Recent Results from LHCb.

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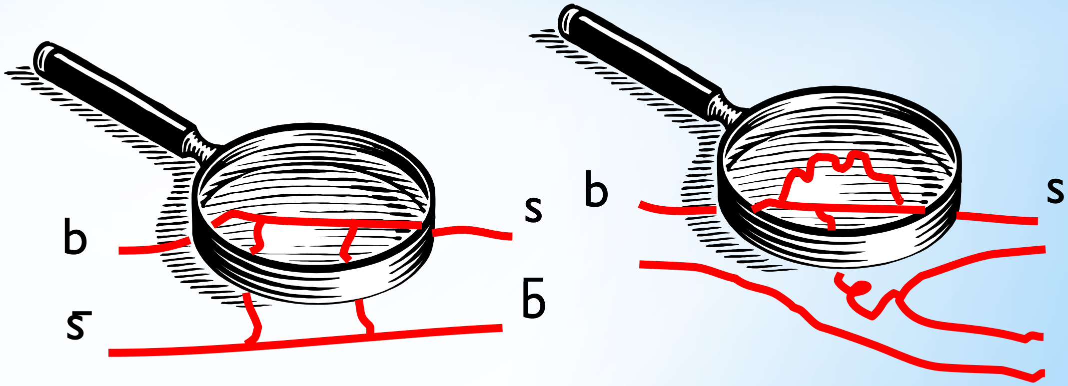
With my gratitude to the speakers at the EPS 2023 conference for their (unknowingly) help with the slides



Introduction: status of searches for NP

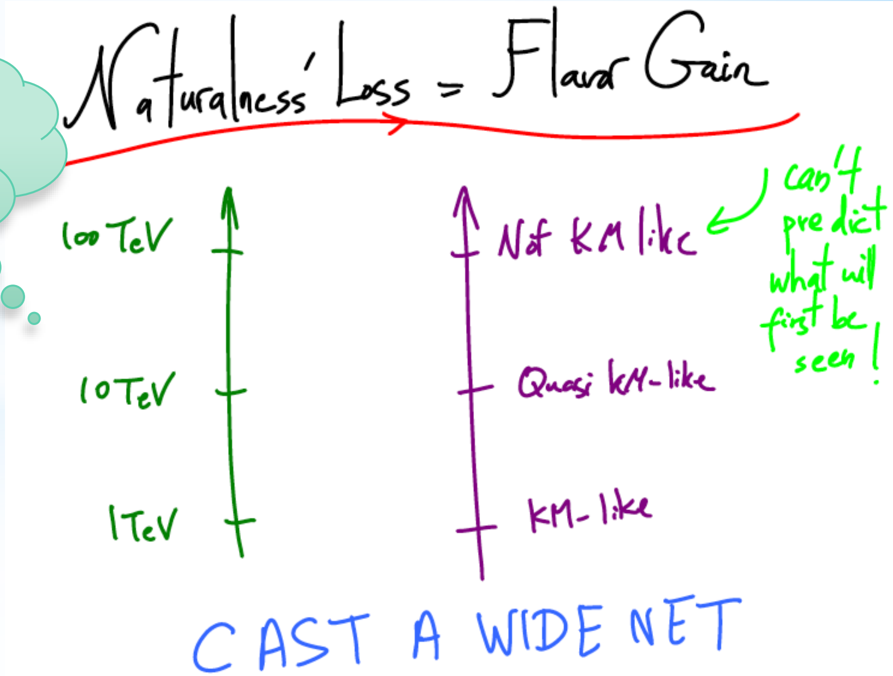
So far, **no significant signs for NP** from direct searches at the LHC while a (the SM?) **Higgs boson** has been found with a mass of ~125 GeV/c^2.

Before LHC/LEP, expectations were that ***"naturally"*** the masses of the **new particles would have to be light** in order to reduce the *"fine tuning"* of the radiative corrections to the Higgs mass.

However, the absence of NP effects observed in precision measurements implied some level of *"fine tuning"* in the flavour sector. Why, if there is NP at the TeV energy scale, it does not show up in precision measurements?

NP FLAVOUR PROBLEM →
Minimal Flavour Violation (MFV).

N.Arkani-Hamed,
Intensity Frontier
Workshop (Nov
2011, Washington)



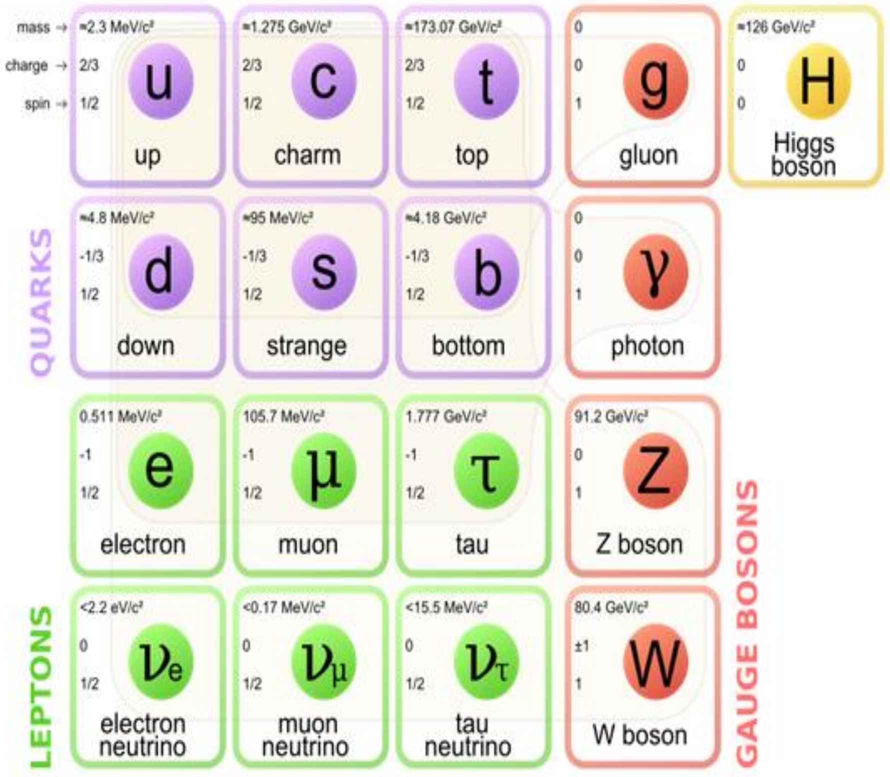
As we push the **energy scale of NP higher**, **<u>hypothesis like MFV look less convincing</u>**
→ **chances to see NP in flavour physics have increased** when Naturalness (in the Higgs sector) seems to be less plausible!

Introduction: flavour in the SM

$$\mathscr{L}_{\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathscr{L}_{\mathrm{Higgs}}(\phi, A_a, \psi_i)$$

The **gauge component** is the **"elegant" part**. There is **no distinction between different generations** and has a **huge degree of symmetry.** We only need to know **α, θ_W, M_W** and **α_s** and everything is determined by the local gauge symmetry group: **$SU(3)_C \times SU(2)_L \times U(1)_Y$**

The **Higgs component**, however, **breaks the flavour symmetry**. It is the **origin of the flavour structure** of the model. It is also the component that is **not stable to quantum corrections.** To describe this part we need a total of **14 parameters!**



mass →
charge →
spin →

QUARKS	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
LEPTONS	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

The Standard Model of elementary particles

SM flavour problem
The origin of masses and mixings, together with the origin of family replications is probably the most pressing problem of the SM.

Introduction: Yukawa Mechanism in the SM.

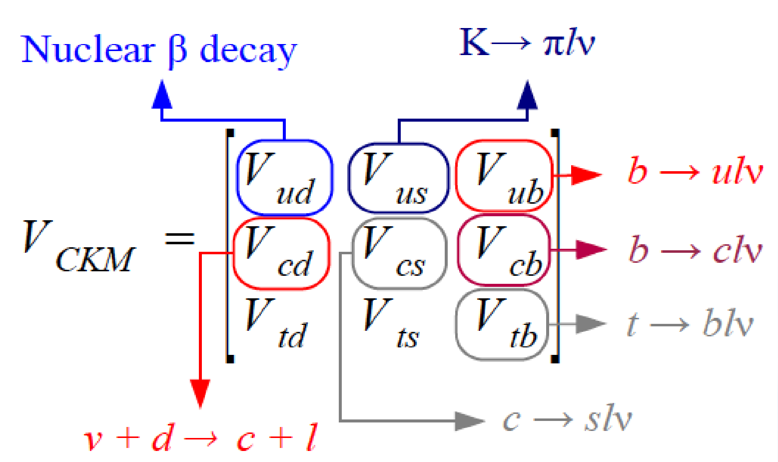
$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i \phi D_R^j + Y_u^{ij}\bar{Q}_L^i\tilde{\phi}U_R^j + Y_e^{ij}\bar{L}_L^i\phi E_R^j + \text{h.c.}$$

$$\lambda_d = \text{diag}(y_d, y_s, y_b)\ , \quad \lambda_u = \text{diag}(y_u, y_c, y_t)\ , \quad y_q = \frac{m_q}{v}\ .$$

$$Y_d = \lambda_d\ , \qquad Y_u = V^\dagger \lambda_u\ ,$$

The quark flavour structure within the SM is described by 6 couplings and 4 CKM parameters. In practice, it is convenient to move the CKM matrix from the Yukawa sector to the weak current sector. But don't be confused, in the SM quarks are allowed to change flavour as a consequence of the Higgs mechanism.

Using **Wolfenstein** parameterization (A, λ,ρ,η):



CKM

$$V = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2-\lambda^4/8(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2+A\lambda^4/2(1-2(\rho+i\eta)) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^5)$$

A = 0.80±0.02
λ= 0.225±0.001

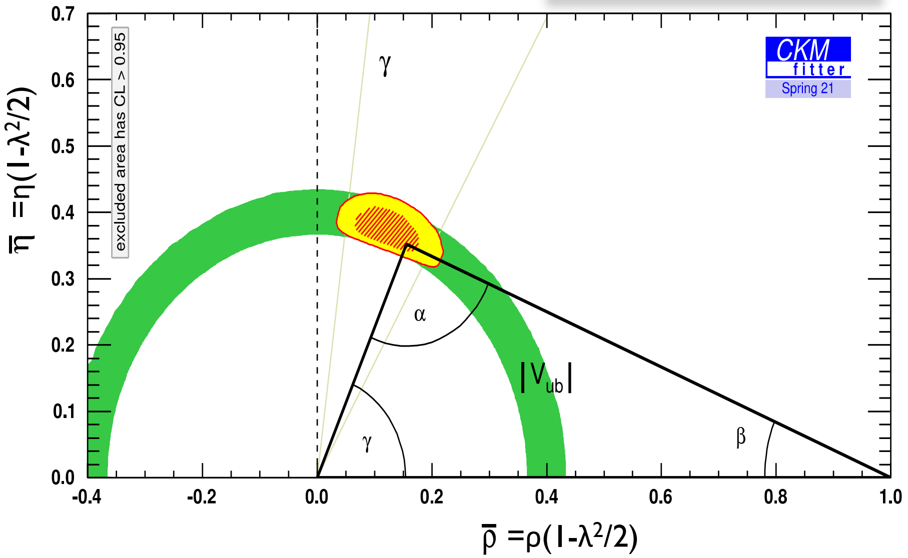
λ= sinθ_c ≈V_{us} measured precisely in K semileptonic decays. Notice that all **V_{ij} couplings** can be accessed experimentally using **tree-level decays**, with the **exception of V_{td} and V_{ts}**

Introduction: tree vs loop measurements

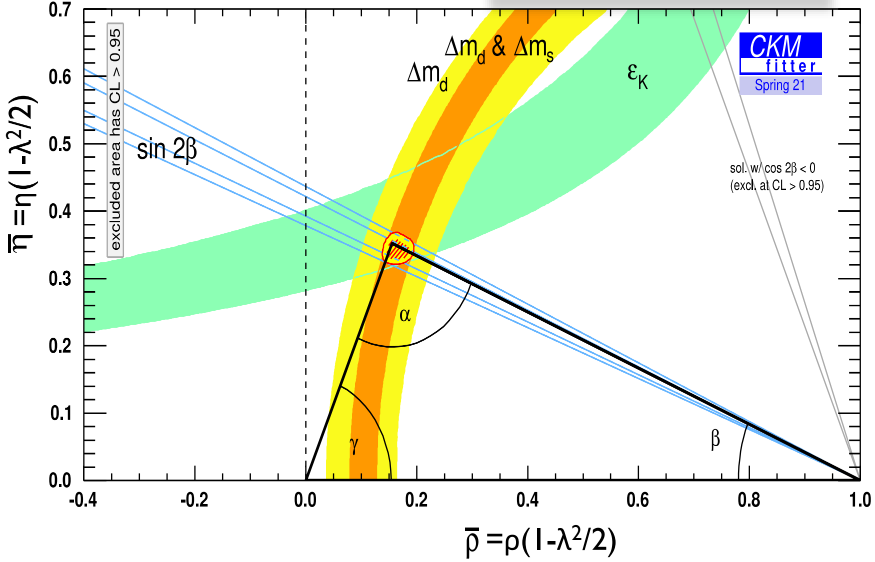
CKM parameters (A, λ, ρ, η) are **not predicted** by the SM. **They need to be measured!**

If we assume **NP enters mainly at loop level**, it is interesting to compare the determination of the parameters **(ρ, η)** from processes dominated by **tree diagrams** **(V_{ub}, V_{cb}, γ,…)** with the ones from **loop diagrams** **(ΔM_d&ΔM_s, $\beta_{(s)}$, ε_K, …)**.

