LHCb physics

Wojciech Wiślicki
National Centre for Nuclear Research

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LHCb: concept and developments

LHCb originally designed for CP violation and rare decays of b and c

- mechanisms of CP violation
- CKM matrix measurements
- physics beyond Standard Model; .. large part of LHCb is a quest for it

Additional physics programs developed

- **exotic hadrons**
- heavy ions
- fixed-target program
- dark-energy sector

Principal results in Runs 1 & 2: 2010-18

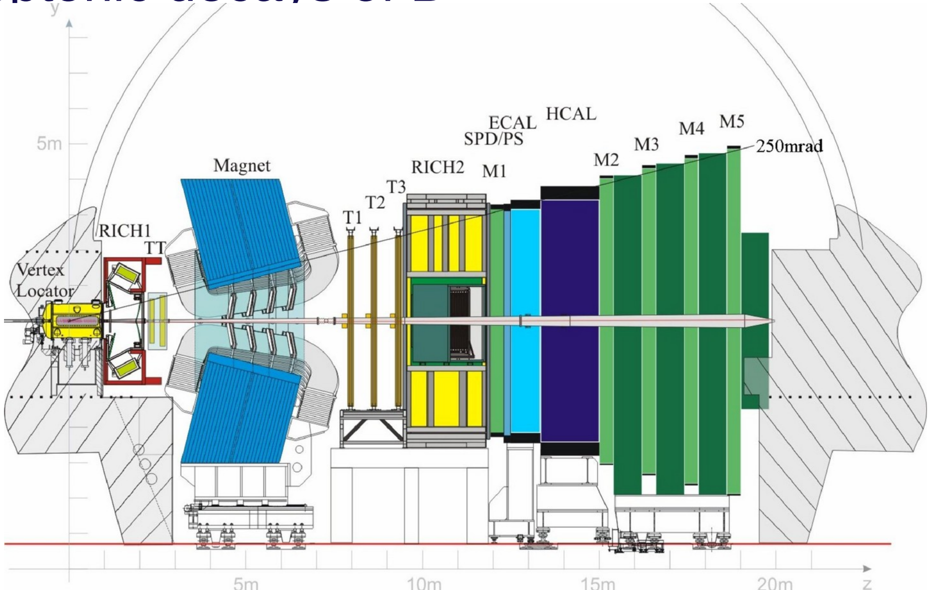
- CP violation in B decays and mixing, oscillations of b, Δm_{Bs}
- Search for **FCNC very rare decays** $B_{(s)} \to \mu^+\mu^-$
- Precise determination of CKM parameters, in particular **γ**
- Discovery of **CP violation in D** oscillations and decay
- Search for lepton-flavour violation in semileptonic decays of B
- Hadronic physics: discovery

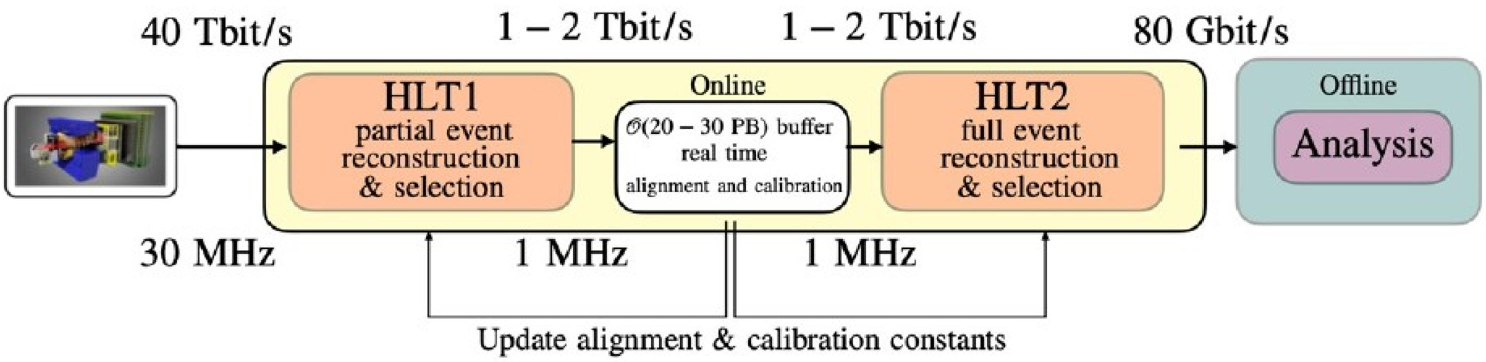
of **(strange) pentaquarks**

and **doubly-charmed tetraquark**

- Contribution to precise

m_W measurement

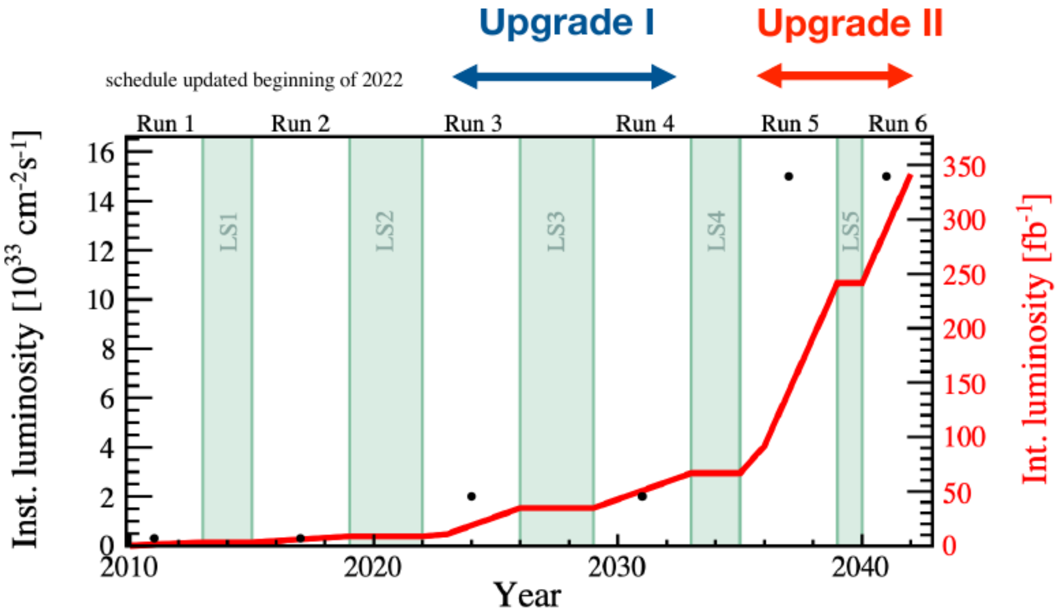




Major trigger upgrade in Run 3
40 MHz, fully software
Order of magnitude rate increase
HLT1 run on 200 GPU cards

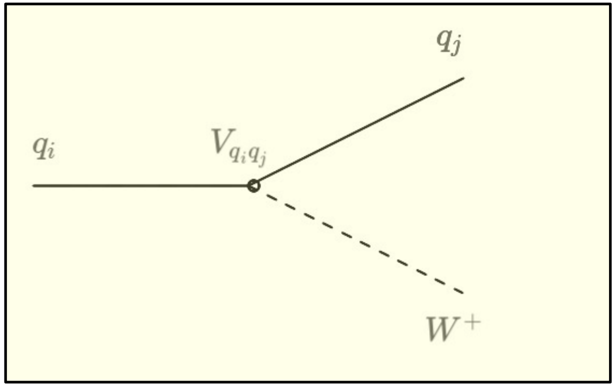
L_{int} = 9 fb^{-1} Run 1&2
= 50 fb^{-1} expected Run 3 & 4

Note Upgrade 3 plan
L_{int} = 680 fb^{-1} expected Run 5 & 6



LHCb's *spécialité*: precision study of flavour physics

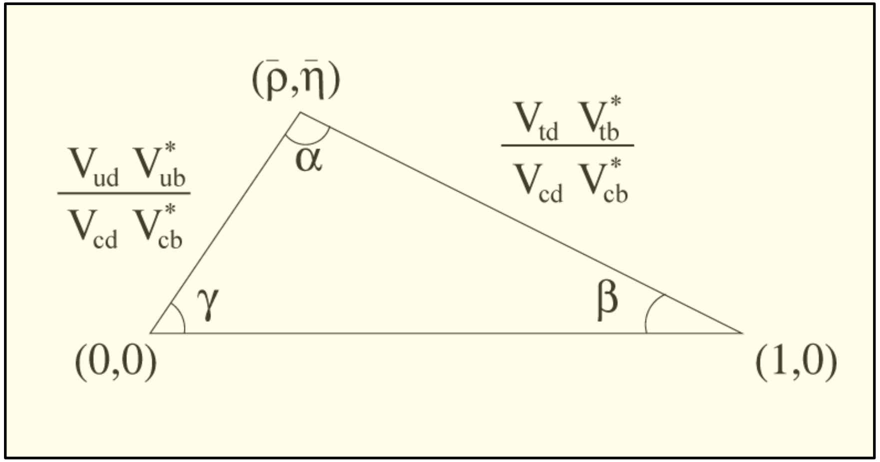
$$\mathrm{L}_{\mathbf{qW}} = -\frac{\mathsf{e}}{2}\mathbf{U}_{\mathbf{L}}^{\dagger}\,\gamma^{\mu}\,\mathrm{V}_{\mathsf{CKM}}\,\mathbf{D}_{\mathbf{L}}\mathbf{W}_{\mu}$$



$$\mathrm{V}_{\mathsf{CKM}} = \begin{bmatrix} \mathbf{V}_{\mathsf{ud}} & \mathbf{V}_{\mathsf{us}} & \mathbf{V}_{\mathsf{ub}} \\ \mathbf{V}_{\mathsf{cd}} & \mathbf{V}_{\mathsf{cs}} & \mathbf{V}_{\mathsf{cb}} \\ \mathbf{V}_{\mathsf{td}} & \mathbf{V}_{\mathsf{ts}} & \mathbf{V}_{\mathsf{tb}} \end{bmatrix} \simeq$$

