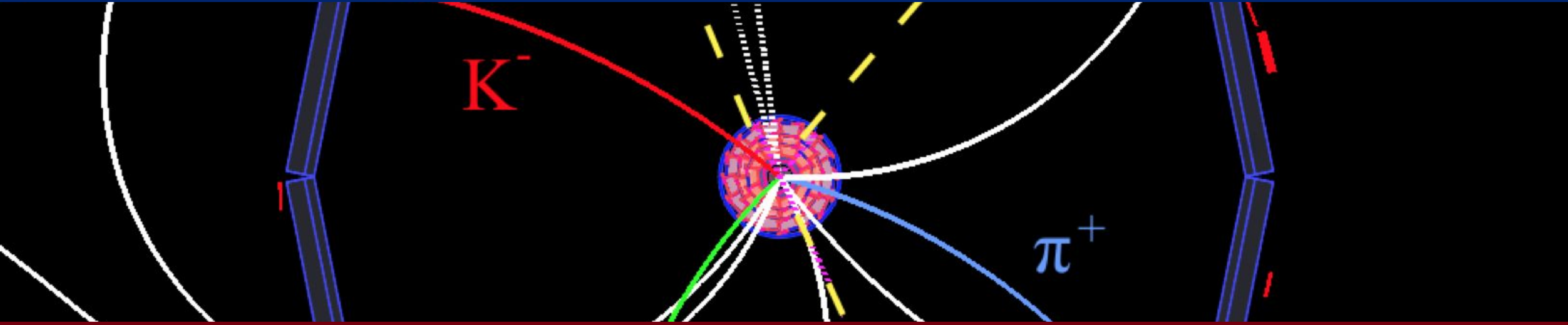
Semileptonic decays into excited charmed mesons



Workshop on Semi-tauonic decays Nagoya 27 Mar 2017

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|V_ub| / |V_cb|
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Introduction

1. **Why are decays into excited charmed mesons important and how can we improve our understanding of them?**

   F. Bernlochner, Z. Ligeti, Phys. Rev. D95, 014022 (2017)

2. **Some brief remarks on model dependence and how we should carry out future R(D) and R(D*) measurements**

1. Excited Charmed mesons

F. Bernlochner, Z. Ligeti, Phys. Rev. D95, 014022 (2017)

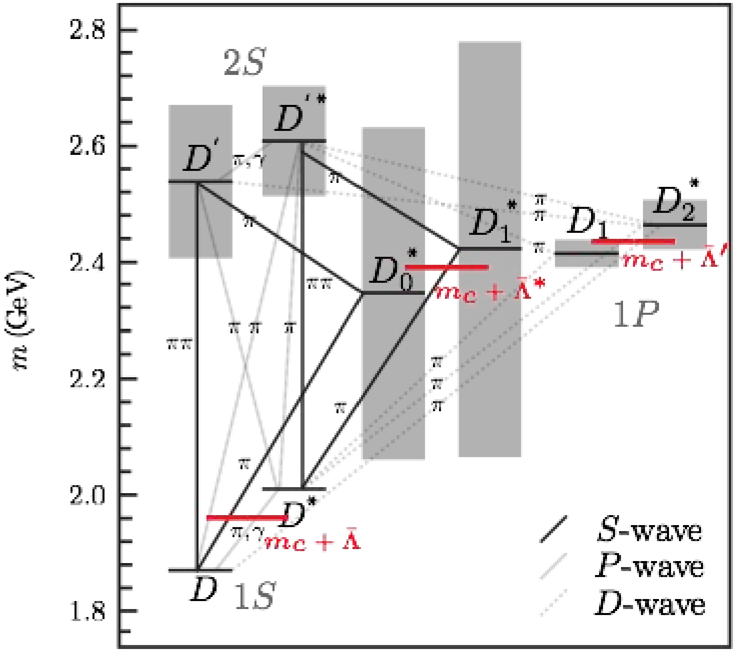
F. Bernlochner, D. Robinson, M. Papucci, Z. Ligeti, in preparation

Overview

Colloquial: excited charmed mesons are called D** = D**(1*P*)

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

- Important background for measurements of D/D*
  - E.g. $|V_{cb}|$ or R(D) & R(D*)
- ~15% of all **B → X_c l ν** decays
  - Relevant for e.g. $|V_{ub}|$ using lepton spectrum or R(X)
- **B → X_c τ ν** seemingly saturated by B → D(*) τ ν
  - Not much space for B → D** τ ν, if due to NP why not enhanced as well?



