# Semileptonic decays to excited charmed mesons as a probe for the Standard Model

Work in Collaboration with **Z. Ligeti (LBNL)**, **arXiv:1606.09300**, submitted to PRD


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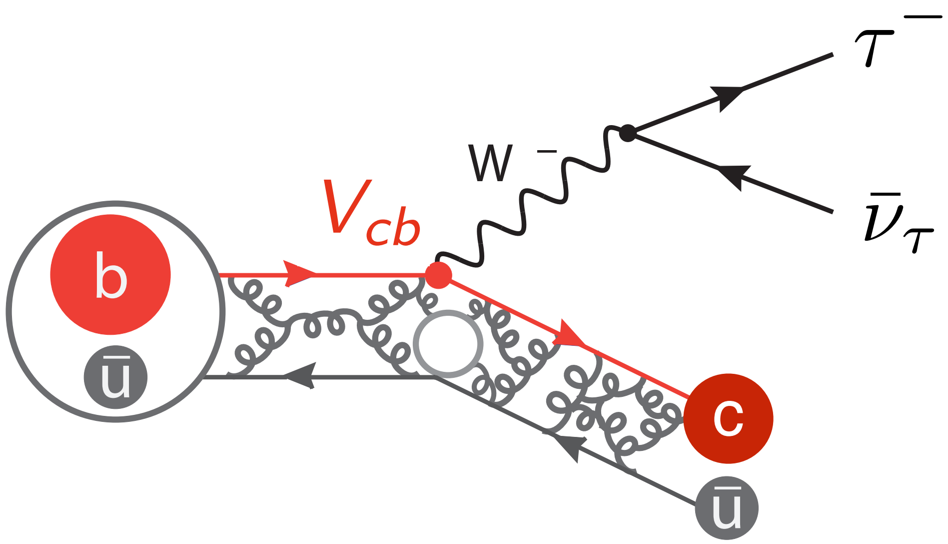
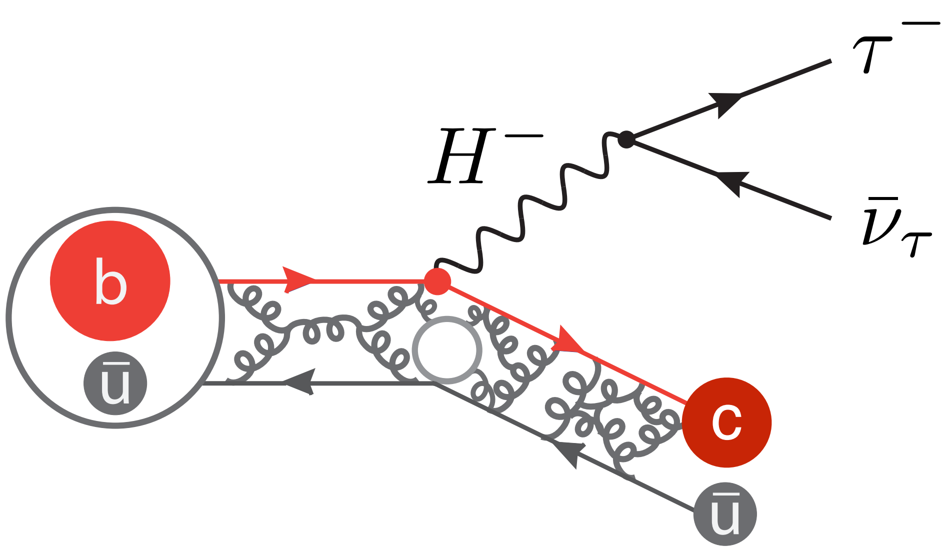



Standard Model




New Physics: E.g. Decay with charged Higgs boson

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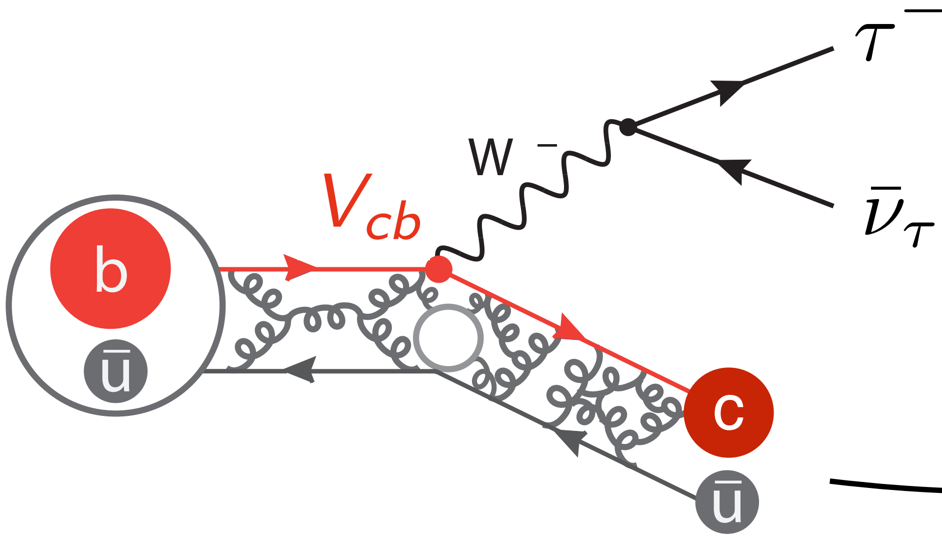
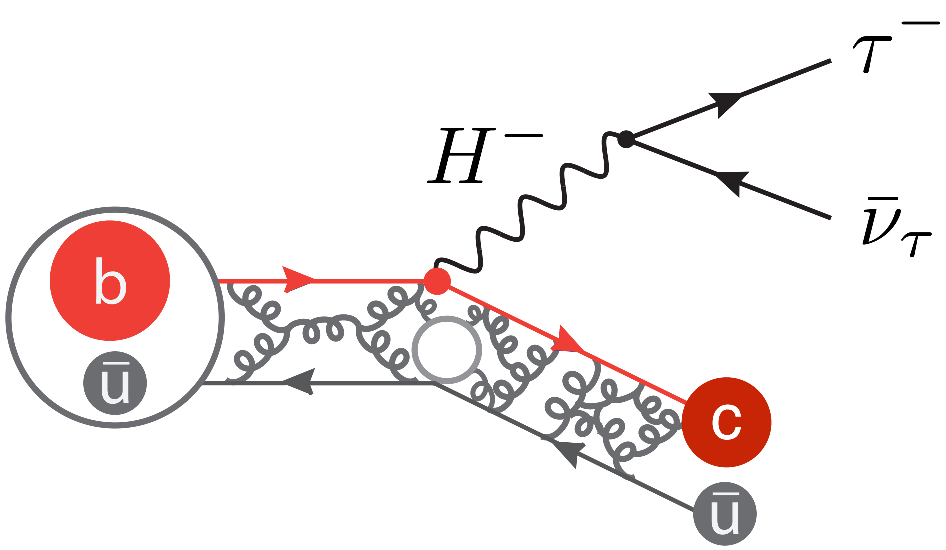



Standard Model

$\langle c\bar{q} \rangle$ Spin 0: D meson
Spin 1: D* meson



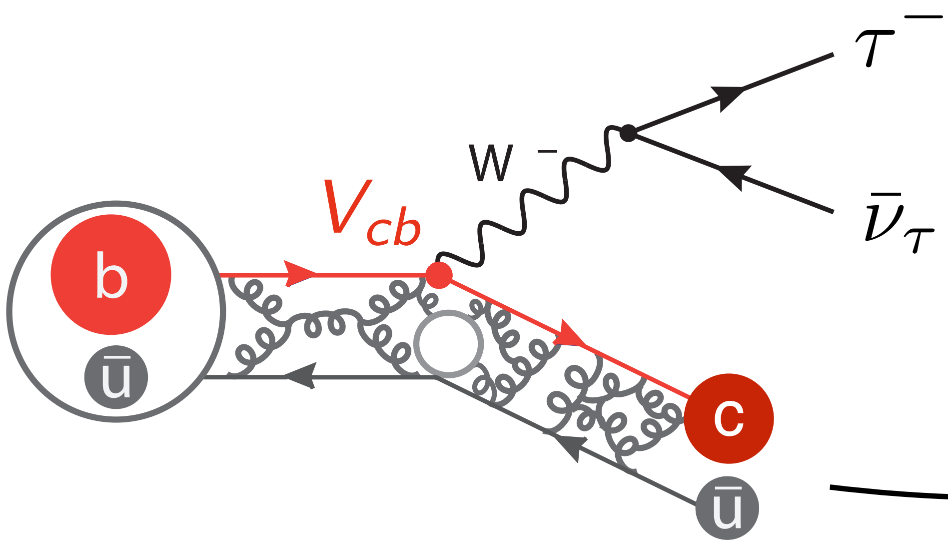

New Physics: E.g. Decay with charged Higgs boson

Observable:

$$\boxed{R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\,\ell\,\bar{\nu}_\ell)}}$$