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 e^{i\varphi} \\ -\lambda & 1-\lambda^2/2 & \lambda^2 \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 \end{bmatrix}$$

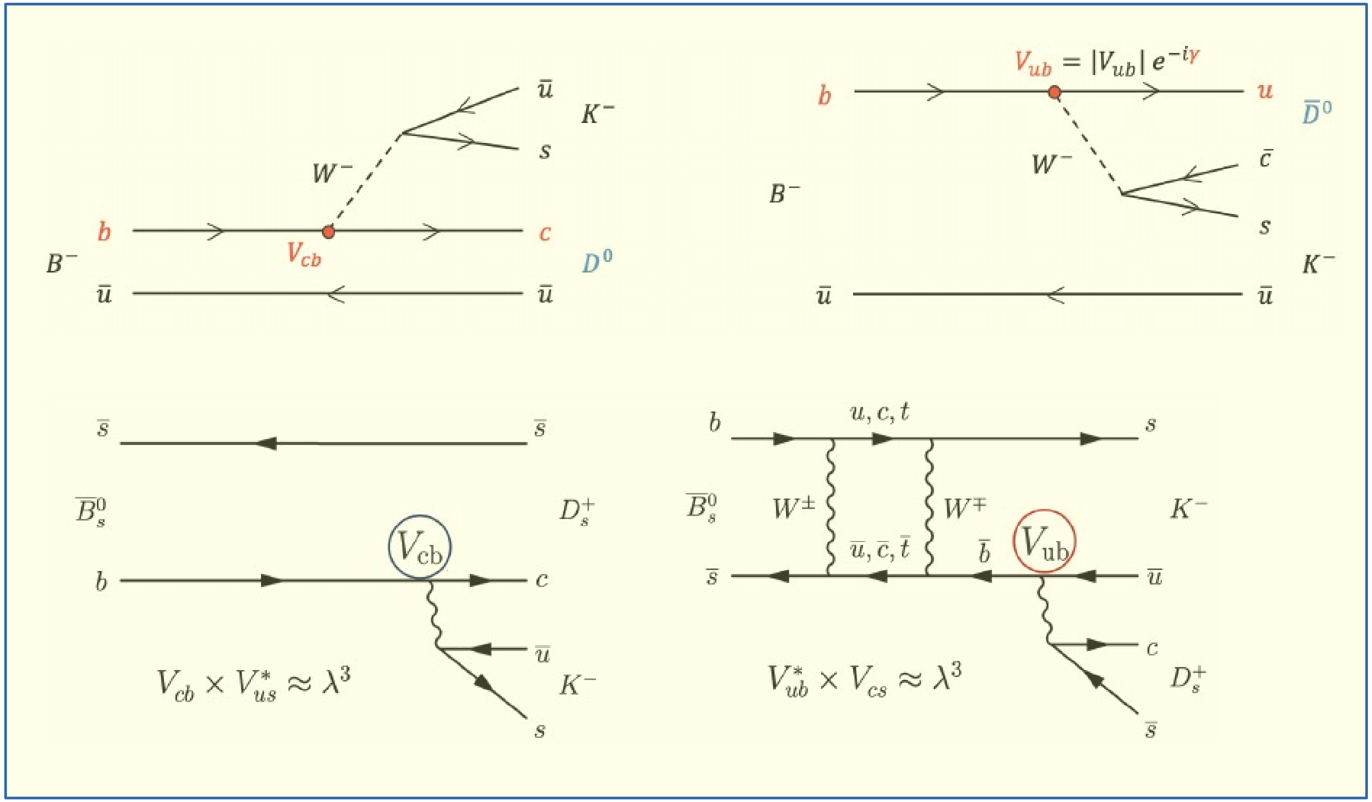
$$e^{i\varphi} = \rho - i\eta, \quad \lambda = 0.22$$



$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\frac{V_{ub}}{V_{cb}}$$

Accessible in tree processes (charged and neutral B-decays) and with impressively small theoretical uncertainties $|\sigma_\gamma| \leq 10^{-7}$

Brod, Zupan JHEP 01 (2014) 051



For interference to occur, $\mathbf{D}$ and $\bar{\mathbf{D}}$ have to decay to same final state, eg. K^+K^-, $\pi^+\pi^-$ etc.

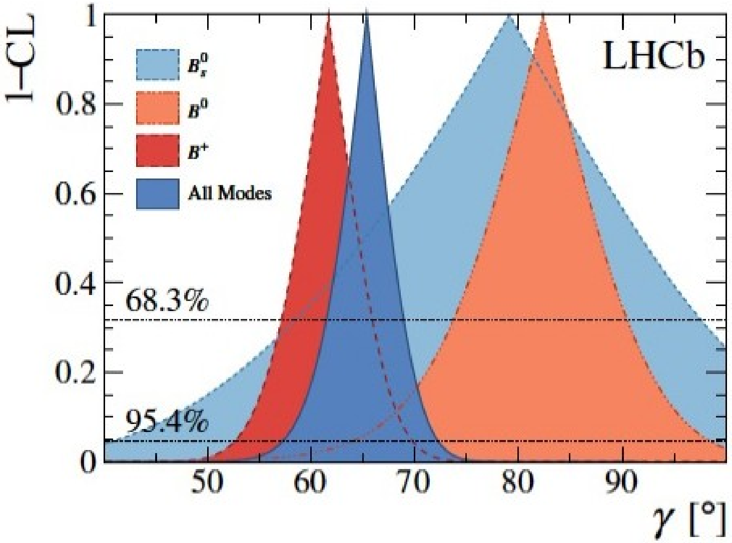
Favourable for D decaying to CP-eigenstates

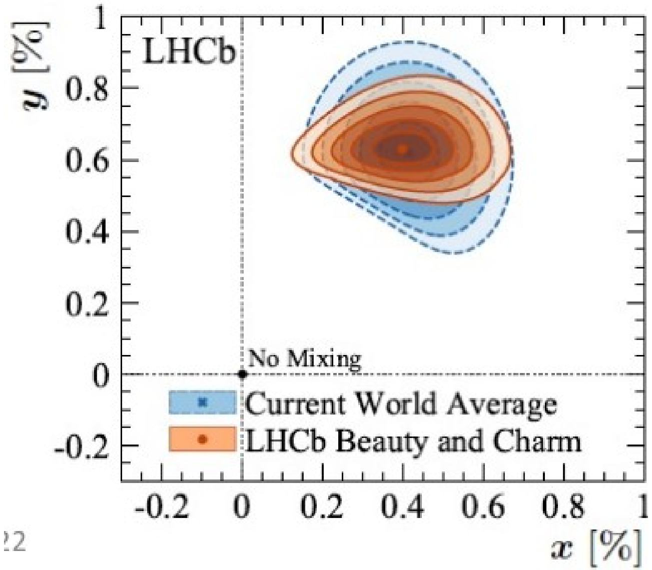
$$\Gamma \sim |1 + r_B e^{i(\delta_B \pm \gamma)}|^2$$

Determination of γ possible with simultaneous fits to interfering decays of B-mesons and mixing in D-mesons; excellent opportunity to use rich array of data (151 observables in total, including other experiments)

$$\Gamma(B^{\pm} \to Dh^{\pm}) = \Gamma(\gamma, \delta_B, \delta_D, x, y)$$

$$x = \frac{\Delta m}{\bar{\Gamma}} \qquad y = \frac{\Delta\Gamma}{2\bar{\Gamma}}$$





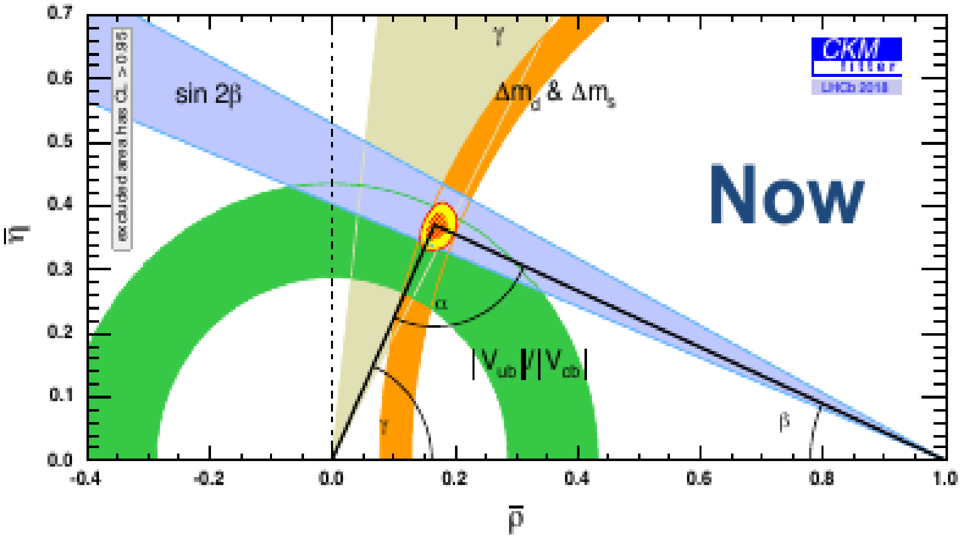
$$\gamma = 65.4^{+3.8}_{-4.2}{}^{\circ}$$