Tree measurements

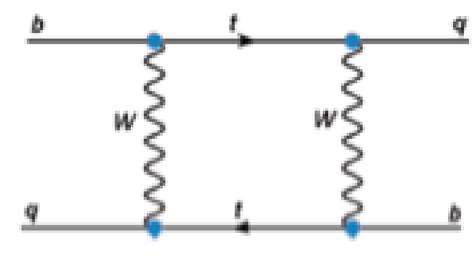


Loop measurements

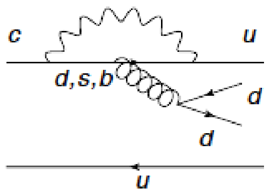


NP allowed at O(30%) in b→d transitions (accuracy in tree level measurements) and O(20%) in b→s transitions (accuracy in loop level measurements).

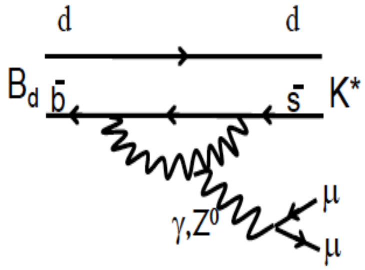
Quantum Loops: FCNC



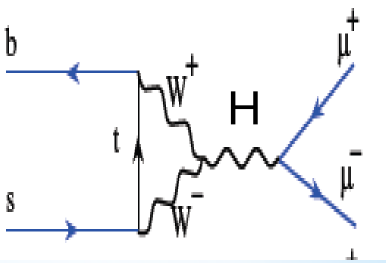
ΔF=2 box



QCD Penguin



EW Penguin



Higgs Penguin

Map of Quark FCNC transitions and type of loop processes:

	b→s ($\|V_{tb}V_{ts}\|\alpha\lambda^2$)	**b→d ($\|V_{tb}V_{td}\|\alpha\lambda^3$)**	**s→d ($\|V_{ts}V_{td}\|\alpha\lambda^5$)**	**c→u ($\|V_{cb}V_{ub}\|\alpha\lambda^5$)**
ΔF=2 box	ΔM_{Bs}, **$A_{CP}(B_s \to J/\Psi\Phi)$**	ΔM_B, **$A_{CP}(B \to J/\Psi K)$**	ΔM_K, ϵ_K	x,y, q/p,Φ
QCD Penguin	$A_{CP}(B \to hhh)$, $B \to X_s\gamma$	$A_{CP}(B \to hhh)$, $B \to X\gamma$	$K \to \pi^0 ll$, ε'/ε	**$A_{CP}(D \to hh)$,** Δa_{CP}
EW Penguin	**$B \to K^{(*)}ll$,** $B \to X_s\gamma$	$B \to \pi ll$, $B \to X\gamma$	$K \to \pi^0 ll$, $K^\pm \to \pi^\pm \nu\nu$	$D \to X_u ll$
Higgs Penguin	**$B_s \to \mu\mu$**	**$B \to \mu\mu$**	**$K \to \mu\mu$**	**$D \to \mu\mu$**

LHCb today and in the future.

← 9 fb^{-1} → ← Goal: 50 fb^{-1} → ← Goal: 300 fb^{-1} →

Upgrade I (LS2) · Consolidation (LS3) · Upgrade II (LS4)

Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024 2025	2026 2027 2028	2029 2030 2031 2032	2033 2034	2035 2036 2037 2038	2039	2040 2041

Runs 1 and 2

40 MHz → pp collisions → **L0** Hardware → 1.1 MHz → Detector readout → **HLT** Software → 12.5 kHz (0.6 GB/s) → Events on disk

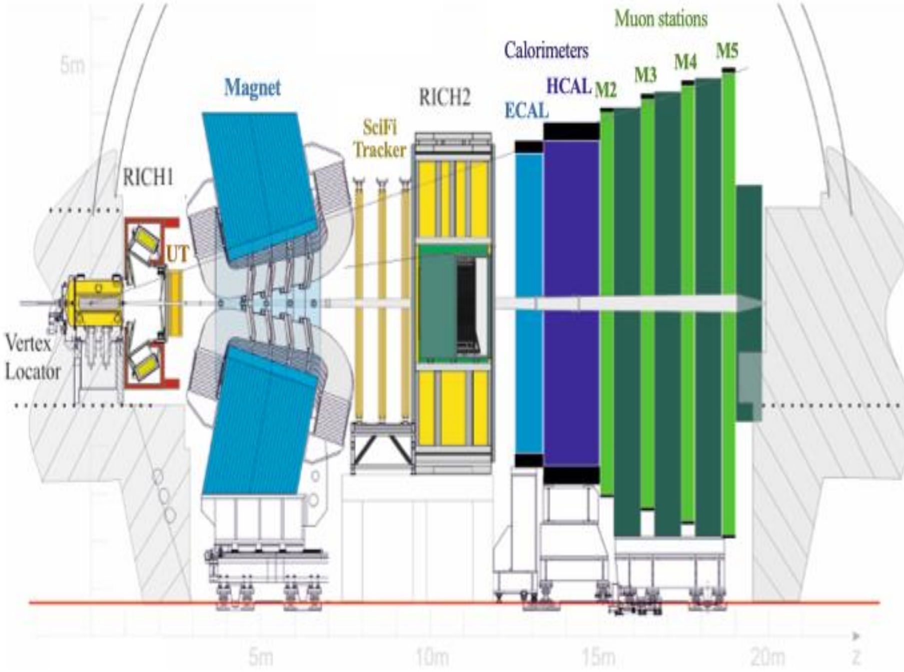
Upgrade I (just installed)

40 MHz → pp collisions → Detector readout → **HLT** Software → 100 kHz (2-5 GB/s) → Events on disk

Flexible software trigger and 3 new/better trackers

Upgrade II (proposed)

Even better granularity, improved calorimeter, and fast timing



Upgrade I (2019-22)
CERN-LHCC-2012-007

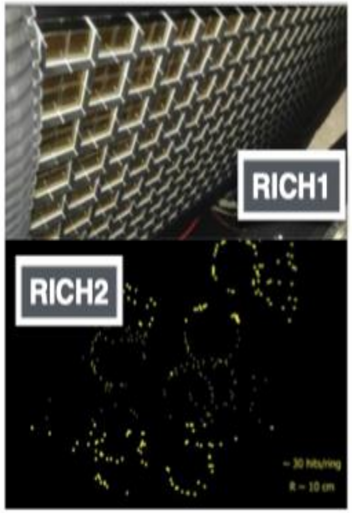
Upgrade II (2033-34)
CERN-LHCC-2017-003
CERN-LHCC-2018-027
CERN-LHCC-2021-012

LHCb Upgrade I installed.

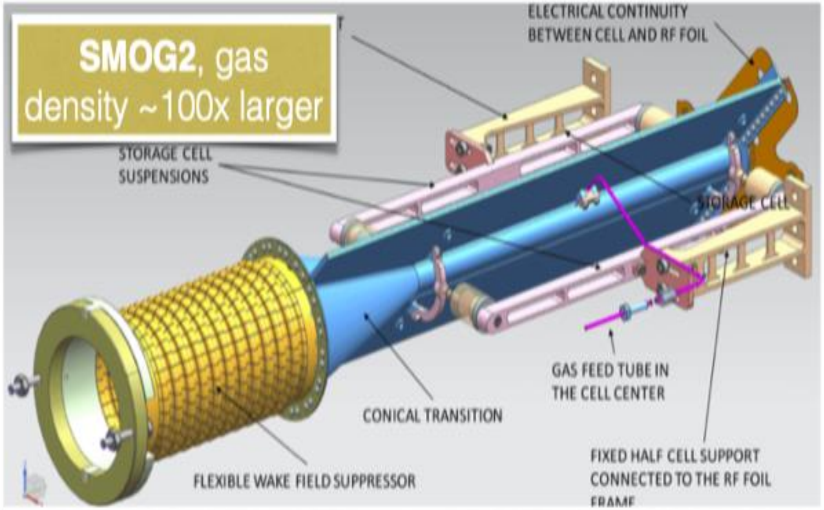
Pixel VELO
only 5 mm from IP

SciFi
11,000 km of scintillating fibers

Upstream Tracker (UT)



SMOG2, gas density ~100x larger

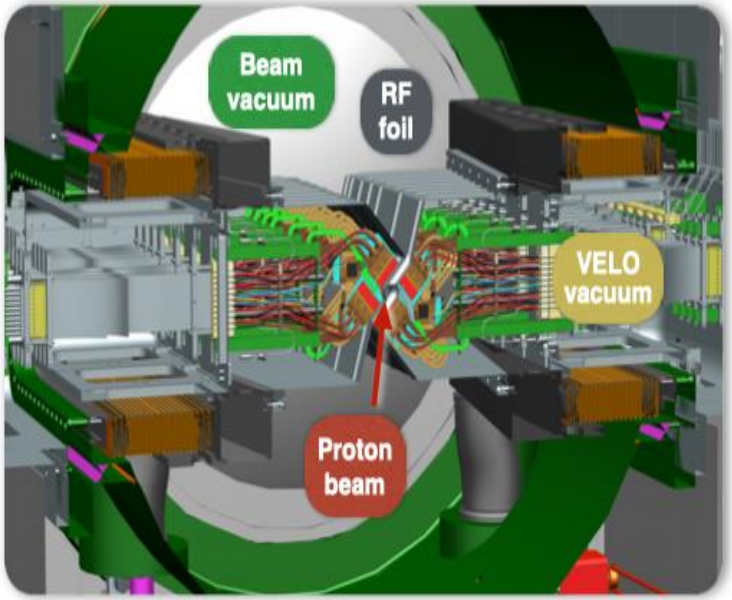


PCIe40 cards with **FPGAs & GPUs** running HLT1

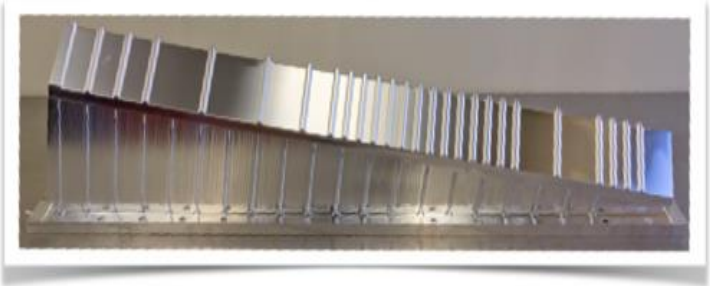
Major project installed successfully and **on budget**

Exciting physics until 2032

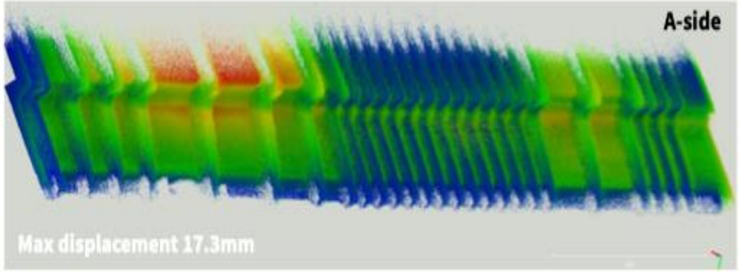
LHC vacuum incident at VELO.



RF foil (150-250 µm thick) **separates** beam/ VELO **vacua** and shields electronics

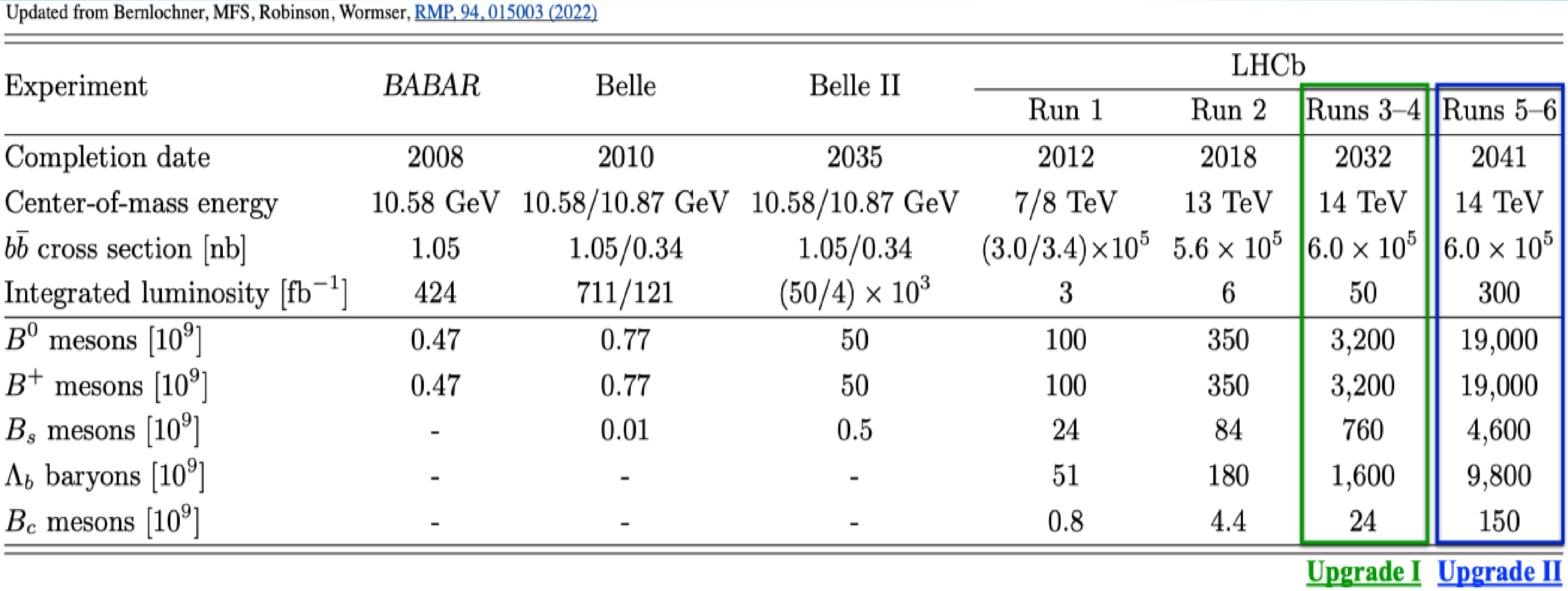


- **Failure** of the **LHC vacuum system** that controls **VELO's Δp** on Jan 10, 2023
  - **Detector modules** & cooling are **not damaged**
  - The system was returned to a safe situation
- **RF foil** underwent **plastic deformation → requires replacement**
  - **Will replace** in the shutdown **at the end of 2023**



- **LHCb physics program** in **2023 affected**
  - VELO cannot be fully closed but opportunities remain

The future is bright.



