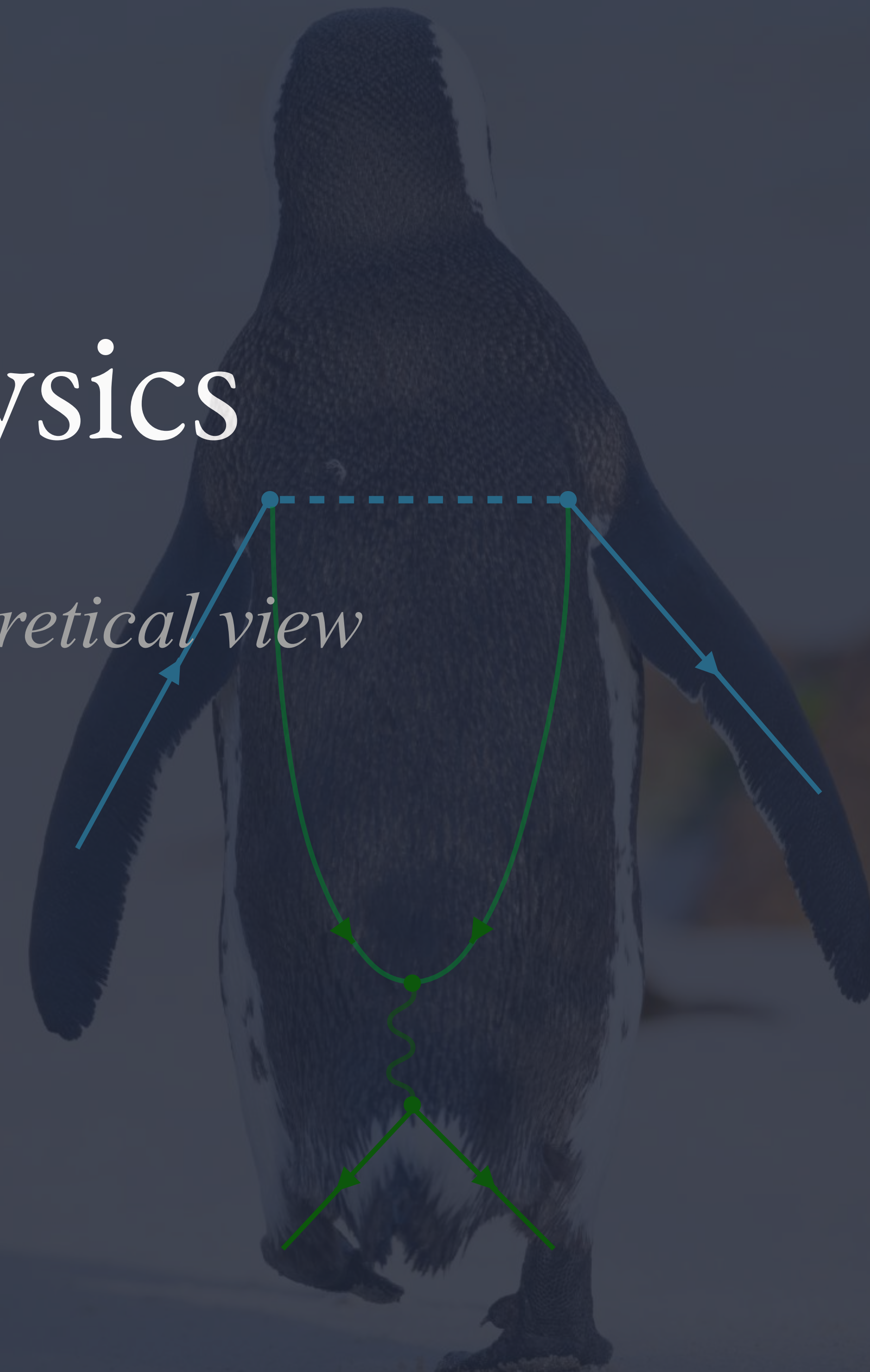
Flavour Physics

An experimental and theoretical view

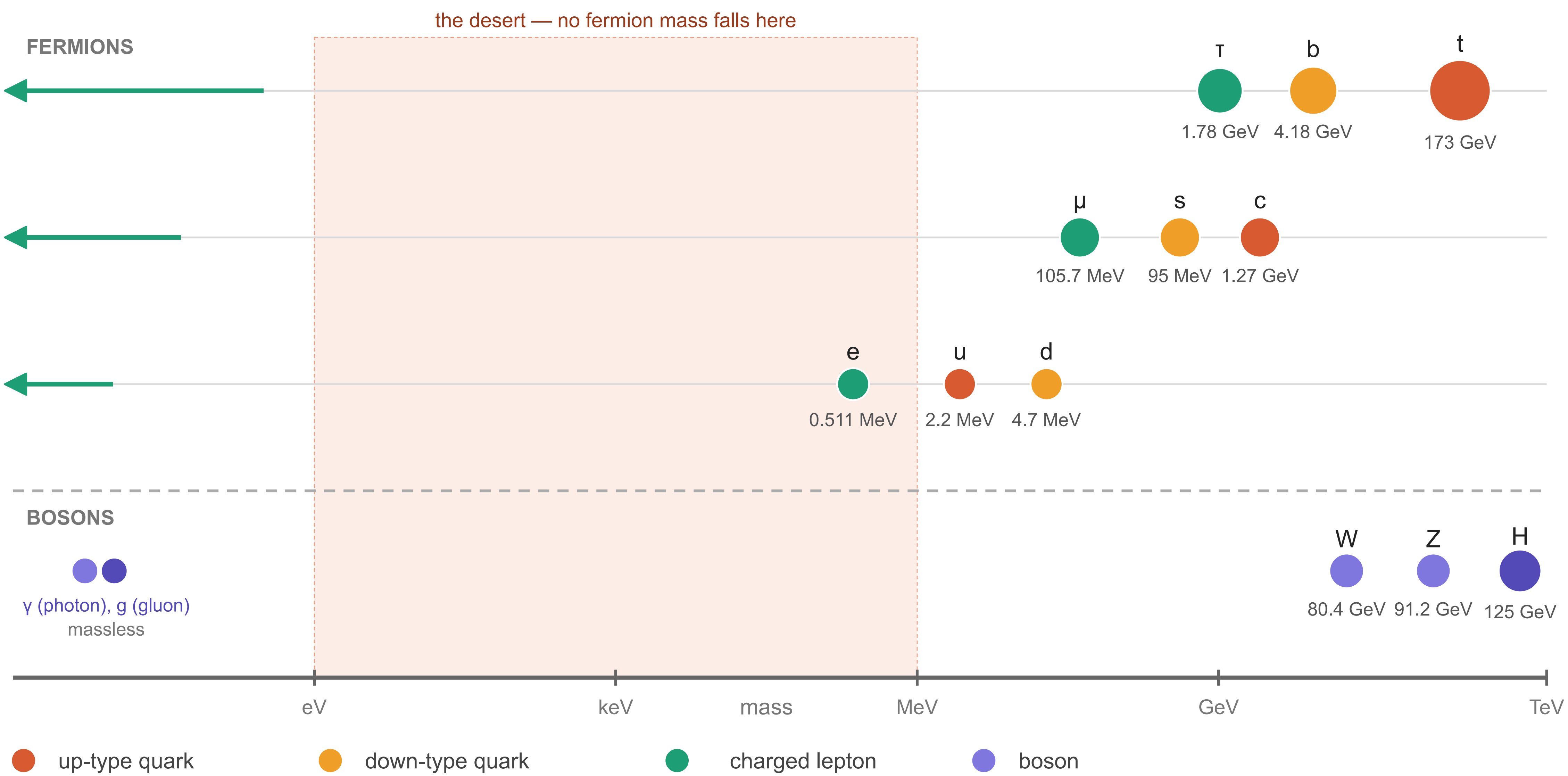


Rafael Silva Coutinho

Centro Brasileiro de Pesquisas Físicas (CBPF)

PHENOEXP Workshop
August 11, 2026

The standard model and its flavour

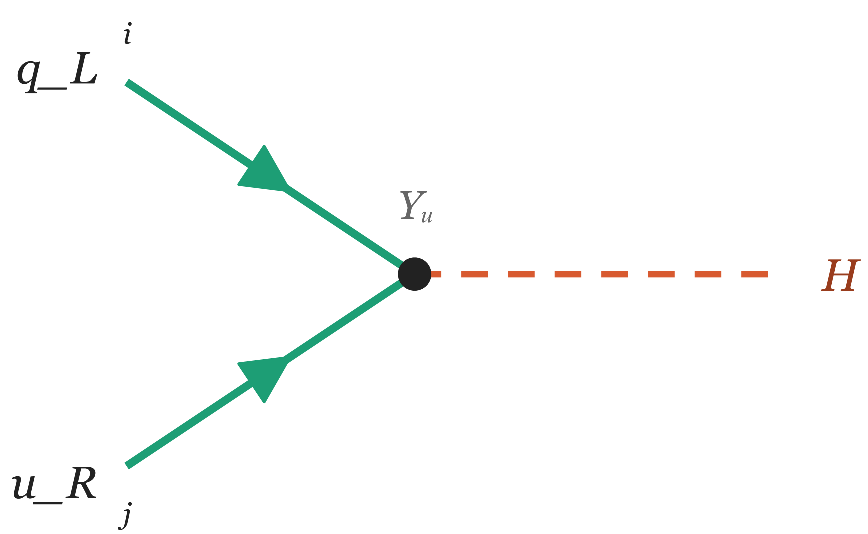


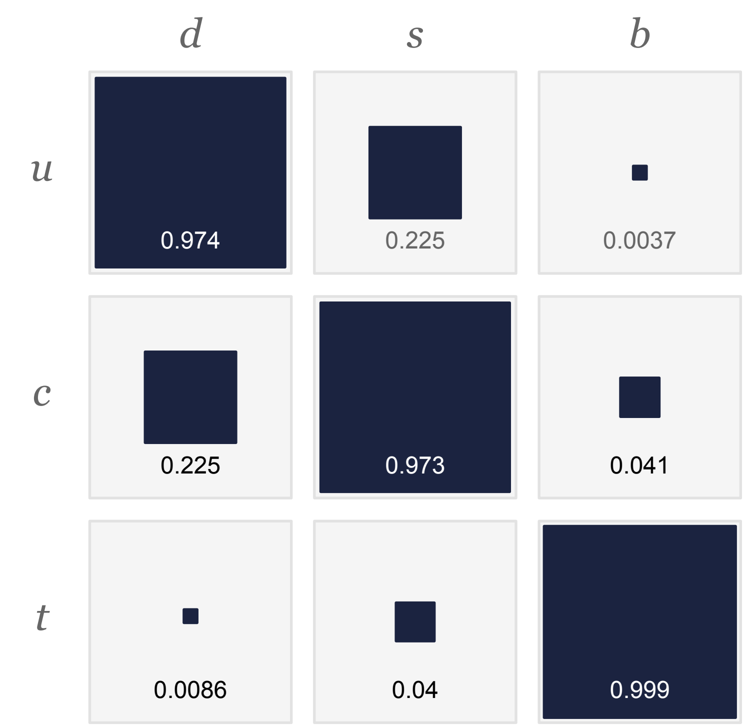
LOTS OF THINGS WE DON'T UNDERSTAND IN THE SM LIVES IN FLAVOUR

THE STANDARD MODEL AND ITS FLAVOUR

IN THE SM, FERMION MASSES ARE THE RESULTS OF THE YUKAWA INTERACTION

$$\mathscr{L}_Y = -\, Y^d_{ij}\overline{Q^I_{Li}}\phi d^I_{Rj} - Y^u_{ij}\overline{Q^I_{Li}}\epsilon\phi^* u^I_{Rj} + h.c.$$





WHILE GAUGE INTERACTION ARE PROTECTED BY SYMMETRY, **YUKAWA COUPLINGS** ARE NOT

$$\frac{-g}{\sqrt{2}}\left(\overline{u_L}, \overline{c_L}, \overline{t_L}\right)\gamma^\mu W^+_\mu V_{\mathrm{CKM}}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \mathrm{h.c.}$$

THE SM HAS NOTHING TO SAY ABOUT WHY

The Standard Model and its Flavour

Flavour physics as a compass to the NP scale ... **strong bounds** from **CP violation** and **flavour-changing** processes:

NP badly violates flavour

generic couplings across generations

NP scale must be very high

~10^3–10^4 TeV

out of reach of any collider

NP mimics SM flavour

couples preferentially to heavier generations

NP scale can be a few TeV

~1–10 TeV

within reach of LHC / HL-LHC

No explanation for hierarchy
Higgs fine-tuning problem

Consistent with the pattern observed
Testable at current colliders

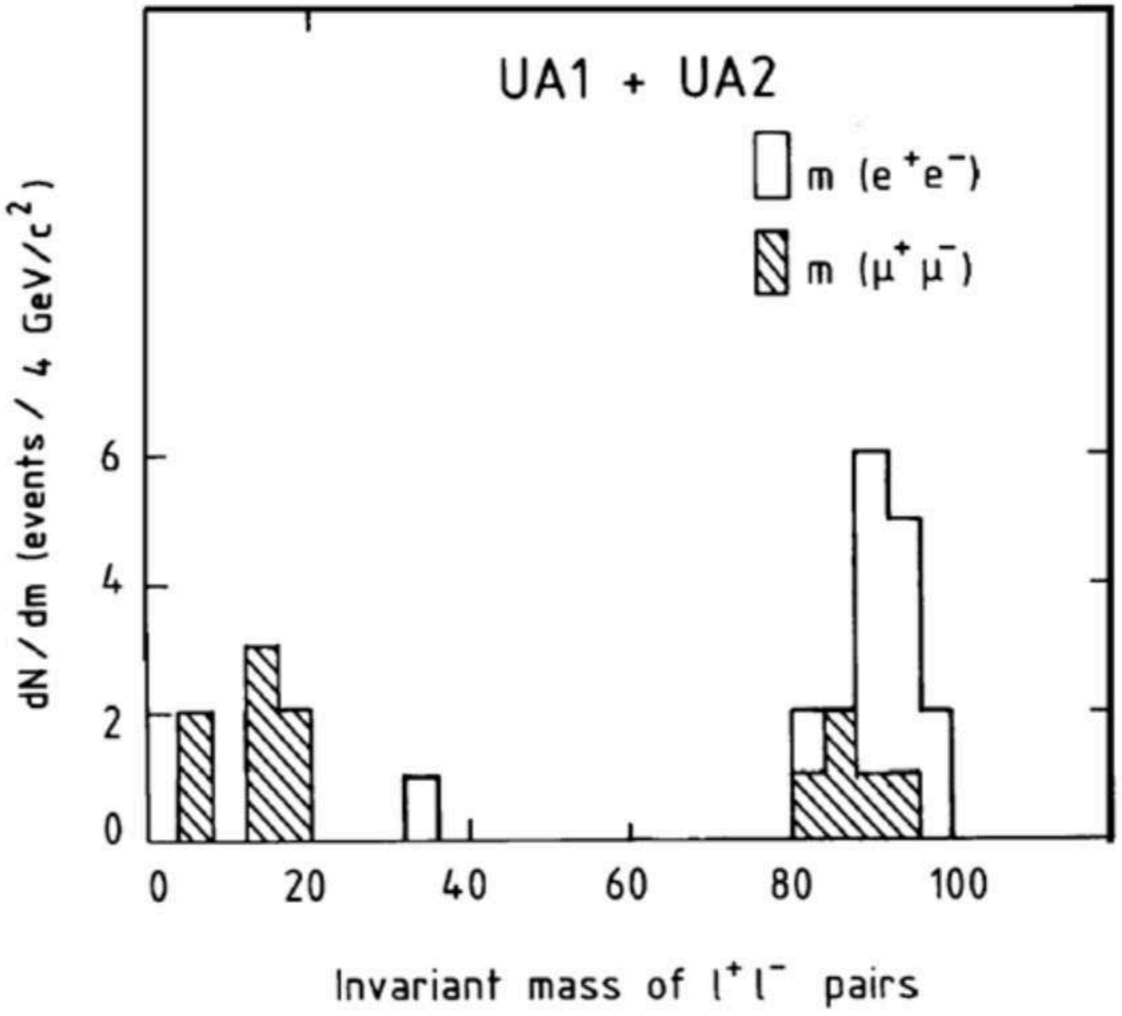
Gino Isidori @ ICHEP 26

THE STANDARD MODEL AND ITS FLAVOUR

DIRECT PRODUCTION OF NEW PARTICLES

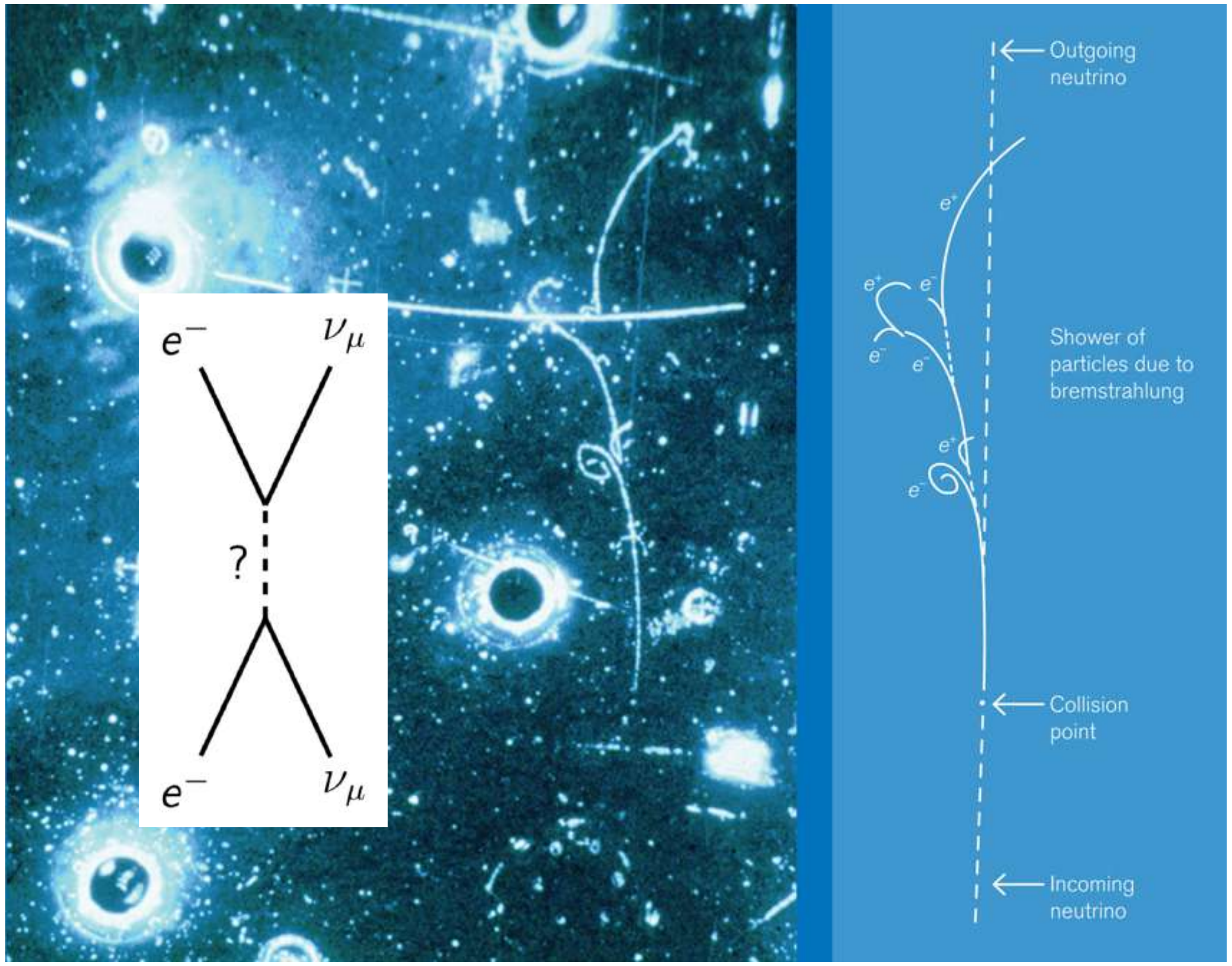
[ENERGY FRONTIER]

[SPS 1983]



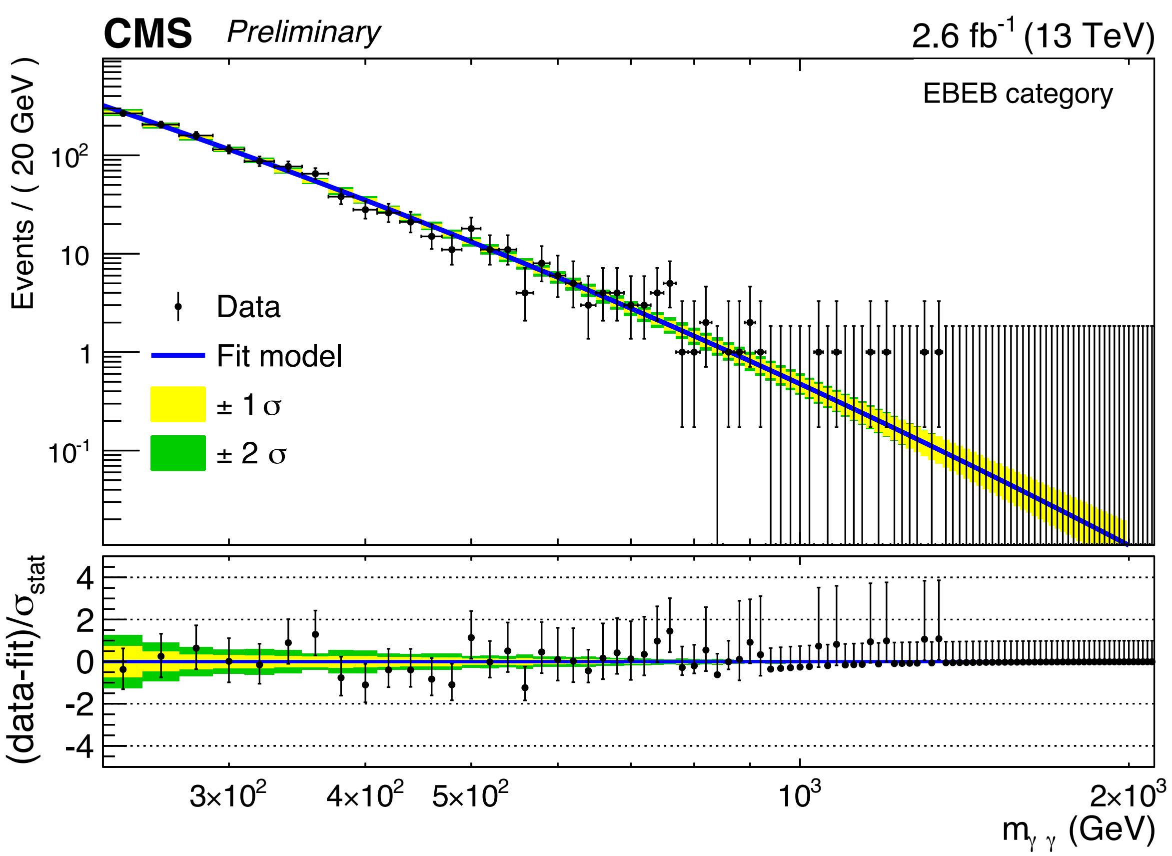
INDIRECT PRODUCTION OF NEW PARTICLES ON WELL-PREDICTED OBSERVABLES

[Gargamelle 1973]



DIRECT PRODUCTION OF NEW PARTICLES [ENERGY FRONTIER]

e.g. initial excess observed at 750 GeV di-photon

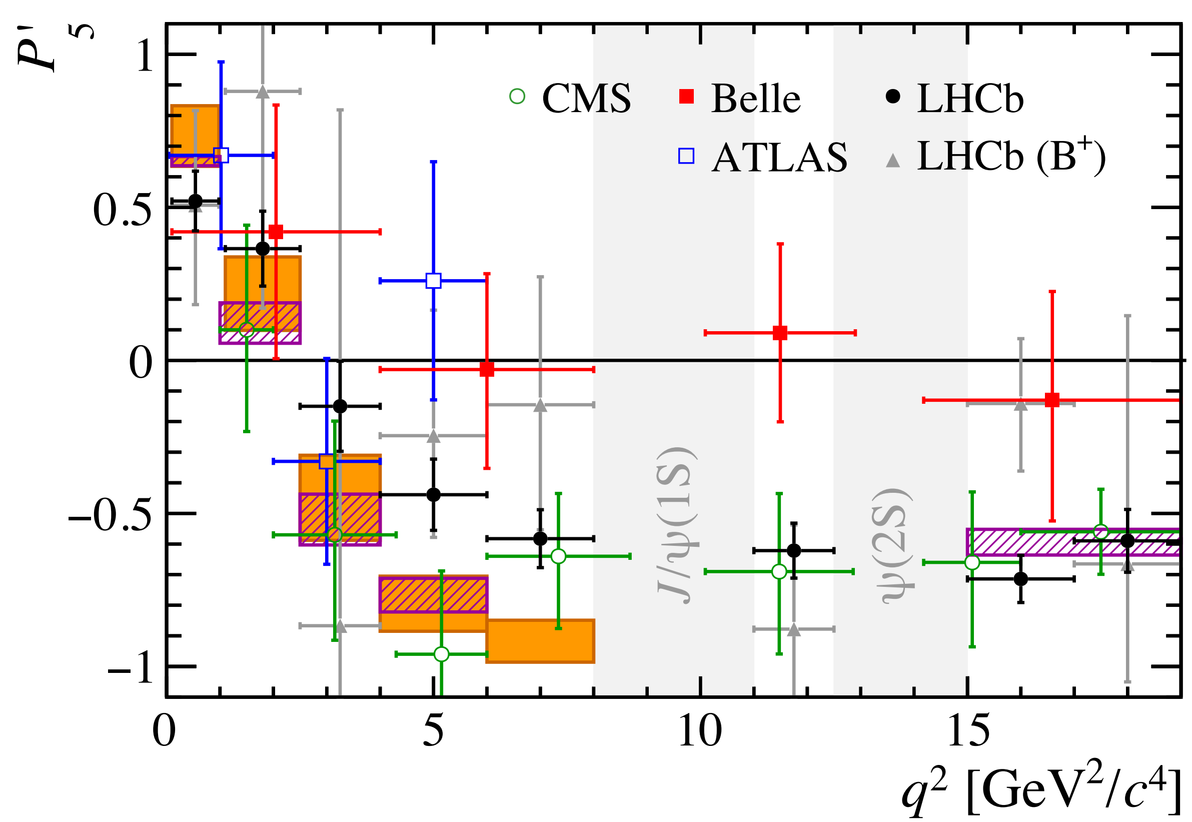


[CMS-PAS-EXO-15-004]

[ATLAS-CONF-2015-081]

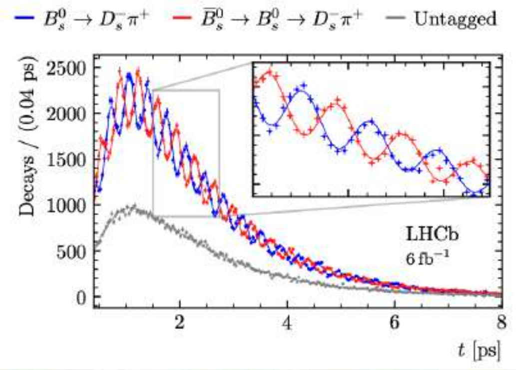
INDIRECT PRODUCTION OF NEW PARTICLES ON WELL-PREDICTED OBSERVABLES

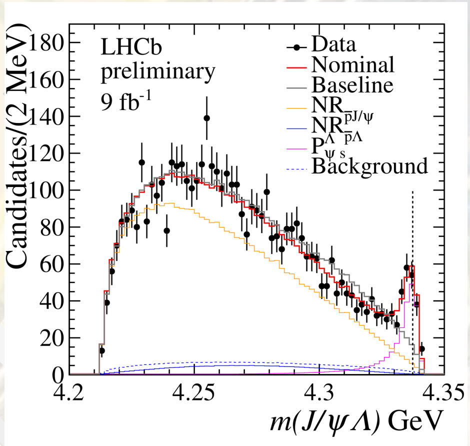
e.g. flavor anomalies!

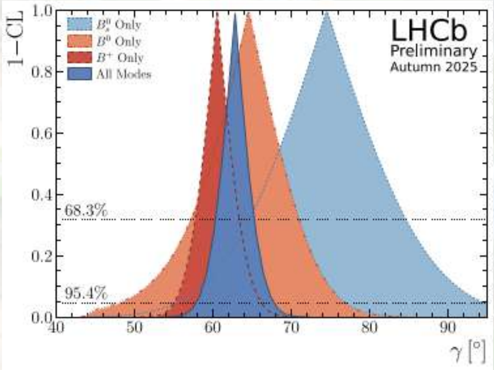


[LHCb, PRL 125 (2020) 011802, PRL 126 (2021) 161802]
[Belle, PRL 118 (2017) 11, 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

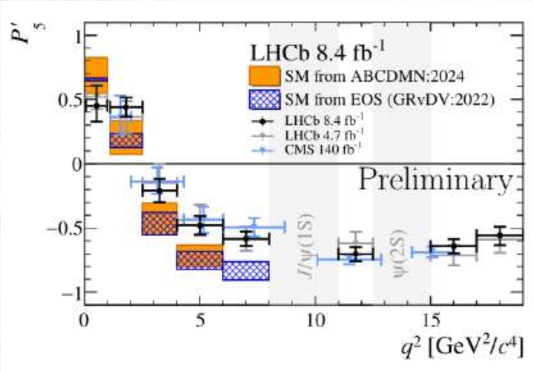
FLAVOUR PHYSICS PROGRAMME

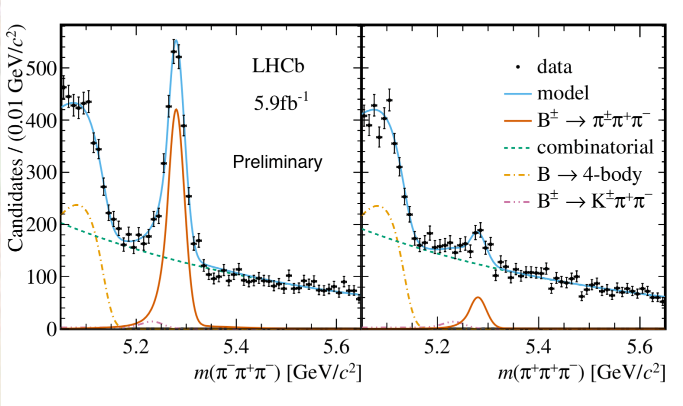


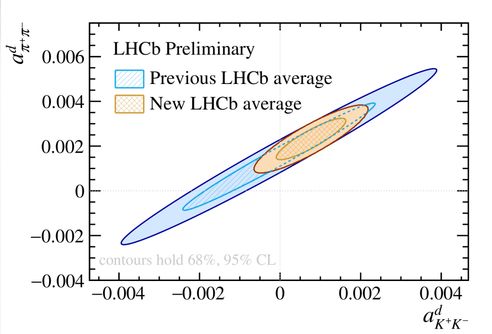


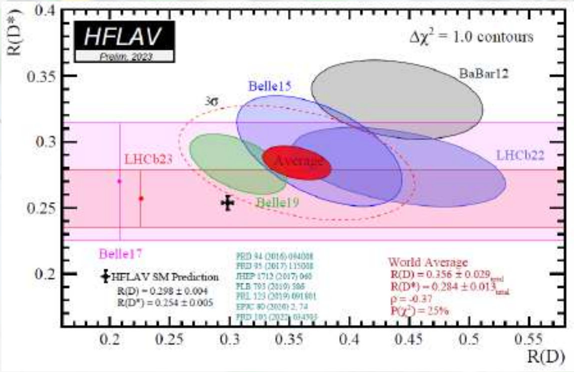


FLAVOUR PHYSICS



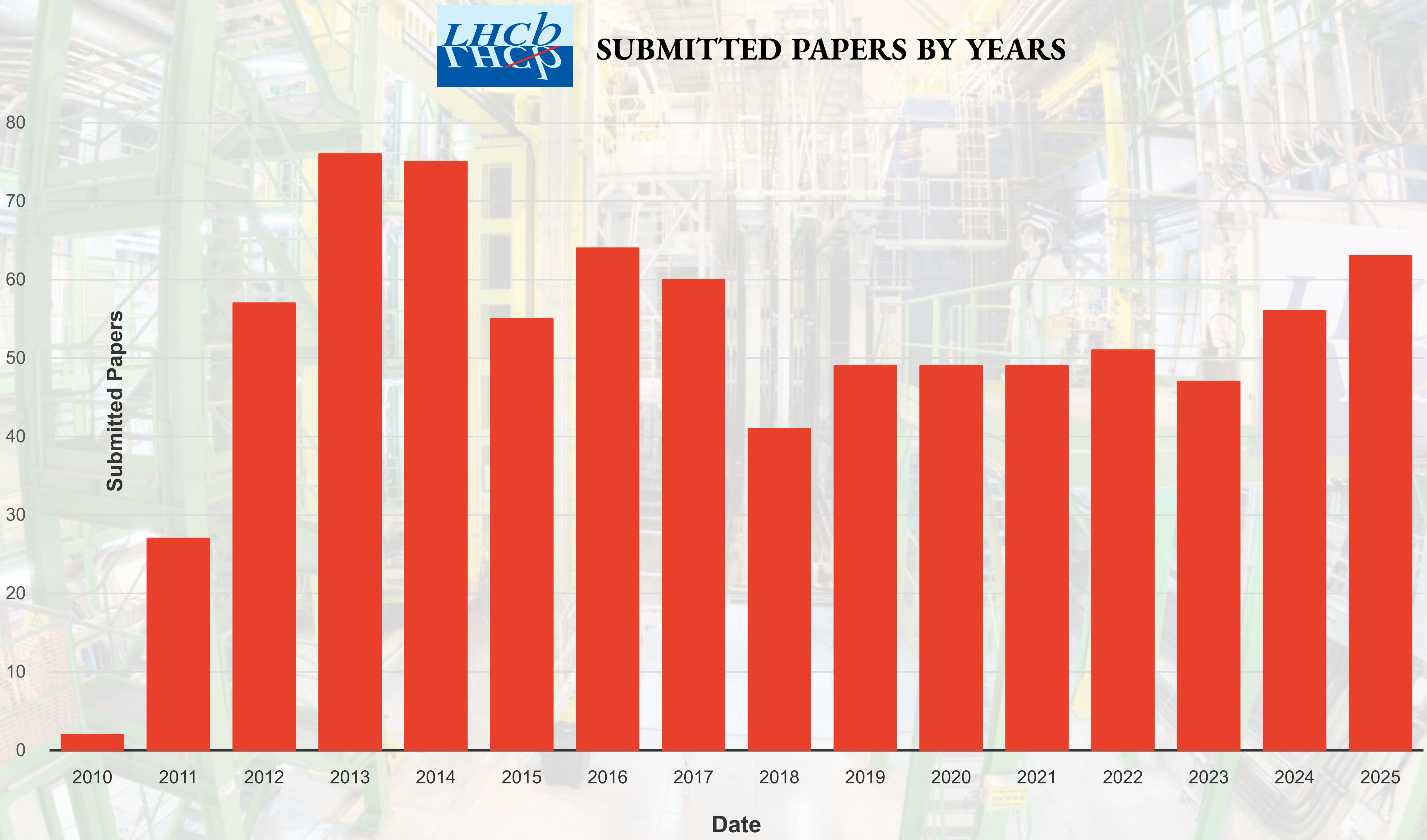






Flavour physics programme

CBPF



FLAVOUR PHYSICS PROGRAMME

CBPF

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]

pdf links DOI cite claim reference search 2,203 citations

Test of lepton universality using $B^+ \to K^+ \ell^+ \ell^-$ decays

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Jun 25, 2014)

