Overview of LHCb results

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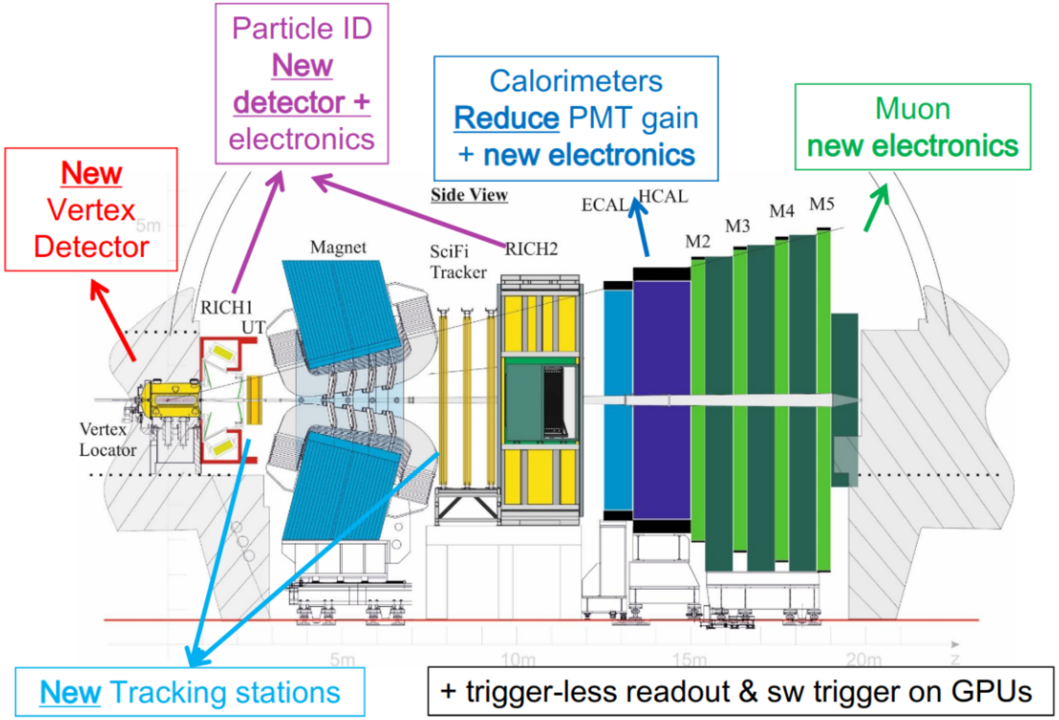
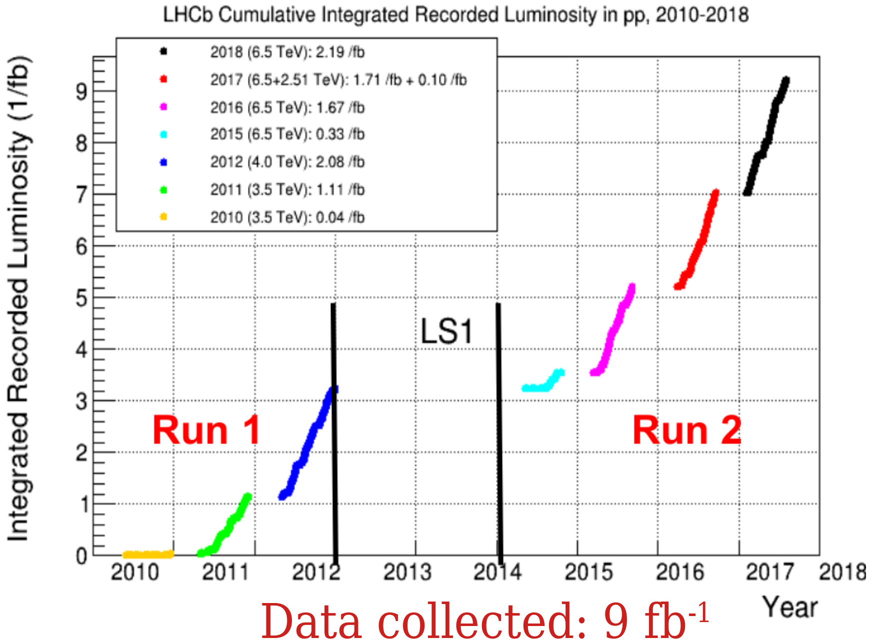
on behalf of the LHCb Collaboration

LHC Days in Split
Diocletian's Palace
Split, Croatia
October 3-8,2022

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…*

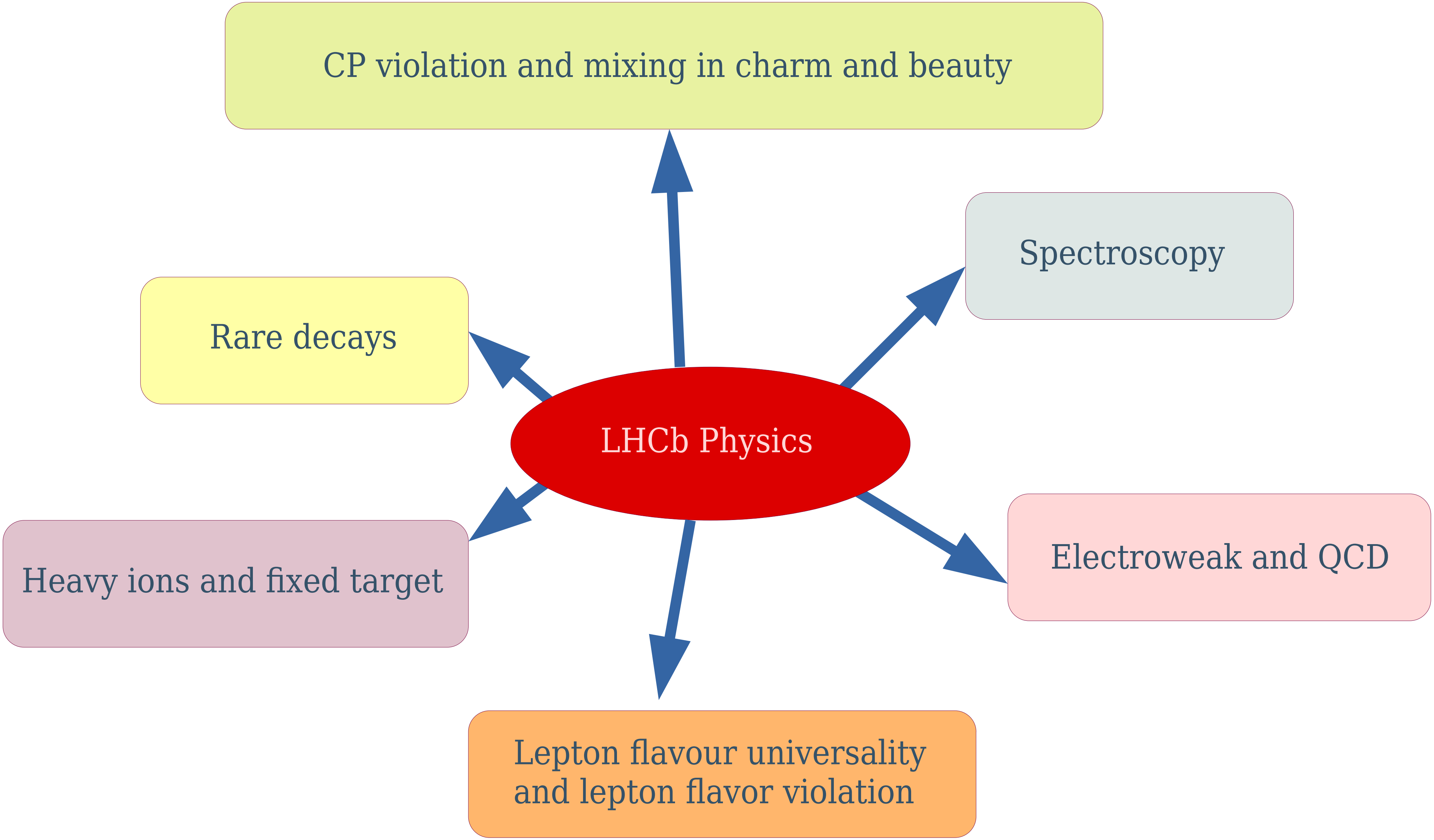




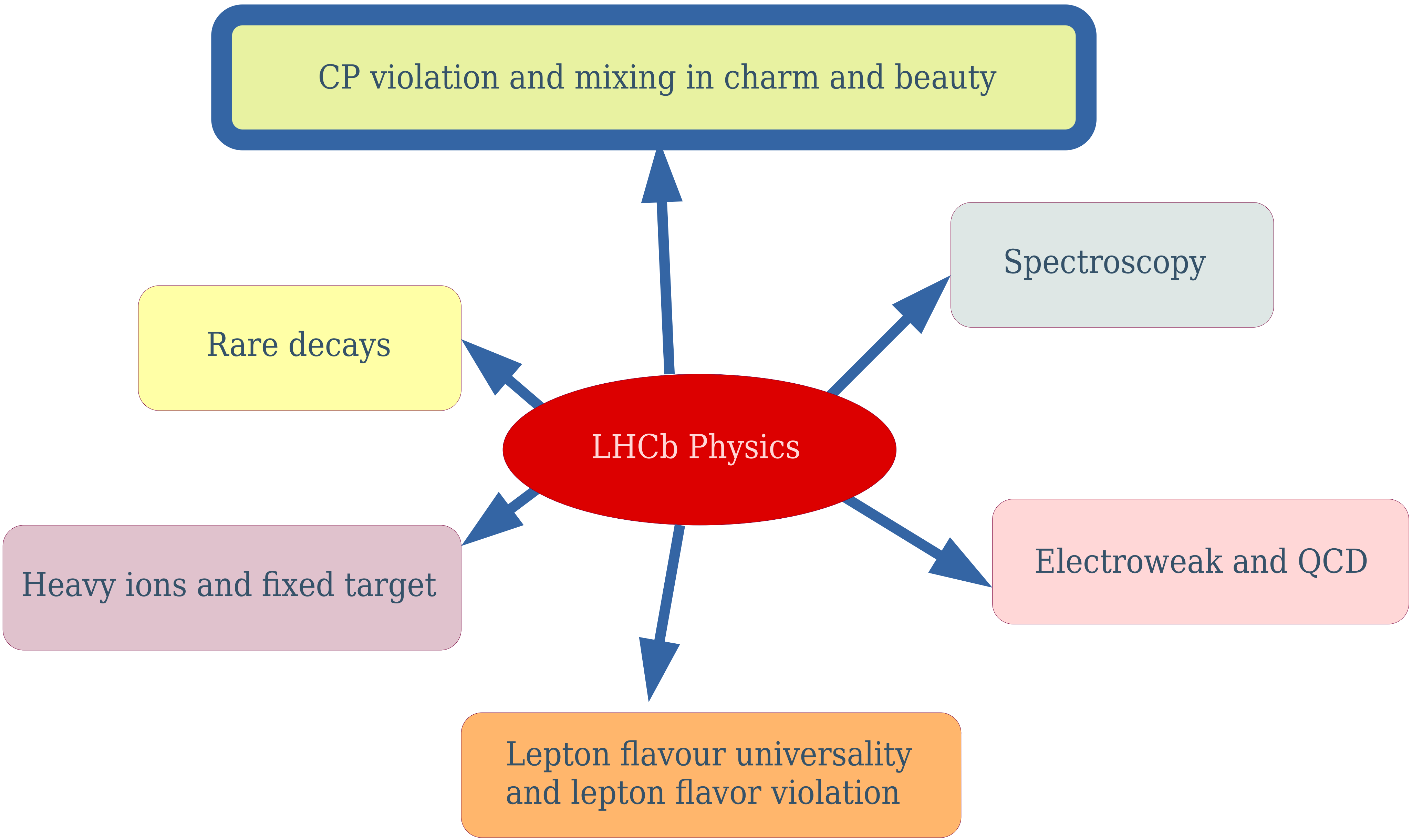
Data collected: 9 fb^{-1}

- 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



Unitarity Triangle Measurements

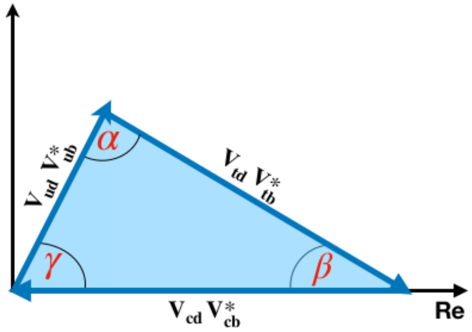
- The CKM matrix describes the quark charged current weak interactions

