Meet the Anomalies: Experimental Perspective on $b \to c\tau\nu_\tau$

Thomas Lück

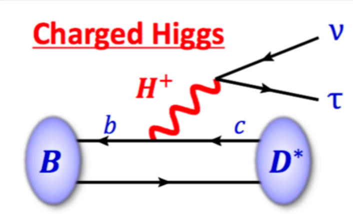
March 24, 2021

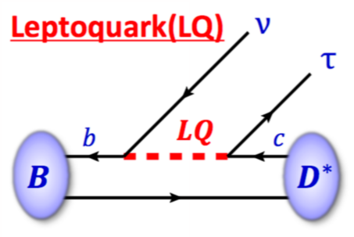
Bundesministerium für Bildung und Forschung

Table of contents

- semitauonic B - decays are sensitive to new physics (NP) contributions
  - branching ratios
  - kinematic distributions
  - polarization of the τ

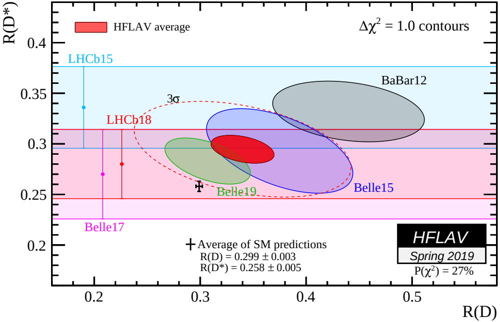
Possible candidates for NP contributions:





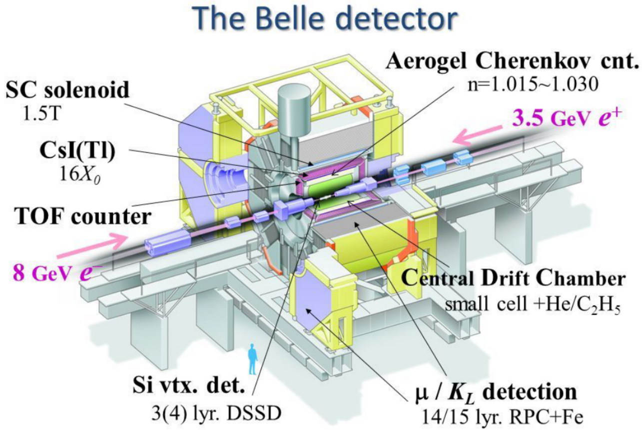
Introduction

- $R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$
- many systematic uncertainties cancel in ratio
- independent of $|V_{cb}|$
- theory very precise due to cancellation of hadronic matrix elements



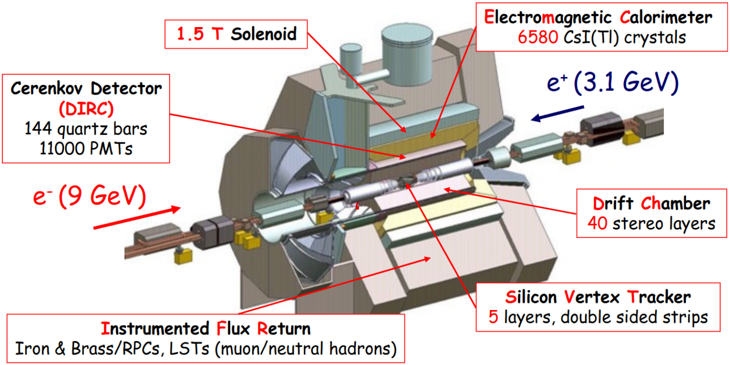
B-Factories (past): Belle

- KEKB in Tsukuba (Japan)
- 8GeV electrons on 3.5GeV positrons
- collected 772 million $B\bar{B}$ pairs



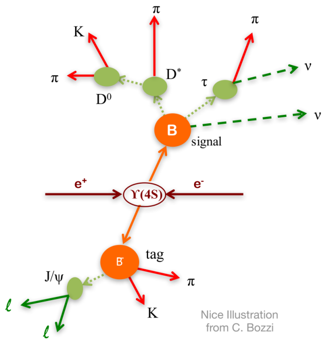
B-Factories (past): BABAR

- PEPII at SLAC in Menlo Park (USA)
- 9GeV electrons on 3.1GeV positrons
- 471 million $B\bar{B}$ pairs collected



