Recent results from LHCb

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on behalf of the LHCb Collaboration

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Rabat-Salè-Kentra
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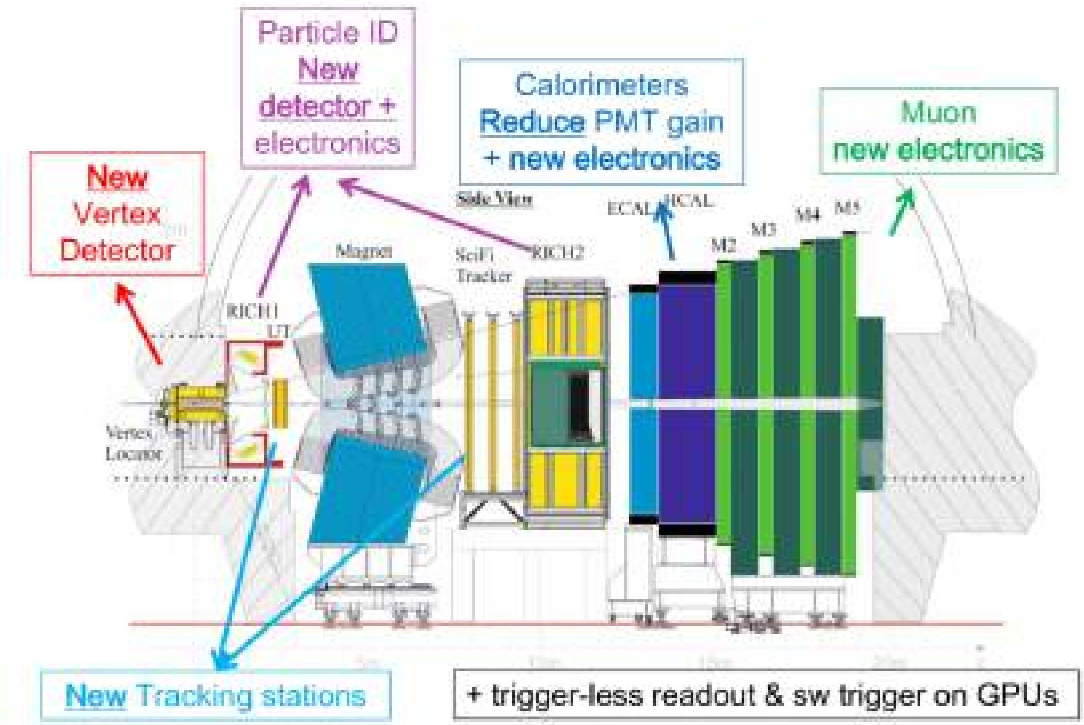
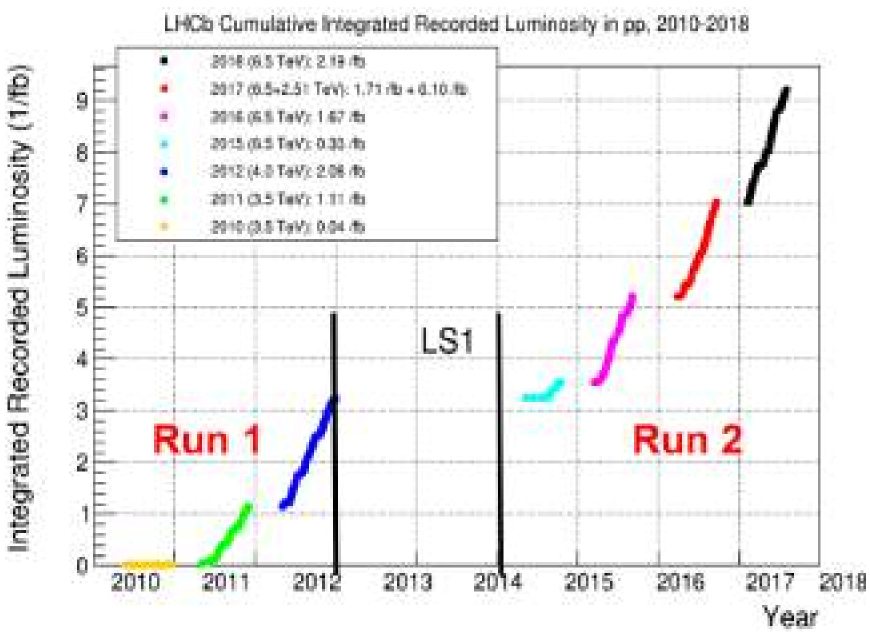
LHCb

- LHCb was originally designed for CP violation and rare beauty & charm decays
- But now it is a general purpose detector: *exotic spectroscopy, EW precision physics, heavy ions, fixed target program…*

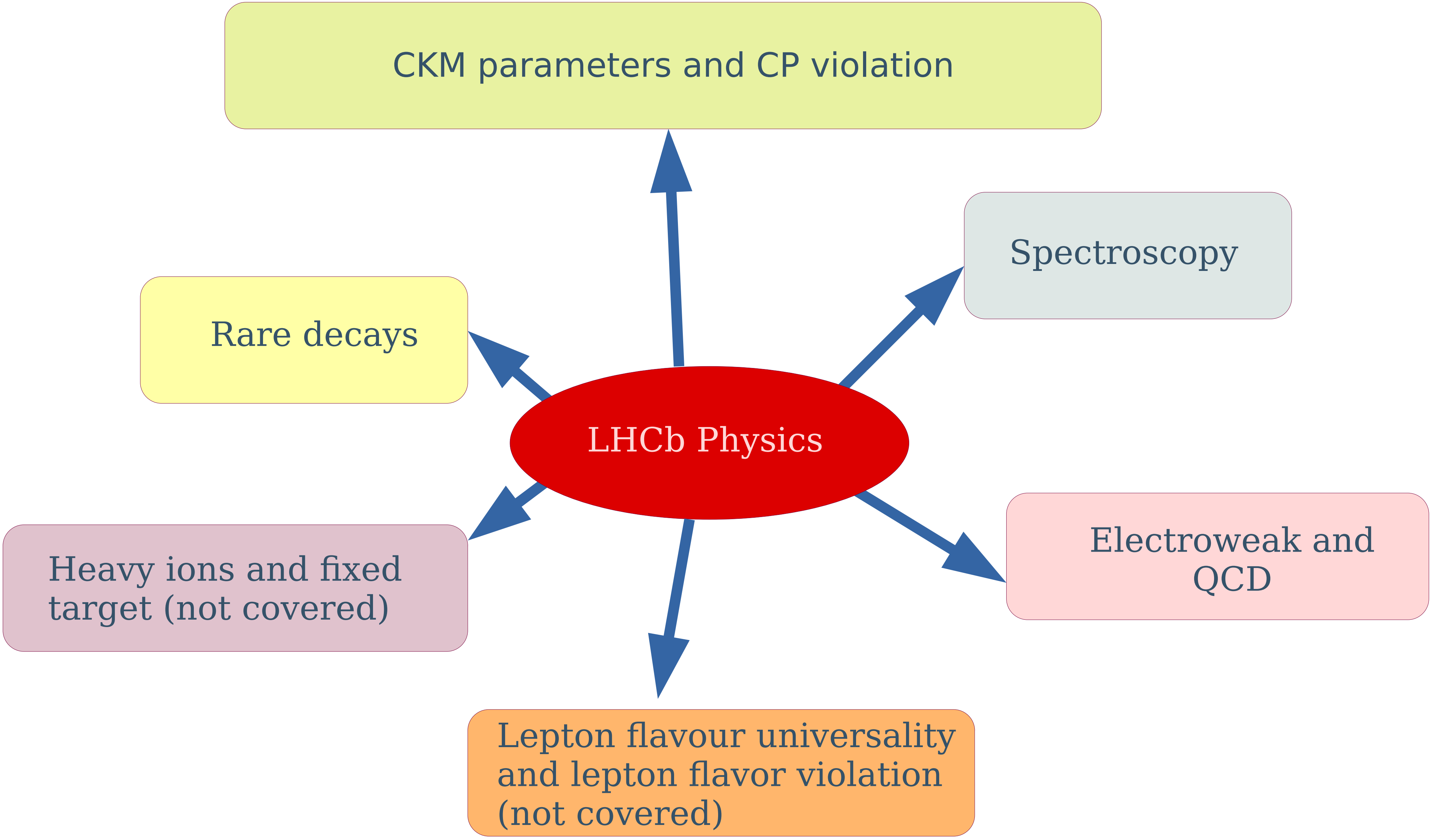




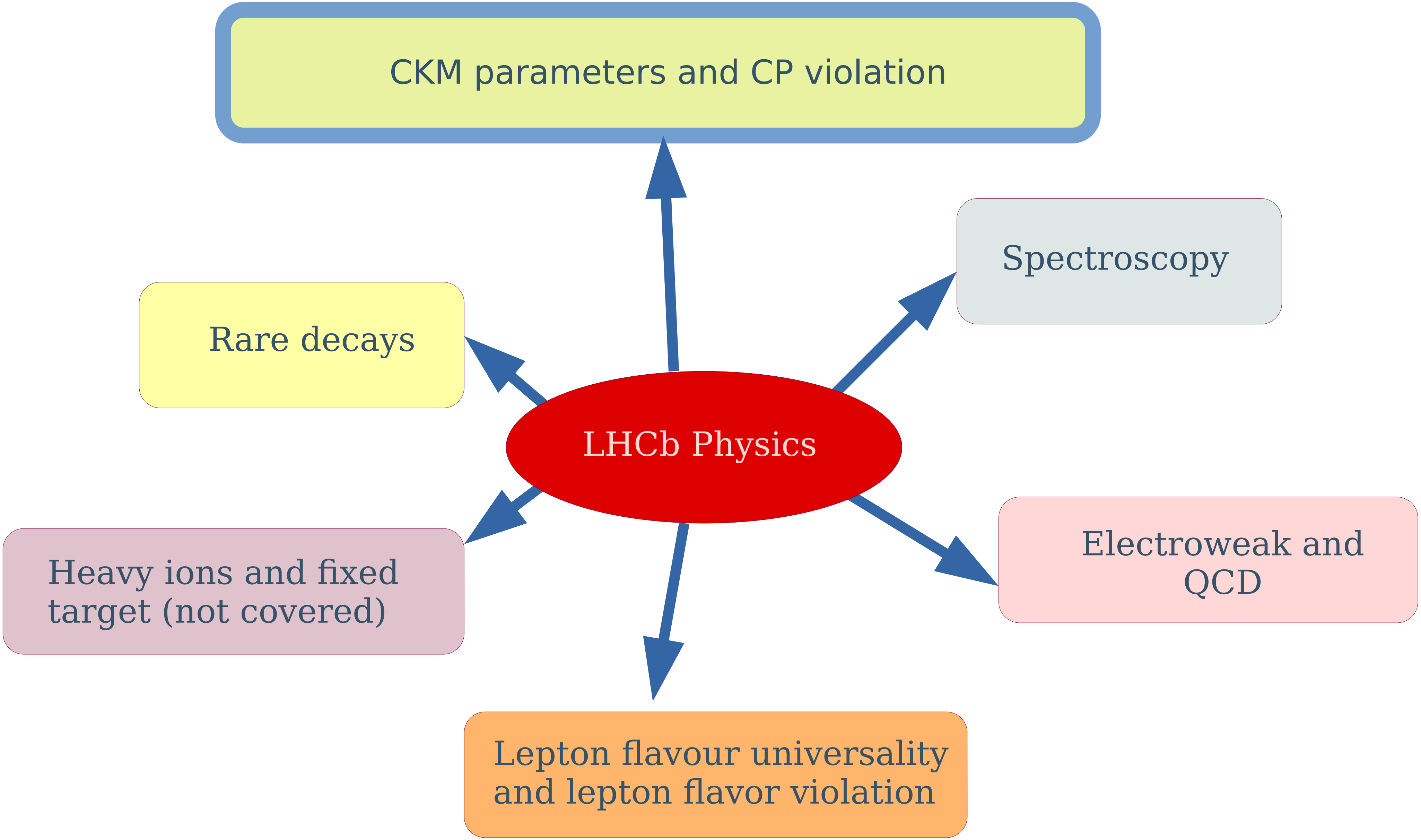
Run1: 3 fb^{-1} @ $\sqrt{s}$ =7-8 TeV
Run2: 6 fb^{-1} @ $\sqrt{s}$ =13 TeV