Published in: *Phys.Rev.Lett.* 113 (2014) 151601 • e-Print: 1406.6482 [hep-ex]

pdf DOI cite claim reference search 1,431 citations

Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)$

LHCb Collaboration • Roel Aaij (CERN) et al. (Jun 29, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 11, 111803, *Phys.Rev.Lett.* 115 (2015) 15, 159901 (erratum) • e-Print: 1506.08614 [hep-ex]

pdf links DOI cite claim reference search 1,359 citations

Angular analysis of the $B^0 \to K^{*0} \mu^+ \mu^-$ decay using 3 fb^{-1} of integrated luminosity

LHCb Collaboration • Roel Aaij (CERN) et al. (Dec 14, 2015)

Published in: *JHEP* 02 (2016) 104 • e-Print: 1512.04442 [hep-ex]

pdf links DOI cite datasets claim reference search 1,058 citations

Observation of CP Violation in Charm Decays

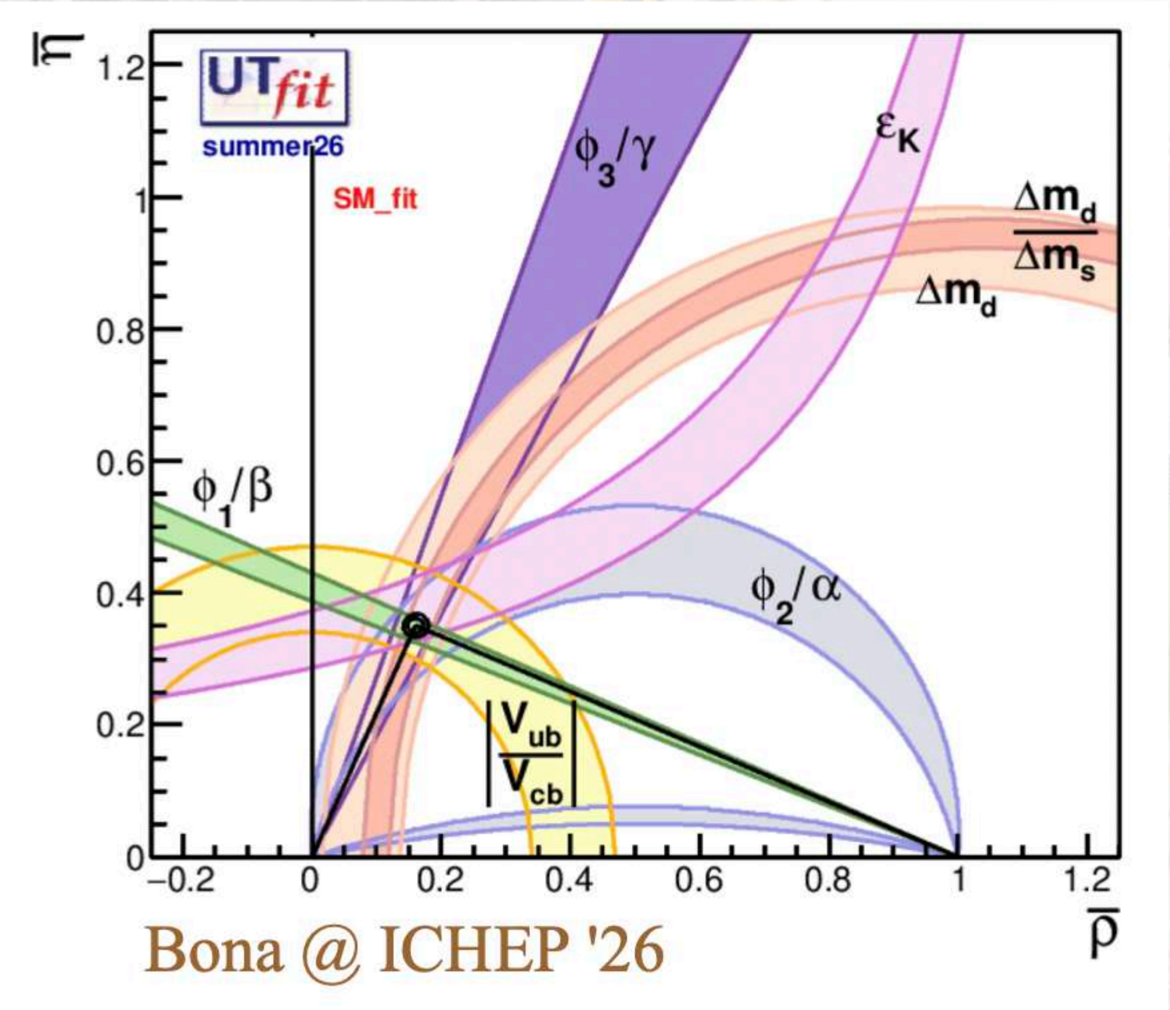
LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Mar 20, 2019)

Published in: *Phys.Rev.Lett.* 122 (2019) 21, 211803 • e-Print: 1903.08726 [hep-ex]

pdf links DOI cite claim reference search 619 citations

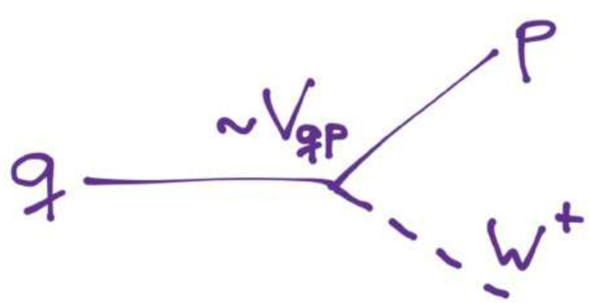
The unitarity triangle

UT angles, phases and complementary measurements

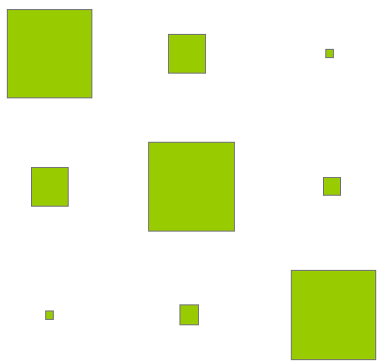


CP VIOLATION IN THE SM

QUARK-MIXING MATRIX [CKM]: $[dsb]_{flavour} = V_{CKM}\,[dsb]_{mass}$



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



DESCRIBED BY 4 INDEPENDENT PARAMETERS, IN PARTICULAR A SINGLE COMPLEX PHASE

$[\gamma]$ $[\beta_c]$

$$V_{\mathrm{CKM}} \cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3\left(\rho-i\eta\right) \\ -\lambda\left[1+A^2\lambda^4\left(\rho+i\eta-\frac{1}{2}\right)\right] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4\left(1+4A^2\right) & A\lambda^2 \\ A\lambda^3\left[1-\left(\rho+i\eta\right)\left(1-\frac{1}{2}\lambda^2\right)\right] & -A\lambda^2\left[1+\lambda^2\left(\rho+i\eta-\frac{1}{2}\right)\right] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$[\beta]$ $[\beta_s]$

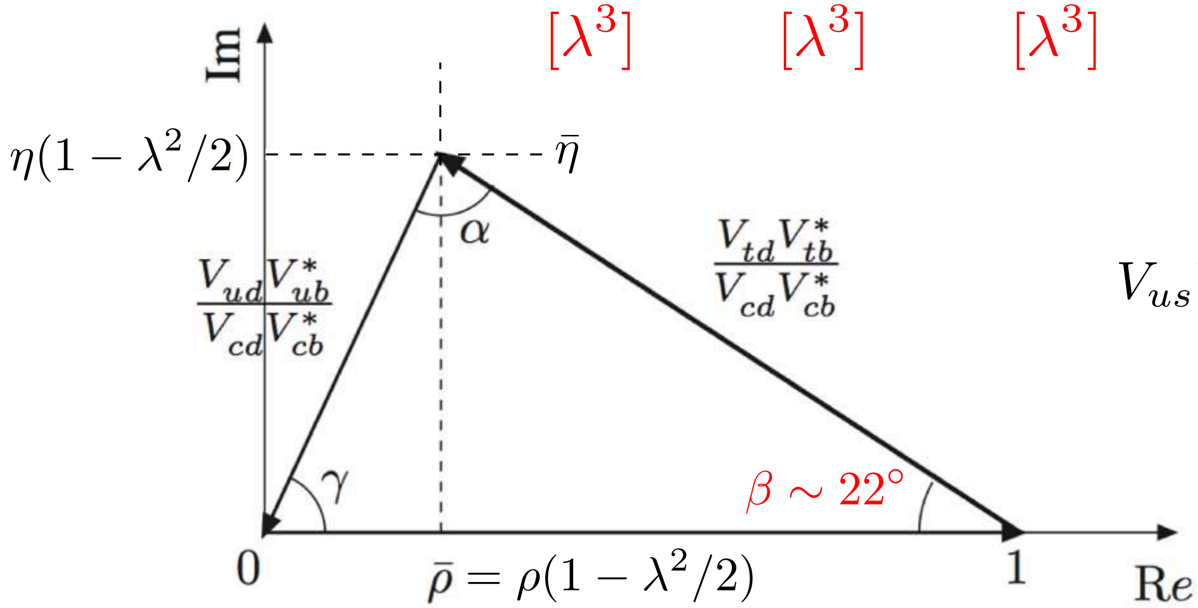
Unitarity triangles

Unitarity of CKM matrix, i.e. $V^{+}_{CKM} V_{CKM} = V_{CKM} V^{+}_{CKM} = 1$

Triangle openness indicates how large $\cancel{CP}$ is expected

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

$[\lambda^3] \quad [\lambda^3] \quad [\lambda^3]$



$V_{us}V_{ub}^* \sim [\lambda^4]$ $\quad$ $V_{ts}V_{tb}^* \sim [\lambda^2]$

$V_{cs}V_{cb}^* \sim [\lambda^2]$ $\quad$ $\beta_s \sim 1^\circ$

$V_{ub}^*V_{cd} \sim [\lambda]$

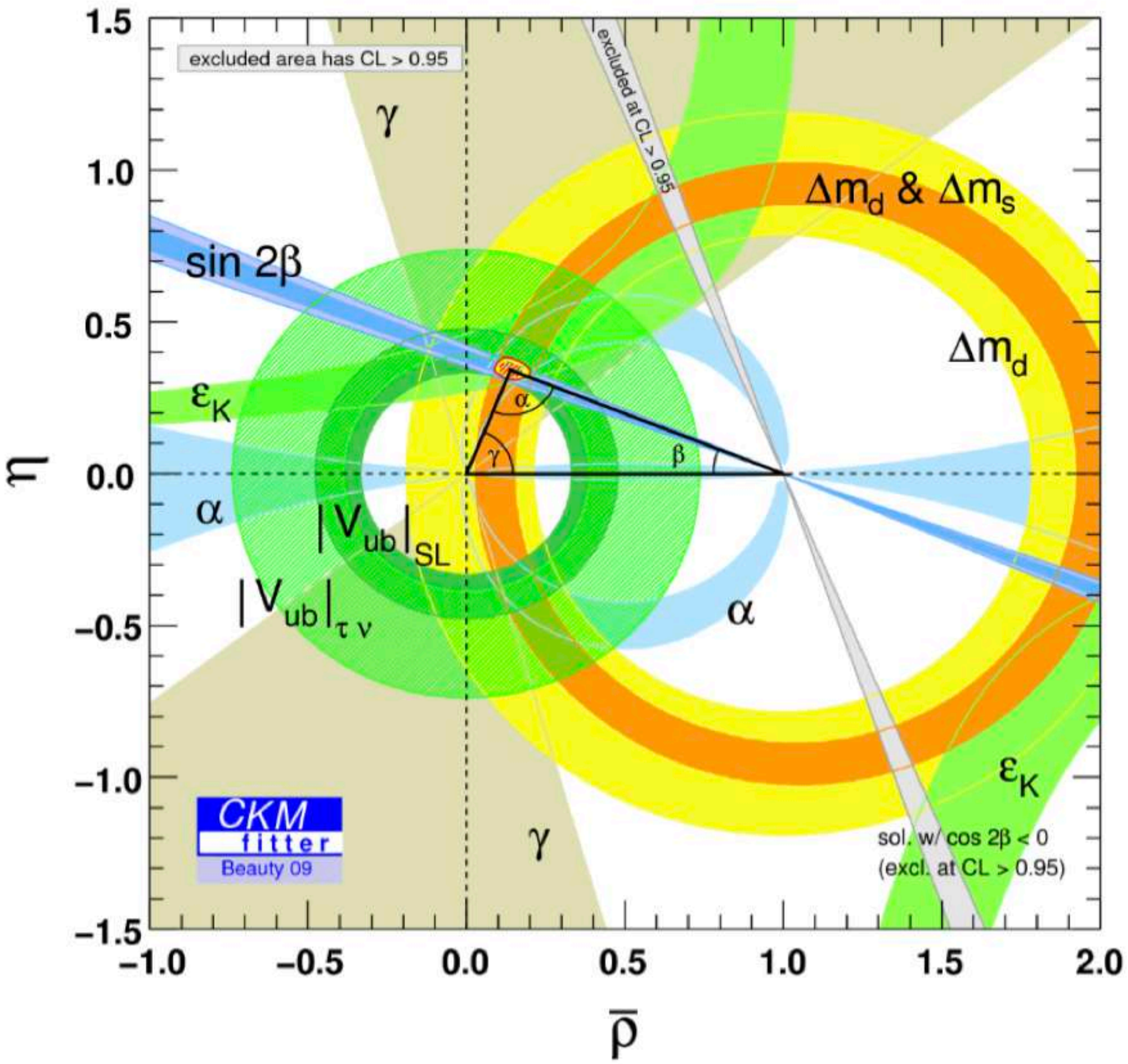
$\beta_c \sim 0.03^\circ$

$V_{us}^*V_{cs} \sim [\lambda]$ $\quad$ $V_{ub}^*V_{cb} \sim [\lambda^5]$

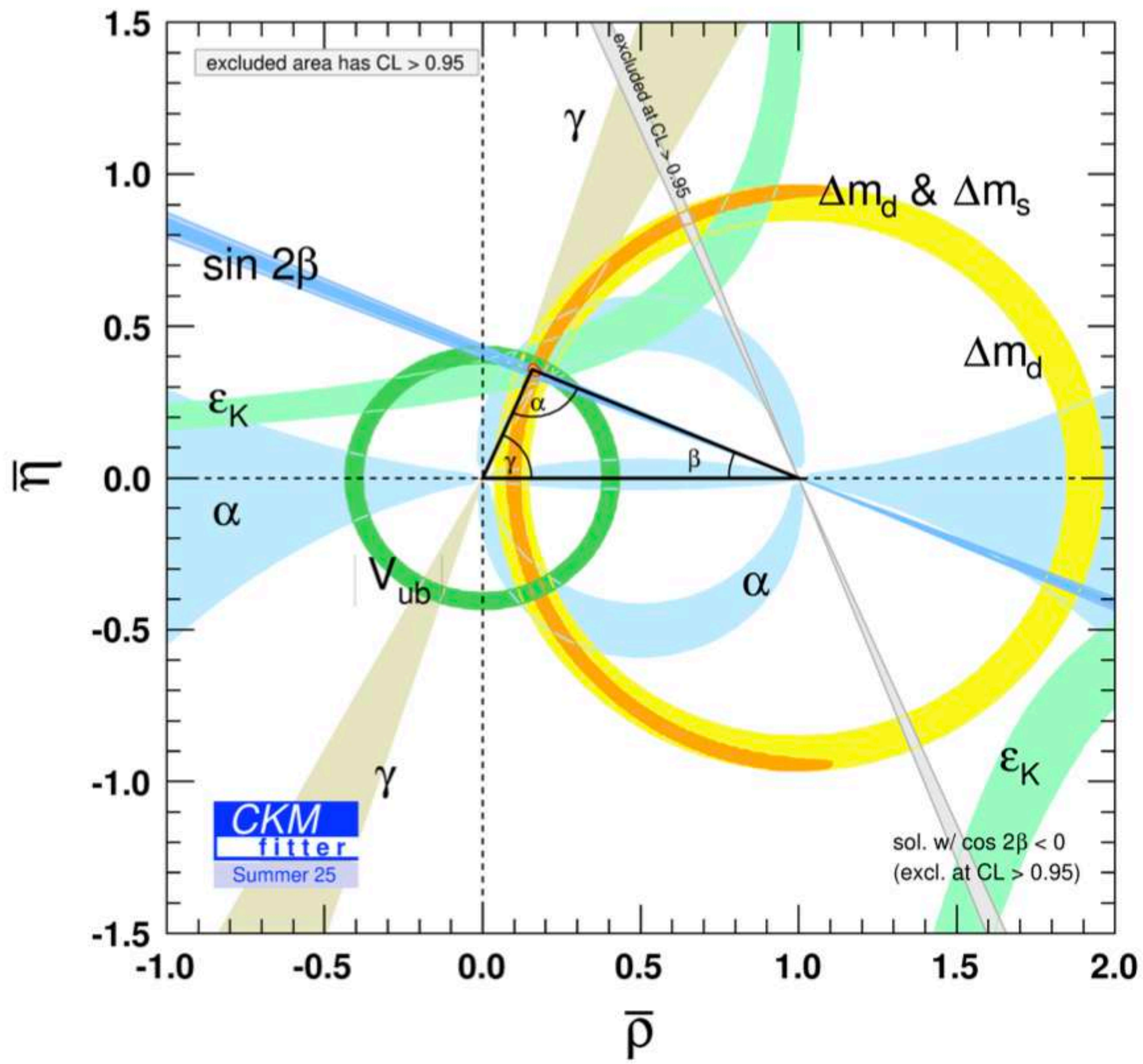
All triangles have same surface area [representative plots only]

THE CKM PICTURE

$\sigma(\gamma) \sim 22^o$



$\sigma(\gamma) \approx 2.6^o$

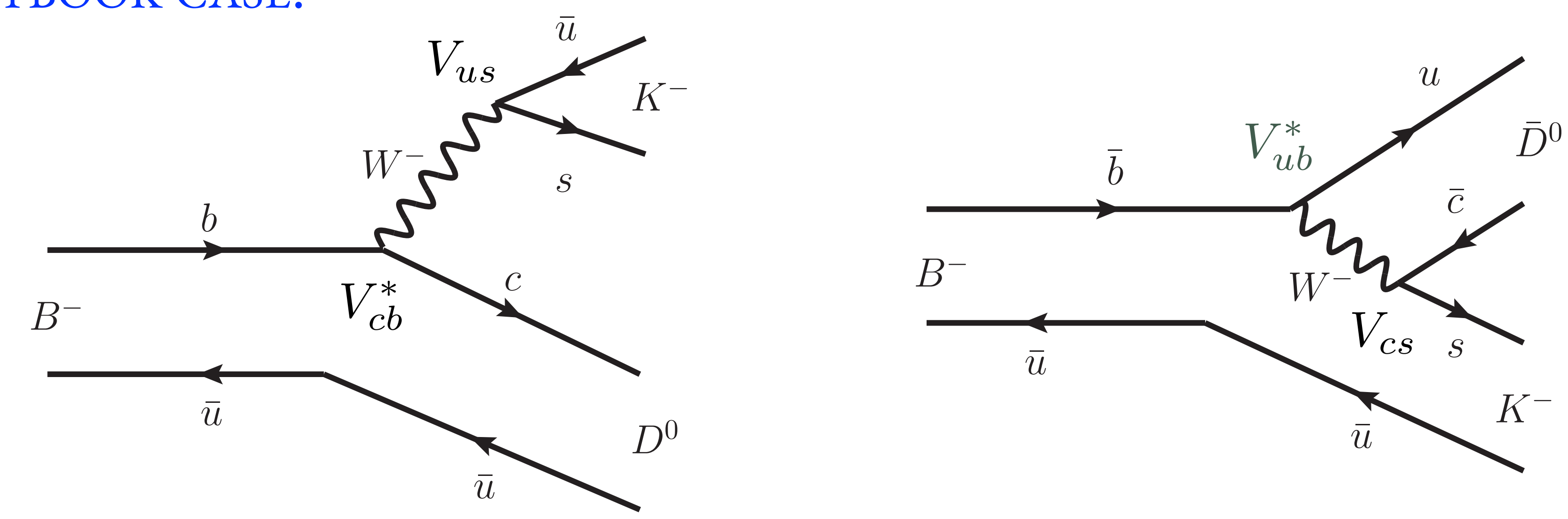


SIGNIFICANT IMPROVEMENT ON THE DETERMINATION OF THE CKM PARAMETERS

CKM PHASE γ

γ IS THE PHASE BETWEEN $V_{ub}^* V_{ud}$ AND $V_{cb}^* V_{cd}$, I.E. REQUIRE INTERFERENCE:

TEXTBOOK CASE:

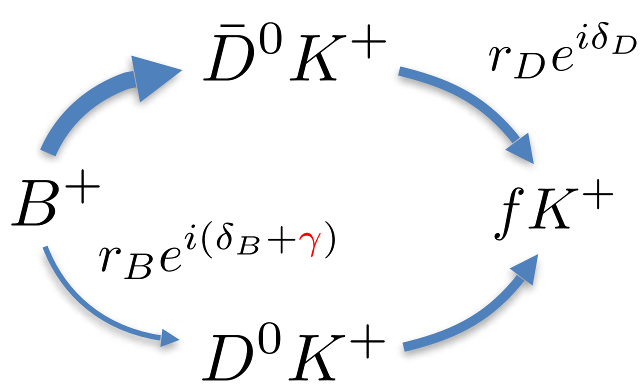


INTERFERENCE OCCURS WHEN D^0 AND $\bar{D}^0$ DECAY TO SAME FINAL STATE

NEGLIGIBLE THEORETICAL UNCERTAINTY, I.E. $\delta\gamma/\gamma \approx \mathcal{O}(10^{-7})$, AND CAN PROBE EXTREMELY HIGH ENERGY SCALES $\sim \mathcal{O}(10^2 - 10^3)$ TEV

JHEP 1401 (2014) 051

DETERMINATION OF γ FROM $B \to DK$ DECAYS:



CP-eigenstates (f = $\pi\pi$, KK):

GLW - **G**ronau, **L**ondon and **W**yler

PLB 253 (1991) 483; PLB 265 (1991) 172

Quasi-flavour-specific states (f = e.g Kπ): (ADS)

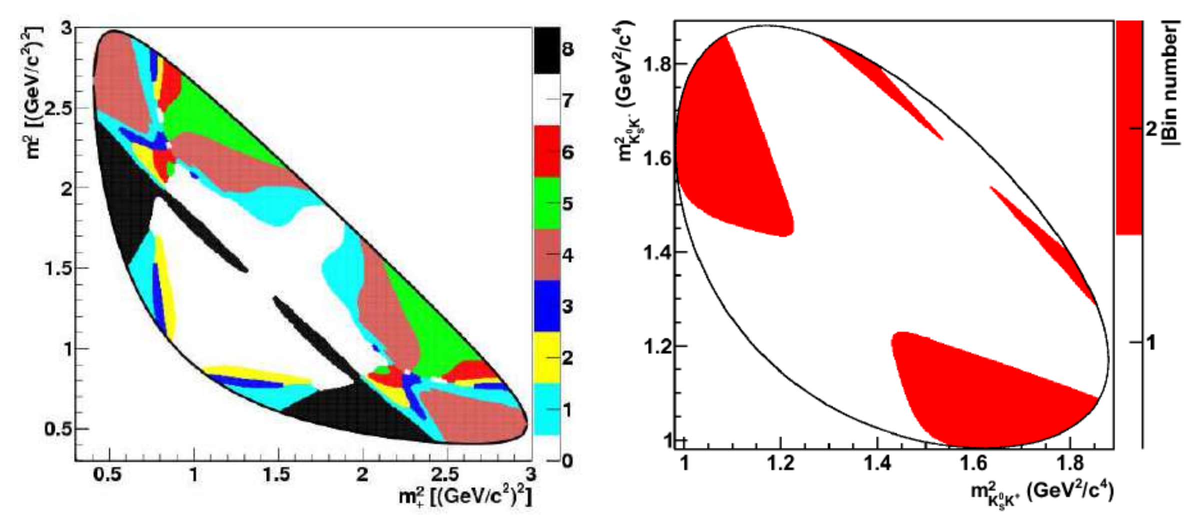
Atwood, **D**unietz and **S**oni

PRL 78 (1997) 3257; PRD 63 (2001) 036005

Giri, Grossman, Soffer and Zupan (GGSZ) deals with self conjugate 3-body final states: f = D $\to K_S\pi\pi$ and K_SKK

PRD 68 (2003) 054018

STRONG PHASE VARIES OVER THE 3-BODY PHASE SPACE



γ determination: yields observed in regions of DP

CKM PHASE γ

LHCb-CONF-2025-003

COMBINATION OF γ, CHARM MIXING AND CP-VIOLATION PARAMETERS

B decay	D decay
$B^{\pm} \to Dh^{\pm}$	$D \to h^{\pm}h'^{\mp}$
$B^{\pm} \to Dh^{\pm}$	$D \to h^{+}h^{-}\pi^{+}\pi^{-}$
$B^{\pm} \to Dh^{\pm}$	$D \to h^{+}h^{-}\pi^{+}\pi^{-}$
$B^{\pm} \to Dh^{\pm}$	$D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$
$B^{\pm} \to Dh^{\pm}$	$D \to h^{\pm}h'^{\mp}\pi^{0}$
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^{+}h^{-}$
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$
$B^{\pm} \to D^{*}h^{\pm}$	$D \to h^{\pm}h'^{\mp}$ (PR)
$B^{\pm} \to D^{*}h^{\pm}$	$D \to K^0_S h^{+}h^{-}$ (PR)
$B^{\pm} \to D^{*}h^{\pm}$	$D \to K^0_S h^{+}h^{-}$ (FR)
$B^{\pm} \to DK^{*\pm}$	$D \to h^{\pm}h'^{\mp}$
$B^{\pm} \to DK^{*\pm}$	$D \to h^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$
$B^{\pm} \to DK^{*\pm}$	$D \to K^0_S h^{+}h^{-}$
$B^{\pm} \to Dh^{\pm}\pi^{+}\pi^{-}$	$D \to h^{\pm}h'^{\mp}$
$B^{0} \to DK^{*0}$	$D \to h^{\pm}h'^{\mp}$
$B^{0} \to DK^{*0}$	$D \to h^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$
$B^{0} \to DK^{*0}$	$D \to K^0_S h^{+}h^{-}$
$B^{0} \to D^{\mp}\pi^{\pm}$	$D^{+} \to K^{-}\pi^{+}\pi^{+}$
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^{+} \to h^{+}h^{-}\pi^{+}$
$B^0_s \to D_s^{\mp}K^{\pm}\pi^{+}\pi^{-}$	$D_s^{+} \to h^{+}h^{-}\pi^{+}$

D decay	Observable(s)
$D^0 \to h^{+}h^{-}$	ΔA_{CP}
$D^0 \to K^{+}K^{-}$	$A_{CP}(K^{+}K^{-})$
$D^0 \to h^{+}h^{-}$	$y_{CP} - y_{CP}^{K^{-}\pi^{+}}$
$D^0 \to h^{+}h^{-}$	ΔY
$D^0 \to K^{\pm}\pi^{\mp}$ (double tag)	$R^{\pm}$, $(x'^{\pm})^2$, $y'^{\pm}$
$D^0 \to K^{\pm}\pi^{\mp}$ (single tag)	$R_{K\pi}$, $\overset{(\sim)}{A}_{K\pi}$, $c_{K\pi}^{(\prime)}$, $\Delta \overset{(\sim)}{c}{}_{K\pi}^{(\prime)}$
$D^0 \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	r, $\kappa y'$, $(x^2+y^2)/4$
$D^0 \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	$r_i^{\pm}$, $(\kappa y'^{\pm})_i$, $x^{2\pm}+y^{2\pm}$
$D^0 \to K^0_S\pi^{+}\pi^{-}$	x, y
$D^0 \to K^0_S\pi^{+}\pi^{-}$	x_{CP}, y_{CP}, Δx, Δy
$D^0 \to K^0_S\pi^{+}\pi^{-}$	x_{CP}, y_{CP}, Δx, Δy
$D^0 \to \pi^{+}\pi^{-}\pi^{0}$	ΔY^{eff}

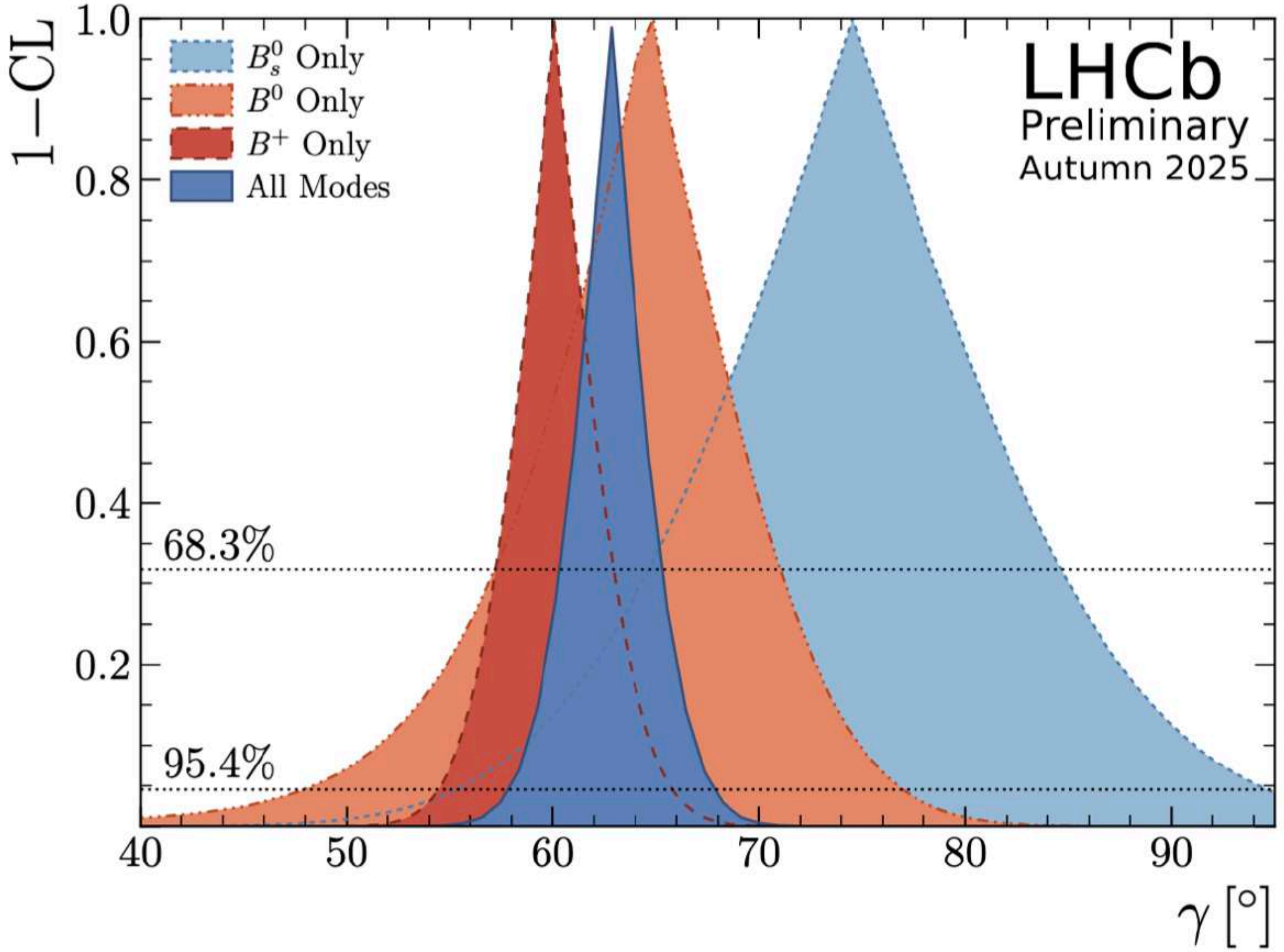
Decay	Parameters	Source
$B^{\pm} \to DK^{*\pm}$	$\kappa_{B^{\pm}}^{DK^{*\pm}}$	LHCb
$B^{0} \to DK^{*0}$	$\kappa_{B^{0}}^{DK^{*0}}$	LHCb
$B^{0} \to D^{\mp}\pi^{\pm}$	β	HFLAV
$B^0_s \to D_s^{\mp}K^{\pm}(\pi\pi)$	ϕ_s	LHCb
$D \to K^{+}\pi^{-}$	$\cos\delta_D^{K\pi}$, $\sin\delta_D^{K\pi}$, $(r_D^{K\pi})^2$, x^2, y	CLEO-c
$D \to K^{+}\pi^{-}$	$A_{K\pi}$, $A_{K\pi}^{\pi\pi\pi^0}$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	BESIII
$D \to h^{+}h^{-}\pi^{0}$	$F^{+}_{\pi\pi\pi^0}$, $F^{+}_{KK\pi^0}$	CLEO-c
$D \to h^{+}h^{-}\pi^{0}$	$F^{+}_{\pi\pi\pi^0}$, $F^{+}_{KK\pi^0}$	BESIII
$D \to \pi^{+}\pi^{-}\pi^{+}\pi^{-}$	$F^{+}_{4\pi}$	CLEO-c+BESIII
$D \to K^{+}K^{-}\pi^{+}\pi^{-}$	$F^{+}_{KK\pi\pi}$	BESIII
$D \to K^{+}\pi^{-}\pi^{0}$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII
$D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII
$D \to K^0_S K^{\pm}\pi^{\mp}$	$r_D^{K^0_S K\pi}$, $\delta_D^{K^0_S K\pi}$, $\kappa_D^{K^0_S K\pi}$	CLEO-c
$D \to K^0_S K^{\pm}\pi^{\mp}$	$r_D^{K^0_S K\pi}$	LHCb

235 OBSERVABLES TO DETERMINE 64 PARAMETERS

CKM PHASE γ

LHCb-CONF-2025-003

MOST PRECISE DETERMINATION OF $\gamma = (62 \pm 2.6)^{\circ}$



LIKELY WILL ACHIEVED $\sigma(\gamma) < 1^{\circ}$ WITH DATA ALREADY COLLECTED AT LHCB

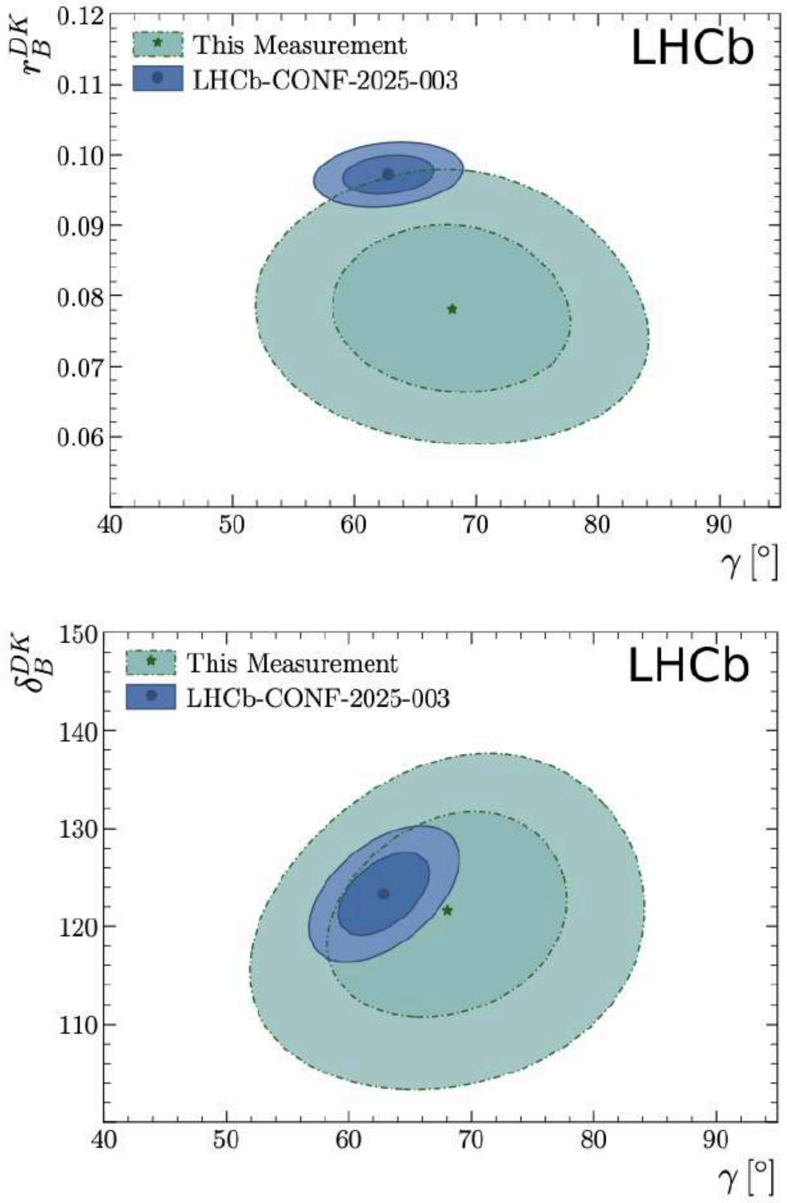
SUB-LEVEL PRECISION ACHIEVABLE IN THE NEAR FUTURE