Updated from Bernlochner, MFS, Robinson, Wormser, RMP, 94, 015003 (2022)

Experiment	*BABAR*	Belle	Belle II	LHCb			
				Run 1	Run 2	Runs 3–4	Runs 5–6
Completion date	2008	2010	2035	2012	2018	2032	2041
Center-of-mass energy	10.58 GeV	10.58/10.87 GeV	10.58/10.87 GeV	7/8 TeV	13 TeV	14 TeV	14 TeV
$b\bar{b}$ cross section [nb]	1.05	1.05/0.34	1.05/0.34	$(3.0/3.4)\times10^5$	5.6×10^5	6.0×10^5	6.0×10^5
Integrated luminosity [fb^{-1}]	424	711/121	$(50/4)\times10^3$	3	6	50	300
B^0 mesons [10^9]	0.47	0.77	50	100	350	3,200	19,000
B^+ mesons [10^9]	0.47	0.77	50	100	350	3,200	19,000
B_s mesons [10^9]	-	0.01	0.5	24	84	760	4,600
Λ_b baryons [10^9]	-	-	-	51	180	1,600	9,800
B_c mesons [10^9]	-	-	-	0.8	4.4	24	150

Upgrade I Upgrade II

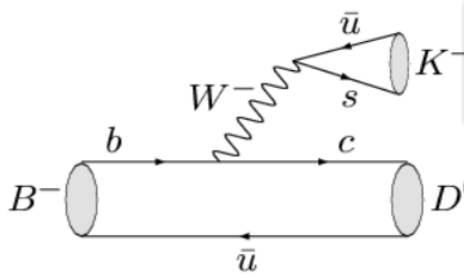
- Upgrade I and II datasets **orders of magnitude larger**

New era of **unprecedented precision** starting at LHCb

Rule of thumb: 1ab^{-1} at Belle-II ~ 1fb^{-1} at LHCb

Tree Level Measurements: Recent LHCb results on $\gamma \cong \arg(V_{ub})$ and LNU in CC

V_{ub} phase (γ): Status EPS 2023

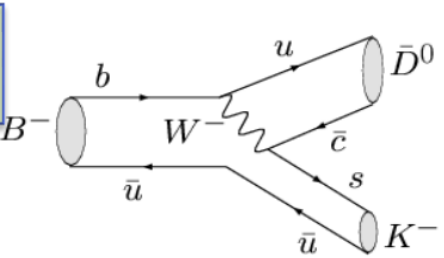


$\tan\gamma \approx \frac{\eta}{\rho}$

color allowed

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

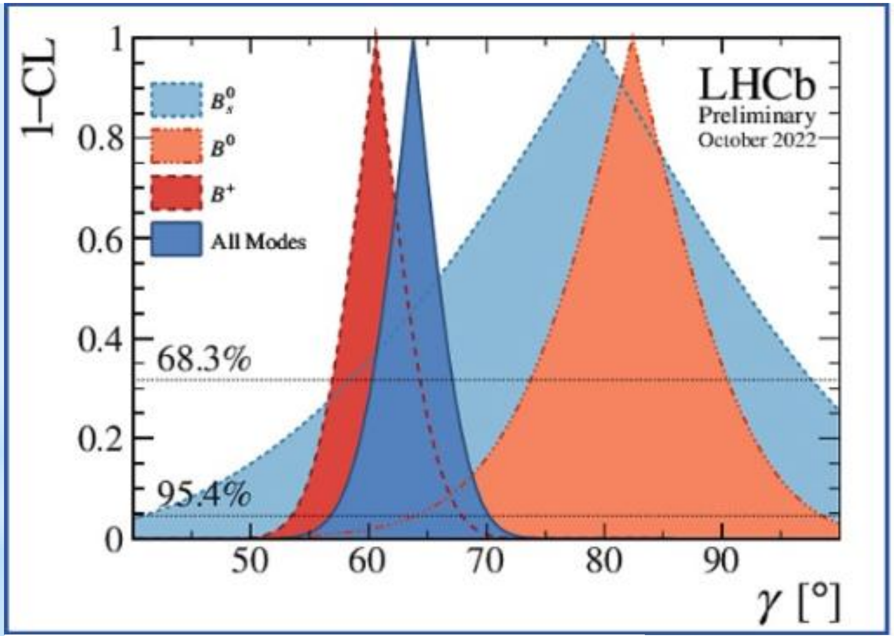
$\sim A\lambda^3$

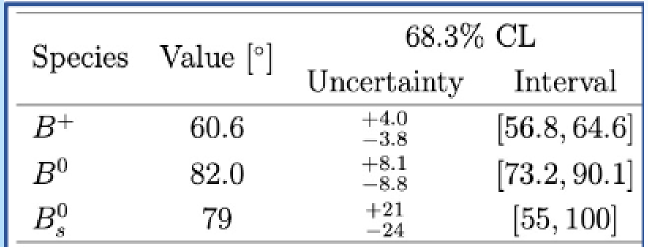


color suppressed

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

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





Species	Value [°]	68.3% CL Uncertainty	68.3% CL Interval
B^+	60.6	$^{+4.0}_{-3.8}$	[56.8, 64.6]
B^0	82.0	$^{+8.1}_{-8.8}$	[73.2, 90.1]
B_s^0	79	$^{+21}_{-24}$	[55, 100]

Combined likelihood from all measurements including charm.

LHCb precision dominates world average,

LHCb-CONF-2022-003

$\gamma(\text{LHCb}) = (63.8^{+3.5}_{-3.7})°$

before LHCb was: 70±28°

to be compared with the CKM fit indirect determination:

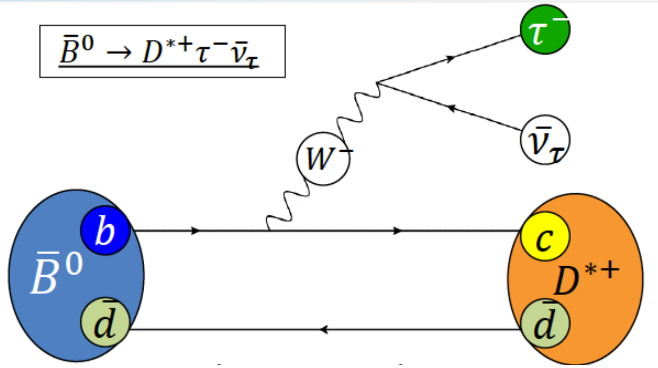
$\gamma(\text{CKMFITTER}) = (65.5^{+1.1}_{-2.7})°$

Theoretical uncertainties are negligible.

LHCb can reach better than 0.4° precision with Upgrade II.

CERN-LHCC-2017-003

Is LU violated in tree decays?



$$R(D) = \frac{\mathcal{B}(B\to D\tau^+\nu_\tau)}{\mathcal{B}(B\to D\ell^+\nu_\ell)}$$

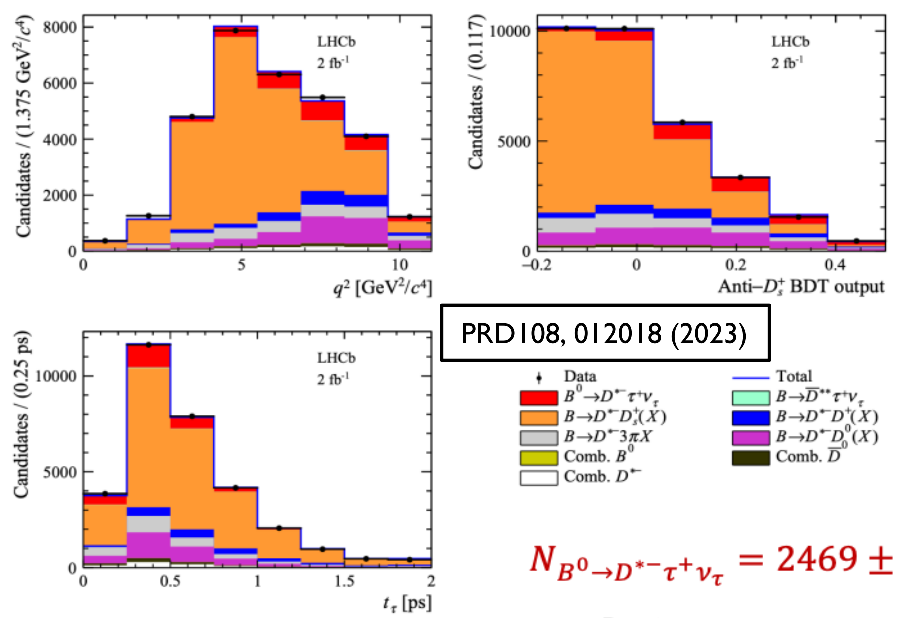
$$R(D^*) = \frac{\mathcal{B}(B\to D^*\tau^+\nu_\tau)}{\mathcal{B}(B\to D^*\ell^+\nu_\ell)}$$

Two new results from LHCb using part of RUN-2 with hadronic τ decays: PRD108, 012018 (2023)

$R(D^*)=0.247\pm0.015\pm0.019$

and simultaneous RD&RD* RUN-1 muonic τ decays: arXiv: 2302.02886 (2023)

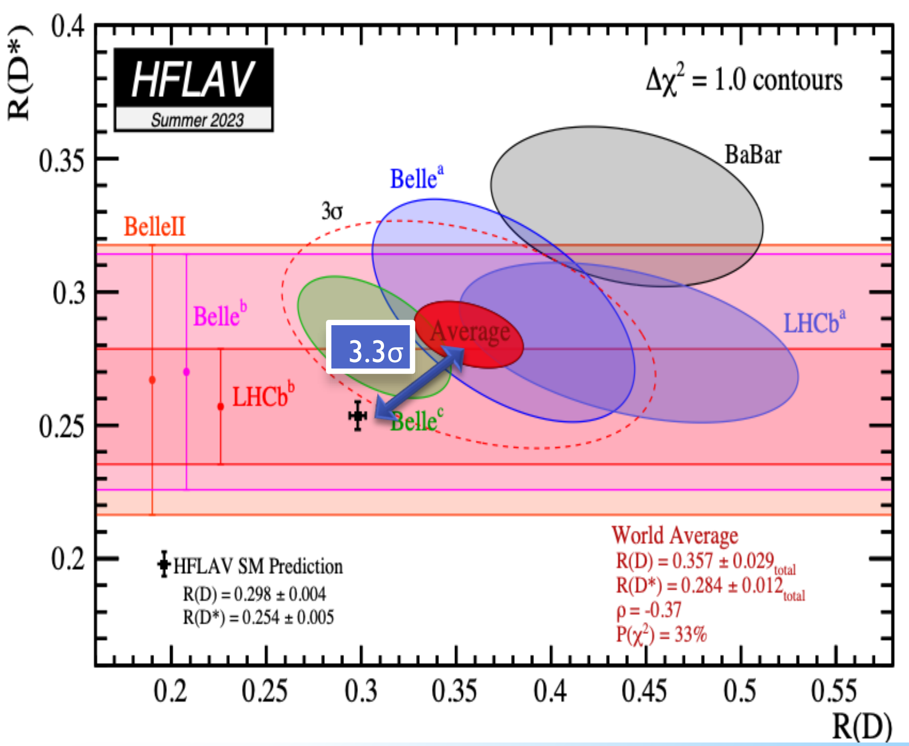
$R(D)=0.441\pm0.060\pm0.066$
$R(D^*)=0.281\pm0.018\pm0.023$



PRD108, 012018 (2023)

$$N_{B^0\to D^{*-}\tau^+\nu_\tau} = 2469 \pm 154$$

$$N^{\text{Run 1}}_{B^0\to D^{*-}\tau^+\nu_\tau} = 1296 \pm 86$$



- Babar (2013)
- Belle(a) (2015)
- Belle(b) (2017)
- Belle(c) (2020)
- LHCb(a) muonic (2023)
- LHCb(b) hadronic (2023)
- Belle II (2023)

Most recents results in better agreement with SM for RD*.

