LFU in charged-current *b* decays in LHCb

Suzanne Klaver, on behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects

CERN, 19 October 2022

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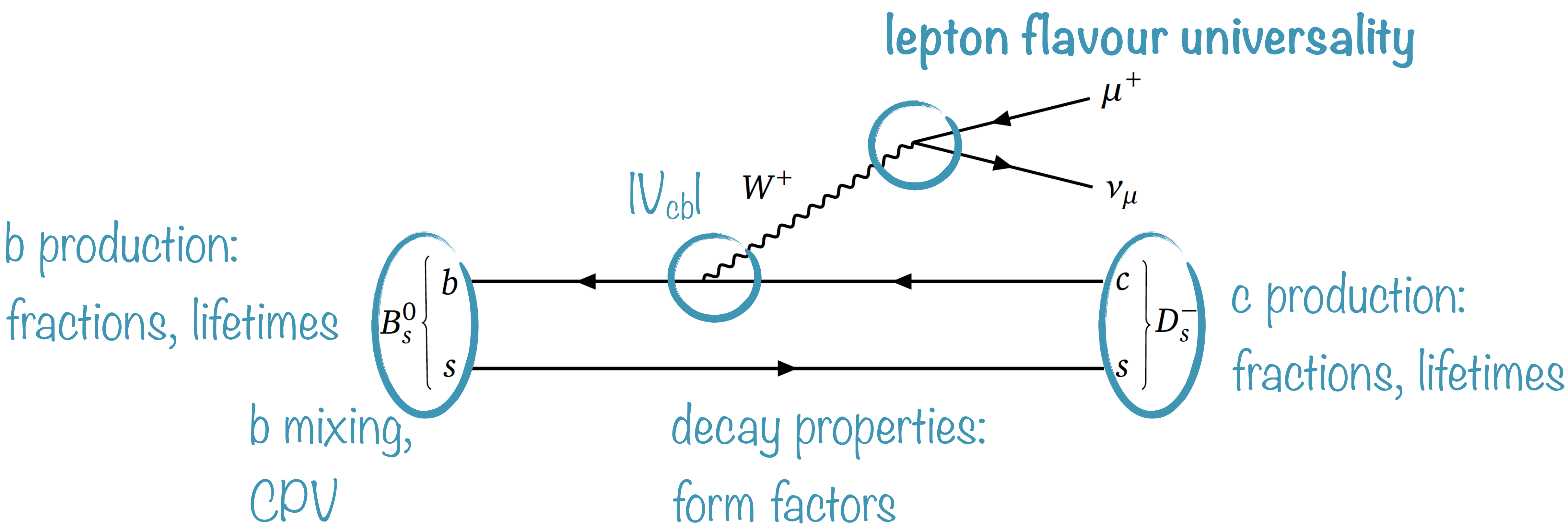
LHCb

Semileptonic *b*-hadron decays in LHCb

- Advantages:
  - large data samples
  - theoretically clean:
    - only 1 hadronic current
    - improvements in lattice calculations
- Challenges:
  - neutrino: partially reconstructed decays
  - large amounts of backgrounds
  - huge simulation samples required



Motivation

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell' \overline{\nu}_{\ell'})}$$

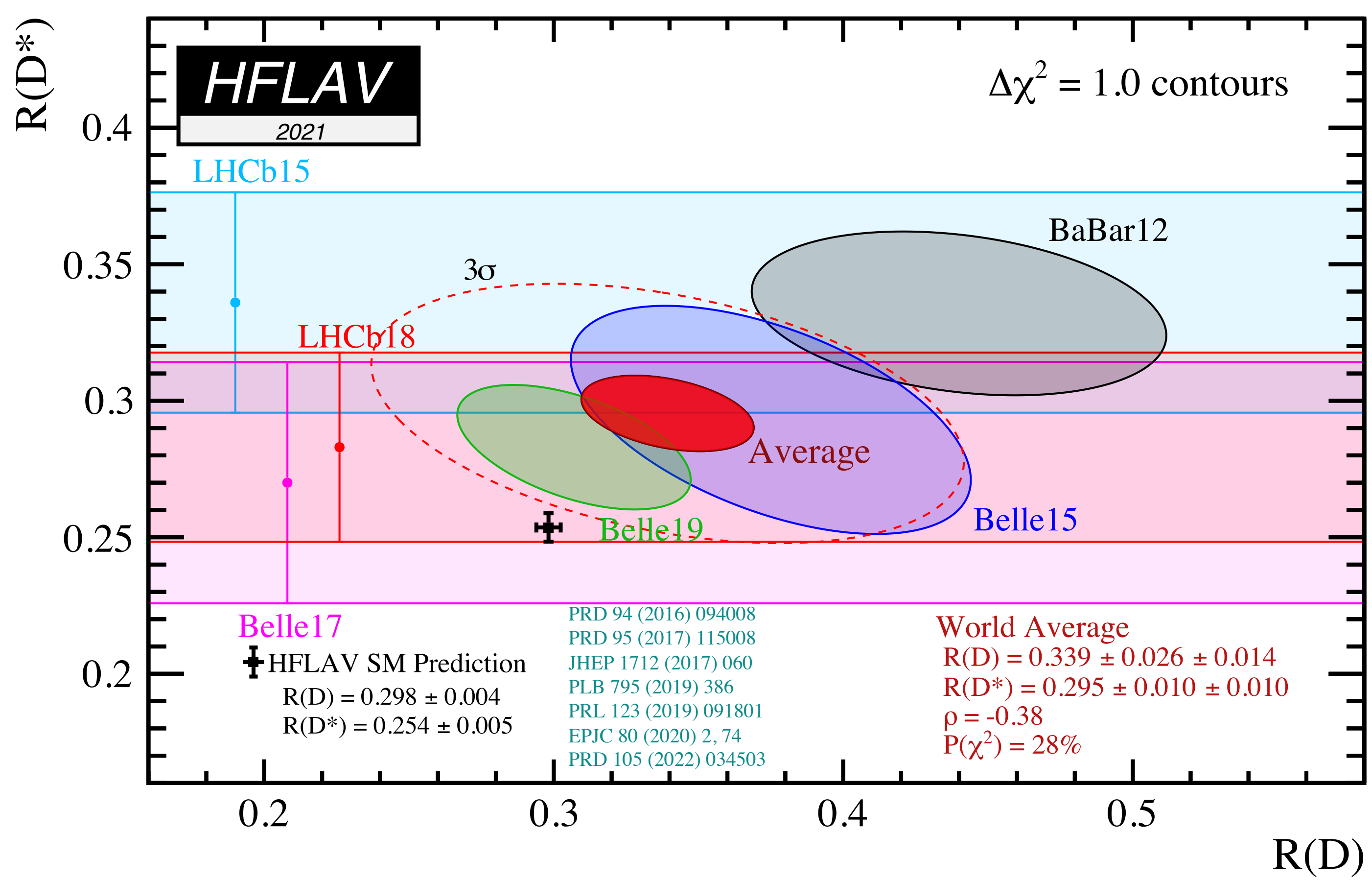
ℓ' = μ (LHCb)

ℓ' = e/μ (B-factories)

- Standard Model: EW couplings to leptons are identical

until yesterday

- Tree-level processes are sensitive to new physics: e.g. leptoquarks
- Predictions are theoretically clean



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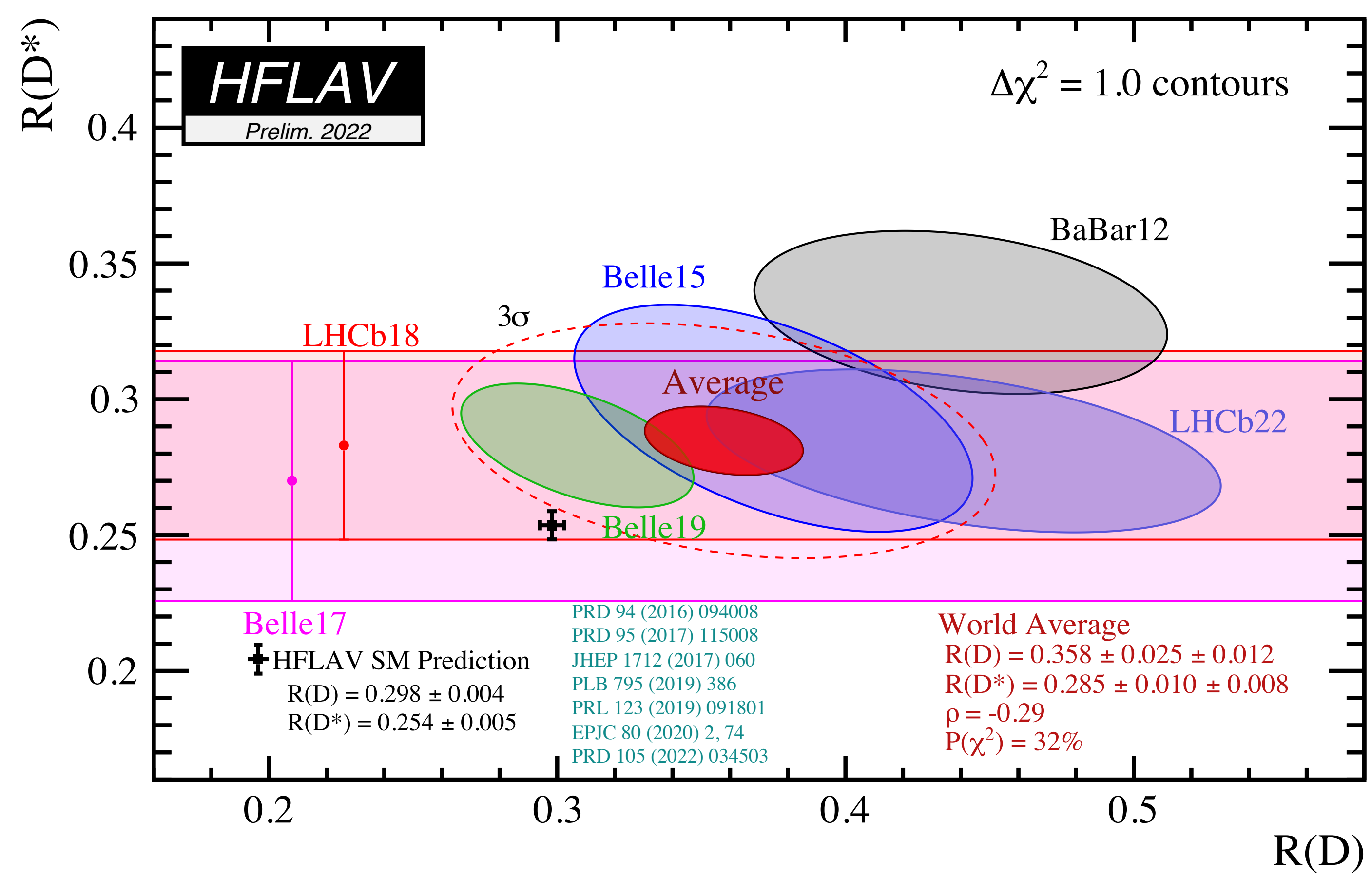
- Standard Model: EW couplings to leptons are identical

updated plot!

