Selected results from LHCb

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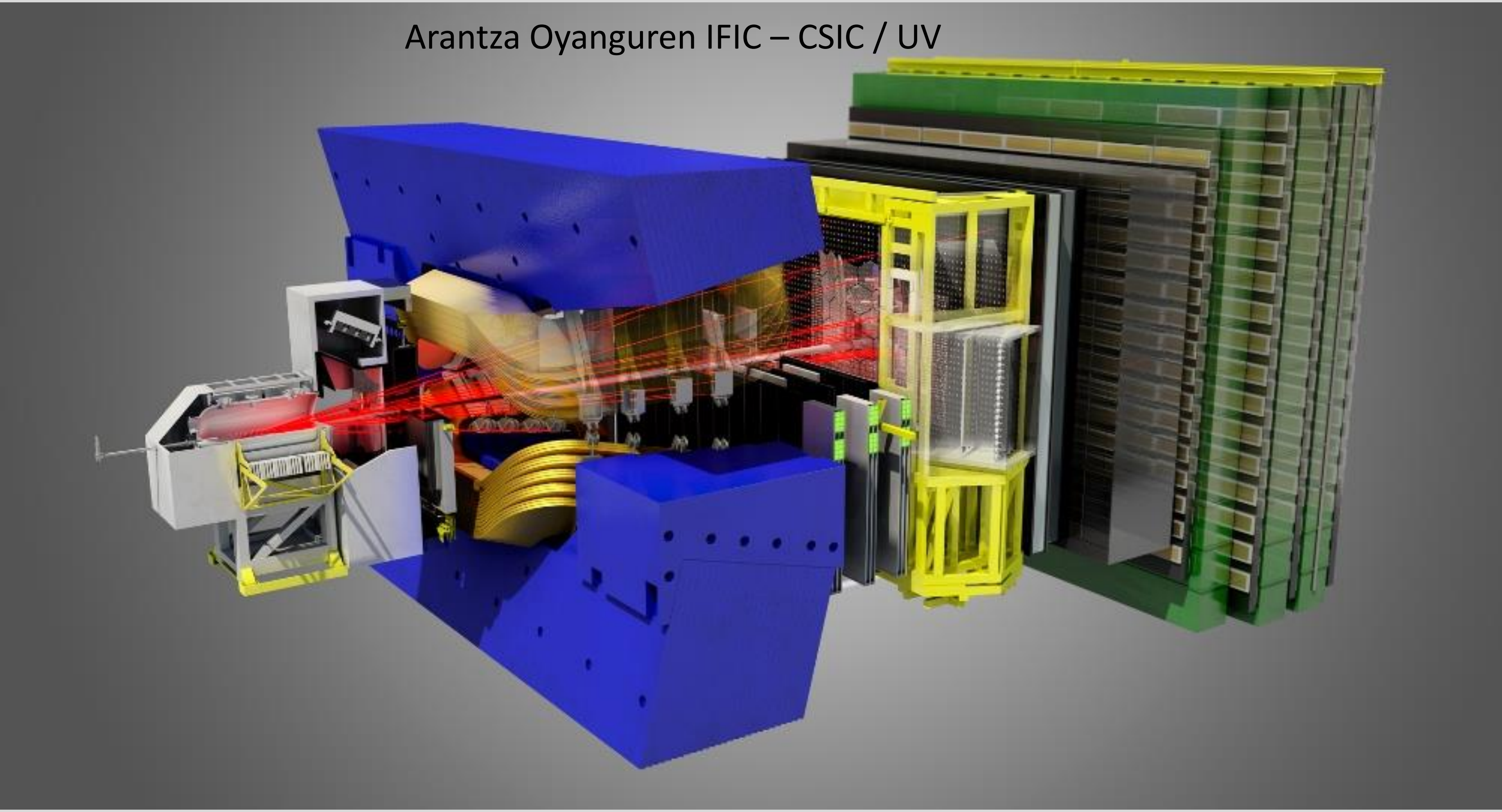


IFIC Scientific Day, L3: flavour and quark matter

9th January 2024

Outline

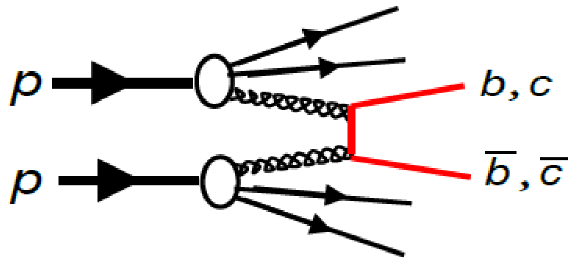
- The LHCb experiment
- Rare B decays
- Semileptonic B decays
- CKM and CP Violation
- Exotics
- The future

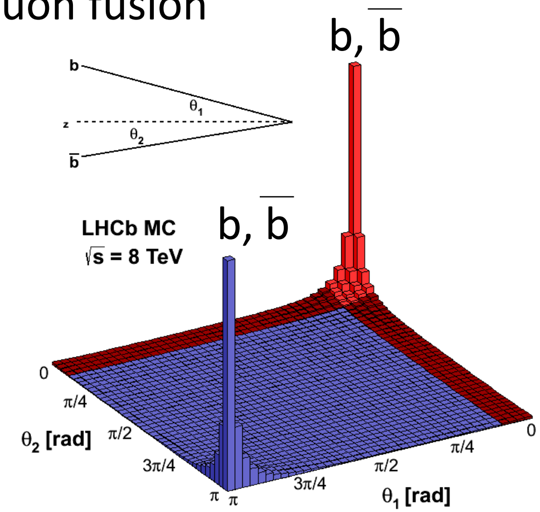
The LHCb experiment

The LHCb experiment

- The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion
  - ~ 300 μb @ √s=7 TeV
  - ~ 600 μb @ √s=13 TeV

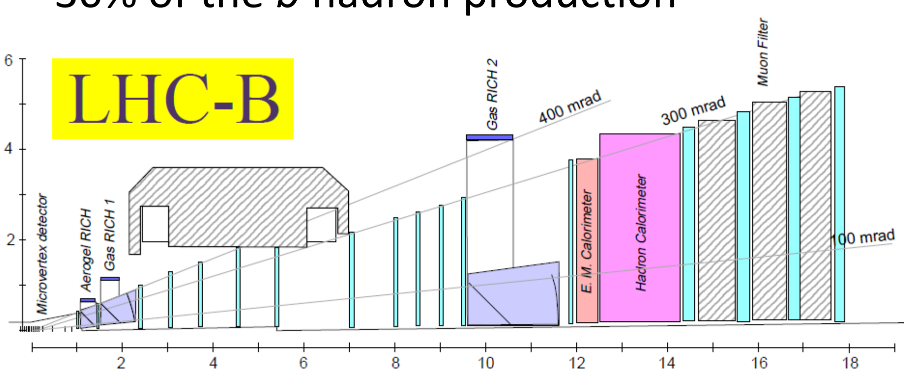
[PRL 118 (2017) 052002]
[JHEP 02 (2021) 023]



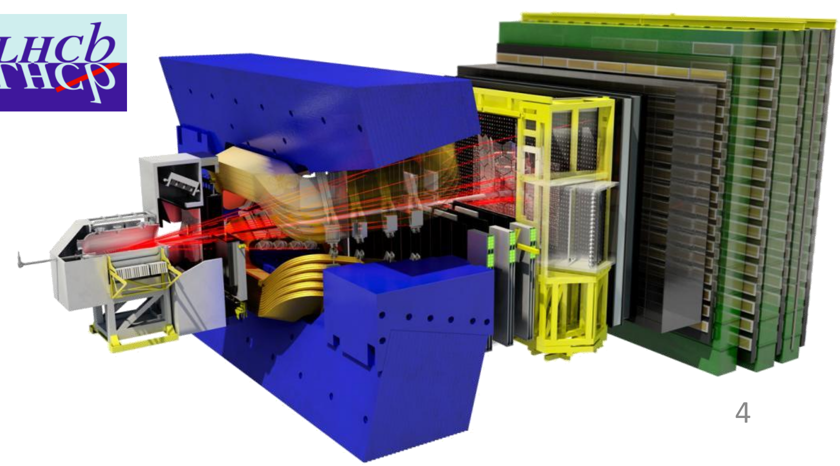


The b quarks hadronize in B, B_s, $B^*_{(s)}$, b-baryons…
→ average B meson momentum ~ 80 GeV

- The LHCb idea: to build a single-arm forward spectrometer:
  - ~ 4% of the solid angle (2 < η < 5),
  - ~30% of the b hadron production



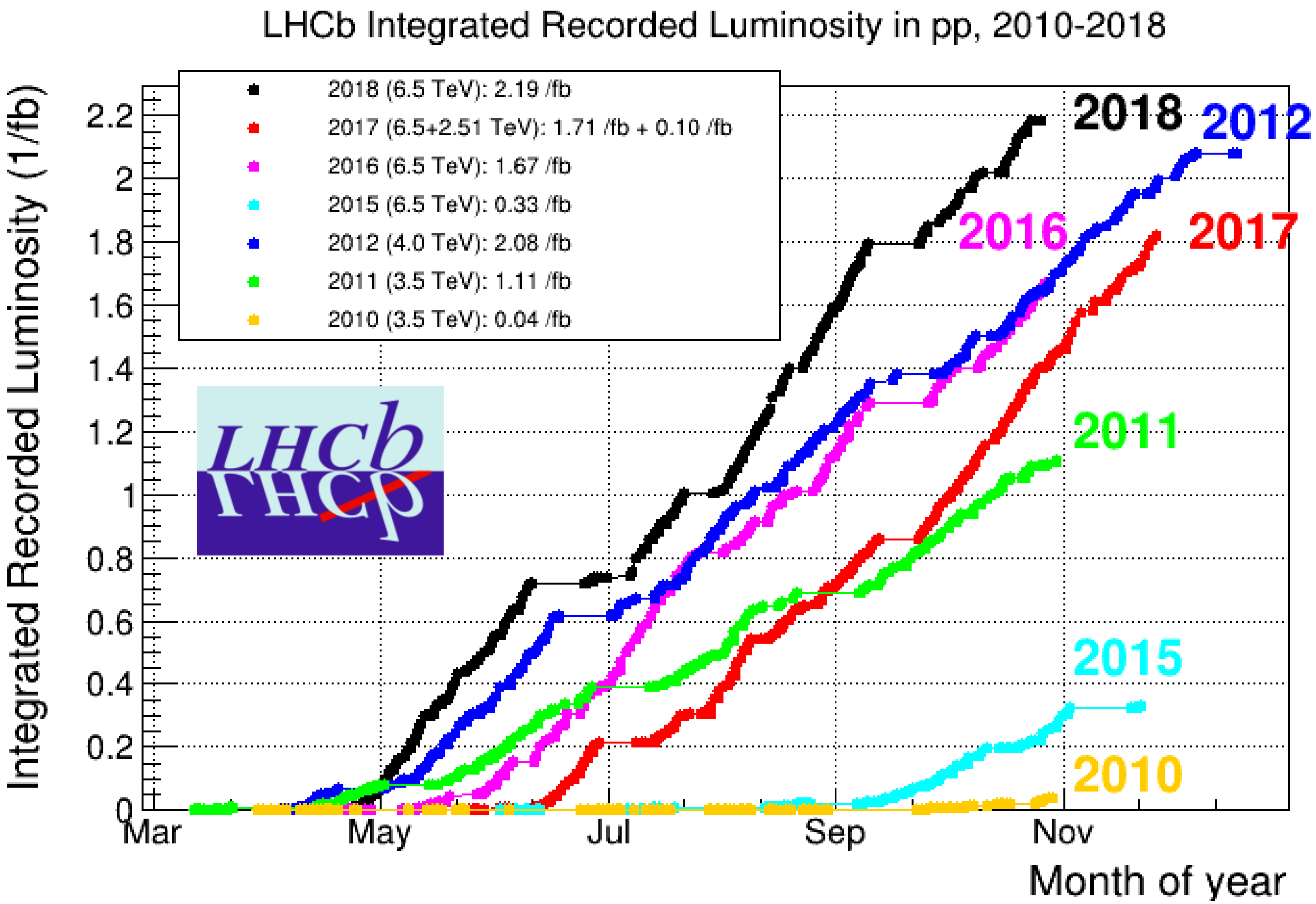
Letter of Intent, 1995



The LHCb experiment

- The data:

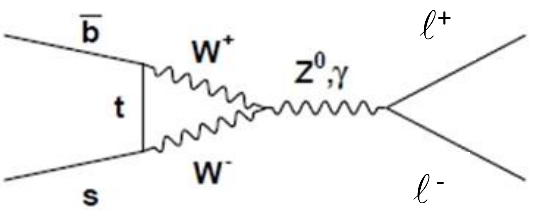
3 (Run1) + 6 (Run2) fb^{-1}
(2011 - 2018)



Rare B decays

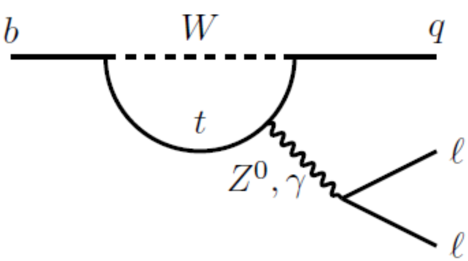
- $b \to s,d$ quark transitions are Flavor Changing Neutral Currents (FCNCs),
  $\to$ in the SM they only can occur through loops (*penguin and box diagrams*), excellent probe for physics beyond the SM

leptonic



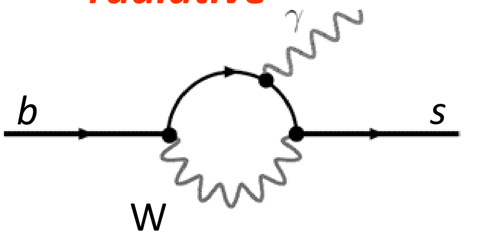
BR ~ 10^{-9}

semileptonic



BR ~ 10^{-7}

radiative



BR ~ 10^{-5}

Experimentally $\to$ leptons/photons with high transverse momenta

Theoretically $\to$ observables can be calculated in terms of Wilson coefficients

Ex: $\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2\alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb}V_{ts}\right|^2 \left|2m_\mu C_{10}\right|^2$

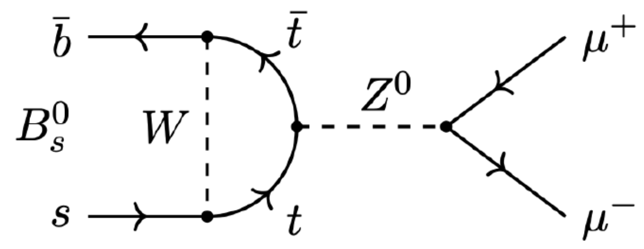
Hadronic uncertainties in decay constants or form factors

Rare B decays: $B_{(s)} \to \mu^+\mu^-$

- Very rare decay: FCNC and helicity suppressed
- Theoretically clean (5% uncertainty)

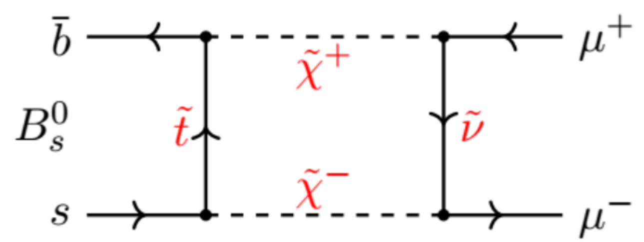
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.62^{+0.15}_{-0.10}) \times 10^{-9}$$

[Bobeth et al. PRL 112 (2014) 101801,
Beneke et al. JHEP 10 (2019) 232]



$$\mathcal{B}(B_d \to \mu^+\mu^-) = (0.99^{+0.05}_{-0.03}) \times 10^{-10}$$

[Buras & Venturini arXiv:2109.11032,
independent of |Vcb|]

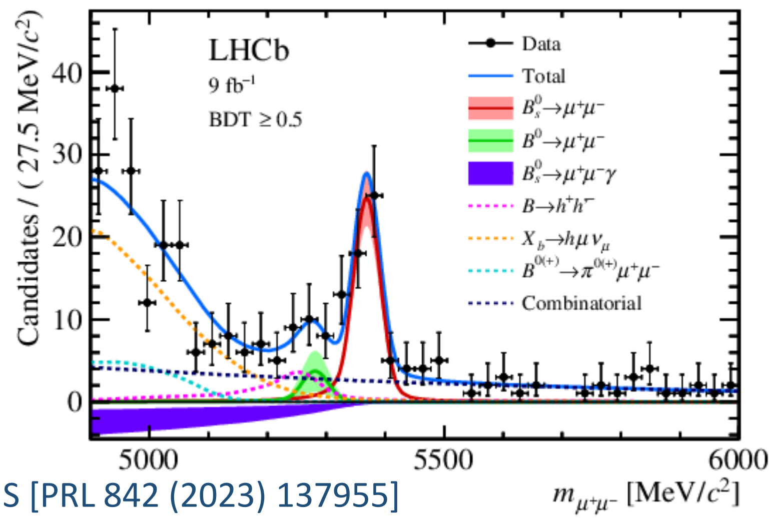


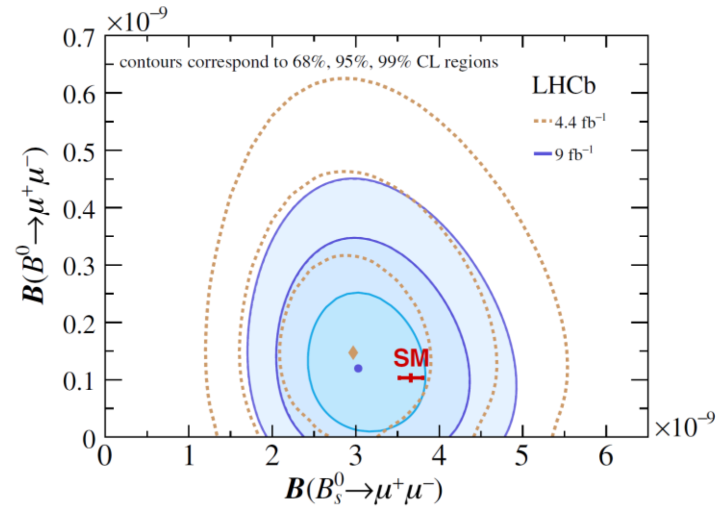
- Very sensitive to new physics scenarios, which predict a larger BR (ex: SUSY)

- Clear experimental signature (with very challenging reconstruction): measurements at LHCb, ATLAS and CMS

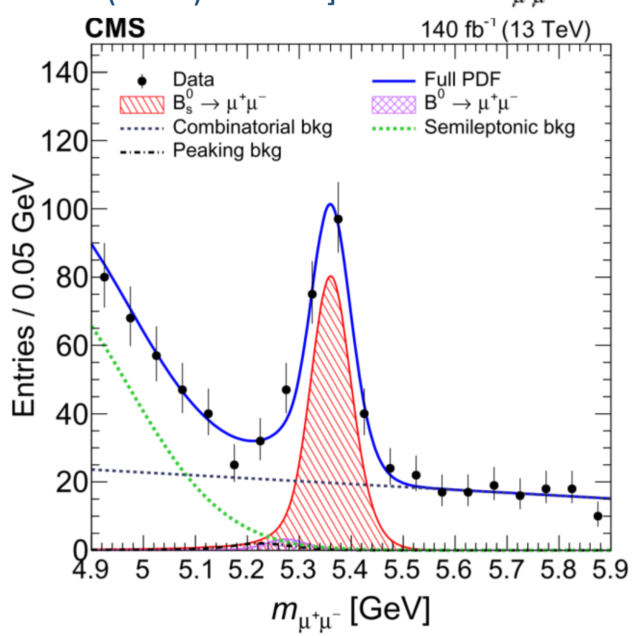
Rare B decays: $B_{(s)} \to \mu^+\mu^-$

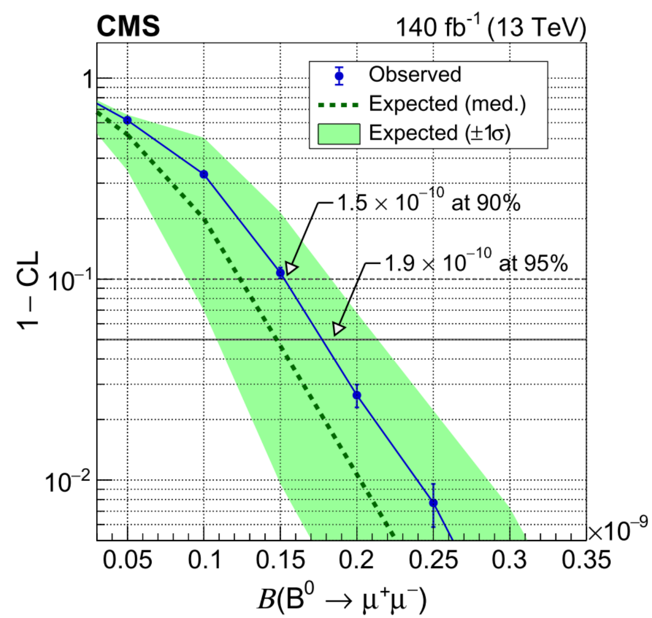
LHCb [PRL 128 (2022) 041801; PRD 105 (2022) 012010]



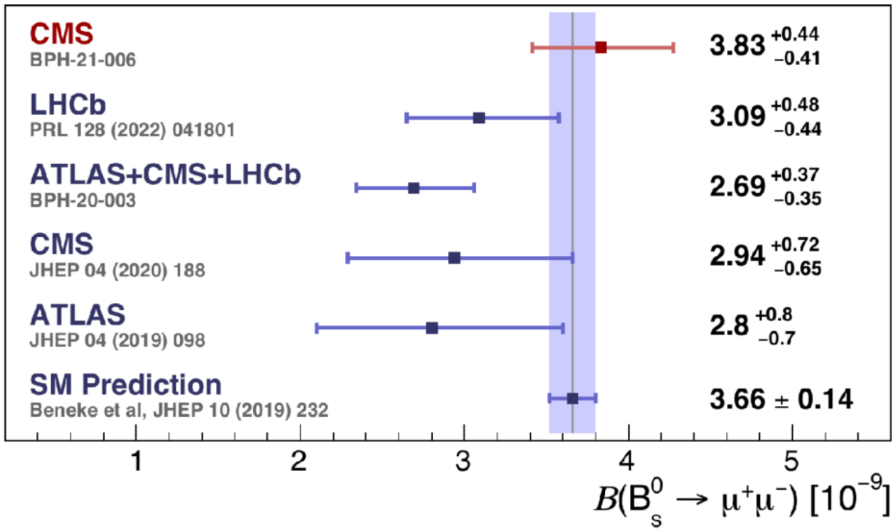


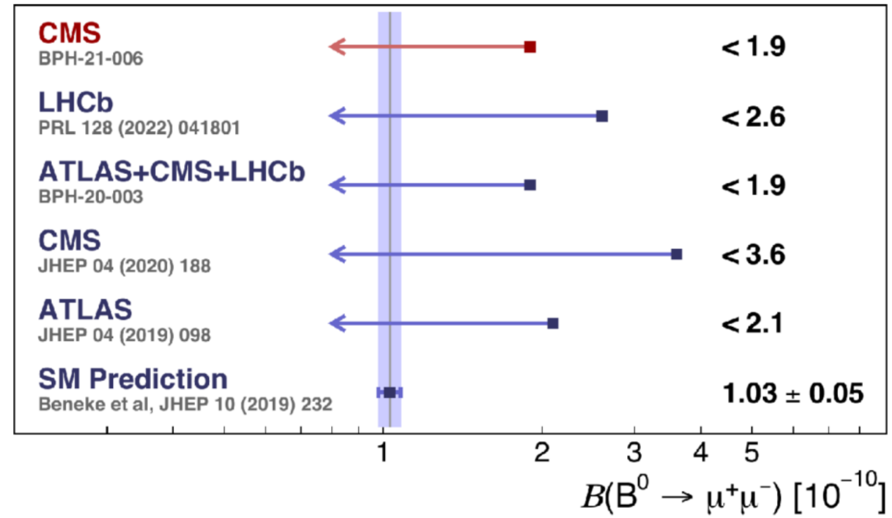
CMS [PRL 842 (2023) 137955]