Decay mode	Branching fraction
$B^+ \to \bar{D}_2^{*0}\, l\, \bar{\nu}$	$(0.30 \pm 0.04) \times 10^{-2}$
$B^+ \to \bar{D}_1^{0}\, l\, \bar{\nu}$	$(0.67 \pm 0.05) \times 10^{-2}$
$B^+ \to \bar{D}_1^{*0}\, l\, \bar{\nu}$	$(0.20 \pm 0.05) \times 10^{-2}$
$B^+ \to \bar{D}_0^{*0}\, l\, \bar{\nu}$	$(0.44 \pm 0.08) \times 10^{-2}$

What do we know about D**(1*P*)

Semileptonic experimental knowledge:

- Measured in D(*) π^+
  - More detailed overview: **Bob Kowalewski's talk**
    - Most of the observed D(*) π^+ can be attributed to D**(1P)
  - Evidence for contributions beyond D**(1P) in D(*) π π

Theory expectation:

- **Two narrow** and **two broad** states
  - Quark-model: combine heavy b with light quarks with orbital angular momentum **L=1**
  - **H**eavy **Q**uark **L**imit
    - spin-parity of light dof conserved: $s_l^{\pi_l}$
  - In decay rate: **narrow >> broad**
    - Violation known as '½ versus 3/2 puzzle'

      arXiv:1411.3563, arXiv:0708.1621 (Eur. Phys. J. C52:975-985, 2007),..

Particle	$s_l^{\pi_l}$	J^P	m (MeV)	Γ (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

Form factors

Starting point: effective Lagrangian: $\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left(\bar{c}\,\gamma_\mu P_L b\right) \left(\bar{\nu}\,\gamma^\mu P_L \ell\right) + \text{h.c.}\,,$

Narrow: D_1, D_2*

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

→ **2 x 4 Form Factors**

Broad: D_0*, D_1*

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

→ **2 + 4 Form Factors**

Large number of unknown functions reduce in HQL into **single** universal **I**sgur-**W**ise function; first systematic analysis by **LLSW (Phys. Rev. Lett. 78, 3995, Phys. Rev. D 57, 308)**

Mass splittings and form factors

Mass of heavy quark spin symmetry doublet:

Energy of light **degree of freedoms**

$$m_{H_\pm} = m_Q + \bar{\Lambda}^H - \frac{\lambda_1^H}{2m_Q} \pm \frac{n_\mp \lambda_2^H}{2m_Q} + \ldots ,$$

Mass of heavy quark

Chromomagnetic and other contributions..

→ Energy of light degrees of freedom enter the form factors

Realization that lead to the LLSW prediction;

Particle	$s_l^{\pi_l}$	J^P	m (MeV)	Γ (MeV)
D_0^*	$\frac{1}{2}^+$	0^+	2330	270
D_1^*	$\frac{1}{2}^+$	1^+	2427	384
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Parameter	$\bar{\Lambda}$	$\bar{\Lambda}'$	$\bar{\Lambda}^*$	$\bar{\Lambda}_s$	$\bar{\Lambda}'_s$	$\bar{\Lambda}^*_s$
Value [GeV]	0.40	0.80	0.76	0.49	0.90	0.77

m (MeV)	Γ (MeV)	reference
2405 ± 36	274 ± 45	FOCUS [13]
2308 ± 36	276 ± 66	Belle [14]
2297 ± 22	273 ± 49	*BaBar* [15]
2360 ± 34	255 ± 57	LHCb [16]
2330 ± 15	270 ± 26	our average

Heavy Quark Limit

Expansion of the form factors to order **1/m**$_{c,b}$

Leading IW function: $\tau = \tau(w)$

Chromomagnetic contributions: $\eta_{b,1,2,3}$

Sub-leading IW functions: $\tau_{1,2}$

Mass splittings: $\bar{\Lambda}(')$

$$
\begin{aligned}
\sqrt{6}\, f_A &= -(w+1)\tau - \varepsilon_b\big\{(w-1)\big[(\bar{\Lambda}' + \bar{\Lambda})\tau - (2w+1)\tau_1 - \tau_2\big] + (w+1)\eta_b\big\} \\
&\quad - \varepsilon_c\big[4(w\bar{\Lambda}' - \bar{\Lambda})\tau - 3(w-1)(\tau_1 - \tau_2) + (w+1)(\eta_{\rm ke} - 2\eta_1 - 3\eta_3)\big]\,, \\
\sqrt{6}\, f_{V_1} &= (1-w^2)\tau - \varepsilon_b(w^2-1)\big[(\bar{\Lambda}' + \bar{\Lambda})\tau - (2w+1)\tau_1 - \tau_2 + \eta_b\big] \\
&\quad - \varepsilon_c\big[4(w+1)(w\bar{\Lambda}' - \bar{\Lambda})\tau - (w^2-1)(3\tau_1 - 3\tau_2 - \eta_{\rm ke} + 2\eta_1 + 3\eta_3)\big]\,, \\
\sqrt{6}\, f_{V_2} &= -3\tau - 3\varepsilon_b\big[(\bar{\Lambda}' + \bar{\Lambda})\tau - (2w+1)\tau_1 - \tau_2 + \eta_b\big] \\
&\quad - \varepsilon_c\big[(4w-1)\tau_1 + 5\tau_2 + 3\eta_{\rm ke} + 10\eta_1 + 4(w-1)\eta_2 - 5\eta_3\big]\,, \\
\sqrt{6}\, f_{V_3} &= (w-2)\tau + \varepsilon_b\big\{(2+w)\big[(\bar{\Lambda}' + \bar{\Lambda})\tau - (2w+1)\tau_1 - \tau_2\big] - (2-w)\eta_b\big\} \\
&\quad + \varepsilon_c\big[4(w\bar{\Lambda}' - \bar{\Lambda})\tau + (2+w)\tau_1 + (2+3w)\tau_2 \\
&\qquad + (w-2)\eta_{\rm ke} - 2(6+w)\eta_1 - 4(w-1)\eta_2 - (3w-2)\eta_3\big]\,.
\end{aligned}
$$

