Flavour physics and rare decays

Featuring results from LHCb, Belle II, ATLAS, CMS, BESIII, NA62, KOTO & MEG II

Tim Gershon

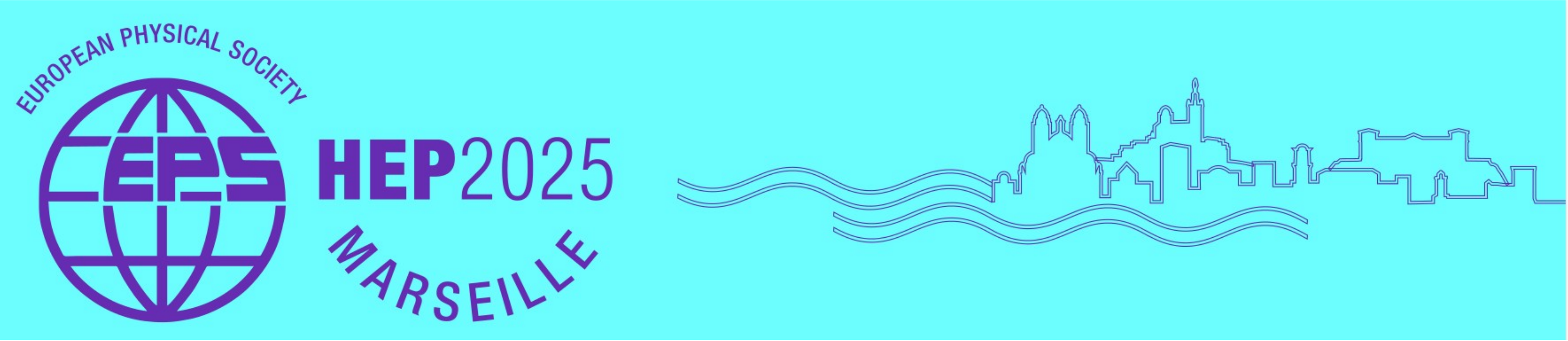
University of Warwick

8th July 2025

From ...


2026 UPDATE
OPEN SYMPOSIUM
European Strategy
for Particle Physics
23-27 JUNE 2025
CERN
INFN
European Strategy
for Particle Physics

... to ...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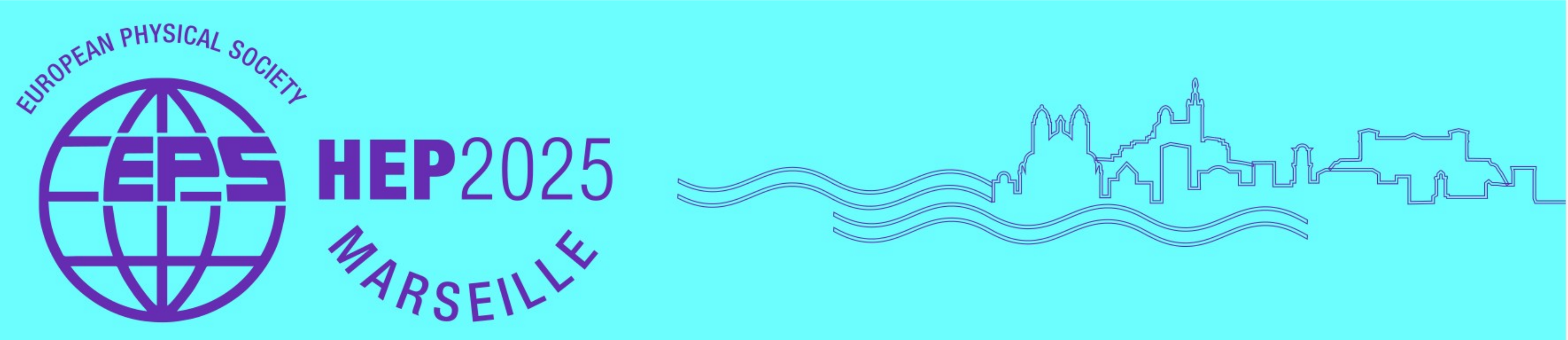
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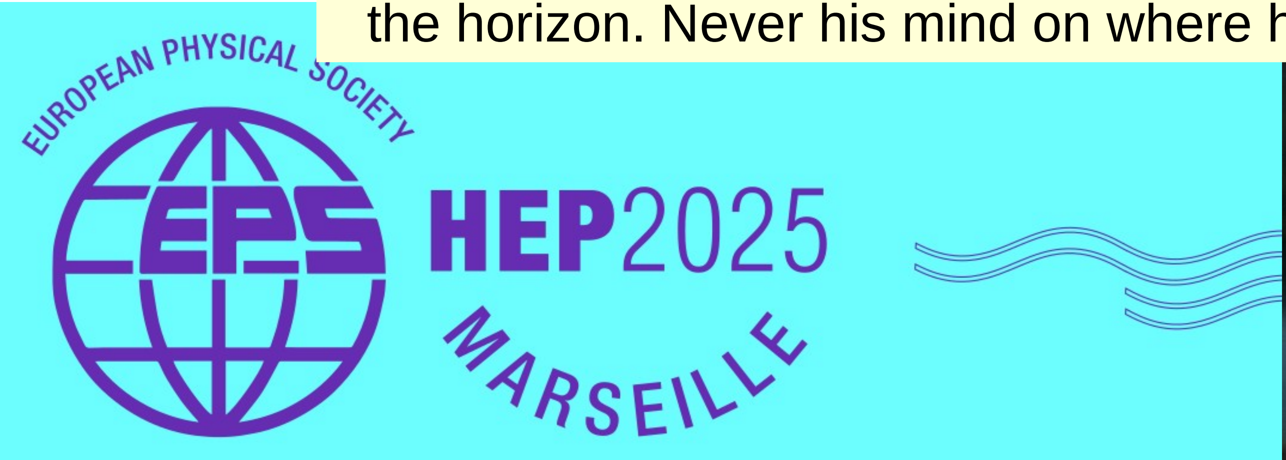
From ...

... to ...

“All his life has he looked away...to the future, to the horizon. Never his mind on where he was!”



This talk

- Focus on ***where we are*** as regards flavour physics and rare decays
  - CP violation
  - Quantum correlations
  - Rare decays

Not possible to cover all relevant topics
Apologies for omissions

- Brief comment on future prospects
- Including results from LHCb, Belle II, ATLAS, CMS, BESIII, NA62, KOTO, MEG II
  - Many thanks to many people for inputs
- Latest highlights from LHCb & Belle II to be covered by Vava Gligorov & Karim Trabelsi tomorrow
  - Details of experimental concepts, detectors, analysis techniques, etc. to be covered there
  - Many other relevant talks in parallel sessions – I hope not to steal your thunder!

Brief history of CP violation

PRL 13 (1964) 138

- 1964: Discovery of $K_L \rightarrow \pi^+\pi^-$
  - Prior understanding: K_L is CP-odd
    - therefore cannot decay to $\pi^+\pi^-$, therefore long-lived
  - Later understood that K_L is not an equal admixture of K^0 and $\overline{K}^0$ states
    - CP-violation
- 1967: Sakharov conditions for evolution of matter-dominated universe

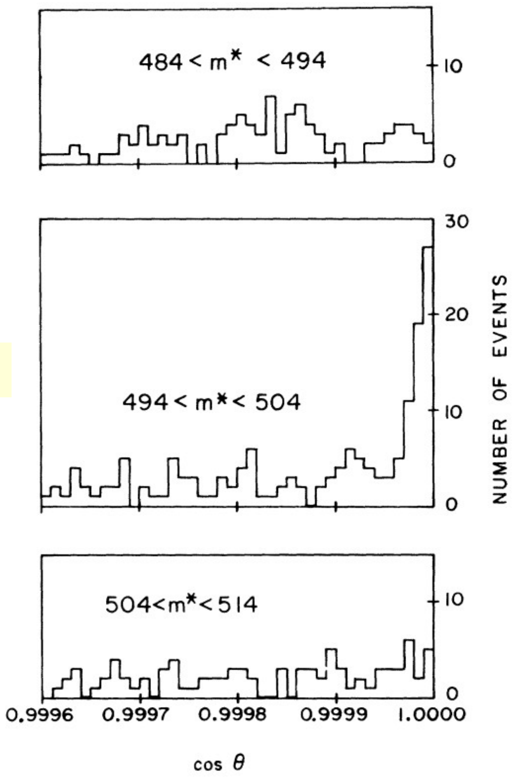
  1) baryon number violation

  2) C & CP violation

  3) thermal inequilibrium

Pisma Zh.Eksp.Teor.Fiz. 5 (1967) 32

- 1973: Kobayashi & Maskawa explanation of CP violation
  - Arises from single complex phase in 3x3 quark mixing matrix
  - Makes many distinctive and important predictions (see later)
- 2025: Observation of CP violation in baryon decays



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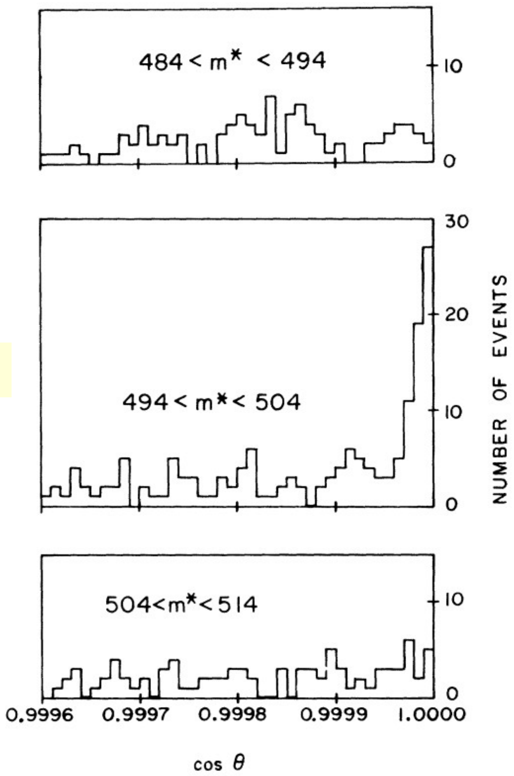
PRL 13 (1964) 138



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  1) baryon number violation

  2) C & CP violation

  3) thermal inequilibrium

Pisma Zh.Eksp.Teor.Fiz. 5 (1967) 32

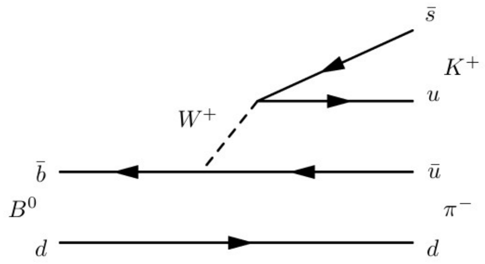
To get a baryon asymmetry, need either CP violation in baryon decays, or a mechanism to convert another asymmetry into baryons

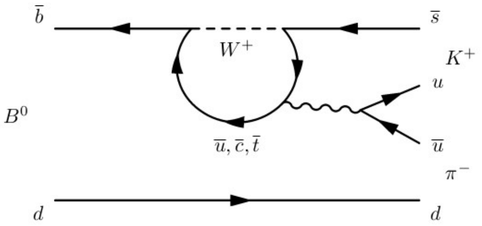
KM theory predicts CP violation in baryon decays but not seen until ...

- 2025: Observation of CP violation in baryon decays

CP violation in decay

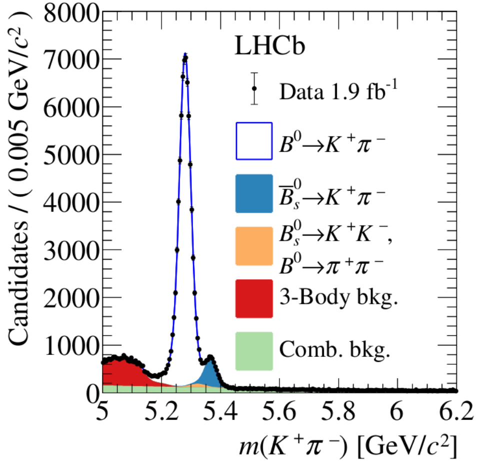
- Caused by interference between two amplitudes with different weak (CP violating) and strong (CP conserving) phases
- Often realised by "tree" and "penguin" diagrams
  - e.g. for $B^0 \rightarrow K^+\pi^-$

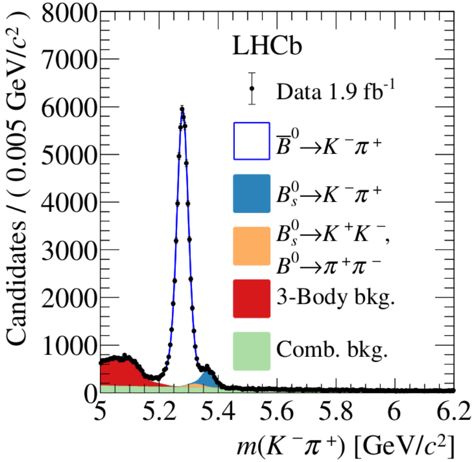




Relative weak phase ~ $\arg(-V_{ub}^* V_{us}/(V_{tb}^* V_{ts}))$ ~ γ

JHEP 03 (2021) 075





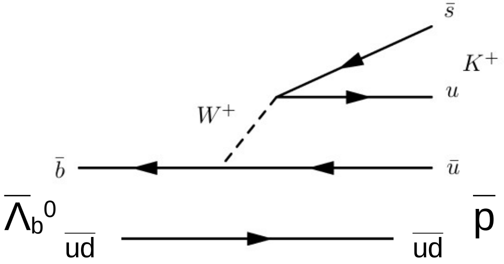
$A_{CP}(B^0 \rightarrow K^+\pi^-) = (-8.24 \pm 0.33 \pm 0.33)\%$

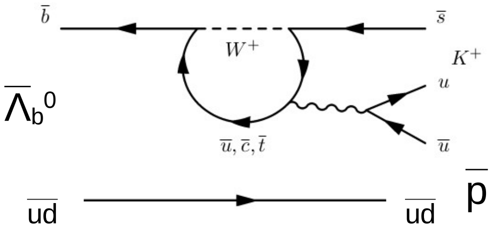
Results account for small corrections due to production & detection asymmetries

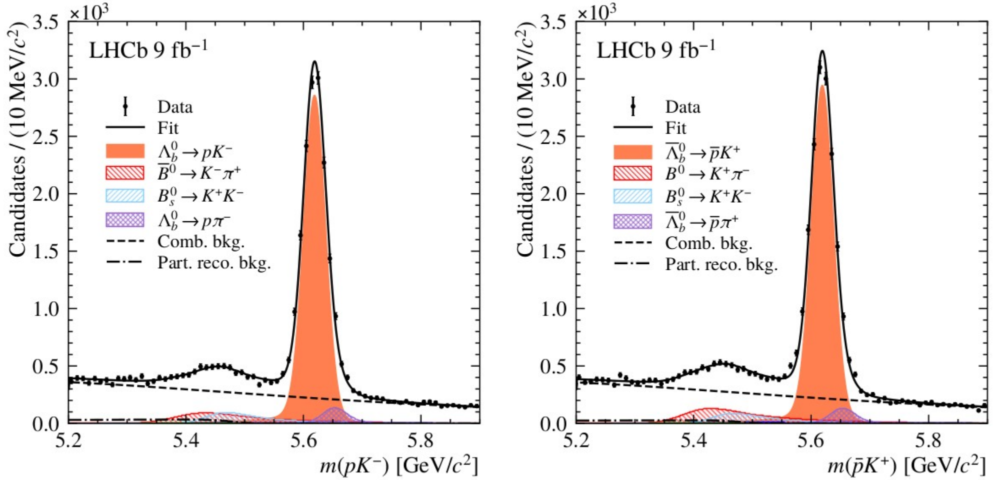
CP violation in decay

- Caused by interference between two amplitudes with different weak (CP violating) and strong (CP conserving) phases
- Often realised by "tree" and "penguin" diagrams
  - e.g. for $B^0 \to K^+\pi^-$
  - so why not for $\overline{\Lambda}_b^0 \to \overline{p}K^+$?

PR D111 (2025) 092004







Relative weak phase ~ $\arg(-V_{ub}^*V_{us}/(V_{tb}^*V_{ts}))$ ~ γ

$A_{CP}(\overline{\Lambda}_b^0 \to \overline{p}K^+) = (-1.1 \pm 0.7 \pm 0.4)\%$

Results account for small corrections due to production & detection asymmetries

Observation of CP violation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays

arXiv:2503.16954
to appear in Nature

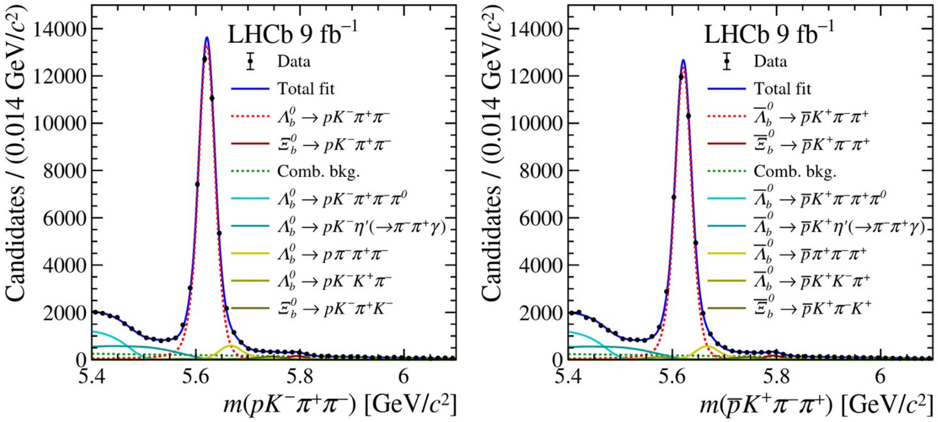
- Large samples of charmless 4-body Λ_b^0 decays available
- Use $\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-$ as reference channel

$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$ 5.2σ from zero

Enhanced CP violation effects appear in localised regions of phase space

- Largest for $m(p\pi^+\pi^-) < 2.7$ GeV/c^2

$$A_{CP} = (5.4 \pm 0.9 \pm 0.1)\%$$



Significant milestone in CP violation history!

