Constraints on extended scalar sectors from flavor at the LHC

Biplab Dey

(including results from ATLAS, CMS and Belle II)

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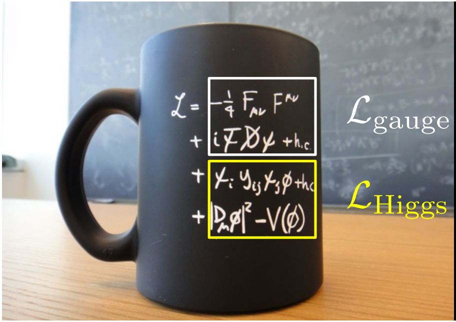
LHCb

Extended Scalar Sectors From All Angles, CERN

Higgs and flavor

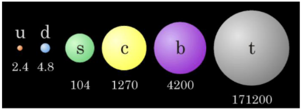


mathematically

elegant symmetries

ad hoc Yukawas

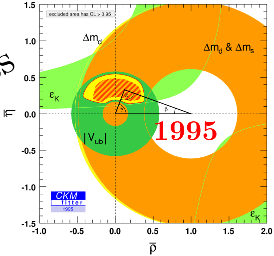
- $\mathcal{L}_{\text{gauge}}$ has huge flavor-degeneracy between the 3 generations.
- Global symmetry: $U(1)_L \times U(1)_B \times U(1)_Y \times U(3)^5_F$.



- Flavor-degeneracy is massively broken by the Higgs Yukawas resulting in strong hierarchy in quark masses.

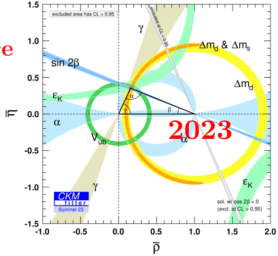
Great success of SM paradigm at the LHC

LHCb +B-factories

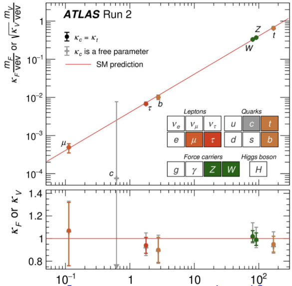


UT closure test

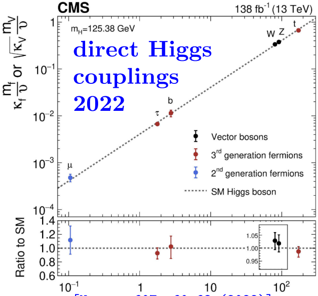
$\Longrightarrow$



LHC GPDs



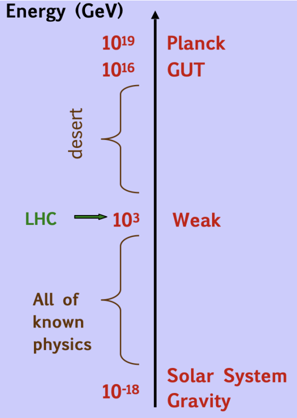
[Nature 607, 52-59 (2022)]



[Nature 607, 60-68 (2022)]

Flavor as a discovery tool

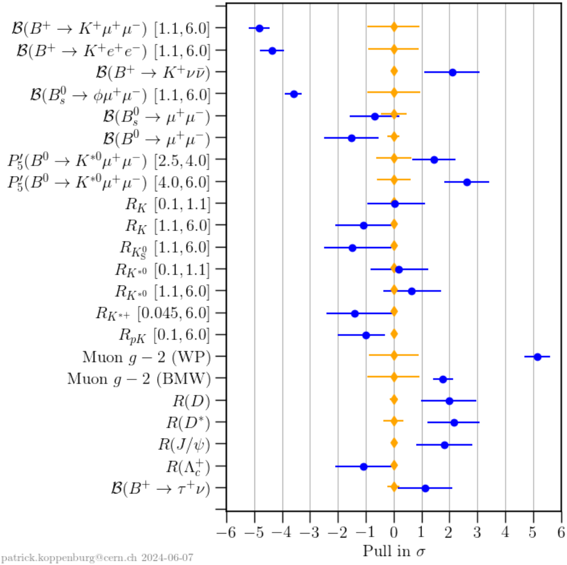
No unambiguous sign of New Physics yet...



[J. Hewett, LISHEP09]

- If $\Lambda_{\rm NP} \gg$ TeV, precision flavor can probe the "desert" via rare/forbidden loop-mediated processes.
- Long history of flavor as an "indirect" probe for new heavy particles:
  - weak nuclear β decay $\Rightarrow$ heavy W/Z
  - $K_L^0 \to \mu^+\mu^-$ GIM suppression $\Rightarrow$ charm
  - B^0-mixing at ARGUS $\Rightarrow$ heavy top
  - SM-like $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ at the LHC $\Rightarrow$ tight limits on MSSM/SUSY

Flavor anomalies over past decade...



- Measurements deviating from SM predictions.
- Anomalies development tracked here.
- Mostly from LHCb involving b-decays.
- Getting to $5\sigma \Rightarrow$ experimental, theory and external (sys.) challenges.

b-FACTORIES: e^+e^- VS pp COLLIDERS

- Running at $e^+e^- \to \Upsilon(4S) \to B\overline{B}$. Low background, $\epsilon_{\text{trigger}} \sim 100\%$. $\mathcal{O}(10^9) B^{0,\pm}$. BelleII $\to \mathcal{O}(10^{10})$.
- Excellent for electrons, neutrals, neutrinos, inclusive and flavor-tagging power.

- $\mathcal{O}(10^{11}) B^{0,\pm}_{(s)}$. UpgradeII $\to \times 100$. Busy environment, initial partonic 4-mom unknown.
- Excellent for exclusive muonic/hadronic modes, PID, vertexing, all b-hadron species (Λ^0_{b}, B^0_s, B^+_c...)