Decay rates with full lepton mass

One thing that was missing in the original paper :

Decay rates with full lepton mass effects:

$$\boxed{\rho_\ell = m_\ell^2/m_B^2}$$

$$
\begin{aligned}
\frac{\mathrm{d}\Gamma_{D_1}}{\mathrm{d}w\,\mathrm{d}\cos\theta} &= 3\Gamma_0\, r^3 \sqrt{w^2-1}\,\left(1+r^2-\rho_\ell-2rw\right)^2 \\
&\times \Bigg\{ \sin^2\theta \left[\frac{\left[f_{V_1}(w-r)+(f_{V_3}+r f_{V_2})(w^2-1)\right]^2}{(1+r^2-2rw)^2} + \boxed{\rho_\ell}\, \frac{f_{V_1}^2 + \left(2f_A^2+f_{V_2}^2+f_{V_3}^2+2f_{V_1}f_{V_2}+2wf_{V_2}f_{V_3}\right)(w^2-1)}{2(1+r^2-2rw)^2} \right] \\
&\quad + (1+\cos^2\theta) \left[\frac{f_{V_1}^2+f_A^2(w^2-1)}{1+r^2-2rw} + \boxed{\rho_\ell}\, \frac{[f_{V_1}^2+(w^2-1)f_{V_3}^2](2w^2-1+r^2-2rw)}{2(1+r^2-2rw)^3} \right. \\
&\qquad \left. + \boxed{\rho_\ell}(w^2-1)\, \frac{2f_{V_1}f_{V_2}(1-r^2)+4f_{V_1}f_{V_3}(w-r)+f_{V_2}^2(1-2rw-r^2+2r^2w^2)+2f_{V_2}f_{V_3}(w-2r+r^2w)}{2(1+r^2-2rw)^3} \right] \\
&\quad - 2\cos\theta\,\sqrt{w^2-1} \left[\frac{2f_Af_{V_1}}{1+r^2-2rw} - \boxed{\rho_\ell}\, \frac{[f_{V_1}(w-r)+(f_{V_3}+rf_{V_2})(w^2-1)][f_{V_1}+f_{V_2}(1-rw)+f_{V_3}(w-r)]}{(1+r^2-2rw)^3} \right] \Bigg\},
\end{aligned}
\tag{9}
$$

Approximations A, B and C

Recoil parameter *w* (the recoil-parameter = v_B x $v_D^{(*)}$) range:

→ For D and D* ranges from 1 - 1.6

→ For D** the effective range is 1 - ~ 1.3

- Can expand decay rate in *w* and truncate expansion
  - Reduces the number of terms, but only accurate at low *w*
    - **Approximation A**
- Can keep all orders
  - Fit **slope** and **normalization** of **leading Isgur-Wise function**
  - To reduce number of free parameters, drop chromomagnetic terms and model sub-leading IW functions
    - **Approximation B**
- Mass splitting between D_0 and D_1* seem to imply that chromomagnetic contributions are not necessarily small
  - Fit **slope** and **normalization** of **leading Isgur-Wise** function and **normalization** of **sub-leading IW functions**
  - Evaluate the impact of chromomagnetic terms
    - **Approximation C**

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Experimental information

Experimental information to constrain form factors:

- Total Decay Rates
- Differential decay rates (D_2*,D_0*)

Decay mode	Branching fraction
$B^+ \to \bar{D}_2^{*0}\, l\, \bar{\nu}$	$(0.30 \pm 0.04) \times 10^{-2}$
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$B^+ \to \bar{D}_0^{*0}\, l\, \bar{\nu}$	$(0.44 \pm 0.08) \times 10^{-2}$

w	$B^+ \to \bar{D}_2^{*0}\, l\, \bar{\nu}$	$B^+ \to \bar{D}_0^{*0}\, l\, \bar{\nu}$
$1.00 - 1.08$	0.06 ± 0.02	0.05 ± 0.02
$1.08 - 1.16$	0.30 ± 0.05	0.02 ± 0.05
$1.16 - 1.24$	0.38 ± 0.03	0.30 ± 0.08
$1.24 - 1.32$	0.26 ± 0.06	0.30 ± 0.09
$1.32 - 1.40$	—	0.33 ± 0.13