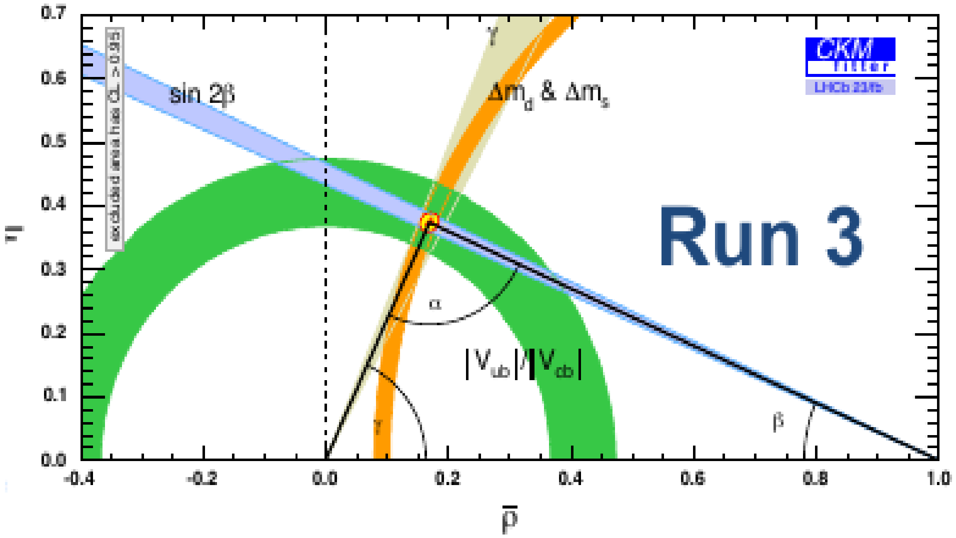
$$x = 0.400^{+0.052}_{-0.053}\%$$

$$y = 0.630^{+0.033}_{-0.030}\%$$

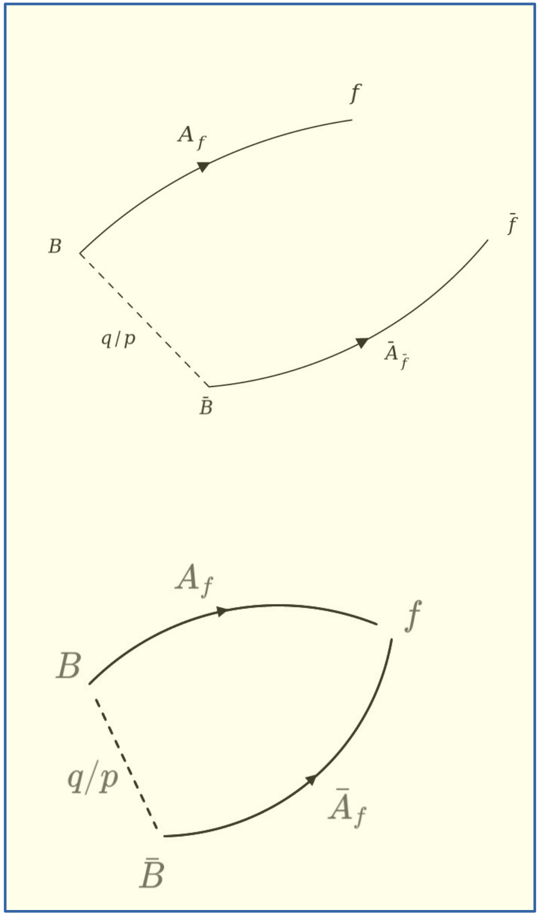
Unitarity triangle uncertainties now and after LHCb Run 3 (taking data right now)

Importance of γ

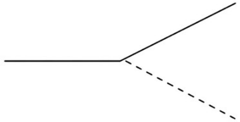


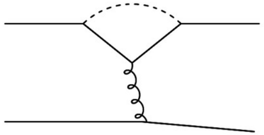


CP violation

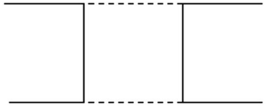


Direct $\Delta F = 1$: $|A_f| \neq |\bar{A}_{\bar{f}}|$





Mixing $\Delta F = 2$: $p \neq q$

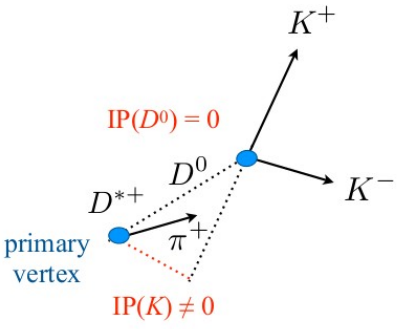


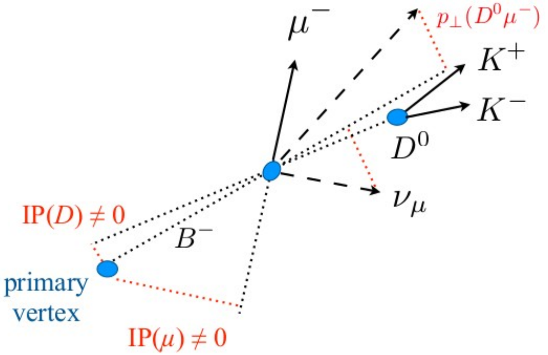
Interference: $\mathrm{Arg}\,\lambda \neq 0$, where $\lambda = \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_f}$

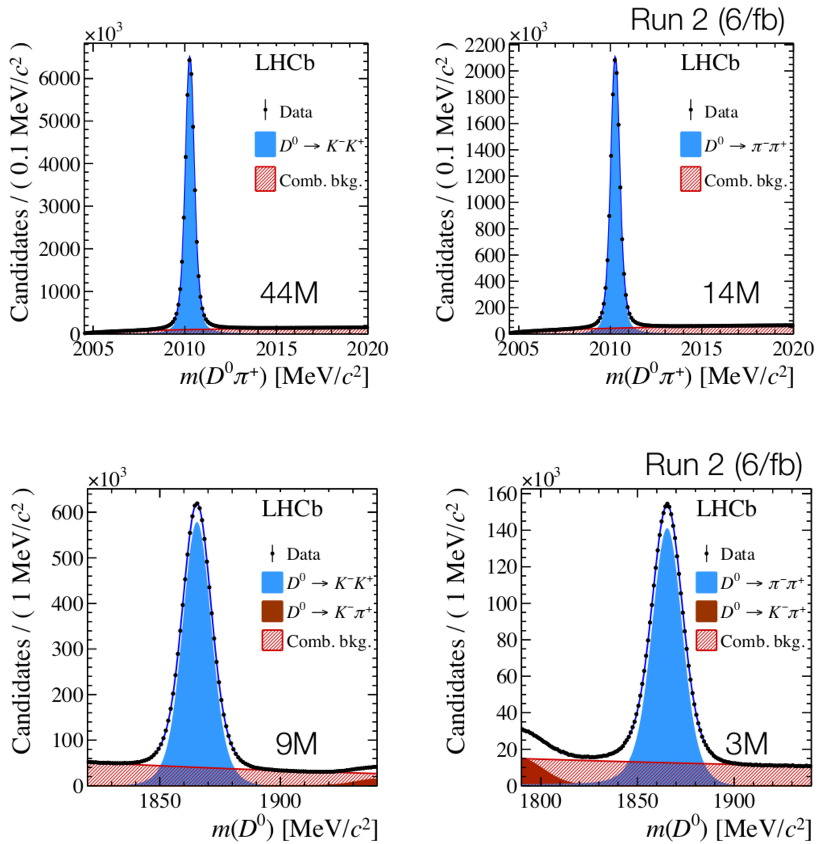
For CP-self conjugate final states (eg. J/ψ, $\pi^+\pi^-$, K^+K^-) penguins go through FCNC and are suppressed; still penguin pollution senstive to NP

CP violation in charm decays

Tiny effect forseen in SM ($<10^{-3}$), sensitive to up flavours







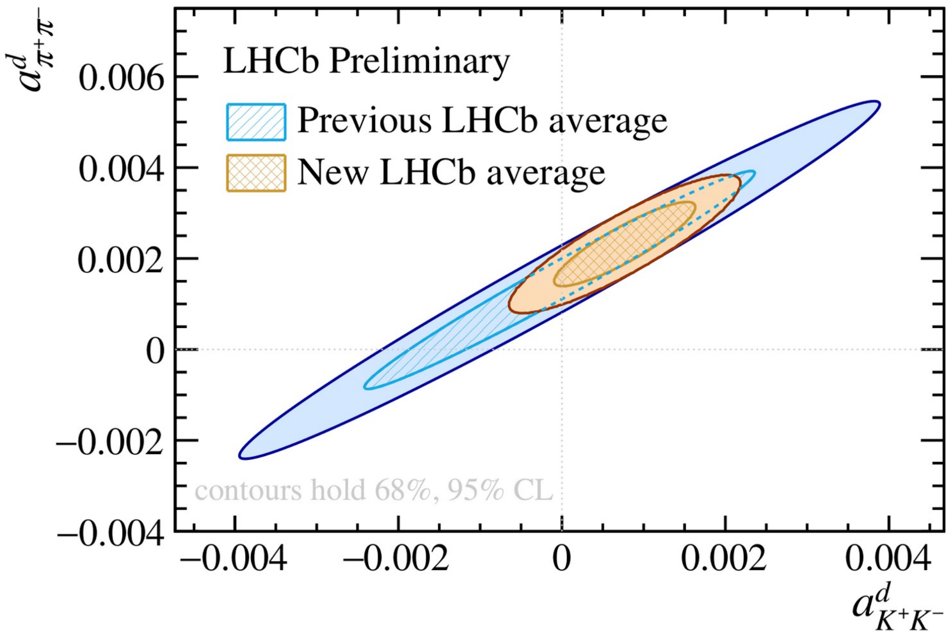
$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$$
$$= (-15.4 \pm 2.9) \times 10^{-4}$$

PRL 122 (2019) 211803

CP violation in charm decays

A bit more is known nowadays ..

