Lepton flavour universality tests with semileptonic B decays at LHCb

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on behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects
23-25 October 2024

Outline

1. Introduction
2. LFU in $b \to c\ell\nu$ at LHCb
3. $R(D^+)$ vs $R(D^{*+})$
4. **NEW:** $R(D^{**})$
5. Summary

Introduction

- Lepton Flavour Universality (LFU) hypothesis: equal gauge bosons couplings to leptons
- Tested in W and Z decays

$Z \to \ell^+\ell^-$

$$\frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}} = 1.0009 \pm 0.0028$$

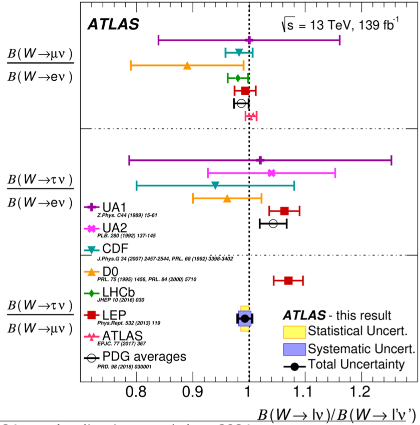
$$\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to\mu^+\mu^-}} = 1.0019 \pm 0.0032$$

Phys. Rept. 427 (2006) 257

Nature Physics 17, 813-818 (2021)

- Ongoing measurements in heavy quark decays by flavour experiments
  - $b \to s\ell\ell$
  - $b \to c\ell\nu$

$W \to \ell\nu$



LFU in $b \to c l \nu$ transitions at LHCb

- Ratios of branching fractions is one choice to test LFU

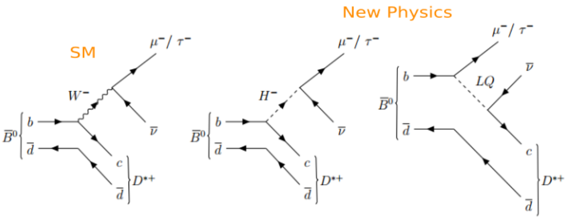
$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \nu)}{\mathcal{B}(H_b \to H_c \mu \nu)}$$

$$H_b = B^0, B^+, B_s, \Lambda_b^0,$$

$$H_c = D^*, D^+, D_s, \Lambda_c^0, J/\Psi$$

- Neutrinos not detected at LHCb: approximation needed to reconstruct the B momentum
- τ decay modes used: $\tau^- \to \mu^- \nu_\mu \nu_\tau$ and $\tau^- \to \pi^+ \pi^- \pi^- \nu_\tau$

Any discrepancy could be a clear sign of New Physics (NP)

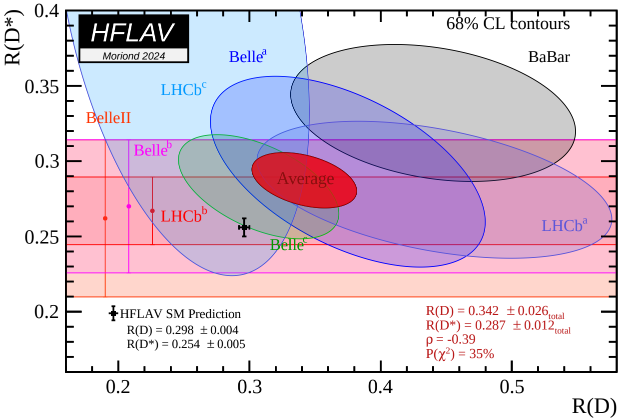


PRD 94, 034001

PRD 90, 074013

PRD 87, 014014

The big picture



Current status:

3.2 σ discrepancy wrt SM predictions

LFU tests in semileptonic B decays at LHCb

Muonic τ decay

$R(D^{*+})$ Run I (2015)

$0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$

▸ PRL 115 111803

$R(D^0)$ vs $R(D^*)$ Run I (2023)

$R(D^*) = 0.281 \pm 0.018(stat) \pm 0.024(syst)$

$R(D^0) = 0.441 \pm 0.060(stat) \pm 0.066(syst)$

▸ PRL 131 111802

$R(D^+)$ vs $R(D^{*+})$ Run II (2024)

