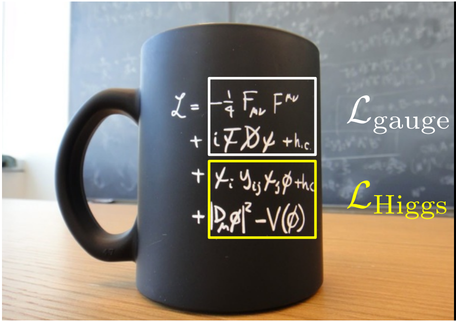
Flavor physics results from LHCb and Belle II

Biplab Dey

(including results from LHCb, Belle(II) and BaBar)

ELTE
EÖTVÖS LORÁND
UNIVERSITY

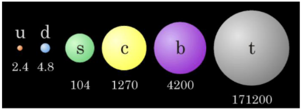
THE (QUARK) FLAVOR SECTOR



$\mathcal{L}_{\text{gauge}}$ mathematically elegant symmetries

$\mathcal{L}_{\text{Higgs}}$ ad hoc Yukawas

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



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

CKM MATRIX AND CP VIOLATION

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{\text{mass}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{flavor}}$$

$B^0_{(s)}$-$\overline{B}^0_{(s)}$ mixing, $\Delta F = 2$
rare B decays, $\Delta F = 1$

semileptonic
$u_i \to d_j \ell^+ \nu_\ell$

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Wolfenstein '83

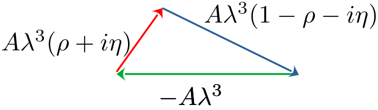
$$\lambda \sim 0.22; \qquad A, |\rho + i\eta| \sim 1$$

- 10 SM parameters in the quark sector: 6 quark masses, 3+1 CKM parameters.
- Strong hierarchy. Weak mixing between generations.

- Single phase ($\equiv \gamma$) in V_{ub} only source of CP violation in the SM.

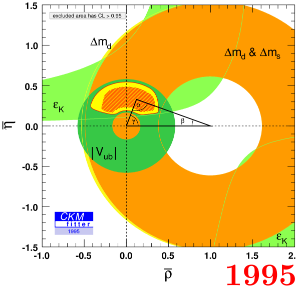
- Unitarity of V_{CKM}: six unitarity triangles
- $b \to d$: “the” UT.

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



GLOBAL FITS SITUATION

CKMFitter
UTFit
Nufit



1995

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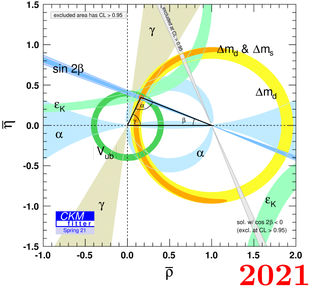
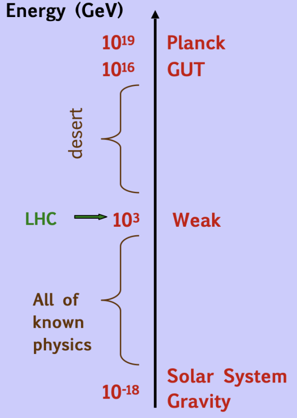


2021

- Tremendous success of the CKM paradigm from B-factories.
- Largest CPV observed in beauty, but also in strange and charm.
- Baryogengesis problem remains: probe CPV in very rare processes.
- Leptogenesis: CPV in neutrino mixing? Unlike V_{CKM}, seems to have strong mixing.

FLAVOR AS A DISCOVERY TOOL



[J. Hewett, LISHEP09]

- 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
- Even if $\Lambda_{\text{NP}} \gg \text{TeV}$, precision flavor can probe the "desert" via rare loop-mediated processes.

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 → $\mathcal{O}(10^{10})$.
- Excellent for electrons, neutrals, neutrinos, inclusive and flavor-tagging power.

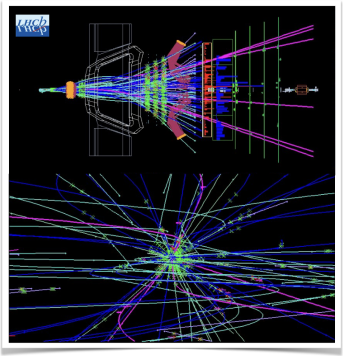
- $\mathcal{O}(10^{11}) B^{0,\pm}_{(s)}$. UpgradeII → ×100. Busy environment, initial partonic 4-mom unknown.
- Excellent for exclusive muonic/hadronic modes, PID, vertexing, all b-hadron species (Λ_{b}^0, B_s^0, B_c^+...)

- $\mathcal{O}(10^{12}) B^{0,\pm}_{(s)}$, 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).

e^+e^- VS pp COLLIDERS: SAMPLE EVENTS

$pp \to X_b B_s^0 X$

$B_s^0 \to \mu^+\mu^-$



LHC

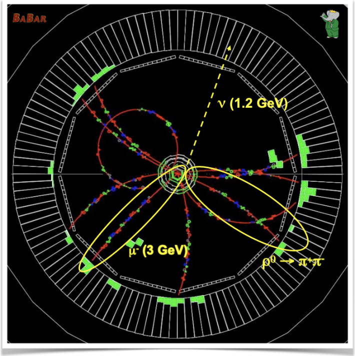
pp collisions have background from $b\bar{b}$ hadronization, underlying event, and pileup

B-factories

Clean e^+e^- collisions only produce two B mesons (for the most part)

$e^+e^- \to B^+_{\text{tag}} B^-_{\text{sig}}$

$B^- \to \rho^0 \mu^- \nu_\mu$

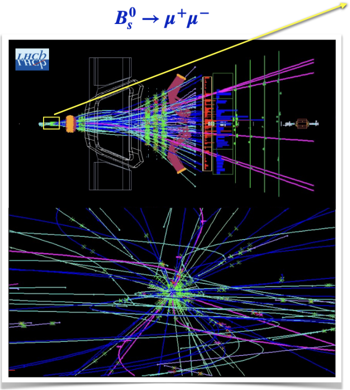


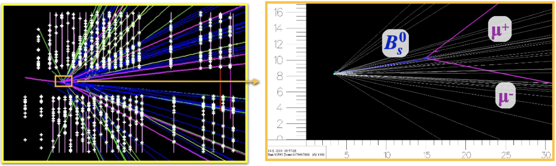
- Triggering is the key at LHCb. L0 (hardware) trigger removed in Upgrade Ia (Run3) ⇒ flexible software (GPU+CPU) trigger.

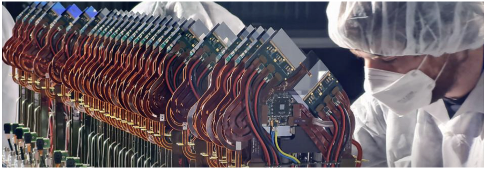
VERTEXING AT LHCB

$pp \to X_b B_s^0 X$

$B_s^0 \to \mu^+\mu^-$







LHCb Upgrade I VeloPix

- At LHC, thanks to the boost, b-hadrons fly $\sim$ cm. VELO closes in ~ 5 mm to the beamline $\Rightarrow \sigma_t \sim 45$ fs.
- Can resolve $\tau \to 3\pi(\nu)$ vertex from the mother b-vertex in $b \to c\tau\nu$.

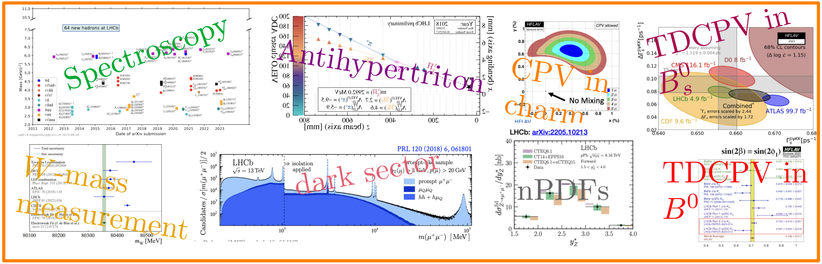
SELECTED PHYSICS RESULTS

Semileptonic b-hadron decays 🎄

Rare b-hadron decays 🐧

“b-anomalies”

$+$



Spectroscopy

Antihypertriton

CPV in charm

TDCPV in B^0_s

W mass measurement

dark sector

nPDFs

TDCPV in B^0

Not covered today

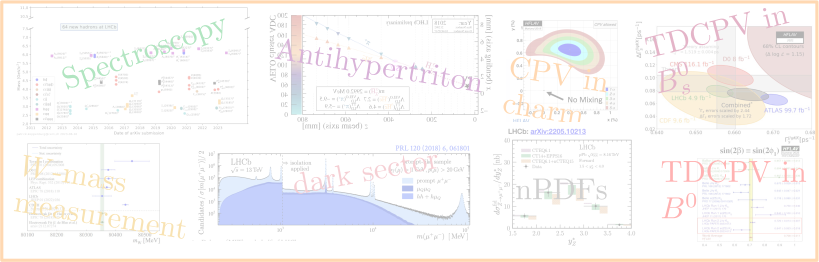
SELECTED PHYSICS RESULTS

Semileptonic b-hadron decays 🎄

Rare b-hadron decays 🐧

“b-anomalies”

+



Not covered today

$|V_{\rm ub}|$ *and* $|V_{\rm cb}|$

$|V_{\mathrm{ub}}|$ AND $|V_{\mathrm{cb}}|$: FLAGSHIP SM VARIABLES

- V_{xb} play critical roles in the unitarity test of V_{CKM}.

