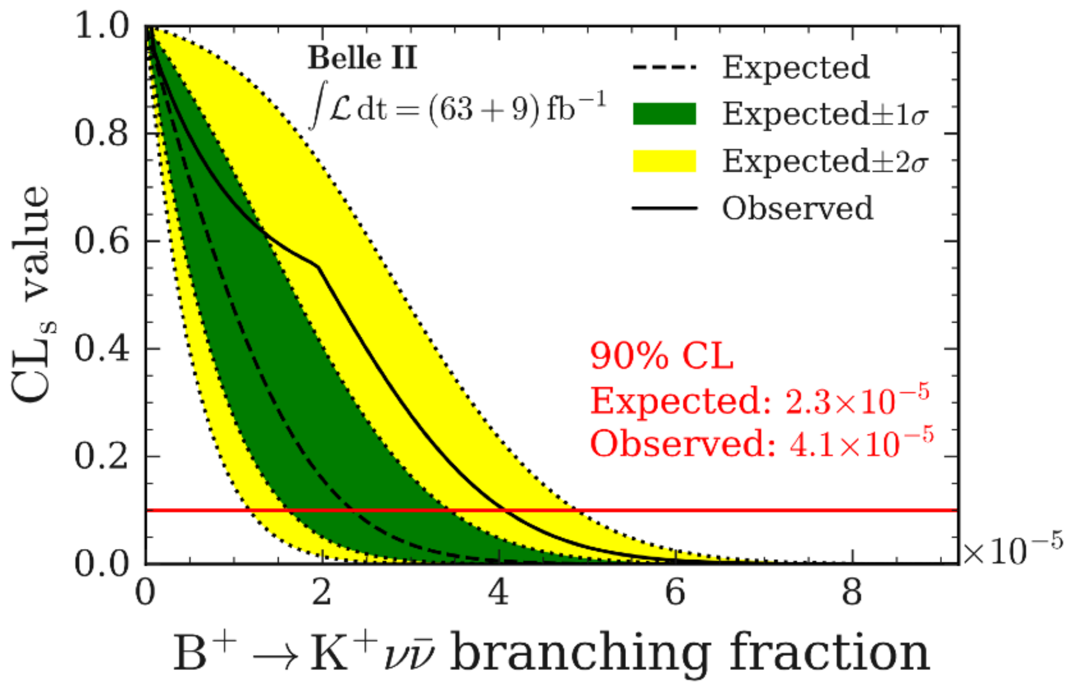
A 50% normalisation uncertainty in the fit is used



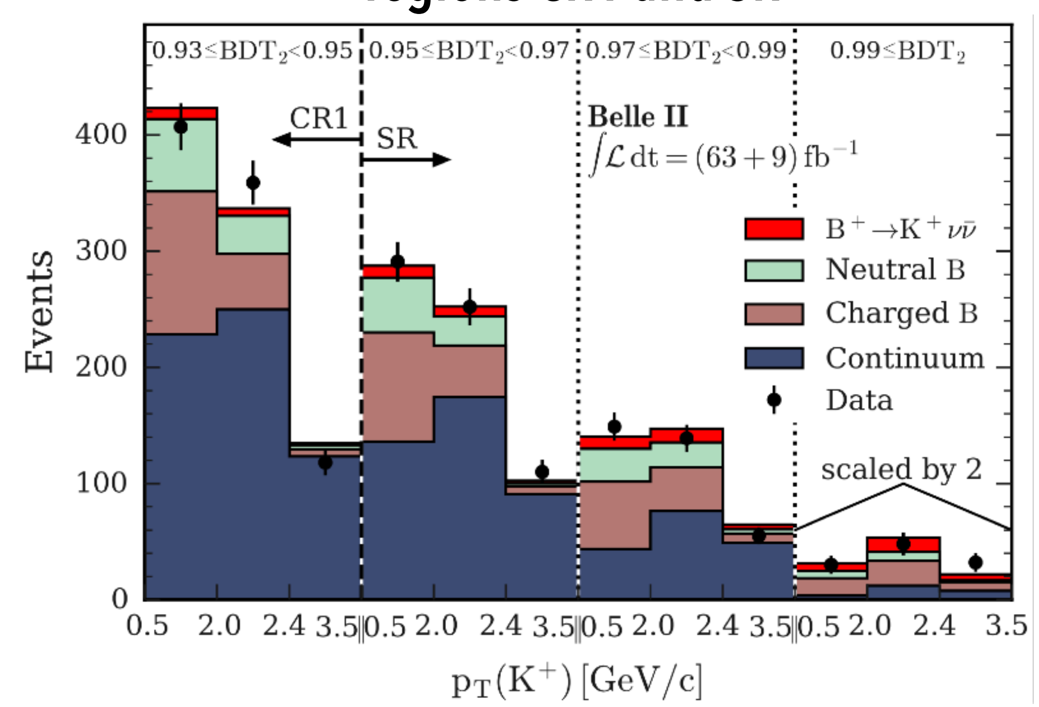
$B^+ \to K^+ \nu\bar{\nu}$ - SIGNAL EXTRACTION

- The signal is extracted with an Extended Maximum Likelihood Binned Fit performed with Pyhf
- The systematic uncertainties (**normalisations of bkg's yields**, BR of the leading B-decays, PID correction, ...) are introduced in the likelihood as nuisance parameters
- The parameter of interest is signal strength μ as the multiplicative factor with respect to the SM expectation
  The fitted value is: $\mu = 4.2^{+2.9}_{-2.8}(\mathrm{stat})^{+1.8}_{-1.6}(\mathrm{syst})$