$R(D^{*+}) = 0.402 \pm 0.081(stat) \pm 0.085(syst)$

$R(D^+) = 0.249 \pm 0.043(stat) \pm 0.047(syst)$

▸ arXiv:2406.03387

$R(J/\psi)$ Run I (2018)

$0.71 \pm 0.17(stat) \pm 0.18(syst)$

▸ PRL 120 121801

Hadronic τ decay

$R(D^{*+})$ Run I (2018)

$0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(ext)$

▸ PRL 120 171802

$R(D^{*+})$ part Run II (2023)

$0.247 \pm 0.015(stat) \pm 0.015(syst) \pm 0.012(ext)$

▸ PRD 108 012018

$R(\Lambda_c^+)$ Run I (2022)

$0.242 \pm 0.026(stat) \pm 0.040(syst) \pm 0.059(ext)$

▸ PRL 128 191803

D^* polarisation (2023)

$0.242 \pm 0.026(stat) \pm 0.040(syst) \pm 0.059(ext)$

▸ LHCb-PAPER-2023-020

$R(D^{**})$ (2024)

$0.13 \pm 0.03(stat) \pm 0.01(syst) \pm 0.03(ext)$

▸ LHCb-PAPER-2024-037 in preparation

LFU tests in semileptonic B decays at LHCb

The focus today:

$R(D^+)$ vs $R(D^{*+})$ Run II (2024)

$R(D^{*+})$=0.402±0.081($stat$)±0.085($syst$)

$R(D^+)$=0.249±0.043($stat$)±0.047($syst$)

arXiv:2406.03387

NEW $R(D^{**})$ (2024)

0.13±0.03($stat$)±0.01($syst$)±0.03(ext)

LHCb-PAPER-2024-0370 in preparation

Muonic τ decay

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PRL 115 111803

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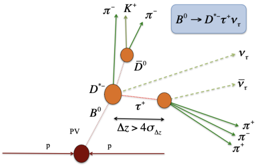
LHCb-PAPER-2024-037 in preparation

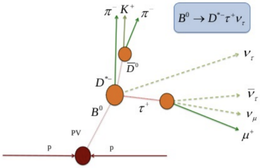
Muonic vs hadronic tau decays at LHCb

Muonic τ decay



- High statistics sample
- $R(D^*)$ directly measured
- Multiple missing neutrinos
- Precise background modelling

Hadronic τ decay



- High purity sample: allowed by being able to fully reconstruct the τ vertex
- $R(D^*)$ needs external input
- Low statistics

Complementary analyses that provide independent result

$R(D^+)$ vs $R(D^{*+})$: strategy

$$R(D^{(*)}) = \frac{BF(B^0 \to D^{(*)}\tau\nu)}{BF(B^0 \to D^{(*)}\mu\nu)} = \frac{N_{sig}}{N_{norm}}\frac{\epsilon_{norm}}{\epsilon_{signal}}$$

- Signal/norm yield ratio determined from the fit to data
- Signal/norm efficiency ratio determined from simulation
- 3D binned template fit in q^2, E_ℓ and m^2_{miss}
- Simultaneous fit across signal + 3 control regions:
  - **Signal region** $\to D^+\mu^-$: $B \to D^{*(+)}\tau\nu$
  - **1** π **region** $\to D^+\mu^-\pi^-$: feed down from $B \to D^{**}\ell\nu$
  - **2** π **region** $\to D^+\mu^-\pi^+\pi^-$: feed down from higher mass D^{**}
  - **1** K **region** $\to D^+\mu^-K^\pm$: feed down from $B \to DDX$
- Each control region designed to address specific background contribution

$R(D^+)$ vs $R(D^{*+})$: fit model

Simulation derived templates

- Form factor parameters varied during fitting via a RooFit-HAMMER interface JINST 17 T04006 (2022) EPJC 80, 883 (2020)
  - $B^0 \to D^+$ and $B^0 \to D^* \to$ **BGL** PRL 74 4603 (1995)
  - $B^0 \to D^{**} \to$ **BLR** PRD 97 075011 (2018)
- Other backgrounds: $B \to DDX$
- Component fractions varied + shape corrections in the fit

Usage of Tracker only simulation

- First analysis to employ this
- Able to fast produce large samples
- Reduce systematic uncertainty due to sample size
- Detector effects not present are fully emulated