COMPATIBLE WITH CKM FITTER $\gamma = (66.3^{+0.7}_{-1.9})^{\circ}$ AND UTFIT $\gamma = (64.9 \pm 1.40)^{\circ}$

CKM PHASE γ

LHCb, arXiv:2605.03501
[arXiv:2604.05701, arXiv:2604.05712]

LHCb Run 3 data! 1st measurement using the upgraded detector



New unbinned Fourier weight methodology

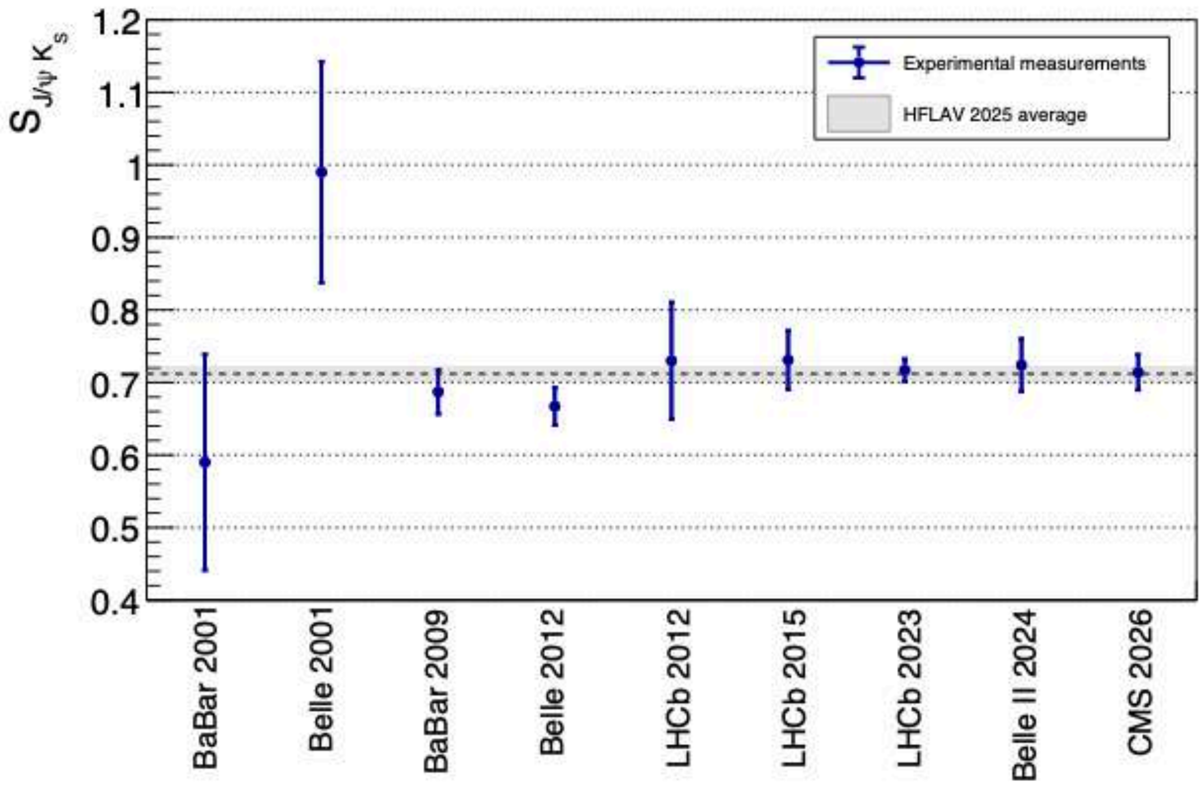
Simultaneous analysis of both LHCb BESIII

$$
\begin{aligned}
\gamma &= (71.3 \pm 5.0)^\circ, \\
r_B^{DK} &= 0.0949^{+0.0086}_{-0.0085}, \\
\delta_B^{DK} &= (121.6^{+5.6}_{-5.9})^\circ, \\
r_B^{D\pi} &= 0.0064^{+0.0021}_{-0.0019}, \\
\delta_B^{D\pi} &= (311^{+17}_{-20})^\circ.
\end{aligned}
$$

Best single measurement of γ

THE OTHER PHASES

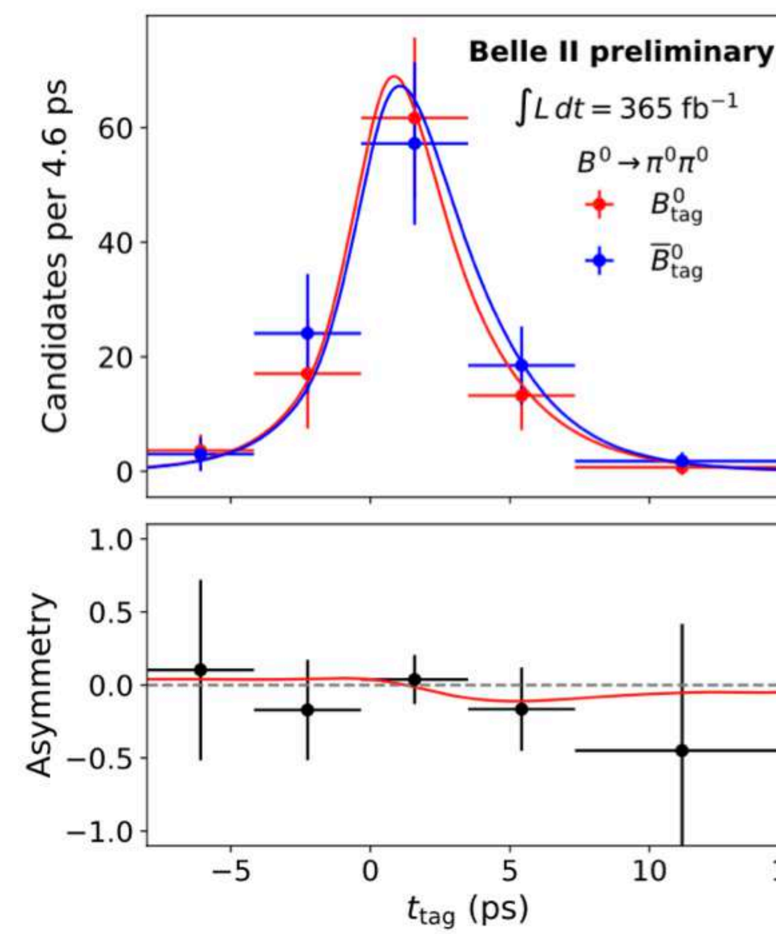
CKM-β PHASE: PRIME EXAMPLE OF CP VIOLATION IN INTERFERENCE BETWEEN MIXING AND DECAY



CMS ALSO ENTERS THE GAME!

CKM-α PHASE: DETERMINATION REQUIRES DISENTANGLING PENGUIN POLLUTION

FIRST MEASUREMENT OF MIXING-INDUCED CP ASYMMETRY IN $B^0 \to \pi^0\pi^0$



arXiv:2606.20797

Multi-body hadronic decays

From (exotic) spectroscopy to CP violation

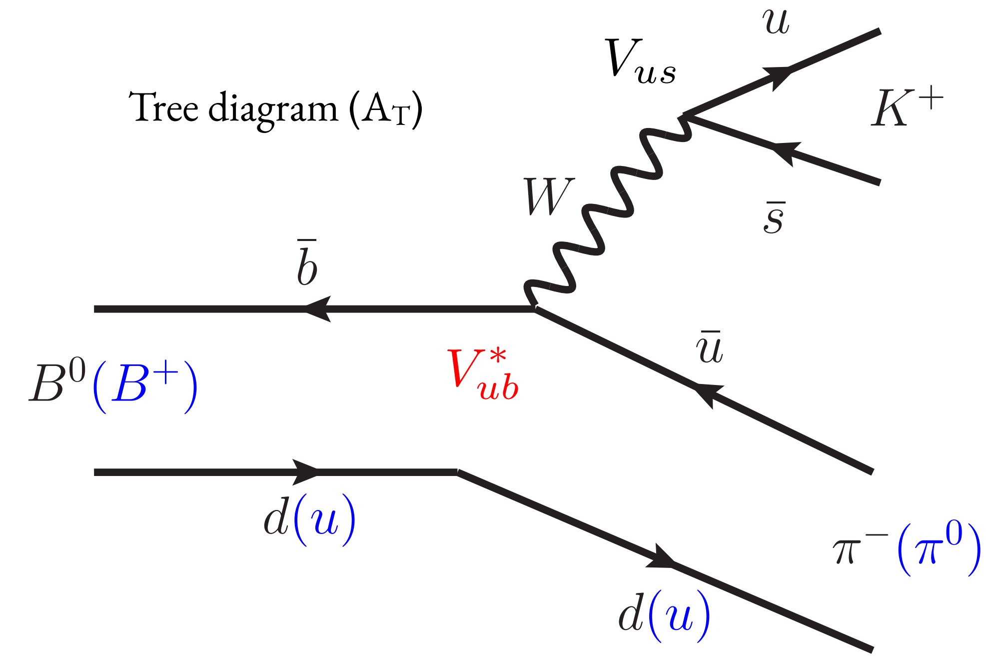
From two to many hadrons

Example: CP violation in two-body decays

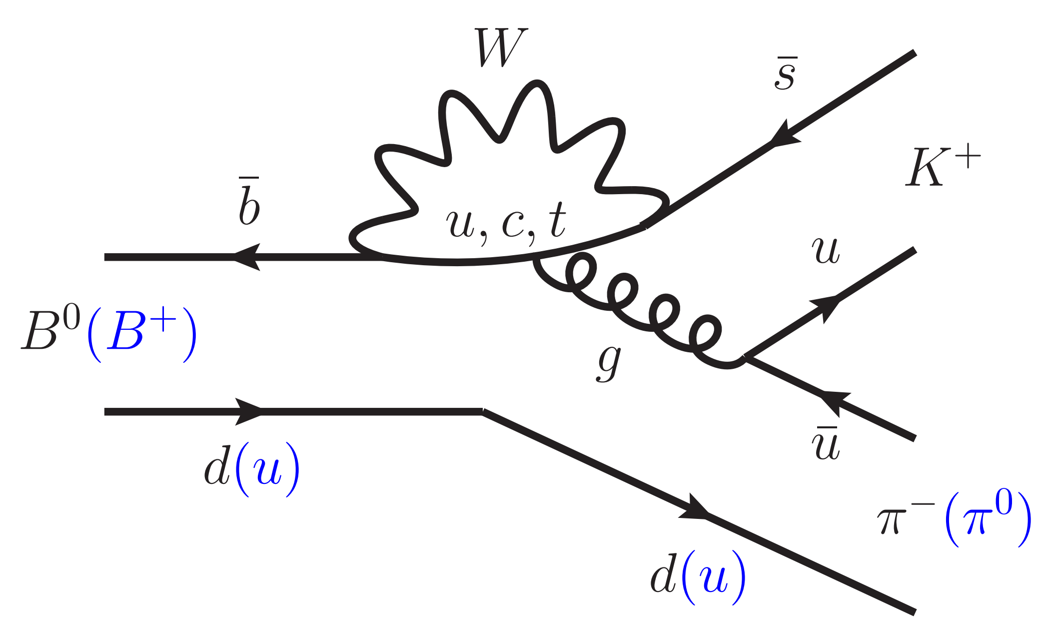
$$\mathcal{A}^{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2} = \frac{2|A_T||A_P|\sin\delta\sin\phi}{|A_T|^2 + |A_P|^2 + 2|A_T||A_P|\cos\delta\cos\phi}$$

δ and φ are the *CP* conserving and *CP* violating relative phases between amplitudes

Tree diagram (A_T)



Penguin diagram (A_P)



Limited information available!

Observables are branching ratio, A^{CP}; unknowns, e.g. A_T, A_P, δ and ϕ

Multi-body decays provide further insights into the dynamics of the system

THREE-BODY DECAYS

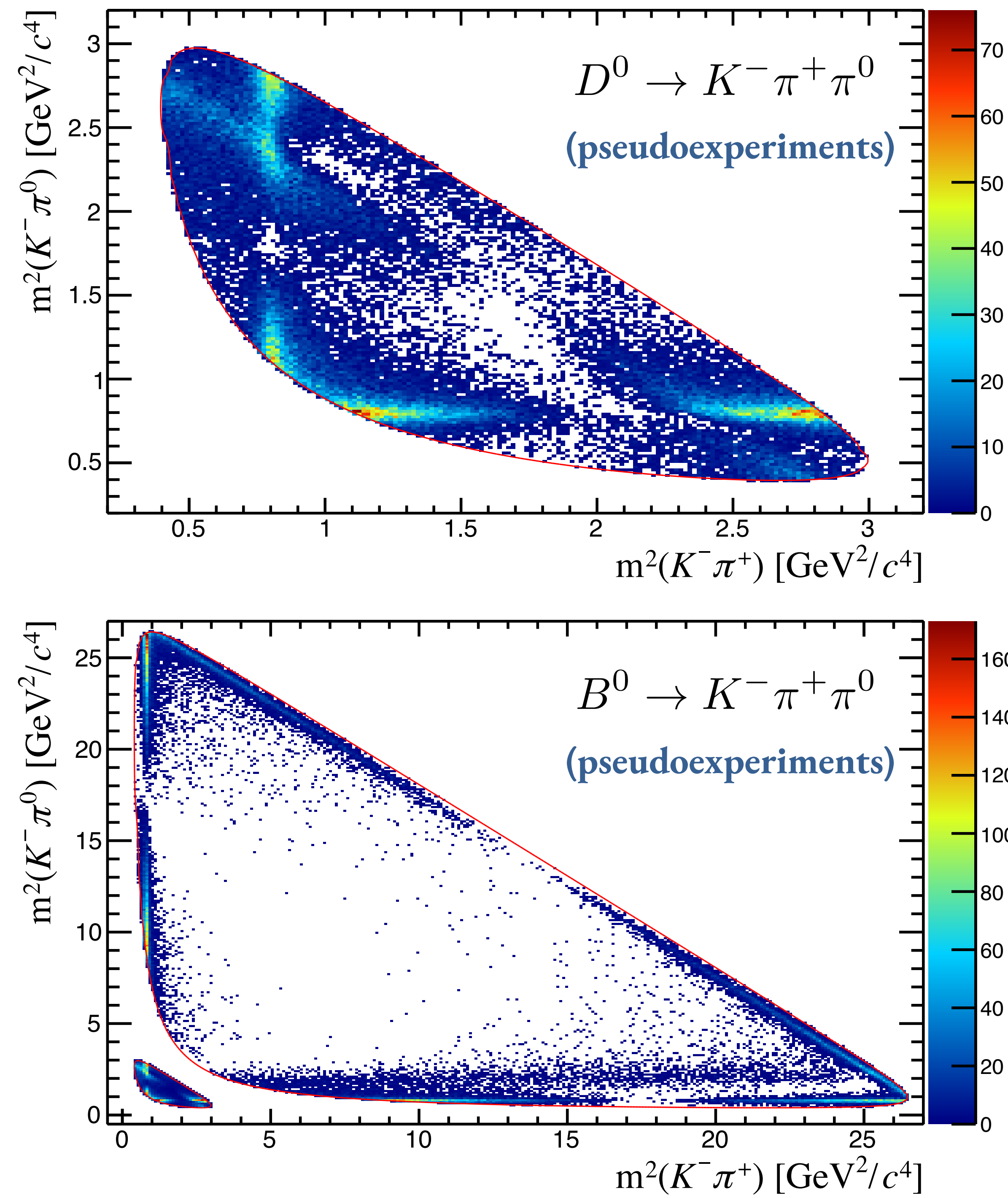
[Laura++, Comput. Phys. Commun. 231 (2018) 198-242]

DIRECT ACCESS TO THE UNDERLYING DYNAMICS OF THE DECAY

$$d\sigma \sim |M_{fi}|^2 d\phi_3 \sim |M_{fi}|^2 dm^2_{ij} dm^2_{jk}$$

AMPLITUDE ANALYSIS:

- RELATIVE PHASE BETWEEN STATES
- SENSITIVITY TO CP VIOLATION EFFECTS
- RESOLVE AMBIGUITIES IN PHASES
- SPECTROSCOPY



MULTI-BODY DECAYS

WITH INCREASED STATISTICS SIMPLIFIED MODELS MIGHT NO LONGER BE SUFFICIENT

AMPLITUDE IS APPROXIMATED AS A COHERENT SUM OF QUASI-BODY CONTRIBUTIONS

CP violating

Strong dynamics
CP conserving

$$\mathcal{A}(m_{12}^2, m_{23}^2) = \sum_{j=1}^{N} \boxed{c_j}\, \boxed{F_j(m_{12}^2, m_{23}^2)}$$

c_l : complex coefficients describing the relative magnitude and phase of the different isobars

F_l : dynamical amplitudes that contain the lineshape and spin-dependence of the hadronic part

$$F_j(L, m_{12}^2, m_{23}^2) = \boxed{R_j(m_{12}^2)} \times \boxed{X_L(|\vec{p}\,|\,r)} \times \boxed{X_L(|\vec{q}\,|\,r)} \times \boxed{T_j(L, \vec{p}, \vec{q})}$$

Resonance mass term (e.g. Breit–Wigner)

Barrier factors - p, q: momenta of bachelor and resonance

Angular probability distribution

Multi-body decays

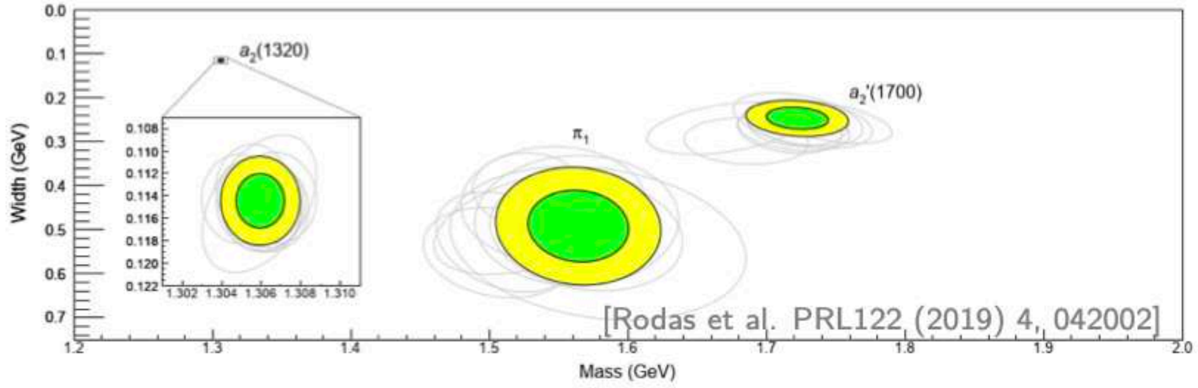
With increased statistics simplified models might no longer be sufficient

Lessons from José Peláez, **paradigm shift**:

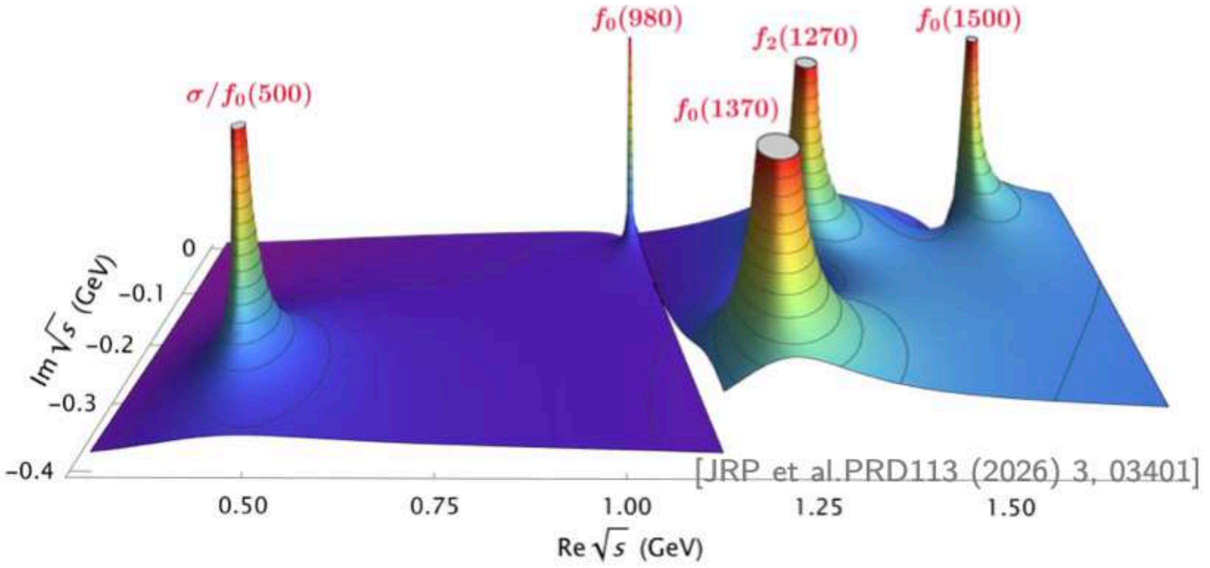
For instance, coupled-channels analysis, introduce threshold behaviour, analyticity conditions (beyond BW)

Non-negotiables:

- **Unitarity:** Exact probability conservation across all open channels.
- **Analyticity:** Causality enforcing physical branch cuts (left- and right-hand cuts), and poles associated to resonances.



[Rodas et al. PRL122 (2019) 4, 042002]



[JRP et al.PRD113 (2026) 3, 03401]

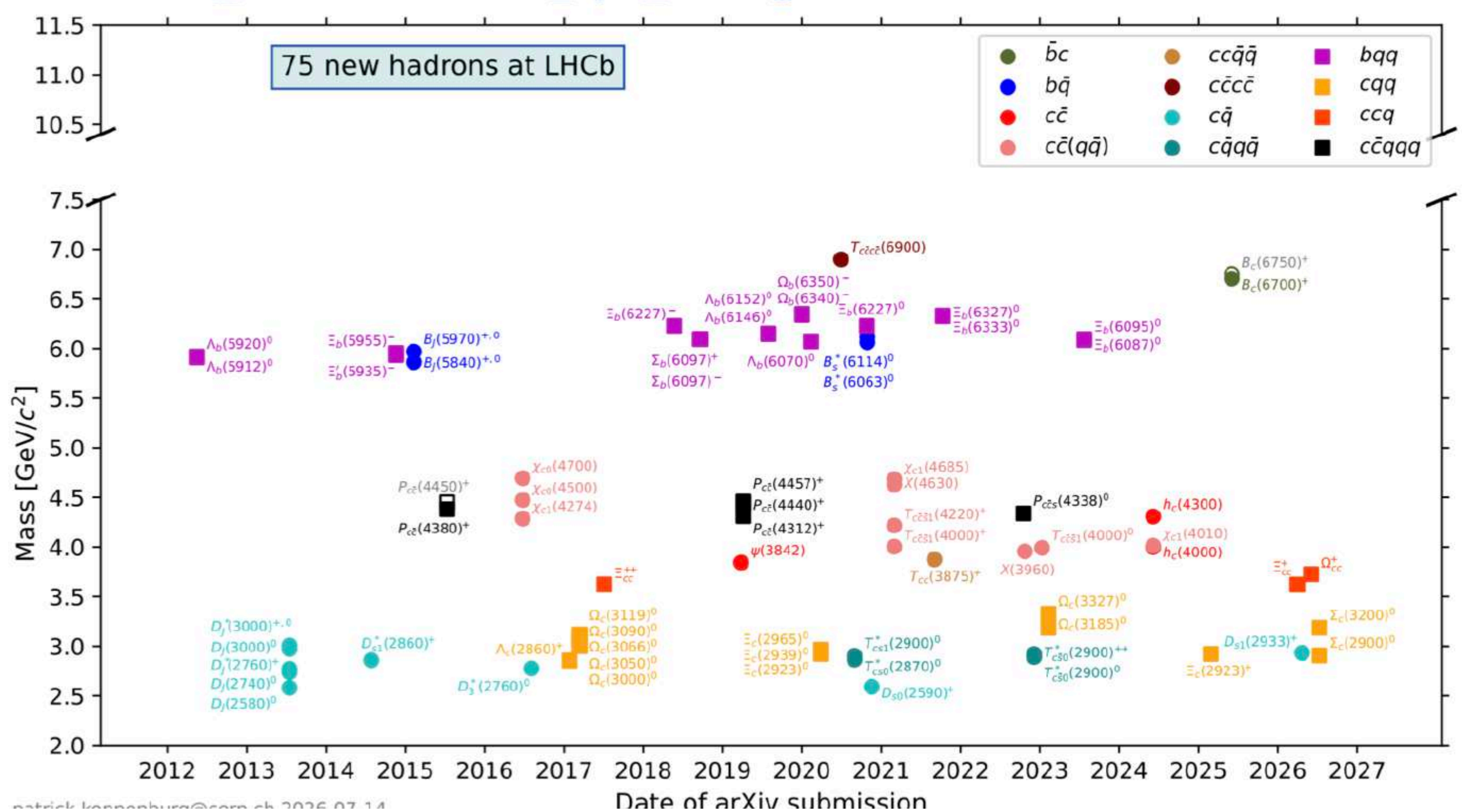
Conventional and exotic spectroscopy

Classical hadrons: mesons [quark + antiquark] or baryons [3 quarks]

Exotic hadrons: in principle anything else, tetraquark, pentaquark, hexaquark, ...

Studied by different experiments:

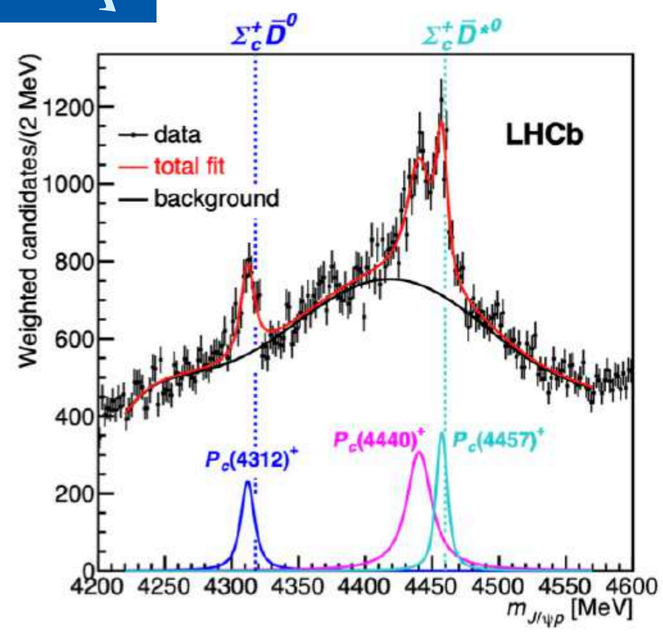
LHCb, BESIII, ATLAS, CMS, Belle, Belle II, BaBar, CDF, D0, ALICE ...



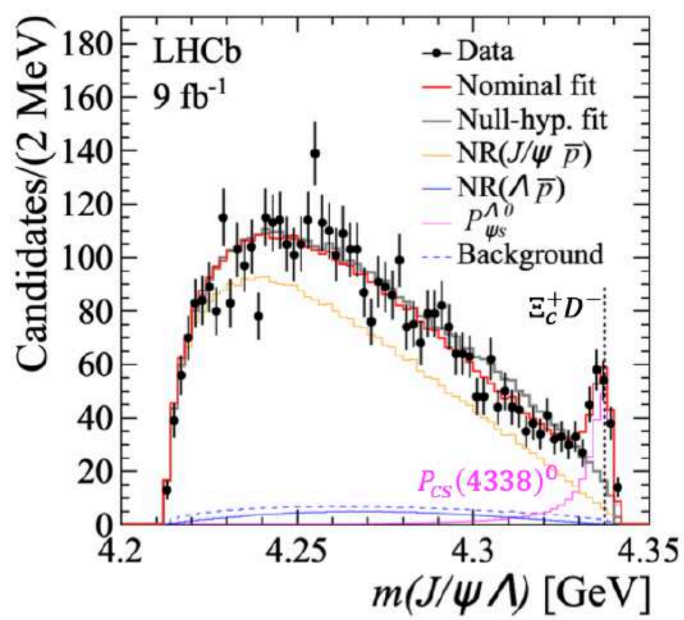
A word on their exotic nature

[PRL 122 (2019) 222001, 131 (2023) 031901, 128 (2022) 062001]
[Sci.Bull. 66 (2021) 1278-1287]

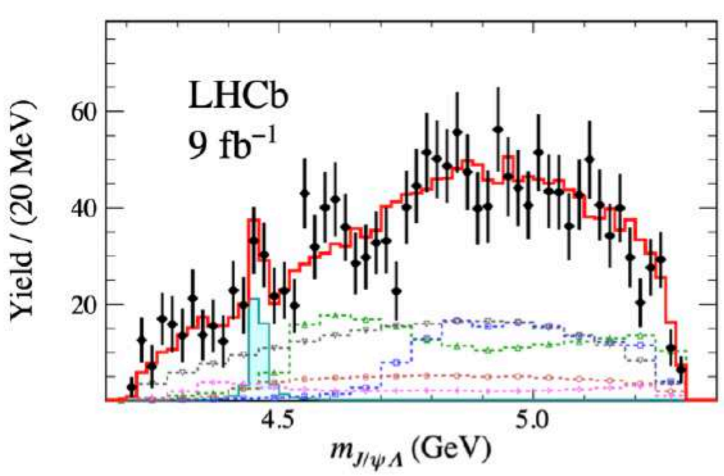
$\Lambda_b^0 \to J/\psi p K^-$



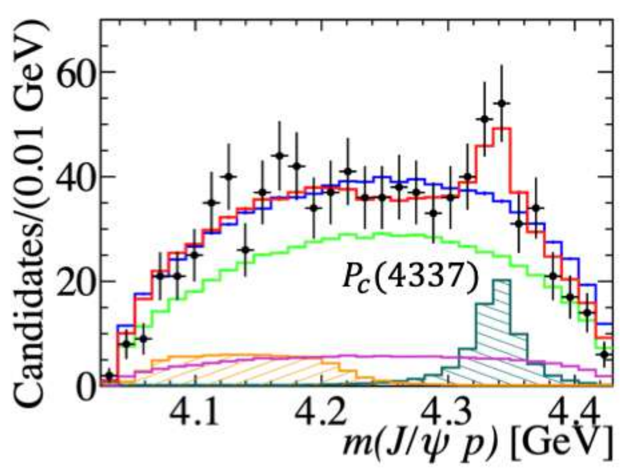
$B^- \to J/\psi \Lambda \bar{p}$



$\Xi_b^- \to J/\psi \Lambda K^-$

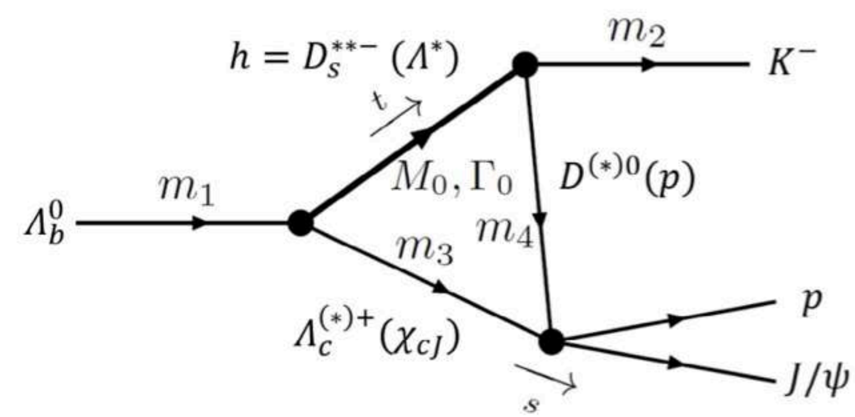


$B_s^0 \to J/\psi p \bar{p}$



Observed pentaquark are usually narrow states close to baryon-meson thresholds

Hadronic molecules? Compact pentaquakrs? Triangles?