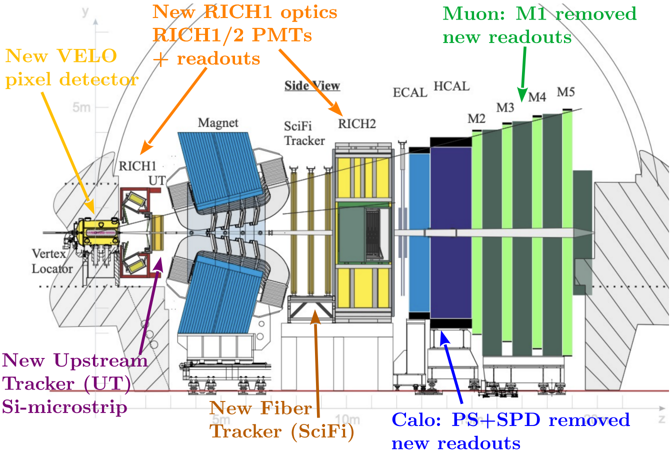
- $\mathcal{O}(10^{12}) B^{0,\pm}_{(s)}$, but very high background. No PID.
- Excellent tracking. Limited b-trigger (low p_T) bandwidth; "B-parking" at CMS (10^{10} b-hadron pairs triggered just in 2018).

LHCb: current status

LHCb in Run 3

[LHCb Upgrade Ia (JINST19(2024)P05065)]

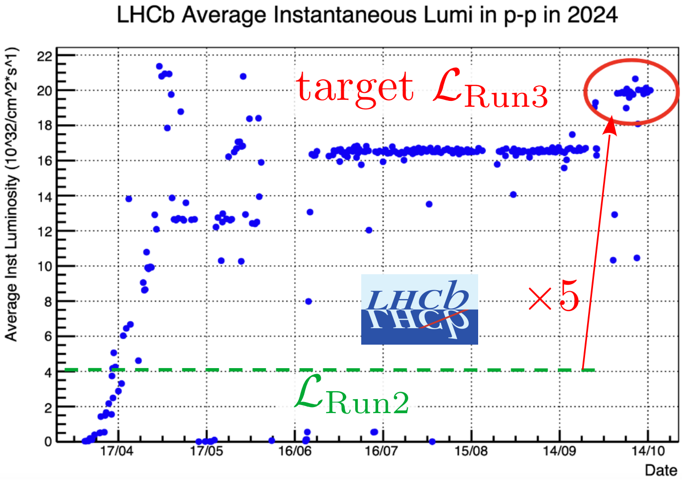
- General purpose forward experiment at the LHC.
- Major Upgrade Ia installed during LS2 (2018-21).



- Level0 h/w trigger removed. Full 40MHz readout.
- Flexible s/w trigger, real-time align & calib
- ×5 pileup, ×2 eff for hadronic lines (multihadrons even more)

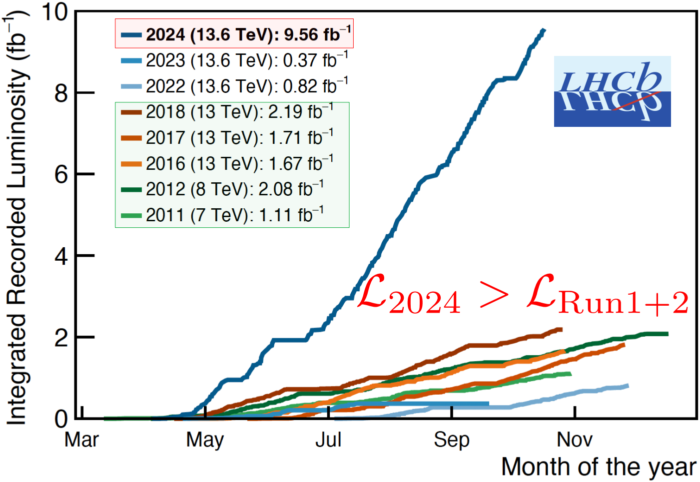
2024 DATA-TAKING

- 2022→2024: commissioning→ stable operation of a ∼ brand new detector + DAQ in a higher pileup environment.



2024 INTEGRATED LUMI

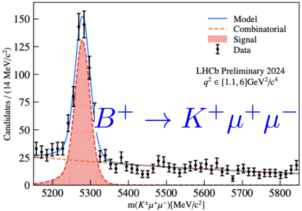
- 2024 Run 3 *pp*-data taking ended last week. Remarkable haul in 2024, thanks to LHC and LHCb U1a DAQ.



Crunching it...

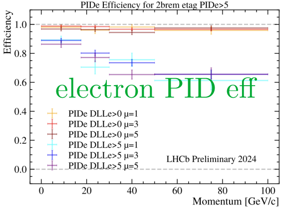
- Understanding and analyzing this large dataset will be the next big challenge. Also, prepare for Run 3 2025.

[LHCb-FIGURE-2024-022]



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

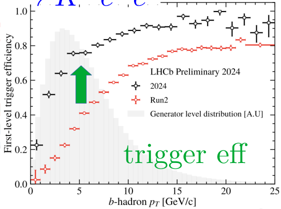
[LHCb-FIGURE-2024-010]



electron PID eff

$B^+ \to K^+e^+e^-$

[LHCb-FIGURE-2024-007]

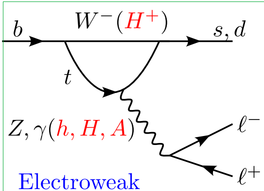


trigger eff

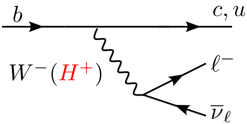
Run 3: purity comparable w/ Run 2 at higher lumi

Higgs @ LHCb Run 1+2: outlook

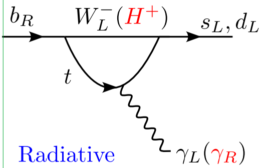
- Run 1+2 (9/fb): levelled lumi ($\mu \sim 1$) for stable run conditions.
- New "proof-of-principle" searches towards upgrades, in addition to core flavor program.