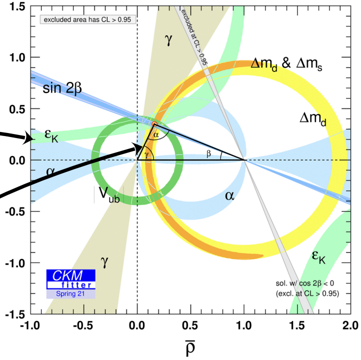
$$\overset{V_{ub}}{}$$

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} \quad V_{cb} \sim 0.04$$

Unitarity Triangle

$$\varepsilon_K \propto |V_{cb}|^4$$

$$\frac{|V_{ub}|}{|V_{cb}|} \sim (10 \pm 0.4)\%$$

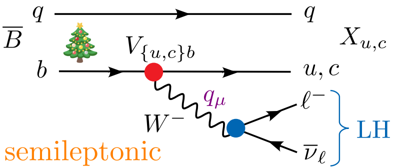


- $\sin 2\beta$ (loop) known to better than 2%. Side opposite is $|V_{\mathrm{ub}}|/|V_{\mathrm{cb}}|$.

- Rare FCNC processes $\propto |V_{cb}|^2 \left[\frac{|V_{tb}^* V_{ts}|^2}{|V_{cb}|^2}\right] \Rightarrow$ theory uncertainty.

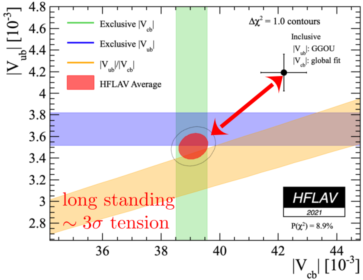
$|V_{\rm ub}|$ AND $|V_{\rm cb}|$: PROCEDURES AND TENSIONS

- Leptonic $B_{u,c}^{+} \to \tau^{+}\nu_{\tau}$: theoretically clean, experimentally hard.



- $X_{u,c}$ is exclusive $\{\pi, \rho, \omega, D^{(*)} \ldots\}$. Or inclusive sum of states.
- Different theory inputs: OPE (inclusive) and FFs (exclusive)

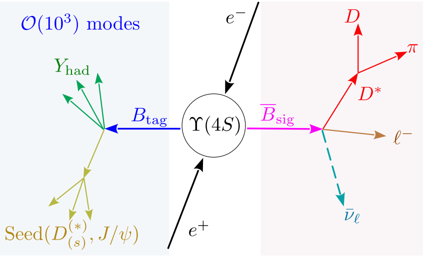
- Exclusive systematically lower than inclusive for both $|V_{\rm ub}|$ and $|V_{\rm cb}|$ by $\sim$ 5-10%.
- QCD effects, experimental issues with the normalizations, or NP?



long standing
$\sim 3\sigma$ tension

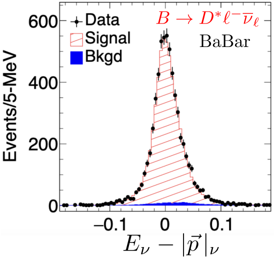
TO TAG OR NOT TO TAG @ B-FACTORIES

- $e^+e^-/pp \to b\bar{b} \to B_{\rm sig} X_b$: use information on "other" b or not.
- $\mathcal{B}(B \to X_c \ell^- \overline{\nu}_\ell) \sim 10\%$. Dominant statistics, but at least one missing neutrino ⇒ hadronic tagging at e^+e^- machines.



Algorithms: Cut-based (BABAR), NN (Belle), GBDT-based FEI (Belle(II))

[PRL 123, 091801 (2019)]



Low $\epsilon_{\rm tag}$ but clean sample.

USP: excellent $\vec{p}_\nu$ reco for angular analyses.

- BF measurements need normalization/control mode. Ensuring that $\epsilon_{\rm tag}$ cancels between signal/norm modes is challenging.

$|V_{cb}|$ FROM TAGGED $B \to D\ell^-\overline{\nu}_\ell$ [2311.15071] (↪ PRD)

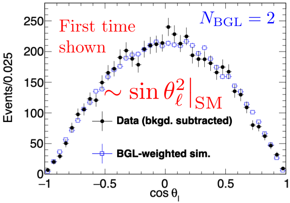
- BGL z-expansion fit to $B \to D$ form-factors f_+ and f_0 (→ lattice, time-like)

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_n^i z^n.$$

$$\text{rate} \propto |f_+(w)|^2$$

- First unbinned non-extended ML 2d fits ($\cos\theta_\ell$, q^2) to *BABAR* + FNAL/MILC. $d\Gamma/dq^2$ from Belle-16 optionally included.

- $\Gamma' = \frac{[\int \text{rate}]_{\text{FF}}}{|V_{\text{cb}}|^2}$. $|V_{\text{cb}}| = \sqrt{\frac{\mathcal{B}}{\Gamma'\tau_B}}$ from updated HFLAV $\mathcal{B}$.



hadronic tagged	$\lvert V_{cb}\rvert^{\text{excl}} \times 10^3$
Belle-16 $\mathcal{B}$ ($B \to D$ BGL)	41.02 ± 0.88
BABAR-10 $\mathcal{B}$ ($B \to D$ BGL)	38.78 ± 1.11
BABAR-19 ($B \to D^*$ BGL)	38.36 ± 0.90

ϵ_{tag} norm. issue?

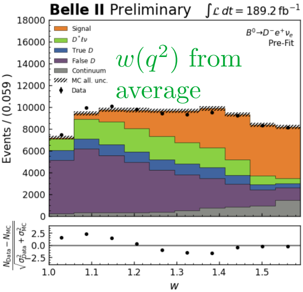
$|V_{\rm cb}|$ FROM UNTAGGED $B \to D\ell^-\overline{\nu}_\ell$ [2210.13143]

- 2019-21(189.2/fb) BelleII data: $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$.

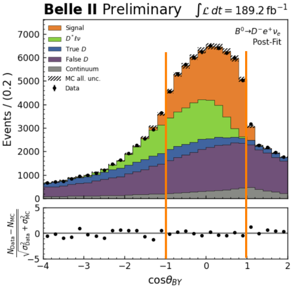
$$Y \equiv [D\ell]_{\rm vis} \text{ and } m_Y > 3\text{GeV}$$

$$\cos\theta_{BY} = \frac{2\,E^*_B E^*_Y - m_B^2 - m_Y^2}{2p^*_B p^*_Y}$$

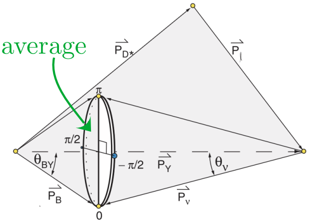
cm frame



$w(q^2)$ from average



average

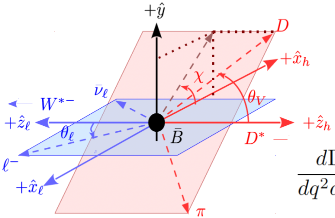


$N_{\rm sig} \sim 100k$

- From $N = 3$ BGL fit, $|V_{\rm cb}| = (38.53 \pm 1.15) \times 10^{-3}$

4D UNBINNED ANGULAR ANALYSIS [PRL123, 091801 (2019)]

- Unbinned 4d BGL FF fit, using $h_{A_1}(1)$ from FNAL/MILC-14.



4d problem

$\{q^2, \theta_\ell, \theta_V, \chi\}$

$$\frac{d\Gamma}{dq^2 d\Omega} \propto \sum_{i=1}^{14} f_i(\Omega)\Gamma_i(q^2)$$

HQET FFs

$$\left\{\begin{aligned} A_1 &= \frac{w+1}{2} r' h_{A_1} \\ A_2 &= \frac{r h_{A_2} + h_{A_3}}{r'} \equiv \frac{R_2 h_{A_1}}{r'} \\ V &= \frac{h_V}{r'} \equiv \frac{R_1 h_{A_1}}{r'} \end{aligned}\right.$$

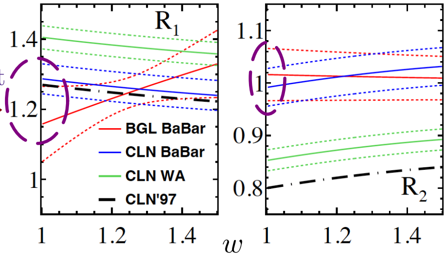
$$m_{\{b,c\}} \to \infty,\ h_{\{A_1,A_3,V\}} \to \zeta(w),\ h_{A_2} \to 0$$

$|V_{cb}| = (38.36 \pm 0.90)\times 10^{-3}$

$R_1(1) \sim 1.3$

$R_2(1) \sim 1.0$

zero-recoil point



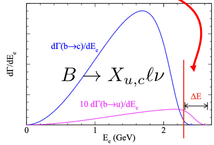
↪ Update in progress

SIMULTANEOUS INCL+EXCL $|V_{\rm ub}|$

[PRL131, 211801 (2023)]

$B \to \pi\ell\nu$

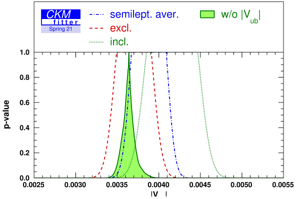
$$\frac{|V_{ub}^{\rm excl}|}{|V_{ub}^{\rm incl}|} \sim 0.84 \pm 0.04,\ \sim 3.7\sigma \text{ tension w/SM}$$

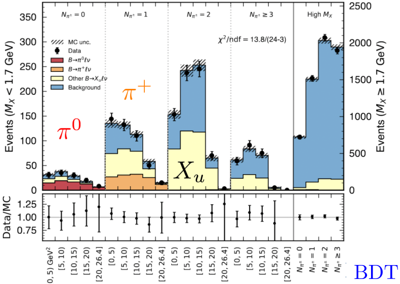


exp. E_ℓ cut ruins OPE ⇒ need non-perturb. shape info

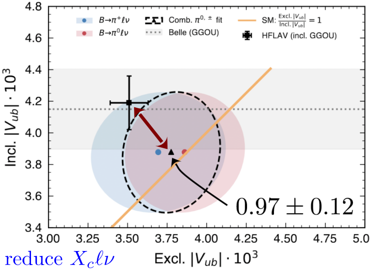
theory: “BLNP-GGOU-SIMBA-DGE-ADFR”

- Global fits prefer exclusive





$E_\ell > 1$GeV



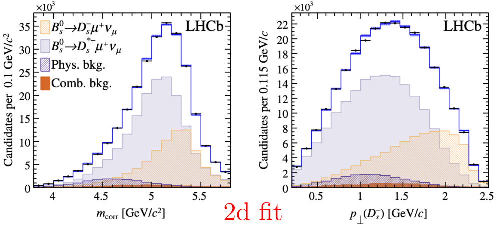
BDT: reduce $X_c\ell\nu$

thrust cut: improve $\pi\ell\nu$

Belle had. tag lower than $|V_{ub}^{\rm incl}|_{\rm WA}$

$|V_{\rm cb}|$ FROM $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ [PRD 101, 072004 (2020)]

- LHCb can leverage $|V_{xb}|$ from $\Lambda_{\rm b}^0$ and B_s^0, inaccessible at Belle(II). [Not covered today: $\Lambda_{\rm b}^0 \to p\mu^-\overline{\nu}_\mu$, $\Lambda_{\rm b}^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu$.]
- Neutrino(s) accessible upto 2-fold ambiguity. Key discriminant is: $m_{\rm corr} \equiv \sqrt{m^2(D_s^{(*)-}\mu^+) + p_\perp^2(D_s^{(*)-}\mu^+)} + p_\perp(D_s^{(*)-}\mu^+)$.
- Additionally, $p_\perp(D_{(s)}^{(*)-})$ found to be sensitive to decay kinematics.
- Uses $B^0 \to D^{(*)-}\mu^+\nu_\mu$ as the control modes (Run 1, 3/fb).