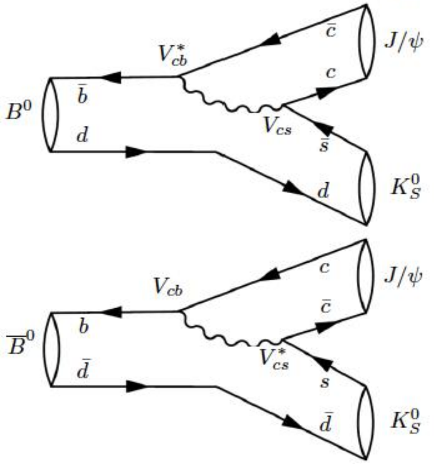
$\Delta F=2$ Box Measurements

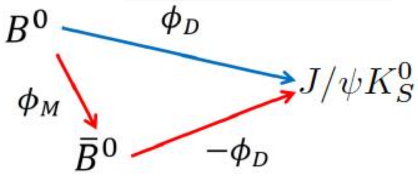
ΔF=2 box in b→d transitions: V_{td} phase

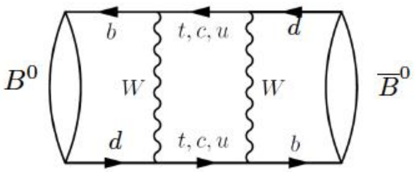
$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

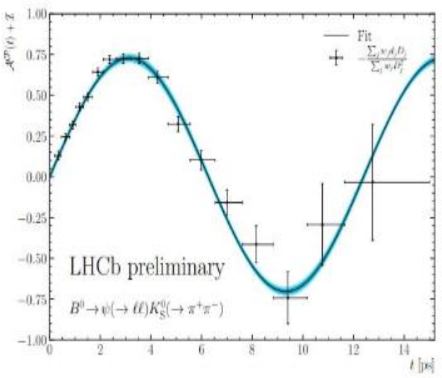
$$2\beta = \phi = \phi_M - 2\phi_D$$

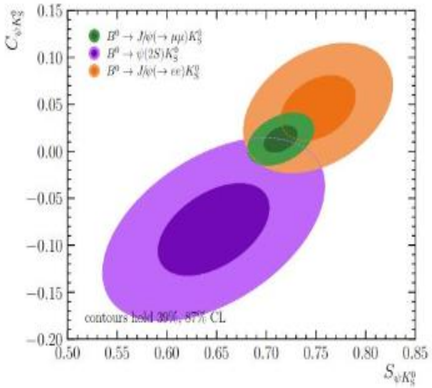
$$\tan b \gg \frac{h}{1-r}$$











LHCb-PAPER-2023-013

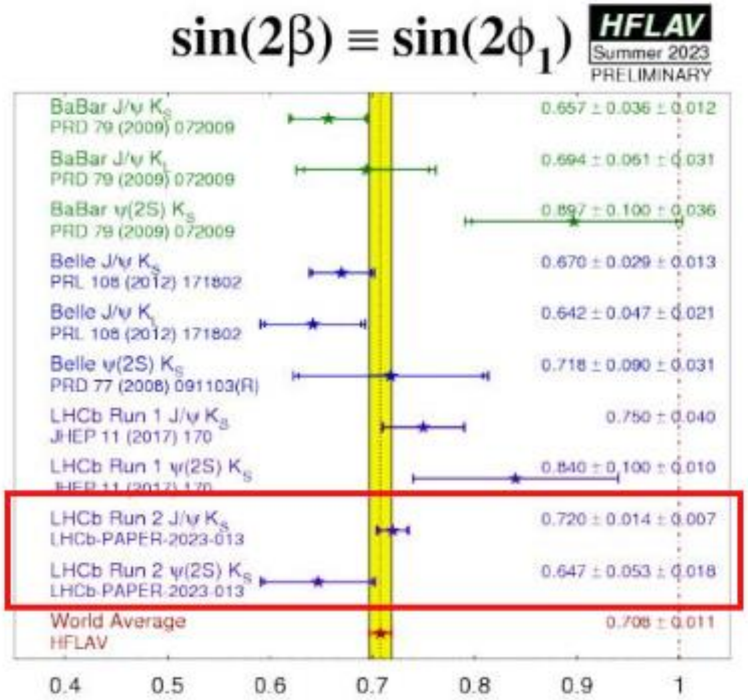
New measurement from LHCb using full RUN-1 and RUN-2 statistics including electron and muon final state and ψ(2S):

sin(2β) = 0.716 ± 0.013 ± 0.008

(2% precision)

wich improves on the precision achieved at the B-factories!

LHCb U1 and **Belle-II** will each reach **~0.8%** while **LHCb U2** potential is **~0.4%!** . Statistics should allow to control penguin contributions.



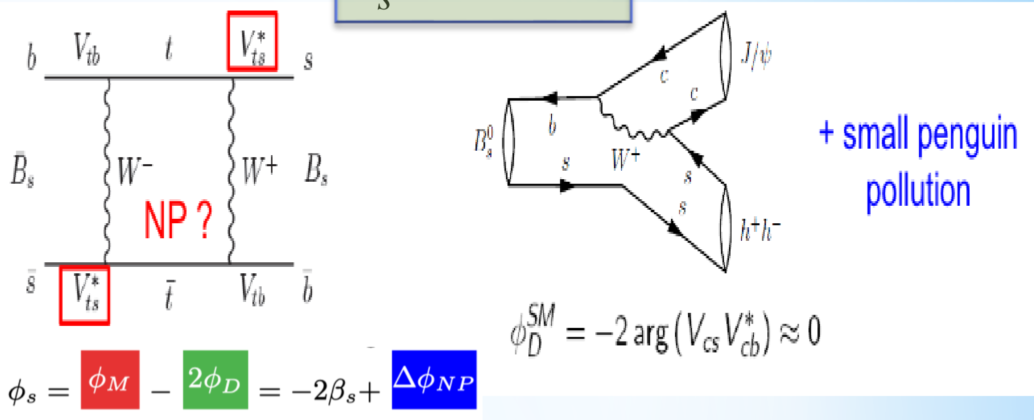
ΔF=2 box in b→s transitions: V_{ts} phase

$f_s » - 2hl^2$

Angular analysis is needed in **B_s→J/ΨΦ** decays, to disentangle statistically the CP-even and CP-odd components.

LHCb new results from **B_s→J/ΨKK** with full RUN-2 statistics.

arXiv: 2308.01468



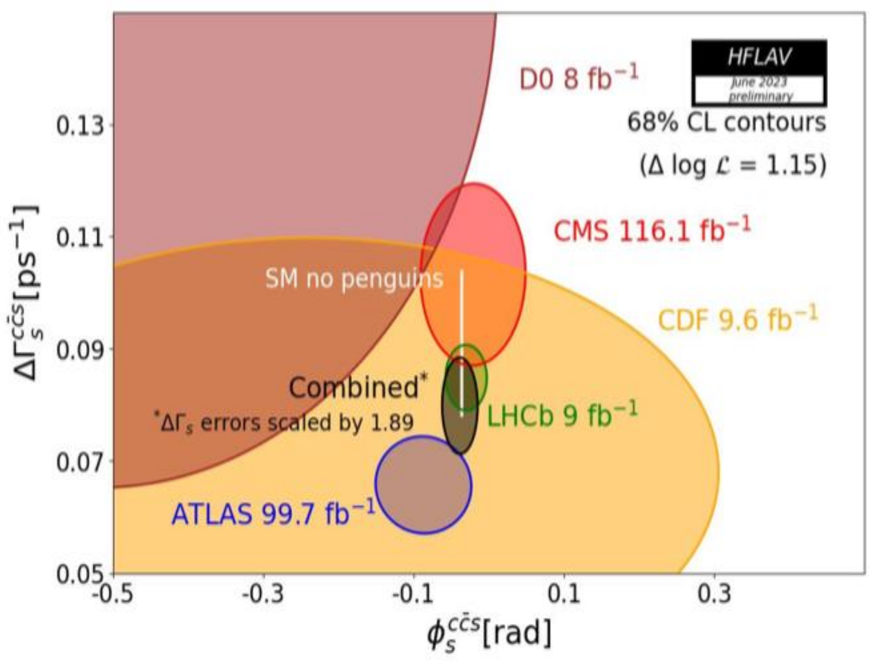
+ small penguin pollution

$$\phi_D^{SM} = -2\arg\left(V_{cs}V_{cb}^*\right) \approx 0$$

$$\phi_s = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_{NP}$$

Combining **RUN-1 and RUN-2 LHCb: B_s→J/ΨΦ+ B_s→J/Ψhh + B_s→$D^+_sD^-_s$:**

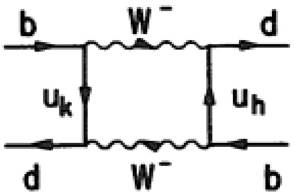
φ_s (LHCb)= (-31±18)mrad



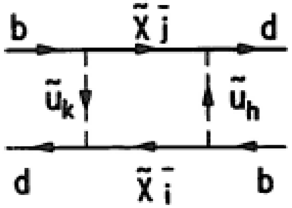
With a current w.a. of **φ_s = (-50±17) mrad** to be compared with **φ_s = $(-36.8^{+0.9}_{-0.6})$mrad** from CKMFITTER ***(±2 mrad using only tree measurements)***. Although, there has been **impressive progress** since the initial measurements at CDF/D0, the uncertainty needs to be further reduced.

LHCb sensitivity with **U2** expected to be better than **3 mrad**.

ΔF=2 box in b→q transitions



SM: $\frac{C_{\rm SM}}{m_W^2}$



NP: $\frac{C_{\rm NP}}{\Lambda^2}$

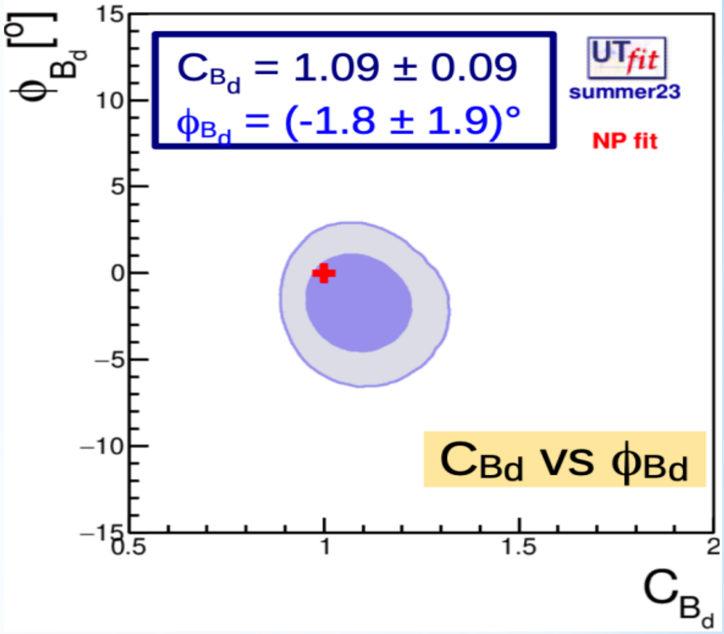
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

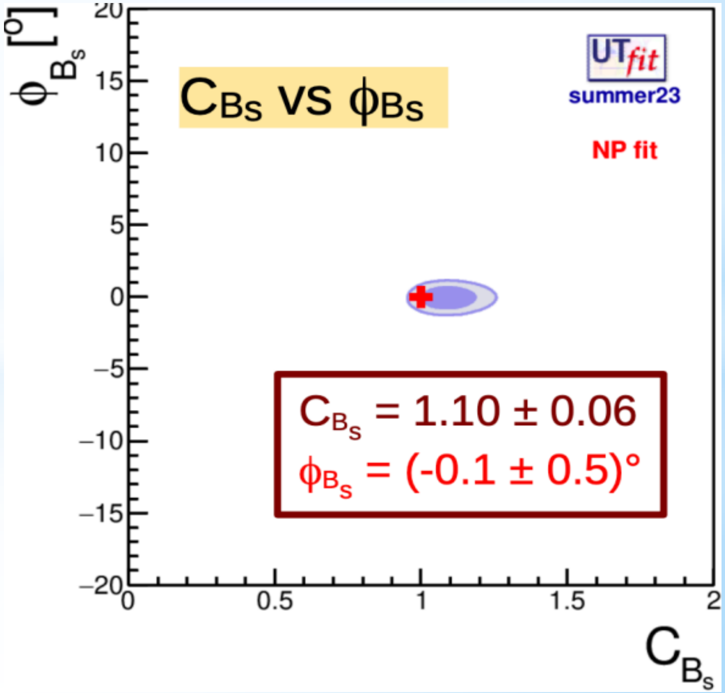
No significant evidence of NP in B_d or B_s mixing .

NP contribution to amplitudes in box diagrams constrained @95%CL to be <35% (<30%) for $B_d(B_s)$.

NP phases in box diagrams constrained @95%CL to be $(-6<\varphi_{NP}<2)°$ $((-1<\varphi_{NP}<1)°)$ for $B_d(B_s)$.

