



Status of B semitauonic analysis at LHCb

Bo Fang^{1,2,3}, Liang Sun², Guy Wormser^{2,3}

Wuhan University¹ & Paris – Saclay University² & IJCLab³

GDR-InF annual workshop 2021
27 Oct 2021

INTENSITY

frontier



Outline

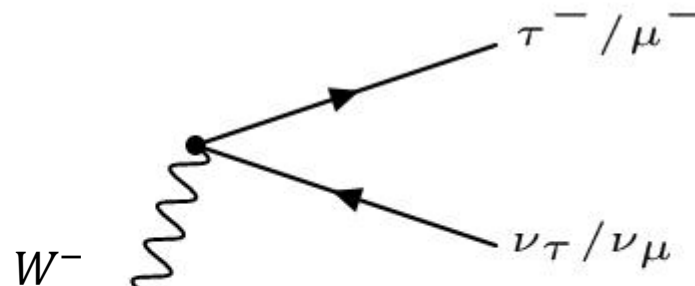
- LFUV and semitauonic B decays
- Details about $R(D^*)$ measurement with hadronic tau decays
- Prospects: growth in statistics and inputs from BESIII
- Summary

Lepton flavour universality (LFU)

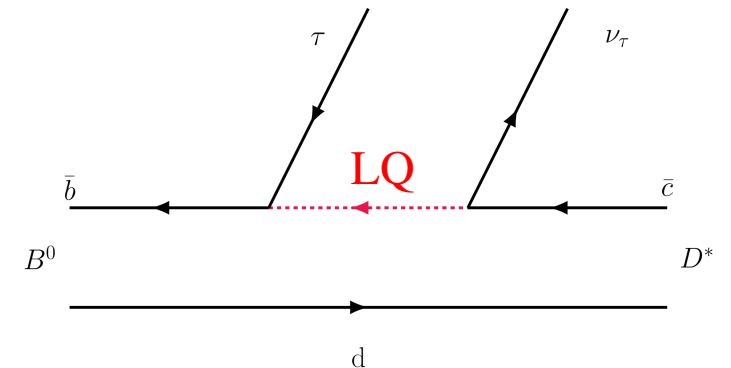
- An approximate lepton ($\ell = e, \mu, \tau$) flavor symmetry among physical observables
- Broken in the Standard Model (SM) only by the charged lepton mass term
- New physics particles coupling to 3rd generation charged lepton can lead to lepton flavour universality **violation** (LFUV)

Semitauconic B decays as tests of LFUV

- $b \rightarrow c \ell \nu$ transitions : $R(X_c) = \frac{BR(X_b \rightarrow X_c \tau \nu_\tau)}{BR(X_b \rightarrow X_c \mu \nu_\mu)}$



e.g. possible contribution from **leptoquark**
[PRL116(2016)081801]