Electroweak



semi-leptonic



Radiative

LHCb Classic

b-anomalies, constraints on extended Higgs models

LHCb Forward GPD

$H \to c\bar{c}, b\bar{b}$
$H \to 2\chi_{\text{LLP}}$

direct Higgs couplings
Higgs $\to$ invisible

$$Rare\ b \to s\ \ penguins$$

Basis of local operators for $b \to s$ penguins

- $(V - A)$ LH operators consistent with SM symmetries:

$$\mathcal{O}_1^u = (\bar{s}\gamma_\mu T^a P_L u)\,(\bar{u}\gamma^\mu T^a P_L b)$$

$$\mathcal{O}_2^u = (\bar{s}\gamma_\mu P_L u)\,(\bar{u}\gamma^\mu P_L b)$$

$$\mathcal{O}_1^c = (\bar{s}\gamma_\mu T^a P_L c)\,(\bar{c}\gamma^\mu T^a P_L b)$$

$$\mathcal{O}_2^c = (\bar{s}\gamma_\mu P_L c)\,(\bar{c}\gamma^\mu P_L b)$$

$$\mathcal{O}_3 = (\bar{s}\gamma_\mu P_L b)\sum_q (\bar{q}\gamma^\mu q)$$

$$\mathcal{O}_4 = (\bar{s}\gamma_\mu T^a P_L b)\sum_q (\bar{q}\gamma^\mu T^a q)$$

$$\mathcal{O}_5 = (\bar{s}\gamma_\mu\gamma_\nu\gamma_\rho P_L b)\sum_q (\bar{q}\gamma^\mu\gamma^\nu\gamma^\rho q)$$

$$\mathcal{O}_6 = (\bar{s}\gamma_\mu\gamma_\nu\gamma_\rho T^a P_L b)\sum_q (\bar{q}\gamma^\mu\gamma^\nu\gamma^\rho T^a q)$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$$

$$\mathcal{O}_8 = \frac{g_s}{16\pi^2} m_b (\bar{s}\, T^a \sigma_{\mu\nu} P_R b) G^{a\mu\nu}$$

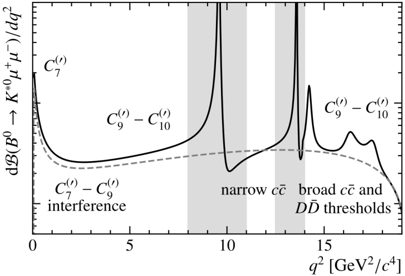
$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

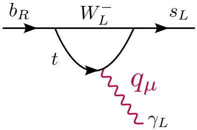
$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- $\mathcal{O}_{1,2}$ (4-quark tree), $\mathcal{O}_{3-6}$ (4-quark penguins), $\mathcal{O}_8$ (gluon penguin)
- $B^0_{(s)} \to \mu^+\mu^-$ sensitive to additional NP scalar $\mathcal{O}_{S,P}$.

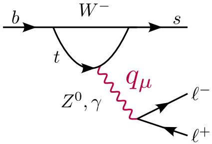
The three dominant contributions

- The dominant $\mathcal{O}_{7,9,10}$ contributions, as a function of q^2:





$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$$ photon



$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$ vector

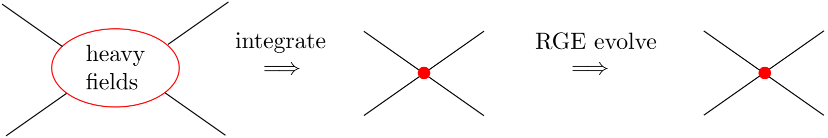
$$\mathcal{A}_{\text{eff}} \sim \frac{C_{\text{SM}}}{m_W^2} + \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2}$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$ axial-vector

- Additional $\mathcal{O}'_{7,9,10}$ as RH (quark) operators, suppressed in the SM, but can be enhanced in NP scenarios.

Wilson coefficients and local FFs

- From SMEFT to weak EFT (WEFT) at m_b scale:

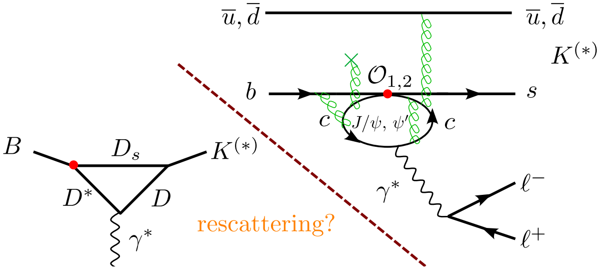


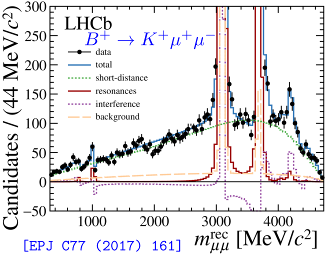
$\mathcal{H}_{\text{eff}} = \sum C_i(m_W)\mathcal{O}_i$ $\qquad$ $\mathcal{H}_{\text{eff}} = \sum C_i(m_b)\mathcal{O}_i$

- The (dimensionless) Wilson coefficients encode the short-distance physics. $\mathcal{A}(i \to f) = \sum C_n(m_b)\langle f|\mathcal{O}_n(m_b)|i\rangle$.
- The long-distance physics (hadronization) is encoded in the *local* form-factors (theory). Eg. $V_\mu^{B\to M}(k,q) \equiv \langle M(k)|\bar{s}\gamma_\mu P_L b|\overline{B}(q+k)\rangle$
- Inputs to rich pheno from multibody amplitude analyses @LHCb: $B \to K\pi\ell^+\ell^-$, $B_s^0 \to \phi\ell^+\ell^-$, $\Lambda_b^0 \to \Lambda^{(*)}\ell^+\ell^-$, $B^0 \to K^{*0}\gamma$, $B_s^0 \to K^+K^-\gamma$, $\Lambda_b^0 \to \Lambda^{(*)}\gamma$.