Need to increase precision to disentangle NP in B_d(Bs) mixing



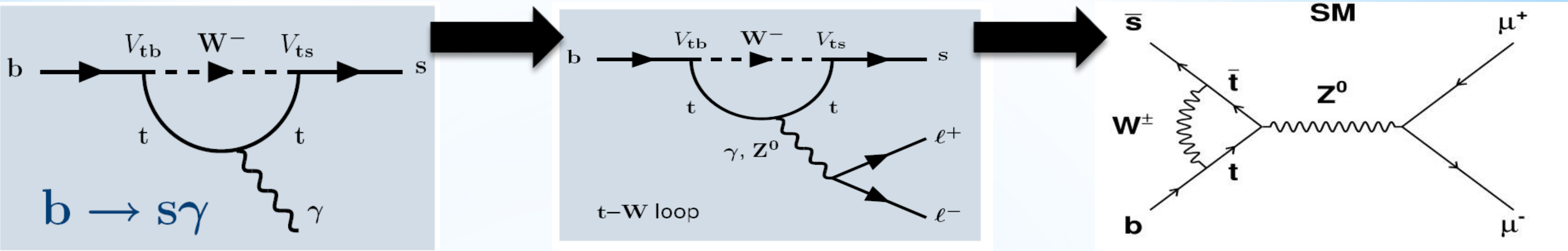


$\Delta F=1$ EW Penguins and LNU in NC

Three impersonations of the EW penguin

α_{QED} suppression

helicity suppression



SM

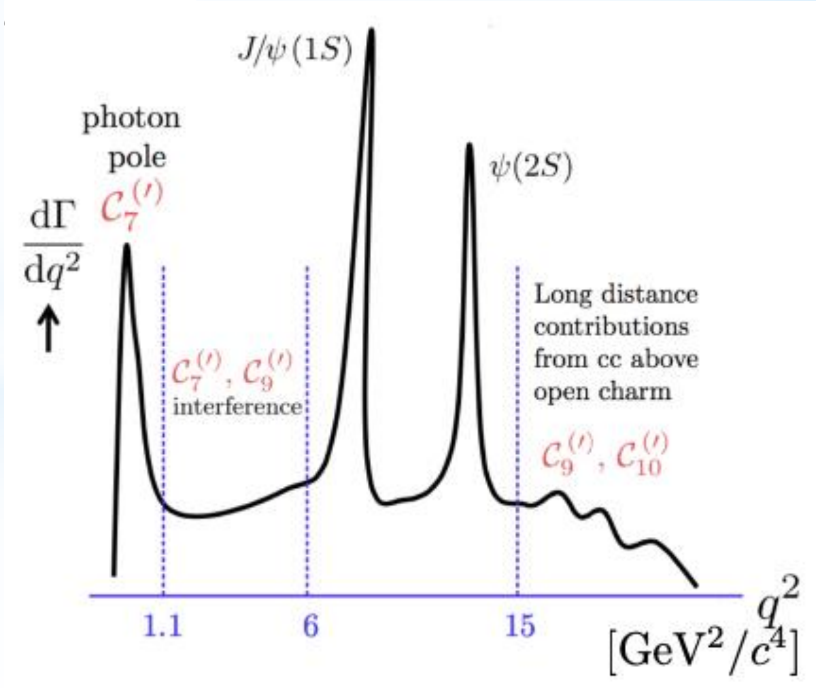
BSM

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

Coupling Strength C_i = Wilson coefficient
→ Sensitive to New Physics

i = 1, 2	Tree
i = 3-6, 8	Gluon penguin
i = 7	Photon penguin
i = 9, 10	Electroweak penguin
i = S, P	Scalar/Pseudoscalar penguin

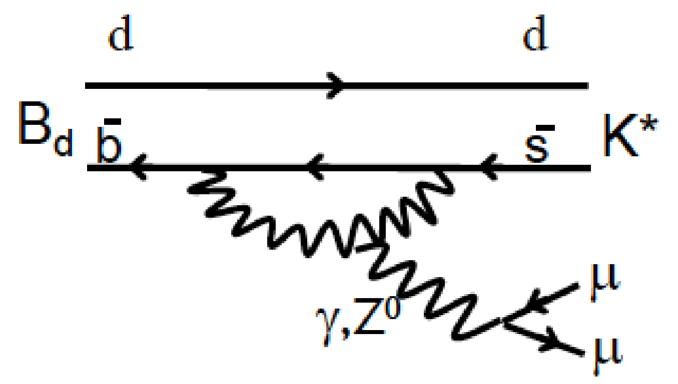
$B_s \to \phi\gamma$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$
$B_d \to K^* \mu^+ \mu^-$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $\mathcal{O}_{9\ell(10\ell)} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu (\gamma_5) \ell$
$B_s \to \mu^+ \mu^-$	$\mathcal{O}_{S(P)} \sim \bar{s}_L b_R \bar{\ell} (\gamma_5) \ell$ h(



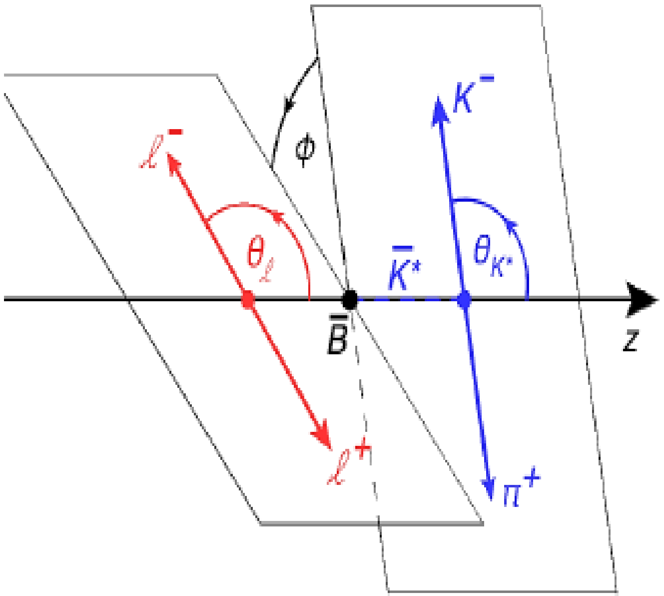
ΔF=1 EW penguins in b→s transitions: $B\to K^*\mu^+\mu^-$ angular analysis

$B\to K^*\mu^+\mu^-$ is the golden mode to test new vector(-axial) couplings in b→s transitions.

$K^*\to K\pi$ is self tagged, hence angular analysis ideal to test helicity structure.

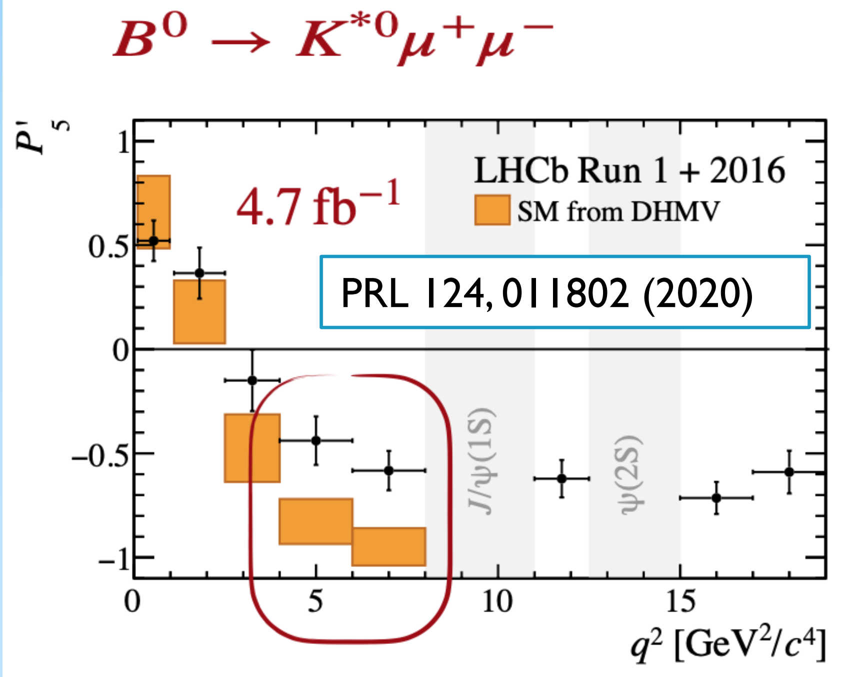


$$\begin{aligned}\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K+\boxed{F_{\mathrm{L}}}\cos^2\theta_K\\ &+\tfrac{1}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K\cos 2\theta_l\\ &-\boxed{F_{\mathrm{L}}}\cos^2\theta_K\cos 2\theta_l+\boxed{S_3}\sin^2\theta_K\sin^2\theta_l\cos 2\phi\\ &+\boxed{S_4}\sin 2\theta_K\sin 2\theta_l\cos\phi+\boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi\\ &+\tfrac{4}{3}\boxed{A_{\mathrm{FB}}}\sin^2\theta_K\cos\theta_l+\boxed{S_7}\sin 2\theta_K\sin\theta_l\sin\phi\\ &+\boxed{S_8}\sin 2\theta_K\sin 2\theta_l\sin\phi+\boxed{S_9}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]\end{aligned}$$



Results from **B-factories and CDF** were very much limited by the statistical uncertainty.

LHCb b→sμ$^+$μ$^-$ full angular analysis



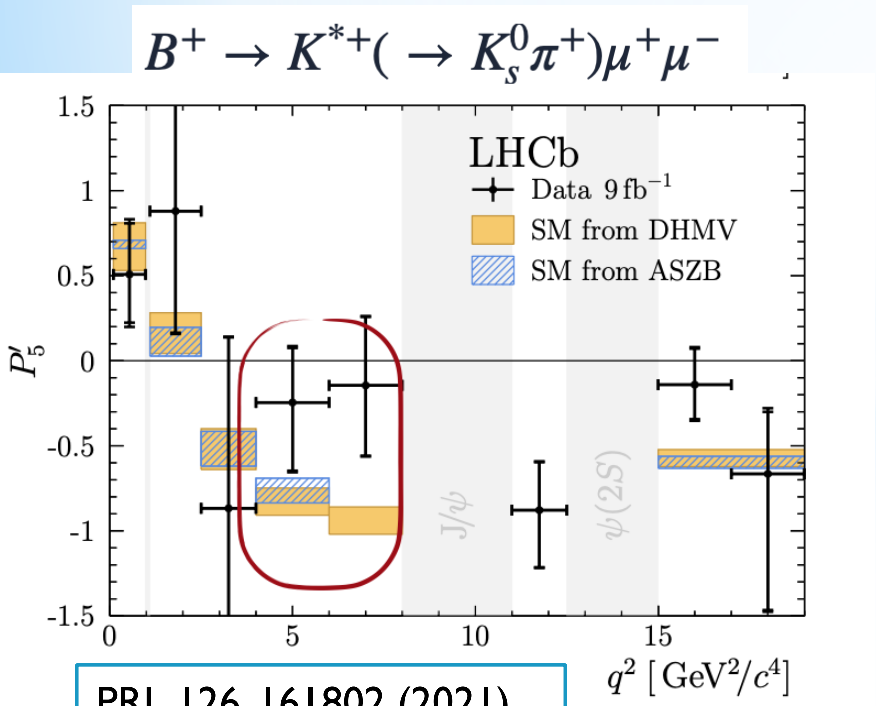
PRL 124, 011802 (2020)

LHCb « Tour de force » full angular analysis performed using RUN-I data + 2016 data.

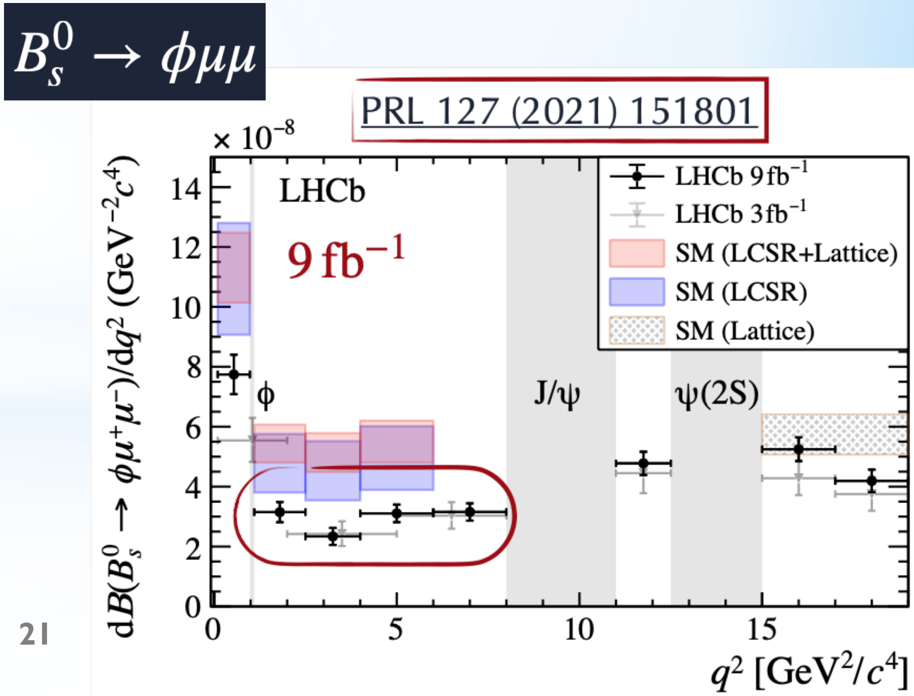
Most of the distributions are in good agreement with the expectations, with some hints for deviations, for example the CP-averaged measurements of S_5. $S_5 \sin 2\theta_K \sin\theta_l \cos\phi$

Complementary analysis using $B^+ \to K^{*+} \mu^+\mu^-$, shows similar behaviour using full RUN-1 and RUN-2 stats.