Rare B decays: $B_{(s)} \to \mu^+\mu^-$





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

LHCb [PRL 128 (2022) 041801; PRD 105 (2022) 012010]

CMS: $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9}$

CMS [PRL 842 (2023) 137955]

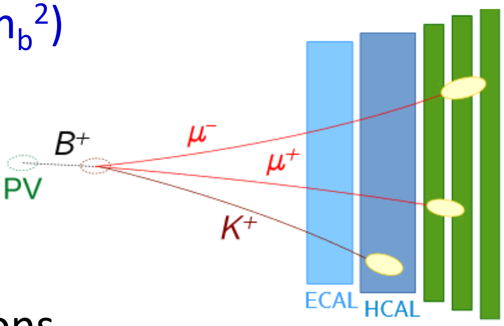
- Uncertainty determined by the knowledge of fragmentation functions (fs/fd, σ ~3%)
- Statistics are a limiting factor.
- $B \to \mu^+\mu^-$ not found yet (BR ~ 10^{-10}) but it should be seen very soon.

Rare B decays: $R_{K, K^*...}$

- In the SM all leptons are expected to behave in the same way

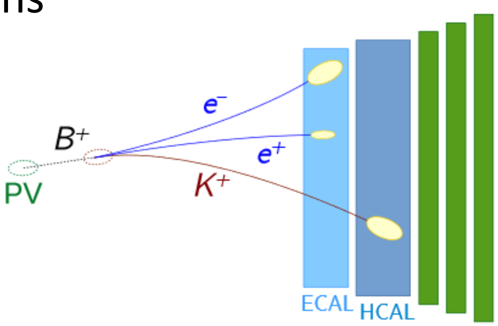
Test of lepton universality:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$ $= 1.000 + O(m_\mu^2/m_b^2)$



- Theory precise due to cancellation of form factors, QED control at % level

- Experimental challenge: bremsstrahlung recovery for electrons

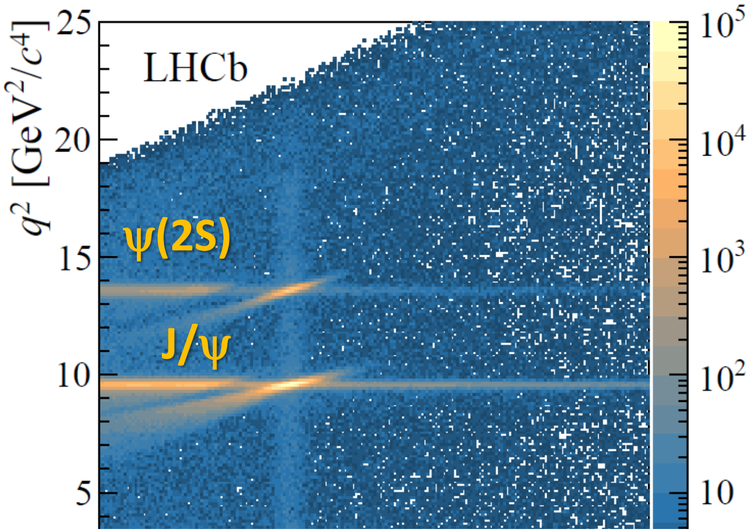


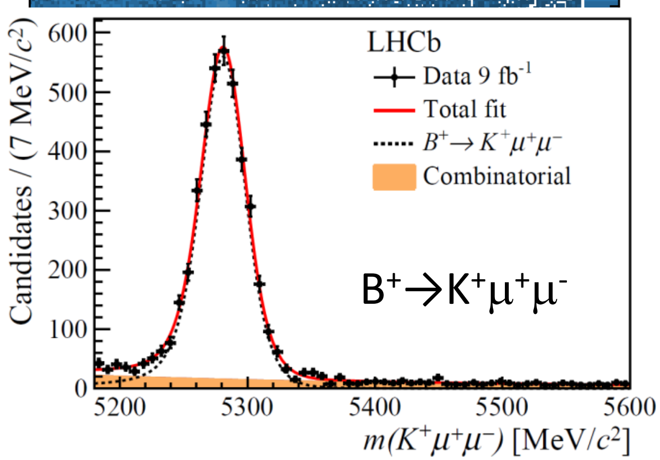
- Double ratio using resonances to cancel systematic uncertainties

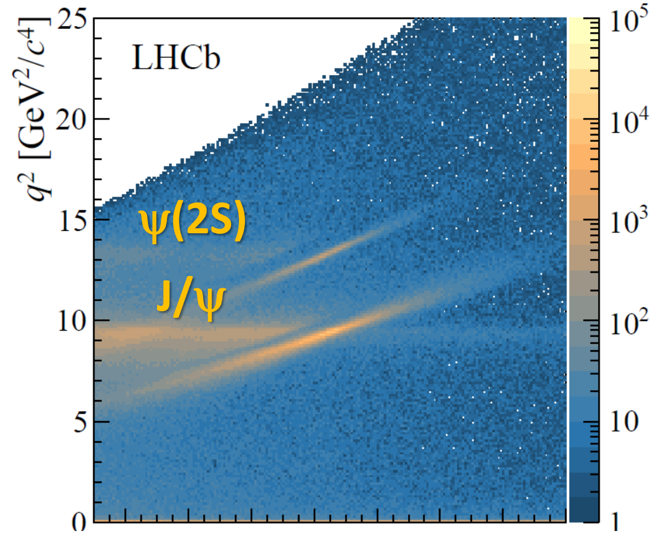
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+ \mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+ e^-))}$$

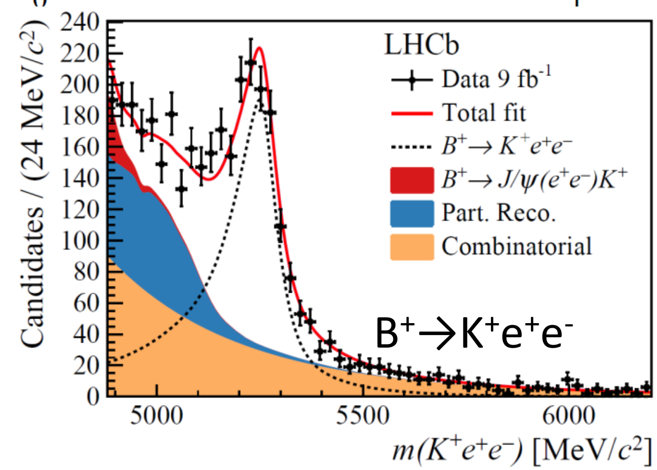
Rare B decays: $R_{K, K^{*}...}$

$$R_{\mathrm{H}}\left[q^2_{\min}, q^2_{\max}\right] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B\to H\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B\to He^+e^-)}{\mathrm{d}q^2}}$$









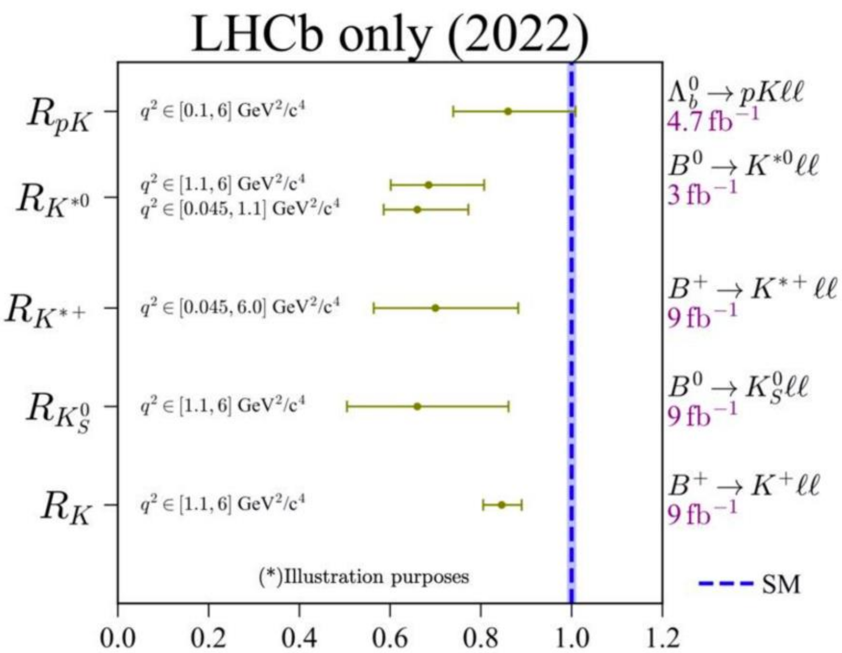
Rare B decays: $R_{K, K^*...}$

- Updated R_K & R_{K^*} 2023 measurement:

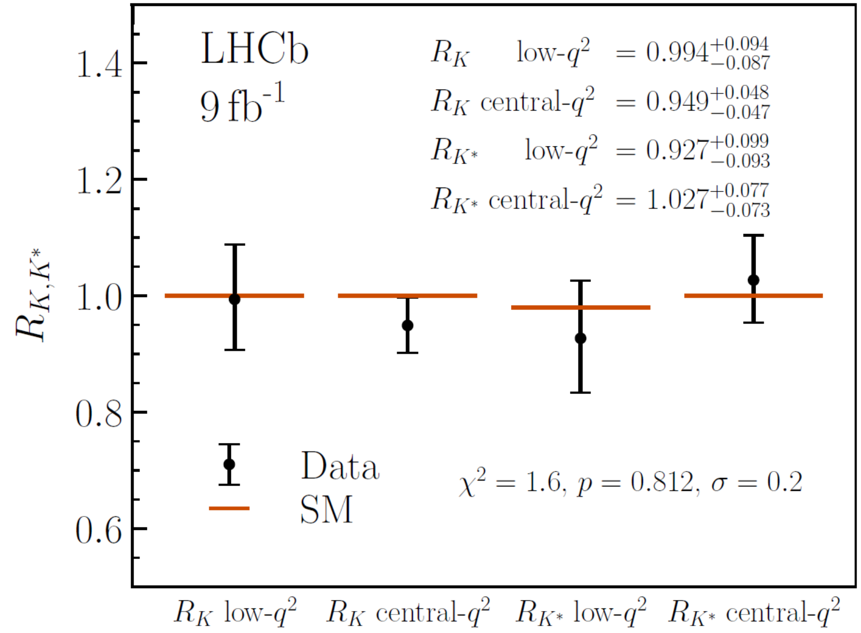
$$R_X = \frac{BR(X_b \to X_s \mu^+ \mu^-)}{BR(X_b \to X_s e^+ e^-)}$$

[PRD 108 (2023) 032002;
PRL 131 (2023) 051803]