Non-local (aka charm loop) contributions

- Non-local contributions from propagating $c\bar{c}$ are the bane:





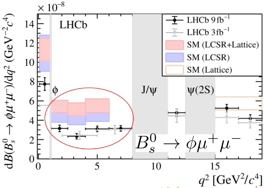
[EPJ C77 (2017) 161]

- At leading order, the $\mathcal{O}_{1,2}$ is factorizable, but leads to strong phases from the resonances (LHCb has measured these).
- Further (soft+hard) gluons lead to *non-factorizable* contributions, that can mimic NP contributions. Need data-driven approaches.

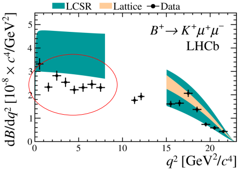
$b \to s\mu^+\mu^-$: EFFECT ON GLOBAL FITS

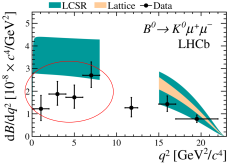
- Both BFs and angular analyses show tensions. C_{10A} constrained by $B_s^0 \to \mu^+\mu^-$ and $C_{7\gamma}$ by $B \to X_s\gamma$. Primary suspect is C_{9V}.

[PRL 127(2021)151801]

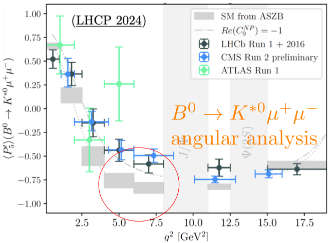


[JHEP 06 (2014) 133]





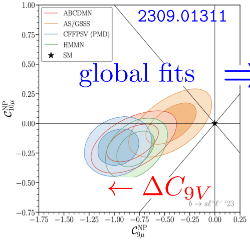
$\mathcal{B}(b \to s\mu^+\mu^-)$ systematically lower than SM

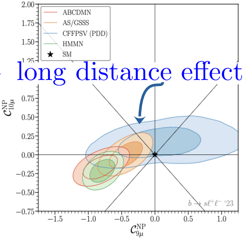


including CMS parked data

2309.01311

global fits $\Longrightarrow$ long distance effects





Three ways to tame hadronic uncertainties

- More model-independent amplitude analyses, including $c\bar{c}$ ansatz. $B^0 \to K^* \mu^+ \mu^-$ for now, but B_s^0, Λ_b^0 to follow. Hovering at $\sim 2\sigma$.

- Lepton Flavor Universality violation (LFUV) in the rates:

$$R_X^{-1} \equiv \frac{\frac{N}{\epsilon}(H_b \to X_s e^+ e^-)}{\frac{N}{\epsilon}(H_b \to X_s J/\psi(e^+ e^-))} \bigg/ \frac{\frac{N}{\epsilon}(H_b \to X_s \mu^+ \mu^-)}{\frac{N}{\epsilon}(H_b \to X_s J/\psi(\mu^+ \mu^-))}$$

  with $\mathcal{B}(J/\psi \to e^+ e^-)/\mathcal{B}(J/\psi \to \mu^+ \mu^-) = 1$ from PDG.
  LHCb-2023 $R(K^{(*)})$ update [PRD108(2023)032002] + CMS-2023 [CMS-PAS-BPH-22-005]: SM-like.

- LFUV in angular observables $Q_i \equiv S_i^\mu - S_i^e$.

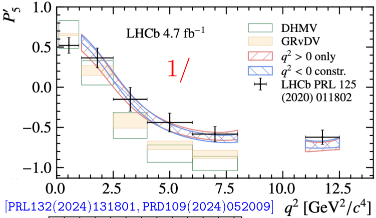
Run 1+2 still "exploratory" $\rightsquigarrow$ need Run 3 and beyond

Two new data-driven fits for $B^0 \to K^{*0}\mu^+\mu^-$

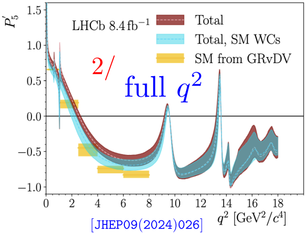
1/ Fit to long-distance $\mathcal{H}_\lambda(q^2)$ as model-independent z-expansion:

$$\mathcal{A}^{L,R}_{\lambda=0,\parallel,\perp} = \mathcal{N}_\lambda \left\{ \left[(C_9 \pm C_9') \mp (C_{10} \pm C_{10}') \right] \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[(C_7 \pm C_7')_{\rm SM} \mathcal{F}^T_\lambda(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right]\right.$$

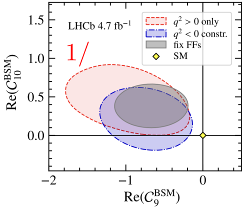
2/ $C^{(\rm eff)}_{9,\lambda} \to C_9 + Y_{q\bar{q},\lambda}(q^2)$. $Y_{q\bar{q}} \in$ sum $\{\rho, \omega, \phi, J/\psi, \ldots, D^{(*)}\overline{D}^{(*)}\}$



[PRL132(2024)131801, PRD109(2024)052009]

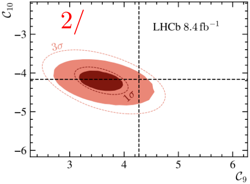


[JHEP09(2024)026]



