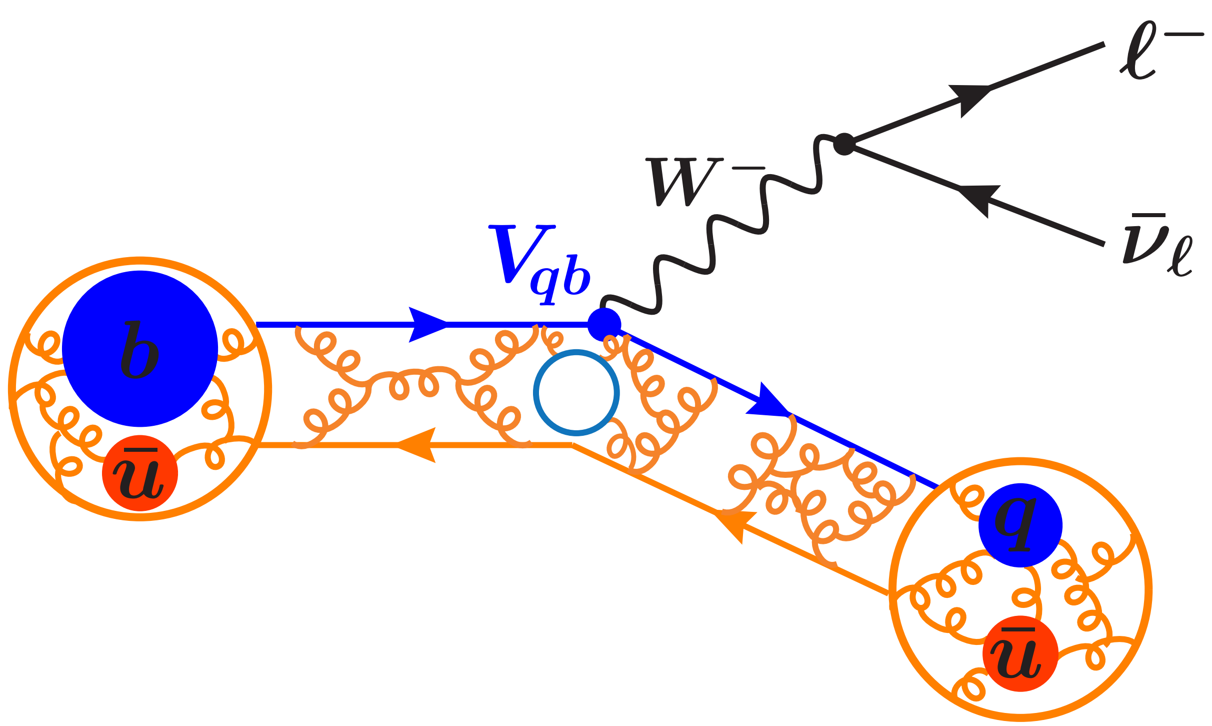
Prospects on understanding $B \to D^{**} l \nu$