- Average is shifted
- Tension with SM moved from **3.3σ to 3.2σ**
- So far measurements mostly done with mesons, but also with $\Lambda_b^0 \to \Lambda_c^+$!



Previous LFU measurements

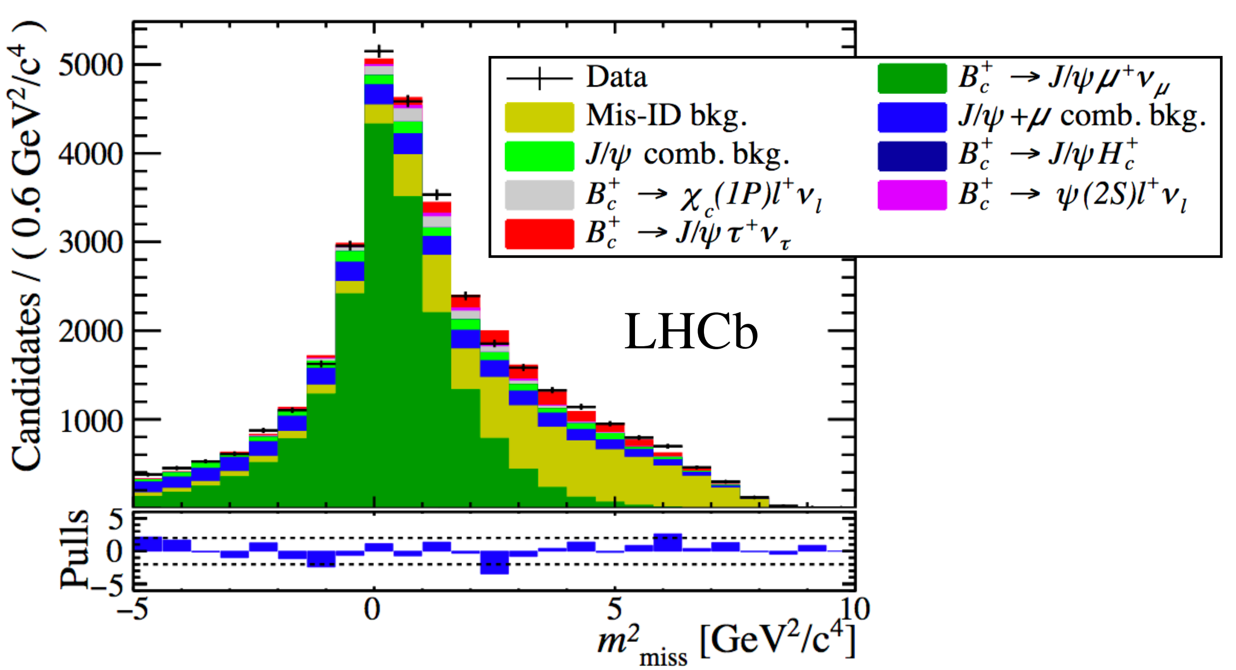
Run 1

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

- Hadronic τ decay
- Compatible with SM within 1σ

$$\mathcal{R}(D^*) = 0.280 \pm 0.018(\text{stat}) \pm 0.029(\text{syst})$$

PRL 120, 121801 (2018)



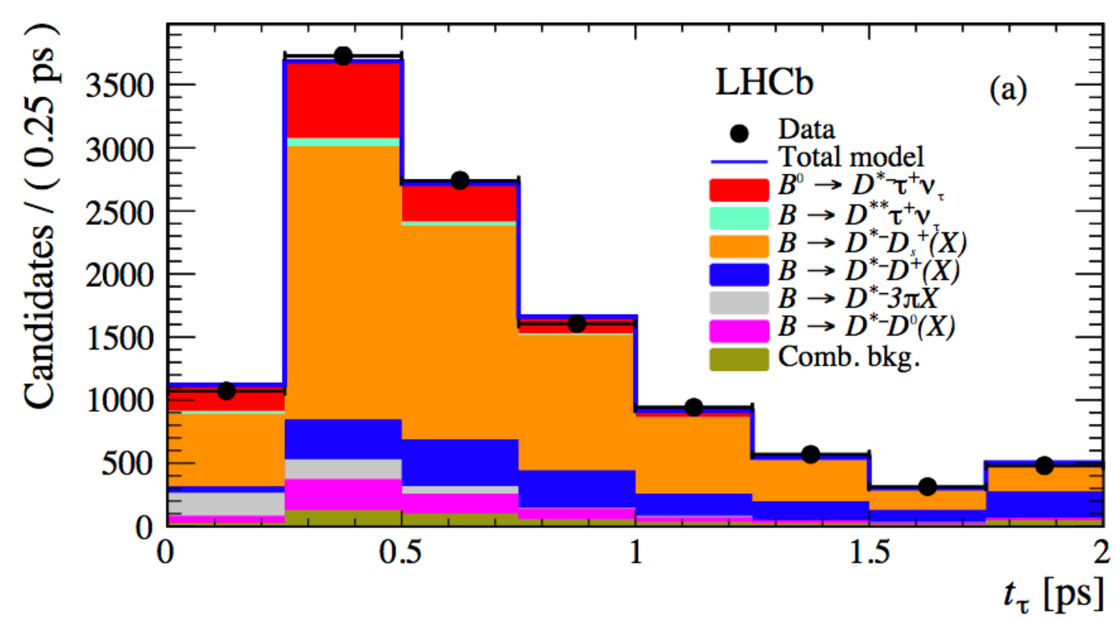
$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

- Muonic τ decay
- Compatible with SM within 2σ

$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$

PRD 97, 072013 (2018)

PRL 120, 171802 (2018)



Observation of the decay

$\Lambda_b \rightarrow \Lambda_c \tau \nu$

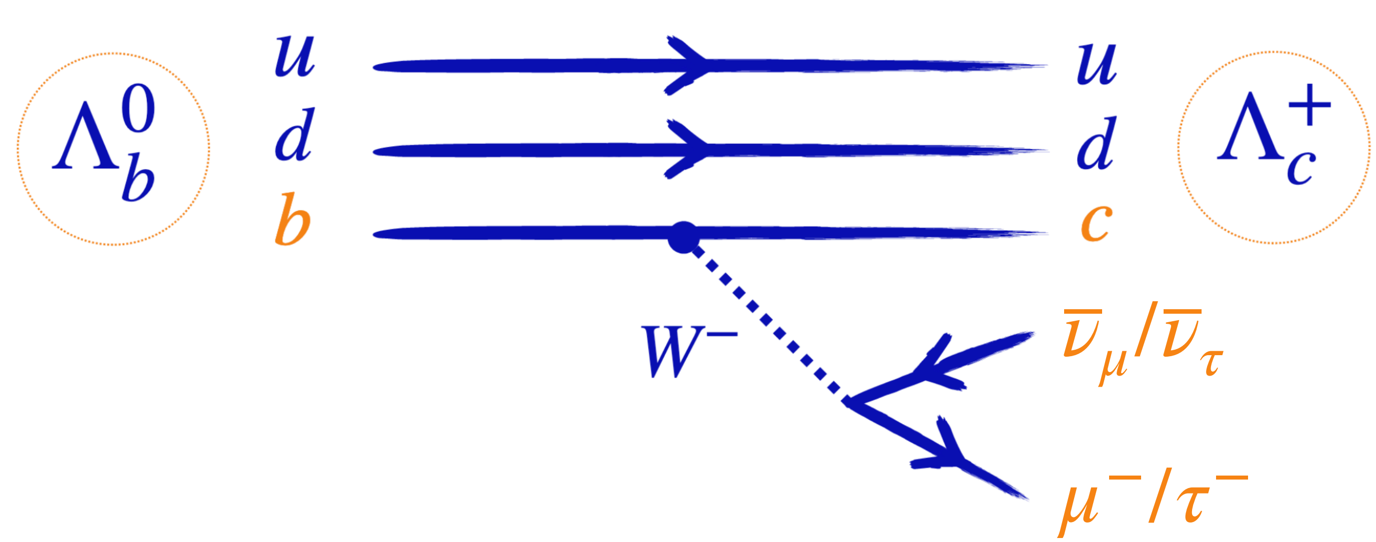
PRL 128, 191803

LFU in $\Lambda_b \to \Lambda_c$ decays

$$\mathscr{R}(\Lambda_c) = \frac{\mathscr{B}(\Lambda_b \to \Lambda_c \tau \nu_\tau)}{\mathscr{B}(\Lambda_b \to \Lambda_c \mu \nu_\mu)}$$

- First $\mathscr{R}(H_c)$ measurement using baryons
- Half-integer spin of initial state
  - complementary constraints to NP w.r.t. $\mathscr{R}(D^{(*)})$ PRD 99 (2019) 055008 JHEP 08 (2017) 131
- Different form factors than $B \to D$ decays
  - NP results in different scenarios
- Precise SM predictions:
  - $\mathscr{R}(\Lambda_c) = 0.324 \pm 0.004$

PRD 99 (2019) 055008 with input from
Lattice QCD FF: PRD 92 034503 (2015)



Analysis strategy

Run 1

- $\mathcal{R}(\Lambda_c) = \dfrac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau \nu_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c \mu \nu_\mu)}$

- Reconstructing τ: hadronic decays:

Decay	$\mathcal{B}$ (%)
$\tau^- \to \pi^-\pi^+\pi^- \nu_\tau$	9.02 ± 0.05
$\tau^- \to \pi^-\pi^+\pi^-\pi^0 \nu_\tau$	4.49 ± 0.05

3-prong decays, only at LHCb

- $\mathcal{R}(\Lambda_c) = \left(\dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} \right)_{\text{measured}} \times \left(\dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)} \right)_{\text{external}}$

signal (numerator), *normalisation* (denominator)