B meson tagging

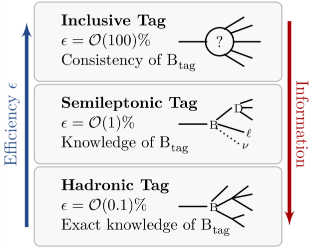
- at e^+e^- machines initial state is known
- tagging: (fully) reconstructing the accompanying B_{tag} meson
- using momentum conservation one can infer the missing 4-momentum:
  - $p_{miss} = p_{e^+e^-} - p_{Bsig} - p_{Btag}$
- semi-leptonic (non-tau) decays identified by peak at $m^2_{miss} = p^2_{miss} = 0$
- semi-tauonic decays will peak at higher m^2_{miss} due to 2 (3) missing neutrinos on signal side



Nice Illustration from C. Bozzi

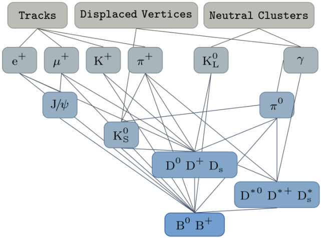
Different types of tagging

- Inclusive tagging:
  - not reconstruct specific decays
  - reconstruct signal side
  - combine all remaining particles in event into tag B candidate
  - low resolution, but high efficiency
- semi-leptonic tagging:
  - reconstruct $B \to D^{(*)}\ell\nu$
  - high branching ratio (BR)
  - missing neutrino $\Rightarrow$ not full kinematic information
- hadronic tagging:
  - reconstruct B_{tag} in hadronic mode
  - full kinematic of B_{tag}
  - low BR and efficiency



F. Bernlochner

- Belle II (FEI) / Belle (FR)
  - reconstruct full decay chain step by step
  - $\mathcal{O}(5000)$ decay channels
  - apply at each step multivariate analysis
  - FR similar to FEI but with NN instead of BDT and different cuts
  - FEI: around 200 BDT to reconstruct full decay chain
- BABAR semi-exclusive reconstruction (SER):
  - reconstruct seed meson: J/Ψ, D, D^*, D_s
  - start adding up to 5 light hadron candidates (K, $\pi^{\pm}$, π^0, K_S) to form a B candidate



	$B^{\pm}$	B^0
Hadronic		
FEI with FR channels	0.53 %	0.33 %
FEI	0.76 %	0.46 %
FR	0.28 %	0.18 %
SER	0.4 %	0.2 %
Semileptonic		
FEI	1.80 %	2.04 %
FR	0.31 %	0.34 %
SER	0.3 %	0.6 %

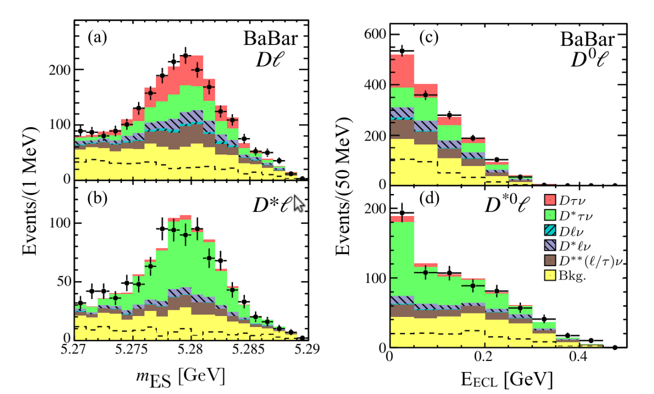
arXiv:1807.08680

$R(D^{(*)})$ with Hadronic tag and leptonic tau decay from B-Factories

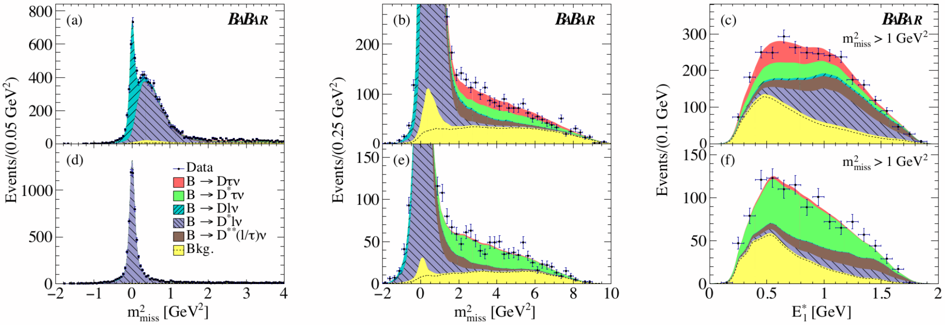
- Belle (arXiv:1507.03233 (2015)) and BABAR (arXiv:1205.5442 (2012)) performed very similar analysis of hadronically tagged B-events and leptonic tau decays: $\tau \to \ell \nu_\tau \nu_\ell$ with full datasets
- signal $B \to D^{(*)}\tau\nu$ and normalization mode $B \to D^{(*)}\ell\nu$
- reconstruct four signal channels $D^{*+}\ell^-$, $D^{*0}\ell^-$, $D^+\ell^-$, $D^+\ell^-$
- signal and normalization mode have same reconstructed final state
- tag side B meson fully reconstructed in hadronic mode
- the momentum transfer is used to select signal events $q^2 = (p_{Bsig} - p_{D^{(*)}})^2 > 4 GeV^2$ $(m_\tau^2 = 3.16 GeV^2)$
- further Bkg suppression done by training multivariate methods and cut on m_{BC}:
  - Belle: use neural net output O_{NB} for signal fit
  - BABAR: cut on multiple BDTs
  - for both important variable: E_{ECL} (next slide)