$\ell = e, \mu$

# Semileptonic decays as a probe for new physics

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$\langle c\bar{q} \rangle$

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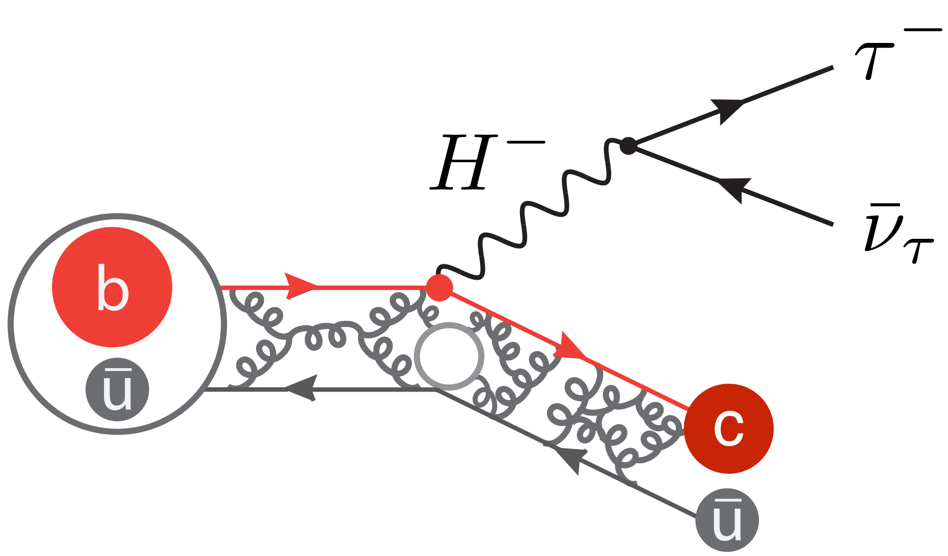
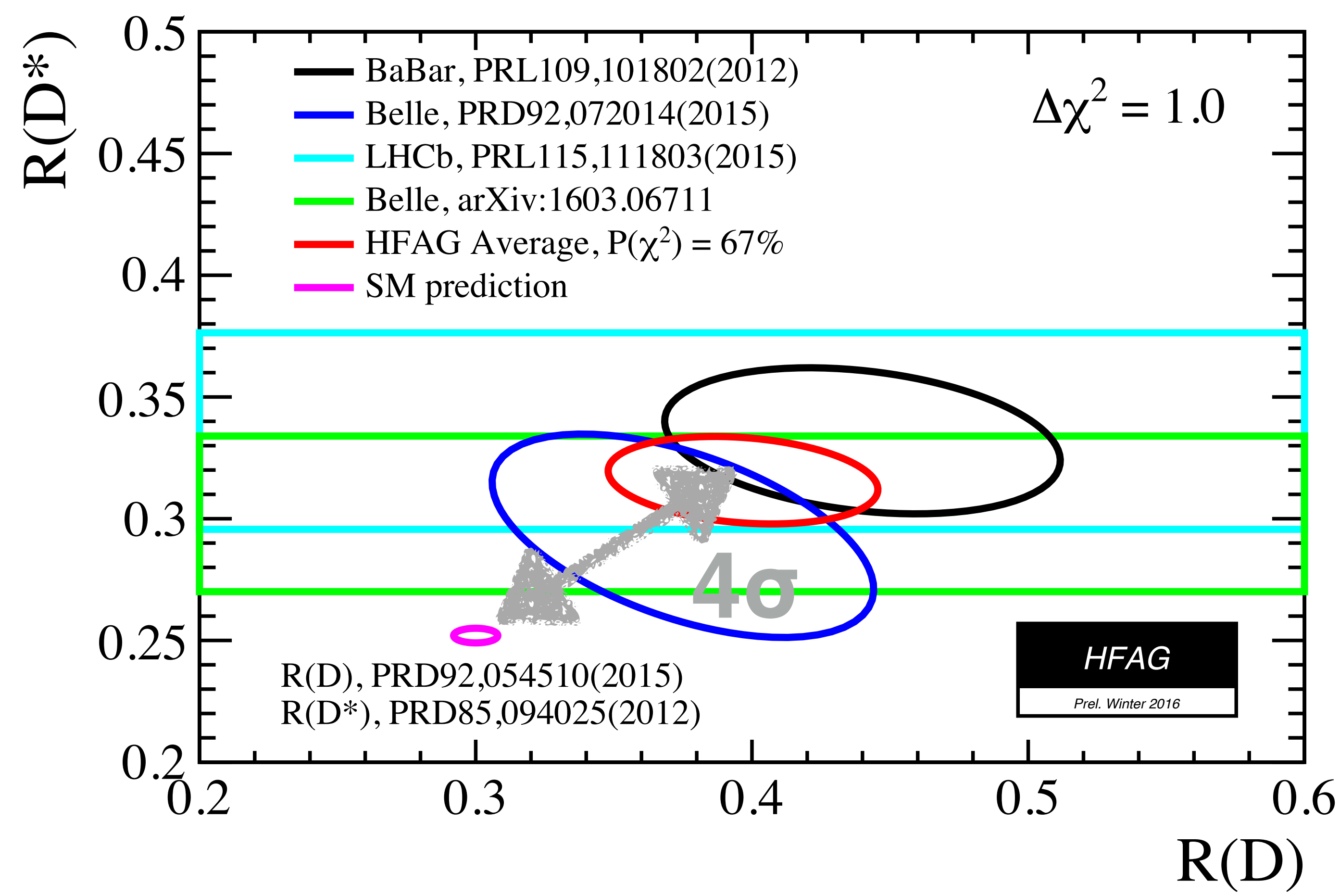
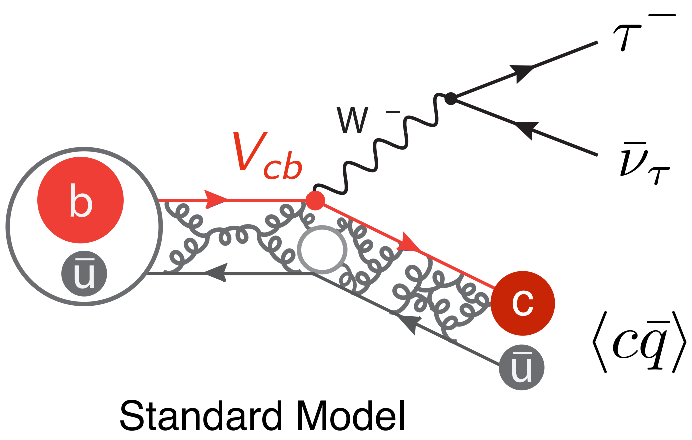


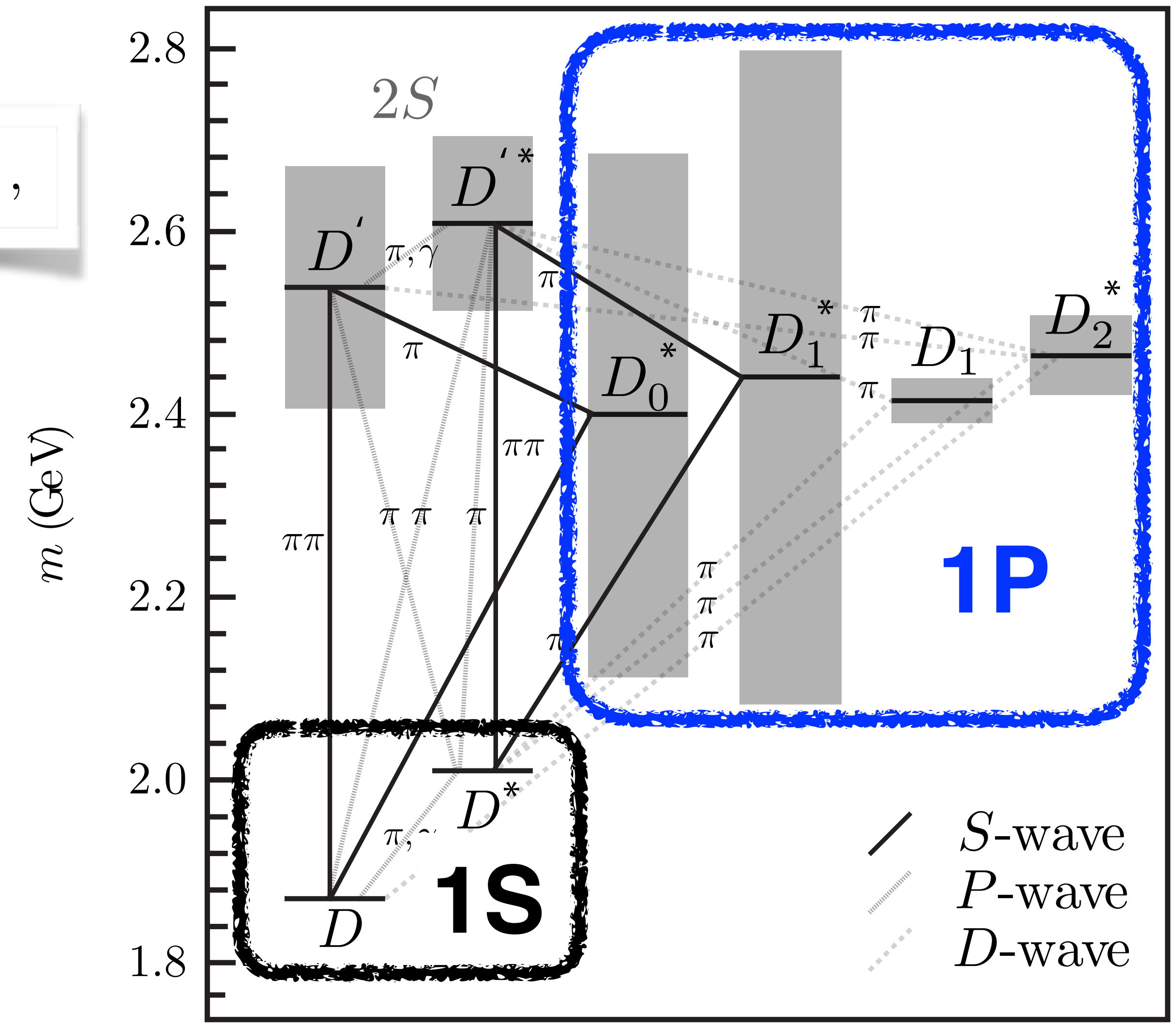

New Physics: E.g. Decay with charged Higgs boson



# Orbital excited states and why to study them




$$D^{**} = \{D_0^*,\, D_1^*,\, D_1,\, D_2^*\}\,,$$




| Particle | $s_l^{\pi_l}$ | $J^P$ | $m$ (MeV) | $\Gamma$ (MeV) |
|---|---|---|---|---|
| $D_0^*$ | $\frac{1}{2}^+$ | $0^+$ | 2330 | 270 |
| $D_1^*$ | $\frac{1}{2}^+$ | $1^+$ | 2427 | 384 |
| $D_1$ | $\frac{3}{2}^+$ | $1^+$ | 2421 | 34 |
| $D_2^*$ | $\frac{3}{2}^+$ | $2^+$ | 2462 | 48 |

