Test of Lepton Flavour Universality in semileptonic *b*-decays, R(H_c)

Jibo HE/何吉波(UCAS)

CEPC味物理–新物理与相关探测技术研讨会

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Large Hadron Collider

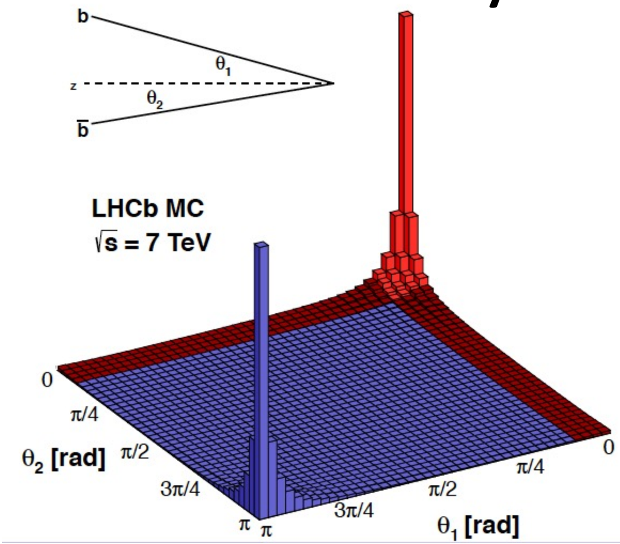
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

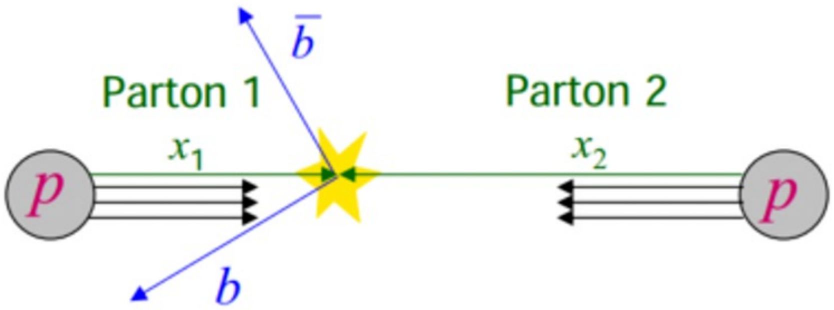
Beauty/charm production

- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb c.f. 1nb @$\Upsilon(4S)$

  (Charm and Beauty:) Flavour factory!

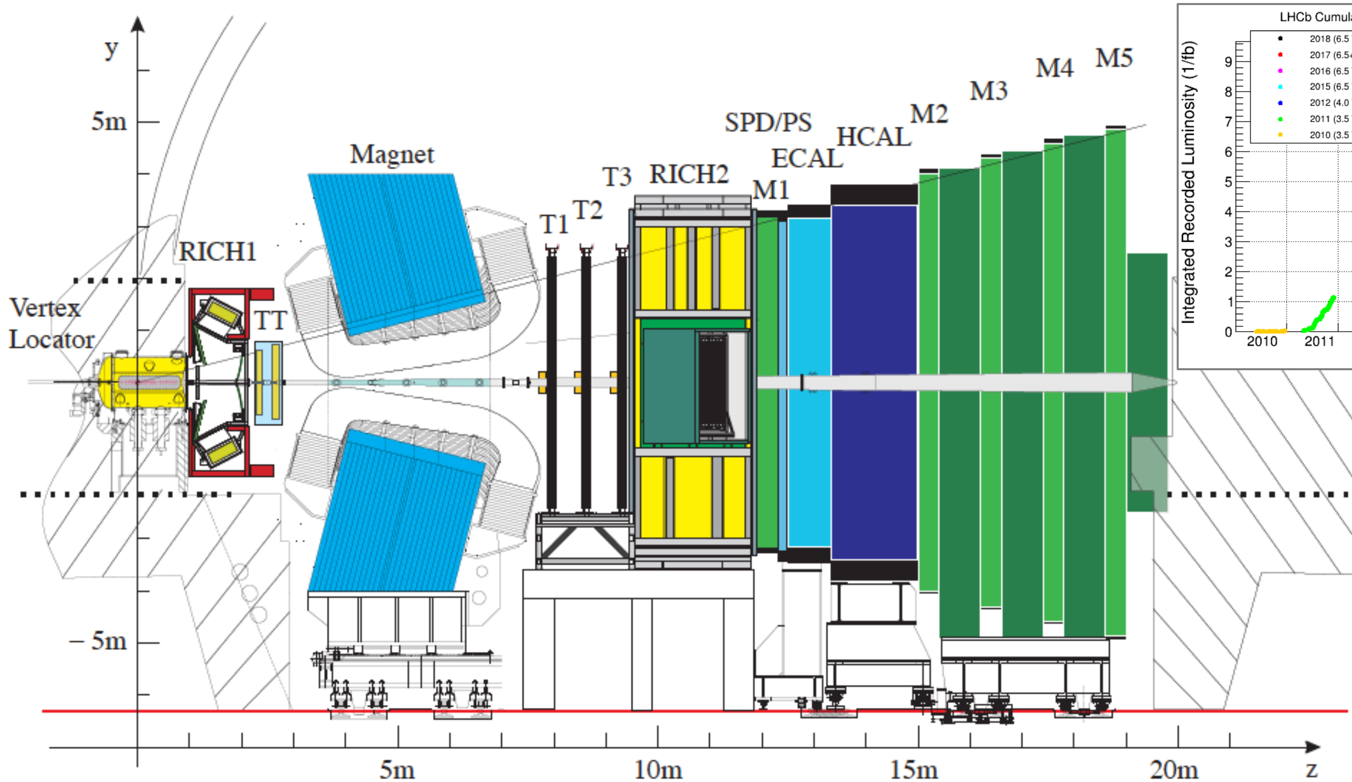
- Predominantly in forward/backward cones

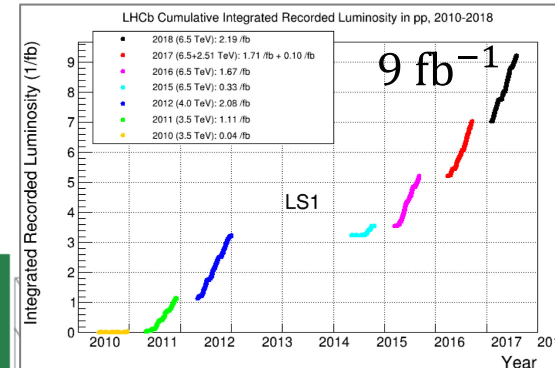




Initial energy of $b\bar{b}$ not known

The LHCb experiment

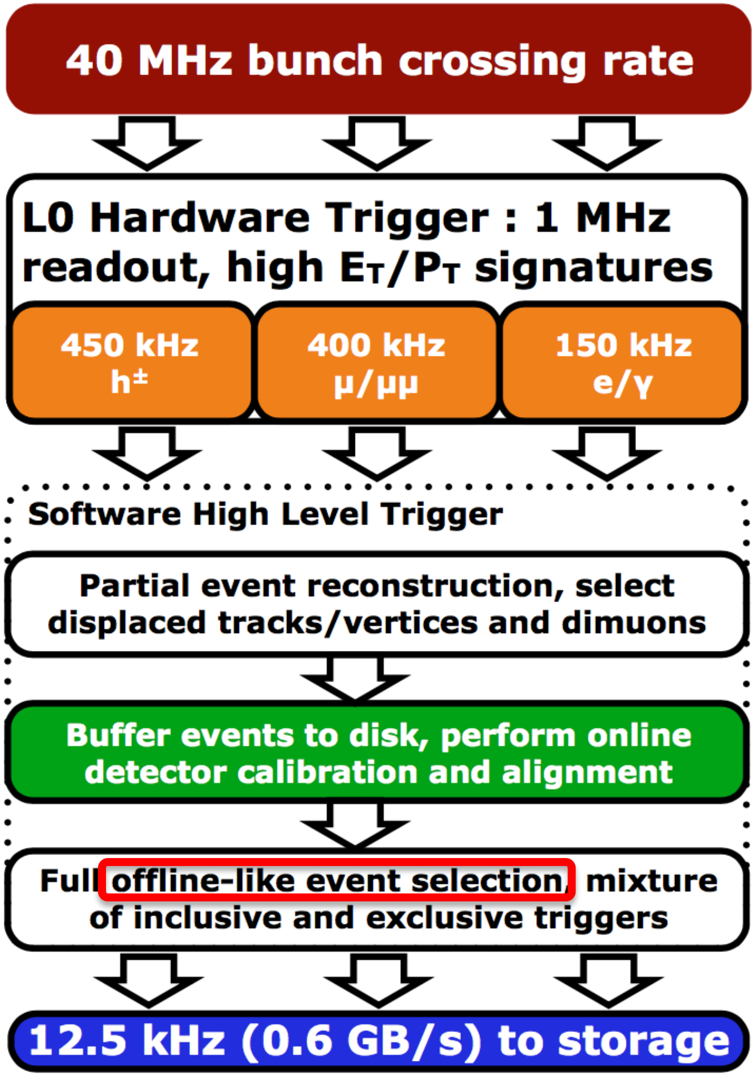




[JINST 3 (2008) S08005]

Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

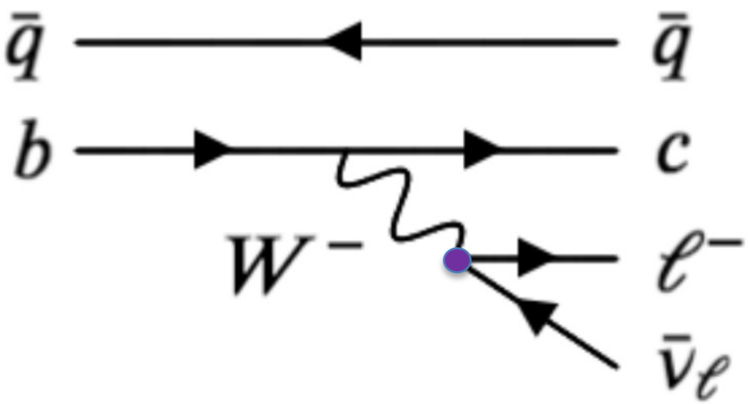
The LHCb trigger (2018)

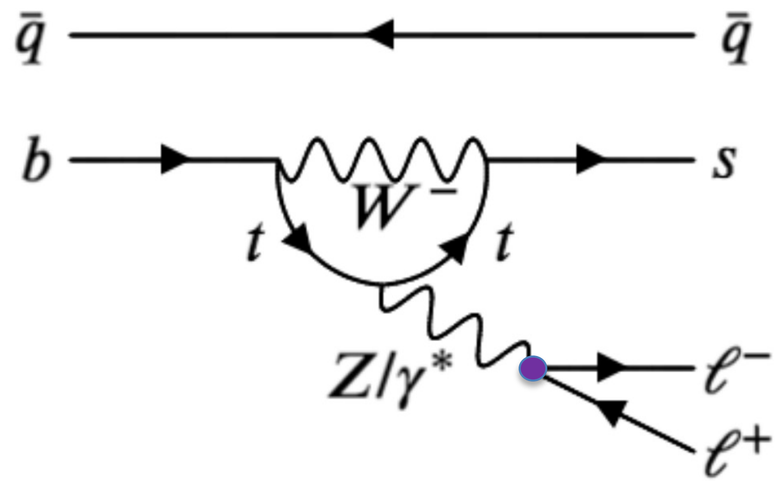


- L0, Hardware
  - $p_T(\mu_1)\times p_T(\mu_2) >$ (1.5 GeV)^2
  - $p_T(\mu) >$ 1.8 GeV
  - $E_T(e) >$ 2.4 GeV
  - $E_T(\gamma) >$ 3.0 GeV
  - $E_T(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_T, IP
  - Stage2, full selection

Lepton flavour universality

- In SM, three lepton families (e, μ, τ) have identical couplings to the gauge bosons





  - which means, e.g.,

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

$\mathcal{O}(10^{-4})$ uncertainty
[C. Bobeth *et al.*, JHEP 12 (2007) 040]

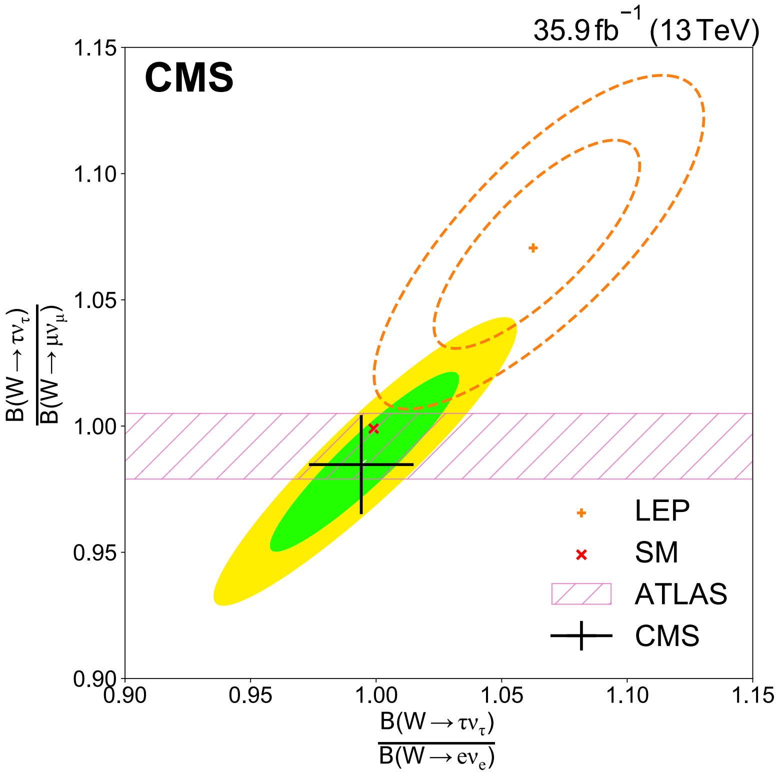
$\mathcal{O}(1\%)$ QED correction
[M. Bordone *et al.*, EJPC 76 (2016) 440]

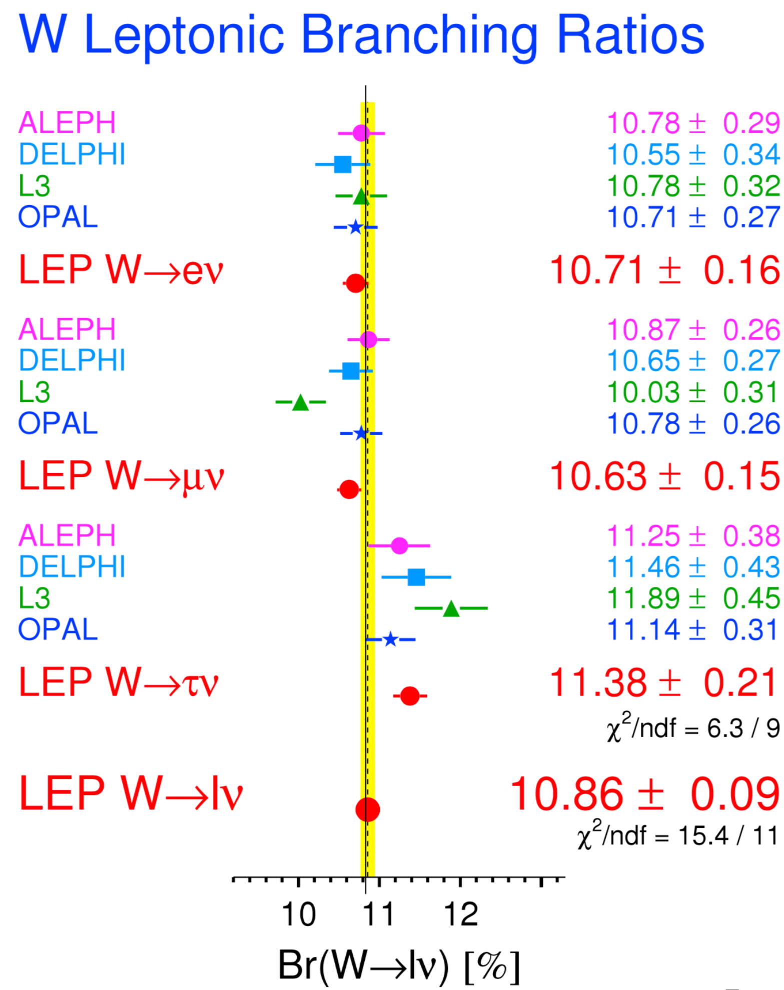
- Lepton flavor universality violation? New Physics!