Analysis strategy

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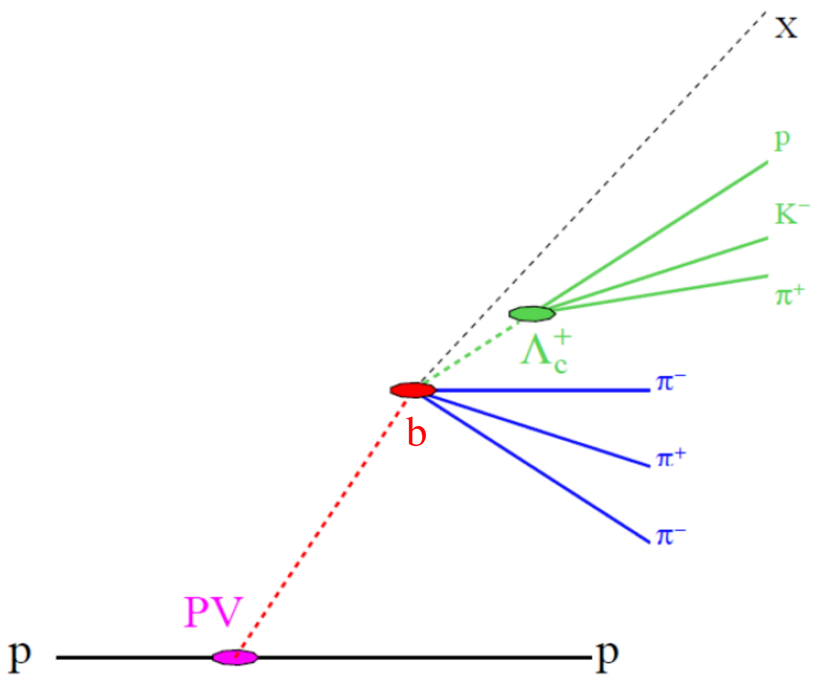
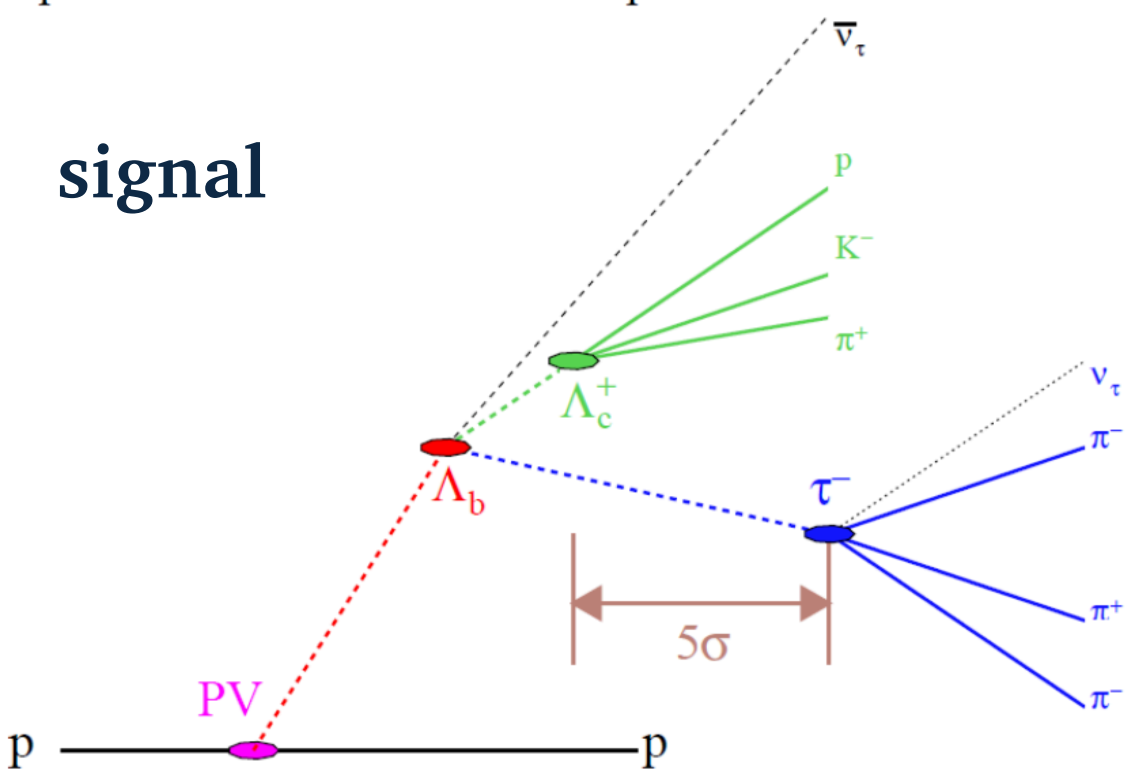
Event selection

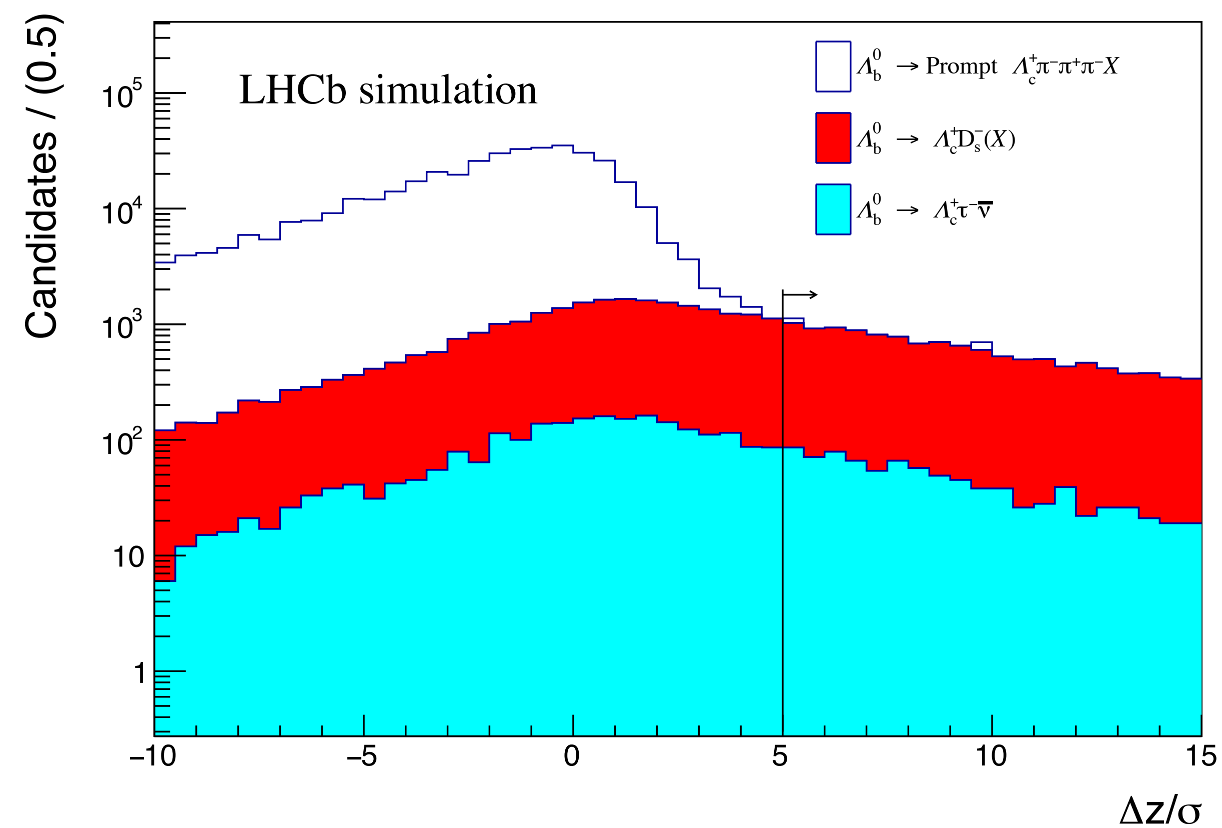
[PRL 128, 191803](PRL 128, 191803)



signal



Cutting at distance between vertices: $\Delta z = z(3\pi) - z(\Lambda_c) > 5\ \sigma_{vtx}$, reduces prompt background to be negligible



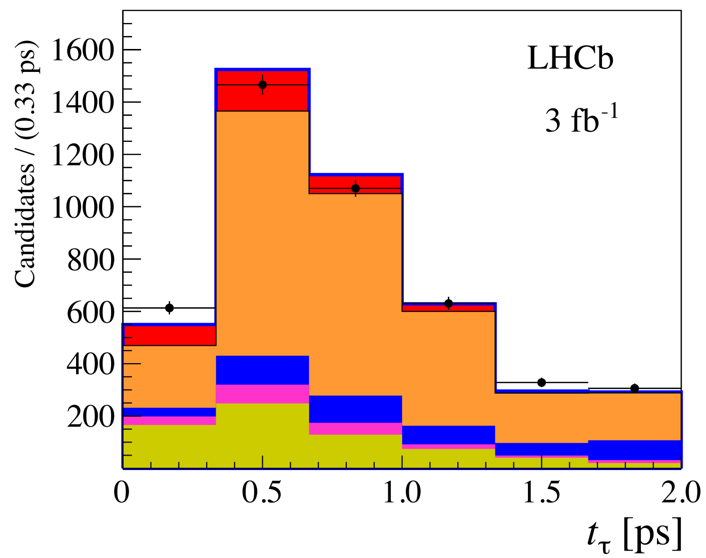
Isolation requirements:

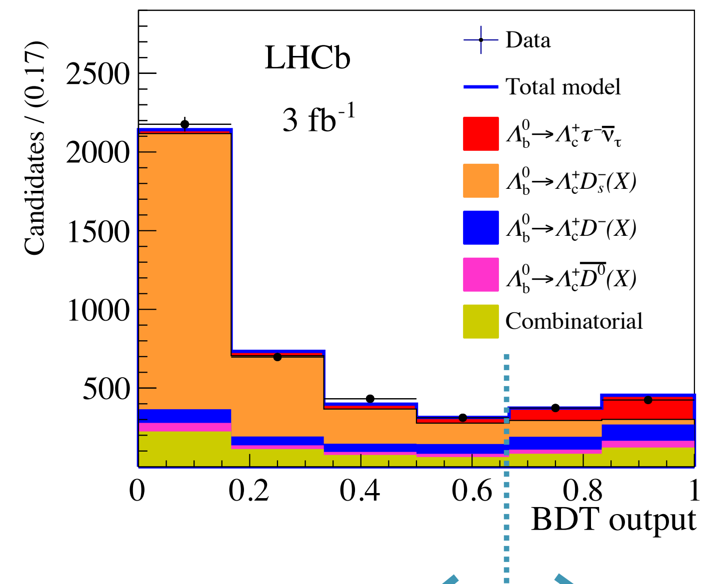
- no extra tracks around 3π

Fit projections

[PRL 128, 191803](#)

- 3D template fit in q^2, t_τ and BDT (suppresses D_s bkgs)