Work in collaboration with Z. Ligeti



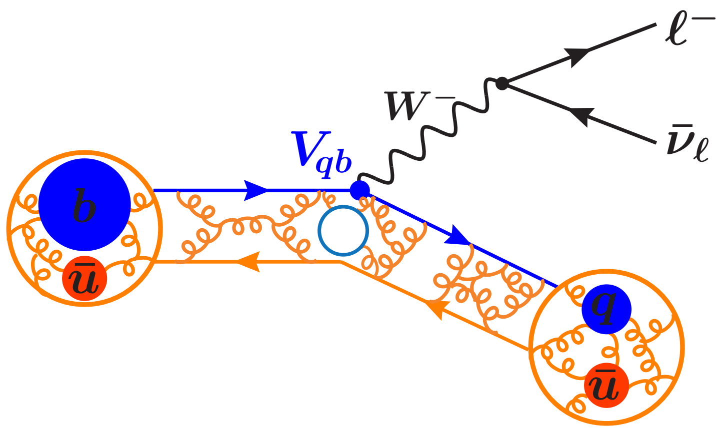
Florian U. Bernlochner

florian.bernlochner@cern.ch

University of Bonn, Germany

universitätbonn

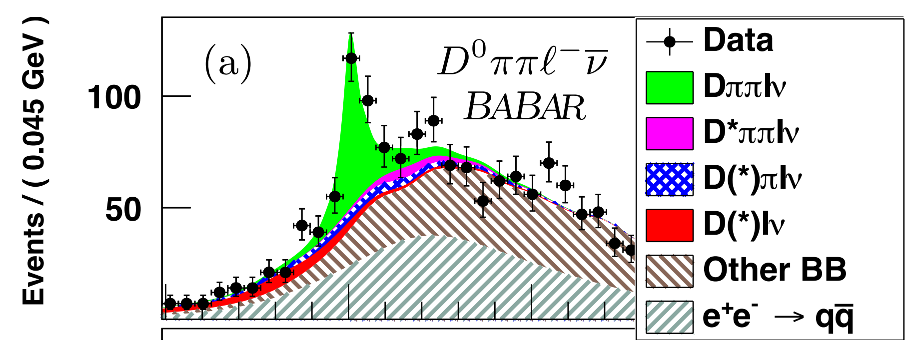
What's the problem with $B \to D^{**} l \nu$ and why you should care



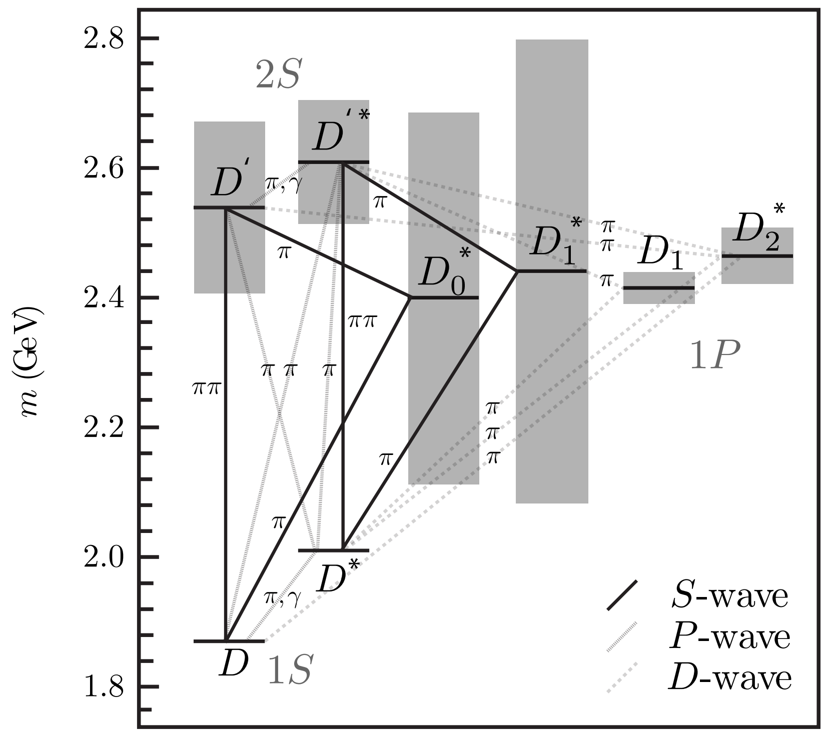
- Transitions involving orbital or other excited X_c states make up about 3% of all $B \to X_c l \nu$ transitions
- Inclusive and all known exclusive $B \to X_c l \nu$ measurements leave a 'gap' of unknown decays:
  - 1.3-1.5% in Branching Fraction; pretty significant
  - BaBar identified 0.52% of these to originate from $B \to D(*) \pi\pi l \nu$
  - Still some missing contributions, possibly from η decays and other $\pi\pi\pi$ final states
- Important backgrounds for $R(D)$ & $R(D^*)$ but also $|V_{cb}|$ measurements (as down feed)
- Could be a complementary probe for semi-tauonic decays as $R(\pi)$