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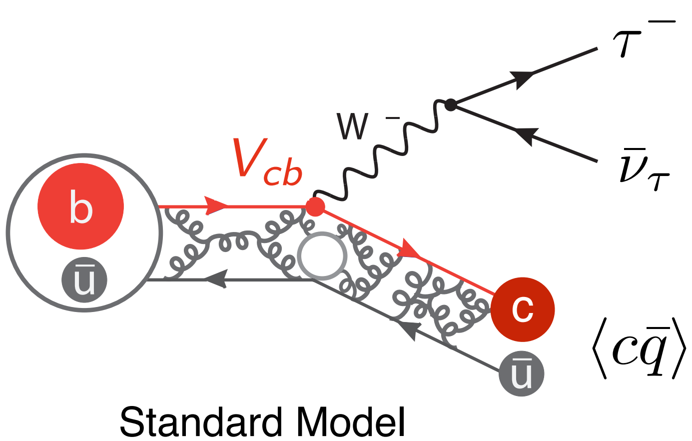


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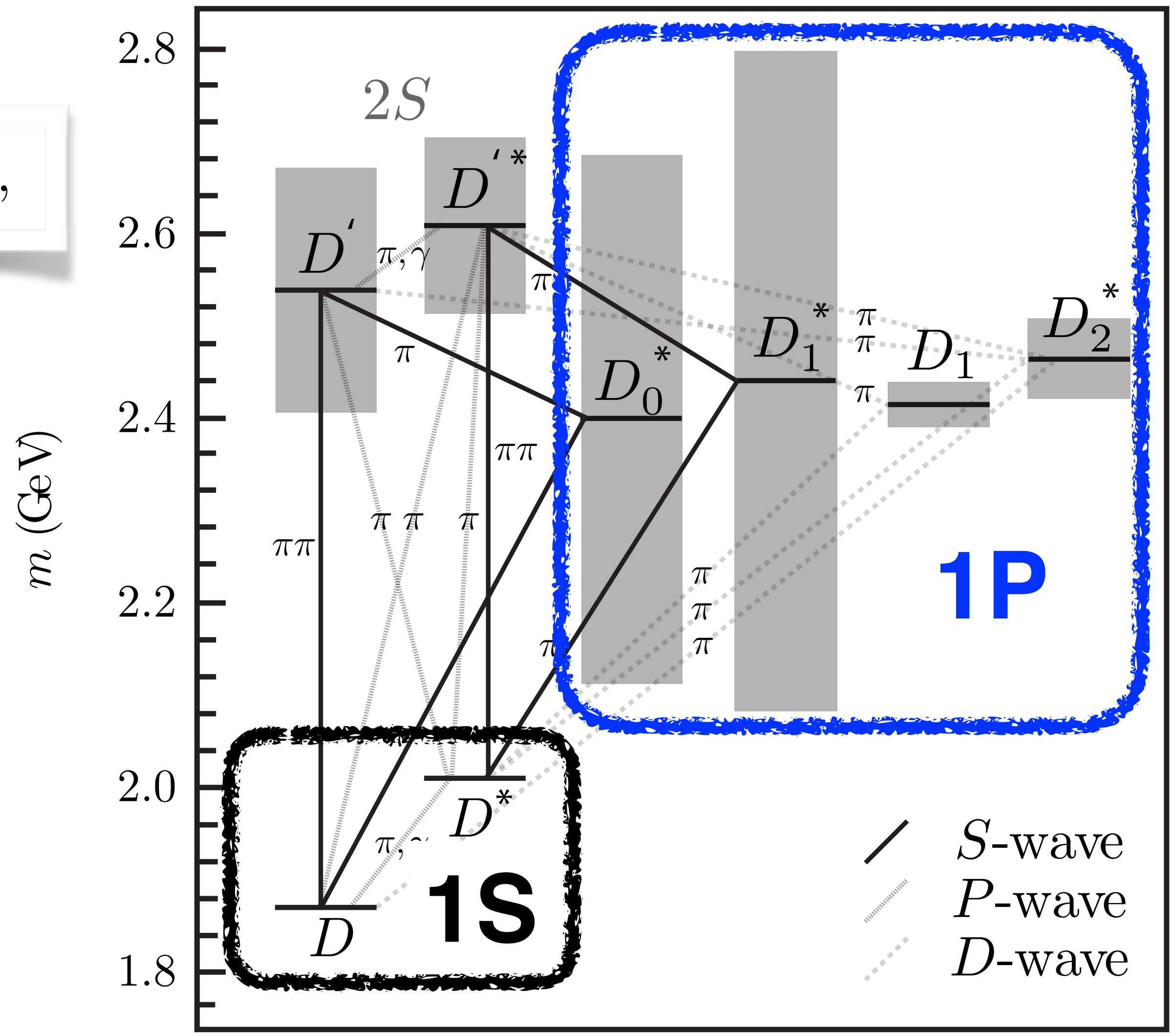


1. Important background for measuring R(D) and R(D*)
   - Poorly understood at this point

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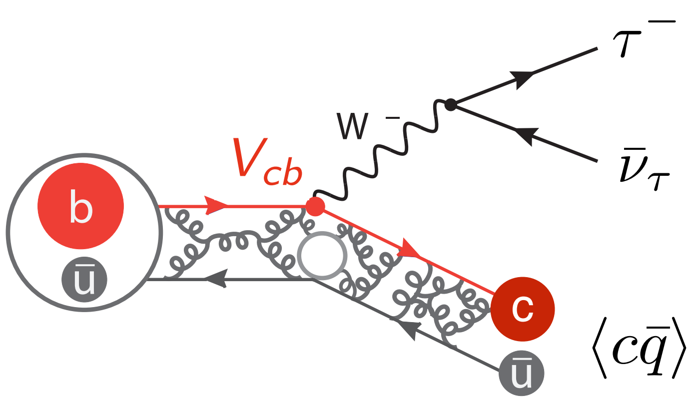
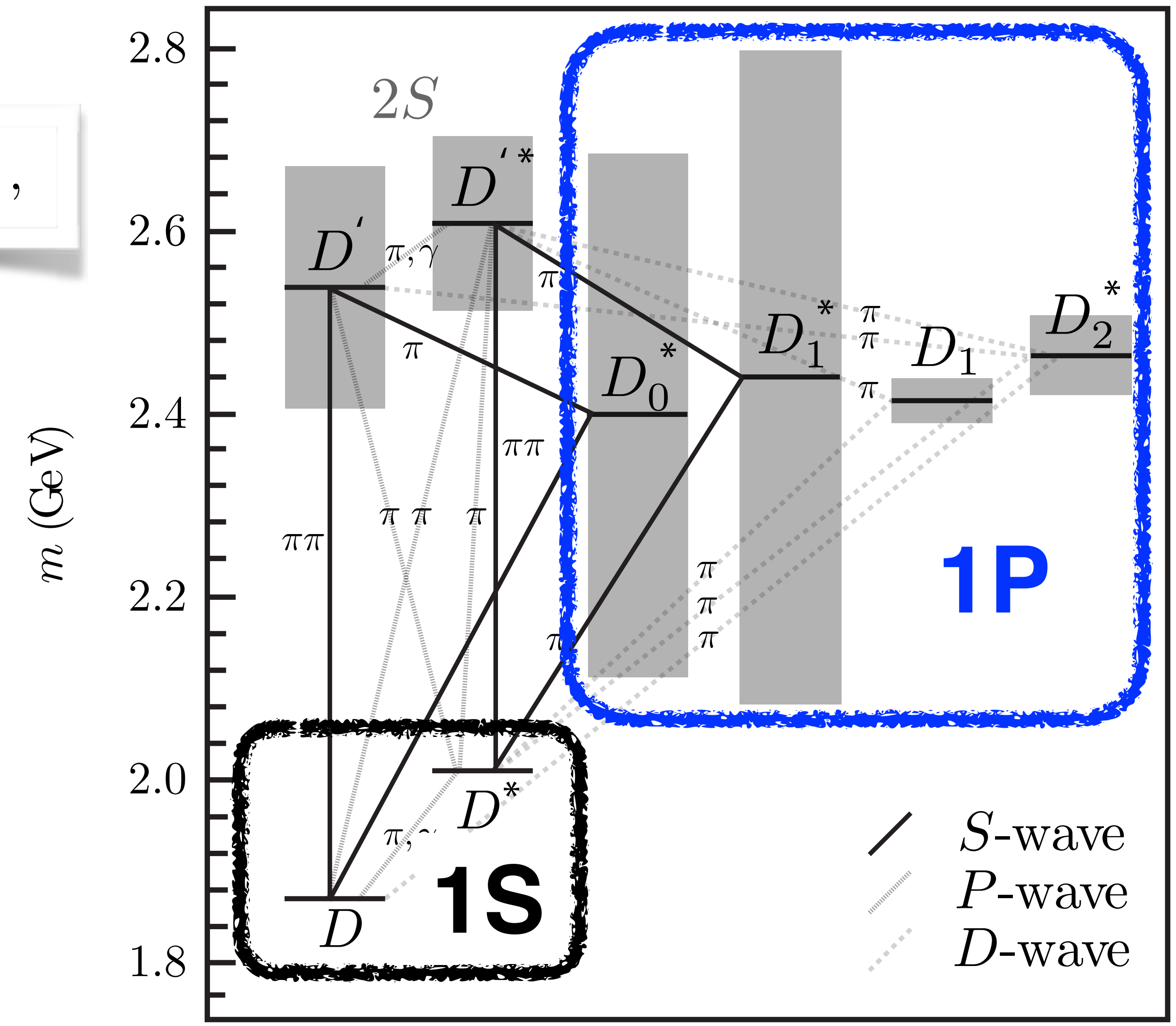



