Flavour Physics
Current Status and Future Prospects

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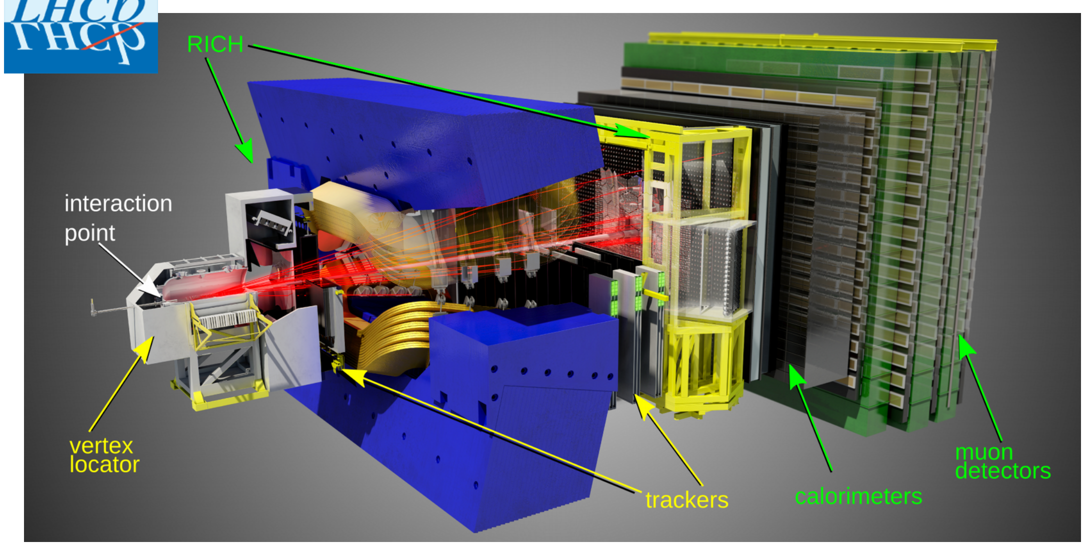
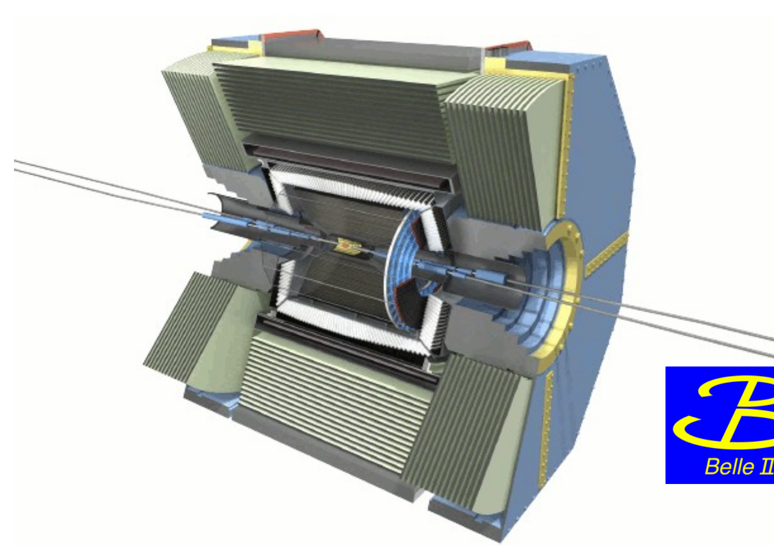
(focusing mostly on LHCb/Belle II's most recent results)

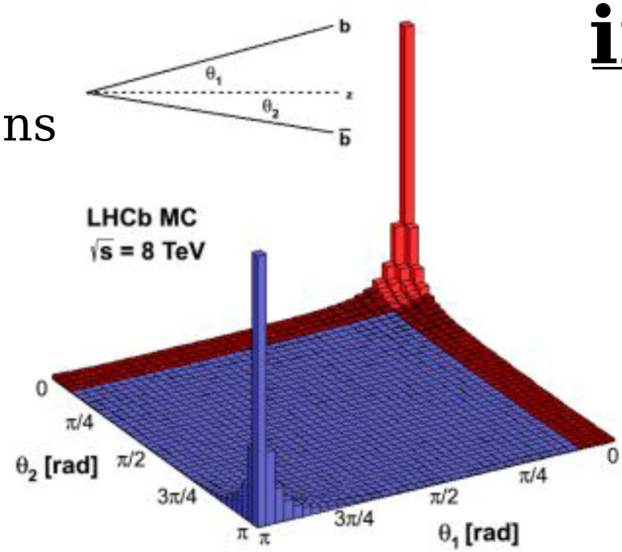


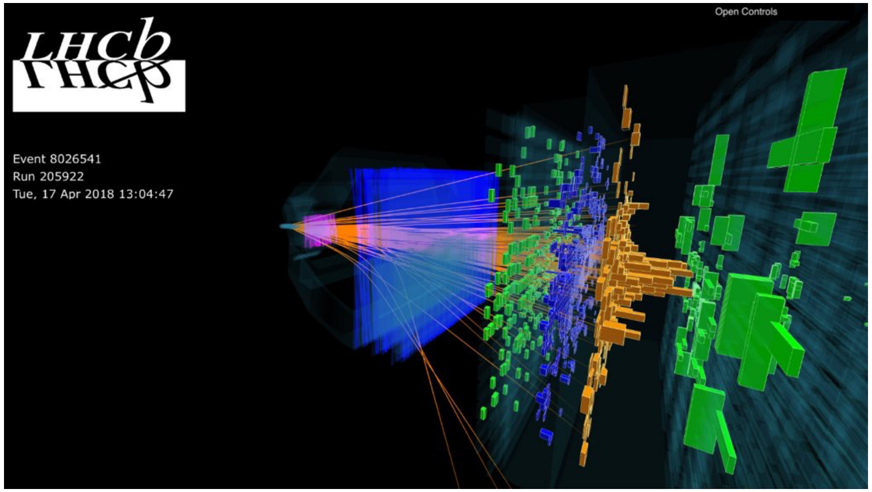


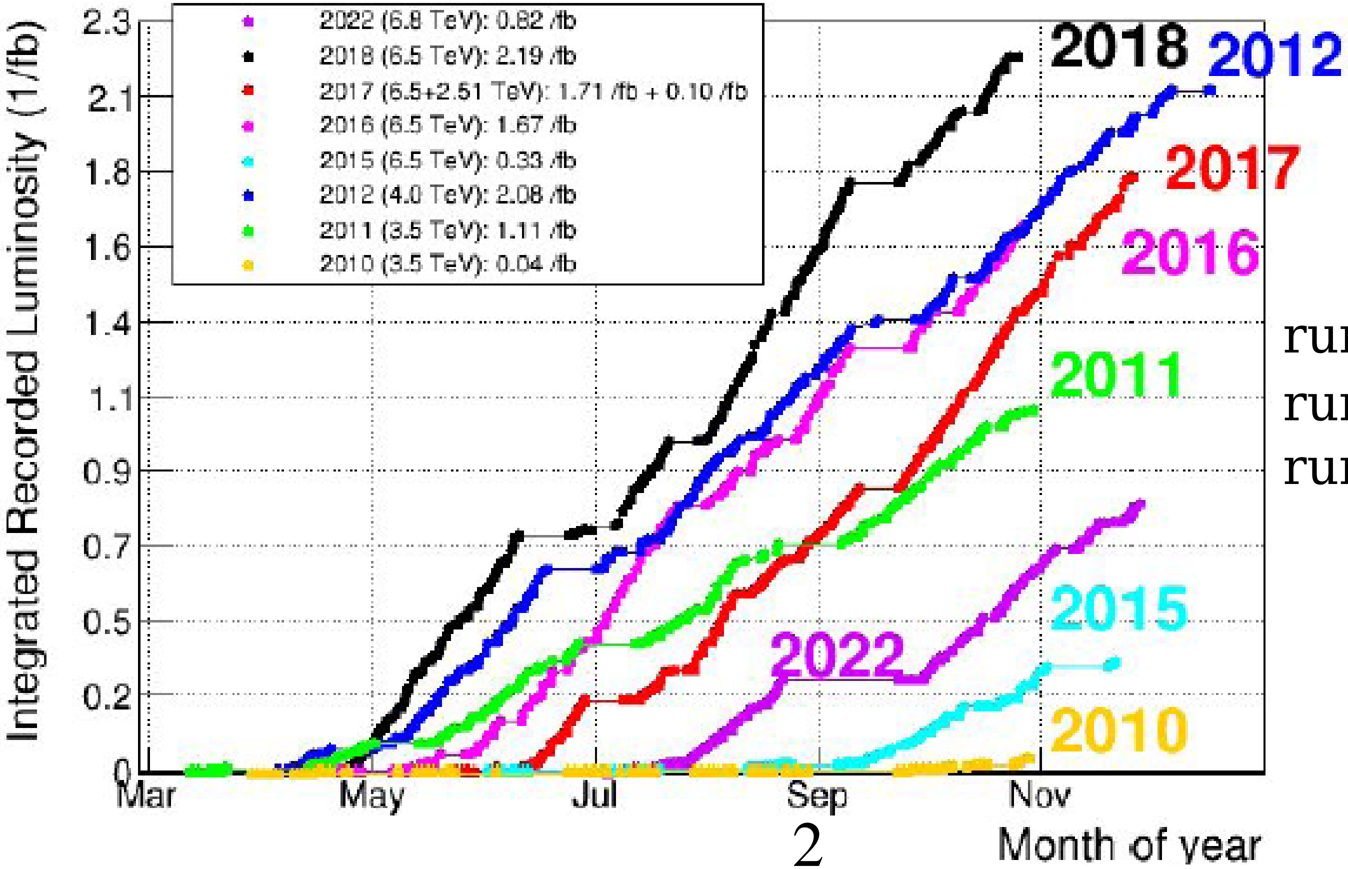
WHEPP XVI, Gandhinagar , 3rd January 2024

LHCb, a flavour-factory,
in a difficult environment...

pp collisions







run 1: 2010-2012 $(3\ \mathrm{fb}^{-1})$
run 2: 2015-2018 $(6\ \mathrm{fb}^{-1})$
run 3: 2022-...

Belle II, a flavour-factory,

(Belle ~ 1 ab^{-1})

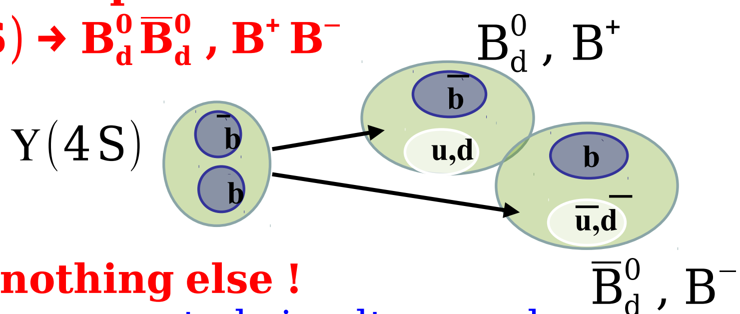
a rich physics program…

◦ 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 ($\sim 1.1 \times 10^9$ $B\bar{B}$ pairs per ab^{-1})**

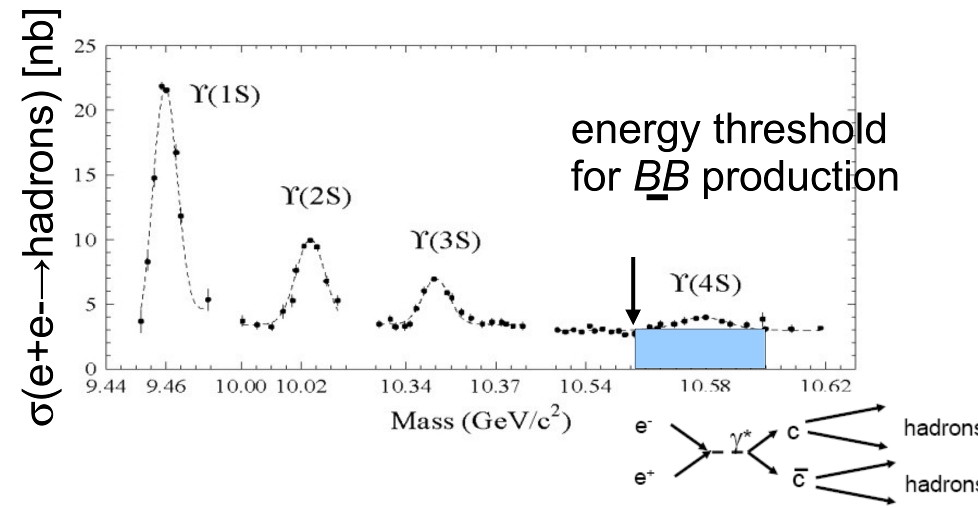
"on resonance" production

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_d^0\bar{B}_d^0$, B^+B^-



◦ **2 B's and nothing else !**

◦ 2 B mesons are created simultaneously in a L=1 coherent state



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

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

– **a (Super) τ factory ($\sim 0.9 \times 10^9$ $\tau^+\tau^-$ 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), 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	$\sim10^{-6}$
Tevatron	2 TeV	5000	$\sim10^{-3}$
LHC	8 TeV	$\sim3\times10^5$	$\sim 5\times10^{-3}$
	14 TeV	$\sim6\times10^5$	$\sim10^{-2}$

$b\bar{b}$ 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]

Belle II run I (2019 - 2022)

data taking from March 2019 to June 2022

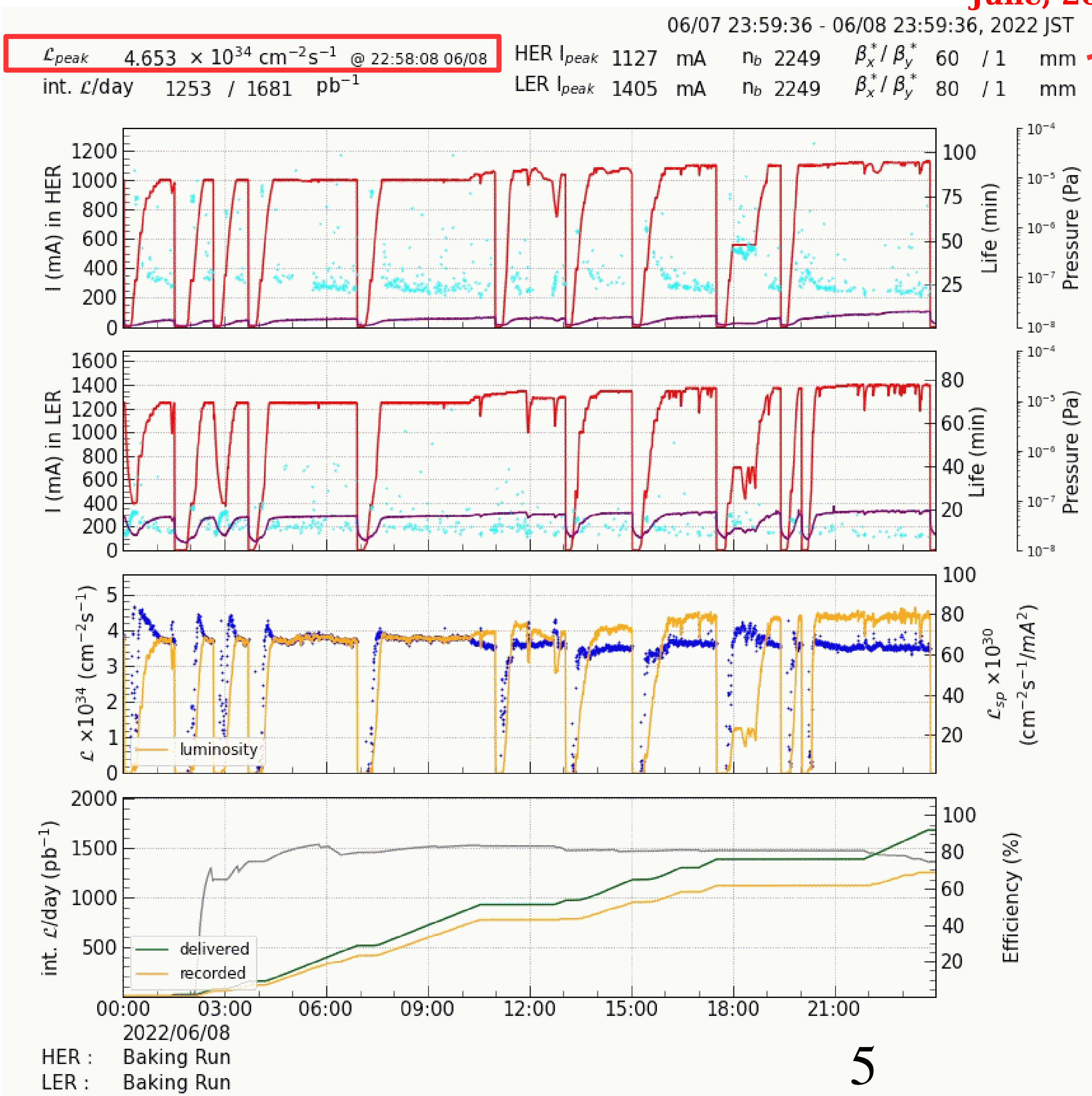
→ despite difficult conditions since March 2020 (Covid, war in Ukraine, energy cost ...)

luminosity : $4.7\times10^{34}/cm^2/s$! > 2 fb^{-1} per day !

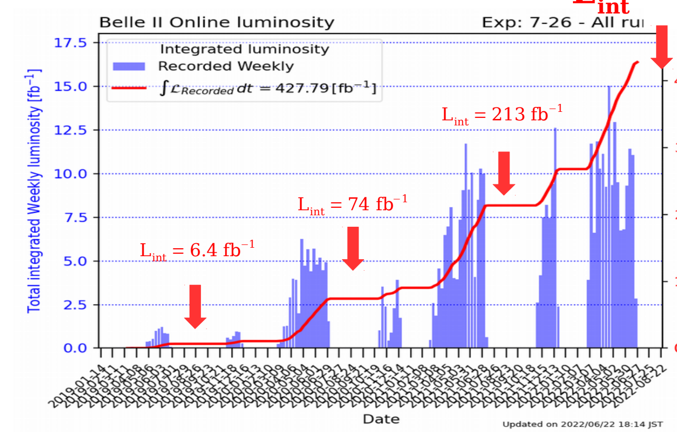
$\beta_y^* = 1$ mm , $I_{LER/HER} = 1.4/1.2$ A

June, 2022

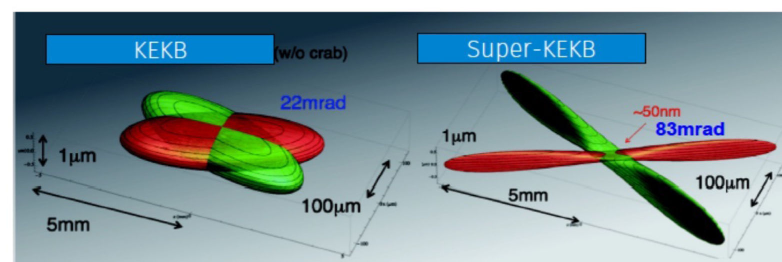
record of KEKB/Belle
$2\times10^{34}/cm^2/s$ currents > 1 A
record of PEPII/BaBar
$1\times10^{34}/cm^2/s$ currents > 2 A



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



$5\times10^{34}/cm^2/s$ ~ 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 10³⁴
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10³⁴

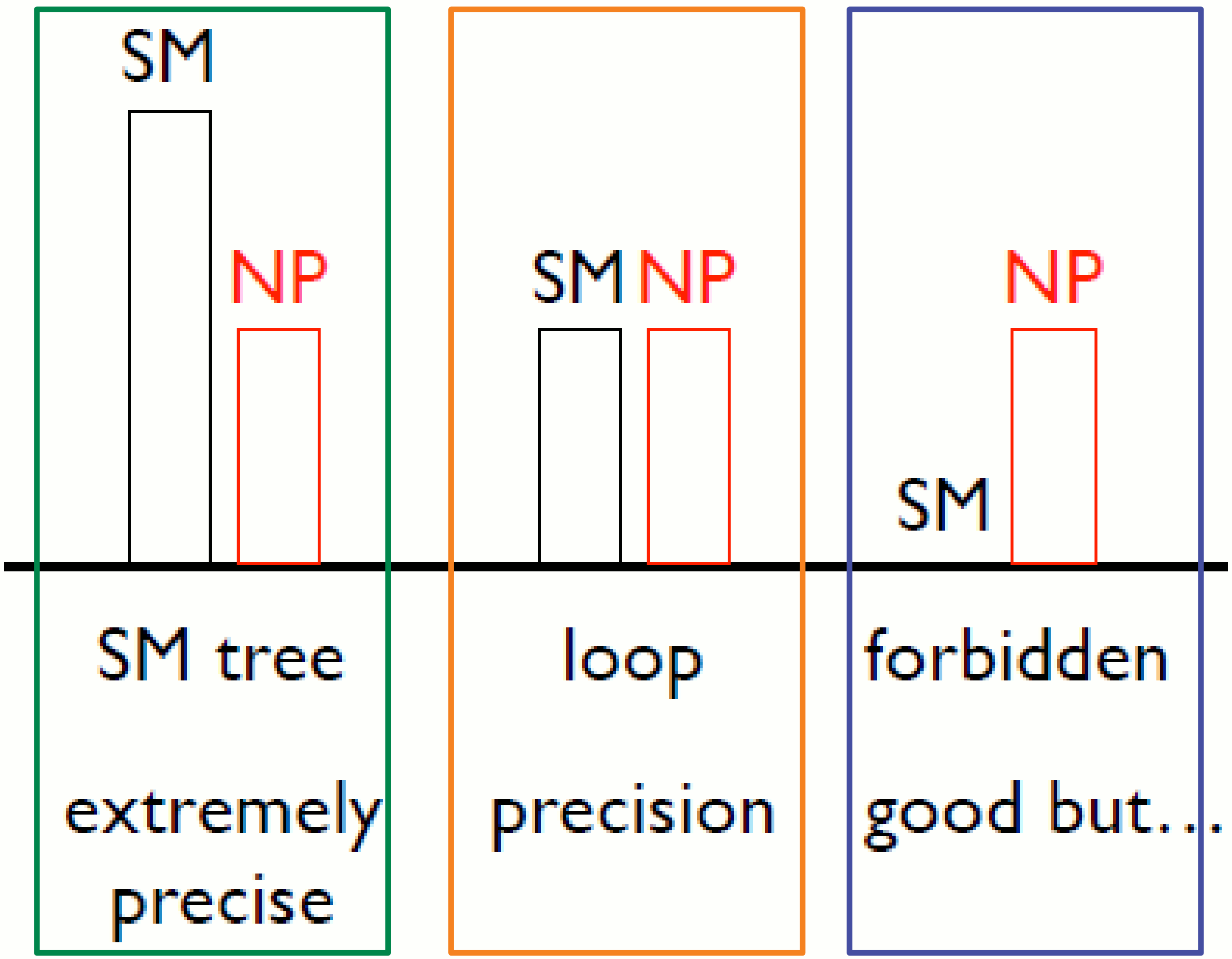
factor 20   factor 2-3

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

Physics at Belle II/LHCb

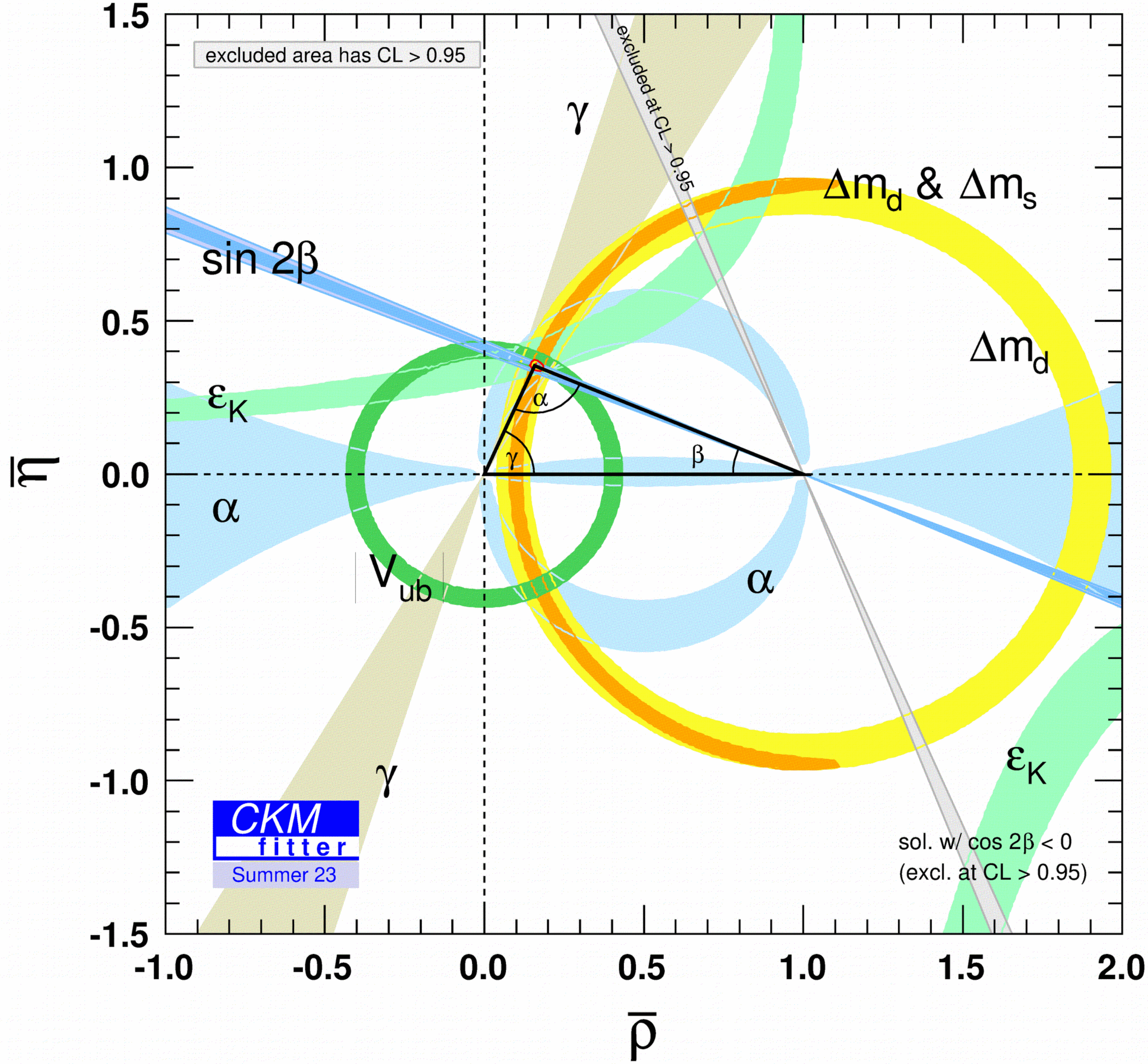
Three classes of SM processes

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



The current status of CKM

(CKMfitter 2023)