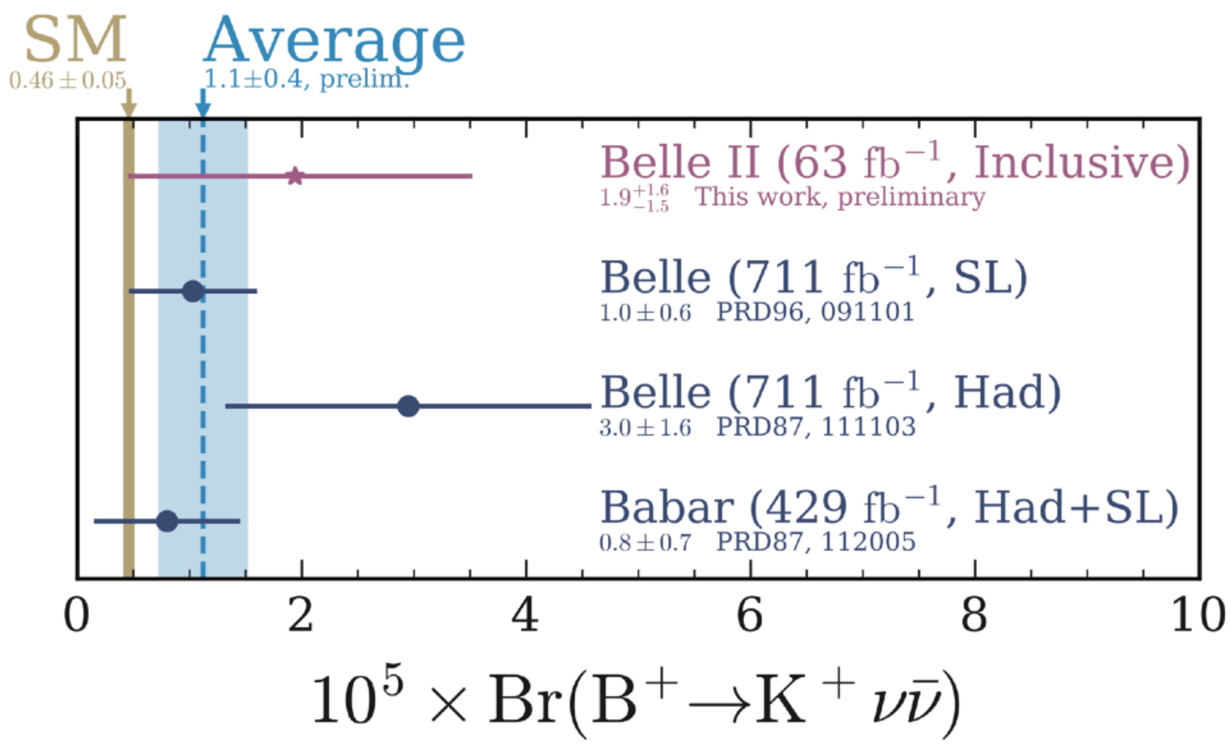
Upper limit derivation with CLs method



Data and post-fit predictions in the regions CR1 and SR



$B^+ \to K^+\nu\bar{\nu}$ - RESULT EXTRACTION



$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{obs} = 1.9^{+1.3}_{-1.3}(stat)^{+0.8}_{-0.7}(syst) \times 10^{-5}$$

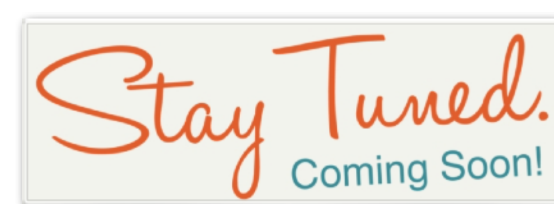
Corresponding to the upper limit

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 4.1 \times 10^{-5} \ @\ 90\,\%\ C.L.$$

Consistent with the SM expectation at 1σ

Despite the much smaller sample (63 fb^{-1} vs 429 and 711 fb^{-1}), the result obtained at Belle II is competitive with the previous searches: the **inclusive method offers improved sensitivity compared to other B-tagging approaches**

The update of the measurement with pre-LS1 dataset is ongoing



SUMMARY

Belle II has integrated in the period 2019-2022 high-quality data corresponding to 400 fb^{-1} (~1/2 Belle)

- Today measurements with 63 fb^{-1} and 190 fb^{-1} have been shown

$\mathrm{b} \rightarrow \mathrm{s}$ transitions allow to effectively probe the physics beyond SM and can be tested at Belle II

- $\mathrm{b} \rightarrow \mathrm{s}\ell\ell$: Can provide independent measurement of LFU ratios and BFs of $\mathrm{B} \rightarrow \mathrm{K}^{(*)}\ell\ell$ from LHCb
- $\mathrm{b} \rightarrow \mathrm{s}\tau\ell, \mathrm{b} \rightarrow \mathrm{s}\nu\bar{\nu}$: Will offer unprecedented sensitivity in $\mathrm{B} \rightarrow \mathrm{K}^{(*)}\tau\bar{\tau}/\mathrm{K}^{(*)}\nu\bar{\nu}$ decays

- More results are coming soon! Rencontres de Moriond since 1966, LP 2023 AHEAD ...

Thank you for your attention!