But, theoretical predictions for CP asymmetries, integrated over multiple resonances, are extremely challenging

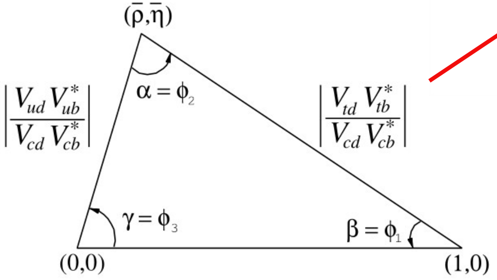
Important next step: amplitude analysis to associate effects to resonances including interference effects

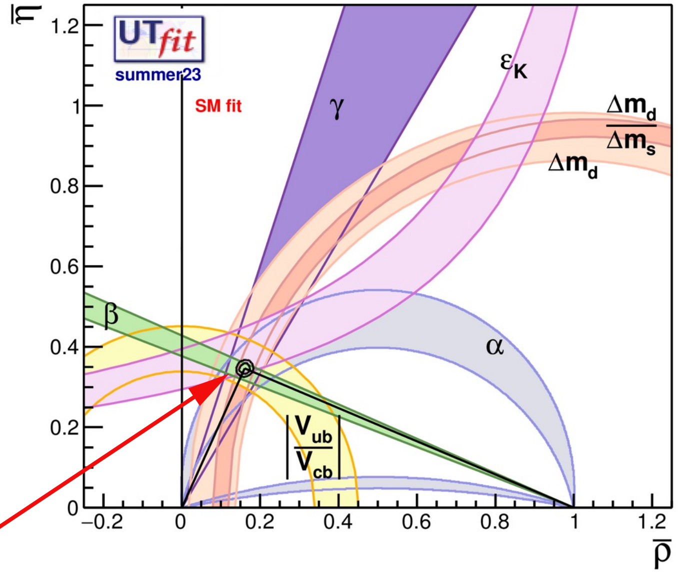
Theoretically interpretable CP violation

- Fortunately, there are some CP-violating observables that do allow clean(-ish) tests of the SM
  - e.g. angles of the unitarity triangle

$$V_{CKM} V_{CKM}^{+} = 1$$

$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$





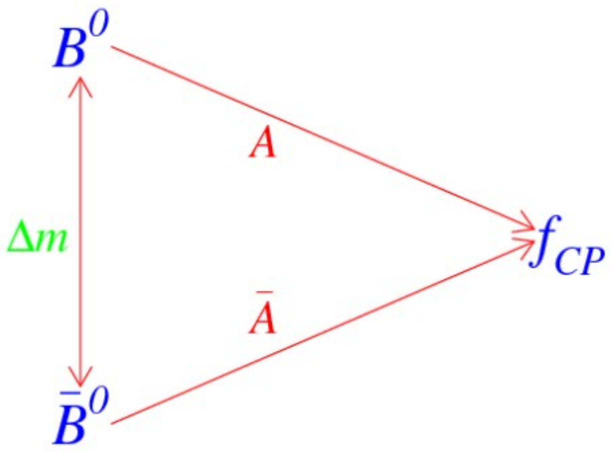
Interference between mixing and decay amplitudes to determine β

$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

- For a B meson known to be B^0 or $\overline{B}^0$ at time t=0, then the rate to decay to a CP eigenstate f_{CP} at later time t is:

$$\Gamma\left(B^0_{phys} \to f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1-\left(S\sin(\Delta m t) - C\cos(\Delta m t)\right)\right)$$

$$\Gamma\left(\overline{B}^0_{phys} \to f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1+\left(S\sin(\Delta m t) - C\cos(\Delta m t)\right)\right)$$

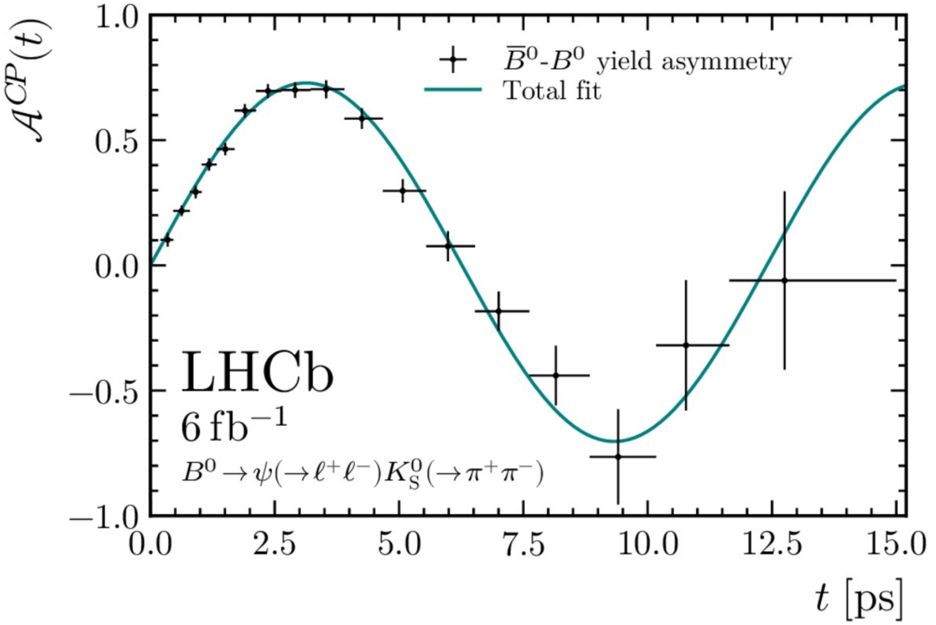


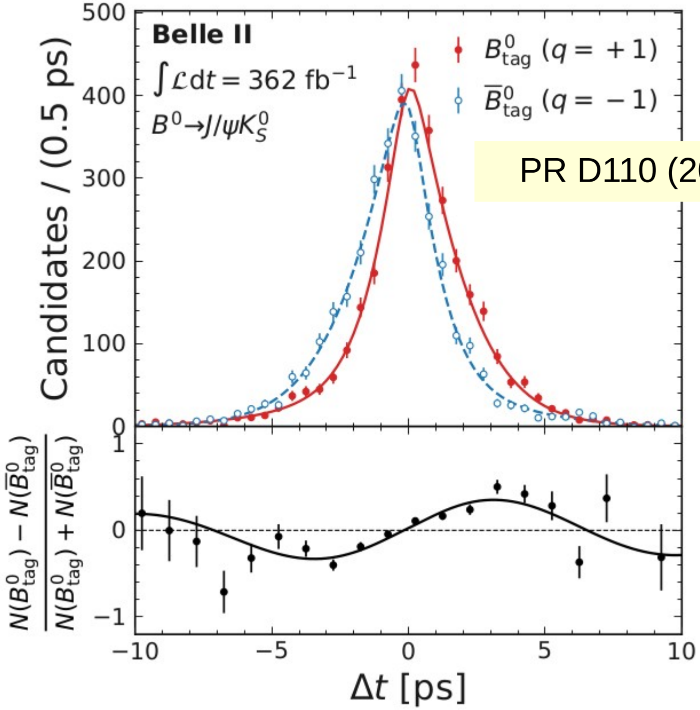
- If a single amplitude dominates, then $|\overline{A}/A|=1$ and C=0 (no CP violation in decay)
- For $B^0 \to J/\psi K_S$, if dominated by $V_{cb}V_{cs}^*$ amplitude, S = sin(2β)
- Possible subdominant penguin "pollution" → theoretical uncertainty in interpretation

Latest measurements of sin(2β)

Flavour-tagging corrected asymmetry

PRL 132 (2024) 021801





PR D110 (2024) 012001

$S(B^0 \to J/\psi K_S) = 0.722 \pm 0.014 \pm 0.007$

$S(B^0 \to J/\psi K_S) = 0.724 \pm 0.035 \pm 0.009$

Signal yield ~ 350,000
Tagging power ~ 4%

Signal yield ~ 6,400
Tagging power ~ 37%

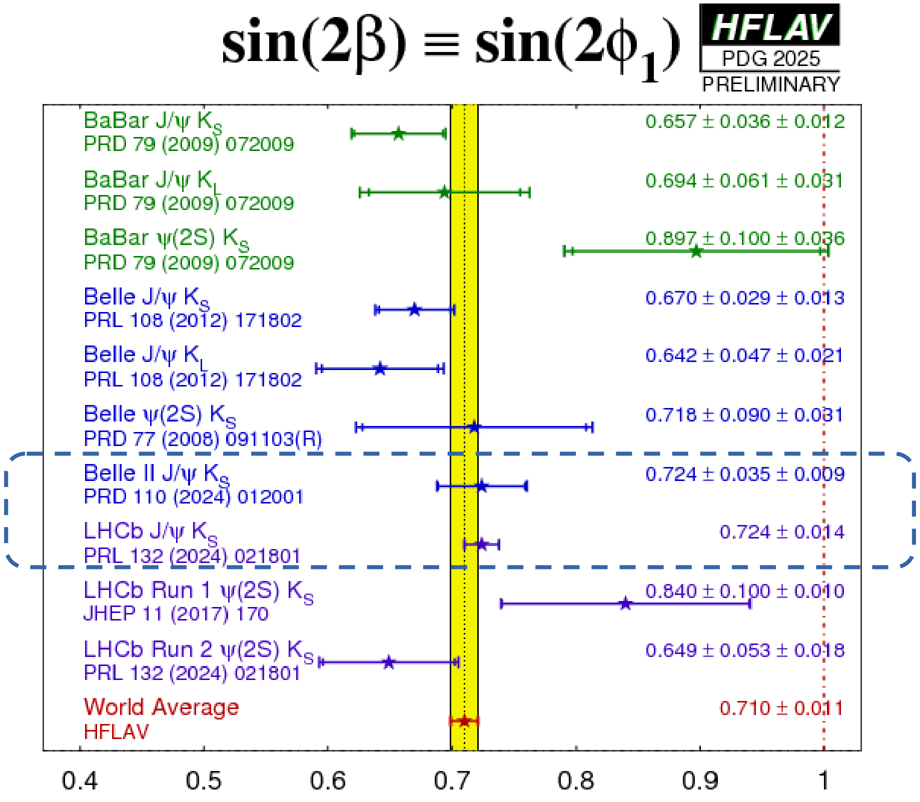
$S(B^0 \to J/\psi K_S)$ world average

- HFLAV average:

  $S(B^0 \to J/\psi K_S) = 0.712 \pm 0.011$

  0.710 ± 0.011 including all $b \to c\bar{c}s$

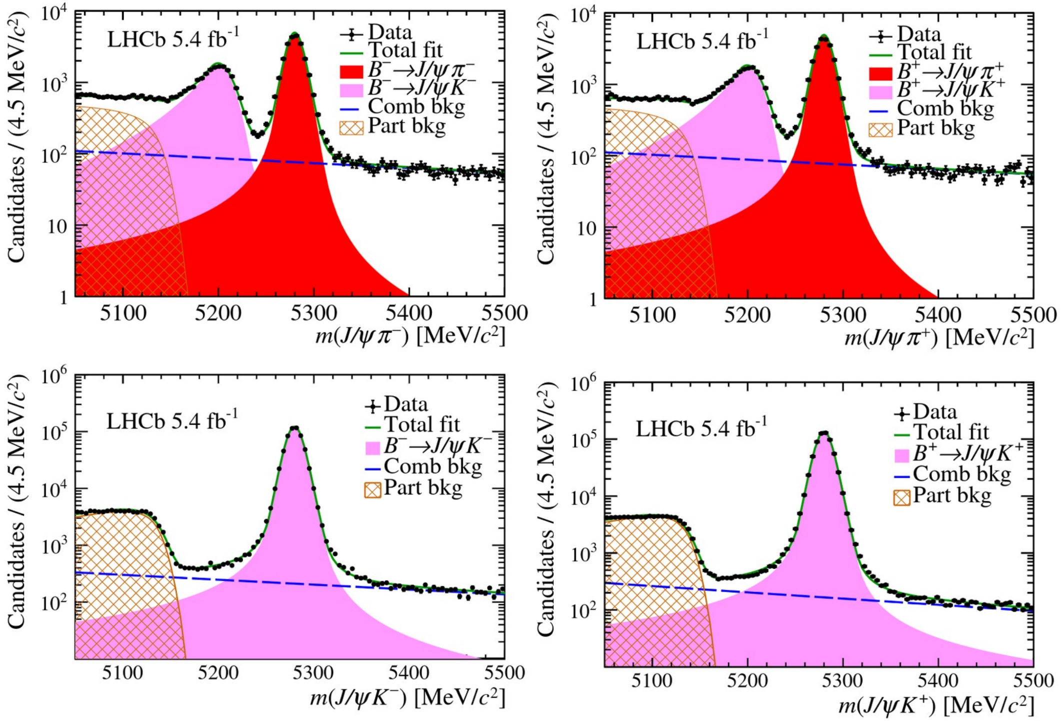
- Is it still safe to interpret this as $\sin(2\beta)$?
  - Or have we entered the realm of penguin pollution?
- Exploit flavour symmetries in $B \to J/\psi P$ ($P = K, \pi$) to test
  - See e.g. arXiv:2506.21675, arXiv:2505.06102



Results from previous slide

New results on B → J/ψπ

PRL 134 (2025) 101801



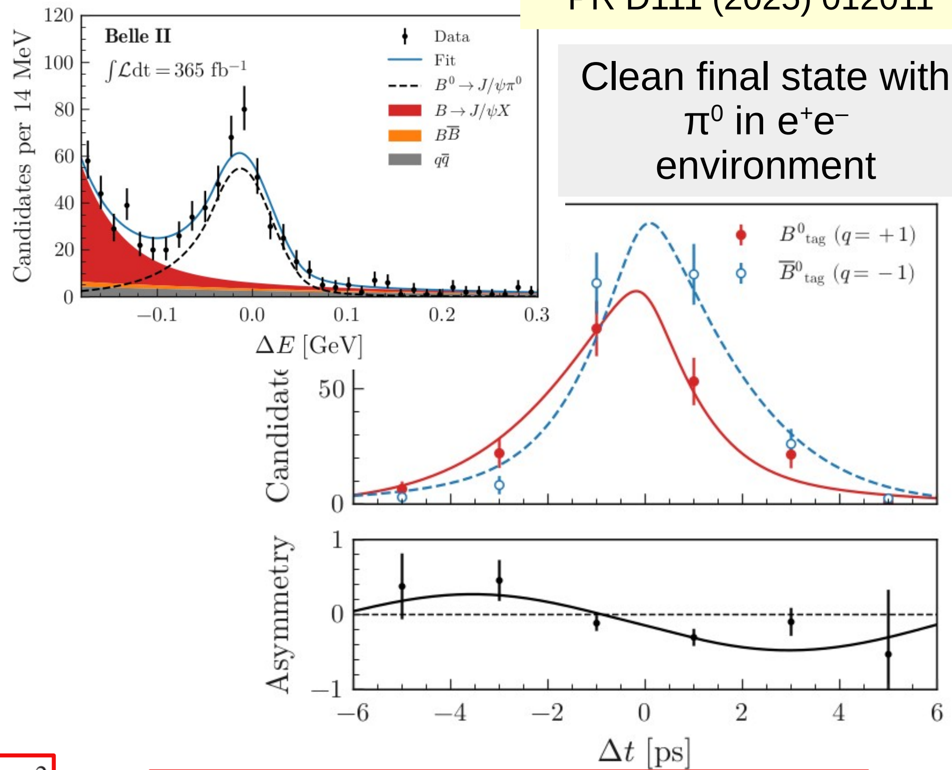
$$\Delta\mathcal{A}^{CP} \equiv \mathcal{A}^{CP}(B^+ \to J/\psi\pi^+) - \mathcal{A}^{CP}(B^+ \to J/\psi K^+) = (1.29 \pm 0.49 \pm 0.08) \times 10^{-2}$$

3.2σ from zero

Effect expected to be dominantly in J/ψπ

PR D111 (2025) 012011

Clean final state with π^0 in e^+e^- environment



$S(B^0 \to J/\psi\pi^0) = -0.88 \pm 0.17 \pm 0.03$

5.0σ from zero

Penguin pollution

- Analysis of arXiv:2506.21675 combines 16 observables from $B_{u,d,s} \to J/\psi\, P$ ($P=K,\pi$) decays using flavour symmetry relations
  - 6 branching fractions
  - 6 parameters of CP violation in decay
  - 4 parameters of CP violation in mixing-decay interference
    - for $B_s \to J/\psi \pi^0$, only a branching fraction upper limit exists

Similar analysis done in arXiv:2505.06102 and other works

- Result:
  - $S(B^0 \to J/\psi K_S) - \sin(2\beta) = +0.001 \pm 0.015$

    c.f. experimental world average $S(B^0 \to J/\psi K_S) = 0.712 \pm 0.011$
    - precision can be improved with new measurements of $S(B_s^0 \to J/\psi K_S)$
    - possible at ATLAS, CMS & LHCb
      - only existing measurement of $S(B_s^0 \to J/\psi K_S)$ LHCb Run 1 [JHEP 06 (2015) 131]
      - CMS have measured effective lifetime ≡ $A_{\Delta\Gamma}(B_s^0 \to J/\psi K_S)$ [JHEP 10 (2024) 247]

How about $\beta_s(B_s \to J/\psi\varphi)$?