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

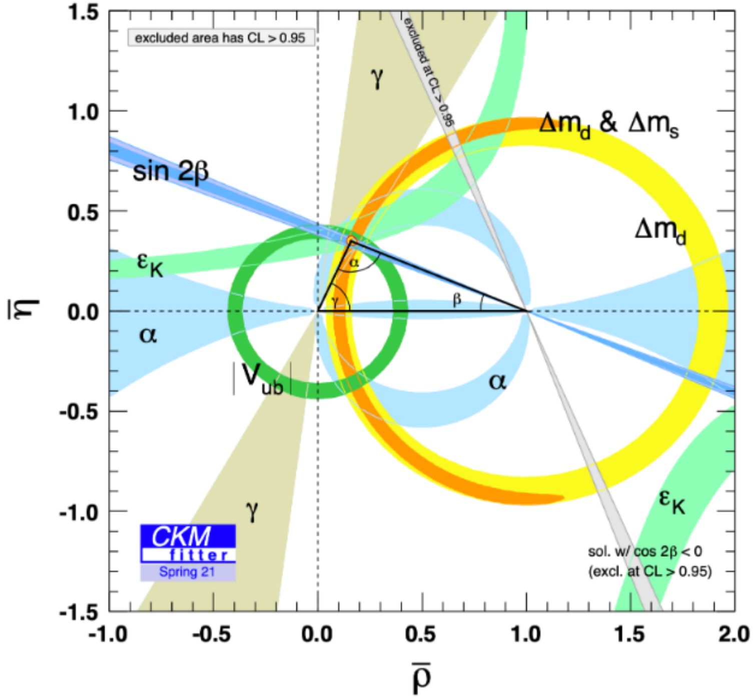
- The unitarity of this matrix leads to

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

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



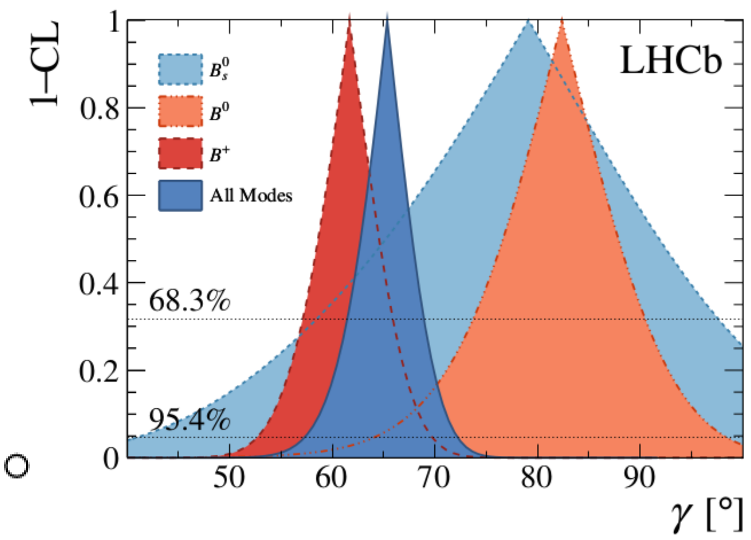
- The key test of the SM is the check of the unitarity of the CKM matrix
  - Magnitudes:
    - measure branching fractions or mixing frequencies
  - Phases:
    - measure the CP violating asymmetries



CKM γ angle

- The interference between b→c and b→u quark transition amplitudes is typically measured in B decays such as $B^{\pm} \rightarrow Dh^{\pm}$ (where D= D^0, $\overline{D}^0$ and h=K, π)

- γ from combination of 15 B decays and 9 D decays LHCb measurements
  - simultaneous fit of γ and D^0 mixing parameters [JHEP 12(2021) 141]
  - Excellent precision on γ
  - New LHCb combination: $\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$



  - Compatible with previous LHCb combination [LHCb-CONF-218-002]
  - Agreement with indirect global CKM fitters $\gamma = (65.5^{+1.1}_{-2.7})^{\circ}$
  - New world average [HFLAV]:

$$\gamma = (66.2^{+3.4}_{-3.6})^{\circ}$$

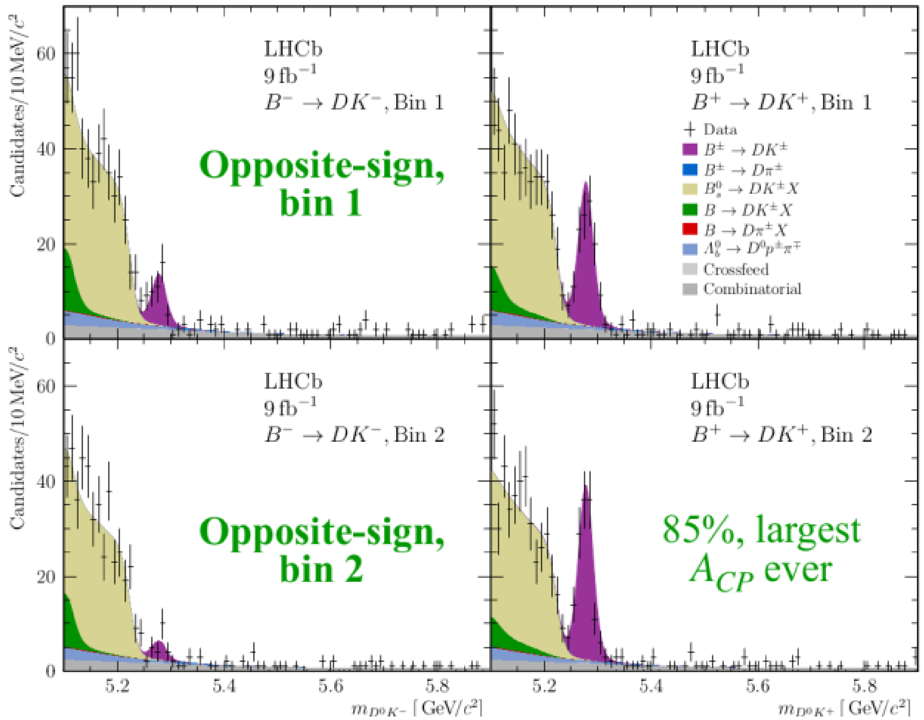
CKM γ angle from $B^\pm \to D(\to K\pi\pi\pi)K^\pm$

- New LHCb measurement with $B^\pm \to D(\to K\pi\pi\pi)K^\pm$ [arXiv:2209.03692]
- Full run1+run2 dataset
- Measurement of the ratio opposite-sign/like-sign:

$$\frac{\Gamma\left(B^\pm \to D\left[K^\mp\pi^\pm\pi^\pm\pi^\mp\right]K^\pm\right)}{\Gamma\left(B^\pm \to D\left[K^\pm\pi^\mp\pi^\mp\pi^\pm\right]K^\pm\right)} = \frac{r_{K3\pi}^2 + (r_B^K)^2 + 2r_{K3\pi}r_B^K R_{K3\pi}\cos(\delta_B^K + \delta_{K3\pi} \pm \gamma)}{1 + (r_{K3\pi}^2 r_B^K)^2 + 2r_{K3\pi}r_B^K R_{K3\pi}\cos(\delta_B^K - \delta_{K3\pi} \pm \gamma)}$$

- Sensitivity improved via measurement in 4 bin of the decay phase-space of the D meson
- Second most precise single determination of γ
- Largest A_{CP} ever measured in one phase-space bin

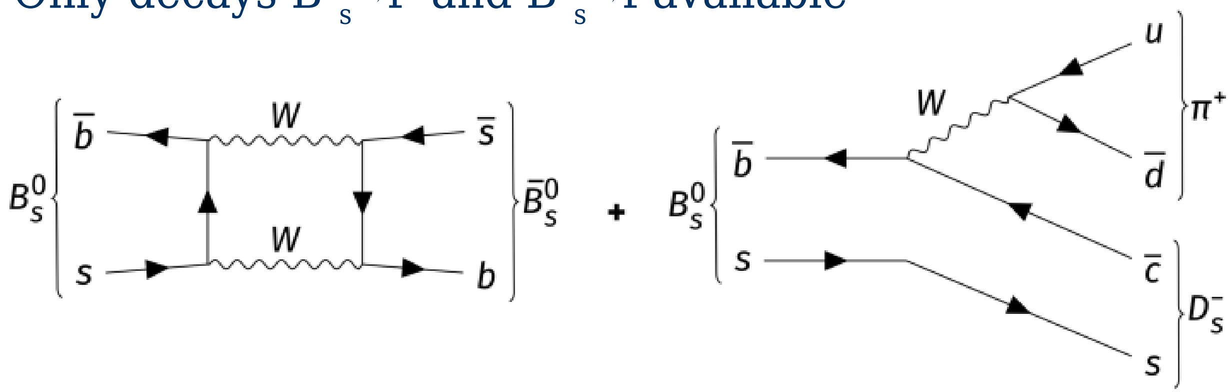
$$\gamma = (54.8^{+6.0}_{-5.8}(\text{stat.})^{+0.6}_{-0.6}(\text{syst.})^{+6.7}_{-4.3}(\text{ext.}))^\circ$$

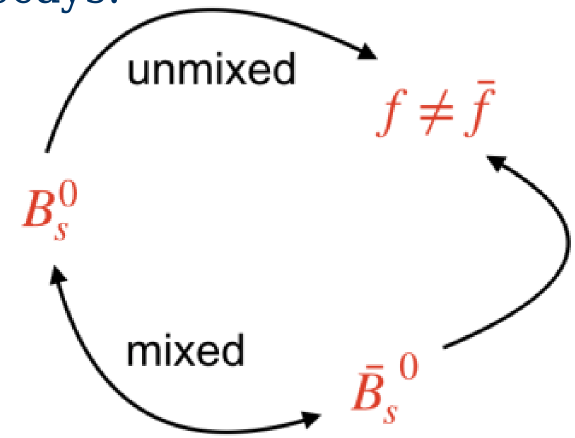


Δm_s with $B^0_s \to D_s^- \pi^+$ decays

[Nature 18 (2022)1-5]

