BSM discovery potential at Belle II

Session E: QCD and New Physics

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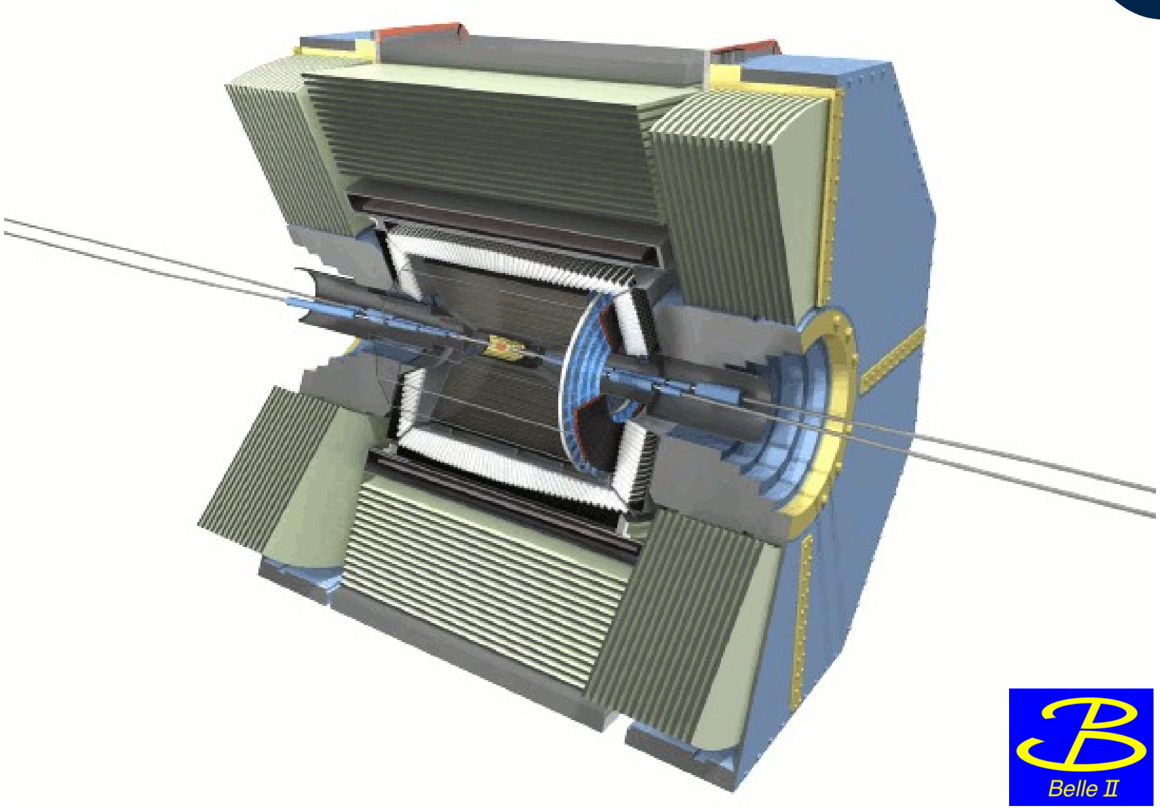


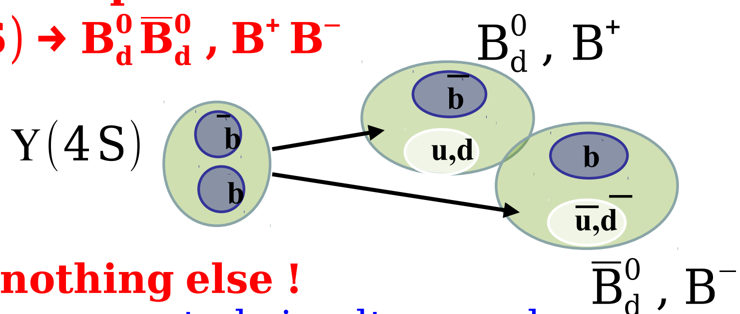
QCHSC 2024, Cairns, 21 August 2024

Belle II, a flavour-factory,

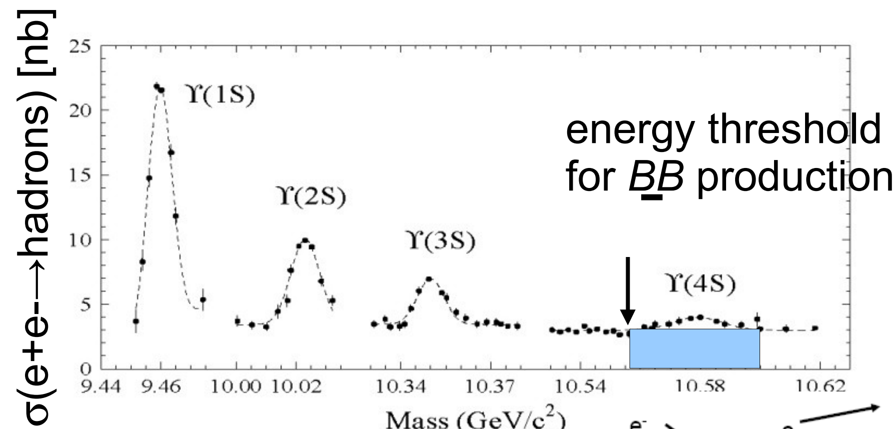
(Belle ~ 1 ab^{-1}) **a rich physics program...**

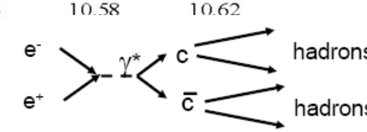
- We plan to collect (**at least**) 50 ab^{-1} of e^+e^- collisions at (or close to) the $\Upsilon(4S)$ resonance, so that we have:
  - **a (Super) B-factory (~1.1×10^9 $B\bar{B}$ pairs per ab^{-1})**

"on resonance" production
$e^+e^- \to \Upsilon(4S) \to B_d^0 \bar{B}_d^0, B^+B^-$



- **2 B's and nothing else !**
- 2 B mesons are created simultaneously in a L=1 coherent state





  - a (Super) charm factory (~1.3×10^9 $c\bar{c}$ pairs per ab^{-1})

(but also charmonium, X, Y, Z, pentaquarks, tetraquarks, bottomonium...)

(see ChengPing Shen and Bruce Yabsley's talks)

  - a (Super) τ factory (~0.9×10^9 $\tau^+\tau^-$ pairs per ab^{-1})
  - exploit the clean e^+e^- environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, ALPs, LLPs ...

⇒ to reach 6×10^{35} $cm^{-2}s^{-1}$

⇒ cumulate 50 ab^{-1} by ~2035

Belle II run I (2019 - 2022)

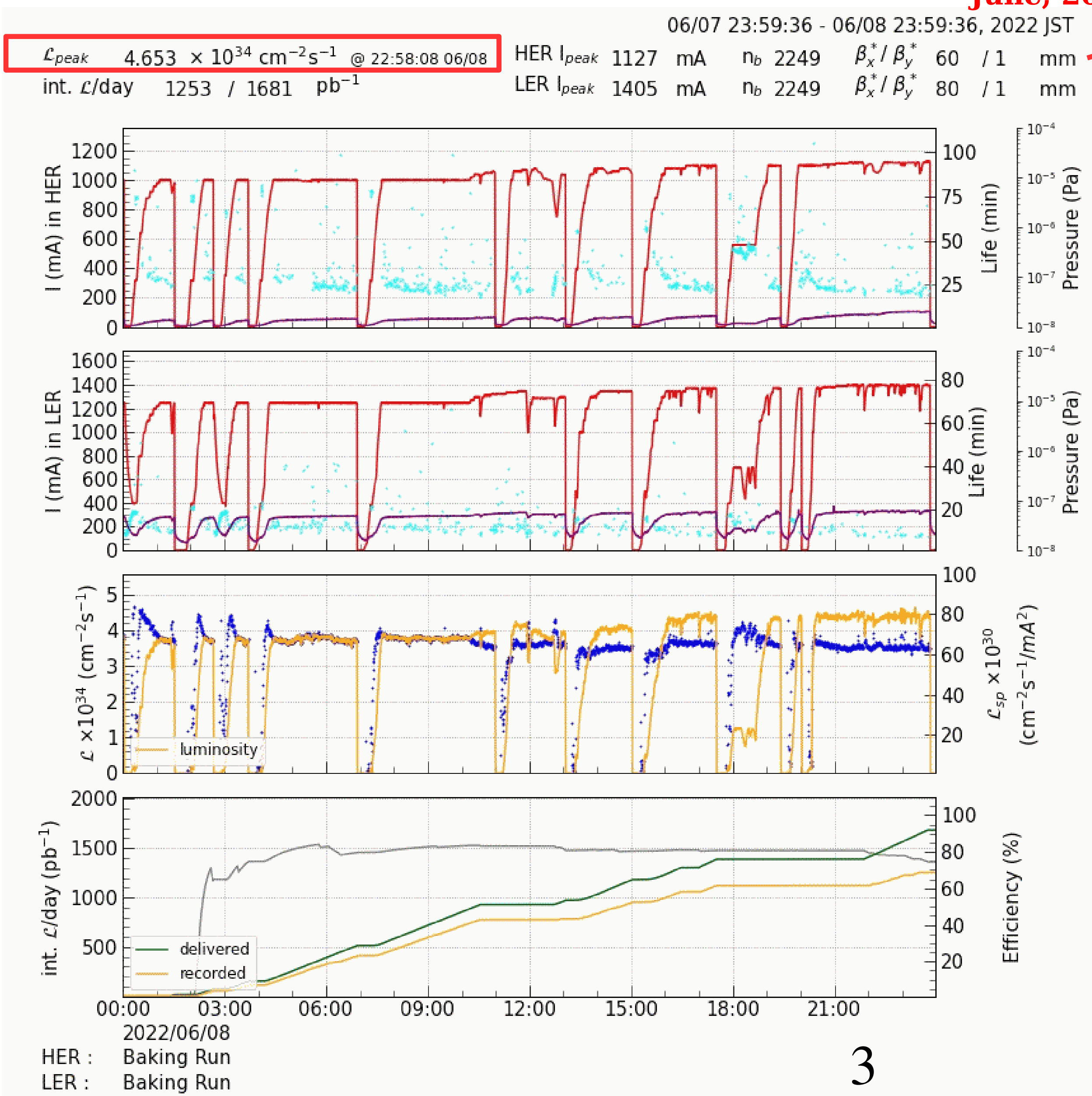
data taking from March 2019 to June 2022

→ despite difficult conditions since March 2020 (Covid, war in Ukraine, energy cost…)

luminosity: 4.7×10^{34}/cm^2/s ! > 2 fb^{-1} per day !

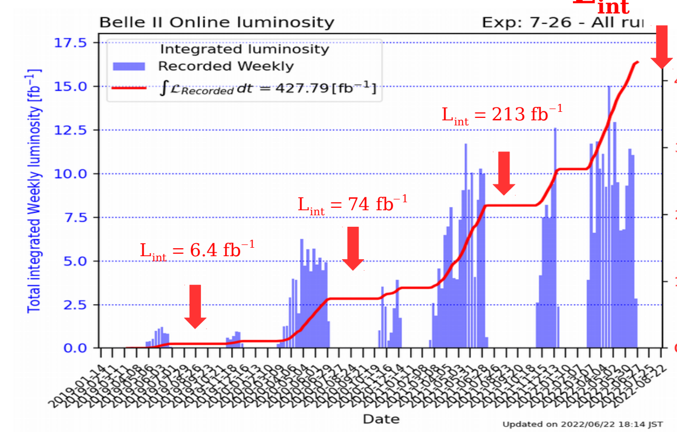
$\beta_y^* = 1$ mm, $I_{LER/HER} = 1.4/1.2$ A

June, 2022

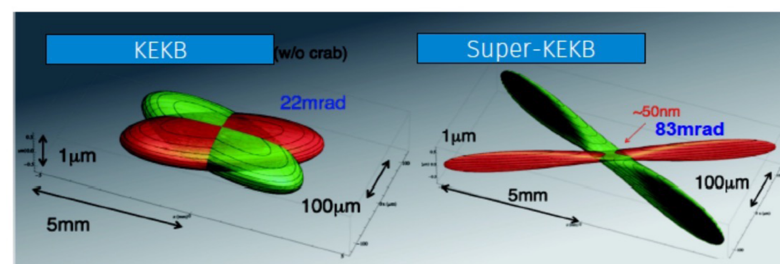


record of KEKB/Belle
2×10^{34}/cm^2/s currents > 1 A
record of PEPII/BaBar
1×10^{34}/cm^2/s currents > 2 A

L_{int} = 428 fb^{-1}



5×10^{34}/cm^2/s
~ 1 BaBar/year



	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm⁻²s⁻¹)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20   factor 2-3

squeezing further β_y^* (→ 0.6 mm)
doubling (or more) the currents
⇒ L > 10^{35}/cm^2/s after LS 1

Belle(II), LHCb side by side

Belle (II)

$e^+e^- \to \Upsilon(4S) \to b\bar{b}$

at $\Upsilon(4S)$: 2 B's (B^0 or B^+) and nothing else ⇒ clean events

(flavour tagging, B tagging, missing energy)

⇒ initial conditions are precisely known

$\sigma_{b\bar{b}} \sim 1\,\text{nb} \Rightarrow 1\ \text{fb}^{-1}$ produces $10^6\ B\bar{B}$

$\sigma_{b\bar{b}}/\sigma_{total} \sim 1/4$

LHCb

$pp \to b\bar{b}X$

production of B^+, B^0, B_s, B_c, Λ_b...
but also a lot of other particles in the event

⇒ lower reconstruction efficiencies

$\sigma_{b\bar{b}}$ much higher than at the $\Upsilon(4S)$

	$\sqrt{s}$ [GeV]	$\sigma_{b\bar{b}}$ [nb]	$\sigma_{b\bar{b}}/\sigma_{tot}$
HERA pA	42 GeV	~30	$\sim 10^{-6}$
Tevatron	2 TeV	5000	$\sim 10^{-3}$
LHC	8 TeV	$\sim 3\times10^5$	$\sim 5\times10^{-3}$
	14 TeV	$\sim 6\times10^5$	$\sim 10^{-2}$

$b\bar{b}$ production cross-section at LHCb ~ 500,000 × BaBar/Belle !!

higher luminosity

$\sigma_{b\bar{b}}/\sigma_{total}$ much lower than at the $\Upsilon(4S)$

⇒ lower trigger efficiencies

B mesons live relatively long

mean decay length $\beta\gamma c\tau \sim 200\ \mu m$

mean decay length $\beta\gamma c\tau \sim 7$ mm

(displaced vertices)

data taking period(s)

[1999-2010] = 1 ab^{-1}
[2019-...] = ...

[run I: 2010-2012] = 3 fb^{-1}
[run II: 2015-2018] = 6 fb^{-1}

(near) future

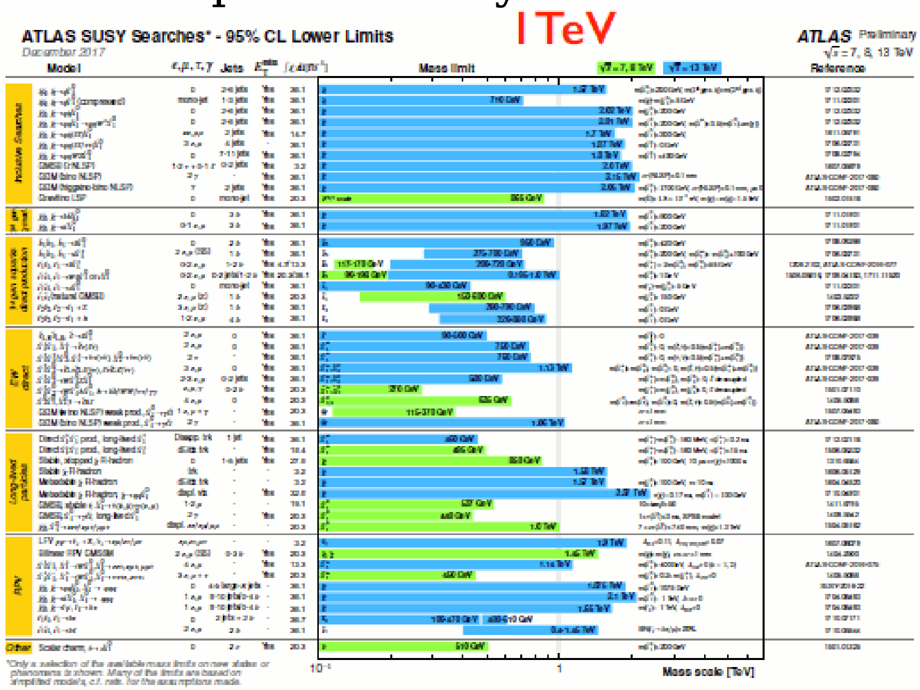
[Belle II from 2019] → 50 ab^{-1}

[LHCb upgrade from 2022]

How do we search for new particles ?

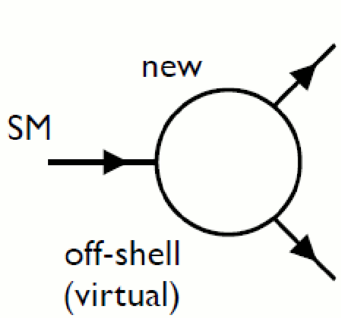
Direct vs Indirect Searches

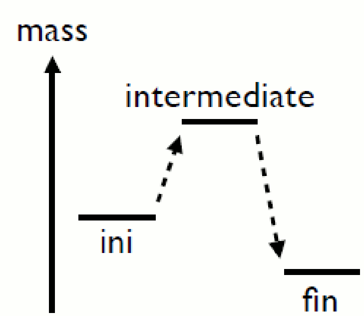
complementarity with LHC



> ~100GeV (1TeV), if interaction is weak (strong)

New particle via quantum effects

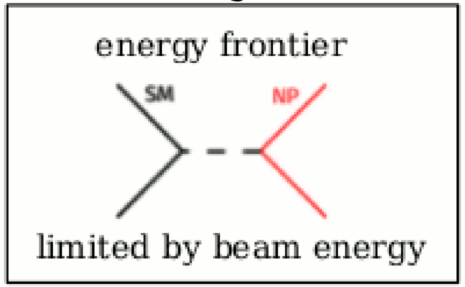


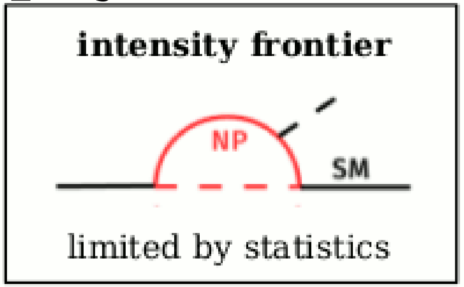


No sharp cutoff for energy scale (cf. LHC search)

— suppressed by $(E/\Lambda)^n$

Why flavor physics ?

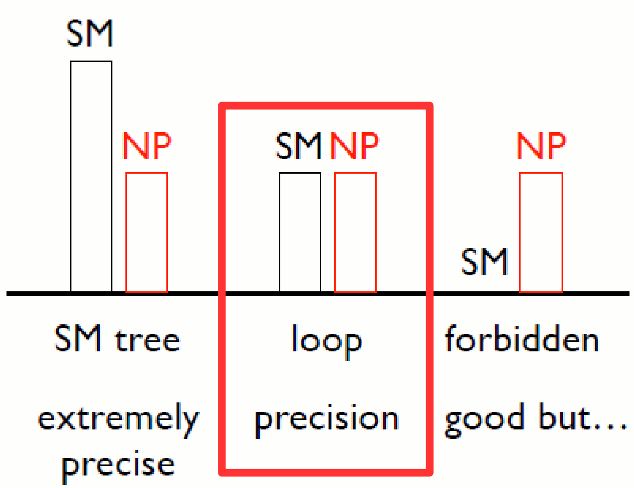




→ **NP beyond the direct reach of the LHC**

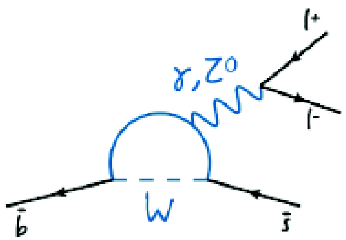
Three classes of SM processes

$$\mathcal{O}_{\rm obs} = \mathcal{O}_{\rm SM} + \mathcal{O}_{\rm NP}$$

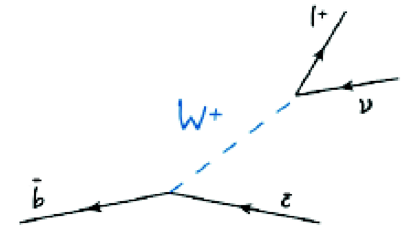


New particles can for example contribute to loop or tree level diagrams **by enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles**

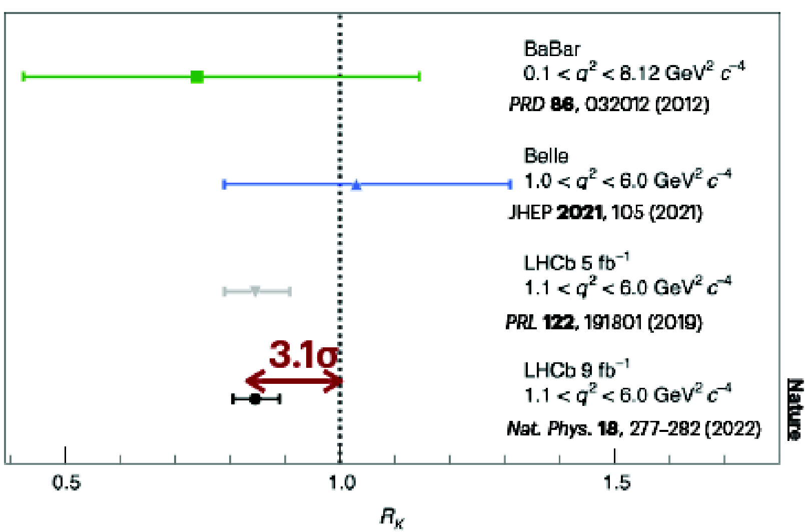
What happened with the B anomalies... ?



Deviations from SM have been measured, among **several observables**, in universality tests of lepton interactions in $b \to s$ and $b \to c$ transitions



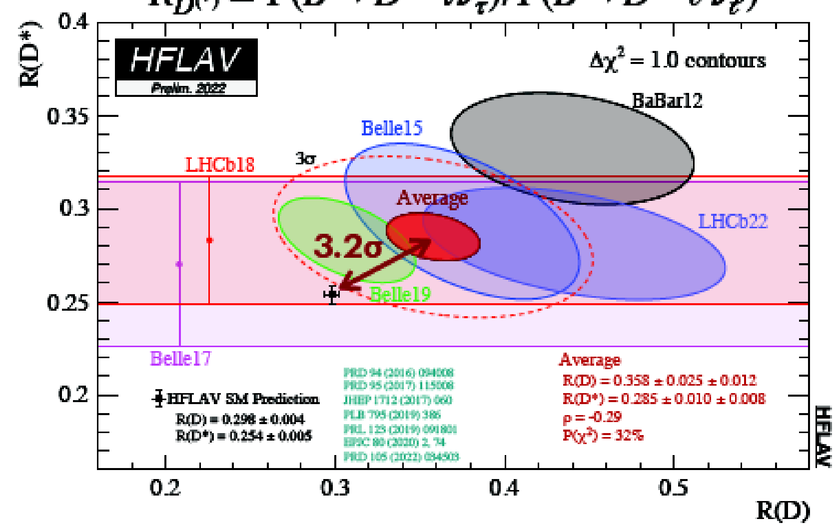
$R_K = \Gamma(B^+ \to K^+ \mu^+ \mu^-)/\Gamma(B^+ \to K^+ e^+ e^-)$



μ vs e: $R_H^{\text{exp}} < R_H^{\text{SM}}$

Lepton Flavor Universality Violation ?