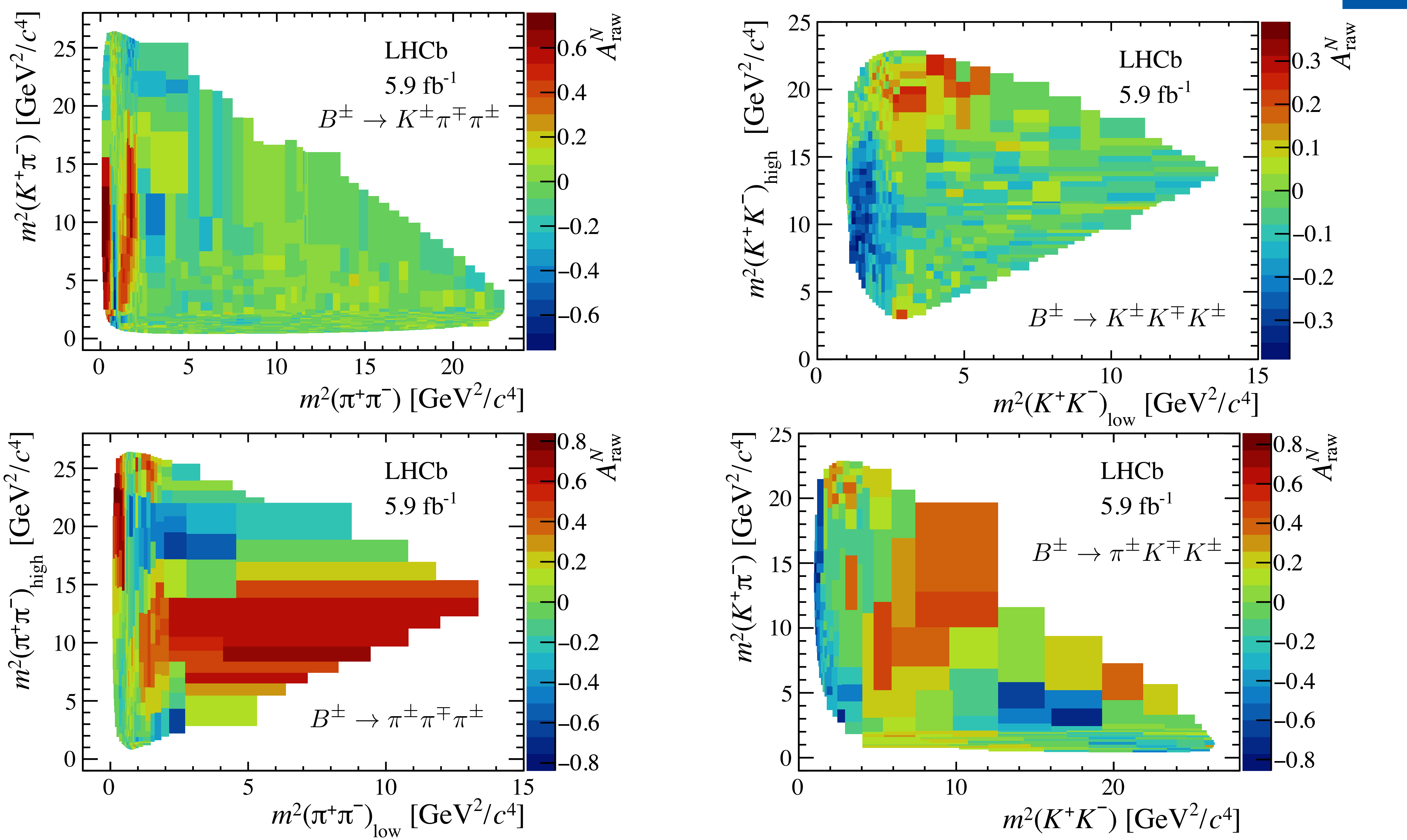


More inputs needed! More data, different productions, final states

CP violation hadronic 3-body decays

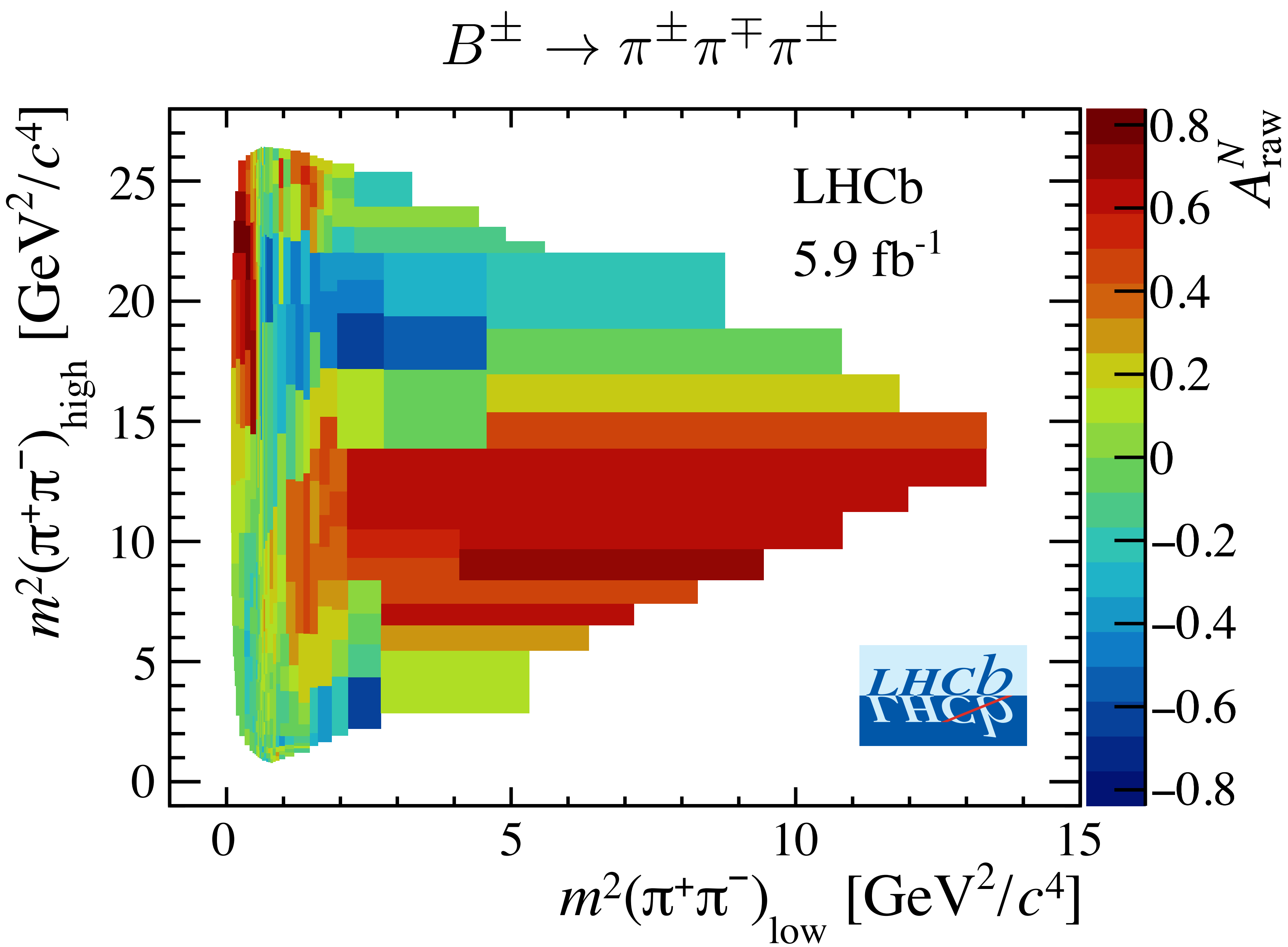
[Phys. Rev. D 108, 012008 (2023)]

Large local asymmetries observed in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ with $h = \pi, K$



[Phys. Rev. D 108, 012008 (2023)]

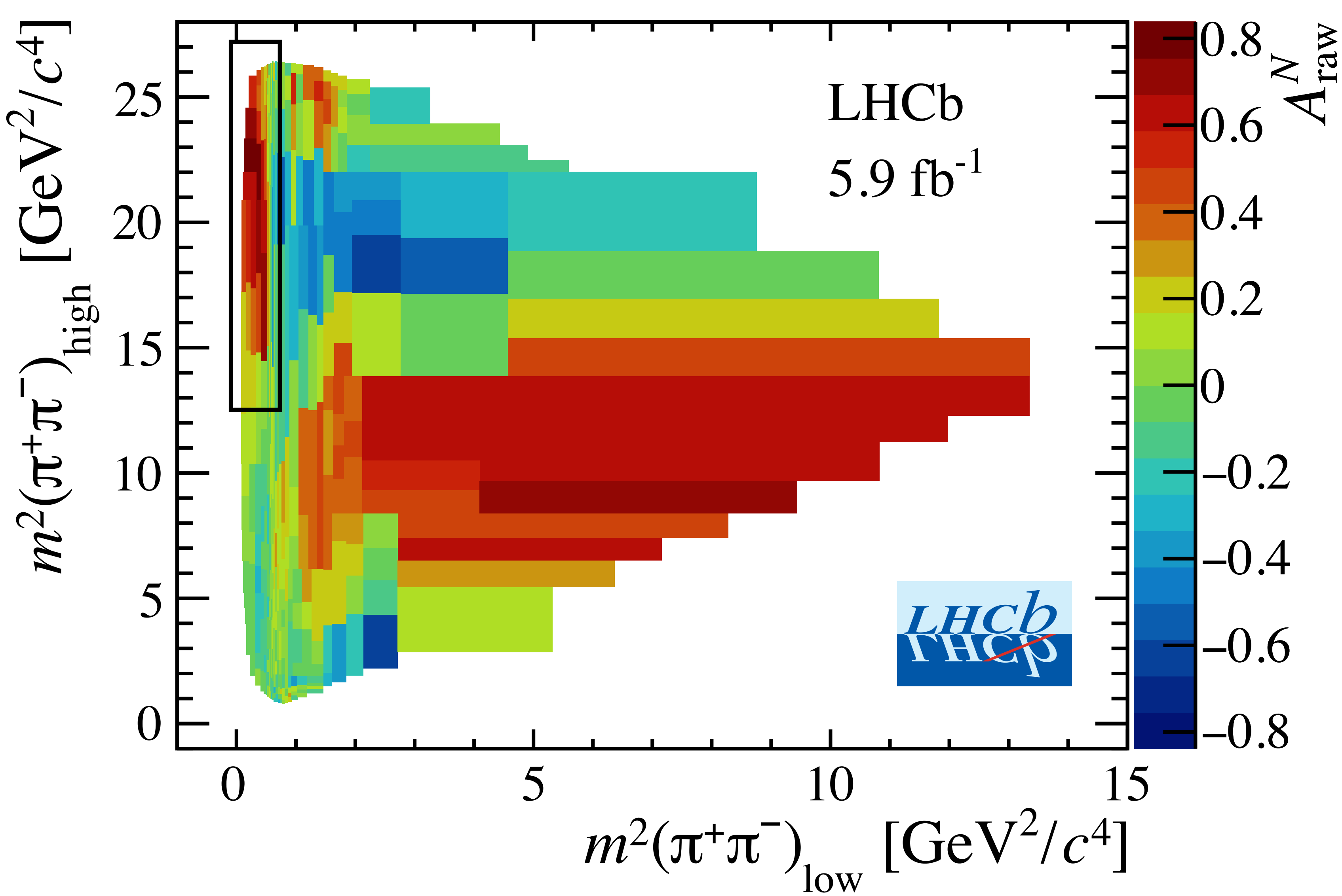
TEXTBOOK OF THE RICH NON-TRIVIAL ANISOTROPY IN THE DALITZ

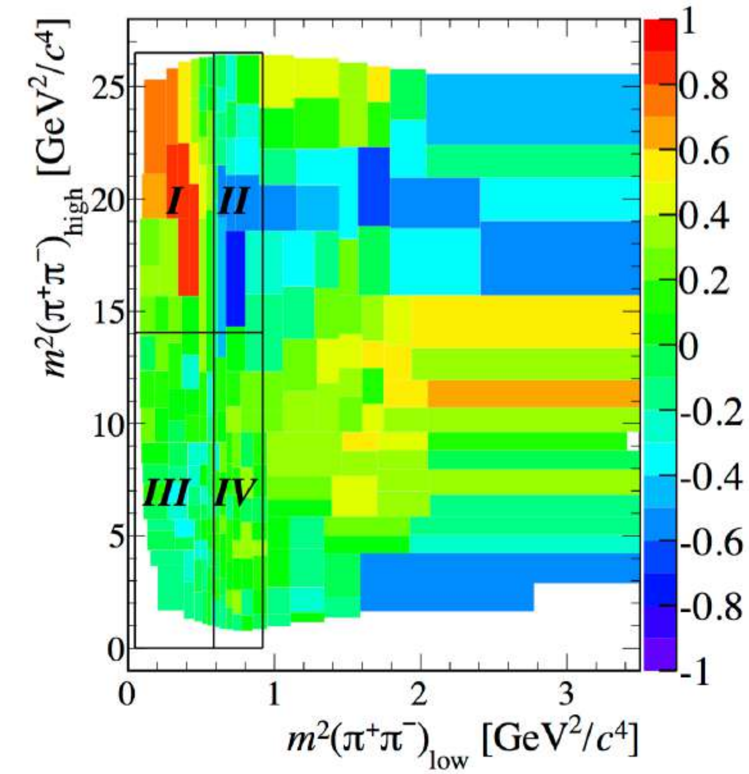


[Phys. Rev. D 108, 012008 (2023)]
[Phys. Rev. D 90, 112004 (2014)]

TEXTBOOK OF THE RICH NON-TRIVIAL ANISOTROPY IN THE DALITZ

$$B^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$$



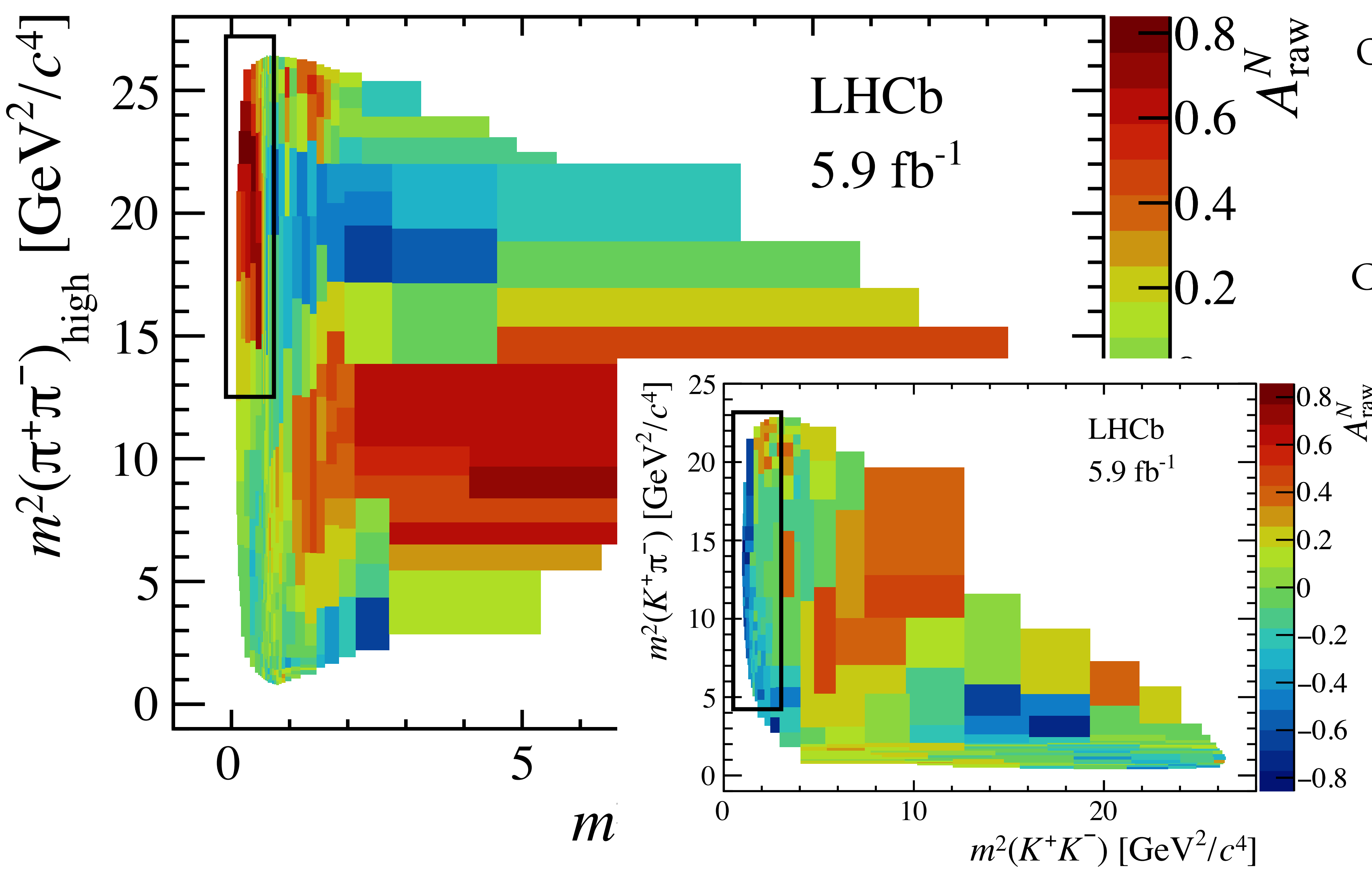


SIGN SHIFT OF A^{CP} IN REGIONS I-II, INDICATE INTERFERENCE BETWEEN S AND P WAVES

[Phys. Rev. D 108, 012008 (2023)]

TEXTBOOK OF THE RICH NON-TRIVIAL ANISOTROPY IN THE DALITZ

$B^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$



OPPOSITE SIGN ASYMMETRY OBSERVED AT LOW $m^2_{\pi\pi}$ AND m^2_{KK}

RESCATTERING EFFECTS IN COUPLE CHANNELS MIGHT BE PRESENTED?

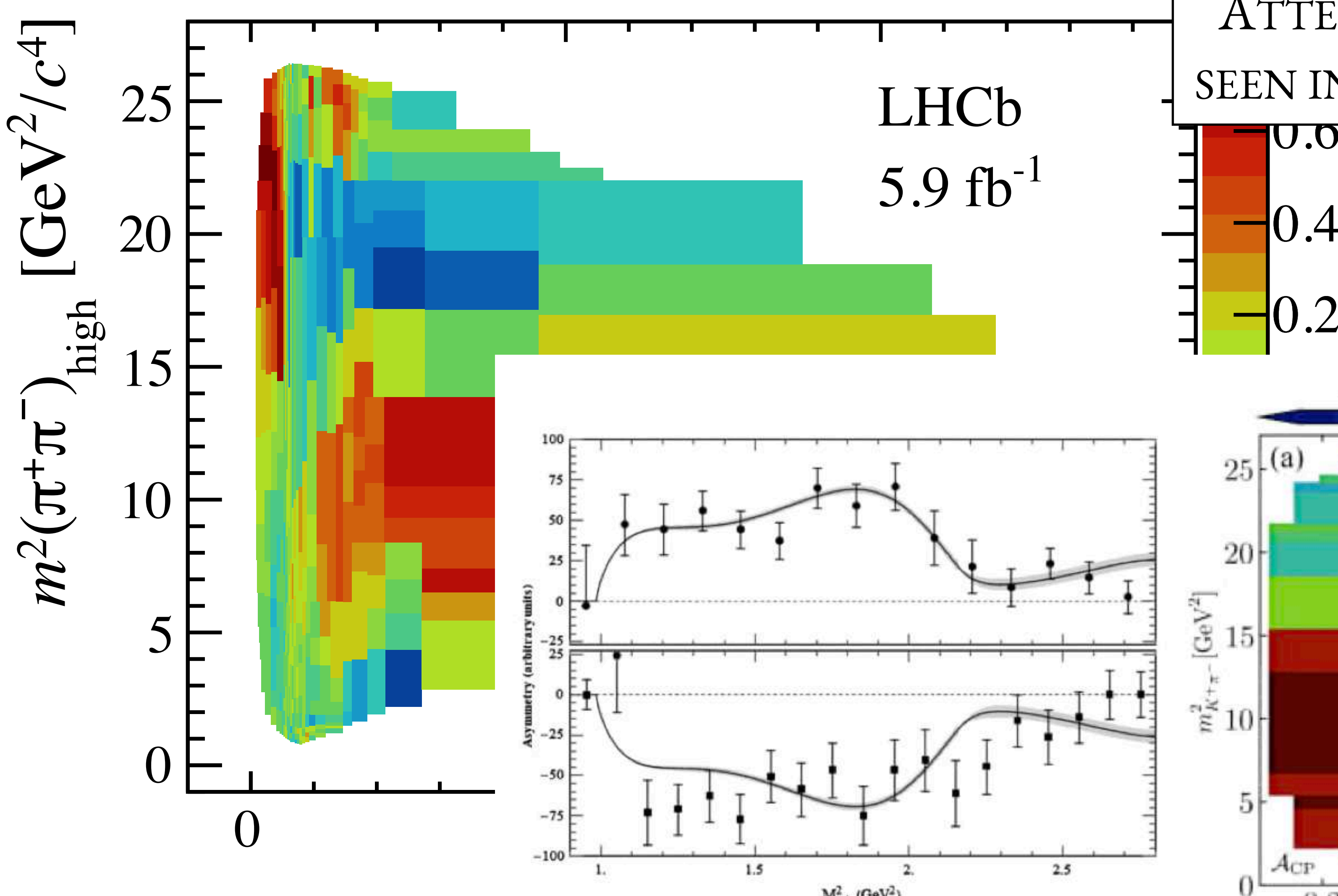
NO TRIVIAL RESONANT CONTRIBUTION IN m^2_{KK} FOR $B^+ \to K^+K^-\pi^+$

CP VIOLATION HADRONIC 3-BODY DECAYS

[Phys. Rev. D 108, 012008 (2023)]

TEXTBOOK OF THE RICH NON-TRIVIAL ANISOTROPY IN THE DALITZ

$B^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$

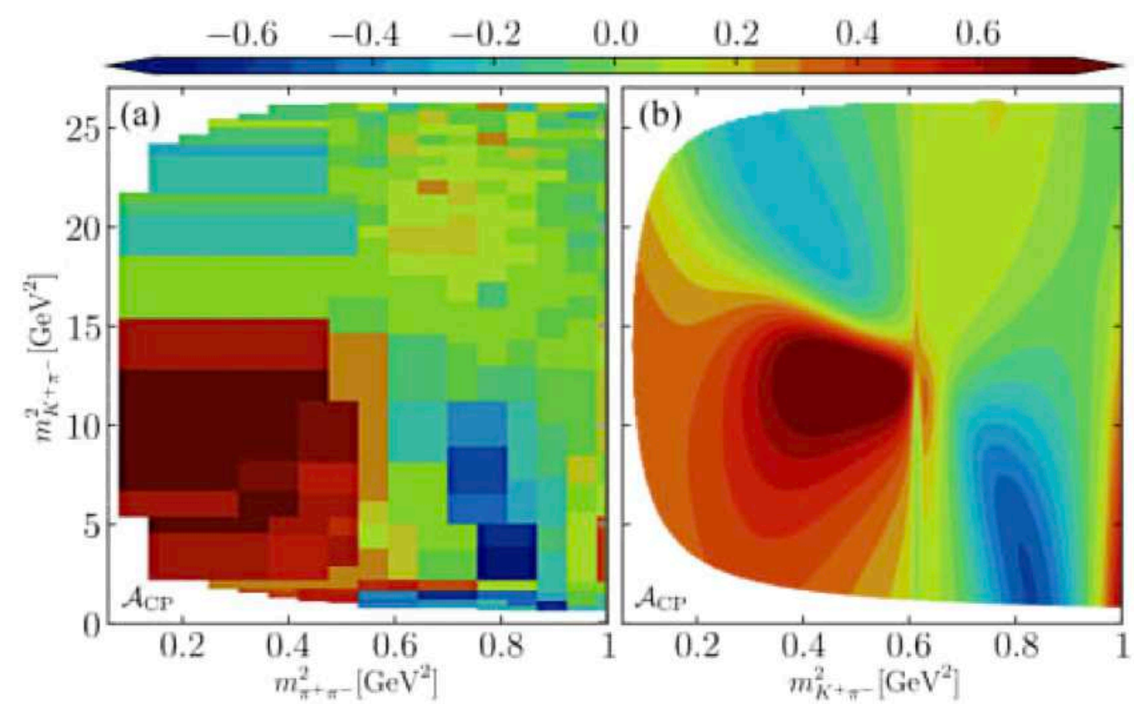


ATTEMPTS TO CONNECT CP VIOLATION SEEN IN $B^+ \to K^+\pi^+\pi^-$ AND $B^+ \to K^+K^+K^-$

[Bediaga et al. PRD 89, 094013 (2014)]

[Alvarez-Garrote et al. PRL 130 (2023) 20, 201901]

[Heuser et al, PRL 136 (2026) 11, 111901]

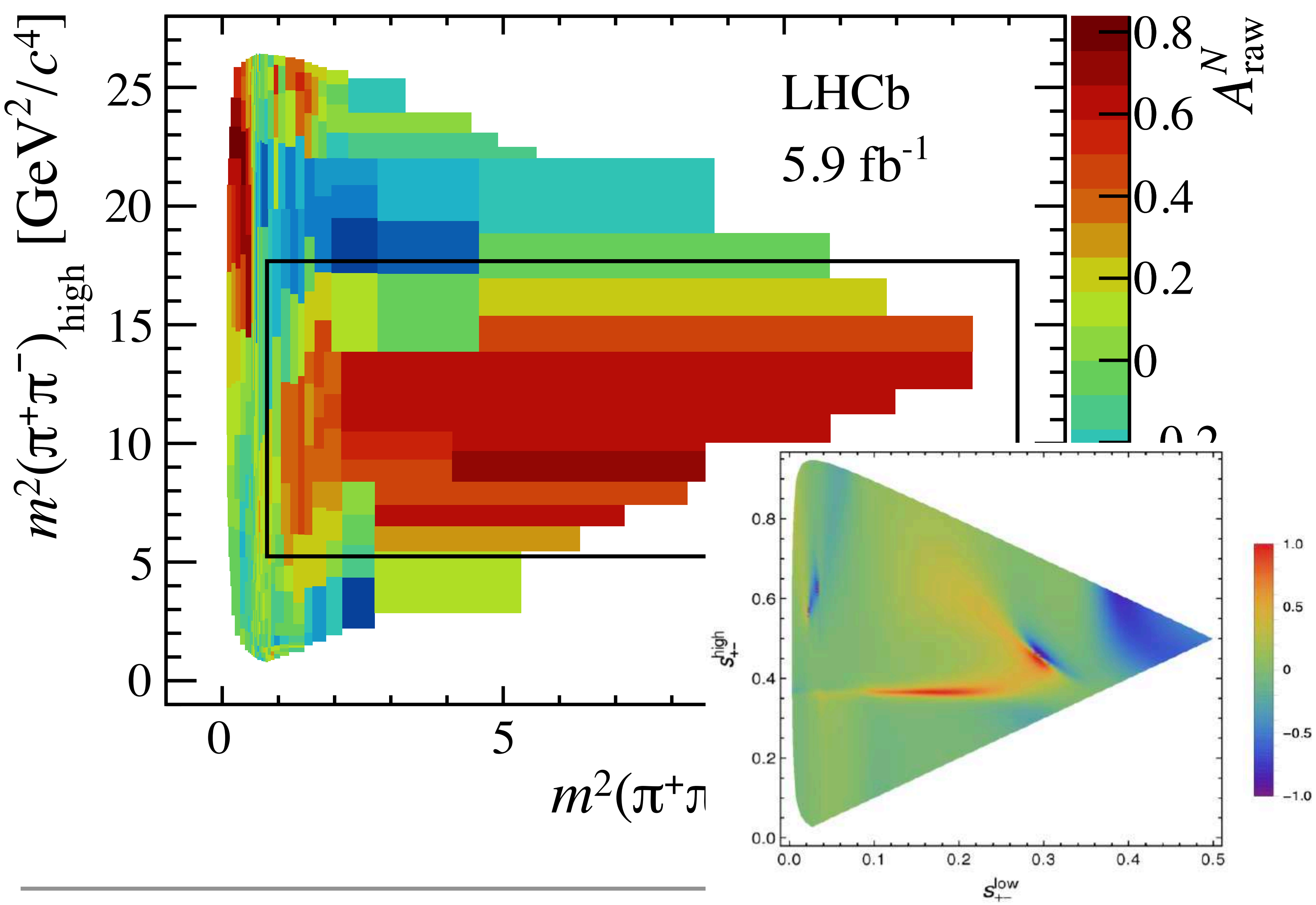


CP VIOLATION HADRONIC 3-BODY DECAYS

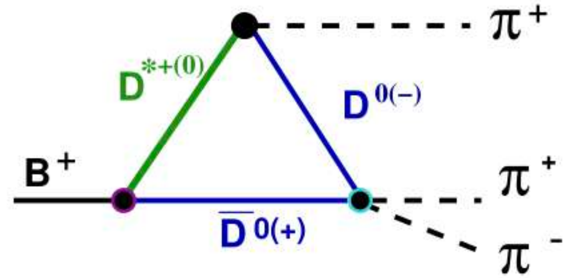
[Phys. Rev. D 108, 012008 (2023)]

TEXTBOOK OF THE RICH NON-TRIVIAL ANISOTROPY IN THE DALITZ

$B^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}$

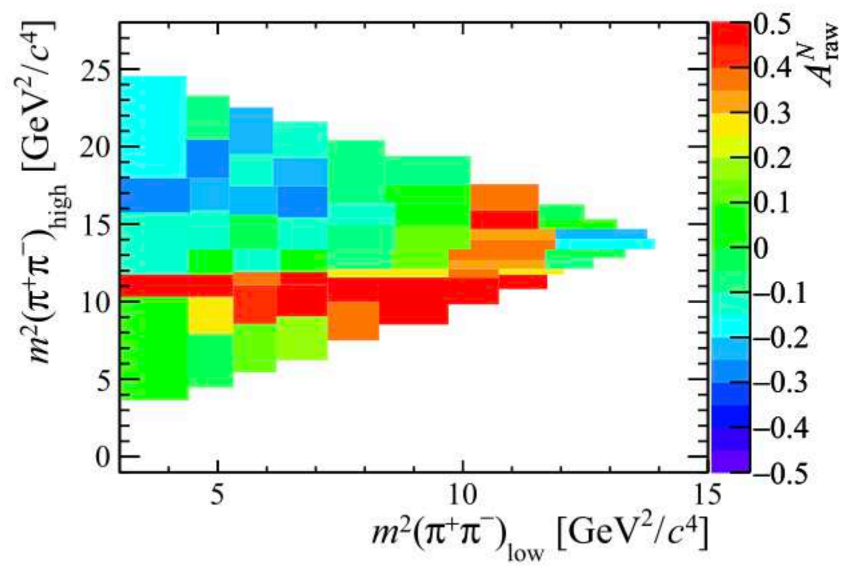


ENHANCED CP VIOLATION AT VERY HIGH $m^2_{\pi\pi}$!



[Klein et al. JHEP 10, 117 (2017)]

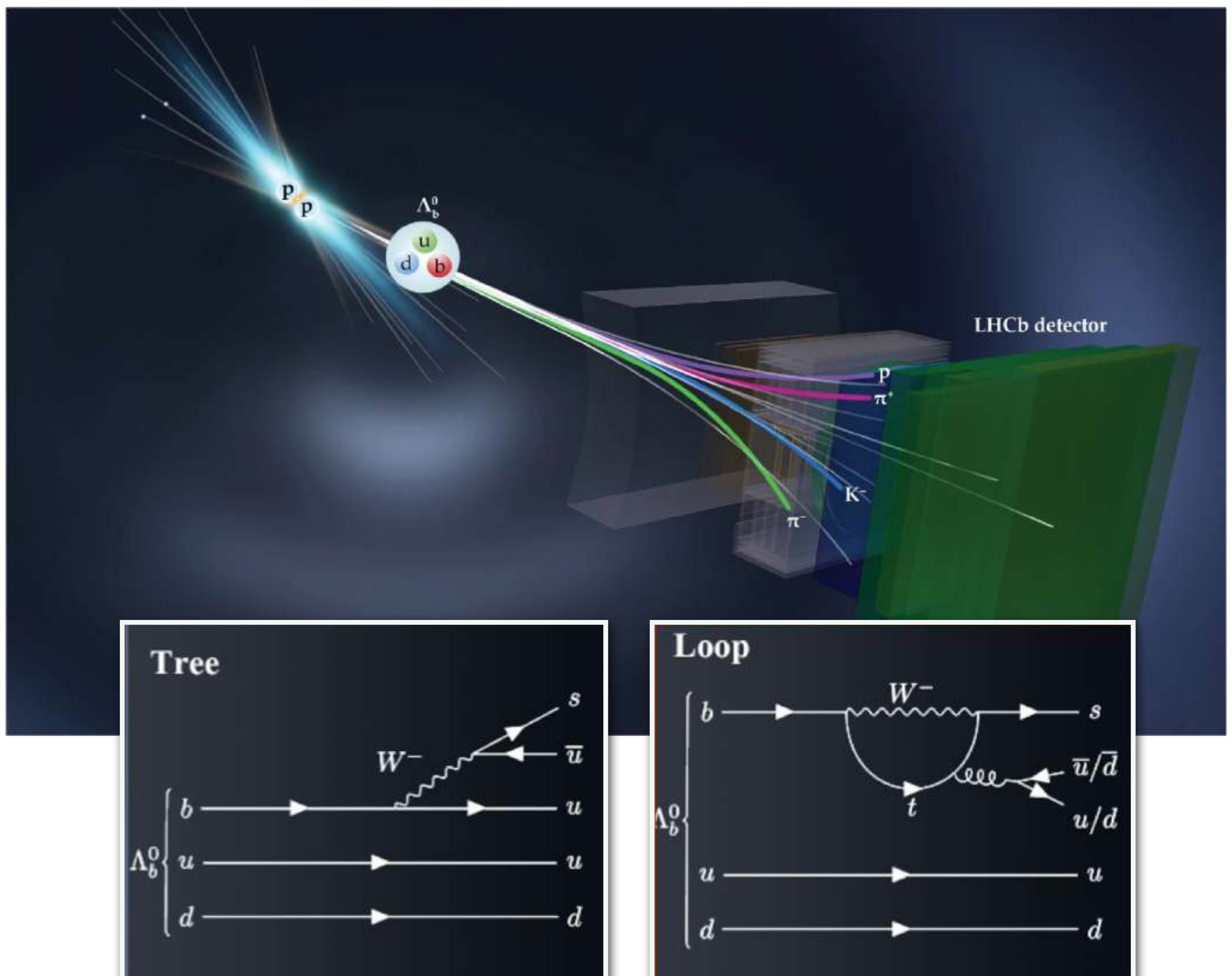
[Bediaga et al. PLB 806 (2020) 135490]



CP violation in b-baryons hadronic decays

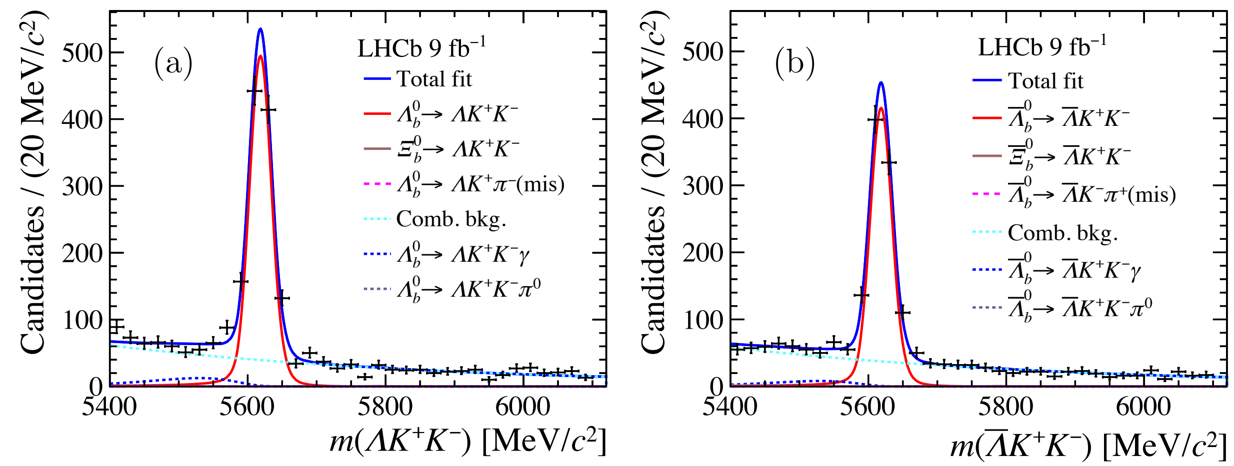
[Nature 643 (2025) 1223]