- Measurement of the Δm_s from the flavour specific $B^0_s \to D_s^- \pi^+$ decays:
  - Only decays $B^0_s \to f$ and $\bar{B}^0_s \to \bar{f}$ available

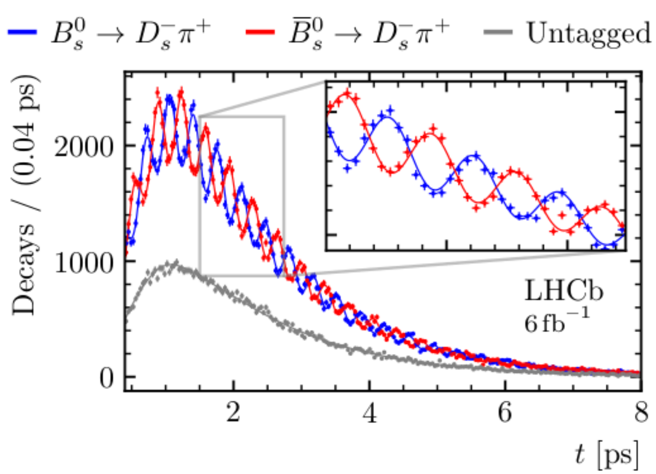


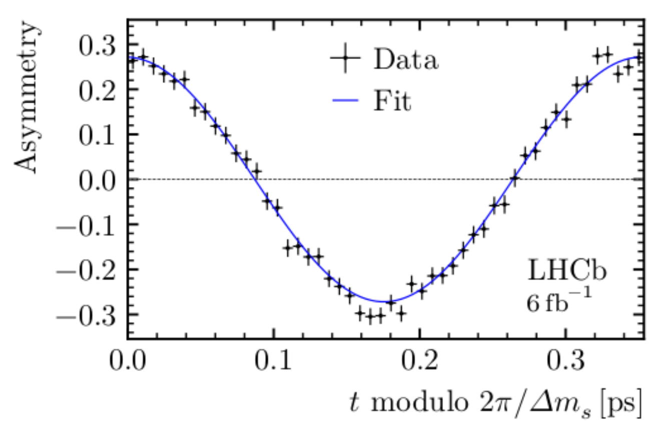


- The Δm_s extracted by the time distribution fit is:

$$\Delta m_s = 17.7683 \pm 0.0051\,(\text{stat}) \pm 0.0032\,(\text{syst})\ \text{ps}^{-1}$$

- It results in the most precise measurement of this parameter.



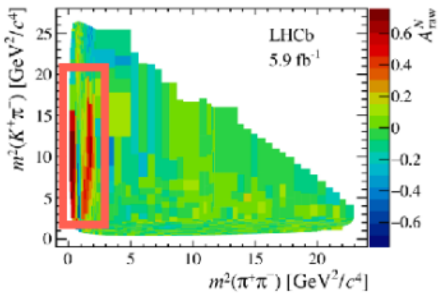


- Observed CP asymmetries in four decay channel

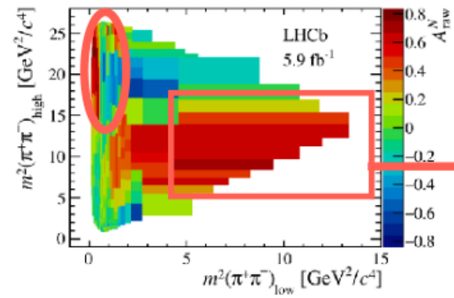
[arXiv:2206.07622]

$$A_{CP} = \frac{A^{\rm corr}_{\rm raw} - A_{\rm P}}{1 - A^{\rm corr}_{\rm raw} A_{\rm P}} \qquad A^{\rm corr}_{\rm raw} \equiv \frac{N^{\rm corr}_{B^-} - N^{\rm corr}_{B^+}}{N^{\rm corr}_{B^-} + N^{\rm corr}_{B^+}} = \frac{(N_{B^-}/R) - N_{B^+}}{(N_{B^-}/R) + N_{B^+}}$$

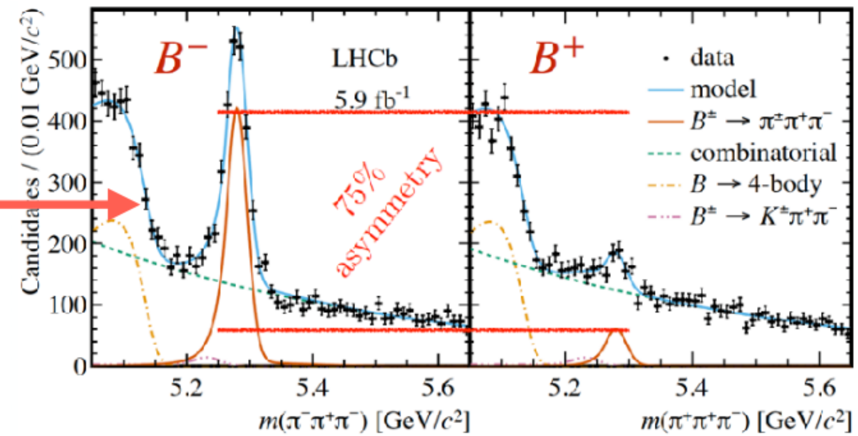
- Run 2 data

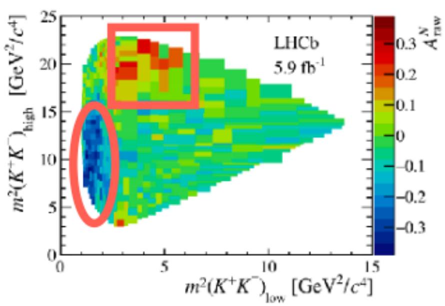


$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

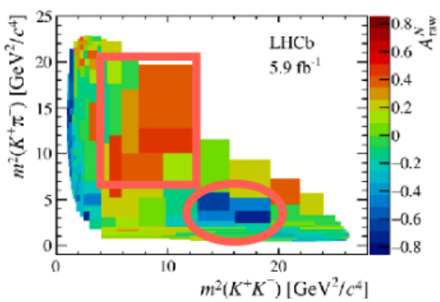


$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$





$B^{\pm} \to K^{\pm}K^{+}K^{-}$



$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$

- $A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003$ (14.1σ)
- $A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003$ (2.4σ)
- $A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003$ (8.5σ)
- $A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003$ (13.6σ)

- Large and interesting localized CP-asymmetries observed
- Possible information about the relation between decay channel rescattering (ππ→ KK)

First charm CPV in a single channel

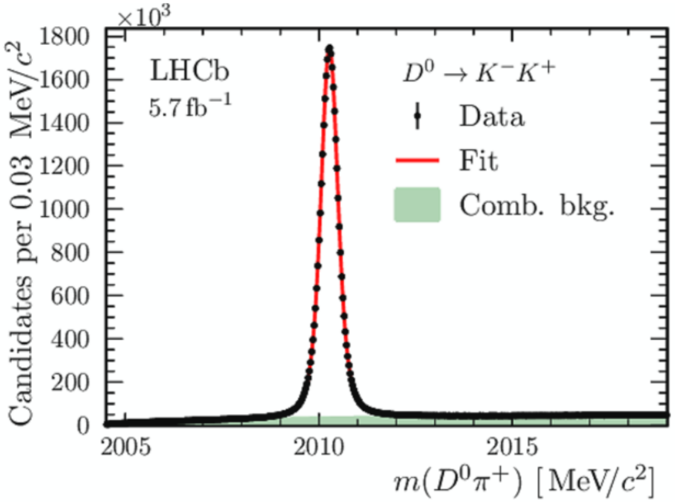
- The time integrated CP asymmetry in the Cabibbo suppressed decay $D^0 \rightarrow K^+K^-$
- CPV in charm small $O(10^{-4}) \rightarrow$ sensitive to NP

[arXiv:2209.03179]

- 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]



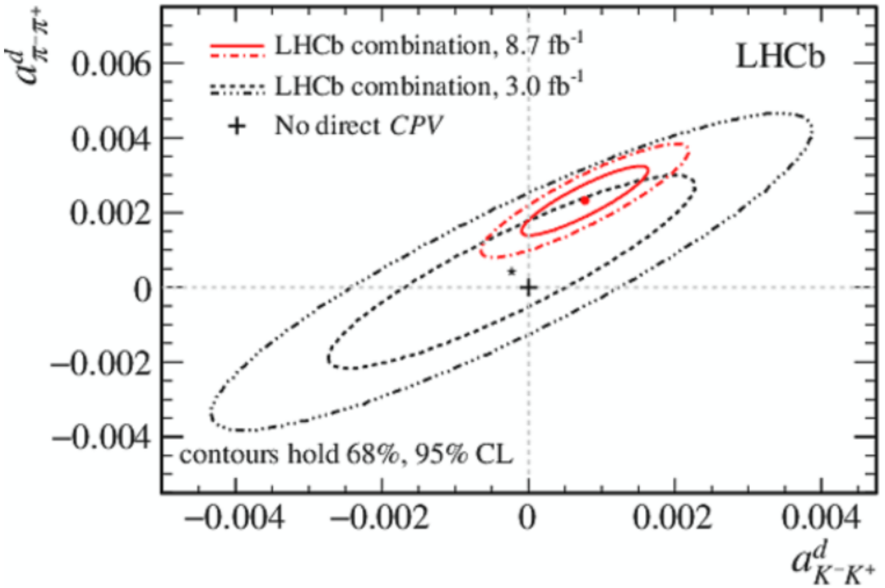
- New measurement of A_{CP} (K^+K^-):

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

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

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

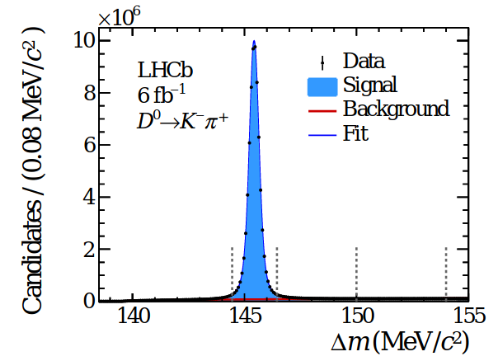
- 3.8σ in $D^0 \rightarrow \pi^-\pi^+$ for direct CP violation



Charm mixing parameters

- Flavour mixing is the transition between a neutral flavoured meson and its antiparticle.
- Charm mixing parameters:

$$x \equiv (m_1 - m_2)/\Gamma, y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma \quad |q/p| \qquad \phi = arg(q\bar{A}_f/pA_f)$$

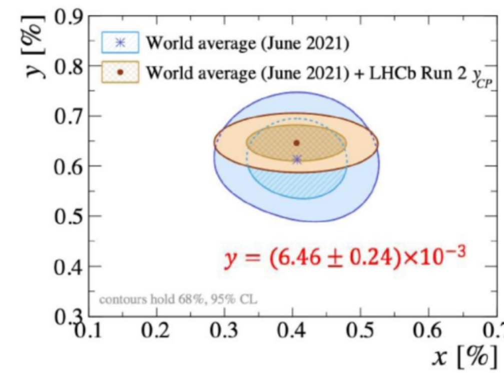


- Study the D^0 meson decays into K^-K^+ , $\pi^-\pi^+$ and $K^- \pi^+$
- The parameter y is measured from decay-time ratios: ($D0 \to K^+\pi^-$ and $D0 \to f$ ($f=K^-K^+,\pi^-\pi^+$))