Pre Dec 2022



Post Dec 2022

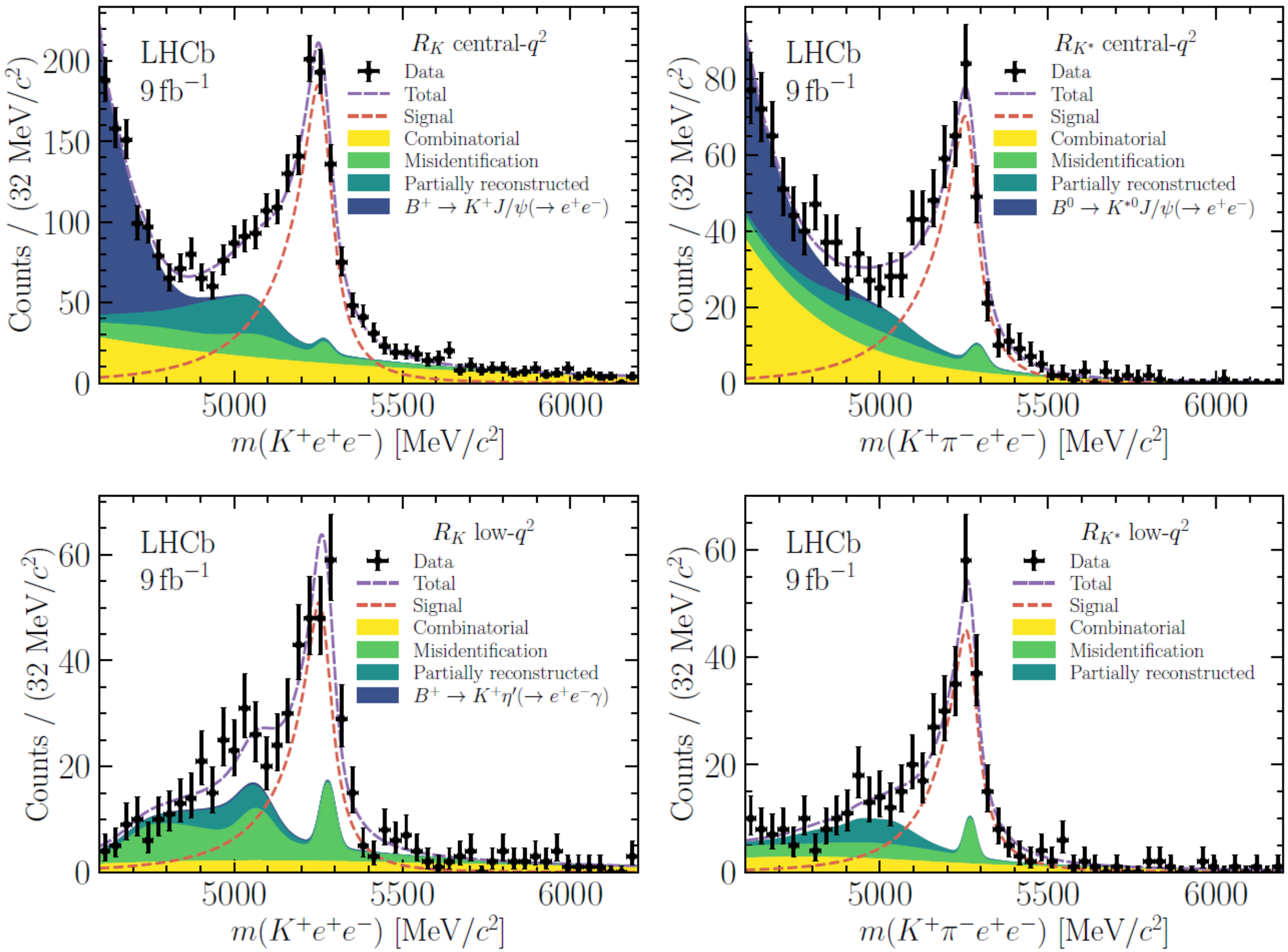


Low q^2 :
$q^2 \in [0.1, 1.1]$ GeV$^2/c^4$

Central q^2 :
$q^2 \in [0.1, 1.1]$ GeV$^2/c^4$

Rare B decays: $R_{K, K^*...}$

- Why? Underestimated peaking background in the electron samples (miss-PID), decreases the signal selection.

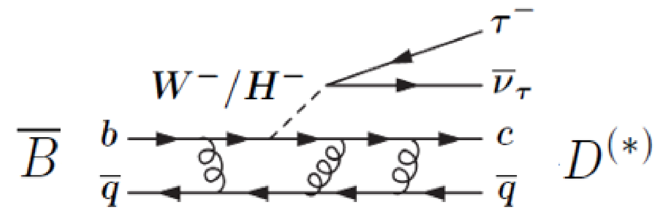


Semileptonic B decays: R_{D}, R_{D*}

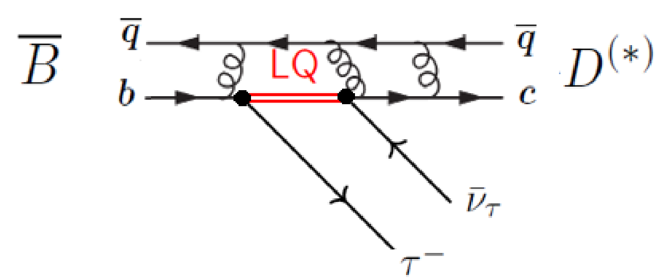
- **Another test of lepton universality** (now at tree level):

Ratio of semi-tauonic and semi-muonic branching fractions:

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$



Sensitive to charged Higgs bosons and leptoquarks



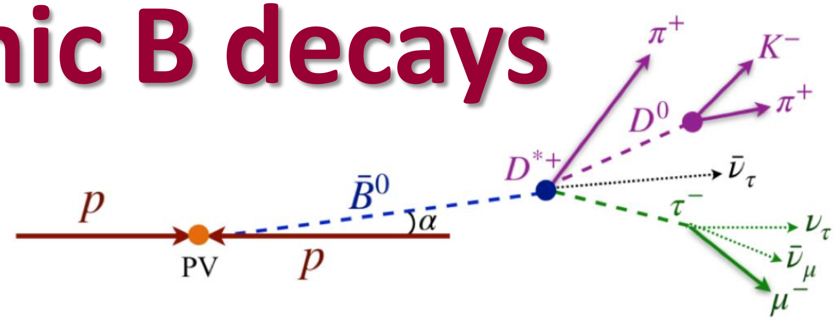
SM predictions very precise : (V_{cb} and form factors (partially) cancel)

$R(D)_{SM}=0.299 \pm 0.003$

$R(D^*)_{SM}=0.252 \pm 0.003$

Based on HQET form factors:
[H. Na *et al.*, PRD 92 (2015) 054510]
[Fajfer, Kamenic, Nišandižć: PRD85 (2012) 094025]
and experimental measurements (HFLAV)
[D.Bigi, Gambino, PRD 94 (2016) 094008]

Semileptonic B decays



- Using tau-leptonic decays: $\tau^- \to \mu^- \nu_\mu \overline{\nu}_\tau$

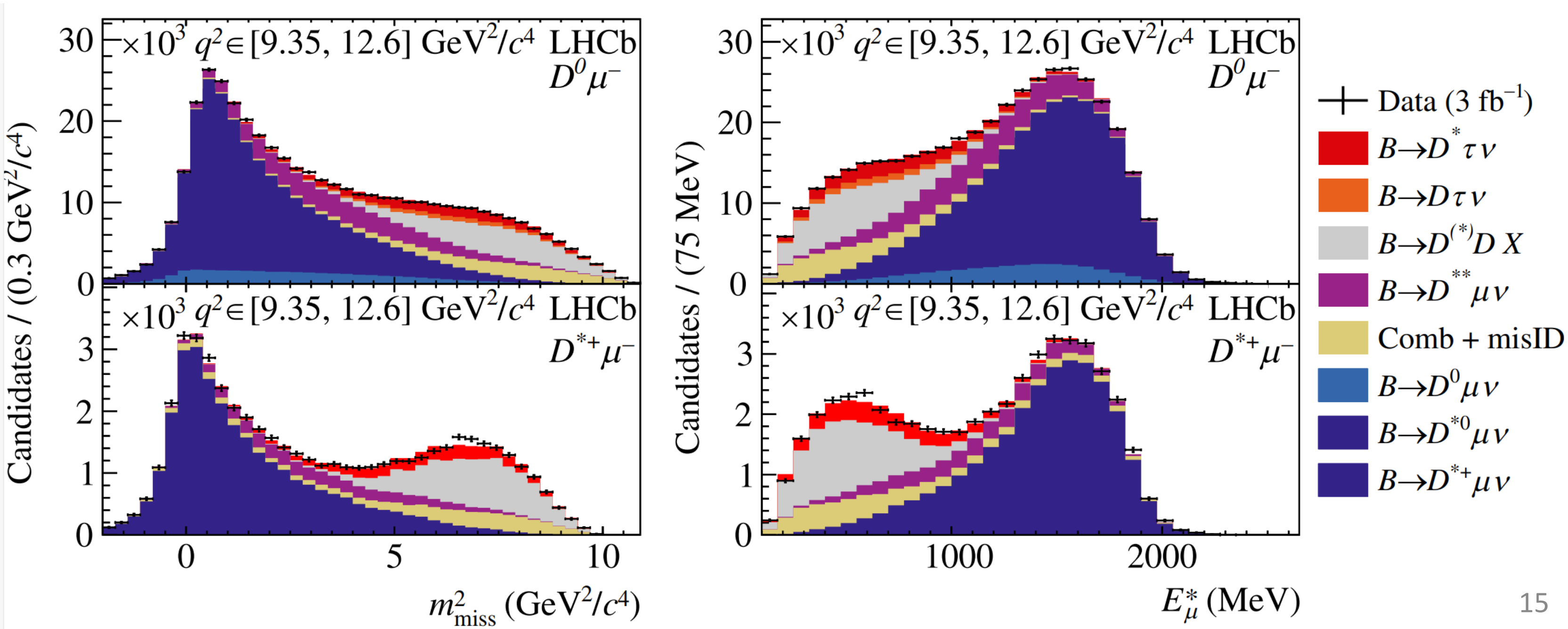
→ Simultaneous analysis of R_D and R_{D*} from muonic decays (Run1, 3 fb^{-1})

→ Information from q^2, missing mass squared $m_{miss}^2 = (P_B - P_{D*} - P_\mu)^2$ and muon energy

[PRL 131 (2023) 111802]

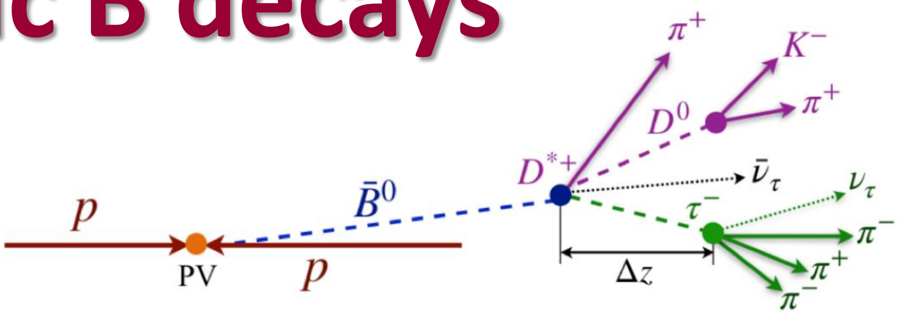
$$\mathscr{R}(D^0) = 0.441 \pm 0.060 \pm 0.066$$
$$\mathscr{R}(D^*) = 0.281 \pm 0.018 \pm 0.024$$

(corr.-0.43)