$\Lambda_b^0 \to pK^-\pi^+\pi^+$

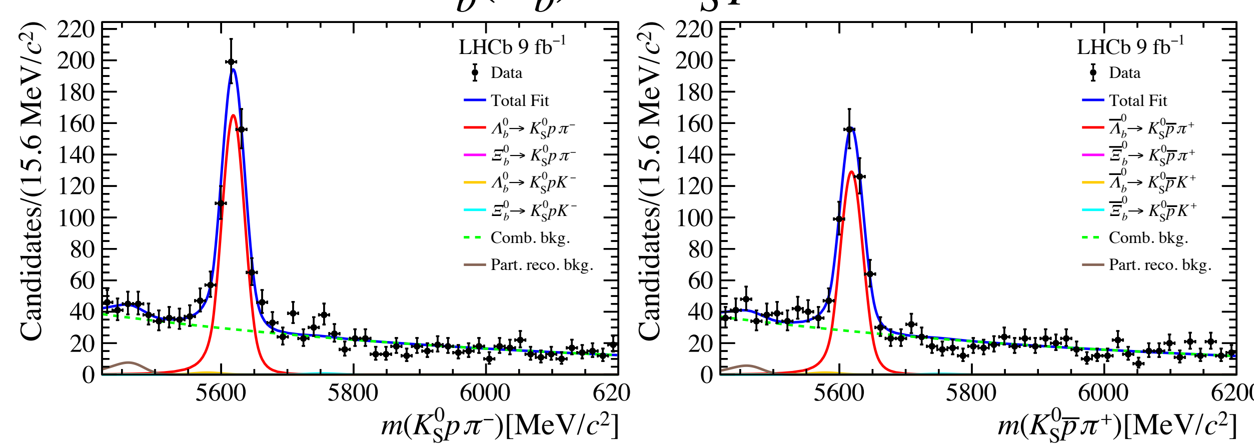


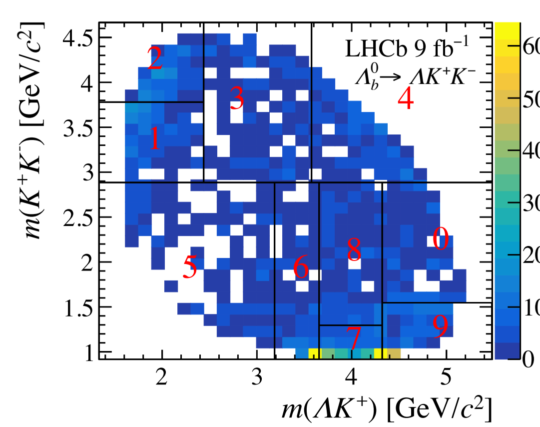
Rich complex phase space to be explored

$\Lambda_b^0(\Xi_b^0) \to \Lambda^0 h^+ h^-$



$\Lambda_b^0(\Xi_b^0) \to K_S^0 p h^+$



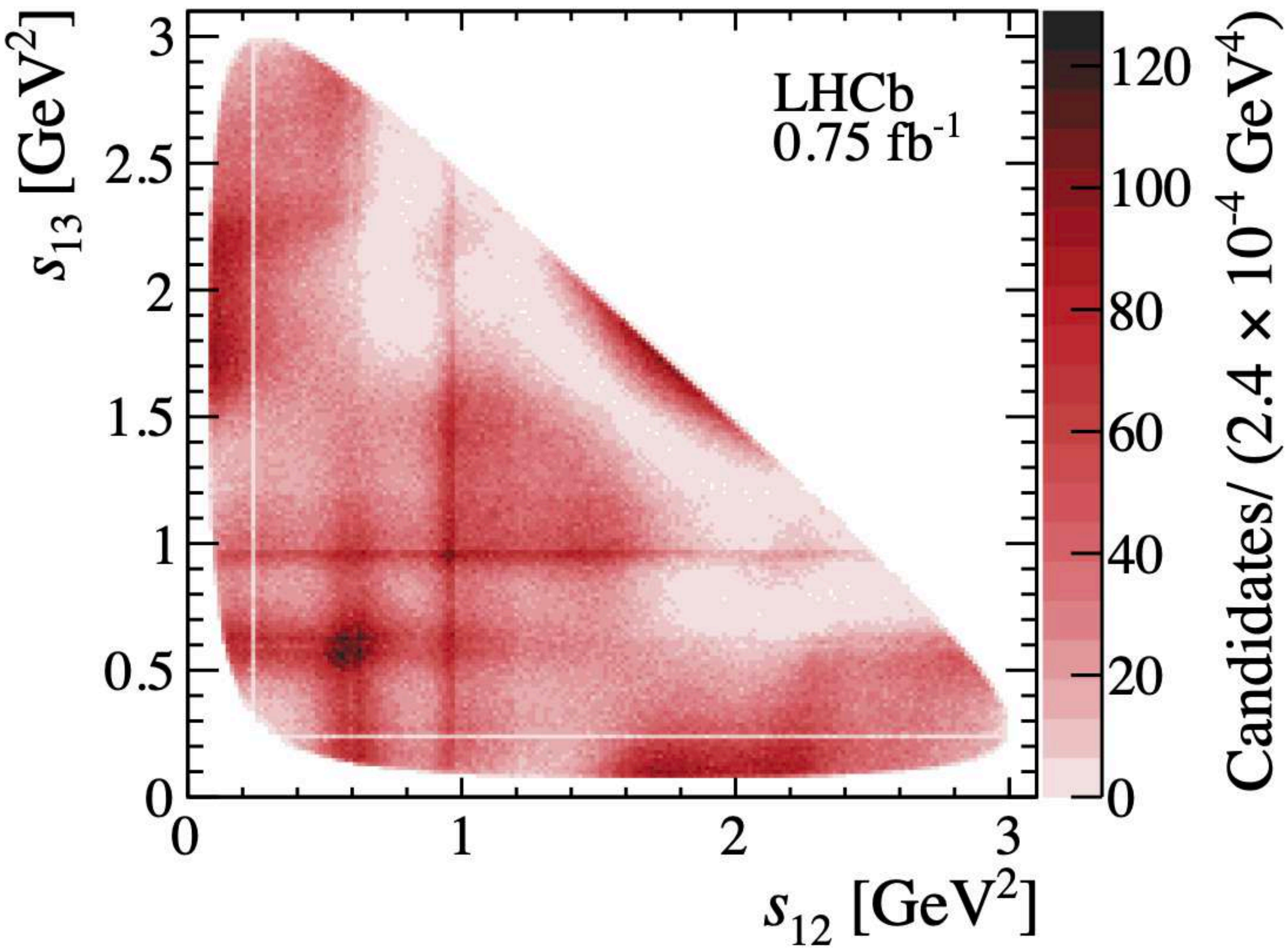


$m(K^+K^-) < 1.10 GeV/c^2$
$A_{CP} = 0.150 \pm 0.062 \pm 0.021$

$m(\Lambda K^+) < 2.90 GeV/c^2$,
$m(K^+K^-) > 2.20 GeV/c^2$
$A_{CP} = 0.165 \pm 0.050 \pm 0.016$

CP violation in charm hadronic 3-body decays

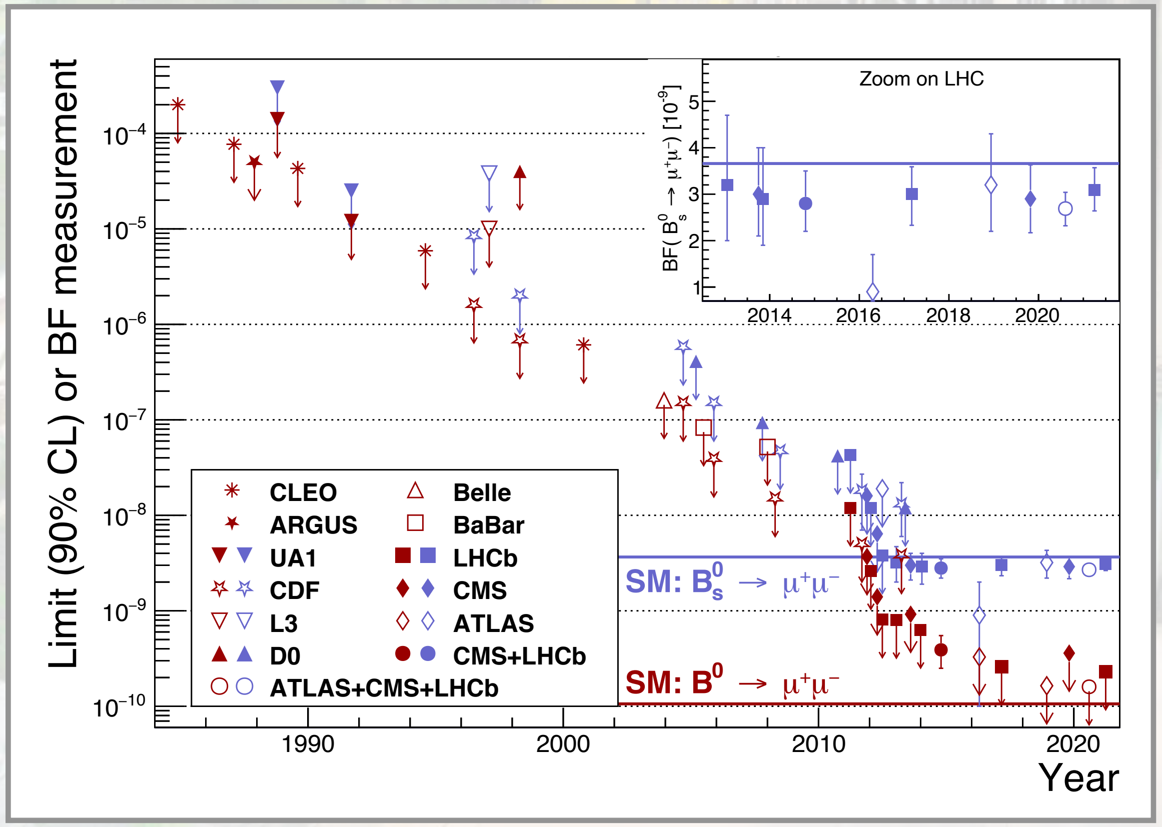
Expected CPV in the SM of the order of 10^{-3}- 10^{-4}, and so far only seen in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

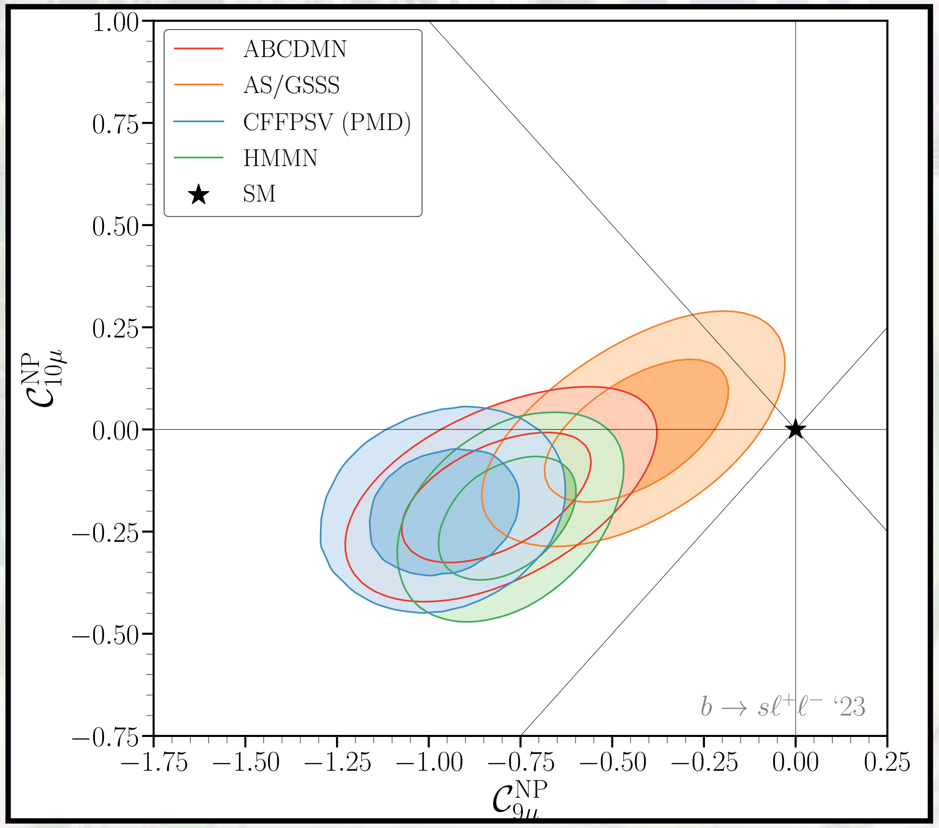


Huge statistics available in charm multi body decays, but no CPV seen yet

Rare decays as a probe of new physics

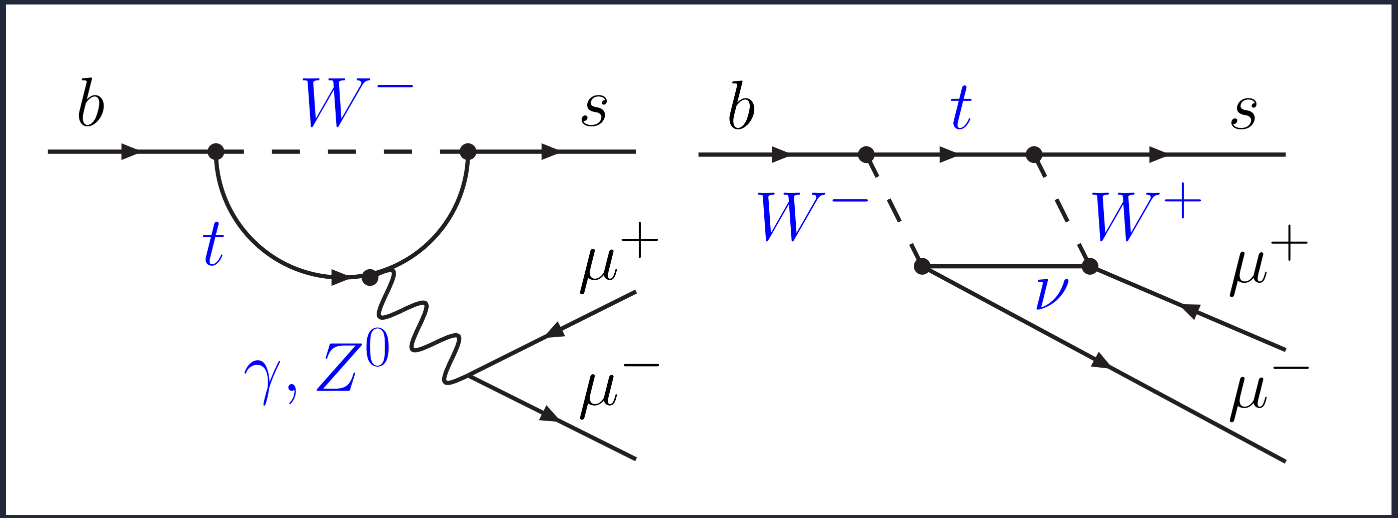
A flavour anomalies storytelling





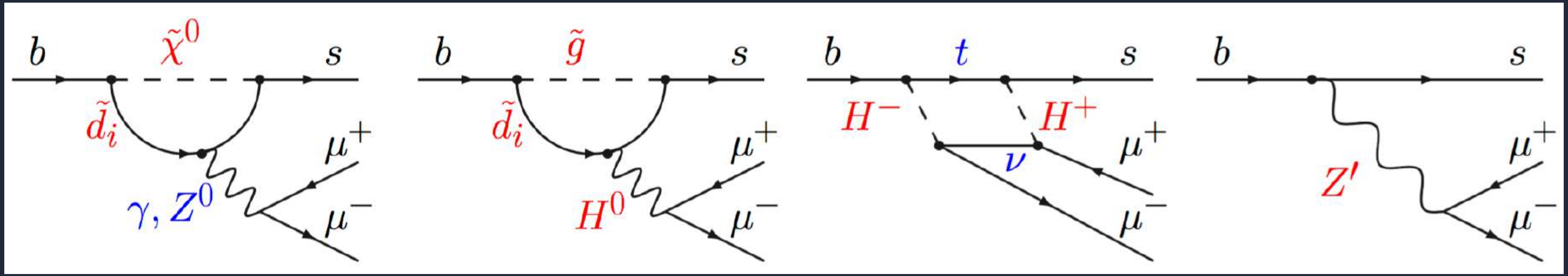
Rare Decays

FCNC: unique glimpse to higher scale



[*e.g.* enhancement/suppression of decay rate, angular distributions and new sources of ~~CP~~]

New particles can contribute at loop and/or tree level



Rare Decays

Rare B decays are a multi-scale problem: $\Lambda^2_{\mathrm{NP}} \gg m_W \gg m_b > \Lambda_{\mathrm{QCD}}$

FCNC effective Hamiltonian described as OPE

Wilson coefficients ("effective coupling")

Local operator

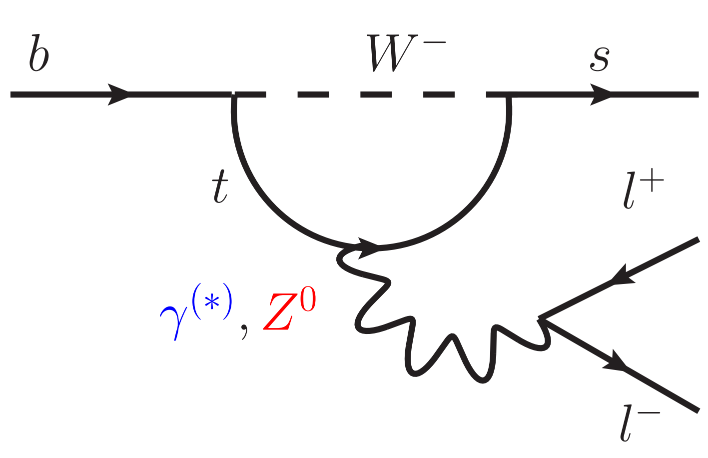
$$\mathcal{H}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts} \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i}$$

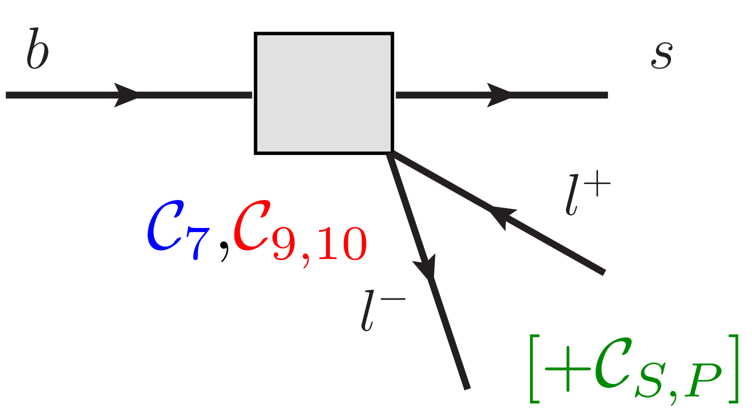
i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

Flavour-violating coupling

$$\Delta\mathcal{H}_{\mathrm{NP}} = \frac{\boxed{\kappa}}{\boxed{\Lambda^2_{\mathrm{NP}}}} \mathcal{O}_i$$

NP scale





- $B^0_{(s)} \to l^+ l^-$
  $[\mathcal{C}_{10}, \mathcal{C}_S, \mathcal{C}_P]$
- $b \to s l^+ l^-$
  $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$

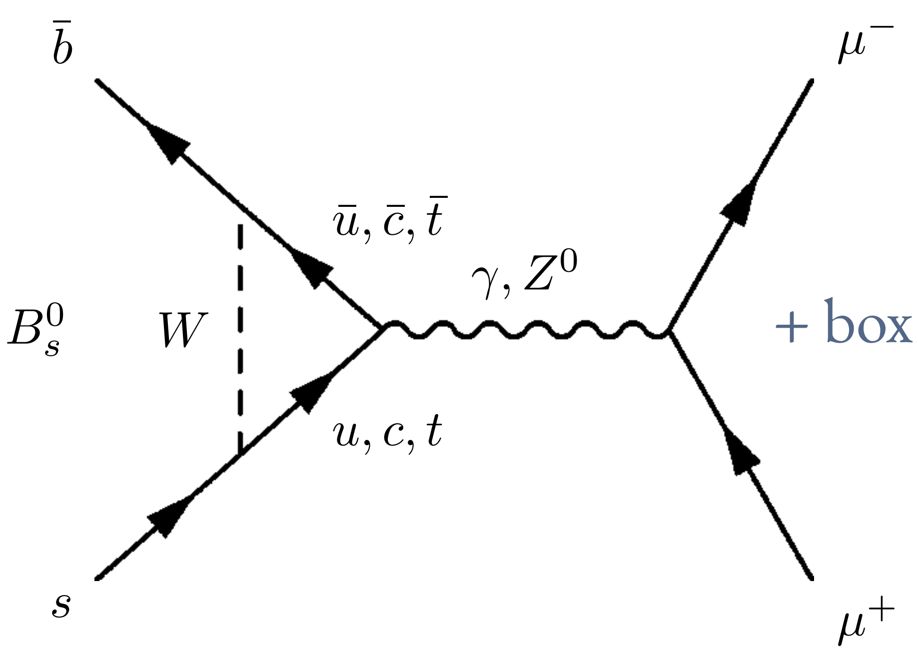
The Golden Channel $B_s^0 \to \mu^+\mu^-$

Clean theoretical predictions

$$B(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

[JHEP 10 (2019) 232]



+ box diagram

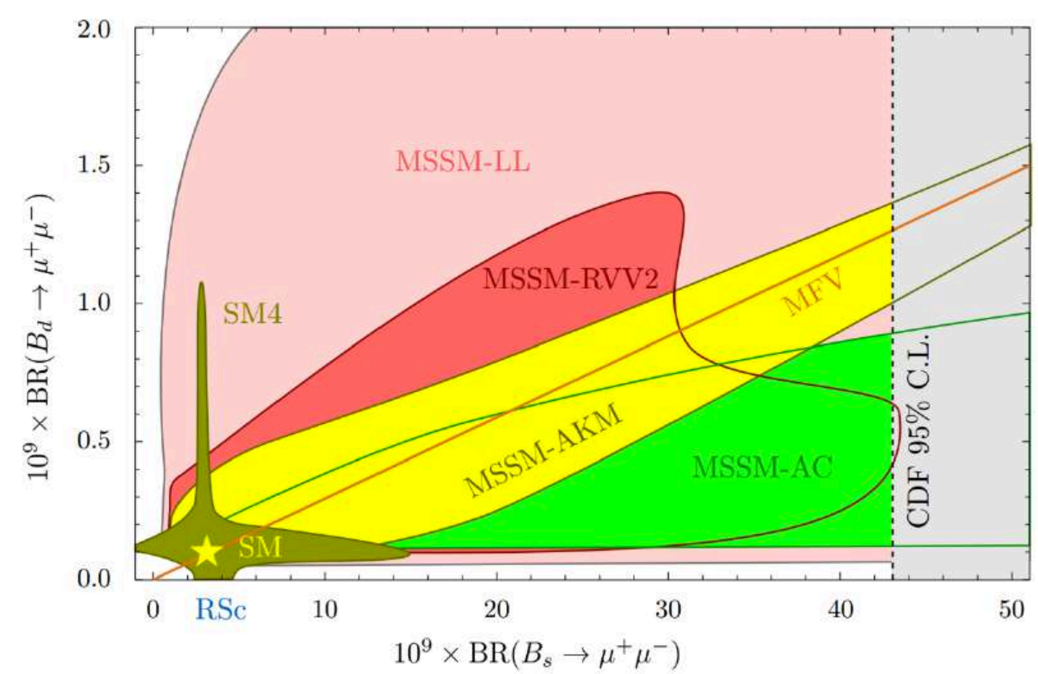
1. Branching Fraction

$$B \propto |V_{tb}V_{tq}|^2 \left[(1 - \frac{4m_\mu^2}{M_B^2})|C_S - C_S'|^2 + |C_P - C_P'|^2 + \frac{2m_\mu}{M_B}(C_{10} - C_{10}')|^2 \right]$$

2. Ratio Of Branching Fractions

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = \frac{\tau_{B_d}}{\tau_{B_s}} \left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{m_{B_d}\sqrt{1-\frac{4m_\mu^2}{m_{B_d}^2}}}{m_{B_s}\sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}}$$

[*Nuovo Cim.C* 035N1 (2012) 249]



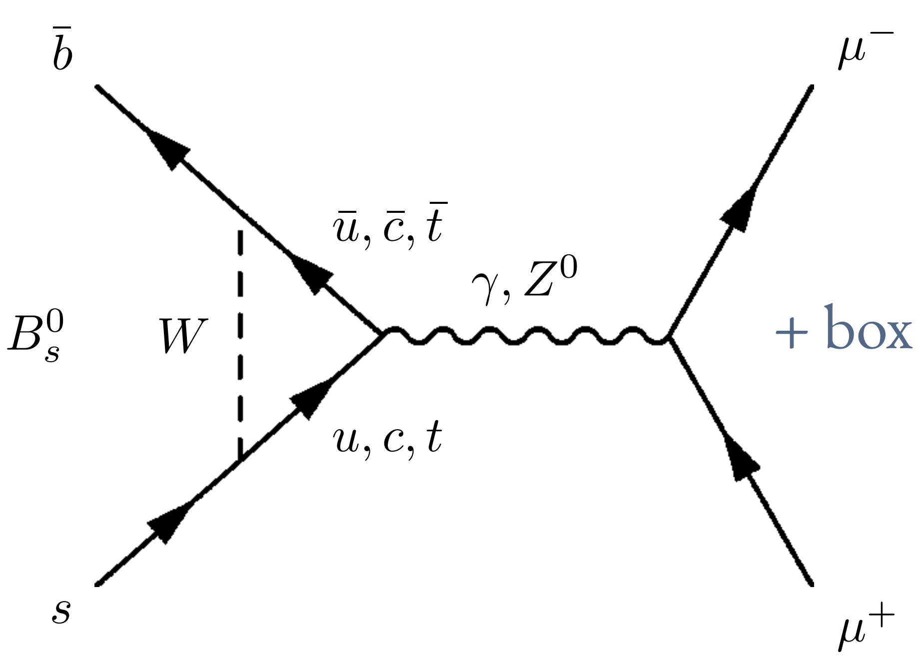
The Golden Channel $B_s^0 \to \mu^+\mu^-$

Clean theoretical predictions

$$B(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

[JHEP 10 (2019) 232]



+ box diagram

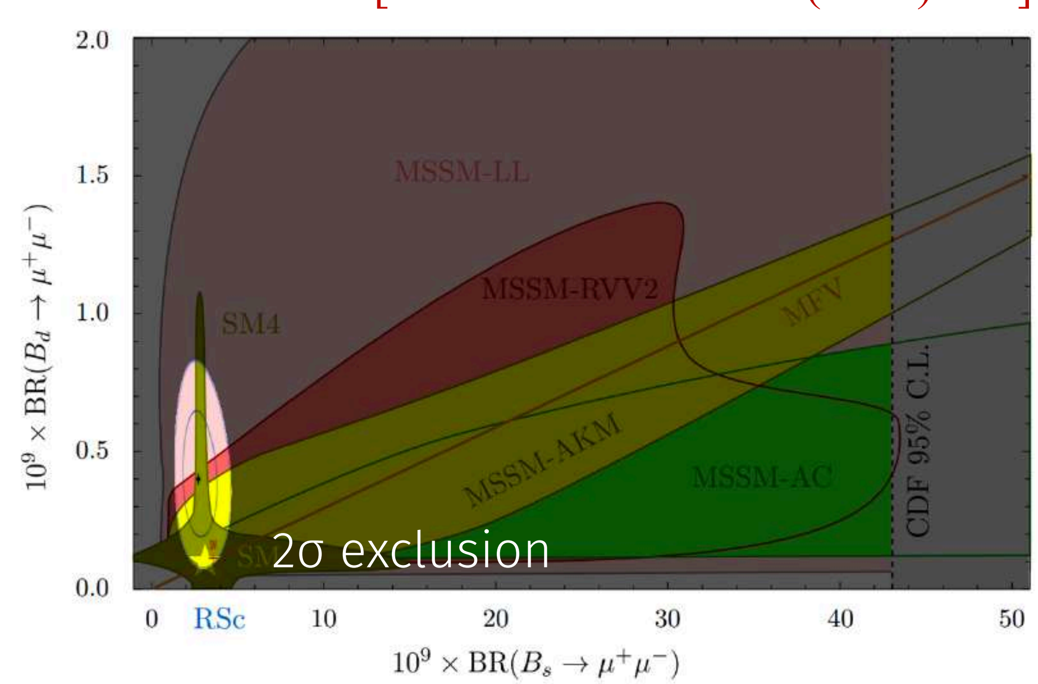
1. Branching Fraction

$$B \propto |V_{tb}V_{tq}|^2 \left[(1 - \frac{4m_\mu^2}{M_B^2})|C_S - C'_S|^2 + |C_P - C'_P|^2 + \frac{2m_\mu}{M_B}(C_{10} - C'_{10})|^2 \right]$$

2. Ratio Of Branching Fractions

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = \frac{\tau_{B_d}}{\tau_{B_s}} \left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{m_{B_d}\sqrt{1 - \frac{4m_\mu^2}{m_{B_d}^2}}}{m_{B_s}\sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}}$$

[*Nuovo Cim.C* 035N1 (2012) 249]



The Golden Channel $B_s^0 \to \mu^+\mu^-$

Clean theoretical predictions

$B(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$

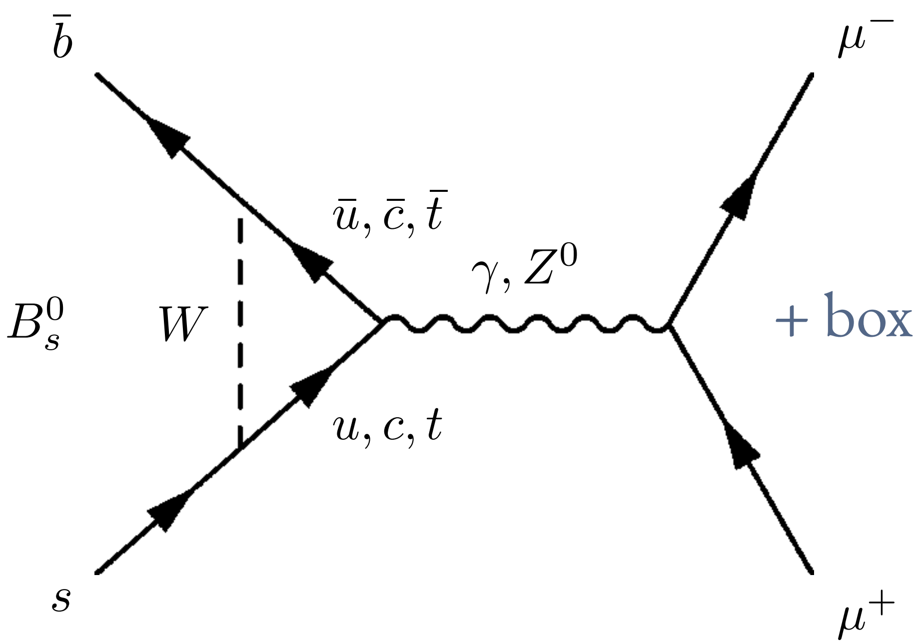
$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$

[JHEP 10 (2019) 232]

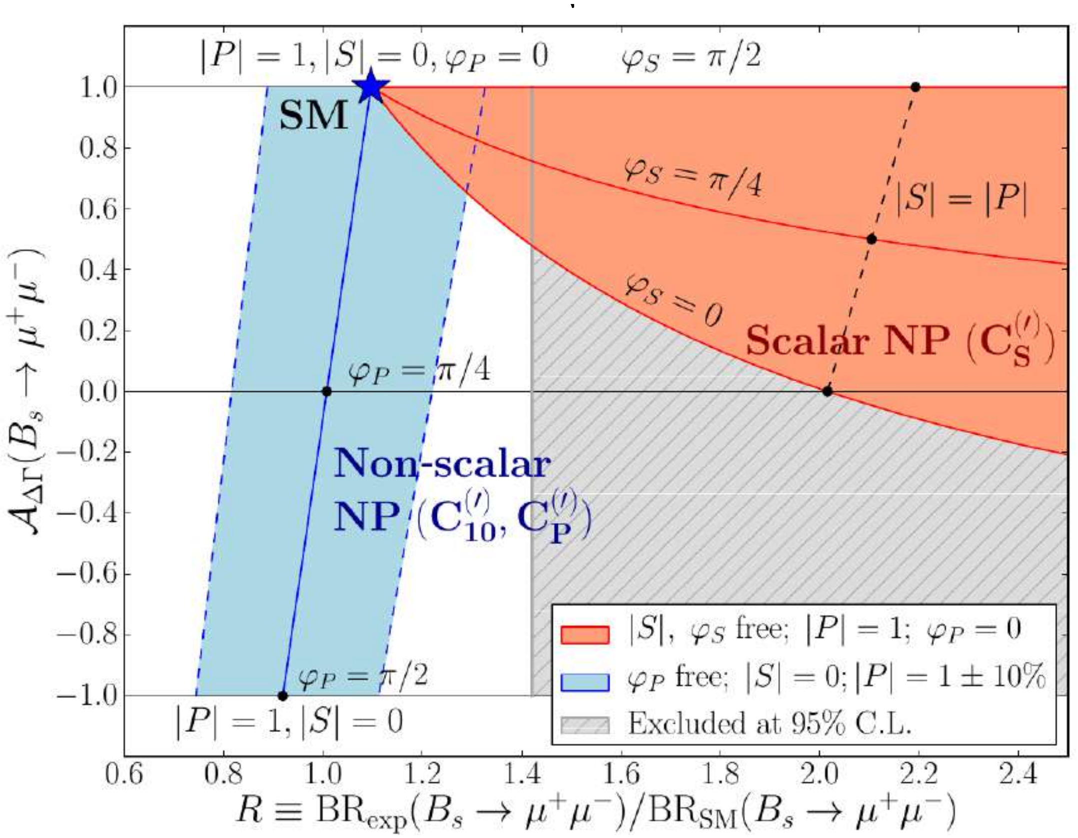
3. Effective Lifetime

$$\tau_{\mu\mu} = \frac{\tau_{B_s}}{(1-y_s^2)} \frac{1 + 2y_s \mathcal{A}_{\Delta\Gamma} + y_s^2}{1 + y_s \mathcal{A}_{\Delta\Gamma}}$$

[PRL 109 (2012) 041801]



+ box diagram



The Golden Channel $B_s^0 \to \mu^+\mu^-$

[LHCb PRL 128 (2022) 041801, CMS PLB 842 (2023) 1379553, ATLAS JHEP 04 (2019) 098]

Combined LHC results [today]

LHCb

$$B(B_s^0 \to \mu^+\mu^-) = (3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (1.2\,^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10}$$

CMS

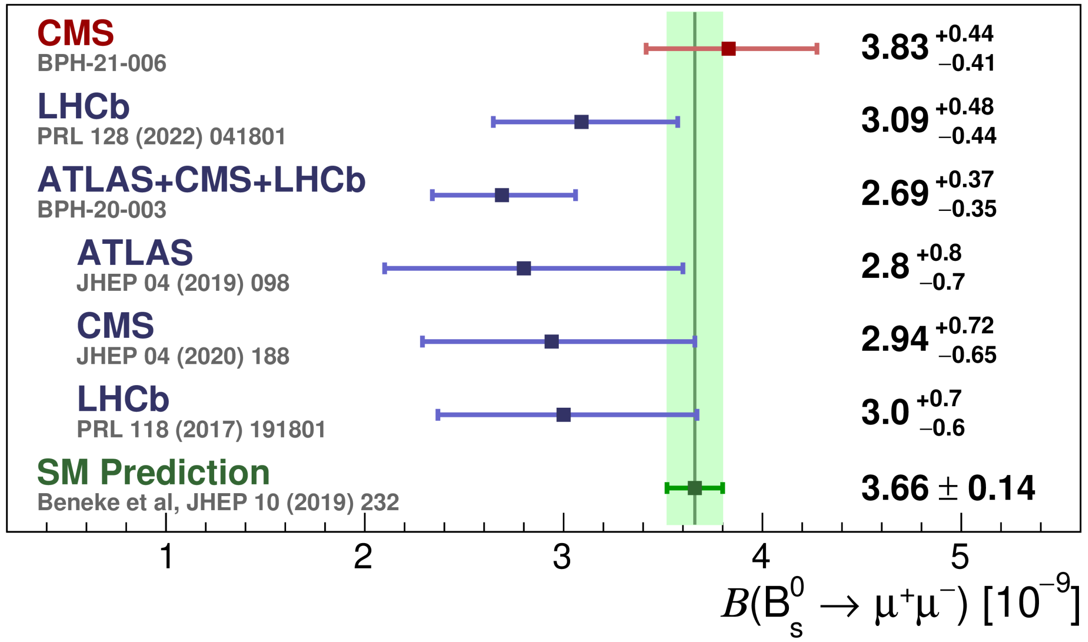
$$B(B_s^0 \to \mu^+\mu^-) = (3.83\,^{+0.38}_{-0.36}\,^{+0.19}_{-0.16}\,^{+0.14}_{-0.13}) \times 10^{-9}$$