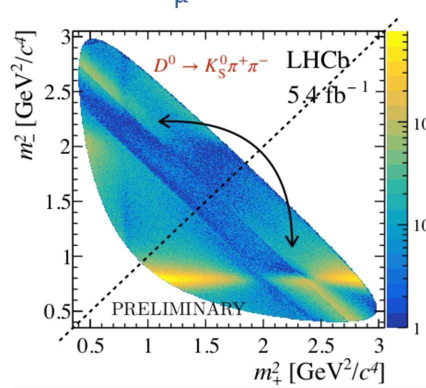
$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y^f_{CP} - y^{K\pi}_{CP})\,t/\tau_{D^0}} \frac{\varepsilon(f,t)}{\varepsilon(K^-\pi^+,t)}$$

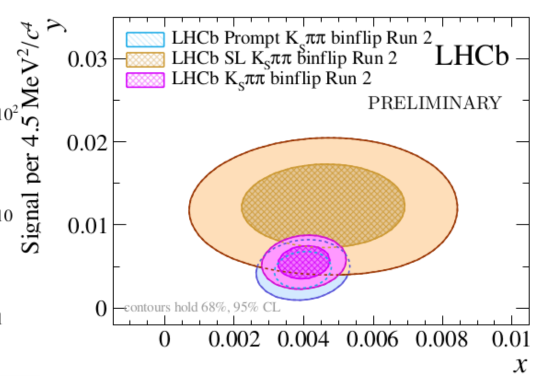
- Combining the two channels: $y_{CP} - y^{K\pi}_{CP} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$

[PRD 105 (2022) 092013)]



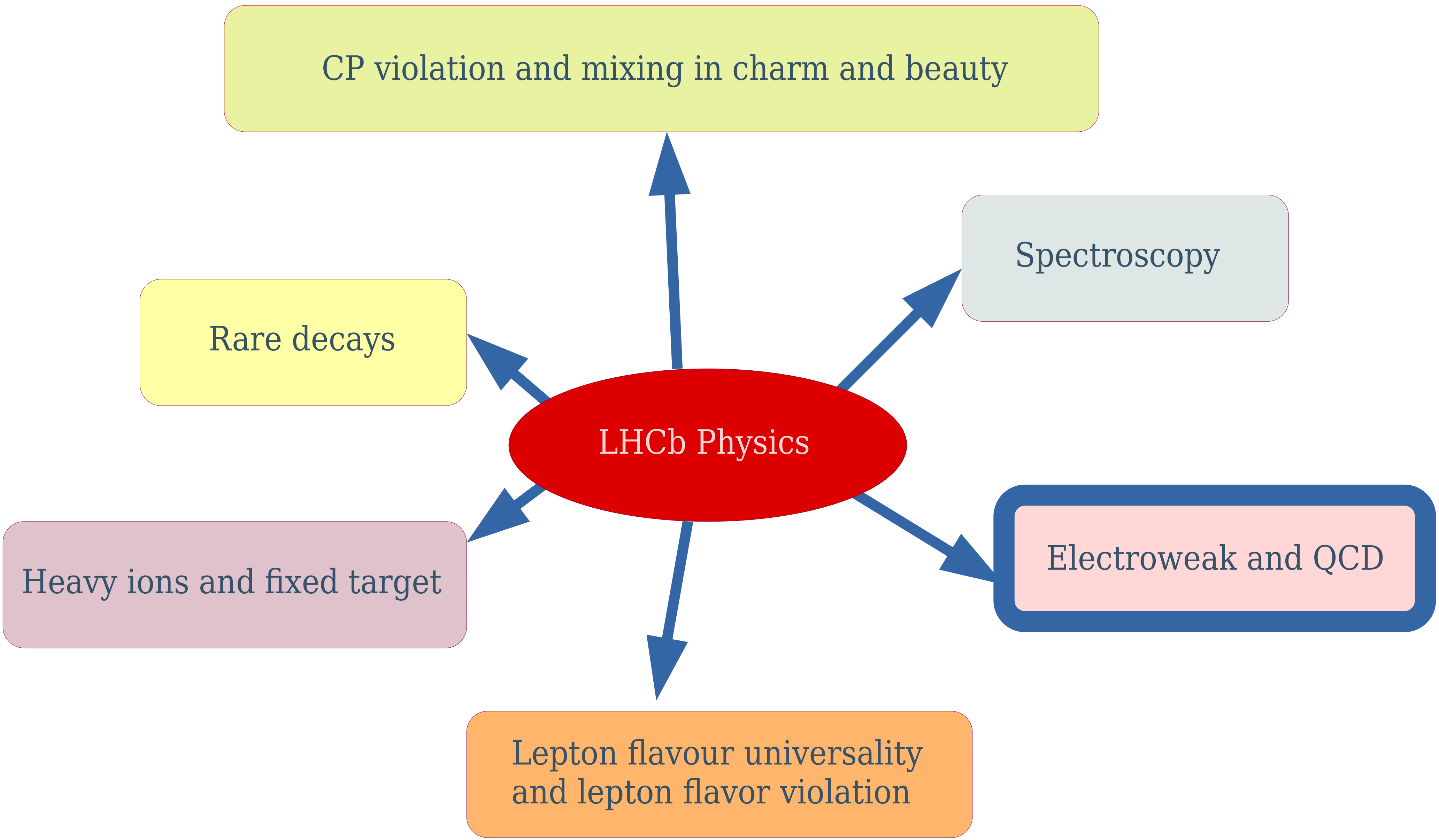
- Charm mixing parameters $D^0 \to K^0_S\pi\pi$ from $\bar{B} \to D^0\mu\nu_\mu$
- Using bin flip method
  - $x_{CP} = [4.29 \pm 1.48(\text{stat.}) \pm 0.26(\text{syst.})] \times 10^{-3}$
  - $y_{CP} = [12.61 \pm 3.12(\text{stat.}) \pm 0.83(\text{syst.})] \times 10^{-3}$
  - $\Delta x = [-0.77 \pm 0.93(\text{stat.}) \pm 0.28(\text{syst.})] \times 10^{-3}$
  - $\Delta y = [3.01 \pm 1.92(\text{stat.}) \pm 0.26(\text{syst.})] \times 10^{-3}$





[arxiv: 2208.06512]

Overview of Physics Results



Z →μ⁺μ⁻ angular coefficients measurement

[arxiv: 2203.01602]

- First study of the angular distribution of μ⁺μ⁻ pairs produced in the forward rapidity region via the Drell-Yan reaction pp→γ∗/Z+X→l⁺l⁻+X

- The coefficients of the five leading terms in the angular distribution are determined as a function of the dimuon transverse momentum and rapidity.

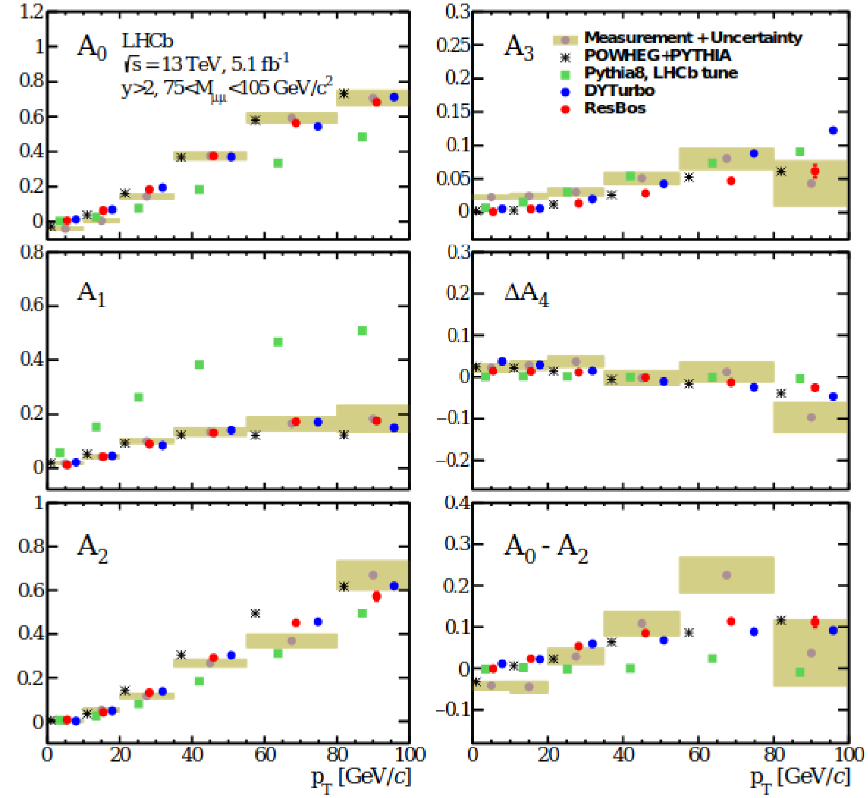
$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi$$
$$+ A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi,$$

- y > 3.5 → complementary to ATLAS and CMS

- Run2 dataset

- The parameters are measured by fitting the two decay angles cosθ and φ of the selected candidates

- The kinematic distribution of the final-state leptons provides a direct probe of the polarization of the intermediate gauge boson, which is sensitive to the underlying QCD production mechanism



W mass

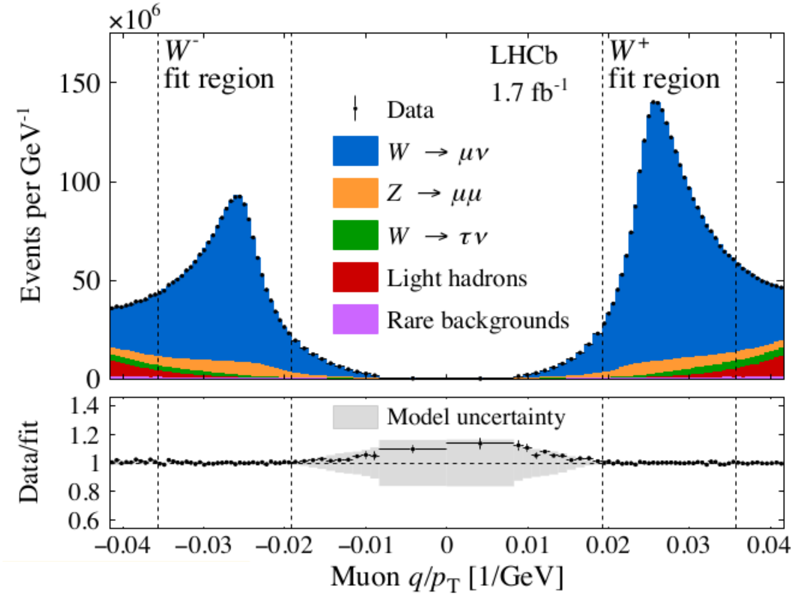
[JHEP01 (2022) 036]