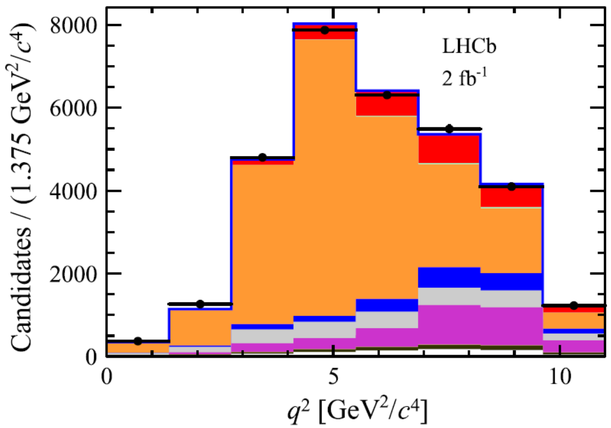
Semileptonic B decays

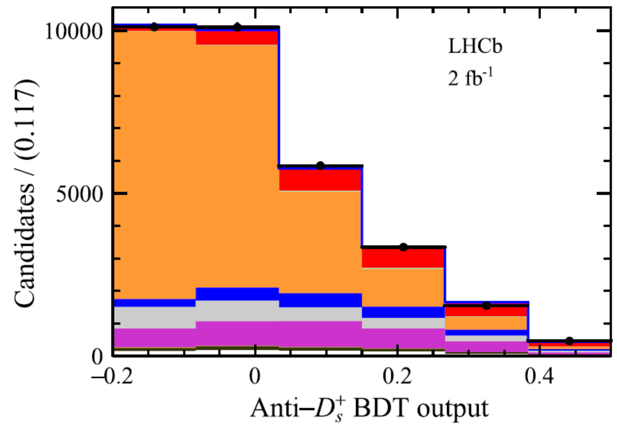
- Using tau-hadronic decays: $\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau$

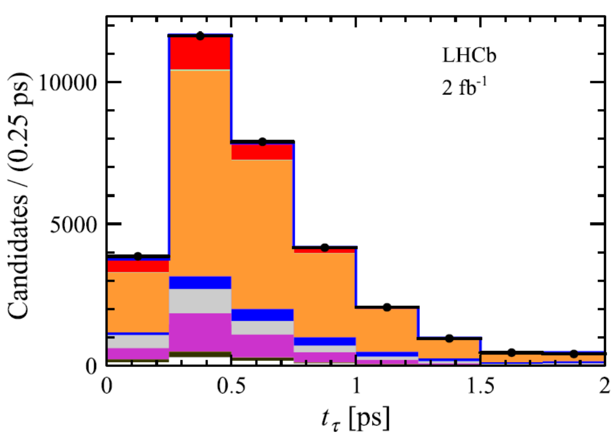


Information from the position of the pions.
Normalised to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

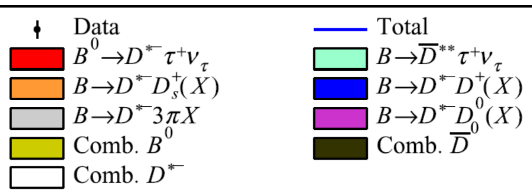
[PRD 108 (2023) 012018]







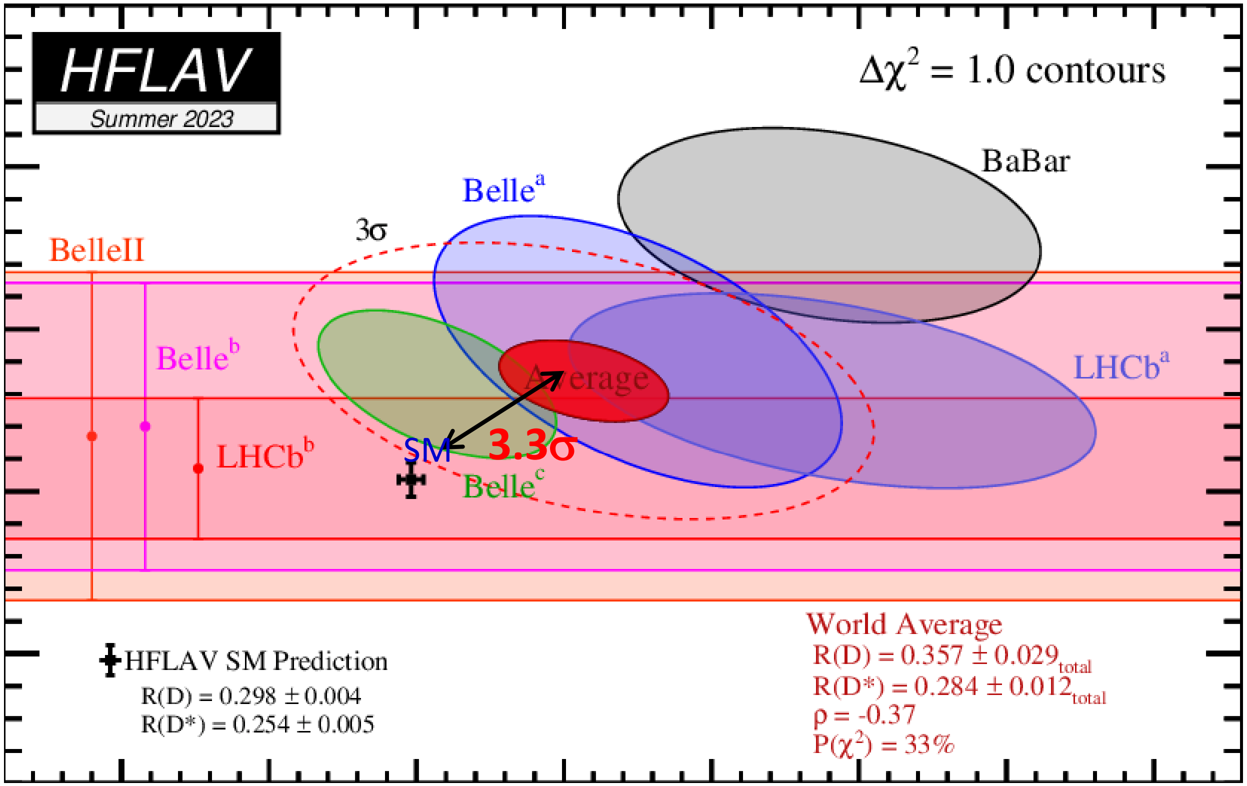
$$\mathscr{R}(D^{*-}) = 0.247 \pm 0.015 \pm 0.015 \pm 0.012$$



(systematics dominated by the size of simulation samples (efficiencies, pdf shape modelling, etc…))

Semileptonic B decays

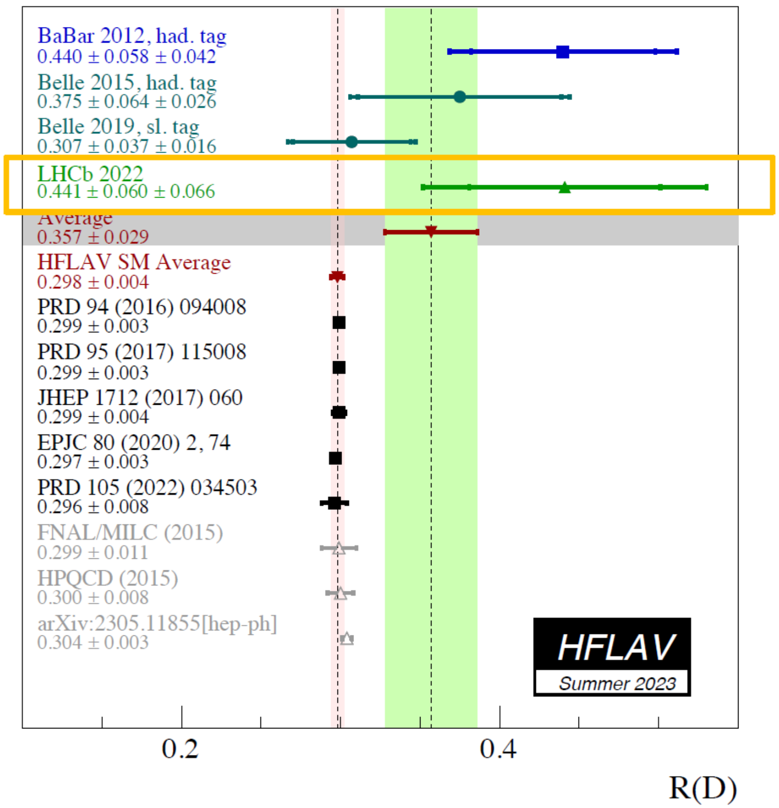
- Present global picture of R_D and R_{D^*}