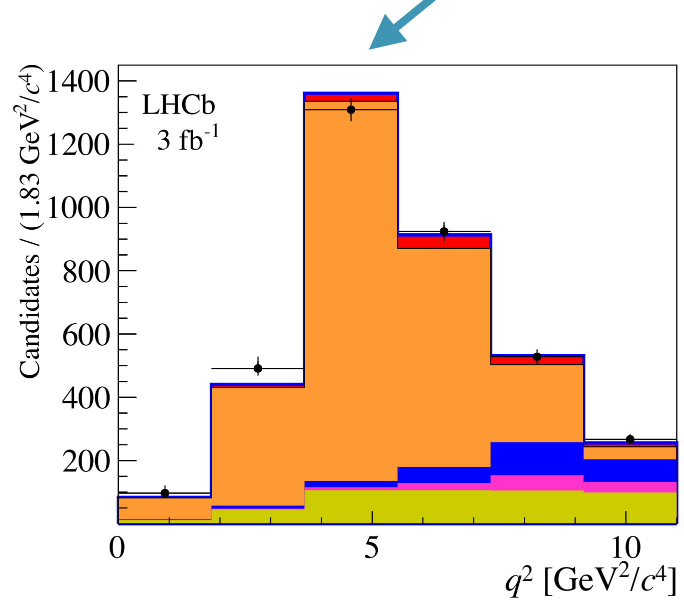


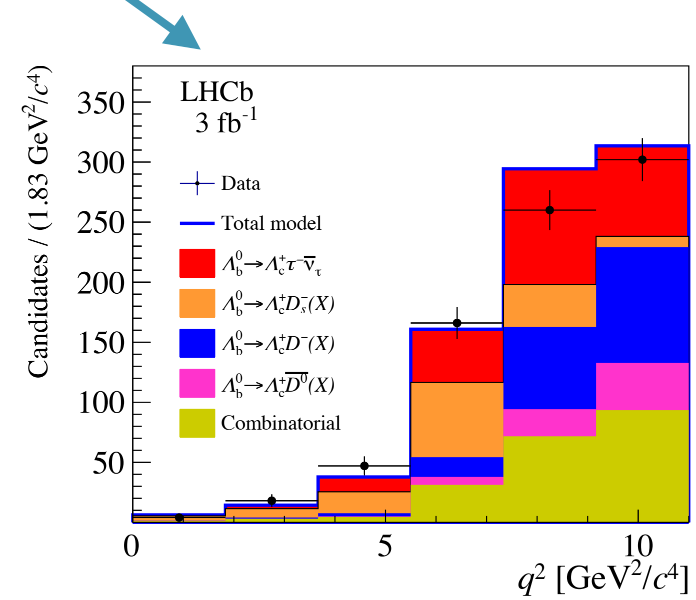


$$q^2 = (p_\ell + p_\nu)^2$$

- Comparing different BDT regions:

Signal yield: 349±40





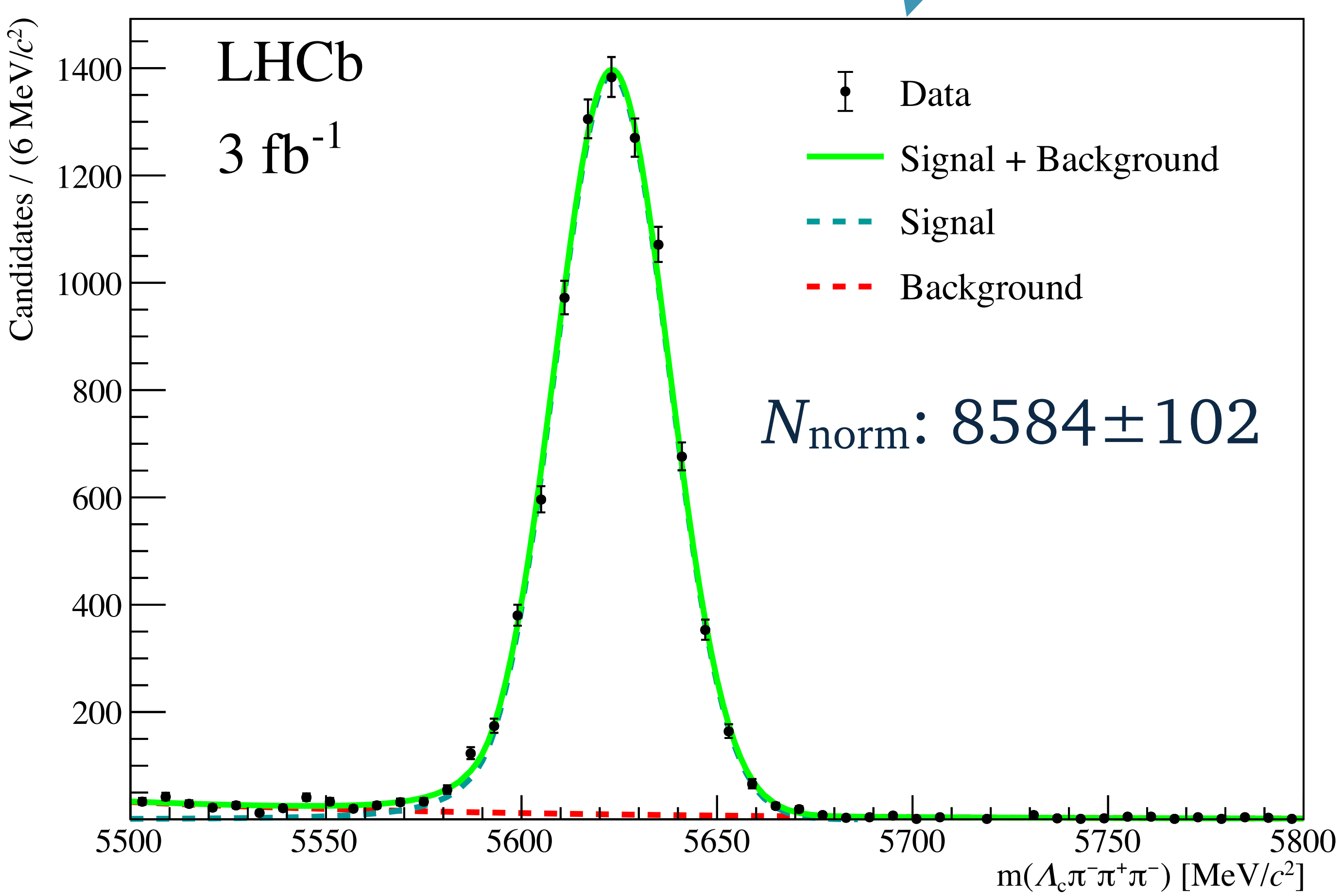
Normalisation channel

[PRL 128, 191803]

- Measure:

$$\mathcal{K}(\Lambda_c) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{1}{\mathcal{B}(\tau^- \to 3\pi(\pi^0)\nu_\tau)}$$

simulations



N_{norm}: 8584±102

$\Lambda_c^* \to \Lambda_c \pi^+\pi^- / \Lambda_c \pi^- / \Lambda_c \pi^+$ decays explicitly vetoed

Systematic uncertainties

PRL 128, 191803

- Largest systematics come from template shape:
  - sample size and shape

Source	$\delta\mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$
Simulated sample size	3.8
Fit bias	3.9
Signal modelling	2.0
$\Lambda_b^0 \to \Lambda_c^{*+}\tau^-\overline{\nu}_\tau$ feeddown	2.5
$D_s^- \to 3\pi Y$ decay model	2.5
$\Lambda_b^0 \to \Lambda_c^+ D_s^- X$, $\Lambda_b^0 \to \Lambda_c^+ D^- X$, $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 X$ background	4.7
Combinatorial background	0.5
Particle identification and trigger corrections	1.5
Isolation BDT classifier and vertex selection requirements	4.5
D_s^- , D^- , $\overline{D}^0$ template shapes	13.0
Efficiency ratio	2.8
Normalisation channel efficiency (modelling of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$)	3.0
Total uncertainty	16.5

Results

PRL 128, 191803

$$\mathcal{R}(\Lambda_c) = \underbrace{\left(\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}\right)_{\text{measured}}}_{\mathcal{K}(\Lambda_c)} \times \left(\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}\right)_{\text{external}}$$

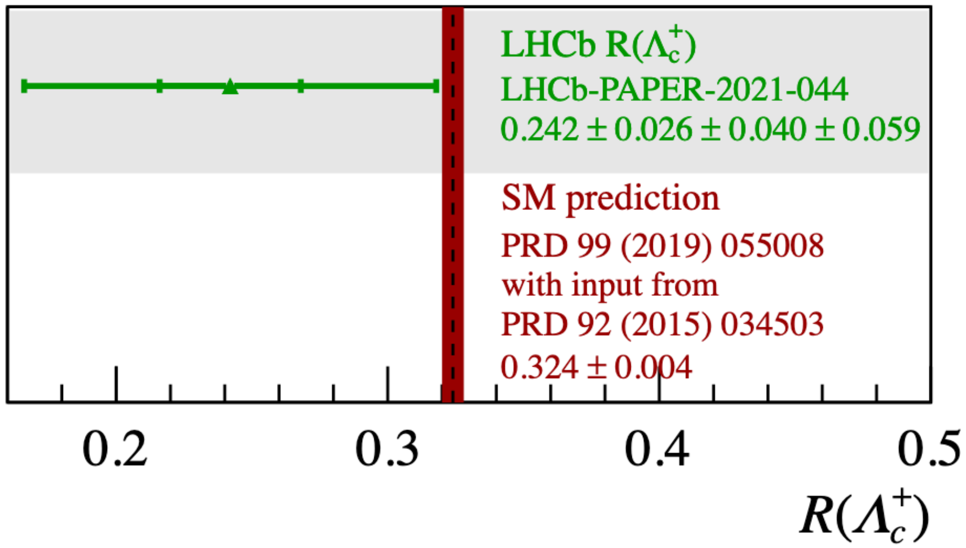
$$\mathcal{K}(\Lambda_c) = 2.46 \pm 0.27(\text{stat}) \pm 0.40(\text{syst})$$

- First observation of $\Lambda_b^0 \to \Lambda_c \tau^- \overline{\nu}_\tau$:

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c \tau^- \overline{\nu}_\tau) = (1.50 \pm 0.16(\text{stat}) \pm 0.25(\text{syst}) \pm 0.23(\text{ext}))\,\%$$

$$\mathcal{R}(\Lambda_c) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})$$

- In agreement with SM predictions within 1σ



Different normalisation

$\Lambda_b \to \Lambda_c \tau \nu$

arXiv:2206.11282

Different normalisation

arXiv:2206.11282

- Interpretation of results by F. Bernlochner, Z. Ligeti, M. Papucci and D. Robinson
- Normalisation comes from PDG fit, including measurements with correlation to the muon mode
- Alternative approach: use SM prediction: $\mathcal{B}(\Lambda_b^0 \to \Lambda_c \mu^- \overline{\nu}_\mu) = |V_{cb}/0.04|^2 (5.27 \pm 0.25)\,\%$
- Results consistent with using PDG value
- Improved measurements of $\mathcal{B}(\Lambda_b^0 \to \Lambda_c 3\pi)$ or directly $\mathcal{B}(\Lambda_b^0 \to \Lambda_c 3\pi)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c \mu^- \overline{\nu}_\mu)$ are needed