Standard Model

$$D^{**} = \{D_0^*,\, D_1^*,\, D_1,\, D_2^*\}\,,$$




1. Important background for measuring R(D) and R(D*)
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2. Offer path to an alternative (but challenging) probe
   - Measurements of R(D**)
   - Important to model inclusive composition

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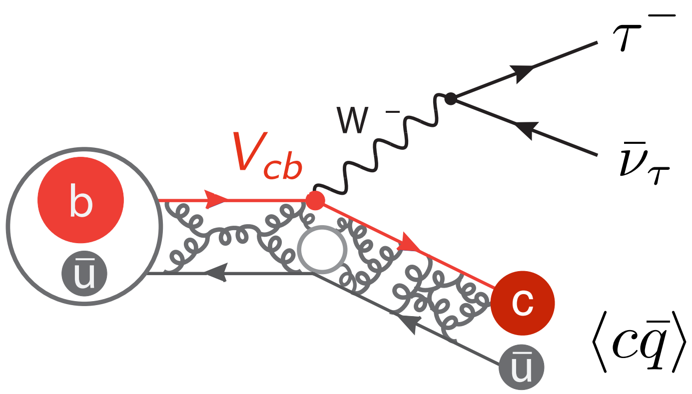
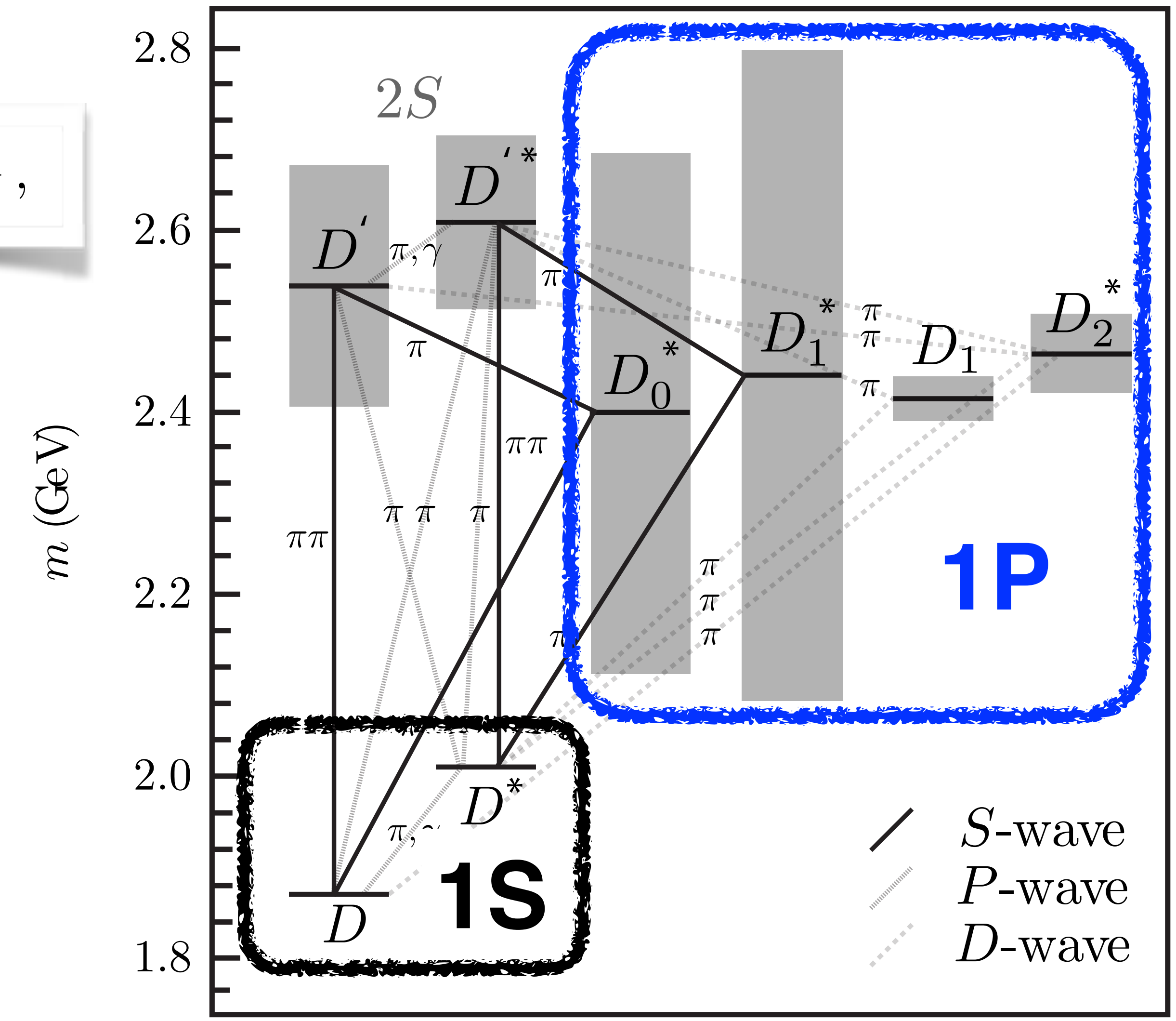
# Orbital excited states and why to study them




$$D^{**} = \{D_0^*, D_1^*, D_1, D_2^*\},$$




1. Important background for measuring R(D) and R(D*)
   - Poorly understood at this point
2. Offer path to an alternative (but challenging) probe
   - Measurements of R(D**)
   - Important to model inclusive composition
3. Important background for certain $|V_{cb}|$ measurements

| Particle | $s_l^{\pi_l}$ | $J^P$ | $m$ (MeV) | $\Gamma$ (MeV) |
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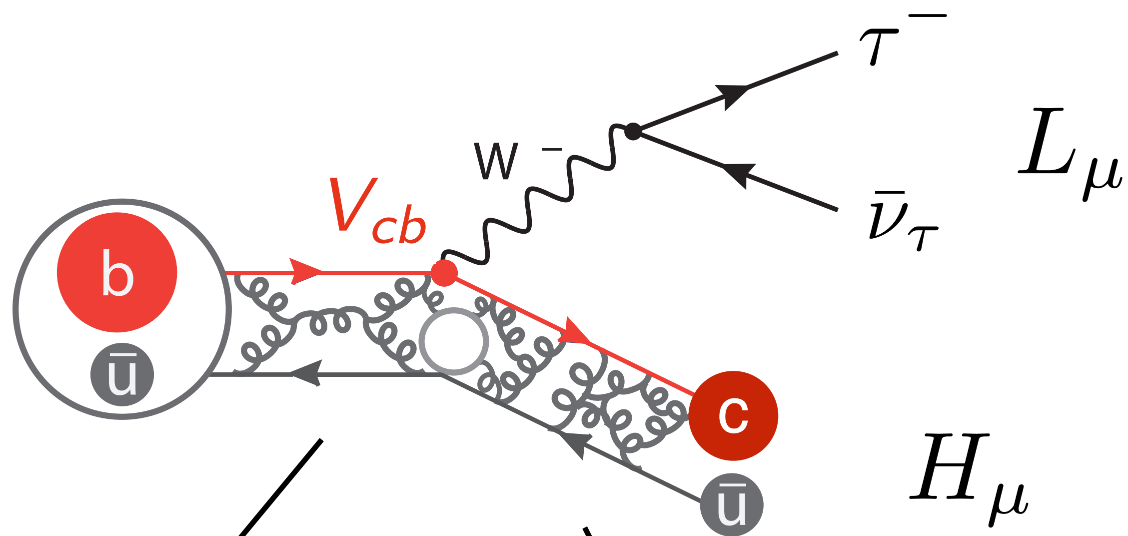
# Starting point for a prediction: the hadronic Currents