Similar angular analysis of $B_s \to \varphi\, \mu^+\mu^-$ using full RUN-1 and RUN-2 data shows consistent behavior in terms of Wilson Coefficients.



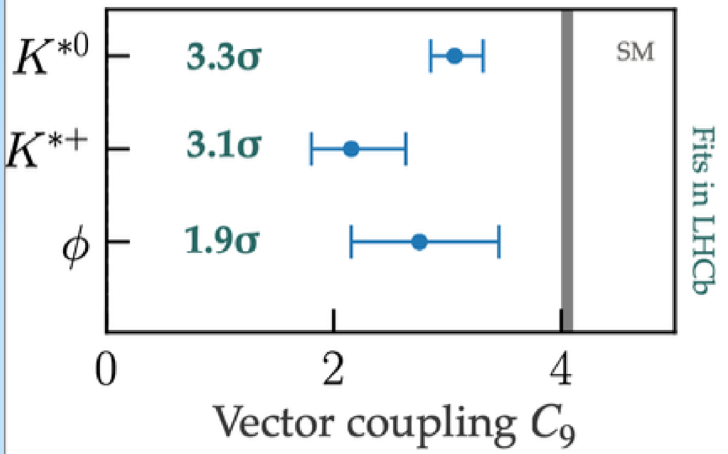
PRL 126, 161802 (2021)



PRL 127 (2021) 151801

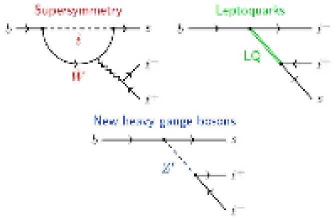
LHCb B→$K^*\mu^+\mu^-$ full angular analysis: NP or QCD?

Persisting set of tensions in b⟶s $\mu\mu$ transitions



Global Wilson coefficients fit seems to indicate a pattern: different observables give a coherent picture

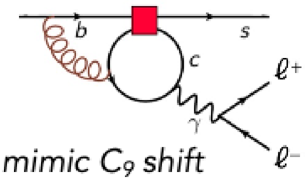
New Physics



or

QCD

$c\bar{c}$ loop



They can mimic C_9 shift

?

New inputs from analyses will help
(finer q^2 bins, unbinned fit over q^2 , other modes…)

Lepton Universality in EW penguins

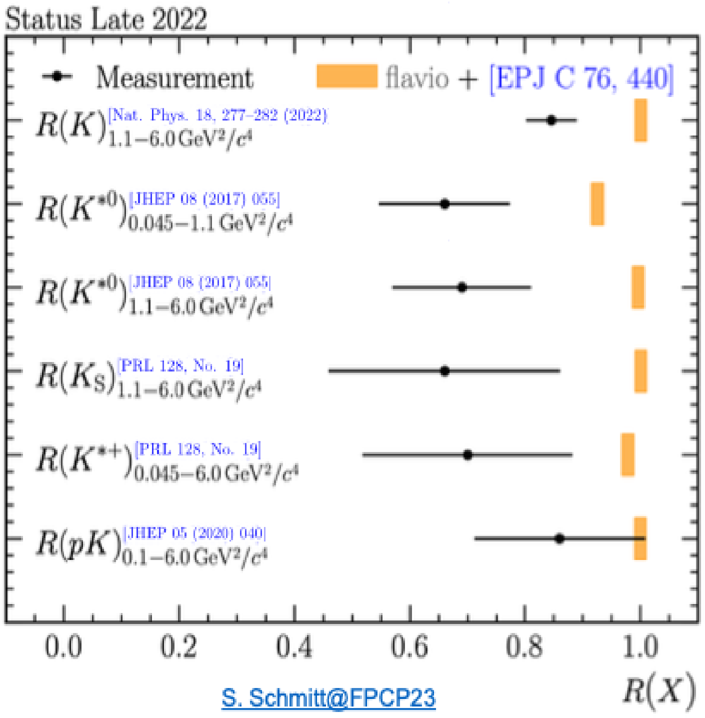
While NP could induce lepton non-universality in b→s ll transitions, hadronic uncertainties cannot do so.

$$R_X = \frac{\int_{q_1}^{q_2} \frac{d\Gamma(B \to X \mu^+\mu^-)}{dq^2}}{\int_{q_1}^{q_2} \frac{d\Gamma(B \to X e^+e^-)}{dq^2}} \qquad \begin{array}{l} B = B^+, B^0, B_s^{\,0}, \Lambda_b^{\,0} \\ X = K^+, K^{*(0,+)}, K_S^{\,0}, \phi, pK, \Lambda\ldots \end{array}$$

- Double ratio respect to resonant modes $B \to J/\psi K$:

$$R_{K^{(*)}} = \frac{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)} \Big/ \frac{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to \mu^+\mu^-))}{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to e^+e^-))}$$

RUN-1&2 LHCb measurement (2022) of $\mathbf{R_K}$ (1.1< q^2 < 6 GeV^2) and **RUN-1** measurement (2017) of $\mathbf{R_{K^*}}$ (1.1< q^2 < 6 GeV^2) indicate a discrepancy (3.1σ and 2.5σ) with the SM.

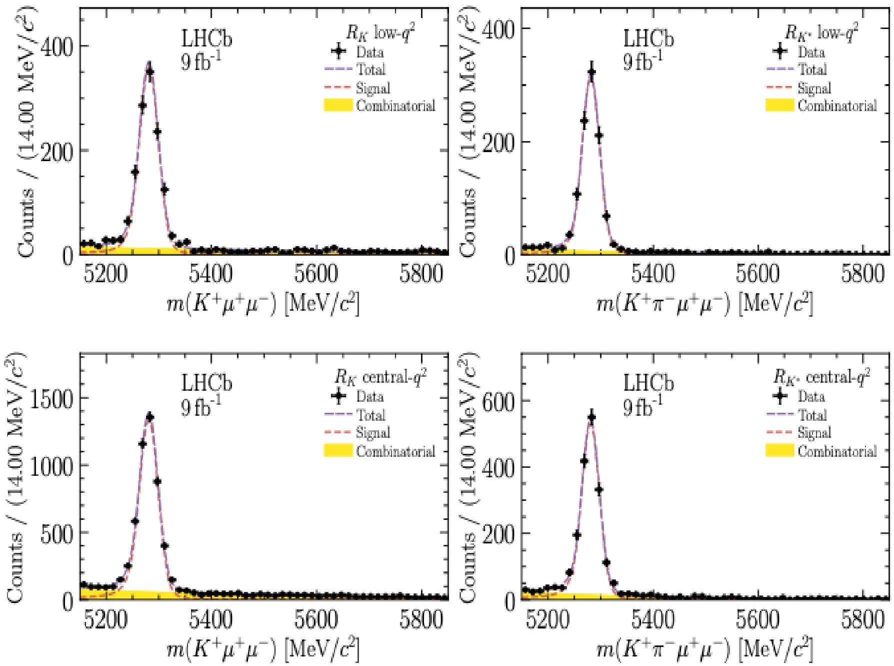


S. Schmitt@FPCP23

Rather than just update R_{K^*} in 2022, LHCb took the approach to come up with a new approach:
- **Simultaneous measurement** of R_K and R_{K^*} in four q^2 bins.
- Work with **higher purity** sample (tighter e-PID).
- Optimized **trigger strategy**.
- **Cross-feed** between K*ee and Kee backgrounds automatically taken into account.

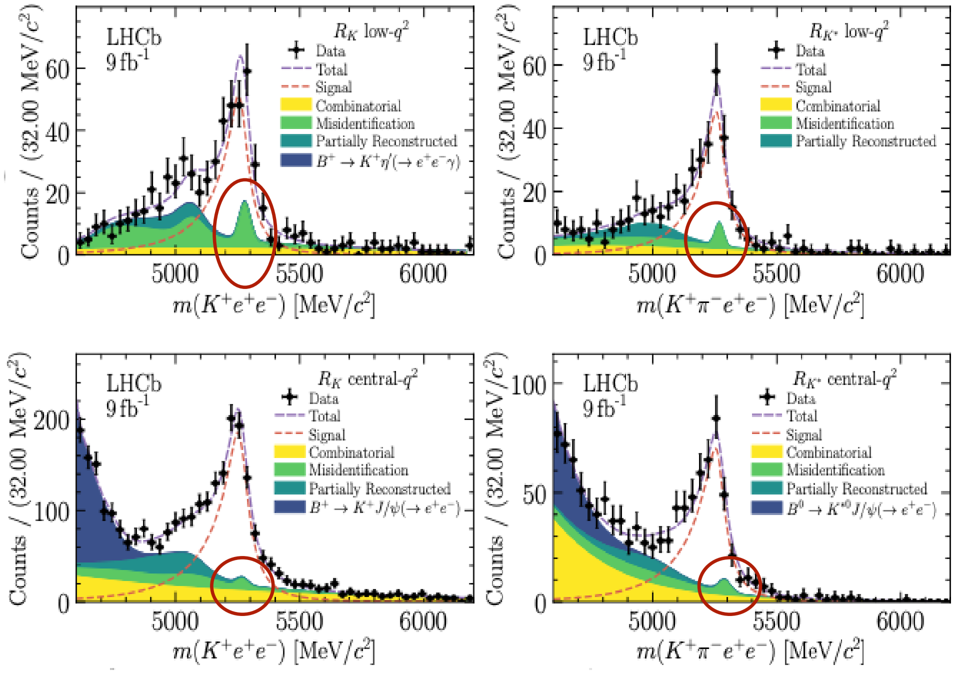
Lepton Universality in EW penguins

Muons



Phys. Rev. D 108 (2023)

Electrons



Phys. Rev. Lett. 131 (2023)

Phys. Rev. D 108 (2023)

Simultaneous measurements allowed to uncover problem in previous analysis:

- **wrong assumption**: exclusive B hadronic decays (f.i. B→KKK) with two missid electrons, not explicitely simulated, thought to be absorbed by combinatorial bkg. Notice that because they don't have bremstrahlung peak is very narrow!

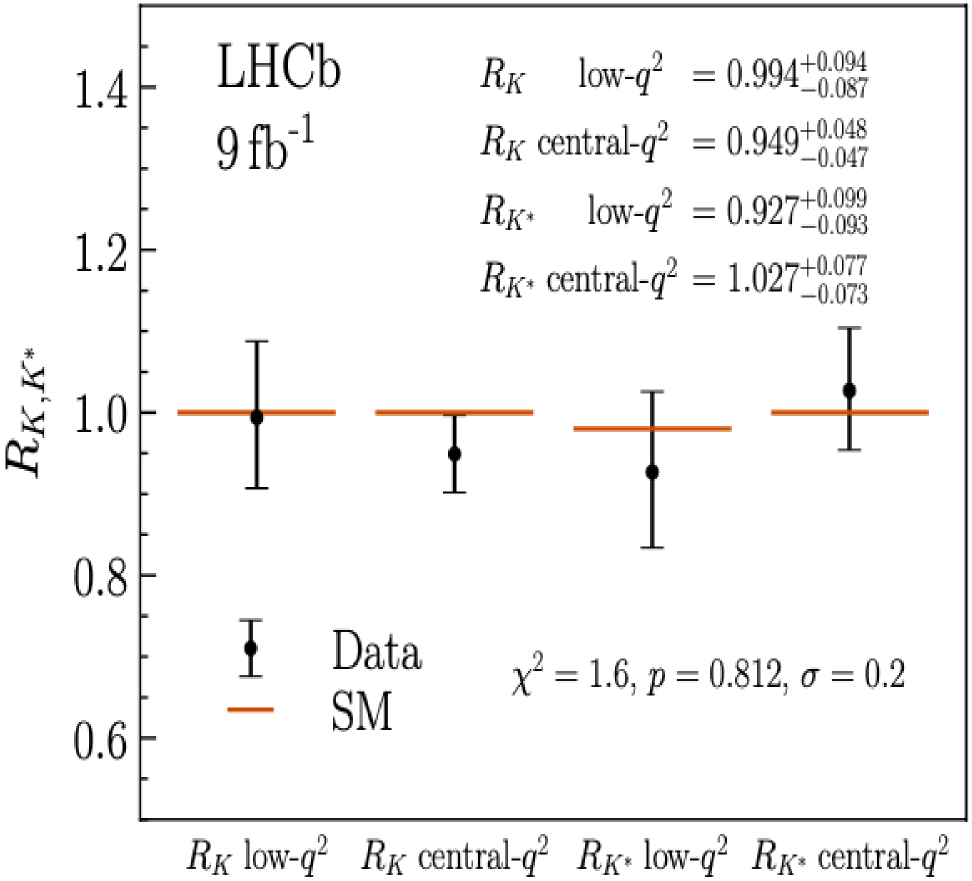
As some of these bkg are poorly understood, decided to use data-driven method to estimate missid bkg. In fact, the R_K central q^2 measurement is the less affected by this problem!