- LHCb is a spectrometer in the forward direction ($2<\eta<5$)
- Excellent vertexing, tracking and particle identification
- Low trigger threshold on hadrons, muons and photons
- Production of all types of *b* and *c* hadrons

Overview of Physics Results



Overview of Physics Results



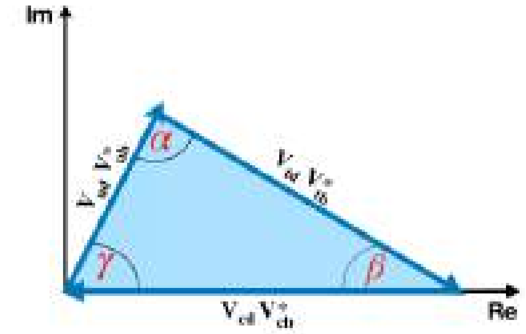
- The CKM matrix describes the quark charged current weak interactions

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

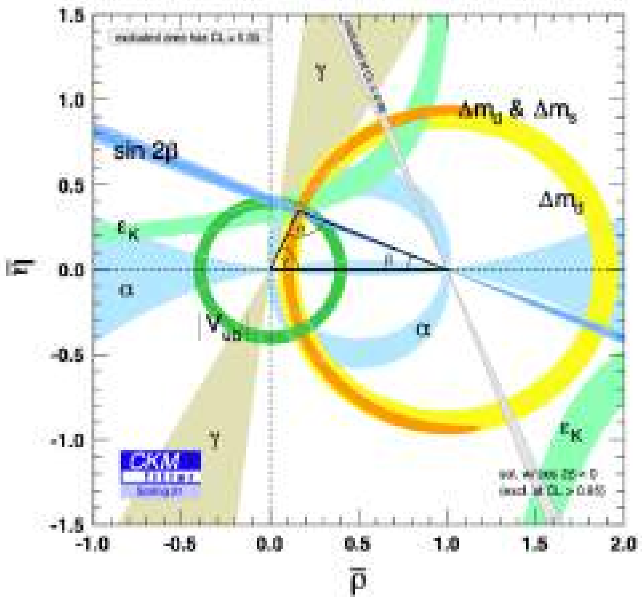
- The unitarity of this matrix leads to

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

- It can be visualized as a triangle in the complex plane



- The key test of the SM is the check of the unitarity of the CKM matrix
  - Magnitudes:
    - measure branching fractions or mixing frequencies
  - Phases:
    - measure the CP violating asymmetries



Measurement of ϕ_s in $B^0_s \to J/\psi K^+K^-$

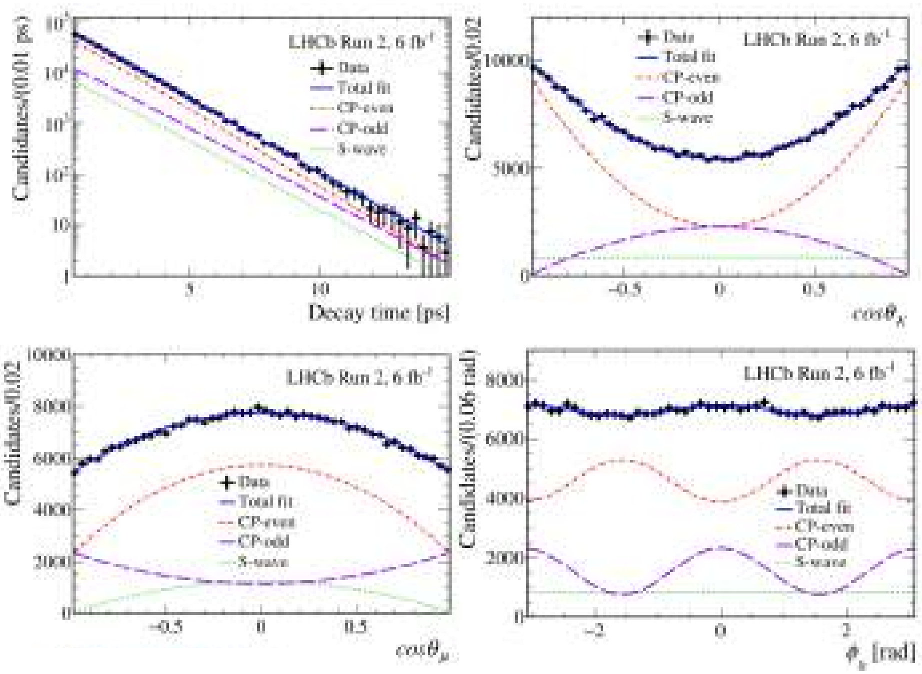
[arXiv:2308.01468]

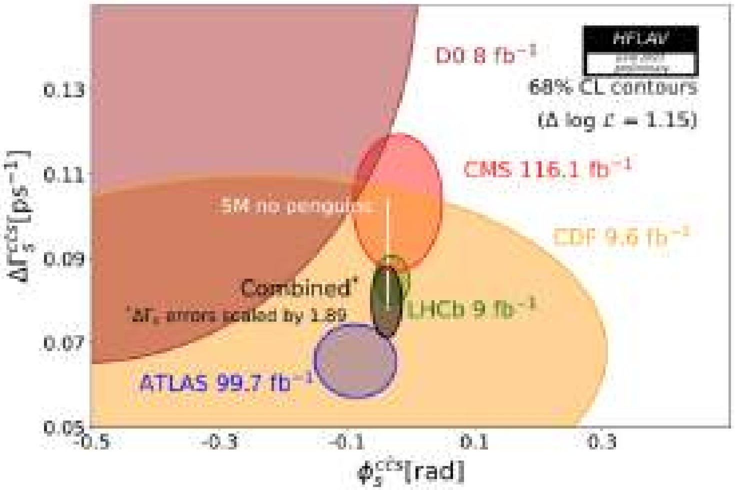
- B decays to CP eigenstates allow to probe the mixing phase $\beta_s = \phi_s/2$ through the interference between decays with and without mixing with a $c\text{-}\bar{c}$ resonance in the final state.

- $B^0_s \to J/\psi K^+K^-$ channel, in the vicinity of $\phi(1020)$ resonance with the full Run 2 dataset.

- To extract ϕ_s, CP even and CP-odd decay amplitude need to be disentangled →
  A weighted simultaneous fit to decay time distribution and decays angles ($\cos\theta_K$, $\cos\theta_\mu$, ϕ_h) in the helicity basis is performed

$$\varphi_s = -0.039 \pm 0.022 \pm 0.006 \text{ rad}$$
$$|\lambda| = 1.001 \pm 0.011 \pm 0.005$$
$$\Gamma_s - \Gamma_d = 0.0056^{+0.0013}_{-0.0015} \pm 0.0014 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024 \text{ ps}^{-1}$$





- Most precise measurement to date and consistent with SM
- $|\lambda|$: consistent with no direct CPV
- $\Gamma_s - \Gamma_d$: consistent with HQE expectation
  [JHEP12 (2017) 068]

Measurement of $\Delta\Gamma_s$ in $B^0_s \to J/\psi\, \pi^+\pi^-$ and $B^0_s \to J/\psi\, \eta'$

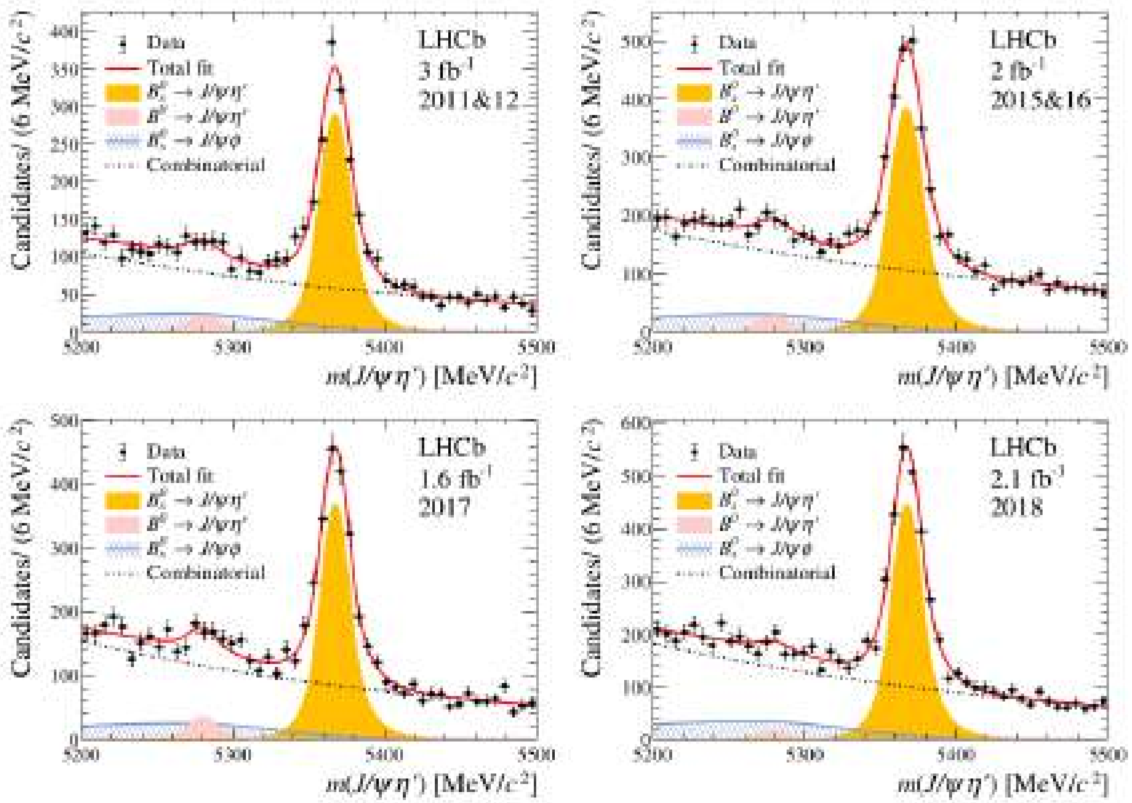
- The decay-width difference between the light and heavy mass eigenstates
- $\Delta\Gamma_s$ can be determined from the decay-width difference between a CP-odd and a CP-even B^0_s mode.