2d fit

$$|V_{cb}|_{\rm CLN} = (41.4 \pm 0.6({\rm stat}) \pm 0.9({\rm syst}) \pm 1.2({\rm ext})) \times 10^{-3},$$

$$|V_{cb}|_{\rm BGL} = (42.3 \pm 0.8({\rm stat}) \pm 0.9({\rm syst}) \pm 1.2({\rm ext})) \times 10^{-3},$$

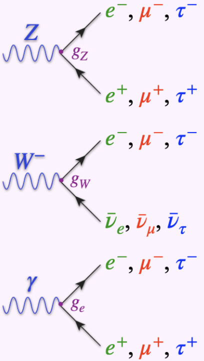
OUTLOOK FOR $|V_{xb}|$

- Many new results from LHCb/Belle(II) + legacy results from *BABAR*.
- Issue still unresolved. Several outstanding issues:
  - $|V_{\mathrm{cb}}|^{\mathrm{excl}}$ from the $B \to D^{(*)}\ell^-\overline{\nu}_\ell$ needs to match (robustly).
  - New `FNAL/MILC`, `HPQCD`, `JLQCD` lattice $B \to D^*$ FFs show internal disagreements.
  - The $\mathcal{B}(B \to X_c\ell^-\overline{\nu}_\ell)$ measurement for $|V_{\mathrm{cb}}|^{\mathrm{incl}}$ is from 2010's. Needs to be updated.
  - For tagging, the assumption of ϵ_{tag} being independent of the signal-side needs to be better validated.
- "Tensions" (aka QCD) remain. What would it take to move to "anomaly" (aka NP)?

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

LEPTON FLAVOR UNIVERSALITY VIOLATION (LFUV)

SM: same electroweak couplings to all lepton gen.



LFU tests

To **0.28%** in Z decays

$$\frac{\Gamma_{Z\to\mu\mu}}{\Gamma_{Z\to ee}} = 1.0009 \pm 0.0028$$

LEP, Phys. Rept. 427 (2006) 257

$$\frac{\Gamma_{Z\to\tau\tau}}{\Gamma_{Z\to ee}} = 1.0019 \pm 0.0032$$

LEP, Phys. Rept. 427 (2006) 257

To **0.8%** in W decays

$$\frac{\mathscr{B}(W\to e\nu)}{\mathscr{B}(W\to \mu\nu)} = 1.004 \pm 0.008$$

CDF + LHC, JPG: NPP, 46, 2 (2019)

$$\frac{\Gamma_{W\to\tau\nu}}{\Gamma_{W\to\mu\nu}} = 0.992 \pm 0.013$$

ATLAS, Nature 17, 813 (2021)

To **0.2%** in meson decays

$$\frac{\Gamma_{J/\psi\to\mu\mu}}{\Gamma_{J/\psi\to ee}} = 1.0016 \pm 0.0031$$

PDG (BESIII), RPP, Chin. Phys. C40 (2016) 100001

$$\frac{\Gamma_{D_s\to\tau\nu}}{\Gamma_{D_s\to\mu\nu}} = 9.95 \pm 0.61$$

HFLAV, Eur. Phys. J. C77 (2017) 895

$$\frac{\Gamma_{\pi\to e\nu}}{\Gamma_{\pi\to\mu\nu}} = (1.234 \pm 0.003) \times 10^{-4}$$

PiENu, Phys. Rev. Lett. 115, 071801 (2015)

$$\mathscr{R}(D) = 0.357 \pm 0.029$$

HFLAV, Summer 2023

$$\mathscr{R}(D^*) = 0.284 \pm 0.012$$

3.3σ tension

$$\frac{\Gamma^{1.1-6}_{B\to K^+\mu\mu}}{\Gamma^{1.1-6}_{B\to K^+ee}} = R_K = 0.95 \pm 0.05$$

LHCb, PRL 131, 051803 (2023)

To **0.14%** in $\tau \to \ell\nu\nu$

$$g_\mu/g_e = 1.0018 \pm 0.0014$$

PDG, A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

$$g_\tau/g_\mu = 1.0030 \pm 0.0015$$

PDG, S. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

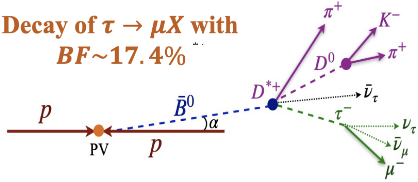
- If NP is CKM-like, will prefer to couple to the 2nd and 3rd generations.

$$R(X_c) \equiv \frac{\mathcal{B}(H_b \to X_c\tau\nu)}{\mathcal{B}(H_b \to X_c\ell\nu)}$$

$$\ell \in \{e, \mu\}$$

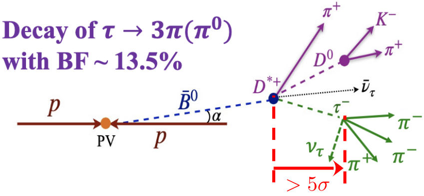
τ RECONSTRUCTION AT LHCB

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)

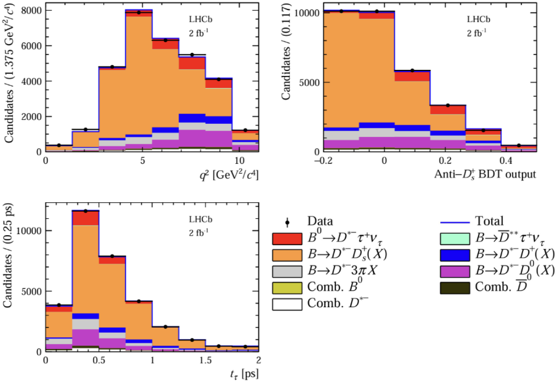


- Cleaner selections.
- Normalization mode is $B \to D^* 3\pi$ ($\Lambda_b^0 \to \Lambda_c 3\pi$). Need external BFs as inputs (→ systematics).
- Better resolutions in the kinematic variables. Two two-fold ambiguities.

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

[PRD 108, 012018 (2023)](Run2, 2015/16)
[PRD 97, 072013 (2015)](Run1)

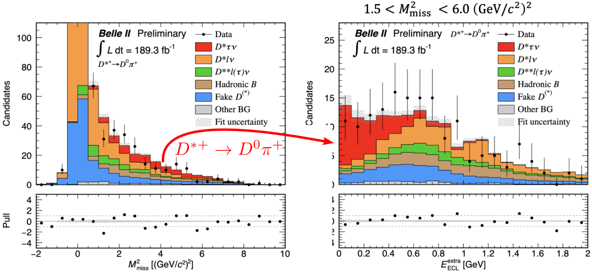
- Run2(2015/16) data: 40% more stats than previous Run1 result.
- Prompt $B \to D^* 3\pi$ suppressed by τ vertex downstream of B.
- Two control regions for $B \to D^{*+} D_s^+ (\to 3\pi) X$ "double charm" bkgd. Anti-D_s^+ BDT.
- 3d template fit to q^2, anti-D_s^+ BDT and τ lifetime.
- In agreement with SM.



First $R(D^*)$ at BelleII, tagged [Lepton-Photon-23]

- Partial (189/fb) BelleII hadronic tagged dataset. Main discriminant is extra calorimeter energy ($E_{\rm ECL}^{\rm extra}$).

- Sidebands: $q^2 < 3.5$ GeV^2 (below τ threshold), $D^{**} \to D^*\pi^0X$, and $\Delta M_{D^*} \equiv M_{D^*} - M_D$. Good data/MC agreement.

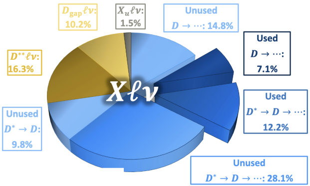


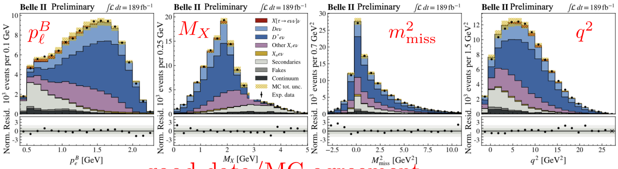
- 2d fit to q^2 and $E_{\rm ECL}^{\rm extra}$.

- $R(D^*)$ consistent with SM, with 40% better sensitivity compared to Belle2 (w/ comparable dataset).