$$\beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

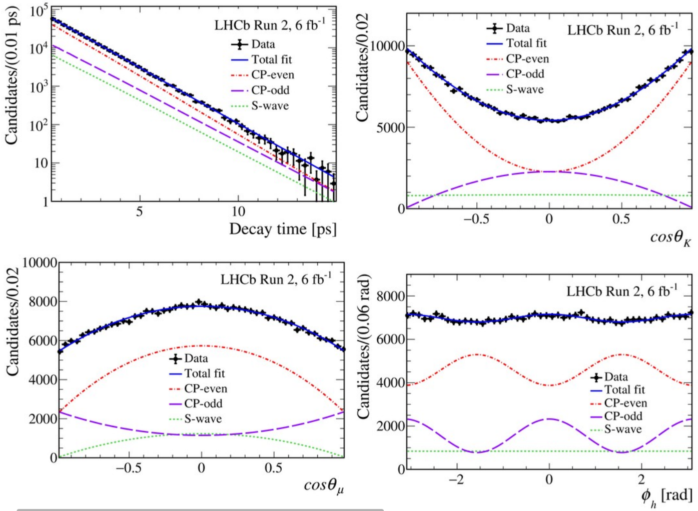
- $B_s \to J/\psi\varphi$ has same dominant quark transitions as $B^0 \to J/\psi K_S$, but
  - B_s–$\overline{B}_s$ mixing involves different CKM elements than B^0–$\overline{B}^0$ mixing
    - probe β_s rather than β
  - φ is a vector, so final state is admixture of CP-even and CP-odd
    - decay-time dependent angular analysis required
    - sensitivity to $\cos(2\beta_s)$ as well as $\sin(2\beta_s)$ – typically β_s fitted directly
  - finite φ width means K^+K^- S-wave must be accounted for
    - treated as CP-odd contribution to signal
  - flavour symmetry relations involve full SU(3) nonet
    - φ, ω, ρ, K^* vector mesons
    - methods to constrain penguin pollution correspondingly more complicated (see, e.g. arXiv:2505.06102)

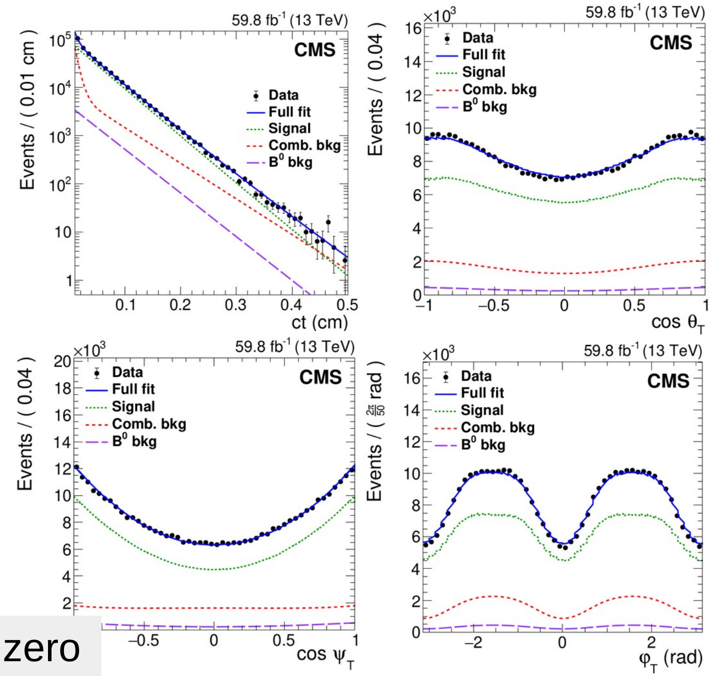
Latest results on $\varphi_s(B_s \to J/\psi\varphi)$

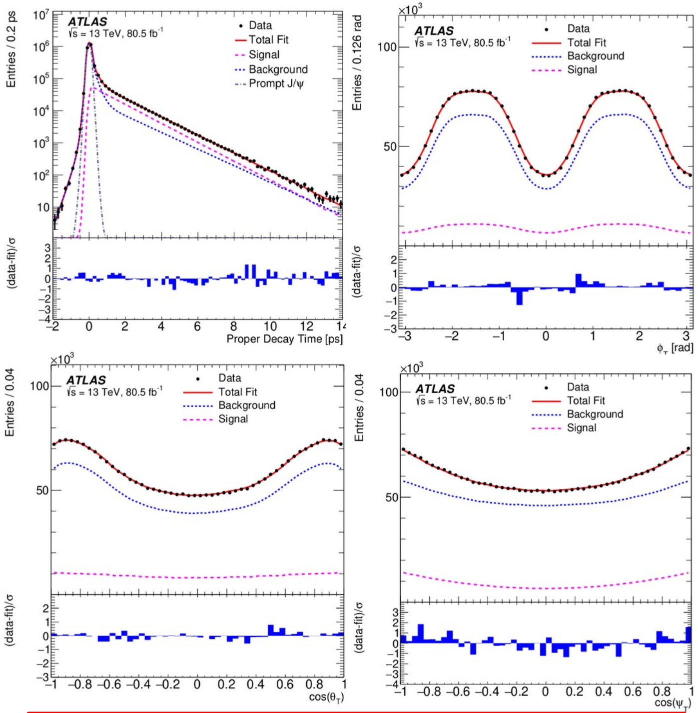
PRL 132 (2024) 051802

arXiv:2412.19952

EPJ C81 (2021) 342







Equality in absence of penguin pollution

3.2σ from zero

$\phi_s = -2\beta_s = -39 \pm 22 \pm 6$ mrad

$\phi_s = -2\beta_s = -73 \pm 23 \pm 7$ mrad

$\phi_s = -2\beta_s = -87 \pm 36 \pm 21$ mrad

Signal yield ~ 350,000
Tagging power ~ 4.3%

Signal yield ~ 490,000
Tagging power ~ 5.6%

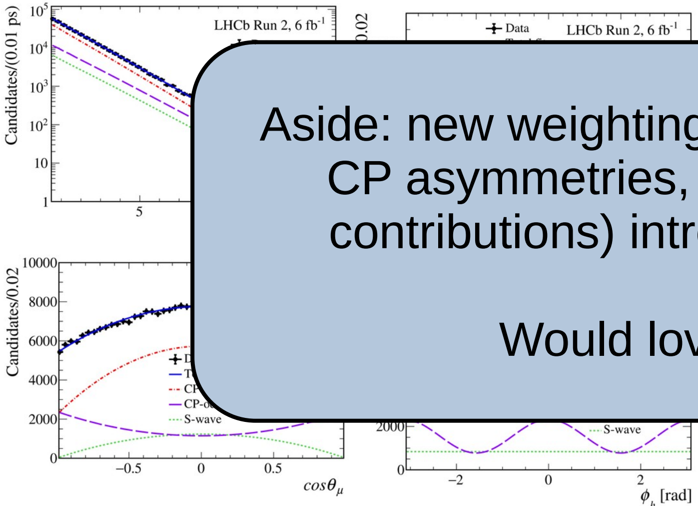
Signal candidates ~ 450,000
Tagging power ~ 1.8%

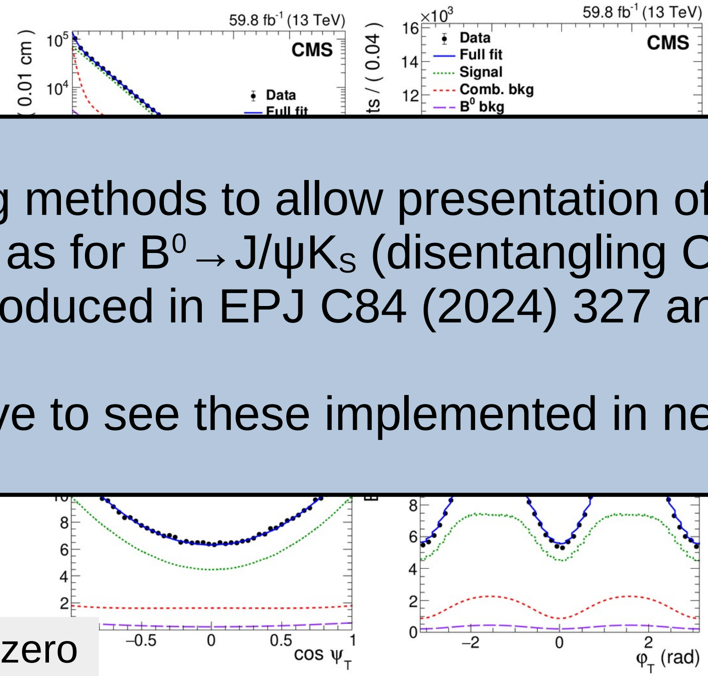
Latest results on $\varphi_s(B_s \to J/\psi\varphi)$

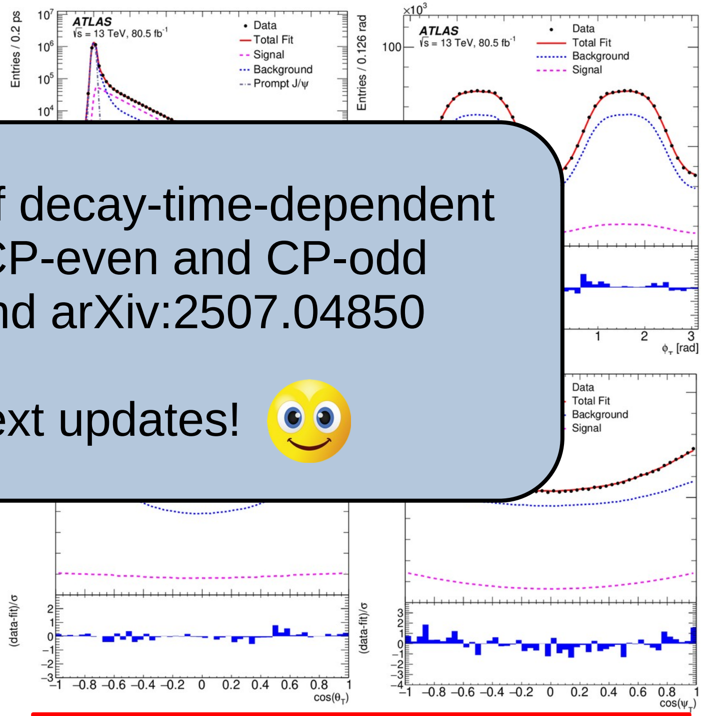
PRL 132 (2024) 051802

arXiv:2412.19952

EPJ C81 (2021) 342







Aside: new weighting methods to allow presentation of decay-time-dependent CP asymmetries, as for $B^0 \to J/\psi K_S$ (disentangling CP-even and CP-odd contributions) introduced in EPJ C84 (2024) 327 and arXiv:2507.04850

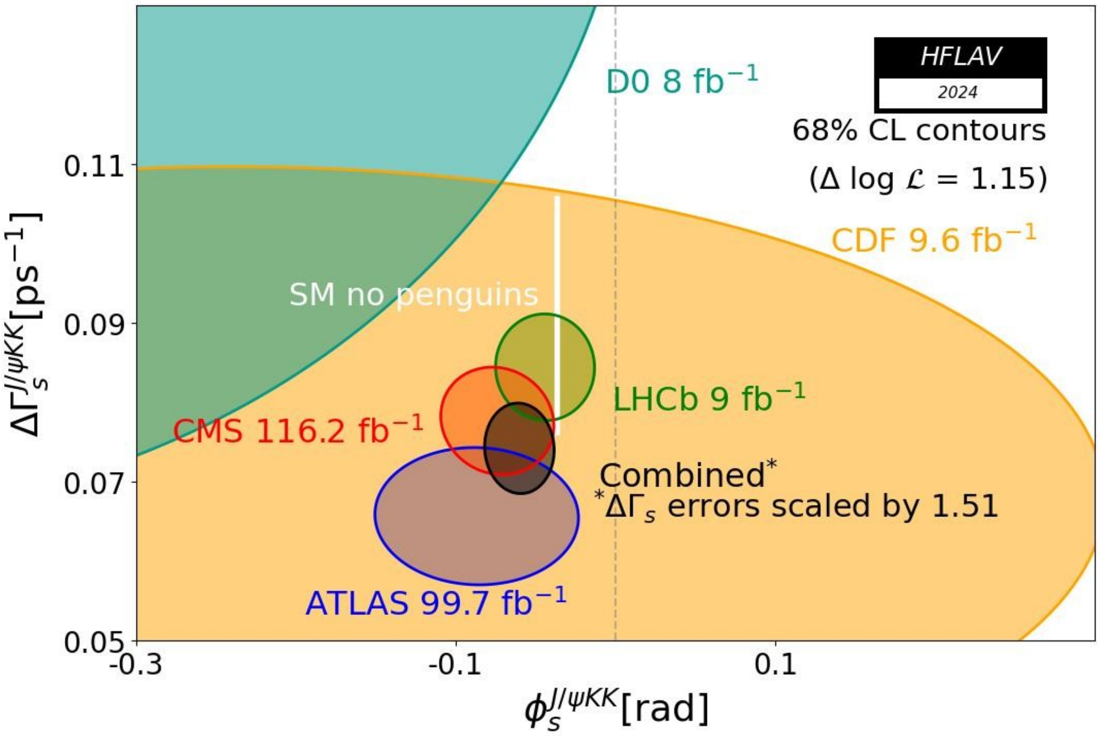
Would love to see these implemented in next updates! 😊

Equality in absence of penguin pollution

3.2σ from zero

$\phi_s = -2\beta_s = -39 \pm 22 \pm 6$ mrad	$\phi_s = -2\beta_s = -73 \pm 23 \pm 7$ mrad	$\phi_s = -2\beta_s = -87 \pm 36 \pm 21$ mrad
Signal yield ~ 350,000 Tagging power ~ 4.3%	Signal yield ~ 490,000 **Tagging power ~ 5.6%**	Signal candidates ~ 450,000 Tagging power ~ 1.8%

World average of $\beta_s(B_s \rightarrow J/\psi\varphi)$



$\varphi_s(B_s \rightarrow J/\psi\varphi) = -2\beta_s(B_s \rightarrow J/\psi\varphi) = -60 \pm 14$ mrad

c.f. precision on $2\beta(B^0 \rightarrow J/\psi K_S) \sim 16$ mrad

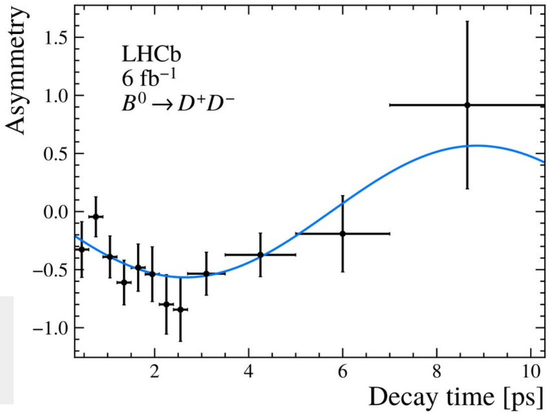
$B_s \to D_s^+ D_s^-$ & $B^0 \to D^+ D^-$

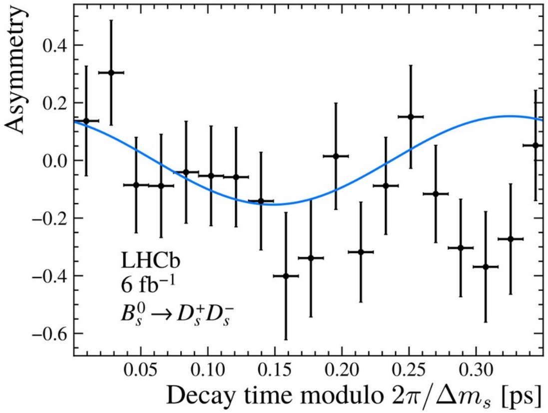
- SU(3) flavour relations can be used to determine penguin pollution effects in $\beta_s(B_s \to J/\psi\varphi)$
  - Several inputs unknown & hard to measure, but approximate methods still possible
- Simpler approach possible where U-spin ($s \leftrightarrow d$) partners available

  [As already seen for $B^0 \to J/\psi K_S \leftrightarrow B_s \to J/\psi K_S$]

JHEP 01 (2025) 061

6.0σ from CP conservation





Precision significantly behind $B_s \to J/\psi\varphi$, but good prospects for improvement with LHCb upgrades

$S(B^0 \to D^+D^-) = -0.549 \pm 0.085 \pm 0.015$

$\varphi_s(B_s \to D_s^+ D_s^-) = -55 \pm 90 \pm 21$ mrad

Digression: Quantum correlations

- All measurements of decay-time-dependent CP violation in $\Upsilon(4S) \to B^0\overline{B}^0$ rely on the quantum entanglement of the final state
  - In this case the state is C odd, i.e. $|\psi\rangle = (|B_1\rangle|\overline{B}_2\rangle - |B_2\rangle|\overline{B}_1\rangle)/\sqrt{2}$
  - New ideas to exploit this still emerging, e.g. arXiv:2506.11196
- Quantum entanglement also used to study hadronic D decay properties in $\psi(3770) \to D^0\overline{D}^0$ decays (also a C odd configuration)
  - These measurements are crucial inputs for charm mixing & CP violation measurements, and for the determination of γ from $B^\pm \to DK^\pm$ and related processes
- Noted long-ago that C even quantum entangled pairs offer various interesting possibilities
  - $|\psi\rangle = (|B_1\rangle|\overline{B}_2\rangle + |B_2\rangle|\overline{B}_1\rangle)/\sqrt{2}$
  - e.g. Sensitivity to CP violation effects from interference between mixing and decay in decay-time-integrated analyses