Experimental test of LFU

- Well established in SM, e.g. $W \to \ell\nu$
  - Some tension at LEP, addressed by ATLAS/CMS

[ATLAS, NP 17 (2021) 813; CMS, PRD 105 (2022) 072008]



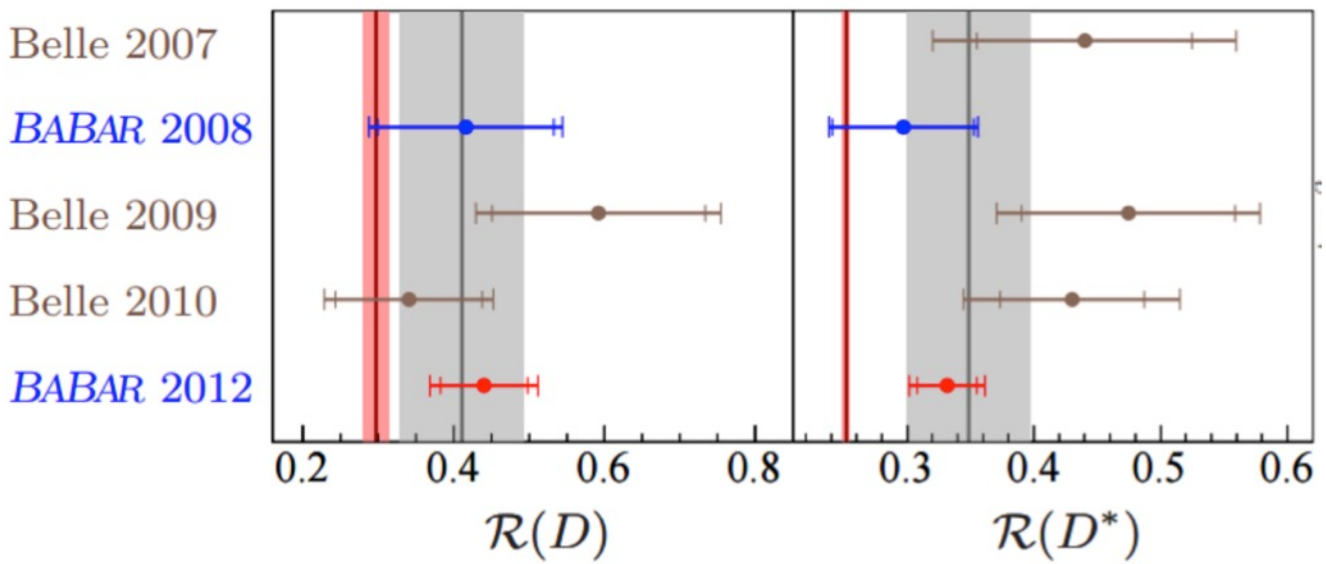


LFU in B system, pre-LHCb

- $R(D^{(*)})$, Babar reported deviation of ~3.2σ

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

[Babar, PRD 88 (2013) 072012]



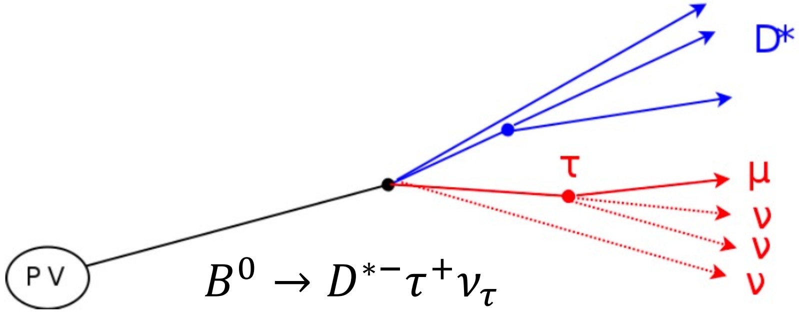
- No deviation seen in FCNC $b \to s\ell^+\ell^-$ decays

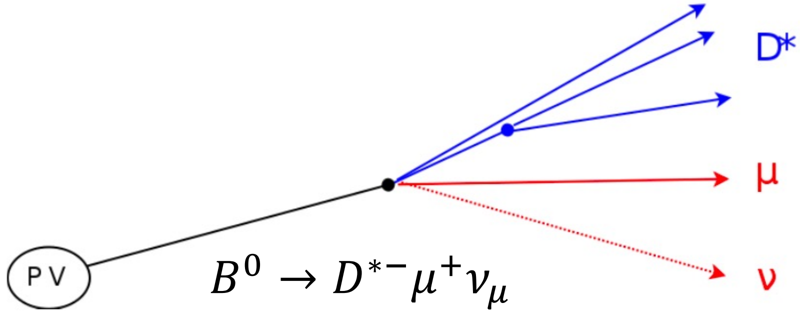
$R(H_c)$, exp. challenge at LHCb

- Definition $R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$
- Signal
  - Missing energy by neutrinos, no narrow peak
  - Use B flight direction, pRec algo* to get $\boldsymbol{p}_B^{\mathrm{pRec}}$

$$m_{\mathrm{miss}}^2 \equiv \left(\boldsymbol{p}_B^{\mathrm{pRec}} - \boldsymbol{p}_{D^{(*)}} - \boldsymbol{p}_\mu\right)^2, \; q^2 = \left(\boldsymbol{p}_B^{\mathrm{pRec}} - \boldsymbol{p}_{D^{(*)}}\right)^2$$

* More in [F. U. Bernlochner *et al.*, RMP 94 (2022) 015003]



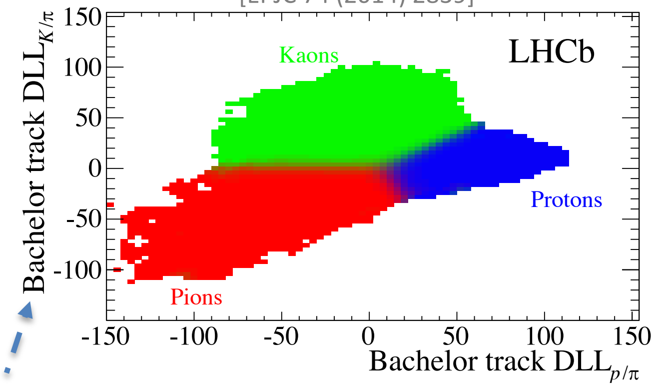


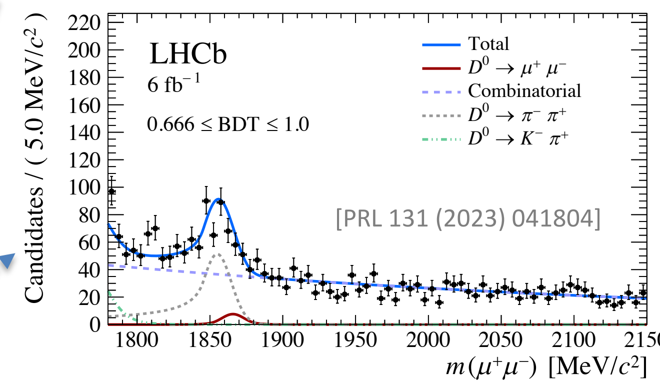
$R(H_c)$, exp. challenge at LHCb

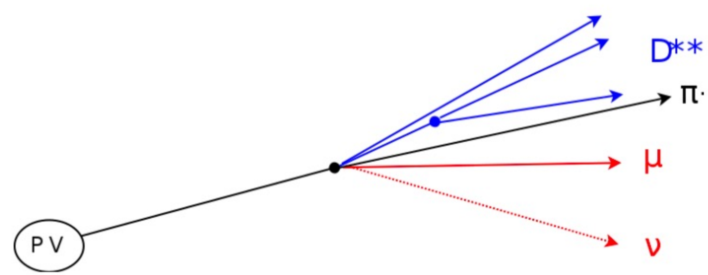
- Background $(H_c + \mu)$
  - Fake H_c H_c sideband
  - Fake μ H_c+Track