Charm state X_c	$\mathcal{B}(B^+ \to X_c \ell^+ \nu)$
D	(2.31 ± 0.09) %
D^*	(5.63 ± 0.18) %
$\sum D^{(*)}$	$(\mathbf{7.94 \pm 0.20})$ %
$D_0^* \to D\pi$	(0.41 ± 0.08) %
$D_1^* \to D^*\pi$	(0.45 ± 0.09) %
$D_1 \to D^*\pi$	(0.43 ± 0.03) %
$D_2^* \to D^{(*)}\pi$	(0.41 ± 0.03) %
$\sum D^{**} \to D^*\pi$	$(\mathbf{1.70 \pm 0.12})$ %
$D\pi$	(0.66 ± 0.08) %
$D^*\pi$	(0.87 ± 0.10) %
$\sum D^*\pi$	$(\mathbf{1.53 \pm 0.13})$ %
$\sum D^{(*)} + \sum D^*\pi$	$(\mathbf{9.47 \pm 0.24})$ %
$\sum D^{(*)} + \sum D^{**} \to D^{(*)}\pi$	$(\mathbf{9.64 \pm 0.23})$ %
Inclusive X_c	$(\mathbf{10.92 \pm 0.16})$ %

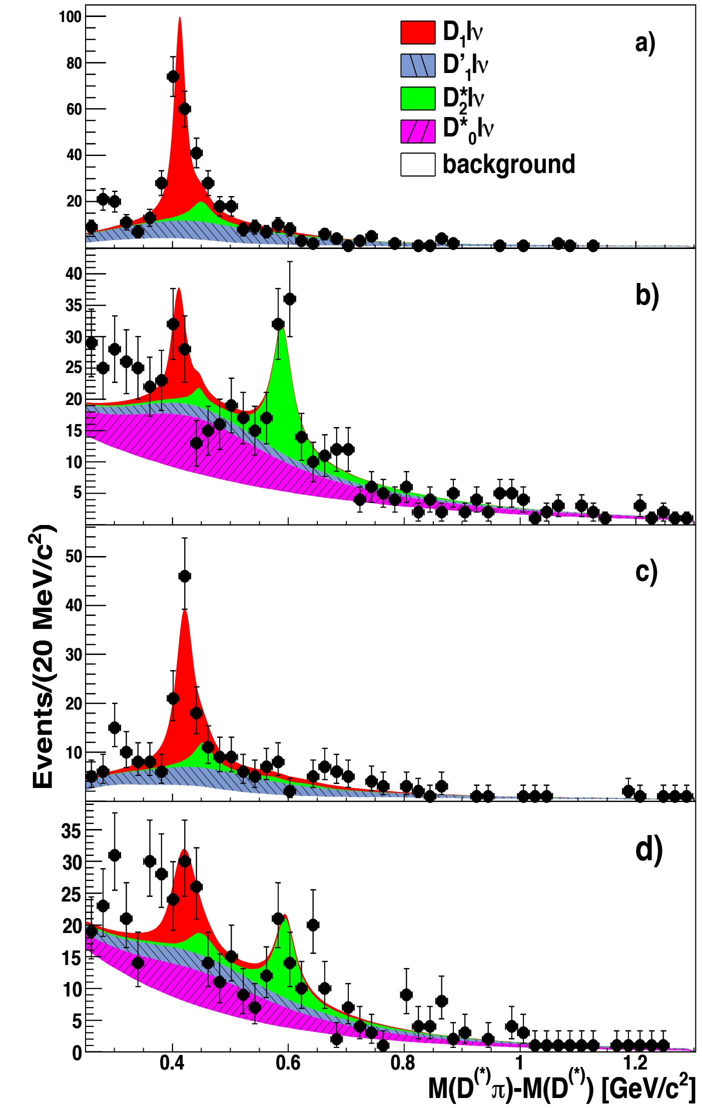
S. Turczyk, CKM 2012



Phys. Rev. Lett. 116, 041801 (2016)



Phys.Rev. D85 (2012) 094033



Phys.Rev.Lett.101:261802,2008

- Excited X_c states: orbital (and to a lesser extend radial and other states)
  - Exclusive orbital 1P states with D** → D(*)π have been experimentally sought for and been found
    - Some tension for broad states (between BaBar & Belle for D_1*)
  - Two doublets, one broad one narrow (due to D- versus S-Wave strong decay transitions)