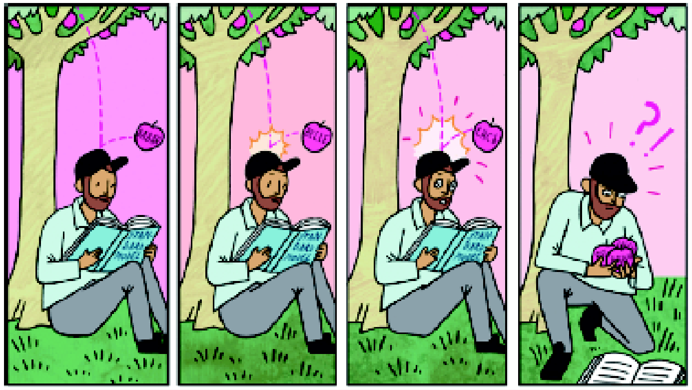
$R_{D^{(*)}} = \Gamma(B \to D^{(*)} \tau \nu_\tau)/\Gamma(B \to D^{(*)} \ell \nu_\ell)$



τ vs e/μ: $R_{D^{(*)}}^{\text{exp}} > R_{D^{(*)}}^{\text{SM}}$

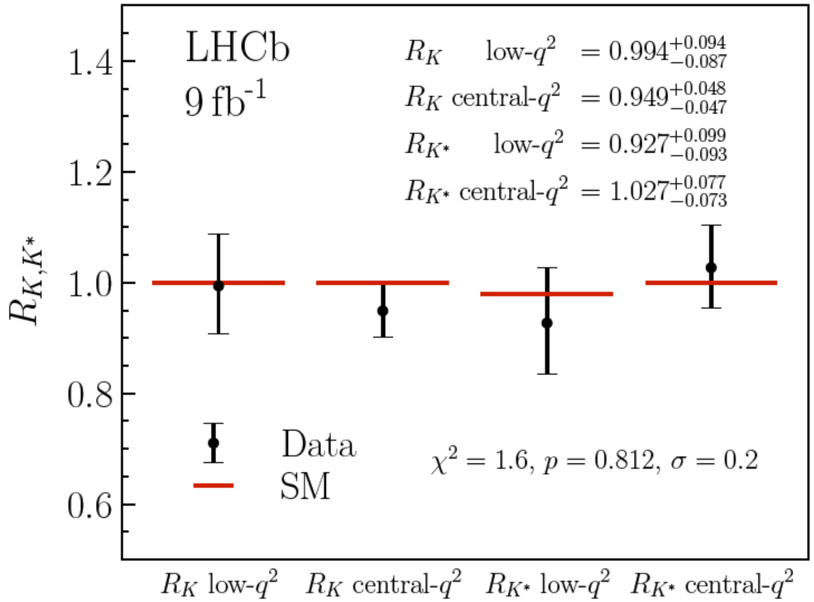
Main players in B-physics

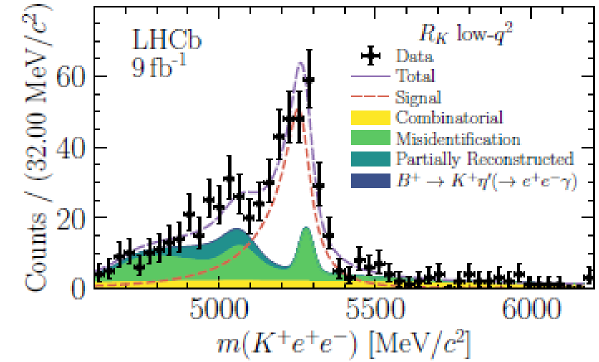
Belle (II), BaBar → B-mesons in e^+e^- collisions
LHCb → *b*-flavored hadrons in *pp* collisions

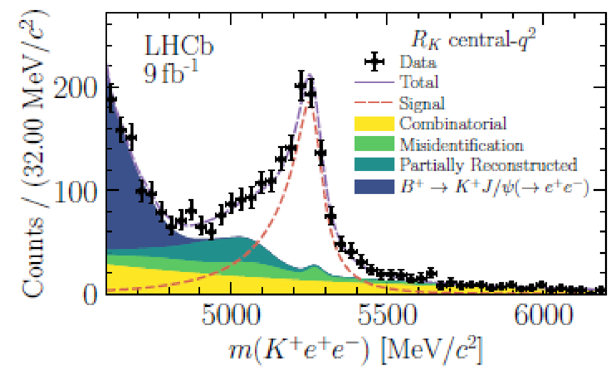


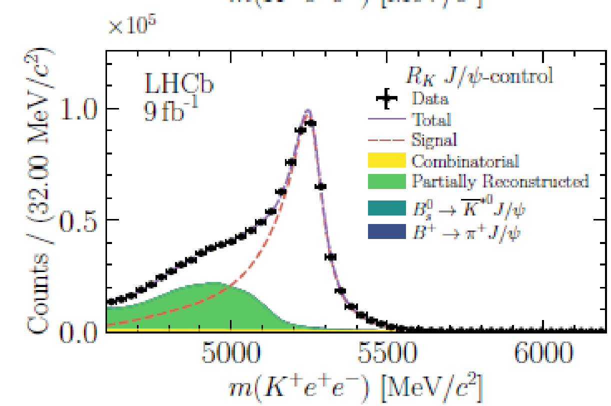
Lepton flavor universality (LFU) in $b \to s l^+ l^-$

[PRL 131 (2023) 051803, PRD 108 (2023) 032002]





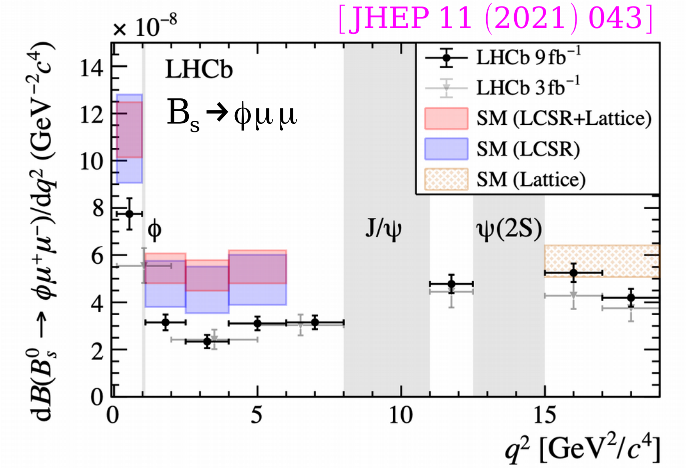




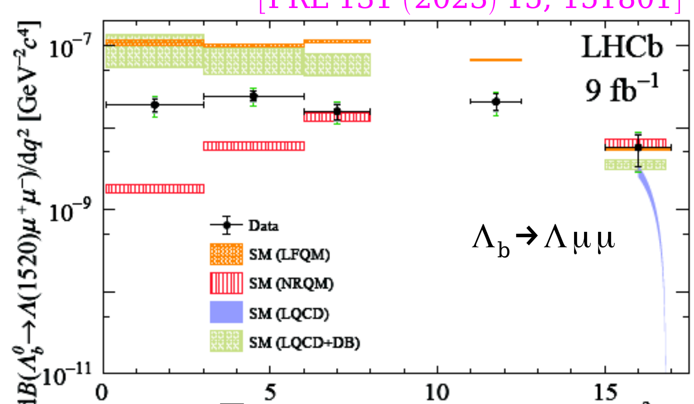
Significant change of the landscape
⇒ Compatible with SM

- BR measurements differ from predictions

[JHEP 11 (2021) 043]



[PRL 131 (2023) 15, 151801]



Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays

Model candidates

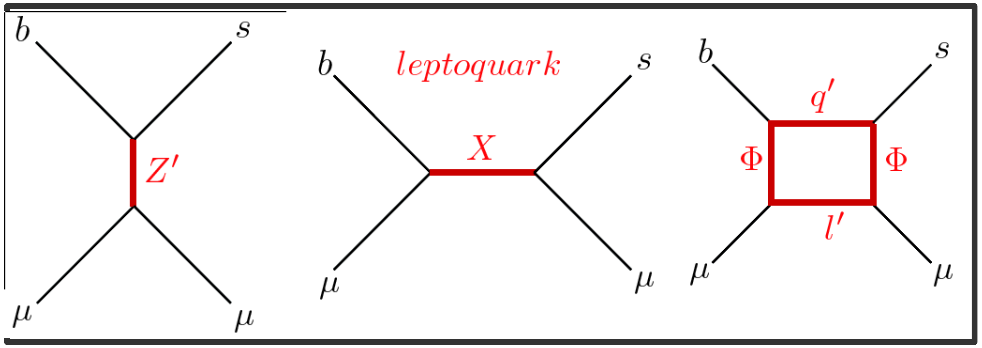
- ✓ Effective operator from Z' exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ **Models with leptoquarks**

- ✓ Effective operator from LQ exchange
- ✓ Yukawa interaction with LQs provide flavor violation

✧ **Models with loop induced effective operator**

- ✓ With extended Higgs sector and/or vector like quarks/leptons
- ✓ Flavor violation from new Yukawa interactions



Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

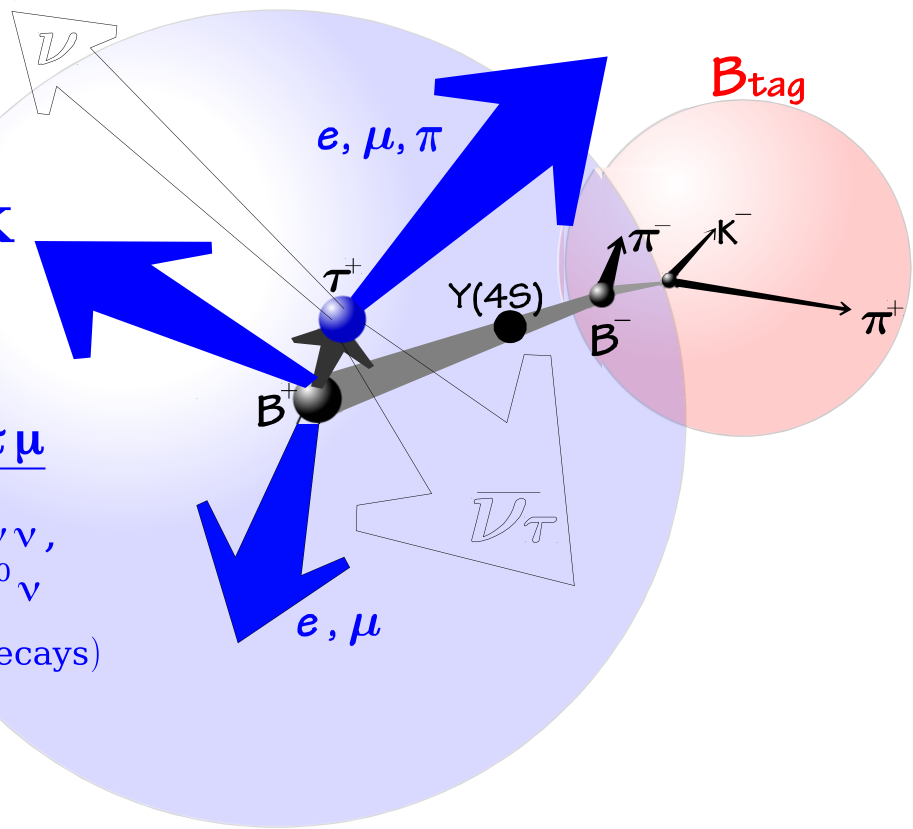
Lot of those models predict also LFV $b \to s e \mu$, $b \to s e \tau$, ...

G.Isidori, FPCP 2020: correlations among $b \to s(d) l l'$ within the U(2)-based EFT

	μμ (ee)	ττ	νν	τμ	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ → 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ → 10^{-6}	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi \tau\tau$ → 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ → 10^{-7}	$B \to \pi \mu e$???

Missing energy modes and B-tagging

Many interesting B-physics studies involve missing energy: $D^{(*)}\tau\nu$, $K\tau l$, $K^{(*)}\tau\tau$, $K^{(*)}\nu\nu$, $\pi l\nu$, τl, $\tau\nu$, $\mu\nu$... which require B-tagging.



$B_{sig} \rightarrow K\tau\mu$

$\tau \rightarrow e\nu\nu$, $\mu\nu\nu$,

$\tau \rightarrow \pi\nu$, $\pi\pi^0\nu$

(70 % of all τ decays)

B_{tag}

hadronic tag

$B \rightarrow D^{(*)}\pi$, $D^{(*)}\rho$...

$\epsilon < 1\%$

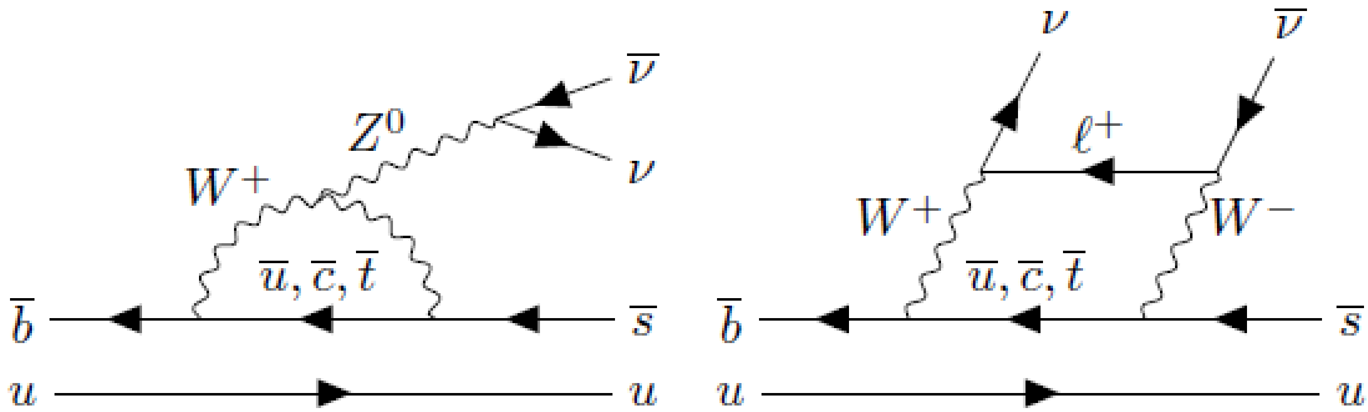
semileptonic tag

$B \rightarrow D^{(*)} l \nu X$

$\epsilon \sim 2\%$

$B \to K \nu \bar{\nu}$

[arXiv:2311.14647]
Phys.Rev.D 109, 112006 (2024)

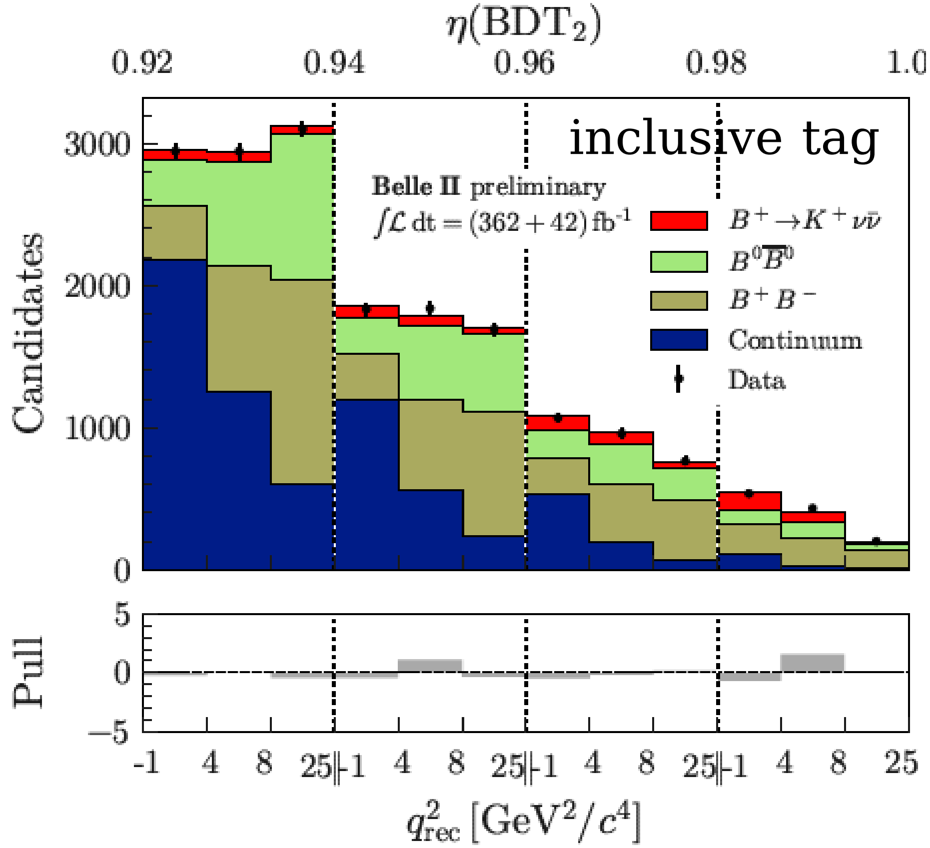


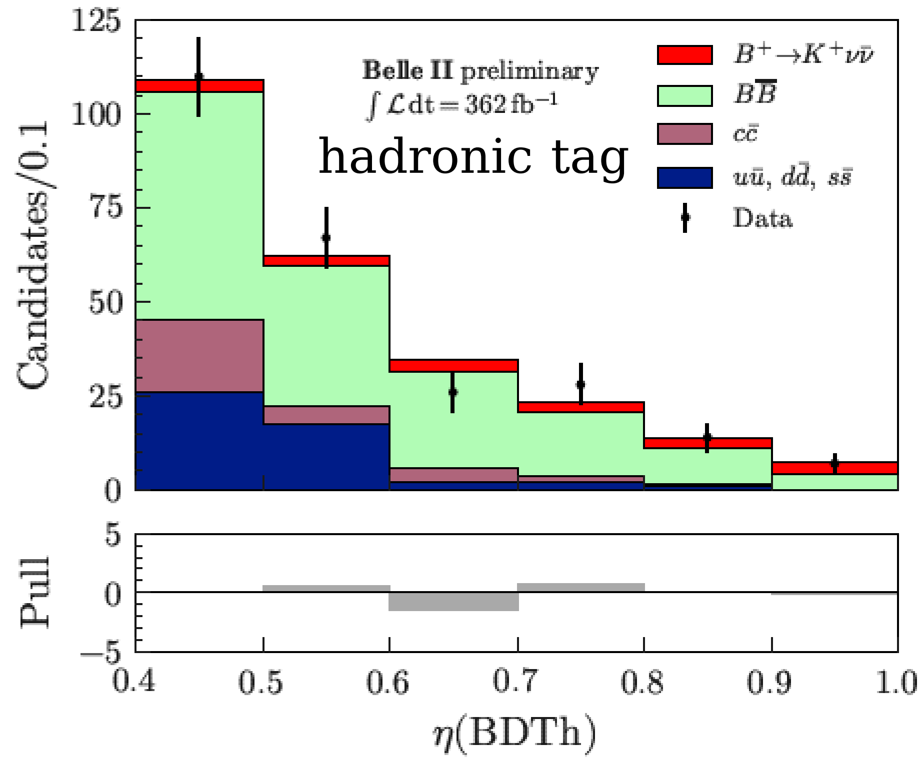
- $B \to K \nu \nu$ is known with high accuracy
  $\mathcal{B}(B \to K \nu \nu) = (5.6 \pm 0.4) \times 10^{-6}$ [arXiv:2207.13371]
- Extensions beyond SM may lead to significant rate increase
- Very challenging experimentally, not yet observed
  - Low branching fraction, high background contributions
  - 3-body kinematics, no good kinematics
- Unique for Belle II

- Two analyses:
  more sensitive **inclusive** (eff = 8%), conventional **hadronic** tagging (eff = 0.4%)
- Use event properties to suppress background with multiple variables combined
- Use classifier output as (one of) the fit variables, use simulation for signal and background templates
- Use multiple control channels to validate simulation with data

Evidence of $B \to K \nu \bar{\nu}$

[arXiv:2311.14647]
Phys.Rev.D109,112006(2024)

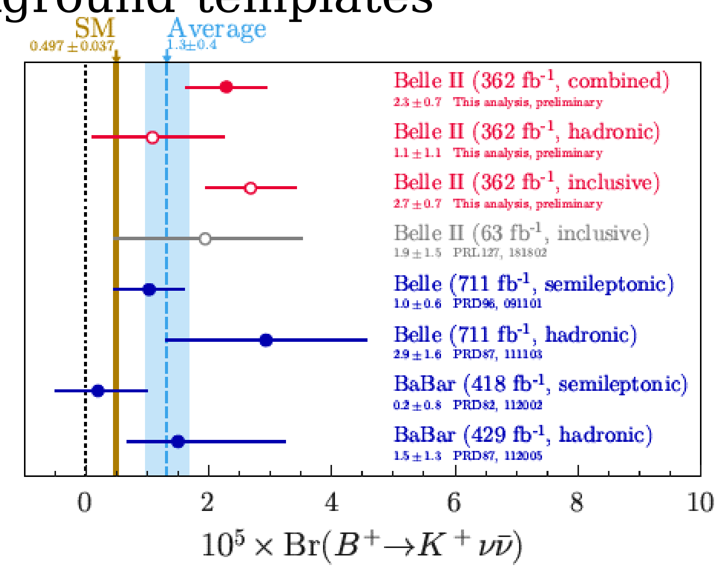




- Maximum likelihood fit to data using signal and background templates

  $\mathbf{B_{incl} = (2.7 \pm 0.5\ (stat) \pm 0.5\ (syst)) \times 10^{-5}}$

  $\mathbf{B_{had} = (1.1\ ^{+0.9}_{-0.8}\ (stat)\ ^{+0.8}_{-0.5}\ (syst)) \times 10^{-5}}$



- For inclusive analysis, evidence for $B \to K \nu \bar{\nu}$ at 3.5σ branching fraction within $\mathbf{3\sigma}$ of SM
- For hadronic tag, the result is consistent with null hypothesis and SM at 1.1σ and 0.6σ

⇒ Combination of two analyses provides first evidence of the decay at 2.7σ from SM

Search for $B \to K^{*0}\tau\tau$ decays

- FCNC processes are suppressed in SM at tree level

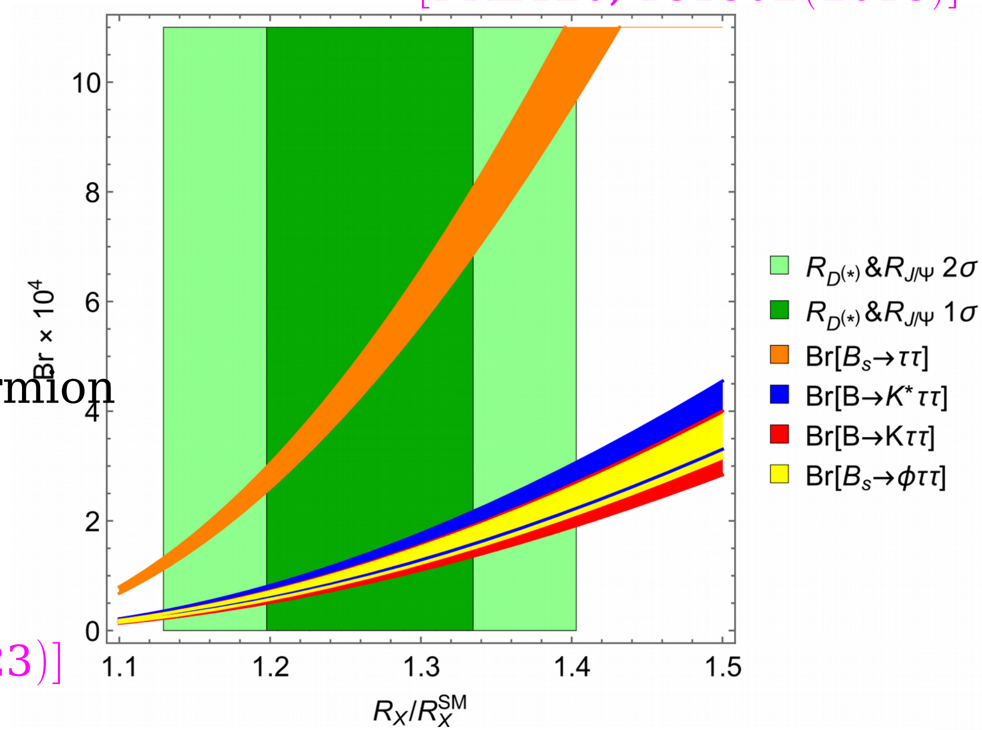
$$BF_{SM} = (1.0 \pm 0.1) \times 10^{-7}$$

[PRD 53, 4964 (1996)]

- NP models that accommodate the $b \to c\tau\nu$ anomalies predict an enhancement of several orders of magnitude with $\tau\tau$ pair in final state

  NP couplings are those involving the third−fermion generation

[PRL 120, 181802 (2018)]



Belle (711 fb^{-1}) $BF < 3.1 \times 10^{-3}$ @ 90% C.L.