    Each reweighted by $\sum F_i P_{i\to\mu}$
    - F_i, probability of a track to be a particlar particle
    - $P_{i\to\mu}$, mis-ID rate, use calib sample, note decay-in-flight
  - True H_c and muon, e.g.,
    - $B \to D^* D(\to \mu X)X$
    - $B \to D^{**}\mu\nu$ isolation

[EPJC 74 (2014) 2839]







$R(D^{(*)})$ using muonic τ decays

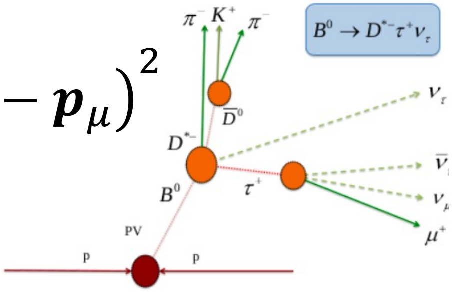
[arXiv:2302.02886, accepted by PRL]

- $\mathcal{B}(\tau \to \mu X)$~17.4%
- 3D fits
  - Signal yields: 44 000
  - Systematics: Simulation size, form factors, …

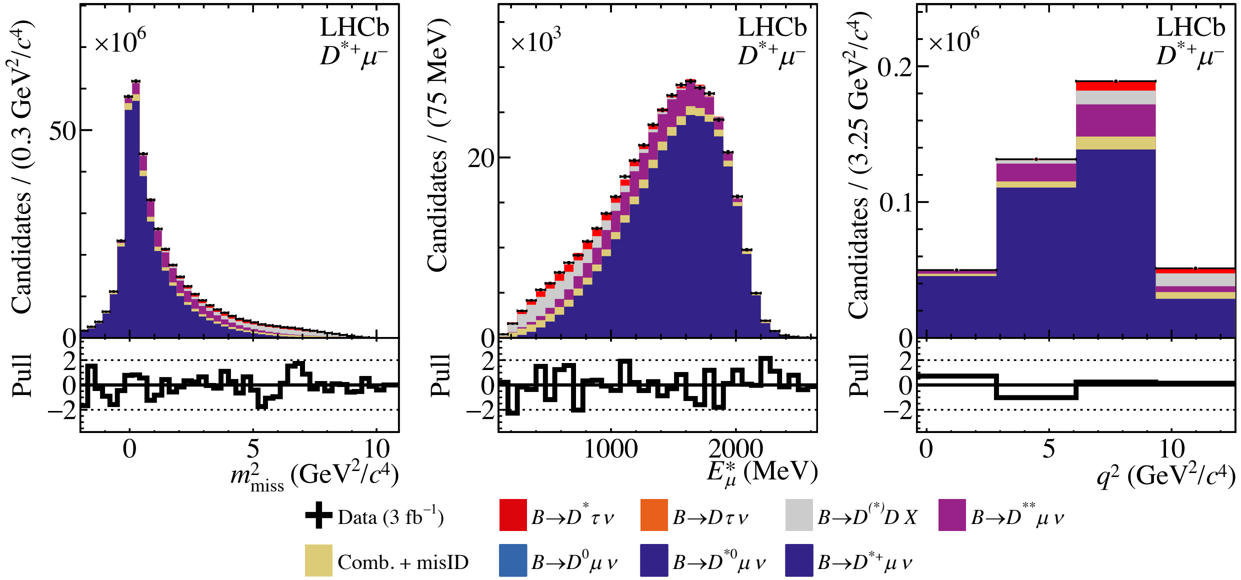
$m^2_{\text{miss}} \equiv \left(\boldsymbol{p}_B^{\text{pRec}} - \boldsymbol{p}_{D^{(*)}} - \boldsymbol{p}_\mu\right)^2$

E^*_μ, energy of μ

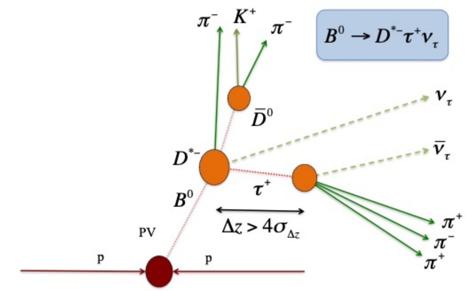
$q^2 = \left(\boldsymbol{p}_B^{\text{pRec}} - \boldsymbol{p}_{D^{(*)}}\right)^2$



R(D*)=0.281 ± 0.018 ± 0.023



$R(D^*)$ using 3-prong τ decays

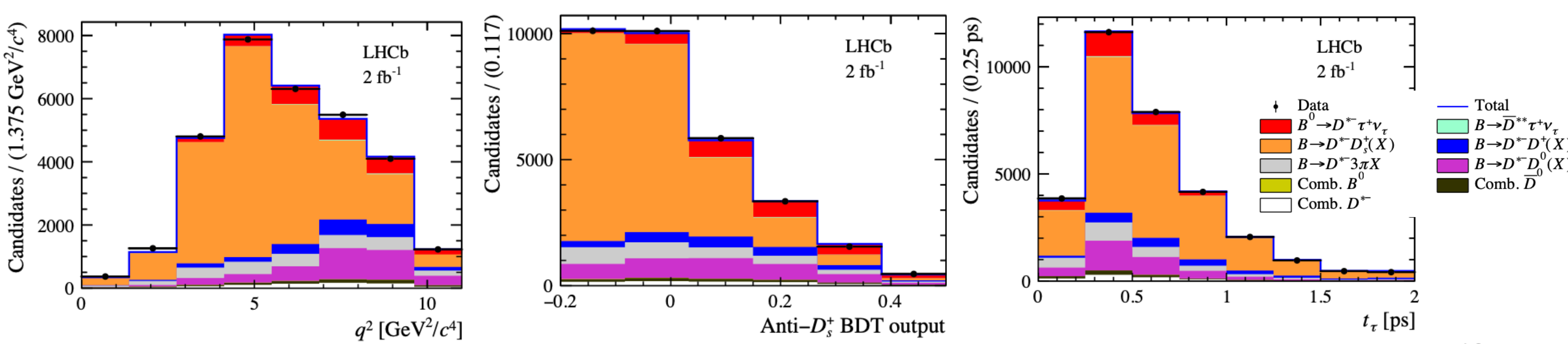


- $\mathcal{B}(\tau \to 3\pi^{\pm}X)$~9%+4%(≥1π⁰)
- Normalized to $B^0 \to D^{*-}3\pi$

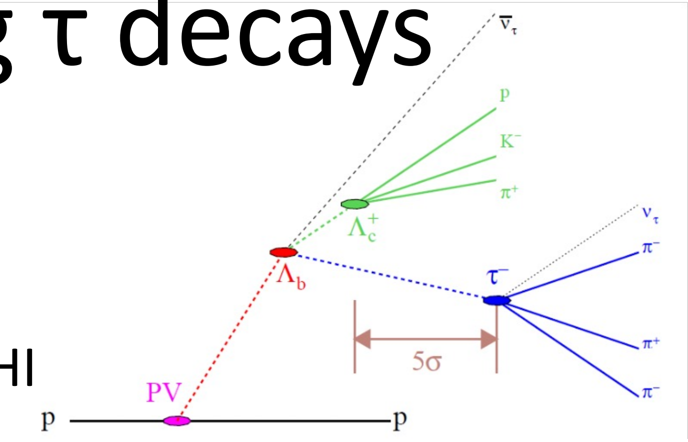
$$R_{had}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)} \quad R(D^*) = R_{had}(D^*) \times \frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^-\nu_\mu)}$$

- 3D fits, R(D*)=0.247 ± 0.015 ± 0.015 ± 0.012
  - Signal yields: 2469 ± 154
  - Systematics: Simulation size, $D \to 3\pi X$ template, …

[PRD 108 (2023) 012018]