- beam constrained mass of tag B:
  - $m_{BC} = \sqrt{\frac{s}{4} - |\vec{p}_{reco}|^2}$ (for BABAR it is called m_{ES})
  - for correctly reconstructed tag B peaks at B - meson mass
- extra energy in the calorimeter E_{ECL}:
  - sum over all calorimeter entries not used for reconstruction
  - for signal AND normalization mode peaks at 0

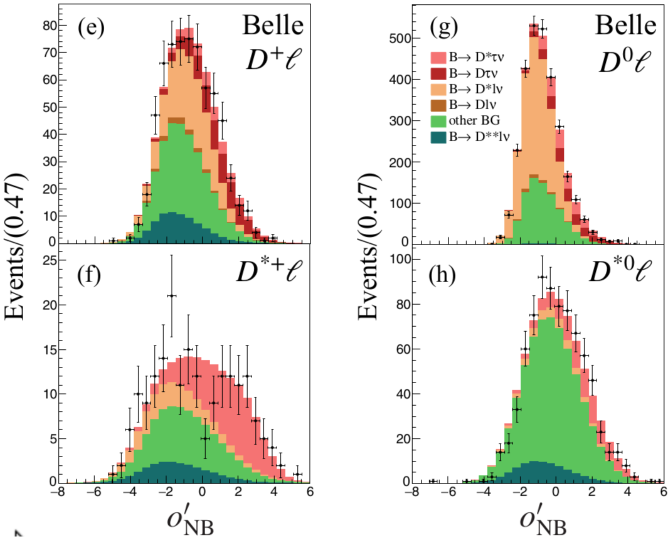
Signal enhanced region BABAR analysis ($m^2_{miss} > 1 GeV^2$)



- BABAR extracts signal yields by a 2D fit to the m^2_{miss} and the lepton energy in the B-rest frame E^*_l
- top: $D\ell$; bottom $D^*\ell$ (neutral + charged)



- Belle estimates signal from simultaneous fit:
  - normalization mode region: m^2_{miss} for $m^2_{miss} < 0.85\,GeV^2$
  - signal mode region: NN output o'_{NB} for $m^2_{miss} > 0.85\,GeV^2$



Results: $R(D^{(*)})$ with hadronic tag, leptonic tau decay from B-Factories

Event yields

Sample	Contribution	*BABAR*	Belle	ϵ ratio
$D\ell$	$B \to D\tau\nu$	489	320	0.40
	$B \to D\ell\nu$	2981	3147	0.64
	$B \to D^{**}l\nu$	506	239	0.29
	Other bkg.	1033	2005	1.18
$D^*\ell$	$B \to D^*\tau\nu$	888	503	0.35
	$B \to D^*\ell\nu$	11953	12045	0.61
	$B \to D^{**}l\nu$	261	153	0.36
	Other bkg.	404	2477	3.74

Result

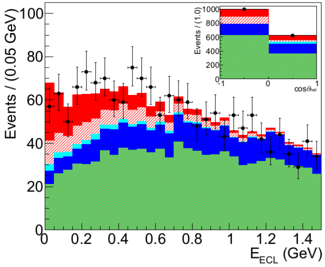
Result	*BABAR*	Belle
$\mathcal{R}(D)$	$0.440 \pm 0.058 \pm 0.042$	$0.375 \pm 0.064 \pm 0.026$
$\mathcal{R}(D^*)$	$0.332 \pm 0.024 \pm 0.018$	$0.293 \pm 0.038 \pm 0.015$