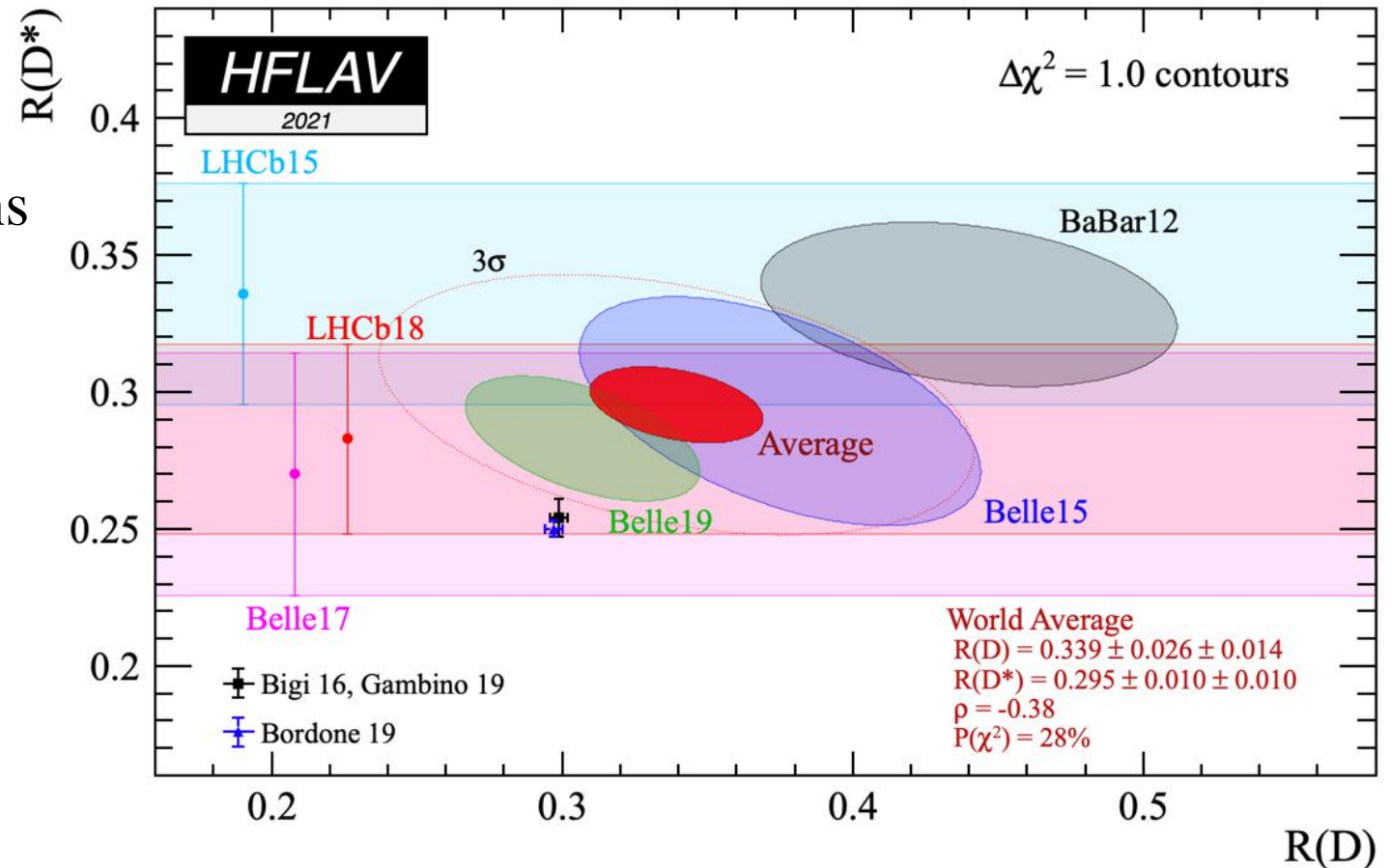


Experimental results about semitauonic B decays

- $R(D)$ and $R(D^*)$ combined results:
3.4 σ extension from SM predictions
- $R(J/\psi)$: $B_c^+ \rightarrow J/\psi \ell^+ \nu_\ell$
~2 σ from SM
[PRL 120, 121801 (2018)]

LHCb15: $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$
[PRL115(2015)111803]

LHCb18: $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau$
[PRL120(2018)171802, PRD97(2018)072013]

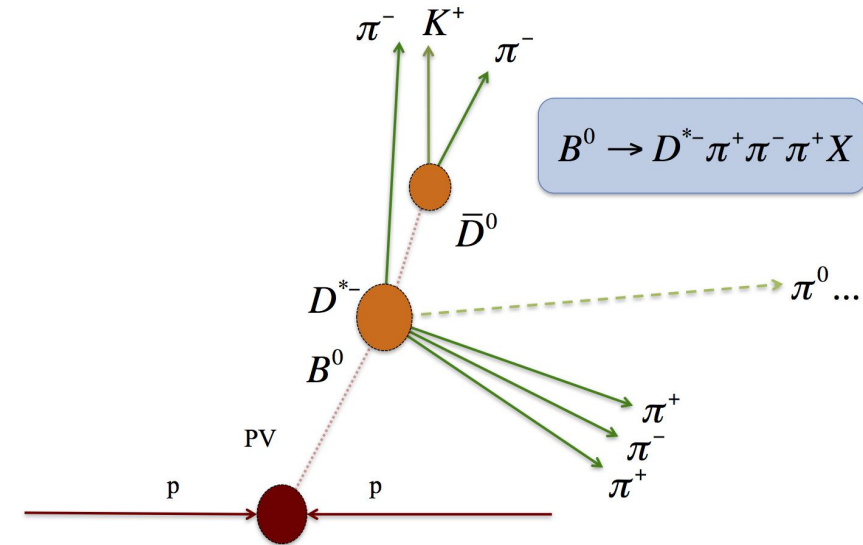
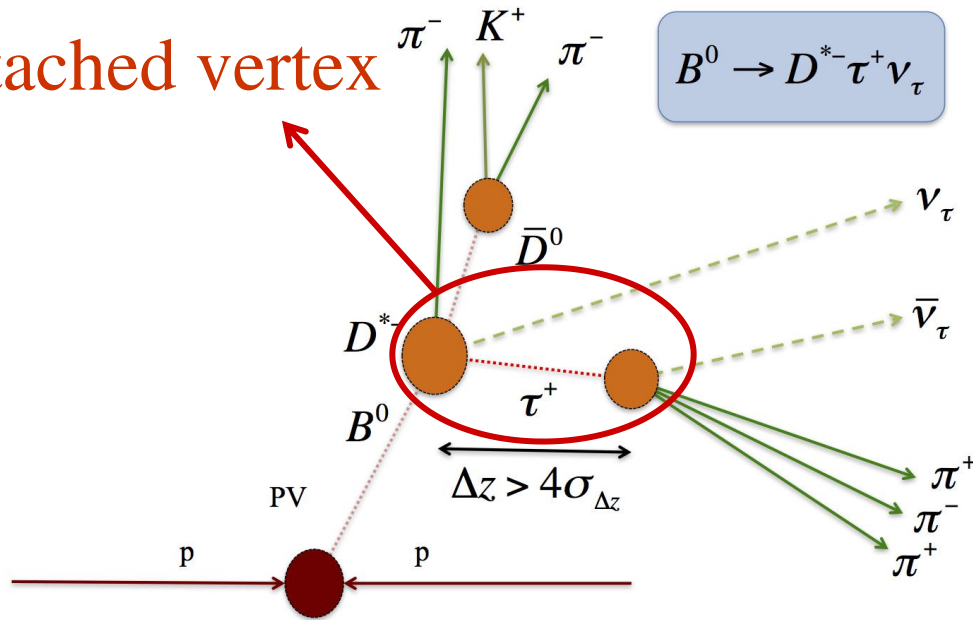


All LHCb results based on 3fb^{-1} data from Run1,
updates are on the way!