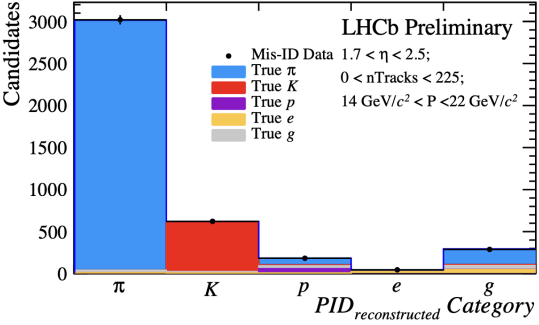
Data/simulation correction

- Multidimensional kinematic reweighting: excellent agreement achieved

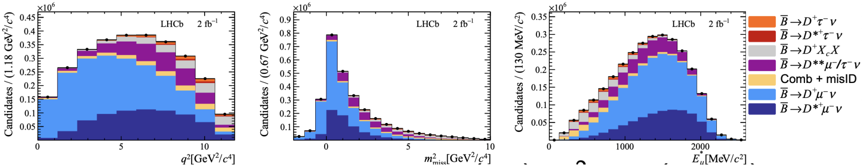
$R(D^+)$ vs $R(D^{*+})$: fit model

Data derived templates

- Combinatorial background: wrong sign $D^+\mu^+$
- μ misID background:
  - Non μ control sample
  - Fitting each particle contribution due to misidentification



$R(D^+)$ vs $R(D^{*+})$: results



$$R(D^{*+}) = 0.402 \pm 0.081(stat) \pm 0.085(syst)$$
$$R(D^+) = 0.249 \pm 0.043(stat) \pm 0.047(syst)$$

World average at 3.2σ tension with SM

Source	$R(D^+)$	$R(D^{*+})$
Form factors	0.023	0.035
$\overline{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.085
Statistical uncertainty	0.043	0.081

Main systematic uncertainties

- Largest systematics coming from the form factor parameterization
- Modelling of *DD* backgrounds
- misID background

$R(D^{**})$ at LHCb: motivation

- Common systematic uncertainty in current $R(D^*)$ measurements is feed down from $B \to D^{**}\ell\nu$ decays
- $R(D^{**})$ helps to set an upper limit on the fraction of $B \to D^{**}\tau\nu$ decays contributing in the $R(D^{**})$ measurements

The D^{**} family:

$\mathbf{D_0^*(2300)} \to D^0\pi$
$\mathbf{D_1(2420)} \to D^*\pi$, $\mathbf{D_2^*(2460)} \to D^*\pi$, $\mathbf{D_1'(2400)} \to D^*\pi$

Theory predictions

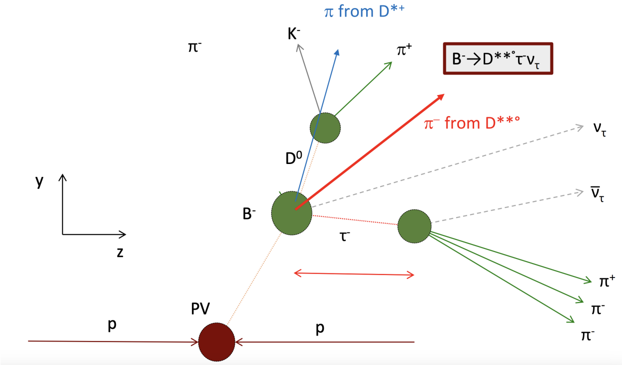
$$R(D_0^*) = 0.08(3), \quad R(D_1') = 0.05(2)$$
$$R(D_1) = 0.10(2), \quad R(D_2^*) = 0.07(1)$$

PRD 97 075011 (2018) PRD 97 075011 (2018)

- Values smaller than $R(D^*)$ due to the smaller phase space available

$R(D^{**})$: goal and strategy **NEW**

- Measure branching fraction of $B^- \to D_1(2420)^0 \tau^- \nu_\tau$ and $B^- \to D_2^*(2460)^0 \tau^- \nu_\tau$
- $D^{**0} \to D^{*+}\pi^-$ and $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ are used
- Same selection as $R(D^*)$ hadronic τ analysis ▸ PRD 108 012018 (2024)
- Allowing one extra track at the B^- vertex $\to$ additional π to build $D^{*+}\pi^-$ decays