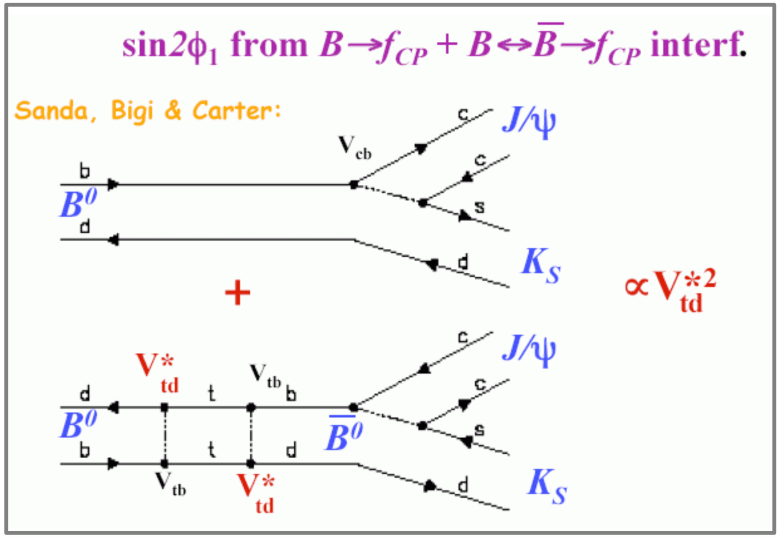
$|V_{ud}|, |V_{us}|, |V_{cb}|, |V_{ub}|_{SL}$

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

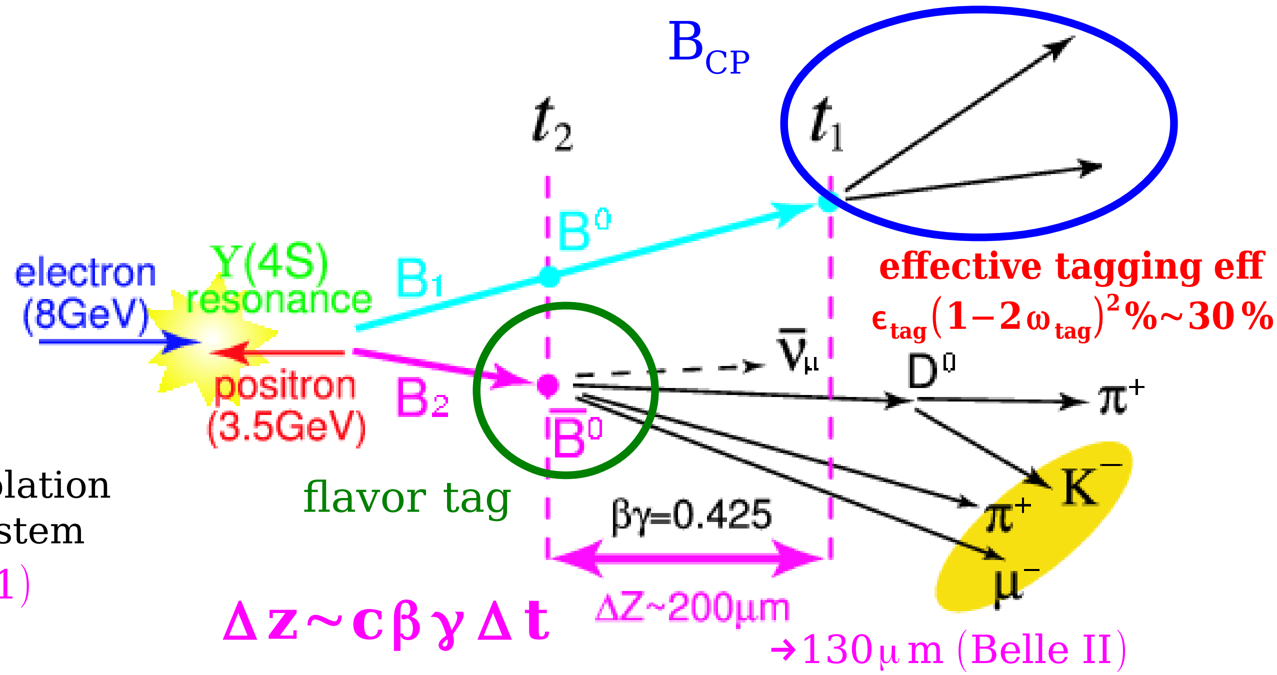
$\Delta m_d, \Delta m_s, \epsilon_K$

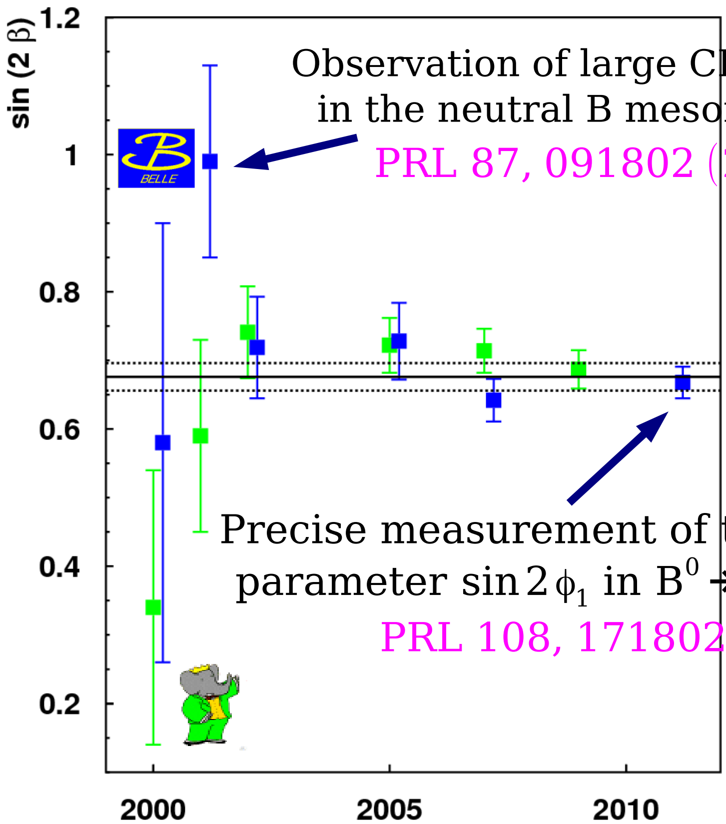
$\alpha, \sin 2\beta, \gamma$

Time−dependent CP asymmetries in decays to CP eigenstates



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





Observation of large CP violation in the neutral B meson system
PRL 87, 091802 (2001)

Precise measurement of the CP violation parameter $\sin 2\phi_1$ in $B^0 \to (c\bar{c})K^0$ decays
PRL 108, 171802 (2012)

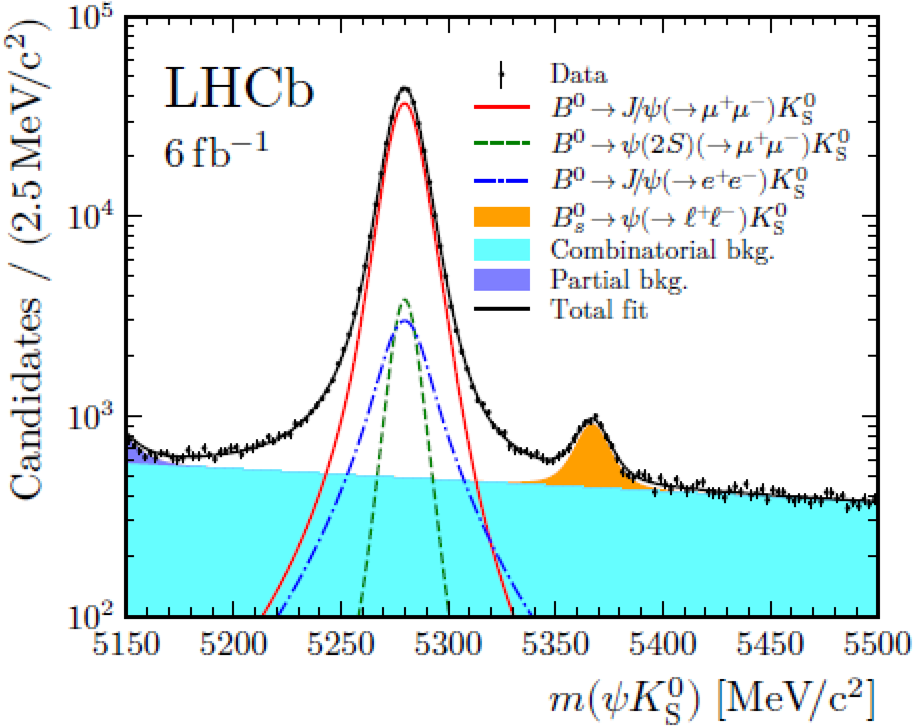
Raison d'être of SVD+PXD
significant resolution improvement for Belle II
(but also improvement of flavour tagging)

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 2β at LHCb/Belle II

- New result from LHCb using Run 2 data (6 fb^{-1})
- $B \to J/\psi(\to \mu^+\mu^-, e^+e^-)K^0_S$, $J/\psi(\to \mu^+\mu^-)K^0_S$



$S(\psi K^0_S) = 0.717 \pm 0.013 \pm 0.008$

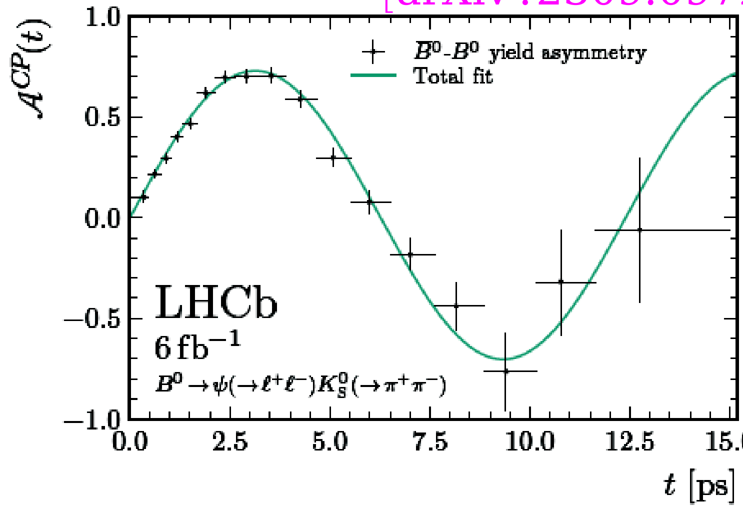
$C(\psi K^0_S) = 0.008 \pm 0.012 \pm 0.003$

⇒ Combined with Run 1:

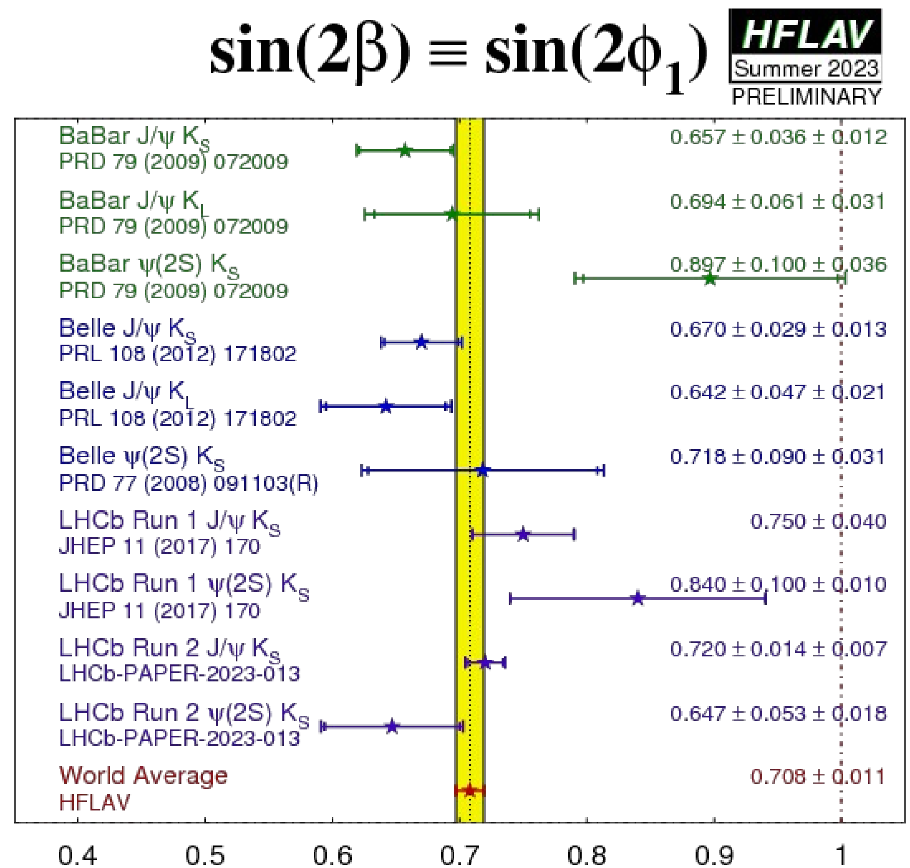
$S(\psi K^0_S) = 0.724 \pm 0.014$

$C(\psi K^0_S) = 0.004 \pm 0.012$

[arXiv:2309.09728]



$\sin(2\beta) \equiv \sin(2\phi_1)$

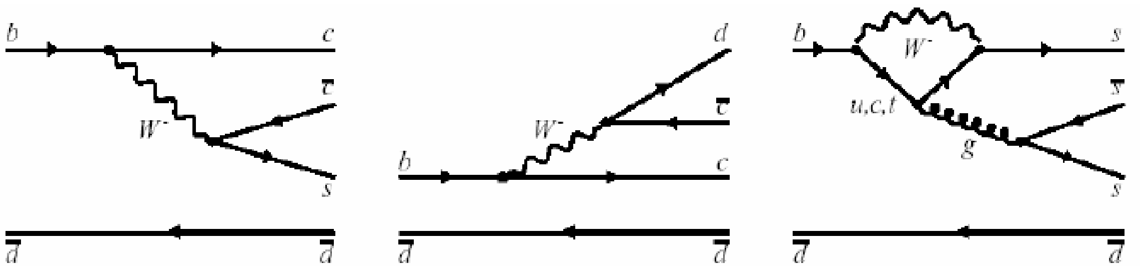


Belle II

$S = 0.724 \pm 0.035 \pm 0.014$
$C = -0.035 \pm 0.026 \pm 0.013$

sin 2β with b→s penguins

dominated by B-factories



$J/\psi K^0_S, \psi(2S)K^0_S, \chi_{c1}K^0_S$, $\eta_c K^0_S, J/\psi K^0_L$, $J/\psi K^{*0}(K^{*0} \to K^0_S \pi^0)$

$D^{*+}D^-, D^+D^-$ $J/\psi \pi^0, D^{*+}D^{*-}$

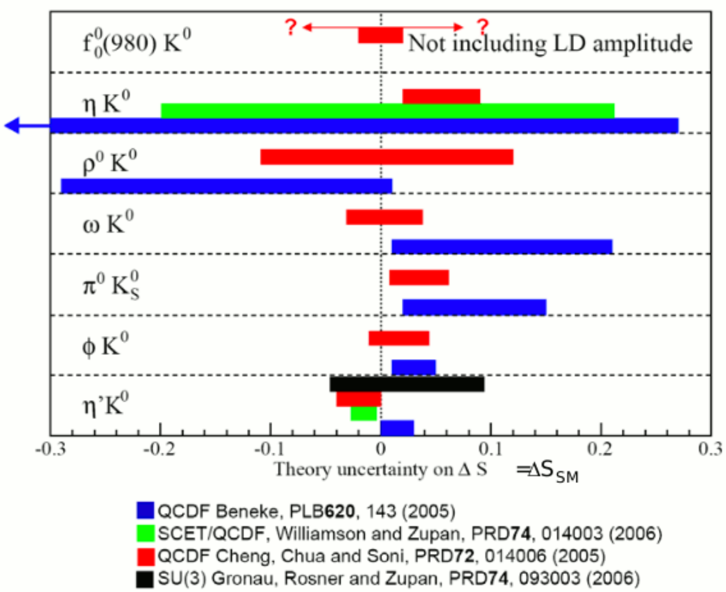
$\phi K^0, K^+K^-K^0_S$, $K^0_S K^0_S K^0_S, \eta' K^0, K^0_S \pi^0$, $\omega K^0_S, f_0(980)K^0_S$

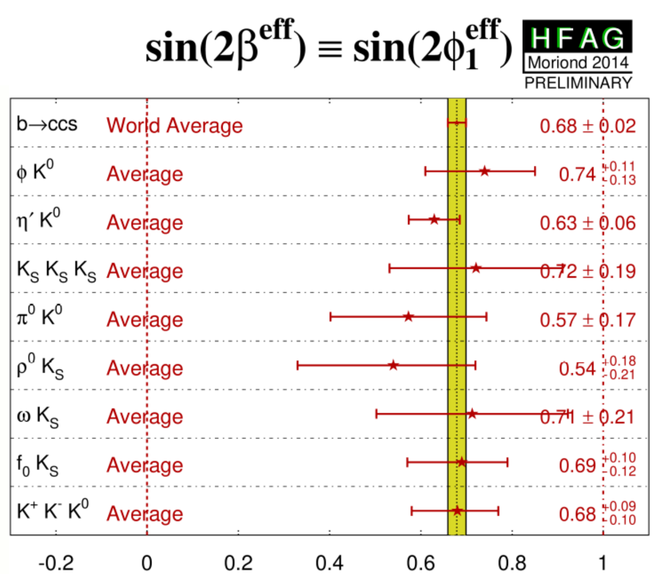
← increasing tree diagram amplitude

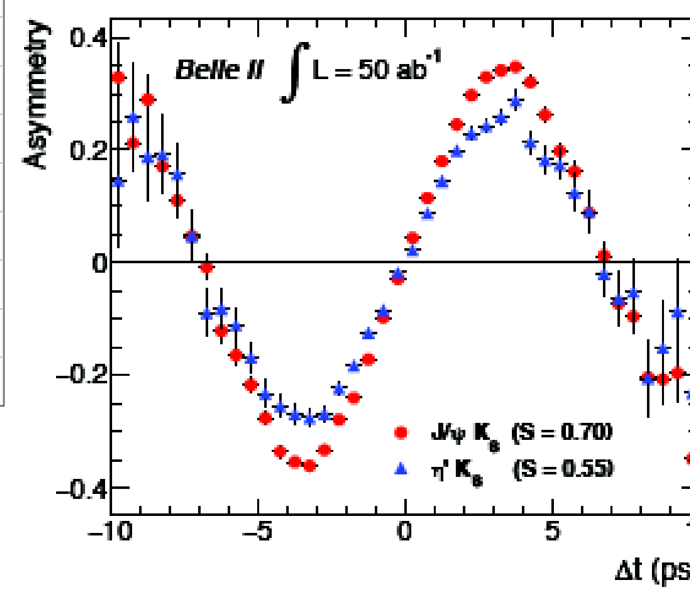
increasing sensitivity to new physics →

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^0_S	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







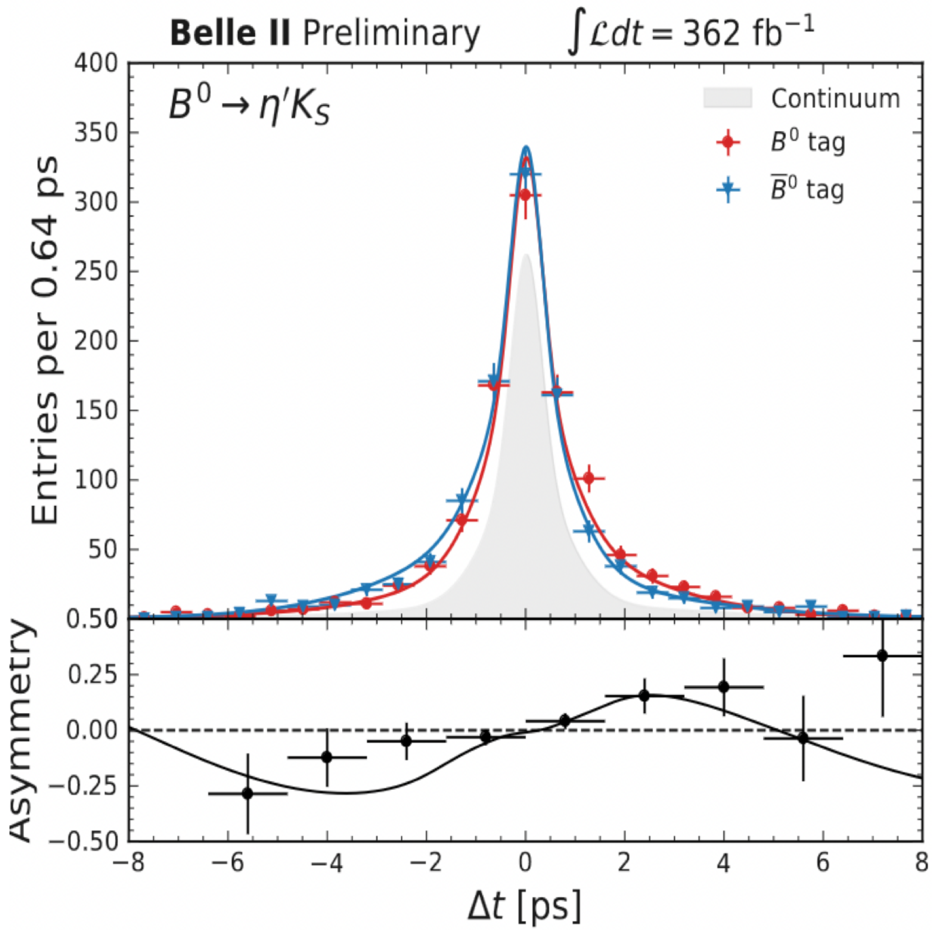
First Belle II measurement of CPV in $B \to \eta' K_S^0$

B^0 mixing phase well measured to be SM using CPV in tree-dominated $B \to J/\psi K_S^0$
Checking consistency with penguin-dominated decays probes generic non-SM and is a central flavor goal unique to Belle II