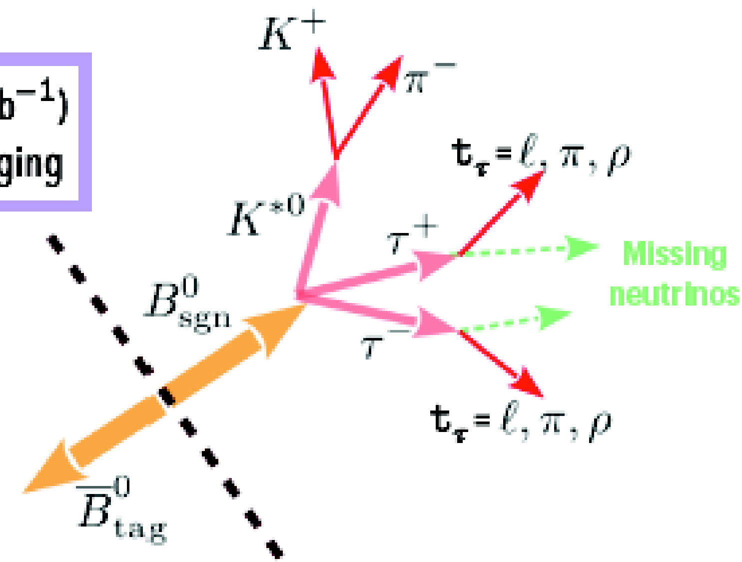
[PRD 108, L011102 (2023)]

Challenges

Similar as $B^+ \to K^+\nu\bar{\nu}$

- Low BF
- No signal peaking kinematic observable
- Large backgrounds+more than 3 prompt track
- Up to **4 neutrinos** orignating from τ
- K^{*0} has **low momentum** due to the phase space

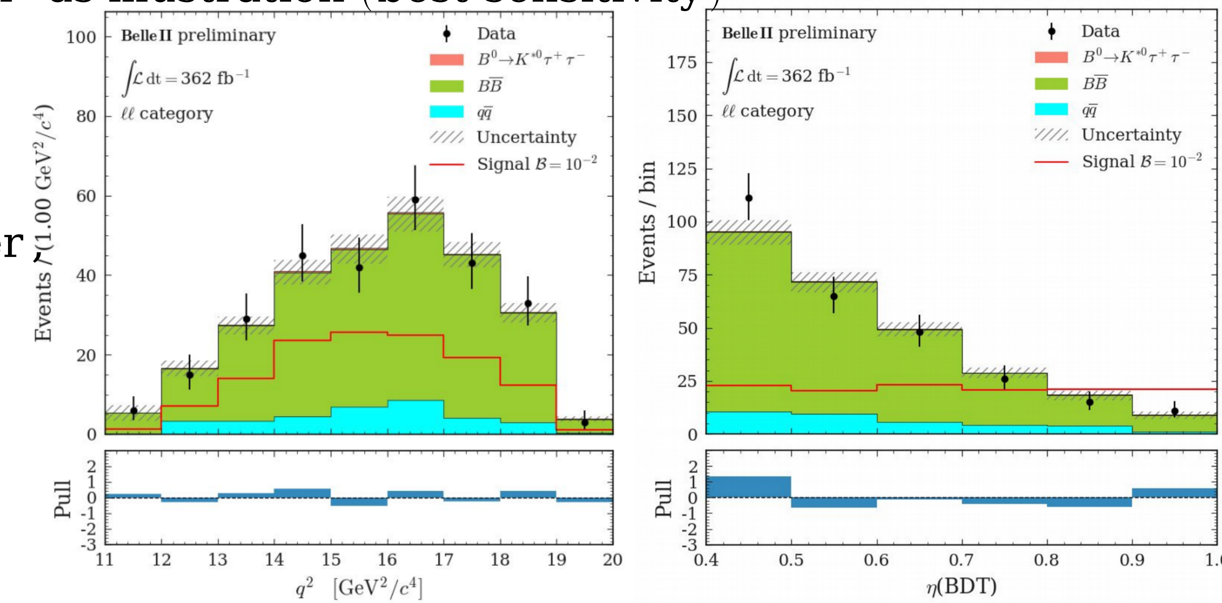
Belle II (364 fb^{-1})
hadronic B-tagging



Search for $B \to K^{*0}\tau\tau$ decays

[PRELIMINARY]

l^+l^- as illustration (best sensitivity)



- Combinations of 4 categories: l^+l^-, $l\pi$, $\pi\pi$, ρX
- BDT trained using missing energy, extra cluster energy in EM calorimeter $M(K^{*0}t_\tau)$, q^2, …
- BDT output η(BDT) is used to extract signal yield with a simultaneous fit to 4 categories

Validation

- total efficiency and peaking $B^0\overline{B^0}$: $B \to J/\psi K^{*0}$ sample, replace $J/\psi K^{*0}$ with $K^{*0}\tau^+\tau^-$ (14% uncertainty)
- Non−peaking $B\bar{B}$: sample with B_{sig} and B_{tag} having same flavor
- $q\bar{q}$ background is scaled by off−resonance data

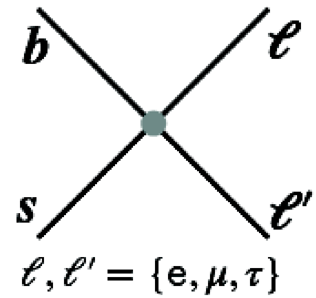
Belle II (364 fb^{-1}) BF $(B \to K^{*0}\tau\tau) < 1.8\times10^{-3}$ @ 90% C.L.

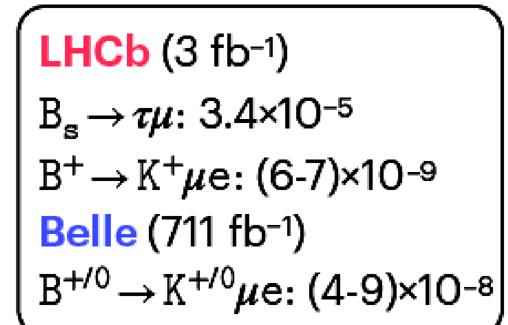
The most stringent limit among the results for $b \to s\tau\tau$ transition

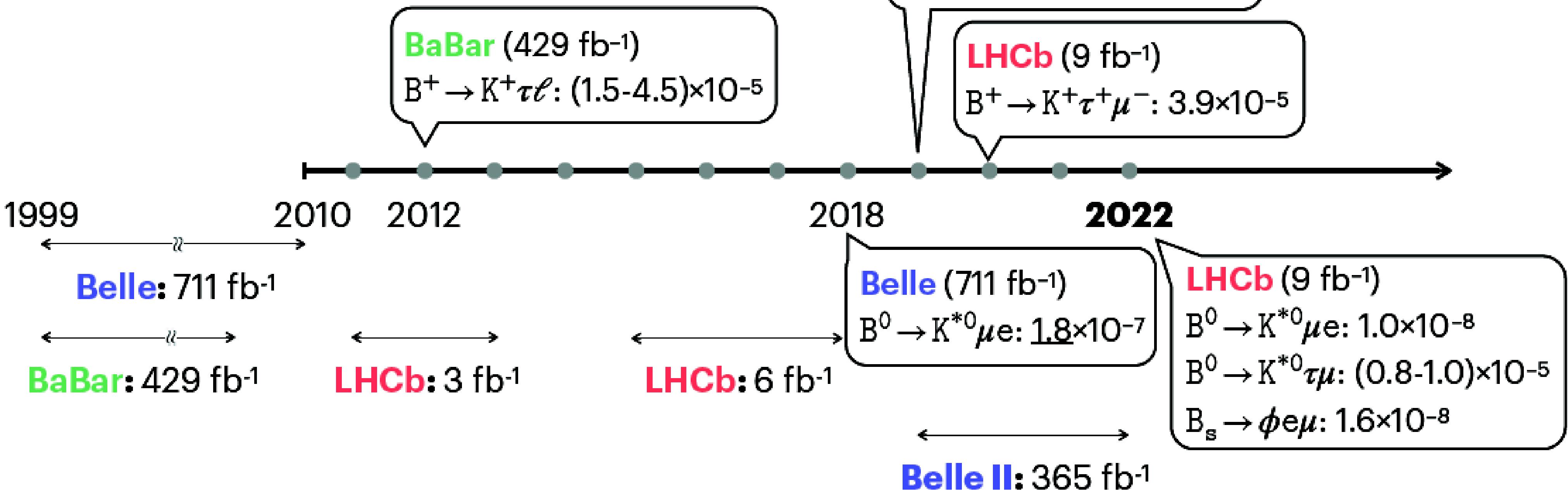
Twice better with only half sample wrt Belle !
Better tagging + more categories + BDT classifer…

EXPERIMENTAL STATUS ON $b \to s\ell\ell'$

Many LFV searches triggered in the last years by the current B-anomalies







Limits on modes with τ's are not as constraining as those with μe because of the **more challenging τ reconstruction**

- **$(2\text{-}5)\times10^{-5}$ range for $B^+ \to K^+\tau\ell$ (BaBar and LHCb)**

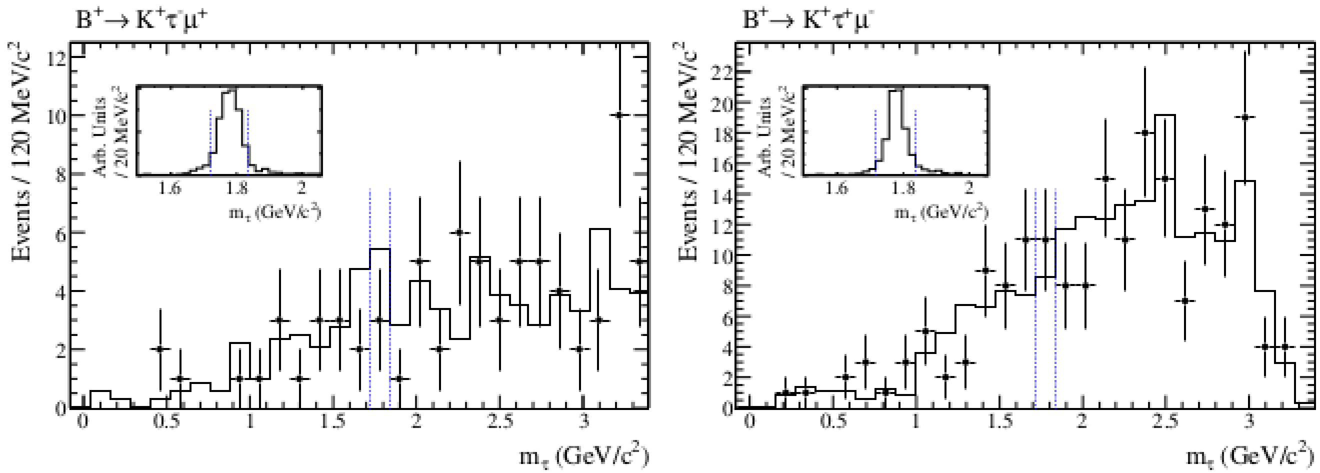
LFV $B \to K \tau l$ ($l = e, \mu$) decays

[BaBar, arXiv:1204.2852]

strategy used: B fully reconstructed (had tag), $\tau^+ \to l^+ \nu_l \nu_\tau$, $(n\pi^0)\pi\nu$, with $n \geq 0$

using momenta of K, l and B, **can fully determine the τ four-momentum**

unique system: no other neutrino than the ones from one tau ($\neq B \to \tau\nu$, $D^{(*)}\tau\nu$...)



$B(B^+ \to K^+ \tau^- \mu^+) < 4.5 \times 10^{-5}$ at 90%CL, $B(B^+ \to K^+ \tau^+ \mu^-) < 2.8 \times 10^{-5}$ at 90%CL

(also results for $B \to K^+ \tau^\pm e^\mp$, $B \to \pi^+ \tau^\pm \mu^\mp$, $B \to \pi^+ \tau^\pm e^\mp$ modes)

[Belle II, arXiv:1808.10567]

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	–	–	< 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

⇒ can we do better ? combining hadronic tag with an more inclusive tag...

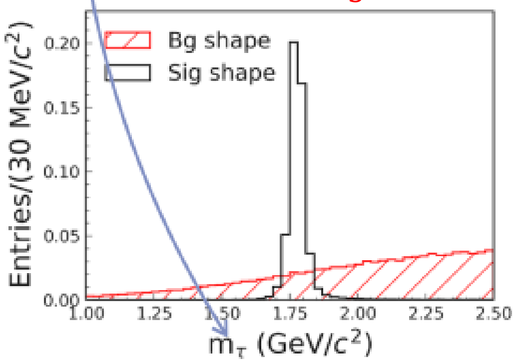
⇒ can do $K^*\tau e$, $K^*\tau\mu$ with similar sensitivity...

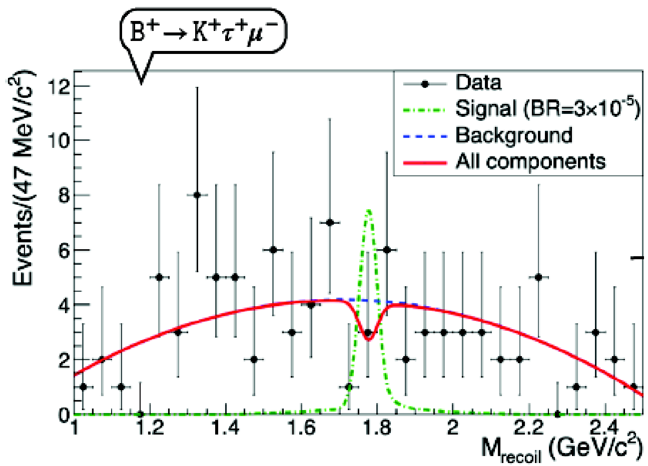
Missing energy modes and B-tagging

Many interesting B-physics studies involve missing energy: $D^{(*)}\tau\nu$, $K\tau l$, $K^{(*)}\tau\tau$, $K^{(*)}\nu\nu$, $\pi l\nu$, τl, $\tau\nu$, $\mu\nu$... which require B-tagging.

$$m_\tau^2 = (p_{e^+e^-} - p_K - p_\ell - p_{B_{tag}})^2$$

neutrinos are all coming from the τ !

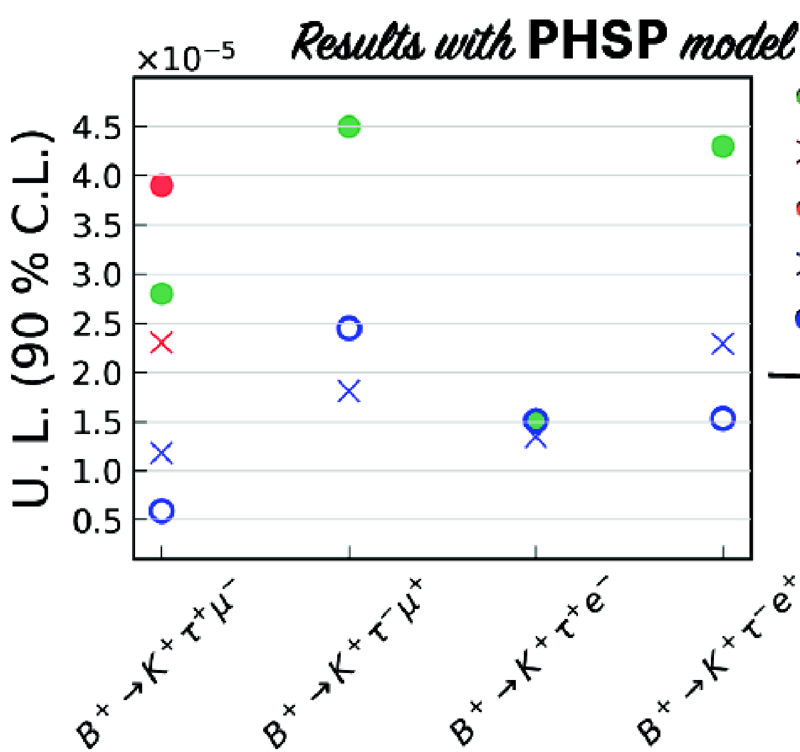




[Belle, PRL 130, 261802 (2023)]

Mode	N_{sig}	ε (%)	$\mathcal{B}^{UL}$ (10^{-5})	$\mathcal{B}^{UL}_{NP}$ (10^{-5})
$B^+ \to K^+\tau^+\mu^-$	-2.1 ± 2.9	0.064	0.59	0.65
$B^+ \to K^+\tau^+e^-$	1.5 ± 5.5	0.084	1.51	1.71
$B^+ \to K^+\tau^-\mu^+$	2.3 ± 4.1	0.046	2.45	2.97
$B^+ \to K^+\tau^-e^+$	-1.1 ± 7.4	0.079	1.53	2.08

PHSP



- BaBar (426 fb-1) — Hadronic B-tagging
- LHCb (9 fb-1) - expected
- LHCb (9 fb-1) — $B^{*0}_{s2} \to B^+K^-$ tagged
- Belle (711 fb-1) - expected
- Belle (711 fb-1) — Hadronic B-tagging

with less than 1 ab^{-1}...competitive with LHCb !

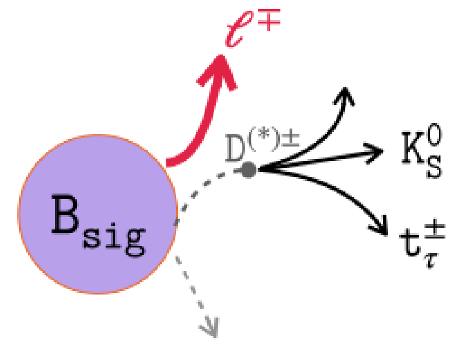
World's best limits for the $B^+ \to K^+\tau\ell$ modes

More to come:
- $B^0 \to K^0_S \tau l$
- $B^+ \to K^+ \tau \tau$

LFV $B \to K_S^0 \tau l \ (l = e, \mu)$ decays

[PRELIMINARY]

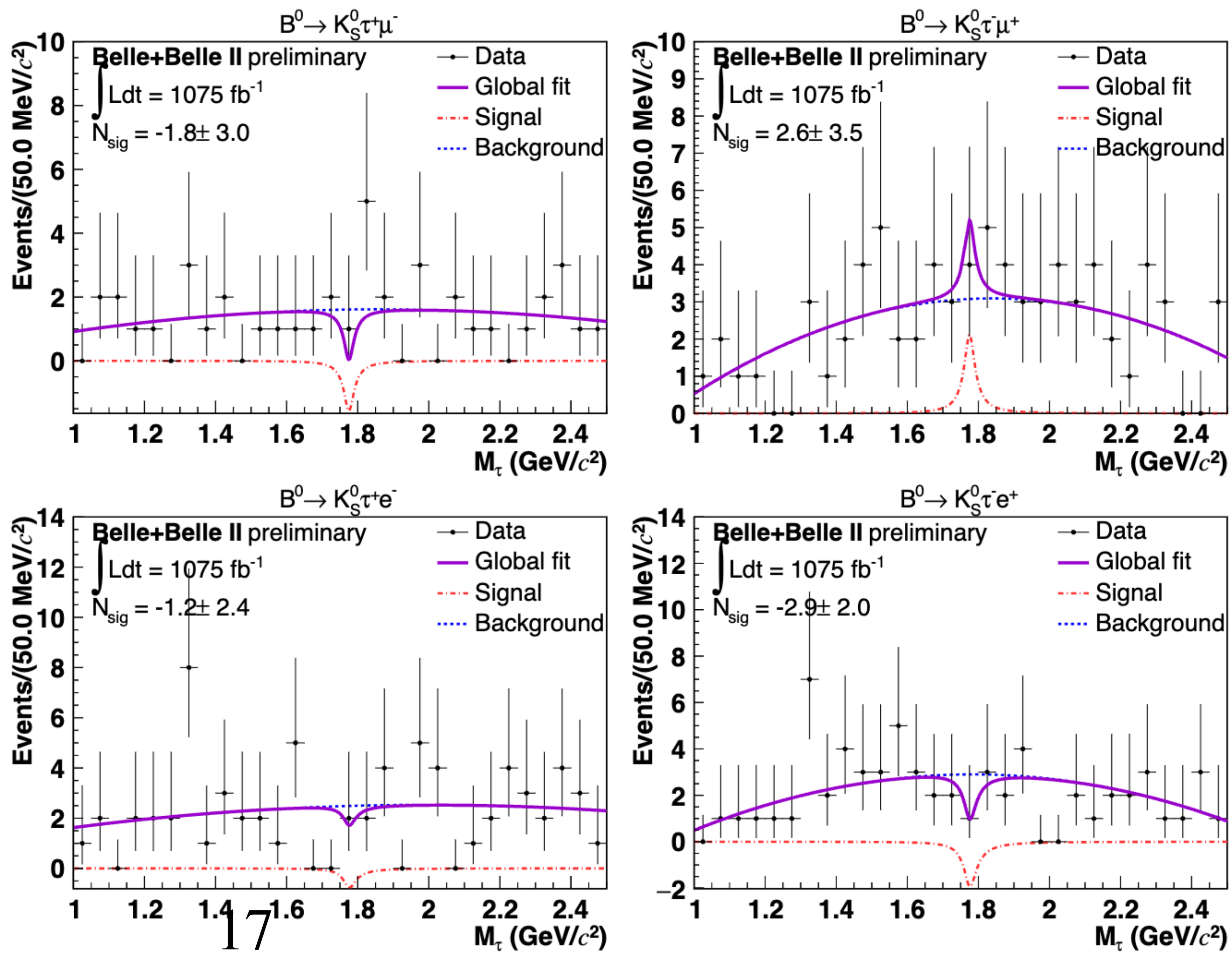
- Belle + Belle II $(711 + 364 \ \mathrm{fb}^{-1})$
- K_S^0 purity is larger than 98%
- Dominant bkg: B semi-leptonic decay
- BDT for remaining bkg suppression



First searches in $B^0 \to K_S^0 \tau^{\pm} l^{\mp}$

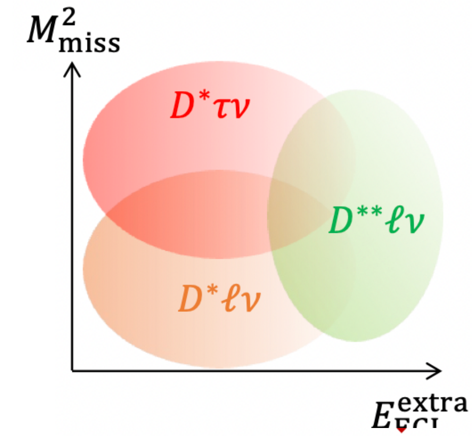
90% CL upper limits:

$$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$



First Belle II result on $B(B\to D^{*}\tau\nu)/B(B\to D^{*}l\nu)$

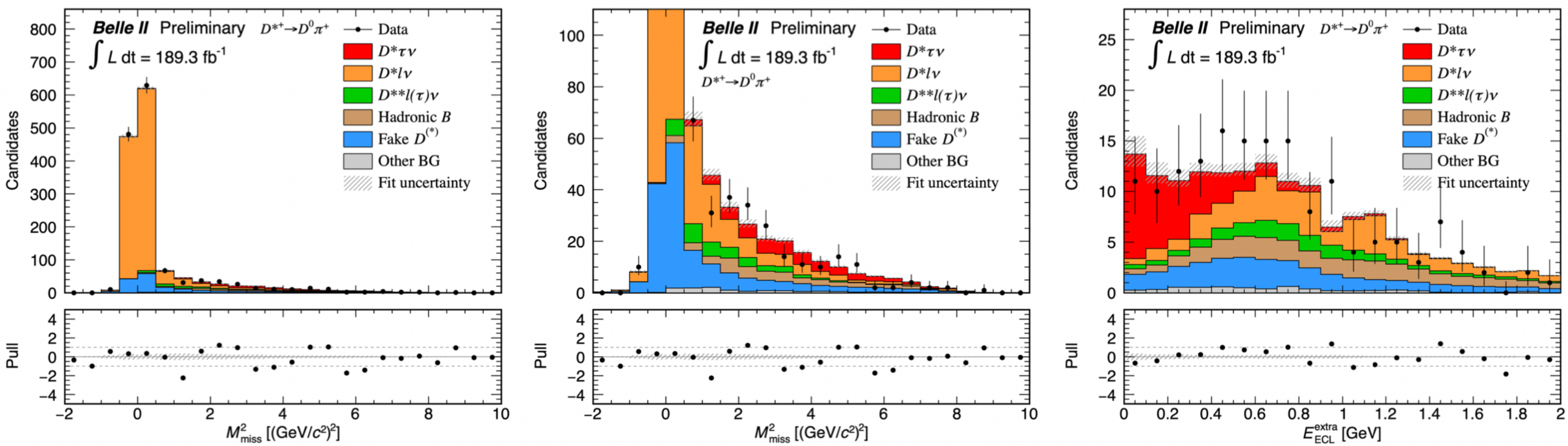
- Half of available sample (200 million $B\overline{B}$ pairs)
- Fully reconstruct the partner B in the event to suppress bckg
- Reconstruct numerator and denominator with ~ same selections
- Two-dimensional fit of missing mass and total residual energy in calorimeter determines signal yields
- Data sidebands validate understanding of sample composition