$R(D^{**})$: backgrounds

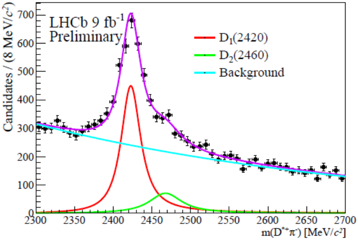
Real D^{**} candidates:

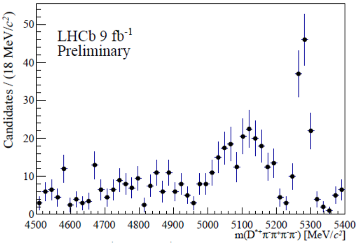
- $D^{**} D_s^- X$
- $D^{**} 3\pi \rightarrow$ suppressed by requiring detached B and τ vertices
- $D^{**} DK \rightarrow$ estimated to be negligible (< 6 events):
    - Control channels with an extra K track at the 3π vertex are used (including $D^- \rightarrow K^+ \pi^- \pi^-$ and $\bar{D}^0 \rightarrow K 3\pi$)

Fake $D^{**} \rightarrow$ true D^* with an extra π:

- random extra π
- extra π from the B vertex: $D^{*+} D^{*-}$, $D^* D^0 K^0 / \pi^-$
- extra π from the τ vertex: $D^{*+} D_s^-$

$R(D^{**})$: backgrounds





D^{**} mass fit:

$N(D_1(2420)^0) = 2456 \pm 75$

$N(D_2^*(2460)^0) = 633 \pm 69$

- Two BDT classifiers:
  - to reduce 5-prong D_s^- decays
  - reject fake D^{**} candidates
- D_s decays associated to $D^{**} \rightarrow$ three distinct regions detected in $D^{*+}\pi^-\pi^-\pi^-\pi^+$
- Gaussian constrain for D_s contributions: D_s^+, D_s^{*-}, D_s^{**-}

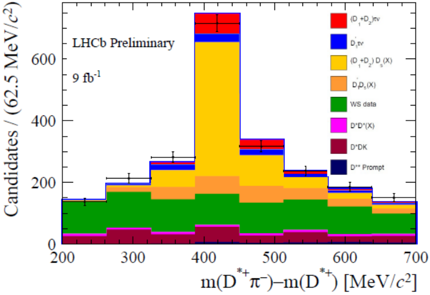
$R(D^{**})$: fit strategy

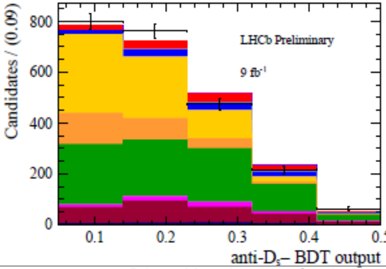
- 3D binned maximimum likelihood fit in: $\mathbf{q^2}$, **anti-$\mathbf{D_s}$ BDT** and $\mathbf{\Delta m = m(D^*\pi) - m(D^*)}$
- Simulation template for the signal: sum of $D_1(2420)$ and $D_2^*(2460)^0$
- Fixed ratio between $D_1(2420)^0$ and $D_2^*(2460)^0$
- Relative contributions of $D_1'(24000)$ wrt $D_1(2420)^0 + D_2^*(2460)^0$ is Gaussian constrained using predictions from
  Rev. Mod. Phys 94 015003 (2022)
- The rest of the templates are built for $D^{**}D_s$, prompt and fake D^* + two templates of type $D^{*-}D^{*+}X$ and $D^{*-}DKX$

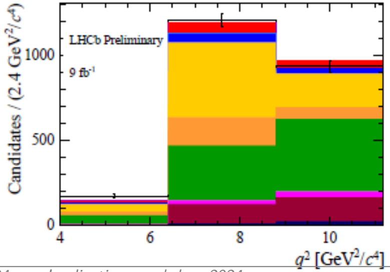
Measured yield from the 3D fit:

$N\big(B^- \to (D_1(2420)^0 + D_2^*(2460)^0 \tau^- \nu\big) = 123 \pm 23\ (\text{stat}) \pm 14\ (\text{syst})$