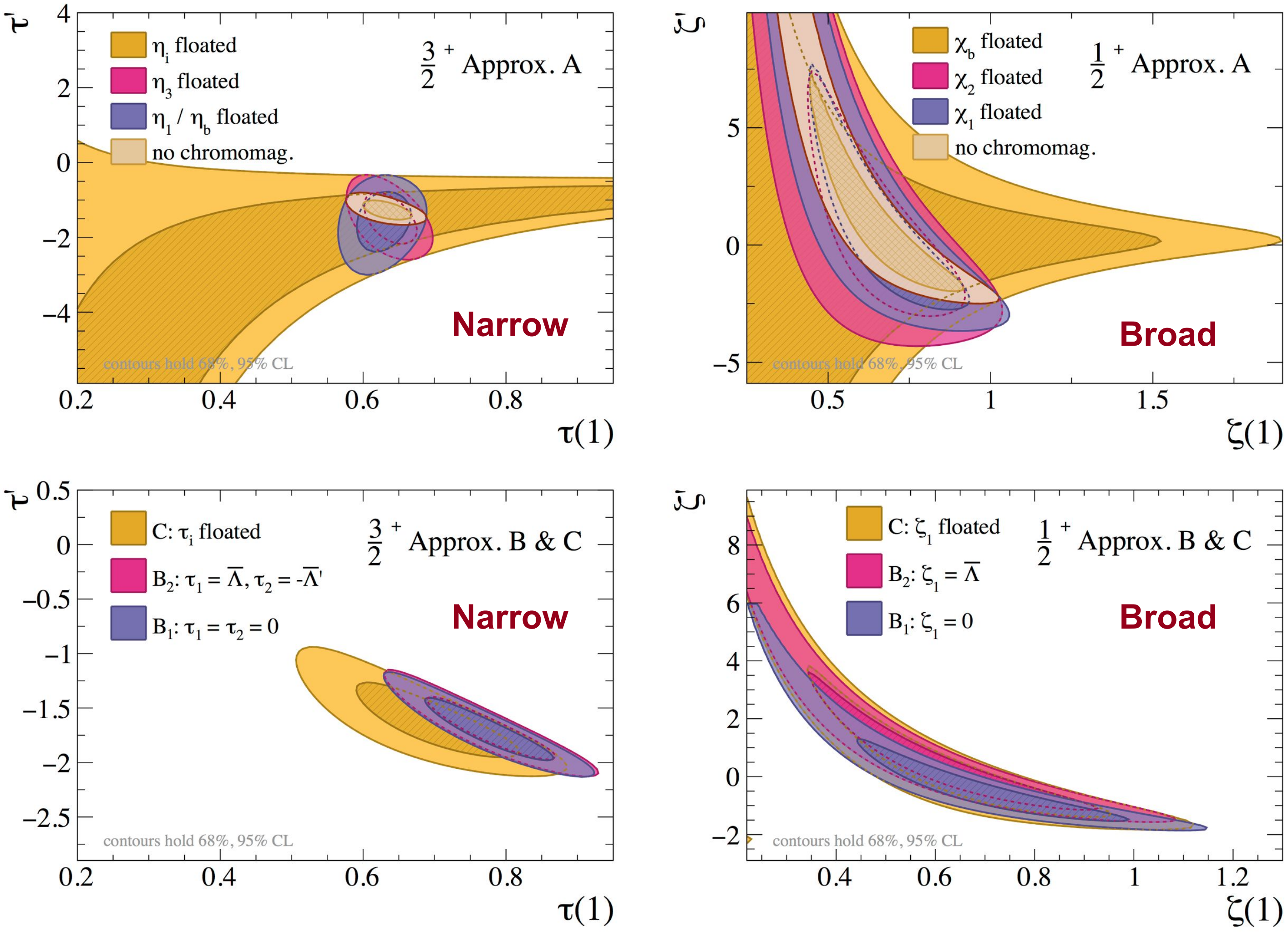
- Non-leptonic rates:

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

Decay mode	Branching fraction
$B^0 \to D_2^{*-} \pi^+$	$(0.59 \pm 0.13) \times 10^{-3}$
$B^0 \to D_1^{-} \pi^+$	$(0.75 \pm 0.16) \times 10^{-3}$
$B^0 \to D_0^{*-} \pi^+$	$(0.09 \pm 0.05) \times 10^{-3}$