Prospects

Overview of ongoing LFU measurements

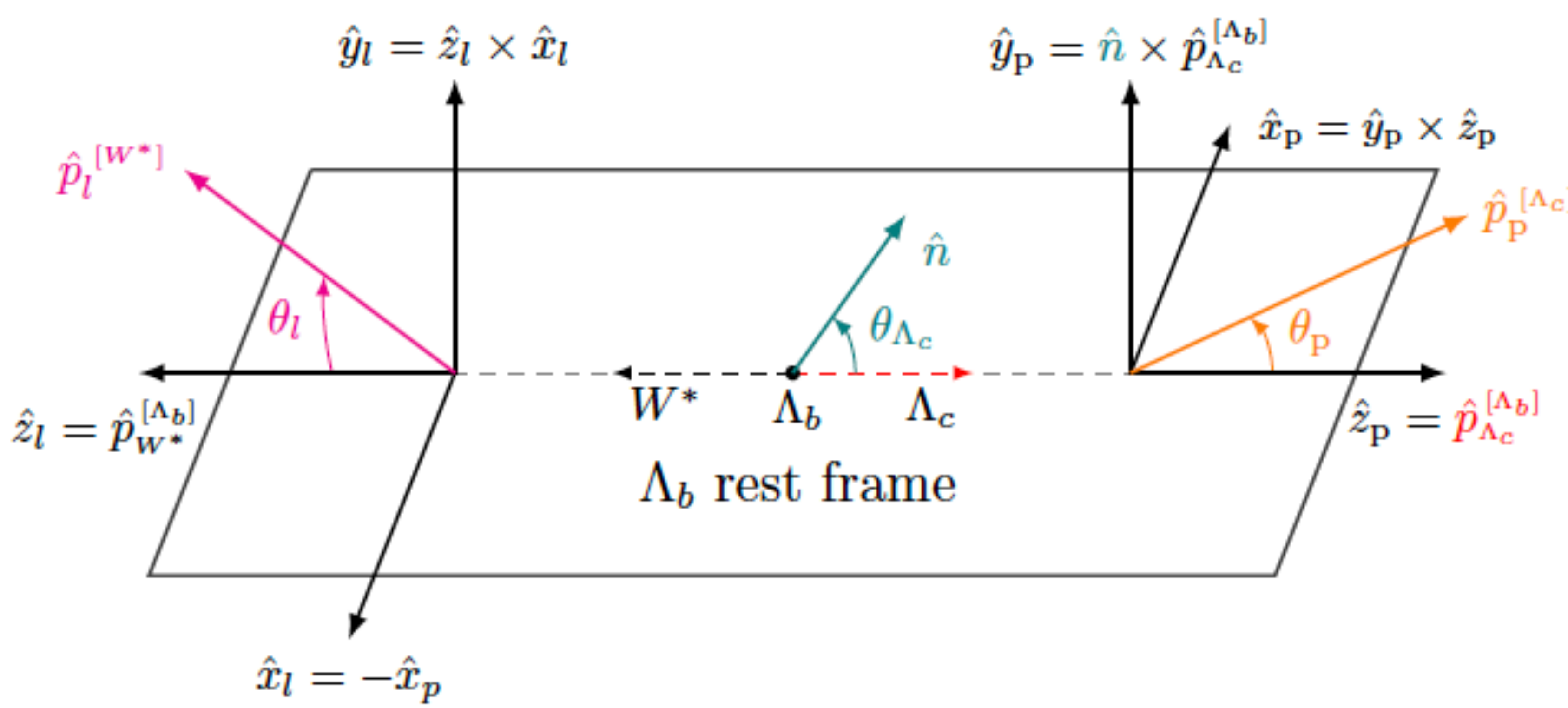
	Run 1: 3 fb^{-1} at 7/8 TeV		Run 2: 6 fb^{-1} at 13 TeV	
mode	muonic	hadronic	muonic	hadronic
$R(D^+)$	✗	✗	✗	✗
$R(D^0)$	✔	✗	✗	✗
$R(D^*)$	✔	✔	✗	✗
$R(\Lambda_c)$	✗	✔	✗	✗
$R(\Lambda_c{}^*)$	✗	✗	✗	✗
$R(J/\phi)$	✔	✗	✗	✗
$R(D_s{}^+)$	✗	✗	✗	✗
$R(D_s{}^{*+})$	✗	✗	✗	✗

- So far only published Run 1 results; Run 2 has four times as much data
- Many analyses in progress; no timelines
- Work ongoing also in $b \to u$ sector; and excited states: $\mathscr{R}(D^{**})$, $\mathscr{R}(D_s^{**})$

Angular analysis: $\Lambda_b \to \Lambda_c \mu\nu$

JHEP 12 (2019) 148

- Enhanced sensitivity to potential NP compared to ratio alone
- Using $\Lambda_b \to \Lambda_c \mu \nu_\mu$ decays, enhanced sensitivity to tensor currents
- Consider Λ_b production
  - polarised: use $\Lambda_c^+ \to pK_S^0$
  - **unpolarised: use $\Lambda_c^+ \to pK^+\pi^-$ and integrate over Λ_c^+ angles**
    - 2D fit: extract q^2 and $\cos\theta_\ell$
    - expected 7.5M signal events in Run 1+2



Extracting Wilson coefficients

JHEP 12 (2019) 148

- Decay density:

$$\frac{d^2\Gamma}{dq^2\ d\cos\theta_l} = \frac{N}{\Gamma}\Bigg[2\pi^2\Bigg\{\cos\theta_l\Bigg(-2\cos\theta_l(|I_7|^2+|I_8|^2)+2I_6^*(\cos\theta_l I_6+I_{10})-\cos\theta_l I_2 I_2^*+ (\cos\theta_l-2)I_3I_3^*+(\cos\theta_l+2)I_4I_4^*+2I_5^*(\cos\theta_l I_5+I_9)\Bigg)+|I_2|^2+|I_3|^2+|I_4|^2+ I_1^*(I_1-\cos\theta_l^2 I_1)+2I_{10}^*(\cos\theta_l I_6+I_{10})+2I_9^*(\cos\theta_l I_5+I_9)+2I_7I_7^*+2I_8I_8^*\Bigg\}\Bigg]$$

- Terms I_i with Wilson coefficients:

$$
\begin{aligned}
I_1 &= a_l c_A(1+C_{V_L}-C_{V_R}) - a_l c_V(1+C_{V_L}+C_{V_R}) - 4b_l(b_T+c_T)C_{T_L}\,,\\
I_2 &= a_l c_A(1+C_{V_L}-C_{V_R}) + a_l c_V(1+C_{V_L}+C_{V_R}) + 4b_l(b_T-c_T)C_{T_L}\,,\\
I_3 &= b_l c_A(1+C_{V_L}-C_{V_R}) + b_l c_V(1+C_{V_L}+C_{V_R}) + 4a_l(b_T-c_T)C_{T_L}\,,\\
I_4 &= b_l c_A(1+C_{V_L}-C_{V_R}) - b_l c_V(1+C_{V_L}+C_{V_R}) - 4a_l(b_T+c_T)C_{T_L}\,,\\
I_5 &= a_l b_A(1+C_{V_L}-C_{V_R}) + a_l b_V(1+C_{V_L}+C_{V_R}) + 4b_l(a_T-d_T)C_{T_L}\,,\\
I_6 &= a_l b_A(1+C_{V_L}-C_{V_R}) - a_l b_V(1+C_{V_L}+C_{V_R}) - 4b_l(a_T+d_T)C_{T_L}\,,\\
I_7 &= -b_A b_l(1+C_{V_L}-C_{V_R}) + b_l b_V(1+C_{V_L}+C_{V_R}) + 4a_l(a_T+d_T)C_{T_L}\,,\\
I_8 &= b_A b_l(1+C_{V_L}-C_{V_R}) + b_l b_V(1+C_{V_L}+C_{V_R}) + 4a_l(a_T-d_T)C_{T_L}\,,\\
I_9 &= a_A a_l(1+C_{V_L}-C_{V_R}) + a_l a_V(1+C_{V_L}+C_{V_R}) - a_P b_l(C_{S_L}-C_{S_R}) + a_S b_l(C_{S_L}+C_{S_R})\,,\\
I_{10} &= a_A a_l(1+C_{V_L}-C_{V_R}) - a_l a_V(1+C_{V_L}+C_{V_R}) - a_P b_l(C_{S_L}-C_{S_R}) - a_S b_l(C_{S_L}+C_{S_R})\,.
\end{aligned}
$$