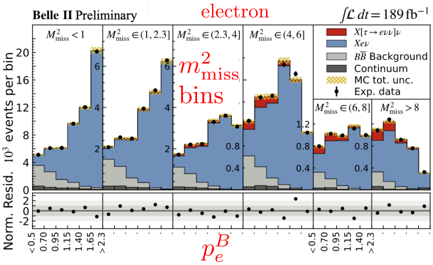
FIRST $R(X_c)$ AT BELLEII, TAGGED

[2311.07248]

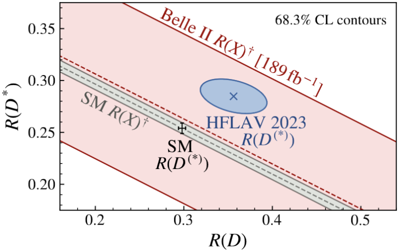




good data/MC agreement



† = with expected SM contributions of $D^{**}_{\rm (gap)}, X_u$ removed



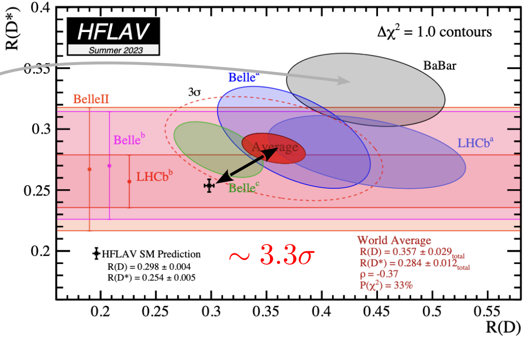
- First *inclusive* measurement of its kind. In agreement with SM predictions ([2207.03432], [1506.08896], [2112.07685]).

$R(D)$-$R(D^*)$ GLOBAL

Theory prediction robust

Oldest (BaBar-2012) shows the largest deviation

LHCb competitive w/ Belle



- Many other SL results, consistent with SM:
  - LHCb: $R(J/\psi)$ `muonic`, $R(\Lambda_c)$ `hadronic`, D^* `pol. hadronic`.
  - BelleII: `e/mu ang. asymm` $B \to D^*$, $R(D^*_{e/\mu})$, $R(X_{e/\mu})$.

SELECTED PHYSICS RESULTS

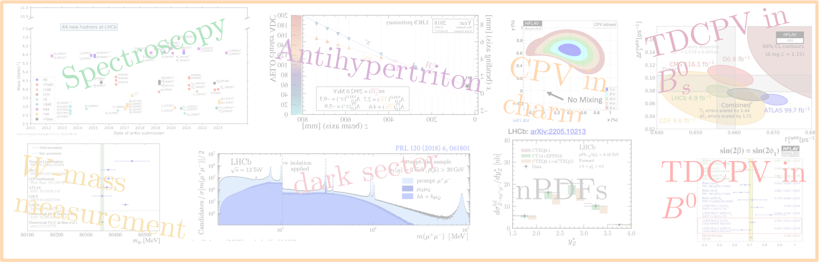
Semileptonic b-hadron decays 🎄

Rare b-hadron decays 🐧

}

“b-anomalies”

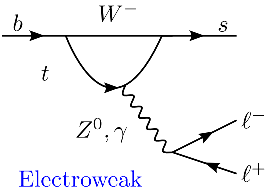
+



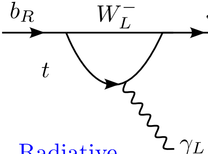
Not covered today

RARE b-DECAYS

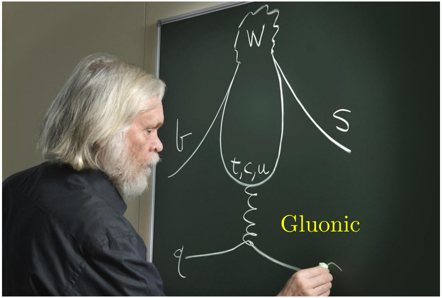
- $b \to s(d)$ flavor changing neutral currents: loop-suppressed in SM.



Electroweak

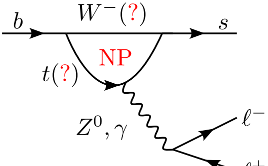


Radiative

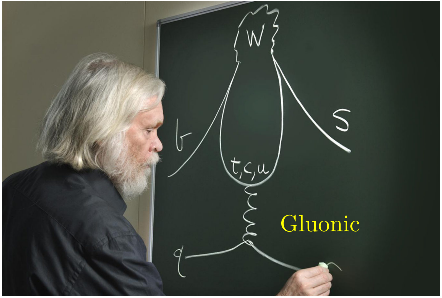


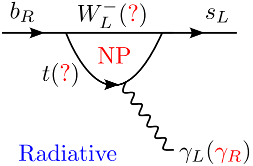
RARE b-DECAYS

- $b \to s(d)$ flavor changing neutral currents: loop-suppressed in SM.
- New Physics (NP) can enter both at loop- and tree-levels.

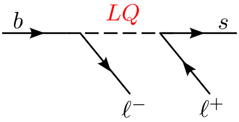


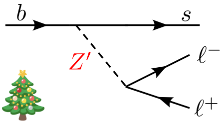
Electroweak





Radiative





EFT TOOLS FOR RARE DECAYS

- Renormalizability requires the $\mathcal{L}_{\text{SM}}$ to have dim $d \leq 4$ operators.

- Eg.: $m_\phi^2 \phi^2$, $m_\psi \overline{\psi}\psi \Rightarrow (m_\phi/E)^2$, (m_ψ/E) UV-safe behavior.

- We can include $d > 4$ operators if we regard the SM as an low energy effective theory. Comes with a cutoff scale, Λ.

$$\mathcal{L}_{\text{eff}}(x) = \mathcal{L}_{\text{SM}}(x) + \sum_{d>4} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}(x)$$

local operators

- Amplitudes will have $(E/\Lambda)^{d-4}$ behavior: bad at high-E, but suppressed at $E \ll \Lambda$. Access to heavy (Λ_{NP}) fields from NP.

- Relevant for RD: $d = 6$ operators. $\mathcal{A}_{\text{eff}} \sim \dfrac{C_{\text{SM}}}{m_W^2} + \dfrac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2}$.

BASIS OF LOCAL OPERATORS FOR $b \to s$ PENGUINS

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

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

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

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

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

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

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

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

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

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

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

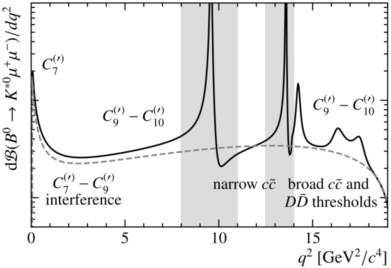
$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

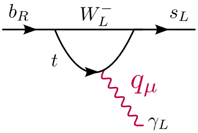
$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- $\mathcal{O}_{1,2}$ (4-quark tree), $\mathcal{O}_{3-6}$ (4-quark penguins), $\mathcal{O}_8$ (gluon penguin)

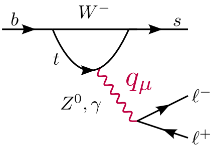
THE THREE DOMINANT CONTRIBUTIONS

- 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



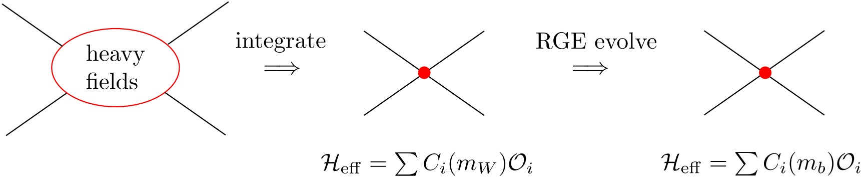
$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$ vector

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

- The primed terms are the RH (quark) operators, suppressed in the SM, but can be enhanced in NP scenarios.

WILSON COEFFICIENTS AND LOCAL FFs

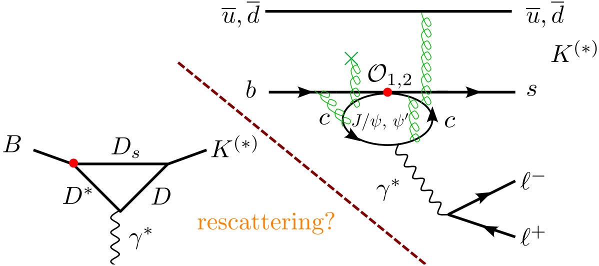
- From SMEFT to weak EFT (WEFT) at m_b scale:

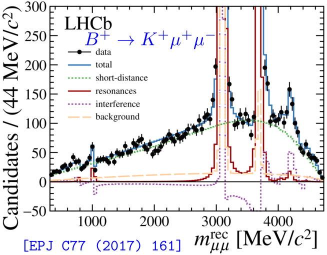


- The (dimensionless) Wilson coefficients encode the short-distance physics. $\mathcal{A}(i \to f) = \sum C_n(m_b)\langle f|\mathcal{O}_n(m_b)|i\rangle$.
- The long-distance physics (hadronization) is encoded in the *local* form-factors (lattice, LCSR, etc,.).
- Eg. $V_\mu^{B\to M}(k,q) \equiv \langle M(k)|\overline{s}\gamma_\mu P_L b|\overline{B}(q+k)\rangle$ for the vector FFs in B-meson decays.

Non-local (aka charm loop) contributions

- Non-local contributions from propagating $c\bar{c}$ are a problem:





[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.

Electroweak penguins

THE GOLDEN CHANNEL: $B^0 \to K^{*0}\ell^+\ell^-$

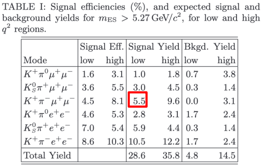
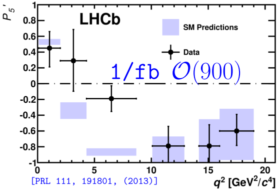


TABLE I: Signal efficiencies (%), and expected signal and background yields for $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$, for low and high q^2 regions.