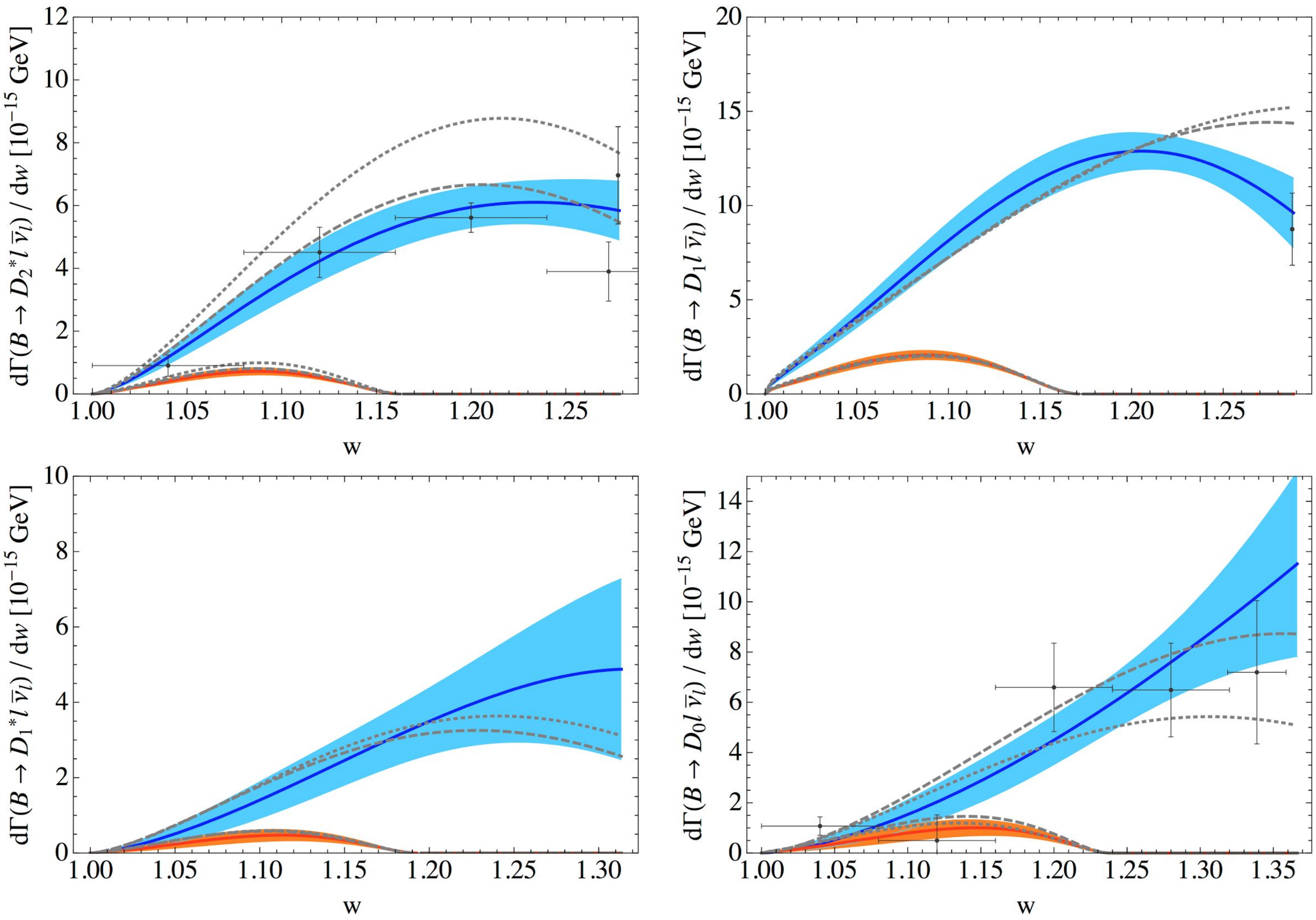
Form factor fit(s)

Likelihood fit to all experimental information



Form factor fit(s)

Likelihood fit of all experimental information:



Predictions for R(D**)

Using these form factors, R(D**) can be predicted

→ Expansion of form factors in **1/m$_{c,b}$** provide all necessary expressions, also for the form factors ~ *m*$_\tau$

Approximation C predictions:

$$R(D_2^*) = 0.07 \pm 0.01\,, \qquad \widetilde{R}(D_2^*) = 0.17 \pm 0.01\,,$$

$$R(D_1) = 0.10 \pm 0.02\,, \qquad \widetilde{R}(D_1) = 0.20 \pm 0.02\,,$$

$$R(D_1^*) = 0.06 \pm 0.02\,, \qquad \widetilde{R}(D_1^*) = 0.18 \pm 0.02\,,$$

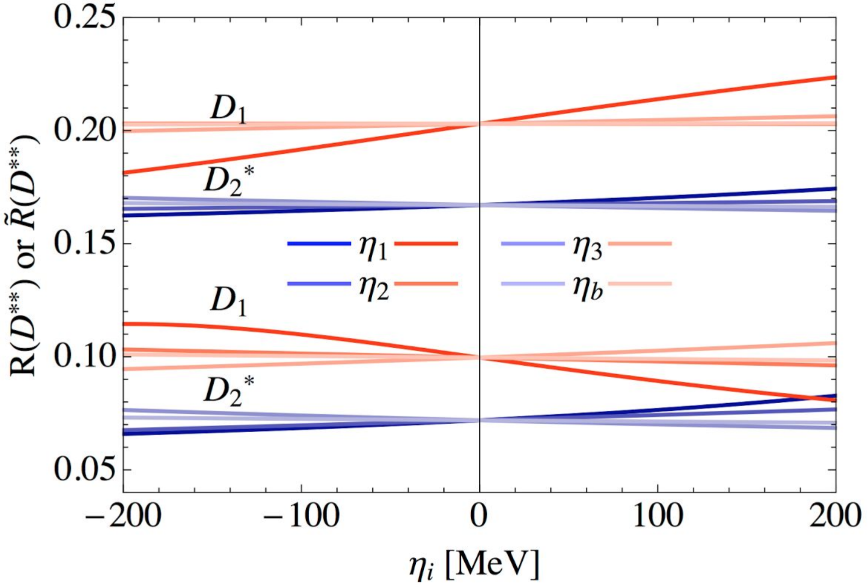
$$R(D_0) = 0.08 \pm 0.04\,, \qquad \widetilde{R}(D_0) = 0.25 \pm 0.06\,,$$