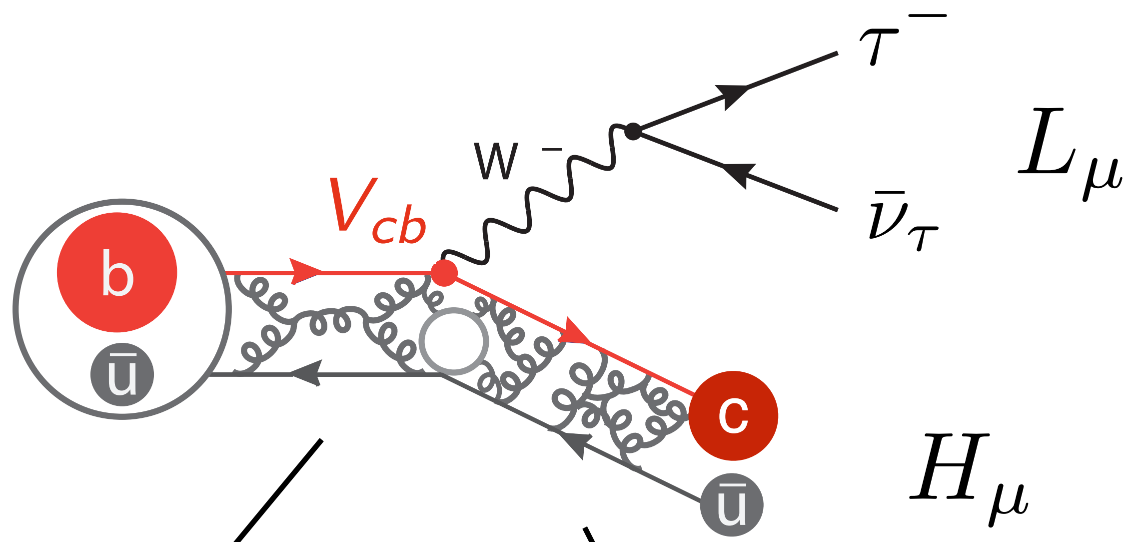

broad orbital states: $D_0^*$, $D_1^*$

$$
\begin{aligned}
\langle D_0^*(v')|V^\mu|B(v)\rangle &= 0,\\
\frac{\langle D_0^*(v')|A^\mu|B(v)\rangle}{\sqrt{m_{D_0^*}\, m_B}} &= g_+\,(v^\mu + v'^\mu) + g_-\,(v^\mu - v'^\mu)\,,\\
\frac{\langle D_1^*(v',\epsilon)|V^\mu|B(v)\rangle}{\sqrt{m_{D_1^*}\, m_B}} &= g_{V_1}\epsilon^{*\mu} + (g_{V_2}v^\mu + g_{V_3}v'^\mu)\,(\epsilon^*\cdot v)\,,\\
\frac{\langle D_1^*(v',\epsilon)|A^\mu|B(v)\rangle}{\sqrt{m_{D_1^*}\, m_B}} &= i\,g_A\,\varepsilon^{\mu\alpha\beta\gamma}\,\epsilon^*_\alpha v_\beta\, v'_\gamma\,. \qquad (6)
\end{aligned}
$$

narrow orbital states: $D_1$, $D_2^*$

$$
\begin{aligned}
\frac{\langle D_1(v',\epsilon)|V^\mu|B(v)\rangle}{\sqrt{m_{D_1}\, m_B}} &= f_{V_1}\epsilon^{*\mu} + (f_{V_2}v^\mu + f_{V_3}v'^\mu)(\epsilon^*\cdot v)\,,\\
\frac{\langle D_1(v',\epsilon)|A^\mu|B(v)\rangle}{\sqrt{m_{D_1}\, m_B}} &= i\,f_A\,\varepsilon^{\mu\alpha\beta\gamma}\epsilon^*_\alpha v_\beta v'_\gamma\,,\\
\frac{\langle D_2^*(v',\epsilon)|A^\mu|B(v)\rangle}{\sqrt{m_{D_2^*}\, m_B}} &= k_{A_1}\,\epsilon^{*\mu\alpha}v_\alpha\\
&\quad + (k_{A_2}v^\mu + k_{A_3}v'^\mu)\,\epsilon^*_{\alpha\beta}\,v^\alpha v^\beta\,,\\
\frac{\langle D_2^*(v',\epsilon)|V^\mu|B(v)\rangle}{\sqrt{m_{D_2^*}\, m_B}} &= i\,k_V\,\varepsilon^{\mu\alpha\beta\gamma}\epsilon^*_{\alpha\sigma}v^\sigma v_\beta v'_\gamma\,, \qquad (5)
\end{aligned}
$$

# Starting point for a prediction: the hadronic Currents




broad orbital states: $D_0^*$, $D_1^*$

narrow orbital states: $D_1$, $D_2^*$

$$\langle D_0^*(v')|V^\mu|B(v)\rangle = 0,$$
$$\frac{\langle D_0^*(v')|A^\mu|B(v)\rangle}{\sqrt{m_{D_0^*}\, m_B}} = g_+\,(v^\mu + v'^\mu) + g_-\,(v^\mu - v'^\mu)\,,$$
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$$\frac{\langle D_1(v',\epsilon)|V^\mu|B(v)\rangle}{\sqrt{m_{D_1}\, m_B}} = f_{V_1}\epsilon^{*\mu} + (f_{V_2} v^\mu + f_{V_3} v'^\mu)(\epsilon^*\cdot v)\,,$$
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$$\frac{\langle D_2^*(v',\epsilon)|A^\mu|B(v)\rangle}{\sqrt{m_{D_2^*}\, m_B}} = k_{A_1}\, \epsilon^{*\mu\alpha} v_\alpha + (k_{A_2} v^\mu + k_{A_3} v'^\mu)\, \epsilon^*_{\alpha\beta}\, v^\alpha v^\beta\,,$$
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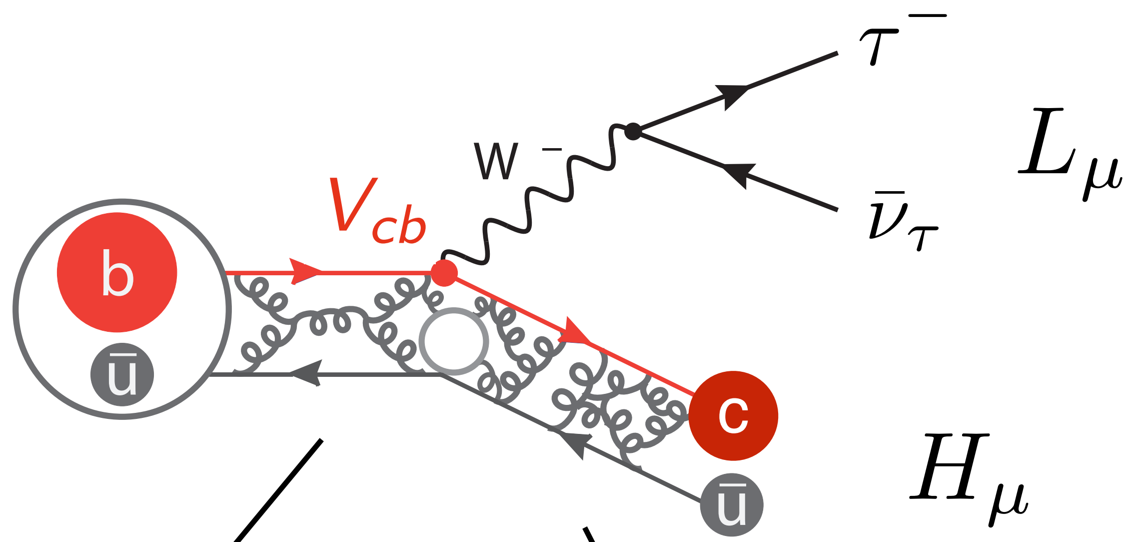
Form factors can be expressed in terms of leading & sub-leading Isgur-Wise functions and meson mass splittings:

LLSW: PRL 78 (1997) 3995, Phys.Rev.D57:308-330,1998

# Starting point for a prediction: the hadronic Currents




broad orbital states: $D_0^*$, $D_1^*$

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Form factors can be expressed in terms of leading & sub-leading Isgur-Wise functions and meson mass splittings:

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Extend this work to include full lepton mass effects, update predictions with available experimental constraints, including predictions for R(D**)

**BL:arXiv:1606.09300, submitted to PRD**

# Example: axial-vector Form Factor of $B \to D_1 \, \ell \, \bar{\nu}_\ell$

$$
\begin{aligned}
\sqrt{6}\, f_A = &-(w+1)\tau - \varepsilon_b \big\{ (w-1) \big[ (\bar{\Lambda}' + \bar{\Lambda})\tau - (2w+1)\tau_1 - \tau_2 \big] + (w+1)\eta_b \big\} \\
&- \varepsilon_c \big[ 4(w\bar{\Lambda}' - \bar{\Lambda})\tau - 3(w-1)(\tau_1 - \tau_2) + (w+1)(\eta_{\mathrm{ke}} - 2\eta_1 - 3\eta_3) \big] \,,
\end{aligned}
$$

leading Isgur-Wise function
sub-leading Isgur-Wise functions
chromomagnetic contributions
mass splittings

form factors function of product of four-velocities of had. decay products: $w = v_B \cdot v_{D^{**}}$

# Example: axial-vector Form Factor of $B \to D_1 \, \ell \, \bar{\nu}_\ell$

$$\sqrt{6}\, f_A = -(w+1)\tau - \varepsilon_b\big\{(w-1)\big[(\bar\Lambda' + \bar\Lambda)\tau - (2w+1)\tau_1 - \tau_2\big] + (w+1)\eta_b\big\}$$
$$- \varepsilon_c\big[4(w\bar\Lambda' - \bar\Lambda)\tau - 3(w-1)(\tau_1 - \tau_2) + (w+1)(\eta_{\rm ke} - 2\eta_1 - 3\eta_3)\big]\,,$$

leading Isgur-Wise function
sub-leading Isgur-Wise functions
chromomagnetic contributions
mass splittings

All parameters but the mass splittings a priori unknown

form factors function of product of four-velocities of had. decay products: $w = v_B \cdot v_{D^{**}}$

# Reducing the number of free parameters

Three approximations studied

**Approximation A**: Expand in small *w* range ⟵ LLSW

- No sub-leading IW at lowest order, drop chromomagnetic terms

$$\tau(w) = \tau(1)\big[1 + (w-1)\,\tau'(1) + \ldots\big]\,, \qquad w = v_B \cdot v_{D^{**}}$$

**Approximation $B_1$ and $B_2$**: keep all terms ⟵ LLSW

- sub-leading IW at lowest order, drop chromomag. terms

$$\text{Approx. B}_1: \begin{cases} \frac{3}{2}^+ \text{ states: } \tau_1 = \tau_2 = 0\,, \\ \frac{1}{2}^+ \text{ states: } \zeta_1 = 0\,, \end{cases}$$