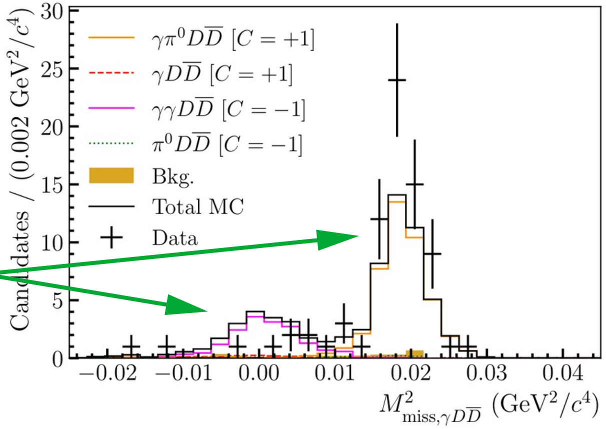
CP even $D^0\bar{D}^0$ pairs at BESIII

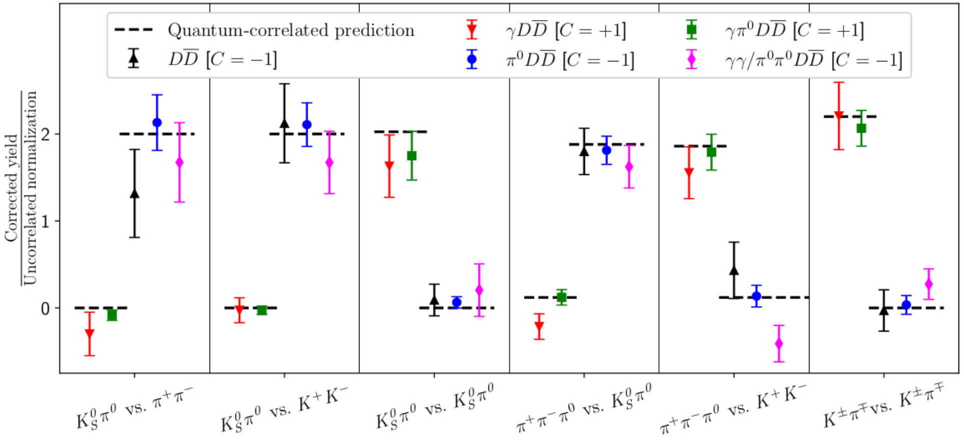
arXiv:2506.07906
arXiv:2506.07907

- CP even $D\bar{D}$ pairs produced in $e^+e^- \to D\bar{D} + \gamma$ (or any odd # γ)
- Data from e^+e^- collisions at $\sqrt{s}$ = 4.13−4.23 GeV, in five final states:
  - C = −1: $D\bar{D}$, $D^*\bar{D}$ / $D\bar{D}^* \to \pi^0 D\bar{D}$, $D^*\bar{D}^* \to \gamma\gamma/\pi^0\pi^0 D\bar{D}$
  - C = +1: $D^*\bar{D}$ / $D\bar{D}^* \to \gamma D\bar{D}$, $D^*\bar{D}^* \to \gamma\pi^0 D\bar{D}$

$D\bar{D}\gamma$ + missing energy reconstructed

Simulation does not include quantum correlations – clear suppression/enhancements observed





New opportunities for studies with larger data samples – very interesting prospects for STCF

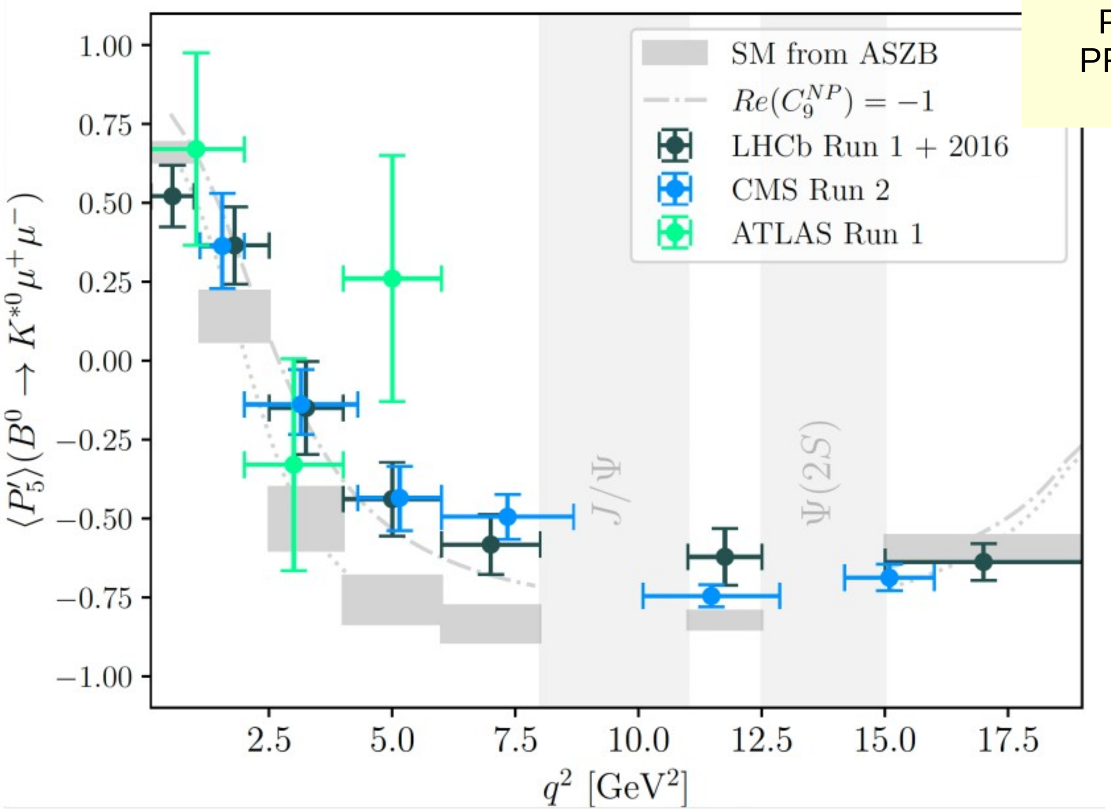
Rare decays

- In recent years, discussion of rare B decays has involved frequent use of the word “anomalies”
- Three sets of observables
  - theoretically pristine: lepton universality violating
    - latest FCNC results consistent with SM
  - theoretically clean: purely leptonic final states
    - latest results ($\mathcal{B}(B \to \mu^+\mu^-)$) consistent with SM
  - theoretically more challenging: branching fractions and angular observables
    - anomalies persist
- Most relevant question: how to overcome theoretical uncertainties?
  - several directions being pursued ...

arXiv:2505.03483, PRL 134 (2025) 181803, PRL 134 (2025) 121803, PRL 131 (2023) 051803, PR D108 (2023) 032002

PL B842 (2023) 137955, PRL 128 (2022) 041801, PR D105 (2022) 012010, JHEP 04 (2019) 098

Angular analyses of $B^0 \rightarrow K^{*0}\mu^+\mu^-$



PL B864 (2025) 139406,
PRL 125 (2020) 011802,
JHEP 10 (2018) 047

Compilation by Eluned Smith, LHCP2024

Clear discrepancy from SM prediction in P_5' observable

Most apparent in bins just below J/ψ resonance

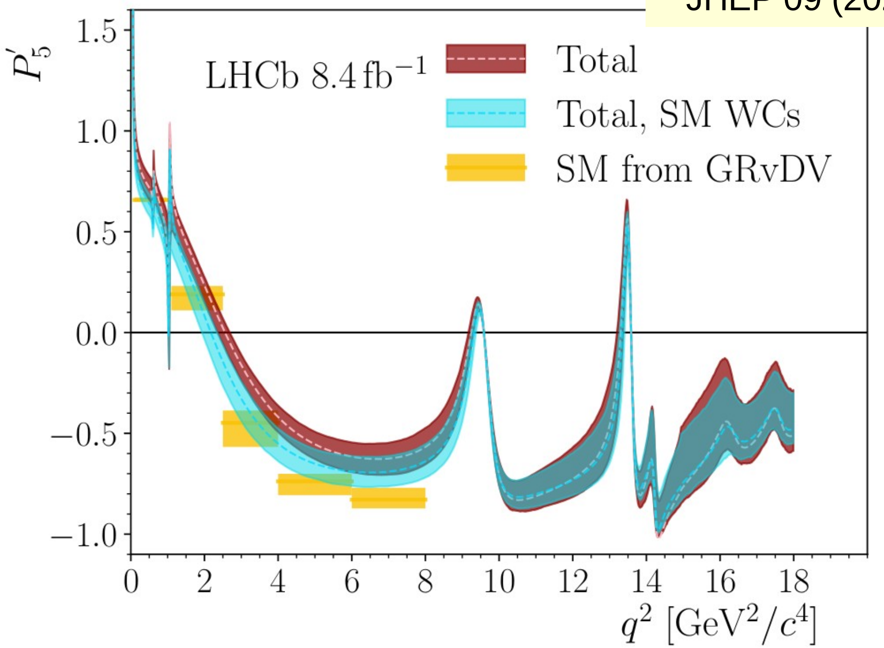
Possibility of long-distance charm-loop contributions?

(Would imply uncertainty on SM prediction underestimated.)

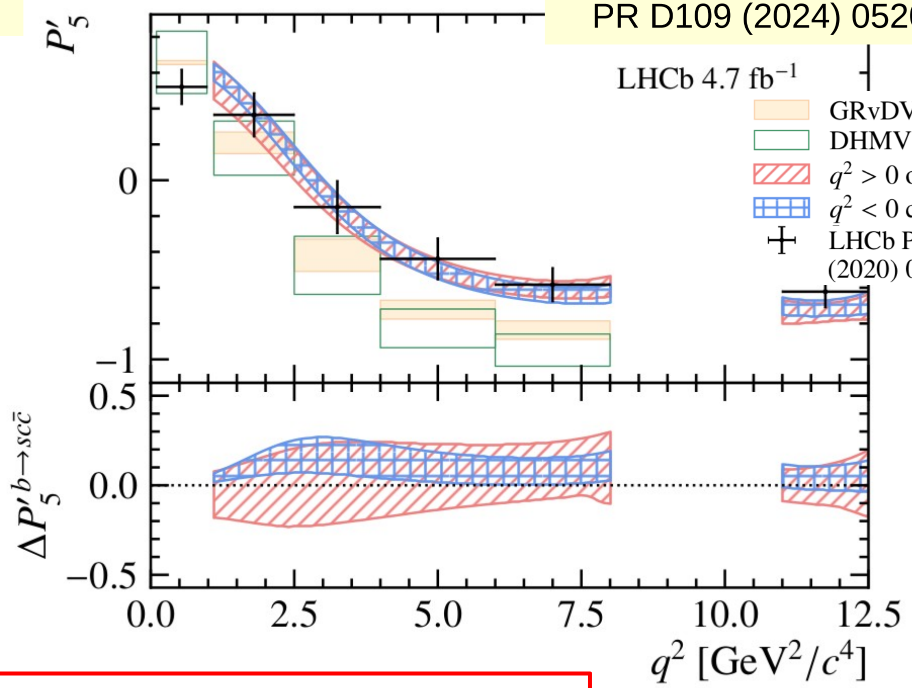
Model-dependent unbinned fits to separate long- and short-distance contributions

Model-dependent unbinned fits of $B^0 \to K^{*0}\mu^+\mu^-$

JHEP 09 (2024) 026



PRL 132 (2024) 131801
PR D109 (2024) 052009

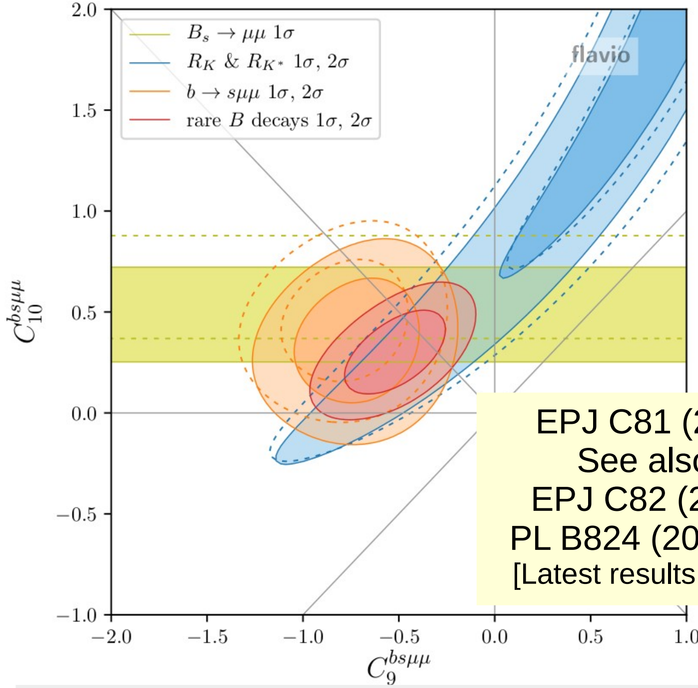


Discrepancy persists but with reduced significance
(expected even with BSM due to extra degrees of freedom)

Global fits to rare decays

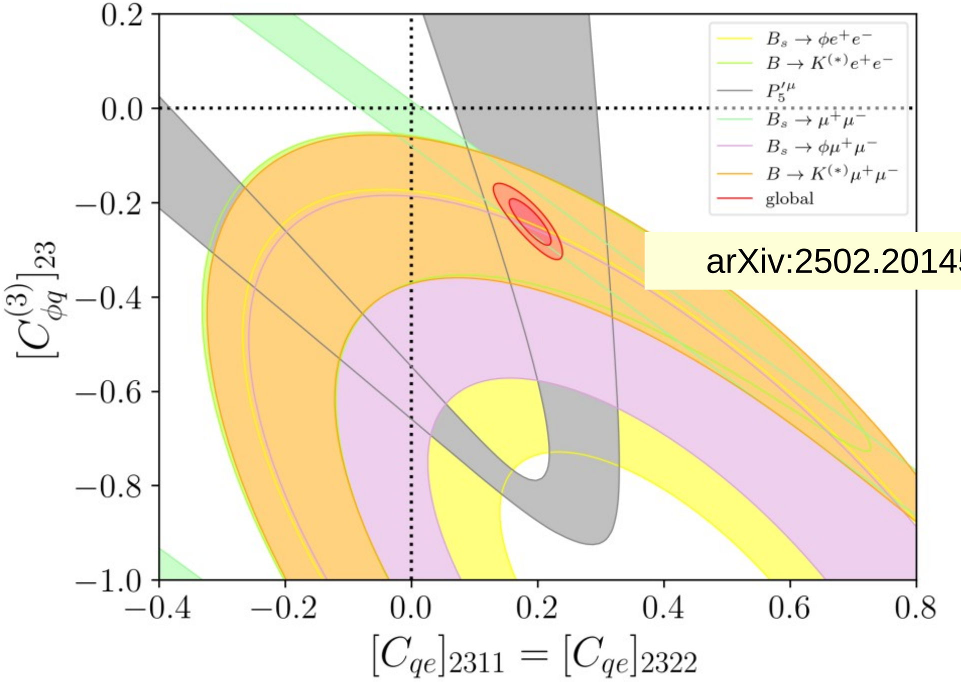
Effective field theory approaches, with (SM+)BSM effects encoded into Wilson coefficients associated with specific operators

WET



EPJ C81 (2021) 952
See also, e.g.,
EPJ C82 (2022) 326,
PL B824 (2022) 136838
[Latest results not included]

SMEFT



arXiv:2502.20145

Clear tension with SM

Strong constraint from SM-like $B(B_s \to \mu^+\mu^-)$ – tension is in vector operator (C_9)

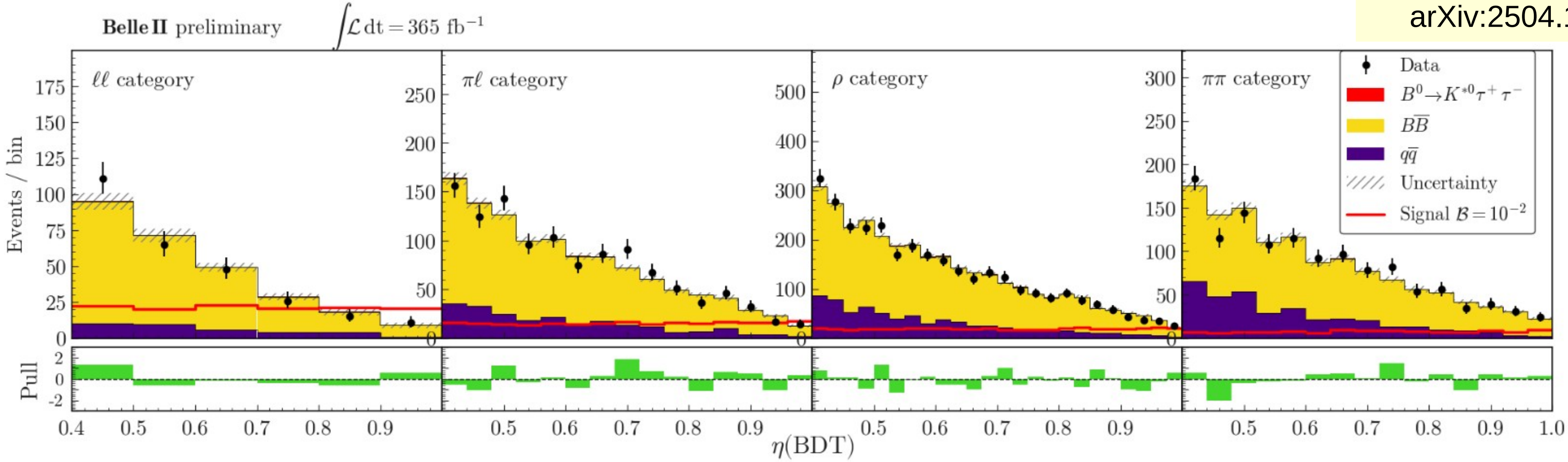
Are there theoretically clean ways to probe C_9?