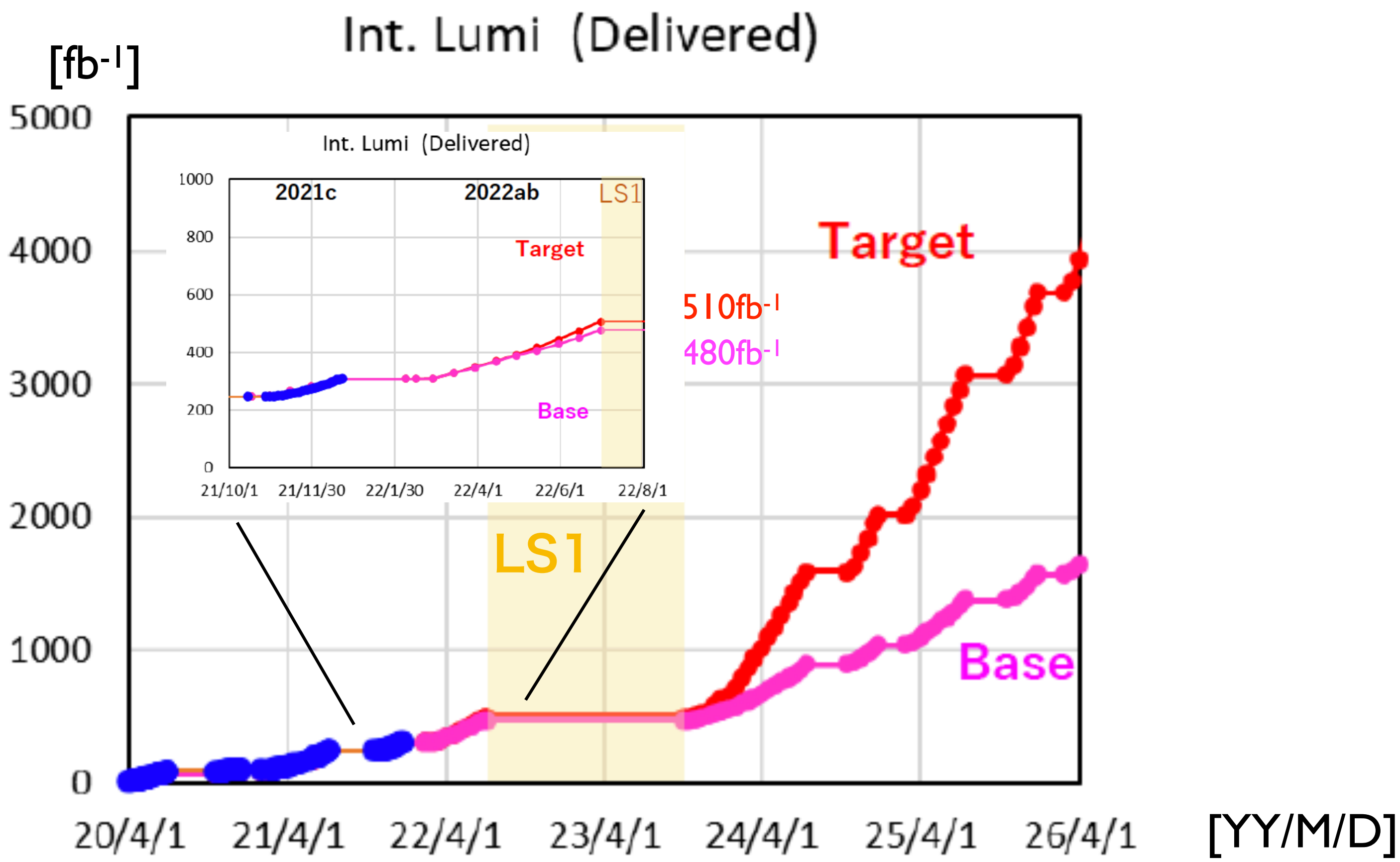
Additional Material

LHC*b* MEASUREMENT

Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027

FROM THE BELLE II PHYSICS BOOK

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%

Table 69: Sensitivities to the modes involving neutrinos in the final states. We assume that $5\,\mathrm{ab}^{-1}$ of data will be taken on the $\Upsilon(5S)$ resonance at Belle II. Some numbers at Belle are extrapolated to $0.71\,\mathrm{ab}^{-1}$ ($0.12\,\mathrm{ab}^{-1}$) for the $B_{u,d}$ (B_s) decay.

Observables	Belle $0.71\,\mathrm{ab}^{-1}$ ($0.12\,\mathrm{ab}^{-1}$)	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077
$\mathrm{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$\mathrm{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–

Observables	
$\mathrm{Br}(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	< 2.1
$\mathrm{Br}(B^+ \to K^+\tau^\pm \mu^\mp) \cdot 10^6$	< 3.3
$\mathrm{Br}(B^0 \to \tau^\pm e^\mp) \cdot 10^5$	< 1.6
$\mathrm{Br}(B^0 \to \tau^\pm \mu^\mp) \cdot 10^5$	< 1.3

LHC*b* MEASUREMENT

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

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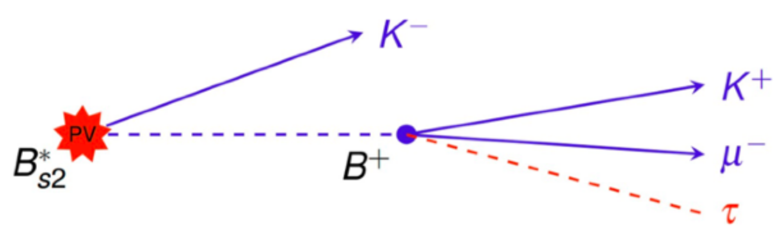
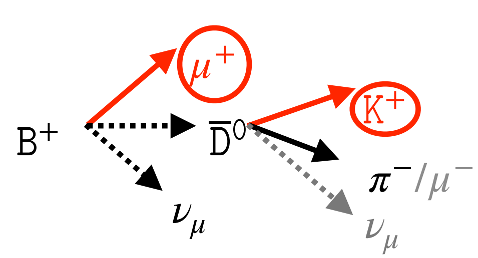
- 9 fb^{-1} @ 7, 8 and 13 TeV (Run1 & Run2)
- Use $B^{*0}_{s2} \to B^+K^-$ decay: about 1% of B^+ production
- $K^+\mu^-$ pair from secondary vertex plus additional track t^+

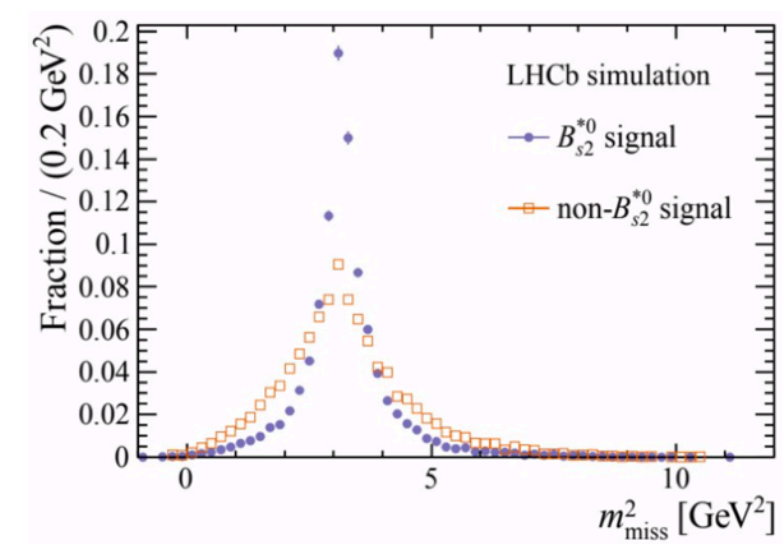


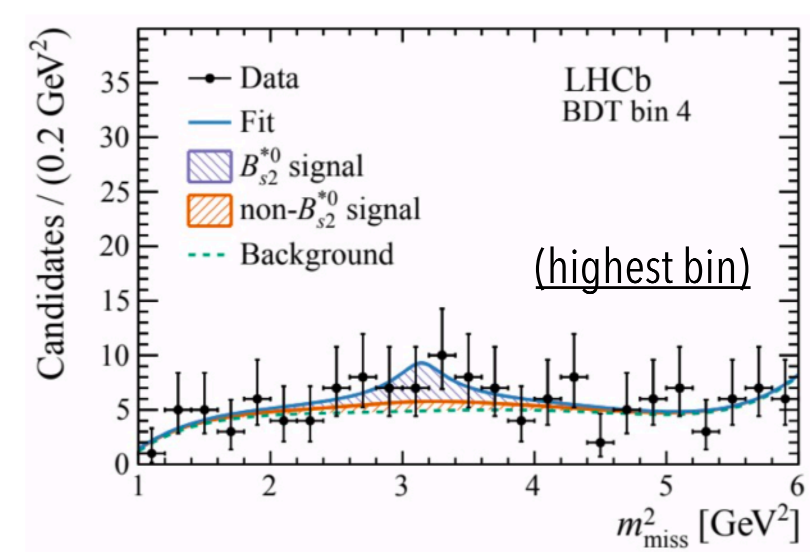
- Expect peak at τ mass also for B not from B^{*0}_{s2} decay, but wider distribution
- $K^+\mu^-\tau^+$ experimentally preferred over $K^+\mu^+\tau^-$ as it has a lower background from sSL B decays, because CF decays of the D mesons are likely to lead to K's of the same charge as the muon



- 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 x 10^{-5}	BaBar
$B^+\to K^+\tau e$	3.0 x 10^{-5}	BaBar
$B^+\to K^+\tau^+\mu^-$	3.9 x 10^{-5}	LHCb