Post-fit distributions for $D^{*+}\to D^0\pi^+$

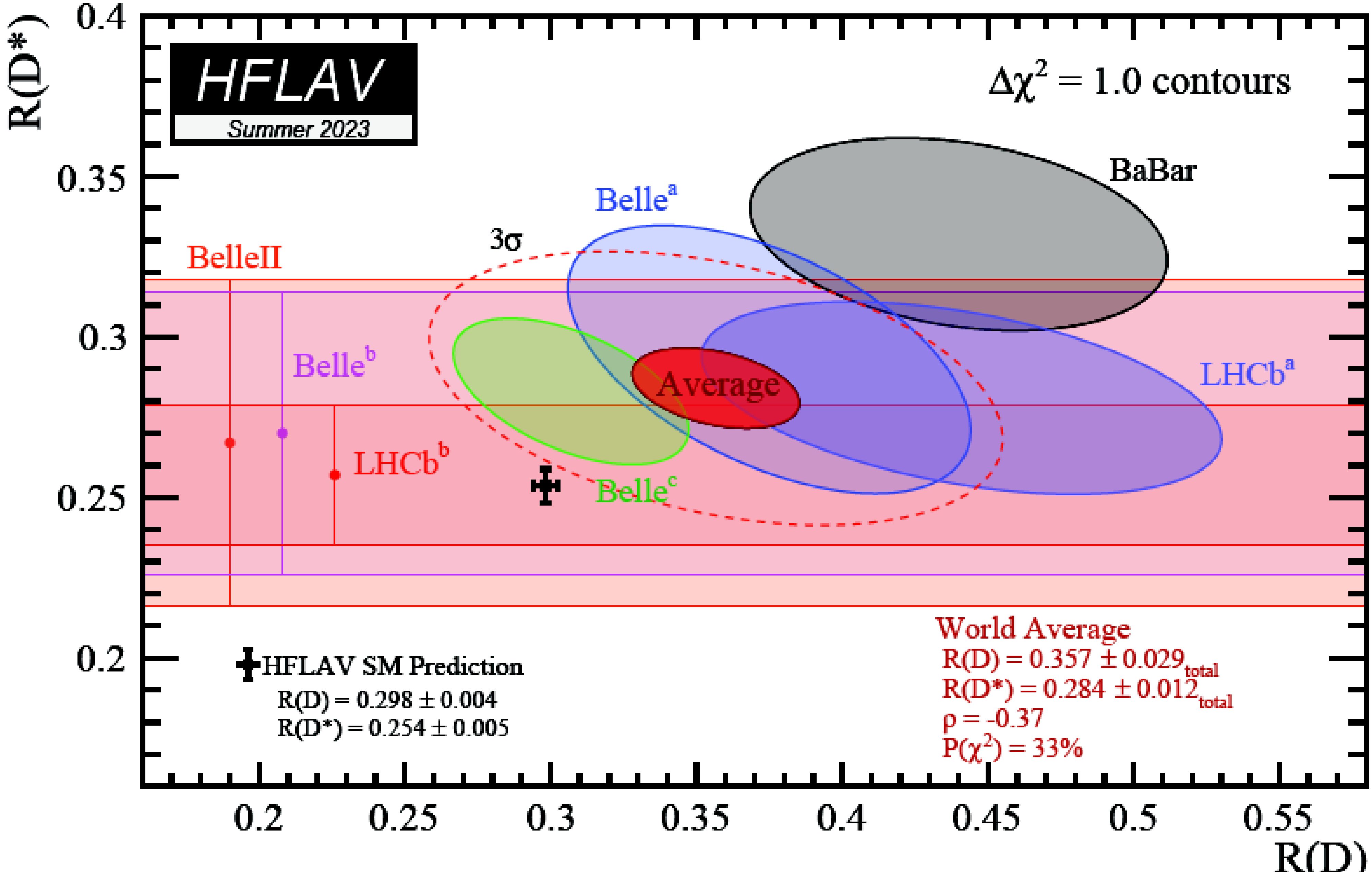
$$M^2_{miss} = (p_B - p_{X_c} - p_\mu)^2$$

$1.5 < M^2_{\rm miss} < 6.0\ ({\rm GeV}/c^2)^2$



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

Not leading, 40% improvement in statistical precision over Belle at the same sample size
Consistent with WA



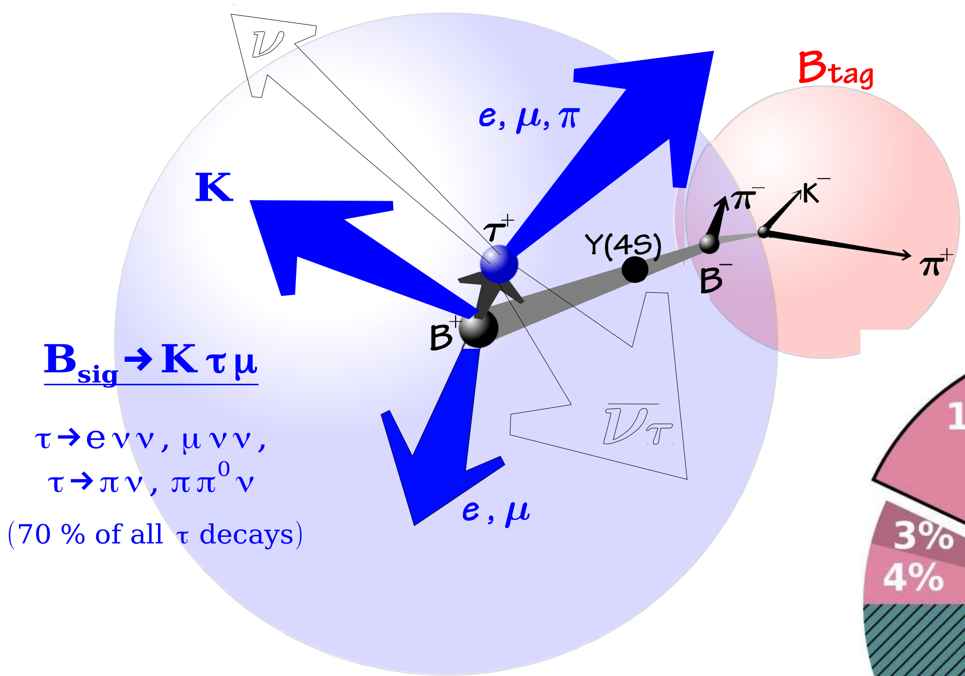
⇒ 3.3σ tension wrt SM

More measurements to come from LHCb and Belle (II)

More observables (e.g. D^* polarization [LHCb, arXiv:2311.05224; Belle, arXiv:1903.03102])

Missing energy modes and B-tagging

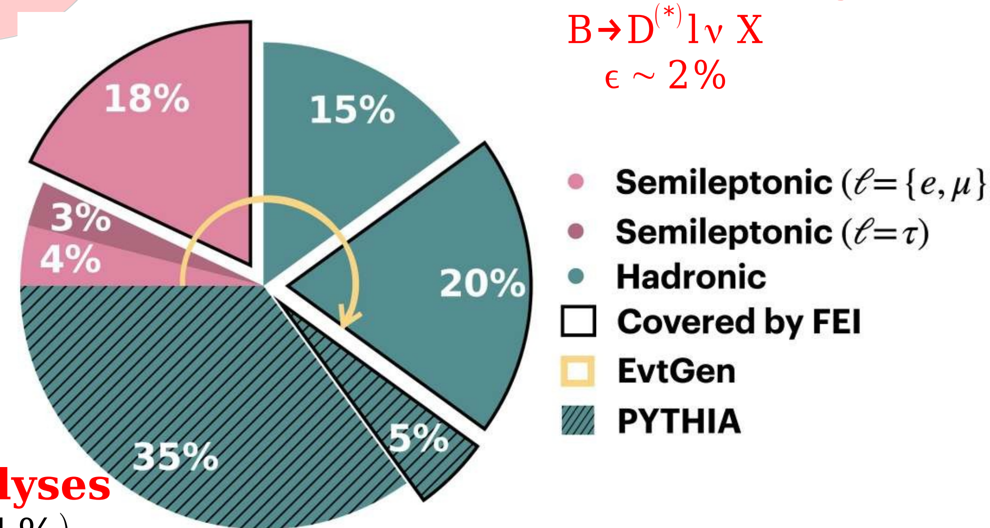
Many interesting B-physics studies involve missing energy: $D^{(*)}\tau\nu$, $K\tau l$, $K^{(*)}\tau\tau$, $K^{(*)}\nu\nu$, $\pi l\nu$, τl, $\tau\nu$, $\mu\nu$... which require B-tagging.



B_{tag}

hadronic tag
$B \to D^{(*)}\pi$, $D^{(*)}\rho$...
$\epsilon < 1\%$

semileptonic tag
$B \to D^{(*)} l \nu X$
$\epsilon \sim 2\%$



B-tagging is key tool for missing energy analyses

- low efficiency (efficiency for hadronic B-tagging < 1%)
- and ML can't save you... B-tagging algorithms are trained using MC samples
- 40% of hadronic B decays generated by PYTHIA...
- and even among the EvtGen part... most BFs measured are old measurements from ARGUS, CLEO...

➜ **calibration is an important and delicate task**

Lot of on-going improvements:

- improve our simulation of all B_{tag} modes included ➜ better B-tagging performance
- also some opportunities to remeasure/study those B decays and intermediate states

Branching fraction of $B^+ \to D^0 \rho^+$ at Belle II

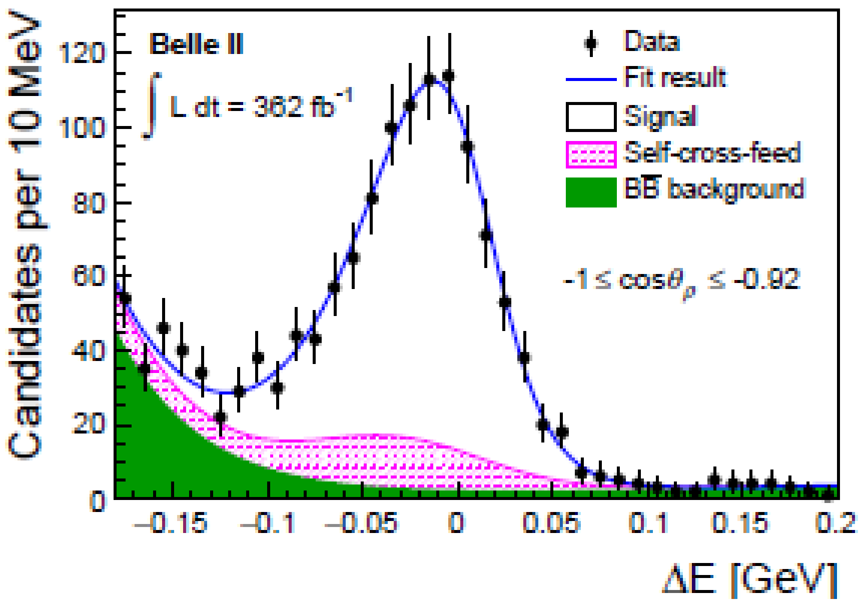
- Test heavy-quark limit and factorization models
  [Nucl. Phys. B 591, 313 (2000)]

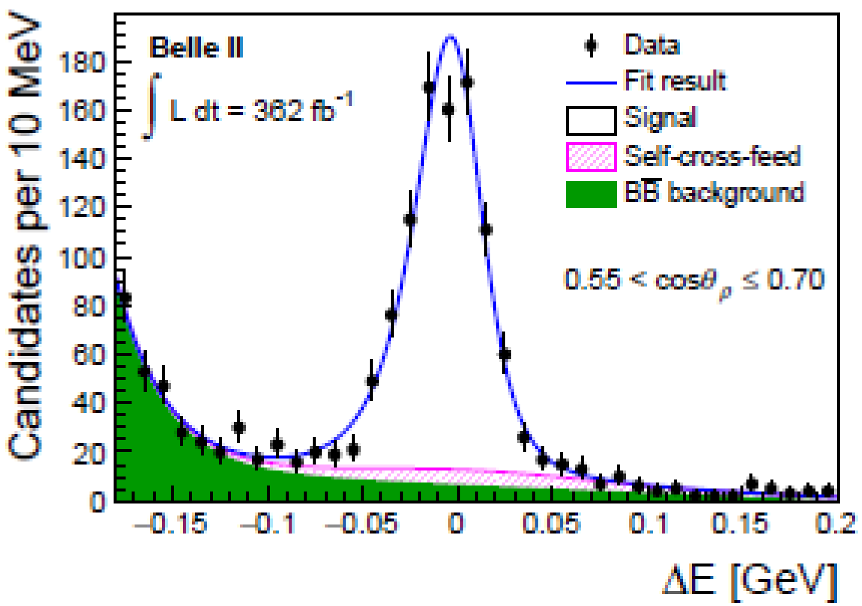
WA BF = $(1.35 \pm 0.18)\%$ driven by CLEO measurement with large uncertainty (14%)
[CLEO, PRD 50, 43 (1994)]

- Signal extracted from fit to ΔE

Challenge: separate $B^+ \to D^0 \rho^+ (\to \pi^+ \pi^0)$ resonant and $B^+ \to D^0 \pi^+ \pi^0$ non-resonant components
Fit performed in bins of helicity angle $(\cos\theta_\rho)$

θ_ρ: angle between π momentum and direction opposite to B momentum in ρ rest frame



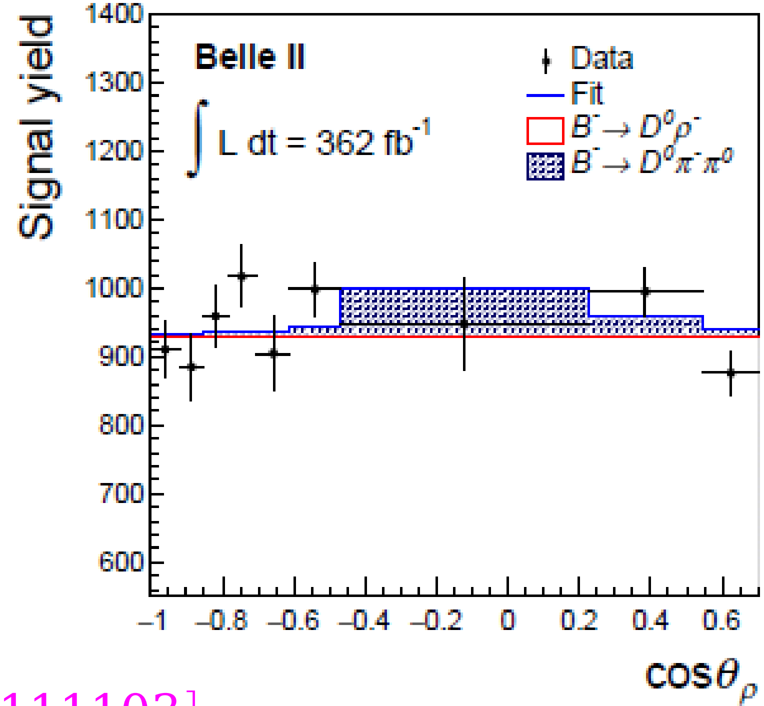


Branching fraction of $B^+ \to D^0 \rho^+$ at Belle II

Template fit in $\cos\theta_\rho$

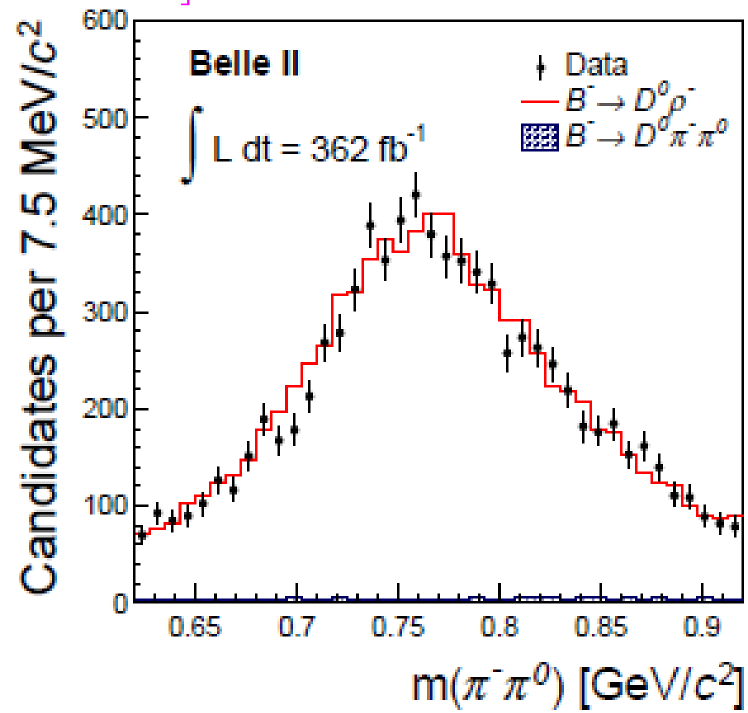
– Flat $\cos\theta_\rho$ distribution for $B \to D\rho$

– Less than 2% contribution of $B^+ \to D^0 \pi^+ \pi^0$ S-wave component



$$BF(B^+ \to D^0 \rho^+) = (0.94 \pm 0.02 \pm 0.05)\%$$

[arXiv:2404.10874, Phys Rev D. 109, L111103]



– World's best result with more than 2× improvement

– Factorisation test: in agreement with prediction

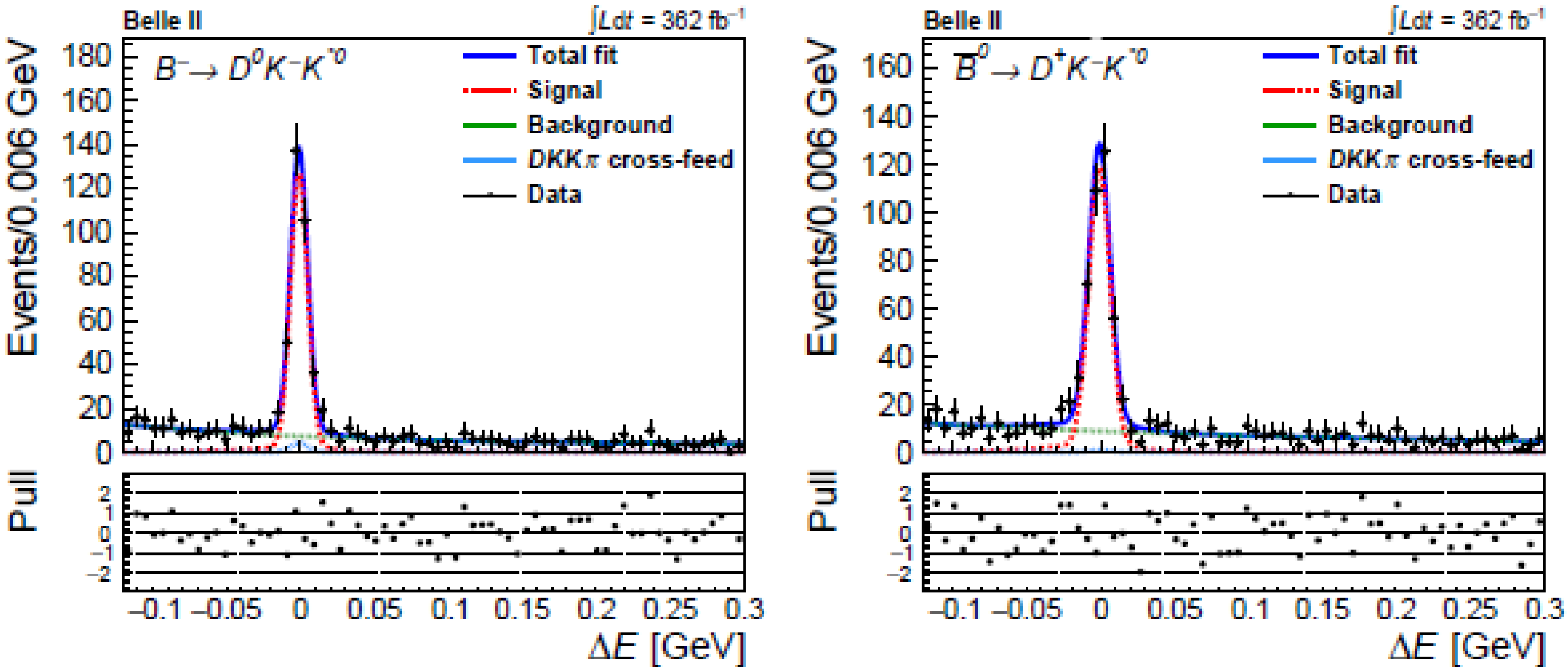
– Systematically limited by uncertainty on π^0 efficiency

$B \to D^{(*)} K K_{(s)}^{(*)0}$ at Belle II

[arXiv:2406.06277, accepted by JHEP]

B→DKK: largely unexplored sector

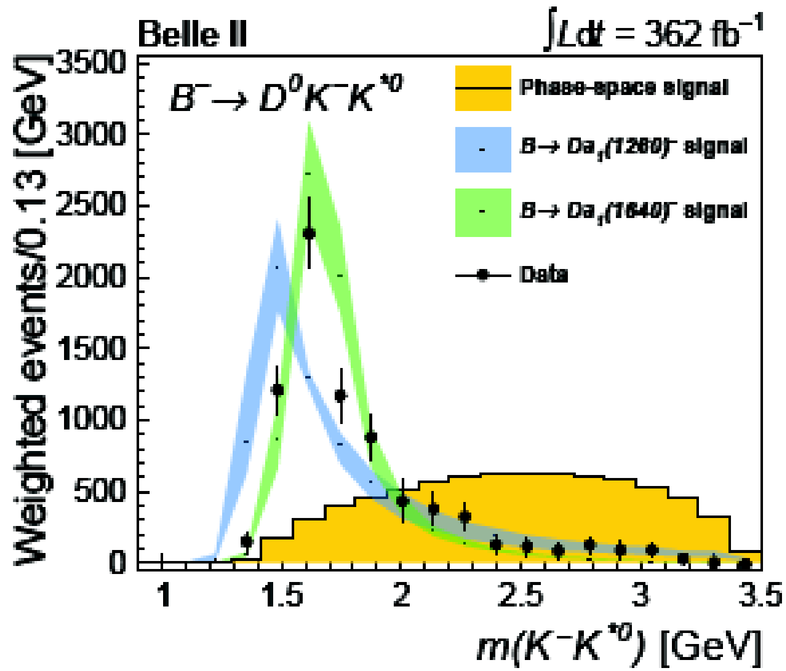
- few % of B branching fraction expected
- Only 0.3% measured so far



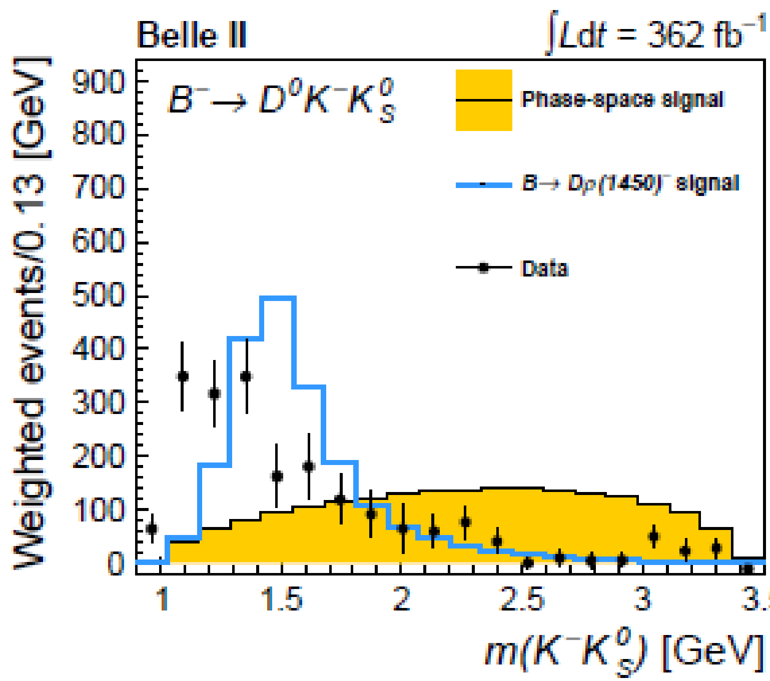
- Challenge: estimate non-resonant B→DKKπ modes (non K^*)
- Signal extracted from fit to ΔE
- Subtract background, and look at invariant mass and Dalitz distributions

$B \to D^{(*)} K K^{(*)0}_{(S)}$ at Belle II

[arXiv:2406.06277, accepted by JHEP]



- Efficiency correction applied in the planes $m(D^{(*)}K^-)$ and $m(K^- K^{(*)0}_{(S)})$
- Extraction of bkg-subtracted and efficiency corrected invariant mass and helicity
- Dominant transitions $J^P = 1^{-/+}$
- $B \to D^{(*)} D_s(\to KK^{(*)})$ are used as control modes



$B \to D^{(*)} K K_{(S)}^{(*)0}$ at Belle II

[arXiv:2406.06277, accepted by JHEP]

Channel	Yield	Average ε	$\mathcal{B}$ $[10^{-4}]$	
$B^- \to D^0 K^- K_S^0$	209 ± 17	0.098	$1.82 \pm 0.16 \pm 0.08$	World's best
$\overline{B}^0 \to D^+ K^- K_S^0$	105 ± 14	0.048	$0.82 \pm 0.12 \pm 0.05$	
$B^- \to D^{*0} K^- K_S^0$	51 ± 9	0.044	$1.47 \pm 0.27 \pm 0.10$	First observation
$\overline{B}^0 \to D^{*+} K^- K_S^0$	36 ± 7	0.046	$0.91 \pm 0.19 \pm 0.05$	First observation
$B^- \to D^0 K^- K^{*0}$	325 ± 19	0.043	$7.19 \pm 0.45 \pm 0.33$	World's best
$\overline{B}^0 \to D^+ K^- K^{*0}$	385 ± 22	0.021	$7.56 \pm 0.45 \pm 0.38$	World's best
$B^- \to D^{*0} K^- K^{*0}$	160 ± 15	0.019	$11.93 \pm 1.14 \pm 0.93$	World's best
$\overline{B}^0 \to D^{*+} K^- K^{*0}$	193 ± 14	0.020	$13.12 \pm 1.21 \pm 0.71$	World's best
$B^- \to D^0 D_s^-$	144 ± 12 / 153 ± 13	0.09 / 0.04	$95 \pm 6 \pm 5$	Precision compatible with WA
$\overline{B}^0 \to D^+ D_s^-$	145 ± 12 / 159 ± 13	0.05 / 0.02	$89 \pm 5 \pm 5$	Precision compatible with WA
$B^- \to D^{*0} D_s^-$	30 ± 6 / 29 ± 7	0.04 / 0.02	$65 \pm 10 \pm 6$	Precision compatible with WA
$\overline{B}^0 \to D^{*+} D_s^-$	43 ± 7 / 37 ± 7	0.04 / 0.02	$83 \pm 10 \pm 6$	

Total 12 channels, first observation for 3 channels
World's best precision for the rest

Summary

- Very active field: many more results than shown (with run 1 data $\sim 400\ \mathrm{fb}^{-1}$)

- Importance to have both the e^+e^- and pp environments

- Belle (II) is a unique environment to study B decays with missing energy
  $B \to K\nu\bar{\nu}$, $K\tau\tau$, $K\tau l$, $\tau\tau$, τl, $D^{(*)}\tau\nu$, $\tau\nu$, $\mu\nu$...
  (and urgently improving our understanding of hadronic B decays and consequently our B-tagging efficiency)

  and τ sector...