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

[Not fundamentally cleaner theoretically, but BSM effects may be larger for heavier leptons]

- Experimentally highly challenging due to missing ν from τ decays & background from $D_{(s)}$ decays
- Exploit kinematic constraints in $e^+e^- \to B_{sig}B_{tag}$, with B_{tag} reconstructed in hadronic decay modes
- Signal-background separation through BDT, separately for different τ final states

arXiv:2504.10042



LHCb amplitude fit of $B^0 \to K^{*0}\mu^+\mu^-$ gives a limit
$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ at 90% CL
JHEP 09 (2024) 026

$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$ at 90% CL

SM prediction $O(10^{-7})$

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

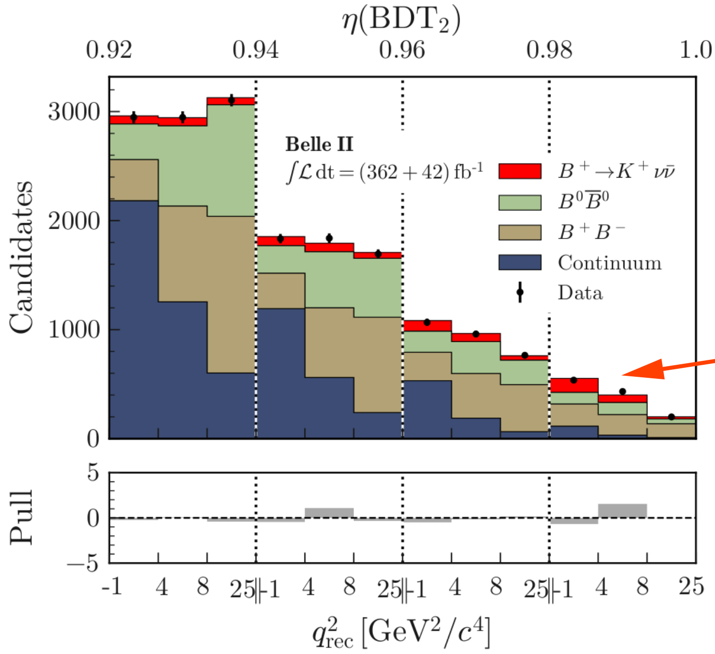
PR D109 (2024) 112006

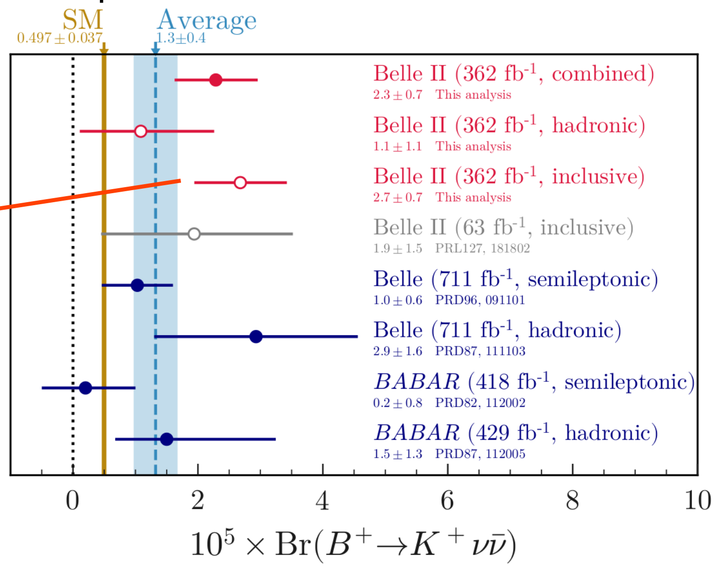
- Experimentally highly challenging due to need to understand and control many possible background channels with missing particles (K_L, n, ν)
- Exploit kinematic constraints in $e^+e^- \to B_{sig}B_{tag}$, with B_{tag} reconstructed inclusively
  - More conventional hadronic B_{tag} reconstruction used for validation and independent measurement
- Signal-background separation through BDT

$$\mathcal{B}(B \to K\nu\bar{\nu}) = \left[2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})\right] \times 10^{-5}$$

3.5σ from zero

Comparable precision to Belle with much smaller data sample

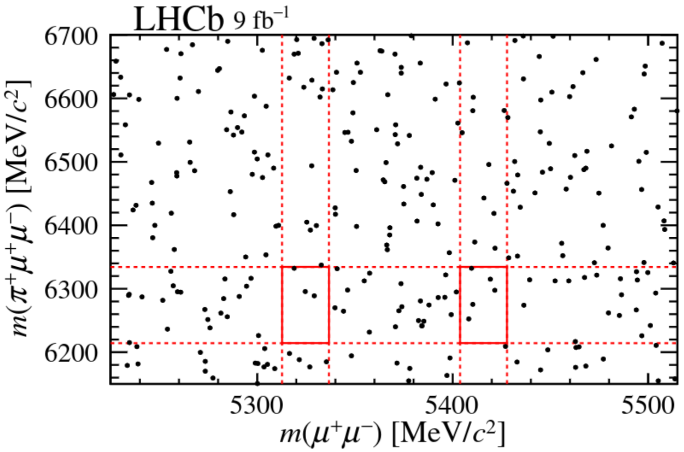


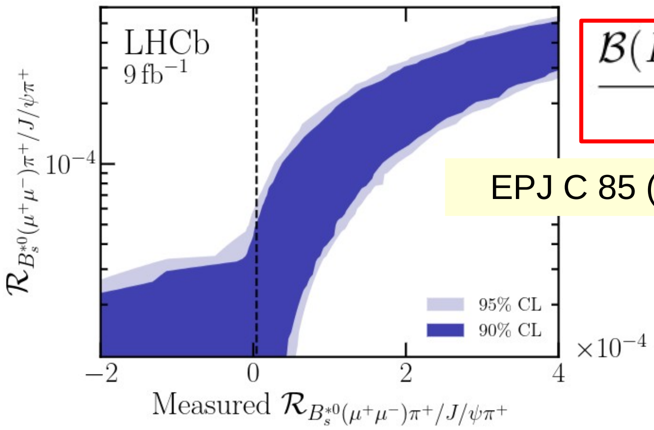


$B_s^* \to \mu^+\mu^-$

- Radical idea: change initial state instead of final state
  - Since B_s^* is spin-1, probes C_9 c.f. C_{10} for $B_s \to \mu^+\mu^-$
- Decay not helicity suppressed: partial width enhanced c.f. $B_s \to \mu^+\mu^-$
  - But B_s^* has EM decays: total width also enhanced; SM prediction $\mathcal{B}(B_s^* \to \mu^+\mu^-) \sim O(10^{-11})$
- Experimentally, background strongly suppressed exploiting $B_c^+ \to B_s^*\pi^+$
  - require large B_c samples – potentially interesting for ATLAS and CMS

PRL 116 (2016) 141801
EPJ C82 (2022) 459





$$\frac{\mathcal{B}(B_c^+ \to B_{(s)}^{*0}(\mu^+\mu^-)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} < 5.0 \times 10^{-5}$$

EPJ C 85 (2025) 20

Missing ingredient:
$\mathcal{B}(B_c^+ \to B_s^*\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$

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

- $K \to \pi\nu\bar{\nu}$ decays long understood as clean BSM probes
  - $B(K^+ \to \pi^+\nu\bar{\nu})_{SM} \sim 8 \times 10^{-11}$; $B(K_L \to \pi^0\nu\bar{\nu})_{SM} \sim 3 \times 10^{-11}$
- Experimental challenge is to achieve high rates with low backgrounds
  - $K^+ \to \pi^+\nu\bar{\nu}$ pursued by NA62 (CERN); $K_L \to \pi^0\nu\bar{\nu}$ pursued by KOTO (JPARC)

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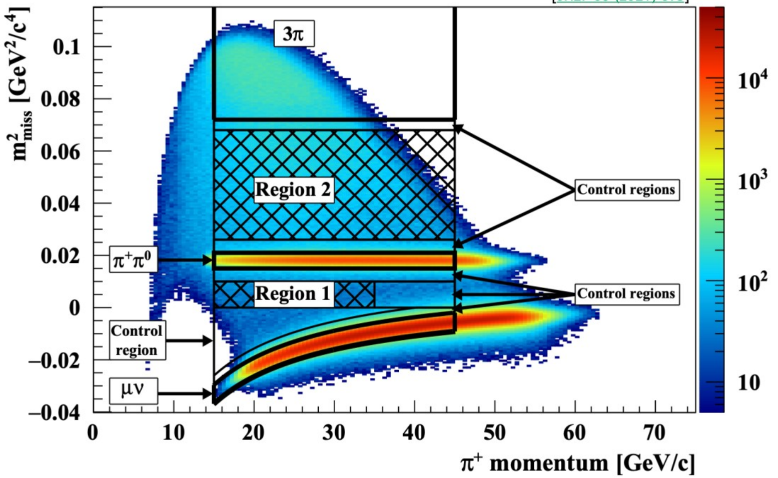
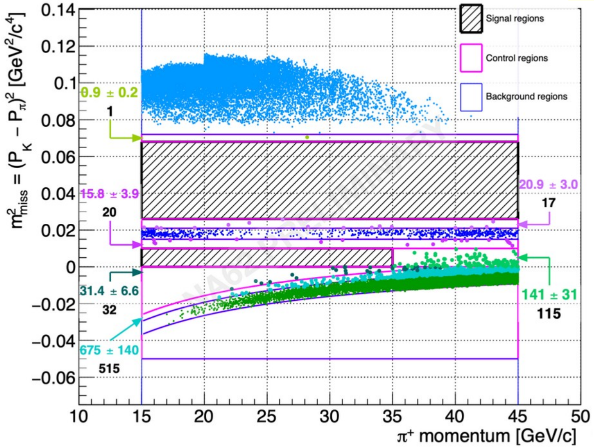
  - $K^+ \to \pi^+\nu\bar{\nu}$ pursued by NA62 (CERN); $K_L \to \pi^0\nu\bar{\nu}$ pursued by KOTO (JPARC)
    - decay in flight of tagged kaons, with excellent momentum and timing resolution, hermetic veto for μ & γ to achieve 10^7 rejection for both $K^+ \to \mu^+\nu$ & $K^+ \to \pi^+\pi^0$

[JHEP 06 (2021) 093]

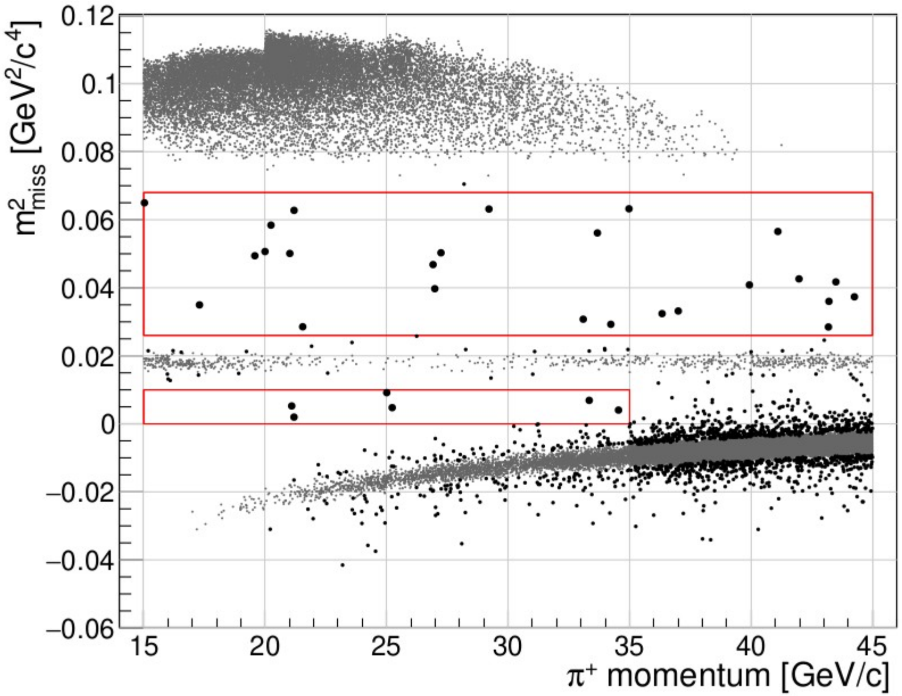


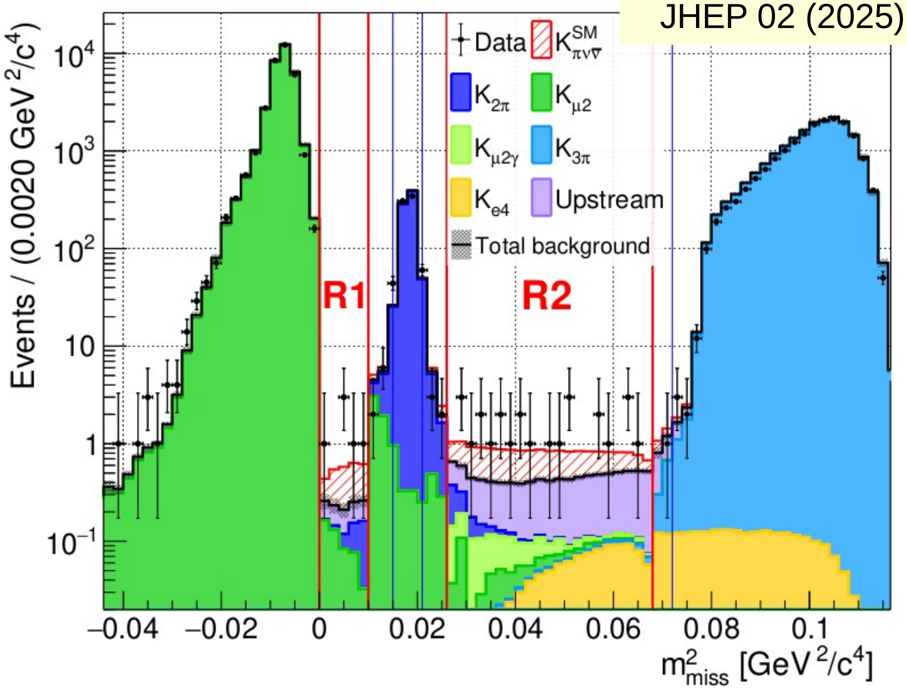
JHEP 02 (2025) 191



Observed yields in data consistent with expectation in 7 background-dominated control regions

NA62 result on $K^+ \to \pi^+ \nu\bar{\nu}$ (2021-22 data)



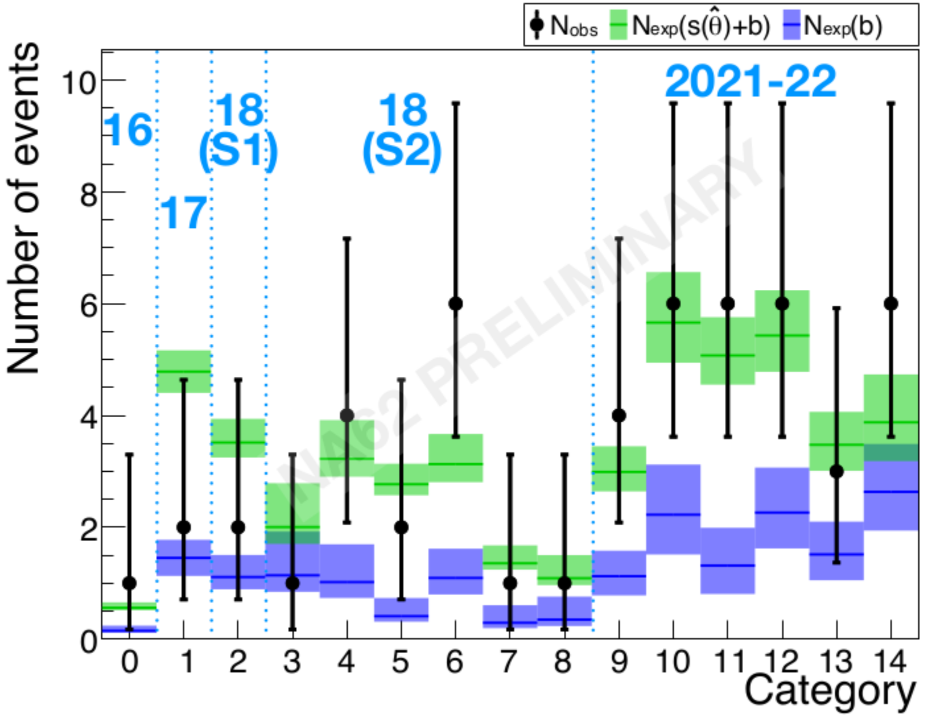


JHEP 02 (2025) 191

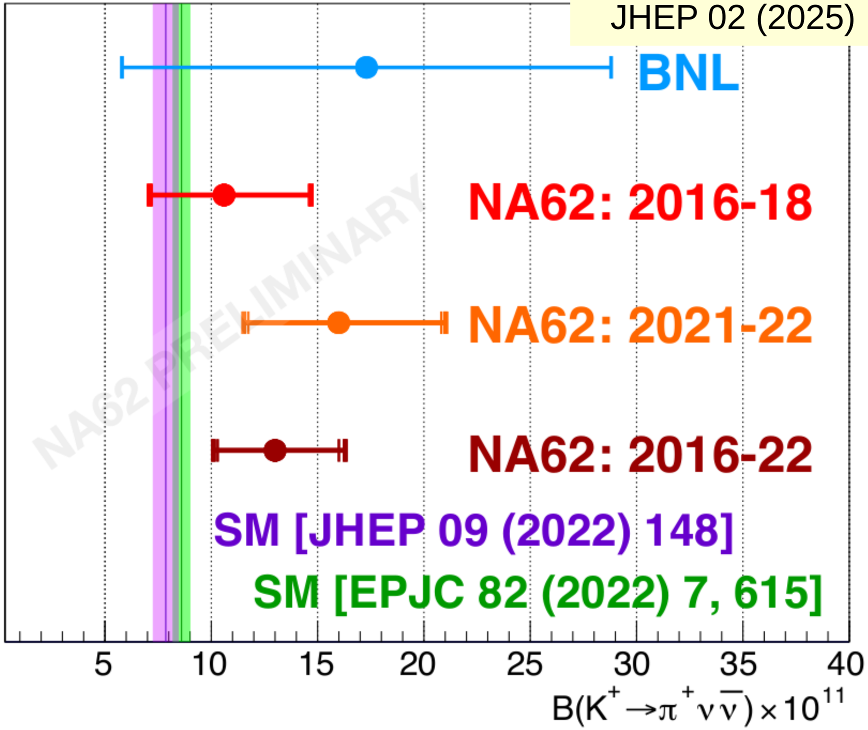
- Total expected background 11 ± 2
- Expected SM signal 10
- Observed decays in signal regions 31

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = \left(16.2\ {}^{+4.9}_{-4.3}\Big|_{\text{stat}}\ {}^{+1.4}_{-1.4}\Big|_{\text{syst}}\right) \times 10^{-11}$$

NA62 result on $K^+ \rightarrow \pi^+\nu\bar{\nu}$ (2016-22 data)



JHEP 02 (2025) 191



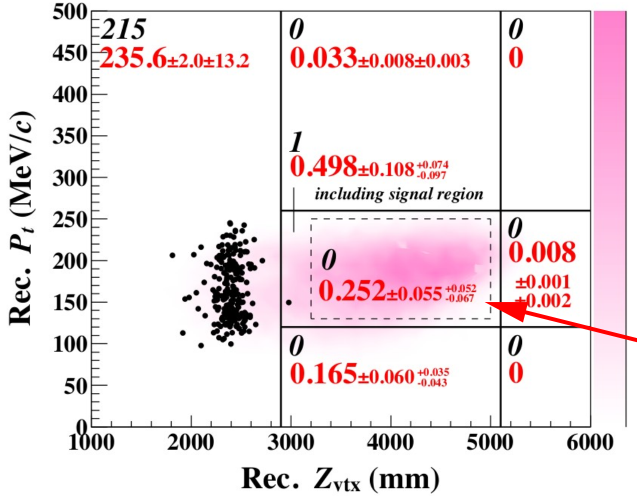
>5σ from zero
Consistent with SM within 2σ
Further data-taking until end of Run 3

$$B(K^+ \rightarrow \pi^+\nu\bar{\nu}) = \left(13.0\,^{+3.0}_{-2.7}\Big|_{stat}\,^{+1.3}_{-1.3}\Big|_{syst}\right) \times 10^{-11}$$