$B^0 \to \eta' K_S^0$ 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

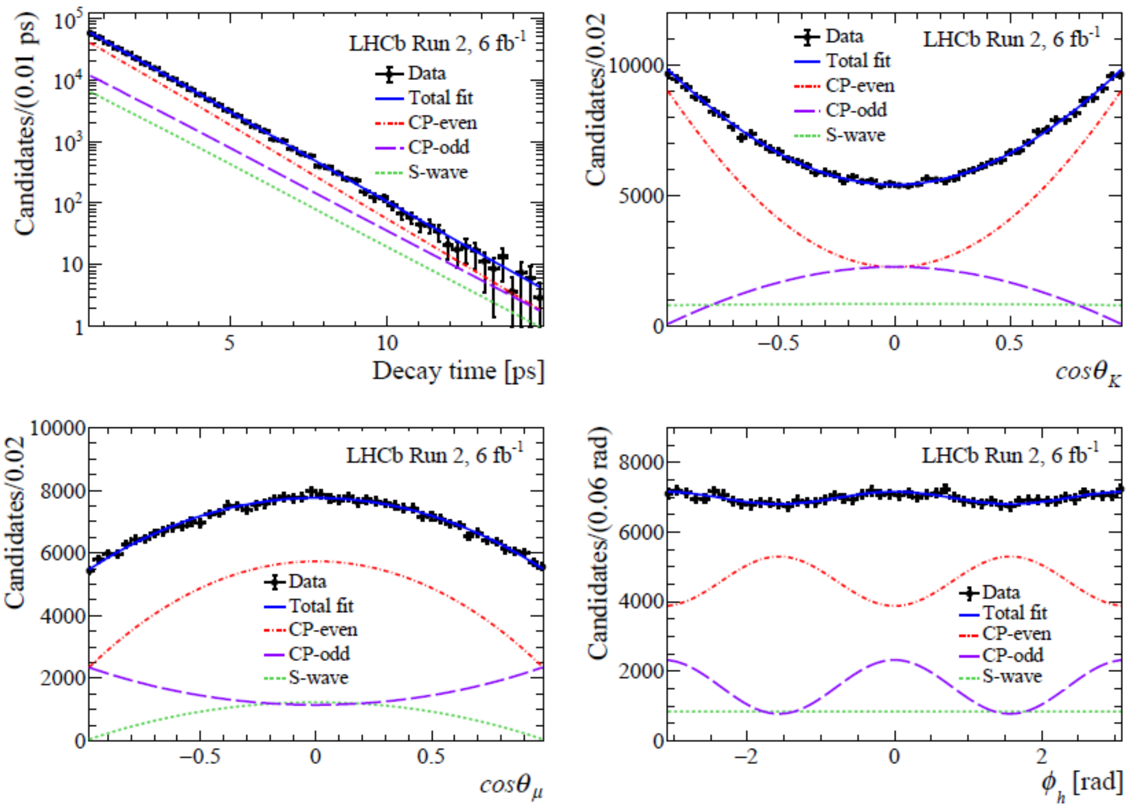


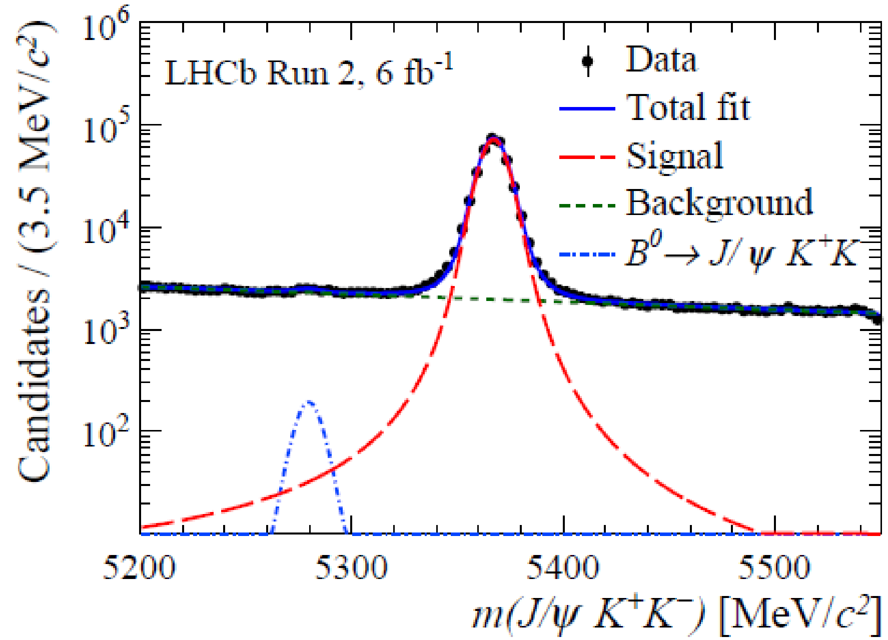
Mode	Experiment	$\sin(2\beta^{eff}) \equiv \sin(2\varphi_1^{eff})$	C_{CP}	Correlation	Reference
$\eta' K^0$	BaBar N(BB)=467M	0.57 ± 0.08 ± 0.02	−0.08 ± 0.06 ± 0.02	0.03 (stat)	PRD 79 (2009) 052003
	Belle N(BB)=772M	0.68 ± 0.07 ± 0.03	−0.03 ± 0.05 ± 0.03	0.03 (stat)	JHEP 1410 (2014) 165
	Average	0.63 ± 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	

$B_s \to J/\psi\,\phi$

[arXiv:2309.09728]

New result from LHCb using Run 2 data (6 fb^{-1})



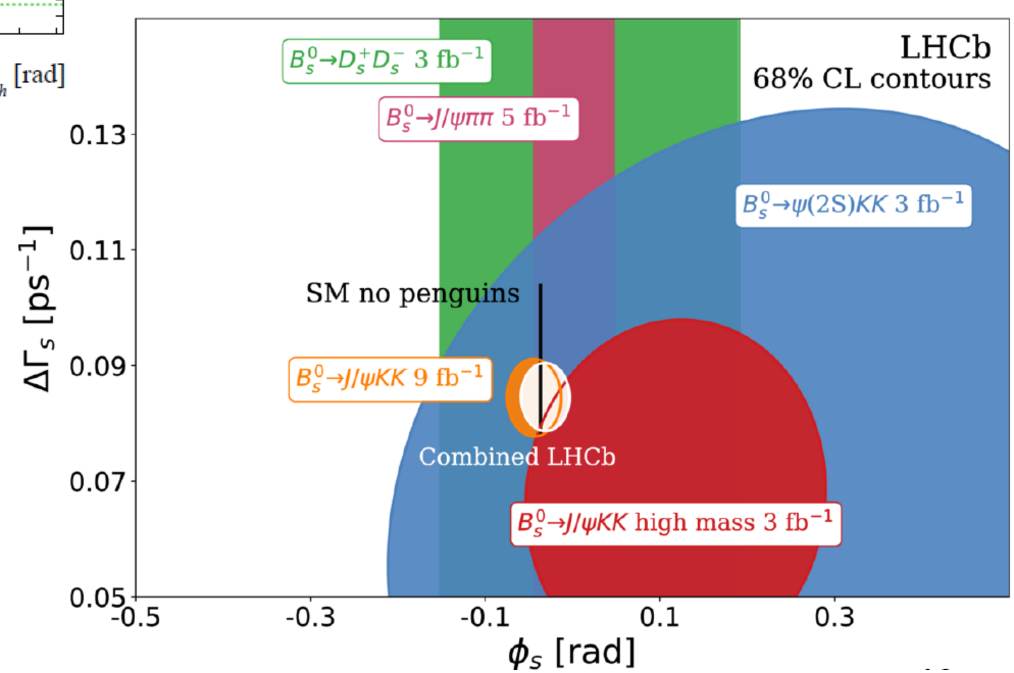


$$\phi_s = -0.039 \pm 0.022 \pm 0.006 \text{ rad}$$

$$|\lambda| = 1.001 \pm 0.011 \pm 0.005$$

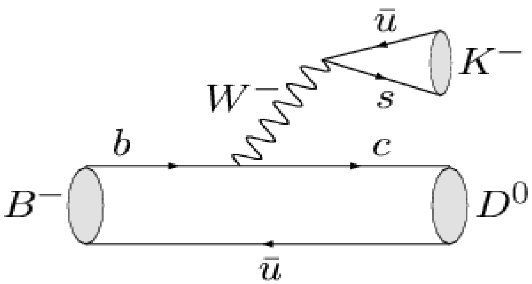
$$\Gamma_s - \Gamma_d = -0.0056\,^{+0.0013}_{-0.0015} \pm 0.0014$$

$$\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024$$



γ measurements from $B^{\pm} \to DK^{\pm}$

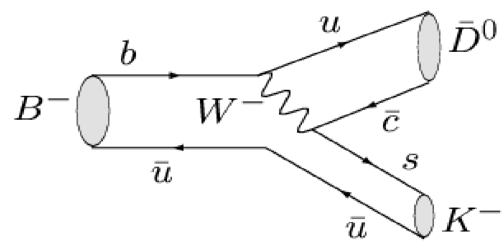
- Theoretically pristine B→DK approach
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$



color allowed

$B^- \to D^0 K^- \sim V_{cb} V_{us}^*$

$\sim A\lambda^3$



color suppressed

$B^- \to \overline{D}^0 K^- \sim V_{ub} V_{cs}^*$

$\sim A\lambda^3(\rho + i\eta)$

relative weak phase is γ
relative strong phase is δ_B

$$r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub} V_{cs}^*|}{|V_{cb} V_{us}^*|} \times [\text{color supp}] = 0.1 - 0.2$$

$B^{\pm} \to D K^{\pm}$
$B^{\pm} \to D^* K^{\pm}$, $D^* \to D\pi^0$
$B^{\pm} \to D^* K^{\pm}$, $D^* \to D\gamma$
$B^{\pm} \to D K^{*\pm}$
$B^0 \to D K^{*0}$
$B^{\pm} \to D K \pi\pi$
$B \to \ldots$

$D \to K^+ K^-$, $\pi^+ \pi^- \ldots$
$D \to K_S \pi^0$, $K_S \eta \ldots$
$D \to K K \pi^0$, $\pi\pi\pi^0 \ldots$
$D \to K_S \pi\pi$, $K_S K K$
$D \to K_S \pi\pi\pi^0$
$D \to \ldots$

BPGGSZ study $B \to D(K_S^0 h^+ h^-) h^-$

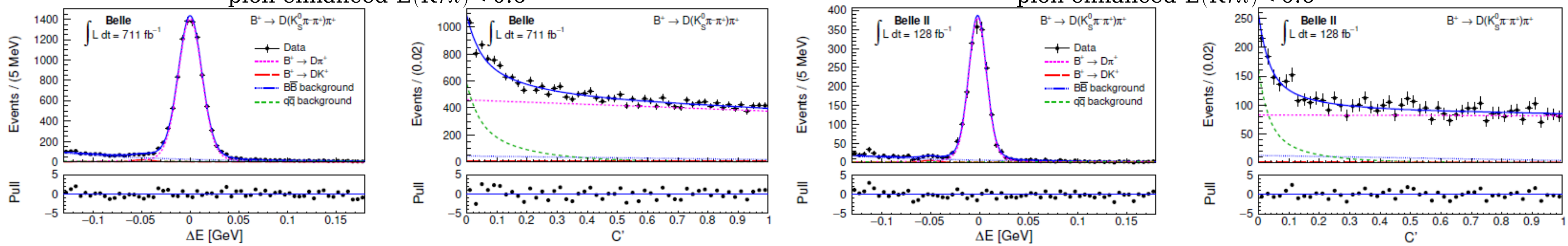
$h = \pi, K$

- Analysis with 711 fb^{-1} Belle data and 128 fb^{-1} Belle II data

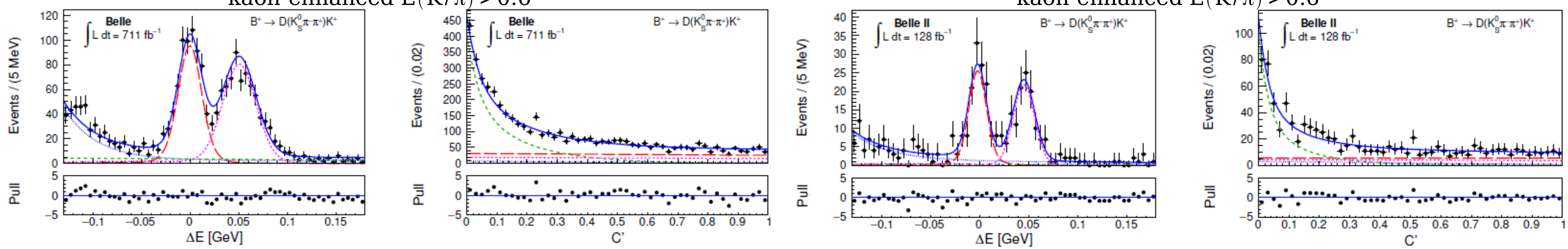
(Belle/Belle II collaboration)
[arXiv:2110.12125, JHEP (2022) 63]

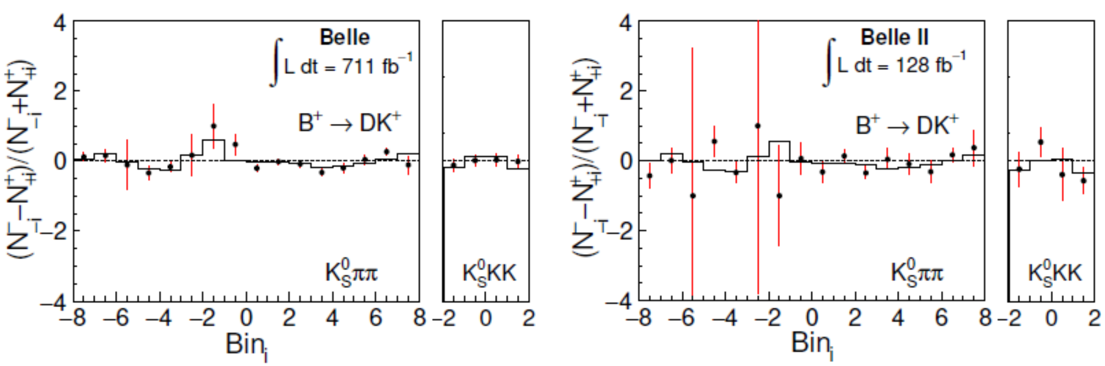
- Unbinned 2D simultaneous fit of ΔE versus C'

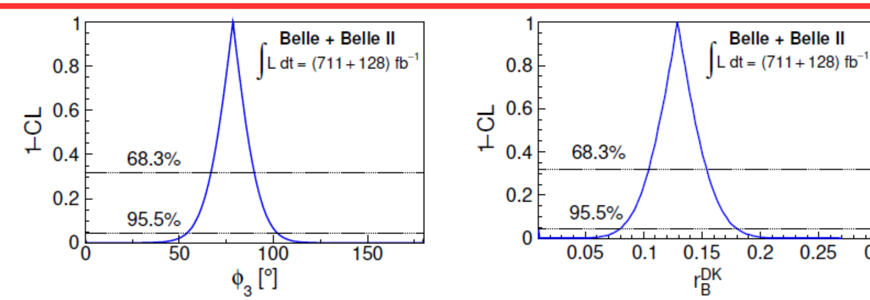
pion enhanced $L(K/\pi) < 0.6$ | pion enhanced $L(K/\pi) < 0.6$



kaon enhanced $L(K/\pi) > 0.6$ | kaon enhanced $L(K/\pi) > 0.6$





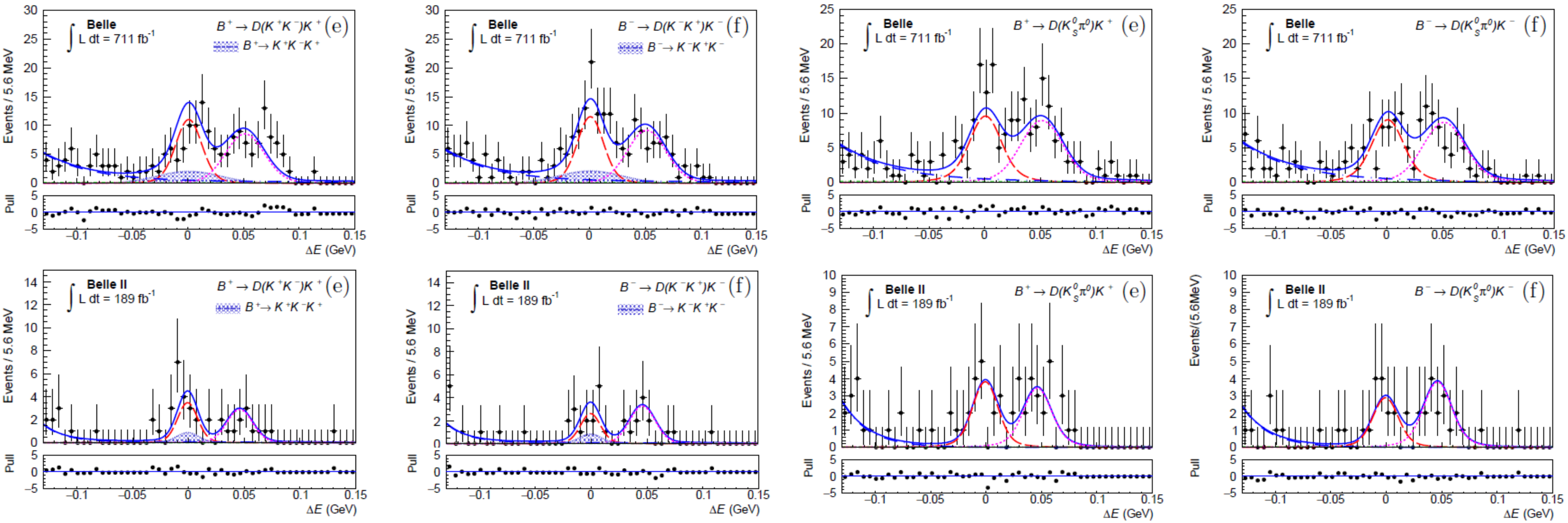


$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ,$$
$$r_B^{D\pi} = 0.017 \pm 0.006 \pm 0.001 \pm 0.001,$$
$$\delta_B^{D\pi} = (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ.$$

$\sigma_{\phi_3} = 14^\circ$ from earlier Belle measurement

GLW study for $B \to D(KK)K$ and $D(K_S^0\pi^0)K$

Fitting simultaneously the $B \to D\pi$ and DK samples, $D \to K\pi$ and… $D \to KK$ and $K_S^0\pi^0$



$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\phi_3,$$

$$\mathcal{A}_{CP\pm} = \pm 2r_B \sin\delta_B \sin\phi_3 \,/\, \mathcal{R}_{CP\pm}.$$

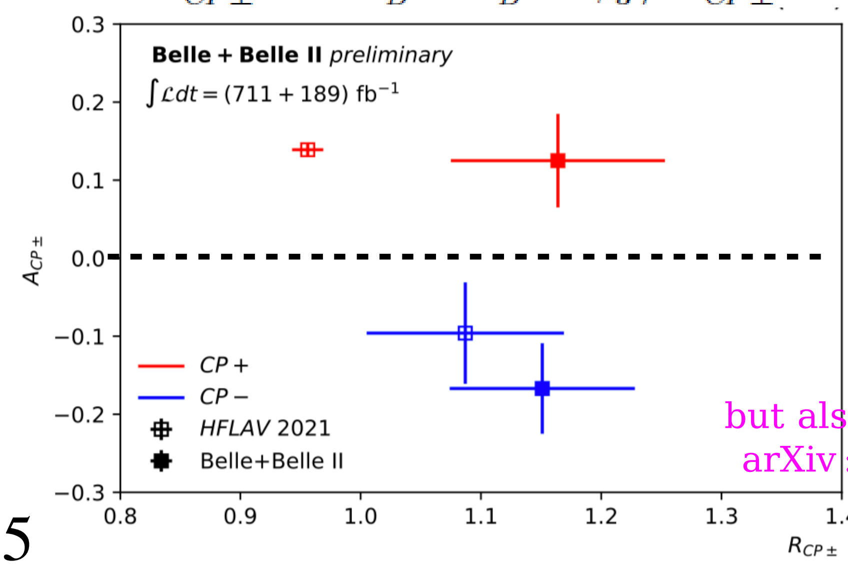
In GLW, CP−odd state accessible only to B-factories [arXiv:2308.05048]

$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036,$$

$$\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019,$$

$$\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$

$$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%.$$



Direct evidence of opposite A_{CP} for even and odd states

but also GLS results arXiv:2306.02940

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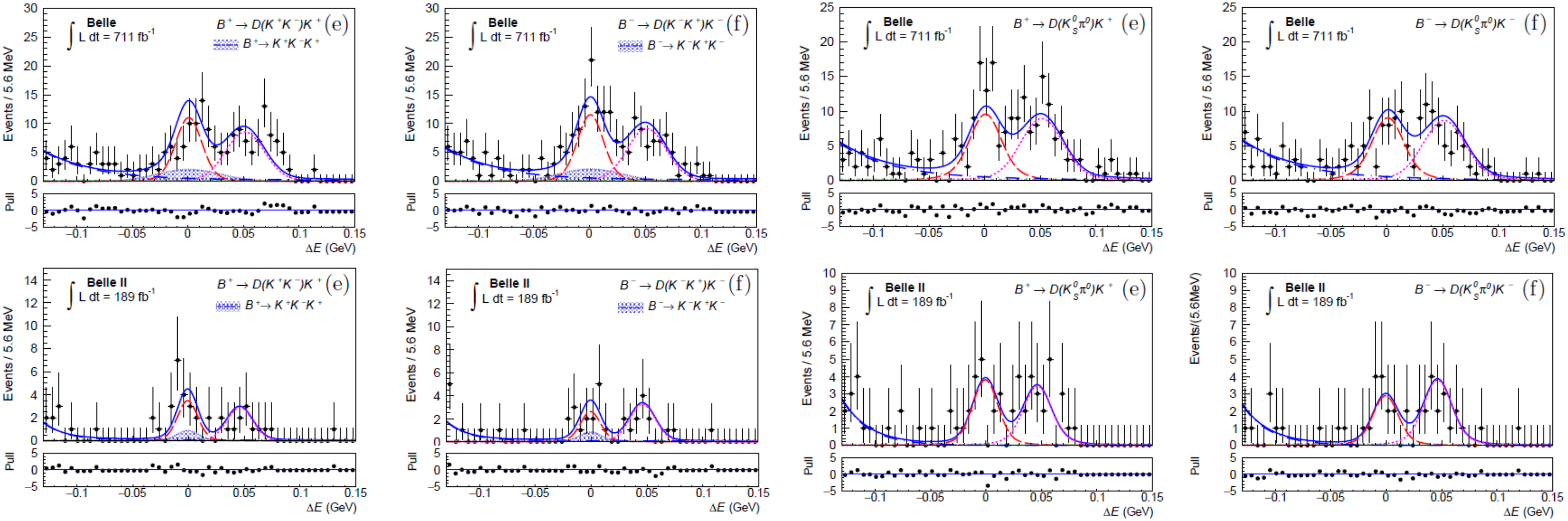

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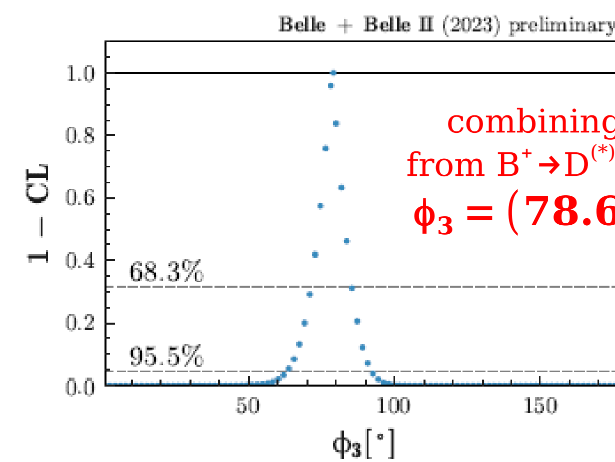


combining inputs from $B^+ \to D^{(*)} h^+$ decays

$\phi_3 = (78.6 \pm 7.3)^\circ$

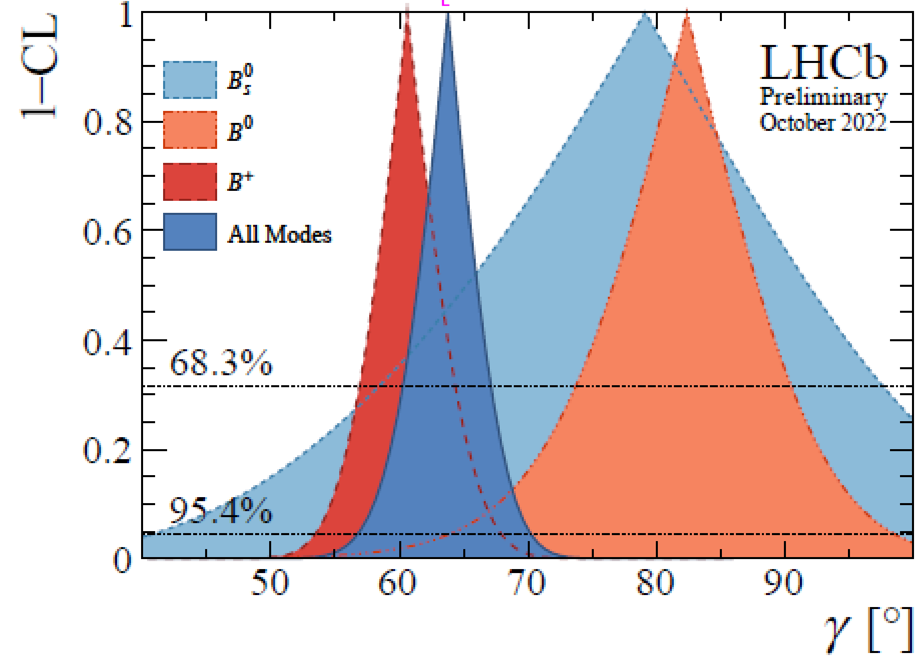
Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$
Best fit value	78.6	0.117	138.4
68.3% interval	[71.4, 85.4]	[0.105, 0.130]	[129.1, 146.5]
95.5% interval	[63, 92]	[0.092, 0.141]	[118, 154]