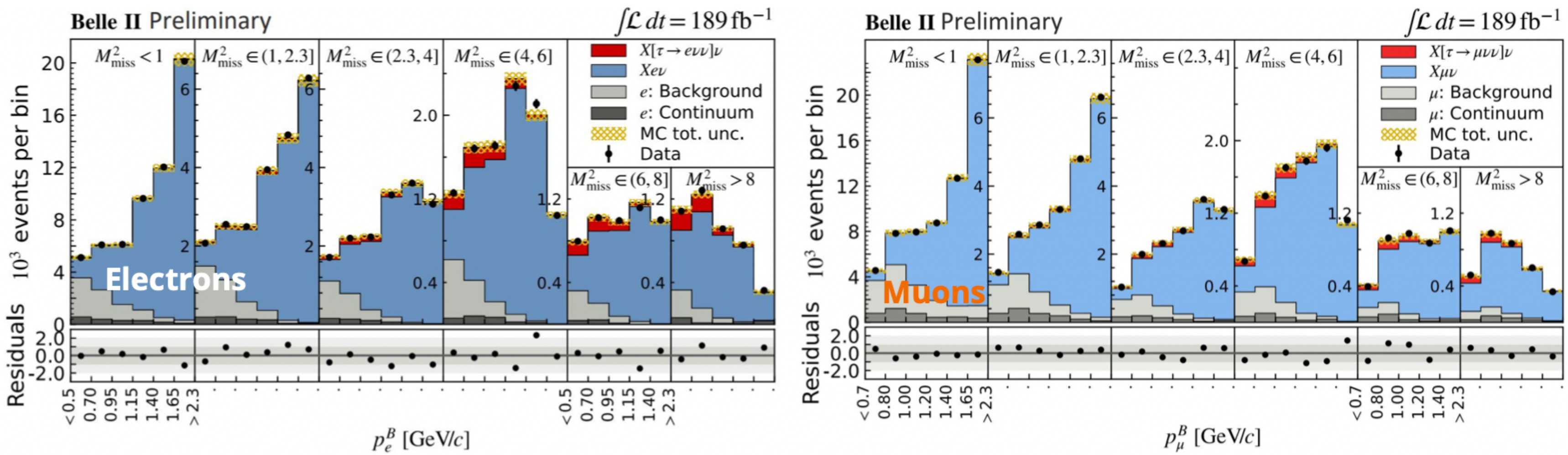
  ...but also perform precise measurements of CKM UT (CPV or not),
  low mutiplicity, dark sector... and many other opportunities

- Resumed data taking (run 2) in 2024, goal is to reach $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$,
  and $o(5\ \mathrm{ab}^{-1})$ by 2029

First B factory result on B(B→[c]τν)/B(B→[c]lν)

[arXiv:2311.07248]

- BF ratio without explicitly reconstructing the charm meson offers an unique, supplementary and theoretically more reliable probe, than $R(D^{(*)})$
- Half of available sample (200 million $B\bar{B}$ pairs)
- Fully reconstruct the partner B in the event to suppress bckg
- Sophisticated event weighting to ensure proper sample-composition, validated in multiple sidebands.
- Two-dimensional fit of lepton momentum and missing mass provides signal yield:



Complex analysis, requiring multiple corrections/reweighting to simulated samples

Excellent agreement between electron and muon channel measurements:

$$R(X_{\tau/e}) = 0.232 \pm 0.020\ (\text{stat}) \pm 0.037\ (\text{syst})$$

$$R(X_{\tau/\mu}) = 0.222 \pm 0.027\ (\text{stat}) \pm 0.050\ (\text{syst})$$

Systematics is largely from data-driven corrections in control regions

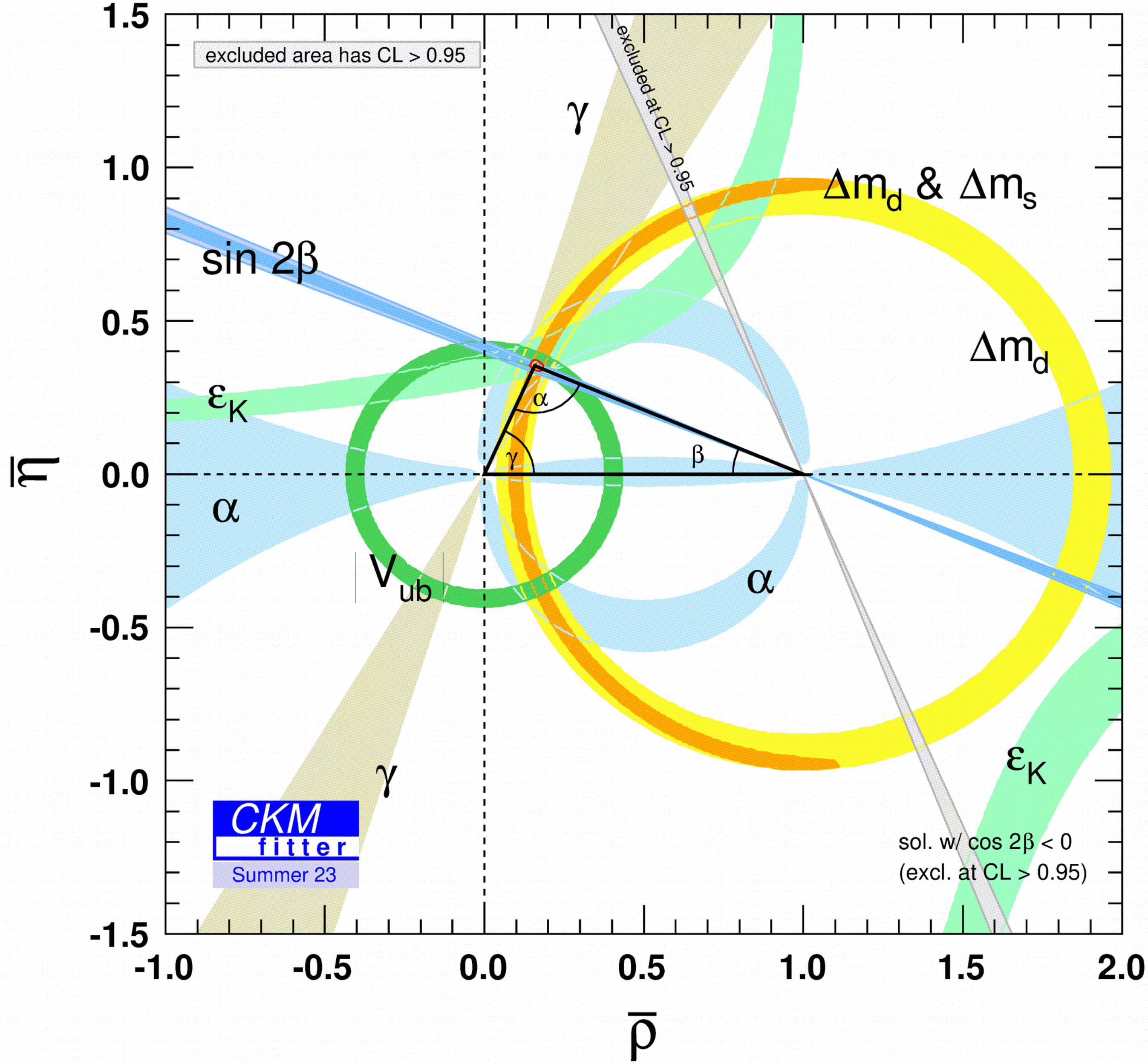
Combined result

***R(X)* = 0.228 ± 0.016(stat) ± 0.036 (syst)**

is consistent with SM 0.223±0.006, but also with measurements of *$R(D^{(*)})$*

First ever such result from B factories

The current status of CKM
(CKMfitter 2023)



$|V_{ud}|, |V_{us}|, |V_{cb}|, |V_{ub}|_{SL}$

$B \to \tau\nu, |V_{ub}|_{\Lambda_b}$

$\Delta m_d, \Delta m_s, \epsilon_K$

$\alpha, \sin 2\beta, \gamma$

$\mathbf{A = 0.822^{+0.005}_{-0.008}}$

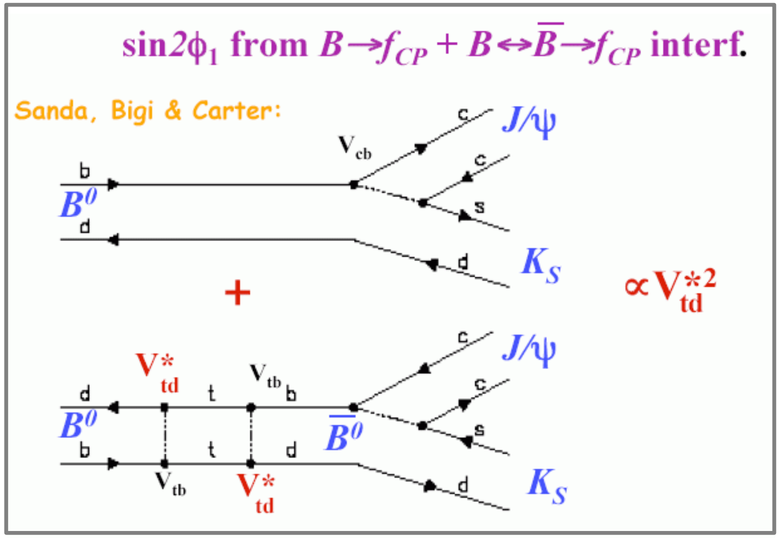
$\mathbf{\lambda = 0.22498^{+0.00023}_{-0.00021}}$

$\mathbf{\bar\rho = 0.156^{+0.011}_{-0.004}}$

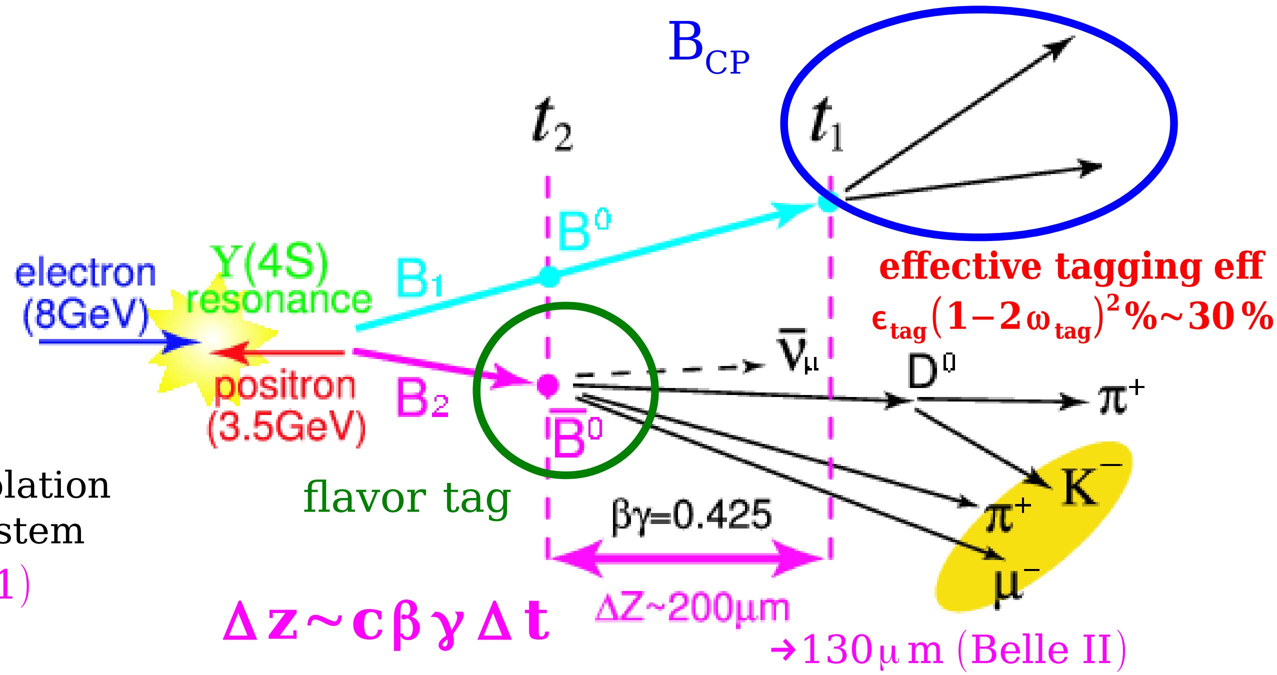
$\mathbf{\bar\eta = 0.355^{+0.005}_{-0.006}}$

(68% CL)

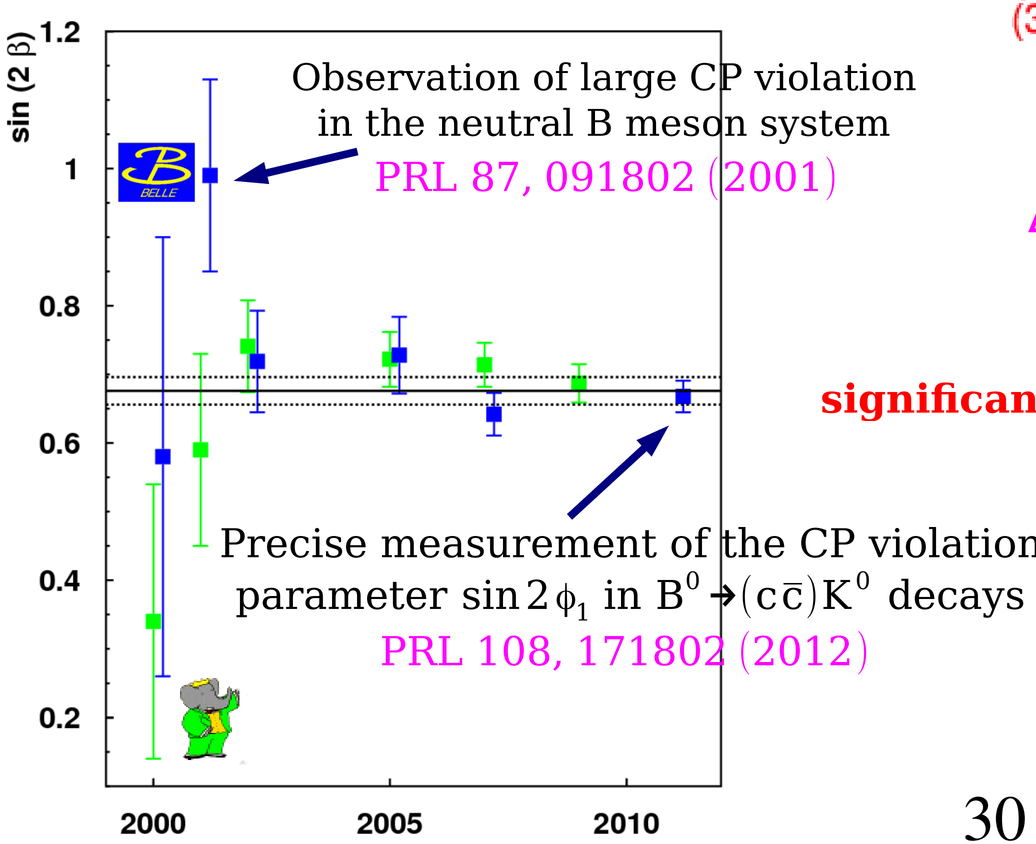
Time−dependent CP asymmetries in decays to CP eigenstates



$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left(1 + q\left(S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t)\right)\right)$$



Raison d'être of SVD+PXD
significant resolution improvement for Belle II
(but also improvement of flavour tagging)

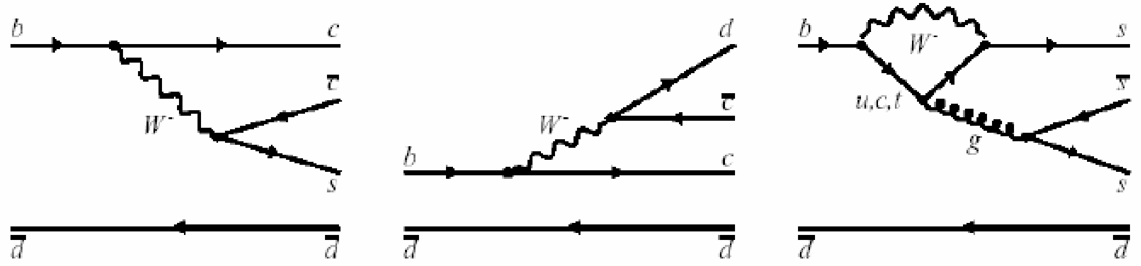


A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's

Critical role of the B factories in the verification of the KM hypothesis

$\sin 2\beta$ with $b \to s$ penguins

dominated by B-factories



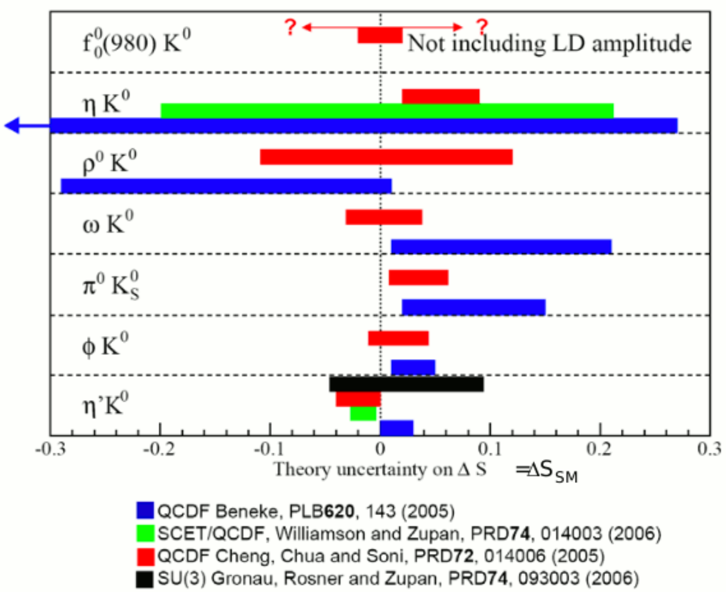
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0$, $\eta_c K_S^0, J/\psi K_L^0$, $J/\psi K^{*0}(K^{*0} \to K_S^0\pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0$, $K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0$, $\omega K_S^0, f_0(980)K_S^0$

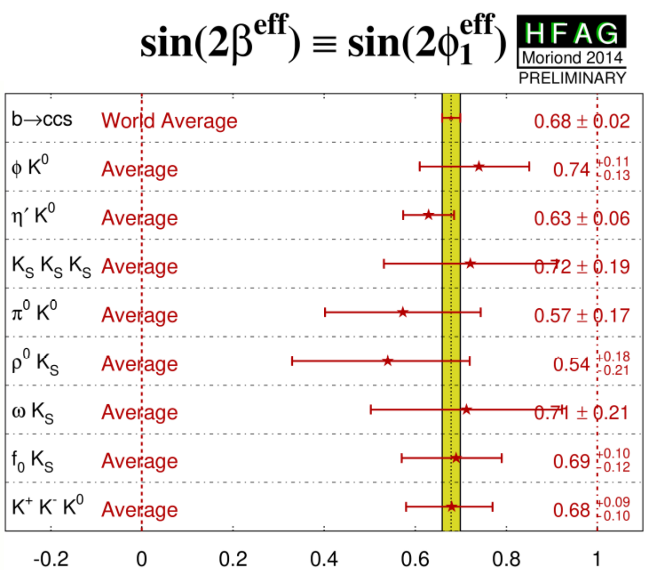
← increasing tree diagram amplitude

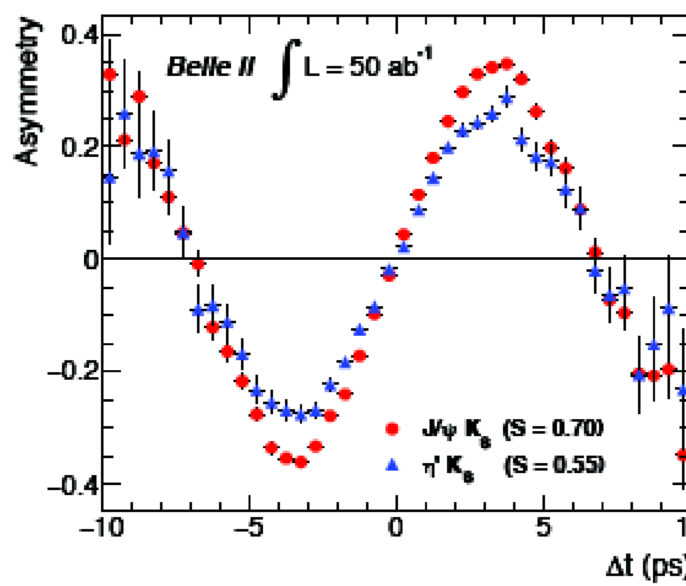
increasing sensitivity to new physics →

More statistics crucial for mode-by-mode studies

Channel	$\int \mathcal{L}$	Event yield	$\sigma(S)$	$\sigma(A)$
ϕK^0	5 ab^{-1}	5590	0.048	0.035
$\eta' K^0$	5 ab^{-1}	27200	0.027	0.020
ωK_S^0	5 ab^{-1}	1670	0.08	0.06
$K_S\pi^0\gamma$	5 ab^{-1}	1400	0.10	0.12
$K_S\pi^0$	5 ab^{-1}	5699	0.09	0.10







First Belle II measurement of CPV in $B \to \eta' K^0_S$

B^0 mixing phase well measured to be SM using CPV in tree-dominated $B \to J/\psi K^0_S$

Checking consistency with penguin-dominated decays probes generic non-SM and is a central flavor goal unique to Belle II