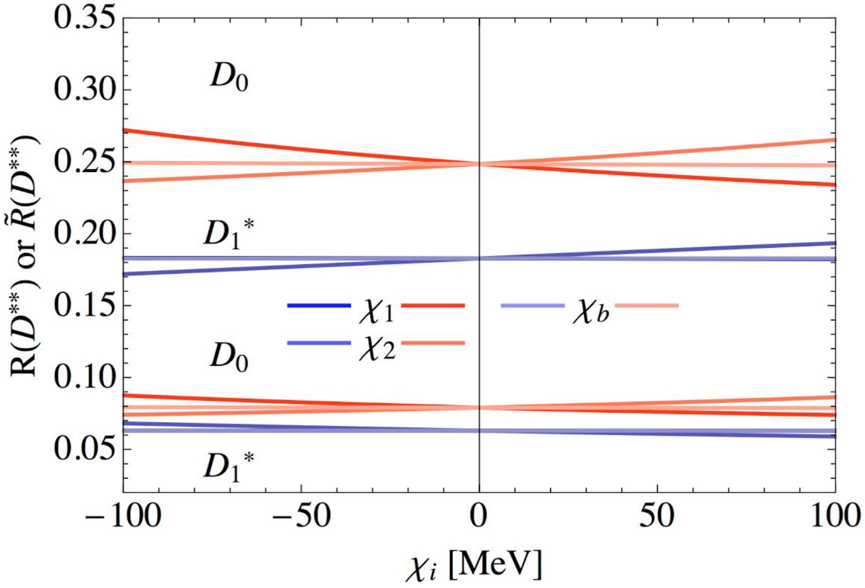
$$R(D^{**}) = 0.085 \pm 0.012\,.$$

Chromomagnetic contributions

Impact of chromomagnetic contributions tested by variations within reasonable bounds

→ Range motivated by constraints when fitting individual contributions, no real sensitivity to fully profile all chromomagnetic terms



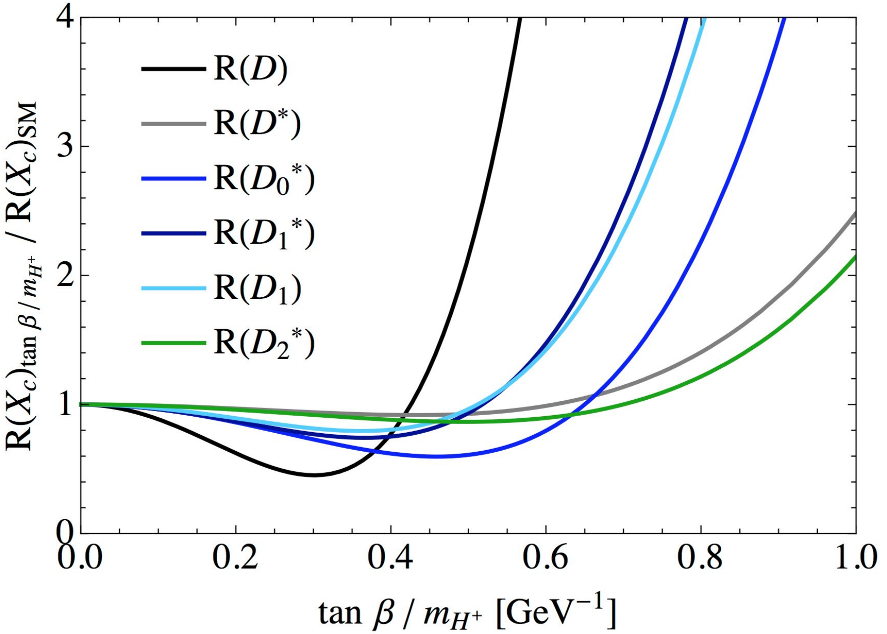


New Physics sensitivity

Additional scalar interaction:

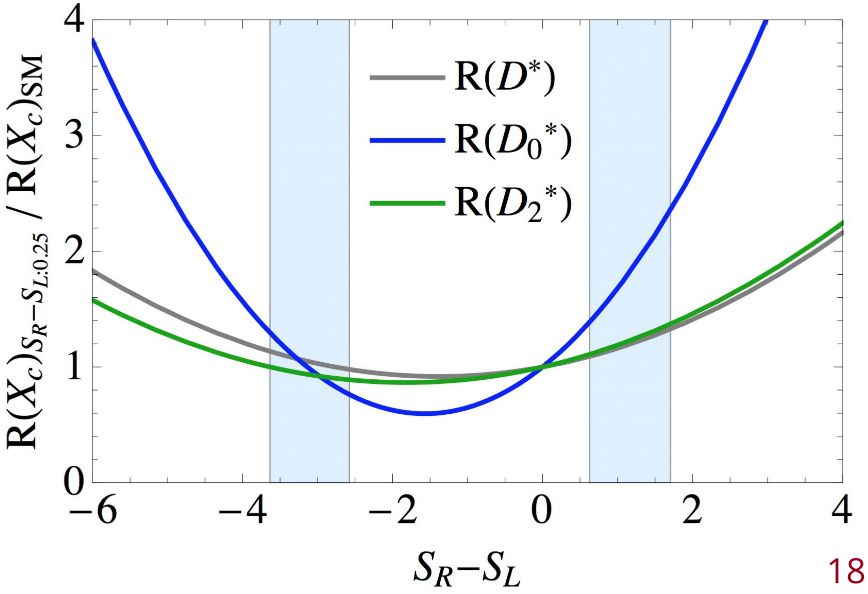
$$H_t \to H_t^{\mathrm{SM}} \left[1 + (S_R \pm S_L) \frac{q^2}{m_\tau (m_b \mp m_c)} \right],$$

→ 2HDM type II **(top)**
→ 2HDM type III **(bottom)**



Full operator analysis left for future work

- FB, D. Robinson, M. Papucci, Z. Ligeti, in preparation



2. Model dependence

Or why we should take any phenomenological fit to R(D) and R(D*) with a grain of salt

Model dependence

The problem: When measuring R(D) and R(D*) we make certain assumptions

Yield of Signal Events → Translate that Yield into a Ratio

Signal Shape

Signal Efficiency

Model dependence

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Yield of Signal Events → Translate that Yield into a Ratio

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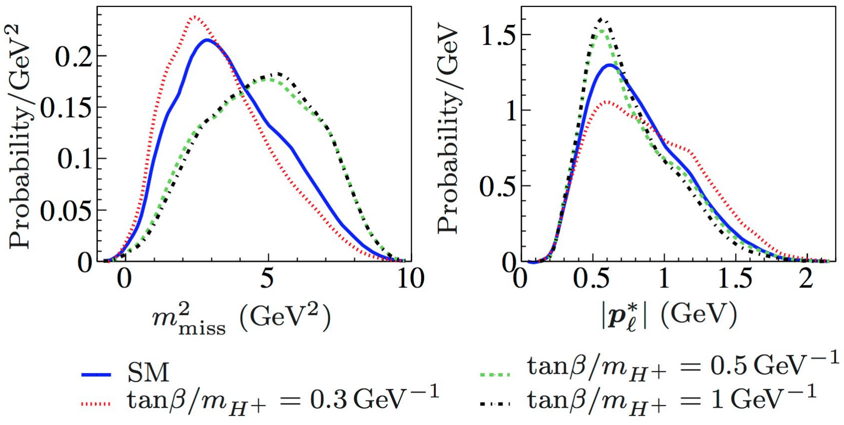
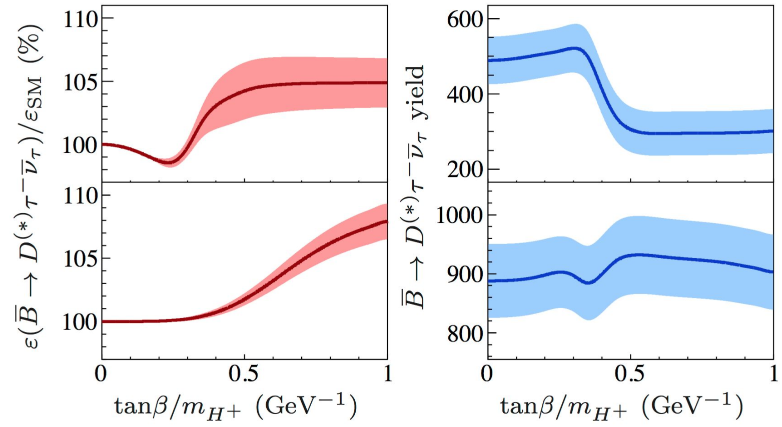




Model dependence

Physics behind this

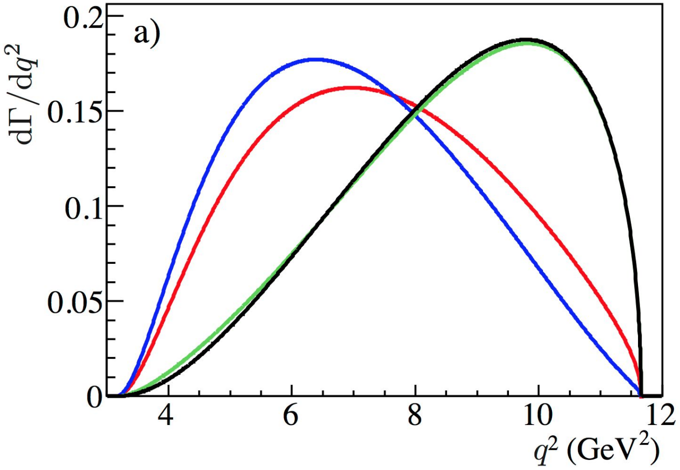
1.) Change of **kinematics** ⟷ Impacts predominantly m_{miss}^2