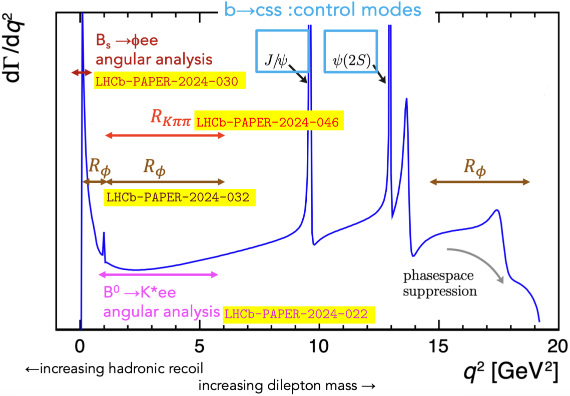
$\Delta C_9 < 0$ preferred but overall tension reduced

both exp. and theory improvements in future

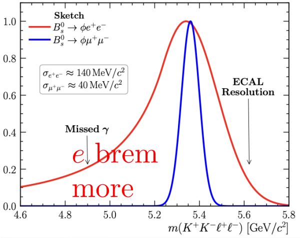


Four new $b \to se^+e^-$ results

- Electron triggers need higher E_T thresholds to tackle ECal occupancy, than muons. Lower statistics than muons.
- Data-driven trigger eff corrections in MC, and $h \to e$ background removal, similar to 2023 $R(K^{(*)})$ paper [PRD108(2023)032002]

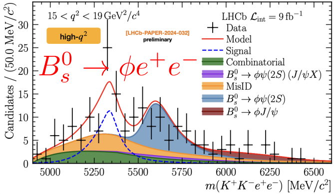


full Run 1+2 (preliminary)

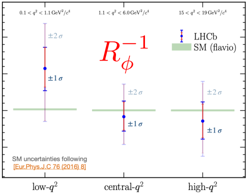


Run 1+2 R_ϕ and $R_{K\pi\pi}$ (preliminary)

- Two new LFUV in the BFs:

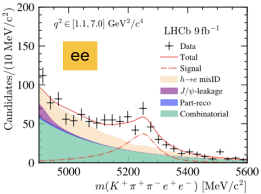


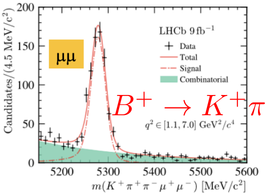
$B_s^0 \to \phi e^+e^-$



Three q^2 bins
First observation
First LFUV at high-q^2
consistent w/ SM

[LHCb-PAPER-2024-032]





$B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$

$$R_{K\pi\pi}^{-1} = 1.31^{+0.18}_{-0.17}(\text{stat})^{+0.12}_{-0.09}(\text{syst})$$

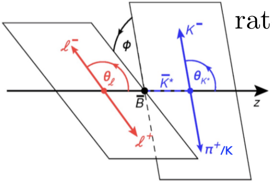
hadron $\to e$ mis-Id

Single q^2 bin
consistent w/ SM

[LHCb-PAPER-2024-046]

LFUV IN $B^0 \to K^{*0}\ell^+\ell^-$ ANGULAR ANALYSIS

- $B^0 \to K^{*0}e^+e^-$ angular analysis in the central q^2 region.
- For LFUV, muonic results from [PRL132(2024)131801]



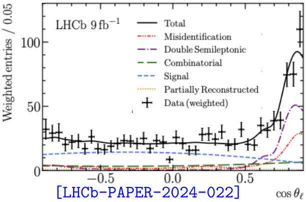
$$\text{rate} \propto \Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

ratios

$$P_1 = \frac{2S_3}{(1-F_L)}, \quad P_2 = \frac{2}{3}\frac{A_{FB}}{(1-F_L)}, \quad P_3 = \frac{-S_9}{(1-F_L)}, \quad P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

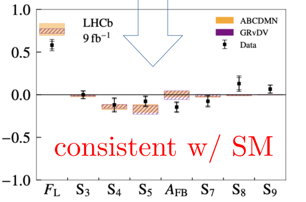
$$Q_i = P_i^\mu - P_i^e$$

$q^2 \in [1.1, 6.0]$ GeV^2

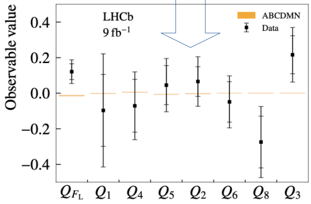


[LHCb-PAPER-2024-022] (preliminary)

[N. Gubernari, M. Reboud, D. Van Dyk, J. Virto, JHEP 09 (2022) 133]
[M. Algueró, A. Biswas, B.Capdevila, S. Descotes-Genon, J. Matias, EPJC 83 (2023) 7, 648]

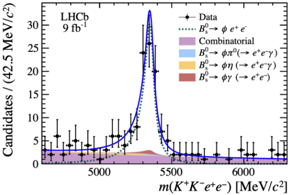


consistent w/ SM



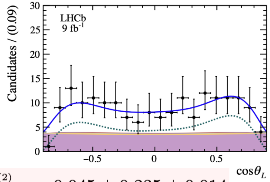
$B_s^0 \to \phi e^+ e^-$ LOW-q^2 ANGULAR ANALYSES

- $q^2 \to 0$ region close to the photon pole sensitive to $C_7^{(\prime)}$. Accessible only via the ee modes. $B^0 \to K^{*0} e^+ e^-$ in [JHEP12(2020)081].
- Corresponding analysis with the B_s^0. CP-averaged for now, but TDCPV also very interesting.



$q^2 \in [0.0009, 0.2615]$ GeV^2
[LHCb-PAPER-2024-030]
(preliminary)

consistent w/ SM



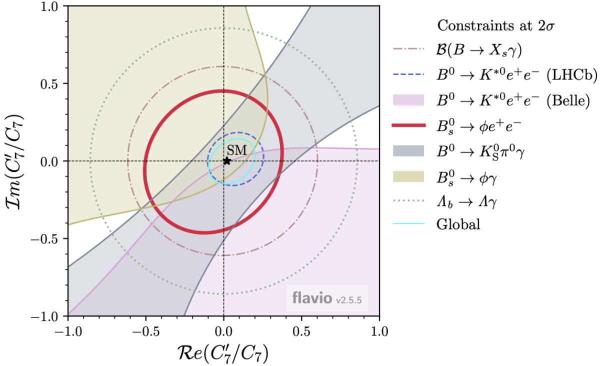
$$A_{\mathrm{T}}^{(2)} = -0.045 \pm 0.235 \pm 0.014$$
$$A_{\mathrm{T}}^{ImCP} = 0.002 \pm 0.247 \pm 0.016\,,$$
$$A_{\mathrm{T}}^{ReCP} = 0.116 \pm 0.155 \pm 0.006\,,$$
$$F_{\mathrm{L}} < 11.5\% \text{ @ } 90\% \text{ CL}\,.$$