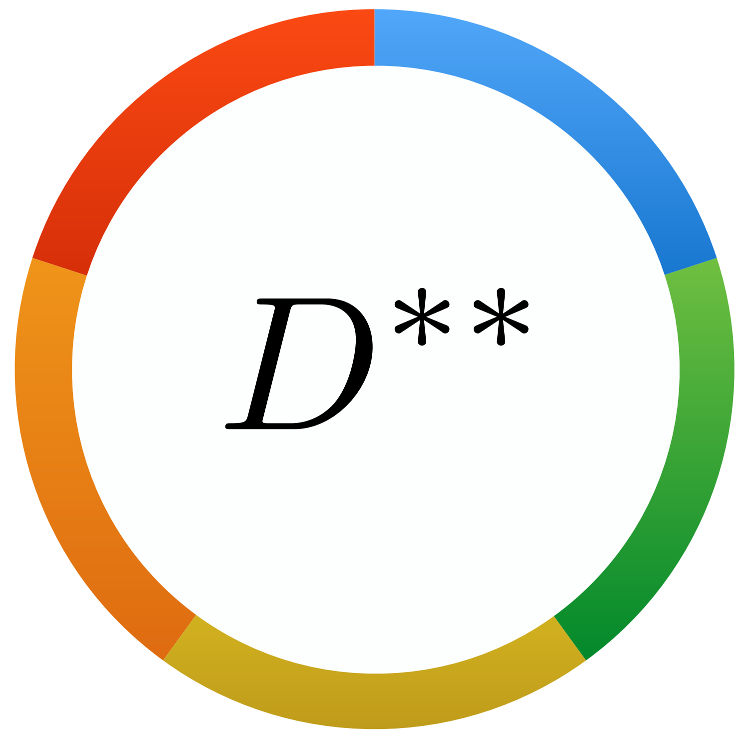
Particle	$s_l^{\pi_l}$	J^P	m (MeV)	Γ (MeV)
D_0^*	$\frac{1}{2}^+$	0^+	2320	265
D_1^*	$\frac{1}{2}^+$	1^+	2427	384
D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48

In what follows: $D^{**} = \{D_0^*,\ D_1^*,\ D_1,\ D_2^*\}$

How can we improve our understanding of these states?

Lattice QCD

Existing Information



New Measurements

Sum rules

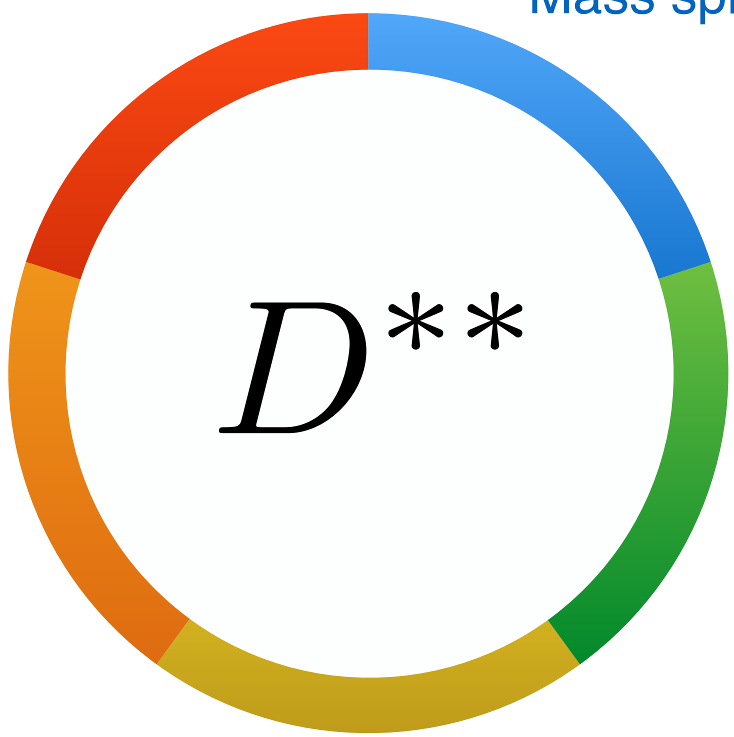
Quark Models

How can we improve our understanding of these states?

Lattice QCD

Existing Information

Mass splittings, Nonleptonic & semileptonic rates



Sum rules

New Measurements

of B and B_s decays

Quark Models

Brief recap what we know about these states from theory

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

- Heavy quark symmetry implies that in $m_Q \to \infty$ limit matrix elements of weak currents between a B meson and an excited charmed D** meson vanish at zero recoil.
  - *i.e.* in $m_Q \to \infty$ limit the D and D* are the only mesons with non-vanishing matrix elements at zero recoil (which in practice does not help you as there is also a kinematic suppression)
  - However, Λ_{QCD}/m_Q corrections produce matrix elements that are non-zero
  - Most phase space of Excited charmed D** mesons is near zero recoil (due to the D** meson mass being higher than D & D*, w = v * v' spans only 1-1.3)