Asymetries of $\pi\ \pi$ and KK determined separately and mixing subtracted; pure direct asymmetries are known



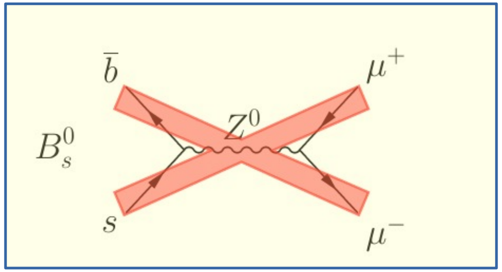
$$a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4}$$

Presented at ICHEP 2022, not yet published

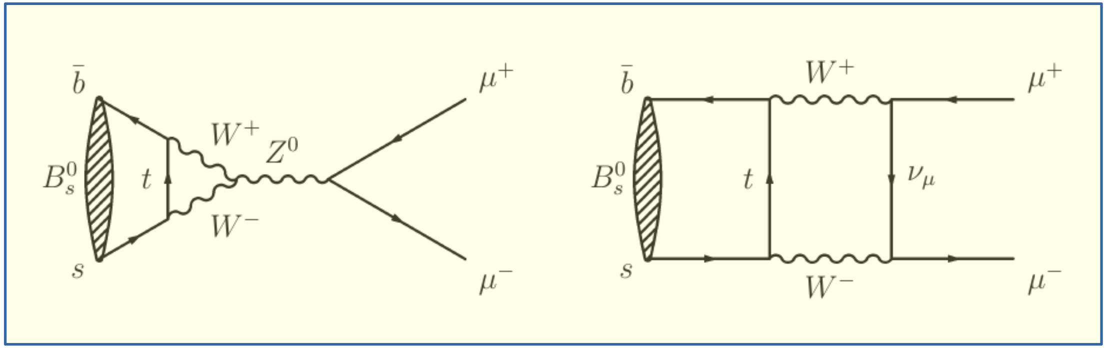
Rare decays: golden channel

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

- LO FCNC suppressed



- Allowed at HO with possible new particles contributing to loops



- Very clean decay: small theoretical uncertainties

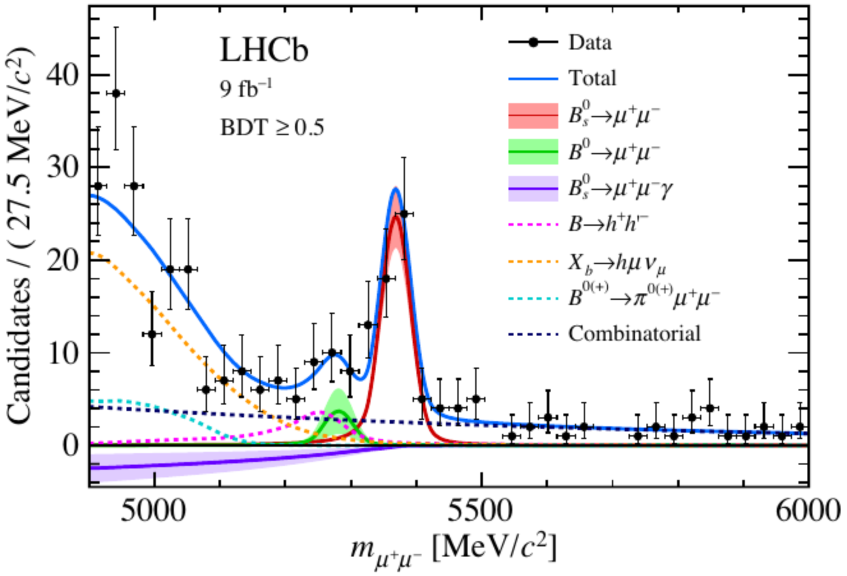
JHEP 10(2019)074512

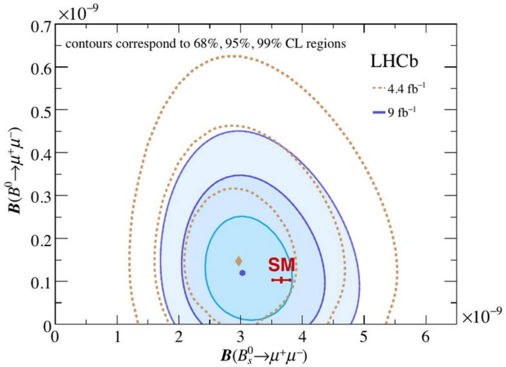
LHCb: PRL 128(2022)041801

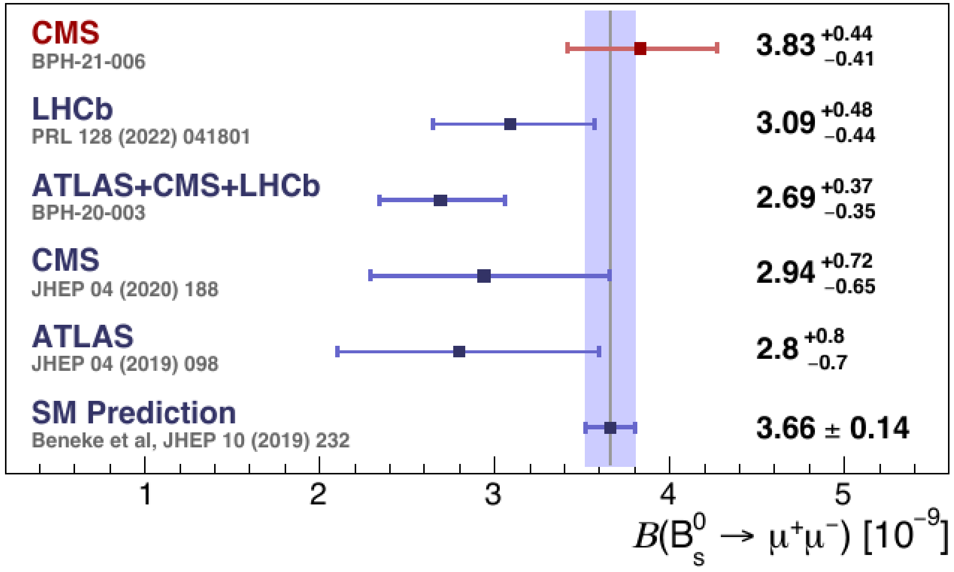
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09^{+0.46+0.15}_{-0.43-0.11}\right)\times 10^{-9}$$

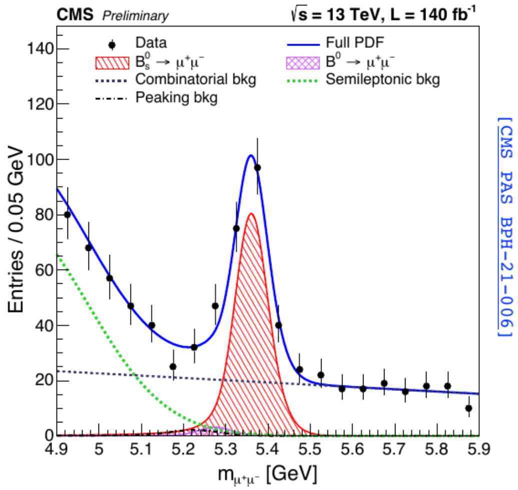
$$\mathscr{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.14) \times 10^{-9}$$

$$\mathscr{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.03 \pm 0.05) \times 10^{-10}$$





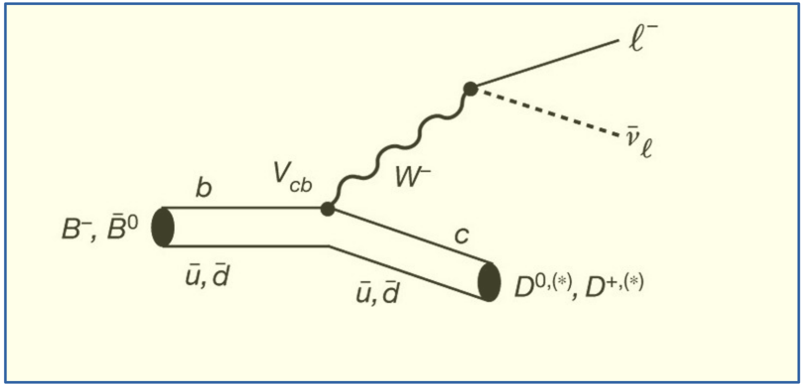




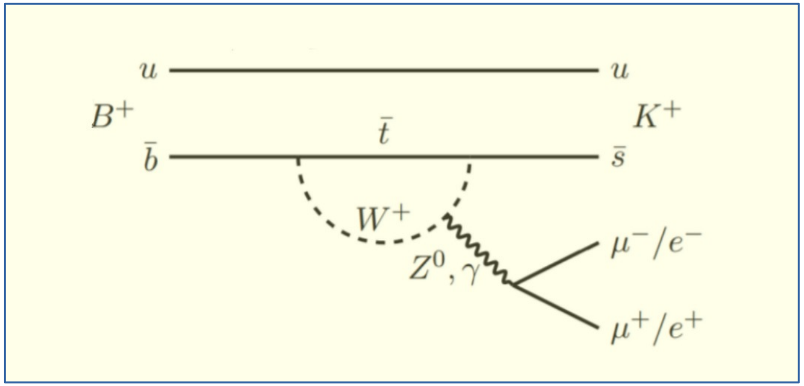
Updated combination of all LHC results expected soon

Semi-leptonic weak decays of heavy flavours

Charged currents,
tree processes $b \rightarrow c$



Neutral currents,
loop processes $b \rightarrow s$



$\mathbf{b \to c}$

$$R(D) = \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\mu\nu)}, \qquad D = D^0, D^{*0}$$