$R(\Lambda_c^+)$ using 3-prong τ decays

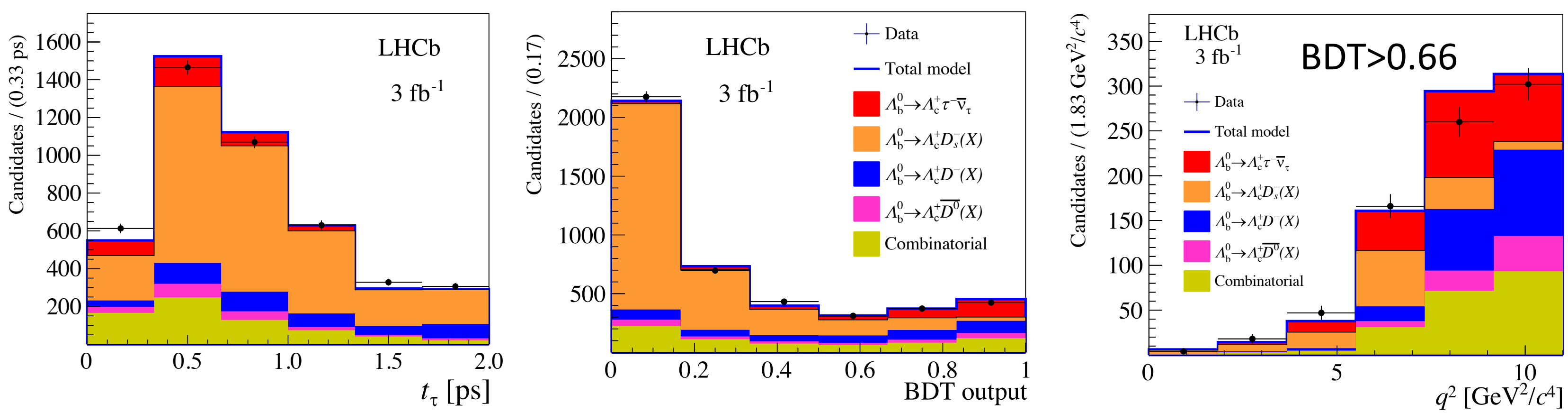


- Noramalized to $\Lambda_b^0 \to \Lambda_c^+ 3\pi$

  $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu) = (6.2 \pm 1.4)\%$ by DELPHI

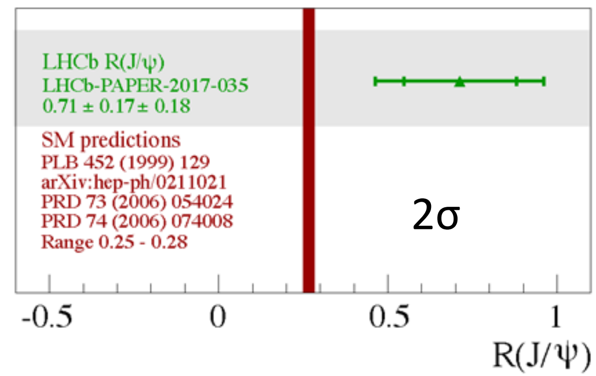
- 3D fits, $R(\Lambda_c^+)$=0.242 ± 0.026 ± 0.040 ± 0.059
  - Signal yields: 349 ± 40
  - Systematics: $D \to 3\pi X$ template, $\Lambda_b^0 \to \Lambda_c^+ D X$

[PRL 128 (2022) 191803]



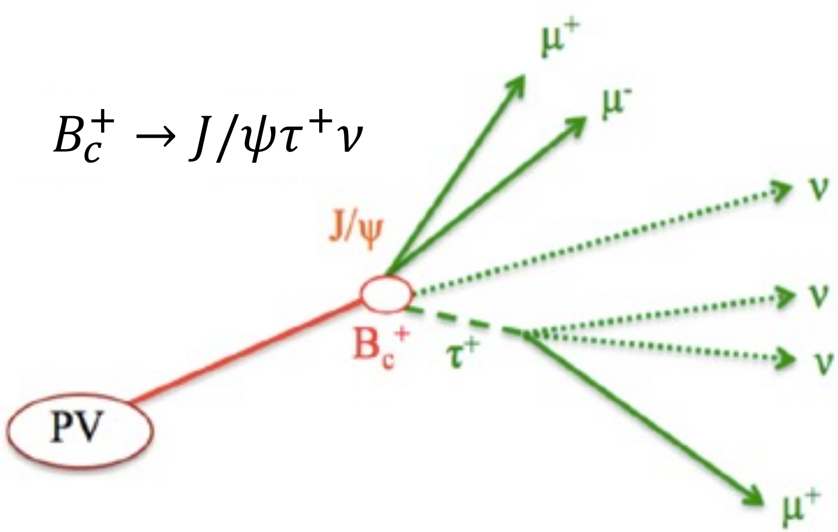
$R(J/\psi)$ using munoic τ decays

- Measure $R(J/\psi)$ using munoic τ decays
  - Pros: 3μ, $\mathcal{B}(\tau \to \mu X)$~17.4%
  - Cros: small $\sigma(B_c^+)$, no τ vertex
- Run-I, 1400 $\pm$ 300 signal (3σ)

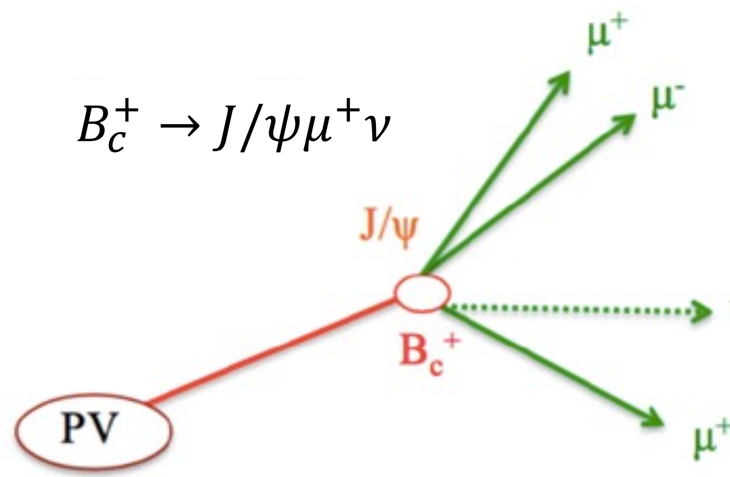


[PRL 120 (2018) 121801]