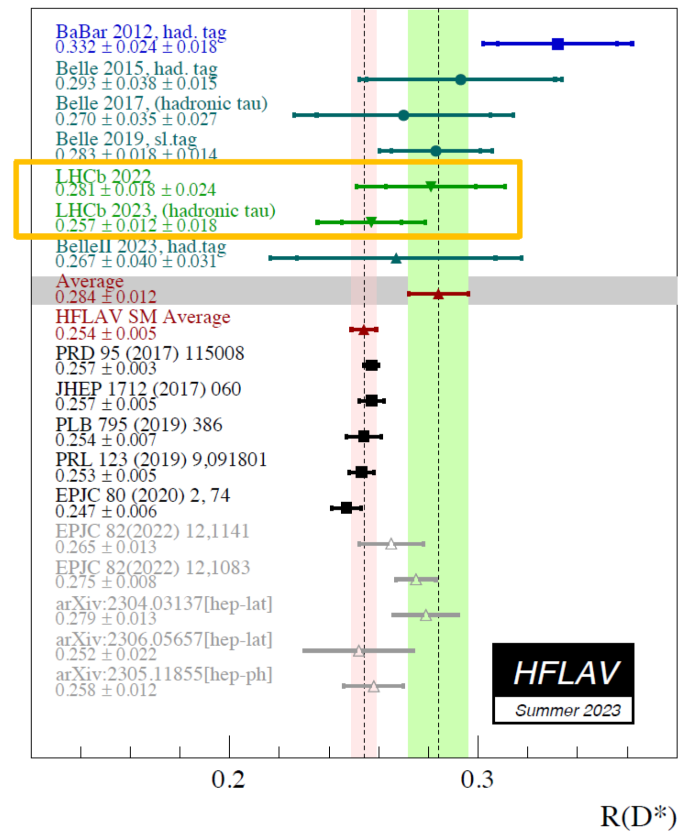
→ Average: **3.3σ** deviation from SM

Semileptonic B decays

- Present global picture of R_D and R_{D^*}

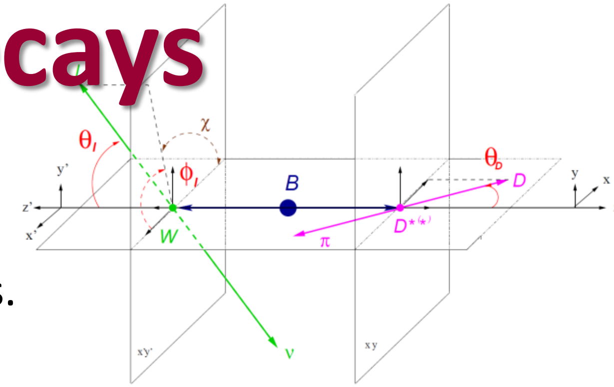


$R(D) \rightarrow 2.0\sigma$ from SM prediction



$R(D^*) \rightarrow 2.2\sigma$ from SM prediction

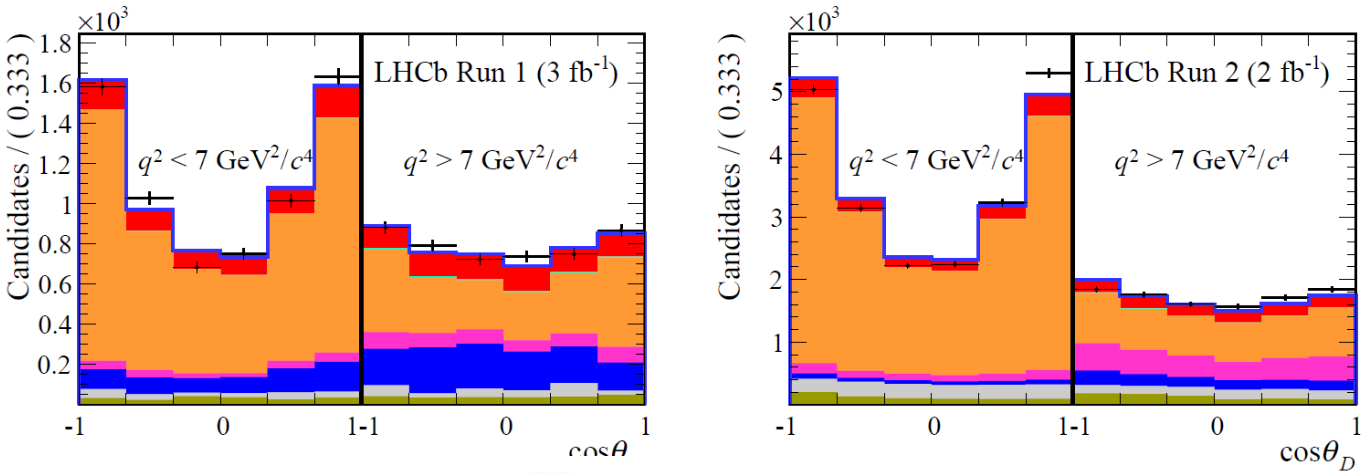
Semileptonic B decays



- Measurement of the D* longitudinal polarization, $F_L(q^2)$, using tau-hadronic decays (3 fb^{-1} (Run1) + 2 fb^{-1} (Run2))
- $F_L(q^2)$ allows to discriminate between new physics scenarios.

[arXiv:2311.05224]

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D \longrightarrow F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$



$$q^2 < 7\,\mathrm{GeV}^2/c^4 \;:\; F_L^{D^*} = 0.51 \pm 0.07\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

$$q^2 > 7\,\mathrm{GeV}^2/c^4 \;:\; F_L^{D^*} = 0.35 \pm 0.08\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$$

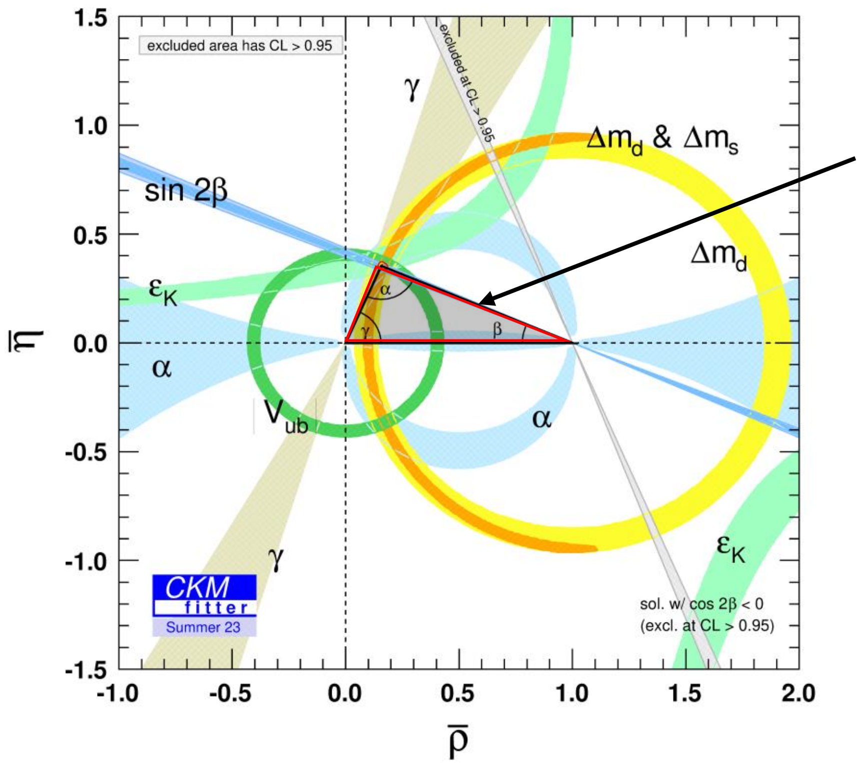
$$\boxed{F_L^{D^*} = 0.43 \pm 0.06\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})}$$

(Compatible with the SM)

CKM and CP Violation

- The CKM matrix can be parameterized in terms of 4 fundamental parameters:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$



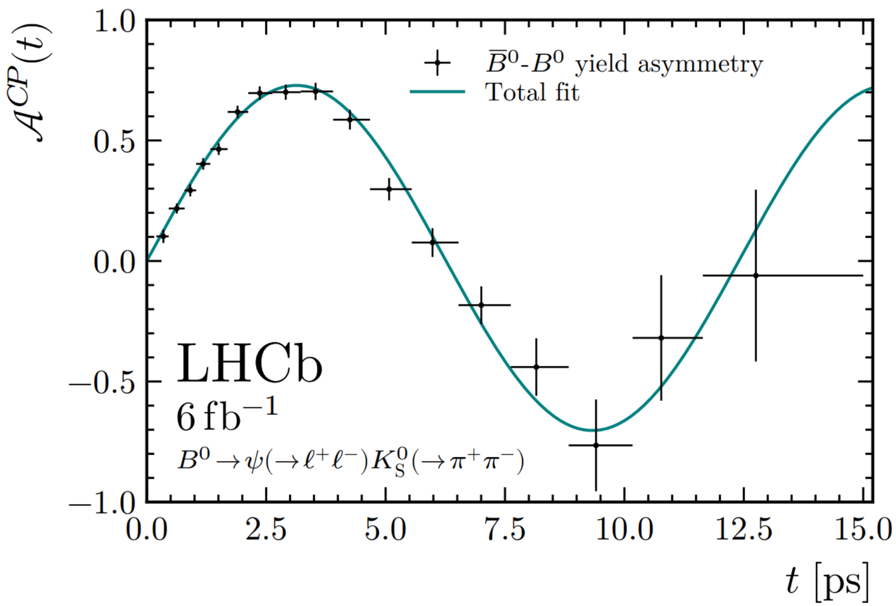
- Flavour observables can be expressed as function of these parameters:
  Unitary Triangle

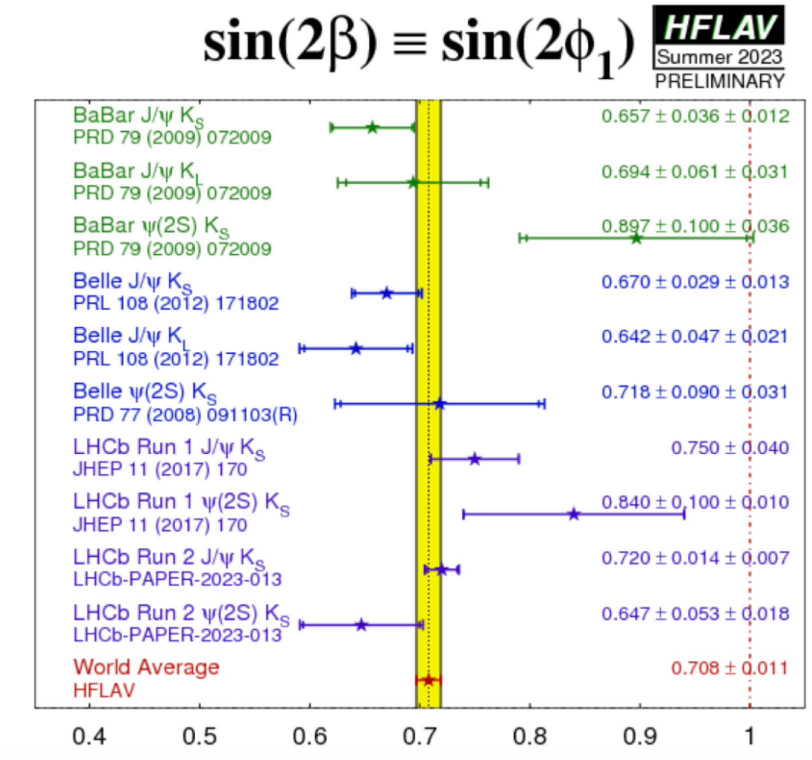
  ➜ Very high level of precision (few %)
  ➜ No inconsistencies

CKM and CP Violation

[arXiv:2309.09728]

- sin2β from the Interference between mixing and decay amplitudes in B decays



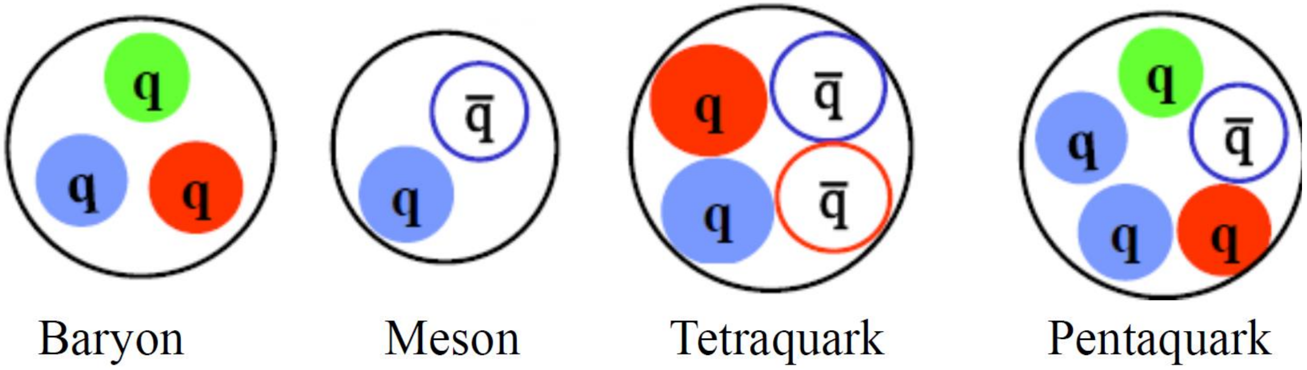


$$S_{\psi K^0_S} = 0.717 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C_{\psi K^0_S} = 0.008 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$

Most precise determinations from a single experiment, compatible with CKM fitters.