- If CP violation is negligible: $$\Gamma(B^0_s(t) \to f) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \eta_{CP}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right]$$

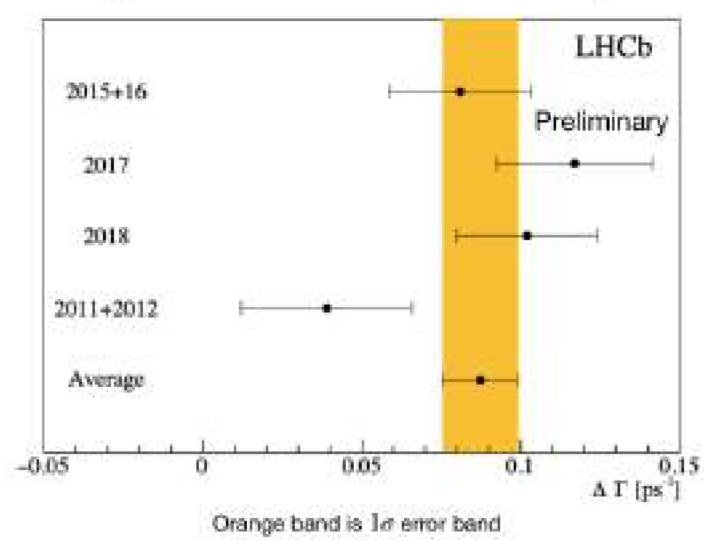
- integrating over a time bin

$$R_i = \frac{N_{\mathrm{L}}}{N_{\mathrm{H}}} \propto \frac{\left[e^{-\Gamma_s t(1+y)}\right]_{t_1}^{t_2}}{\left[e^{-\Gamma_s t(1-y)}\right]_{t_1}^{t_2}} \cdot \frac{(1-y)}{(1+y)} \quad \Rightarrow \quad R_i = A_i \cdot \frac{N_{\mathrm{L}}^{\mathrm{RAW}}}{N_{\mathrm{H}}^{\mathrm{RAW}}}$$

$y = \Delta\Gamma_s / 2\Gamma_s$ — $N_{L(H)}$: CP-even(odd) modes — efficiency in each decay time bin



$$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009\ \mathrm{ps}^{-1}$$



- 1st measurement using η′ channel
- In agreement with the SM

[LHCb-PAPER-2023-025]

Measurement of sin(2β)

- B decays to CP eigenstates allow to probe the mixing phase β through the interference between decays with and without mixing
- $$\mathcal{A}^{CP}(t) = \frac{\Gamma(\overline{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\overline{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} = \frac{S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

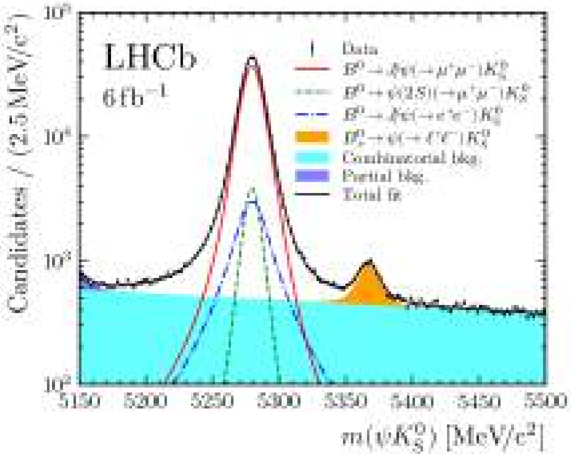
  where

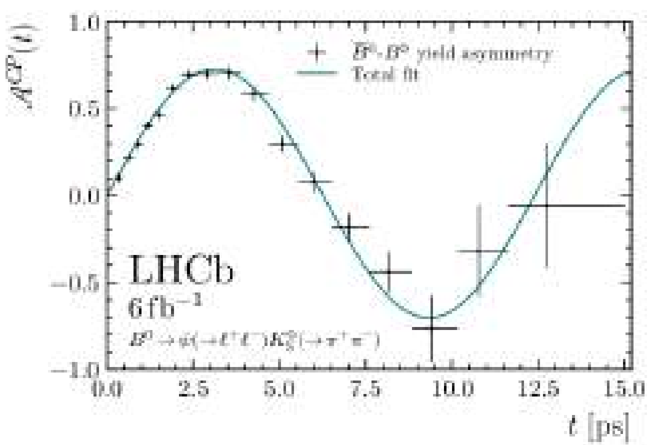
$$S = \sin(2\beta + \Delta\phi_d + \Delta\phi_d{}^{\mathrm{NP}})$$

- Decay channels: $B^0_s \to J/\psi(\to \mu^+\mu^-)K^0_s$, $B^0_s \to \psi(2s)(\to \mu^+\mu^-)K^0_s$, $B^0_s \to J/\psi(\to e^+e^-)K^0_s$ with $K^0_S \to \pi\pi$
- $$P(t,d,\eta) \propto [1 + d(1-2\omega^+(\eta))]P_{B^0}(t) + [1 + d(1-2\omega^-(\eta))]P_{\bar{B}^0}(t)$$

$$P_{B^0(\bar{B}^0)}(t) \propto \{(1 \mp A_P)(1 \mp \Delta\epsilon_{tag})e^{-\Gamma_d t'}(1 \mp S\sin(\Delta m_d t') \pm C\cos(\Delta m_d t'))\} \otimes R(t-t') \cdot \epsilon(t)$$

- Simultaneous fit of all channels
- Combination run2 and run1 data





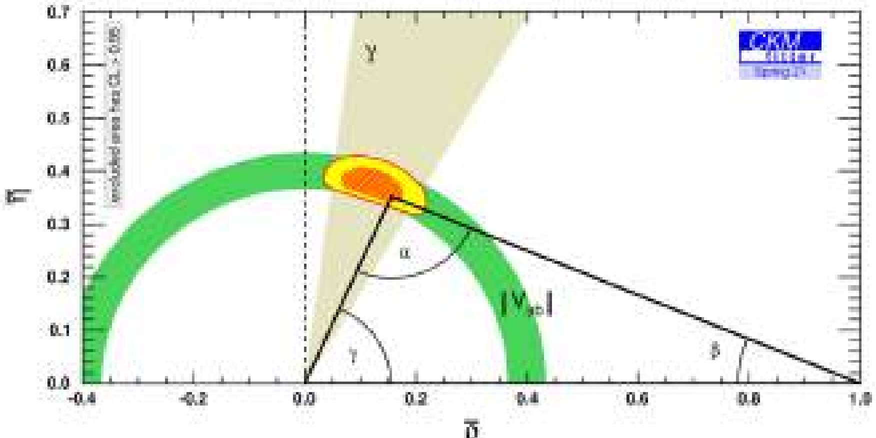
$$S^{\text{Run 1\&2}}_{J/\psi K^0_S} = 0.726 \pm 0.014\,(\text{stat+syst})$$
$$C^{\text{Run 1\&2}}_{J/\psi K^0_S} = 0.010 \pm 0.012\,(\text{stat+syst})$$

- Most precise single measurement
- Agreement with CKMfitter predictions

[LHCb-PAPER-2023-013]

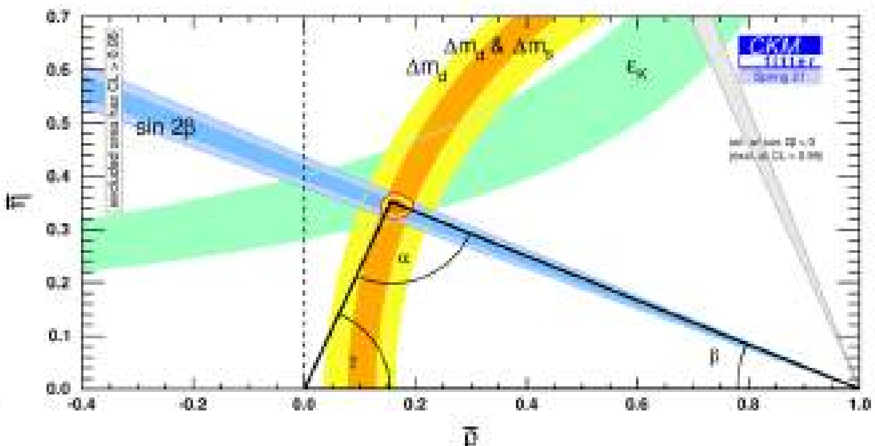
CKM γ angle

- γ is the phase difference between b→c and b→u quark transition
  - measurable in purely tree level o indirectly
  - have negligible theoretical uncertainty as hadronic parameters determined in data



Tree level direct measurements

$$\gamma = 72.1^{+5.4}_{-5.7}{}^{\circ}$$



Loop-level indirect measurements

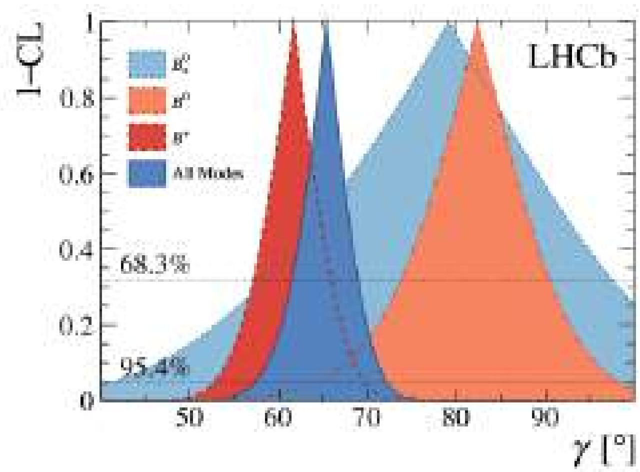
$$\gamma = 65.5^{+1.1}_{-2.7}{}^{\circ}$$

[HFLAV]

- LHCb combination:
- simultaneous fit of γ and D^0 mixing parameters

$$\gamma = (63.8^{+3.5}_{-3.7})^{\circ}$$

[JHEP 12(2021)141]



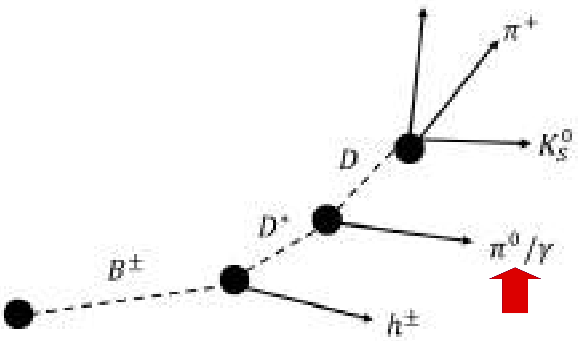
γ angle

- It is typically measured in B decays such as $B^{\pm} \to Dh^{\pm}$ (where D= D^0, D^0 and h=K, π)
- Measurement technique depends on D-decay mode

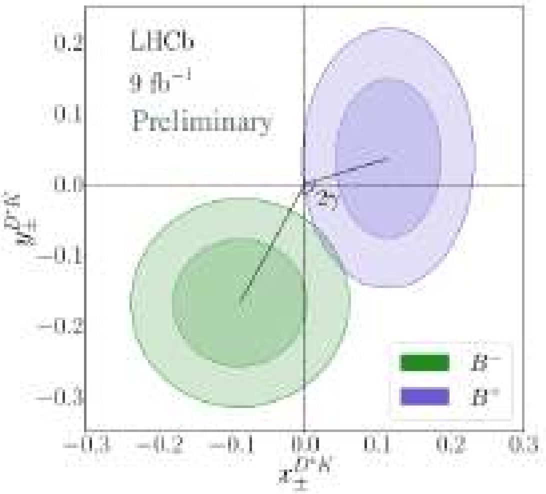
$$|A(B^-)|^2 \propto A_D^2 + r_B^2 A_{\bar{D}}^2 + 2A_D A_{\bar{D}} r_B \cos(\delta_B - \gamma)$$

$$|A(B^+)|^2 \propto A_{\bar{D}}^2 + r_B^2 A_D^2 + 2A_D A_{\bar{D}} r_B \cos(\delta_B + \gamma)$$