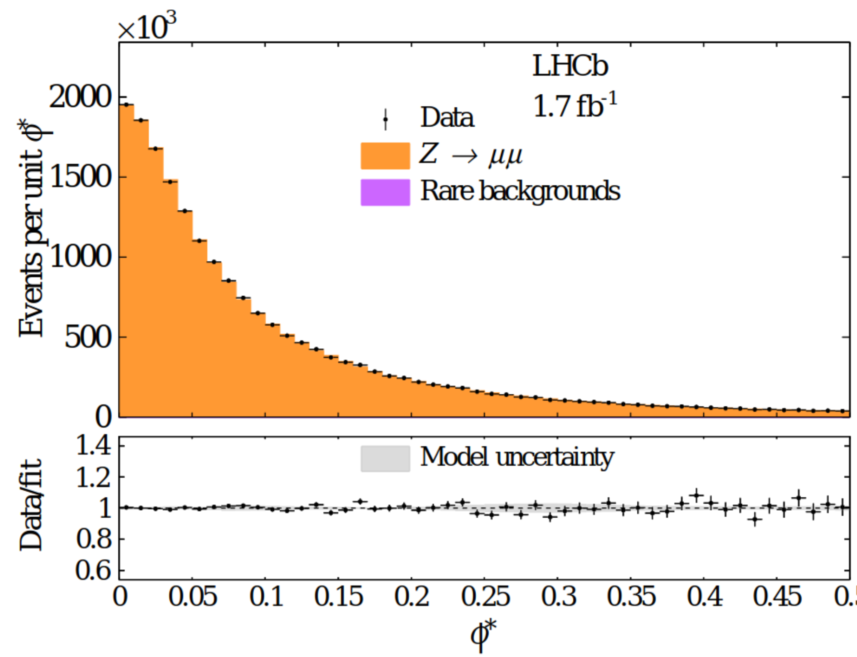
- Measurement of the W boson mass
- Complementary to Atlas and CMS
- 2016 dataset
- Simultaneous fit to muon p_T from $W \rightarrow \mu\nu_\mu$ and ϕ^* of $Z \rightarrow \mu\mu$

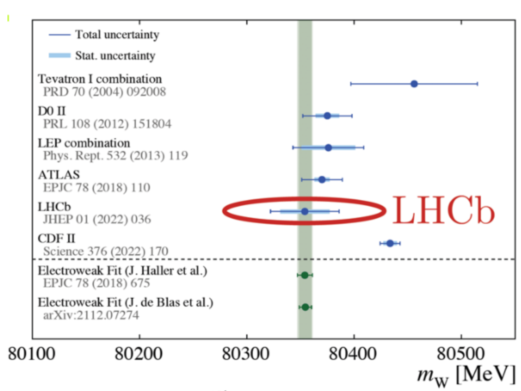
$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M}$$

- Determination of the charge dependent curvature biases and momentum scaling
- Offline reprocessing of the alignment with Z decays

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







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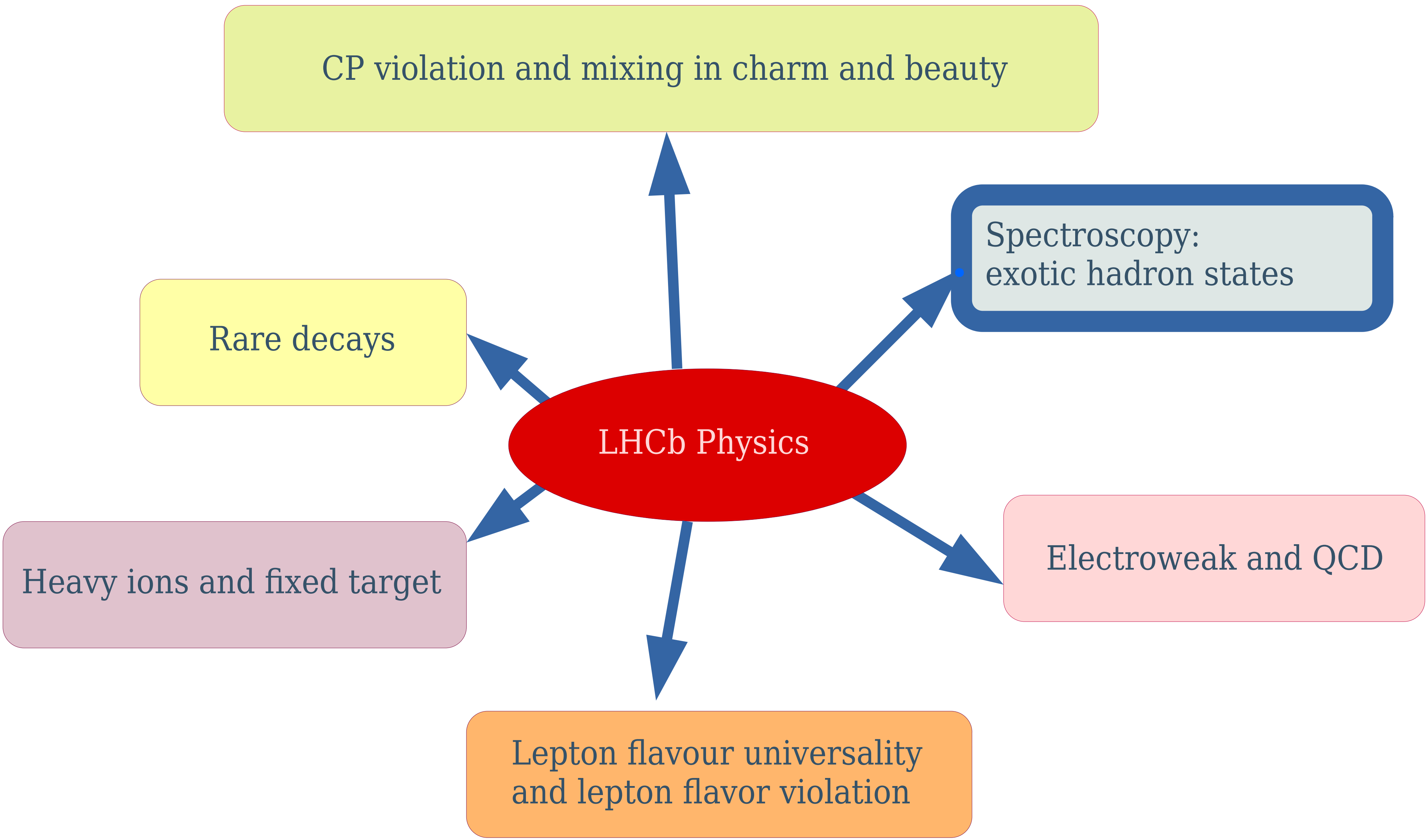
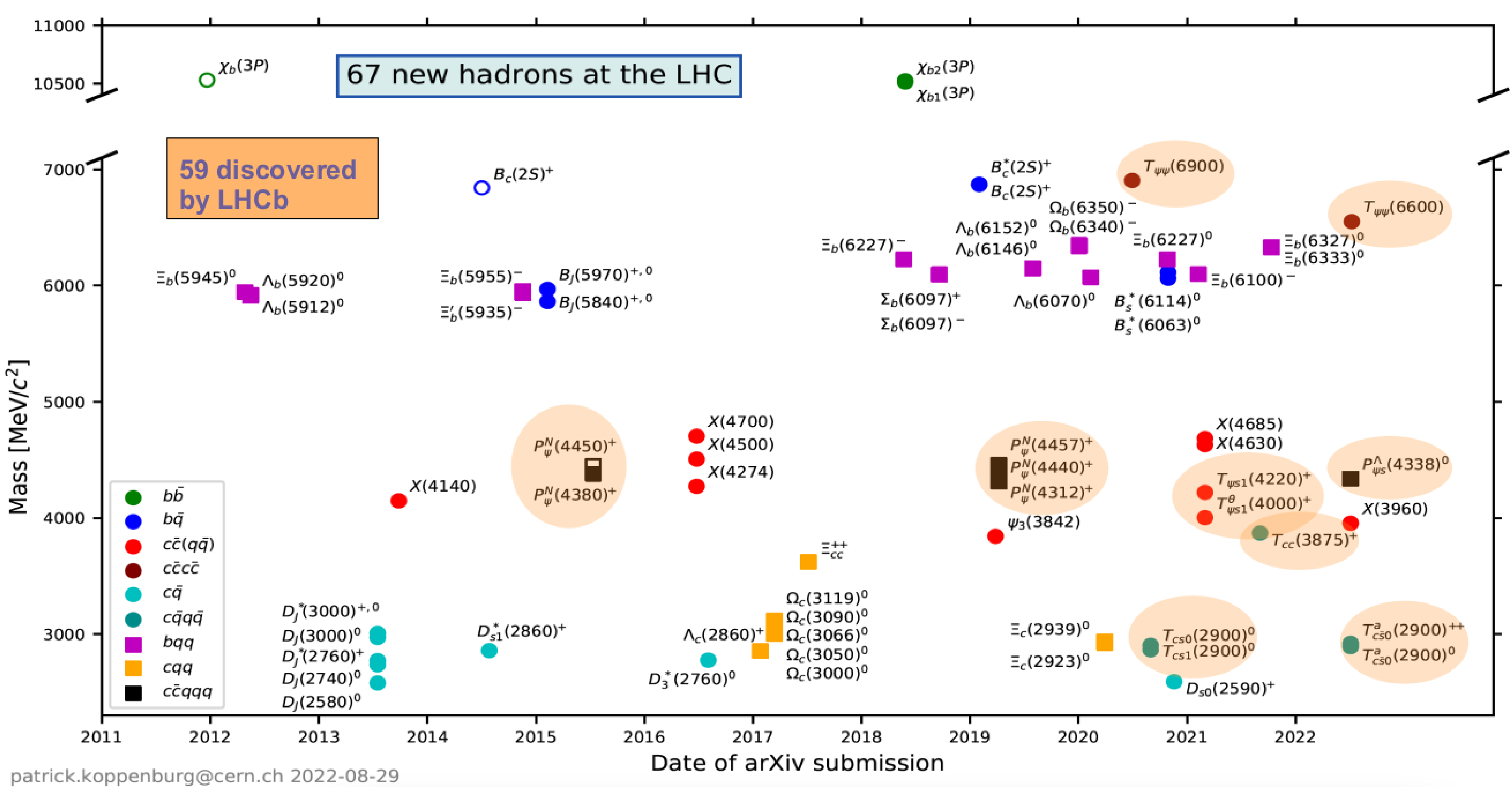


Hadron states

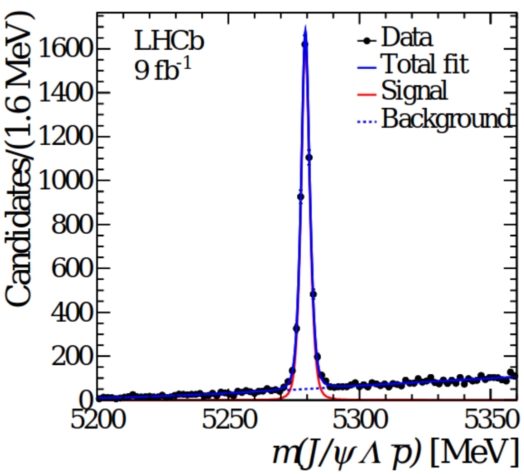


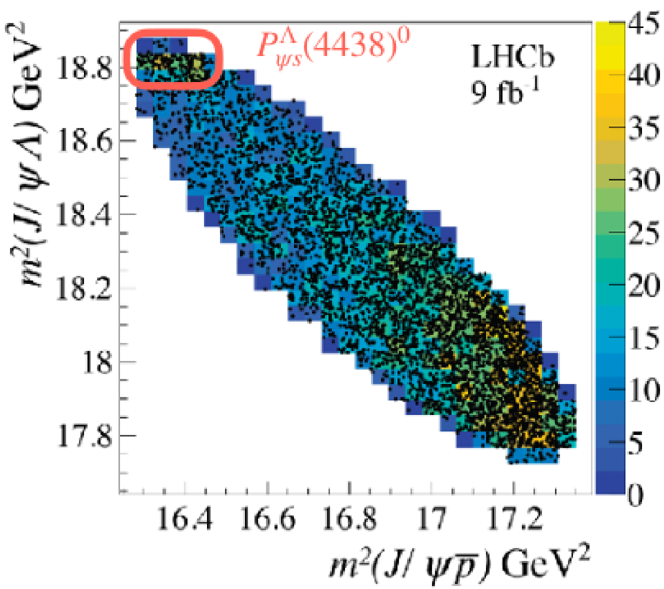
- New naming scheme proposed by LHCb [arXiv:2206.15233]
- Tetraquark and pentaquark: Tightly bounded states? Hadronic molecules?
  - Nature of exotic states still unclear