SUPERKEKB

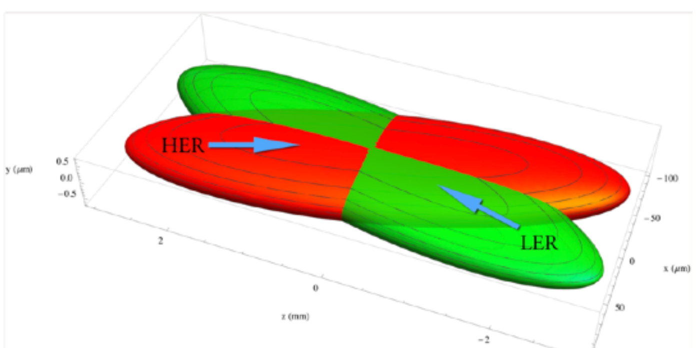
$$\mathscr{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

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

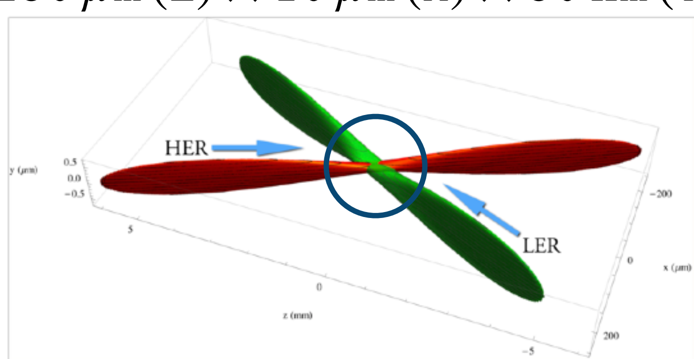
} Wrt to 1st generation B factories

Beamspot

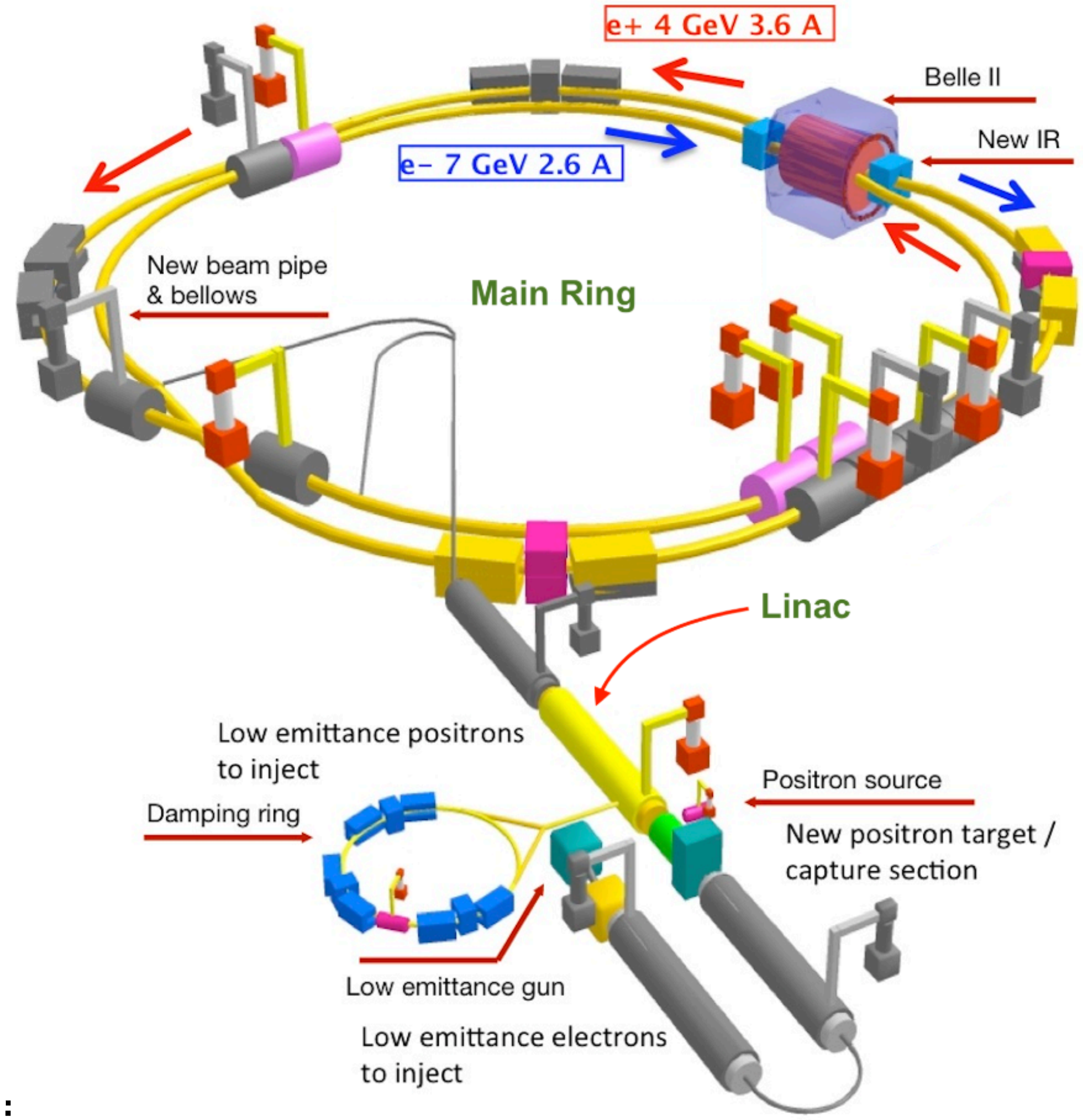
$250\,\mu\mathrm{m}\,(Z) \times 10\,\mu\mathrm{m}\,(X) \times 50\,\mathrm{nm}\,(Y)$