Latest KOTO limit on $B(K_L \to \pi^0 \nu\bar{\nu})$

PRL 134 (2025) 081802

- $K \to \pi\nu\bar{\nu}$ decays long understood as clean BSM probes
  - $B(K^+ \to \pi^+\nu\bar{\nu})_{SM} \sim 8 \times 10^{-11}$; $B(K_L \to \pi^0\nu\bar{\nu})_{SM} \sim 3 \times 10^{-11}$
- Experimental challenge is to achieve high rates with low backgrounds
  - $K^+ \to \pi^+\nu\bar{\nu}$ pursued by NA62 (CERN); $K_L \to \pi^0\nu\bar{\nu}$ pursued by KOTO (JPARC)
    - decay in flight of neutral kaons, cannot be tagged so rely on narrow beam and use beam axis and $m(\pi^0)$ constraint to determine decay vertex and π^0 p_T; highly hermetic detector to reject background



$B(K_L \to \pi^0\nu\bar{\nu}) < 2.2 \times 10^{-9}$ at 90% CL
Improves previous limit by factor 1.4
Based on 2021 data; goal to reach $O(10^{-10})$ and below

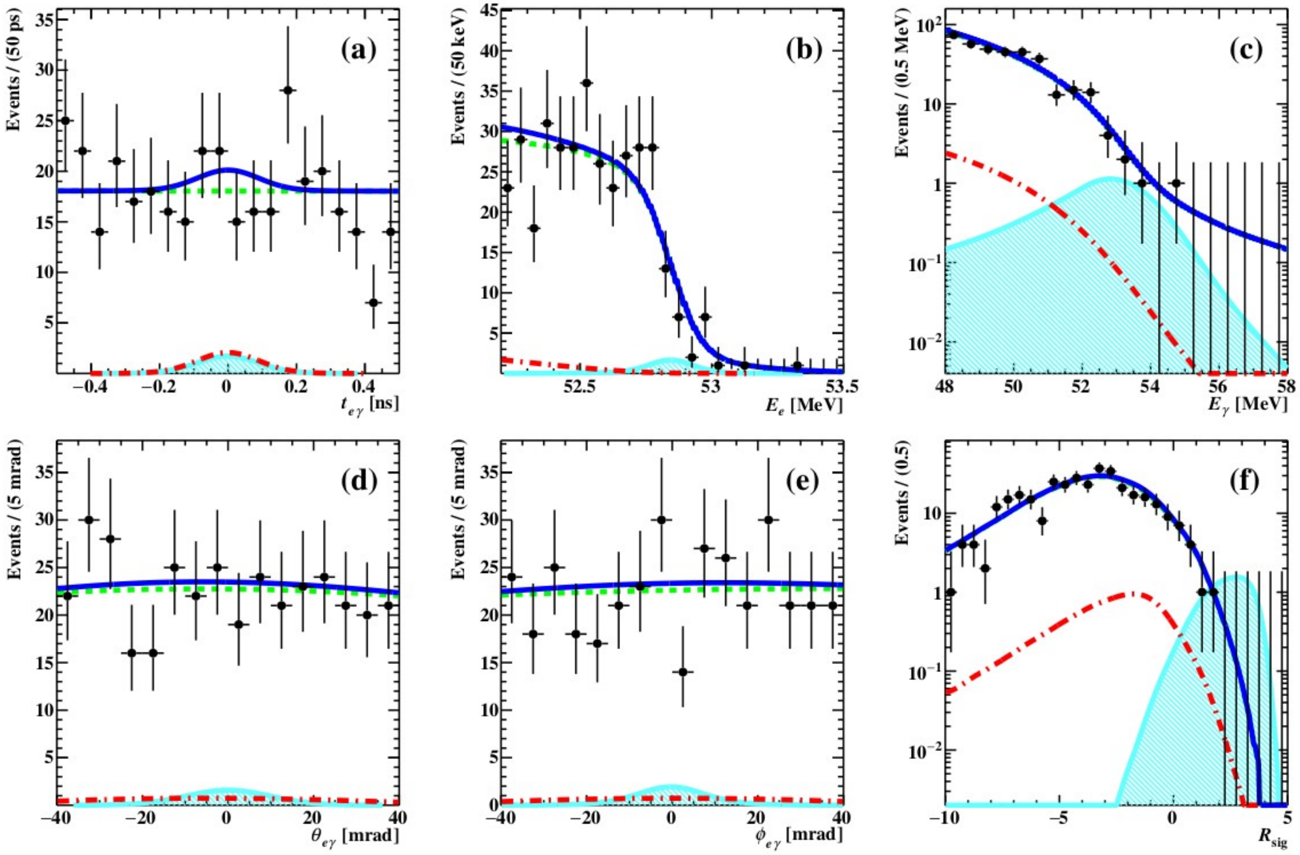
Source		Number of events
$K^{\pm}$		$0.042 \pm 0.014\ ^{+0.004}_{-0.028}$
K_L	$K_L \to 2\gamma$ (beam-halo)	$0.045 \pm 0.010 \pm 0.006$
	$K_L \to 2\pi^0$	$0.059 \pm 0.022\ ^{+0.050}_{-0.059}$
Neutron	Hadron-cluster	$0.024 \pm 0.004 \pm 0.006$
	CV-η	$0.023 \pm 0.010 \pm 0.005$
	Upstream-π^0	$0.060 \pm 0.046 \pm 0.007$
Total		$0.252 \pm 0.055\ ^{+0.052}_{-0.067}$

Crucial to be background-free

Crucial to be background-free

MEG II result on $B(\mu \to e\gamma)$

arXiv:2504.15711



Eight discriminating variables (5 shown) combined into fitted likelihood function (transformed to R_{sig} for illustration)

No signal excess observed

$B(\mu^+ \to e^+\gamma) < 1.5 \times 10^{-13}$ at 90% CL

[×2.4 higher sensitivity c.f. MEG]

Uses 2021-22 data; ×2 more data collected in 23-24 & more anticipated 25-26

Target sensitivity 6×10^{-14}

The future

- Exciting prospects in medium term with HL-LHC, ATLAS and CMS upgrades (3/ab), LHCb Upgrade II (300/fb) and Belle II (50/ab), plus completion of BESIII &, potentially, STCF
  - Samples sizes for B, D & τ decays will increase typically by a factor of 100
    - Precision improved by factor 10 for most observables
- Further progress in kaon physics from NA62 & KOTO (plus LHCb)
  - KOTO2 proposal can push further on K_L rare decays
  - Currently no clear plan to push further on some interesting K observables
- Will flavour physics still be interesting by mid-2040s?
  - Certainly, because still scope for further improvement
    - In particular for experimentally challenging decays involving τ &/or ν

Expected improvements from HL-LHC, Belle II and Tera-Z (FCC-ee or CEPC)

	γ	quarks	μ	e	τ	ν
$3_q \to 2_q$	$b \to s\,\gamma$	$B_s \leftrightarrow \bar{B}_s$	$b \to s\,\mu\mu$ $b \to c\,\mu\nu$	$R_{bs}\,(e/\mu)$ $R_{bc}\,(e/\mu)$	$b \to s\,\tau\tau$ $b \to c\,\tau\nu$	$b \to s\,\nu\nu$
$3_q \to 1_q$	$b \to d\,\gamma$	$B_d \leftrightarrow \bar{B}_d$	$b \to d\,\mu\mu$ $b \to u\,\mu\nu$	$R_{bd}\,(e/\mu)$ $R_{bu}\,(e/\mu)$	$b \to d\,\tau\tau$ $b \to u\,\tau\nu$	$b \to d\,\nu\nu$
$2_q \to 2_q,\ 1_q$	$c \to u\,\gamma$	$D \leftrightarrow \bar{D}$				$c \to u\,\nu\nu$
$3_l \to 2_l,\ 1_l$	$\tau \to \mu\,\gamma$ $\tau \to e\,\gamma$	$\tau \to \mu\,qq$ $\tau \to e\,qq$	$\tau \to \mu\,\mu\mu$ $\tau \to \mu\,ee$	$\tau \to \mu\,ee$ $\tau \to e\,ee$		$\tau \to \mu\,\nu\nu$ $\tau \to e\,\nu\nu$

Progress from HL-LHC & Belle-II:

- (pink) σ reduction by 4 – 10 times

Possible Tera-Z impact [6×10^{12} Z]:

- (yellow) Further σ reduction by 5 – 10
- (green) Further σ reduction ≥ 10

Summary by Gino Isidori at ESPPU Open Symposium 2025

Expected improvements from HL-LHC, Belle II and Tera-Z (FCC-ee or CEPC)

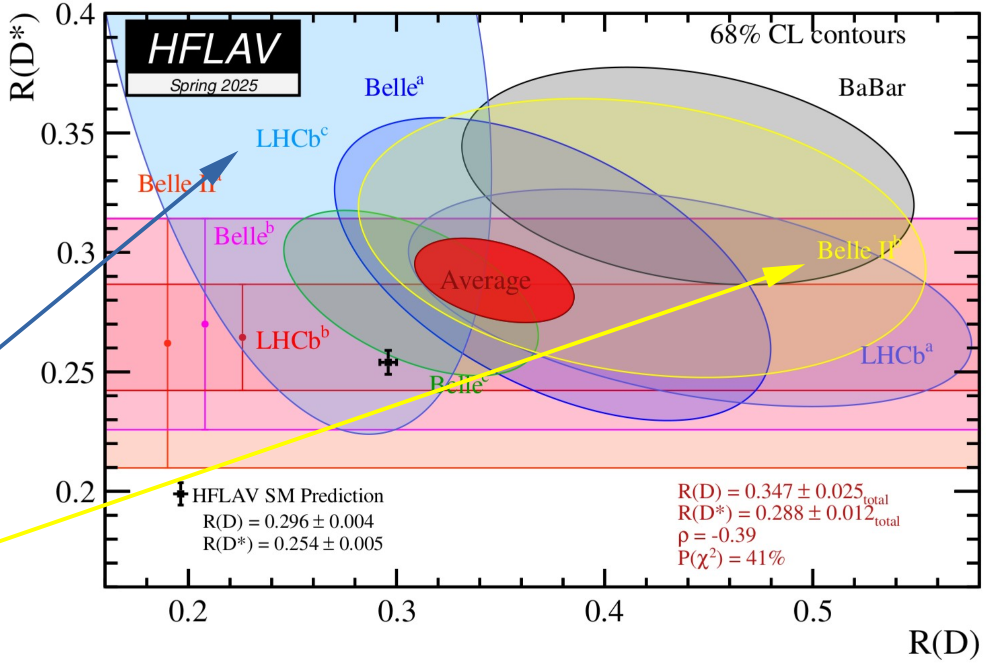
	γ	quarks	μ	e	τ	ν
$3_q \to 2_q$	$b \to s\,\gamma$	$B_s \leftrightarrow \bar{B}_s$	$b \to s\,\mu\mu$ $b \to c\,\mu\nu$	$R_{bs}\,(e/\mu)$ $R_{bc}\,(e/\mu)$	$b \to s\,\tau\tau$ $b \to c\,\tau\nu$	$b \to s\,\nu\nu$
$3_q \to 1_q$	$b \to d\,\gamma$	$B_d \leftrightarrow \bar{B}_d$	$b \to d\,\mu\mu$ $b \to u\,\mu\nu$	$R_{bd}\,(e/\mu)$ $R_{bu}\,(e/\mu)$	$b \to d\,\tau\tau$ $b \to u\,\tau\nu$	$b \to d\,\nu\nu$
$2_q \to 2_q,\ 1_q$	$c \to u\,\gamma$	$D \leftrightarrow \bar{D}$				$c \to u\,\nu\nu$
$3_l \to 2_l,\ 1_l$	$\tau \to \mu\,\gamma$ $\tau \to e\,\gamma$	$\tau \to \mu\,qq$ $\tau \to e\,qq$	$\tau \to \mu\,\mu\mu$ $\tau \to \mu\,ee$	$\tau \to \mu\,ee$ $\tau \to e\,ee$		$\tau \to \mu\,\nu\nu$ $\tau \to e\,\nu\nu$

Tera-Z adds greatest improvement just where it is needed most!

Summary by Gino Isidori at ESPPU Open Symposium 2025

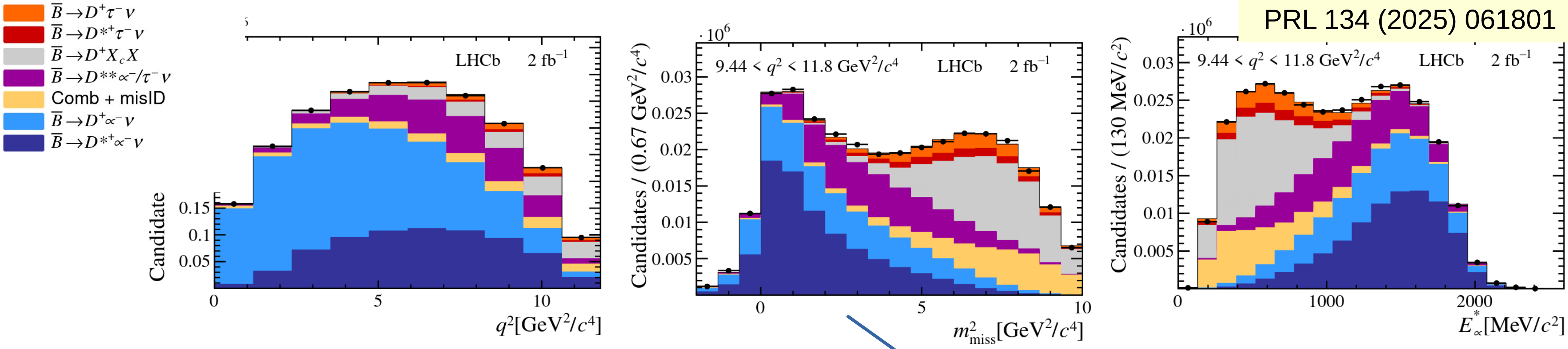
Interest in decays involving τ &/or ν

- Most significant anomaly today is in the branching fractions of $B \to D^{(*)}\tau\nu$ decays
  - R ratios to $\mathcal{B}(B \to D^{(*)}l\nu)$, $l = \tau$ c.f. e,μ
  - World averages for R(D)-R(D*) discrepant with SM predictions at 3.8σ
  - Theoretically clean; experimentally challenging
- Latest new results



LHCb results on R(D$^+$) and R(D^{*+})

PRL 134 (2025) 061801

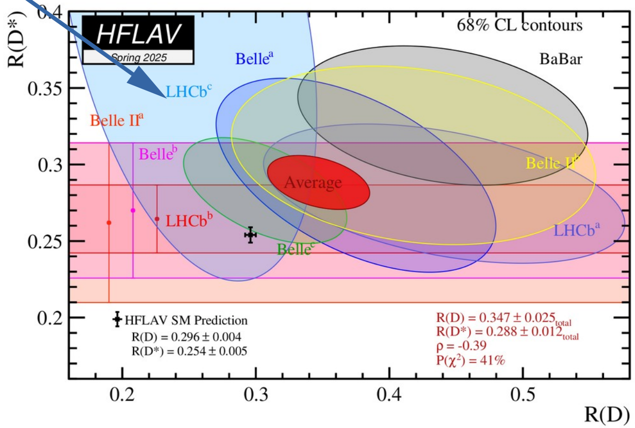


First LHCb R(D$^{(*)}$) result reconstructing D$^+$ (previous LHCb analyses reconstructed D^0)

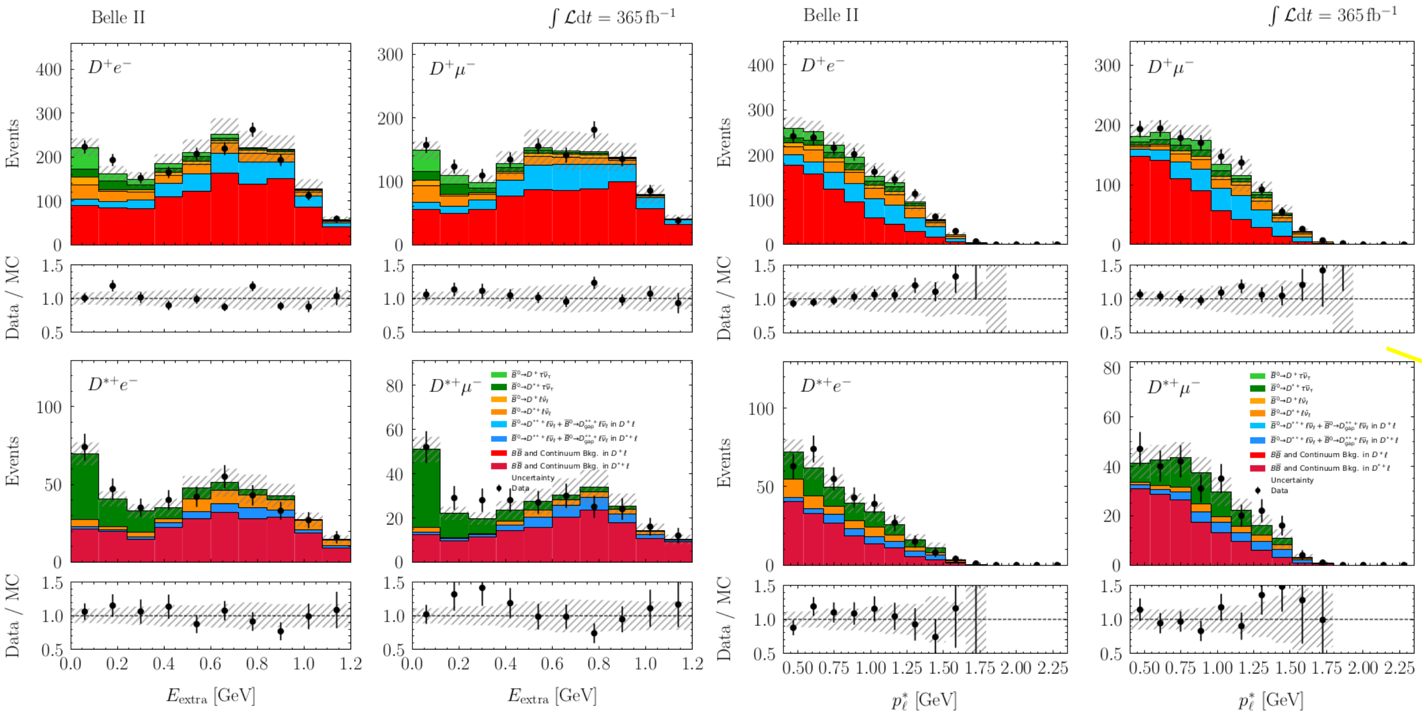
$\tau \to \mu \nu \bar{\nu}$ decay used

$D^+ \to K^- \pi^+ \pi^+$ & $D^{*+} \to D^+ \pi^0$ (π^0 not reconstructed)

separate $\bar{B}^0 \to D^+ \tau^- \bar{\nu}$ and $\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}$ from $\bar{B}^0 \to D^+ \mu^- \bar{\nu}$ and $\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}$ and backgrounds using 3D fit to kinematic variables