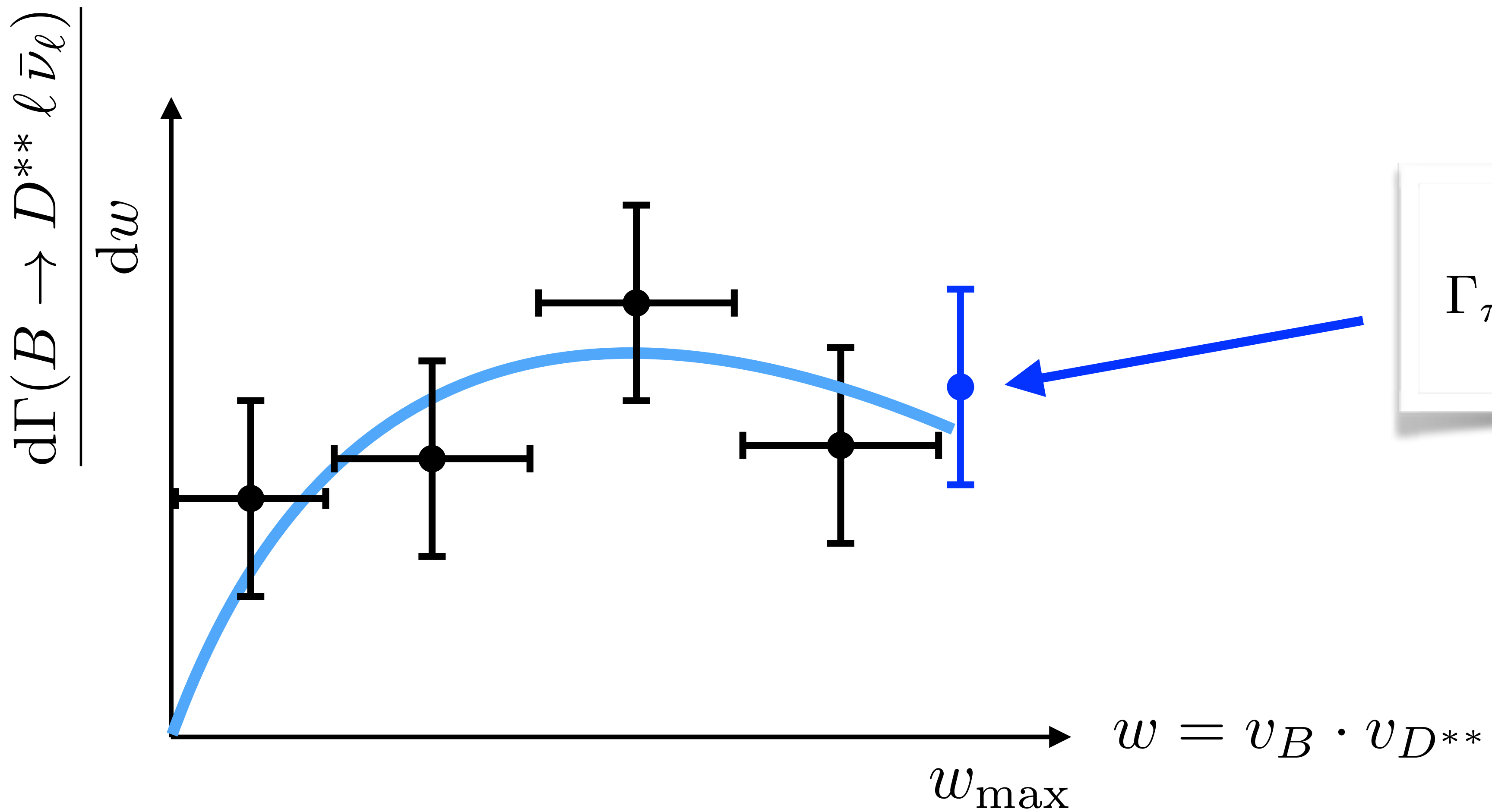
$$\text{Approx. B}_2: \begin{cases} \frac{3}{2}^+ \text{ states: } \tau_1 = \bar\Lambda\tau,\ \tau_2 = -\bar\Lambda'\tau\,, \\ \frac{1}{2}^+ \text{ states: } \zeta_1 = \bar\Lambda\zeta\,. \end{cases}$$

**Approximation C:** $\text{Approx. C}: \begin{cases} \frac{3}{2}^+ \text{ states: } \tau_1 = \hat\tau_1\tau,\ \tau_2 = \hat\tau_2\tau\,, \\ \frac{1}{2}^+ \text{ states: } \zeta_1 = \hat\zeta_1\zeta\,, \end{cases}$ ⟵ New

# Experimental constraints

Three types of experimental constraints

- Total semileptonic branching fractions (all four states)
- Differential semileptonic branching fractions (for $D_0^*$ and $D_2^*$)
- Non-leptonic branching fraction measurements (for $D_1$ and $D_2^*$)



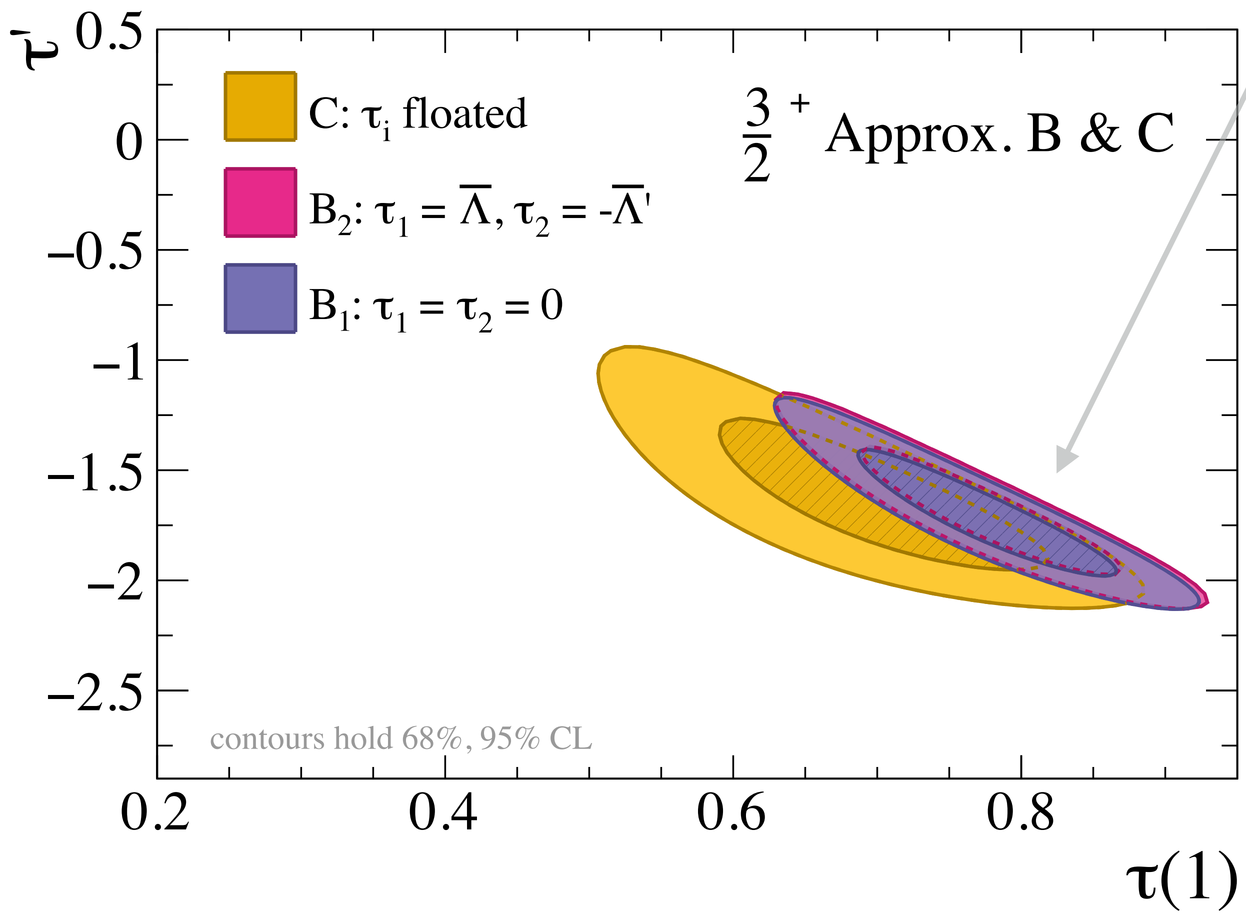

$B^0 \to D^{**\,-}\pi^+$

$$\Gamma_\pi = \frac{3\pi^2\,|V_{ud}|^2\,C^2 f_\pi^2}{m_B^2\,r}\left(\frac{\mathrm{d}\Gamma_{\mathrm{sl}}}{\mathrm{d}w}\right)_{w_{\max}}$$