$R(D^{**})$: final fit projections







$R(D^{**})$: systematic uncertainties

Source	Relative systematic uncertainty in %
Form factors	3.7
$D_2^*(2460)^0$ fraction	4.4
Finite size of the simulated sample	4.1
Variables and binning choices	5
Other potential background	3.6
Efficiency determination	4.3
Selection and analysis	2
Vertex resolution effects	4.0
WS background description	2
Total	11.4

Among largest systematic uncertainties:

- Form factors:
  - D^{**} generated using ISGW ‣ PRD 39 799 (1989)
    $\rightarrow$ systematic uncertainty wrt LLSW ‣ PRD 57 308 (1998) and BLR ‣ PRD 97 075011 (2018) implemented in HAMMER ‣ EPJC 80 883 (2020)
- Fixed ratio between D_1^0 and D_2^{*0} in the fit

$R(D^{**})$: results

- Evidence of $B^- \to (D_1(2420)^0 + D_2^{*0})\tau\nu$ estimated to be **3.5** σ
- $B^- \to D^{*+} D_s^- \pi^-$ used as normalisation channel

$$\frac{B(B^- \to (D_1(2420)^0 + D_2^{*0}(2460)\tau\nu}{B(B^- \to (D^1(2420)^0 + D_2^{*0})D_s^{*-}} = 0.19 \pm 0.05$$

- Using $B^- \to D^{*+} D_s^- \pi^-$ BF measured in ▸ JHEP08 (2024) 165

$$B(B^- \to (D^1(2420)^0 + D_2^{*0})\tau\nu \times B((D^1(2420)^0, D_2^{*0})) =$$
$$(0.051 \pm 0.013\ (\text{stat}) \pm 0.006\ (\text{syst}) \pm 0.009\ (\text{ext}))\%$$

measured for the first time

- Using the BFs for the muonic channels from the PDG:

$$\mathbf{R(D_1(2420)^0 + D_2^{*0}(2460)) = 0.13 \pm 0.03\ (stat) \pm 0.01\ (syst) \pm 0.02 (ext)}$$

SM prediction ▸ Rev. Mod. Phys 94 015003 (2022) $R(D_1(2420)^0 + D_2^{*0}(2460)) = 0.09 \pm 0.02$

Compatible within 1 σ of the SM prediction

Feed down into $R(D^*)$

- Using the measured yield in $B \to D^{**}\tau\nu$ we can predict the amount of background when measuring $R(D^*)$
- For 9 fb^{-1} the fraction of $B \to D^{**}\tau\nu$ is estimated to be 14.3 % at 95 % C.L.
- Fraction within 2.5 σ of what is used in $R(D^*)$ hadronic
  ▸ PRD 108 012018 (2023)

Summary and ongoing analyses

LHCb result on test of LFU

- $R(D^+)$ vs $R(D^{*+}) \rightarrow$ new world average still at 3 σ

First LHCb result on $R(D^{**})$

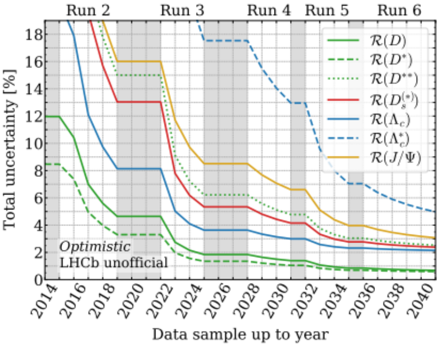
- First BF measurement of $B^- \rightarrow (D_1(2420)^0 + D_2^{*0}(2460)\tau\nu$
- $R(D^{**})$ compatible with SM prediction

Next to come:

- Ongoing LFU analyses: $\mathcal{R}(D^*)$ - (electron - muon), $\mathcal{R}(D_s^*)$, $\mathcal{R}(J/\Psi)$
- Study New Physics sensitivity: measuring angular and Wilson coefficients
- Angular analyses: $B \rightarrow D^*\mu\nu$, $B \rightarrow D^*\tau\nu$, $\Lambda_b \rightarrow \Lambda_c\mu\nu$

Summary and ongoing analyses

- Semileptonic decays can give us hints towards BSM physics
- LHCb has performed several LFU measurements and has still an ongoing physics programme towards LFU null tests
- Ongoing analyses are also exploiting the angular structure of the decays
- Run 3 data-taking period from 2022 - uncertainties at LHCb to scale with the accumulated sample size



▸ Rev. Mod. Phys 94 015003 (2022)

▸ arXiv:1808.08865

Thank you!