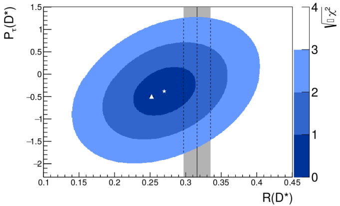
Uncertainties

Result	Contribution	Uncertainty [%] *BABAR* Sys.	*BABAR* Stat.	Belle Sys.	Belle Stat.	Ratio
$\mathcal{R}(D)$	$B \to D^{**}l\nu$	5.8		4.4		0.76
	MC stats	5.7		4.4		0.78
	$B \to Dl\nu$	2.5		3.3		1.30
	Other bkg.	3.9		0.7		0.18
	Particle ID	0.9		0.5		0.54
	Total systematic	**9.6**		**7.1**		**0.74**
	Total statistical		**13.1**		**17.1**	**1.31**
	Total	**16.2**		**18.5**		**1.14**
$\mathcal{R}(D^*)$	$B \to D^{**}l\nu$	3.7		3.4		0.90
	MC stats	2.8		3.6		1.31
	$B \to D^*l\nu$	1.0		1.3		1.31
	Other bkg.	2.3		0.7		0.29
	Particle ID	0.9		0.5		0.54
	Total systematic	**5.6**		**5.2**		**0.93**
	Total statistical		**7.1**		**13.0**	**1.83**
	Total	**9.0**		**14.0**		**1.56**

Measurement of the τ-polarization: Belle arXiv:1709.00129

- $R(D^*)$ with hadronically tagged $B \to D^*\tau\nu$ with $\tau^\pm \to \pi^\pm\nu_\tau$ and $\tau^\pm \to \rho^\pm\nu_\tau$
- reconstructed the τ polarization by exploiting that ONLY 1 neutrino in tau decay:
  - tau direction not directly accessible
  - in $\tau\nu$ rest frame $\Rightarrow$ angle between τ and h, $\cos\theta_{\tau h}$, known (h = e, π, ρ)
  - related to τ helicity angle by: $\cos\theta_h = \frac{1}{\vec{p}_h^{\tau}}(\gamma|\vec{p}_h|\cos\theta_{\tau h} - \beta\gamma E_h)$
- fit to E_{ECL} in two bins of $\cos\theta_{\tau h}$



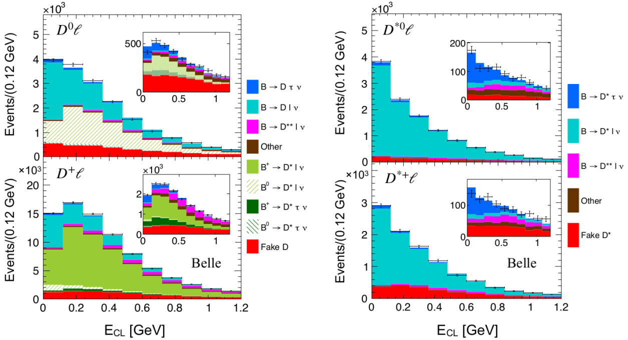


$R(D^{(*)})$ with Semileptonic tag and leptonic τ decay: Belle arXiv:1910.05864 (2019)

- the tag B-meson is reconstructed semi-leptonically: $B \to D^{(*)}\ell\nu$
- four signal channels $D^{(*)}\ell$ are reconstructed
- not full kinematic information for the tag side
- use the angle between the B-meson and the $D^{(*)}\ell$ system to estimate quality of B-tag:
  - assuming neutrino $m_\nu \approx 0$ one can derive:
  - $\cos\theta_{D^{(*)}\ell} = \frac{2E_{beam}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|\vec{p}_B||\vec{p}_{D^{(*)}\ell}|}$
  - for decays where only neutrino is missing $[-1, 1]$ (with tails due to resolution and Bremstrahlung)

$R(D^{(*)})$ with Semileptonic tag and leptonic τ decay: Belle arXiv:1910.05864 (2019)

- a BDT is trained to distinguish signal and normalization mode using m^2_{miss}, $\cos\theta_{D^{(*)}\ell}$ for the signal side, and total visible energy $E_{vis} = \sum_i E_i$
- the signal is estimated by a 2D extended ML fit to E_{ECL} and the BDT output



$R(D^{(*)})$ with Semileptonic tag with leptonic τ decay: Belle arXiv:1910.05864 (2019)

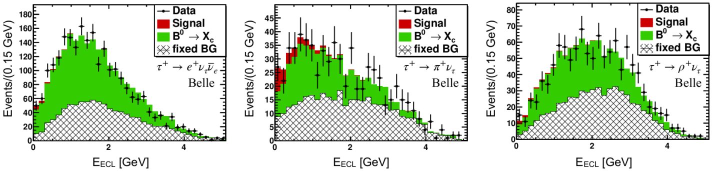
Results

- $R(D) = 0.307 \pm 0.037(stat) \pm 0.016(syst)$
- $R(D^*) = 0.283 \pm 0.018(stat) \pm 0.014(syst)$
- the most precise estimation yet
- in good agreement with the SM values