γ measurements at LHCb

B decay	D decay	Ref.	Dataset
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	29	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	30	Run 1
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	18	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	19	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	31	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	32	Run 1&2
$B^\pm \to D^* h^\pm$	$D \to h^+h^-$	29	Run 1&2
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	33	Run 1&2(*)
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	33	Run 1&2(*)
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	34	Run 1
$B^0 \to DK^{*0}$	$D \to h^+h^-$	35	Run 1&2(*)
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	35	Run 1&2(*)
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	36	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	37	Run 1
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	38	Run 1
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	39	Run 1&2

D decay	Observable(s)	Ref.	Dataset
$D^0 \to h^+h^-$	ΔA_{CP}	24, 40, 41	Run 1&2
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	16, 24, 25	Run 2
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	42	Run 1
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	15	Run 2
$D^0 \to h^+h^-$	ΔY	43–46	Run 1&2
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	47	Run 1
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	48	Run 1&2(*)
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	49	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	x, y	50	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	51	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	52	Run 2
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	17	Run 2

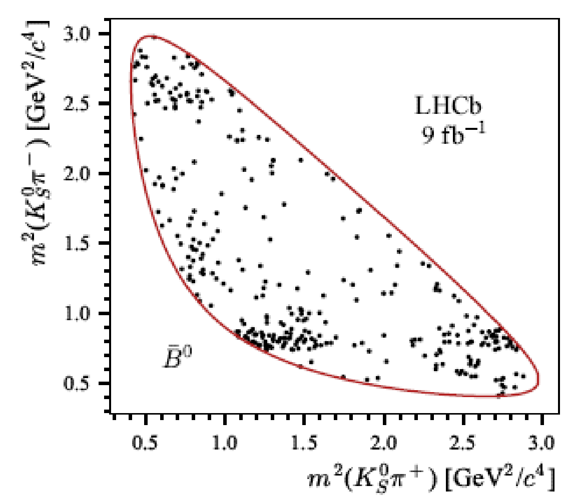
[LHCb-CONF-2022-003]



$\gamma = (63.8^{+3.5}_{-3.7})^\circ$

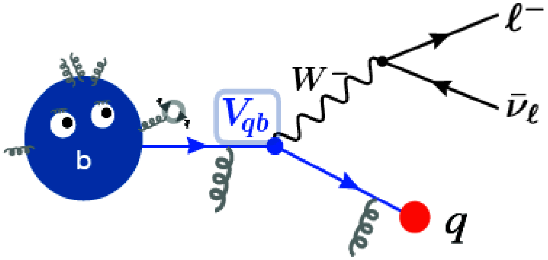
[Global fit by CKMfitter: $\gamma = (65.3^{+0.7}_{-1.9})^\circ$]

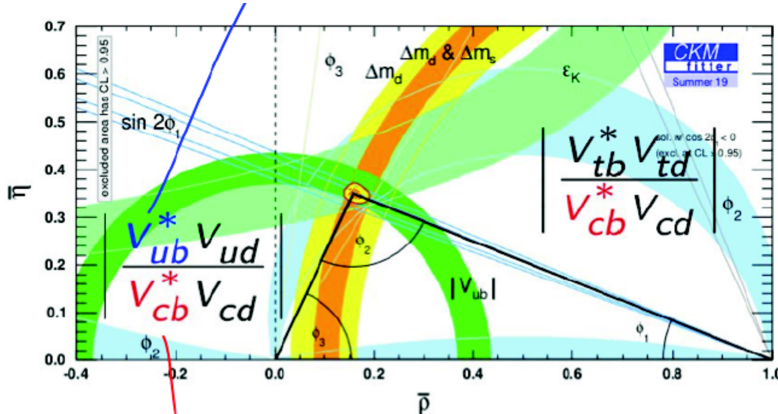
A few more new results came this year (not included above)
e.g. $B^0 \to DK^*$ with $D \to K^0_S h^+ h^-$ [arXiv:2309.05514]
$\gamma = (49^{+22}_{-19})^\circ$

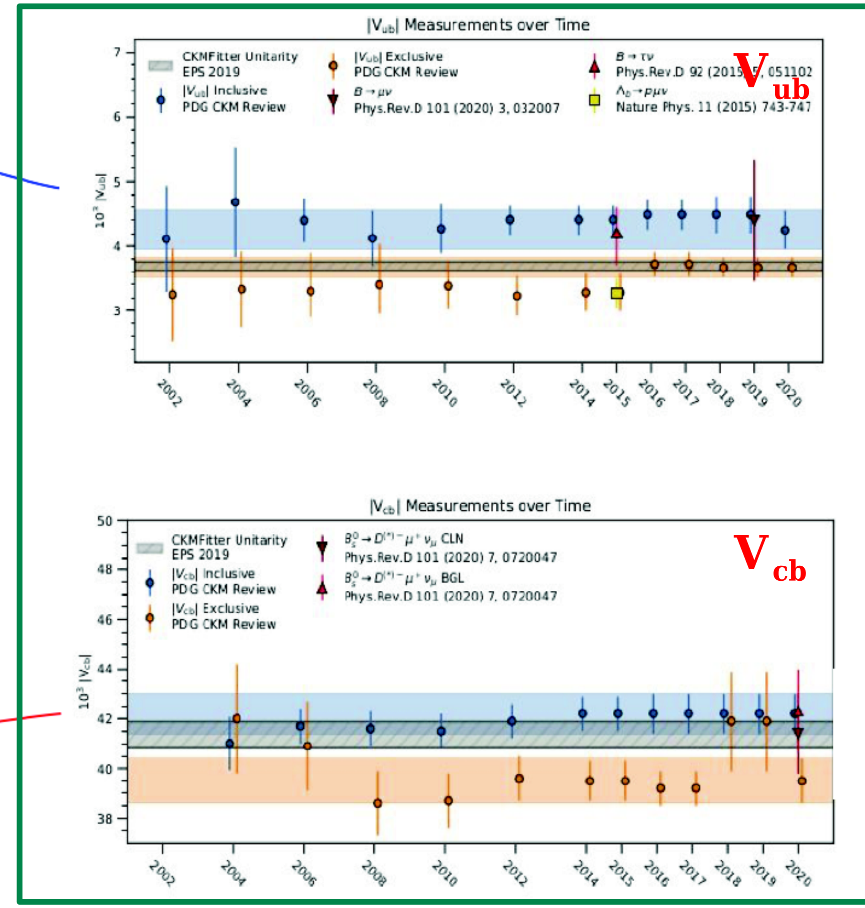


Semi-leptonic B decays

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



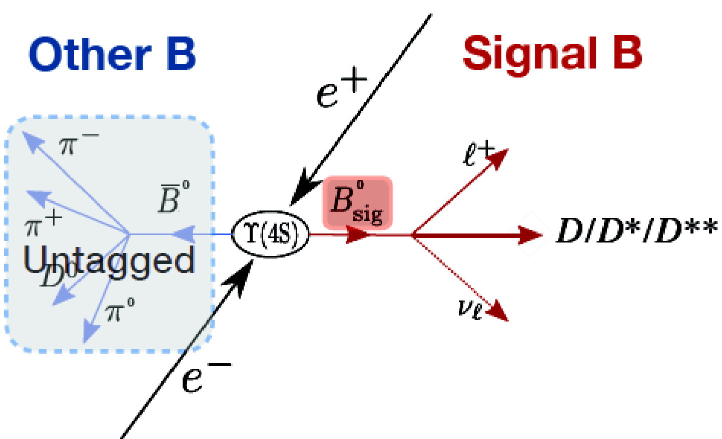




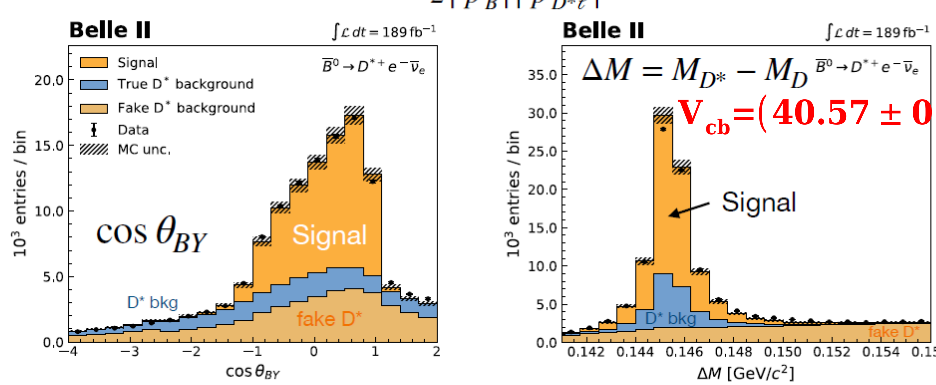
$V_{cb}^{exc} = (39.10 \pm 0.50)\times 10^{-3}$, $V_{cb}^{inc} = (42.16 \pm 0.51)\times 10^{-3}$

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

[Belle II, arXiv:2310.01170]



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



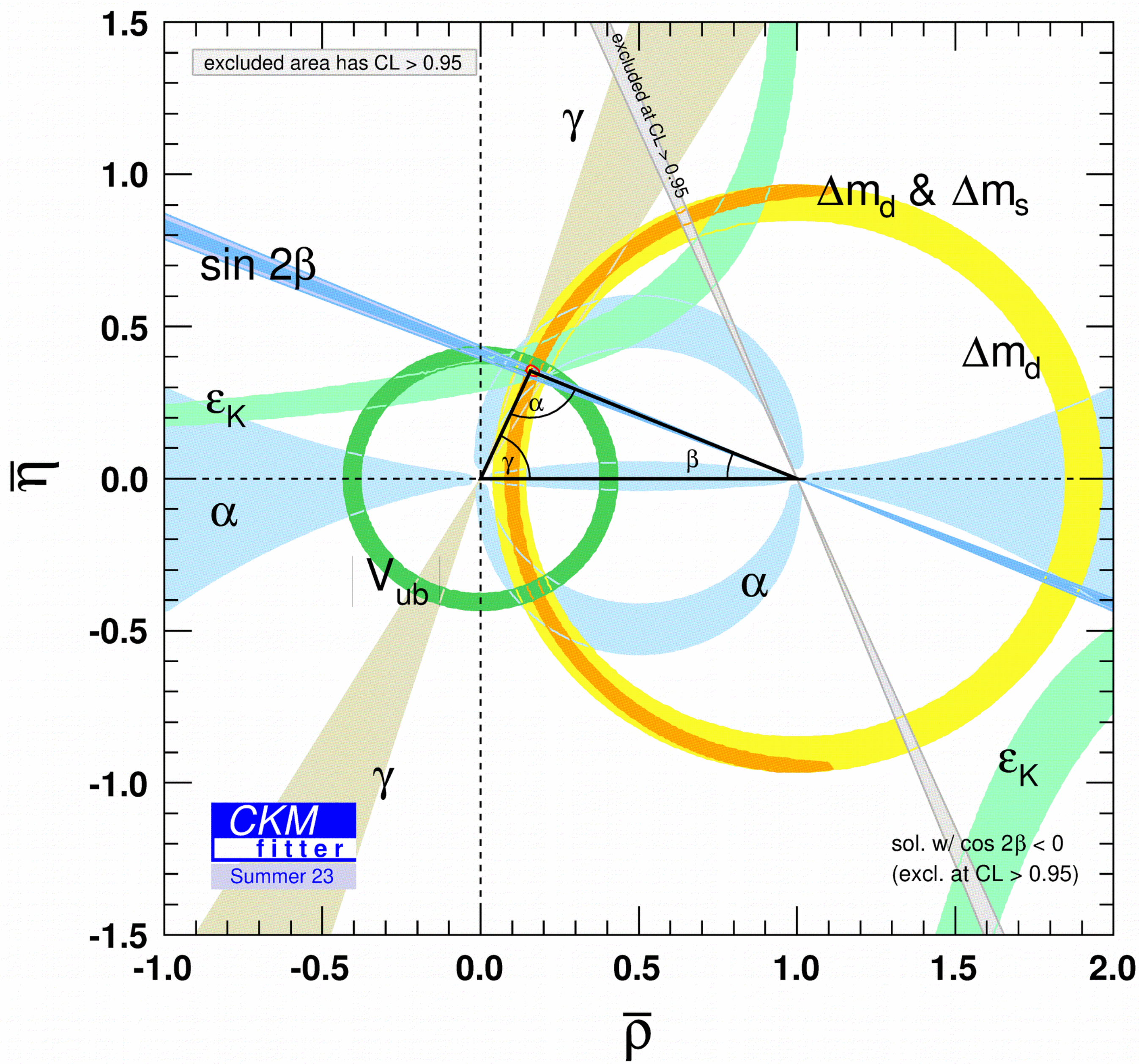
$V_{cb} = (40.57 \pm 0.31 \pm 0.95 \pm 0.58)\times 10^{-3}$

with more stat

⇒ tagged analyses

The current status of CKM

(CKMfitter 2023)



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

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

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

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

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

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

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

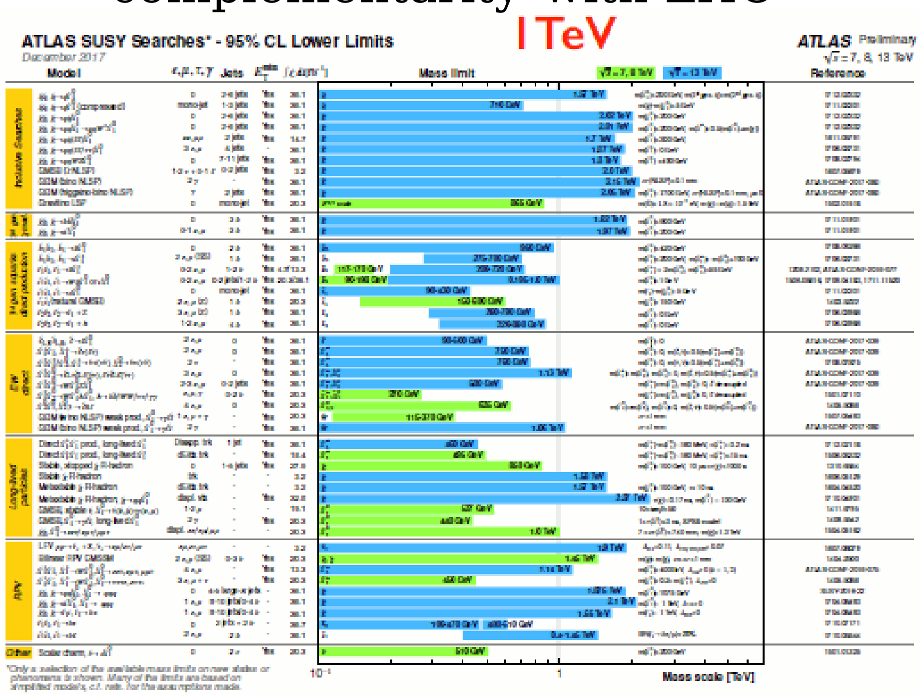
$\mathbf{\bar{\eta} = 0.355^{+0.005}_{-0.006}}$

(68% CL)

How do you we search for new particles ?

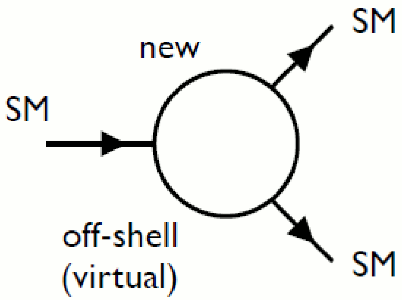
Direct vs Indirect Searches

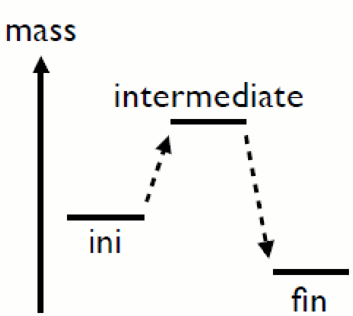
complementarity with LHC



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

New particle via quantum effects

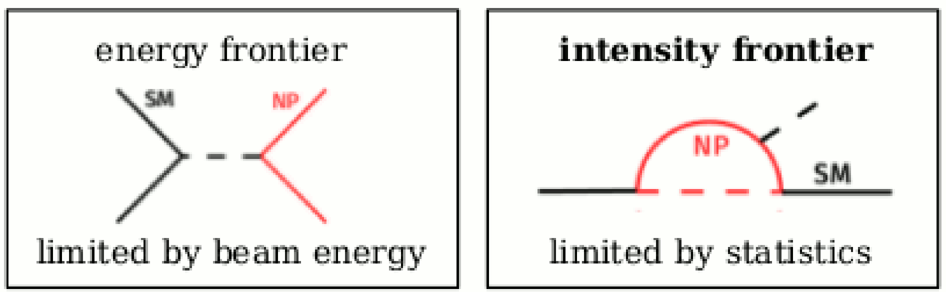




No sharp cutoff for energy scale (cf. LHC search)

— suppressed by $(E/\Lambda)^n$

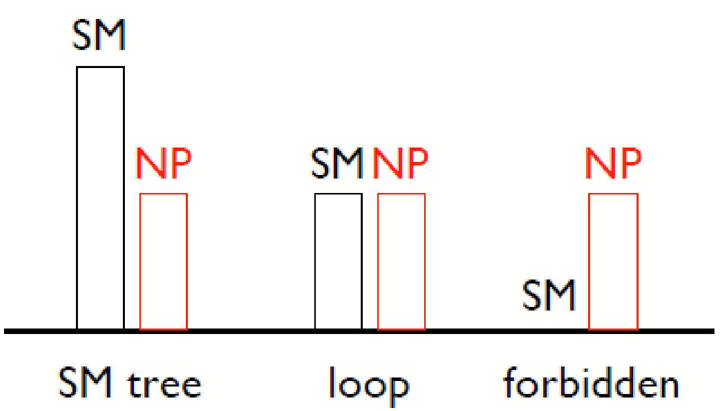
Why flavor physics ?



→ **NP beyond the <u>direct</u> reach of the LHC**

Three classes of SM processes

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

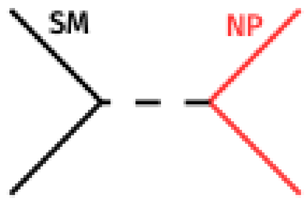


extremely precise | precision | good but…

Rare B decays

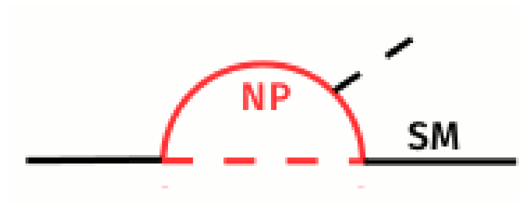
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism
- Any new particle generating new diagrams can change the amplitudes

energy frontier



limited by beam energy

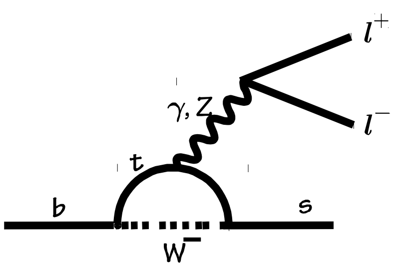
intensity frontier

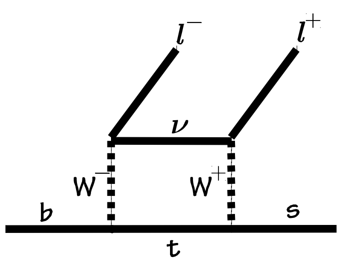


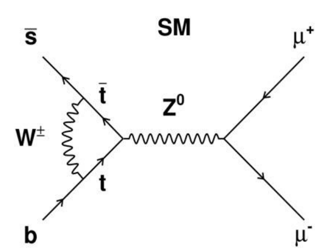
limited by statistics

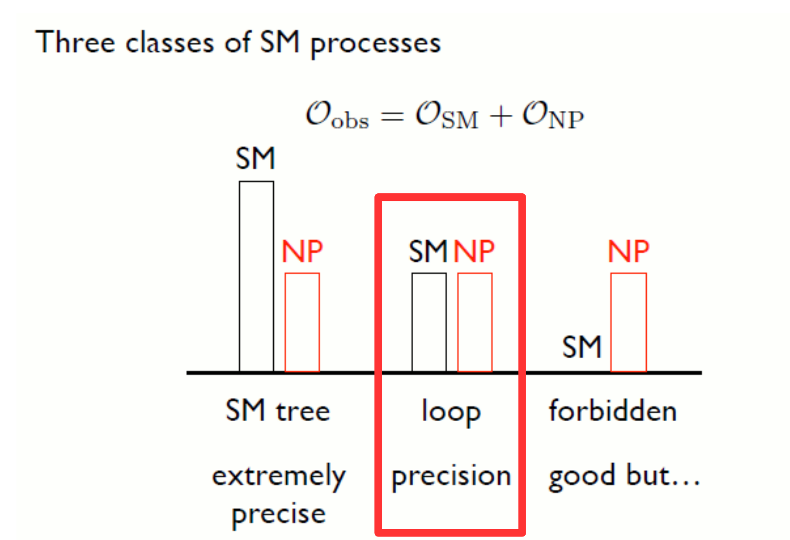
→ **NP beyond the direct reach of the LHC**