- **LHCb γ measurements with multibody D decays**
  - $B^{\pm} \to D^* K^{\pm}$ (full reconstructed)[LHCb-PAPER-2023-012]
  - $B^{\pm} \to D^* K^{\pm}$ (partially reconstructed)[LHCb-PAPER-023-029] with $D \to K^0_s h^+ h^-$



- The measurements are performed by analyzing the signal yields variation across the D decay phase space
  - They are independent of any amplitude model
  - direct measurement of strong phase between D and D from BESIII and CLEO

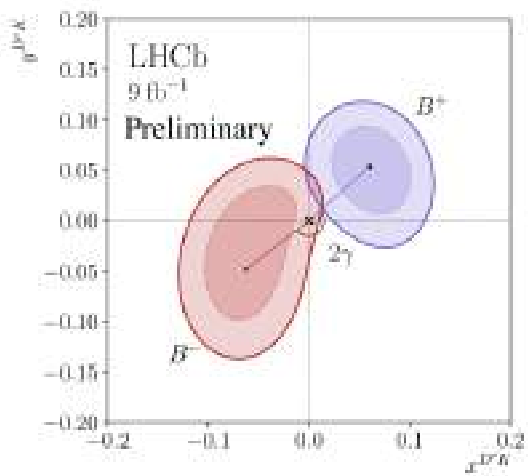


$$\gamma = (69^{+13}_{-14})^\circ$$

$$r_B^{D^*K} = 0.15 \pm 0.03$$

$$\delta_B^{D^*K} = (311 \pm 15)^\circ$$

[LHCb-PAPER-2023-012]



$$\gamma = (92^{+21}_{-17})^\circ$$

$$r_B^{D^*K} = 0.080^{+0.022}_{-0.023}$$

$$\delta_B^{D^*K} = (310^{+15}_{-20})^\circ$$

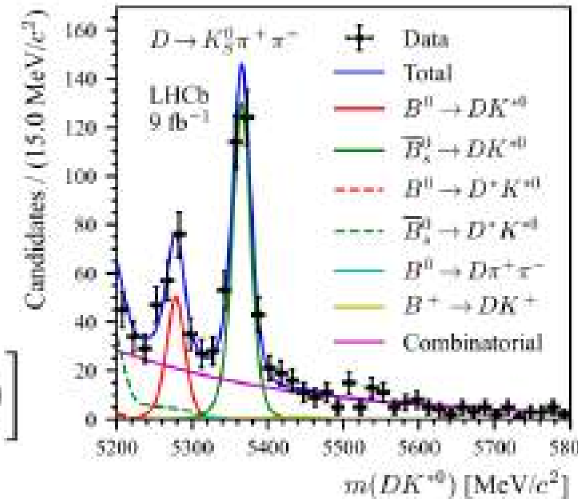
[LHCb-PAPER-2023-029]

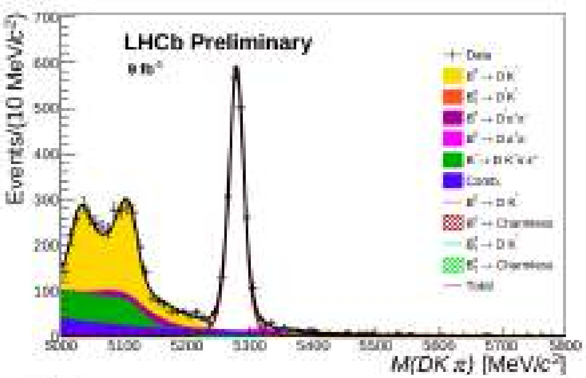
γ angle

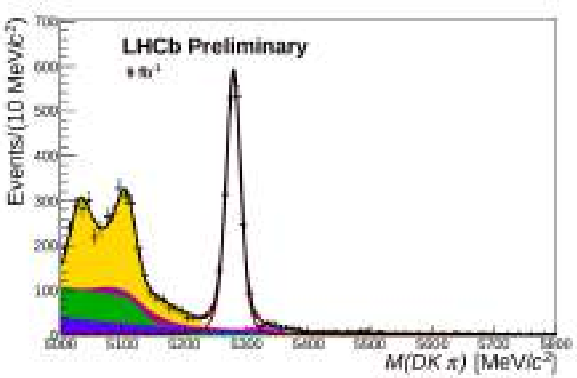
- Gain complementary info from $B^0 \to DK^*(892)^0$:
  - interference 3 times larger that for $B^\pm \to Dh^\pm$

- **$B^0 \to DK^*(892)^0$ with $D \to K^0_s h^+h^-$** [LHCb-PAPER-2023-009]
  - The γ angle is determined by examining the distributions of signal decays in phase space bins of the self-conjugate $D \to K^0_s h^+h$
  - $$N_i(B^0) = h^{B^0}\left[F_{-i} + (x_+^2 + y_+^2)F_i + 2\kappa\sqrt{F_iF_{-i}}(x_+c_i - y_+s_i)\right]$$

$$x_\pm \equiv r_{B^0}\cos(\delta_{B^0} \pm \gamma)$$
$$y_\pm \equiv r_{B^0}\sin(\delta_{B^0} \pm \gamma)$$







- **$B^0 \to DK^*(892)^0$ with the ADS and GLW D-decays finale states** [LHCb-CONF-2023-003]
  - Fit to selected data through a simultaneous unbinned extended maximum-likelihood fit of the B^0 candidate reconstructed mass or each flavour of each D final state
  - Results from $D \to K^0_s h^+h$ broke the degeneracy

Reduces B^+/B^0 tension ⟶ $\gamma = (49^{+23}_{-18})^\circ$

Consistent with expectations ⟶ $r_{B^0} = 0.271^{+0.068}_{-0.066}$

$\delta_{B^0} = (236^{+19}_{-21})^\circ$

γ angle

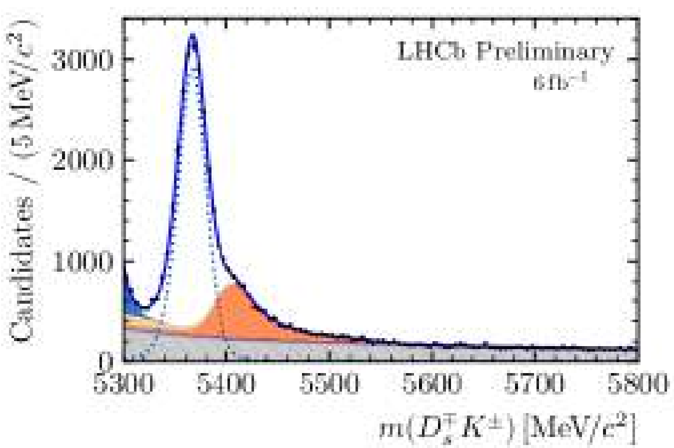
- **Measurement of CP asymmetry in $B^0_s \to D_s^- K^+$** [LHCb-CONF-2023-004]
- With $D_s^- \to K^+\pi^+\pi^-$, $D_s^- \to K^-K^+\pi^-$, $D_s^- \to \pi^-K^+\pi^-$
- Time dependent measurement of γ

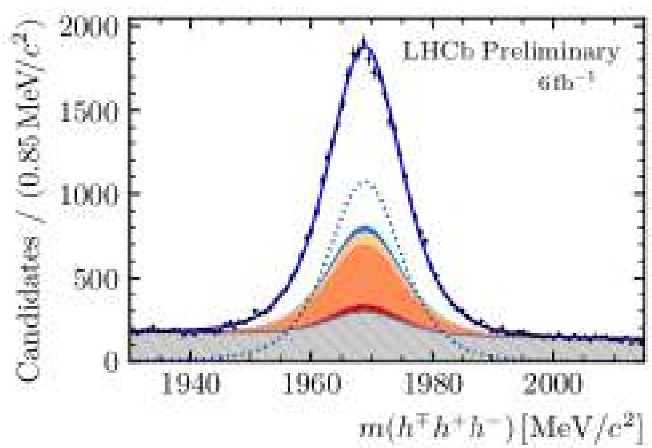
$$\Gamma\left(B_s^0(t) \to f/\bar{f}\right) \sim e^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + C_{f/\bar{f}}\cos\left(\Delta m_s t\right) + A^{\Delta\Gamma}_{f/\bar{f}}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) - S_{f/\bar{f}}\sin\left(\Delta m_s t\right)\right)$$

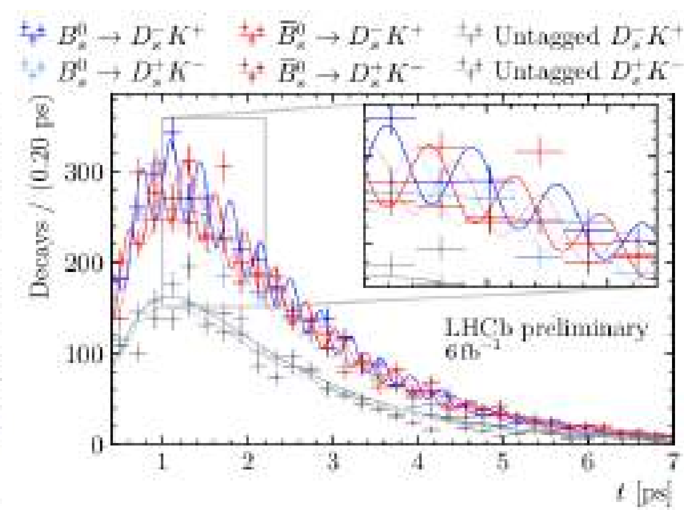
$$C_f = C_{\bar{f}} = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2} \qquad A_f^{\Delta\Gamma} = \frac{-2\, r_{D_sK}\cos\left(\delta - (\gamma - 2\beta_s)\right)}{1 + r_{D_sK}^2} \qquad S_f = \frac{2\, r_{D_sK}\sin\left(\delta - (\gamma - 2\beta_s)\right)}{1 + r_{D_sK}^2}$$

$$A_{\bar{f}}^{\Delta\Gamma} = \frac{-2\, r_{D_sK}\cos\left(\delta + (\gamma - 2\beta_s)\right)}{1 + r_{D_sK}^2} \qquad S_{\bar{f}} = \frac{2\, r_{D_sK}\sin\left(\delta + (\gamma - 2\beta_s)\right)}{1 + r_{D_sK}^2}$$

- Simultaneous fit of all modes and runII years
- External input: $\Delta\Gamma_s$, Γ_s, detection asymmetry
- Significant CP violation in the interference







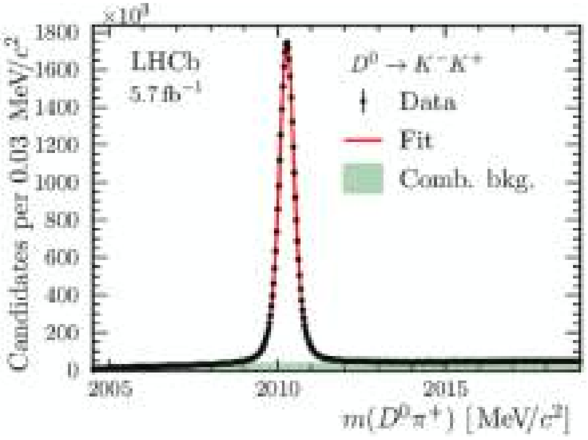
- External input: [arXiv:2308.01468]

$$\phi_s = -2\beta_s$$

$$\gamma = (74 \pm 11)^\circ\,,$$
$$\delta = (346.9 \pm 6.6)^\circ\,,$$
$$r_{D_sK} = 0.327 \pm 0.038\,,$$