Angular analysis: $\Lambda_b \to \Lambda_c \mu\nu$

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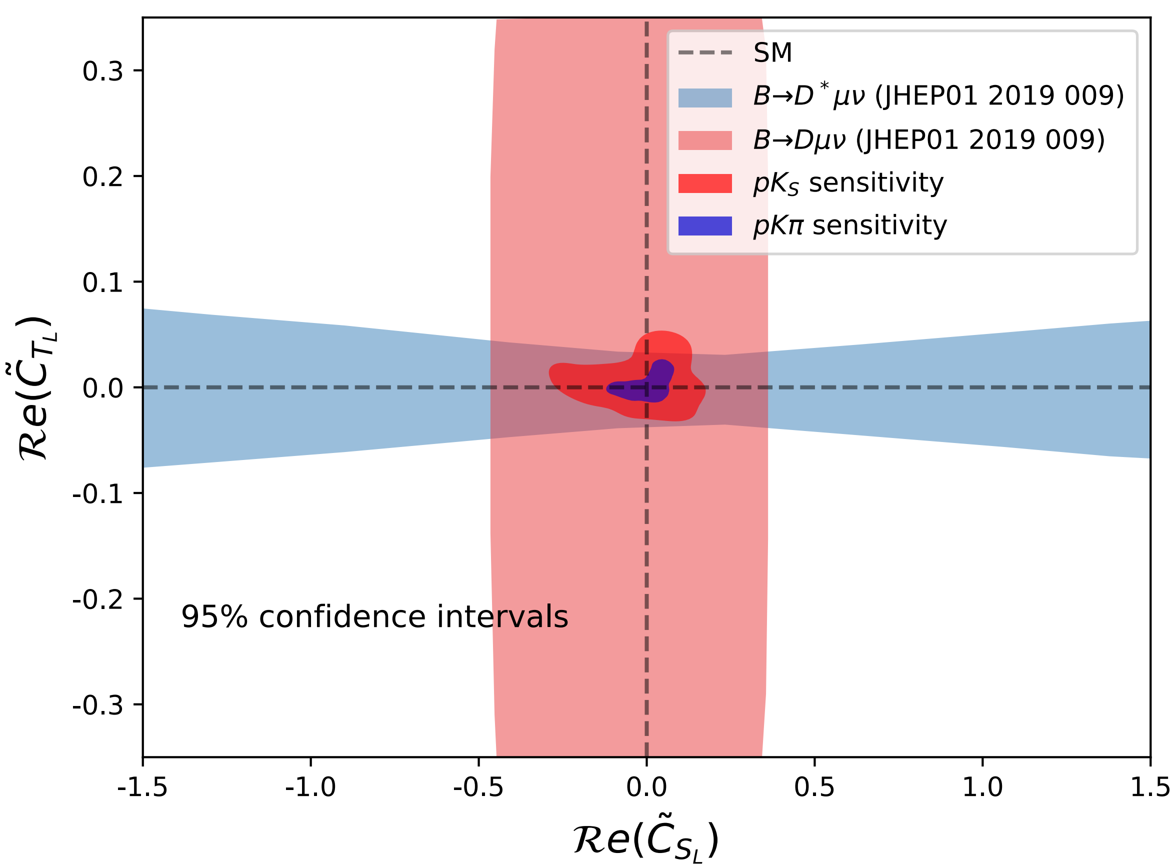
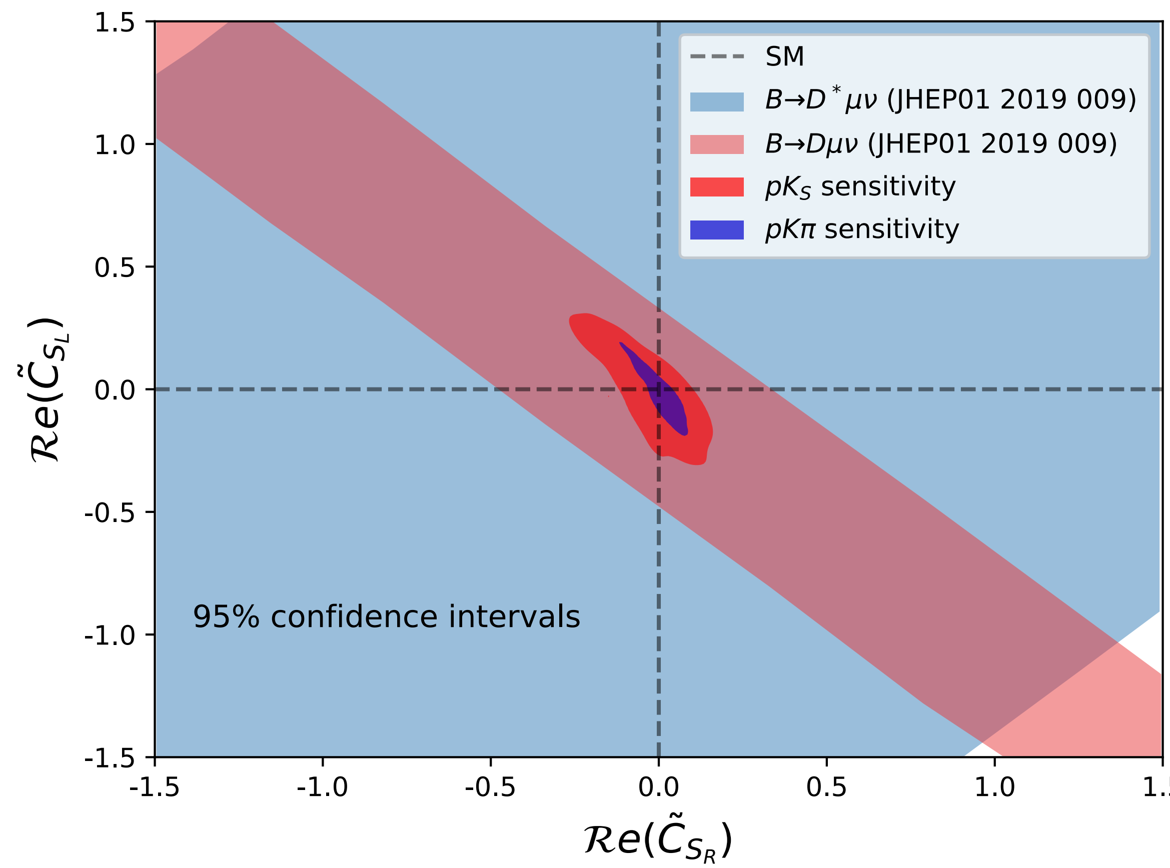
- Two-dimensional sensitivity plots Wilson coefficients
- Improvement compared to existing $B \to D^{(*)}$ decays
    - even better with τ decays in future





Angular analysis $B^0 \to D^*\tau\nu$

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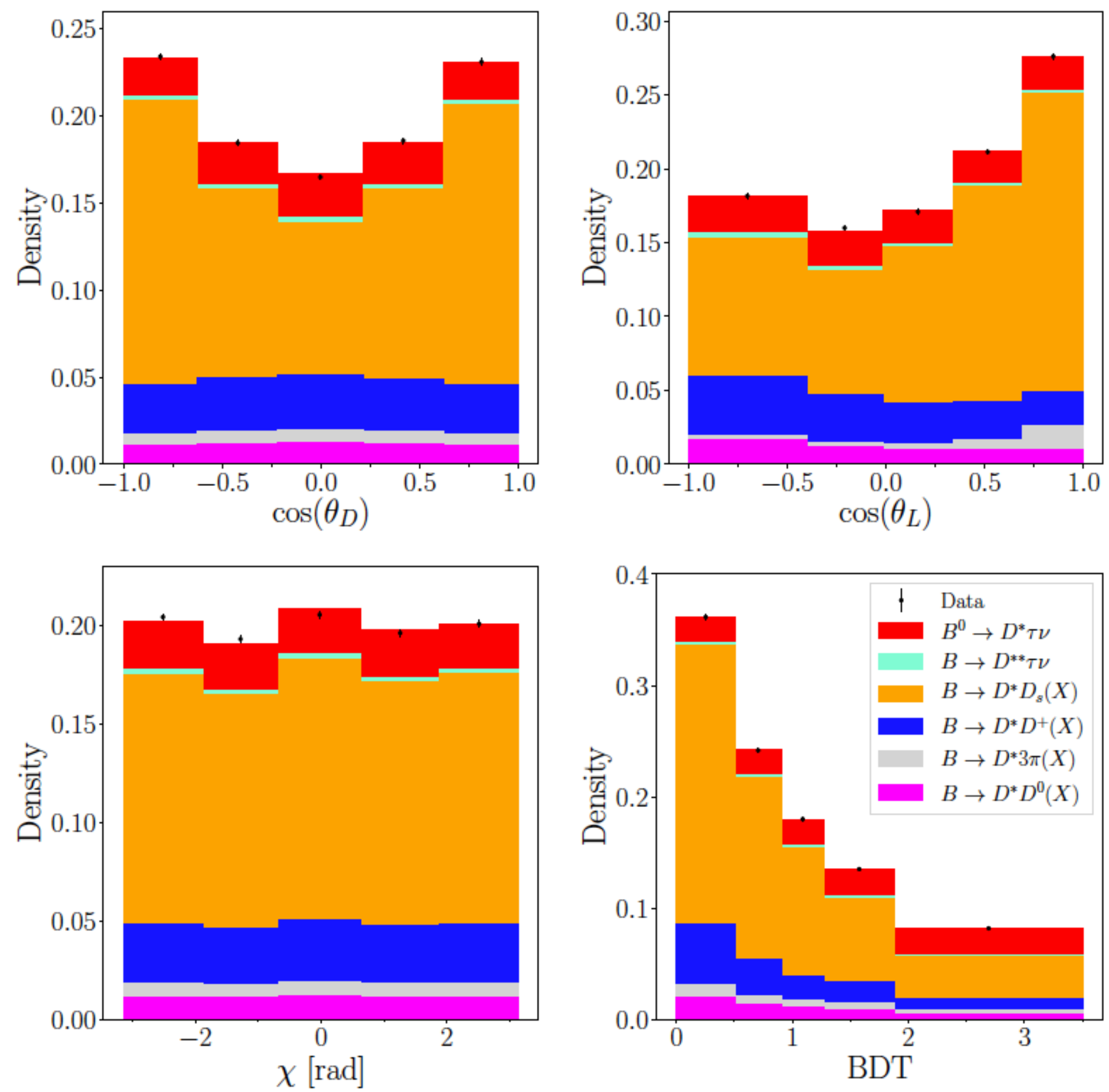
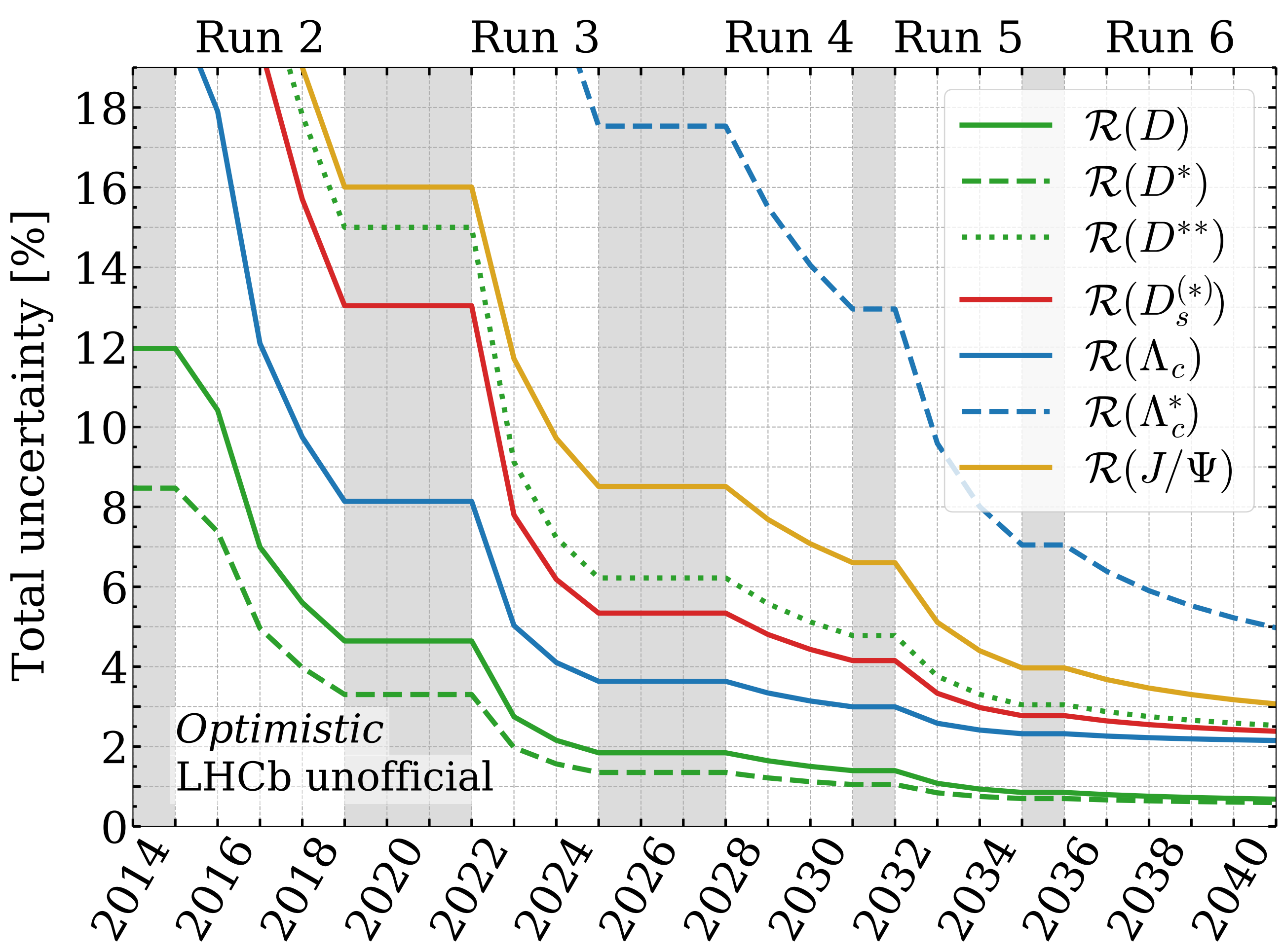
- Angular analysis with τ decays
- Prospects with the Run 1+2 data sample shown here
- Using 4D fit on angular variables $\cos\theta_D$, $\cos\theta_\ell$, χ and BDT to suppress bkgs
    - extract Wilson coefficients