KEKB



SuperKEKB



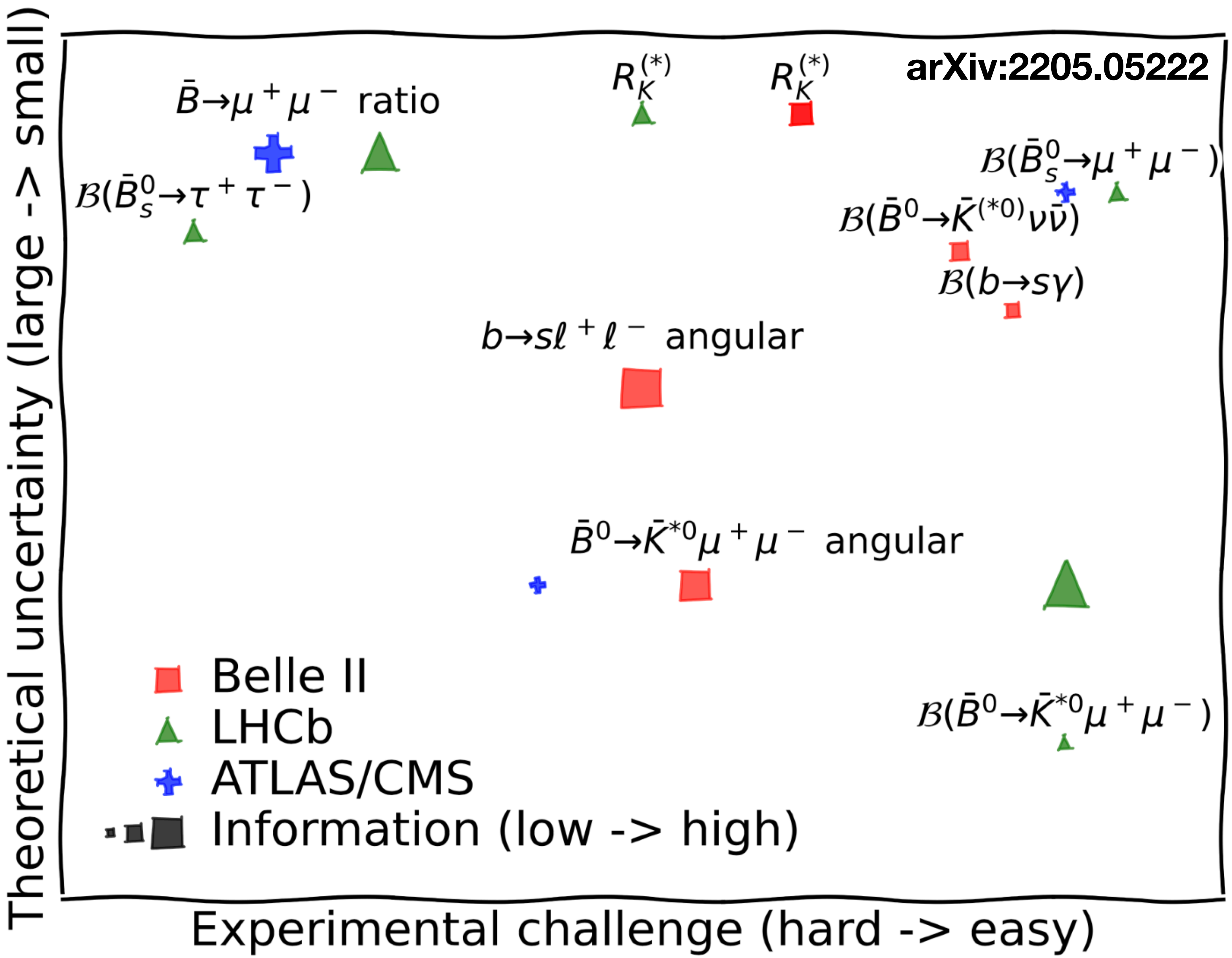
	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (mm) LER/HER	Φ (mrad)	I (A)	L ($cm^{-2}s^{-1}$) x10^{35}
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	0.2
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	8
		Factor 20			Factor 2-3	