Mode	Signal Eff.		Signal Yield		Bkgd. Yield	
	low	high	low	high	low	high
$K^+\pi^0\mu^+\mu^-$	1.6	3.1	1.0	1.8	0.7	3.8
$K^0_S\pi^+\mu^+\mu^-$	3.6	5.5	3.0	4.5	0.3	1.4
$K^+\pi^-\mu^+\mu^-$	4.5	8.1	$\boxed{5.5}$	9.6	0.0	3.1
$K^+\pi^0e^+e^-$	4.6	5.3	2.8	3.1	1.7	2.4
$K^0_S\pi^+e^+e^-$	7.0	5.4	5.9	4.4	0.3	1.4
$K^+\pi^-e^+e^-$	8.6	10.3	10.5	12.2	1.7	2.4
Total Yield			28.6	35.8	4.8	14.5

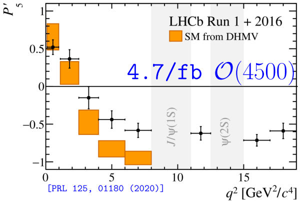
[PRD 79, 031102 (2009)], BaBar $\mathcal{O}(50)$

$\Longrightarrow$



1/fb $\mathcal{O}(900)$

[PRL 111, 191801, (2013)]

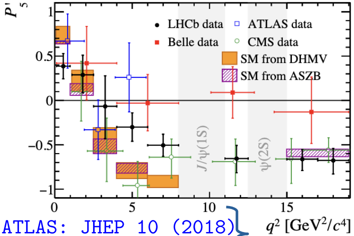


4.7/fb $\mathcal{O}(4500)$

[PRL 125, 01180 (2020)]

- Full Run1+2 @ LHCb ~ 10000. Not a rare decay anymore.
- Allows detailed angular analyses to extract binned observables such as P_5' (theoretically "clean").

- Competitive results also from ATLAS/CMS.
- Higher lumi than LHCb, but B-physics trigger bandwidth and K/π mis-ID (no RICH) are issues .



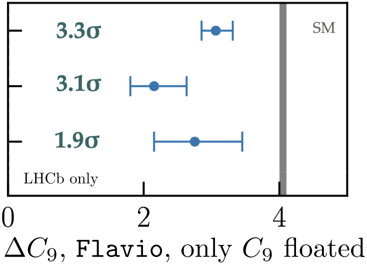
ATLAS: JHEP 10 (2018)
CMS: PLB 781 (2018)
$\Big\}$ 20/fb,2012

MORE $B \to V\mu^+\mu^-$...

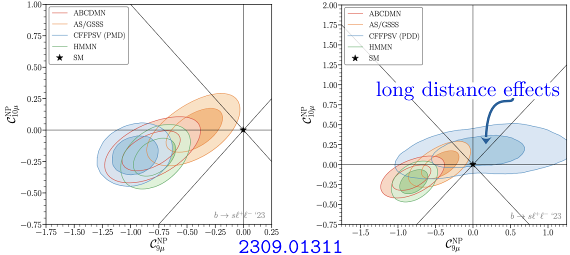
$B^0 \to K^{*0}\mu^+\mu^-$
[PRL 125 011802 (2020)]

$B^+ \to K^{*+}\mu^+\mu^-$
[PRL 126 161802 (2021)]

$B_s \to \phi\mu^+\mu^-$
[JHEP 11 043 (2021)]



- CMS has also looked at $B^+ \to K^{*+}\mu^+\mu^-$. [JHEP 04 124 (2021)]
- Numerous global analyses, different data sub-sets, statistical analyses...
- NP or QCD effects?



2309.01311

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

LHCb-PAPER-2023-032 (↪PRD)
LHCb-PAPER-2023-033 (↪PRL)

- Same dataset as published Run1+2016 q^2-binned analysis.

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

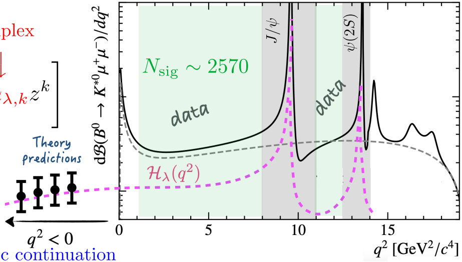
- Directly extract out (real) $C^{(\prime)\rm NP}_{9,10}$ from *unbinned* fit. $\mathcal{F}_\lambda(q^2)$ FF's from LCSR + lattice. $C_i^{\rm SM}$ from theory. $\mathcal{H}_\lambda$ from z-expansion fit.

$$z(q^2) \equiv \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

$$\mathcal{H}_\lambda \equiv \frac{1 - z z_{J/\psi}}{1 - z_{J/\psi}} \frac{1 - z z_{\psi(2S)}}{1 - z_{\psi(2S)}} \frac{1}{\phi_\lambda(z)} \left[\sum_k \overset{\substack{\text{complex}\\ \downarrow}}{\alpha_{\lambda,k}} z^k\right]$$

$$\underset{q^2 \to M^2_{\psi_n}}{\rm Res} \frac{\mathcal{H}_\lambda(q^2)}{\mathcal{F}_\lambda(q^2)} = \frac{M_{\psi_n} f^*_{\psi_n} \mathcal{A}^{\psi_n}_\lambda}{M_B^2 \mathcal{F}_\lambda(M^2_{\psi_n})}$$

[2206.03797]
[2212.10516]

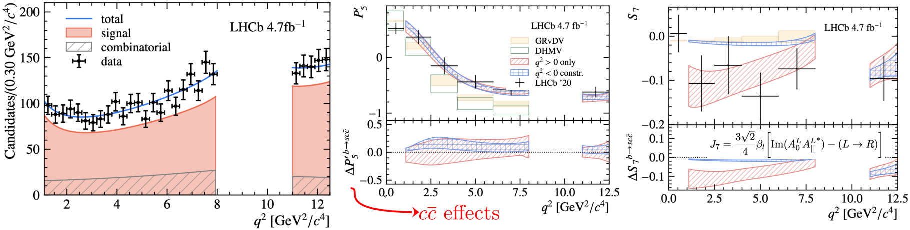


- Full rate also includes $K\pi$ S-wave.

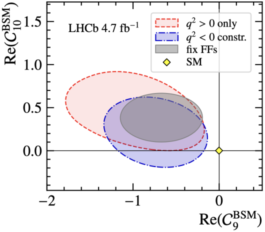
UNBINNED $B^0 \to K^{*0}\mu^+\mu^-$

LHCb-PAPER-2023-032 (↪PRD)
LHCb-PAPER-2023-033 (↪PRL)

- Excellent consistency w/ 2020 binned results. Some effect of the LCSR ($q^2 < 0$) $\mathcal{H}_\lambda$ info seen in S_7 observable.



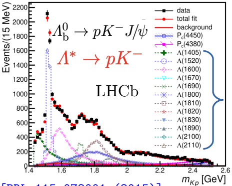
- Data still prefers negative $C_9^{\rm NP}$, but tension in C_9 reduced to $\sim 1.8\sigma$ and 1.4σ global.
- Will be extended to full Run 1+2, but significant uncertainty due to FFs (both P- and S-wave).



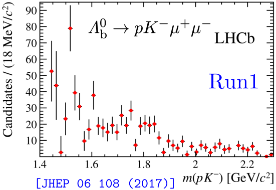
$\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$

[PRL 131 151801 (2023)]
[JHEP 06 108 (2017)]

- Broad overlapping $\Lambda^* \to pK^-$ states.
- Detailed study very challenging: theory+exp.
  $\hookrightarrow$ JHEP 02 189 (2023)

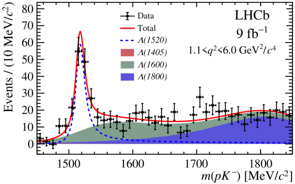


[PRL 115 072001 (2015)]

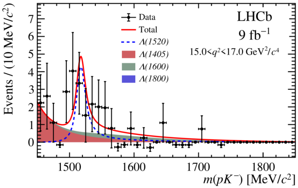


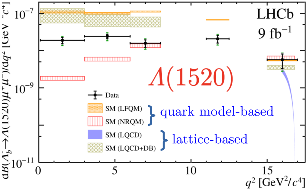
[JHEP 06 108 (2017)]

- $\Lambda(1405)(\frac{1}{2}^-)$, $\Lambda(1520)(\frac{3}{2}^-)$, $\Lambda(1600)(\frac{1}{2}^+)$, $\Lambda(1800)(\frac{1}{2}^-)$ included.
- Integrated over angles (small interferences as sys.). $d\Gamma/dq^2$ for $\Lambda(1520)$ provided. Theory models need to be revisited.



[PRL 131 151801 (2023)]





Λ(1520)

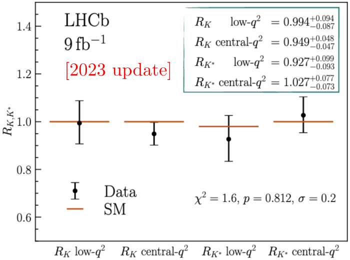
quark model-based

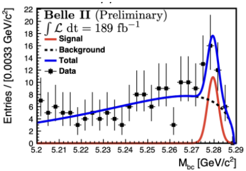
lattice-based

$R_{K^{(*)}}$ status at LHCb/ Belle(II)

[PRL 131 051803 (2023)]
[PRD 108 032002 (2023)]
[PRL 126 161801 (2021)]
[2206.05946]

- *Very* clean theory: $R_{K^{(*)}} = \dfrac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B\to K^{(*)}J/\psi(\to\mu^+\mu^-))}{\mathcal{B}(B\to K^{(*)}e^+e^-)/\mathcal{B}(B\to K^{(*)}J/\psi(\to e^+e^-))}$
- Electrons hard at LHCb (trigger, brem). "Flutter" in the community from 2022 paper: R_K found 3.1σ from SM.
- LHCb 2023-update agrees with SM: peaking component from e-misID.



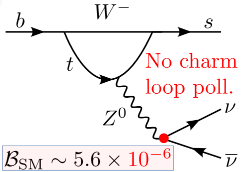


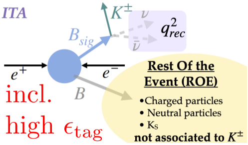
$$\mathcal{B}(B\to K^*(892)\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B\to K^*(892)e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B\to K^*(892)\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6},$$

- BelleII: 1st steps towards $R_{K^{(*)}}$. Many other R_{X_s} analyses ongoing at LHCb, also using $R_{\phi\to\ell^+\ell^-}$ as sanity check.