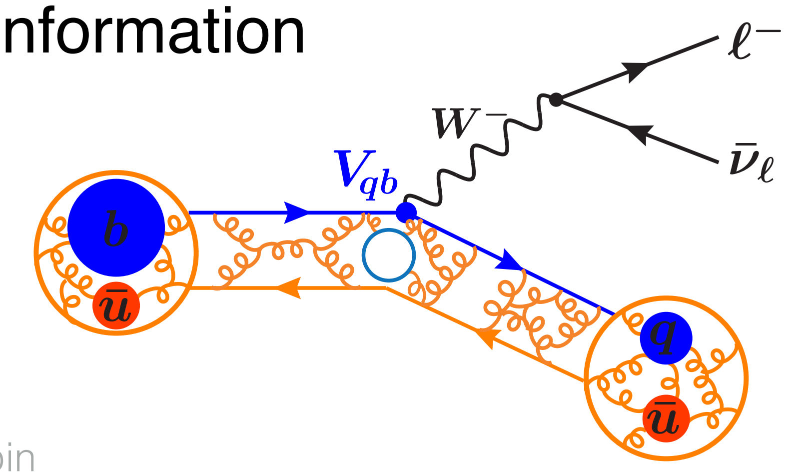
- Heavy quark effective theory, i.e. the limit of QCD where the heavy quark mass goes to infinity, provides some model independent information

O(Λ_{QCD}/m_Q) terms

$$\mathcal{L} = \mathcal{L}_{\rm HQET} + \delta\mathcal{L} + \ldots\,.$$

full QCD Lagrangian

HQET Lagrangian, independent of the heavy quark mass and its spin



Brief recap what we know about these states from theory

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

- Matrix elements of *vector* and *axial-vector* currents between ***B*** ***mesons*** and ***D₁*** and ***D₂**** mesons can be parametrized with **2 x 4** form factors

$$\frac{\langle D_1(v',\epsilon)|\,V^\mu\,|B(v)\rangle}{\sqrt{m_{D_1}\,m_B}} = f_{V_1}\,\epsilon^{*\mu} + (f_{V_2}v^\mu + f_{V_3}v'^\mu)\,(\epsilon^*\cdot v)\,,$$

$$\frac{\langle D_1(v',\epsilon)|\,A^\mu\,|B(v)\rangle}{\sqrt{m_{D_1}\,m_B}} = i\,f_A\,\varepsilon^{\mu\alpha\beta\gamma}\epsilon^*_\alpha v_\beta v'_\gamma\,,$$

$$\frac{\langle D_2^*(v',\epsilon)|\,A^\mu\,|B(v)\rangle}{\sqrt{m_{D_2^*}\,m_B}} = k_{A_1}\,\epsilon^{*\mu\alpha}v_\alpha + (k_{A_2}v^\mu + k_{A_3}v'^\mu)\,\epsilon^*_{\alpha\beta}\,v^\alpha v^\beta\,,$$

$$\frac{\langle D_2^*(v',\epsilon)|\,V^\mu\,|B(v)\rangle}{\sqrt{m_{D_2^*}\,m_B}} = i\,k_V\,\varepsilon^{\mu\alpha\beta\gamma}\epsilon^*_{\alpha\sigma}v^\sigma v_\beta v'_\gamma\,,$$

- Form factors: dimensionless functions of w = v * v', the product of the four-velocities of the B & D** meson

$$\frac{\mathrm{d}^2\Gamma_{D_1}}{\mathrm{d}w\,\mathrm{d}\cos\theta} = 3\Gamma_0\,r_1^3\sqrt{w^2-1}\Big\{\sin^2\theta\left[(w-r_1)f_{V_1}+(w^2-1)(f_{V_3}+r_1 f_{V_2})\right]^2 + (1-2r_1w+r_1^2)\left[(1+\cos^2\theta)\,[f_{V_1}^2+(w^2-1)f_A^2] - 4\cos\theta\sqrt{w^2-1}\,f_{V_1}\,f_A\right]\Big\}, \quad (2.2)$$