BACKUP

HAMMER - Helicity Amplitude Module for Matrix Element Reweightingt

- Tool that weights a MC sample from the generation amplitude to a new desired one ▸ Hammer ▸ arXiv:2002.00020v2

Theoretical approach

The decay rate ($B \to X l \nu_l$):

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{(2\pi)^3} V_{ij}^2 \frac{(q^2 - m_l^2)^2 p_X}{12 m_B^2 q^2} (H_+^2(q^2) + H_-^2(q^2) + H_0^2(q^2)(1 + \frac{m_l^2}{2q^2}) + \frac{3}{2} \frac{m_l^2}{2q^2} H_s^2(q^2))$$

where $H_i(q^2)$ are the helicity amplitudes.
Reweighting to New Physics scenarios, e.g. by adding extra scalar, vector or tensor couplings can be done with the weight vector for each event calculated as:

$$\omega_i = \frac{\Gamma_{old}}{\Gamma_{new}} \frac{d^n \Gamma_{new}/dx}{d^n \Gamma_{old}/dx}$$

where Γ_{old} is the decay rate for the model implemented in the Monte Carlo and Γ_{new} is the the decay rate for updated model

BGL and CLN form factor parameterisation

$$\frac{d\Gamma(B\to D^*\ell\nu)}{dq^2}=\frac{G_F^2|V_{cb}^2||\eta_{EW}|^2|\vec{p}|^2q^2}{96\pi^3m_{B^0}^2}\left(1-\frac{m_\ell^2}{q^2}\right)\times\left[\ (|H_+|^2+|H_-|^2+|H_0|^2)\left(1-\frac{m_\ell}{2q^2}\right)+\frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2\right]$$

Helicity amplitudes in BGL

PRL 74 4603 (1995)

$$r=\frac{m_B}{m_{D^*}}$$

$$\omega(q^2)=\frac{m_B^2+m_{D^*}^2-q^2}{2m_{D^*}m_B}$$

$$H_\pm(\omega)=f(\omega)\mp m_Bm_{D^*}\sqrt{\omega^2-1}g(\omega)$$

$$H_0(\omega)=\frac{F_1(\omega)}{\sqrt{q^2}}$$

$$H_t(\omega)=m_B(\frac{r\omega^2-1}{1+r^2-2r\omega}F_2(\omega))$$

$$f(z)=\frac{1}{P_{1+}(z)\phi_f(z)}\sum_{n=0}^{N}b_nz^n$$

$$F_1(z)=\frac{1}{P_{1+}(z)\phi_{F_1}(z)}\sum_{n=0}^{N}c_nz^n$$

$$g(z)=\frac{1}{P_{1-}(z)\phi_g(z)}\sum_{n=0}^{N}a_nz^n$$

$$F_1(z)=\frac{1}{P_{0-}(z)\phi_{F_2}(z)}\sum_{n=0}^{N}d_nz^n$$

Helicity amplitudes in CLN

Nucl. Phys. B 530 1 (1998)

$$H_\pm(\omega)=m_B\sqrt(r)(\omega+1)h_{A_1}(\omega)\left[1\mp\sqrt{\frac{\omega-1}{\omega+1}}R_1(\omega)\right]$$

$$H_0(\omega)=m_B\sqrt(r)(\omega+1)\frac{1-r}{\sqrt(q^2)}h_{A_1}(\omega)\left[1+\frac{\omega-1}{1-r}(1-R_2(\omega))\right]$$

$$h_{A_1}(\omega)=h_{A_1}(1)[1-8\rho_{D^*}^2z(\omega)+(53\rho_{D^*}^2-15)z^2(\omega)-(231\rho_{D^*}^2-91)z^3(\omega)]$$

$$R_1(\omega)=R_1(1)-0.12(\omega-1)+0.05(\omega-1)^2$$

$$R_2(\omega)=R_2(1)+0.11(\omega-1)+0.06(\omega-1)^2$$

$$R_0(\omega)=R_0(1)-0.11(\omega-1)+0.01(\omega-1)^2$$