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

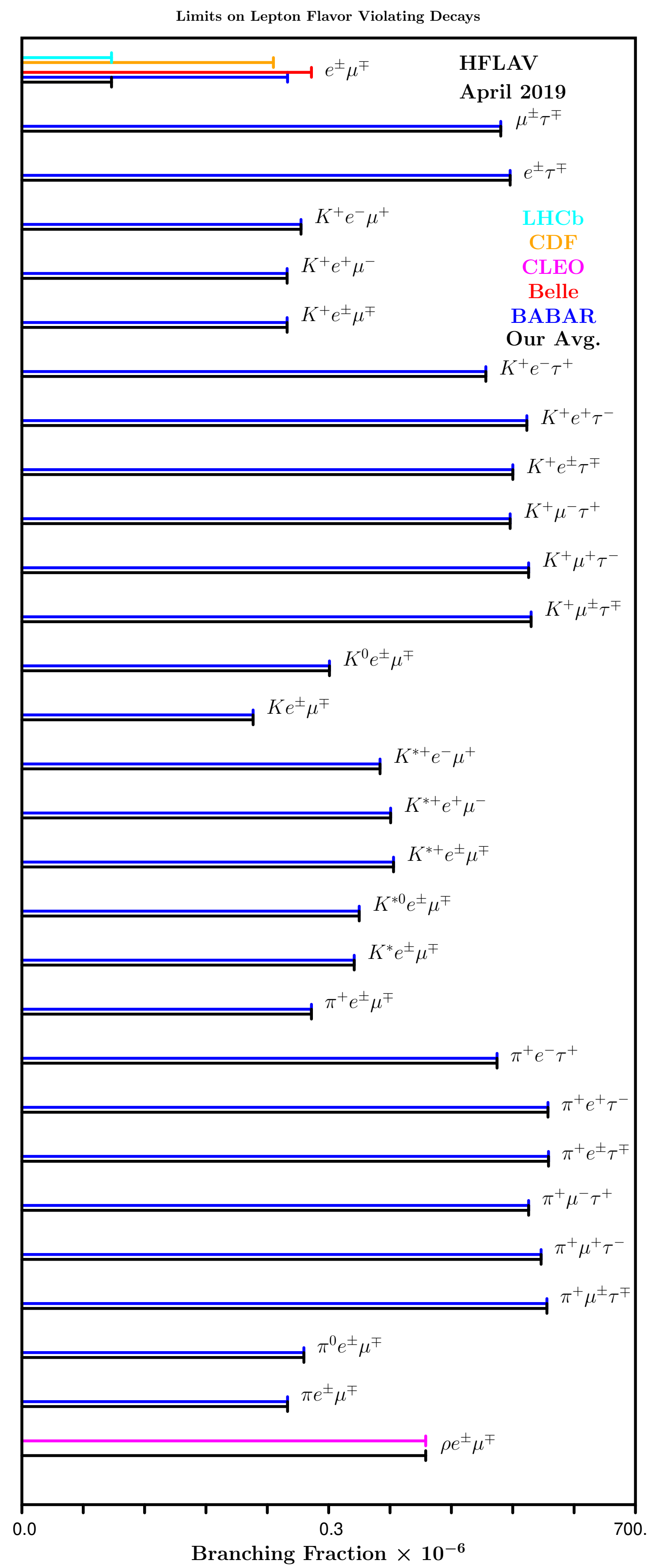
B-ANOMALIES OBSERVABLES



TABLES

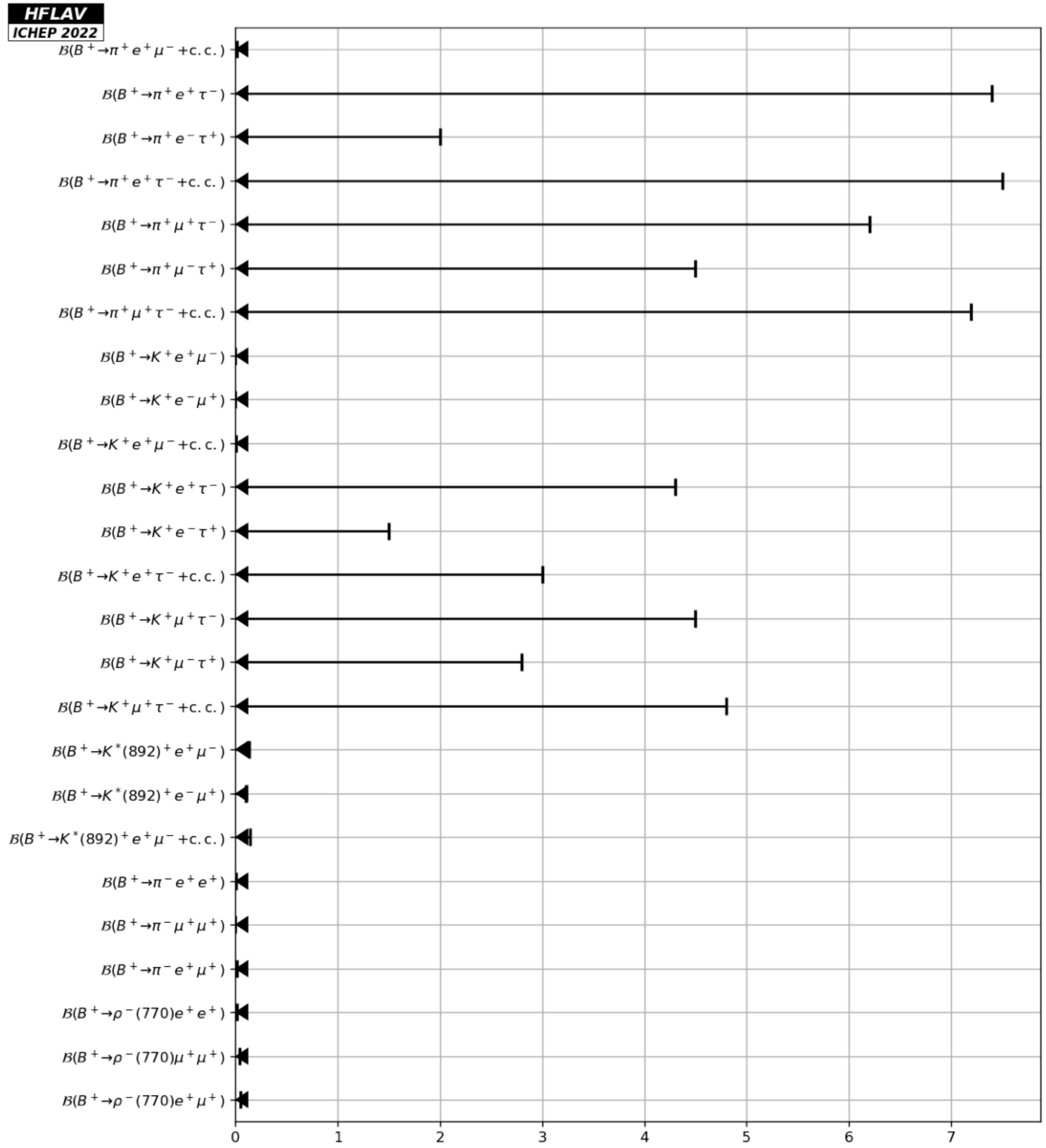
Decay Mode	$N_{B\overline{B}}$ (10^6)	$\mathcal{B}$ upper limit (90% C.L.)
Lepton flavor violating modes (light flavors):		
$B^0 \to \mu^\pm e^\mp$	85	17×10^{-8}
$B^0 \to \mu^\pm e^\mp$	384	9.2×10^{-8}
$B^+ \to \pi^+ \mu^\pm e^\mp$	230	17×10^{-8}
$B^0 \to \pi^0 \mu^\pm e^\mp$		14×10^{-8}
$B \to \pi \mu^\pm e^\mp$		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}