CP-averaged rate
$$\propto \Big\{ \frac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k + \left[\frac{1}{4}(1-F_L)\sin^2\theta_k - F_L\cos^2\theta_k\right]\cos 2\theta_l + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_k\sin^2\theta_l\cos 2\tilde{\phi} + (1-F_L)A_T^{ReCP}\sin^2\theta_k\cos\theta_l + \frac{1}{2}(1-F_L)A_T^{ImCP}\sin^2\theta_k\sin^2\theta_l\sin 2\tilde{\phi}\Big\}$$

$$A_T^{(2)}(q^2 \to 0) = \frac{2Re(C_7 C_7^{\prime *})}{|C_7|^2 + |C_7^\prime|^2} + \Delta_1{}^2$$
$$A_T^{ImCP}(q^2 \to 0) = \frac{2Im(C_7 C_7^{\prime *})}{|C_7|^2 + |C_7^\prime|^2} + \Delta_2{}^2$$

$B_s^0 \to \phi e^+ e^-$ LOW-q^2 ANGULAR ANALYSES

- Places constraints on RH currents in $b \to s\gamma$:

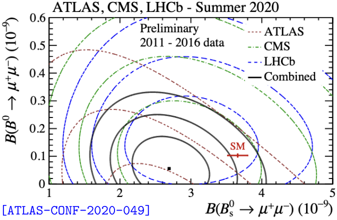


[LHCB-PAPER-2024-030-002]

(preliminary)

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

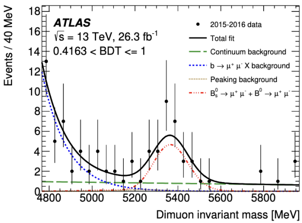
- Loop+hel. suppressed in the SM. B^0_d yet to be observed.
- 2020 LHC combination: $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ $\sim 2.4\sigma$ below SM (mostly driven by ATLAS).

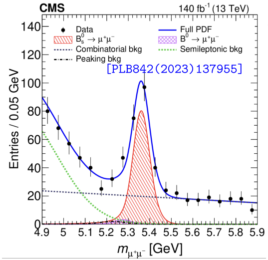


[ATLAS-CONF-2020-049]

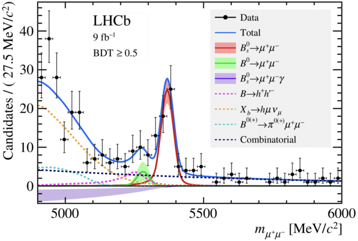
- Full Run 2 CMS and LHCb, both consistent w/ SM.
- Higher lumi at GPDs, while better mass resolution at LHCb:

[JHEP04(2019)098]



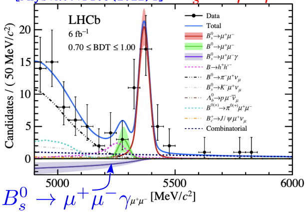


[PRL 128, (2022) 041801]

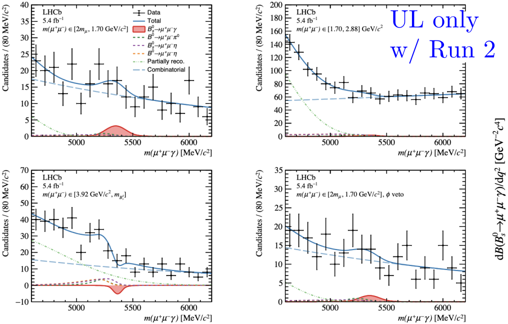


$B_s^0 \to \mu^+\mu^-\gamma$: FIRST DIRECT SEARCH [JHEP07(2024) 101]

[Phys.Rev.D105(2022)1] $B_s^0 \to \mu^+\mu^-$

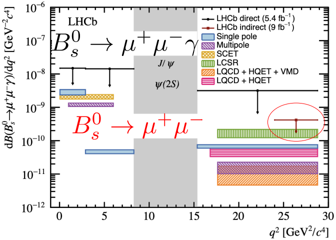


- Unlike $B_s^0 \to \mu^+\mu^-$, no hel. suppression in $B_s^0 \to \mu^+\mu^-\gamma$. Indirect limit from high-q^2 ISR in $B_s^0 \to \mu^+\mu^-$. Now, reconstructed γ.
- Sensitivity to $C_{7,9}$ in addition to C_{10}. Theory $\mathcal{B} \sim 10^{-9}$ to 10^{-10} depends on $B_s^0 \to \gamma$ FF.



[JHEP07(2024)101]

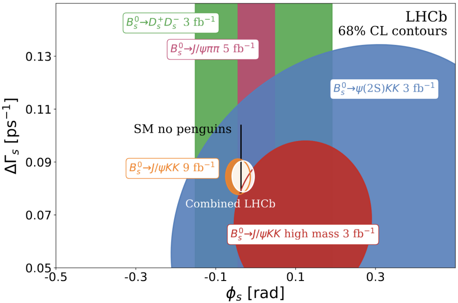
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm I} < 3.6\ (4.2) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm II} < 6.5\ (7.7) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm III} < 3.4\ (4.2) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm I,\ with\ \phi\ veto} < 2.9\ (3.4) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm comb.} < 2.5\ (2.8) \times 10^{-8},$$



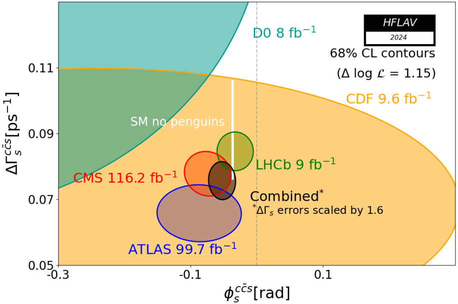
ϕ_s FROM B_s^0 MIXING IN $b \to sc\bar{c}$

- In the SM, $B_s^0 - \overline{B}_s^0$ mixing angle $\phi_s \equiv 2\arg[-(V_{ts}V_{tb}^*/(V_{cs}V_{cb}^*)]$, is small, precisely known and sensitive to penguins.
- CKMFitter-2023: $\beta_s = 0.01882^{+0.00026}_{-0.00054}$
- Consistent w/ SM, but statistics limited.