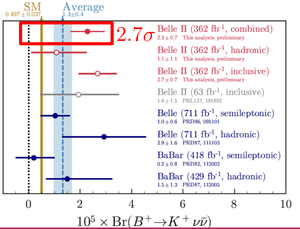
$B^+ \to K^+ \nu_\ell \bar{\nu}_\ell$ AT BELLEII

[2311.14647]
[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.
- $B^+ \to K^+ +$ inv: hard experimentally.
- Conventionally, hadronic tag. New: inclusive tag.
- Data/MC checks from control samples: $q\bar{q} + B\overline{B}$ $(B \to D^{(*)}(\to K^+ X)\ell\nu, B^+ \to K^+ K_L K_{L,S}, B^+ \to K^+ nn, B^+ \to K^+ D^{(*)}$, $B^+ \to K^+ \left[J/\psi(\to \mu\mu)\right]_{\rm miss}, B^+ \to \pi^+ K^0)$



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

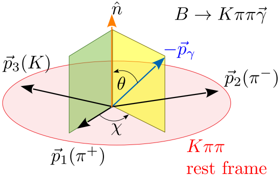
Radiative penguins

ACCESSING $C_7^{(\prime)}$ AND SEARCH FOR RH CURRENTS

- In the SM, the photon from $\vec{b} \to \vec{s}\,\vec{\gamma}$ is almost purely LH. RH current suppressed ($C_7' \sim \frac{m_s}{m_b} C_7$) and is a sensitive NP probe.
- Need angular analysis, to pull out the interferences.
- LHCb probes this in various ways:
    - Very low q^2 angular analysis of $B^0 \to K^{*0} e^+ e^-$ [JHEP 12 081 (2020)] + $B_s^0 \to \phi e^+ e^-$ (→ ongoing).
    - Angular analysis of $B^+ \to K^+ \pi^+ \pi^- \gamma$ [PRL 112 161801 (2014)]
    - TDCPV of $B_s^0 \to \phi\gamma$ [PRL 118 021801 (2017)]
    - TDCPV of $B^0 \to K_S^0 \pi^+ \pi^- \gamma$ (→ ongoing).
    - Angular analysis of $\Lambda_b^0 \to \Lambda^0 \gamma$ [PRD 105 L051104 (2022)]

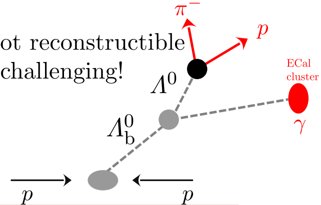
$\Lambda_b^0 \to \Lambda^0\gamma$

[PRD 105 L051104 (2022)]
[PRL 123 031801 (2019)]



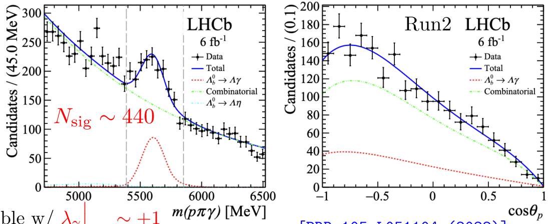
- Nominally need 3-body $H_s \to P_1P_2P_3$ (defines a coordinate-frame) decay in $H_b \to H_s\vec{\gamma}$, to access the photon pol.
- Up-down asymmetry is *proportional* to λ_γ (photon pol) via the hadronic current $\mathcal{J}_\mu^{\text{had}}$
- $\Lambda^0 \to p\pi^-$ is an exception due to the self-analyzing nature of the weak decay. The Λ^0 pol. effectively provides the "3rd direction". $d\Gamma/d\cos\theta \propto (1-\alpha_\Lambda\lambda_\gamma\cos\theta) \Rightarrow$ direct access to λ_γ

SV not reconstructible very challenging!



$\boxed{\lambda_\gamma = 0.82^{+0.17}_{-0.26}\,(\text{stat.})^{+0.04}_{-0.13}\,(\text{syst.})}$

compatible w/ $\lambda_\gamma\big|_{\text{SM}} \sim +1$

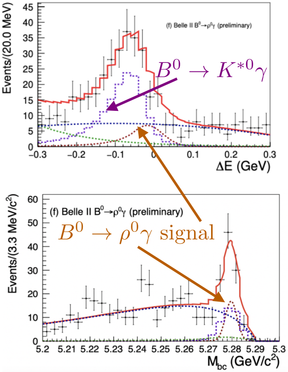


[PRD 105 L051104 (2022)]

$B^{0,\pm} \to \rho^{0,\pm}\gamma$ AT BELLE+BELLEII

[EPSHEP-23]

- Compared to LHCb, Belle(II) has γ/π^0 separation and better E_γ resolution. Also, no xfeed from B_s^0 and Λ_b^0 due to hadron mis-id.
- $B \to \rho\gamma$ is a CS $b \to d$ penguin and large bkgd from $B \to K^*\gamma$. Seen at both BaBar and Belle. Accessible also at LHCb.



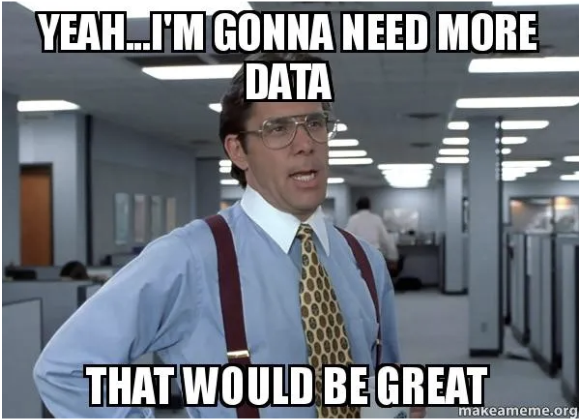
$B^0 \to K^{*0}\gamma$

$B^0 \to \rho^0\gamma$ signal

Simultaneous fit to M_{bc} ΔE, $m(\pi\pi)$

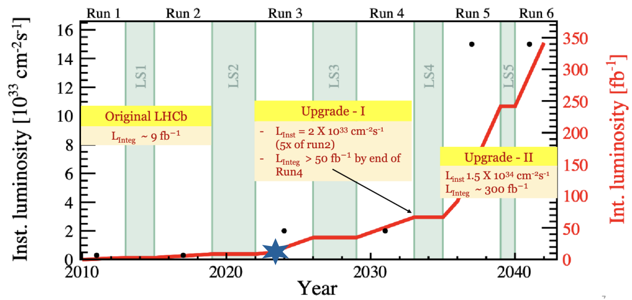
$$\boxed{\begin{aligned}BR(\rho^+\gamma) &= (12.87^{+2.02+1.00}_{-1.92-1.17})\times 10^{-7}\\ BR(\rho^0\gamma) &= (7.45^{+1.33+1.00}_{-1.27-0.80})\times 10^{-7}\\ A_I &= (14.2^{+11.0+8.9}_{-11.7-9.1})\%\\ A_{CP} &= \left(-8.4^{+15.2+1.3}_{+15.3-1.4}\right)\%\end{aligned}}$$

Consistent with SM

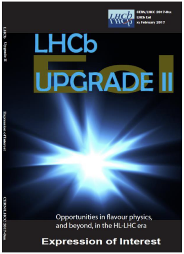

YEAH...I'M GONNA NEED MORE DATA
THAT WOULD BE GREAT
makeameme.org

LHCb UPGRADES

[↪ Brij Jashal's HQL23 talk]



- Ambitious plan to collect 300/fb by end of Run 6.
- Precision timing (10's of ps) to kill pileup.
- Flexible software trigger.
- FTDR approved by LHCC.



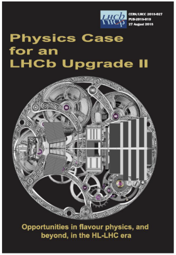
LHCb UPGRADE II

EoI

Opportunities in flavour physics, and beyond, in the HL-LHC era

Expression of Interest

[CERN-LHCC-2017-003]



Physics Case for an LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era

[CERN-LHCC-2018-027]

Framework TDR

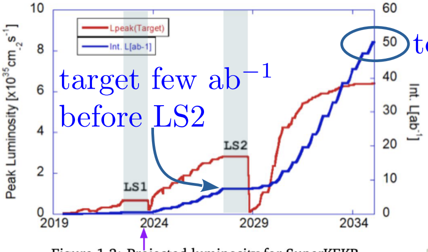
LHCb UPGRADE II

Technical Design Report

[CERN-LHCC-2021-012]

BELLEII UPGRADES

[↪ Peter Lewis' HQL23 talk]



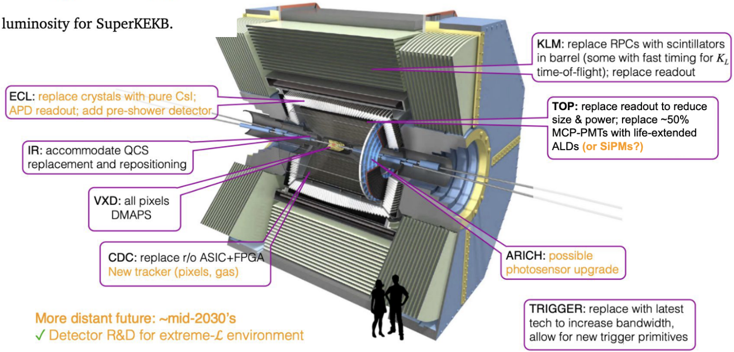
target few ab^{-1} before LS2

towards 50/ab

Figure 1.3: Projected luminosity for SuperKEKB.

LS2 upgrades

+ beyond



KLM: replace RPCs with scintillators in barrel (some with fast timing for K_L time-of-flight); replace readout

ECL: replace crystals with pure CsI; APD readout; add pre-shower detector

TOP: replace readout to reduce size & power; replace ~50% MCP-PMTs with life-extended ALDs (or SiPMs?)