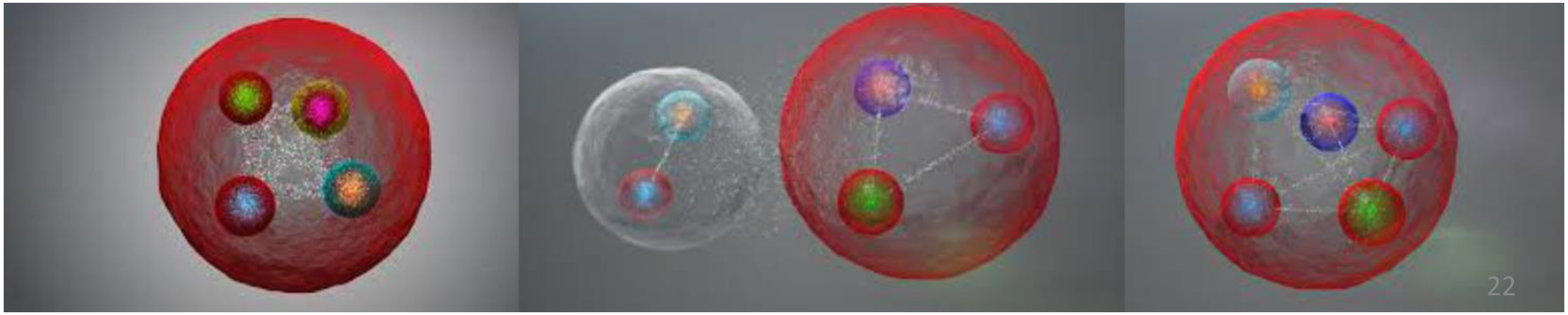
Exotics

• There are several possibilities for combining quarks with color into colorless hadrons, as predicted from the origin of the Quark Model [M. Gell-Mann, PL8 (1964) 214]



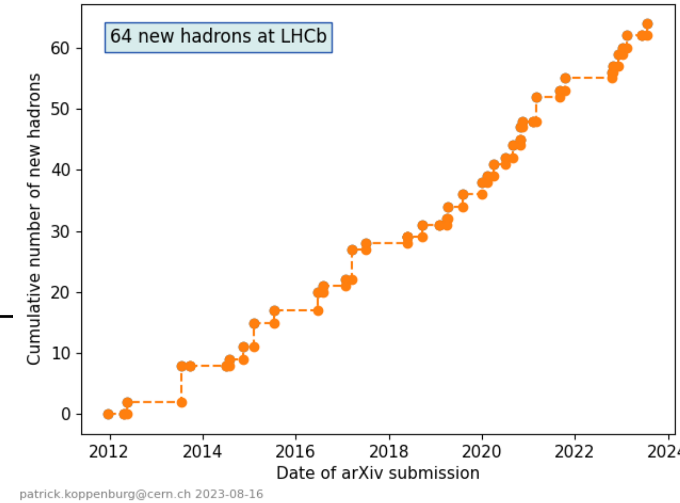
• Several of these states have been announced since 1970, but have disappeared with time and new data analysis…

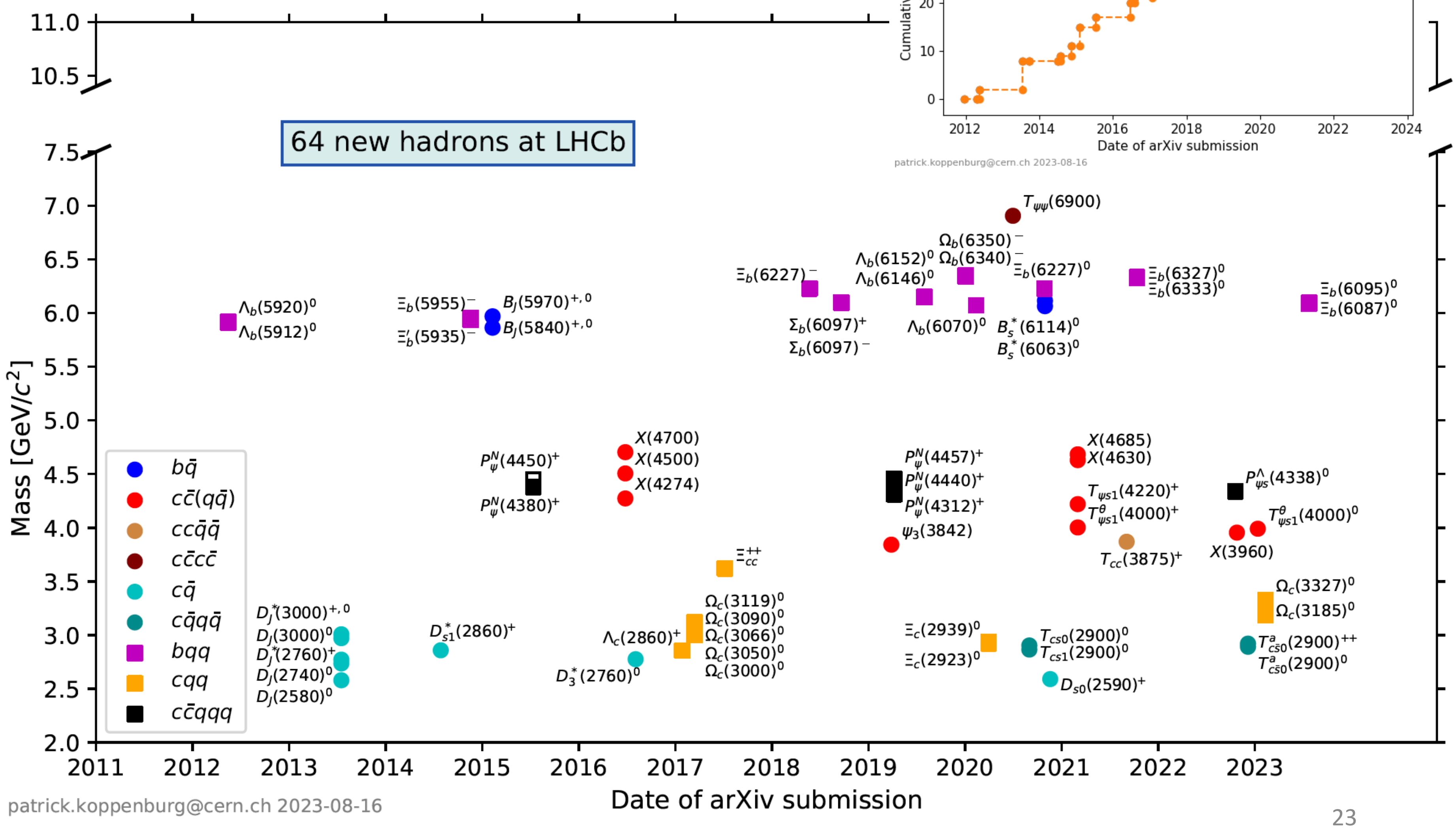
• Important for our understanding of the matter structure and QCD!



Exotics

- More than 60 new hadrons discovered in the last decade!! (most of them by LHCb):





Future

- More exotics (in progress, search at IFIC):

Stable Sexaquarks:

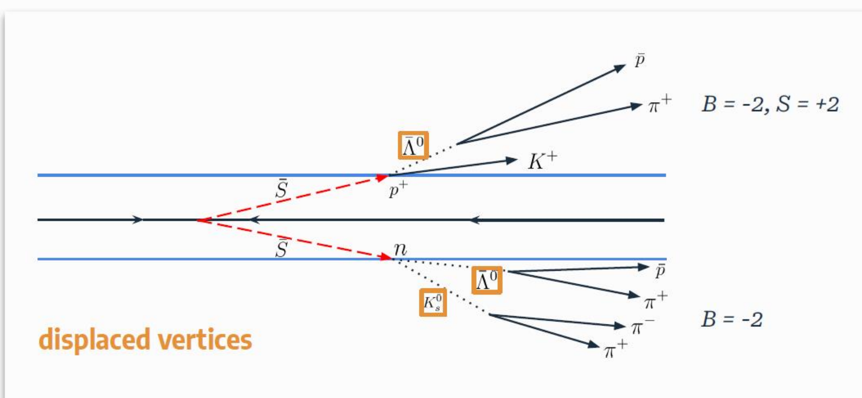
Refers to a specific particle proposed by G. Farrar with *uuddss* quark content [arXiv:2306.03123]

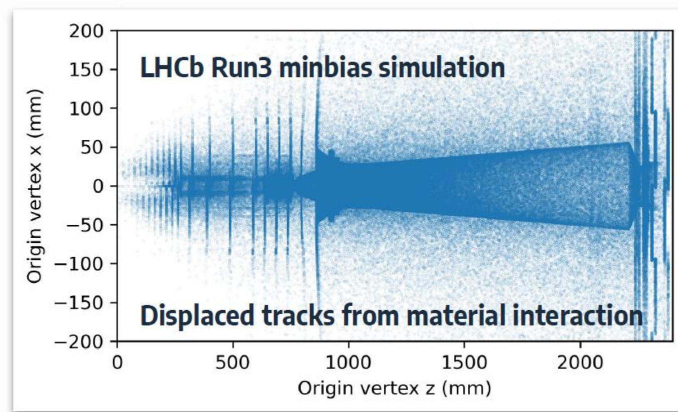
- Electric charge 0
- Spin, Isospin and SU(3) flavour single
- Baryon number 2

Could be a dark matter candidate
Could solve the g-2 muon puzzle

- $\bar{S} + n \rightarrow \bar{\Lambda}^0 K^0_s$ (+ n pions) $\longrightarrow$ proves $\bar{S}$ has B=-2
- $\bar{S} + p^+ \rightarrow \bar{\Lambda}^0 K^+$(+ n pions) $\longrightarrow$ proves $\bar{S}$ has B=-2 and S=+2

(PhD Jiahui Zhuo)





Future

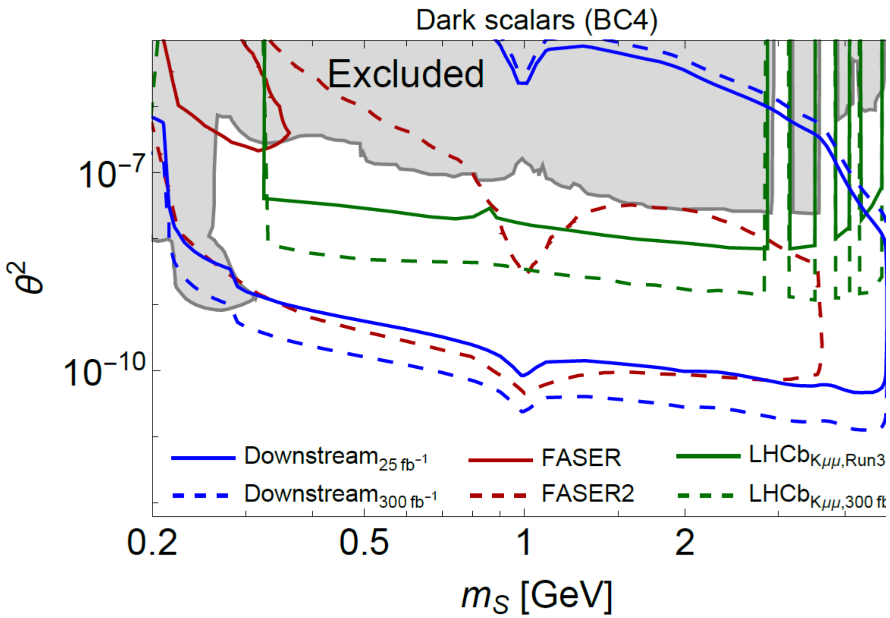
- More exotics (in progress, search at IFIC):

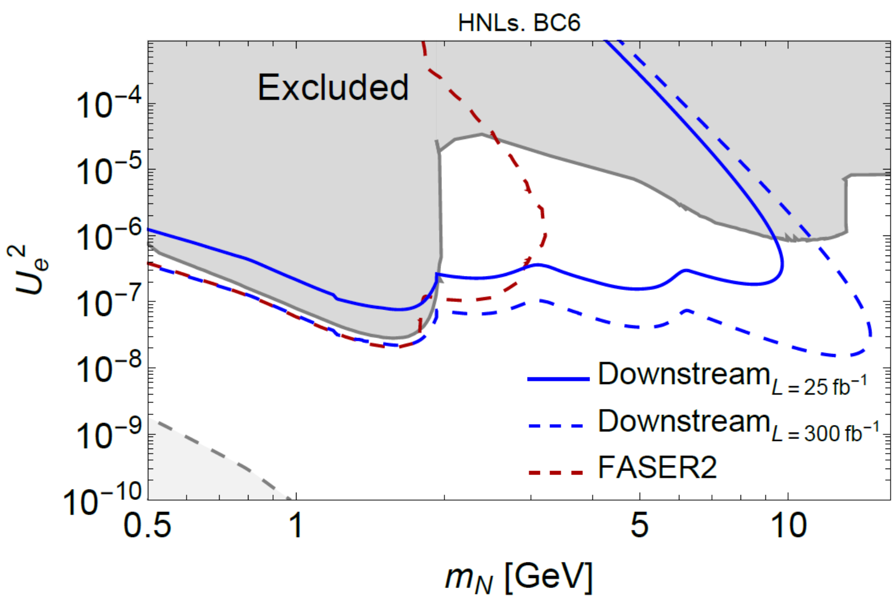
[New LLPs:](#) [arXiv:2312.14016]

The development of new algorithms in the new trigger scheme at LHCb based on GPUs increases a lot the sensitivity to new long lived particles with tau > 100 ps.