Run 3

- Completely new software-only trigger!
  - no more required p_T cut on the muon in L0
  - exploit this to improve signal purity for τ decays
- Luminosity increase:
  - 9 fb^{-1} (Run 1-2)
  - 23 fb^{-1} (Run 1-3)
  - 50 fb^{-1} (Run 1-4)
  - 300 fb^{-1} (Run 1-5)

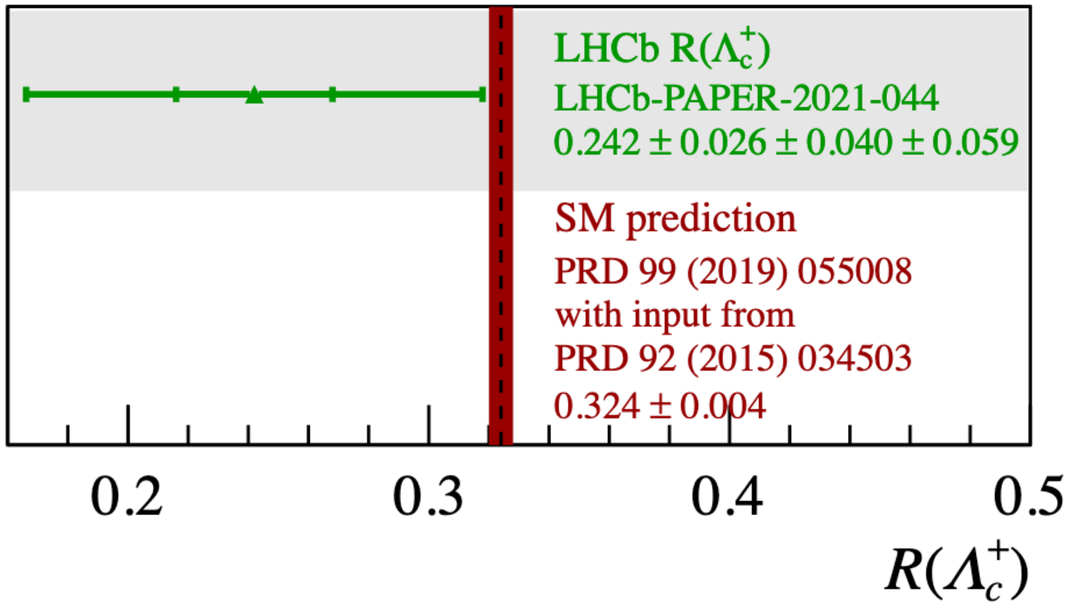


arXiv:2101.08326

Conclusions

PRL 128, 191803

- First observation of $\Lambda_b \to \Lambda_c \tau \nu$ at 6.1σ
  - in agreement with SM predictions



<u>Outlook:</u>

- Measurements so far often limited by MC statistics; much improvements made for future measurements
- Many $\mathscr{R}(H_c)$ measurements ongoing; both hadronic and muonic τ decays
- Also angular analyses ongoing
- Getting a better understanding of discrepancies and potential NP!

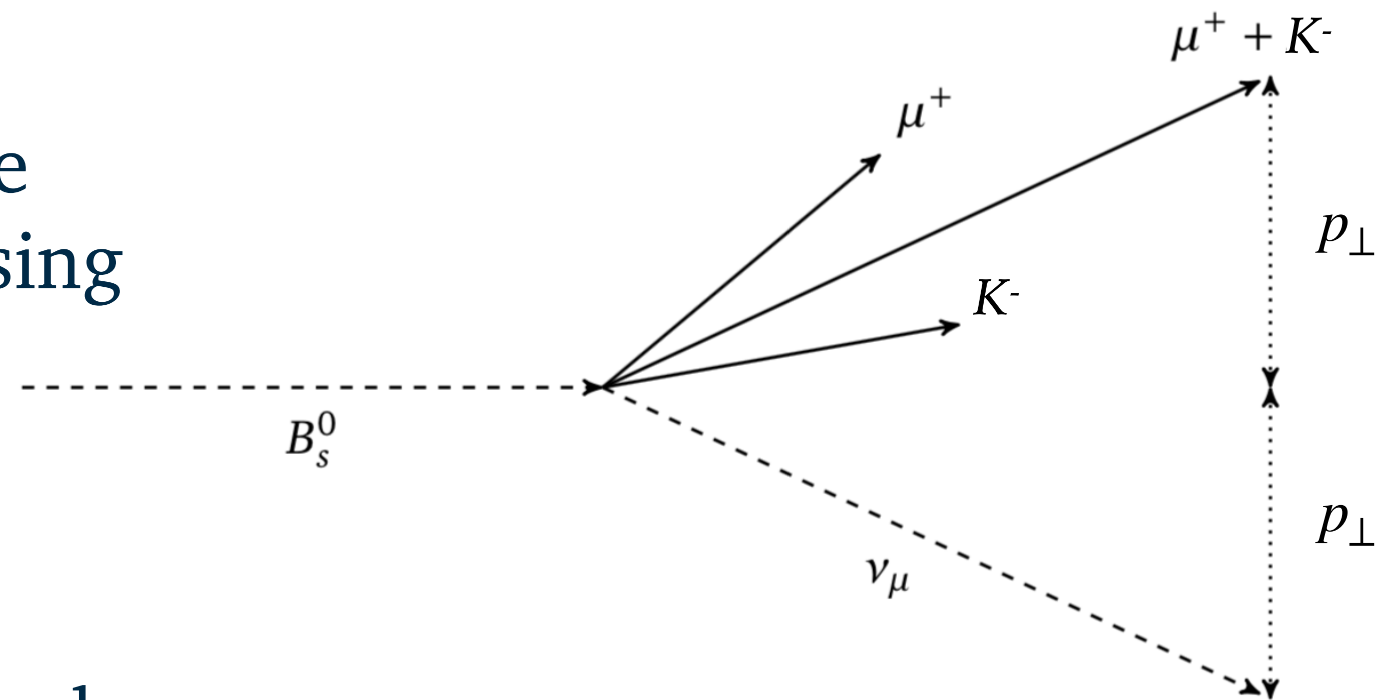
Backup

Useful variables and tools in SL

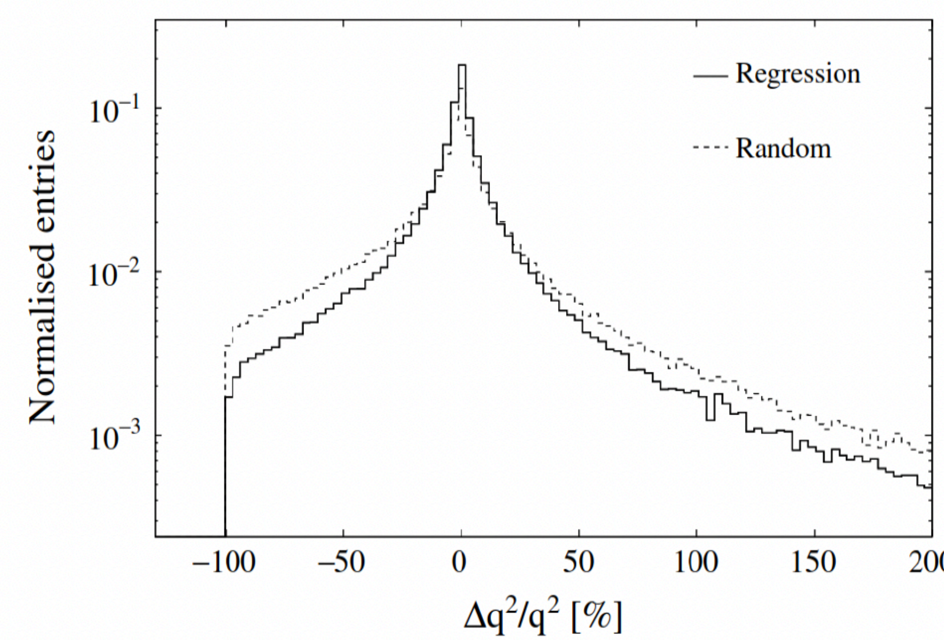
Corrected mass:

- use flight direction of visible particles to reconstruct missing mass:

$$m_{\text{corr}} = \sqrt{m_{Y\mu}^2 + p_\perp^2/c^2} + p_\perp/c$$



- quadratic ambiguity improved using MVA based on flight direction JHEP 02 (2017) 21