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**



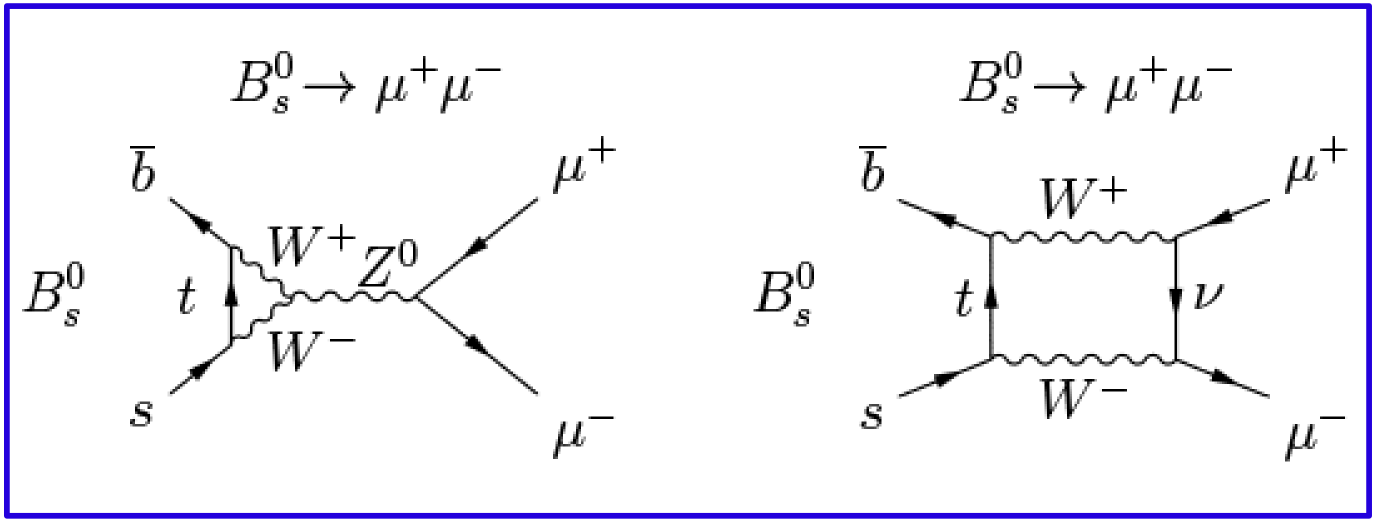






$B_{(s)} \to \mu\mu$: ultra rare processes…

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

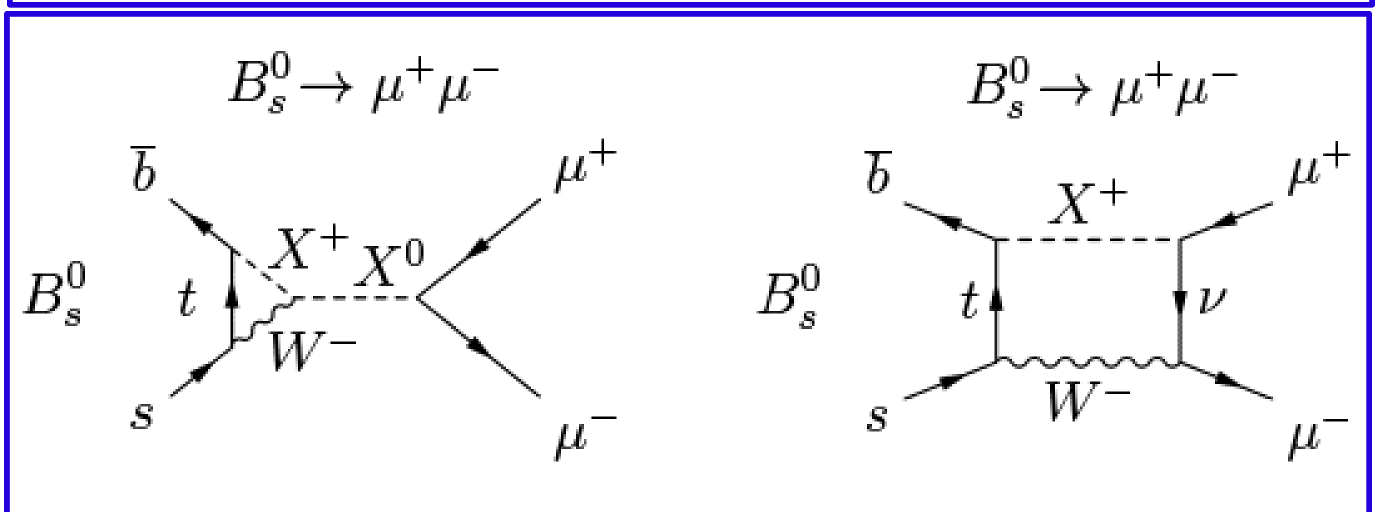


higher-order FCNC allowed in SM

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

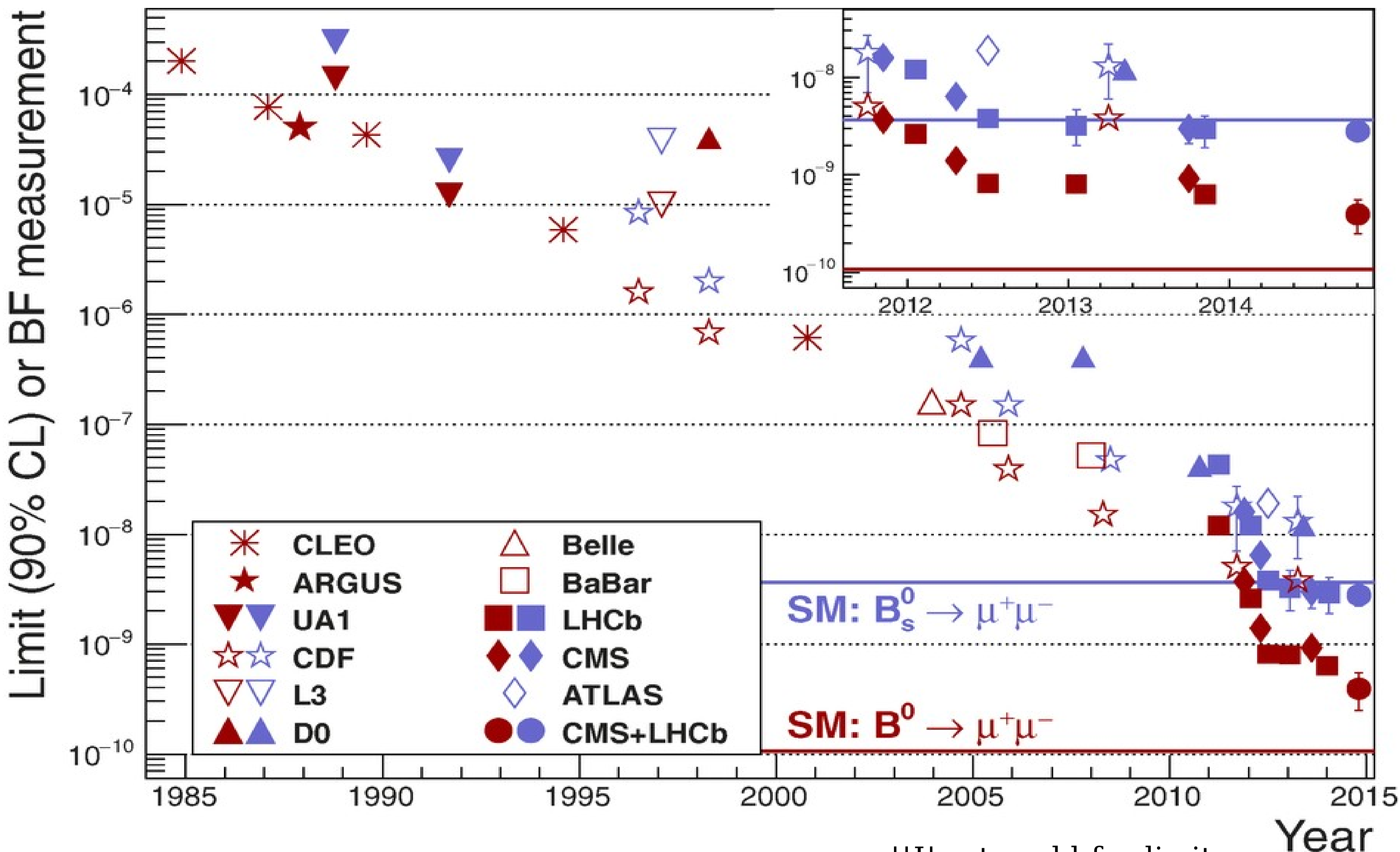
$B(B_d \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$

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



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

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

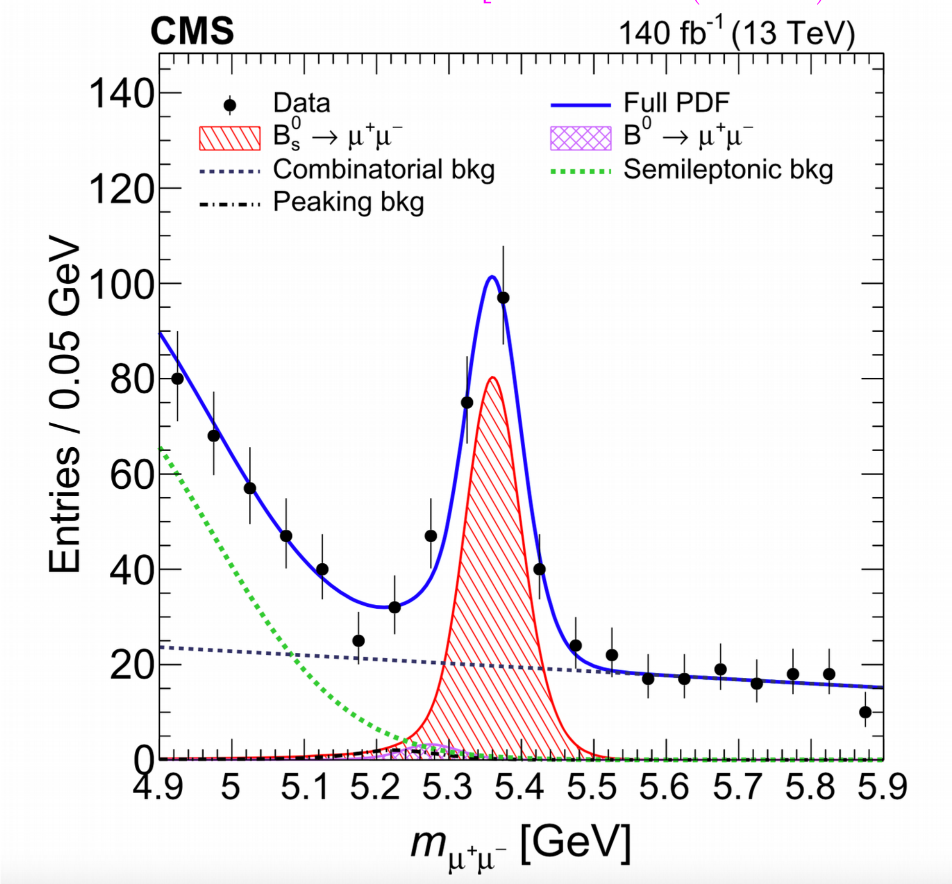


''I'm too old for limits,
I want to see signals''
(Francis Halzen)

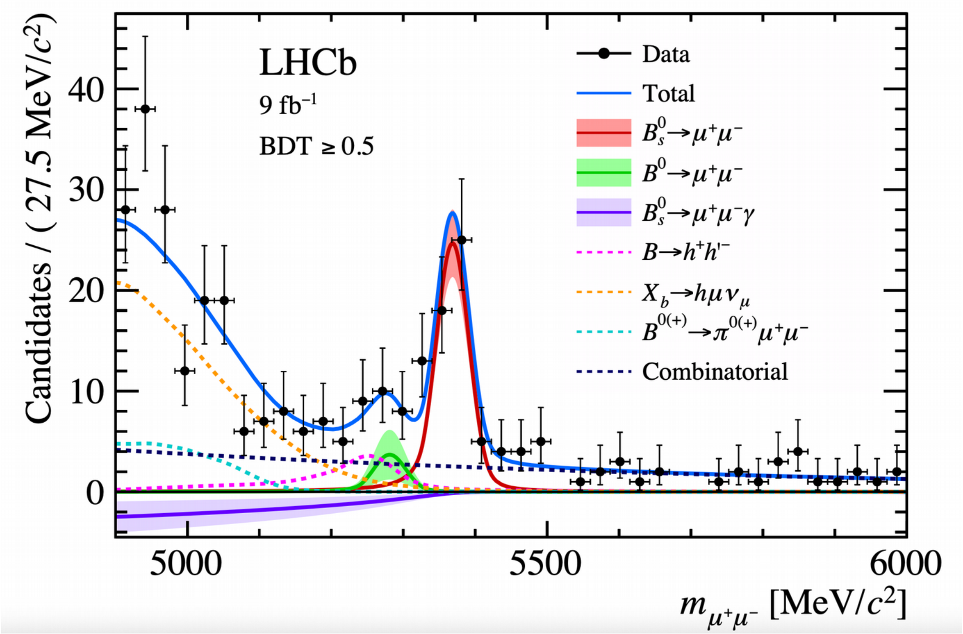
$B_{(s)} \to \mu\mu$: ultra rare processes…

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

[PLB 842 (2023) 137955]



[PRL 128 (2022) 041801]

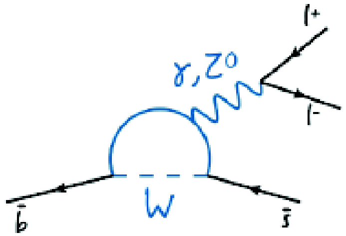


$$B(B_s^0 \to \mu^+\mu^-) = (3.83\,^{+0.38}_{-0.36}\,^{+0.19}_{-0.16}\,^{+0.14}_{-0.13}(f_s/f_u)) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ @ 95\% CL}$$

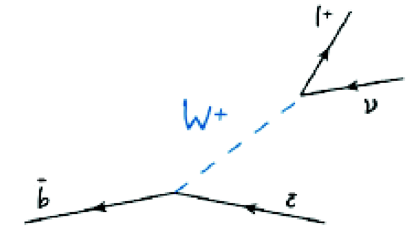
$$B(B_s^0 \to \mu^+\mu^-) = (3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \text{ @ 95\% CL}$$

Pioneer measurements for effective lifetime already available

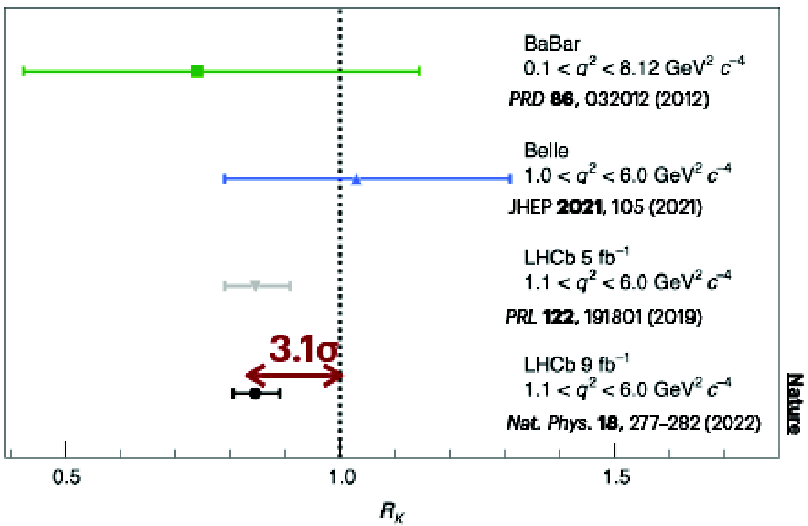
what happened with the B anomalies… ?



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



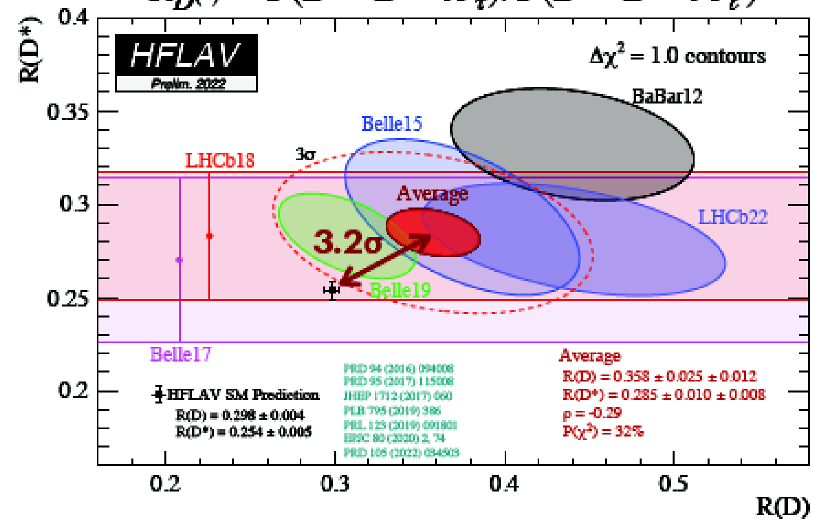
$R_K = \Gamma(B^+ \to K^+\mu^+\mu^-)/\Gamma(B^+ \to K^+e^+e^-)$



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

Lepton
Flavor
Universality
Violation

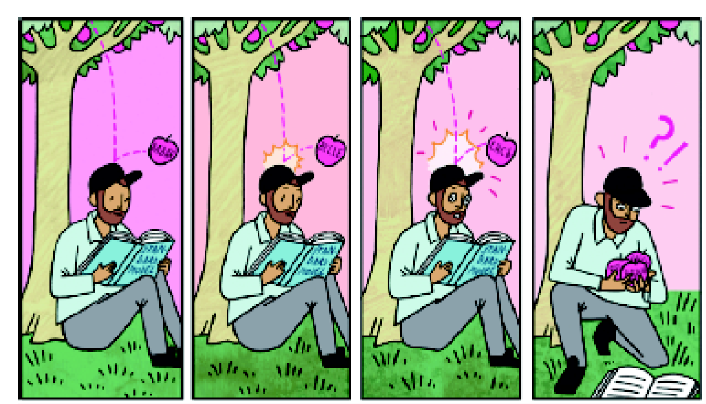
$R_{D^{(*)}} = \Gamma(B \to D^{(*)}\tau\nu_\tau)/\Gamma(B \to D^{(*)}\ell\nu_\ell)$



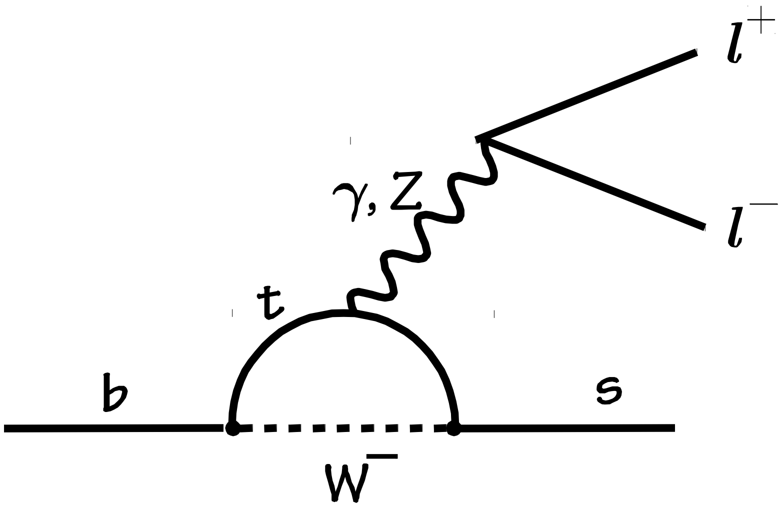
τ vs e/μ: $R_{D^{(*)}}^{\rm exp} > R_{D^{(*)}}^{\rm SM}$

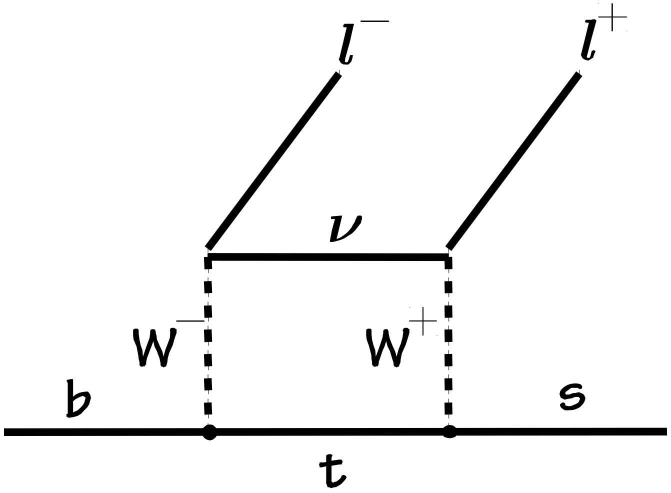
Main players in B-physics

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



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





$\Rightarrow$ 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...

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

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?

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

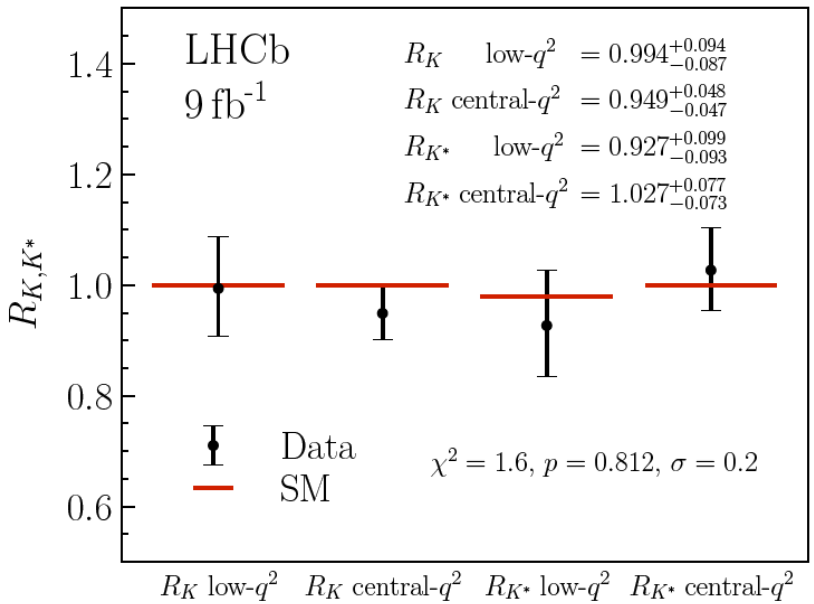
SM expectation

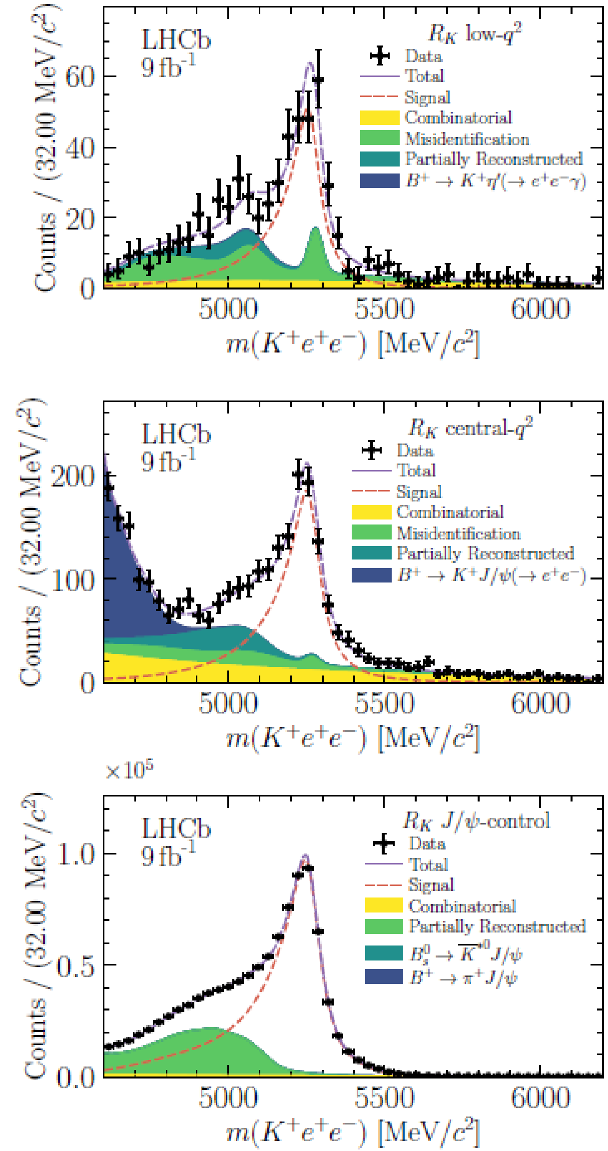
$$R_Y = 1 + \mathcal{O}\left(\frac{m^n_{i,j}}{m^n_X}\right)$$

Experimental results

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

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

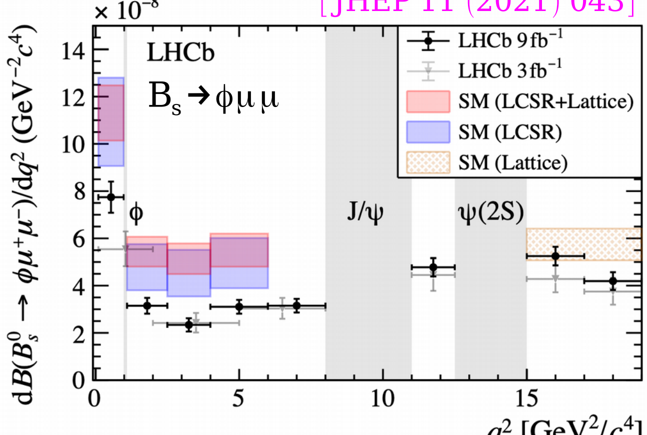




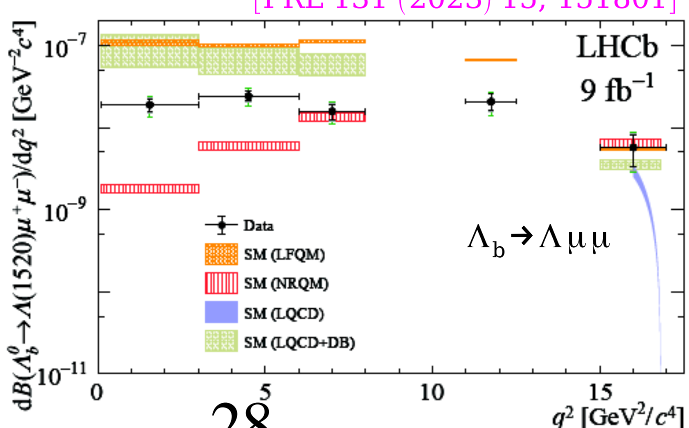
Significant change of the landscape
⇒ Compatible with SM

- BR measurements differ from predictions

[JHEP 11 (2021) 043]



[PRL 131 (2023) 15, 151801]

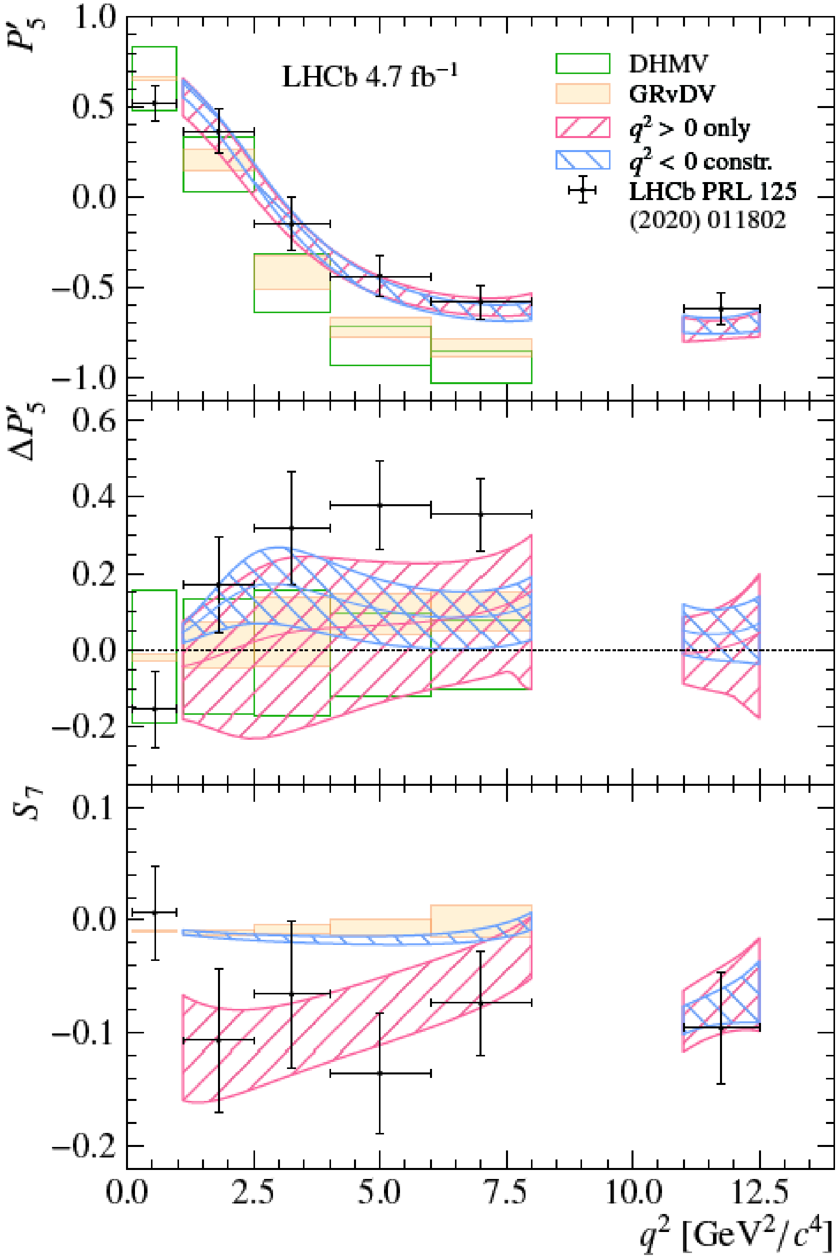


Unbinned $B \to K^{*0} \mu^+ \mu^-$

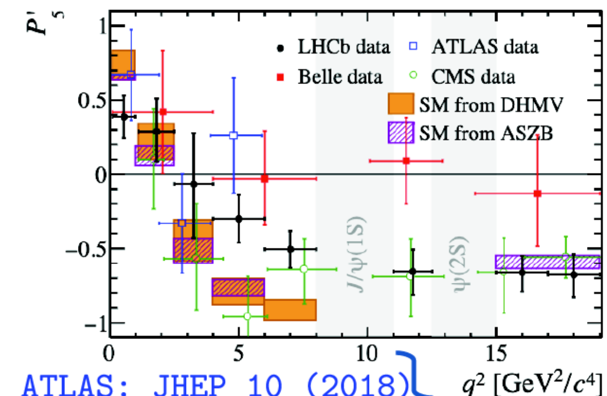
[arXiv:2312.09102, arXiv:2312.09115]