$B_c^+ \to J/\psi \tau^+ \nu$



$B_c^+ \to J/\psi \mu^+ \nu$

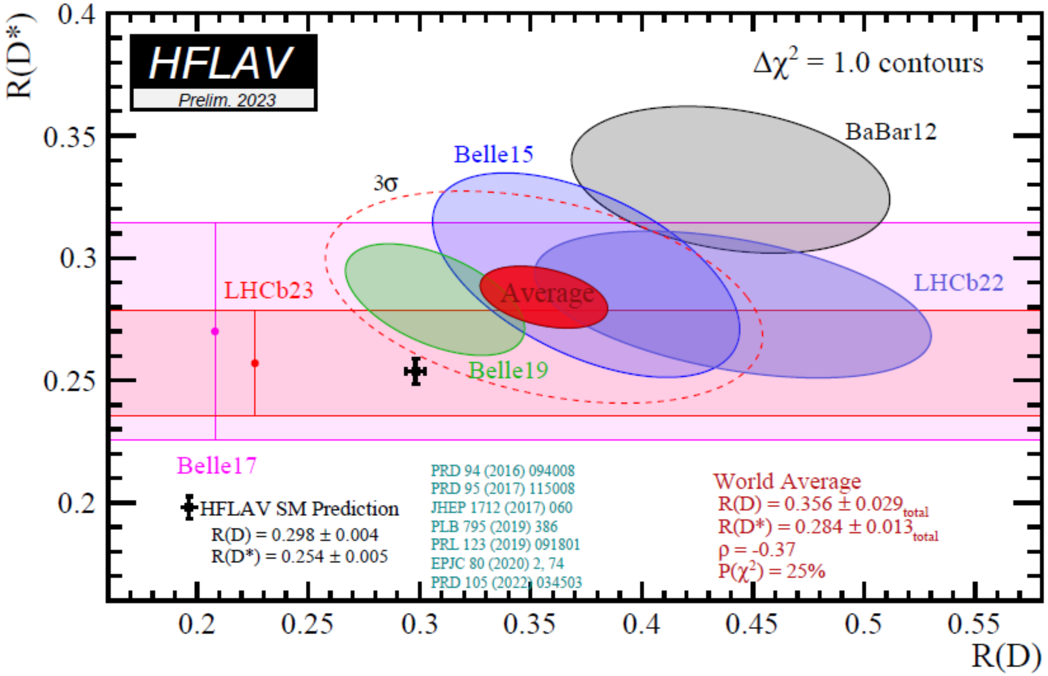


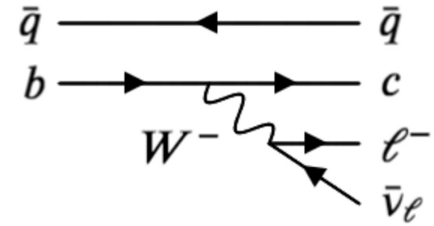
Systematics, one example

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	**Correlation**
Statistical uncertainty	1.8	6.0	-0.49
Simulated sample size	1.5	4.5	
$B \to D^{(*)}DX$ template shape	0.8	3.2	
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (\overline{B} \to D^* D_s^- (\to \tau^-\overline{\nu}_\tau) X)$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	0.5	0.5	
Combinatorial	< 0.1	0.1	
Resolution	< 0.1	0.1	
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7	
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.8	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
MisID template unfolding	0.7	1.2	
Baryonic backgrounds	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D^0)$	
Total systematic uncertainty	2.4	6.6	-0.39
Total uncertainty	3.0	8.9	-0.43

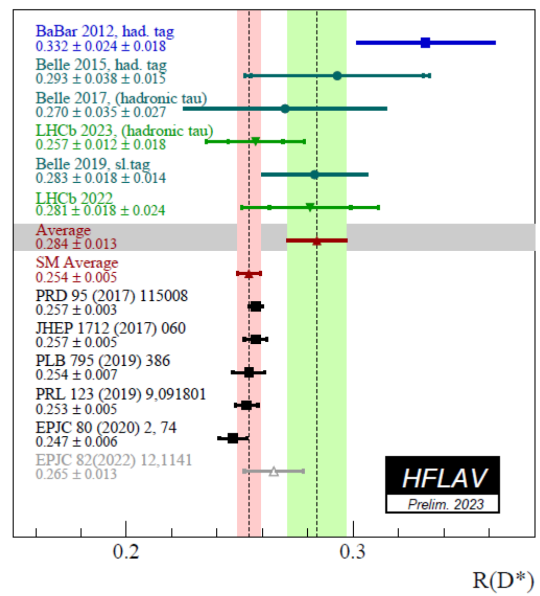
Summary of LFU in $b \to c\ell\nu$ decays

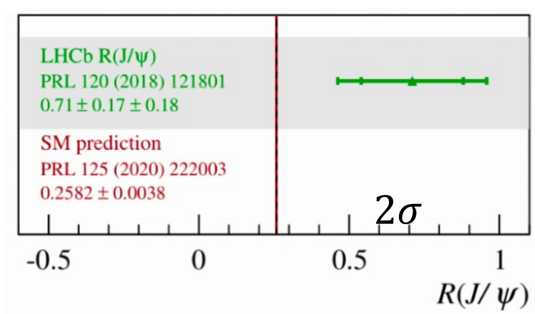
- Deviations from SM seen by Babar/Belle/LHCb