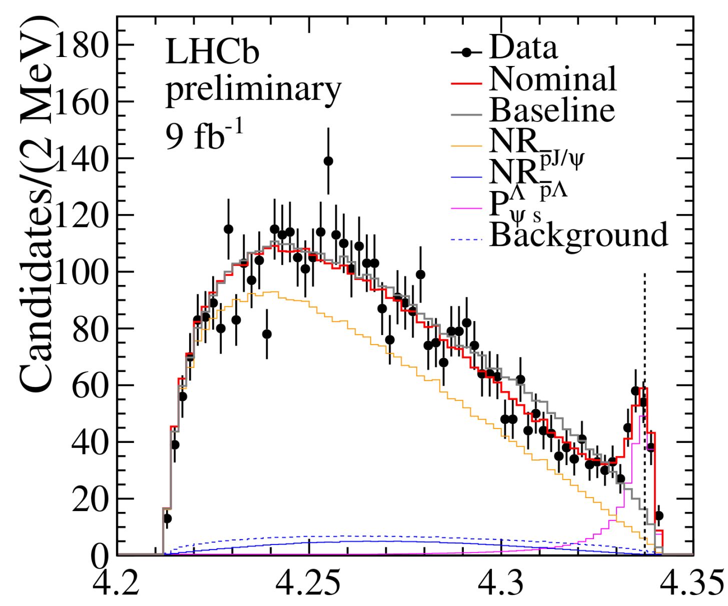
→ → → Mengzhen Wang's talk

First strange pentaquark $P^{\Lambda}_{\psi s}(4438)^0$

- $P^{\Lambda}_{\psi s}(4438)^0$: $c\bar{c}sud$, charmed, open strange, I=0
- Observation of a $J/\psi\Lambda$ resonance in $B^{-}\rightarrow J/\psi\Lambda(\rightarrow p\pi)\bar{p}$ decays close to $\Xi_c^{+}D^{-}$ threshold (>10σ significance)
- All LHCb dataset
- Horizontal band visible in the region at 18.8 GeV^2 in $m^2(J/\psi\Lambda)$
- A 6D amplitude analysis has been performed
- The best fit amplitude model used to fit the data comprises a narrow $J/\psi\Lambda$ structure with spin-parity $J^P = 1/2^{-}$



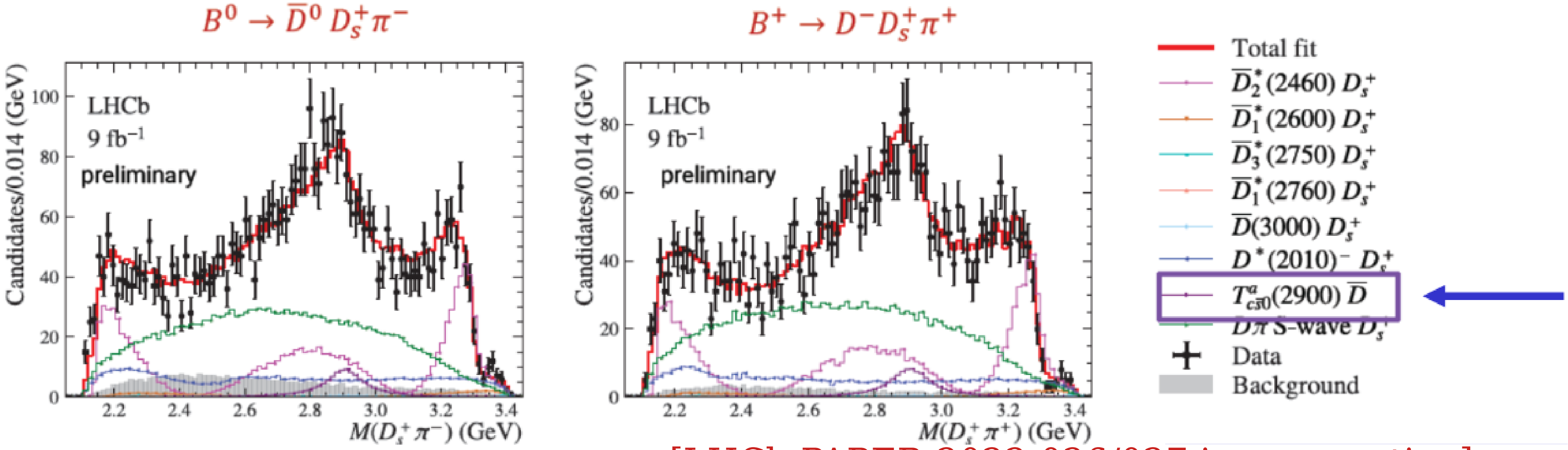




[LHCb-PAPER-2022-031 in preparation]

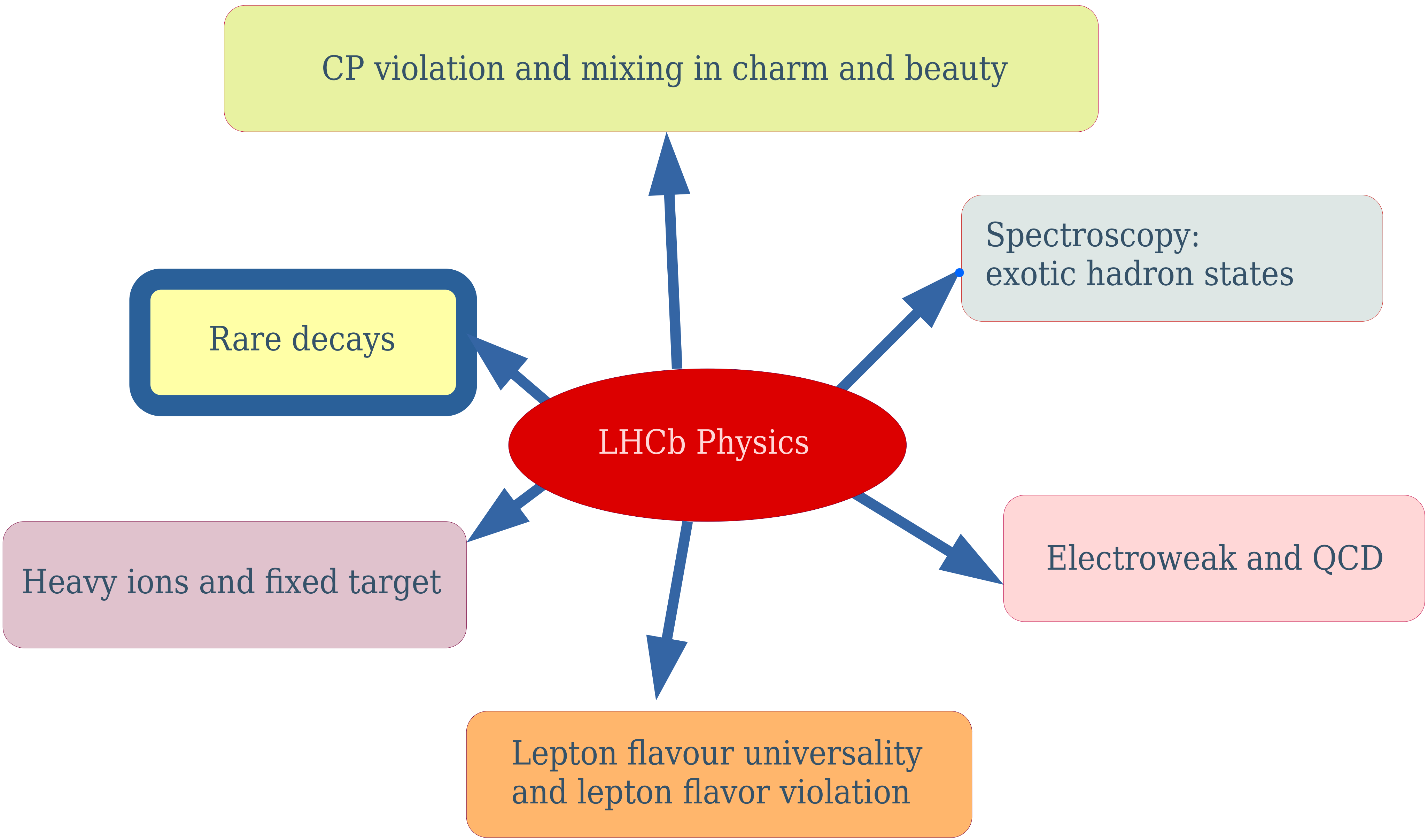
Doubly charged tetraquark

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



[LHCb-PAPER-2022-026/027 in preparation]

Overview of Physics Results

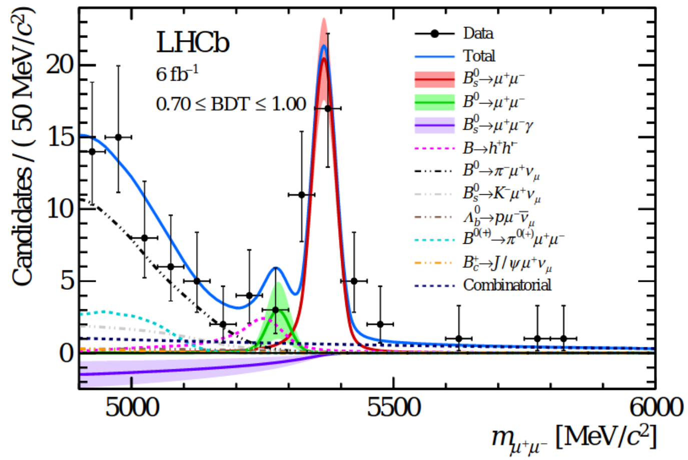


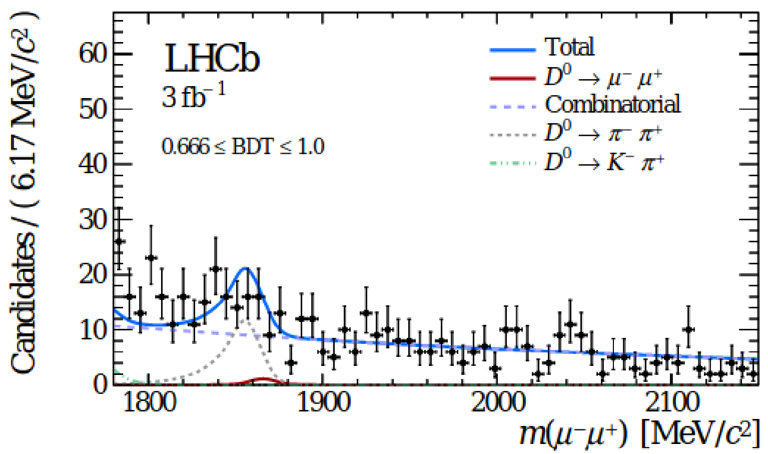
$B_{(s)} \to \mu^+\mu^-$ and $D^0 \to \mu^+\mu^-$