Details about $R(D^{*-})$ measurement with hadronic tau decays

[PRL120(2108)171802, PRD 97(2018)072013]

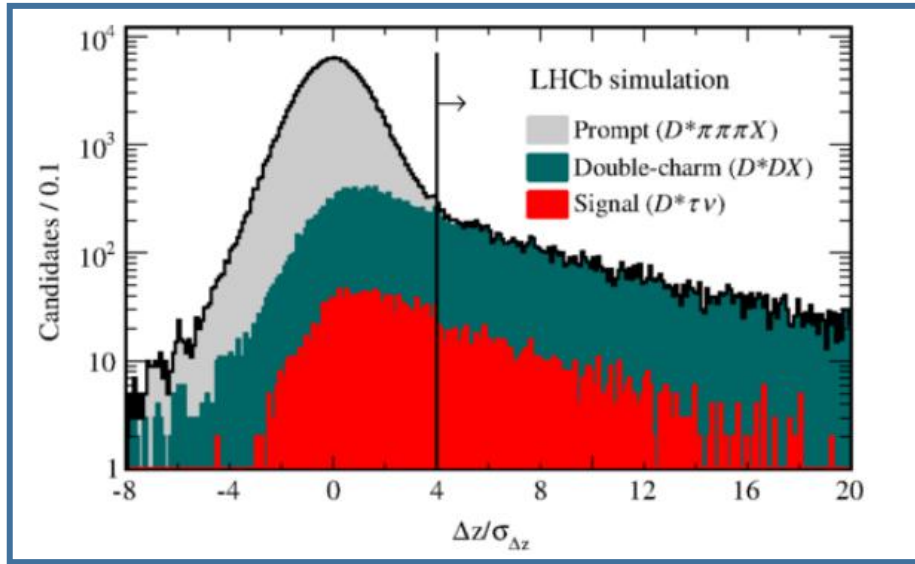
Detached vertex



- Advantage for hadronic tau decays: three prong decays allow for the reconstruction of tau vertex & no background from normal semileptonic decays
- Target measurement: $K(X_c) = \frac{BR(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{BR(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)}$. Same charged final states in signal and normalization channels.

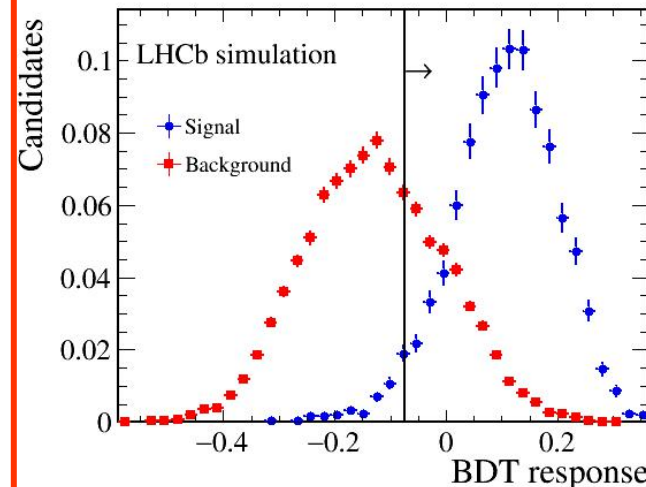
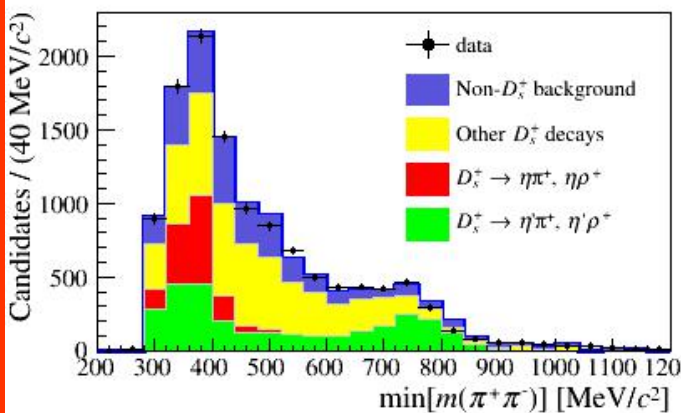
Details about $R(D^*)$ measurement with hadronic tau decays

[PRL120(2108)171802, PRD 97(2018)072013]



- Main backgrounds:
 - $B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+ X$
 - $B^0 \rightarrow D^{*-} D X (D = D_s^+, D^0, D^+)$
- After the detached vertex cut, the largest background from $B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+ X$ decays is suppressed by ~ 3 orders of magnitude

While $\min[m(\pi^+ \pi^- \text{ from } \tau^+)]$ will peak at ρ mass (770 MeV)

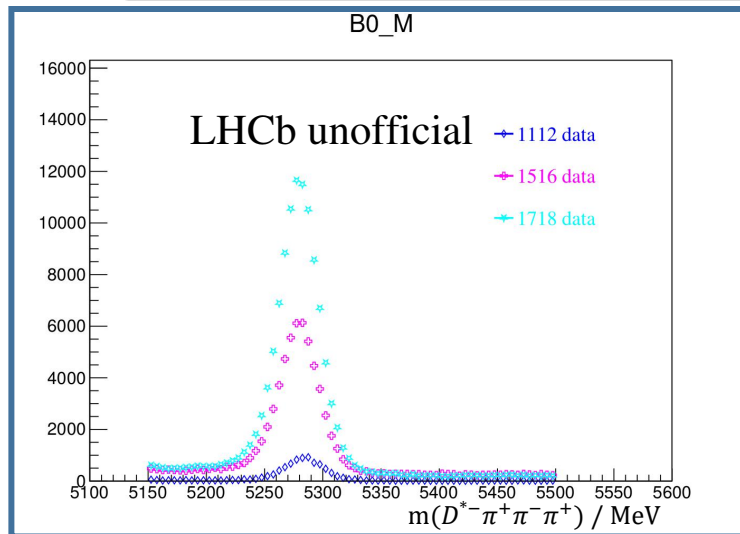


- The dominant double charm background $B^0 \rightarrow D^{*-} D_s^+ X$ is reduced by a boosted decision tree (BDT) based on 3π dynamics and resonant structure
- $B^0 \rightarrow D^{*-} D^0 X$ is well constrained by charged-particle isolation method