$w = v\cdot v'$

$$\frac{\mathrm{d}^2\Gamma_{D_2^*}}{\mathrm{d}w\,\mathrm{d}\cos\theta} = \frac{3}{2}\,\Gamma_0\,r_2^3\,(w^2-1)^{3/2}\Big\{\frac{4}{3}\,\sin^2\theta\left[(w-r_2)k_{A_1}+(w^2-1)(k_{A_3}+r_2k_{A_2})\right]^2 + (1-2r_2w+r_2^2)\left[(1+\cos^2\theta)\,[k_{A_1}^2+(w^2-1)k_V^2] - 4\cos\theta\sqrt{w^2-1}\,k_{A_1}\,k_V\right]\Big\},$$

Angle between the charged lepton and the charmed meson in the rest frame of the virtual W boson

Brief recap what we know about these states from theory

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

- Form factors can be parametrized by a set of 'Isgur-Wise' functions at each order in Λ_{QCD}/m_Q.
- The matrix element of the b → c flavour changing current can be written as

$$\bar{c}\,\Gamma\,b = \bar{h}^{(c)}_{v'}\,\Gamma\,h^{(b)}_{v} = \boxed{\tau(w)}\,\mathrm{Tr}\left\{v_\sigma \bar{F}^{\sigma}_{v'}\,\Gamma\,H_v\right\}.$$

Heavy quark field(s) in the effective theory

Isgur Wise Function

Trace of fields that are annihilated or created

  - The Isgur-Wise function is a dimensionless function parametrizing the strong dynamic.

- At order Λ_{QCD}/m_Q there are corrections originating from matching the b → c current onto the effective theory

$$\bar{c}\,\Gamma\,b = \bar{h}^{(c)}_{v'}\left(\Gamma - \frac{i}{2m_c}\overleftarrow{\not{D}}\Gamma + \frac{i}{2m_b}\Gamma\overrightarrow{\not{D}}\right)h^{(b)}_{v}\,.$$

- **LLSW expansion**: all of these contributions can be expressed in terms of sub-leading 'Isgur-Wise' functions and measurable meson mass splittings

Brief recap what we know about these states from theory

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

- Other Λ_{QCD}/m_Q and α_s corrections arise from modifications in the Lagrangian

O(Λ_{QCD}/m_Q) + α_s terms

$$\mathcal{L} = \mathcal{L}_{\rm HQET} + \delta\mathcal{L} + \ldots .$$

full QCD Lagrangian

HQET Lagrangian, independent of the heavy quark mass and its spin

- Heavy quark symmetry in the first term is broken by Λ_{QCD}/m_Q terms:

$$\delta\mathcal{L} = \frac{1}{2m_Q}\left[O^{(Q)}_{{\rm kin},v} + O^{(Q)}_{{\rm mag},v}\right],$$

  - **Kinetic energy term**: breaks flavour symmetry, but leaves spin symmetry intact
  - **Chromomagnetic term**, breaks both symmetries

- Lead to additional terms in expansion.

Concrete example: $B \to D_1 \, l \, \nu$ Form factors

$$w = v \cdot v' \qquad \epsilon_{b/c} = \frac{1}{2m_{b/c}}$$

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

Leading 'IW'

chromomagnetic terms

mass splittings

subleading 'IW's

kinetic terms

factor which makes that leading order matrix element vanishe at w = 1

Concrete example: $B \to D_1 \, l \, \nu$ Form factors

orbital mass
ground state mass

$$\bar\Lambda' - \bar\Lambda = \frac{m_b\,(\overline{m}'_B - \overline{m}_B) - m_c\,(\overline{m}'_D - \overline{m}_D)}{m_b - m_c} \simeq 0.39\,\text{GeV}\,,$$

quark mass in a common scheme

$w = v \cdot v'$ $\qquad \epsilon_{b/c} = \dfrac{1}{2m_{b/c}}$

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

Leading 'IW' | chromomagnetic terms | mass splittings | Measured

subleading 'IW's | kinetic terms | factor which makes that leading order form factor vanishe at w = 1

Concrete example: $B \to D_1\, l\, \nu$ Form factors

$w = v \cdot v'$ $\quad \epsilon_{b/c} = \dfrac{1}{2m_{b/c}}$

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

Leading 'IW' | chromomagnetic terms | mass splittings

$$\tau = \tau(0)\,(1 + (w-1)\,\tau')$$

subleading 'IW's | kinetic terms | factor which makes that leading order form factor vanishe at w = 1