First charm CPV in a single channel

- **The time integrated CP asymmetry in the Cabibbo suppressed decay $D^0 \to K^+K^-$**
  [Phys. Rev. Lett. 131 (2023) 091802]
- CPV in charm small $O(10^{-4})$ → sensitive to NP



- CPV in charm observed in time integrated difference of CP asymmetries:

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$$

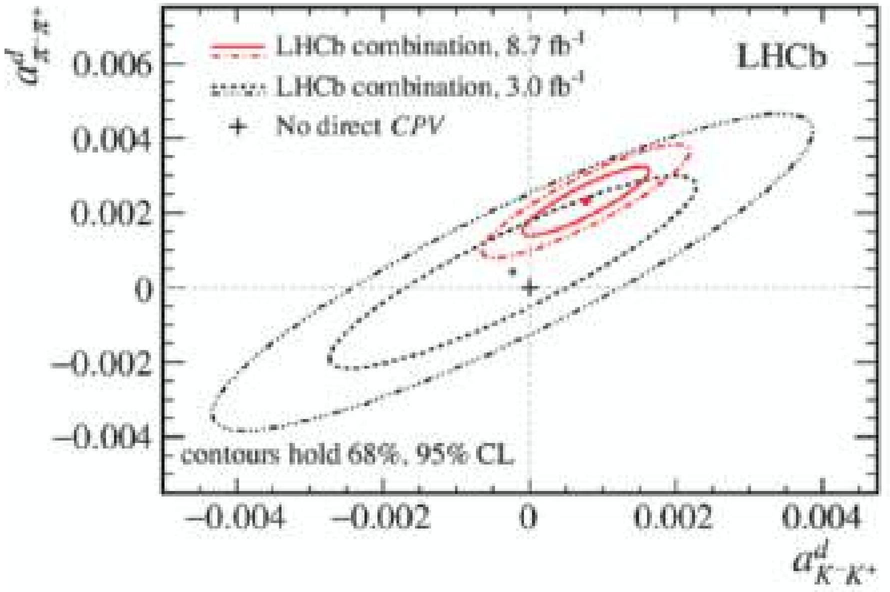
  - The first measurement of CPV in the charm system (5.3σ)
    [Phys. Rev. Lett. 122 (2019) 211803]

- measurement of $A_{CP}(K^+K^-)$:

$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$$

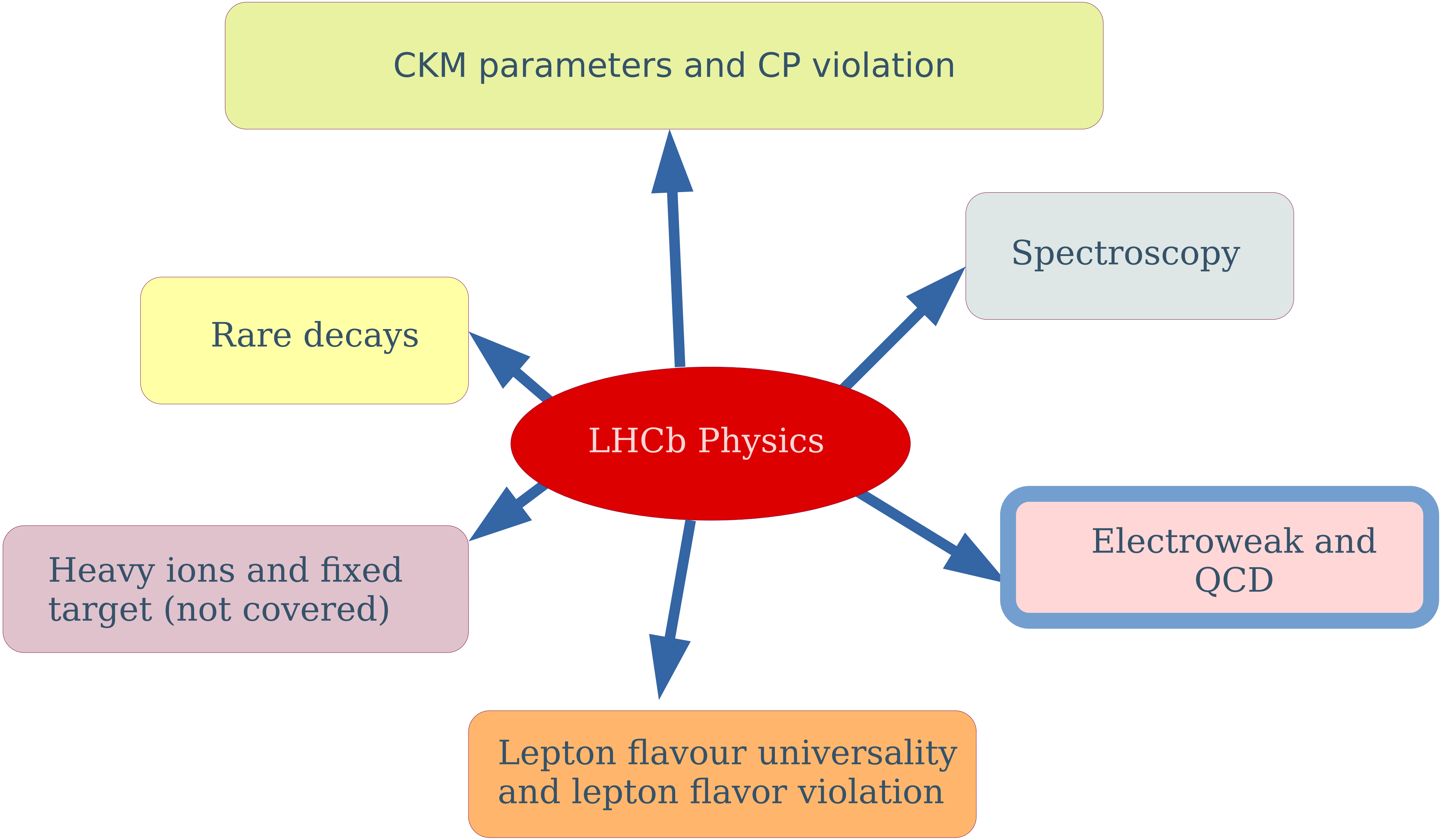
- then determine the direct CP asymmetries using ΔA_{CP}

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$



- First evidence for direct CP violation in specific D^0 decays: 3.8σ in $D^0 \to \pi^-\pi^+$

Overview of Physics Results



W mass

[JHEP01 (2022) 036]

- Measurement of the W boson mass

- Complementary to Atlas and CMS
- 2016 dataset

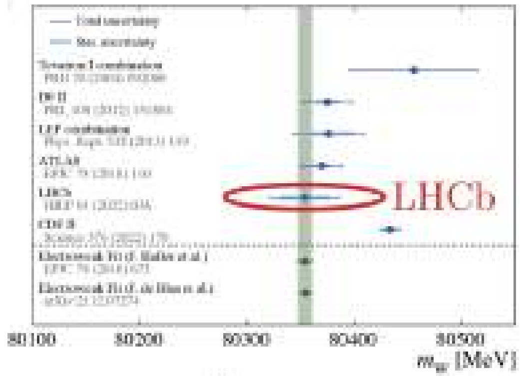
- Simultaneous fit to muon p_T from $W \to \mu\nu_\mu$ and ϕ^* of $Z \to \mu\mu$

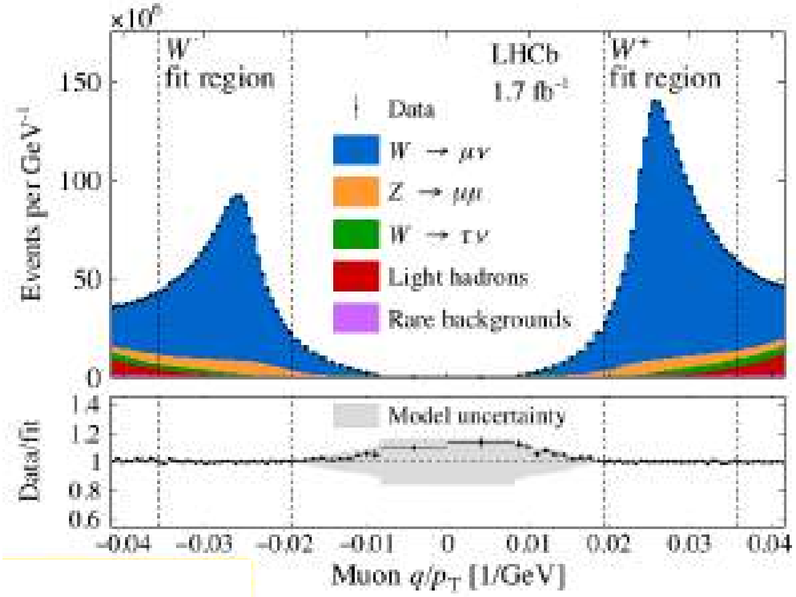
$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M}$$

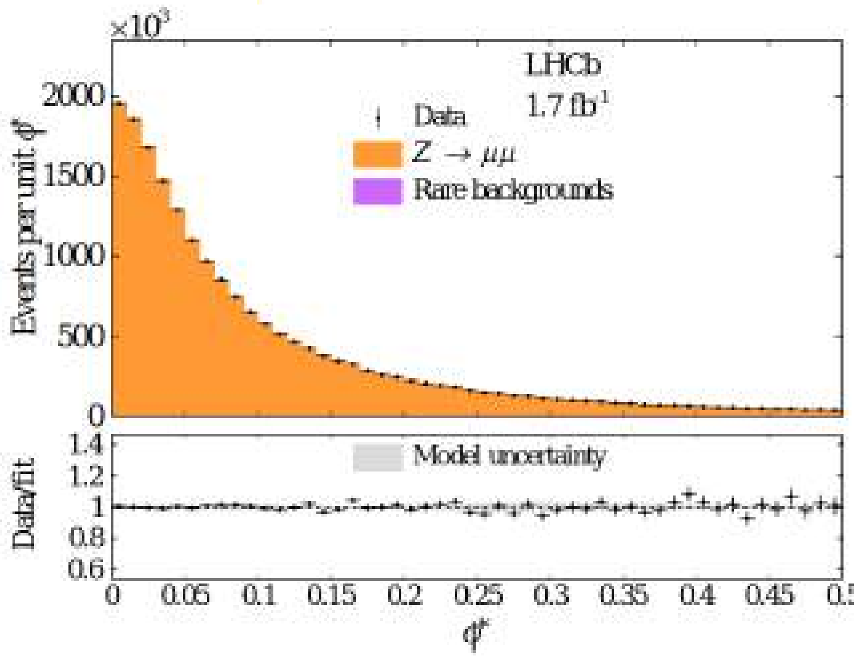
- Determination of the charge dependent curvature biases and momentum scaling

- Offline reprocessing of the alignment with Z decays

$$m_W = 80354 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 9_{\rm PDF}\ \text{MeV}$$