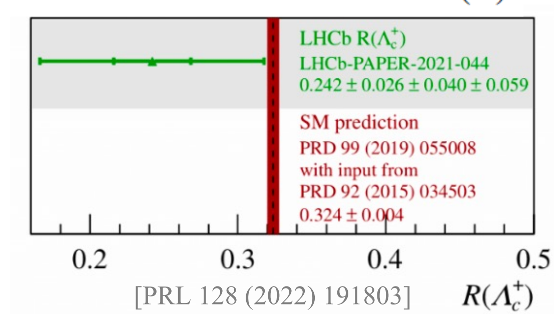




$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$

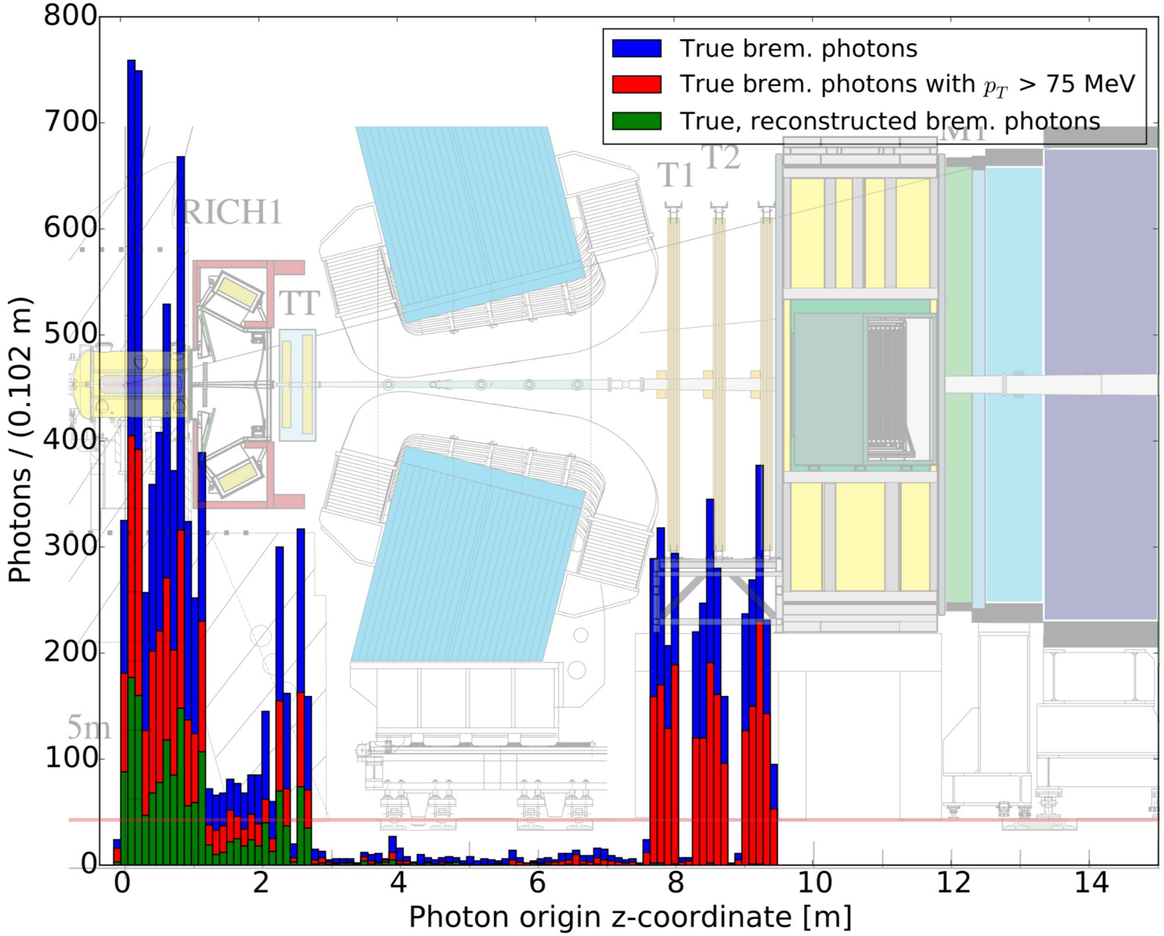


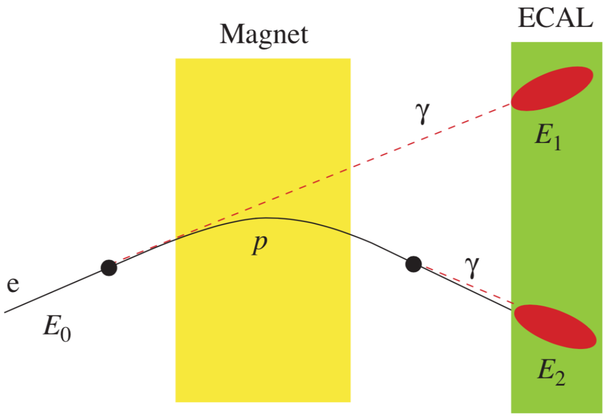


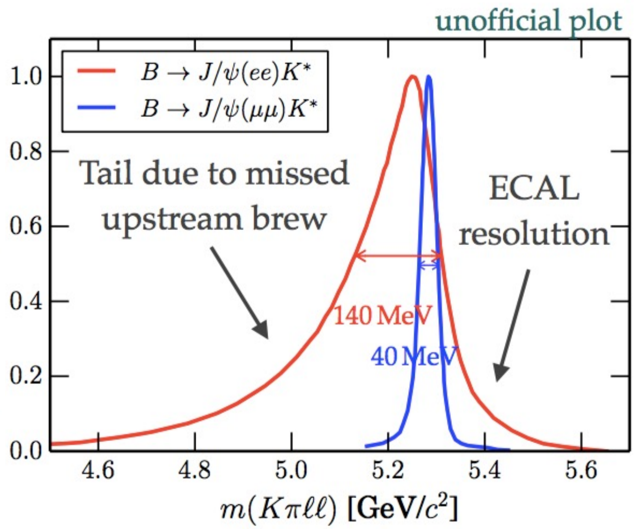


$R(H_c)$ with electron at LHCb?

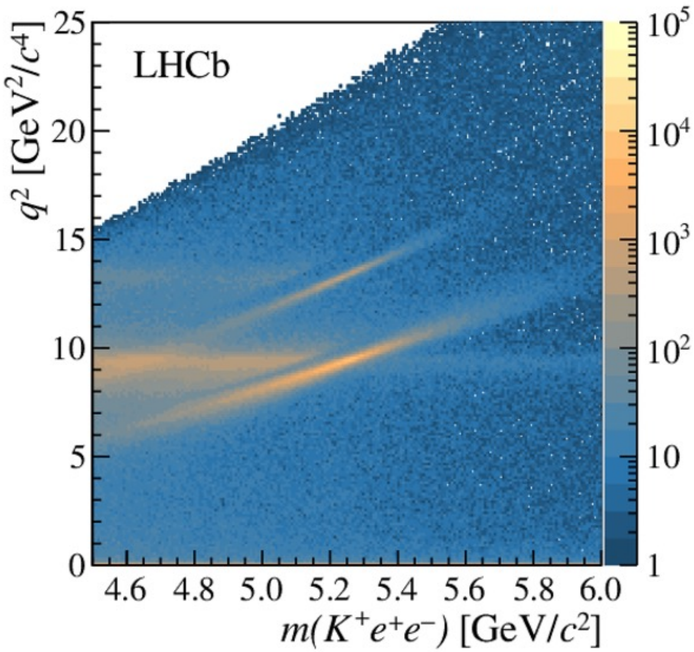
- Even more challenging, due to Bremsstrahlung



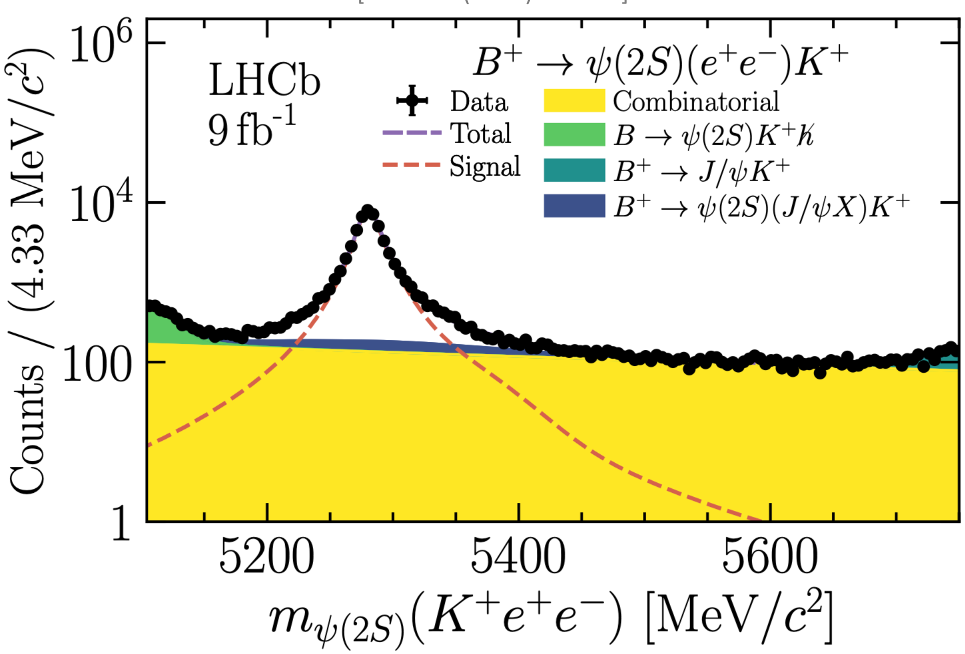




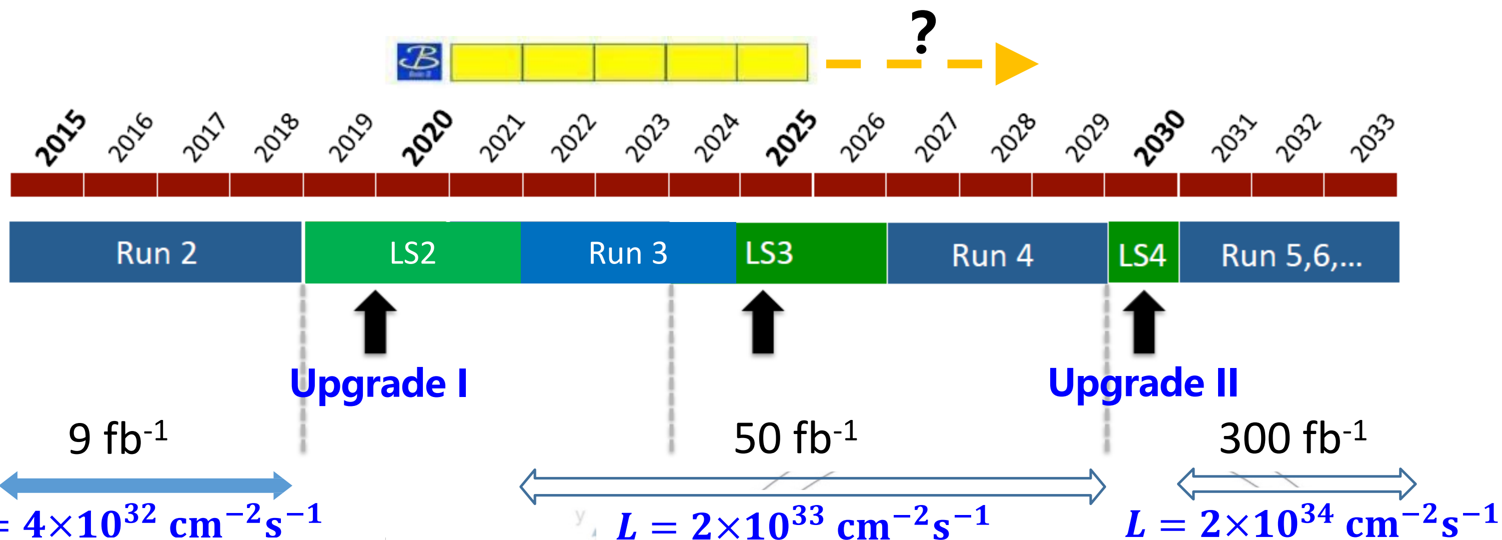
- Partially Rec'ed Bkg compensated by Brem. over-correction and enters the signal region, challenging even for fully Rec'ed decays
- $B^+ \to K^+\ell^+\ell^-$ in high-q² not public yet, take plots in low/central q² paper to illustrate