[PRL132(2024)051802], LHCb:

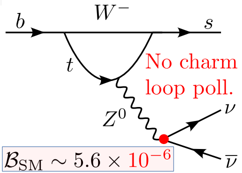


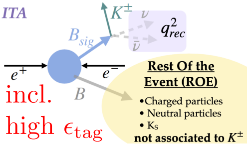
[HFLAV LHC combination]:

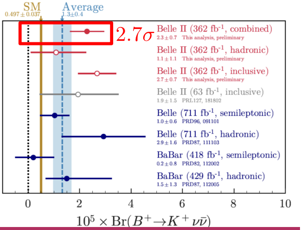


$B^+ \to K^+ \nu_\ell \bar{\nu}_\ell$ at BelleII

[PRD109, 112006(2024)]
[PRL 127 181802 (2021)]





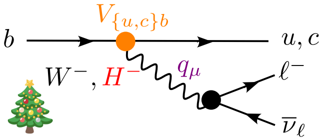


- Access to 3rd gen. in EWP (also $B^0 \to K^0 \tau^- \tau^+$)
- Theory prediction from lattice: 6% precision. Previous best UL at 1.6×10^{-5} at 90% CL.
- $B^+ \to K^+ +$ invisible: no access at LHCb.
- Conventionally, hadronic tag. New: inclusive tag.
- Data/MC checks from control samples: $q\bar{q} + B\overline{B}$ $(B \to D^{(*)}(\to K^+X)\ell\nu, B^+ \to K^+ K_L K_{L,S}, B^+ \to K^+ nn, B^+ \to K^+ D^{(*)}$, $B^+ \to K^+ [J/\psi(\to \mu\mu)]_{\rm miss}, B^+ \to \pi^+ K^0)$

- Two-step BDT(ITA). ITA/HTA agrees.
- ITA: 2.3σ tension w/ BABAR-SL tag.
- Combined: 3.5σ evidence, 2.7σ deviation from SM.

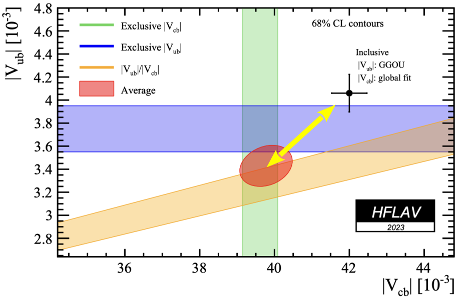
$b \to c\tau^- \overline{\nu}_\tau$ *and friends*

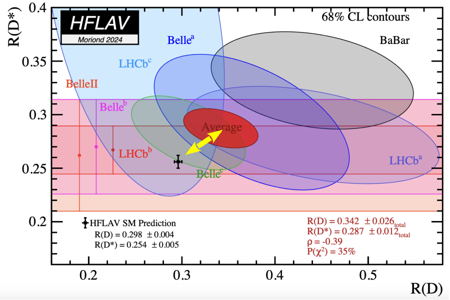
The two towers



- Hard at LHCb because of missing ν's
- $R_X \equiv \mathcal{B}(H_b \to X_c\tau^-\overline{\nu}_\tau)/\mathcal{B}(H_b \to X_c\ell^-\overline{\nu}_\ell)$. $\ell = \mu$ at LHCb.

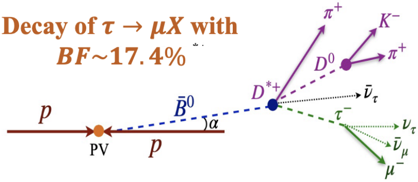
- $\sim 3\sigma$ tensions in $|V_{xb}|$ and $R(D^{(*)})$. $|V_{xb}|$ probably SM/exp. issue.





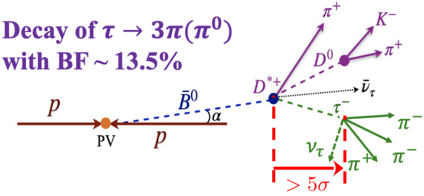
τ RECONSTRUCTION AT LHCB

Muonic (BelleII+LHCb)



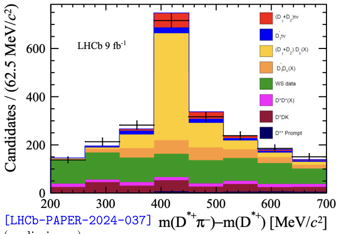
- Higher statistics
- Same final state as $B \to D^*\mu\nu$ normalization mode. Many systematics cancel.
- Multiple missing ν's. Infer p_B using boost approx. $p_B^{\parallel} \propto p_{\text{vis}}^{\parallel}$

Hadronic (LHCb)



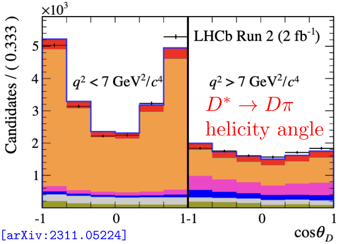
- Cleaner selections.
- Normalization mode is $B \to D^*3\pi$ ($\Lambda_b^0 \to \Lambda_c 3\pi$). Need external BFs as inputs ($\to$ systematics).
- Better resolutions in the kinematic variables. Two two-fold ambiguities.