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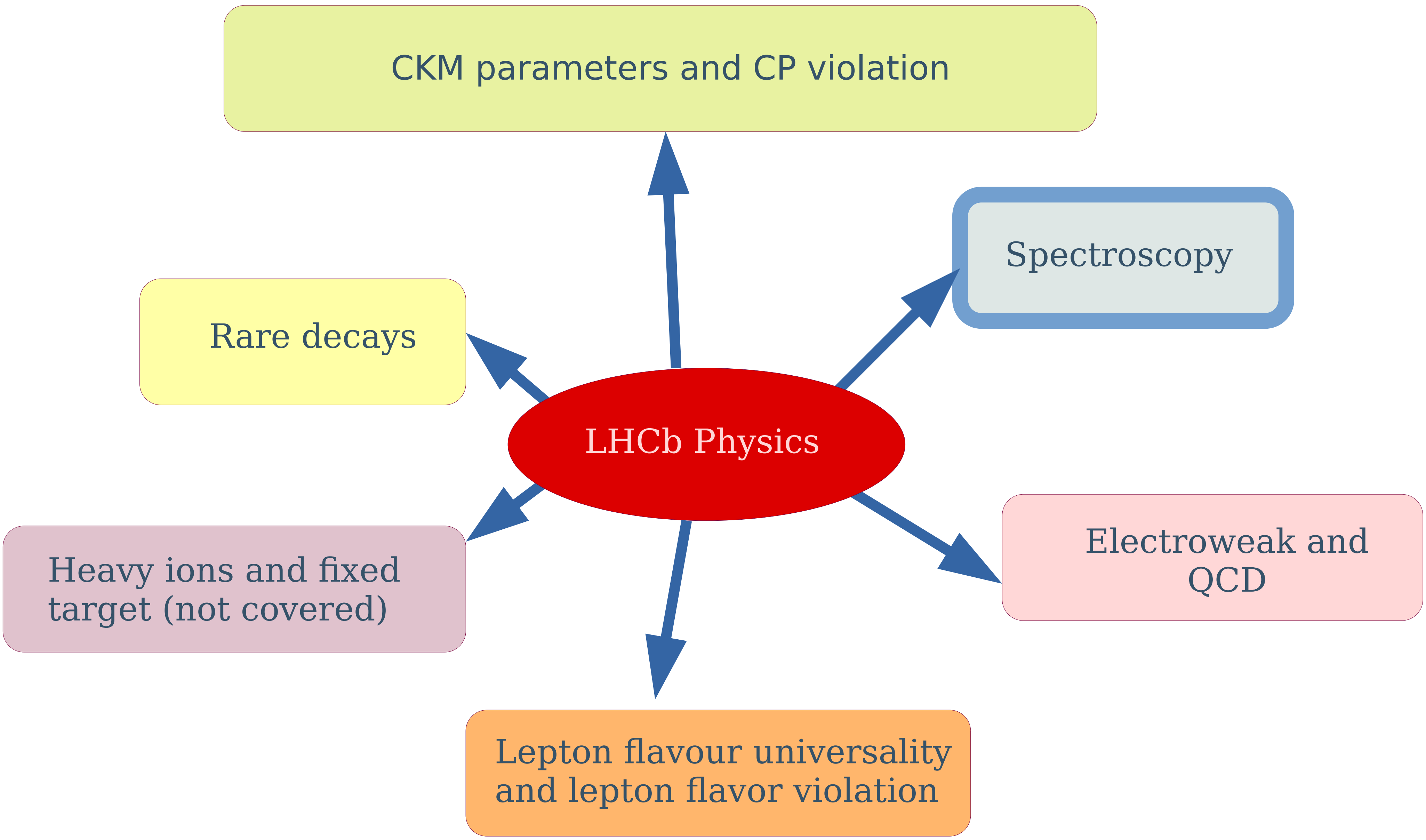
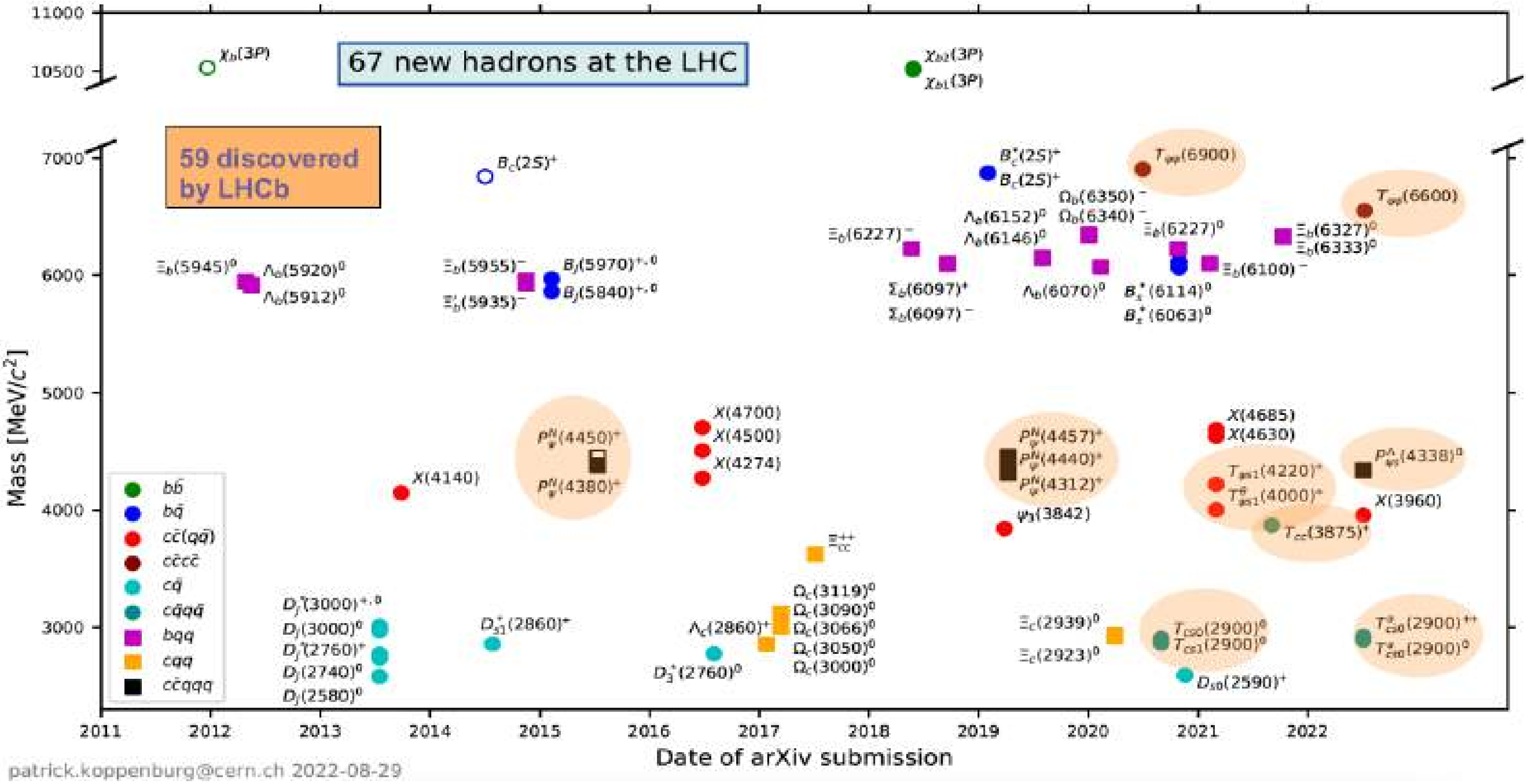


Hadron states

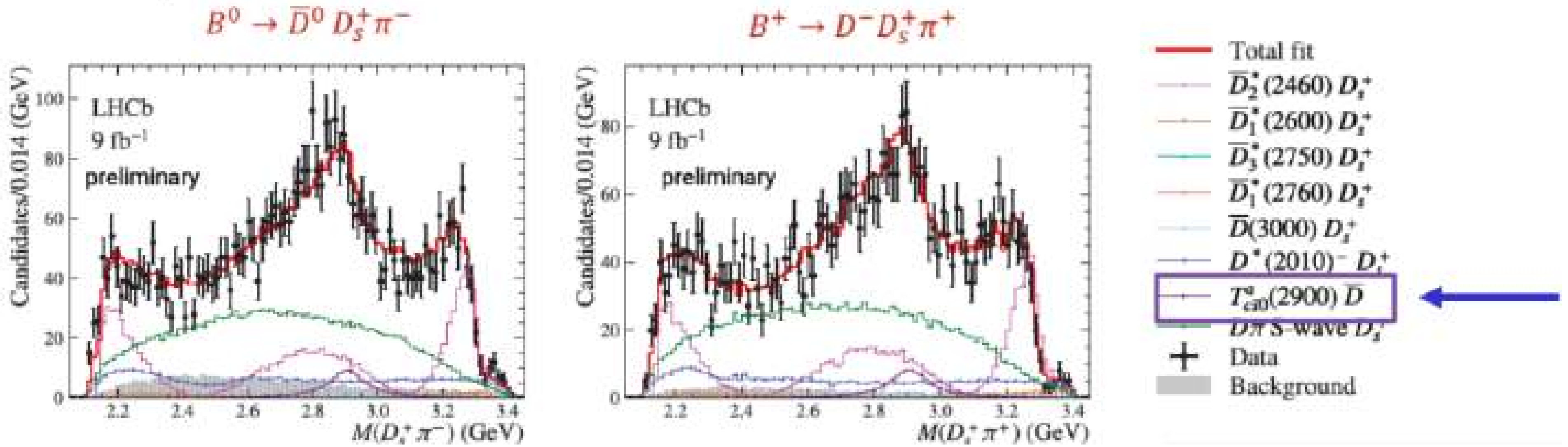


[arXiv:2206.15233]

- Tetraquark and pentaquark: Tightly bounded states? Hadronic molecules?
  - Nature of exotic states still unclear

Doubly charged tetraquark

- First observation of isospin triplet 4-states in $D_s^+\pi^-$ spectrum
- Combined amplitude analysis for $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^0 \to D^- D_s^+ \pi^-$
- $m(D_s^+\pi^-)$ well described by adding tetraquark states $T^a_{c\overline{s}0}(2900)^0$ $T^a_{c\overline{s}0}(2900)^{++}$
- $$M = 2.908 \pm 0.011 \pm 0.020\,\text{GeV}$$ $$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\text{GeV}$$
- Significance: > 9σ
- spin-parity $J^P = 0^-$



[Phys. Rev. Lett. 131, 041902]