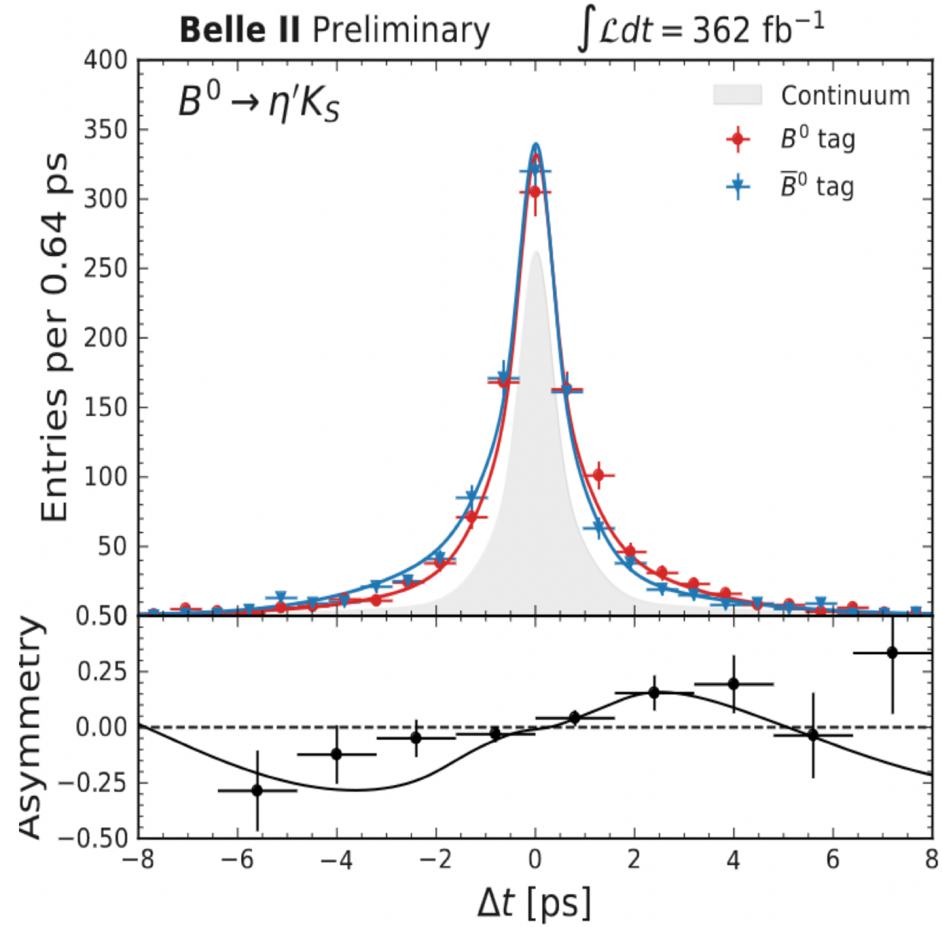
$B^0 \to \eta' K^0_S$ is best:

high BF and o(%) theoretical uncertainty

$C = 0.19 \pm 0.08 \pm 0.03$

$S = 0.67 \pm 0.10 \pm 0.04$

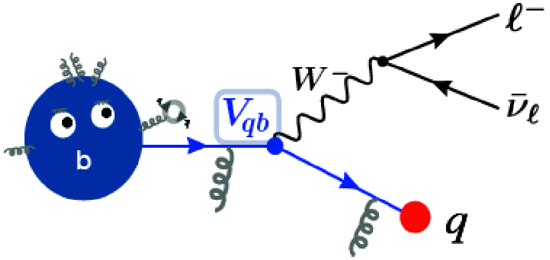
Contributes to world average with sensitivity close to Belle's and BaBar's

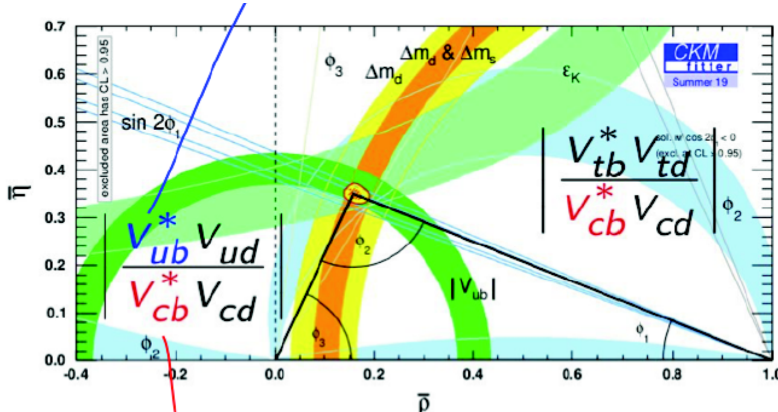


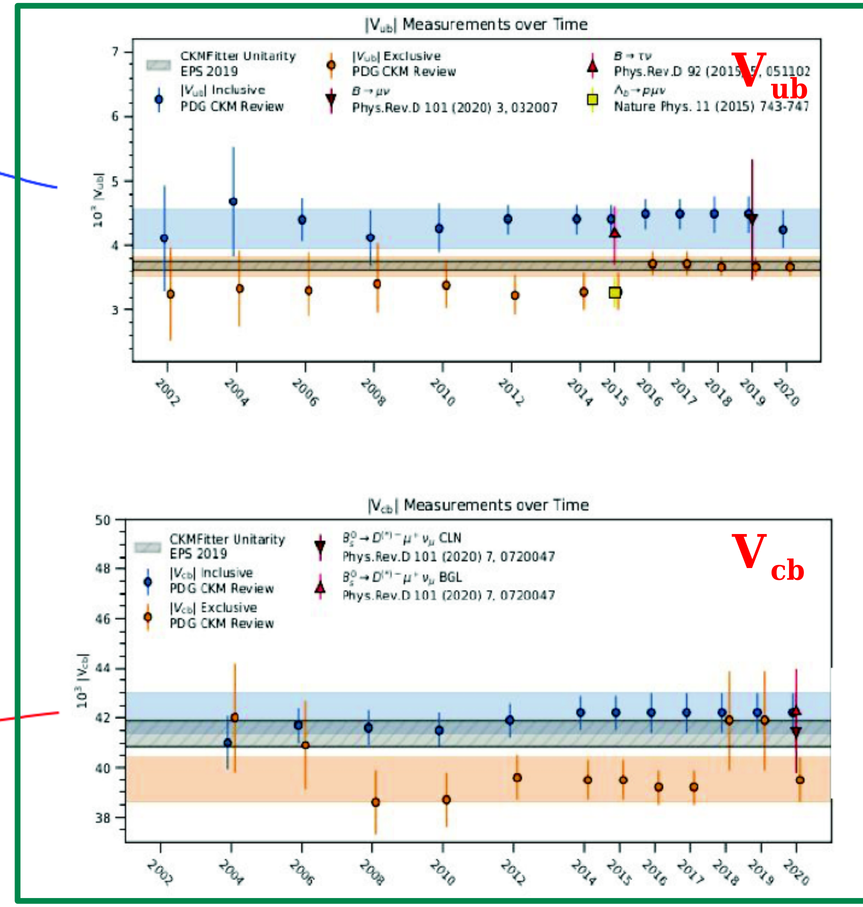
Mode	Experiment	sin(2β^eff) ≡ sin(2φ₁^eff)	C_{CP}	Correlation	Reference
$\eta' K^0$	BaBar N(BB)=467M	0.57 ± 0.08 ± 0.02	−0.08 ± 0.06 ± 0.02	0.03 (stat)	PRD 79 (2009) 052003
	Belle N(BB)=772M	0.68 ± 0.07 ± 0.03	−0.03 ± 0.05 ± 0.03	0.03 (stat)	JHEP 1410 (2014) 165
	Average	0.63 ± 0.06	−0.05 ± 0.04	0.02	HFLAV correlated average χ^2 = 1.3/2 dof (CL=0.53 ⇒ 0.6σ)
	Figures:	eps.gz png	eps.gz png	eps.gz png	

Semi-leptonic B decays

responsible for some of the long-standing **discrepancies** since about a decade



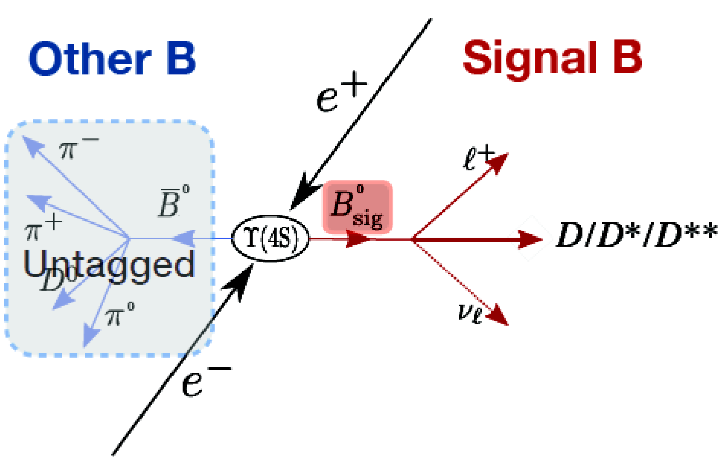




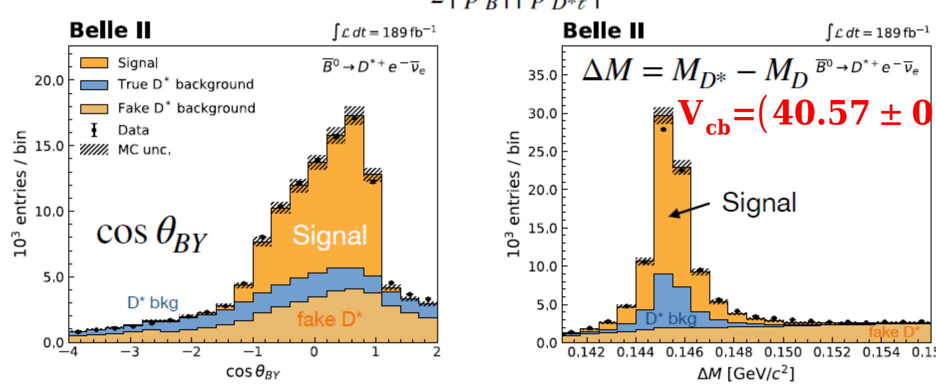
$V_{cb}^{exc} = (39.10 \pm 0.50) \times 10^{-3}$, $V_{cb}^{inc} = (42.16 \pm 0.51) \times 10^{-3}$

high efficiency, can't directly access signal B rest frame

[Belle II, arXiv:2310.01170]



2D Fit of $\cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}$ $\quad \Delta M = m_{D^*} - m_D$



with more stat
⇒ tagged analyses

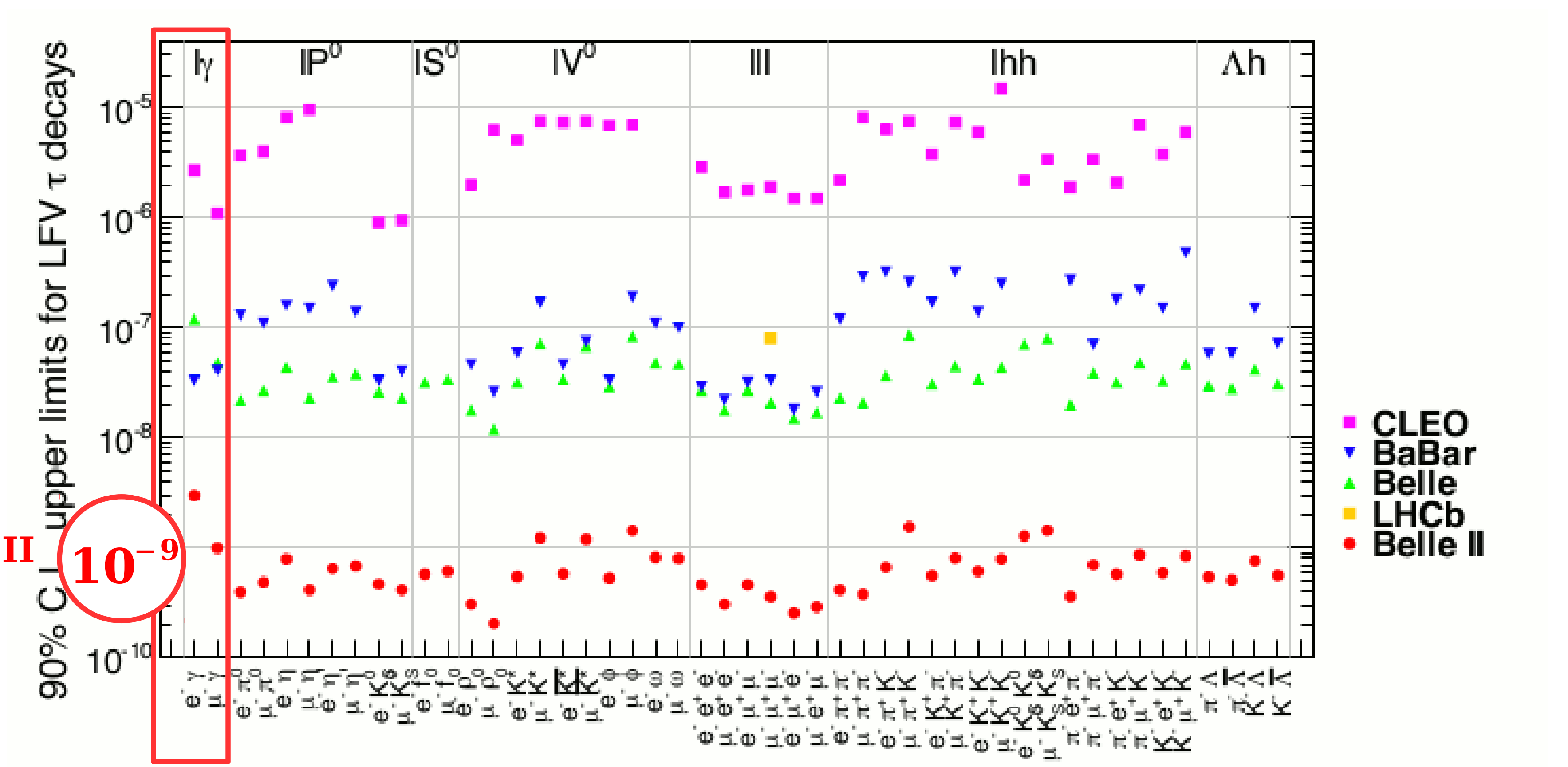
"τ center"

- **Belle II is also a τ-factory!**
- **lepton flavour violating decays of the τ as NP probe**

⇒ LFV accidental symmetry of SM, many NP models can naturally break this symmetry

Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-40}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

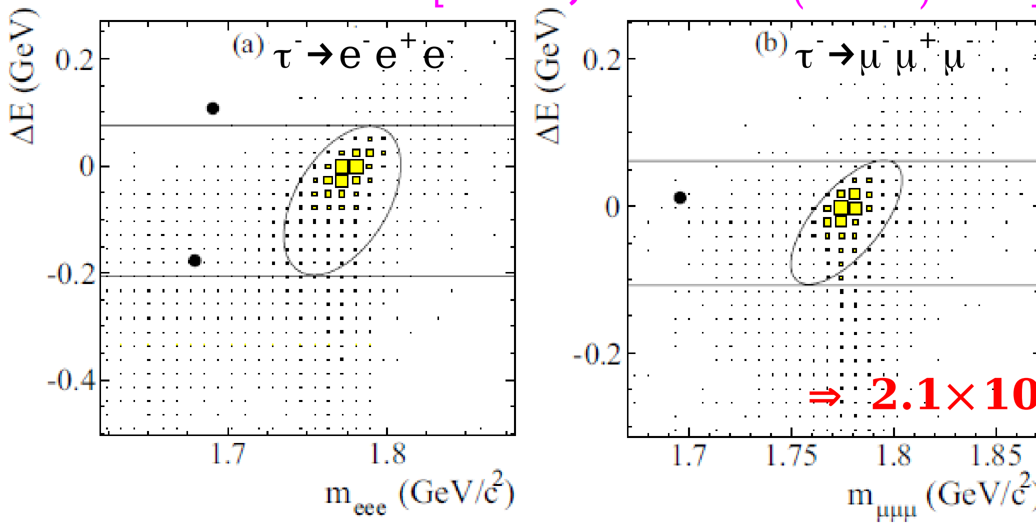
expected Belle II sensitivity



cLFV : beyond the Standard Model

τ LFV searches at Belle II will be extremely clean with very little background (if any), thanks to pair production and double-tag analysis technique.

[Belle, PLB 687 (2010) 139]

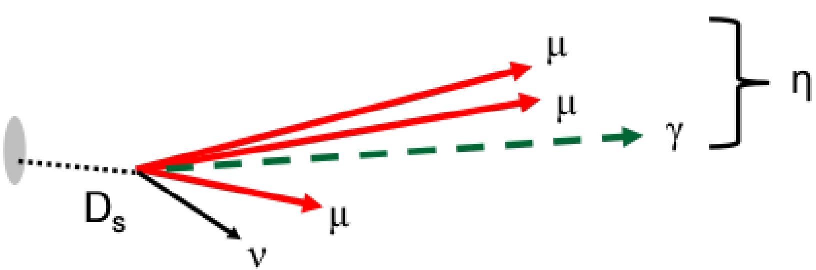


⇒ 2.1×10^{-8} at 90% CL

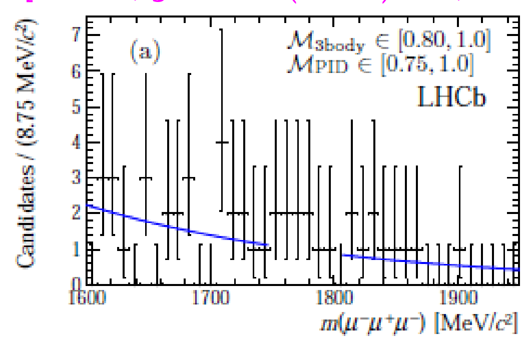
how to improve further ?

…considering $\tau \to \mu/e\, h^+ h^-$
in function of one prong tag categories
…for τ → 3 muons,
improve μ-ID at low mom (ECL info)

In contrast, hadron collider experiments must contend with larger combinatorial and specific backgrounds



[LHCb, JHEP02(2015)121, 2 fb^{-1}]



⇒ 4.6×10^{-8} at 90% CL

Background modes normalised to $D_s \to \eta(\mu\mu\gamma)\mu\nu$ (BR ~ 10^{-5})

Decay channel	Relative abundance
$D_s \to \eta(\mu\mu\gamma)\mu\nu$	1
$D_s \to \varphi(\mu\mu)\mu\nu$	0.87
$D_s \to \eta'(\mu\mu\gamma)\mu\nu$	0.13
$D \to \eta(\mu\mu\gamma)\mu\nu$	0.13
$D \to \omega(\mu\mu)\mu\nu$	0.06
$D \to \rho(\mu\mu)\mu\nu$	0.05

CMS, full Run 2 dataset: 2.9×10^{-8} at 90% CL

Most improvement in coming decade is expected from Belle II, which can reach 1×10^{-9} [arXiv:1011.0352] and will do even better if can achieve ~ zero bckgd

$\tau \to 3\mu$ at Belle II

arXiv:2405.07386
accepted by JHEP

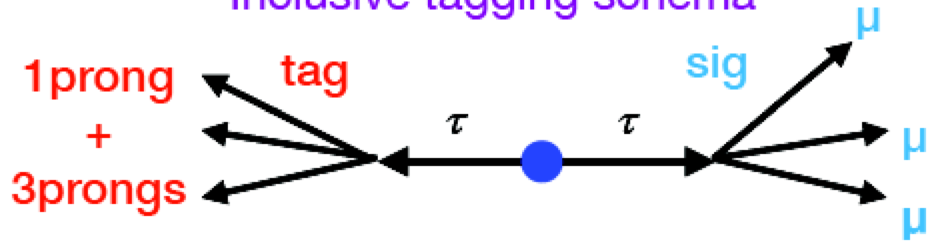
Analysis selection and results: inclusive approach

BDT trained on 32 variables:
inputs from signal τ^-, event tag side, event shape and kinematics

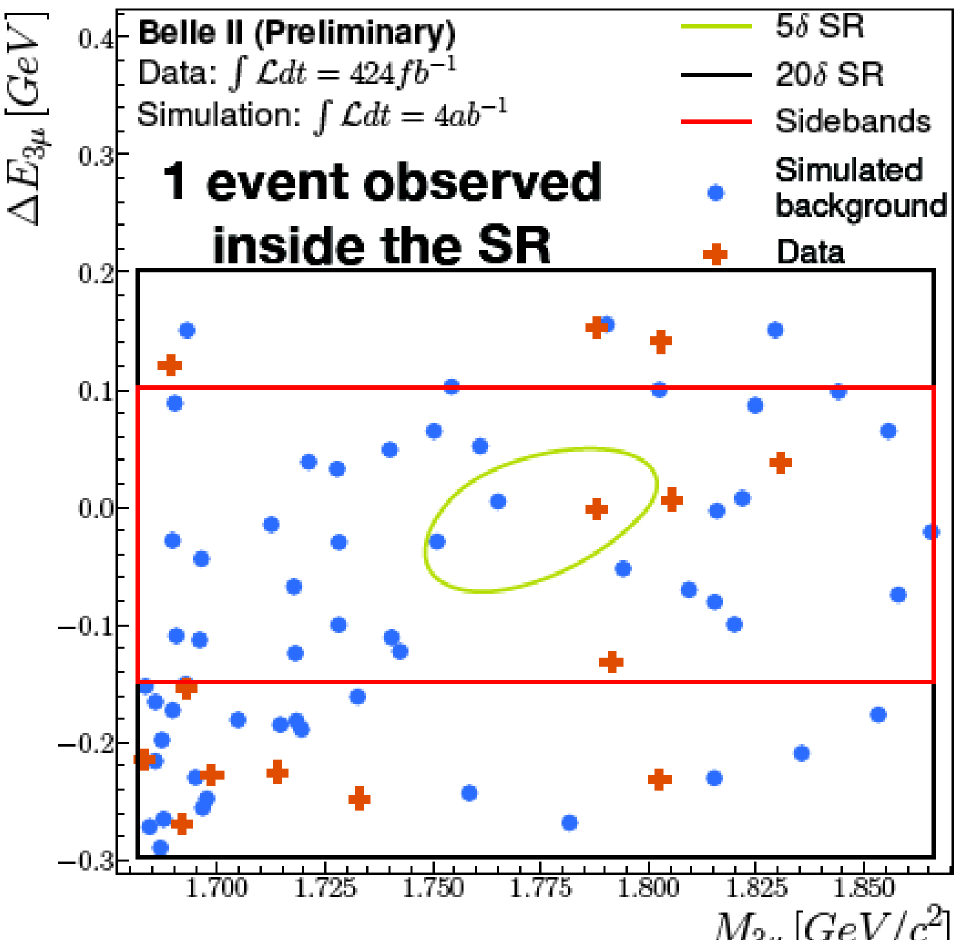
$\epsilon_{sig} = (20.42 \pm 0.06)\%$ (3 × larger than Belle)

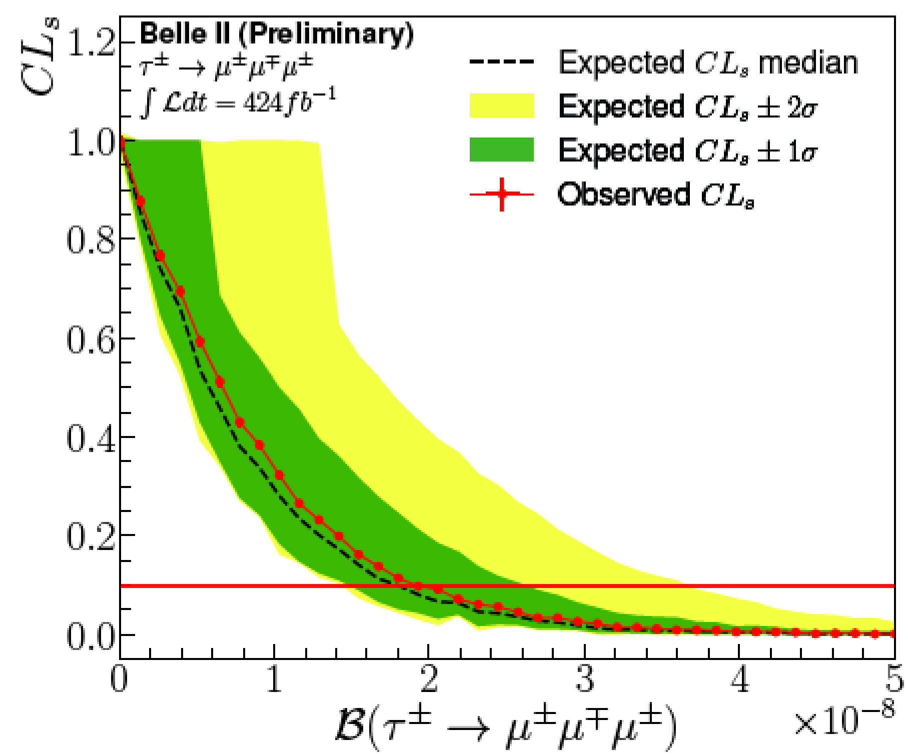
Expected BKG: $0.5^{+1.4}_{-0.5}$ evts

Inclusive tagging schema



No significant excess in 424 fb^{-1} of data





Obtained most stringent limit
1.9×10^{-8}

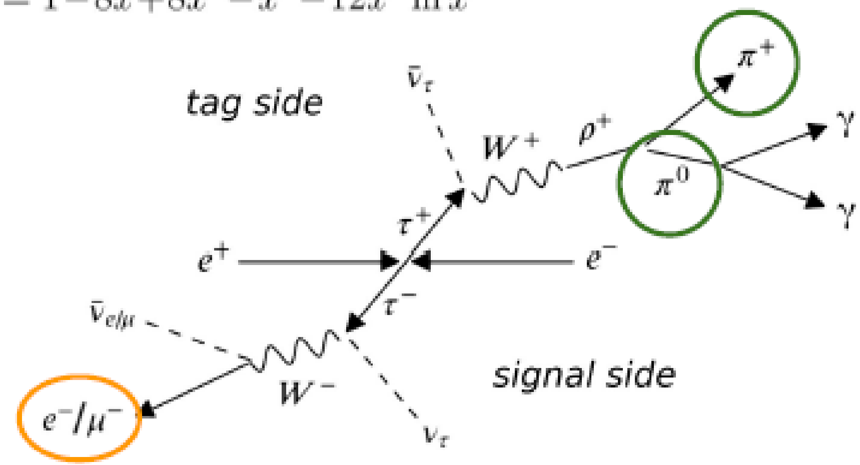
more results coming: $\tau \to \Lambda\pi$ (arXiv:2407.05117),
and soon $\tau \to e l^+ l^-$ modes