IR: accommodate QCS replacement and repositioning

VXD: all pixels DMAPS

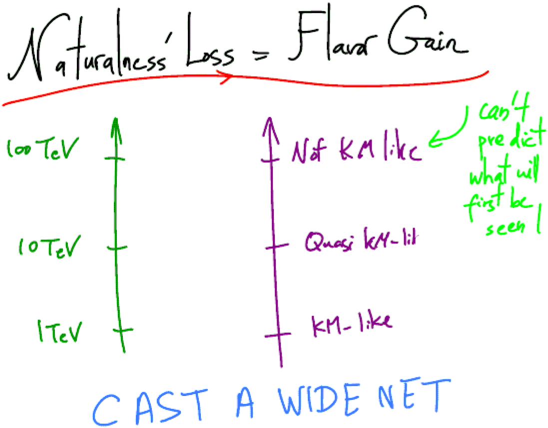
CDC: replace r/o ASIC+FPGA
New tracker (pixels, gas)

ARICH: possible photosensor upgrade

TRIGGER: replace with latest tech to increase bandwidth, allow for new trigger primitives

More distant future: ~mid-2030's
✓ Detector R&D for extreme-$\mathcal{L}$ environment

OUTLOOK



Nima Arkani Hamed
Intensity Frontier Workshop'11

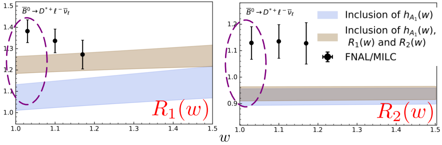
Backup

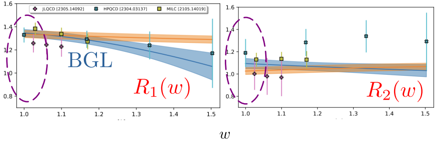
(UN)TAGGED FFS AT BELLE(II)

[`2310.01170, BelleII untagged`]
[`2310.20286, Belle tagged`]
[`PRD108, 012002(2023), Belle tagged`]

- `BelleII`, 189/fb, untagged.
- Binned fits in the $4 \times 1d$ variables.
- Some tension with $w > 1$ `FNAL/MILC`.

- Full `Belle`, tagged dataset.
- Fits to 12 angular coefficients in 4×36 bins in 4d variables.
- With $w > 1$ `FNAL/MILC`, `HPQCD`, `JLQCD` included.





$$|V_{\rm cb}| = (40.57 \pm 1.15) \times 10^{-3} \text{ (only } h_{A_1}(1))$$

$$|V_{\rm cb}| = (40.3 \pm 1.2) \times 10^{-3} \ (h_{A_1}(w))$$

$$|V_{\rm cb}| = (38.3 \pm 1.1) \times 10^{-3} \ (h_{A_1}(w), R_{1,2}(w))$$

$$|V_{\rm cb}| = (41.0 \pm 0.7) \times 10^{-3} \text{ (all } w > 1)$$

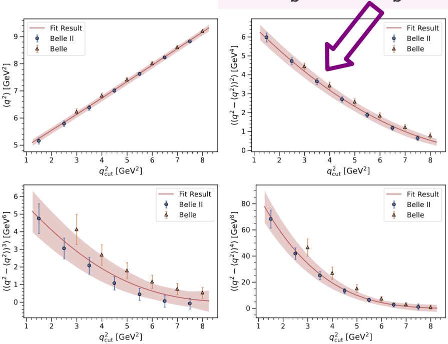
- Various other combinations with varying p-values

$|V_{cb}^{\rm incl}|$ FROM q^2 MOMENTS

[PRD104, 11201(2021), Belle]
[2205.06372, BelleII]
[JHEP10068(2022), q^2 moments]
[2310.20324, global fit]

$$\mathrm{Br}(\bar{B}\to X_c\ell\bar{\nu}) \propto \frac{|V_{cb}|^2}{\tau_B}\Bigg[\Gamma_{\mu_3}\mu_3+\Gamma_{\mu_G}\frac{\mu_G^2}{m_b^2}+\Gamma_{\tilde{\rho}_D}\frac{\tilde{\rho}_D^3}{m_b^3} +\Gamma_{r_E}\frac{r_E^4}{m_b^4}+\Gamma_{r_G}\frac{r_G^4}{m_b^4}+\Gamma_{s_B}\frac{s_B^4}{m_b^4}+\Gamma_{s_E}\frac{s_E^4}{m_b^4}+\Gamma_{s_{qB}}\frac{s_{qB}^4}{m_b^4}\Bigg]$$

"old" measurements



HO terms from new q^2 moments data from Belle(II)

$$|V_{cb}^{\rm incl}| = 41.49(1.5\%)$$

→ improved precision

$$|V_{cb}^{\rm incl}| = 41.97(1.1\%)$$

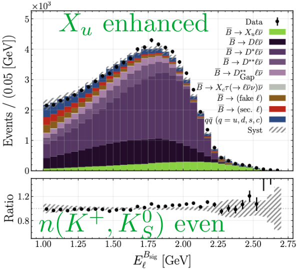
→new global fit (q^2, E_ℓ, m_X)

- The BF's are from `Belle-07` and `BaBar-10` and could be updated.

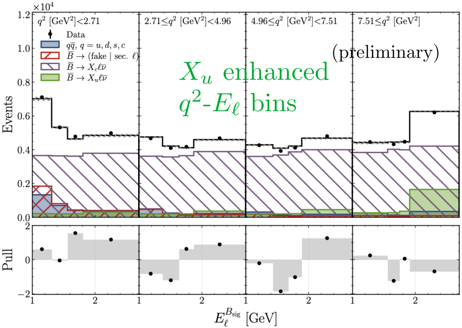
RATIO OF INCLUSIVE $|V_{\rm ub}|/|V_{\rm cb}|$

[2311.00458]

- BelleII's FEI at Belle. Data-driven control of X_c in $E_\ell > 1$ GeV

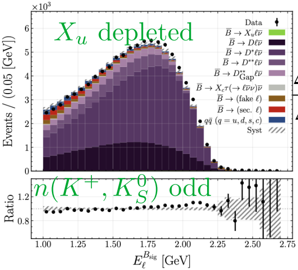

X_u enhanced

$n(K^+, K^0_S)$ even


(preliminary)

X_u enhanced

q^2-E_ℓ bins


X_u depleted

$n(K^+, K^0_S)$ odd

$$\frac{\Delta\mathcal{B}(X_u)}{\Delta\mathcal{B}(X_c)} = 1.96(11.6\%) \quad \left[\frac{|V_{ub}|}{|V_{cb}|}\right]^{\rm BLNP} = 0.0972(8.1\%)$$

$\Delta\mathcal{B}(B \to X_c \ell \nu)$
as external input

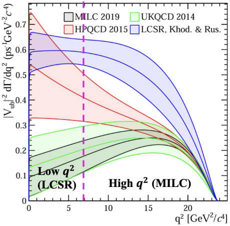
$$|V_{ub}|^{\rm GGOU} = 0.00415(7.9\%)$$

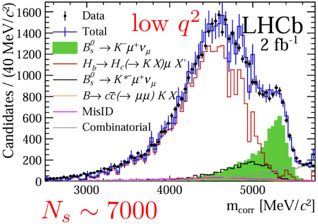
$$|V_{ub}|^{\rm BLNP} = 0.00425(6.3\%)$$

consistent w/ $|V_{ub}^{\rm incl}|_{\rm WA}$

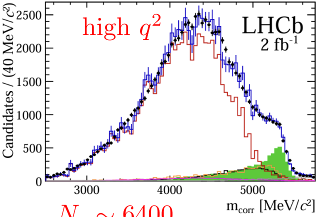
$|V_{ub}|/|V_{cb}|$ FROM $B_s^0 \to K^-\mu^+\nu_\mu$ [PRL 126, 081804 (2021)]

- Uses $B_s^0 \to D^-\mu^+\nu_\mu$ as the control modes (Run 1, 2/fb). Isolation variables for background reduction.



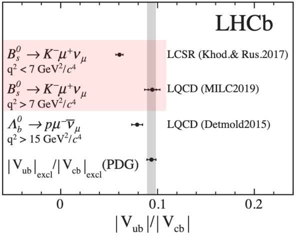


$N_s \sim 7000$



$N_s \sim 6400$

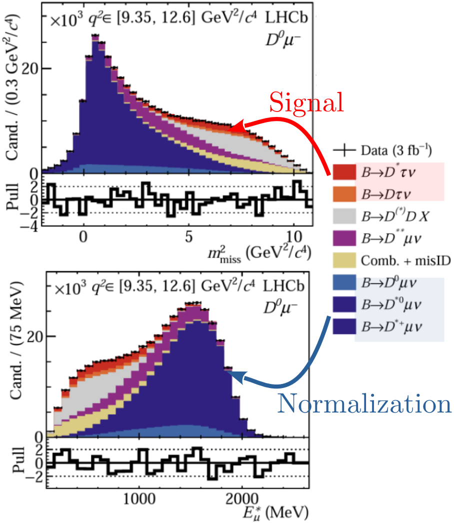
$$\underbrace{\frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu)}}_{\text{experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2}\underbrace{\frac{\Gamma_{FF,K}}{\Gamma_{FF,D_s}}}_{\text{theory}}$$



COMBINED $R(D)$-$R(D^*)$

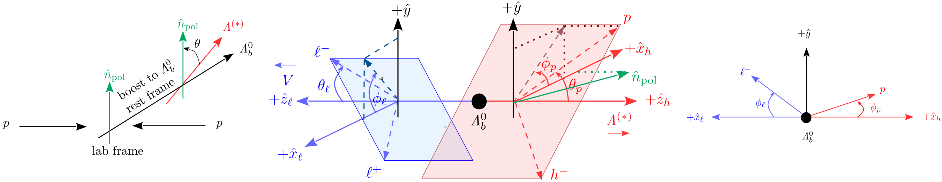
[PRL 131, 111802 (2023)]
[PRL 115, 111803 (2015)]