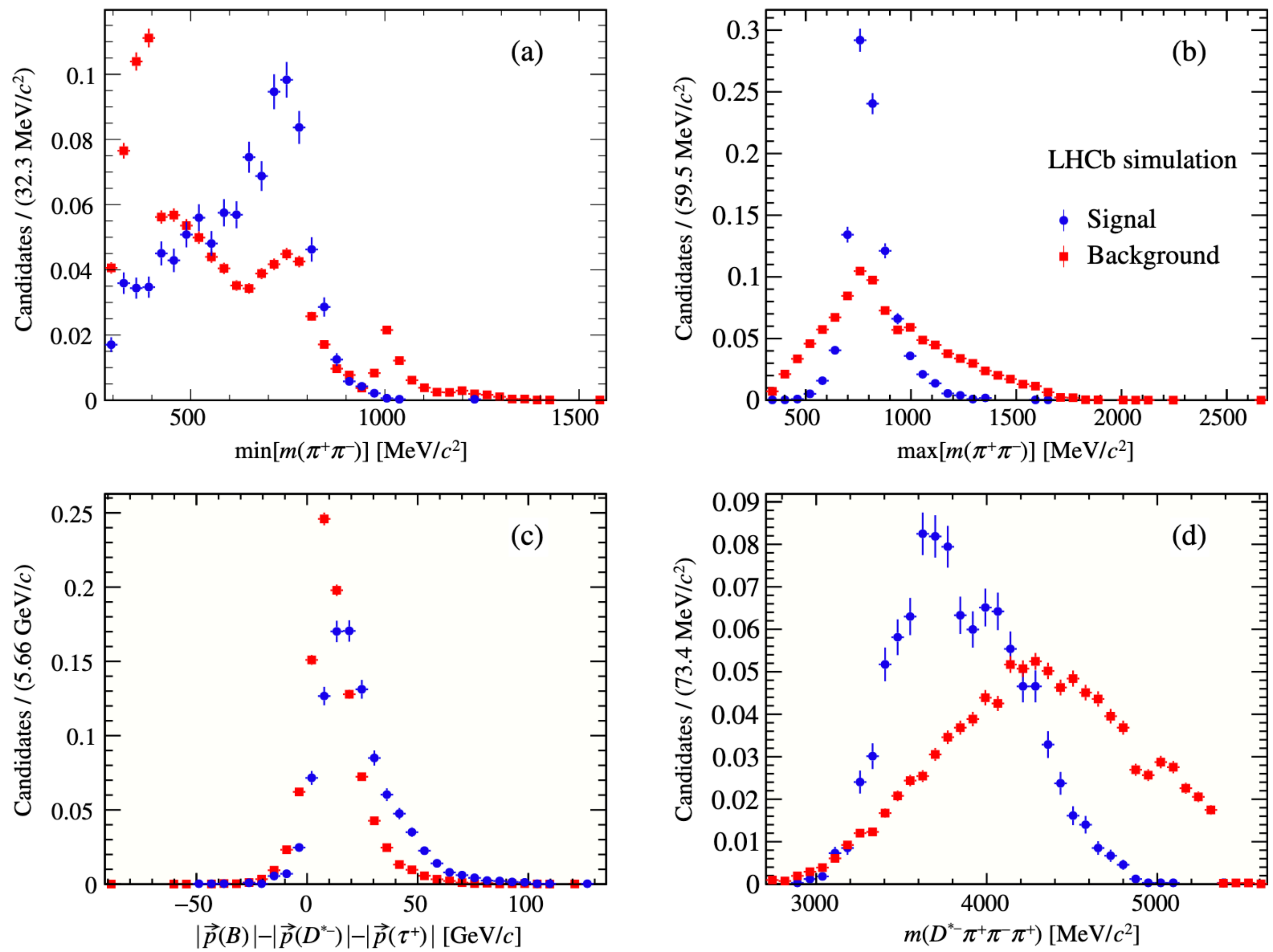
Isolation:

- isolation requirements applied to reduce backgrounds (tracks + neutrals)

Anti-Ds BDT for R(Λ_c)

PRD 97, 072013 (2018)

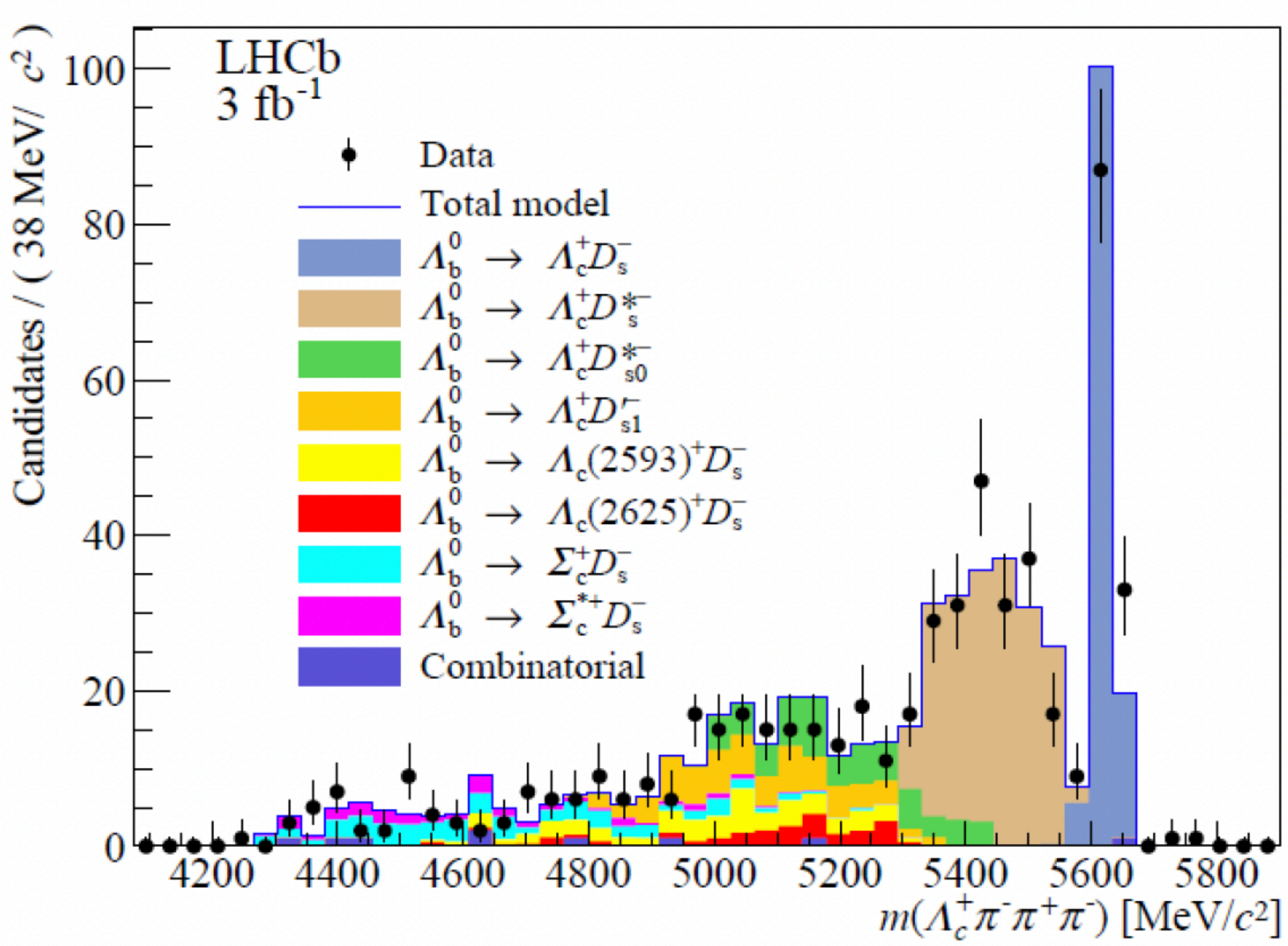
- Use 3π dynamics to separate D_s from τ decays:
  - τ decays through: $a_1(1260)^+ \to \rho^0\, \pi^+$
  - $D_s \to 3\pi$ Y decays through: η and η'



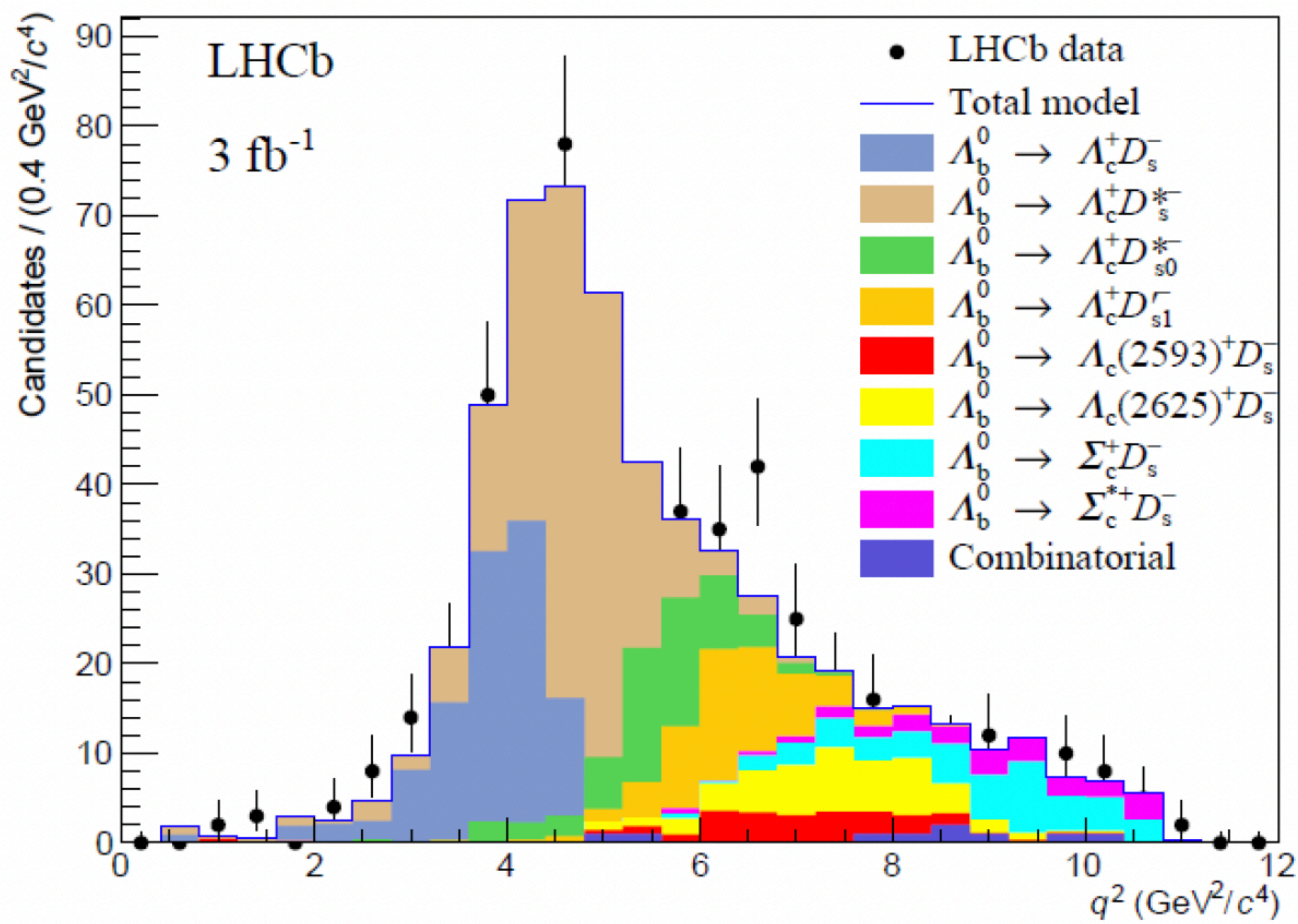
Double-charm backgrounds

PRL 128, 191803

Exclusive $\Lambda_c D_s(X)$ control sample:



Fit to the $\Lambda_b \to \Lambda^+_c \pi^- \pi^+ \pi^-$ mass distribution



Projection on q^2