Lepton universality tests at Belle II

precise test of μ-e universality by measuring

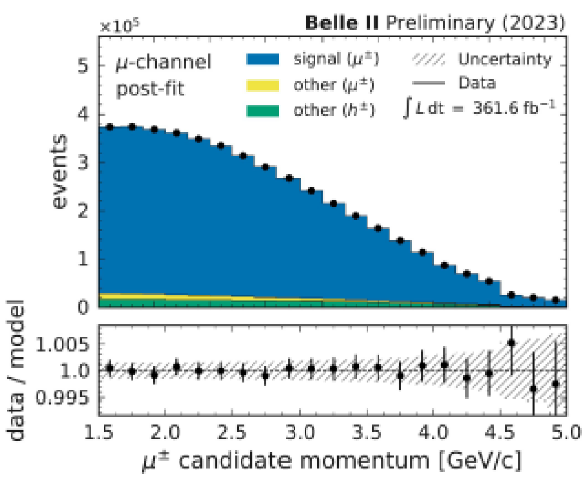
$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma))}\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

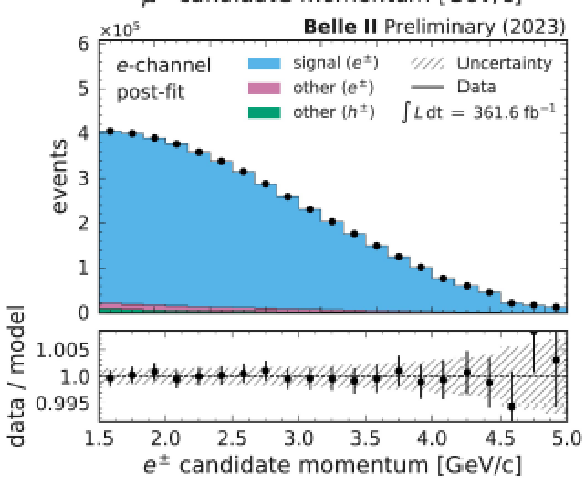
$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$



ratio of leptonic branching fractions

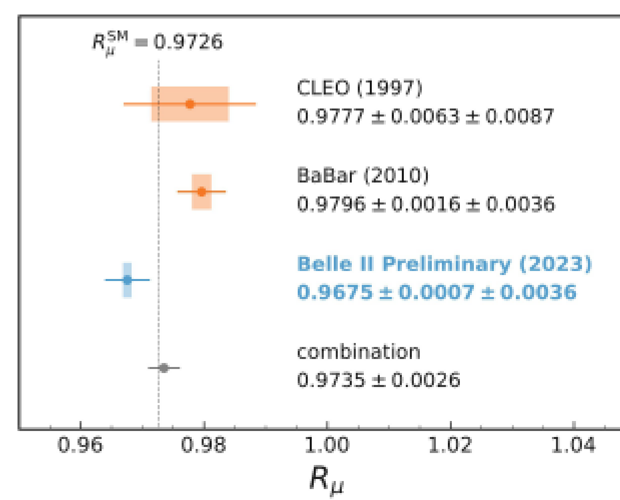
$$R_\mu \equiv \frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma))} \stackrel{\text{SM}}{=} 0.9726$$



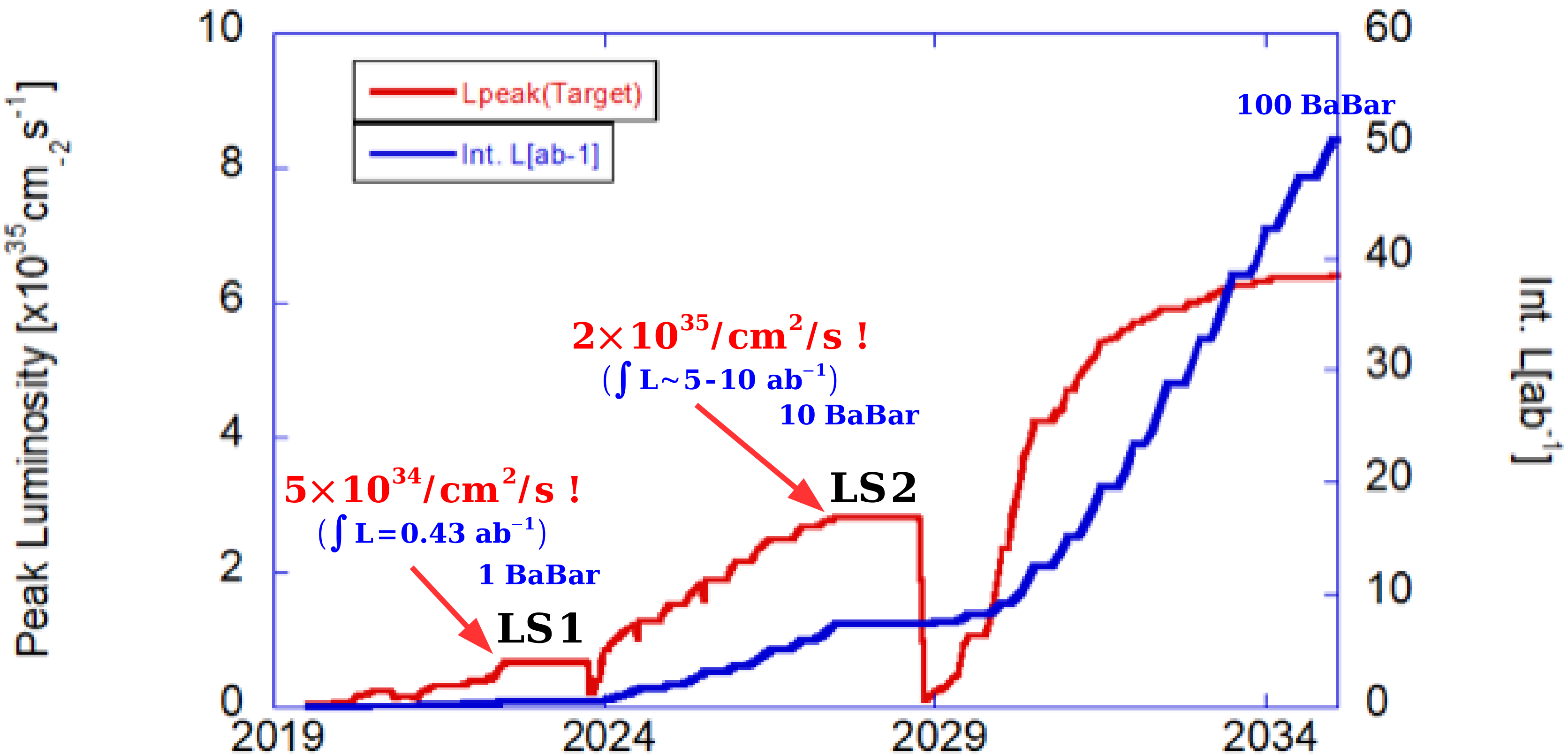


Source	Uncertainty [%]
Charged-particle identification:	
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05
Trigger	0.10
Imperfections of the simulation:	
Modelling of FSR	0.08
Normalisation of individual processes	0.07
Modelling of the momentum distribution	0.06
Tag side modelling	0.05
π^0 efficiency	0.02
Modelling of ISR	0.01
Photon efficiency	< 0.01
Photon energy	< 0.01
Size of the samples	
Simulated samples	0.06
Luminosity	0.01
Charged-particle reconstruction:	
Particle decay-in-flight	0.02
Tracking efficiency	0.01
Detector misalignment	< 0.01
Momentum correction	< 0.01
Total	0.37

$R_\mu = 0.9675 \pm 0.0037$



Belle II calendar



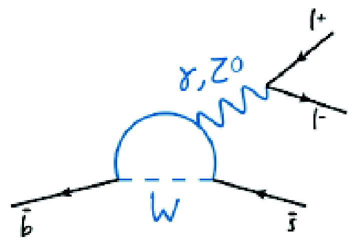
run 1 (→ June 2022): integrated luminosity ~0.43 ab^{-1}, 4-5×10^{34}/cm^2/s
PXD complete (2 layers) to be installed during **LS1** (2022-2023)
(+ beampipe + TOP PMTs)

run 2 (→ 2027): integrated luminosity 5-10 ab^{-1}, 2×10^{35}/cm^2/s

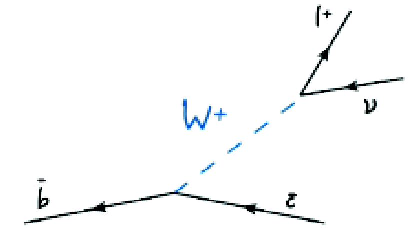
2028: collider upgrade (QCS+RF) → installation upgraded detector

run 3 (→ 2035): 50 ab^{-1}

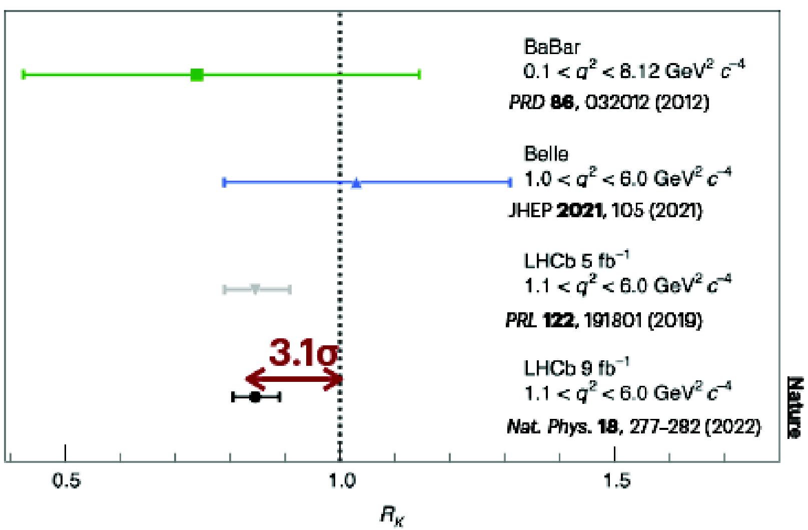
what happened with the B anomalies... ?



Deviations from SM have been measured, among **several observables**, in universality tests of lepton interactions in b → s and b → c transitions



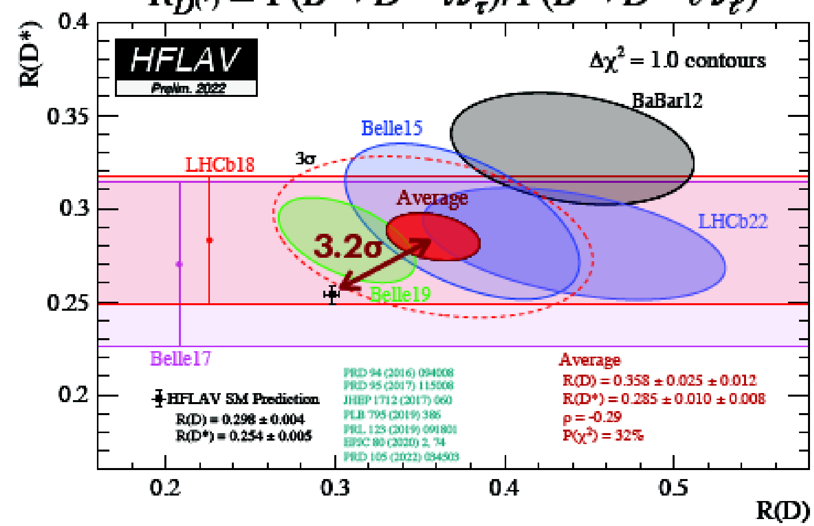
$R_K = \Gamma(B^+ \to K^+\mu^+\mu^-)/\Gamma(B^+ \to K^+e^+e^-)$



μ vs e: $R_H^{\mathrm{exp}} < R_H^{\mathrm{SM}}$

Lepton Flavor Universality Violation ?

$R_{D^{(*)}} = \Gamma(B \to D^{(*)}\tau\nu_\tau)/\Gamma(B \to D^{(*)}\ell\nu_\ell)$

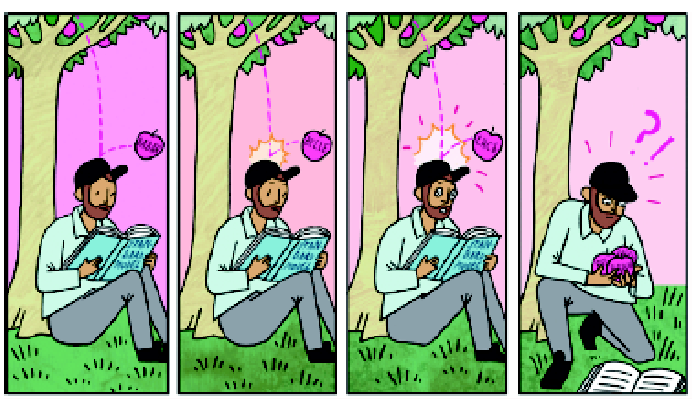


τ vs e/μ: $R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}}$

Main players in B-physics

Belle (II), BaBar → B-mesons in e^+e^- collisions

LHCb → *b*-flavored hadrons in *pp* collisions



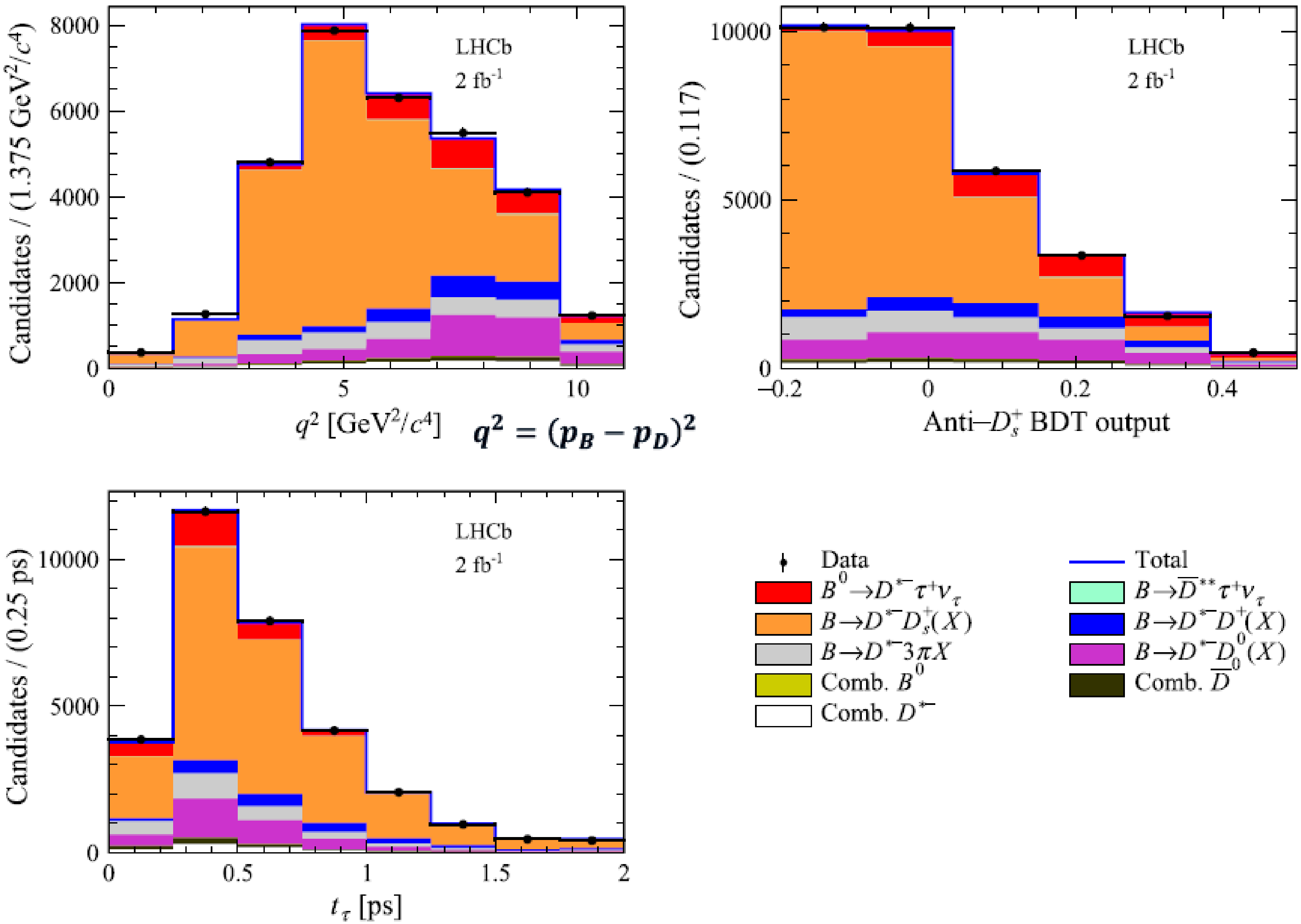
R(D*) at LHCb

$B^0 \to D^{*-}\tau^+\nu_\tau,\ \tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau$

$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} = \frac{N_{\rm sig}}{N_{\rm norm}}\frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} \times \frac{1}{\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau) + \mathcal{B}(\tau^+ \to 3\pi\pi^0\bar{\nu}_\tau)}$$

Run 2 : 2 fb^{-1}

[PRD 108 (2023) 012018]



$q^2 = (p_B - p_D)^2$

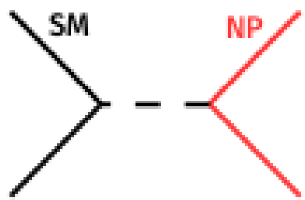
$R(D^*) = 0.247 \pm 0.015 \pm 0.015 \pm 0.012\ (\text{ext})$

$\Rightarrow$ **$R(D^*)_{\rm comb} = 0.257 \pm 0.012 \pm 0.014 \pm 0.012\ (\text{ext})$**

Rare B decays

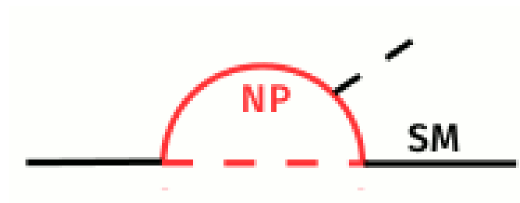
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism
- Any new particle generating new diagrams can change the amplitudes

energy frontier



limited by beam energy

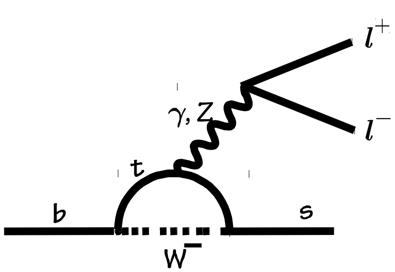
intensity frontier

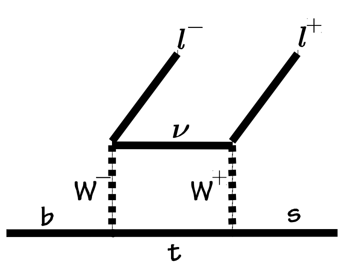


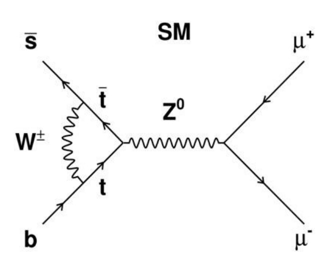
limited by statistics

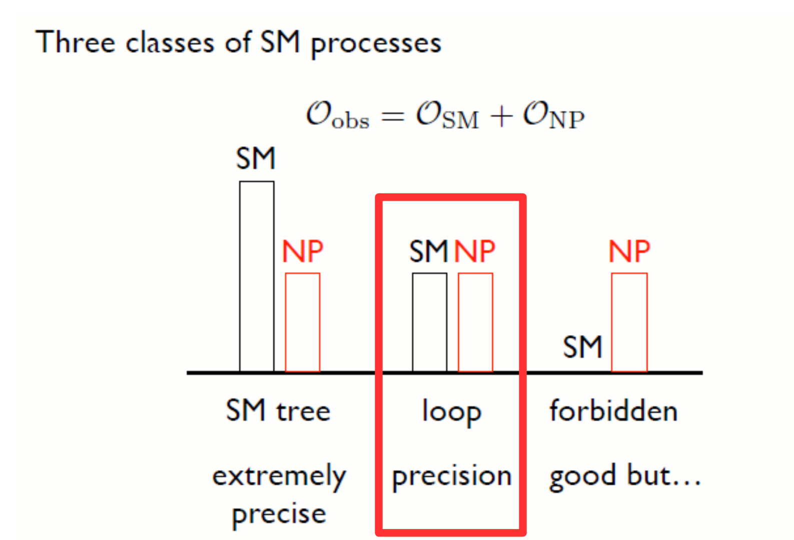
➜ NP beyond the <u>direct</u> reach of the LHC

New particles can for example contribute to loop or tree level diagrams **by enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles**



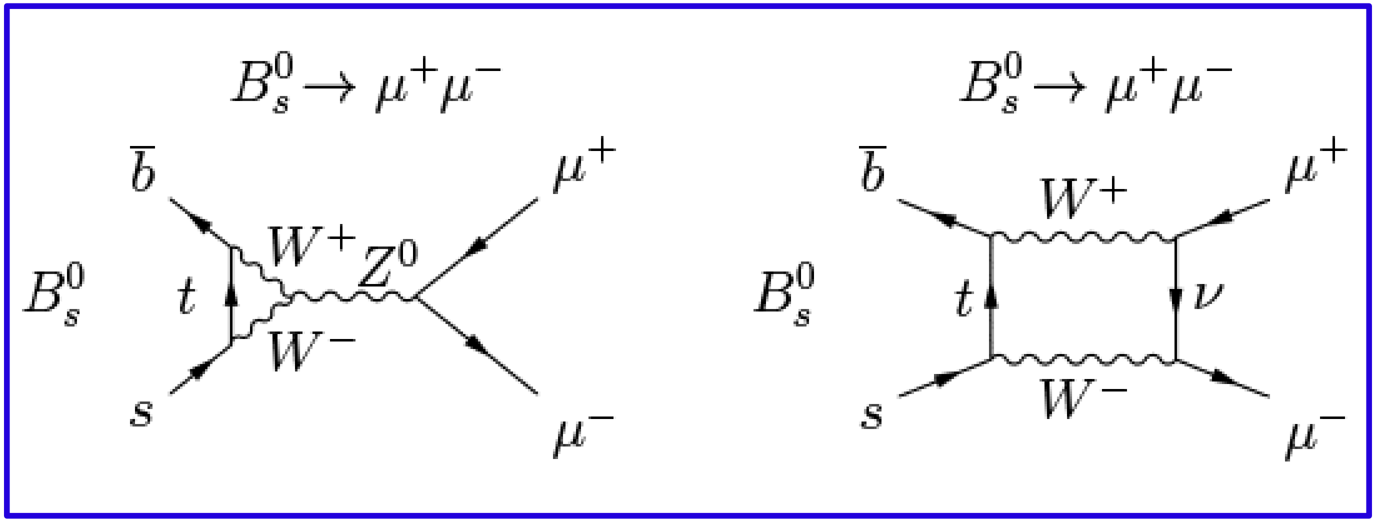






$B_{(s)} \rightarrow \mu\mu$: ultra rare processes…

loop diagram + suppressed in SM + theoretically clean =
an excellent place to look for new physics