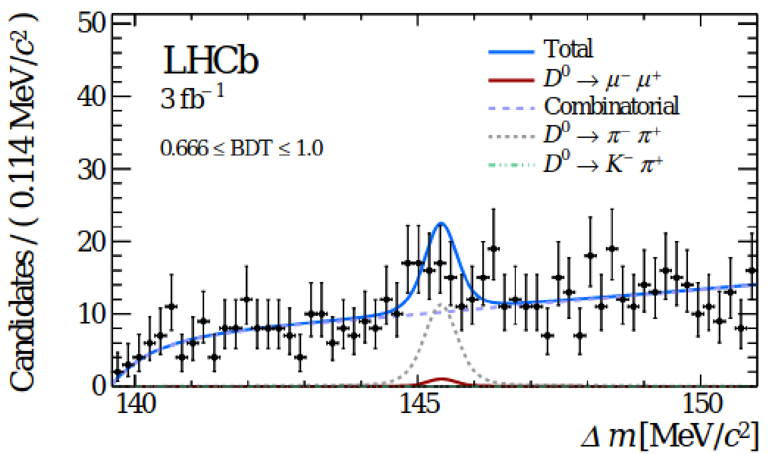
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}) \times 10^{-9}$$

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

[Phys. Rev. D105 (2022) 012010]





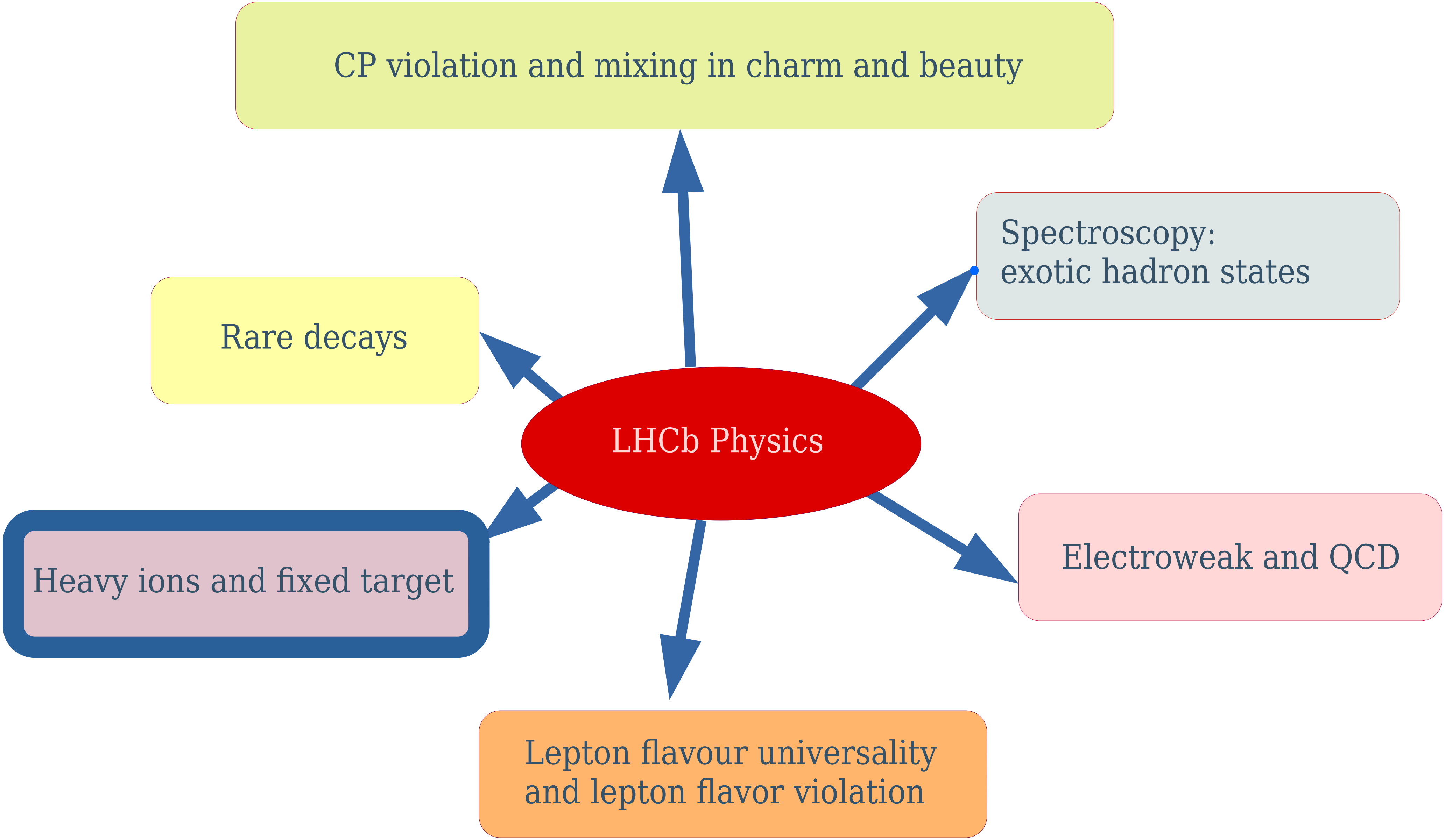


- $D^0 \to \mu^+\mu^-$: unique probe of up-type quark FCNC
- Using $D^* \to D^0\pi^+$
- Normalization channel: $D^0 \to h^- h^+$ (K,π)
- Simultaneous fit to $m(\mu^+\mu^-)$ and $m(D^*)$ - $m(D^0)$
- Most stringent limit of FCNC in charm sector

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

[LHCb-PAPER-2022-029 in preparation]

Overview of Physics Results



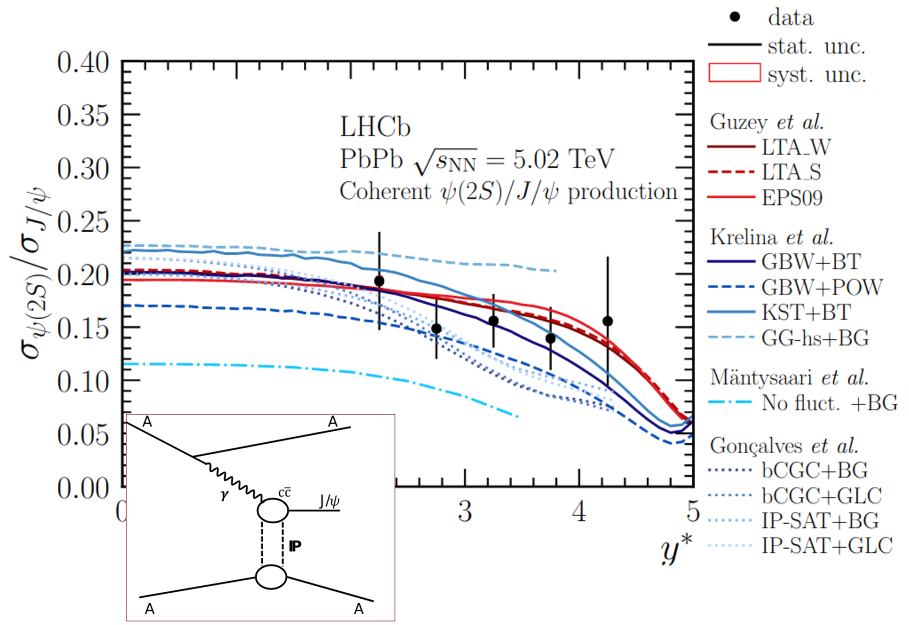
Heavy ions and fixed target

- Charmonium production in ultra-peripheral collisions Pb-Pb at 5.02 TeV
- The cross-sections of coherent J/ψ and ψ(2S) production

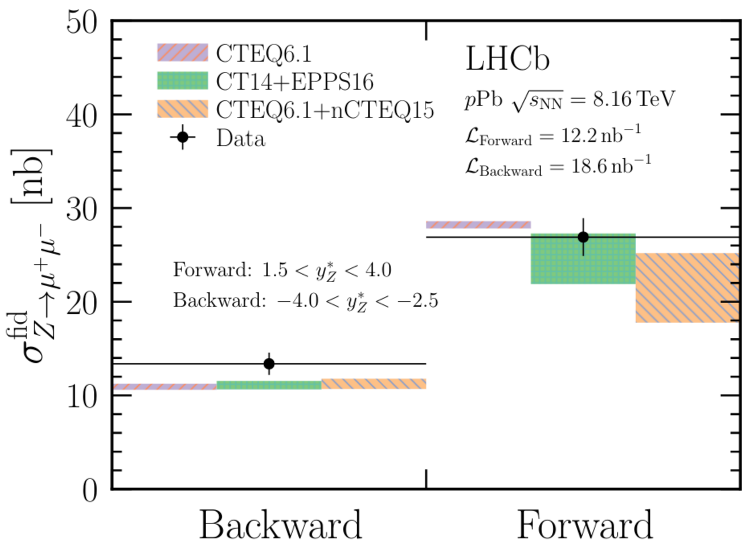
$$\frac{d\sigma^{coh}_{\psi(2S)}/dy^*}{d\sigma^{coh}_{J/\psi}/dy^*} = \frac{N^{coh}_{\psi(2S)} \times \varepsilon_{J/\psi} \times \mathcal{B}(J/\psi \to \mu^+\mu^-)}{N^{coh}_{J/\psi} \times \varepsilon_{\psi(2S)} \times \mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$$

$$\sigma^{coh}_{J/\psi} = 5.965 \pm 0.059 \pm 0.232 \pm 0.262\,\text{mb}$$

$$\sigma^{coh}_{\psi(2S)} = 0.923 \pm 0.086 \pm 0.028 \pm 0.040\,\text{mb}$$



[arxiv:2206.08211]



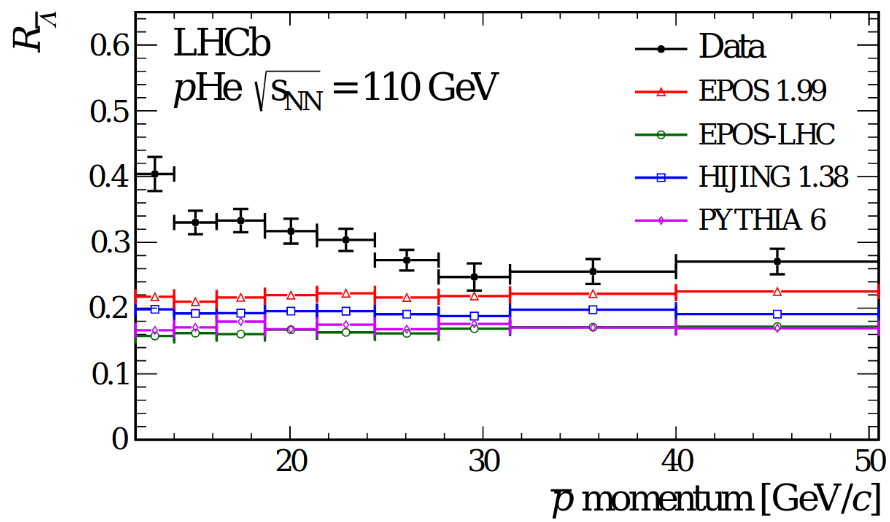
- Measurement of the Z boson production cross-section in p-Pb at 8.16 TeV
- The results are in good agreement with the predictions from nuclear parton distribution functions, providing strong constraining power at small Bjorken-x.