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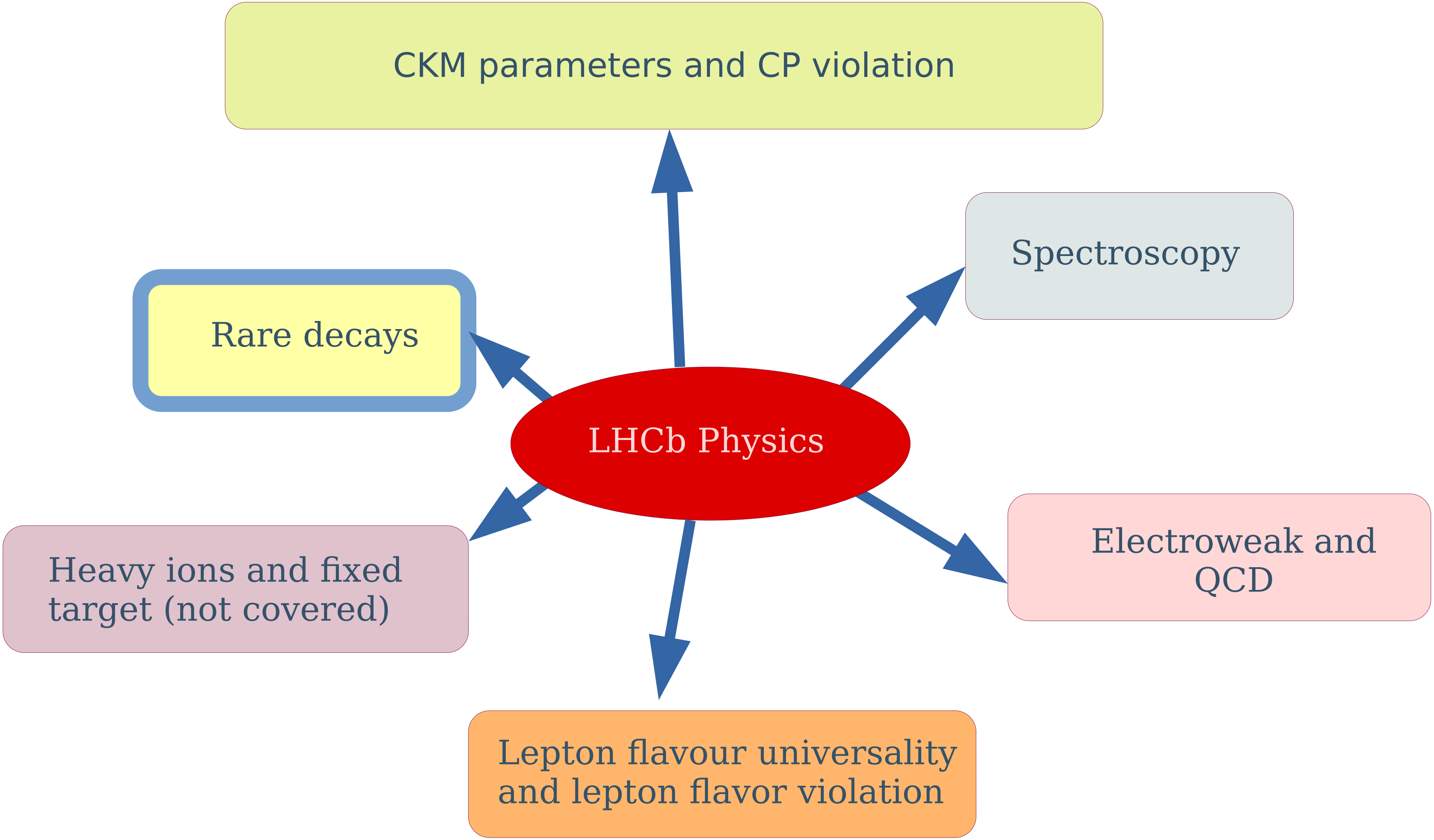
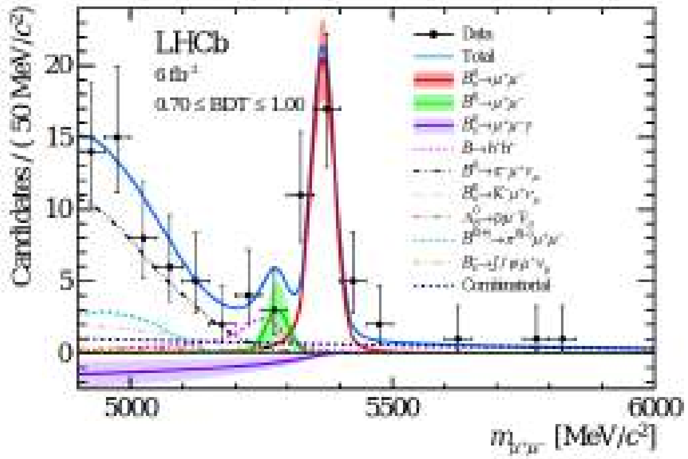


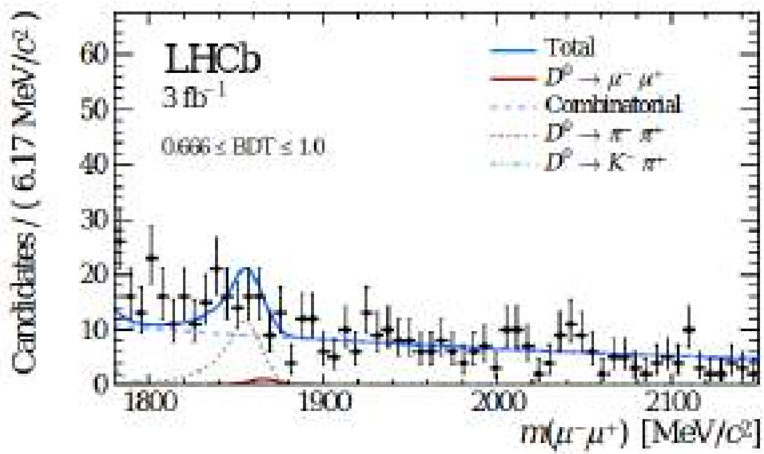
$B_{(s)}\to\mu^+\mu^-$ and $D^0\to\mu^+\mu^-$

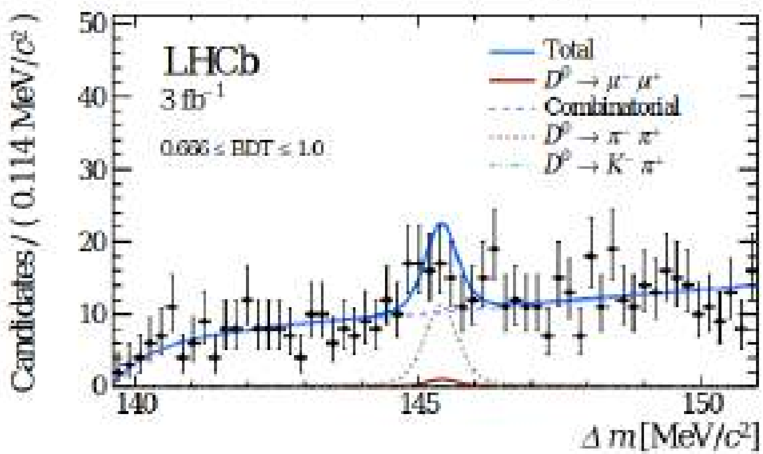
$$\mathcal{B}(B_s^0\to\mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right)\times 10^{-9}$$

- $B_s^0\to\mu^+\mu^-$ found with significance >10 sigma
- no evidence yet for $B^0\to\mu^+\mu^-$ (1.7 sigma)

[Phys. Rev. D105 (2022) 012010]







- $D^0\to\mu^+\mu^-$: unique probe of up-type quark FCNC
- Using $D^*\to D^0\pi^+$
- Normalization channel: $D^0\to h^-h^+$ (K,π)
- Simultaneous fit to $m(\mu^+\mu^-)$ and $m(D^*)$ - $m(D^0)$
- Most stringent limit of FCNC in charm sector

$$\mathcal{B}(D^0\to\mu^+\mu^-) < 2.94\,(3.25)\times 10^{-9} \text{ at } 90\ (95)\%\ \text{CL}$$

[Phys. Rev. Lett. 131 (2023) 041804]

Search for new physics in rare Λ_b

[Phys. Rev. Lett. 131 (2023) 151801]

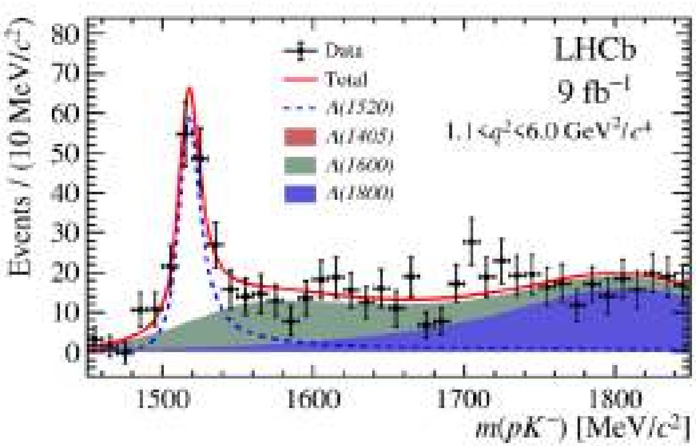
- The flavour changing neutral-current (FCNC) transition $b \to s l^+ l^-$ proceeds through electroweak loop diagrams in the SM
  - a sizeable contribution could be introduced by BSM physics
- LHCb has a unique access to all b hadron species
  - Λ_b baryon: spin ½ → complementary to B

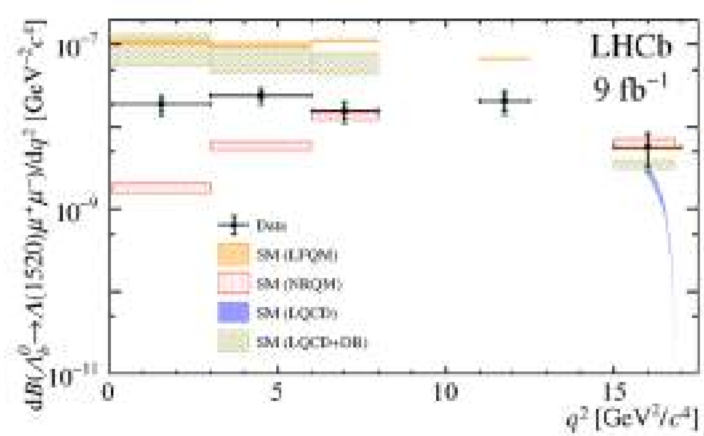
- **Measurement of Branching fraction of $\Lambda_b \to \Lambda(1520)(\to pK^-)\mu^+\mu^-$**
  - bins of squared dimuon mass q^2

$$\left[\frac{d\mathcal{B}(\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-)}{dq^2}\right]_{q^2_{\rm min}}^{q^2_{\rm max}} = \frac{1}{(q^2_{\rm max} - q^2_{\rm min})} \frac{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi)\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\Lambda(1520) \to pK^-)} \frac{N_{\Lambda(1520)\mu^+\mu^-}}{N_{pK^- J/\psi}} \frac{\varepsilon_{pK^- J/\psi}}{\varepsilon_{\Lambda(1520)\mu^+\mu^-}}$$