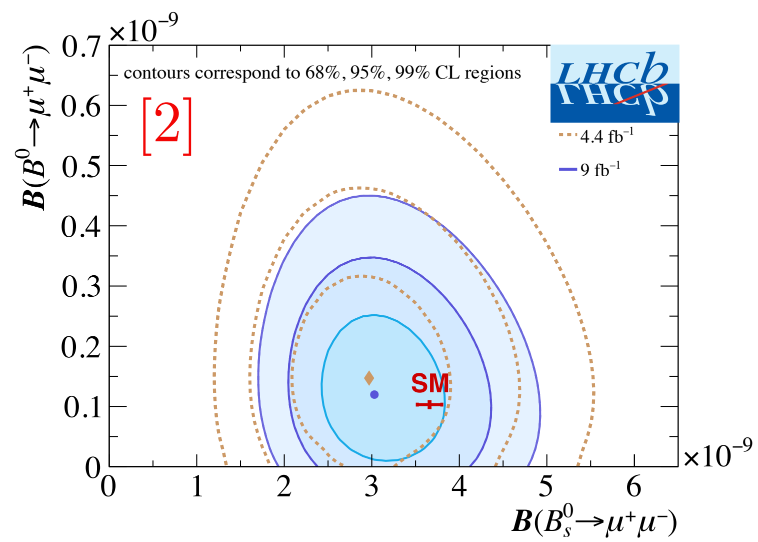
$$B(B^0 \to \mu^+\mu^-) = (0.37\,^{+0.75}_{-0.67}\,^{+0.08}_{-0.09}) \times 10^{-10}$$

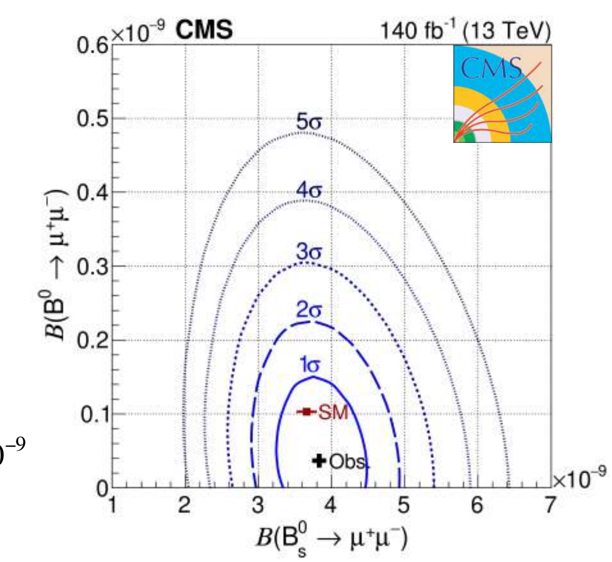
ATLAS

$$B(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.8}_{-0.7}) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$







Current world average dominated by LHCb+CMS

CBPF

The $B^0 \to K^{*0}\mu^+\mu^-$ Decay Mode

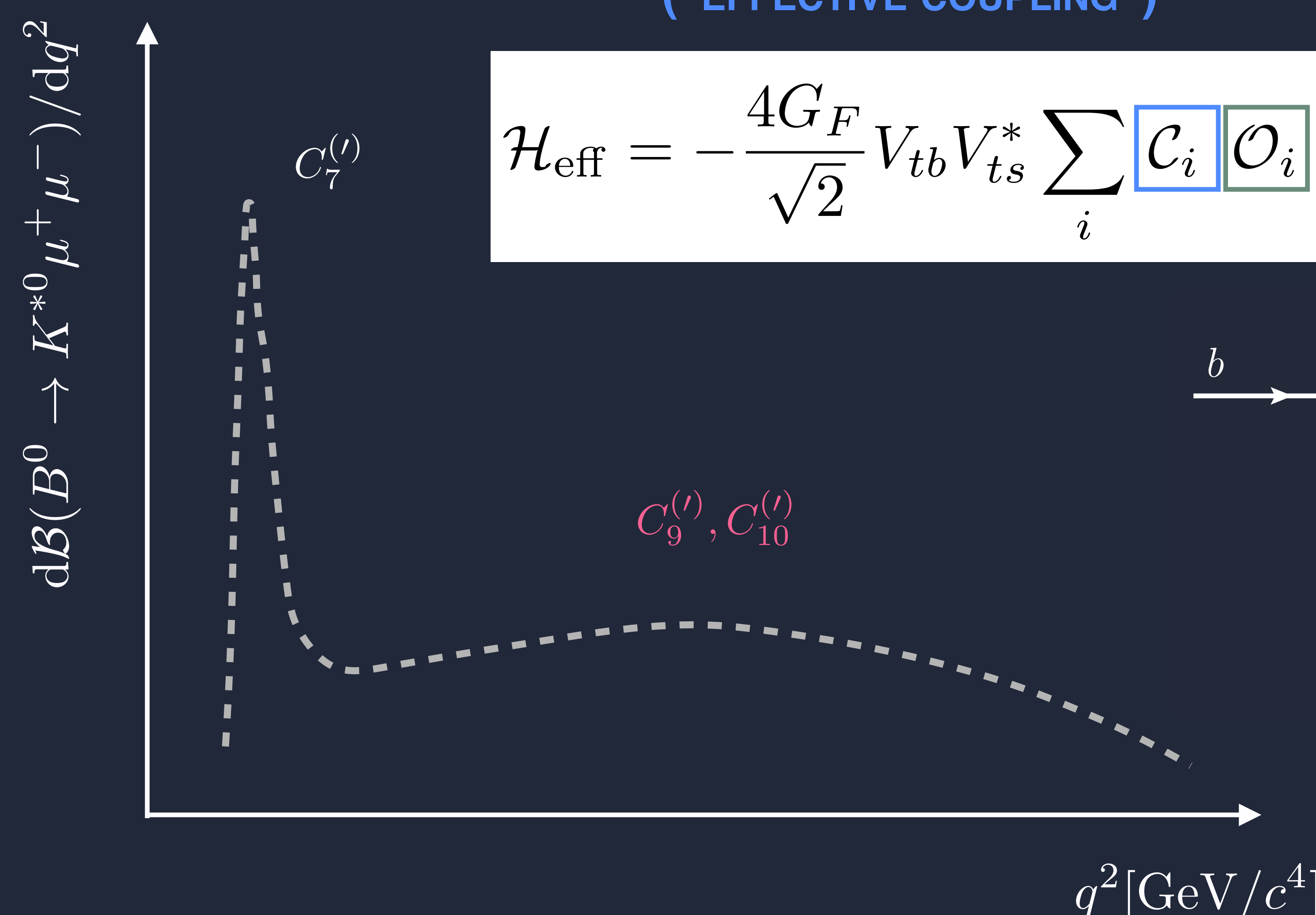
$$\mathcal{A}_\lambda^{L,R} \propto \left[\boxed{(C_9 \pm C_9') \mp (C_{10} \pm C_{10}')}\right] \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[\boxed{(C_7 \pm C_7')}\mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]$$

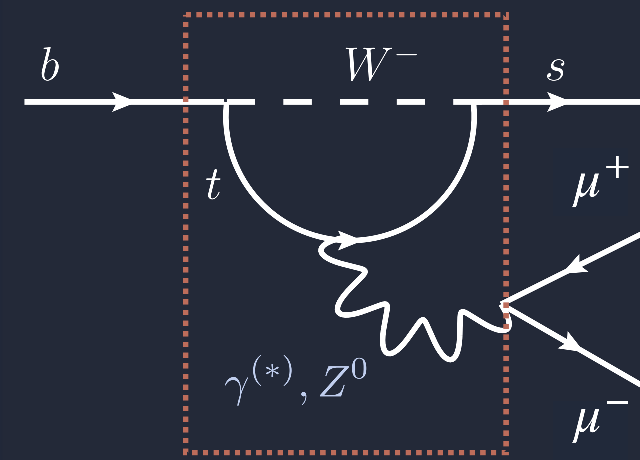
Wilson coefficients ("effective coupling")

Local operator

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \boxed{\mathcal{C}_i}\,\boxed{\mathcal{O}_i}$$

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin



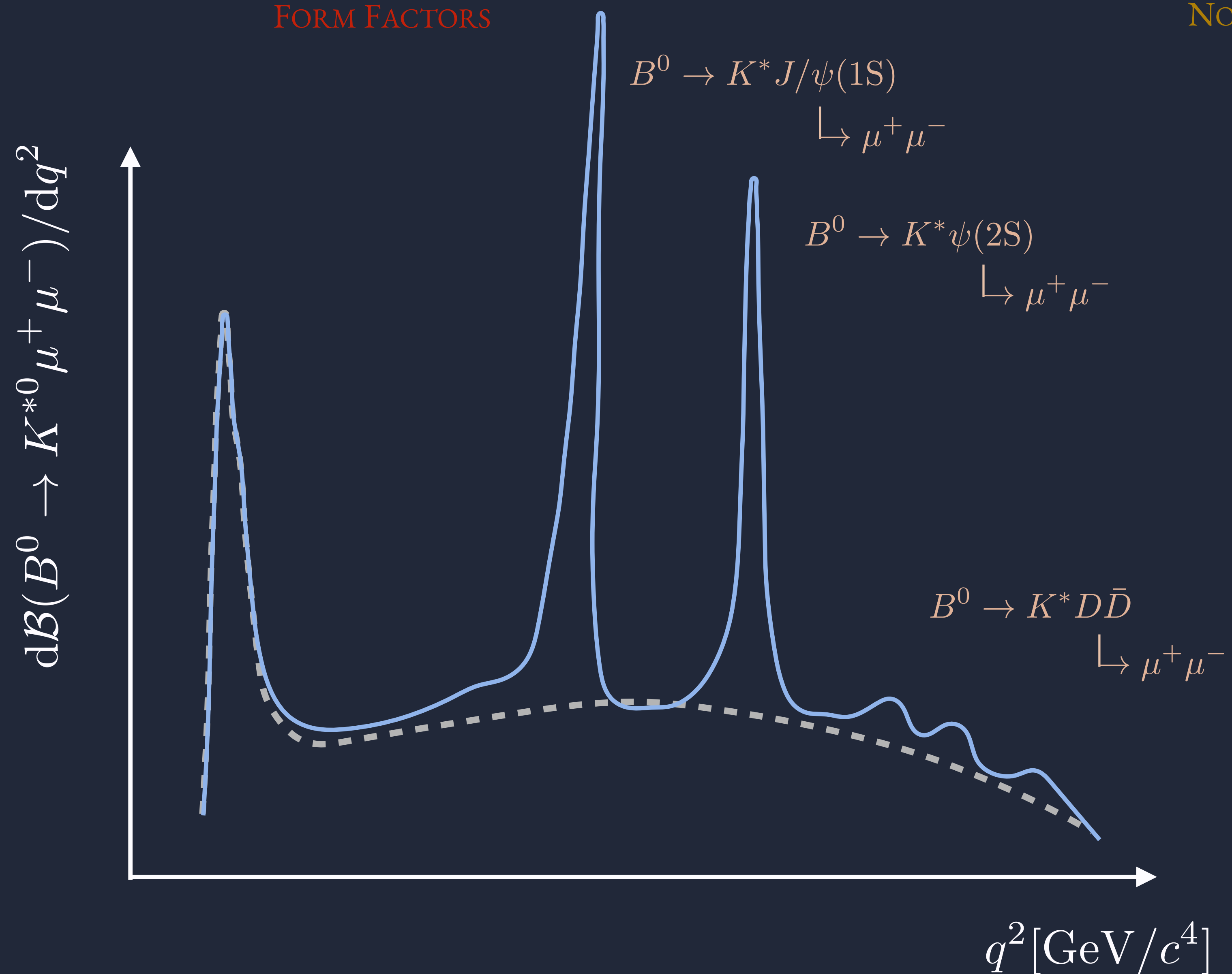


$\mathcal{C}_7, \mathcal{C}_{9,10}$

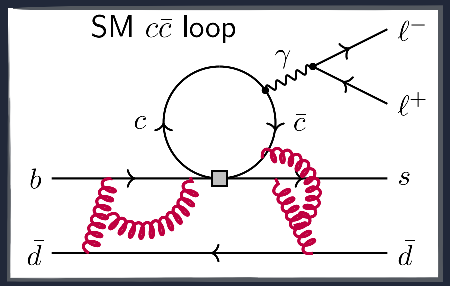
The $B^0 \to K^{*0}\mu^+\mu^-$ Decay Mode

$$\mathcal{A}_\lambda^{L,R} \propto \left[(C_9 \pm C_9') \mp (C_{10} \pm C_{10}')\right]\underline{\mathcal{F}_\lambda(q^2)} + \frac{2m_b M_B}{q^2}\left[(C_7 \pm C_7')\underline{\mathcal{F}_\lambda^T(q^2)} - 16\pi^2 \frac{M_B}{m_b}\underline{\mathcal{H}_\lambda(q^2)}\right]$$

Form Factors



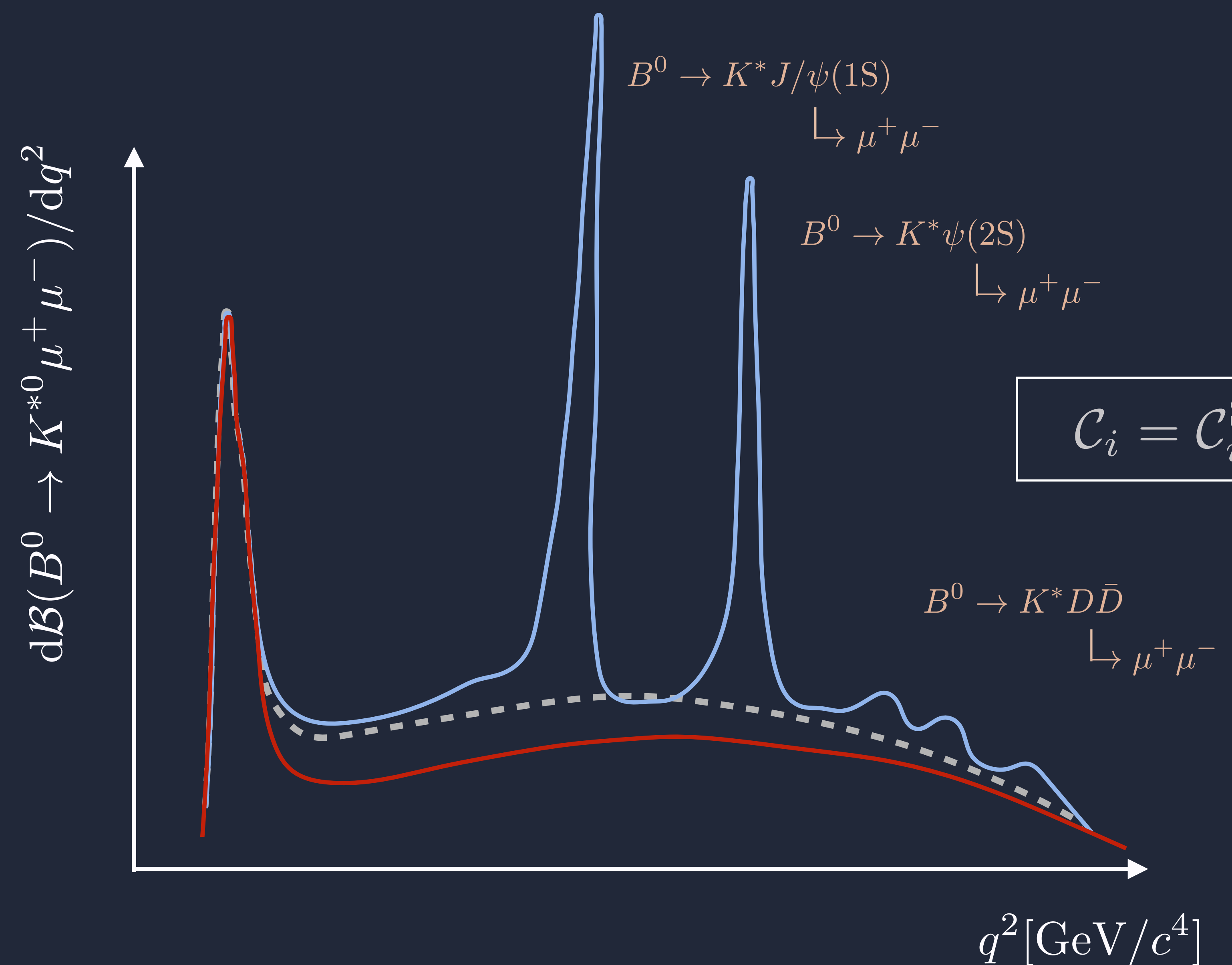
Non-Local contributions
"Charm Loops"



$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9^{\text{SM}} + \mathcal{C}_9^{c\bar{c}}$$

The $B^0 \to K^{*0}\mu^+\mu^-$ Decay Mode

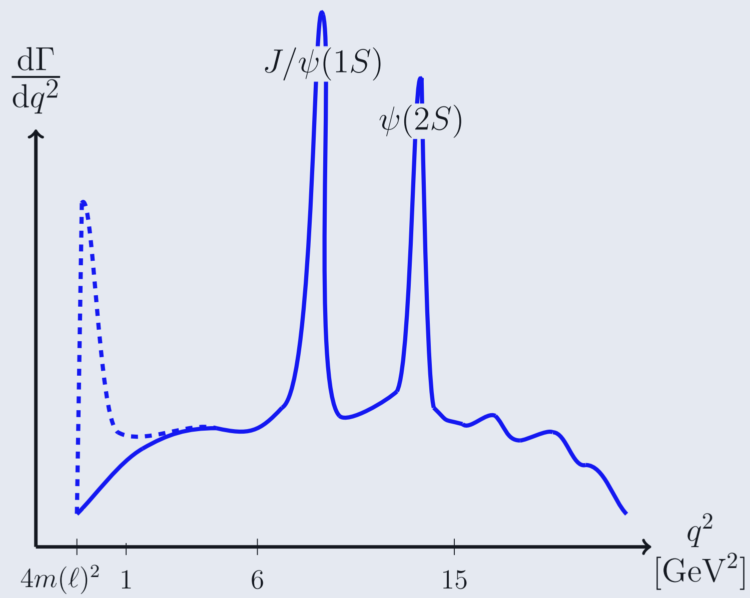
$$\mathcal{A}_\lambda^{L,R} \propto \left[(C_9 \pm C_9') \mp (C_{10} \pm C_{10}')\right]\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[(C_7 \pm C_7')\mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]$$



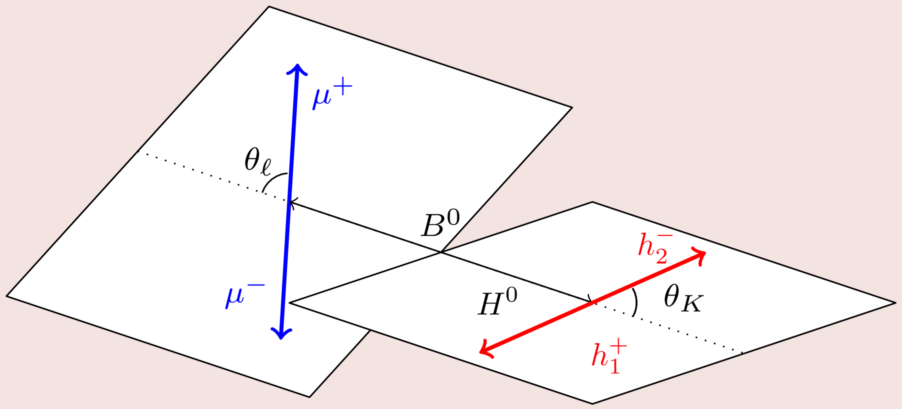
$$\mathcal{C}_i = \mathcal{C}_i^{\mathrm{SM}} + \mathcal{C}_i^{\mathrm{NP}} + \mathcal{C}_i^{\mathrm{had}}$$

THE FLAVOUR ANOMALIES IN $b \to s\mu^+\mu^-$

[Branching ratio]



[Angular distributions]



$$\frac{d^4\Gamma}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi} \sum_i \underbrace{I_i(q^2)}_{\to\, F_L,\, S_i,\, P_5'} f_i(\vec{\Omega})$$

HIGHER THEORY UNCERTAINTIES

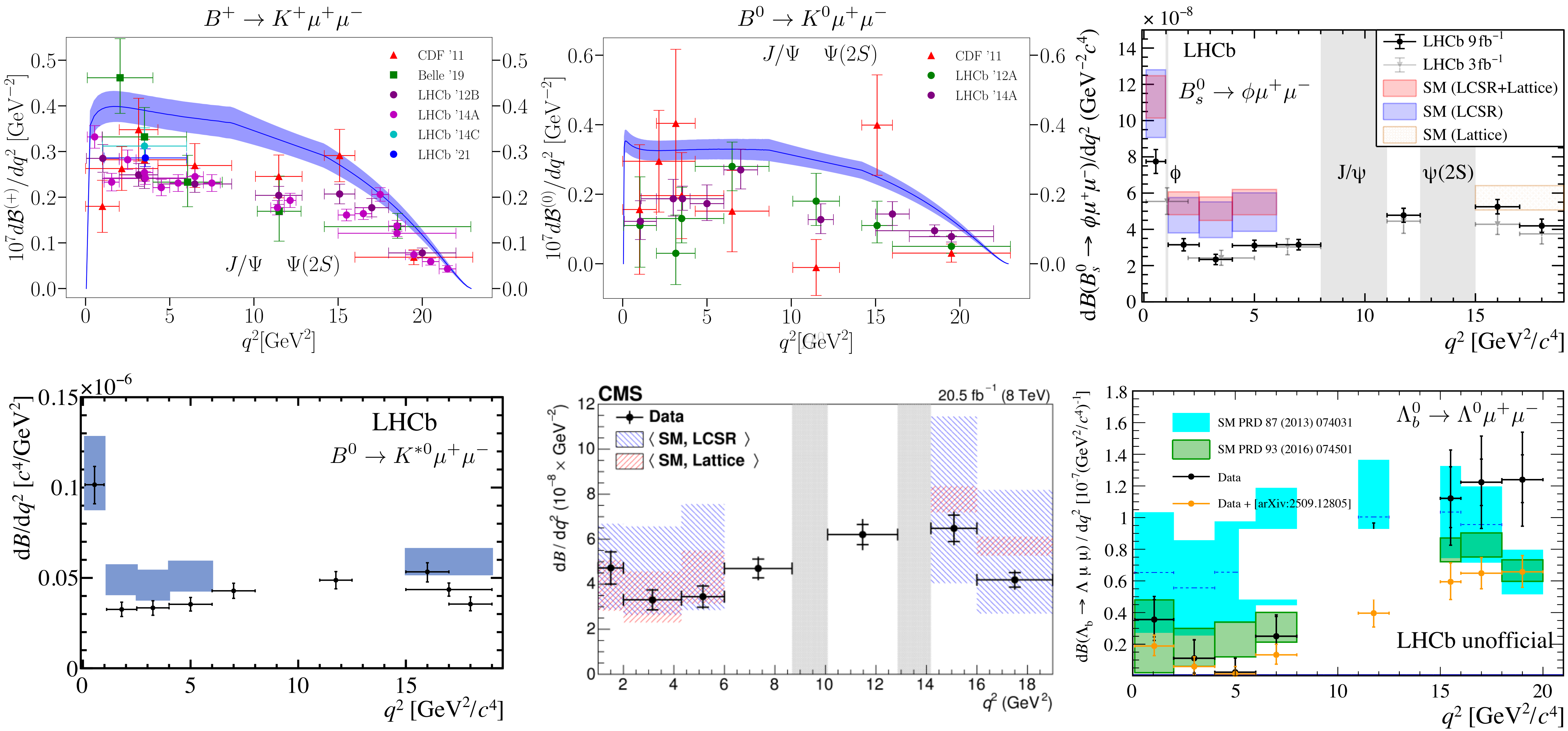
LOWER THEORY UNCERTAINTIES

$$B^0 \to \underbrace{K^{*0}}_{\text{spin-1}}[K\pi]\mu^+\mu^-$$

$$\mathcal{A}_\lambda^{(\ell)\,L,R} = \mathcal{N}_\lambda^{(\ell)} \left\{ (C_9^{(\ell)} \mp C_{10}^{(\ell)}) \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[C_7^{(\ell)} \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

$b \to s\mu^+\mu^-$ DECAY RATES

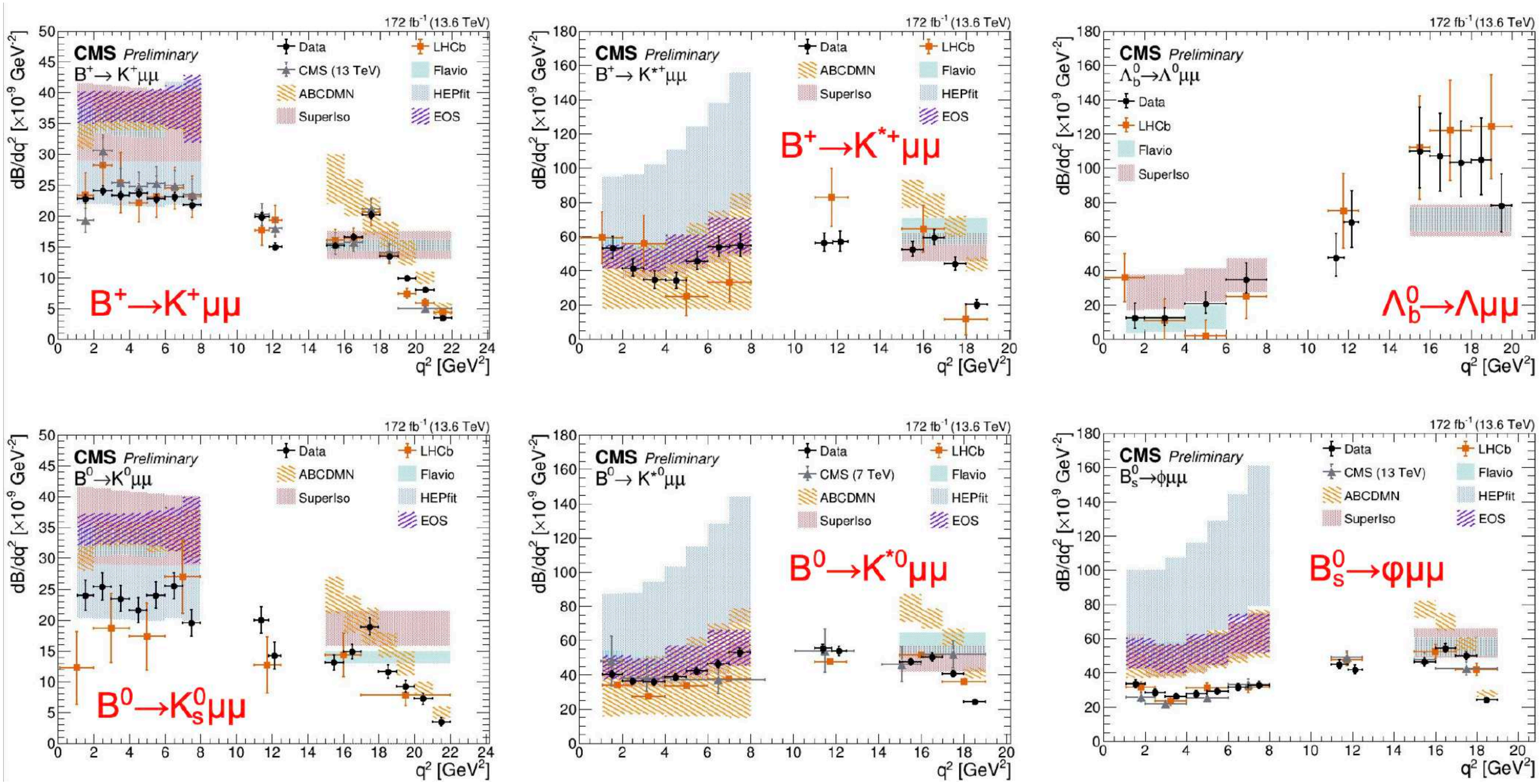
[LHCb, JHEP 06 (2014) 133, 11 (2016) 047, 06 (2015) 115, PRL 127 (2021) 151801, CMS, PLB 753 (2016) 424]



IMPORTANT RESULTS FROM LATTICE QCD [HPQCD, PRD 107 (2023) 1] AND UPDATE ON $\Lambda^0_b \to J/\psi\Lambda$

$b \to s\mu^+\mu^-$ DECAY RATES

[CMS-PAS-BPH-24-005 (in preparation)]

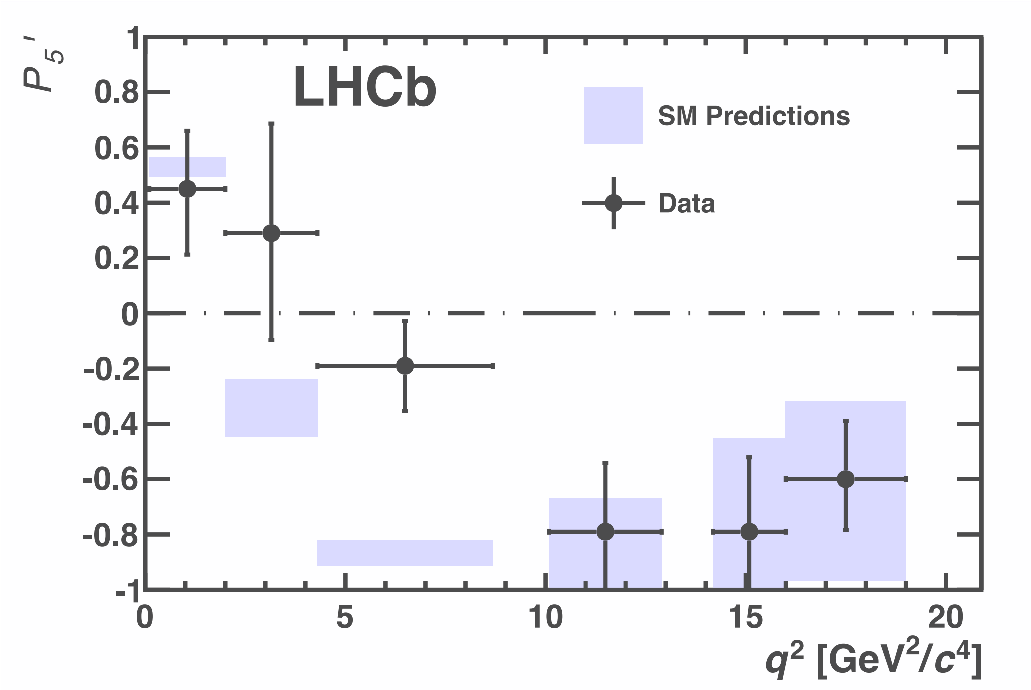


$b \to s\mu^+\mu^-$ ANGULAR ANALYSES

[LHCb, JHEP 06 (2014) 133, 11 (2016) 047, 06 (2015) 115, PRL 127 (2021) 151801, CMS, PLB 753 (2016) 424]

(IN)FAMOUS P_5'

(10TH + 3) YEAR ANNIVERSARY!



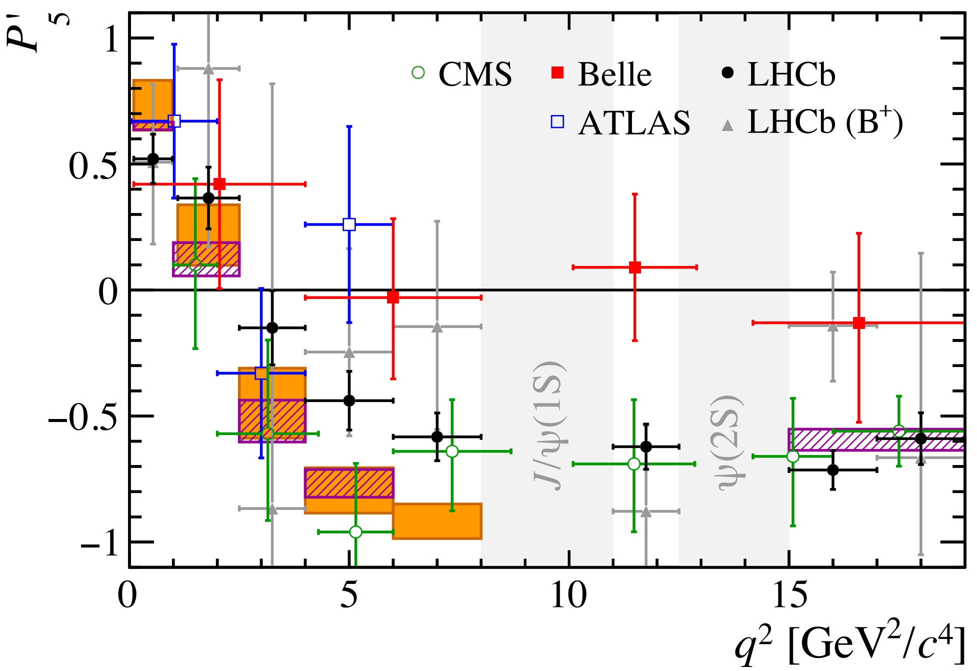
LEADING FORM FACTORS UNCERTAINTIES ARE CANCELLED

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

[JHEP 1204 (2012) 104]

[W. Altmannshofer, D. Straub, EPJC 75 (2015) 8]

[S. Descotes-Genon, L. Hofer, J. Matias, J. Virto, JHEP 12 (2014) 125]