Concrete example: $B \to D_1\, l\, \nu$ Form factors

$w = v \cdot v'$ $\qquad \epsilon_{b/c} = \dfrac{1}{2m_{b/c}}$

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

Can be absorbed into leading 'IW' function at the cost of an error of ~$(\Lambda_{QCD}/m_Q)^2$

Leading 'IW'

chromomagnetic terms

mass splittings

subleading 'IW's

kinetic terms

factor which makes that leading order form factor vanishe at w = 1

Concrete example: $B \to D_1\, l\, \nu$ Form factors

$w = v \cdot v'$ $\quad \epsilon_{b/c} = \frac{1}{2m_{b/c}}$

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

Leading 'IW'

chromomagnetic terms

mass splittings

Neglected or modelled as term x leading 'IW' function

subleading 'IW's

kinetic terms

factor which makes that leading order form factor vanishe at w = 1

Concrete example: $B \to D_1\, l\, \nu$ Form factors

$w = v \cdot v'$ $\quad \epsilon_{b/c} = \dfrac{1}{2m_{b/c}}$

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

Leading 'IW'

chromomagnetic terms

mass splittings

Assumed to have negligible impact what is supported by small mass difference between D**(1P) states

subleading 'IW's

kinetic terms

factor which makes that leading order form factor vanishe at w = 1

Determination of the leading IW normalization from data

- We are left with 4 unknowns:
  - the normalization of the leading ‘IW’ function $\tau(0)$
  - the slope of the leading ‘IW’ function τ'
  - two sub-leading ‘IW’ functions τ_1, τ_2

Determination of the leading IW normalization from data

- We are left with 4 unknowns:
  - the normalization of the leading 'IW' function $\tau(0)$ ← From measured $B \to D_1\, l\, \nu$ rate
  - the slope of the leading 'IW' function τ' ← From quark model expectations (-1.5 +/- 1)
  - two sub-leading 'IW' functions τ_1, τ_2 ← Modelled as leading 'IW' times mass splitting or neglected
- Quark model relation to map narrow and broad IW function
- Comparison between model prediction and HFAG:

	LLSW [%]	PDG [%]
$B^+ \to D_2^* l\, \nu$	0.40 ± 0.13	0.30 ± 0.04
$B^+ \to D_1\, l\, \nu$	0.67 ± 0.18	0.67 ± 0.05
$B^+ \to D_0^* l\, \nu$	0.56 ± 0.27	0.44 ± 0.08
$B^+ \to D_1^* l\, \nu$	0.20 ± 0.09	0.20 ± 0.05