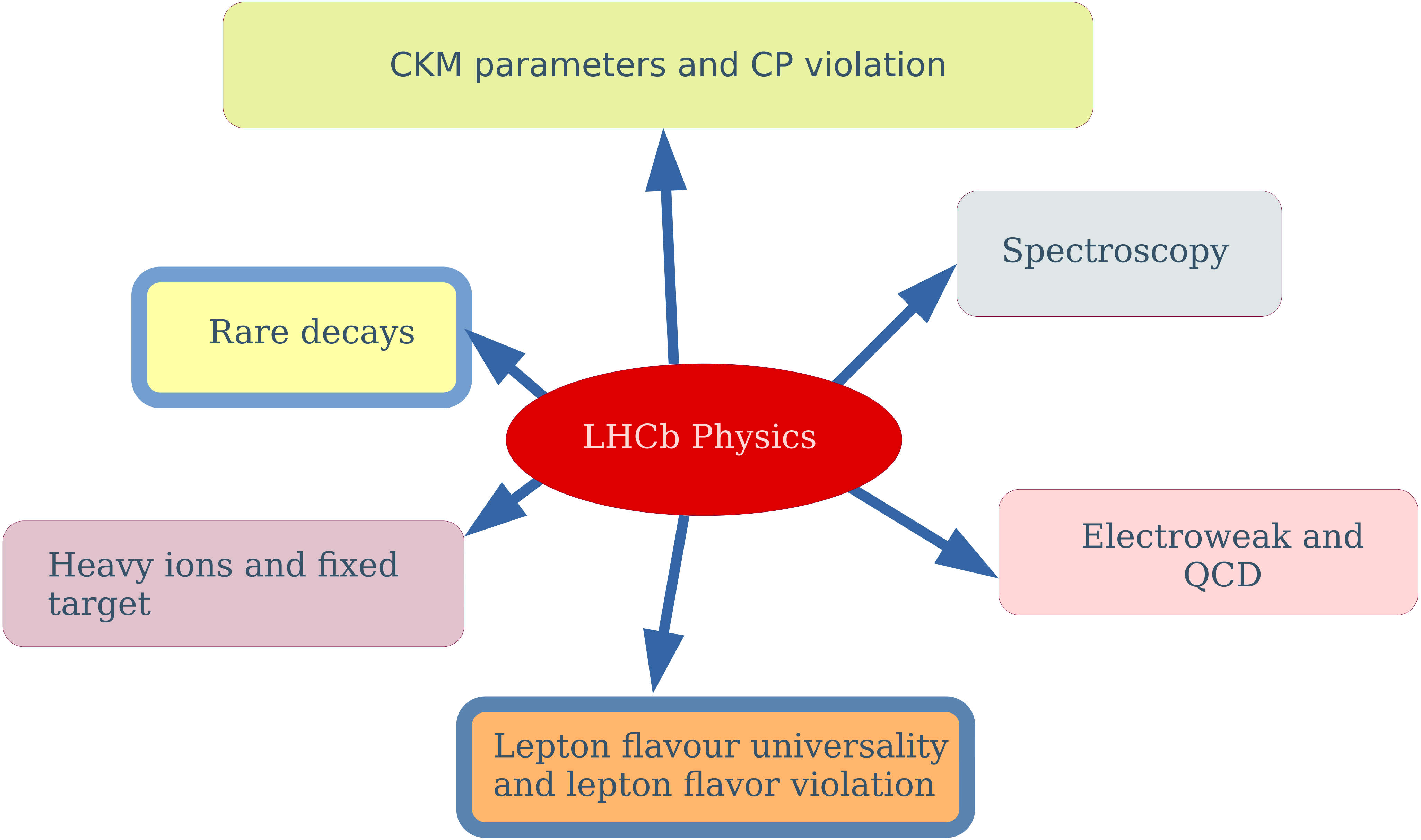
  - Extraction of $\Lambda(1520)$ from other states by fitting m(pK)

  - Large differences with prediction at low and mid q^2
  - Need better theory understanding of FF



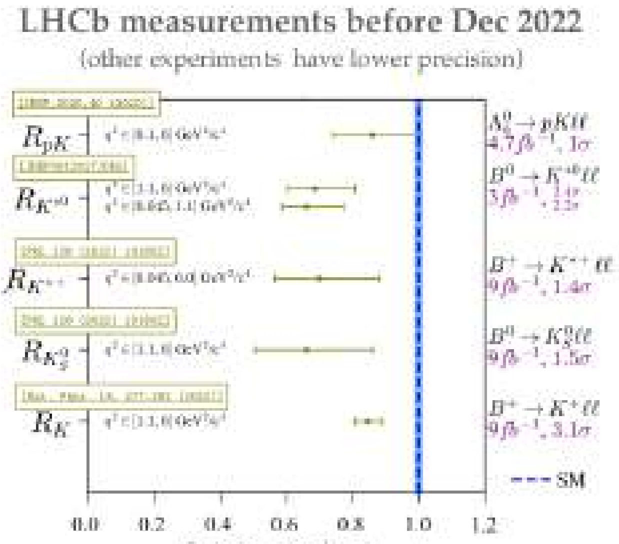


Overview of Physics Results



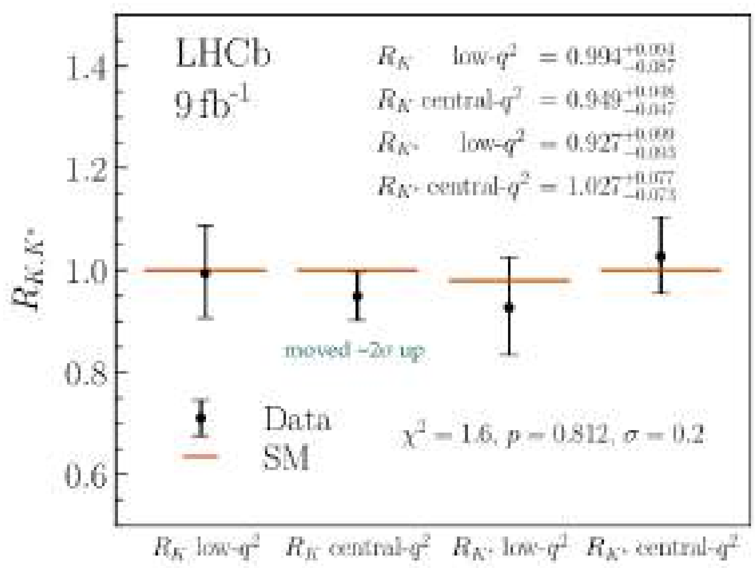
Lepton flavour universality with rare decays

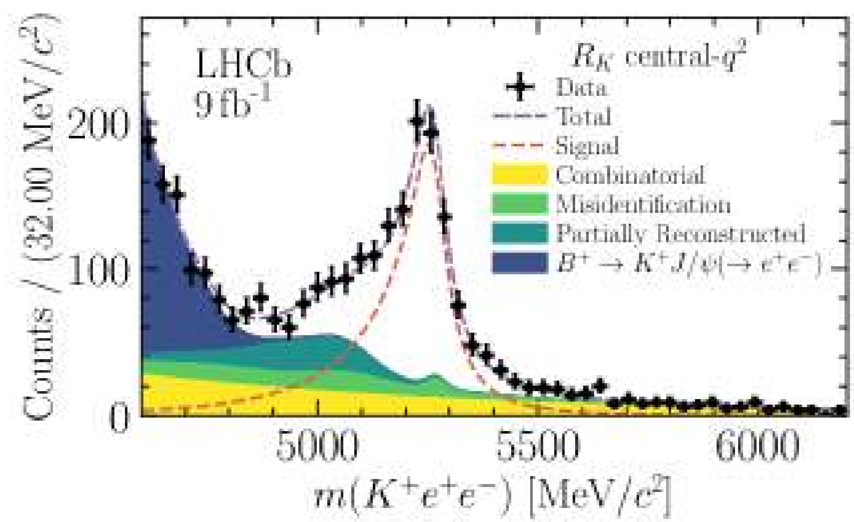
- LFU: Equal electroweak coupling of gauge bosons to all charged leptons.



$$R_H \equiv \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$

- New simultaneous analysis of the two most sensitive channels $B \to K^{(*)}ll$
- Found PID dependence on R_{K^*}
- Additional MisID component identified thanks to simultaneous analysis
-
  - Triple misID $B \to D(\to K_{\to e}\pi_{\to e})\pi_{\to K}$
  - Double misID $B \to KK_{\to e}K_{\to e}$
- Now estimates misID from data control region enriched in $\pi \to e$ and $\pi \to K$ misID





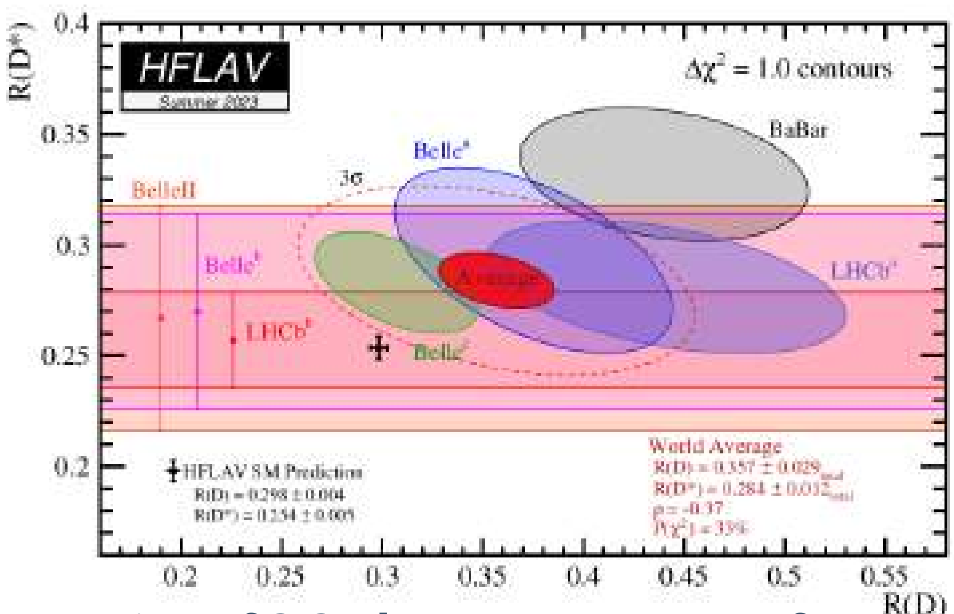
LFU with semileptonic decays

- LFU in b→clυ decays

- $\tau \to \mu \overline{\nu_\mu} \nu_\tau$
  - Simultaneous measurement of
  - R(D⁰) and R(D*) with $D^0\mu^-$ and $D^{*+}\mu^-$ samples (run1)
  - [Phys. Rev. Lett. 131, 111802]

$$\mathcal{R}(D^*) = 0.281 \pm 0.018 \pm 0.024$$
$$\mathcal{R}(D^0) = 0.441 \pm 0.060 \pm 0.066$$
$$\text{correlation } \rho = -0.43$$

- In agreement with SM at 1.9σ



Tension of 3.3σ between average of measurement and SM prediction

- $\tau \to 3\pi\nu_\tau$
  - $$\mathcal{R}(D^{*-}) = \underbrace{\left[\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}\right]}_{\mathcal{K}(D^{*-}),\text{measured}} \times \underbrace{\left[\frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}\right]}_{\text{external}}$$
  - 2015-2016 data

$$\mathcal{R}(D^{*-}) = 0.247 \pm 0.015\,(\text{stat}) \pm 0.015\,(\text{syst}) \pm 0.012(\text{ext})$$

- In agreement with SM within 1σ

  [Phys. Rev. D 108, 012018]

- Additional sensitivity to NP comes from B → D*lυ angular distributions → fist LHCb measurement of longitudinal D* polarization, complementary to R(D*)

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

- In agreement with SM

  [LHCb-PAPER-2023-020]

Conclusion

- Broad physics program at LHCb
- Successful Run1 and Run2: 3+6 fb^{-1}, still many analysis ongoing
- Upgrade Phase I: commissioning ongoing
  - 10 times more data (20 times more hadronic events)
  - Complementarity with Belle
  - Synergy between LHCb, ATLAS and CMS on some important channels
- Strong program beyond flavour exploiting unique acceptance

Original 2009-2018 | Upgrade I 2022-2032 | Upgrade II 2033-