[arxiv:2205.10213]

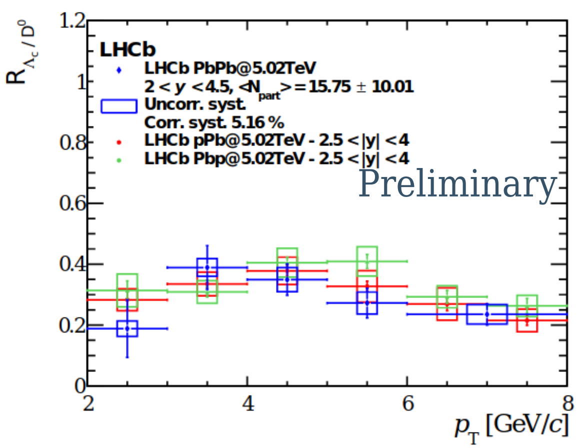
Heavy ions and fixed target

- SMOG : gas injection system for fixed-target physics
- Measurement of antiproton production from antihyperon decays in p-He collisions at a cms energy of 110 GeV.
- Important input for antiproton flux calculation in cosmic rays.
- Significantly larger than predictions of commonly used hadronic production models, but consistent with ALICE and CMS results.

[arxiv:2206.08221]



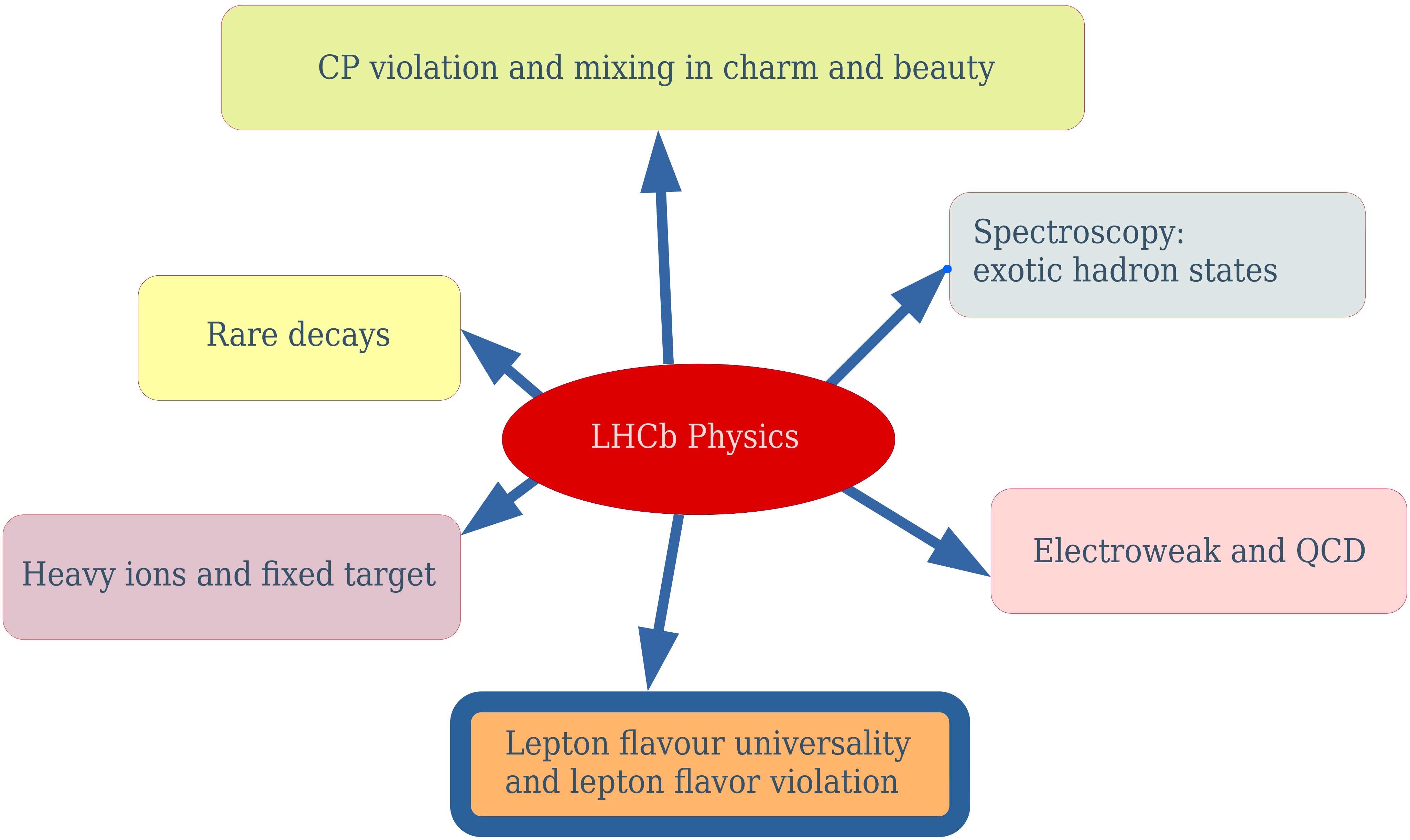
$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda} X \to \bar{p}\pi^+ X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}$$



- Measurement of the Λ_c/D^0 production ratio in Pb-Pb collisions at 5.02 TeV
- The results are not consistent with ALICE measurement.

[LHCb-PAPER-2021-045 in preparation]

Overview of Physics Results

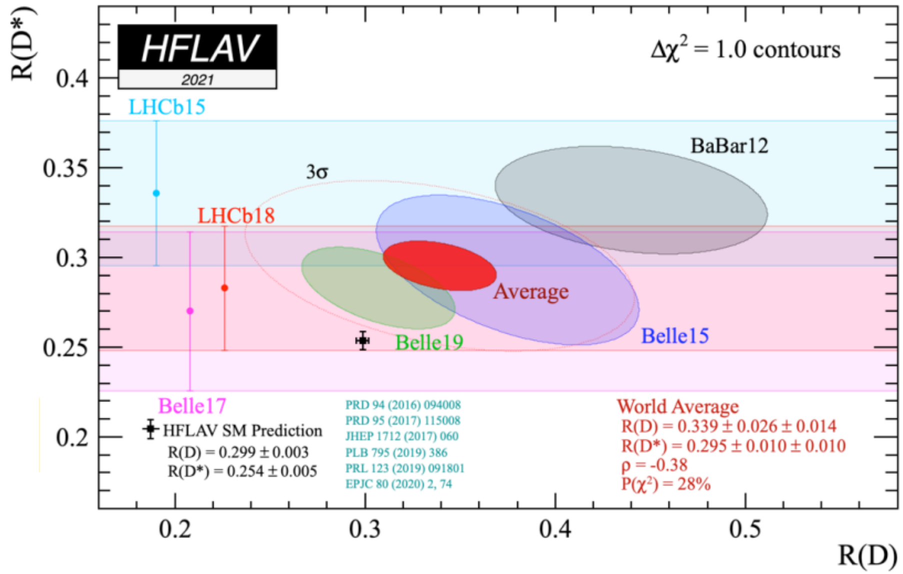


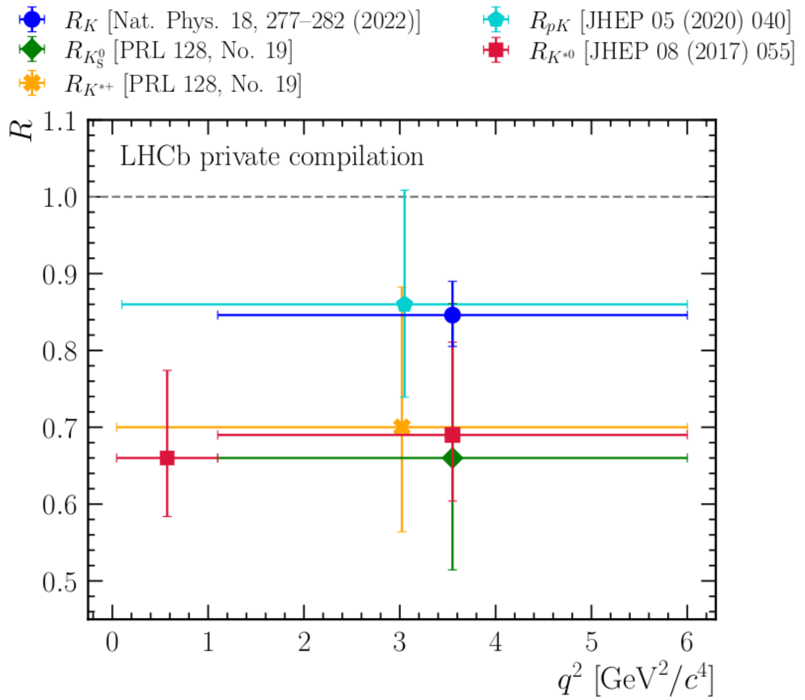
Lepton flavour universality

- LFU in b→clυ decays:

$$R(X_c) = \frac{X_b \to X_c \tau^+ \nu_\tau}{X_b \to X_c \ell^+ \nu_\ell}$$

  - Tree level processes involving 2nd and 3rd generation show 3.3σ tension with SM
  - Observation of $\Lambda_b \to \Lambda_c \tau \upsilon$
  - $\mathcal{R}(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$
  - agreement with SM [PRL 128 (2022) 191803]





- LFU in b→sll decays:

$$R(X_s) = \frac{B_q \to X_s \mu^+ \mu^-}{B_q \to X_s e^+ e^-}$$

  - R_K about 3.1σ below SM prediction [Nature Physics 18 (2022) 277-282]
  - $R_{K^0_s}$ [Phys. Rev. Lett. 128, 191802]
  - Several analysis ongoing

→ → → Renato Quagliani's talk

Lepton flavour violation

- Search for $B^0_{(s)} \to p\mu$:

$$\mathcal{B}(B^0 \to p\mu^-) < 2.6(3.1) \times 10^{-9} \text{ @90\%(95\%) C.L.}$$
$$\mathcal{B}(B^0_s \to p\mu^-) < 1.2(1.4) \times 10^{-8} \text{ @90\%(95\%) C.L.}$$

[LHCb-PAPER-2022-022 in preparation]

- Search for $B^0 \to K^{*0}\tau\mu$:

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5} \text{ @90\%(95\%) C.L.}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2(9.8) \times 10^{-6} \text{ @90\%(95\%) C.L.}$$

[arXiv:2209.09846]

- Search for $B^0 \to K^{*0}\mu e$ and $B^0 \to \phi\mu e$:

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7(6.9) \times 10^{-9} \text{ @90\%(95\%) C.L.}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8(7.9) \times 10^{-9} \text{ @90\%(95\%) C.L.}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1(11.7) \times 10^{-9} \text{ @90\%(95\%) C.L.}$$
$$\mathcal{B}(B^0_s \to \phi\mu^\pm e^\mp) < 16.0(19.8) \times 10^{-9} \text{ @90\%(95\%) C.L.}$$

[arXiv:2207.04005]

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