Lepton Universality in EW penguins

- Most precise and accurate LFU test in $b \to s\ell\ell$ transitions.
- Results show agreement with Standard Model at 0.2σ.
- Dominated by statistical uncertainties.
- Main source of systematics: hadronic misIDs.

$$\text{low-}q^2 \begin{cases} R_K &= 0.994 \,^{+0.090}_{-0.082}\,(\text{stat})^{+0.029}_{-0.027}\,(\text{syst}) \\ R_{K^*} &= 0.927 \,^{+0.093}_{-0.087}\,(\text{stat})^{+0.036}_{-0.035}\,(\text{syst}) \end{cases}$$

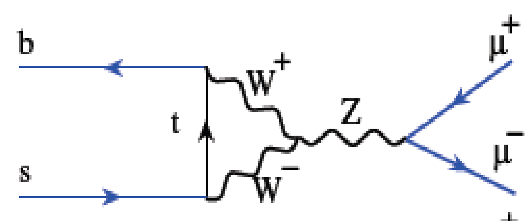
$$\text{central-}q^2 \begin{cases} R_K &= 0.949 \,^{+0.042}_{-0.041}\,(\text{stat})^{+0.022}_{-0.022}\,(\text{syst}) \\ R_{K^*} &= 1.027 \,^{+0.072}_{-0.068}\,(\text{stat})^{+0.027}_{-0.026}\,(\text{syst}) \end{cases}$$



Phys. Rev. Lett. 131 (2023)

Phys. Rev. D 108 (2023)

ΔF=1 Higgs penguins in b→d,s transitions



The pure leptonic decays of **K,D and B** mesons are a particular interesting case of EW penguin. The **helicity suppression** of the vector(-axial) terms, makes these decays particularly sensitive to new (pseudo-)scalar interactions →**Higgs penguins!**

These decays are well predicted theoretically, and experimentally are exceptionally clean. Within the SM,

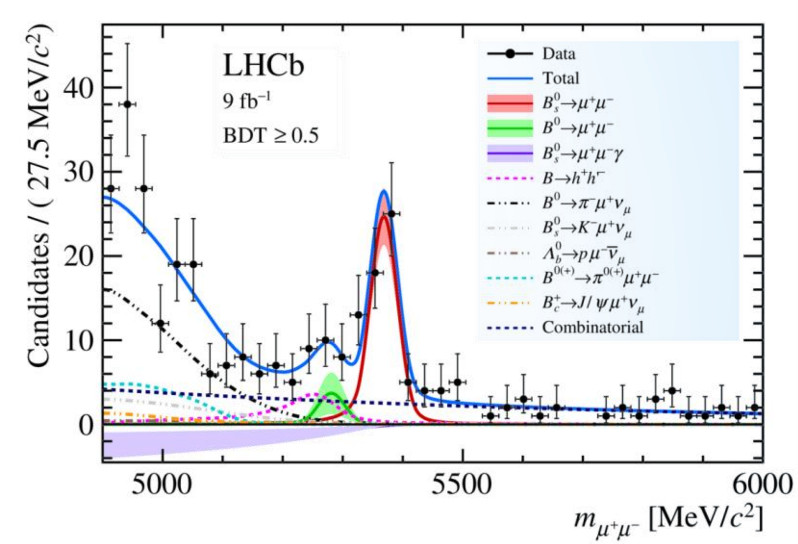
$BR_{SM}(B_s \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$
$BR_{SM}(B_d \to \mu\mu) = (1.06 \pm 0.05) \times 10^{-10}$

The combined RUN-1&2 analyses from LHCb results:

$BR(B_s \to \mu\mu) = (3.09^{+0.46+015}_{-0.43-0.11}) \times 10^{-9}$ (16% precision)
$BR(B_d \to \mu\mu) < 2.6 \times 10^{-10}$ @95%C.L. (70% precision)

PRD105 012010 (2022)

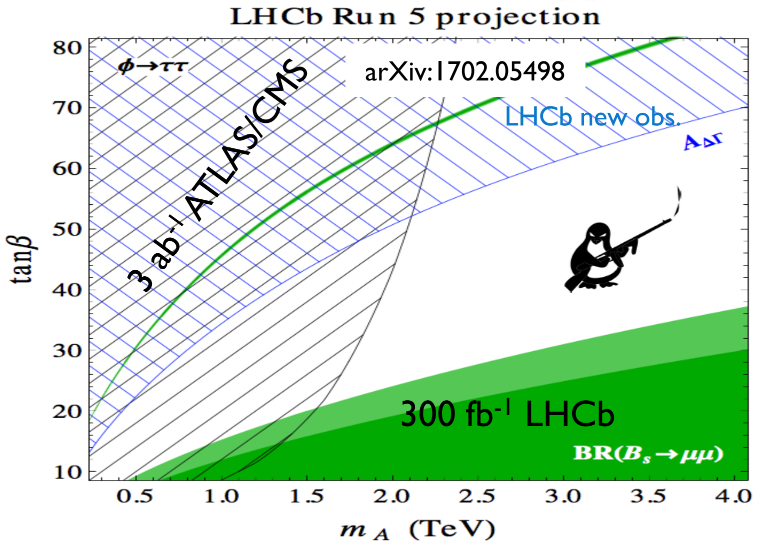
Compatible with the SM.



LHCb U2 could bring precision down to **4%** (compared with ~12% from GPDs). Next goal is the observation of the decay **$B_d \to \mu\mu$.** LHCb U2 could reach **9%** precision (compared with (15-25)% from GPDs).

In addition, the large stats in U2 would allow O(100) effectively flavor tagged $B_s \to \mu\mu$ decays and allow new observables like time dependent CP asymmetry.

$$\frac{\Gamma(B_s^0(t) \to \mu^+\mu^-) - \Gamma(\bar{B}_s^0 \to \mu^+\mu^-)}{\Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s^0 \to \mu^+\mu^-)} = \frac{S_{\mu\mu}\sin(\Delta m_s t)}{\cosh(y_s t/\tau_{B_s}) + A_{\Delta\Gamma}^{\mu\mu}\sinh(y_s t/\tau_{B_s})}$$



ΔF=1 Higgs penguins in c→u and s→d transitions

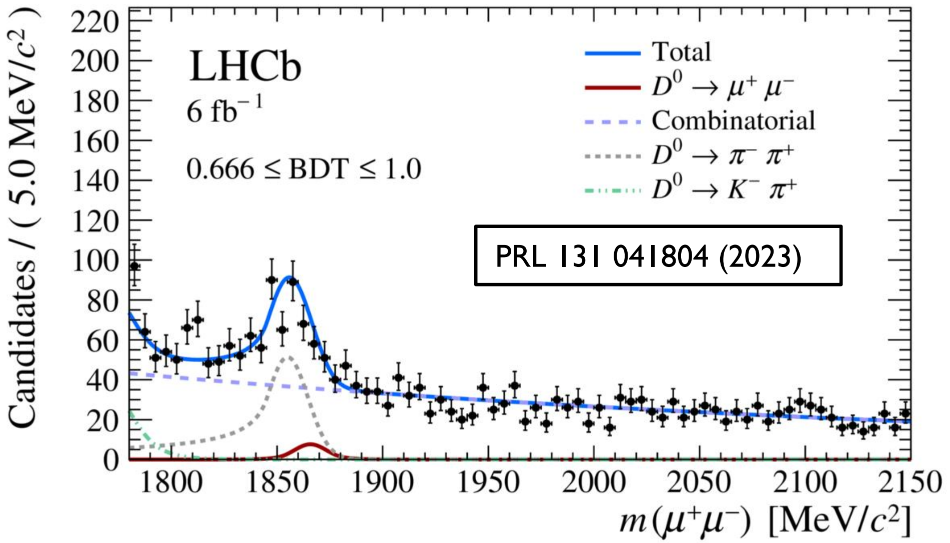
The $D^0 \to \mu\mu$ decay is dominated by long-distance contributions and the SM prediction is less precise:

$BR(D^0 \to \mu\mu)_{SM} < 2\times10^{-11}$ using u.l. from Belle in $BR(D^0 \to \gamma\gamma)$

The combined RUN-1&2 analyses from LHCb results:

$\boxed{BR(D^0 \to \mu\mu) < 3.5\times10^{-9}\ @95\%C.L.}$

LHCb U2 could bring limit down to **10^{-10}.**



PRL 131 041804 (2023)

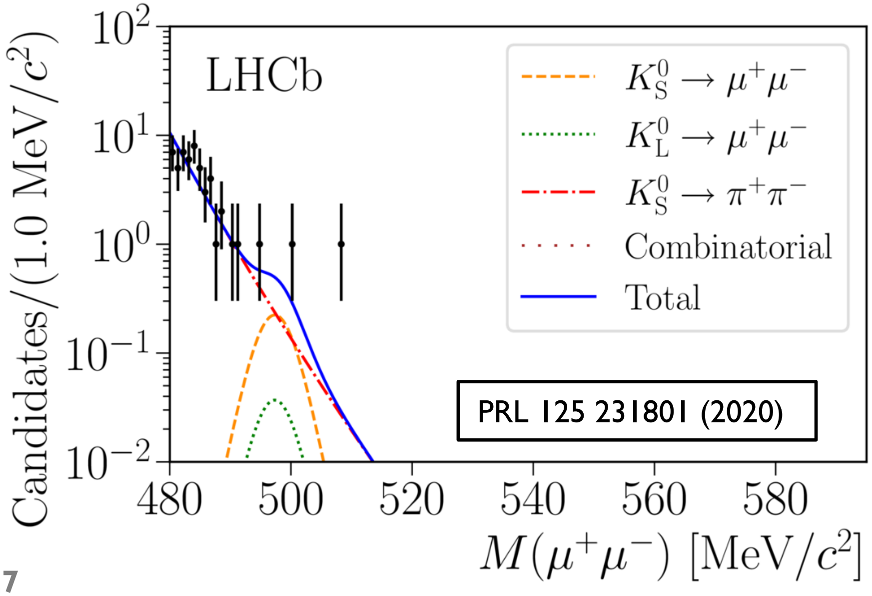
The $K_s \to \mu\mu$ decay has also important long-distance contributions which dominate the precision of the SM prediction:

$BR(K_s \to \mu\mu)_{SM} = (5.18 \pm 1.50_{LD} \pm 0.02_{SD})\times10^{-12}$.

The combined RUN-1&@ analyses from LHCb results:

$\boxed{BR(K_s \to \mu\mu) < 2.4\times10^{-10}\ @95\%C.L.}$

LHCb U2 could bring down the precision to **the SM level.**



PRL 125 231801 (2020)

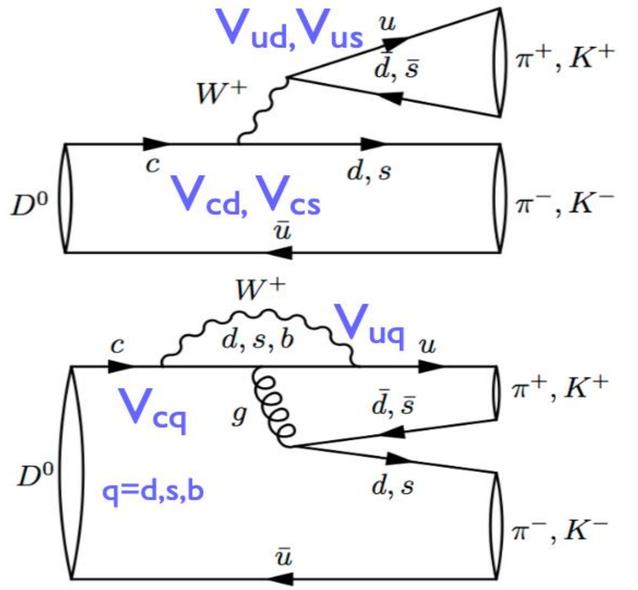
$\Delta F=1$

penguins in c→u transitions

ΔF=1 QCD penguins in c→u transitions: Direct CP violation in D→hh

$$\boxed{A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}}$$

$f = \bar{f} = K^+K^-$
or
$f = \bar{f} = \pi^+\pi^-$

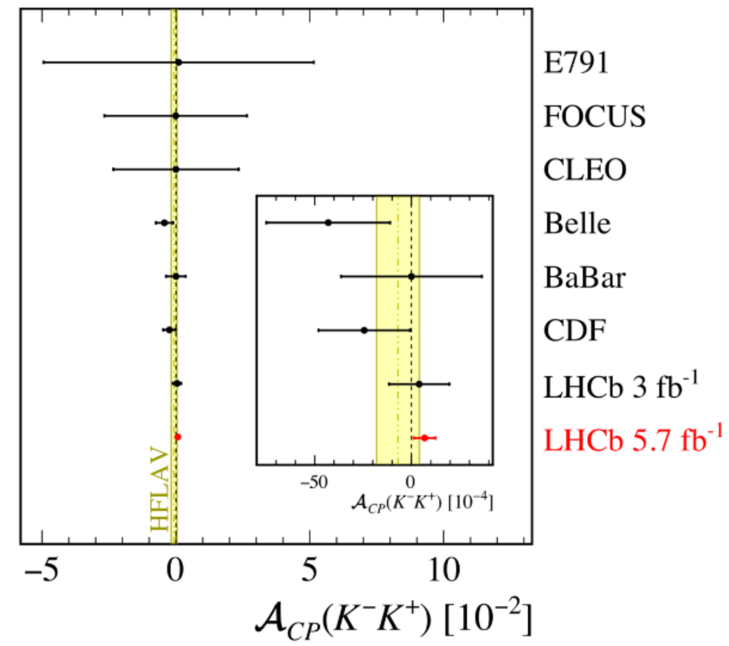


$$A_{\text{raw}} = A_{CP} + A_{\text{production}} + A_{\text{detection}}$$

So far LHCb measured ΔACP=ACP(KK)-ACP(ππ) to reduce the effect of production and detection asymmetries. New approach is to use control samples, Cabibbo favoured decays, where no CP violation is expected to measure these nuisance parameters.

$$A_{CP}(K^-K^+) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$$

arXiv: 2209.03179 (2022)

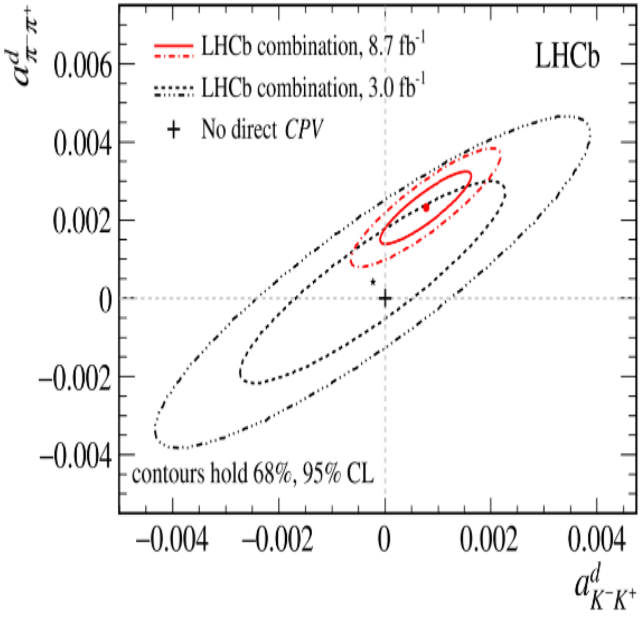


$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$$

$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

Inconsistent with the CP symmetry hypothesis (3.8σ)

First evidence for direct CP violation in a specific charm decay, $D^0 \rightarrow \pi^-\pi^+$



Not only flavour

Latest News on Tetraquarks and Pentaquarks

First Observation of a **Doubly Charged Tetraquark** and its neutral partner, in a combined amplitude analysis of B→anti-D $D_s^+\pi^-$ and $B^+\to D^-D_s^+\pi^+$.