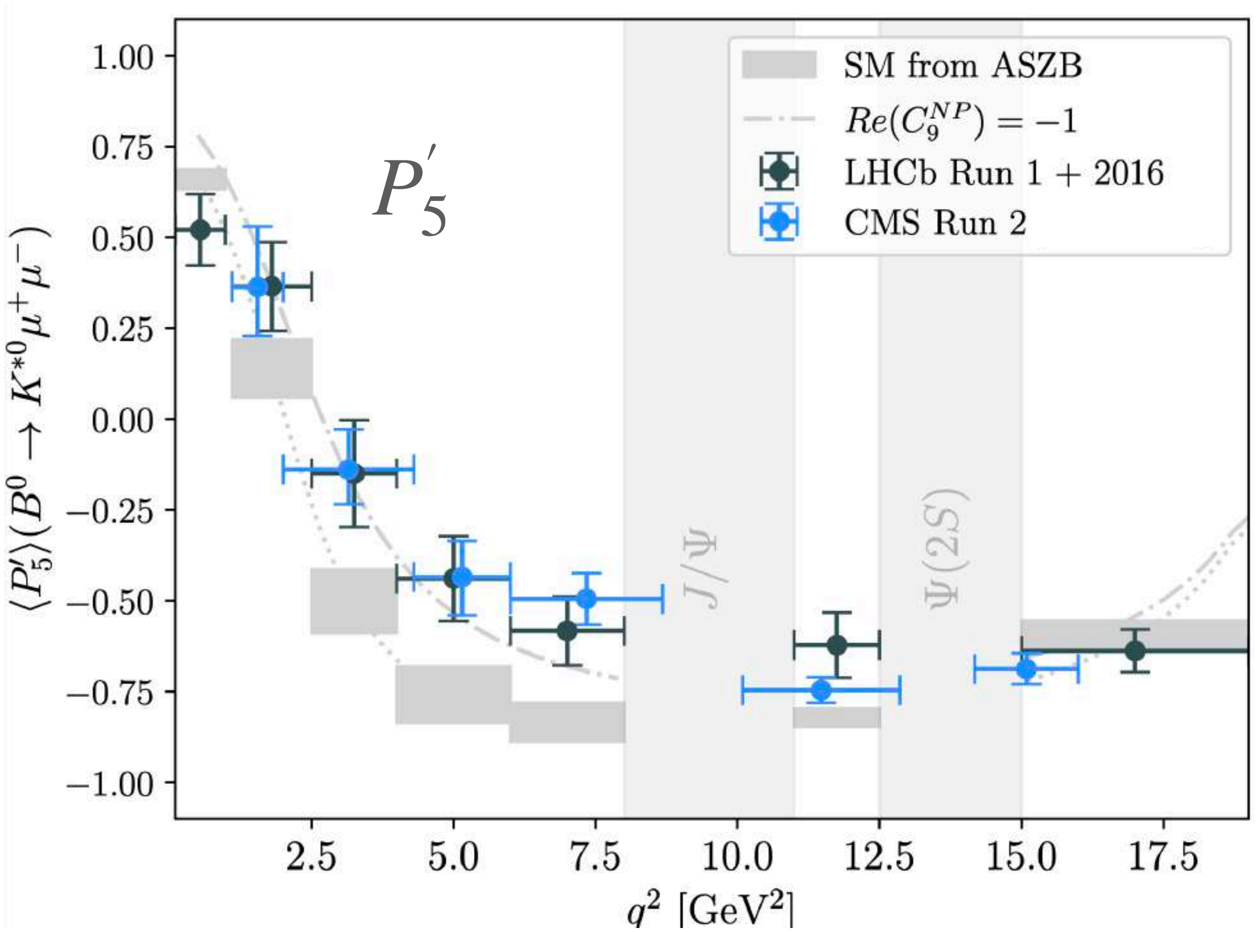


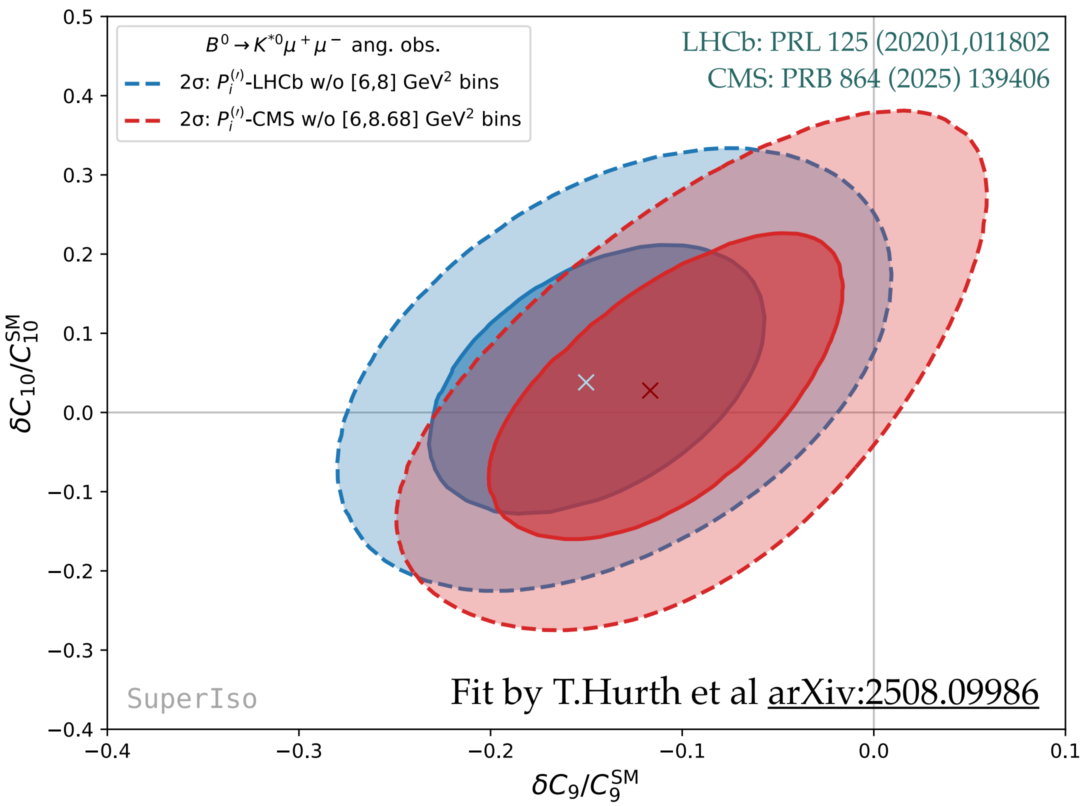
SIMILAR DISCREPANCY WRT THE SM PREDICTIONS + OTHER CHANNELS

$b \to s\mu^+\mu^-$ ANGULAR ANALYSES

[LHCb, PRL 125 (2020) 011802, CMS, PRB 864 (2025) 139406]

(IN)FAMOUS P_5'



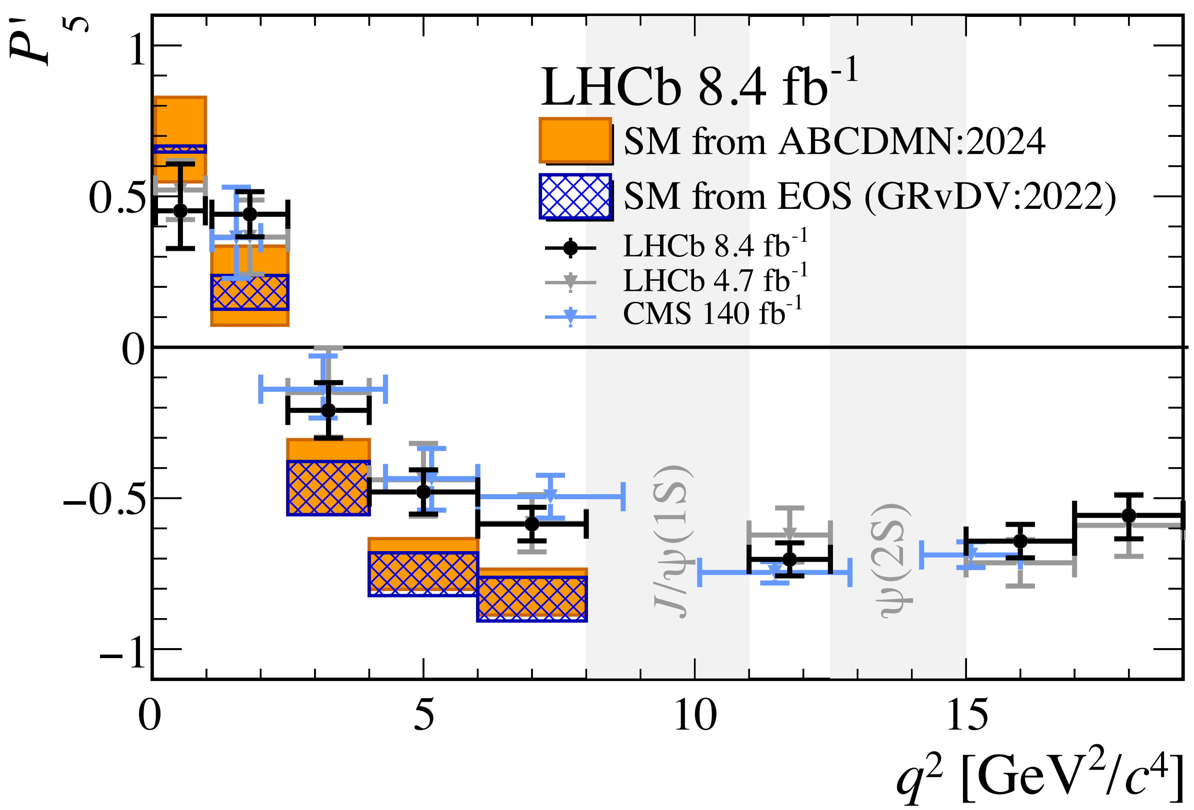


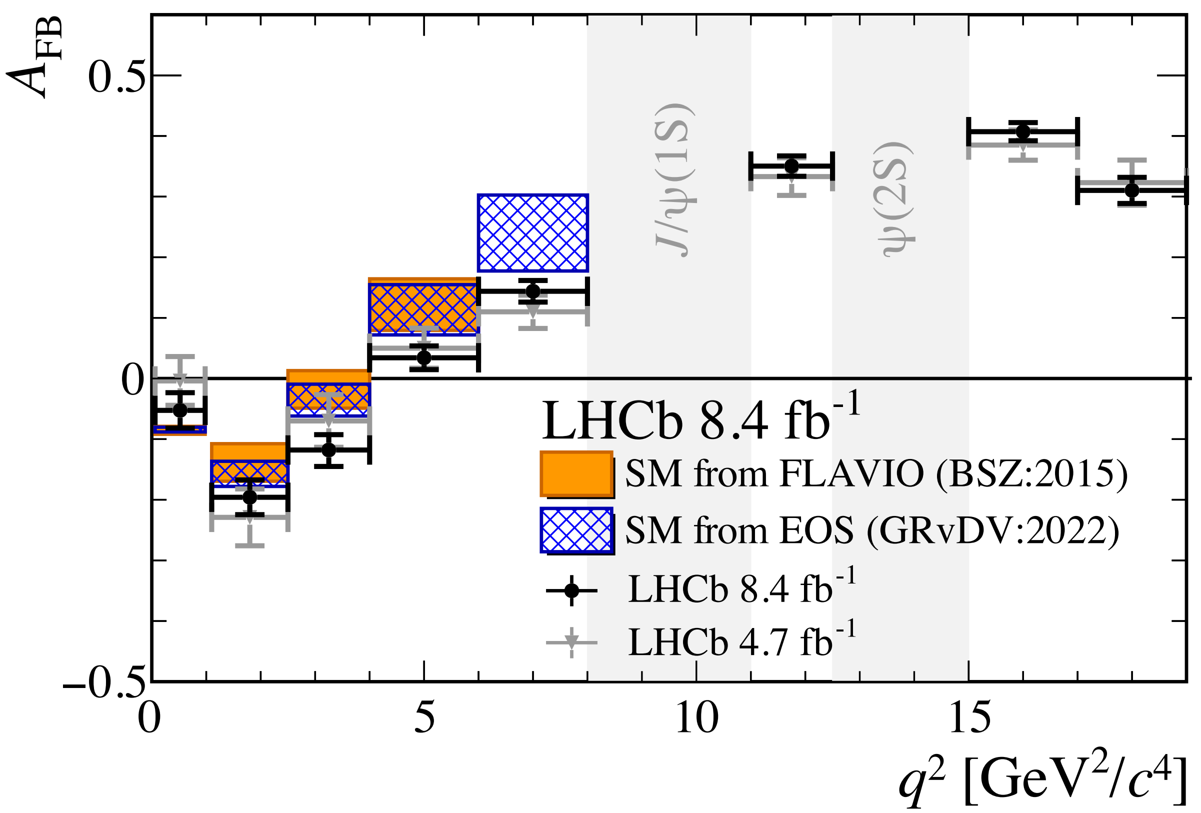
CMS RUN 2 RESULTS ARE CONSISTENT WITH PREVIOUS LHCB ONE AND PATTERN OF DISCREPANCY WRT THE SM

$b \to s\mu^+\mu^-$ ANGULAR ANALYSES

[LHCb-PAPER-2025-041 (in preparation), CMS, PRB 864 (2025) 139406]

(IN)FAMOUS P_5'





P_5' IN EXCELLENT AGREEMENT WITH BOTH CMS AND PREVIOUS LHCB

TENSION NOW ARE ALSO MORE PRONOUNCED IN A_{FB}

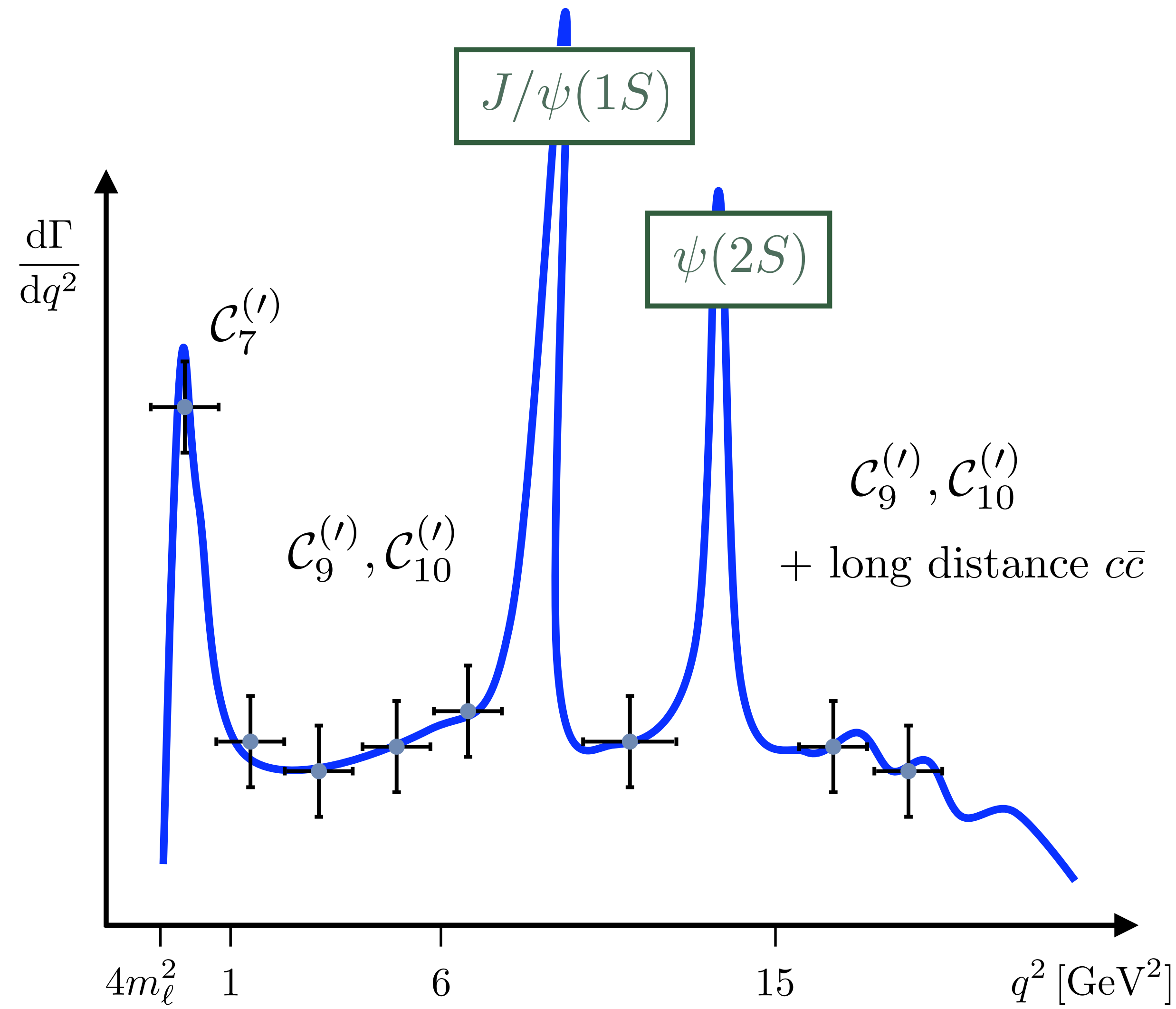
[M. Algueró, A. Biswas, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet, EPJC 83 (2023) 7, 648

[N. Gubernari, M. Reboud, D. Van Dyk, J. Virto, JHEP 09 (2022) 133]

$b \to s\mu^+\mu^-$ AMPLITUDE ANALYSES

[LHCb, PRL 132 (2024) 131801, PRD 109 (2024) 052009), JHEP 09 (2024) 026]

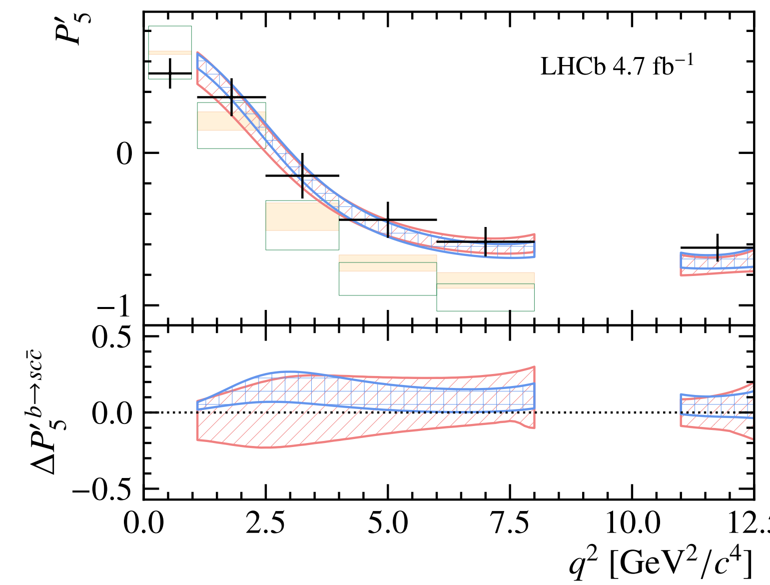
TO "BIN" OR NOT TO "BIN"



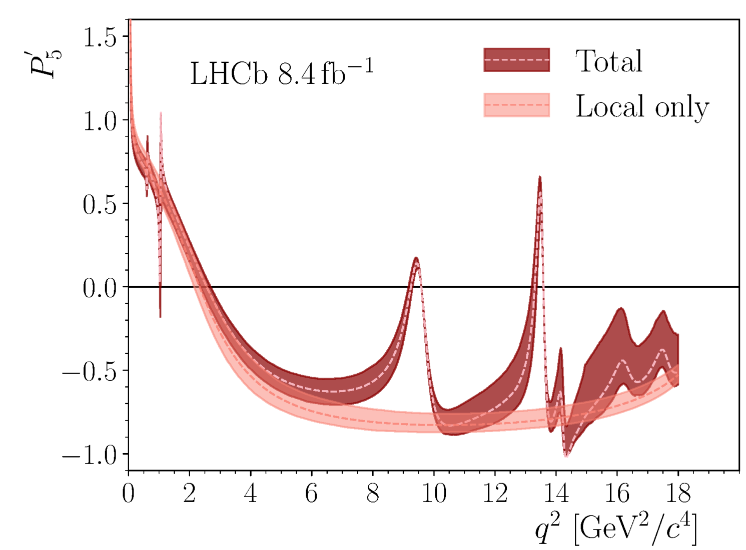
[Angular]: A_{FB}, F_L, P'_5, …

[Amplitude]: C_9, C_{10}, hadronic terms …

Z-EXPANSION



ISOBAR MODEL



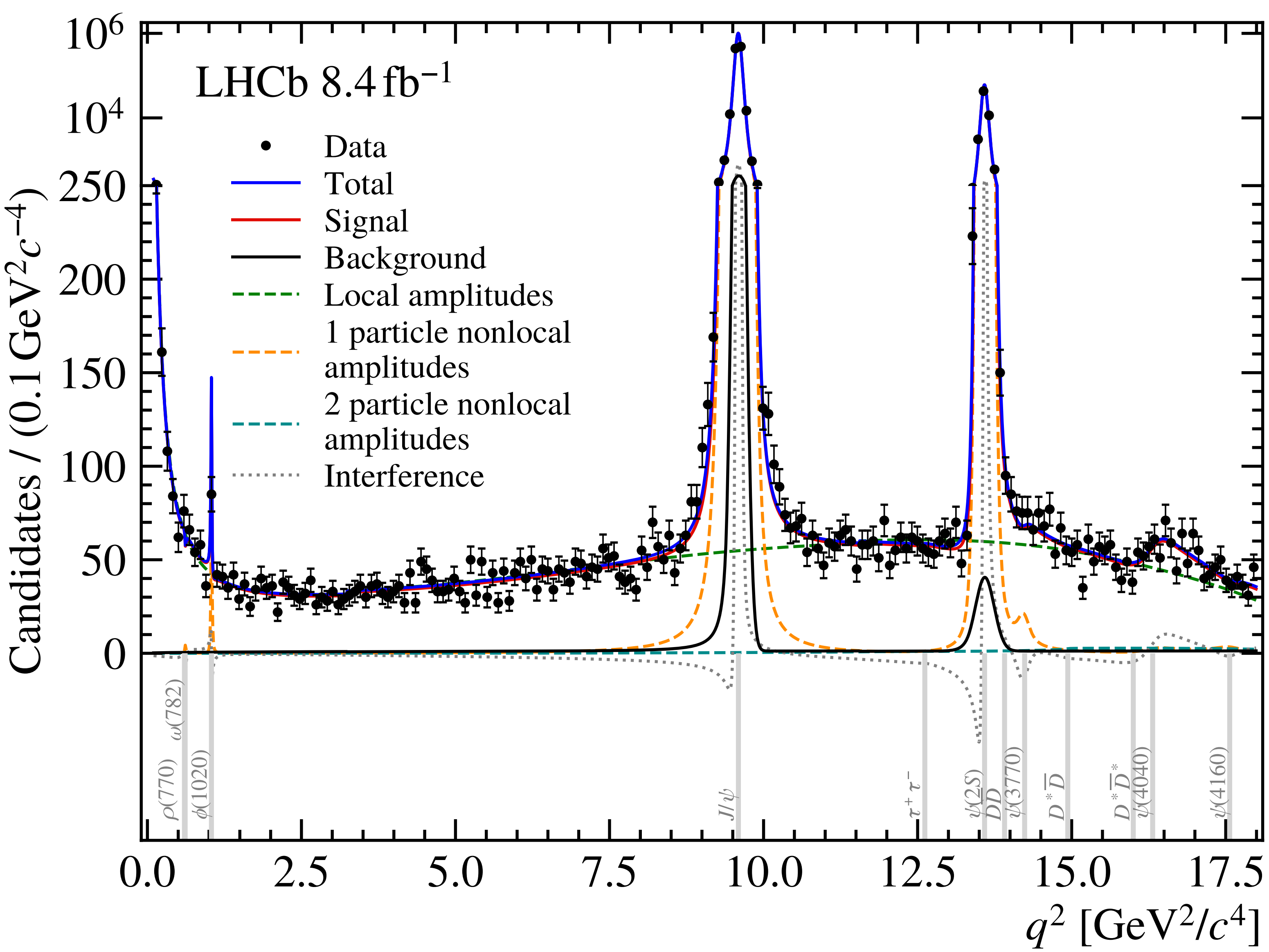
EXCELLENT AGREEMENT WITH ANGULAR ANALYSES

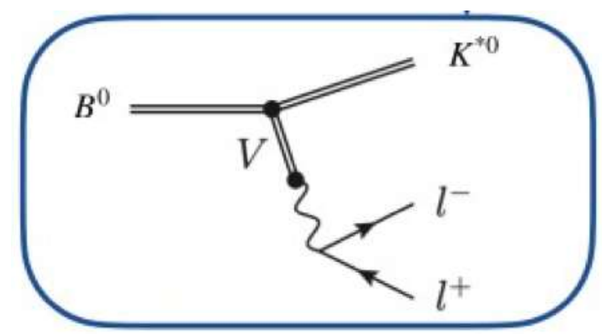
$b \to s\mu^+\mu^-$ AMPLITUDE ANALYSES

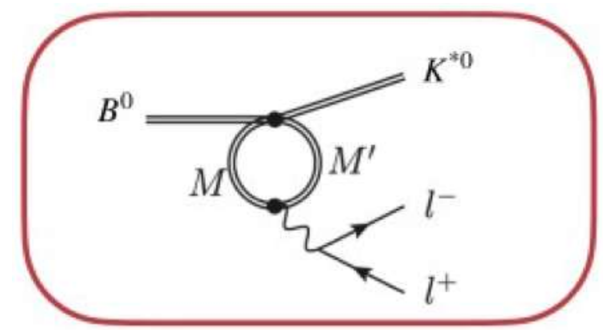
[LHCb, JHEP 09 (2024) 026]

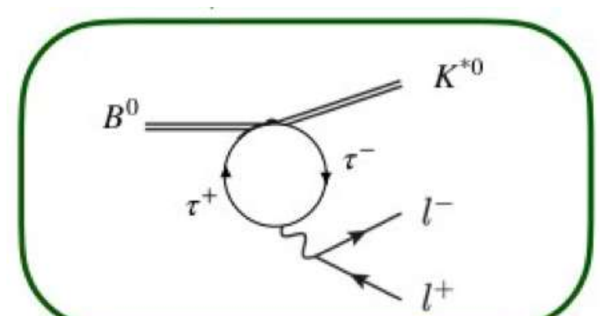
AN "ISOBAR MODEL" APPROACH:

$$C_9^{eff,\lambda}(q^2) = C_9^{\mu} + Y_{c\bar{c}}^{(0),\lambda} + \boxed{\left(Y_{c\bar{c}}^{1P,\lambda}(q^2) + Y_{light}^{1P,\lambda}(q^2)\right)} + \boxed{Y_{c\bar{c}}^{2P,\lambda}(q^2)} + \boxed{Y_{\tau\bar{\tau}}(q^2)}$$









On the theoretical uncertainties

[Gubernari, Reboud, van Dyk, Virto; arXiv:2305.06301]

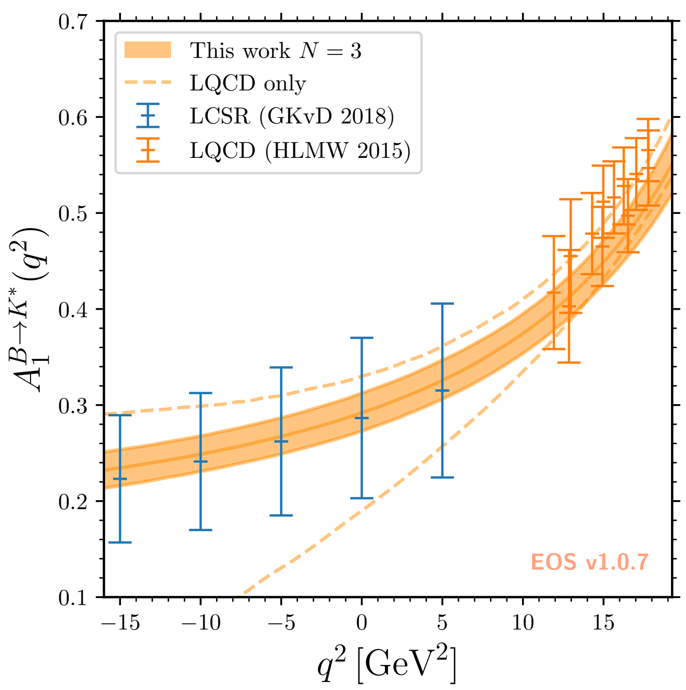
Local form factors (FFs) constrained to:

- Light-cone sum rules

  [Gubernari, Kokulu, van Dyk; JHEP 01 (2019) 150]

- Lattice QCD

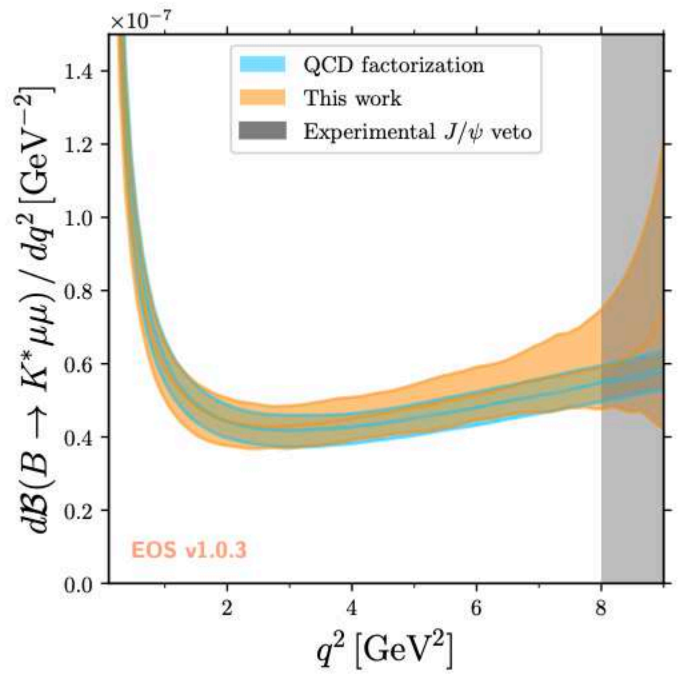
  [Horgan, Liu, meinel, Wingate;
  PRD 89 (2014) 094501
  PoS LATTICE2014 (2015) 372]



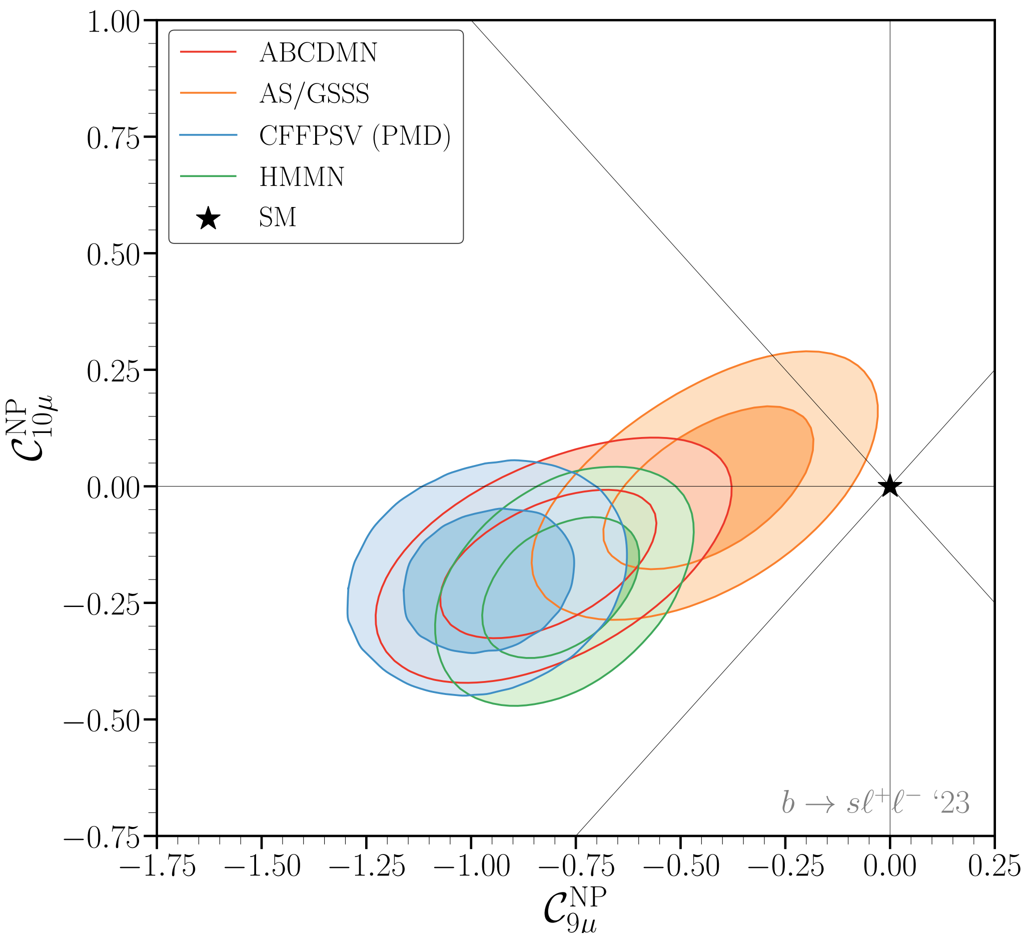
Exploit Analytical Properties of Hadronic Matrix, i.e. analycity, unitarity and known resonances

Bobeth, Chrzaszcz, van Dyk, Virto; EPJC 78 (2018) 451
Gubernari, van Dyk, Virto; JHEP 02 (2021) 088
Gubernari, Reboud, van Dyk, Virto; JHEP 09 (2022) 133

$$\mathcal{H}_\lambda(z) = \frac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \times \ldots \times \sum_n \boxed{\alpha_{\lambda,n}} \boxed{z^n}$$



$b \to s\ell^+\ell^-$ ANOMALIES INTERPRETATION

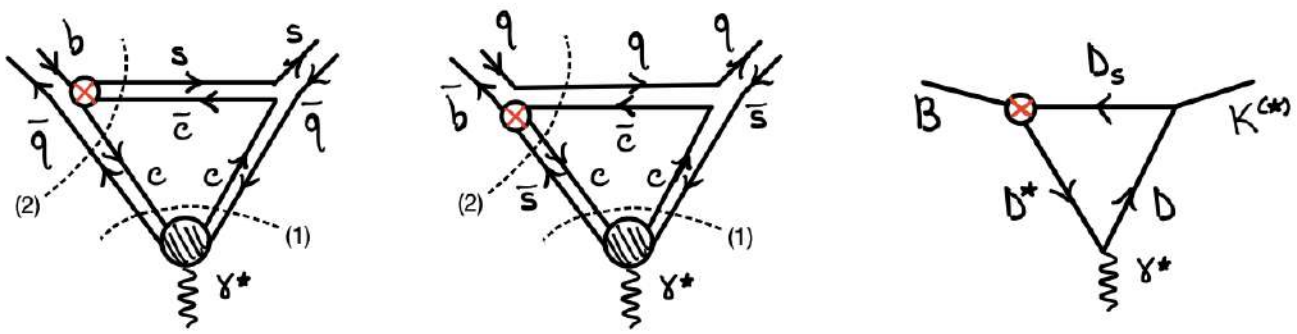


STILL REMAINS A PREFERENCE FOR A SHIFT IN C_9^{NP}

ARE WE GOING TO BE ABLE TO CLAIM NEW PHYSICS?

HADRONIC PHYSICS COMES AGAIN!