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

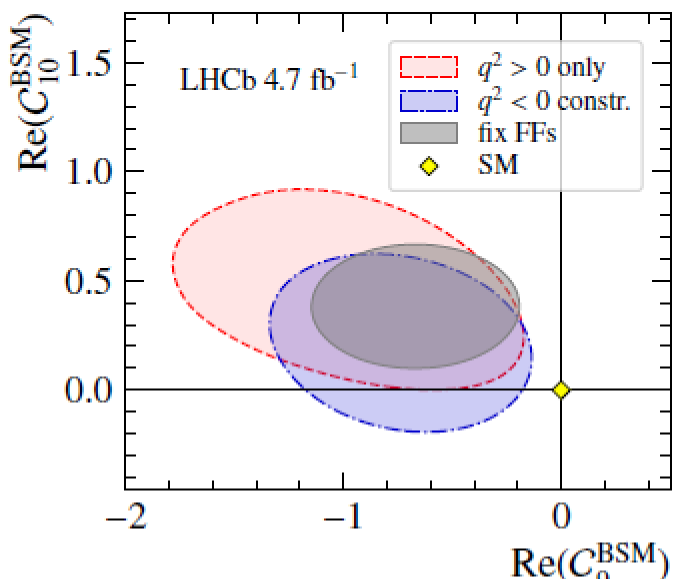


[LHCb, PRL 125 (2020) 01180]



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



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

Model candidates

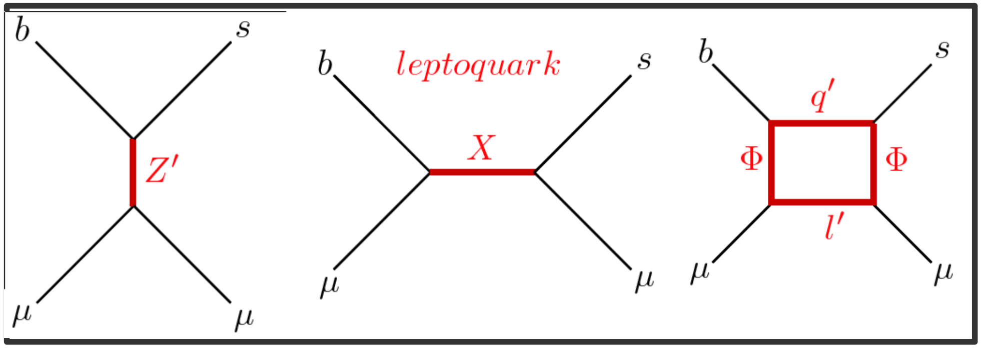
- ✓ Effective operator from Z' exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ **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

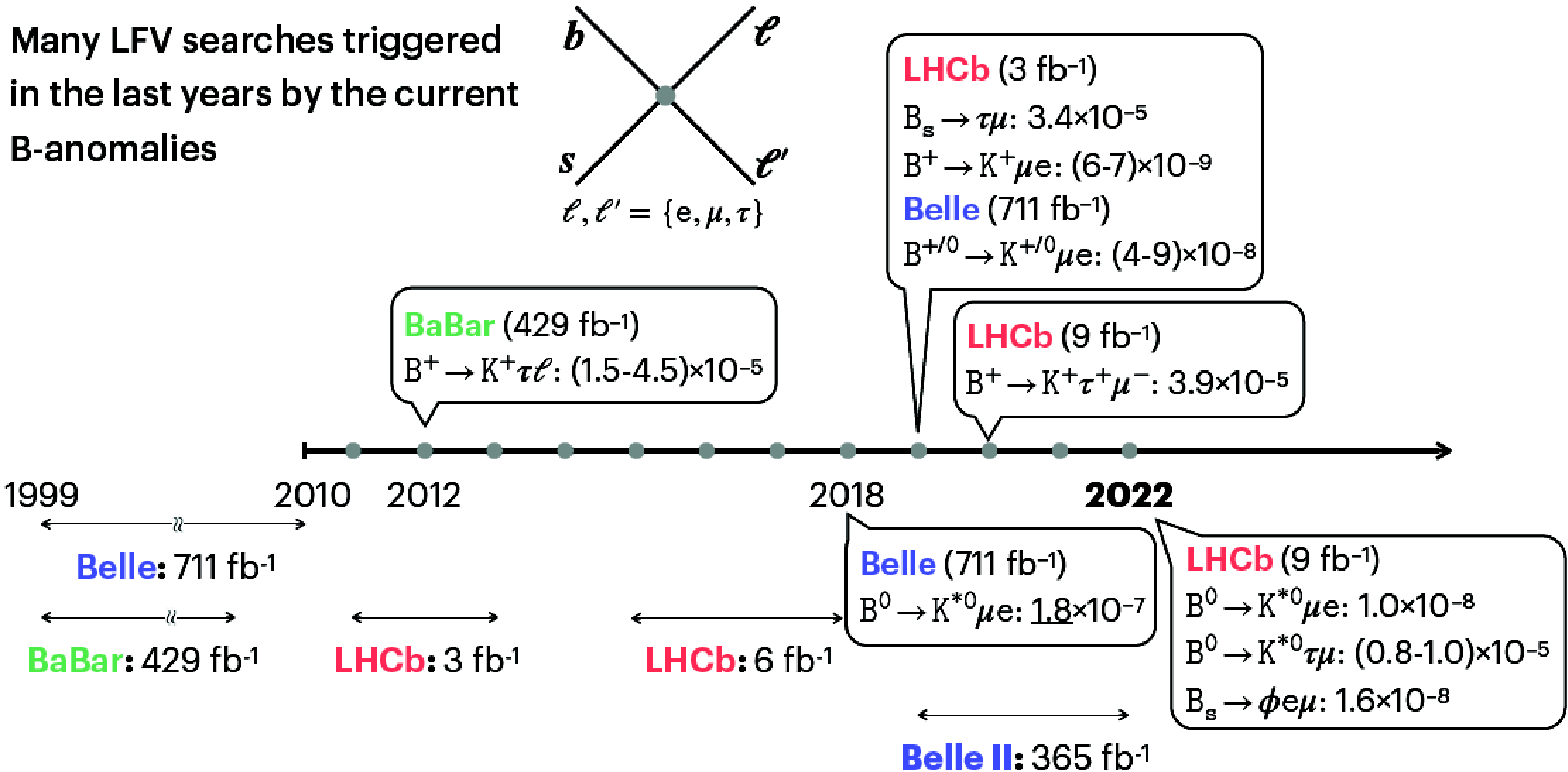
Lot of those models predict also LFV $b \to s e\mu$, $b \to s e\tau$, ...

G.Isidori, FPCP 2020: correlations among $b \to s(d) l l'$ within the (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_π]	$B \to \pi \tau\tau$ → 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ → 10^{-7}	$B \to \pi \mu e$???

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

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

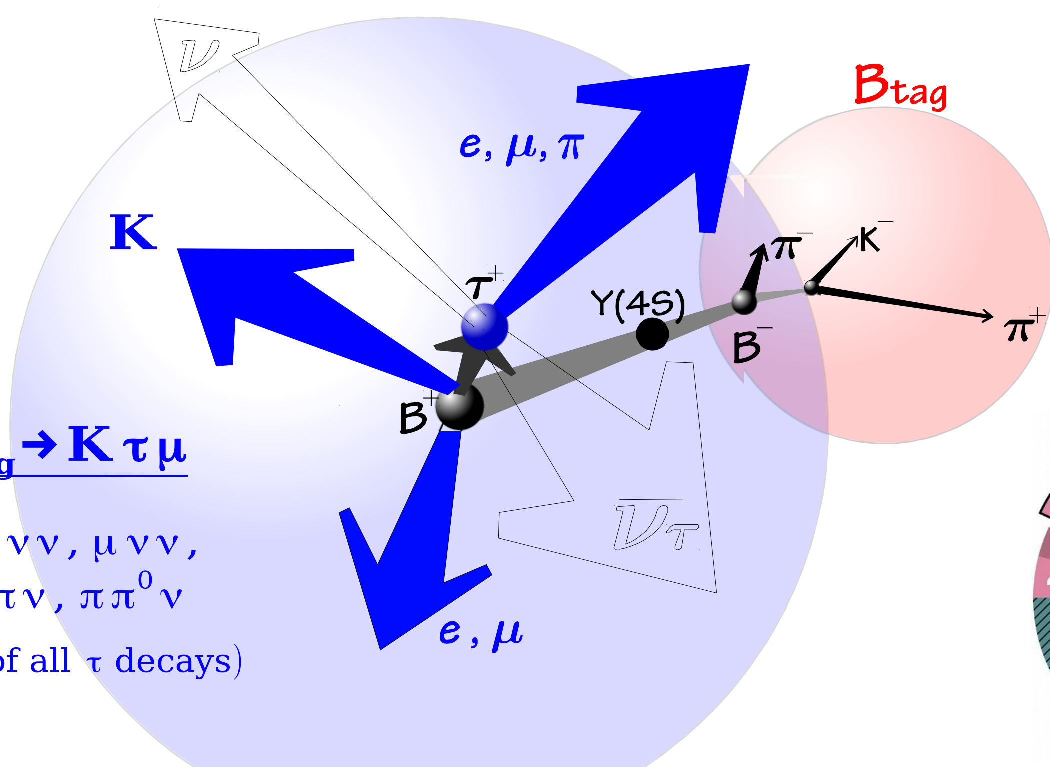


Limits on modes with τ's are not as constraining as those with μe because of the **more challenging τ reconstruction**

- **(2-5)×10^{-5} range for $B^+ \to K^+\tau\ell$ (BaBar and LHCb)**

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.



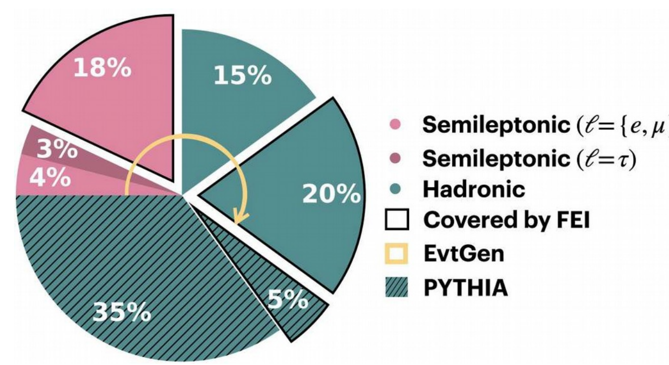
$B_{sig} \to K\tau\mu$

$\tau \to e\nu\nu, \mu\nu\nu,$
$\tau \to \pi\nu, \pi\pi^0\nu$
(70 % of all τ decays)

B_{tag}

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

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 from ARGUS, CLEO...

➔ calibration is essential

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

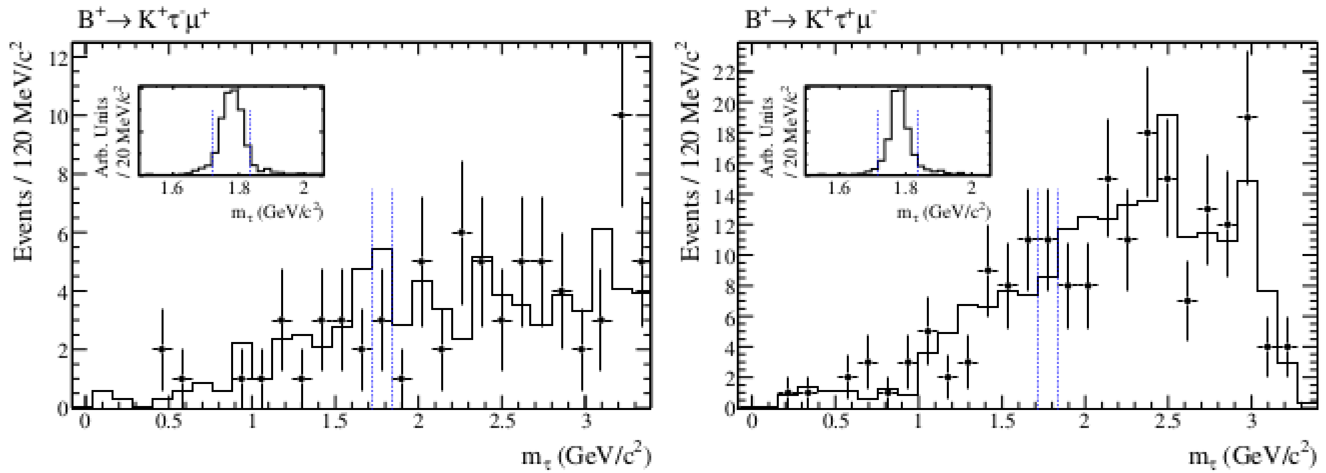
LFV $B \to K \tau l$ ($l = e, \mu$) decays

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

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

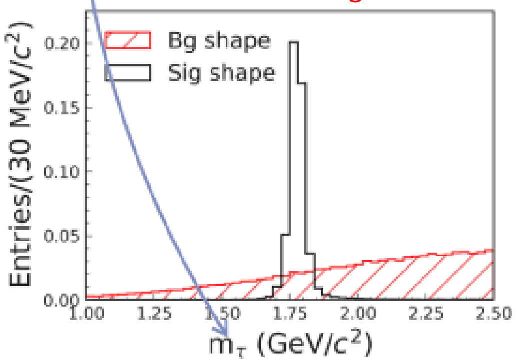
⇒ **can do $K^*\tau e$, $K^*\tau\mu$ with similar sensitivity...**

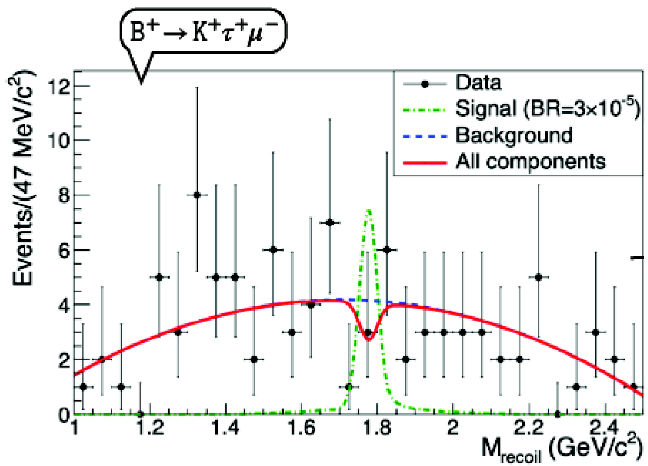
Missing energy modes and B-tagging

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 !



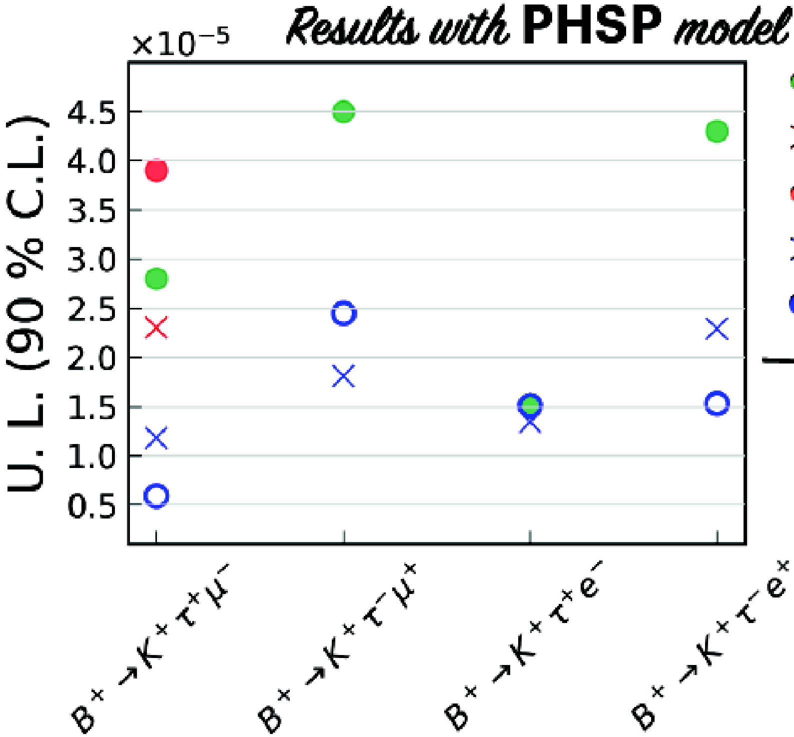


[Belle, PRL 130, 261802 (2023)]

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

Results with* PHSP *model



- 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

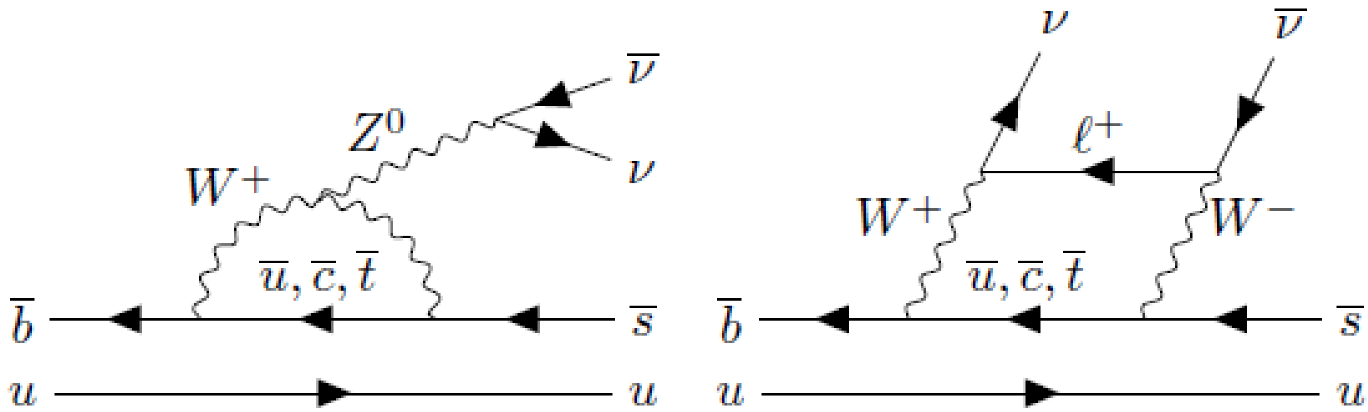
with less than 1 ab^{-1}...competitive with LHCb !

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

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

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

[arXiv:2311.14647]

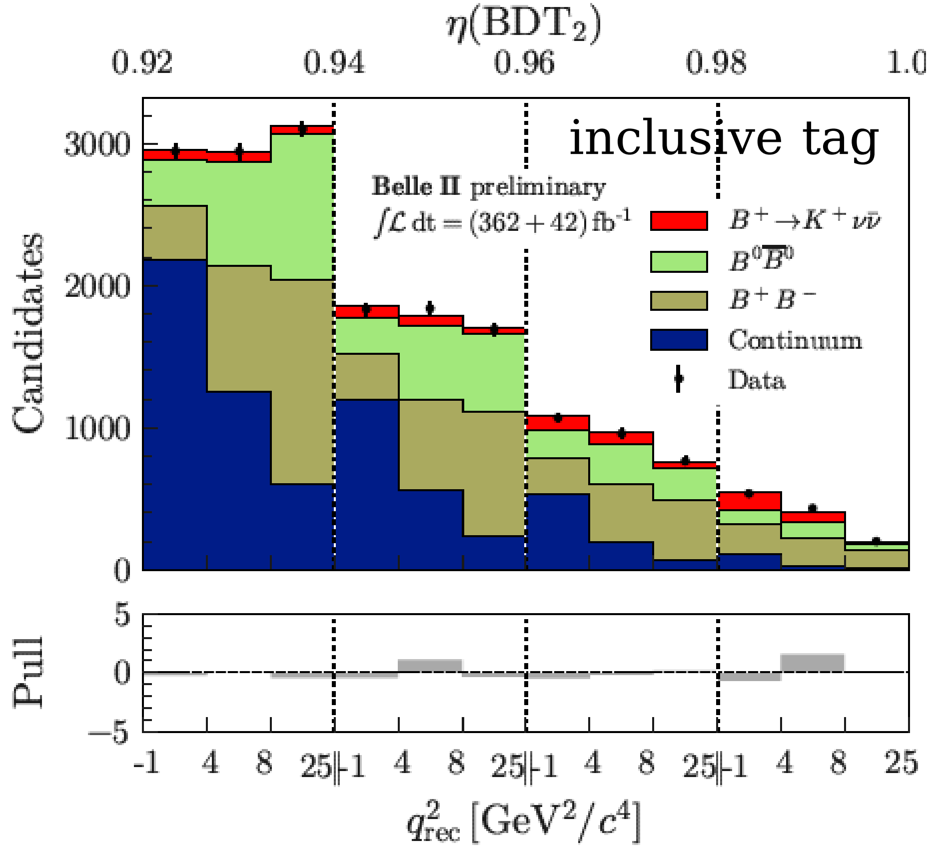


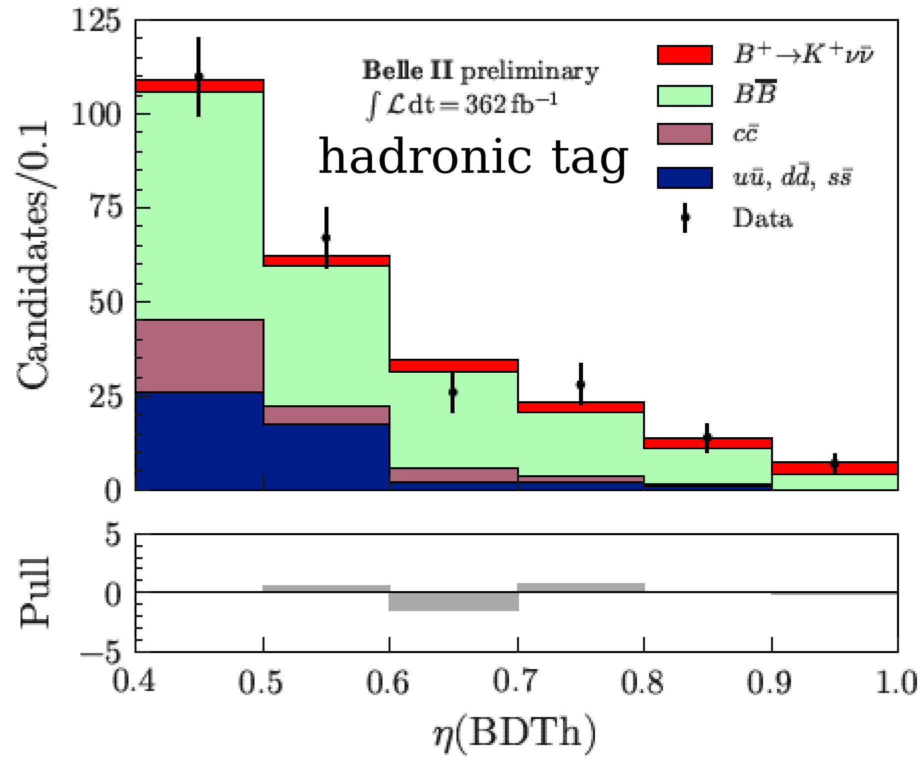
- $B \to K \nu \nu$ is known with high accuracy
  $B(B \to K \nu \nu) = (5.6 \pm 0.4) \times 10^{-6}$ [arXiv:2207.13371]
- Extensions beyond SM may lead to significant rate increase
- Very challenging experimentally, not yet observed
  - Low branching fraction, high background contributions
  - 3-body 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→Kνν̄