Nb., interesting difference in detection principles at LHCb and BELLE

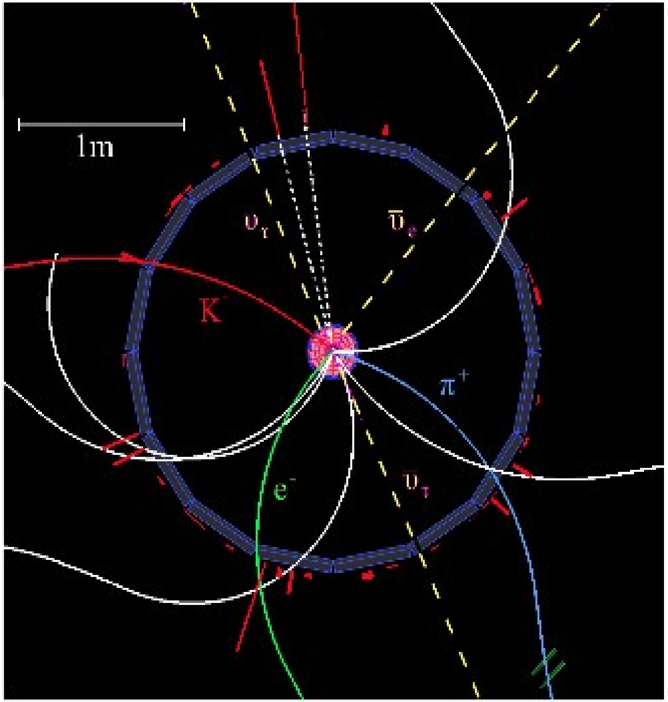
BELLE

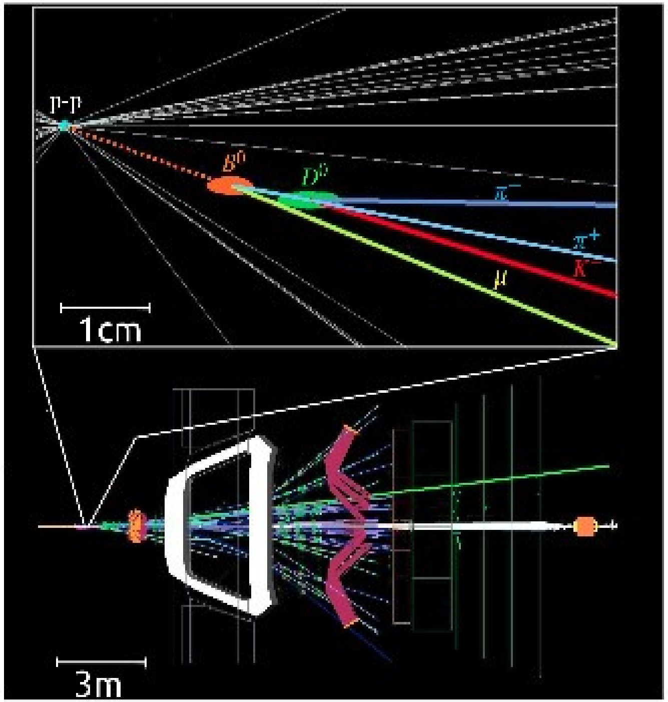
$\Upsilon(4S) \to B^+B^-$

$B^- \to D^0\tau^-\nu_\tau$

$D^0 \to K^-\pi^+$

$\tau^- \to e^-\bar{\nu}_e\nu_\tau$





LHCb

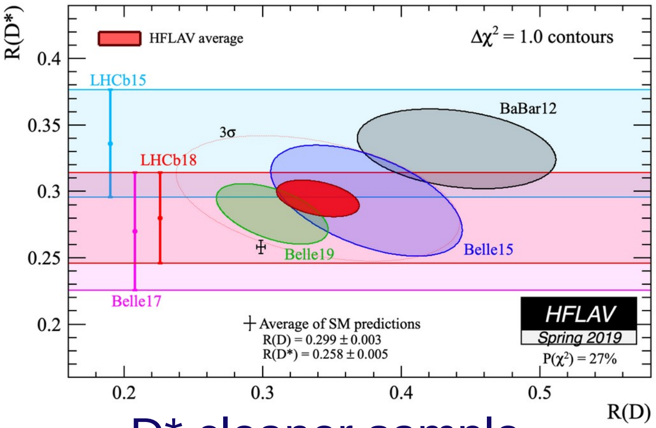
$B^0 \to D^{*+}\tau^-\bar{\nu}_\tau$

$D^{*+} \to D^0\pi^+$

$D^0 \to K^-\pi^+$

$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$

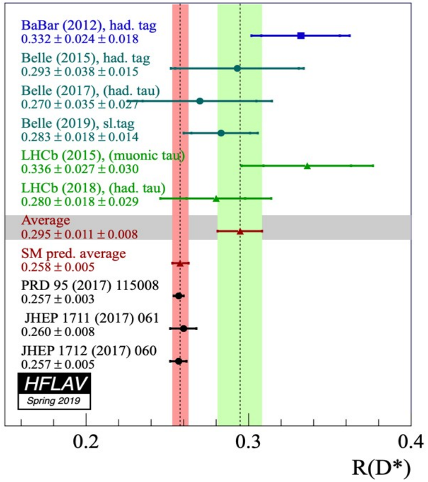
b→c HFLAV averages

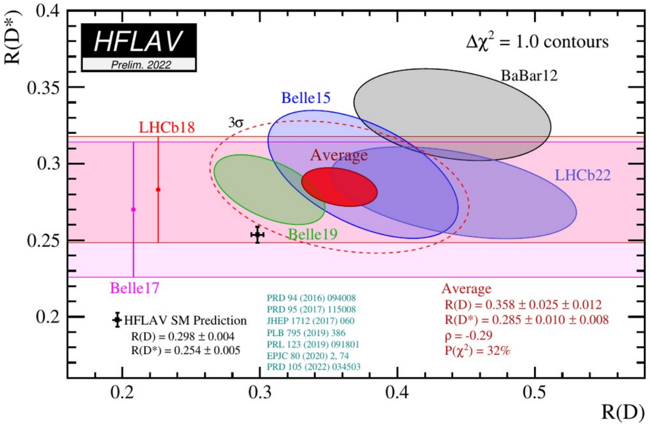


D* cleaner sample

≧ 3σ disagreement with SM on 2D plot

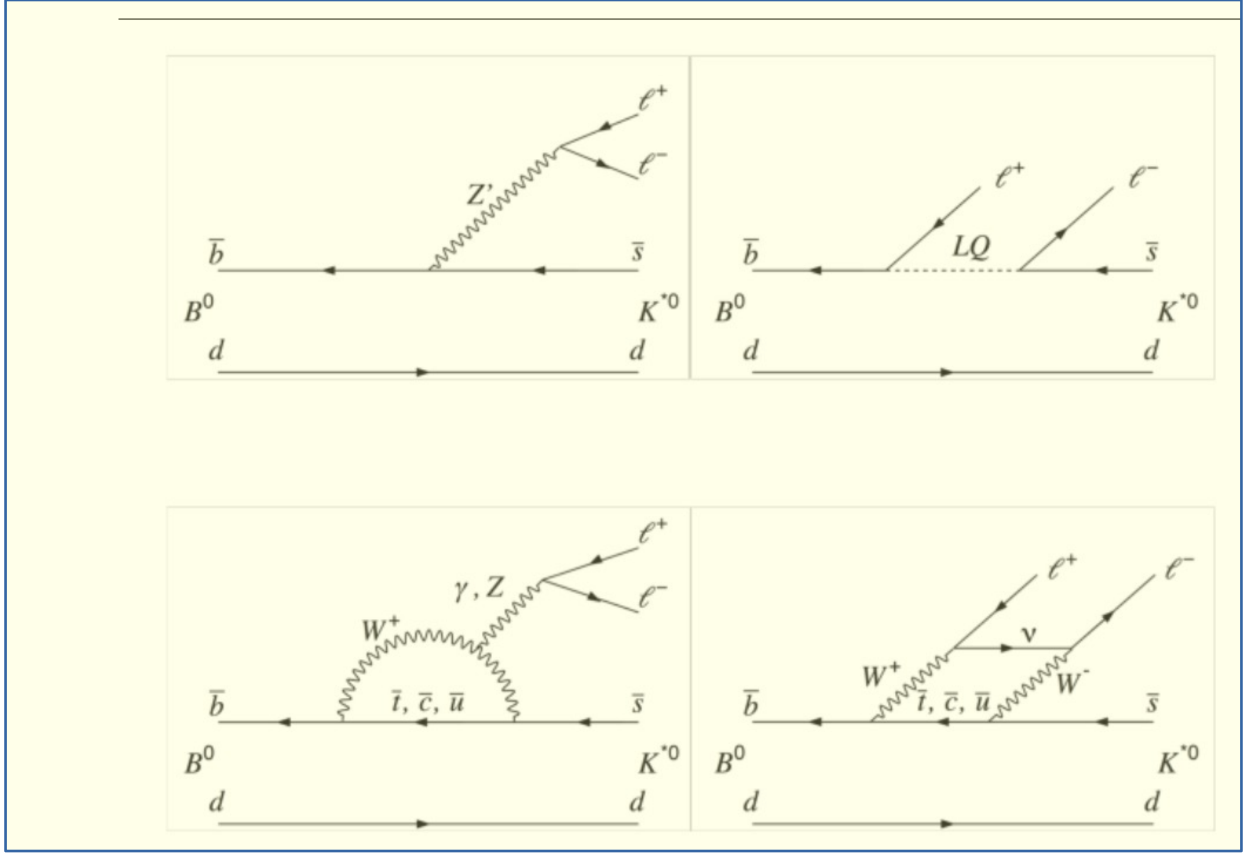
Less pronounced on $R(D^*)$ only





Out of stove LHCb result (CERN seminar 18 Oct, unpublished)
Both R(D) and $R(D^*)$ measured
Still ~3σ tension, soon to be strenghtened statistically