- Run1 (3/fb) dataset with muonic τ reconstruction.
- Signal $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$, $B^- \to \{D^{*0}, D^0\}\tau^-\overline{\nu}_\tau$
- Isolation variables against feedown ($\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell$) and double charm ($\overline{B} \to D^{(*)}DX$)
- 3d template fit to q^2 (4 bins), $m^2_{\rm miss}$ and E^*_μ.
- Simultaneous fits to signal + background enriched control samples (data-driven)
- Agree with SM at 1.9σ



ANGULAR ANALYSES AS A TOOL FOR NP SEARCHES

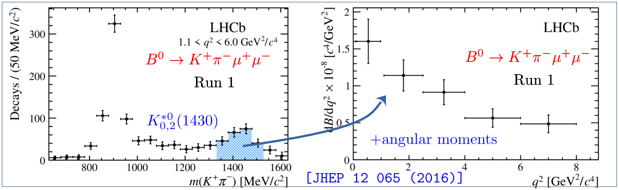
- Huge LHC statistics allow precision measurements of angular observables in $b \to s\ell^+\ell^-$ and $b \to s\vec{\gamma}$. Direct access to C_i^{NP}.
- Eg., $\vec{\Lambda}_{\mathrm{b}}^0 \equiv |[ud]\vec{b}\rangle$ reflects the properties of the b-quark, with $[ud]$ as spectator diquark.
- $\vec{\Lambda}_{\mathrm{b}}^0 \to \Lambda^*(\to pK^-)\ell^+\ell^-$: $\{q^2 \equiv m^2_{\ell^+\ell^-}, k^2 \equiv m^2_{pK}\} + \{\theta_\ell, \theta_p, \phi_\ell, \phi_p\}$



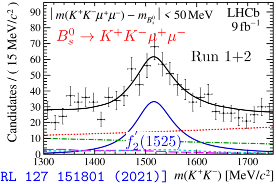
- If Λ_{b}^0 is unpolarized, $\phi_\ell = 0$, $\chi \equiv \phi_p$. Similar definitions for $B^0 \to K^+\pi^-\ell^+\ell^-$, $B_s^0 \to K^+K^-\ell^+\ell^-$.

ACCESS TO $B \to T\mu^+\mu^-$

- Till now, most of the work on spin-1 $K^*(892)$ and $\phi(1020)$ states.
- Spin-2 (tensor) states, $K_2^*(1430) \to K\pi$ and $f_2'(1525) \to K^+K^-$ also accessible at LHCb.
- Complementary information, compared to spin-1 states.



[JHEP 12 065 (2016)]



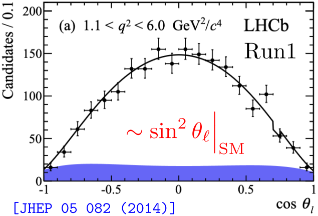
[PRL 127 151801 (2021)]

- These excited states also accessible in radiative $B^0_{(s)}$ decays at LHCb, with significant statistics (CERN-THESIS-2020-004).

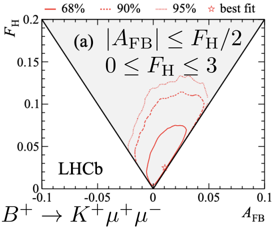
ANGULAR ANALYSIS OF $B \to K\mu^+\mu^-$ [JHEP 05 082 (2014)]

- In SM, almost pure $\sin^2\theta_\ell$. Look for non-zero $F_{\rm H}$ and $A_{\rm FB}$ in rate $\propto \frac{3}{4}(1-F_{\rm H})\sin^2\theta_\ell + \frac{1}{2}F_{\rm H} + A_{\rm FB}\cos\theta_\ell \Rightarrow$ SM null test.

- Run1:
  $N_{\rm sig}^{B^+} \sim 4746$,
  $N_{\rm sig}^{B^0} \sim 176$.

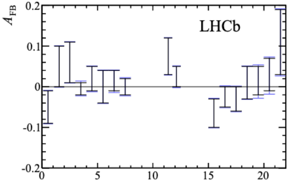


[JHEP 05 082 (2014)]

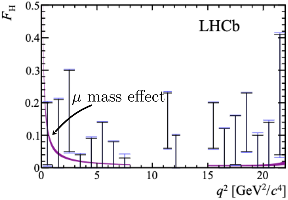


$B^+ \to K^+\mu^+\mu^-$

- Sensitive to new scalar + tensor operators, but consistent with SM atm.



[JHEP 05 082 (2014)]

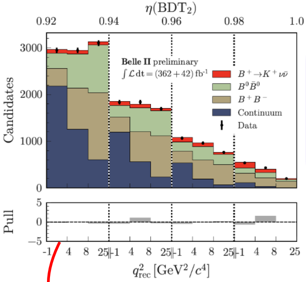


$B^+ \to K^+ \nu_\ell \bar{\nu}_\ell$ AT BELLEII

[2311.14647]
[PRL 127 181802 (2021)]

ITA

$$\mu = 5.4 \pm 1.0\,(\text{stat}) \pm 1.1\,(\text{syst}) = \frac{\text{BF}}{\text{BF}_{\text{SM}}}$$



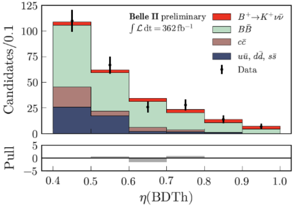
3.5 σ significance wrt bkg-only hypothesis

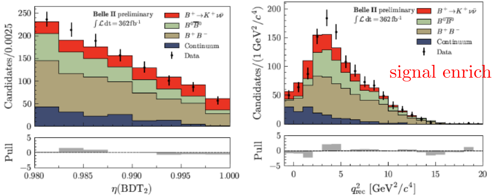
2.9 σ deviation from SM

HTA

$$\mu = 2.2^{+1.8}_{-1.7}\,(\text{stat})^{+1.6}_{-1.1}(\text{syst})$$

- Compatible with the Background-only hypothesis at the level of **1.1 σ**
- Compatible with the SM at the level of **0.6 σ**



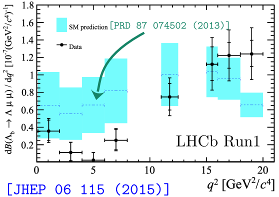


signal enriched

$\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ MOMENTS ANALYSIS

[JHEP 09 146 (2018)]
[JHEP 06 115 (2015)]
[PLB 725 25 (2013)]

- Since Λ^0 is a narrow state, FFs from lattice exist.
- However, since Λ^0 is long-lived, reconstruction efficiency is not optimal.



[JHEP 06 115 (2015)]

- Angular moments analysis in the high-q^2 region:

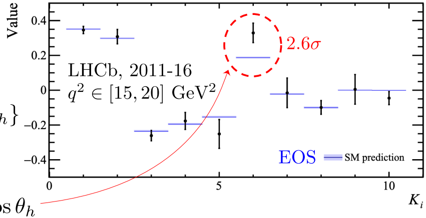
$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2}\sum_i^{34} K_i f_i(\vec{\Omega})$$

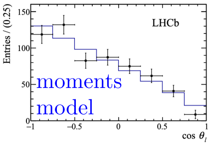
$$\vec{\Omega} \equiv \{\overbrace{\cos\theta, \phi_\ell,}^{\text{polarized } \Lambda_b^0,\ i>12} \cos\theta_\ell, \cos\theta_h, \phi_h\}$$

$$A_{FB}^{\ell} = \frac{3}{2}K_3 \to \cos\theta_\ell$$

$$A_{FB}^{h} = K_4 + \frac{1}{2}K_5 \to \cos\theta_h$$

$$A_{FB}^{\ell h} = \frac{3}{4}K_6 \to \cos\theta_\ell\cos\theta_h$$



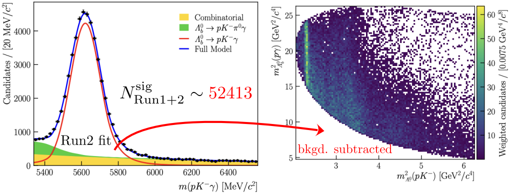


[JHEP 09 146 (2018)]

$\Lambda_b^0 \to pK^-\gamma$

LHCb-PAPER-2023-036 (↪JHEP)

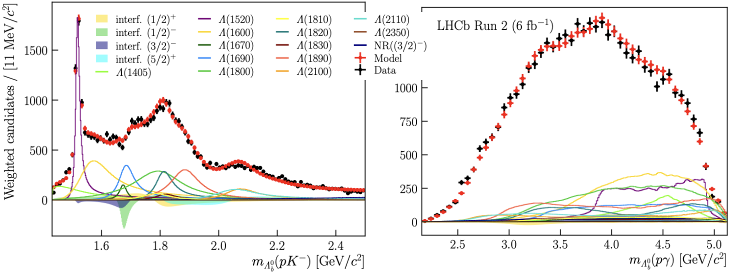
- High statistics due to photon pole.
- Variables: $\{m_{pK}, \cos\theta_h\}$.



- PDG resonances, $L \leq 3$ waves. Additional $\frac{3}{2}^-$ non-res. component.
- Takeaway: m_{pK} spectrum show “non-trivial” q^2 dependence.

fit fractions

Observable	Value
$\Lambda(1405)$	3.6
$\Lambda(1520)$	10.4
$\Lambda(1600)$	15.1
$\Lambda(1670)$	1.4
$\Lambda(1690)$	7.3
$\Lambda(1800)$	15.9
$\Lambda(1810)$	0.8
$\Lambda(1820)$	8.2
$\Lambda(1830)$	0.9
$\Lambda(1890)$	11.9
$\Lambda(2100)$	7.5
$\Lambda(2110)$	6.8
$\Lambda(2350)$	1.0
NR(3/2$^-$)	1.9



$\Lambda_b^0 \to \Lambda^0\gamma$: GLOBAL $C_7^{(\prime)}$ FIT

[PRD 105 L051104 (2022)]
[PRL 123 031801 (2019)]

- Reduces a 4-fold ambiguity in the $C_7^{\rm NP}$ phase to a 2-fold ambiguity.