Prospects: growth in statistics

[arXiv:2101.08326]

Experiment	BABAR	Belle	Belle II	LHCb			
				Run 1	Run 2	Runs 3–4	Runs 5–6
Completion date	2008	2010	2031	2012	2018	2031	2041
Center-of-mass energy	10.58 GeV	10.58/10.87 GeV	10.58/10.87 GeV	7/8 TeV	13 TeV	14 TeV	14 TeV
$b\bar{b}$ cross section [nb]	1.05	1.05/0.34	1.05/0.34	$(3.0/3.4) \times 10^5$	5.6×10^5	6.0×10^5	6.0×10^5
Integrated luminosity [fb^{-1}]	424	711/121	$(40/4) \times 10^3$	3	6	40	300
B^0 mesons [10^9]	0.47	0.77	40	170	580	4,200	32,000
B^+ mesons [10^9]	0.47	0.77	40	170	580	4,200	32,000
B_s mesons [10^9]	-	0.01	0.5	40	140	1,000	7,600
Λ_b baryons [10^9]	-	-	-	90	300	2,200	16,000
B_c mesons [10^9]	-	-	-	1.3	4.4	32	240



Mass spectrum of reconstructed B^0 from roughly pre-selected $B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+$ candidates

- Hopefully, owing to
 - increase in integrated luminosity
 - larger \sqrt{s} leads to larger production cross section
 - improved trigger and selection

The stat. uncertainty of hadronic $R(D^*)$ can reduce to below 3%

16/11/2021

GDR-InF annual workshop 2021

Prospects: inputs from BESIII

Relative Systematic uncertainties on $R(D^*)$

Source	$\delta R(D^{*-})/R(D^{*-})$ [%]
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D_s^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \rightarrow 3\pi X$ decay model	2.5
$B \rightarrow D^{*-}D_s^+X$, $B \rightarrow D^{*-}D^+X$, $B \rightarrow D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \rightarrow D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Normalization channel efficiency (modeling of $B^0 \rightarrow D^{*-}3\pi$)	2.0
Total uncertainty	9.1

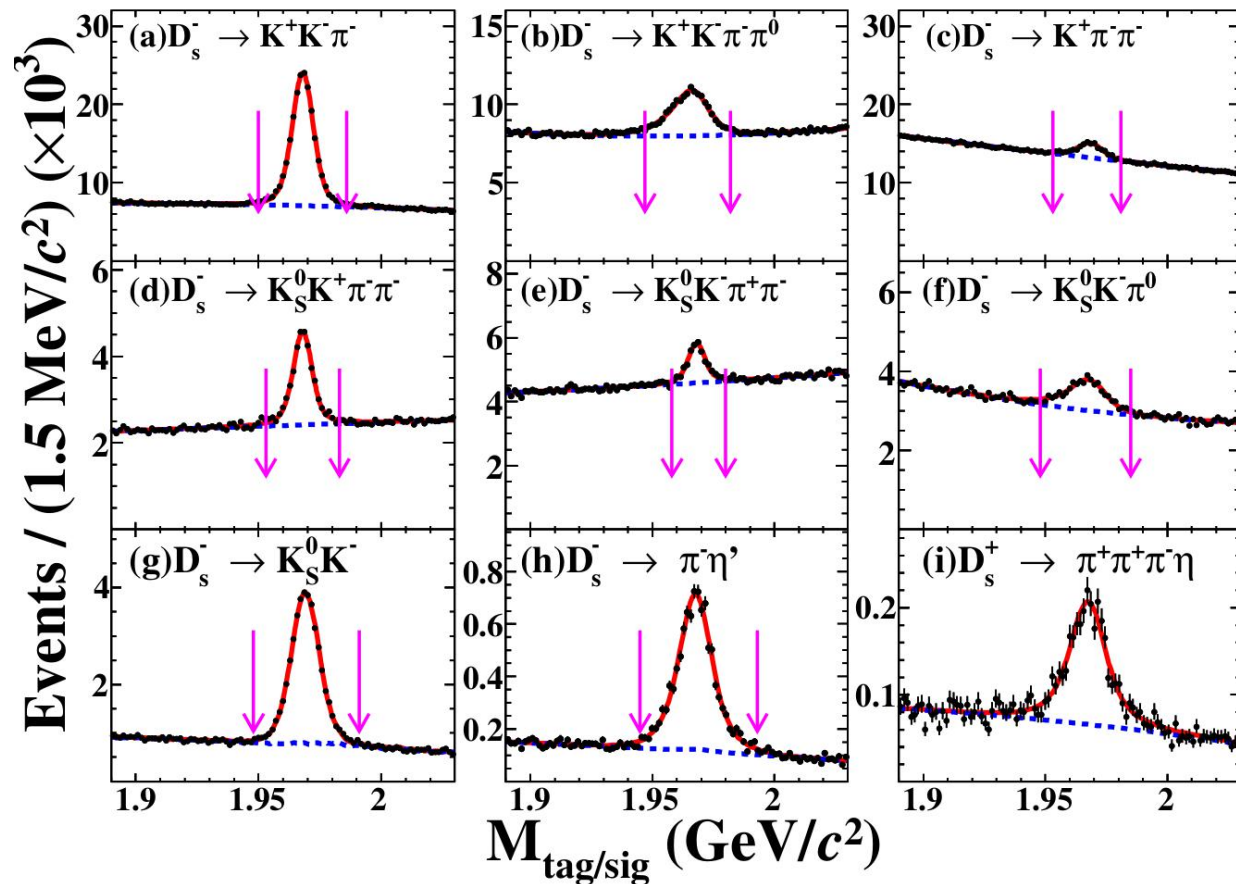
[PRL120(2108)171802, PRD 97(2018)072013]