$b \to s$ and search for lepton-flavour universality violation



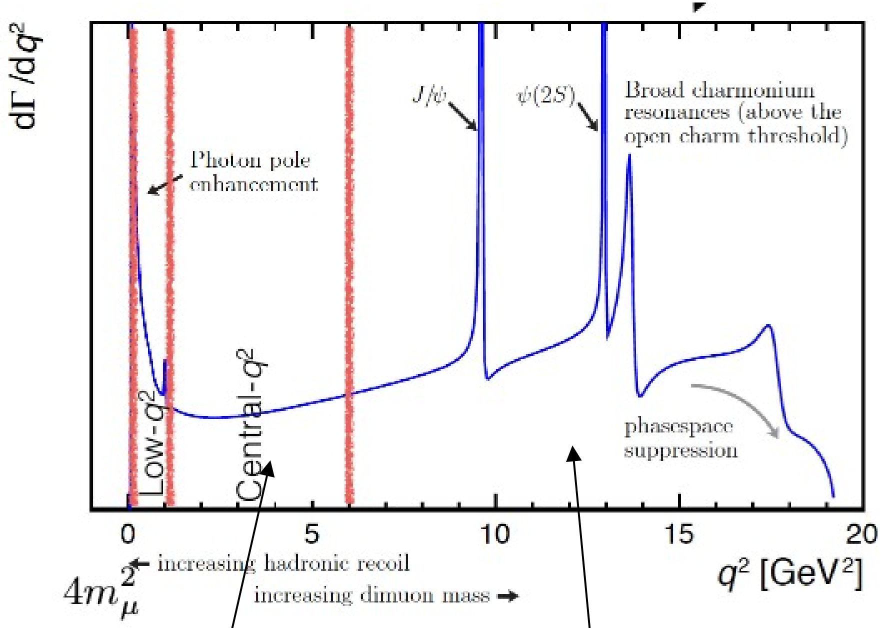
In SM coupling of leptons to gauge bosons is flavour independent

$$R_K = \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)} = 1$$

R_K free from QCD uncertainties (nasty in had. modes)

$R_K \neq 1$ signals disagreement with SM

b → s, LFV



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

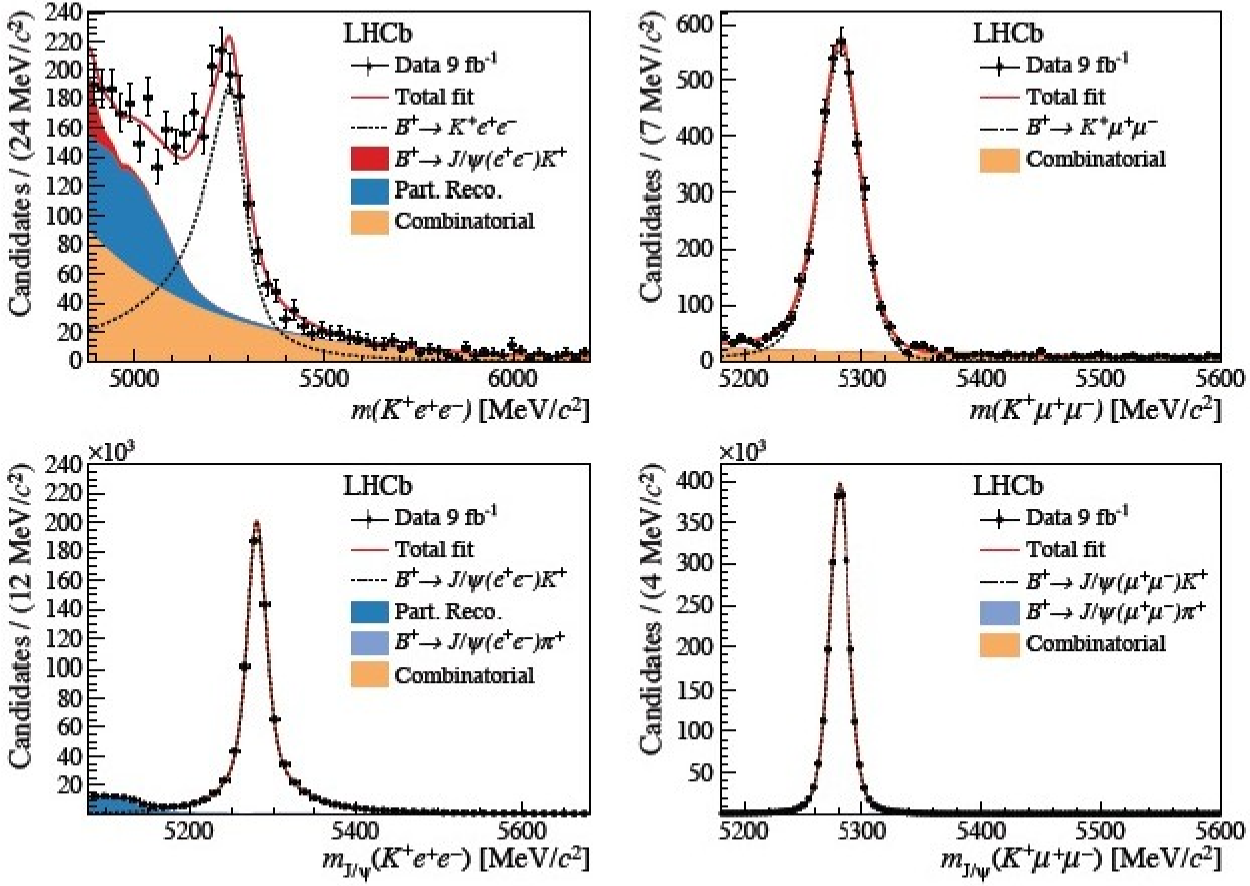
$$B^+ \to K^+ J/\Psi(\mu^+\mu^-)$$

$$R_K = \frac{\int_{1.1}^{6} d\Gamma_{K^+\mu^+\mu^-}(q^2)}{\int_{1.1}^{6} d\Gamma_{K^+e^+e^-}(q^2)}$$

Expected consistent
with 1 at % level (SM)

Important experimental cross-check:
in resonance region must be 1.0
as final states K^+ J/ψ are identical

b → s, LFV

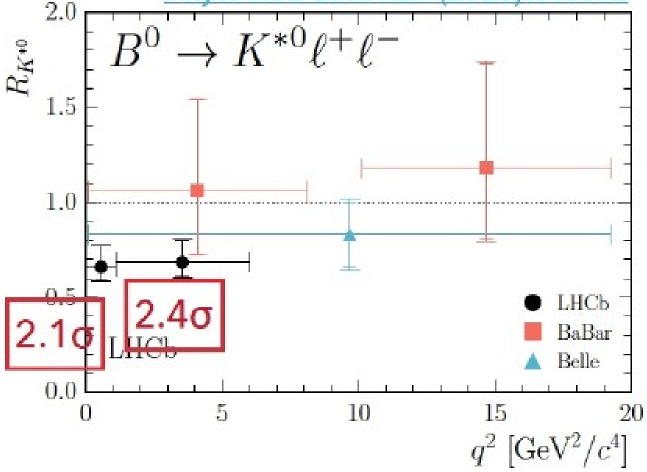


$$R_{J/\psi} = \frac{\Gamma(B \to K\, J/\psi(\mu\mu))}{\Gamma(B \to K\, J/\psi(ee))} = 0.981 \pm 0.020$$

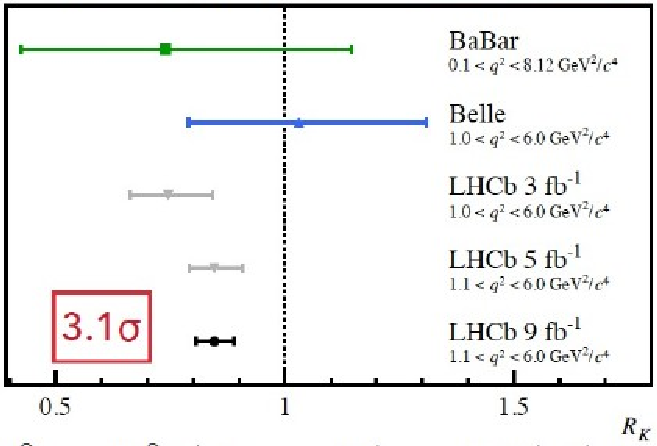
$$R_K = \frac{\Gamma(B \to K\mu\mu)}{B \to Kee} \Big/ \frac{\Gamma(B \to KJ/\psi(\mu\mu))}{B \to KJ/\psi(ee)} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