Result	Contribution	Uncertainty [%] Sys.	Stat.
$\mathcal{R}(D)$	$B \to D^{**}\ell\bar{\nu}_\ell$	0.8	
	PDF modeling	4.4	
	Other bkg.	2.0	
	$\epsilon_{\rm sig}/\epsilon_{\rm norm}$	1.9	
	Total systematic	**5.2**	
	Total statistical		**12.1**
	Total	**13.1**	
$\mathcal{R}(D^*)$	$B \to D^{**}\ell\bar{\nu}_\ell$	1.4	
	PDF modeling	2.3	
	Other bkg.	1.4	
	$\epsilon_{\rm sig}/\epsilon_{\rm norm}$	4.1	
	Total systematic	**4.9**	
	Total statistical		**6.4**
	Total	**8.1**	

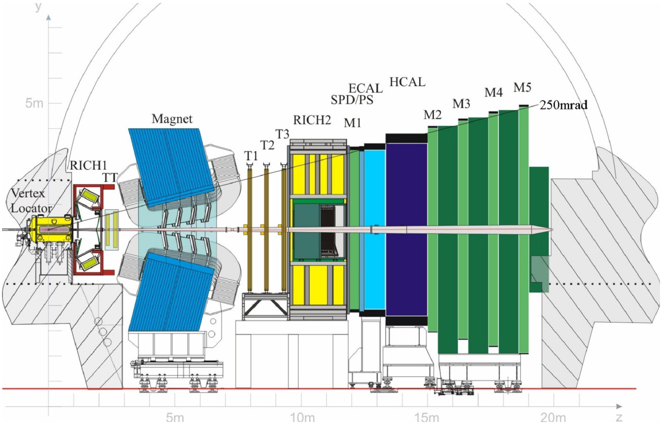
$R(\pi)$ by Belle (arXiv:1509.06521)

- measurement of $R(\pi^-) = \frac{\mathcal{B}(B^0 \to \pi^- \tau^+ \nu)}{\mathcal{B}(B^0 \to \pi^- \ell^+ \nu)}$
- challenging due to CKM suppression ($\approx$40 times smaller than $b \to c\tau\nu$)
- hadronically reconstruct the tag B
- combination three different channels: $\tau \to \rho\nu$; $\tau \to e\nu\nu$; $\tau \to \pi\nu$
- use extra energy in calorimeter, E_{ECL}, to fit signal yield
- Result:
  - measured: $R(\pi) = 1.05 \pm 0.51$
  - SM prediction: $R(\pi)_{SM} = 0.641 \pm 0.016$



LHCb detector

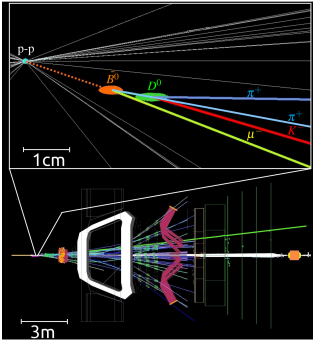
- $b\bar{b}$ produced in gluon-gluon-fusion $\Rightarrow$ forward boost
- low lumi but $b\bar{b}$ cross section $\approx \times 10^5$ compared to B-factories
- $\approx 750 \times 10^9$ $B\bar{B}$ events at 7TeV and 13TeV (750 $\times$ Belle+BABAR)

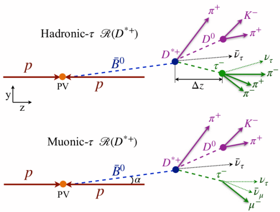


- only Run1 data ($3fb^{-1}$)
- reconstruct exclusively $D^{*+} \rightarrow D^0\pi^+$ with $D^0 \rightarrow K^-\pi^+$
- leptonic mode for tau decay: $\tau \rightarrow \mu\nu$
- no other charged particle from same common vertex
- vertex has to be significantly displaced from IP
- use "rest frame approximation" to approximate the B meson momentum

Rest frame approximation

- due to missing neutrinos B-momentum can not be completely reconstructed
- exploit large boost along beam axis at LHCb: $\beta\gamma \approx 50$
    - assume velocity along the beam direction of B-meson is the same as velocity of reconstructed $D^{*-}\mu$ system
    - direction of B meson estimated by position of the displaced vertex
    - $|p_B| = \frac{m_B}{m_{D^*\mu}}(p_{D^*\mu})_z\sqrt{1+\tan^2\alpha}$ with α angle between B and beam