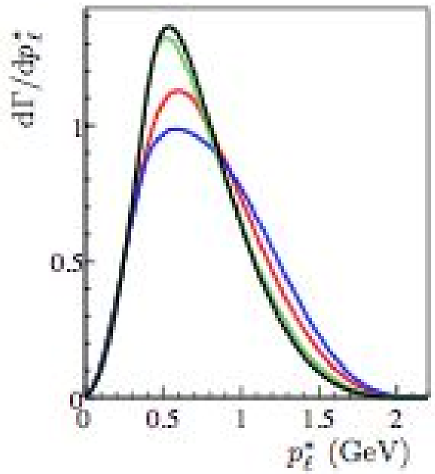
2.) Change of **fraction of LH *versus* RH** ⟷ changes p_l

→ Fraction affects in $\tau \rightarrow l \nu \nu$ kinematic of secondary ***l*** drastically

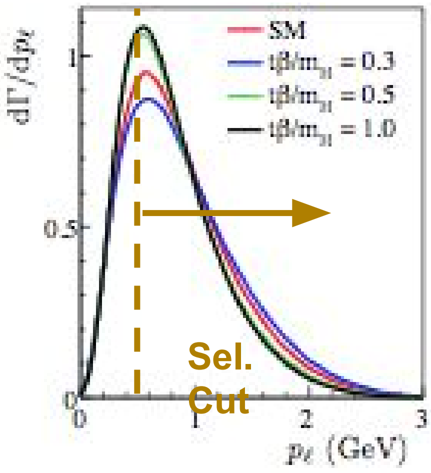
LH τ^- : ***l*** *emitted preferentially in τ* flight direction

RH τ^- : *opposite is true*





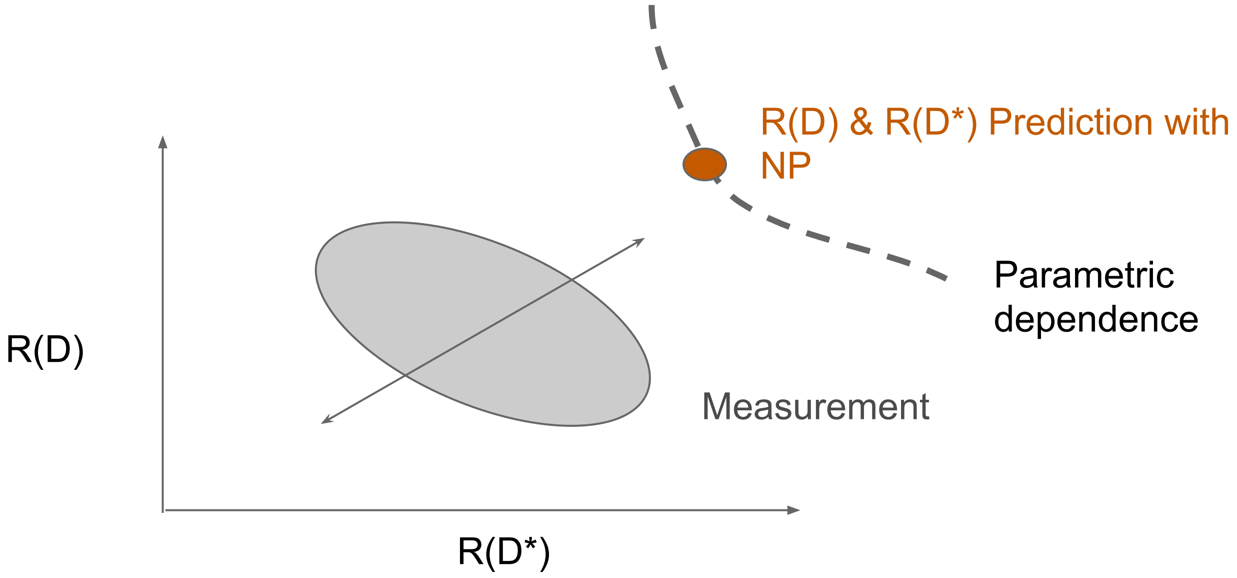
B-Meson frame



Lab frame

Thus

If your favorite model fit to $R(D^{(*)})$ **alters the kinematics (most of the operators you add will)** and the **RH/LH fraction (most of the operators will)**, beware of drawing too strong conclusions: the measured values depend on these details



Can we do better?

Alternatives:

- **Fiducial measurements**
  - Make the experimental cuts part of the definition of $R(D^{(*)})$
    - Not clear this is fully feasible; does not resolve kinematic dependence of signal shapes
      - Measuring $R(D^{(*)})$ as a function of q^2 might resolve the latter
- Maintain an interface to **recast analyses**
  - Some effort in the LHC community to setup things this way
- **Measure pseudo-observables** that allow interpretations later
  - Make measurements in Wilson coefficients and quote limits
    - Can be easily combined across experiments
    - Consistency important

Needs a dialogue between Experiments and also between the Theory community and the Experiments. Maybe this workshop is a good opportunity to start such a discussion.