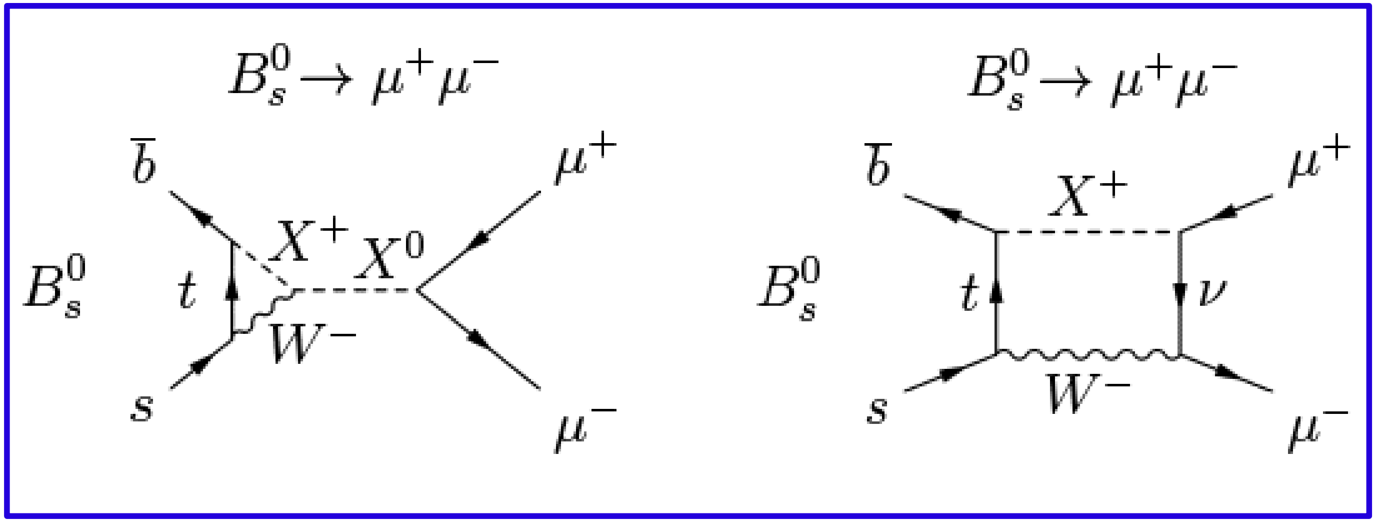


higher-order FCNC allowed in SM

$\mathcal{B}(B_s \rightarrow \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$

$\mathcal{B}(B_d \rightarrow \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$

[Beneke et al, JHEP 10 (2019) 232]

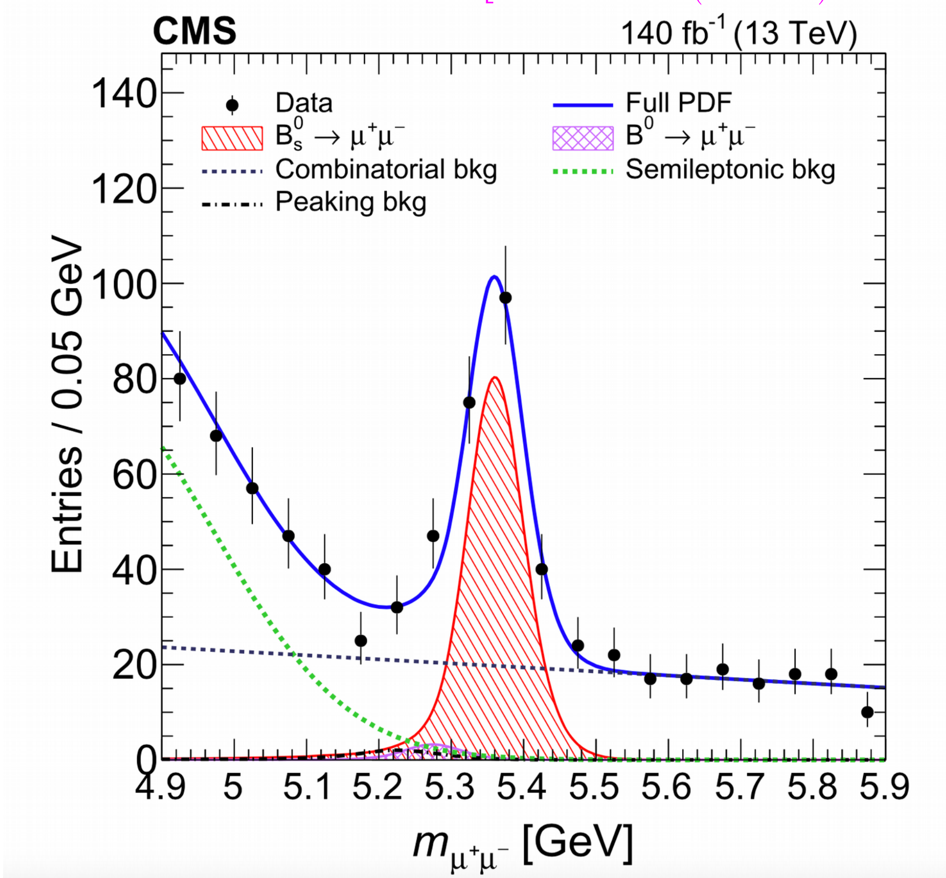


same decay in theories extending the SM (some of NP scenarios may boost the $B \rightarrow \mu\mu$ decay rates)

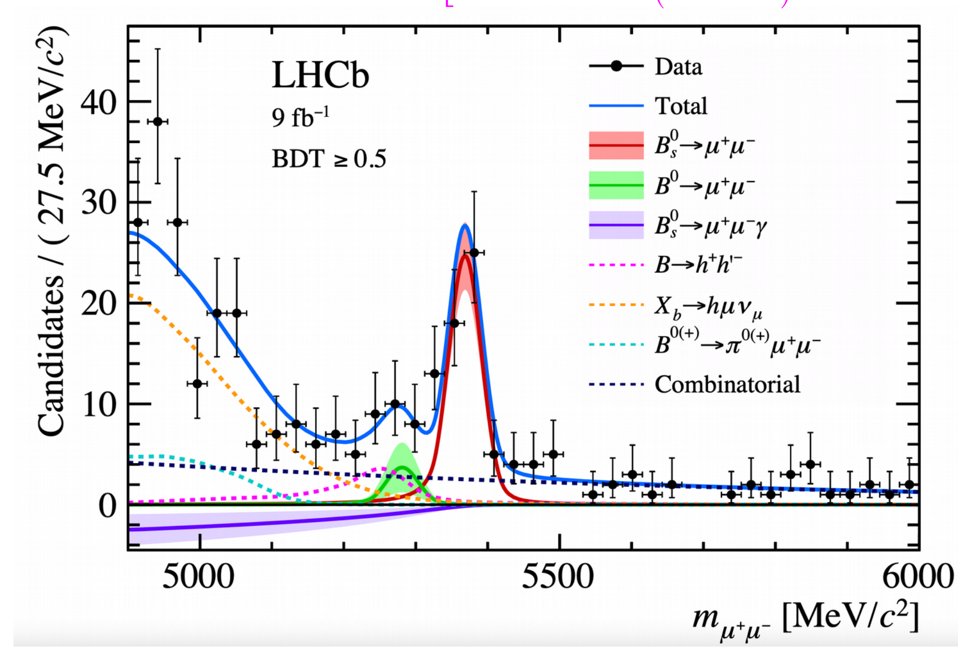
$B_{(s)} \to \mu\mu$: ultra rare processes…

- Observation by CMS and LHCb in 2014
- Clean experimental signature: ATLAS, CMS and LHCb

[PLB 842 (2023) 137955]



[PRL 128 (2022) 041801]

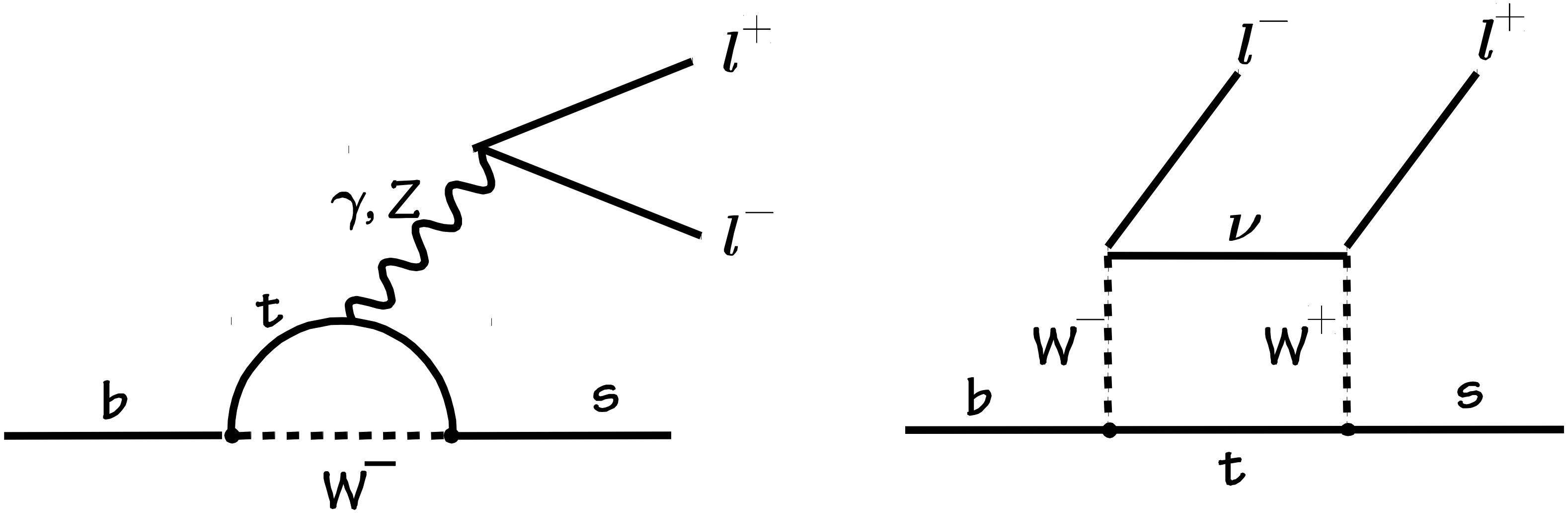


$$B(B^0_s \to \mu^+\mu^-) = (3.83\,^{+0.38}_{-0.36}\,^{+0.19}_{-0.16}\,^{+0.14}_{-0.13}(f_s/f_u)) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ @ } 95\%\,CL$$

$$B(B^0_s \to \mu^+\mu^-) = (3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \text{ @ } 95\%\,CL$$

Pioneer measurements for effective lifetime already available

$b \to s\, l^+ l^-$



⇒ 2 orders of magnitude smaller than $b \to s\gamma$ but rich NP search potential

Amplitudes from
- electromagnetic penguin: C_7
- vector electroweak: C_9
- axial-vector electroweak: C_{10}

may interfere w/ contributions from NP

Many observables:
- Branching fractions
- Isospin asymmetry (A_I), Lepton forward-backward asymmetry (A_{FB}), CP asymmetry ...
- and much more ...

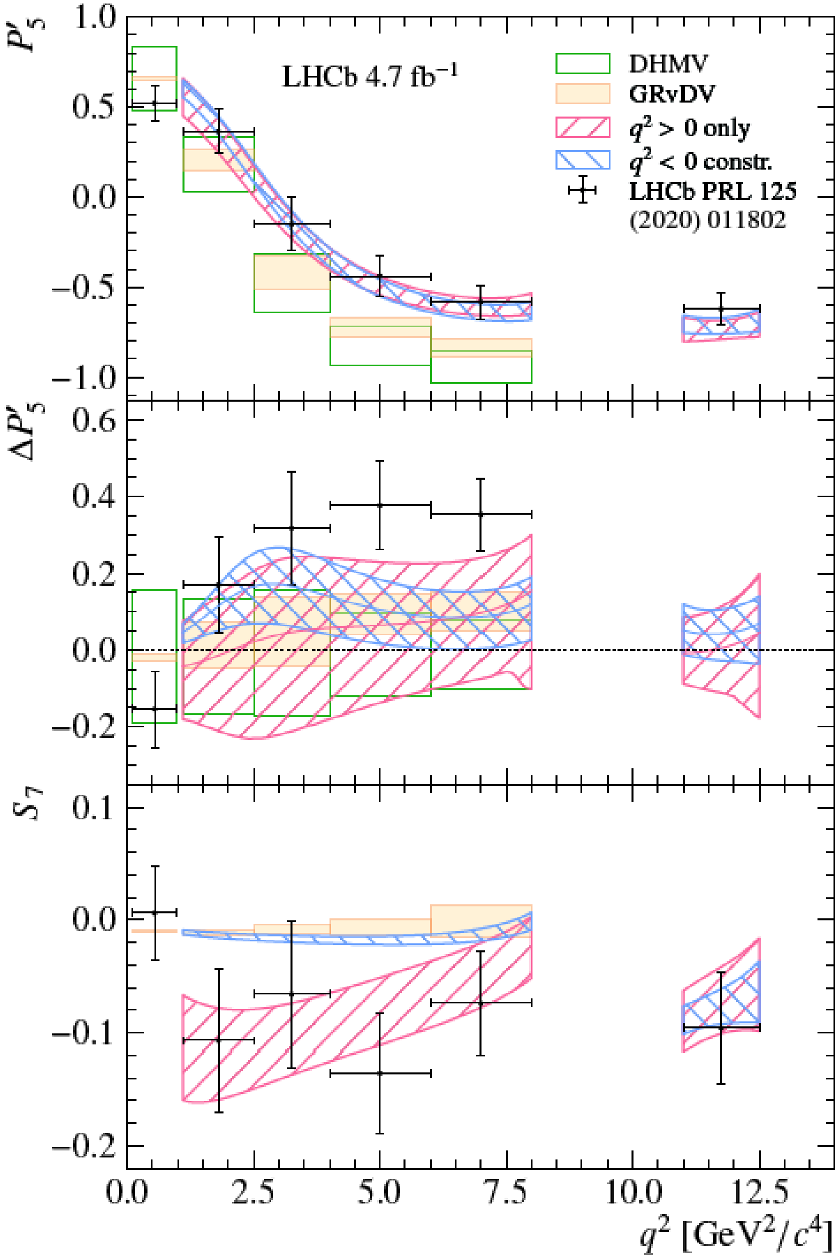
⇒ Exclusive $(B \to K^{(*)} l^+ l^-)$, Inclusive $(B \to X_s\, l^+ l^-)$

Unbinned $B \to K^{*0}\mu^+\mu^-$

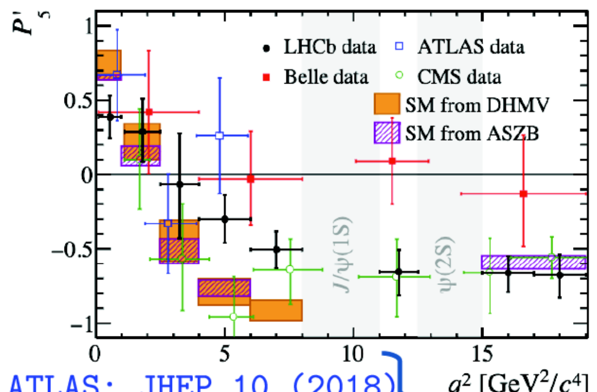
[arXiv:2312.09102, arXiv:2312.09115]

first unbinned amplitude analysis of $B \to K^{*0}\mu\mu$ (same dataset as Run 1+2016 q^2 binned)

⇒ determines simultaneously the short- and long-distance contribution

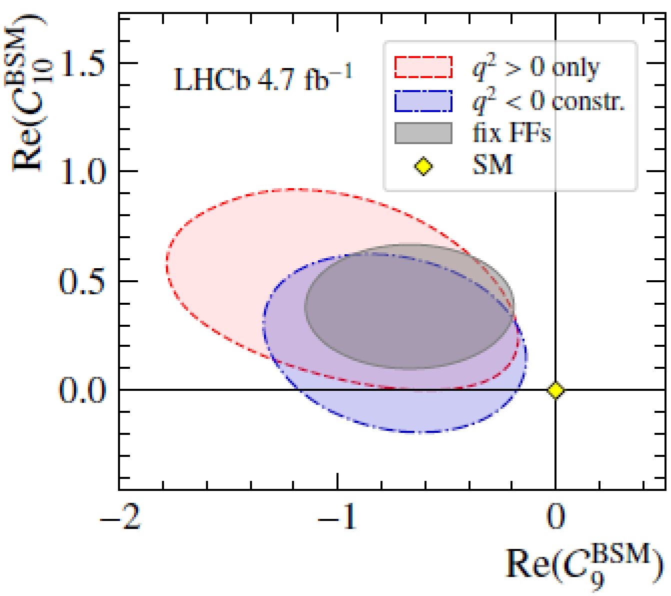


[LHCb, PRL 125 (2020) 01180]



ATLAS: JHEP 10 (2018)
CMS: PLB 781 (2018)
20/fb,2012

Data still prefers negative C_9^{NP}, but tension in C_9 reduced to ~ 1.8σ and 1.4σ global



Lepton flavor universality (LFU) in $b \to s l^+ l^-$

How do the SM gauge bosons couple to charged leptons of different flavors?

Universality in neutral current interactions

$$U^\dagger U = V^\dagger V = \mathbb{I}_{3\times 3} \;\Rightarrow\; \mathcal{L}^\ell_{\rm nc} \equiv \left(\overline{\widehat{e}}\gamma_\mu \widehat{e} + \overline{\widehat{\mu}}\gamma_\mu \widehat{\mu} + \overline{\widehat{\tau}}\gamma_\mu \widehat{\tau}\right)(g_\gamma A^\mu + g_Z Z^\mu)$$

The photon and Z-boson couple
with the same strength to the three lepton families

Universality

How do we test this feature of the Standard Model?

$$R_Y = \frac{\mathrm{BR}\left(X \to Y e_i^+ e_i^-\right)}{\mathrm{BR}\left(X \to Y e_j^+ e_j^-\right)} \qquad i \neq j$$

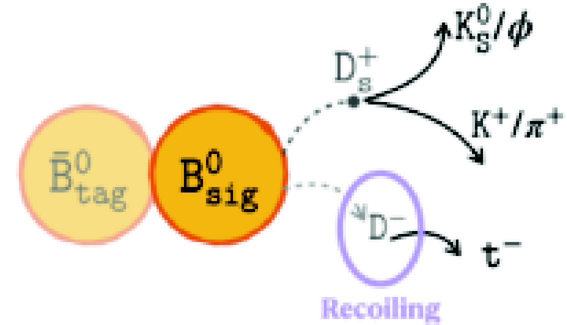
SM expectation

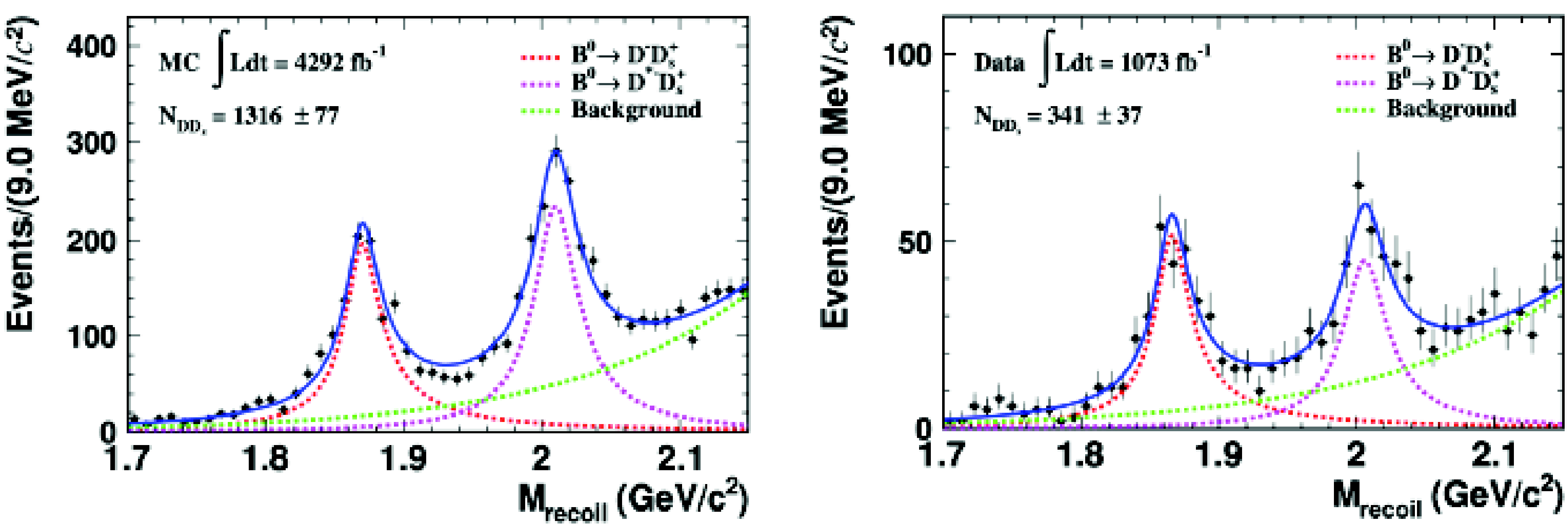
$$R_Y = 1 + \mathcal{O}\left(\frac{m^n_{i,j}}{m^n_X}\right)$$

Experimental results

Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$: Validation

- Use $B^0 \to D_s^+ D^-$ to validate recoiling signal PDF and BDT training:
  - consistent resolutions in data/simulation
  - obtain BDT efficiency correction factor





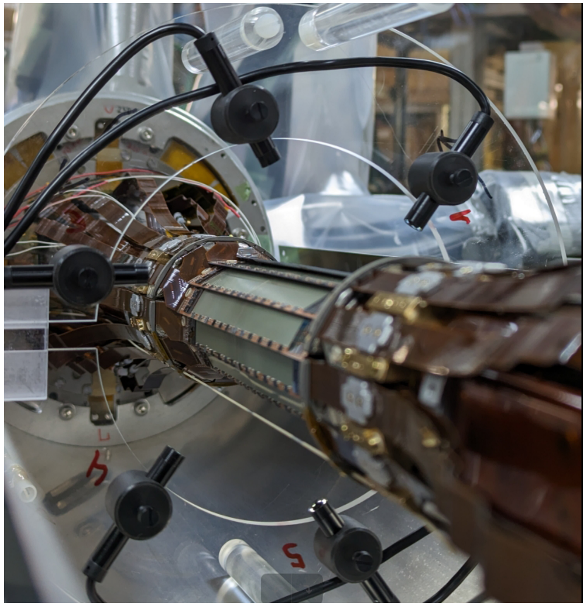
Long-shutdown (LS1) activity and plans

Belle II stopped taking data in Summer 2022 for a long shutdown

– accelerator improvements: injection, non-linear collimators, monitoring...
– additional shielding and increased resilience against beam bckg

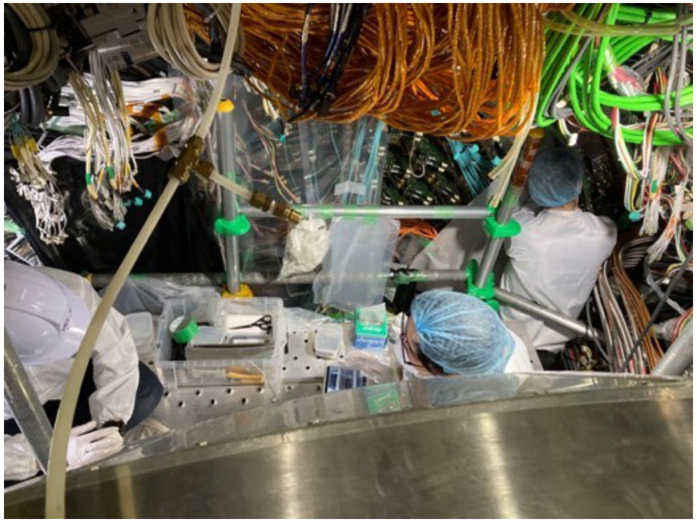
– replacement of beam-pipe
– installation of 2-layered pixel vertex detector
– replacement of photomultipliers of the central PID detector (TOP)
– completed transition to new DAQ boards (PCIe40)
– work on other detectors as CDC, KLM...
– improved data-quality monitoring and alarm system

PXD2 at KEK since March



VXD extraction in May

TOP MCP-PMT replacement work



CDC FE reinstallation work

LHCb and Belle II datasets: present and future

(M.H. Schune)