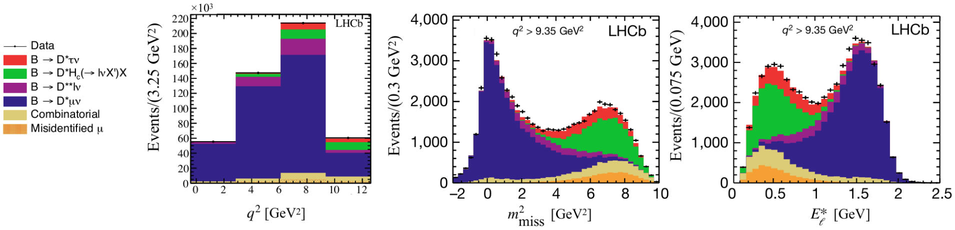
arXiv:1703.01766

- the signal is extracted from a 3D binned ML fit in m^2_{miss}, q^2, E^*_l

Result

$R(D^{*+}) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$

Contribution	Uncertainty [%] Sys.	Stat.
Simulated sample size	6.2	
Misidentified μ bkg.	4.8	
$B \to D^{**} l\nu$ bkg.	2.1	
$B \to D^* l\nu$ FFs	1.9	
Hardware trigger	1.8	
Double-charm bkg.	1.5	
MC/data correction	1.2	
Combinatorial bkg.	0.9	
Particle ID	0.9	
Total systematic	**8.9**	
Total statistical		**8.0**
Total	**12.0**	



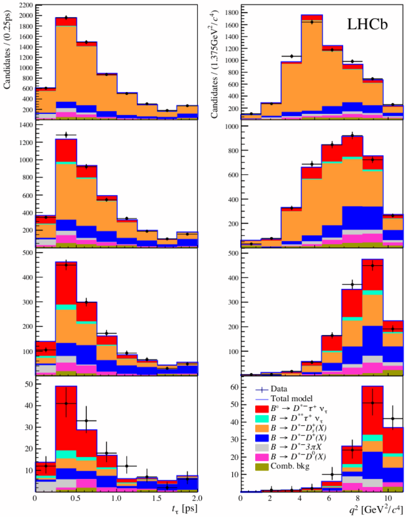
$R(D^{*+})$ with $\tau^- \to \pi^-\pi^+\pi^-\nu$: LHCb arXiv:1708.08856 (2018)

- similar to previous LHCb analysis $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$
- use $\tau^- \to \pi^-\pi^+\pi^-\nu$ for τ decay
- allows to reconstruct the τ vertex:
  - used to suppress background by requiring τ vertex at least 4 σ downstream of B-vertex
  - reconstruction of the τ decay time used in the fit
- disadvantage: normalization not reconstructed simultaneously:
  - chose $B \to D^*\pi\pi\pi$ as normalization
  - $R(D^*) = \left(\frac{\mathcal{B}(B\to D^*\tau\nu)}{\mathcal{B}(B\to D^*\pi\pi\pi)}\right)_{fit} \left(\frac{\mathcal{B}(B\to D^*\pi\pi\pi)}{\mathcal{B}(B\to D^*\mu\nu)}\right)_{ext}$
  - depends on external input branching ratios
- BDTs are used to suppress hadronic background

$R(D^{*+})$ with $\tau^- \to \pi^-\pi^+\pi^-\nu$: LHCb arXiv:1708.08856

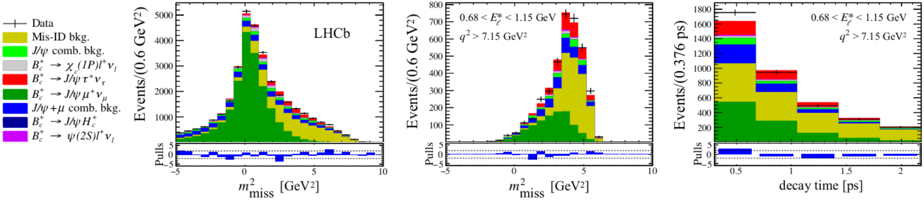
- signal yield from 3D binned likelyhood fit to q^2, τ decay time t_τ, and BDT output
- $R(D^{*+}) = 0.280 \pm 0.018(stat) \pm 0.025(syst) \pm 0.013(ext)$

Contribution	Uncertainty [%] Sys.	Ext.	Stat.
Double-charm bkg.	5.4		
Simulated sample size	4.9		
Corrections to simulation	3.0		
$B \to D^{**} l\nu$ bkg.	2.7		
Normalization yield	2.2		
Trigger	1.6		
PID	1.3		
Signal FFs	1.2		
Combinatorial bkg.	0.7		
Modeling of τ decay	0.4		
Total systematic	**9.1**		
$\mathcal{B}(B \to D^*\pi\pi\pi)$		3.9	
$\mathcal{B}(B \to D^*\ell\nu)$		2.3	
$\mathcal{B}(\tau^+ \to 3\pi\nu)/\mathcal{B}(\tau^+ \to 3\pi\pi^0\nu)$		0.7	
Total external		**4.6**	
Total statistical			**6.5**
Total		**12.0**	



$R(J/\Psi)$: LHCb arXiv:1711.05623 (2018)