b → s, LFV

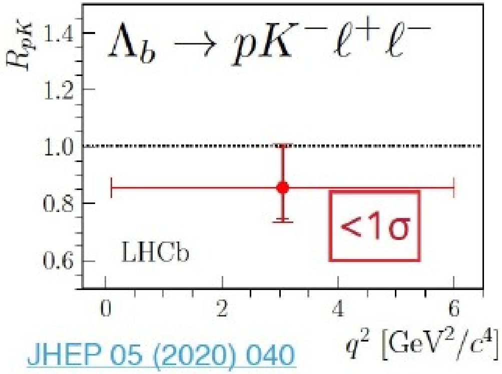
Phys. Rev. Lett. 125 (2020) 011802



$B^+ \to K^+\ell^+\ell^-$ arXiv:2103.11769

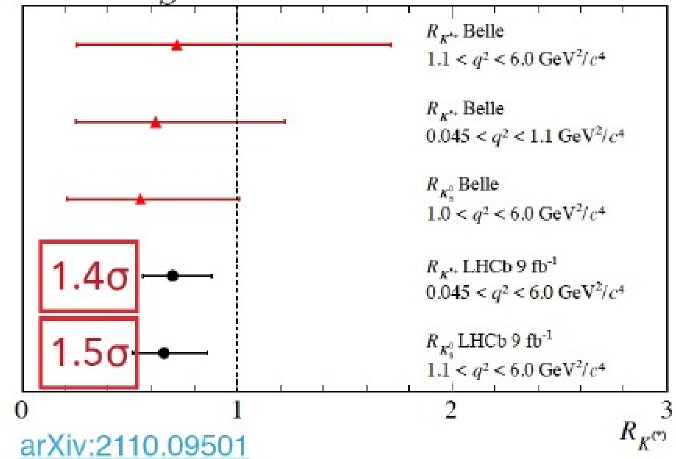


Summary of LHCb and combined with BaBar and Belle



JHEP 05 (2020) 040

$B^0 \to K^0_S\ell^+\ell^-$ $B^+ \to K^{*+}\ell^+\ell^-$



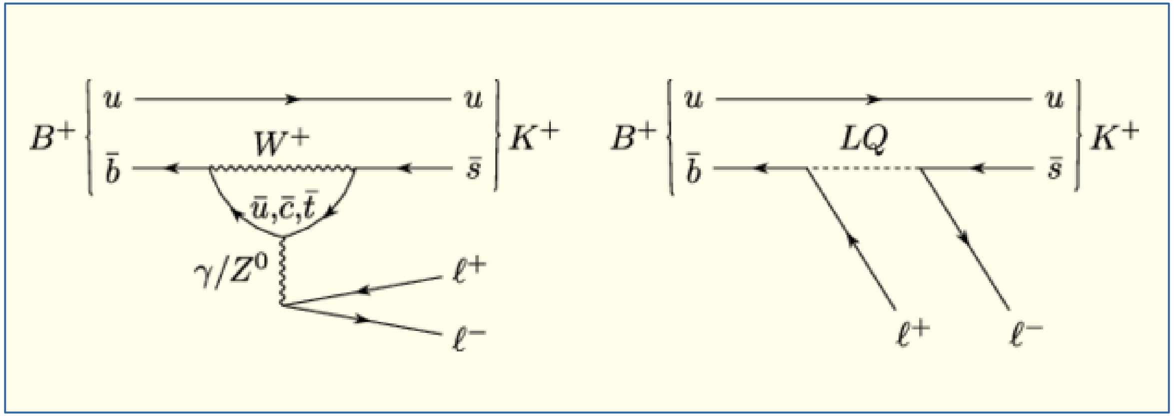
arXiv:2110.09501

What do LHCb's E-W results mean for SM?

Standard Model Effective Field Theory (SMEFT)

$$H_{eff} = G_F V_{tb} V_{ts}^* \sum_i C_i O_i$$

i=9, 10
E-W vector and axial penguins

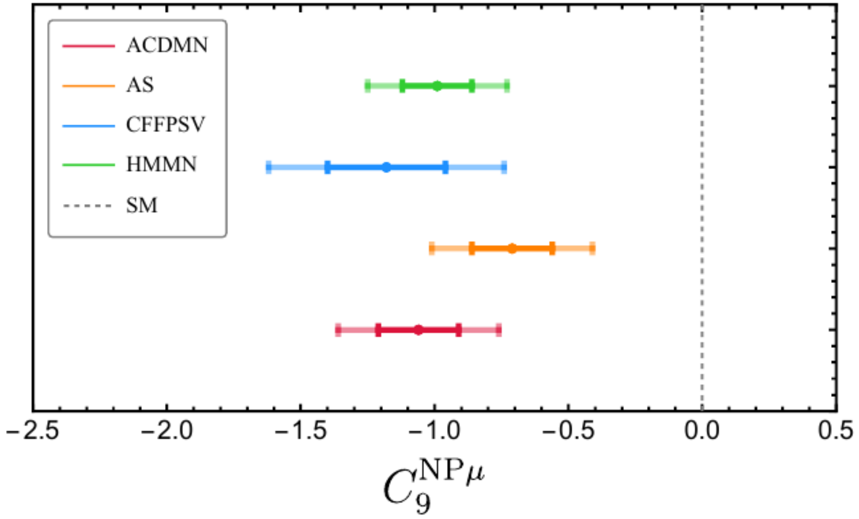


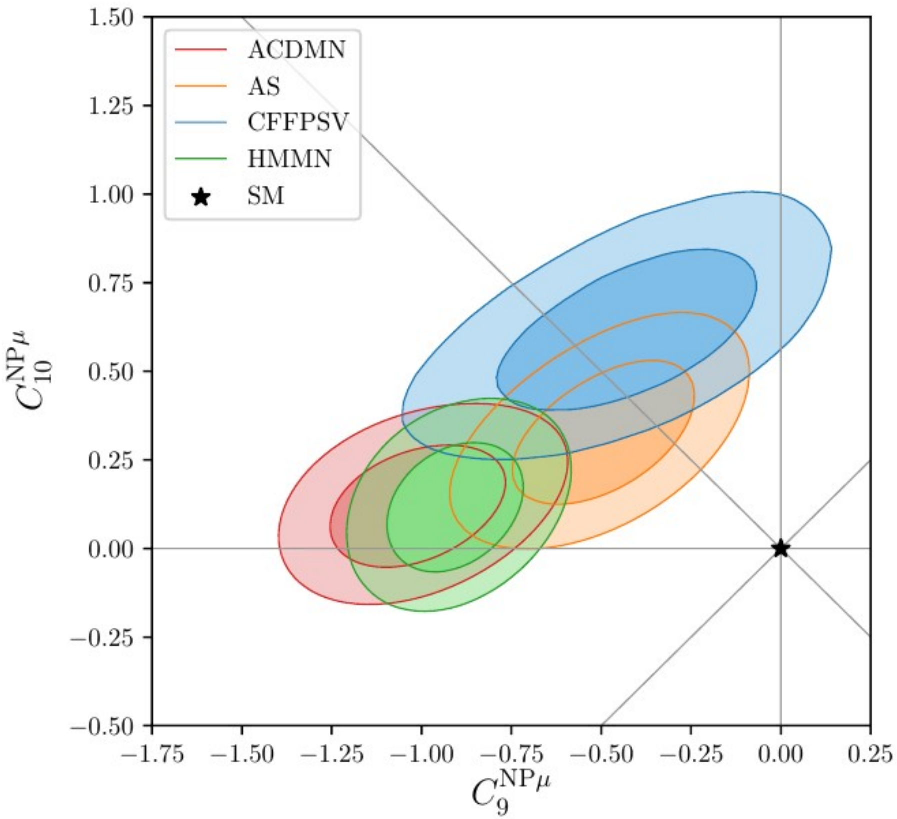
NP would allow chirality-flip operators O_9' and O_{10}'; corresponding Wilson coeffs should be non-zero when determined from fits

What do LHCb's E-W results mean for SM?

A number of groups doing global fits; summary by B. Capdevila et al.