[arXiv:2311.14647]





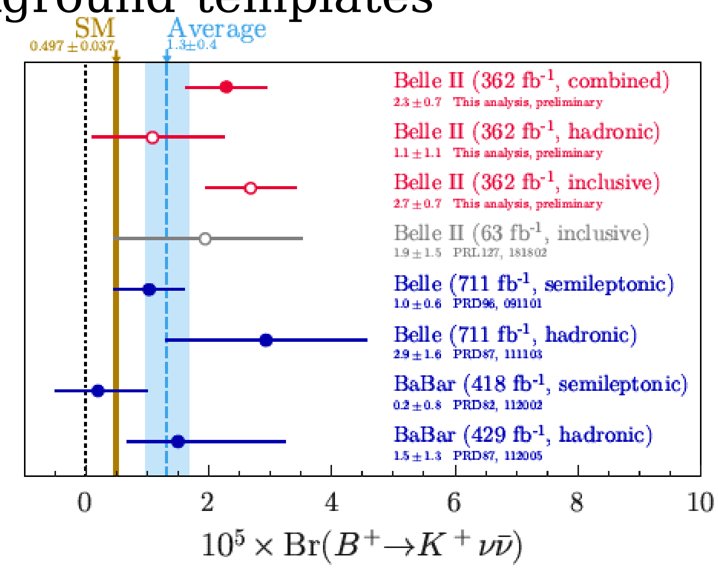
- Maximum likelihood fit to data using signal and background templates

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

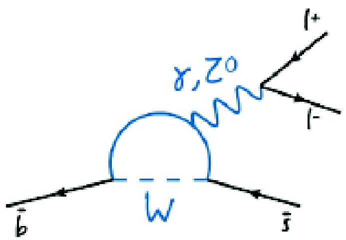
$$\mathbf{B_{had} = (1.1\ ^{+0.9}_{-0.8}\ (stat)\ ^{+0.8}_{-0.5}\ (syst)) \times 10^{-5}}$$

- For inclusive analysis, evidence for B→Kνν̄ at 3.5σ branching fraction within **3σ** of SM
- For hadronic tag, the result is consistent with null hypothesis and SM at 1.1σ and 0.6σ

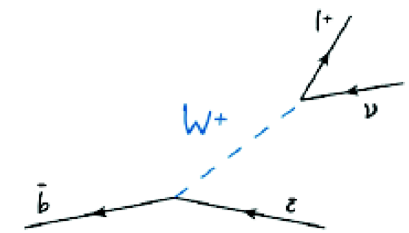
⇒ Combination of two analyses provides first evidence of the decay at 2.7σ from SM



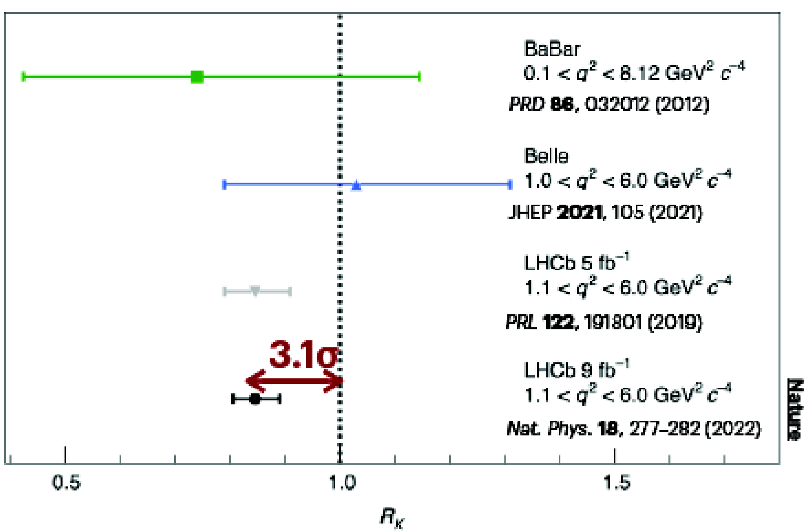
what happened with the B anomalies… ?



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



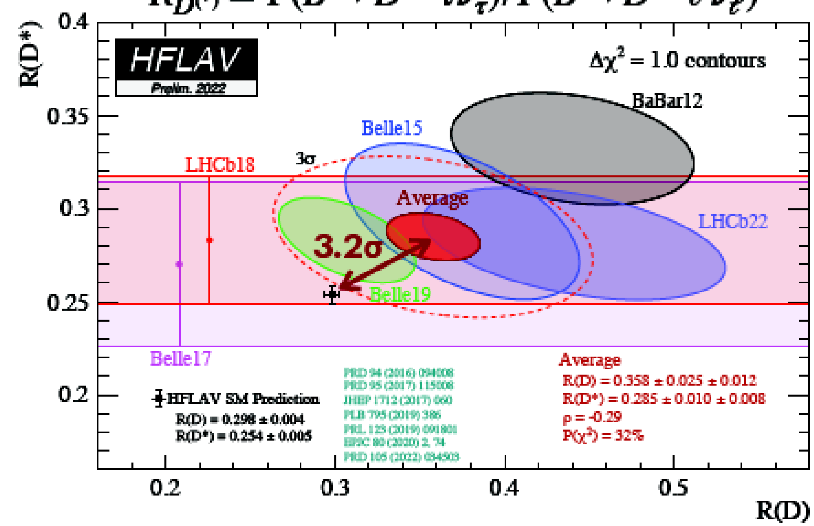
$$R_K = \Gamma(B^+ \to K^+ \mu^+ \mu^-)/\Gamma(B^+ \to K^+ e^+ e^-)$$



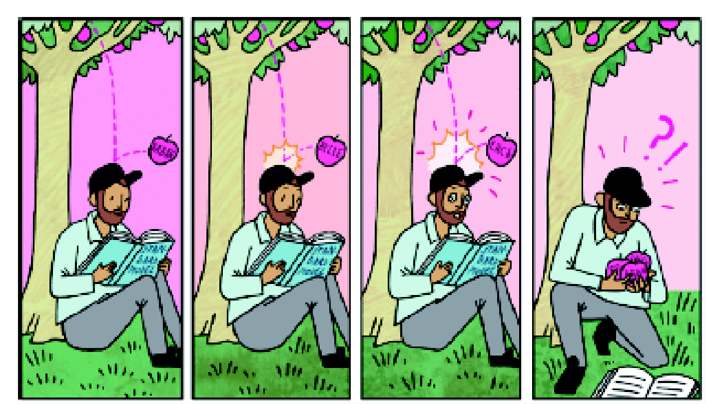
μ vs e: $R_H^{\rm exp} < R_H^{\rm SM}$

Lepton
Flavor
Universality
Violation
?

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



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



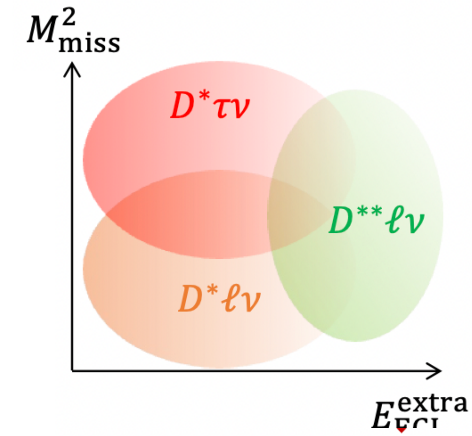
Main players in B-physics

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

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

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

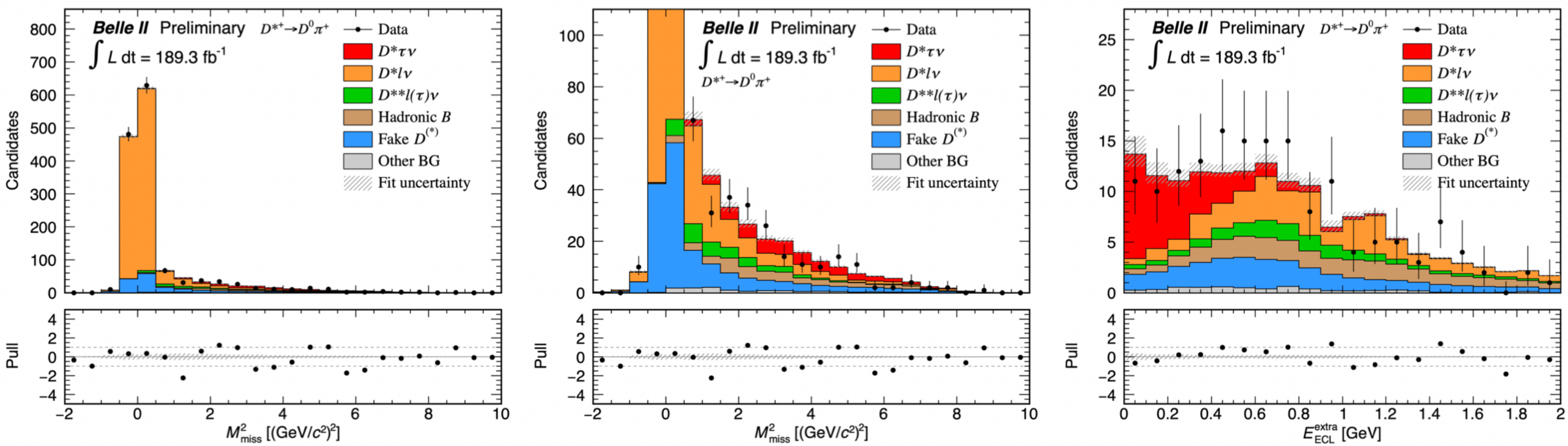
- Half of available sample (200 million $B\overline{B}$ pairs)
- Fully reconstruct the partner B in the event to suppress bckg
- Reconstruct numerator and denominator with ~ same selections
- Two-dimensional fit of missing mass and total residual energy in calorimeter determines signal yields
- Data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



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

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

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



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

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

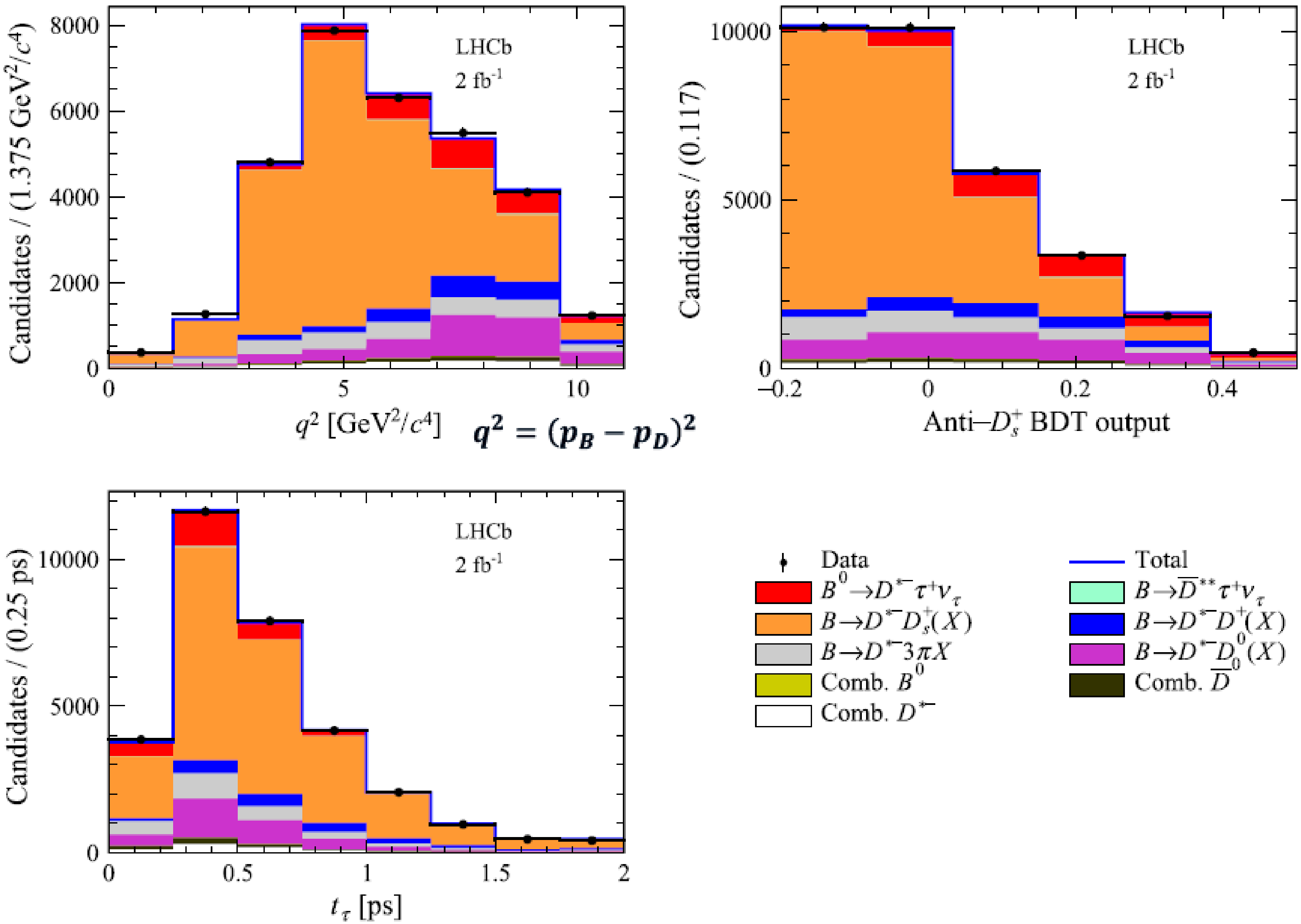
R(D*) at LHCb

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

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

Run 2: 2 fb^{-1}

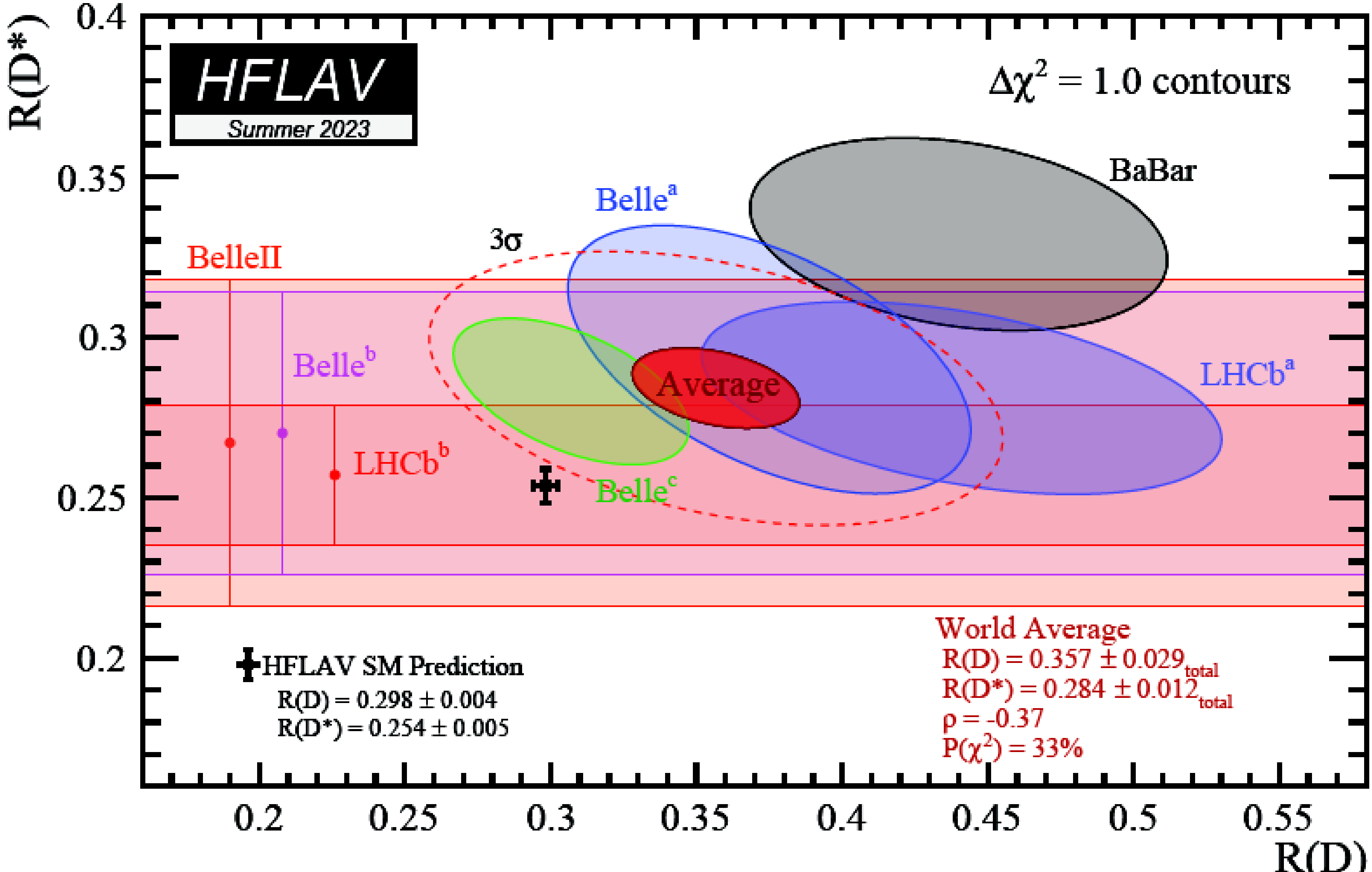
[PRD 108 (2023) 012018]



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

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

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



⇒ 3.3σ tension wrt SM

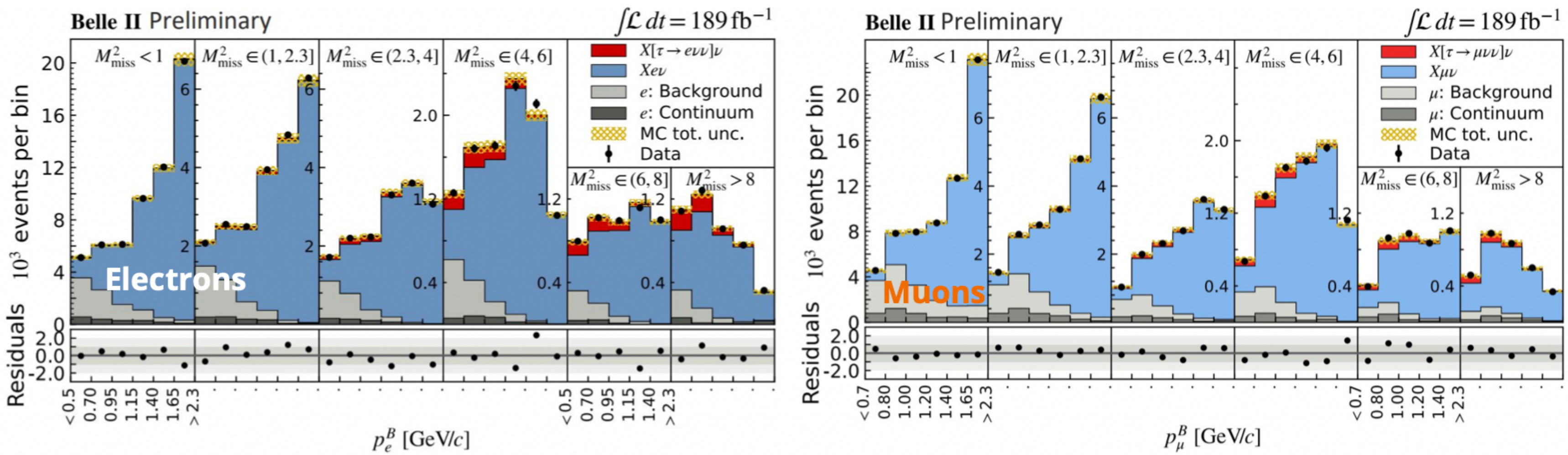
More measurements to come from LHCb and Belle (II)

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

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 $R(D^{(*)})$

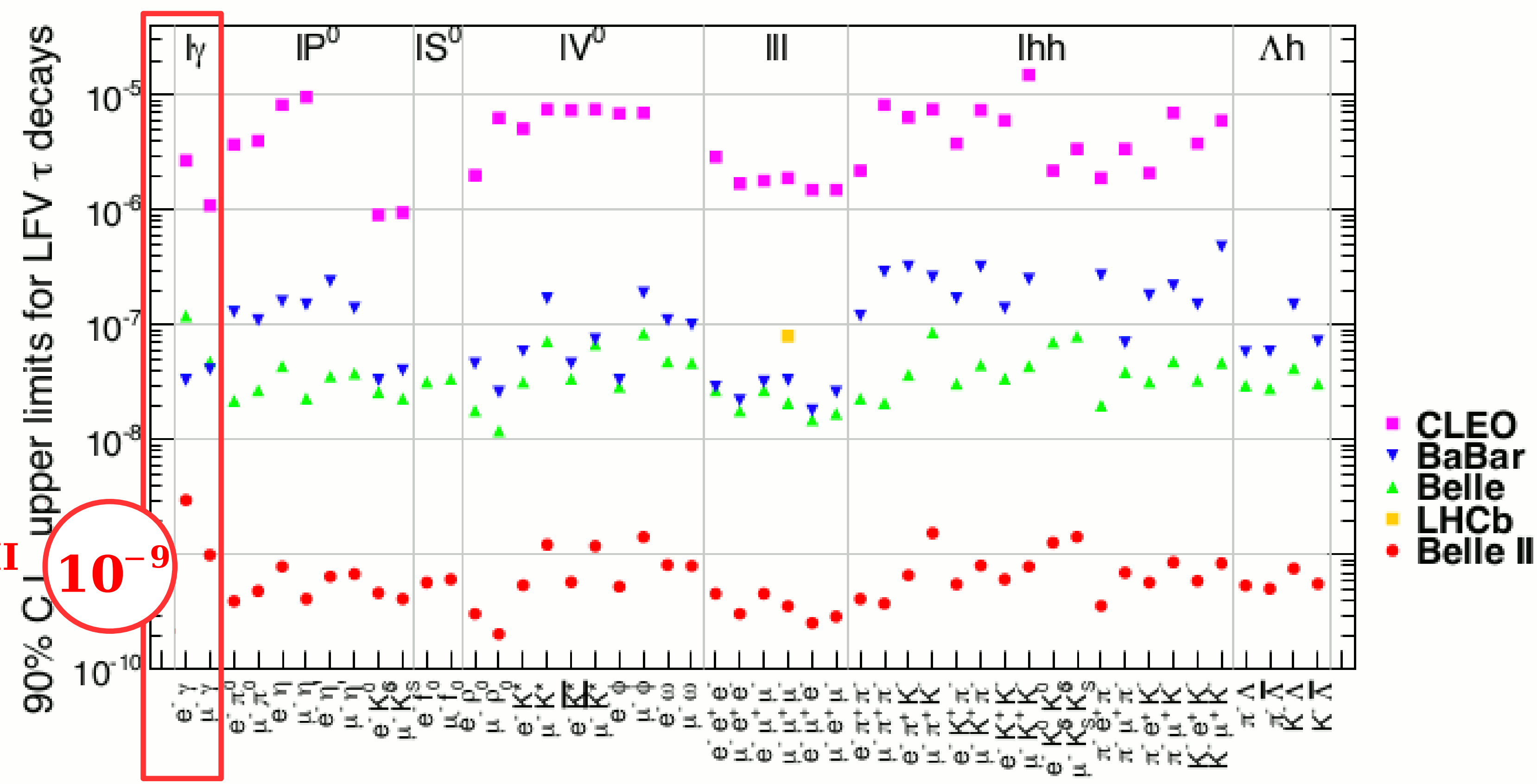
First ever such result from B factories

"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	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
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}

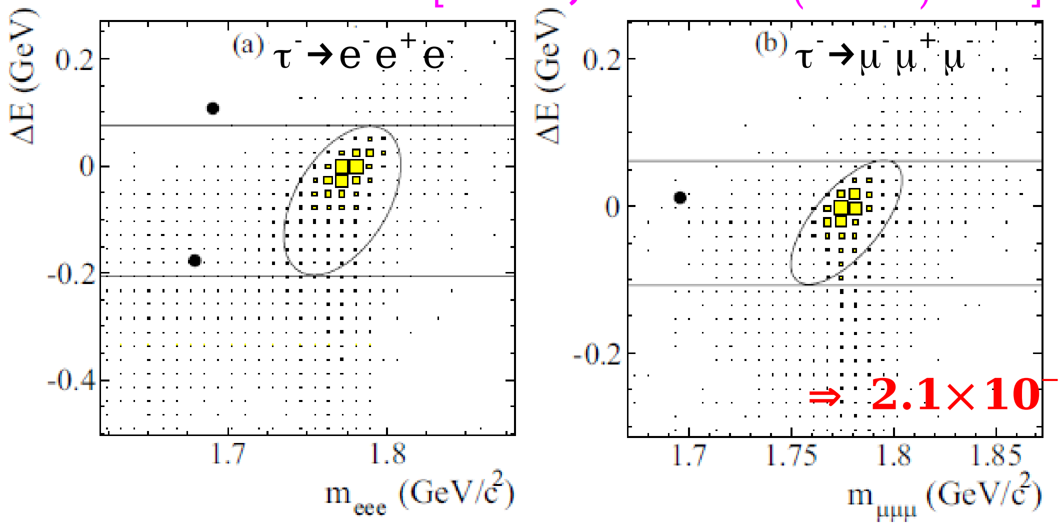


expected Belle II sensitivity 10^{-9}

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]

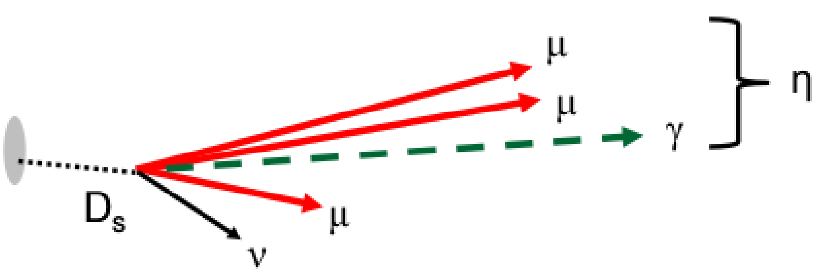


⇒ 2.1×10^{-8} at 90%CL

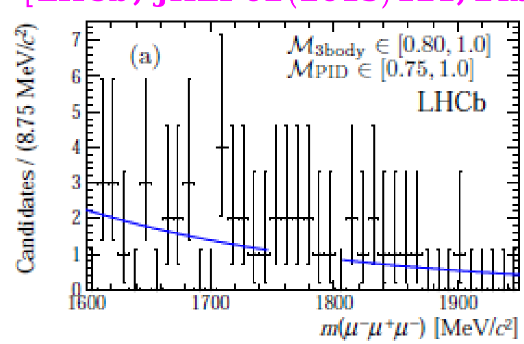
how to improve further ?