CHARM RE-SCATTERING MIGHT NOT BE ACCOUNTED IN CURRENT CALCULATIONS

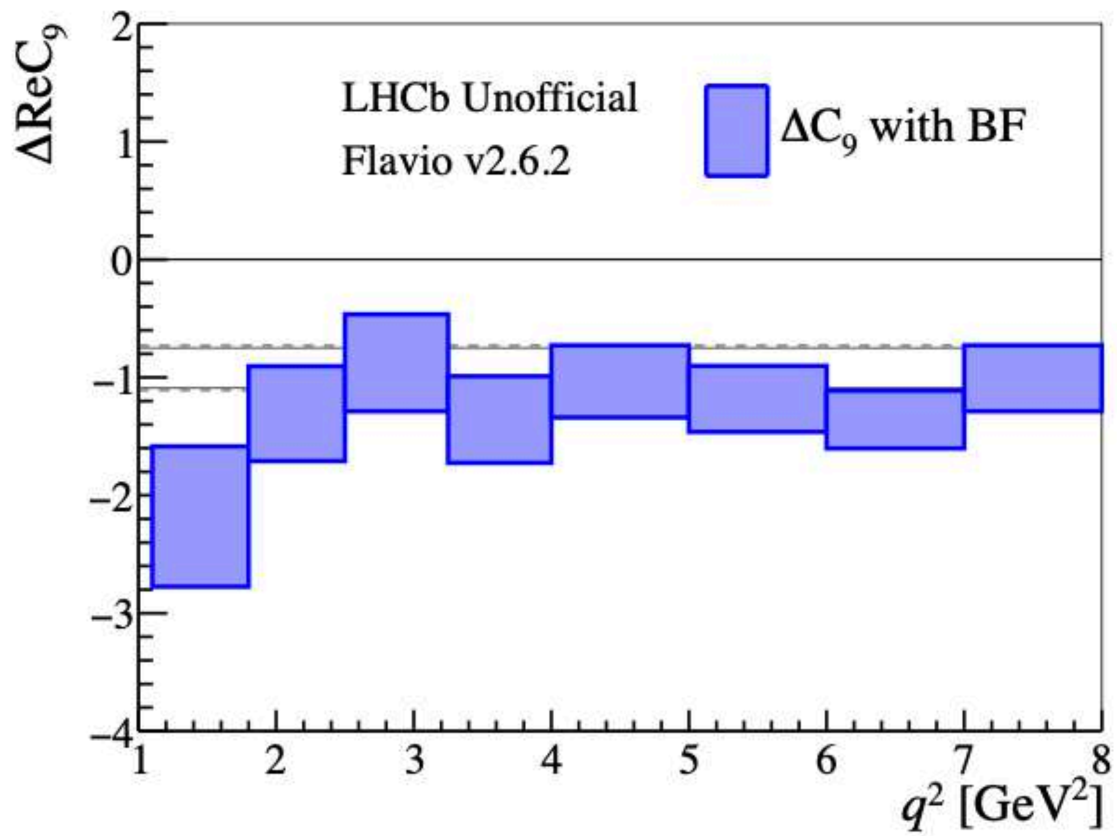


[Ciuchini, Fedele, Franco, Paul, Silvestrini, Valli, 2212.10516]

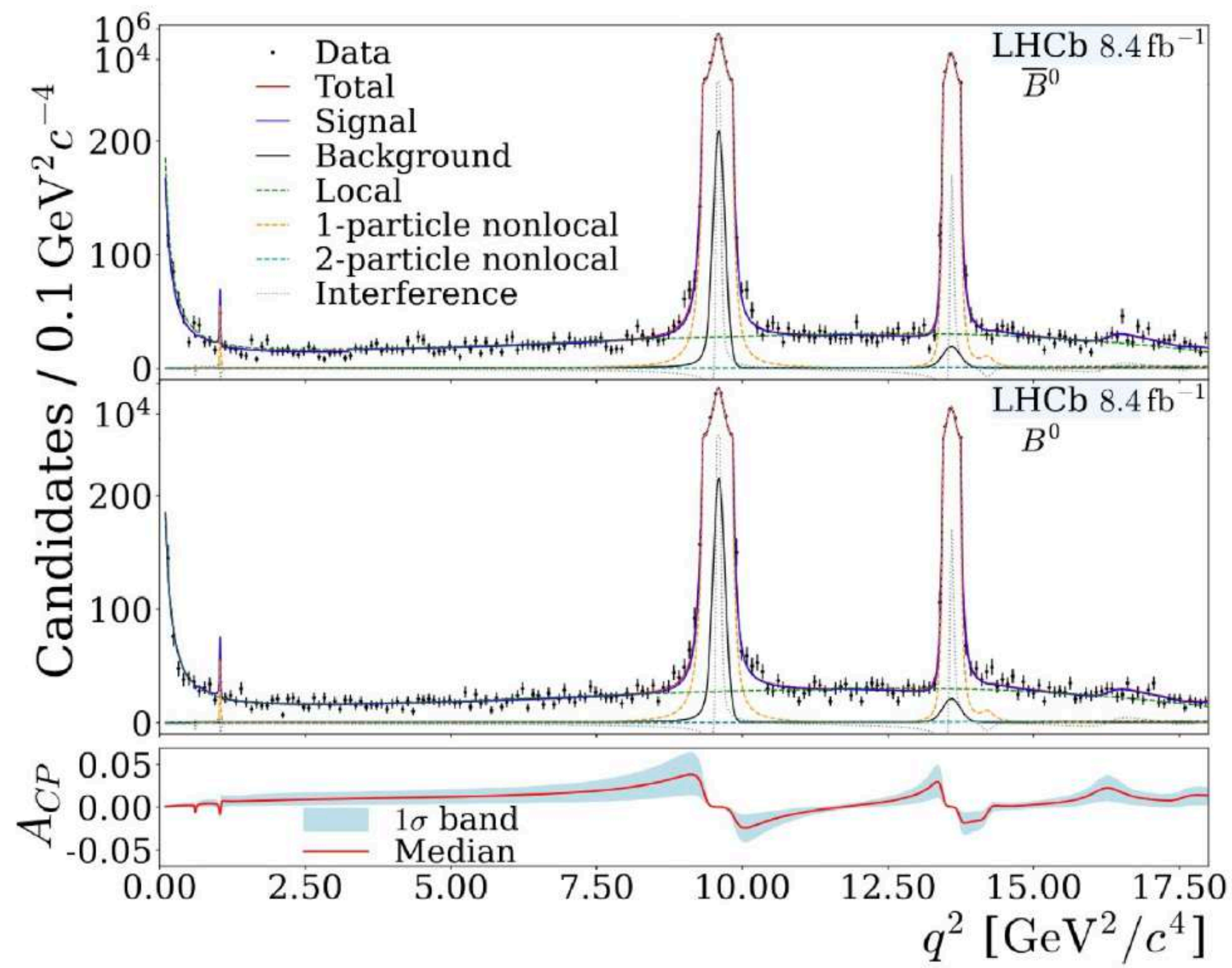
A HIGH LEVEL OF CONSPIRACY SEEMS TO BE REQUIRED TO EXPLAIN THE ANOMALIES DUE TO THESE CONTRIBUTIONS

Isidori, Polonsky, Tinari, 2405.17551, 2507.17824]

NO CLEAR DEPENDENCE OF C_9^{NP} ON q^2 OBSERVED



MORE DATA CAN SIMPLY INDICATE IF SUCH PATTERN REMAINS CLOSE TO CHARMONIUM CONTRIBUTIONS



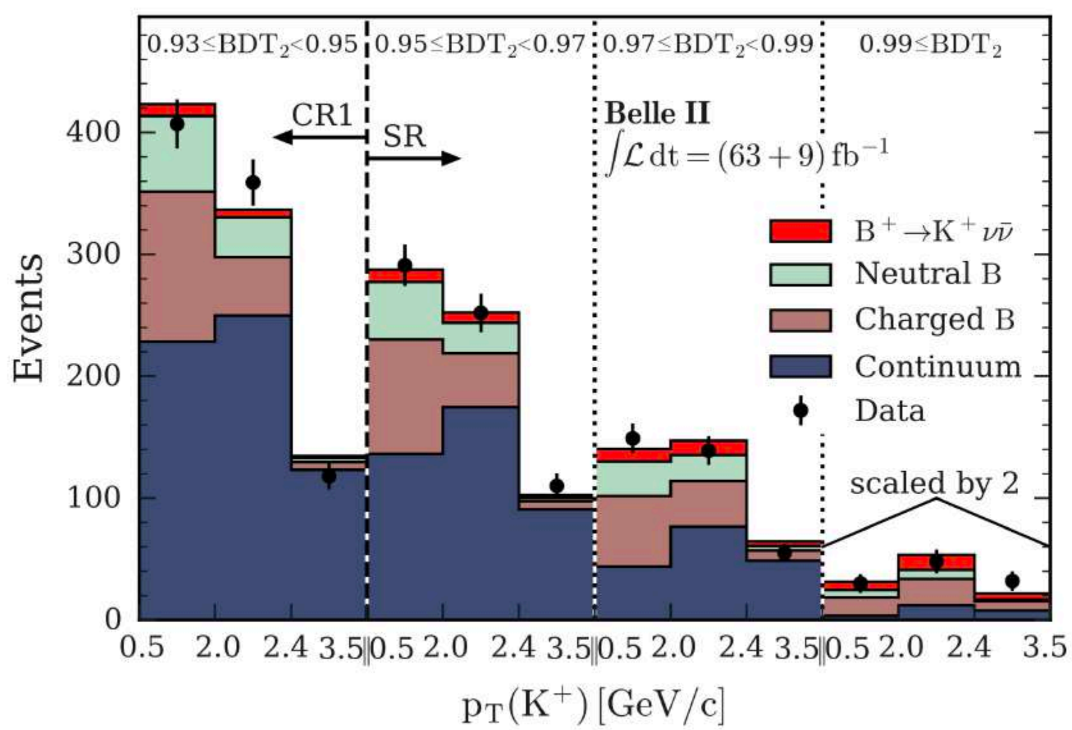
IF NP INTRODUCES NEW WEAK PHASE(S), ANY NONZERO CP VIOLATION WOULD BE A CLEAR SIGNATURE

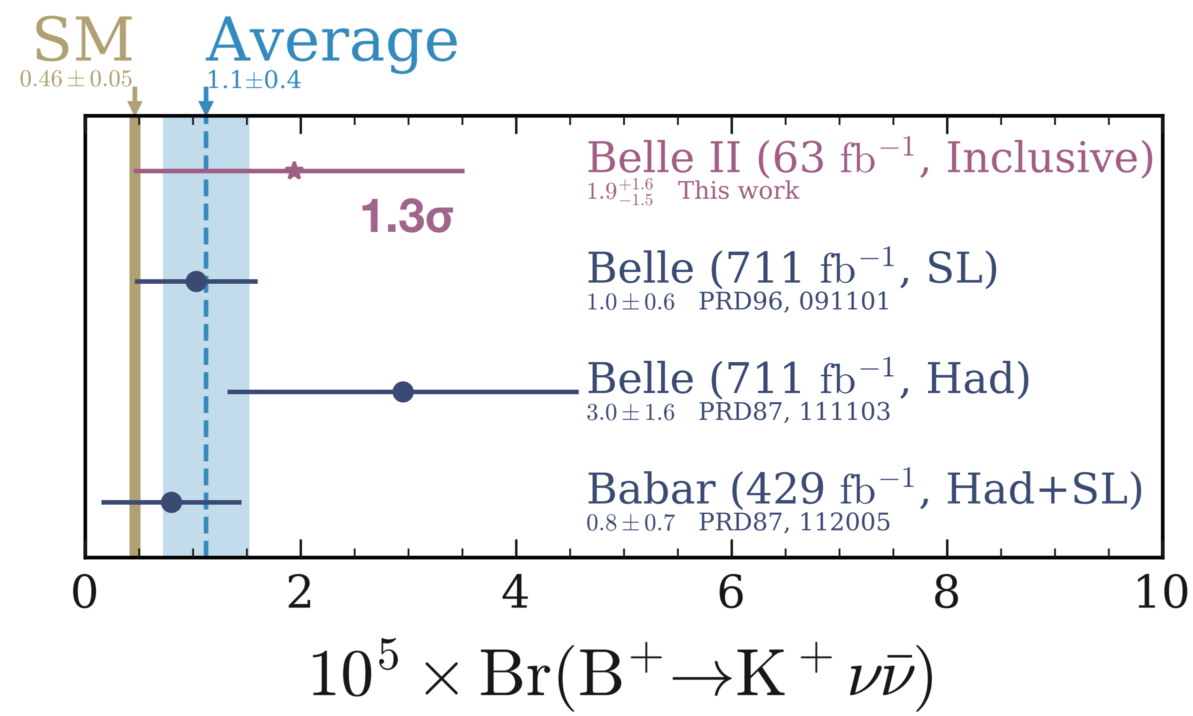
$b \to s\ell^+\ell^-$ ANOMALIES PATHS

[Belle II, PRL 127 (2021) 18, 181802]

UNIQUE PHYSICS REACH TO STUDY FINAL STATES WITH MISSING ENERGY, E.G. $B \to K^{(*)}\nu\nu$

Set a competitive limit with only 63 fb^{-1}!



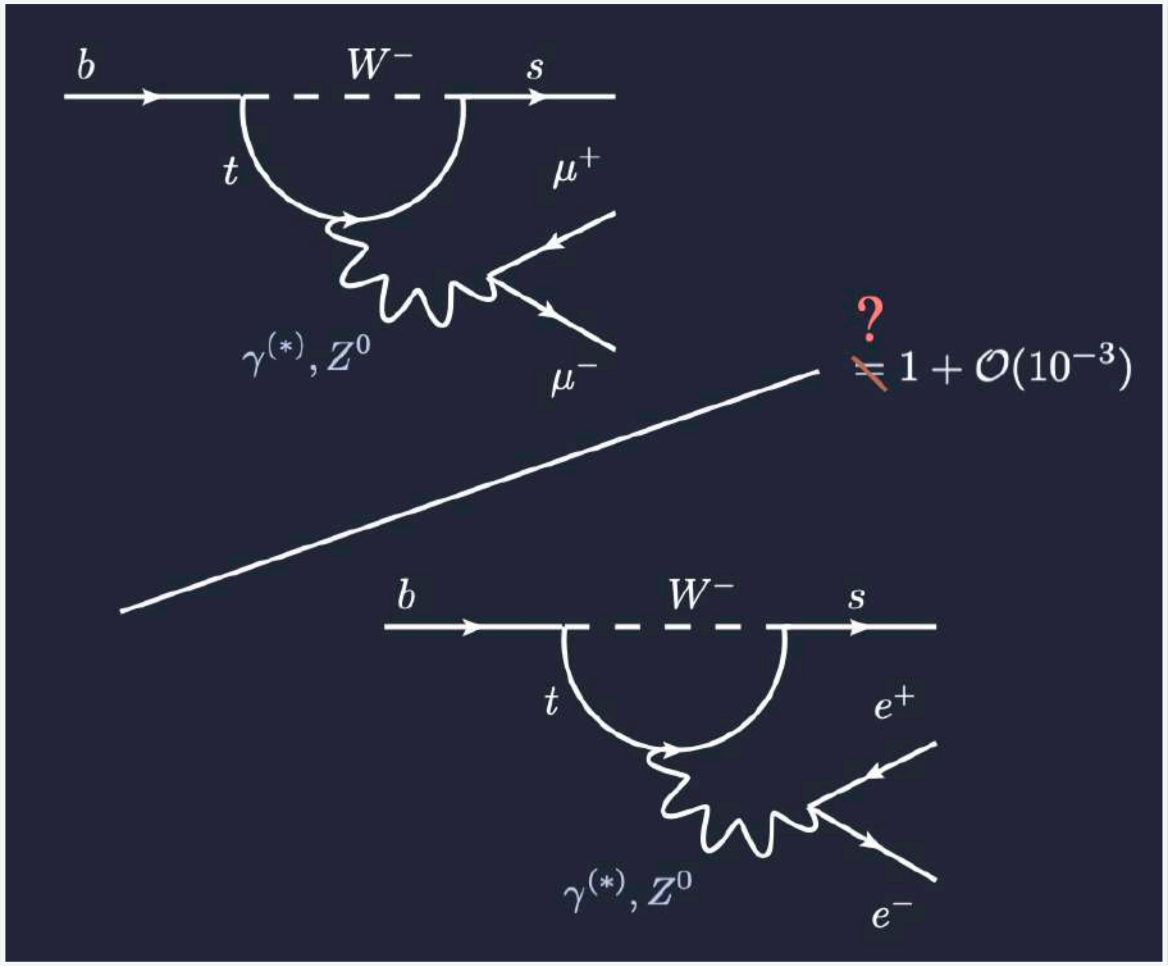


Exciting physics range to be explored!

Decay	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

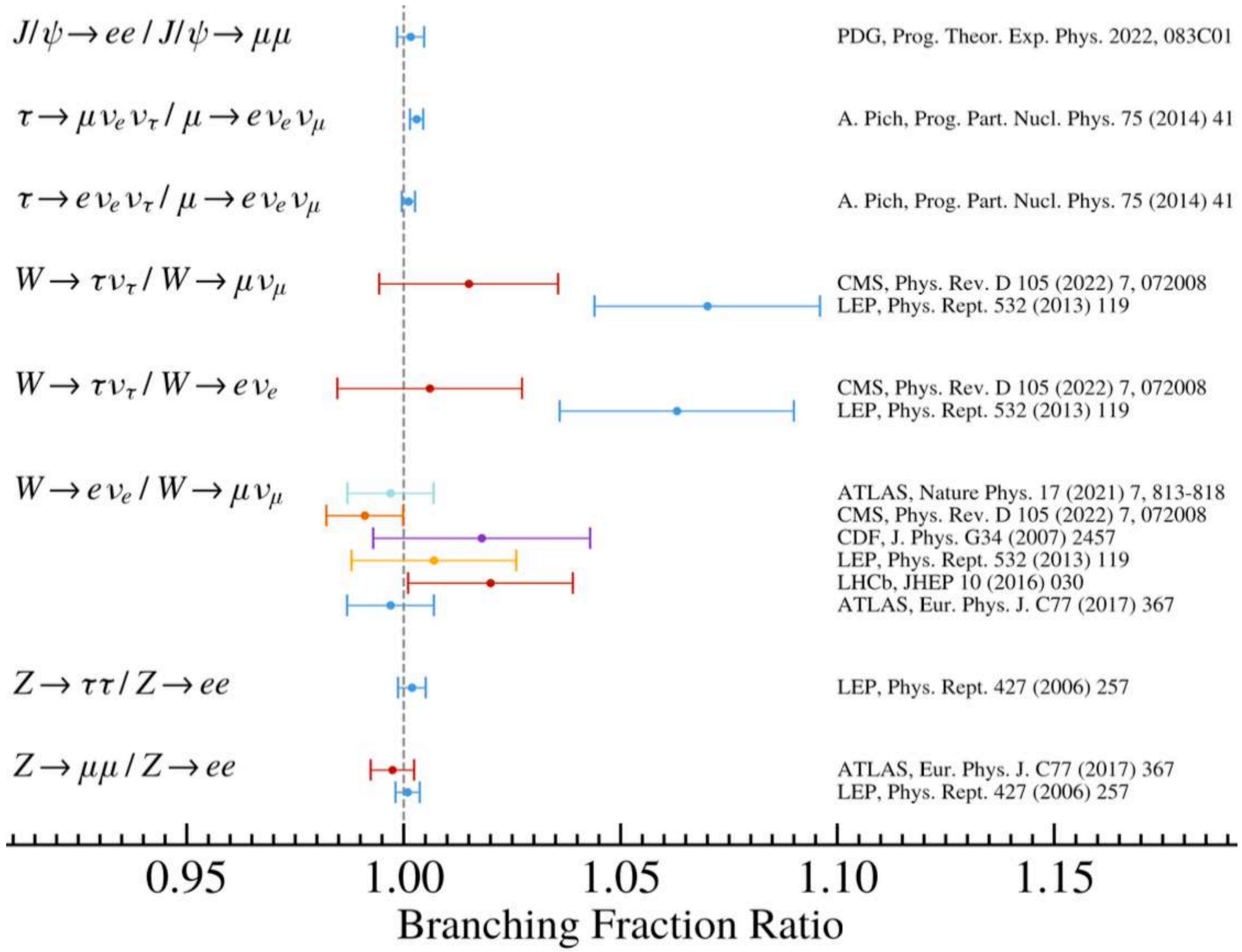
Lepton-flavour universality

From $b \to s\ell^+\ell^-$ to $b \to c\ell\nu$

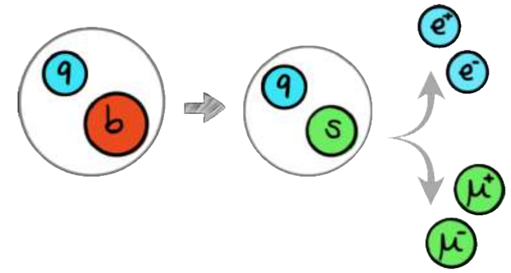


LEPTON FLAVOUR UNIVERSALITY

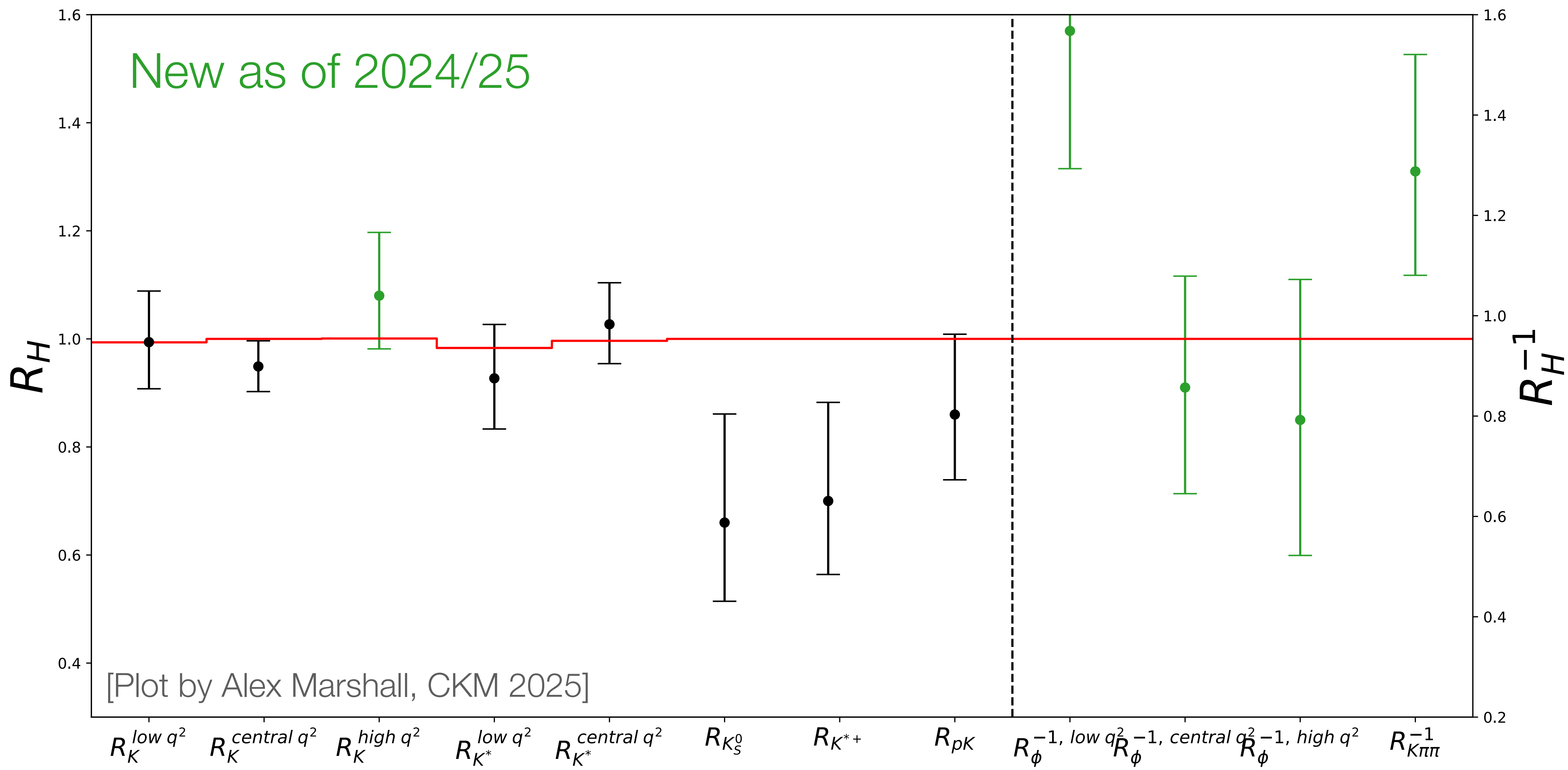
IN THE SM THE COUPLINGS OF THE GAUGE BOSONS ARE LEPTON UNIVERSAL



Lepton Flavour Universality



[PRD 108 (2023) 3, 032002; Nature Physics 19 (2023) 1517; JHEP 05 (2020) 040; PRL 128 (2022) 19, 191802; JHEP 08 (2017) 055; JHEP 07 (2025) 198; PRL 134 (2025) 19, 181803; PRL 134 (2025) 12, 121803]

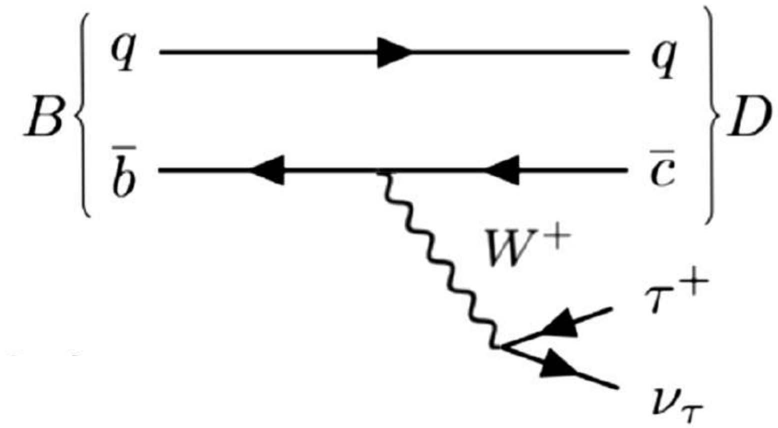


Neutral current show compatibility with LFU
(similar deviations seen in muons and electrons)

+ [R_K, Prog. Phys. 87 (2024) 077802]

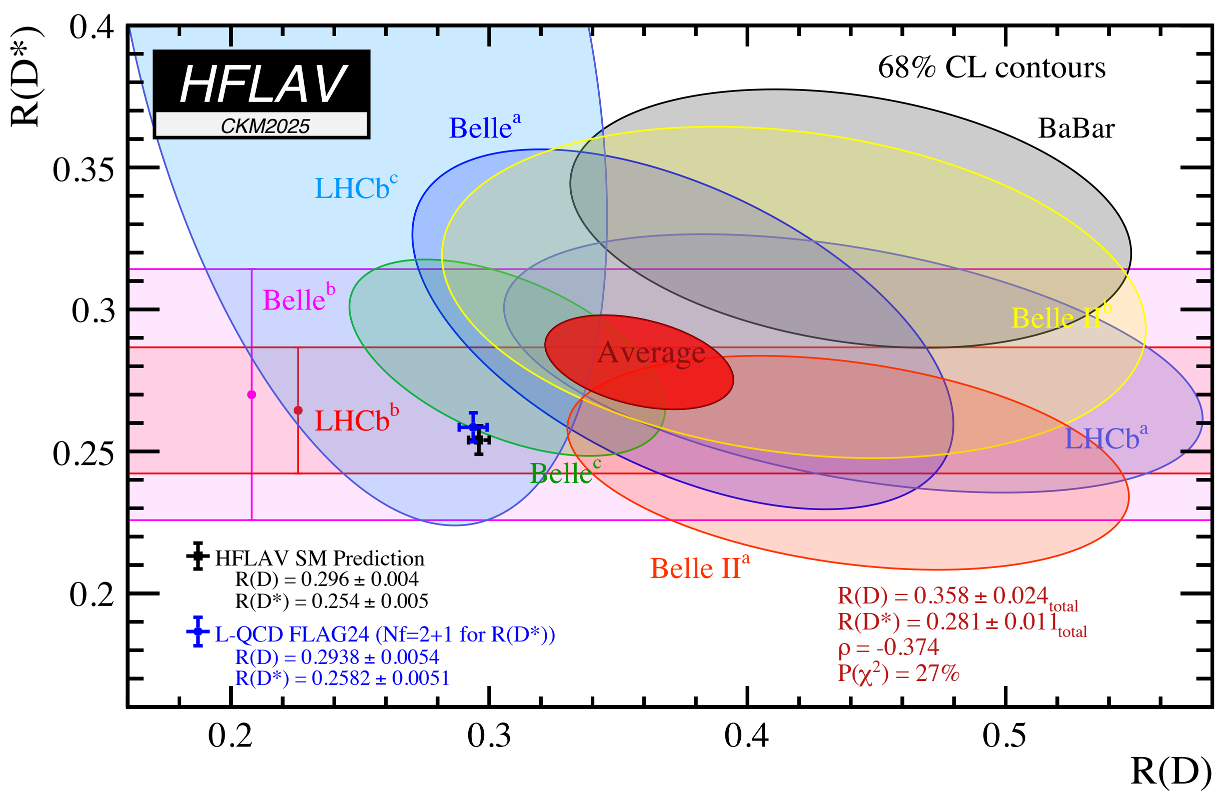
LEPTON FLAVOUR UNIVERSALITY

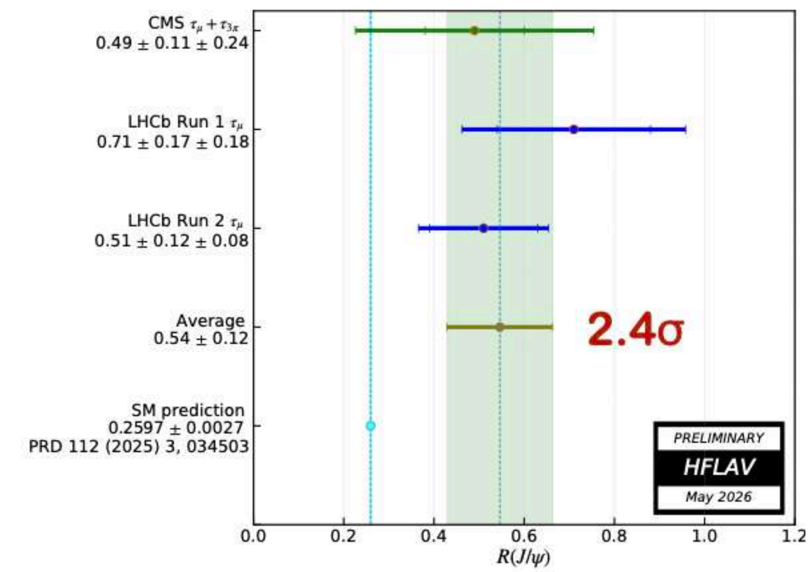
$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu \nu_\mu)}$$

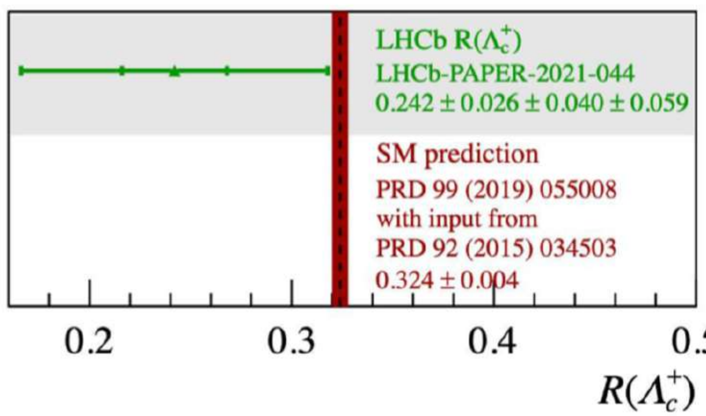


$\mathcal{H}_b = B^0, B^+_{(c)}, \Lambda^0_b, B^0_s \ldots$ $\quad \ell' = e/\mu$ (B-factories)

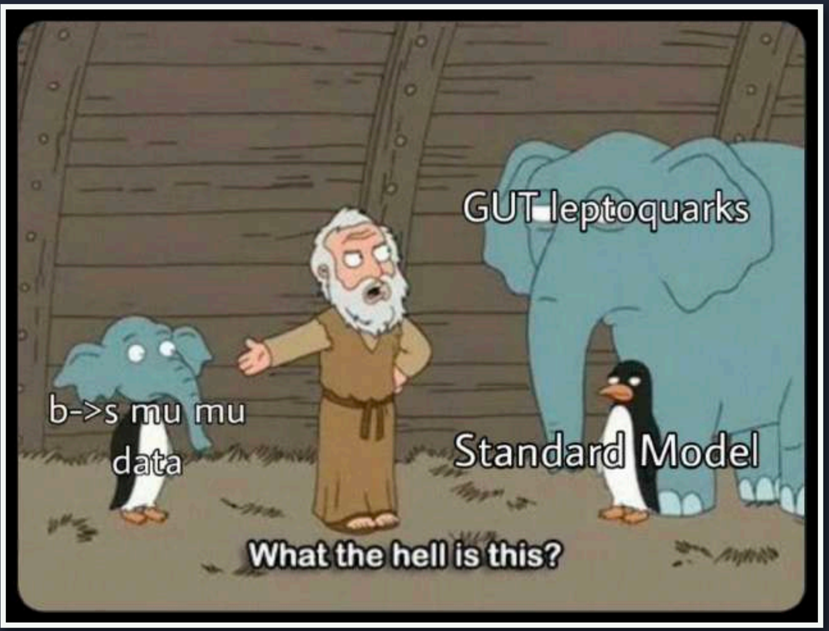
$\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi \ldots$ $\quad \ell' = \mu$ (LHCb, CMS)







DEVIATIONS WRT SM OF COMBINATION $R(D), R(D^*)$ AT $\sim 3.7\sigma$



Summary

- CKM picture remains remarkably consistent
- Rich information on hadronic decays requires a closer synergy between theory-experiment

i.e. current models are insufficient to uniquely retrieve underlying physics in data

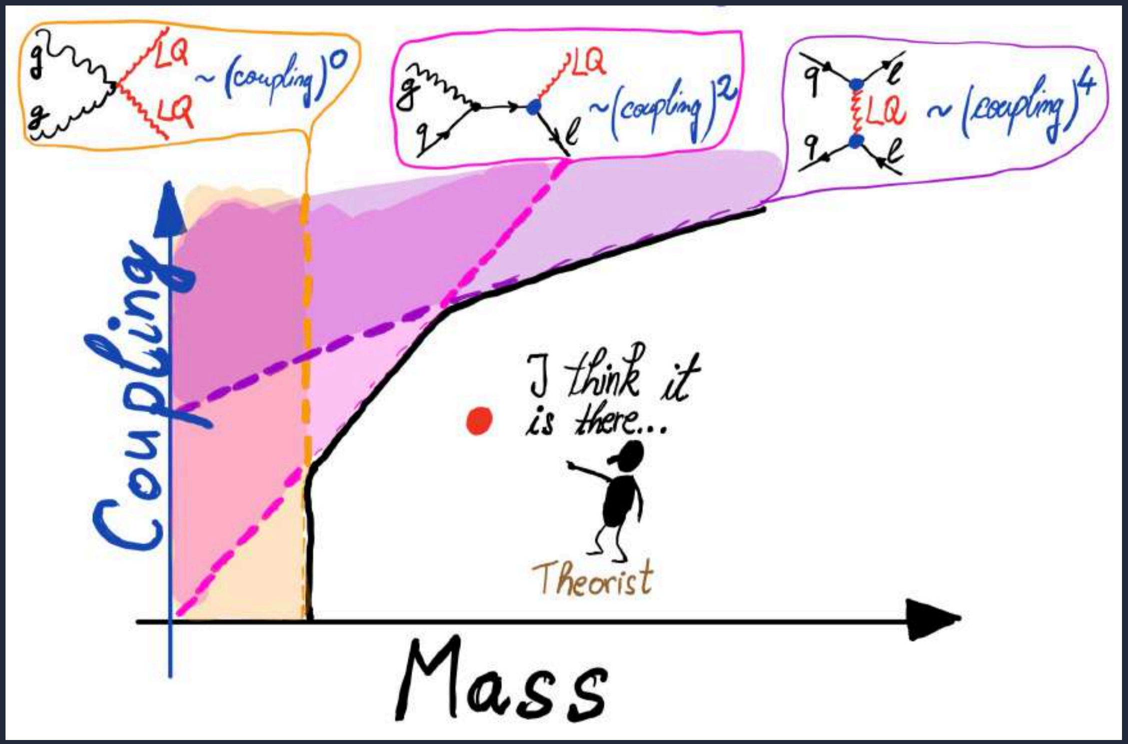
What Comes Next?

- Long-standing $b \to s\mu^+\mu^-$ anomalies interpretation still hindered by SM hadronic uncertainties

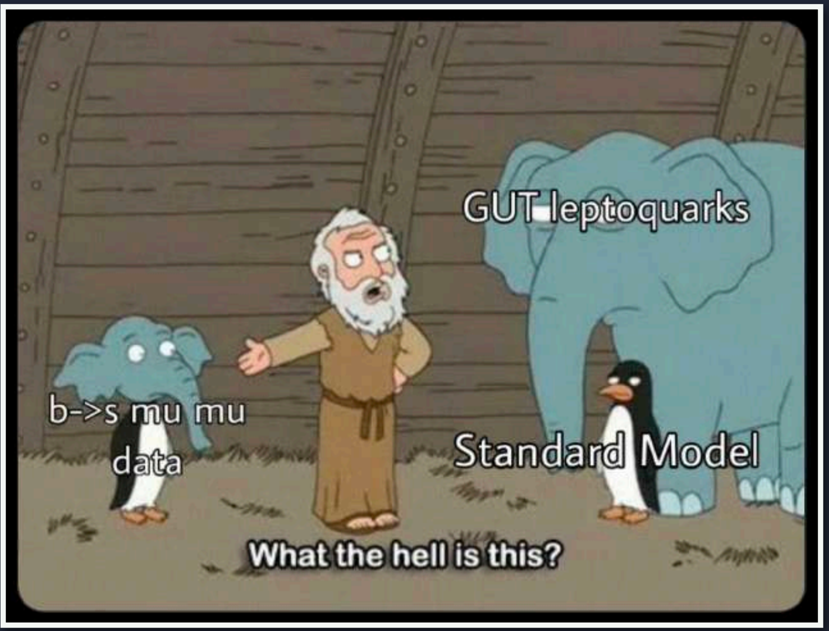
How to unambiguously solve this puzzle?

- A Precision Flavour Physics Era Ahead Of Us!

[New ideas, new channels, new observables ...]



Compass to LHC searches?



Summary

- CKM picture remains remarkably consistent
- Rich information on hadronic decays requires a closer synergy between theory-experiment

i.e. current models are insufficient to uniquely retrieve underlying physics in data

What Comes Next?

- Long-standing $b \to s\mu^+\mu^-$ anomalies interpretation still hindered by SM hadronic uncertainties

How to unambiguously solve this puzzle?

- A Precision Flavour Physics Era Ahead Of Us!

[New ideas, new channels, new observables ...]

Compass to LHC searches?