- energies at LHCb also allow the production of higher mass bottom mesons and hadrons
- investigate $B_c \to J/\Psi\tau\nu$ to measure $R(J/\Psi) = \frac{\mathcal{B}(B_c \to J/\Psi\tau^+\nu)}{\mathcal{B}(B_c \to J/\Psi\mu^+\nu)}$
- binned 4D fit to q^2, m^2_{miss}, lepton energy E^*_l, and tau life time t_τ
- Results:
  - measured: $R(J/\Psi) = 0.71 \pm 0.17(stat) \pm 0.18(syst)$
  - SM prediction: $R(J/\Psi) = 0.2582(38)$
  - around 2 σ above SM



Summary $R(D^{(*)})$ measurements

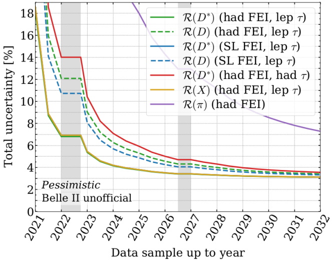
Result	Experiment	τ decay	Tag	Systematic uncertainty [%] MC stats	$D^{(*)}l\nu$	$D^{**}l\nu$	Other bkg.	Other sources	Total uncert. [%] Syst.	Stat.	Total
$\mathcal{R}(D)$	*BABAR* [a]	$\ell\nu\nu$	Had.	5.7	2.5	5.8	3.9	0.9	**9.6**	**13.1**	**16.2**
	Belle[b]	$\ell\nu\nu$	Semil.	4.4	0.7	0.8	1.7	3.4	**5.2**	**12.1**	**13.1**
	Belle[c]	$\ell\nu\nu$	Had.	4.4	3.3	4.4	0.7	0.5	**7.1**	**17.1**	**18.5**
$\mathcal{R}(D^*)$	*BABAR* [a]	$\ell\nu\nu$	Had.	2.8	1.0	3.7	2.3	0.9	**5.6**	**7.1**	**9.0**
	Belle[b]	$\ell\nu\nu$	Semil.	2.3	0.3	1.4	0.5	4.7	**4.9**	**6.4**	**8.1**
	Belle[c]	$\ell\nu\nu$	Had.	3.6	1.3	3.4	0.7	0.5	**5.2**	**13.0**	**14.0**
	Belle[d]	$\pi\nu$, $\rho\nu$	Had.	3.5	2.3	2.4	8.1	2.9	**9.9**	**13.0**	**16.3**
	LHCb[e]	$\pi\pi\pi(\pi^0)\nu$	—	4.9	4.0	2.7	5.4	4.8	**10.2**	**6.5**	**12.0**
	LHCb[f]	$\mu\nu\nu$	—	6.3	2.2	2.1	5.1	2.0	**8.9**	**8.0**	**12.0**

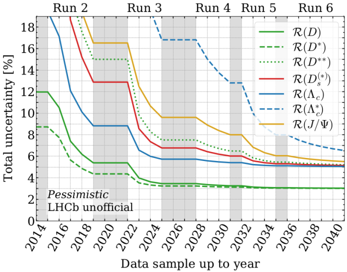
How to improve the precision

- obviously more statistics (LHCb, Belle II)
- some of the biggest uncertainties:
  - "gap problem": difference between measured inclusive and sum of exclusive $b \to c\ell\nu$
  - background from not well measured $B \to D^{**}\ell\nu$ decays
  - not well measured cross feed from $B \to D^{**}\tau\nu$ decays
  - LHCb significant backgrounds from not well measured hadronic B decays
  - all above can be reduced by improved measurements (e.g. Belle II)
- MC statistics another big contribution to systematics:
  - producing more MC!?
  - costs time and money, as time=money $\Rightarrow$ money^2
  - new approaches:
    - generator level filtering of events (reduces expensive detector simulation)
    - fast simulation: mimic detector response by fast methods (e.g. GAN)

What to expect from upcoming LHCb and Belle II analyses

- arXiv:2101.08326: possible projection of development of uncertainties as function of collected data sample
- put in assumption how statistical and systematic uncertainties behave with increasing size of datasets