…considering $\tau\to\mu/e\,h^+h^-$
in function of one prong tag categories
…for τ→3muons,
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, 2fb^{-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
$D_s\to\phi(\mu\mu)\mu\nu$	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

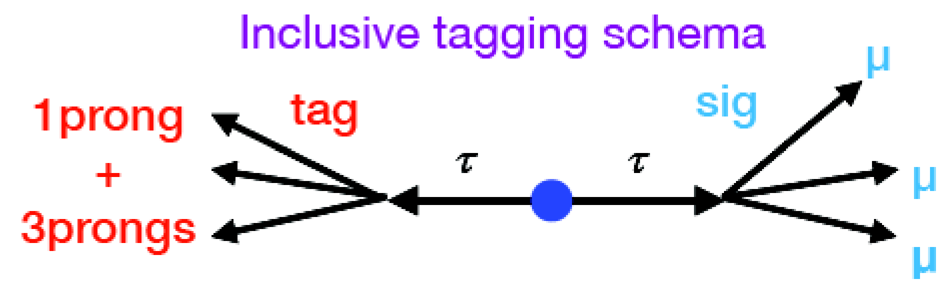
CMS, full Run 2 dataset: 2.9×10^{-8} at 90%CL

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

τ→3μ at Belle II

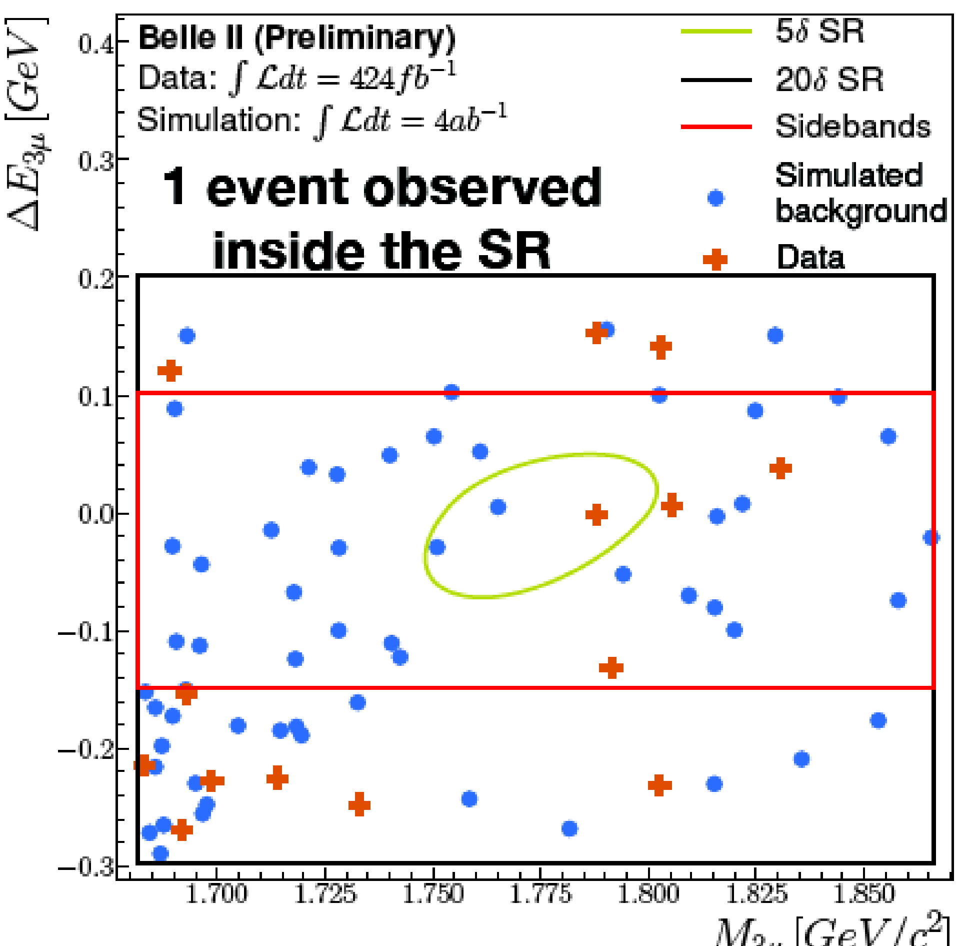
Analysis selection and results: inclusive approach

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

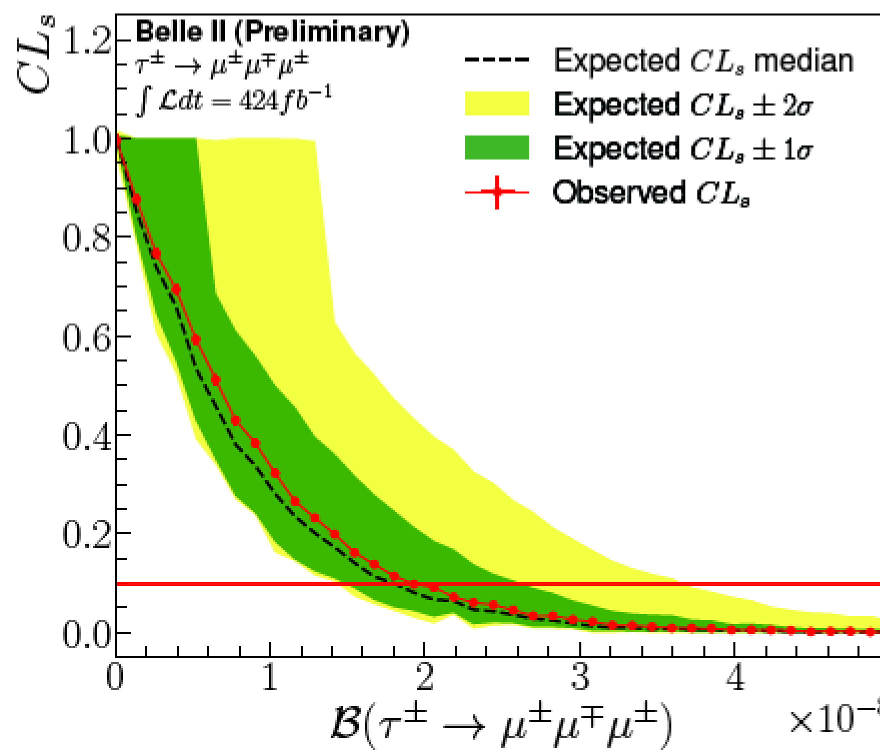


$\epsilon_{sig} = (20.42 \pm 0.06)\%$ (3 × larger than Belle)

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



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



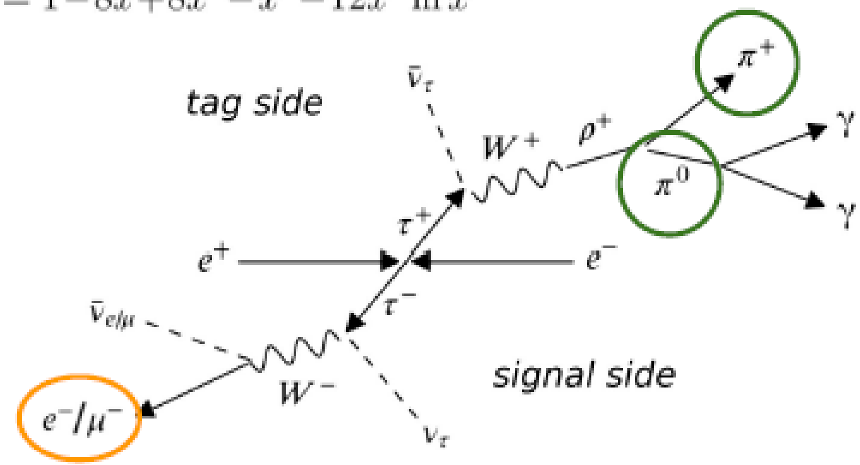
Obtained most stringent limit
1.9×10^{-8}

Lepton universality tests at Belle II

precise test of μ-e universality by measuring

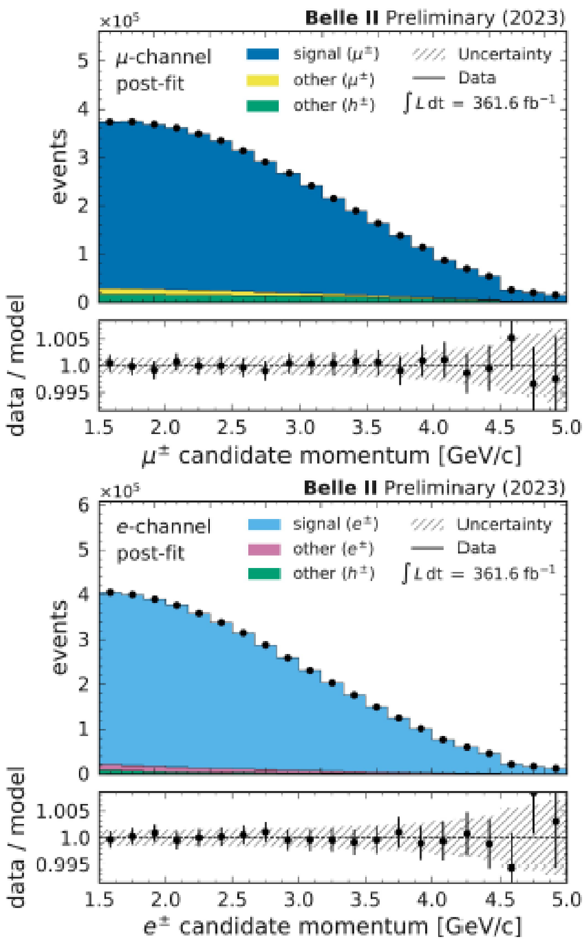
$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{\mathcal{B}\left(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma)\right)}{\mathcal{B}\left(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma)\right)} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

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



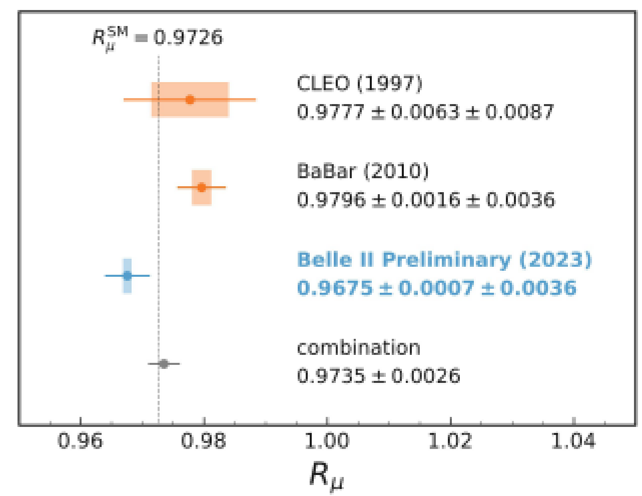
ratio of leptonic branching fractions

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



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

$R_\mu = 0.9675 \pm 0.0037$



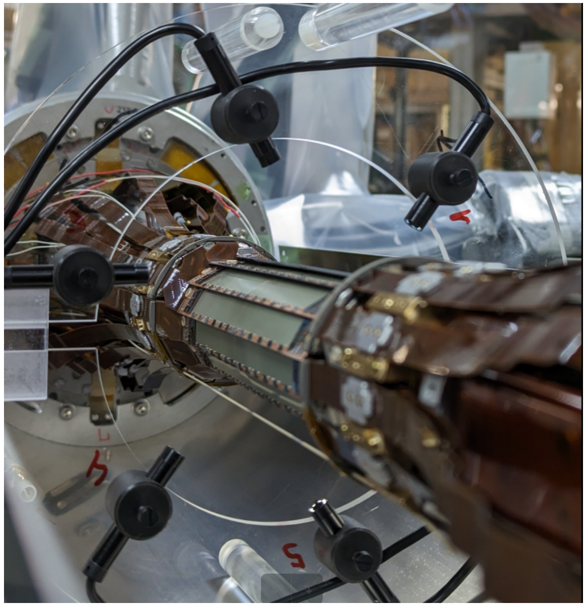
Long-shutdown (LS1) activity and plans

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

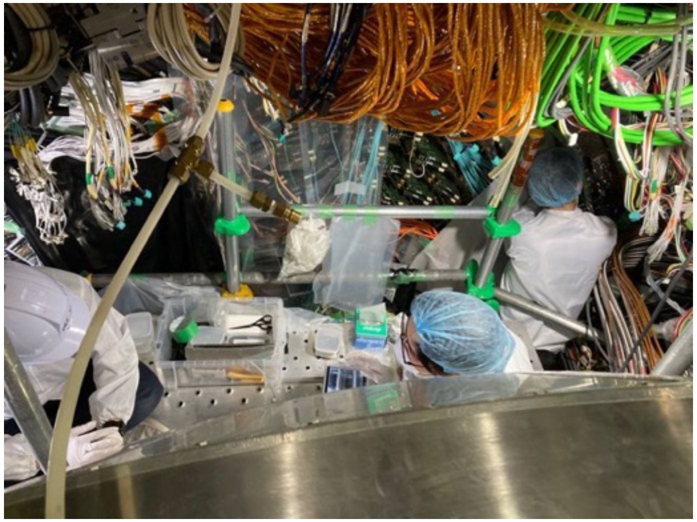
- replacement of beam-pipe
- installation of 2-layered pixel vertex detector
- replacement of photomultipliers of the central PID detector (TOP)
- completed transition to new DAQ boards (PCIe40)
- work on other detectors as CDC, KLM…
- improved data-quality monitoring and alarm system

PXD2 at KEK since March



VXD extraction in May

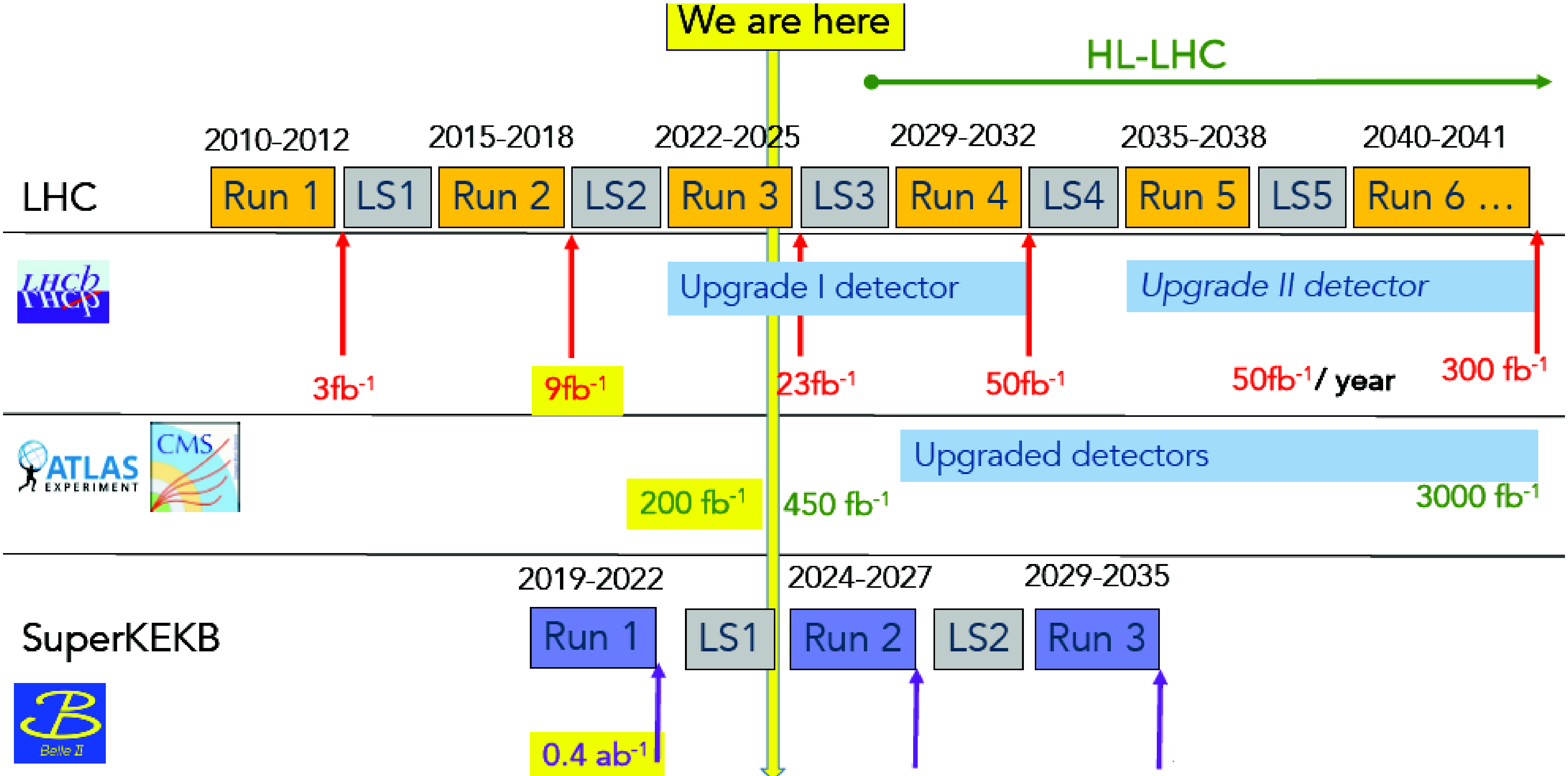
TOP MCP-PMT replacement work



CDC FE reinstallation work

LHCb and Belle II datasets: present and future

(M.H. Schune)



5-10 ab^{-1} 50 ab^{-1}

Summary

- Very active field: many more results than shown !

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

- LHCb brought many interesting results in Run 1&2, with world leading measurements in the flavour sector

- Belle (II) is a unique environment to study modes with missing energy
  $B \to K\nu\bar{\nu}$, $K\tau\tau$, $K\tau l$, $\tau\tau$, τl, $D^{(*)}\tau\nu$, $\tau\nu$, $\mu\nu$...
  ...but also perform precise measurements of CKM UT (CPV or not),
  τ sector, low mutiplicity, dark sector... and many other opportunities

Leptonic decays

$$B^0_{(s)} \to \ell^+\ell^-$$

$$BR(B^0_{(q)} \to \ell^+\ell^-) = \frac{\tau_B G_F^4 M_W^2 \sin^4\theta_W}{8\pi^5}|C_{10}V_{tb}V^*_{tq}|F_B^2 m_B m_\ell^2 \times \sqrt{1-\frac{4m_\ell^2}{m_B^2}}$$

Branching ratio proportional to the lepton mass squared

$$\frac{BR(B^0_{(q)} \to \tau^+\tau^-)}{BR(B^0_{(q)} \to \mu^+\mu^-)} \sim \frac{m_\tau^2}{m_\mu^2} \qquad \frac{BR(B^0_{(q)} \to \mu^+\mu^-)}{BR(B^0_{(q)} \to e^+e^-)} \sim \frac{m_\mu^2}{m_e^2}$$

Helicity suppression, same reason why the pion decays into muon instead of electron ⇒ true only in SM

$$\frac{BR(B^0_{(d)} \to \mu^+\mu^-)}{BR(B^0_{(s)} \to \mu^+\mu^-)} = \frac{\tau_{B^0_d}}{\tau_{B^0_s}}\frac{m_{B^0_d}}{m_{B^0_s}}\frac{F_{B^0_d}}{F_{B^0_s}}\left(\frac{V_{td}}{V_{ts}}\right)^2$$

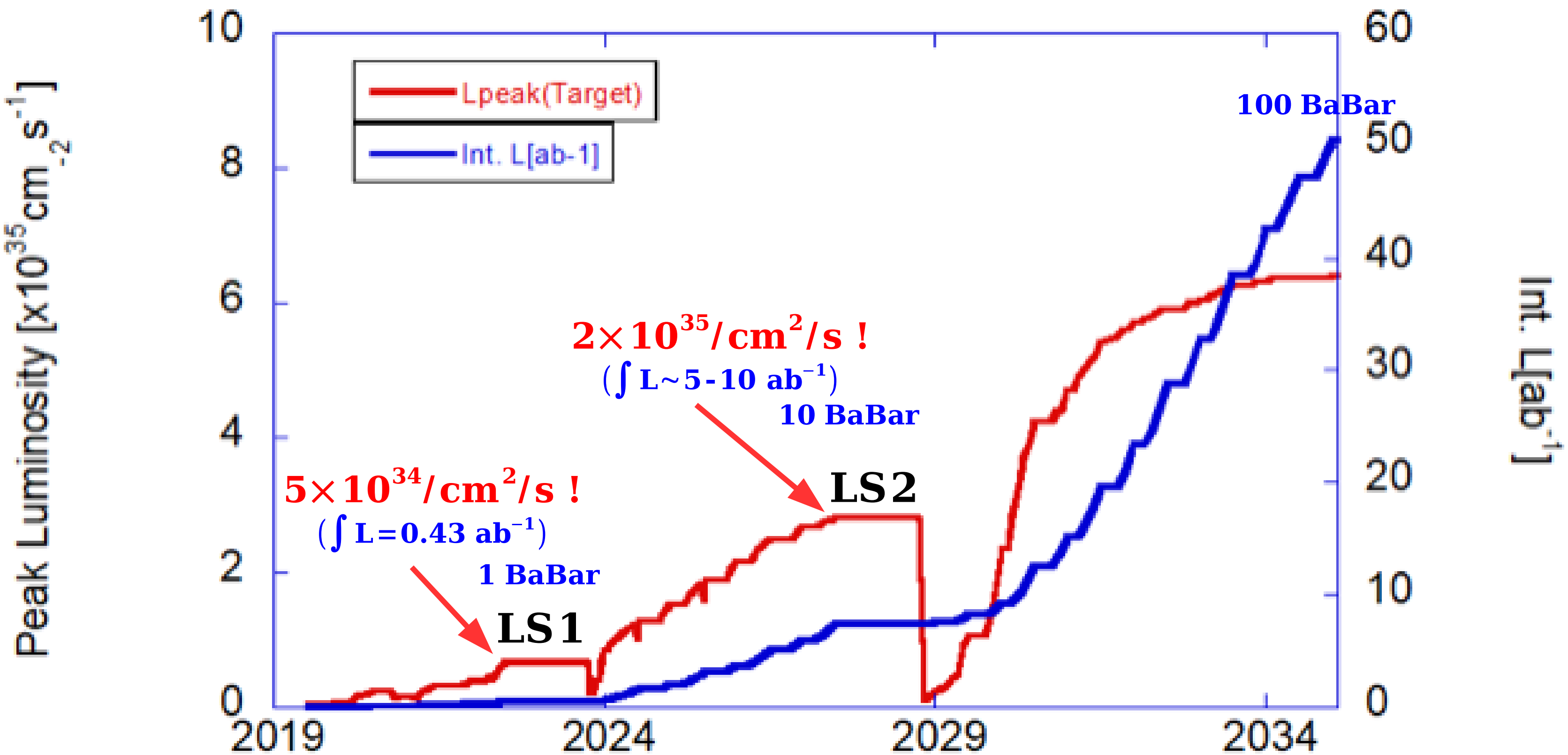
All parameters either measurable or calculable with high precision valid only in Minimal Flavour Violating Models

(where the flavour structure is described only by CKM)

In a ''general'' NP scenarios, the branching ratio of B leptonic decay is given by

$$BR(B^0_s \to \mu^+\mu^-) \propto \left(1-\frac{4m_\ell^2}{m_B^2}\right)|C_S - C'_S|^2 + |(C_P - C'_P)^2 + 2\frac{m_\ell^2}{m_B^2}(C_{10} - C'_{10})|^2$$

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}