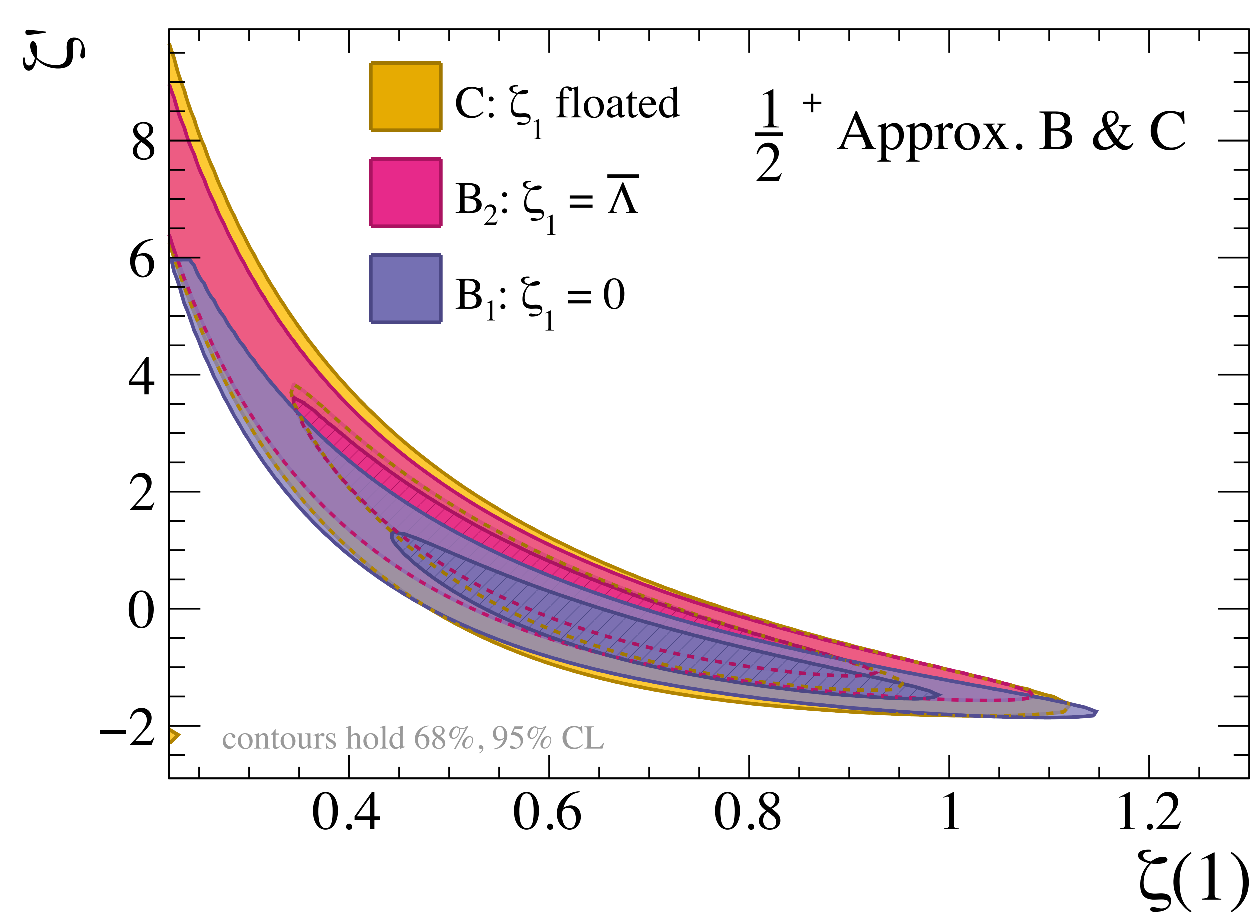
# Narrow and Broad state results:

Allowed 68% and 95% regions with different
assumptions for the sub-leading Isgur-Wise function normalization
for the normalization and slope of the leading Isgur-Wise function

narrow orbital states: $D_1$, $D_2^*$

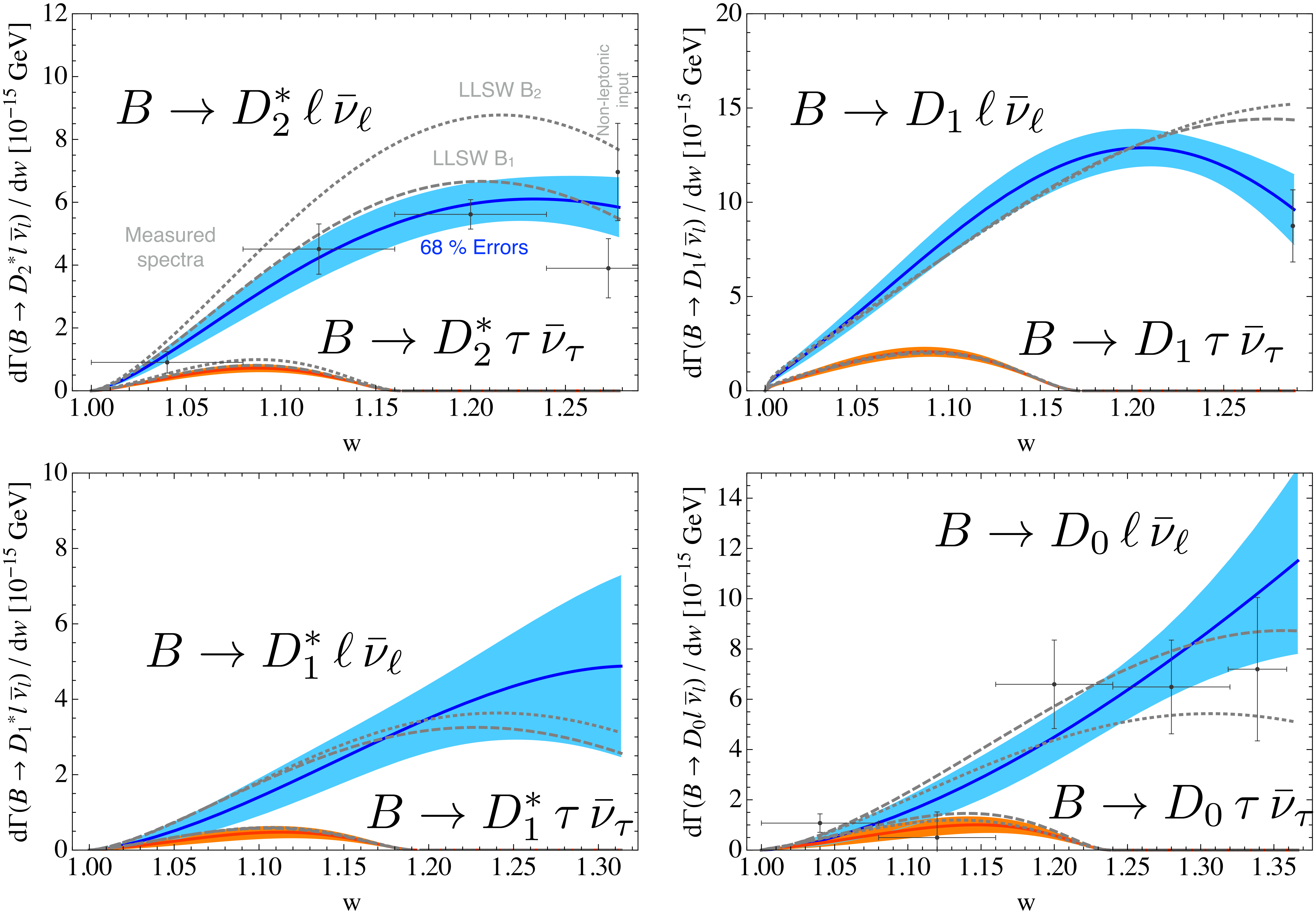



broad orbital states: $D_0$, $D_1^*$




$$\tau(w) = \tau(1)\,(1 + (w-1)\,\tau')$$

$$\zeta(w) = \zeta(1)\,(1 + (w-1)\zeta')$$



$B \to D_2^* \ell \bar{\nu}_\ell$
$B \to D_2^* \tau \bar{\nu}_\tau$
LLSW B2
LLSW B1
Non-leptonic input
Measured spectra
68 % Errors
$d\Gamma(B \to D_2^* l \bar{\nu}_l) / dw \, [10^{-15}$ GeV$]$
w
$B \to D_1 \ell \bar{\nu}_\ell$
$B \to D_1 \tau \bar{\nu}_\tau$
$d\Gamma(B \to D_1 l \bar{\nu}_l) / dw \, [10^{-15}$ GeV$]$
w
$B \to D_1^* \ell \bar{\nu}_\ell$
$B \to D_1^* \tau \bar{\nu}_\tau$
$d\Gamma(B \to D_1^* l \bar{\nu}_l) / dw \, [10^{-15}$ GeV$]$
w
$B \to D_0 \ell \bar{\nu}_\ell$
$B \to D_0 \tau \bar{\nu}_\tau$
$d\Gamma(B \to D_0 l \bar{\nu}_l) / dw \, [10^{-15}$ GeV$]$
w

# Approximation C Predictions

$$R(D^{**}) = \frac{\mathcal{B}(B \to D^{**}\tau\,\bar{\nu})}{\mathcal{B}(B \to D^{**}l\,\bar{\nu})}\,, \qquad \widetilde{R}(X) = \frac{\displaystyle\int_{m_\tau^2}^{(m_B-m_X)^2} \frac{\mathrm{d}\Gamma(B \to X\tau\bar{\nu})}{\mathrm{d}q^2}\,\mathrm{d}q^2}{\displaystyle\int_{m_\tau^2}^{(m_B-m_X)^2} \frac{\mathrm{d}\Gamma(B \to Xl\bar{\nu})}{\mathrm{d}q^2}\,\mathrm{d}q^2}\,.$$

matching overlap increases
correlation, reduces theory error

# Approximation C Predictions

$$R(D^{**}) = \frac{\mathcal{B}(B \to D^{**}\tau\,\bar\nu)}{\mathcal{B}(B \to D^{**}l\,\bar\nu)}\,, \qquad \widetilde{R}(X) = \frac{\displaystyle\int_{m_\tau^2}^{(m_B-m_X)^2} \frac{\mathrm{d}\Gamma(B \to X\tau\bar\nu)}{\mathrm{d}q^2}\,\mathrm{d}q^2}{\displaystyle\int_{m_\tau^2}^{(m_B-m_X)^2} \frac{\mathrm{d}\Gamma(B \to Xl\bar\nu)}{\mathrm{d}q^2}\,\mathrm{d}q^2}\,.$$

$$\begin{aligned}
R(D_2^*) &= 0.07 \pm 0.01\,, & \widetilde{R}(D_2^*) &= 0.17 \pm 0.01\,,\\
R(D_1) &= 0.10 \pm 0.02\,, & \widetilde{R}(D_1) &= 0.20 \pm 0.02\,,\\
R(D_1^*) &= 0.06 \pm 0.02\,, & \widetilde{R}(D_1^*) &= 0.18 \pm 0.02\,,\\
R(D_0) &= 0.08 \pm 0.04\,, & \widetilde{R}(D_0) &= 0.25 \pm 0.06\,, \qquad (38)
\end{aligned}$$