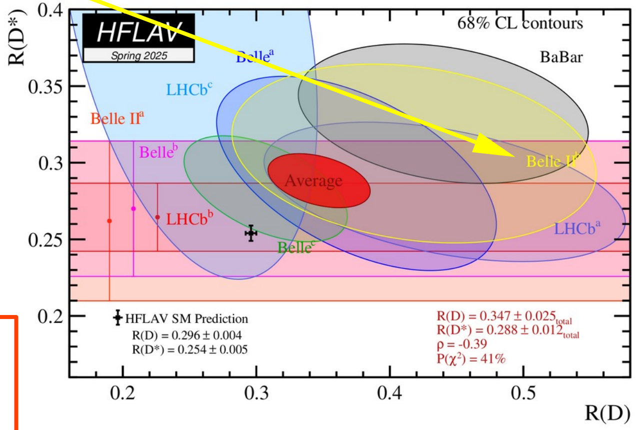


Belle II results on R(D$^+$) and R(D^{*+})



arXiv:2504.11220

Υ(4S) → B$_{sig}$B$_{tag}$
with B$_{tag}$ reconstructed
in semileptonic decay
using full event
interpretation algorithm



τ → μνν̄ & eνν̄ decays used; D^{*+} → D^{0}π$^+$, range of D$^+$ & D^0 decays
separate fits to D$^+$e, D$^+$μ, D^{*+}e, D^{*+}μ samples
each fit separates B̄^{0} → D$^{(*)+}$τν̄ from B̄^{0} → D$^{(*)+}$lν̄ and backgrounds

Summary

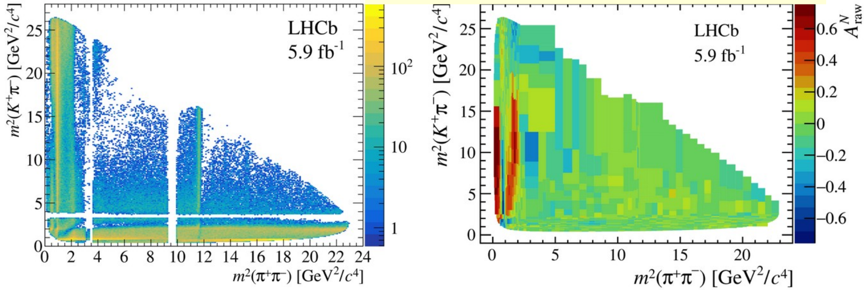
- Huge amount of progress in recent years
  - Precision in many areas now sufficient that subleading effects need to be accounted for
    - e.g. penguin pollution in $\beta_{(s)}$ measurements, long-distance effects in rare decays
  - Methods exist to do this and are being pursued
    - exciting new ideas still appearing
- Improvements in analysis techniques giving better than anticipated precision
  - e.g. machine learning techniques in selection and flavour tagging
- Far too much to cover, apologies if I missed your favourite topic
    - charm mixing, CP violation and rare decays, beauty and charm lifetimes, determinations of CKM angles γ and α, determinations of $|V_{cb}|$ and $|V_{ub}|$, polarisation in $B \to VV$ decays, hadron spectroscopy including discoveries of exotic hadrons, searches for lepton flavour violation and other SM null tests, …
- Data still to exploit and much more on the way – near and longer term prospects are bright
  - More in talks by Vava Gligorov, Karim Trabelsi and Sophie Renner

Back up

Enhanced CP violation effects in multibody decays

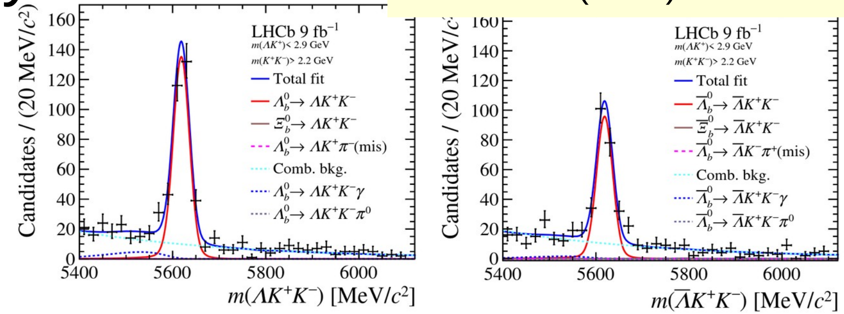
- Resonances cause variation of strong phases
  - if tree/penguin ratio also varies across phase-space, expect localised regions with large CP violation effects
- Observed in B meson decays
  - e.g. in $B^+ \to K^+\pi^+\pi^-$

PR D108 (2023) 012008



- Searched for in multiple Λ_b & Ξ_b decays
  - e.g. in $\Lambda_b^0 \to \Lambda K^+K^-$

PRL 134 (2025) 101802

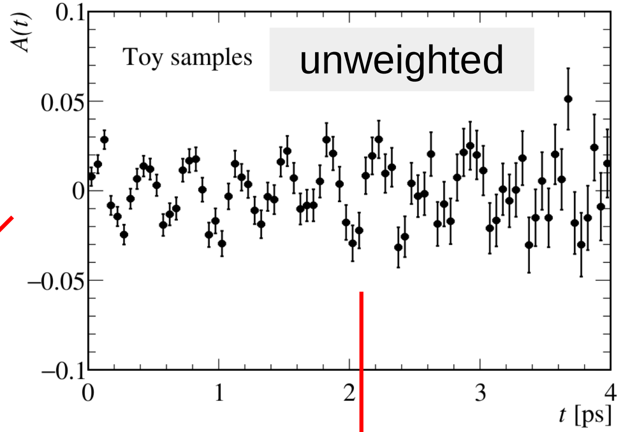


A_{CP} = (16.5 ± 4.8 ± 1.7)% 3.2σ from zero
in N* dominated region
[A_{CP} measured using $\Lambda^0_b \to \Lambda^+_c(\Lambda\pi^+)\pi^-$ as reference channel]

Visualisation of asymmetries in $B_s \to J/\psi\phi$ decays

EPJ C84 (2024) 327, arXiv:2507.04850

Very large sample of $B_s \to J/\psi\phi$ pseudodata, simplified model not including experimental effects

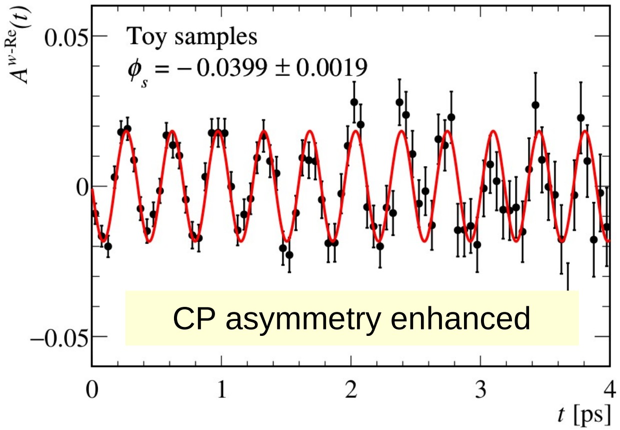


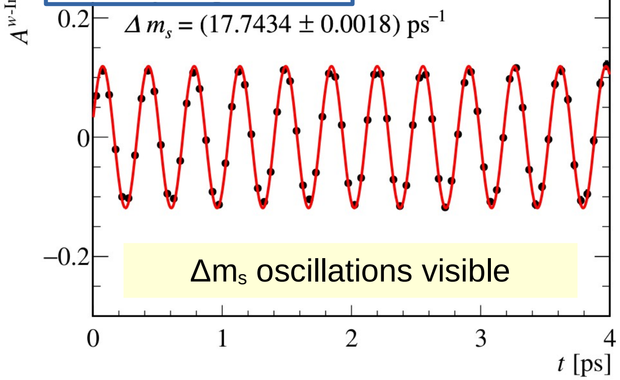
Application of weights, as functions of total B_s (A) and $\overline{B}_s$ ($\overline{A}$) amplitudes at each position in final-state phase space f [Weights also given in terms of transversity amplitudes]

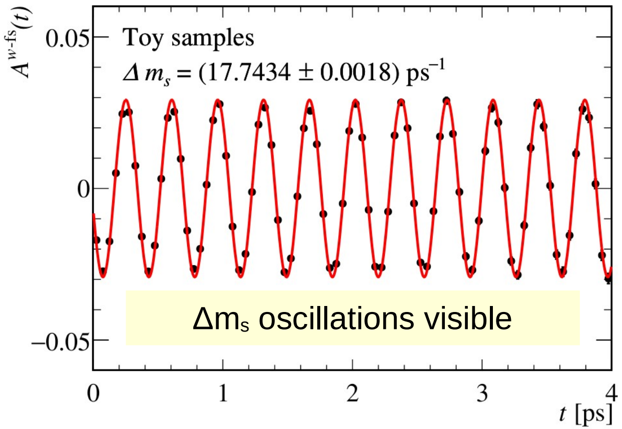
$$w_f^{\mathcal{R}e} = \frac{2\,\mathcal{R}e(\mathcal{A}_f^* \overline{\mathcal{A}}_f)}{|\mathcal{A}_f|^2 + |\overline{\mathcal{A}}_f|^2}$$

$$w_f^{\mathcal{I}m} = \frac{2\,\mathcal{I}m(\mathcal{A}_f^* \overline{\mathcal{A}}_f)}{|\mathcal{A}_f|^2 + |\overline{\mathcal{A}}_f|^2}$$

$$w_f^{\mathrm{fs}} = \frac{|\mathcal{A}_f|^2 - |\overline{\mathcal{A}}_f|^2}{|\mathcal{A}_f|^2 + |\overline{\mathcal{A}}_f|^2}$$





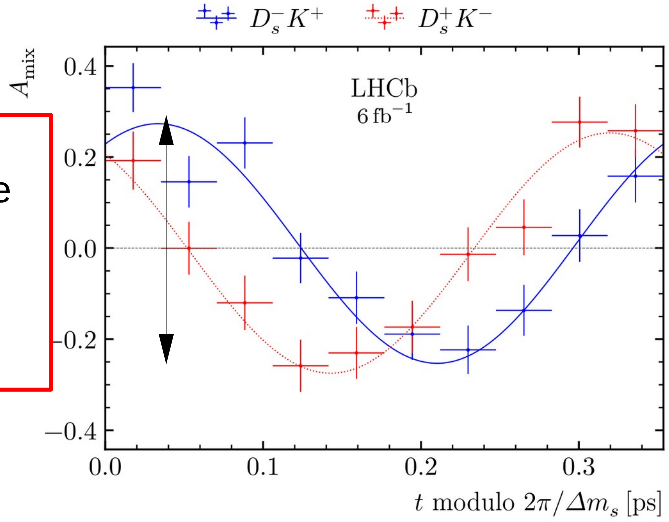


Penguin-free approaches

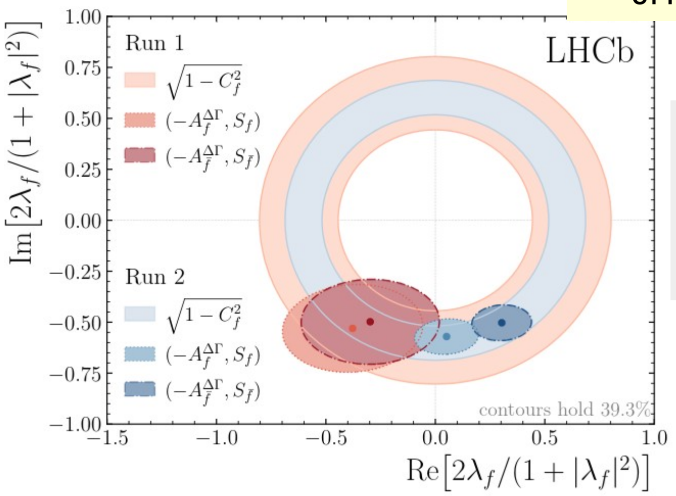
- Penguin contributions impossible if no $q\bar{q}$ pair in final state
  - e.g. $B^0 \to D^-\pi^+/D^+\pi^-$ (probes $2\beta+\gamma$) and $B_s \to D_s^-K^+/D_s^+K^-$ (probes $\gamma-2\beta_s$)
  - since γ well-known from $B^\pm \to DK^\pm$ and related processes (also penguin-free), can interpret results as measurements of 2β & $-2\beta_s$
    - [until now, interpretation mainly in terms of γ taking meaured $2\beta_{(s)}$ as input]

Magnitudes of oscillations determine
$S_f = -0.53 \pm 0.21 \pm 0.06$
$S_{\bar{f}} = -0.50 \pm 0.20 \pm$

8.6σ from
CP conservation
($S_f = -S_{\bar{f}}$)



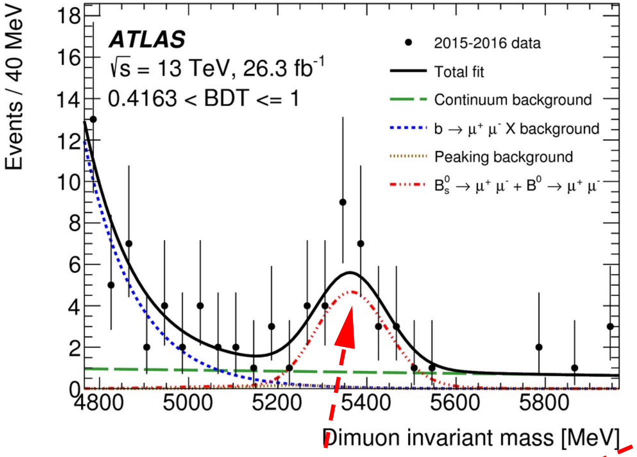
JHEP 03 (2025) 139



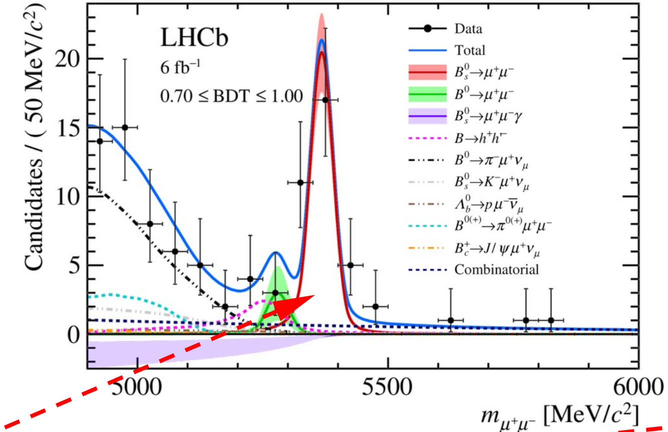
Complex numbers with phases given by $\delta\pm(\gamma-2\beta_s)$