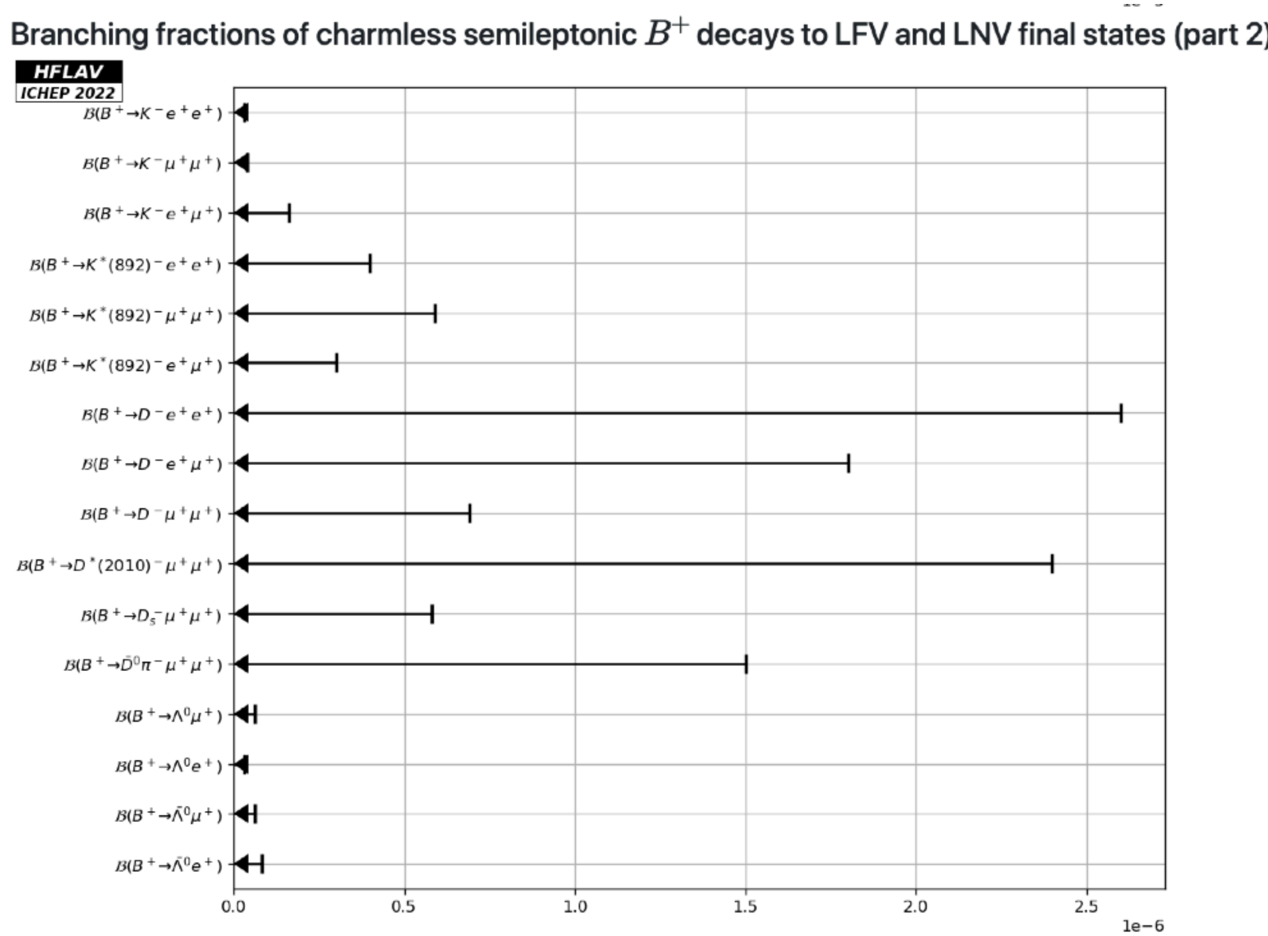


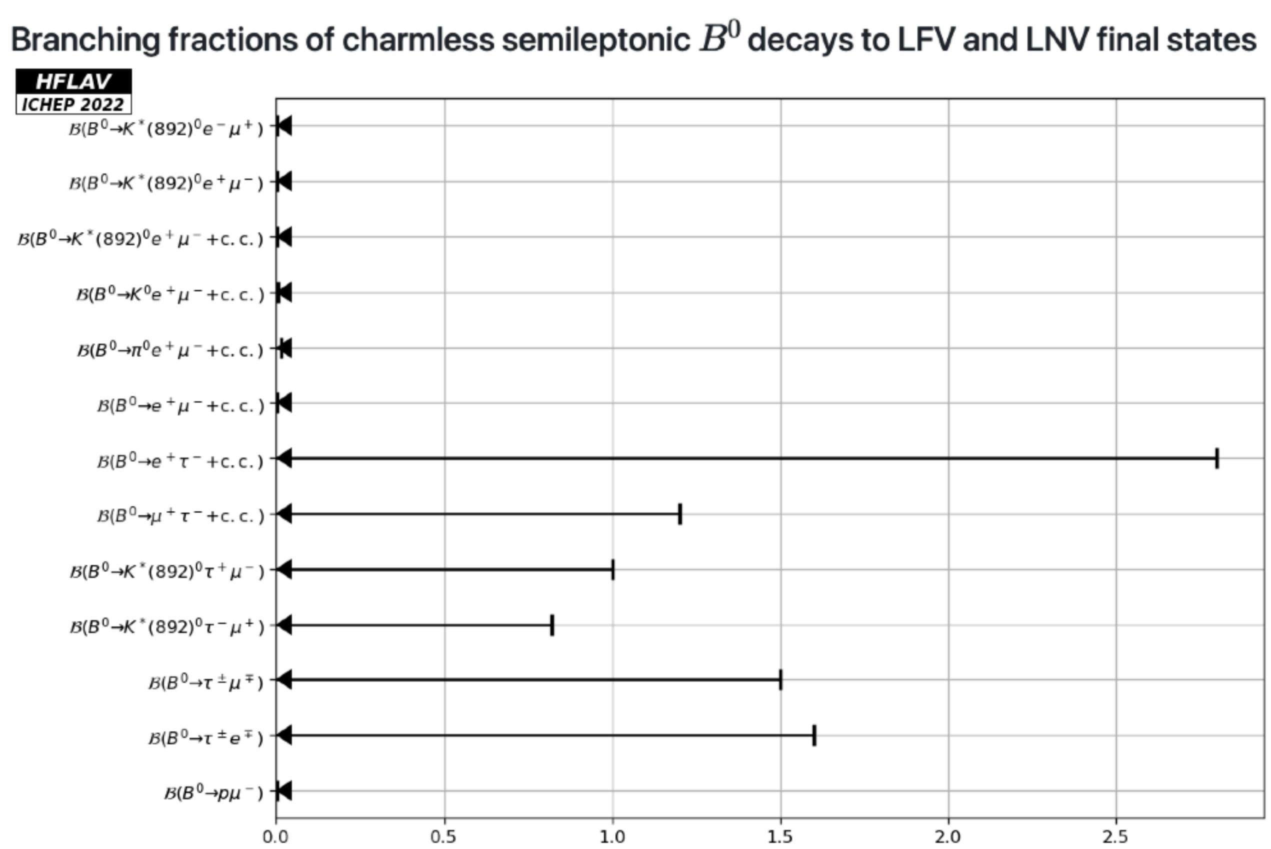
TABLES

Branching fractions of charmless semileptonic B^+ decays to LFV and LNV final states (part 1)



TABLES


Branching fractions of charmless semileptonic B^+ decays to LFV and LNV final states (part 2)
HFLAV
ICHEP 2022
$\mathcal{B}(B^+\to K^- e^+ e^+)$
$\mathcal{B}(B^+\to K^- \mu^+ \mu^+)$
$\mathcal{B}(B^+\to K^- e^+ \mu^+)$
$\mathcal{B}(B^+\to K^*(892)^- e^+ e^+)$
$\mathcal{B}(B^+\to K^*(892)^- \mu^+ \mu^+)$
$\mathcal{B}(B^+\to K^*(892)^- e^+ \mu^+)$
$\mathcal{B}(B^+\to D^- e^+ e^+)$
$\mathcal{B}(B^+\to D^- e^+ \mu^+)$
$\mathcal{B}(B^+\to D^- \mu^+ \mu^+)$
$\mathcal{B}(B^+\to D^*(2010)^- \mu^+ \mu^+)$
$\mathcal{B}(B^+\to D_s^- \mu^+ \mu^+)$
$\mathcal{B}(B^+\to \bar{D}^0 \pi^- \mu^+ \mu^+)$
$\mathcal{B}(B^+\to \Lambda^0 \mu^+)$
$\mathcal{B}(B^+\to \Lambda^0 e^+)$
$\mathcal{B}(B^+\to \bar{\Lambda}^0 \mu^+)$
$\mathcal{B}(B^+\to \bar{\Lambda}^0 e^+)$
0.0
0.5
1.0
1.5
2.0
2.5
1e−6