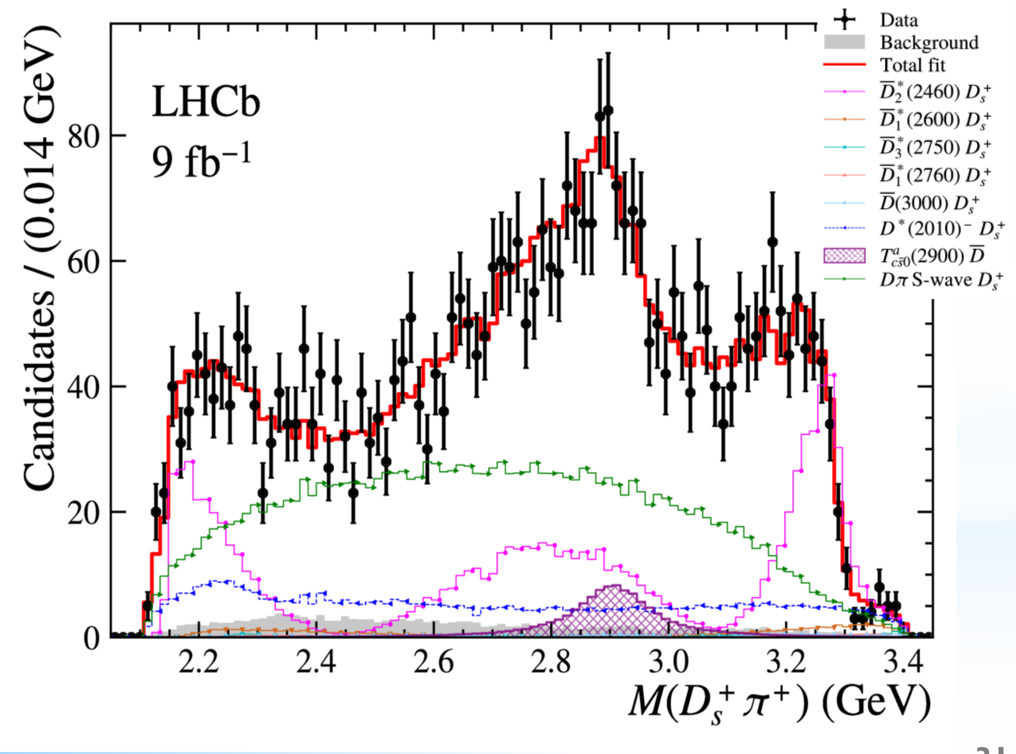
$T^a_{c\bar{s}0}(2900)^{++}\ [c\bar{s}u\bar{d}]$

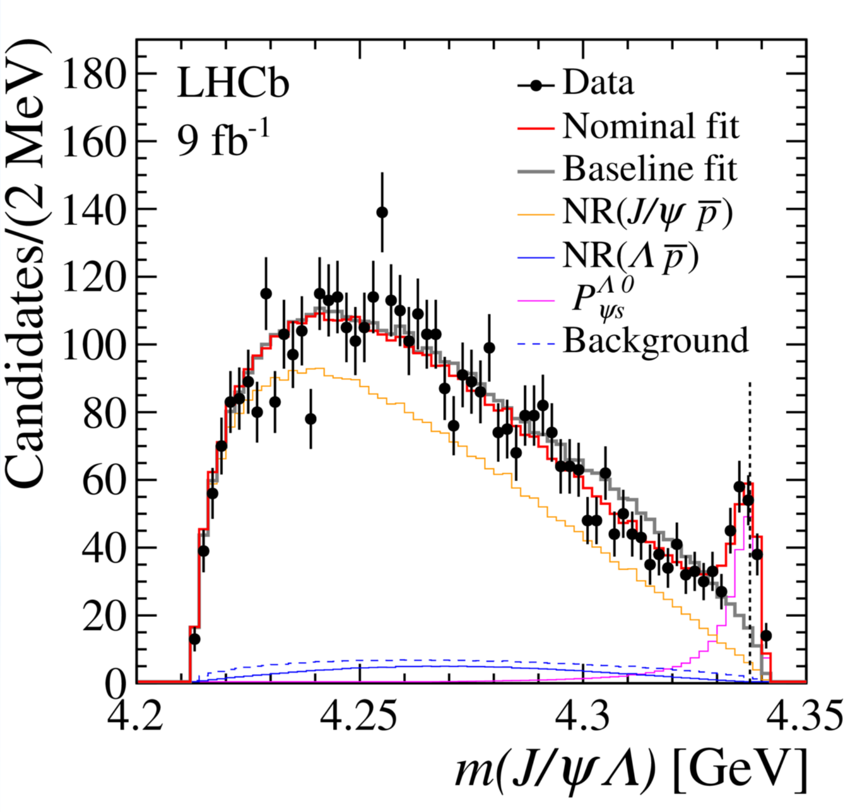
$T^a_{c\bar{s}0}(2900)^{0}\ [c\bar{s}d\bar{u}]$

PRL 131, 041902 (2023)

First Observation of a **Pentaquark with strangeness** in $B^-\to J/\psi\ \Lambda$ anti-p decays.

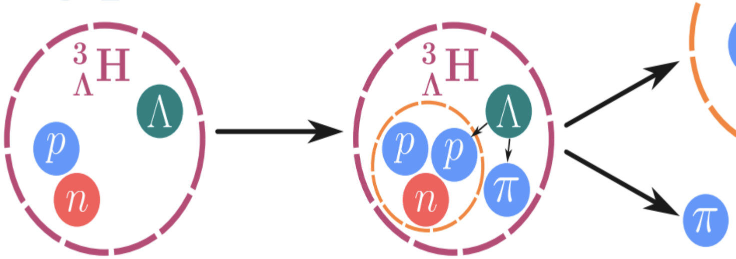
$P^{\Lambda}_{\psi s}(4338)^0\ [c\bar{c}uds]$



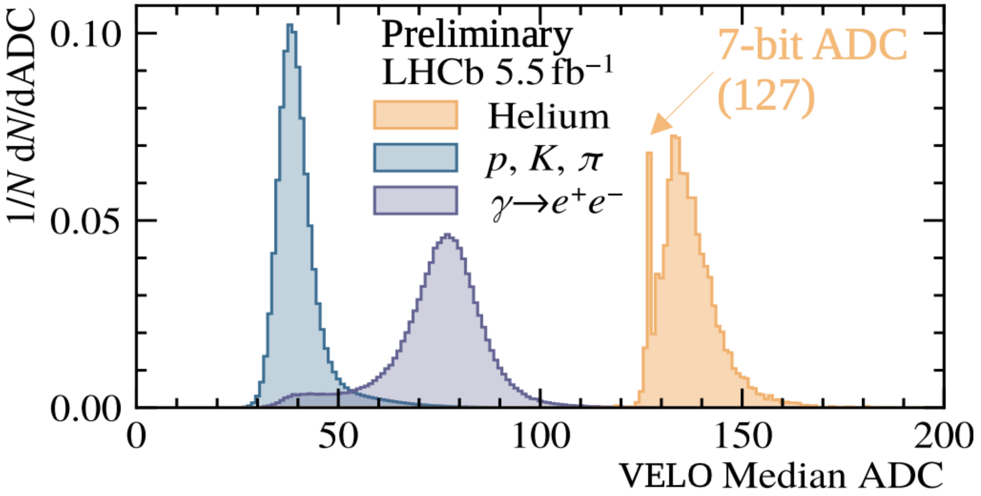


Observation of (anti)Hypetriton in LHCb

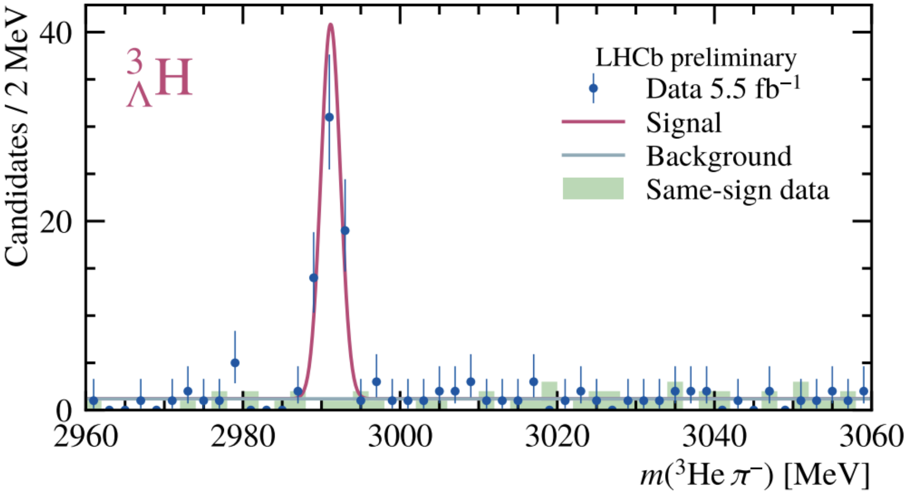
Hypertriton

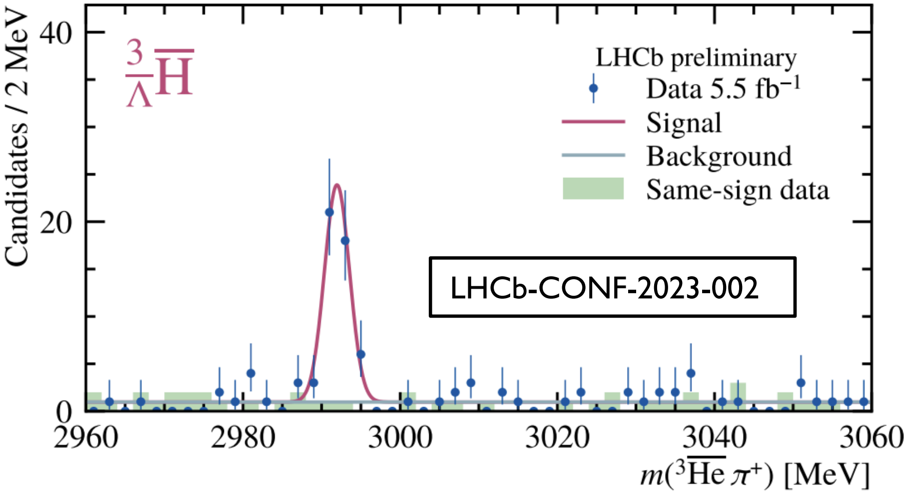


- Access to hyperon-nucleon interaction
  ⇒ Implications for **neutron stars**
- Hypertriton “life-time puzzle”:
  - Tension between STAR and ALICE



- **Fit results:**
  - Yields: Preliminary
    $N({}^3_\Lambda\mathrm{H}) = 61 \pm 8$
    $N({}^3_\Lambda\overline{\mathrm{H}}) = 46 \pm 7$
  - Statistical mass precision: 0.16 MeV





LHCb-CONF-2023-002

Conclusions

Messages to take home

The **SM** has **no explanation for flavour**. **FCNC** is one of the most powerful tools to get **indirect information about NP**, that ideally should provide an explanation for the quark and lepton masses and mixings parameters.

There are **few interesting anomalies in flavour physics to be followed up**, mostly in **b→sll** transitions, but also in **semileptonic B decays**.

Currently **precision measurements of FCNC** processes still **allow O(30%) NP** contributions. **LHCb upgrades** program will **test NP at the few % level** in **both b→d and b→s** transitions. Will reach **SM sensitivity** in the **indirect CPV in charm** decays.

There is a priori as many good reasons to find NP by measuring precisely the couplings of the new scalar boson, as by precision measurements in the flavour sector! **They both are proving the Yukawa sector of the SM.**

We don't know yet what is the scale of NP→ cast a wide net!