- Regarding charm mesons decays, need inputs from BESIII
 - Inclusive $D_s^+ \rightarrow \pi^+\pi^-\pi^+X$
 - $\eta\pi, \eta\rho, \eta'\pi, \eta'\rho, \omega\pi, \omega\rho, \phi\pi, \phi\rho$
 - $M3\pi$ where M is $(\pi^0, \eta, \eta', K^0, \omega, \phi)$
- Cooperations between LHCb and BESIII on this project is ongoing
- These inputs are critical for the [complete R\(X\) program](#) of LHCb

I'm working on the measurement of branching fraction of $D_s^+ \rightarrow \pi^+\pi^-\pi^+\eta'$ at BESIII

Prospects: inputs from BESIII

- Recent result on this project from BESIII:
 - Branching fraction of $D_s^+ \rightarrow \pi^+ \pi^- \pi^+ \eta$



$$\mathcal{B}(D_s^+ \rightarrow \pi^+ \pi^+ \pi^- \eta) = (3.12 \pm 0.13_{\text{stat.}} \pm 0.09_{\text{syst.}})\%$$

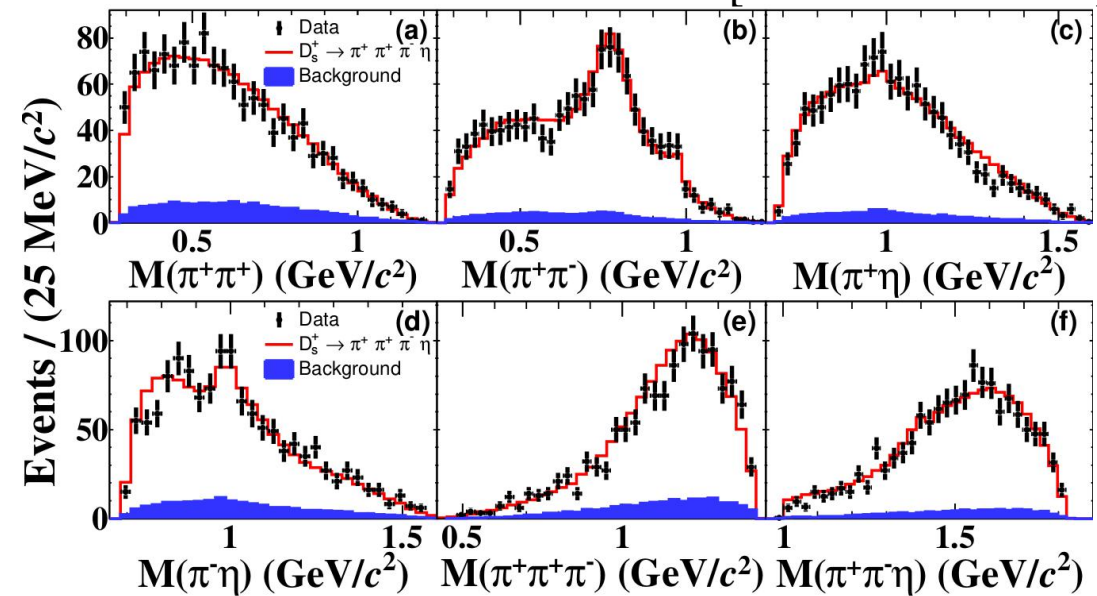
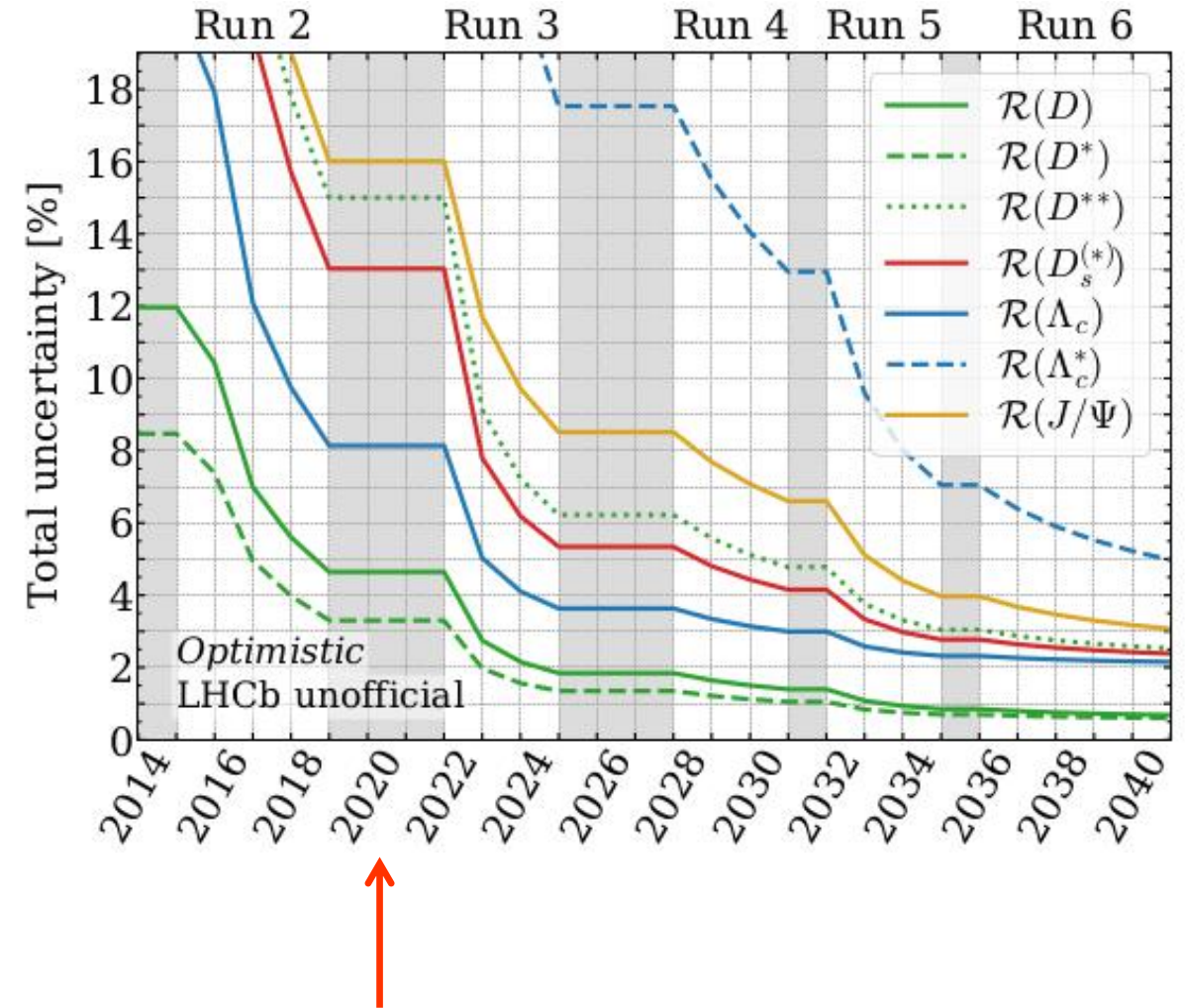
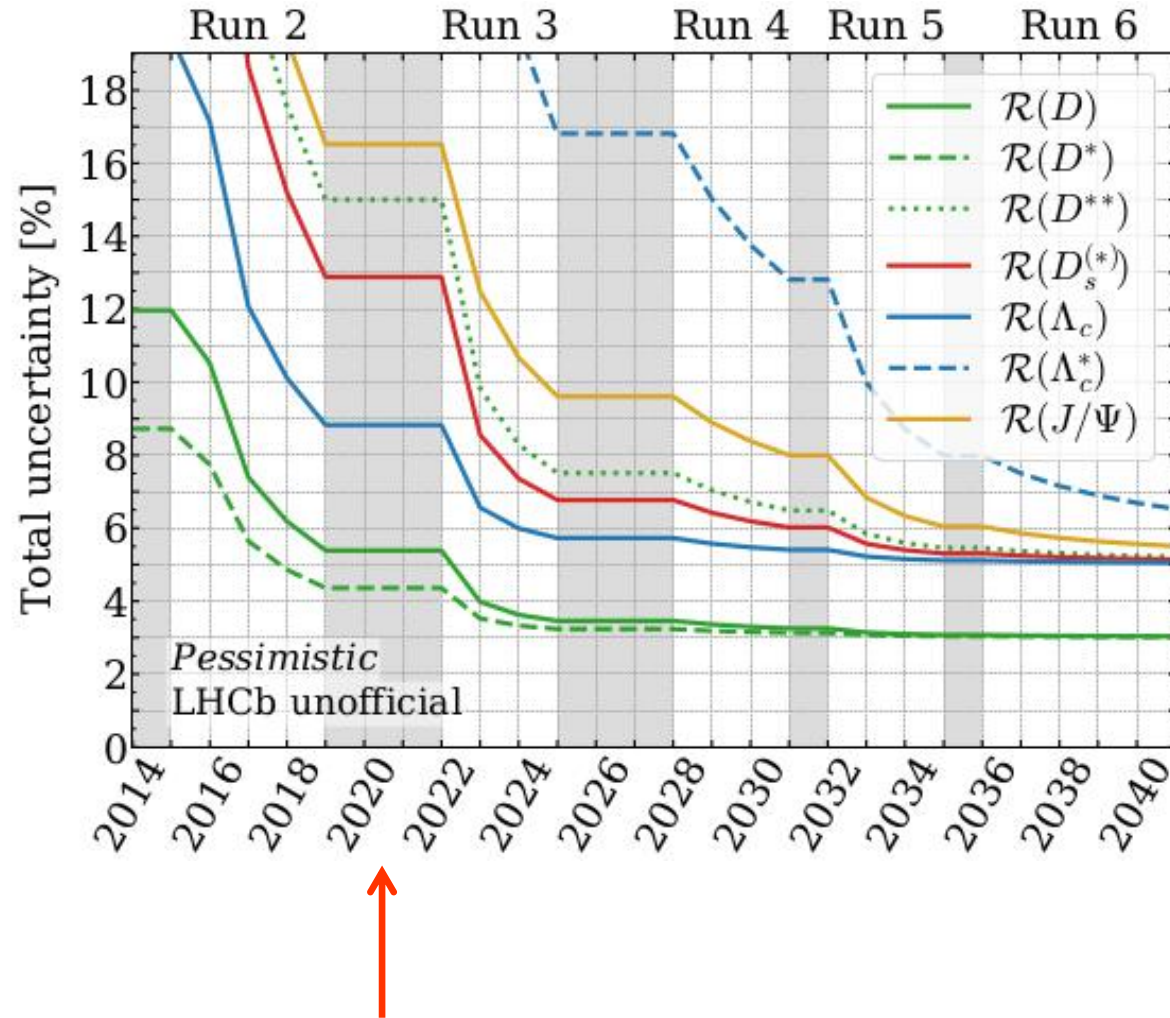


TABLE I: Phases and FFs for various intermediate processes. The first and the second uncertainties are statistical and systematic, respectively.