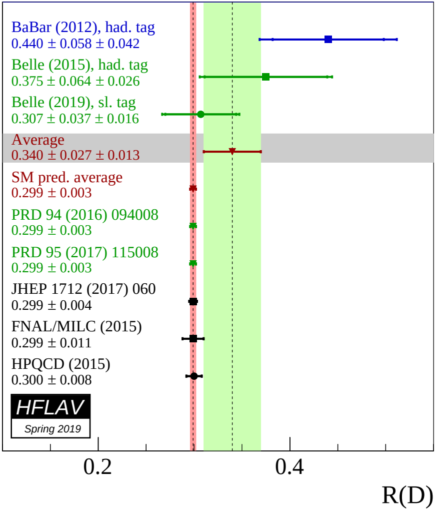


arXiv:2101.08326

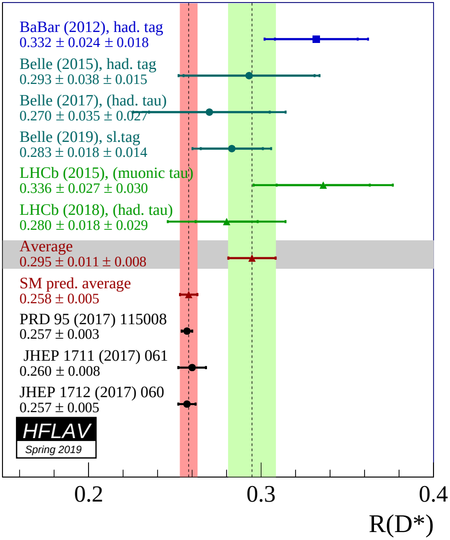
Summary

- around 3 σ deviation for $R(D^{(*)})$ between experimental world average and SM prediction
- measurements from different experiments and several channels
- new channels are investigated e.g. $R(\pi)$ or $R(J/\Psi)$
- further channels will be added in future $R(X)$, $R(D^{**})$
- increasing LHCb dataset will provide further precision improvement
- Belle II will soon join the hunt for $R(D^{(*)})$ with new e^+e^- collision data
- work needed to decrease the systematics

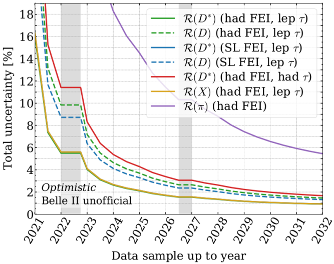
$R(D)$ HFLAV

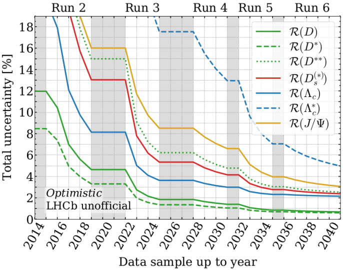

BaBar (2012), had. tag
0.440 ± 0.058 ± 0.042
Belle (2015), had. tag
0.375 ± 0.064 ± 0.026
Belle (2019), sl. tag
0.307 ± 0.037 ± 0.016
Average
0.340 ± 0.027 ± 0.013
SM pred. average
0.299 ± 0.003
PRD 94 (2016) 094008
0.299 ± 0.003
PRD 95 (2017) 115008
0.299 ± 0.003
JHEP 1712 (2017) 060
0.299 ± 0.004
FNAL/MILC (2015)
0.299 ± 0.011
HPQCD (2015)
0.300 ± 0.008
HFLAV
Spring 2019
0.2
0.4
R(D)

$R(D^*)$ HFLAV



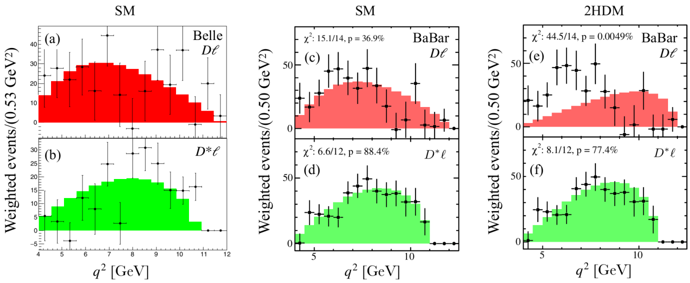
BaBar (2012), had. tag
0.332 ± 0.024 ± 0.018
Belle (2015), had. tag
0.293 ± 0.038 ± 0.015
Belle (2017), (had. tau)
0.270 ± 0.035 ± 0.027
Belle (2019), sl.tag
0.283 ± 0.018 ± 0.014
LHCb (2015), (muonic tau)
0.336 ± 0.027 ± 0.030
LHCb (2018), (had. tau)
0.280 ± 0.018 ± 0.029
Average
0.295 ± 0.011 ± 0.008
SM pred. average
0.258 ± 0.005
PRD 95 (2017) 115008
0.257 ± 0.003
JHEP 1711 (2017) 061
0.260 ± 0.008
JHEP 1712 (2017) 060
0.257 ± 0.005
HFLAV
Spring 2019
0.2
0.3
0.4
R(D*)





arXiv:2101.08326

q^2 spectrum BABAR and Belle: arXiv:2101.08326



Handling of D^{**} background (BABAR): reconstruct $D^{(*)}\pi^0\ell\nu$