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

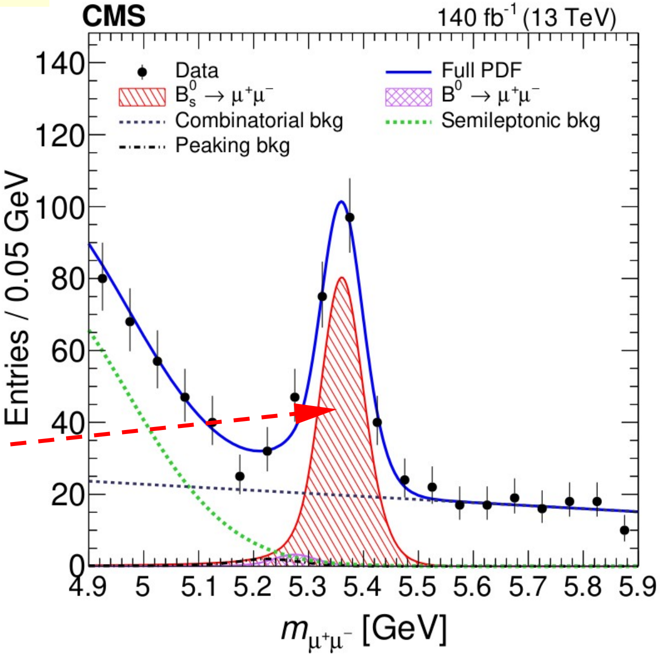
JHEP 04 (2019) 098

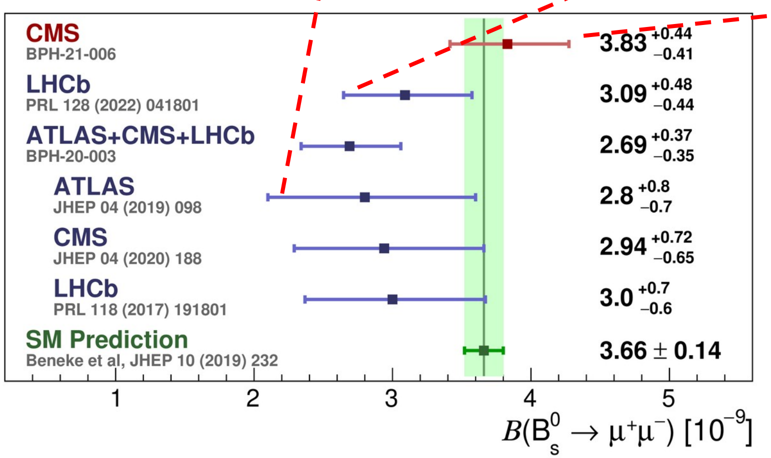


PRL 128 (2022) 041801, PR D105 (2022) 012010



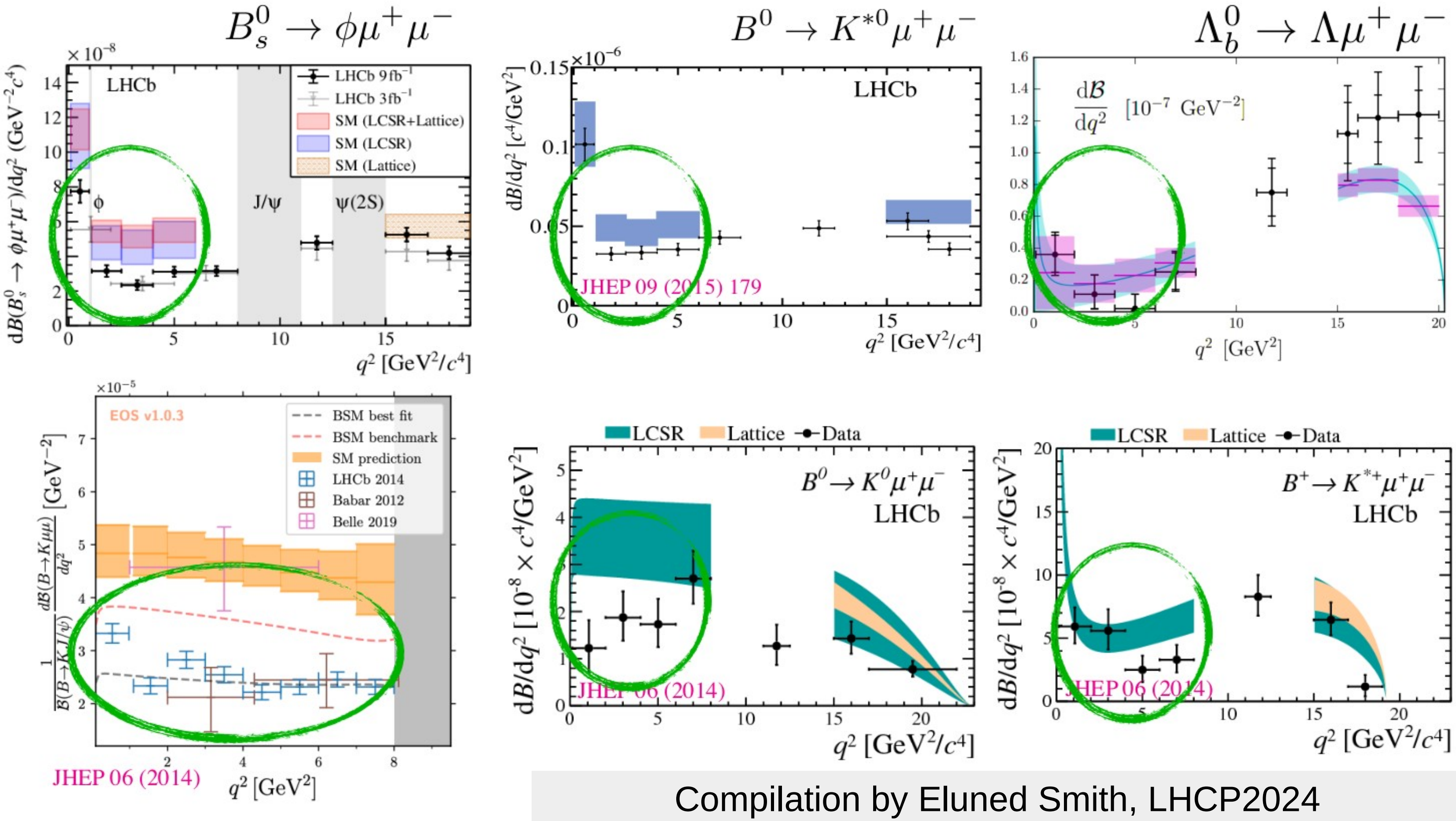
PL B842 (2023) 137955





Final Run 1+2 results, plus new results with Run 3 data, highly anticipated!
Reaching interesting sensitivity for $B^0 \to \mu^+\mu^-$

$b \to s\mu^+\mu^-$ branching fractions

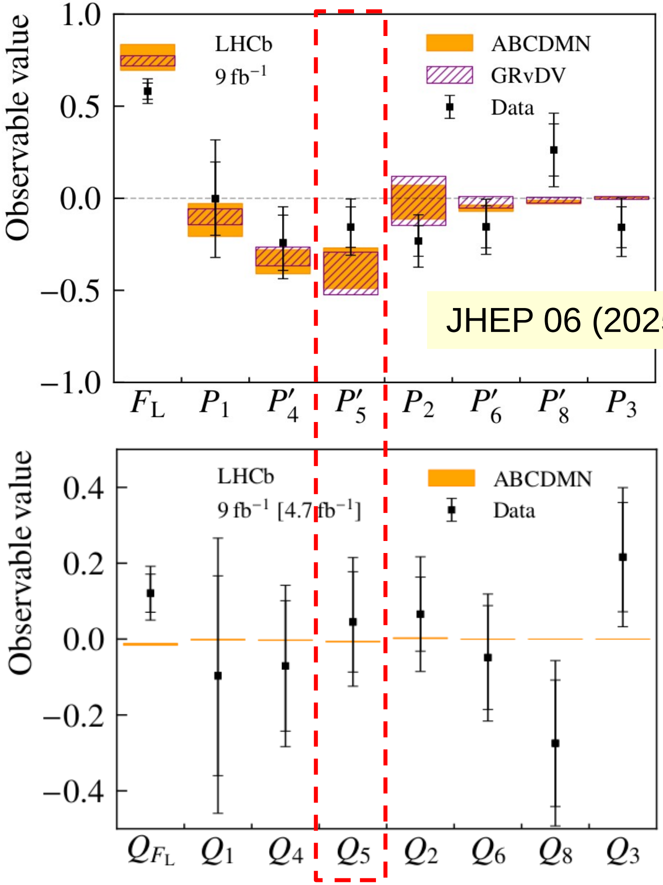


Compilation by Eluned Smith, LHCP2024

Angular analyses of b → se⁺e⁻ decays

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

Single q^2 bin: 1.1-6.0 GeV^2

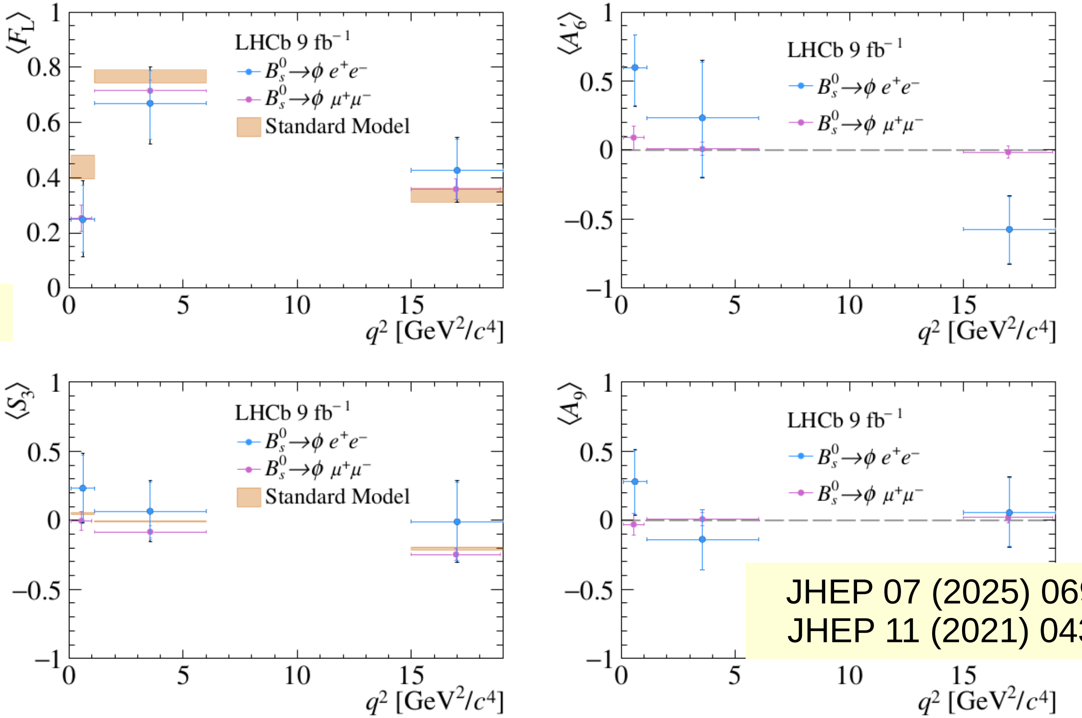


Difference from $B \to K^{*0} \mu^+ \mu^-$

JHEP 06 (2025) 140

$B_s \to \phi e^+ e^-$

P_5' unmeasurable without flavour tagging

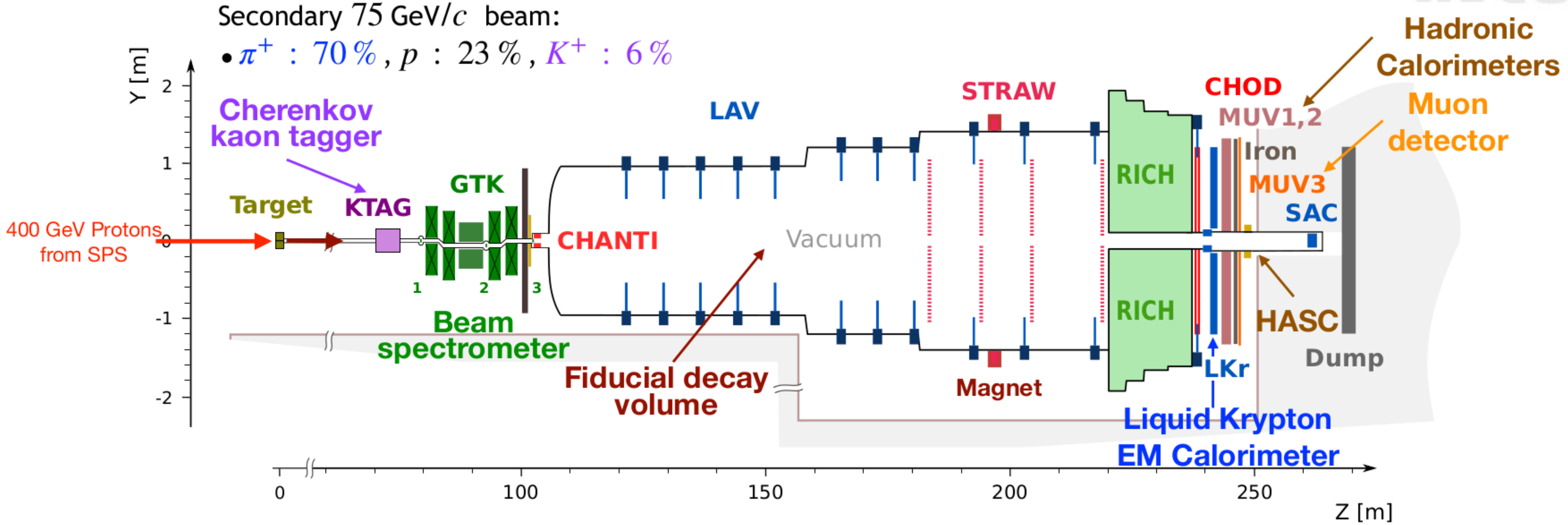


JHEP 07 (2025) 069
JHEP 11 (2021) 043

Also studies at very low q^2 to probe virtual photon polarisation:
JHEP 03 (2025) 047, PR D110 (2024) 072005, JHEP 12 (2020) 081

NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

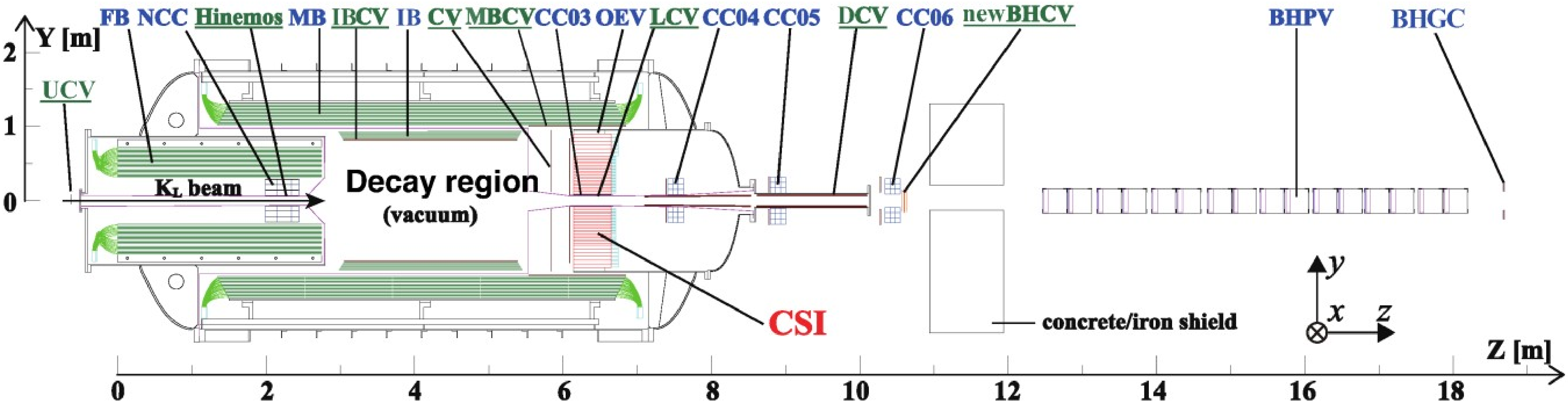


- Designed & optimised for study of $K^+ \to \pi^+ \nu\bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV,LKr,IRC,SAC (γ)

Slide from Joel Swallow, CERN seminar Sept. 24

KOTO detector

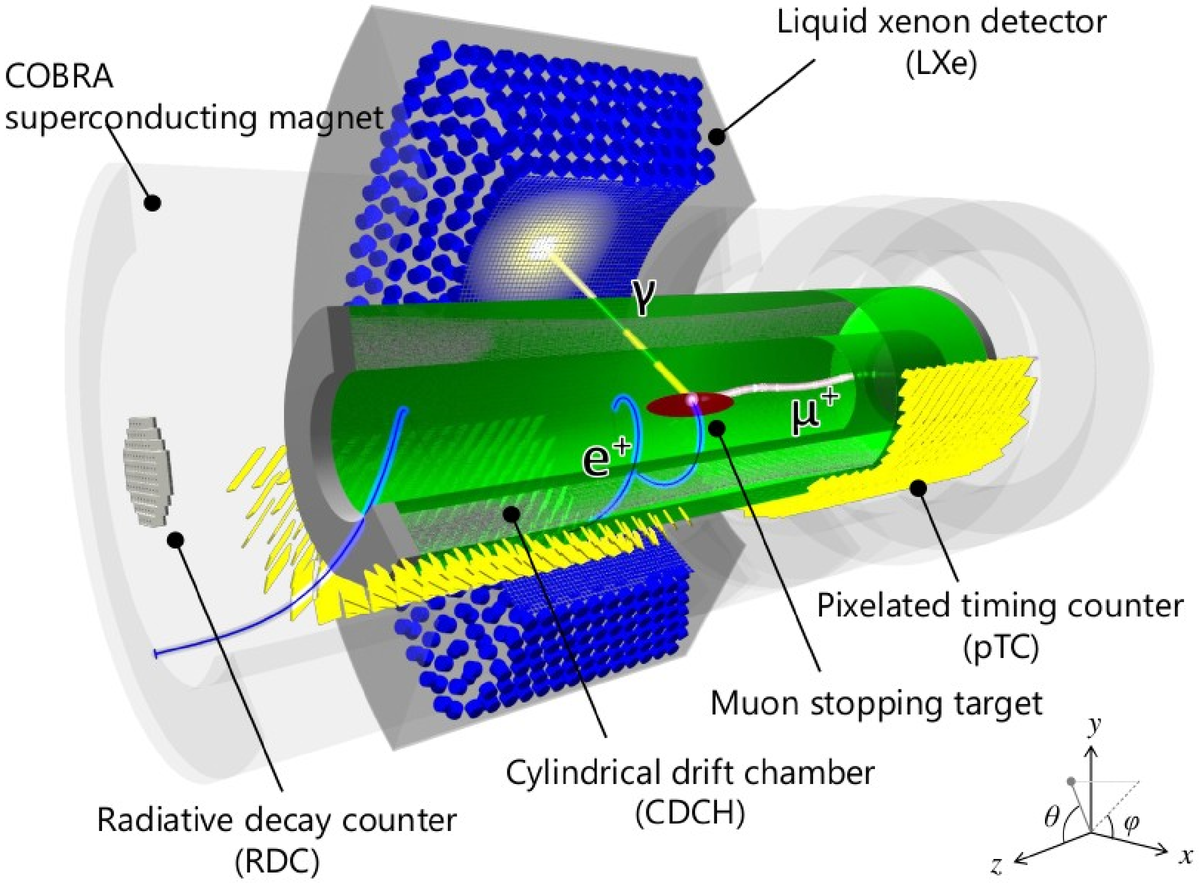
PRL 134 (2025) 081802



Signal signature $\pi^0 \to \gamma\gamma$ reconstructed in CsI calorimeter
All the rest is vetoes and beam monitoring

MEGII detector

EPJ C84 (2024) 190



Significant improvements compared to MEG

- ×3.6 improvement in e momentum resolution
- ×1.5 improvement in e-γ time resolution
- ×4 improvement in rate of data collection