(B. Jashal (IFIC) CERN-THESIS-2023-249)

Dark bosons, Heavy Neutral Leptons, etc…





Future

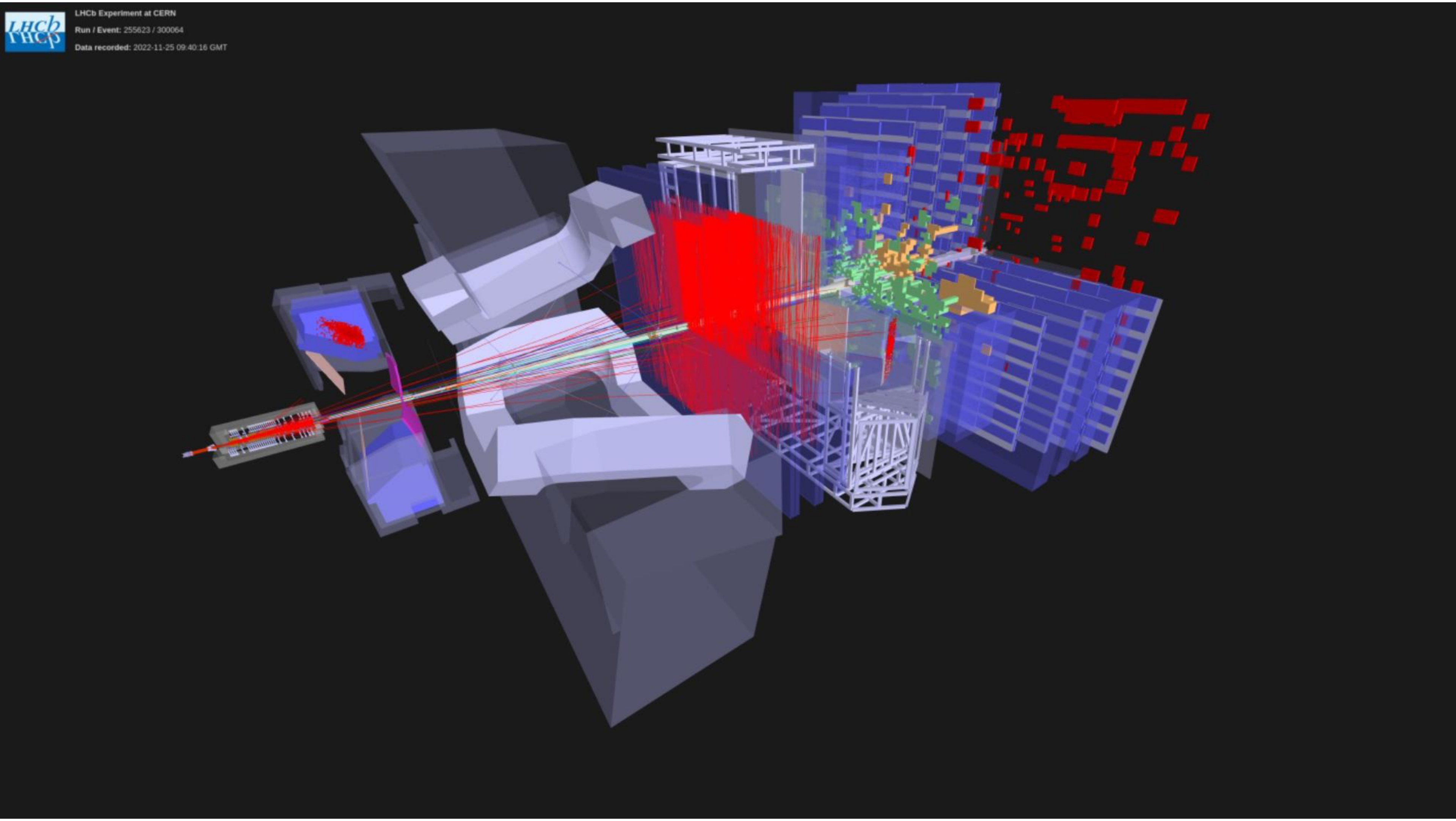
- 2023 has not been a good year for LHCb…

  - $R_{K,K*}$ and other observables have “model standardized”.
  - Incident in the VELO detector, not possible to close it.
  - The UT detector (central tracker) not ready to run in global.
  - In addition to other LHC problems…

- A positive view:
  - We have learnt a lot about PID at LHCb.
  - At IFIC we have developed a new trigger algorithm and reconstruction techniques that hugely increase the LHCb potential for exotic searches. [arXiv:2312.14016]

Let’s cross fingers to acquire good and surprising data in 2024!

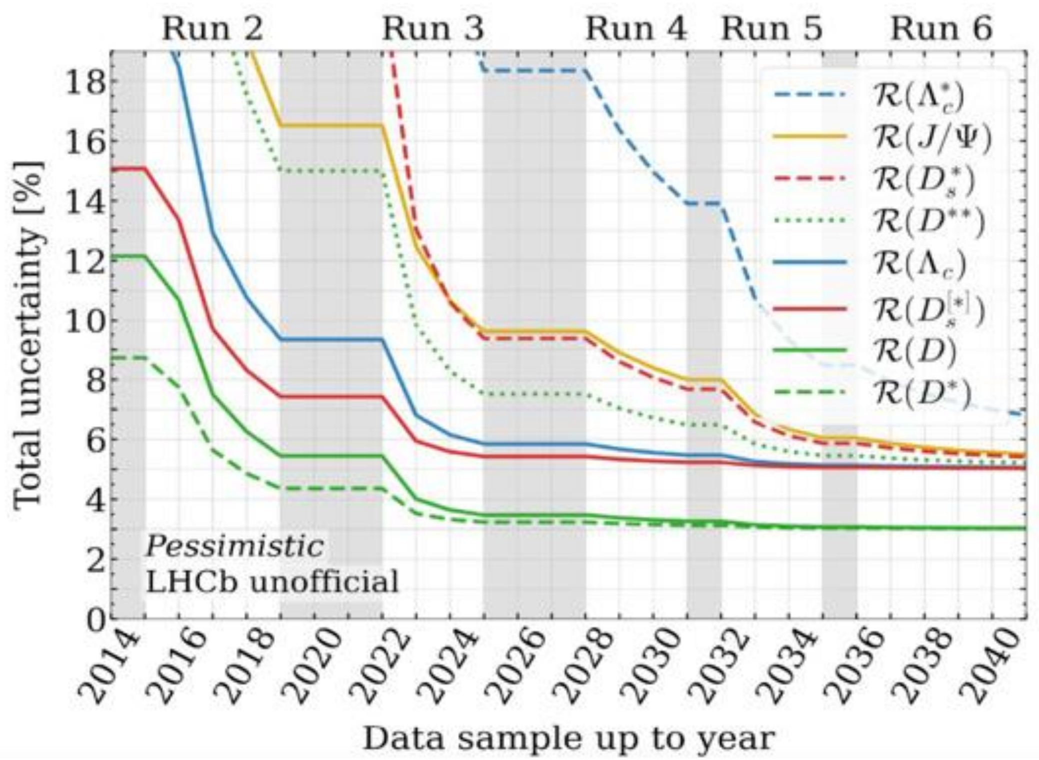
Thanks!


LHCb
LHCb Experiment at CERN
Run / Event: 255623 / 300064
Data recorded: 2022-11-25 09:40:16 GMT

Backup

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B^0_s \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a^d_{\rm sl}$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a^s_{\rm sl}$ ($B^0_s \to D^-_s\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K^0_{\rm S}\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—		—	—	0.2
$A^{(2)}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A^{\rm Im}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

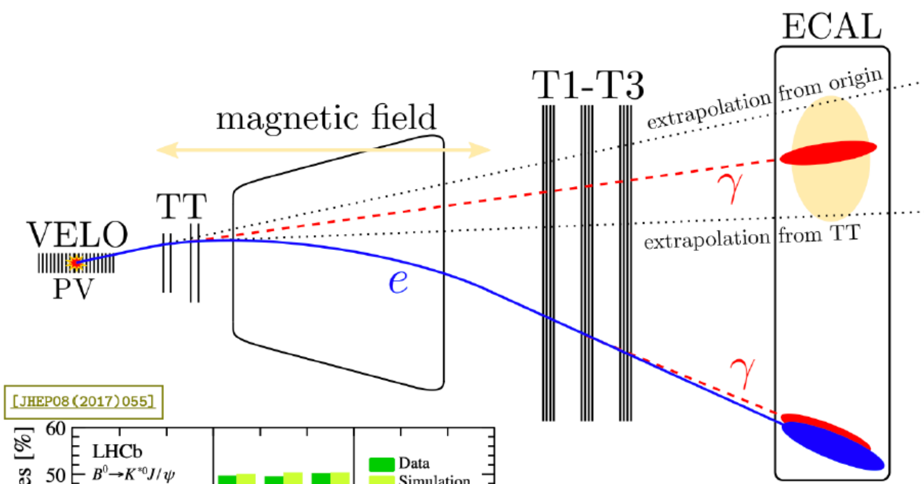
Backup

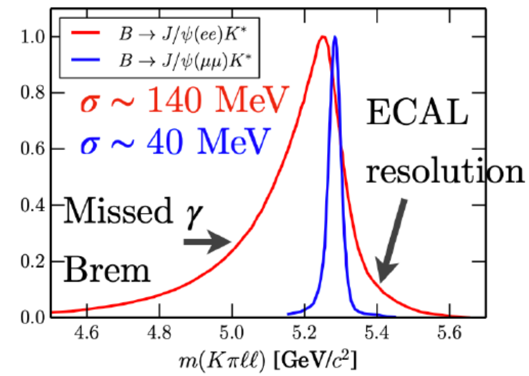


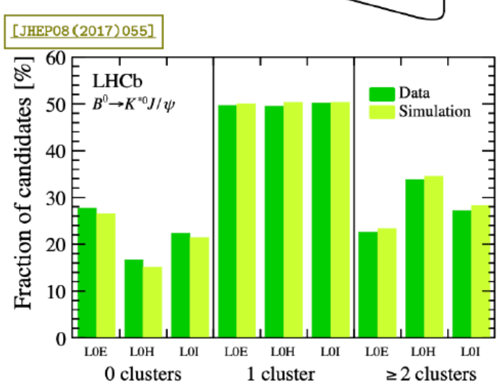
Run 2
Run 3
Run 4
Run 5
Run 6
Total uncertainty [%]
0
2
4
6
8
10
12
14
16
18
2014
2016
2018
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040
Data sample up to year
$\mathcal{R}(\Lambda_c^*)$
$\mathcal{R}(J/\Psi)$
$\mathcal{R}(D_s^*)$
$\mathcal{R}(D^{**})$
$\mathcal{R}(\Lambda_c)$
$\mathcal{R}(D_s^{[*]})$
$\mathcal{R}(D)$
$\mathcal{R}(D^*)$
Pessimistic
LHCb unofficial

Backup

electrons and energy loss







$\simeq$

- Brem recovery is O(50%) efficient
- Well described in simulation

Wider fit range than muons

- more background,
- more sensitive to peaking structures
- lineshapes are brem-dependent