Amplitude	Phase	FF(%)
$a_1(1260)^+(\rho(770)^0 \pi^+) \eta$	0.0(fixed)	$55.4 \pm 3.9 \pm 2.0$
$a_1(1260)^+(f_0(500) \pi^+) \eta$	$5.0 \pm 0.1 \pm 0.1$	$8.1 \pm 1.9 \pm 2.1$
$a_0(980)^+ \rho(770)^0$	$2.5 \pm 0.1 \pm 0.1$	$6.7 \pm 2.5 \pm 1.5$
$\eta(1405)(a_0(980)^- \pi^+) \pi^+$	$0.2 \pm 0.2 \pm 0.1$	$0.7 \pm 0.2 \pm 0.1$
$\eta(1405)(a_0(980)^+ \pi^-) \pi^+$	$0.2 \pm 0.2 \pm 0.1$	$0.7 \pm 0.2 \pm 0.1$
$f_1(1420)(a_0(980)^- \pi^+) \pi^+$	$4.3 \pm 0.2 \pm 0.4$	$1.9 \pm 0.5 \pm 0.3$
$f_1(1420)(a_0(980)^+ \pi^-) \pi^+$	$4.3 \pm 0.2 \pm 0.4$	$1.7 \pm 0.5 \pm 0.3$
$[a_0(980)^- \pi^+]_S \pi^+$	$0.1 \pm 0.2 \pm 0.2$	$5.1 \pm 1.2 \pm 0.9$
$[a_0(980)^+ \pi^-]_S \pi^+$	$0.1 \pm 0.2 \pm 0.2$	$3.4 \pm 0.8 \pm 0.6$
$[f_0(980) \eta]_S \pi^+$	$1.4 \pm 0.2 \pm 0.3$	$6.2 \pm 1.7 \pm 0.9$
$[f_0(500) \eta]_S \pi^+$	$2.5 \pm 0.2 \pm 0.3$	$12.7 \pm 2.6 \pm 2.0$

Prospects: estimated precision evolution

[arXiv:2101.08326]



Summary

- LFUV is a hint towards physics beyond SM
- Semitauonic B decays are important tests of LFUV, updates based on larger samples collected by LHCb are ongoing
- Cooperation with BESIII insures critical inputs about charm mesons decays, which will increase the precision of complete R(X) program at LHCb
- My works on both sides:
 - BESIII: measurement of branching fraction of $D_s^+ \rightarrow \pi^+ \pi^- \pi^+ \eta'$
 - LHCb: $R(D^*)$ hadronic measurement using 2017-2018 data samples (4 fb^{-1})

Thank you for listening!