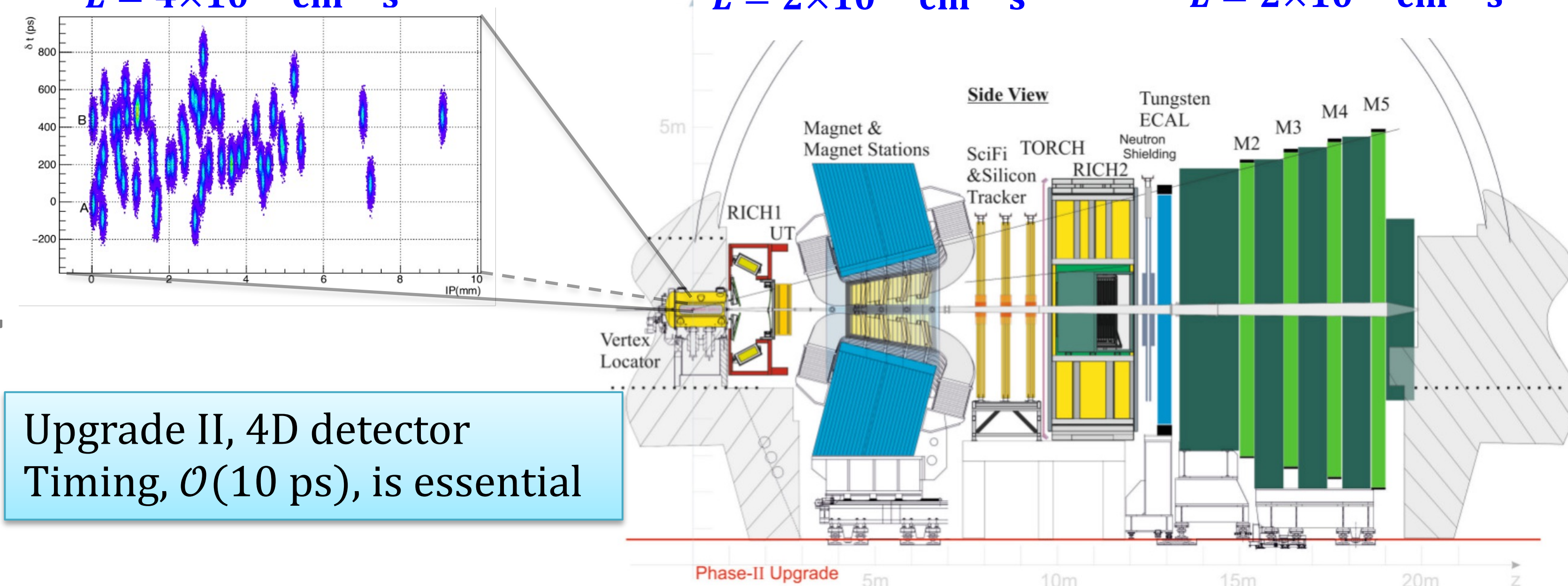


[PRD 108 (2023) 032002]



The LHCb upgrades





Upgrade II, 4D detector
Timing, $\mathcal{O}(10\text{ ps})$, is essential

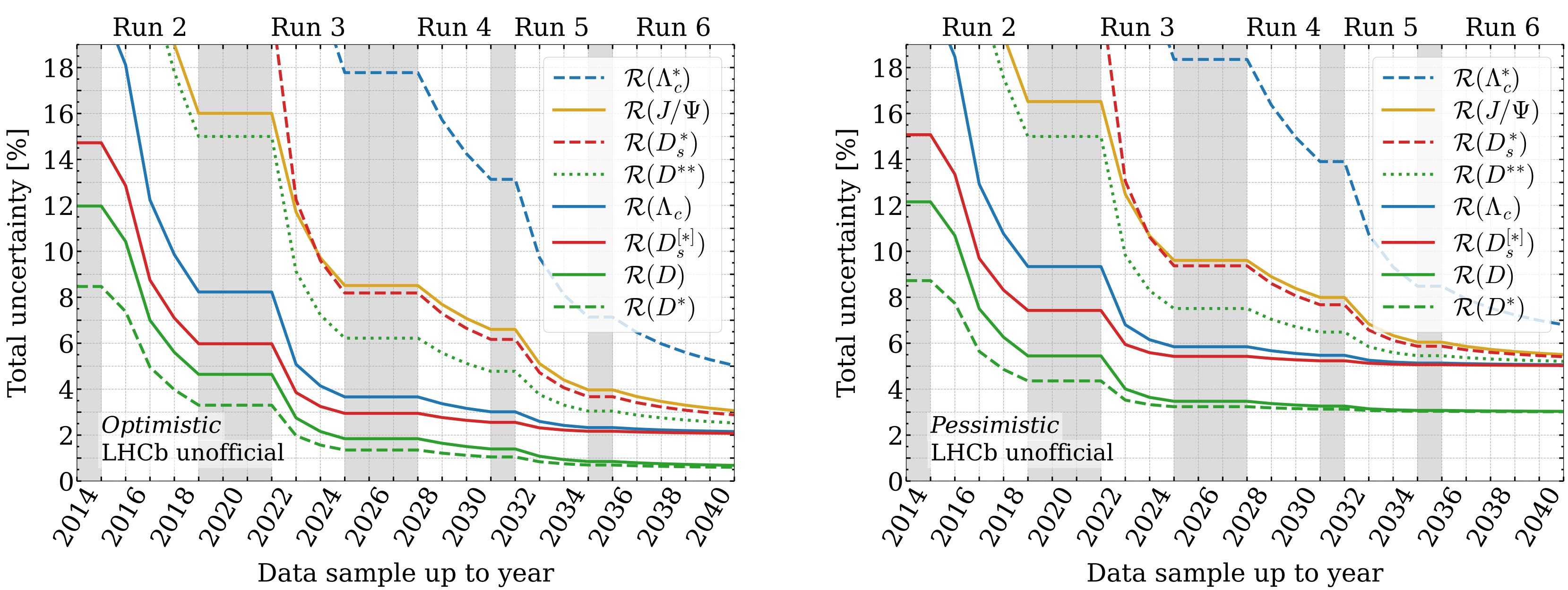
[CERN-LHCC-2018-027, 2021-012]

Prospects

- LHCb upgrades (2025: 23 fb^{-1}, Upgrade-II: 300 fb^{-1})

Observable	Current LHCb	LHCb 2025	Belle-II	LHCb Upgrade-II	ATLAS &CMS
$R(D^*)$	0.026	0.0072	0.005	0.002	
$R(J/\psi)$	0.24	0.071		0.02	?

[CERN-LHCC-2018-027, 2021-012]

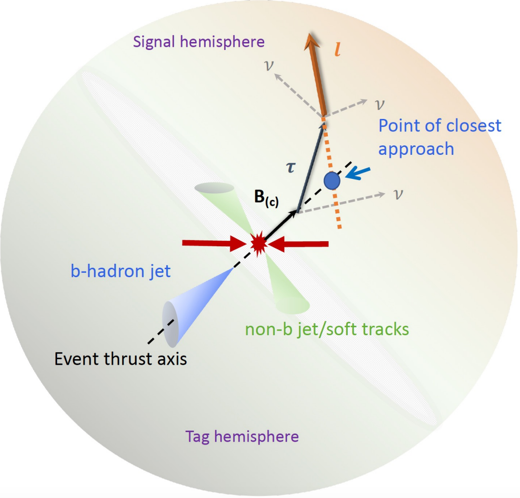


[F. U. Bernlochner *et al.*, RMP 94 (2022) 015003]

How about CEPC?

- Having both advantages
  - Access to all *b*-hadrons, as LHCb
  - Good ablility of dealing with missing energy, as *B*-factories

    $B_c^+ \to \tau^+ \nu$, [T. Zheng *et al.*, CPC 45 (2021) 023001]



- Detector requirements
  - Excellet vertexing, tracking
  - Hadron + lepton PID? Yes
  - Flexible trigger? Yes

Summary

- LHCb has tested lepton flavour universality in semileptonic *b*-decays
  - $R(D), R(D^*), R(\Lambda_c^+)$ and $R(J/\psi)$,

    some deviations from SM seen, to be confirmed or refuted with more data
- Efforts from both theo. and exp. sides needed to improve precision further, e.g.,
  - Form factors
  - $B \to DDX, D \to 3\pi X$
- CEPC will be a main player in this field