Branching fractions of charmless semileptonic B^0 decays to LFV and LNV final states
HFLAV
ICHEP 2022
$\mathcal{B}(B^0\to K^*(892)^0 e^- \mu^+)$
$\mathcal{B}(B^0\to K^*(892)^0 e^+ \mu^-)$
$\mathcal{B}(B^0\to K^*(892)^0 e^+ \mu^- + c.c.)$
$\mathcal{B}(B^0\to K^0 e^+ \mu^- + c.c.)$
$\mathcal{B}(B^0\to \pi^0 e^+ \mu^- + c.c.)$
$\mathcal{B}(B^0\to e^+ \mu^- + c.c.)$
$\mathcal{B}(B^0\to e^+ \tau^- + c.c.)$
$\mathcal{B}(B^0\to \mu^+ \tau^- + c.c.)$
$\mathcal{B}(B^0\to K^*(892)^0 \tau^+ \mu^-)$
$\mathcal{B}(B^0\to K^*(892)^0 \tau^- \mu^+)$
$\mathcal{B}(B^0\to \tau^\pm \mu^\mp)$
$\mathcal{B}(B^0\to \tau^\pm e^\mp)$
$\mathcal{B}(B^0\to p \mu^-)$
0.0
0.5
1.0
1.5
2.0
2.5
1e−5

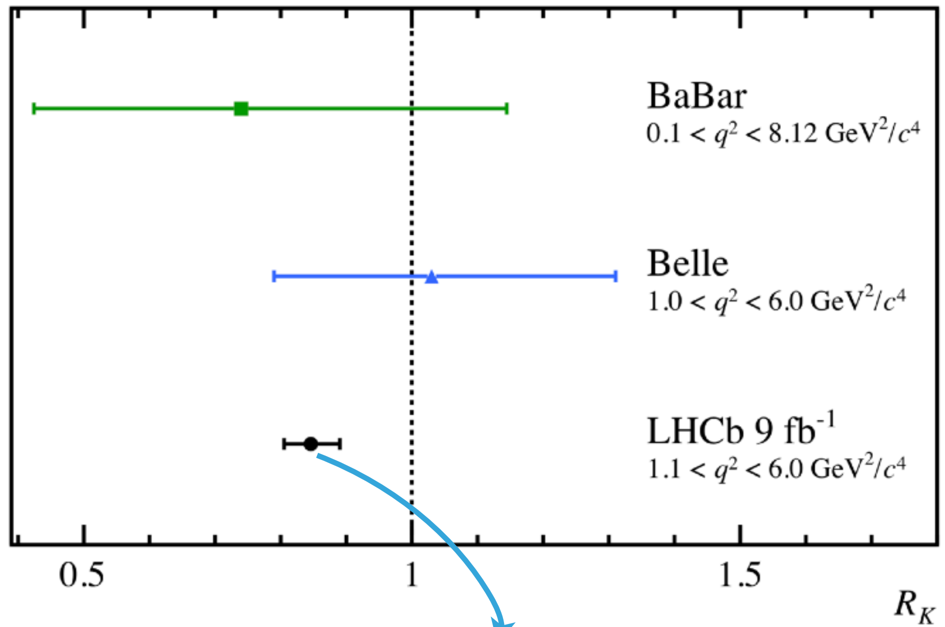
STATUS OF R_K AND PROSPECTS

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**

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

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



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]

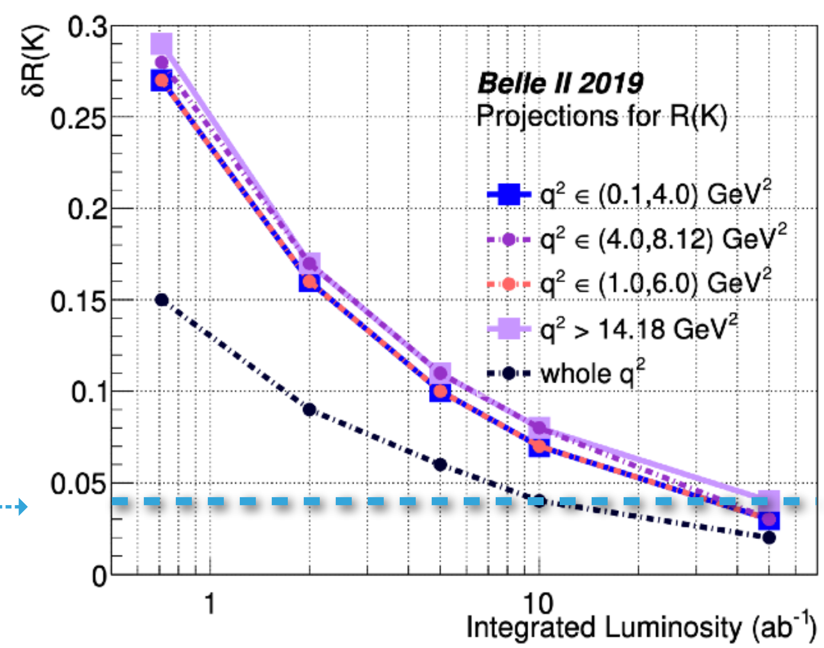
LHCb 2021

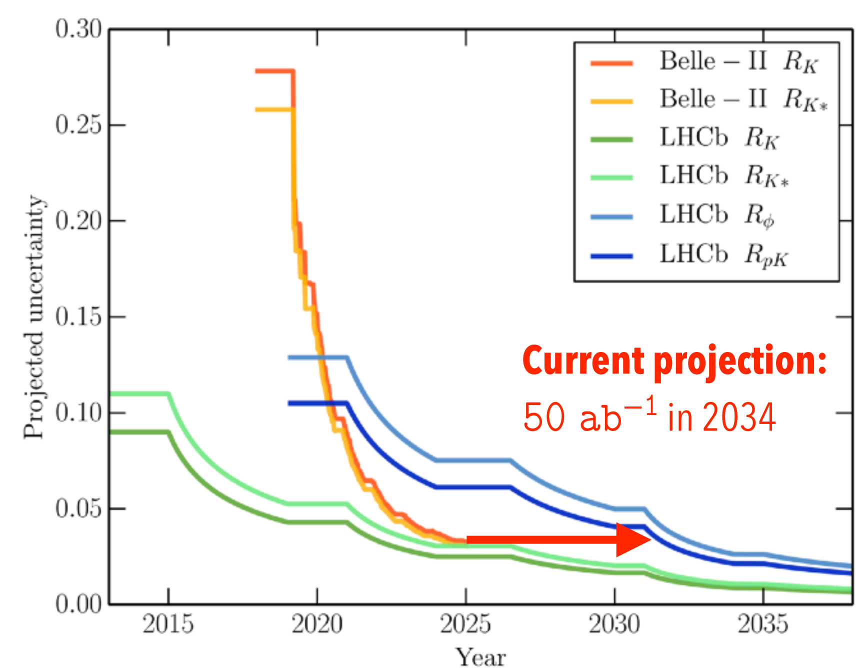
$$R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$$
for $q^2 \in [1.1, 6.0]\ GeV^2/c^4$ (9 fb^{-1})

[arXiv:2103.11769v1]

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

Current LHCb precision ⇢





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