Assuming $C_{10} = -C_9$

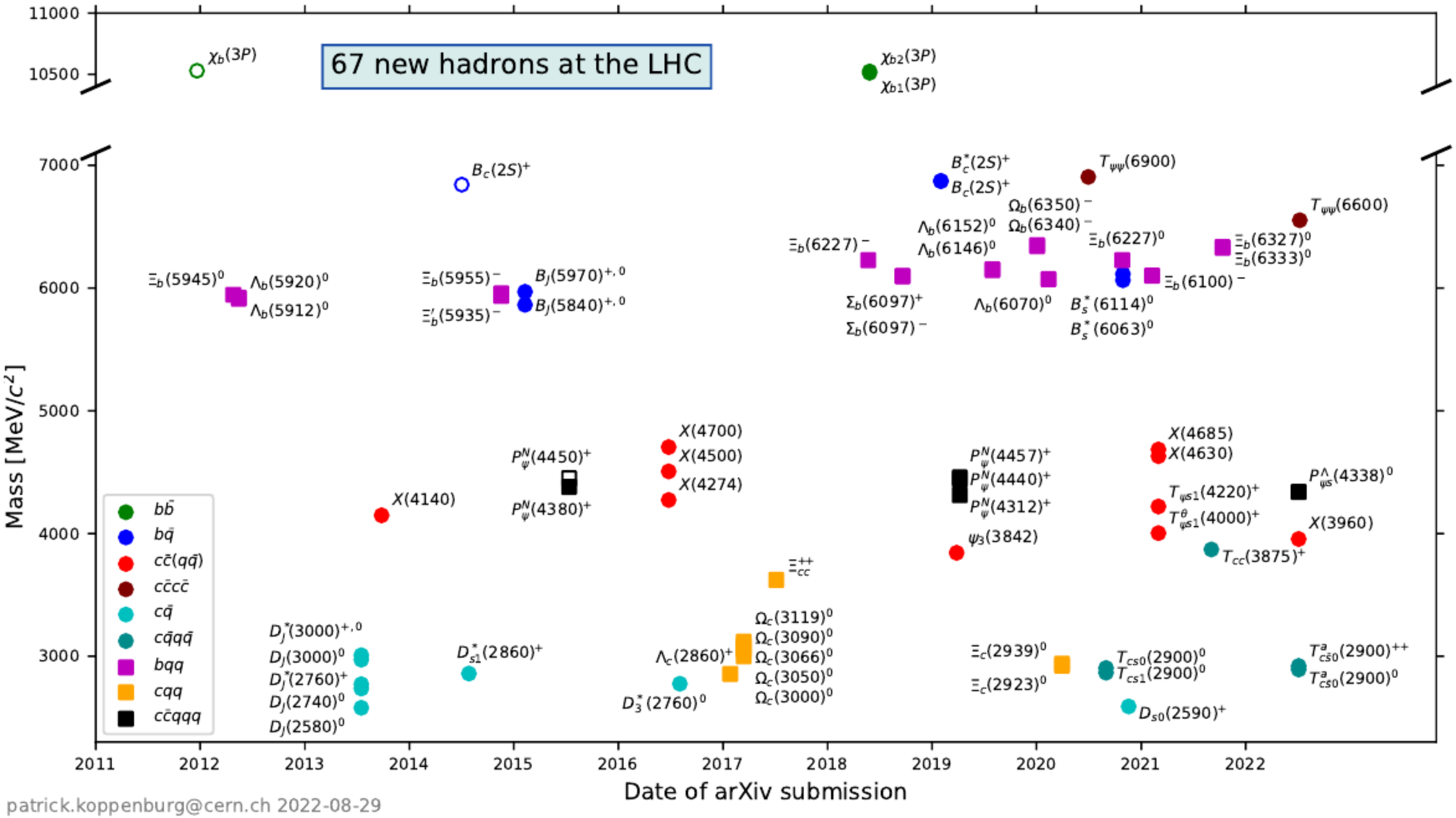




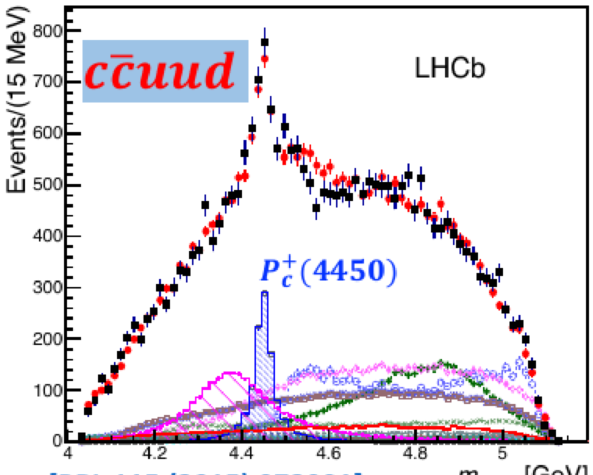
Discrepancy between data and SM; intriguing but no evidence; LHCb the main data provider

Hadron spectroscopy at LHCb

Of 67 new hadronic states discovered at LHC, 59 belong to LHCb

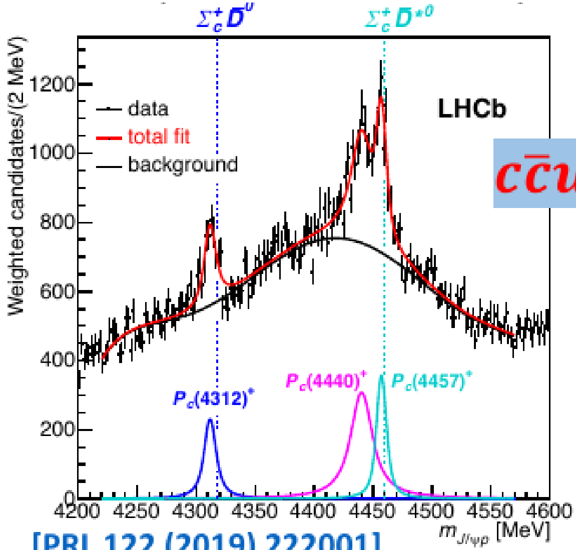


Pentaquarks



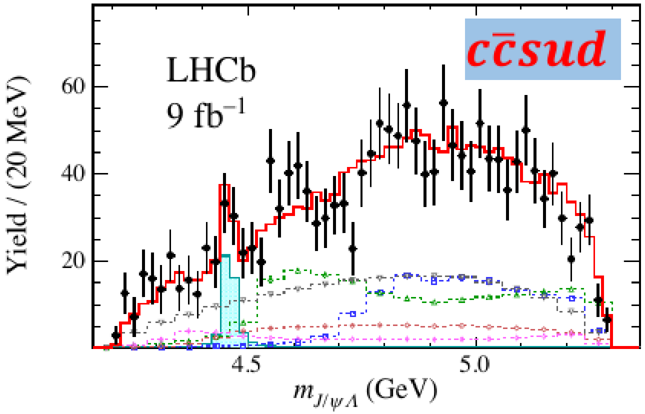
[PRL 115 (2015) 072001]

$\mathrm{P}_{\psi}^{\mathrm{N}}(4450)^+$ in $\Lambda_b \to J/\psi p K^-$



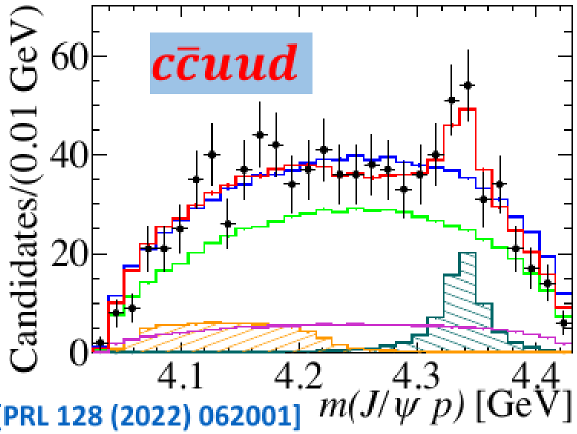
[PRL 122 (2019) 222001]

$\mathrm{P}_{\psi}^{\mathrm{N}}(4312)^+$ and $\mathrm{P}_{\psi}^{\mathrm{N}}(4450)^+$ resolved into $\mathrm{P}_{\psi}^{\mathrm{N}}(4440)^+$, $\mathrm{P}_{\psi}^{\mathrm{N}}(4457)^+$



[Science Bulletin 66 (2021) 1278]

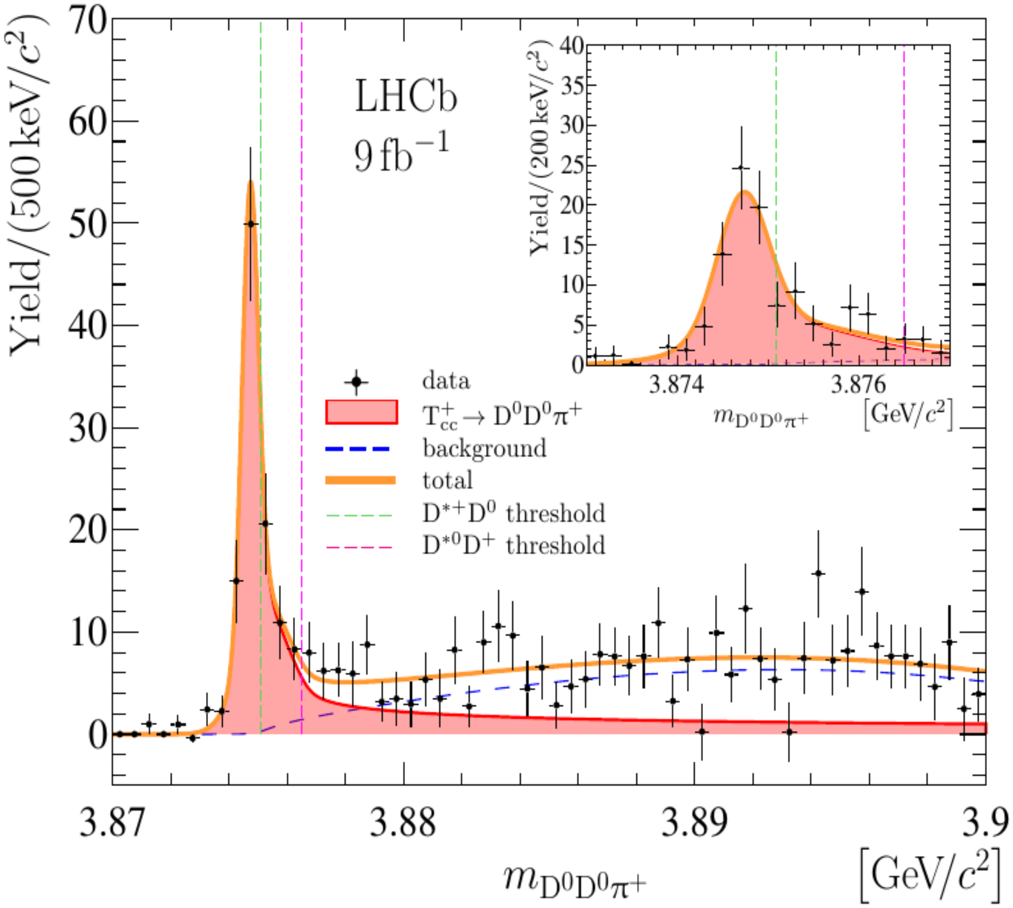
$\mathrm{P}_{\psi}^{\Lambda}(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$



[PRL 128 (2022) 062001]

$\mathrm{P}_{\psi}^{\mathrm{N}}(4337)^+$ in $B_s^0 \to J/\psi p \bar{p}$

Doubly charmed tetraquark



$\mathbf{D^0D^0\pi^+}$ produced promptly in same pp collision

Narrow state below $\mathbf{D^{*+}D^0}$ threshold

$\mathbf{\Gamma = 410 \pm 165 \pm 43^{+18}_{-38}}$ keV

Longer living ($>$ **10x**) than known multiquark states

Consistent with quark content $\mathbf{cc\bar{u}\bar{d}}$ isoscalar $\mathbf{T_{cc}^{+}}$

Nature Comm. 13(2022)3351

Summarizing..

Main directions of research to be continued in Run-3:

CP violation (discovery of CPV in c, tiny but significant effect)
Lepton-flavour universality
CKM matrix tests
Rare decays
..

Joint analyses becoming more important (Standard Model Effective Field Theory)

Unexpectedly, hadronic exotics appears to be the major program; discoveries of strange pentaquark, doubly-charmed tetraquarks, ..

Challenges in experimental techniques: beam intensity, time resolution, trigger rates, computing capacities, etc.