errors include estimated uncertainty
from missing chromomagnetic contributions

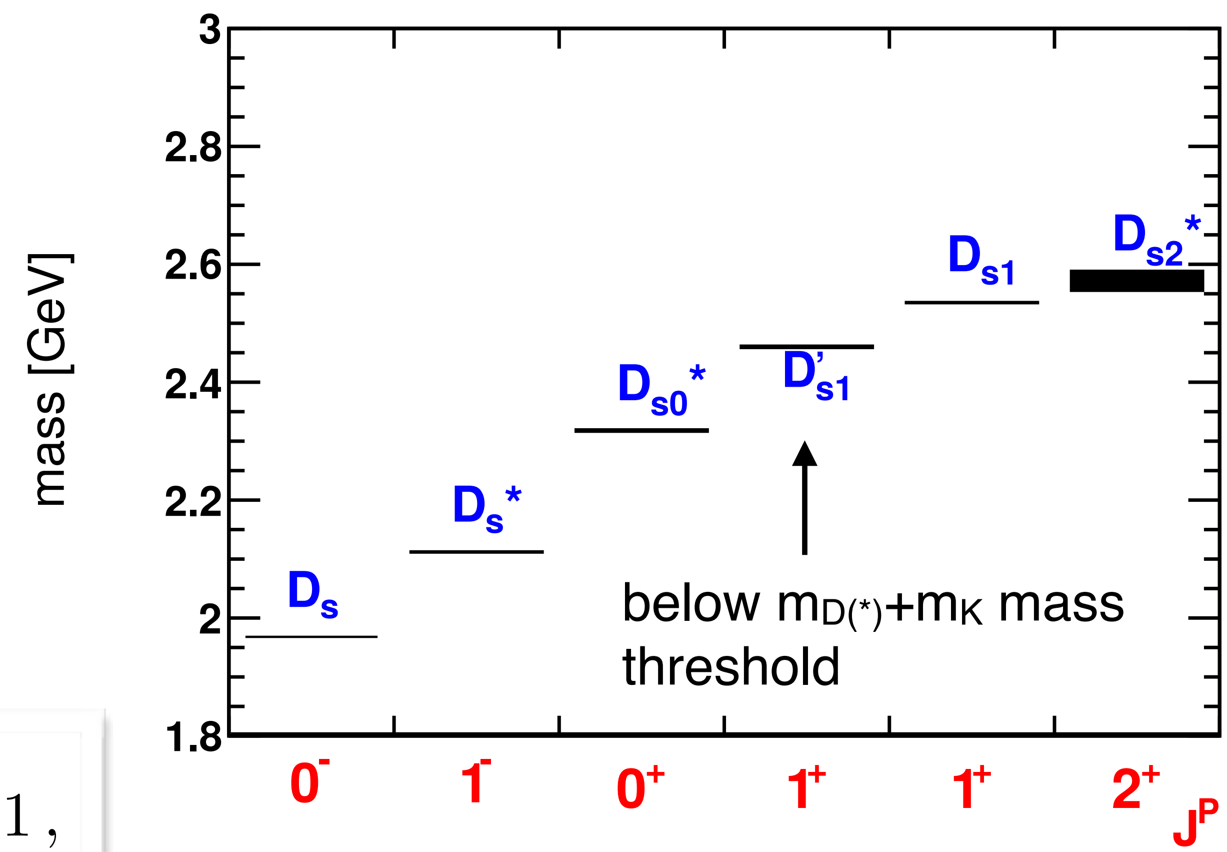
$$R(D^{**}) = 0.085 \pm 0.012\,.$$

$$\mathcal{B}(B \to D^{**}\tau\bar\nu) = (0.14 \pm 0.03)\%.$$

# Approximation C Predictions for $B_s \to D_s^{**}\,\ell\,\bar{\nu}_\ell$

## Interesting channels

- $D_{s0}^*$ and $D_{s1}^*$ very narrow
- Prediction can be made from fitted form factor parameters, not taking into account any SU(3) breaking effects




$$
\begin{aligned}
R(D_{s2}^*) &= 0.07 \pm 0.01\,, & \widetilde{R}(D_{s2}^*) &= 0.16 \pm 0.01\,,\\
R(D_{s1}) &= 0.09 \pm 0.02\,, & \widetilde{R}(D_{s1}) &= 0.20 \pm 0.02\,,\\
R(D_{s1}^*) &= 0.07 \pm 0.03\,, & \widetilde{R}(D_{s1}^*) &= 0.20 \pm 0.02\,,\\
R(D_{s0}^*) &= 0.09 \pm 0.04\,, & \widetilde{R}(D_{s0}^*) &= 0.26 \pm 0.05\,.
\end{aligned}
$$

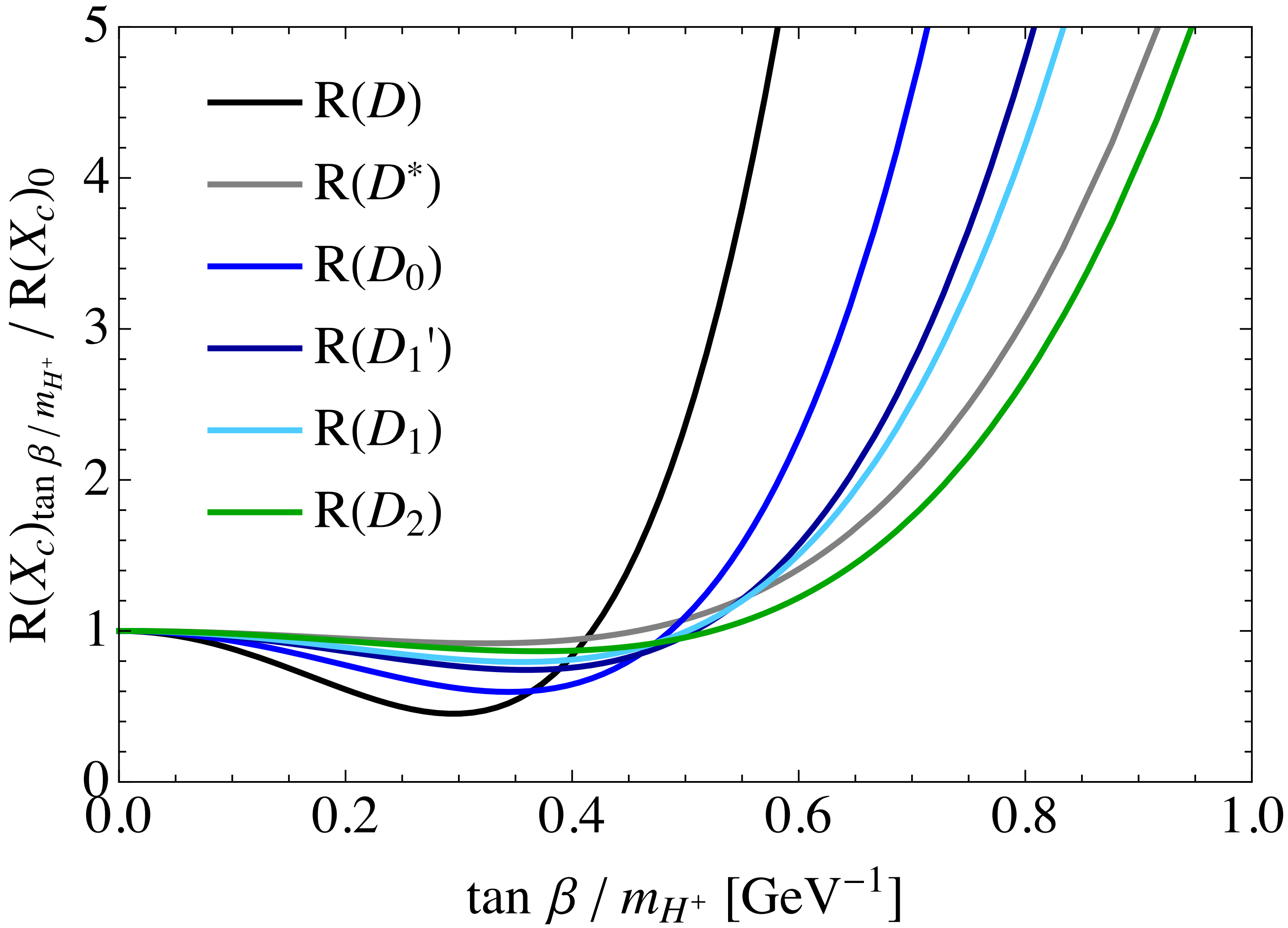
errors include estimated uncertainty
from missing chromomagnetic contributions

# Helicity amplitudes & New Physics

Included helicity amplitudes in paper; easy to make predictions for New Physics

Example: 2HDM Type II

$$H_t \to H_t^{\mathrm{SM}}\left(1 - \frac{\tan^2\beta}{m_{H^\pm}^2}\frac{m_b\, q^2}{m_b - m_c}\right).$$



# Summary

## Presented predictions for $R(D^{**})$ & $R(D_s^{**})$

- Alternative (but experimentally) challenging path to study the discrepancies observed in $R(D)$ and $R(D^*)$
- Can be used to model the signal mix for inclusive $R(X = D + D^* + D^{**})$ contributions, as 1S + 1P contributions almost saturate the inclusive rate
- Predictions for $R(D_{s0}^*)$ (spin 0 1P $D_s$ state) offers an interesting probe to validate the enhancement in $R(D)$ that might be within the reach of LHCb due to the clear narrow signal.
- Full expressions in Helicity amplitudes available for all four states, allows to make predictions for various New Physics models easily.

Thank you for your attention!

# Backup slides

# Dependence on chromomagnetic operators