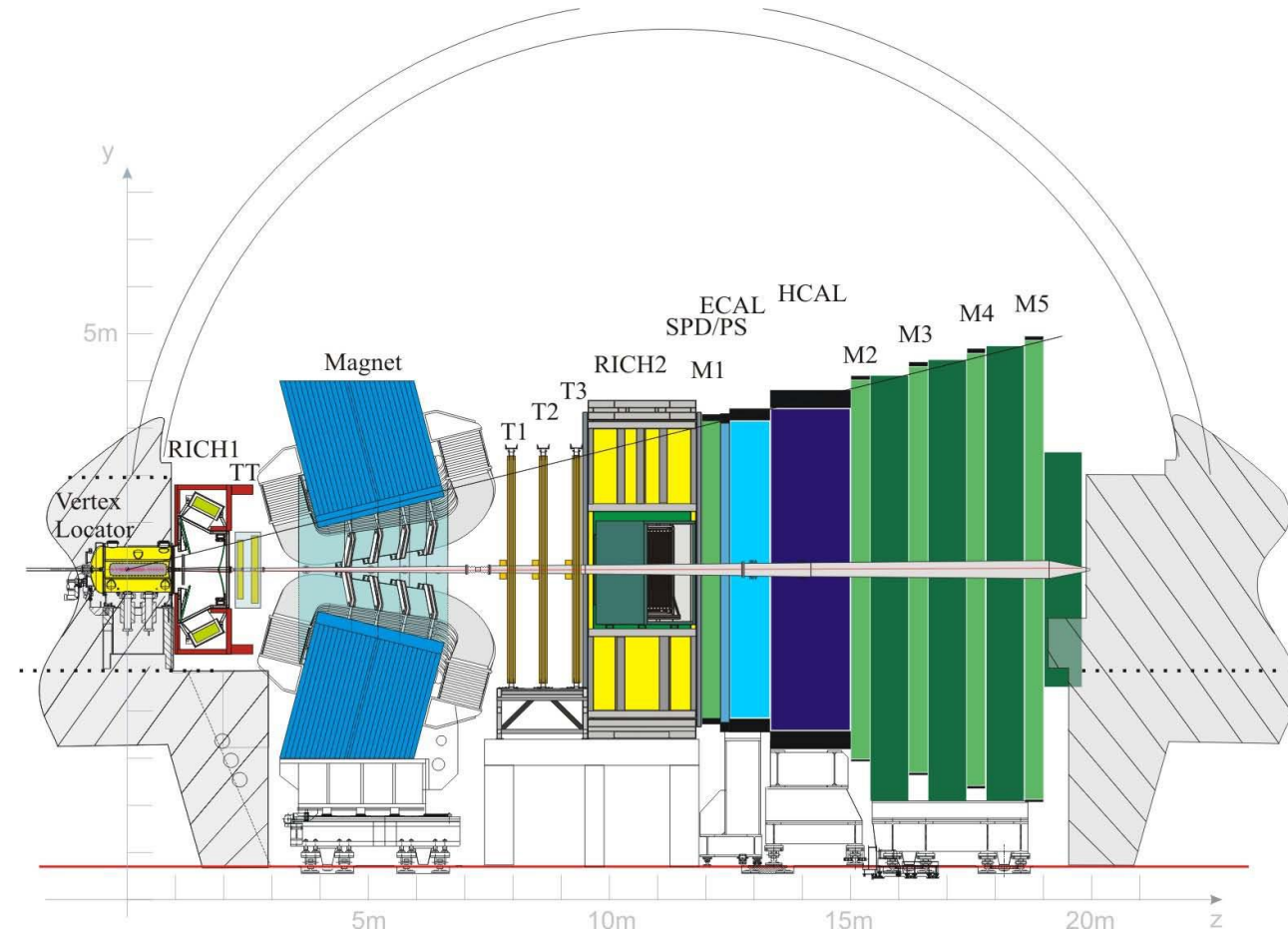
Backup

The LHCb detector

Int. J. Mod. Phys. A 30 1530022 (2015)
JINST 3 (2008) S08005

A single-arm forward spectrometer, designed for the study of heavy flavor physics

- **Excellent vertex, IP and decay-time resolution**
 $\sigma(\text{IP}) \approx 20\mu\text{m}$ for high- p_T tracks
 $\sigma(\tau) \approx 45\text{fs}$ for $B_s^0 \rightarrow J/\psi\phi$ and $B_s^0 \rightarrow D_s^- \pi^+$ decays
- **Very good momentum resolution**
 $\delta p/p \approx 0.5\%-1\%$ for $p \in (0,200)$ GeV
 $\sigma(m_B) \approx 24$ MeV for two-body decays
- **Hadron and muon identification**
 $\varepsilon_{K \rightarrow K} \approx 95\%$ for $\varepsilon_{\pi \rightarrow K} \approx 5\%$ up to 100 GeV
 $\varepsilon_{\mu \rightarrow \mu} \approx 97\%$ for $\varepsilon_{\pi \rightarrow \mu} \approx 1\%-3\%$
- **$2 < \eta < 5$ range (LHCb acceptance): $\sim 3 \times 10^4/\text{s } b\bar{b}$ pairs @ 7 TeV**
 $\sim \times 2$ yield @ 13 TeV; $\sim \times 20$ yield for $c\bar{c}$ pairs



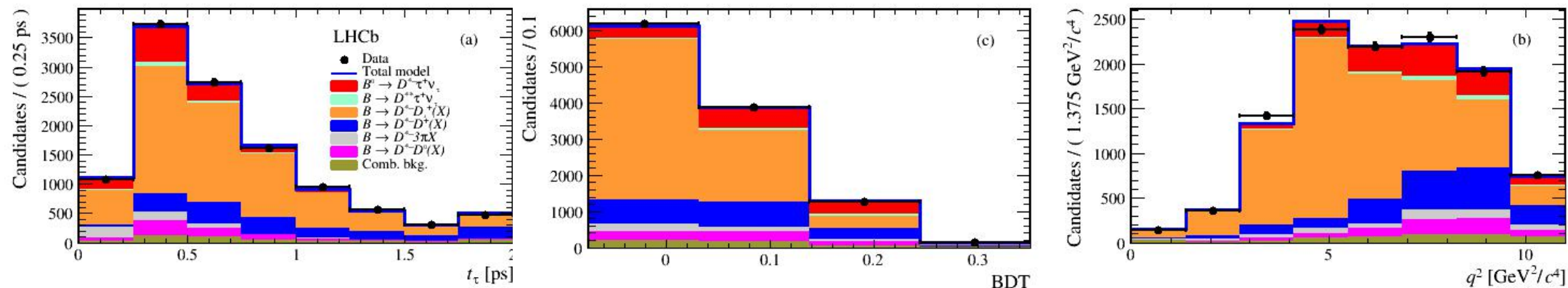
Details about $\mathcal{R}(D^{*-})$ measurement with hadronic tau decays

[PRL120(2108)171802, PRD 97(2018)072013]

- Signal yield determined by a 3D binned template fit
 - q^2 ($\equiv |P_{B^0} - P_{D^{*-}}|^2$)
 - t_τ , τ decay time
 - BDT output (trained to reduce $B^0 \rightarrow D^{*-} D_s^+ X$ background)
- Templates obtained from simulation and study of control samples

$$\mathcal{R}(D^{*-}) = 0.291 \pm 0.019(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})$$

1 σ above SM prediction



Future prospects about control of other systematic uncertainties

1. Limited size of MC simulation samples:

[arXiv:2101.08326]

Hardware (GPU computation)

Fast simulation

Aggressive generator-level selections

2. Modeling of $B \rightarrow D^{(*)} \ell \nu$:

Precise parametrizations of hadronic matrix elements

3. $B \rightarrow D^{**} \ell \nu$ and $B \rightarrow D^{**} \tau \nu$ backgrounds:

Data-driven fits of form factors, LQCD results

Improved measurements of $B \rightarrow D^{**} \ell \nu$ relative BR and kinematic distributions

Measurements involving a hadronized $W \rightarrow D_s^+$

Direct measurement of $B \rightarrow D^{**} \tau \nu$ for the narrow D^{**} states

4. Other background contributions:

Inputs from Belle II, LHCb and BESIII

5. External branching fraction uncertainties:

More precise measurements from LHCb or Belle II