Other semitauonic results



[LHCb-PAPER-2024-037]
(preliminary)

- First evidence, $B^- \to D^{**0}(\to D^{*+}\pi^-)\tau^-\overline{\nu}_\tau$
- Important bkgd for $R(D^{(*)})$
- $R(D_1(2420)^0 + D_2^*(2460)^0) =$
  $0.13 \pm 0.03(\text{stat}) \pm 0.01(\text{syst}) \pm 0.02(\text{ext})$
- Consistent w/ SM at 1σ



[arXiv:2311.05224]

- D^* polarization in, $B^0 \to D^{*-}\tau^+\nu_\tau$

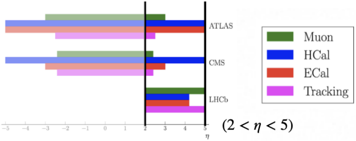
$F_L^{D^*} = 0.51 \pm 0.07 \pm 0.03$	at $q^2 < 7$ GeV$^2/c^4$	LHCb
$F_L^{D^*} = 0.35 \pm 0.08 \pm 0.02$	at $q^2 > 7$ GeV$^2/c^4$	
$F_L^{D^*} = 0.495 \pm 0.017$	at $q^2 < 7$ GeV$^2/c^4$	Theory
$F_L^{D^*} = 0.383 \pm 0.006$	at $q^2 > 7$ GeV$^2/c^4$	

- Consistent w/ SM, but statistics limited.

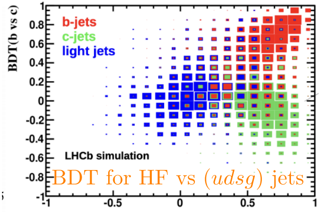
- Run 1 $R(\Lambda_c)$ [PRL128(2022)191803] also consistent w/ SM.

Direct Higgs searches

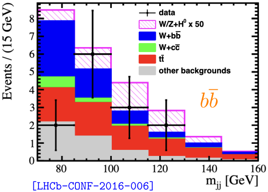
$H \to b\bar{b}(c\bar{c})$ in forward jets at LHCb



- Excellent tracking, vertexing, lepton-id in the forward region. HF jet tagging.
- $b\bar{b}(c\bar{c})$+lepton: sensitive to WH/ZH.

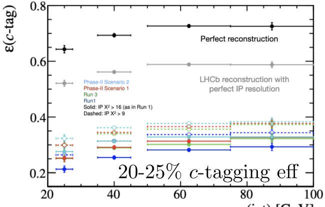


[JINST10(2015)P06013]



[LHCb-CONF-2016-006]
Run1 unpublished

- No signal in Run 1. UL: $y^b < 7y^b_{\rm SM}$, $y^c < 80y^c_{\rm SM}$



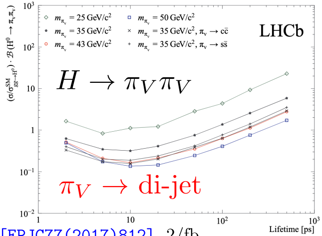
[LHCB-PUB-2018-009]

- Run 2: regression for jet energy correction (jj mass) and DNN for jet identification.
- Upgrade II 300/fb projection: $y^c \sim 2y^c_{\rm SM}$ sensitivity possible.

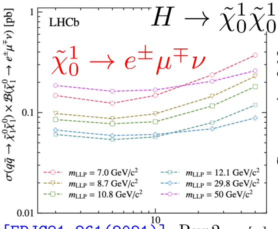
Exotic Higgs → LLPs at LHCb

- Lower mass reach than GPDs due to softer triggers.

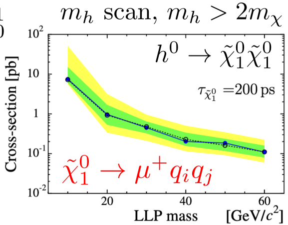
1DV in VELO



[EPJC77(2017)812], 2/fb



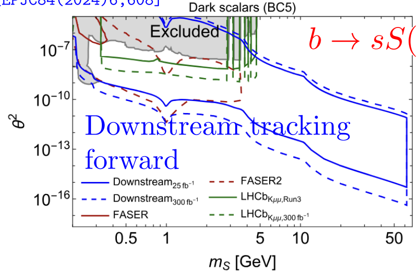
[EPJC81,261(2021)], Run2 τ_{LLP} [ps]



[EPJC82(2022)4,373], Run2

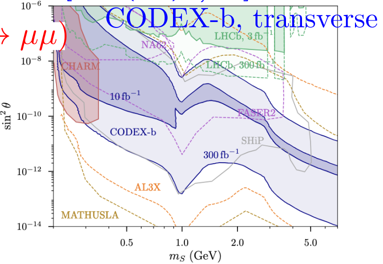
outside VELO

[EPJC84(2024)6,608]

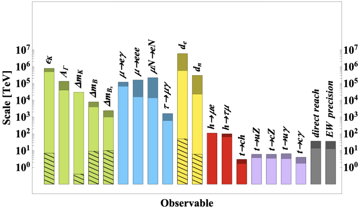


$b \to sS(\to \mu\mu)$

[EPJC80(2020)12,1177]



Summary and outlook



- Flavor constraints are a critical part of NP search paradigm.
- Around 2σ $(b \to s\ell^+\ell^-)$ and 3σ $(b \to c\tau\nu)$ tensions still persistent.
- Leptoquarks, Z', charged Higgs...?

- *Much more data is coming in Run 3+*. Large program at LHCb:
  - Both $b \to c$ and $b \to s$ with baryons (Λ_b^0, Ω_b, Σ_b, Ξ_b) and B_c^+.
  - TDCPV in $b \to s$: $B_s^0 \to \phi\mu^+\mu^-$, $B^0 \to K_S^0\pi^+\pi^-\gamma$, $B^0 \to K_S^0\phi\gamma$.
- Higgs to HF Yukawa couplings can be probed at LHCb.
- LHCb can probe dark Higgs portal both at low and high transversity, with downstream tracking and CODEX-b.