Beyond LLSW — or what we can do today

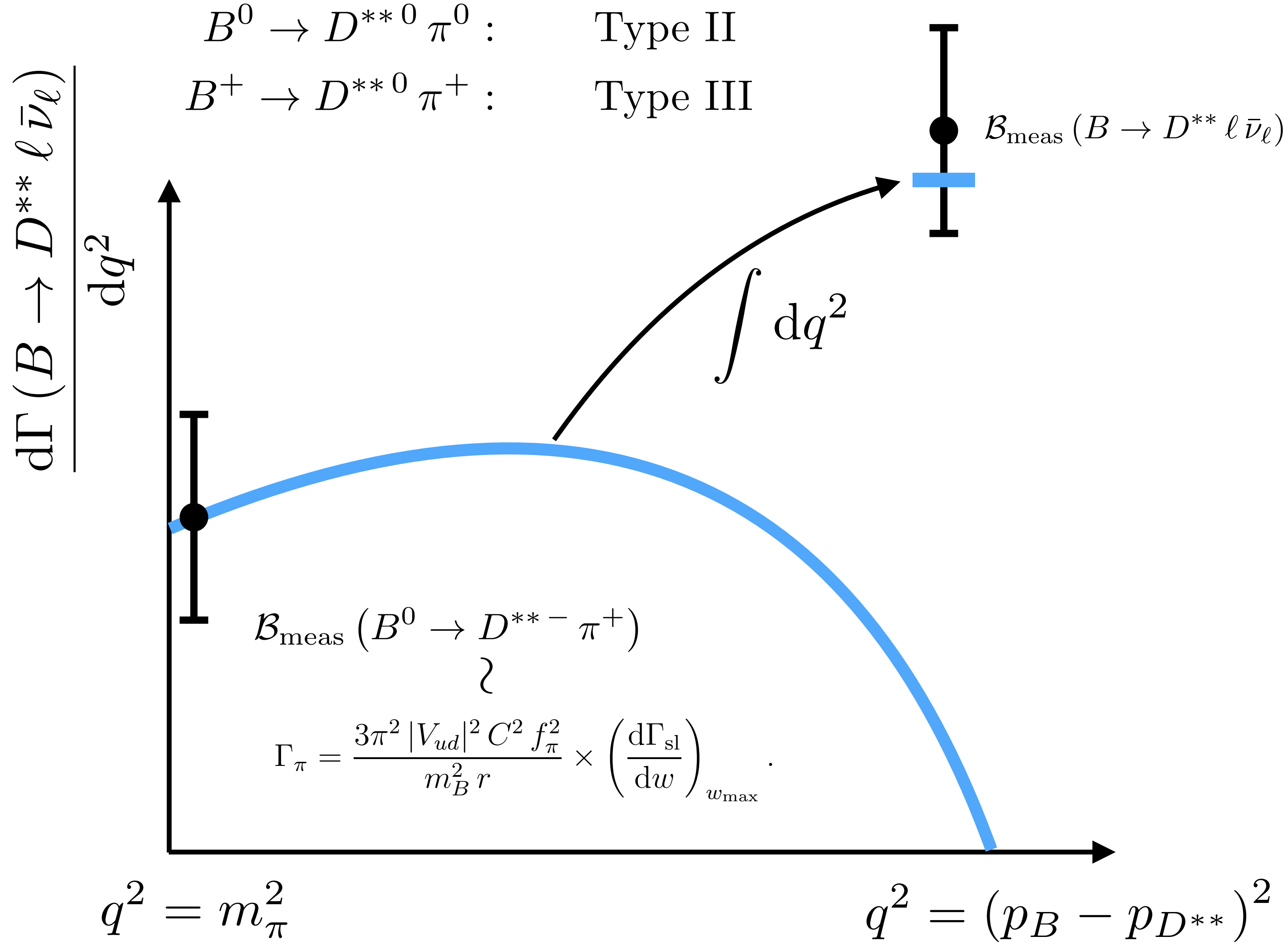
- Today we have some more information
  - Better mass measurements for D**
  - Branching fraction measurements for all 4 states
  - Nonleptonic measurements

Particle	$s_l^{\pi_l}$	J^P	m (MeV)	Γ (MeV)
D_0^*	$\frac{1}{2}^+$	0^+	2320	265
D_1^*	$\frac{1}{2}^+$	1^+	2427	384
D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48

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

$B^0 \to D^{**\,0}\pi^0$: Type II

$B^+ \to D^{**\,0}\pi^+$: Type III



- Can try to extract simultaneously normalization and slope of leading ‘IW’ function and cross check LLSW

Beyond LLSW — or what we can do today

FB & Zoltan Ligeti: manuscript in preparation

- Today we have some more information
  - Better mass measurements for D**
  - Branching fraction measurements for all 4 states
  - Nonleptonic measurements

Particle	$s_l^{\pi_l}$	J^P	m (MeV)	Γ (MeV)
D_0^*	$\frac{1}{2}^+$	0^+	2320	265
D_1^*	$\frac{1}{2}^+$	1^+	2427	384
D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48

$$B^0 \to D^{**\,-}\pi^+ : \quad \text{Type I}$$
$$B^0 \to D^{**\,0}\pi^0 : \quad \text{Type II}$$
$$B^+ \to D^{**\,0}\pi^+ : \quad \text{Type III}$$

- An interesting feature of the current data is that it appears possible that the m_{D1} - m_{D0^*} split may be substantially larger than the m_{D2} - m_{D1} split (past ~ 40 MeV, now ~ 100 MeV)
  - The smallness of this split was the key argument to drop the chromomagnetic operator matrix elements (cf. previous slides)
  - Currently exploring the consequences of relaxing this constraint

m (MeV)	Γ (MeV)	reference
2405 ± 38	274 ± 40	FOCUS [10]
2308 ± 36	240 ± 66	Belle [11]
2297 ± 22	273 ± 49	BaBar [12]
2360 ± 34	255 ± 57	LHCb [15]
2320 ± 17	265 ± 25	our average

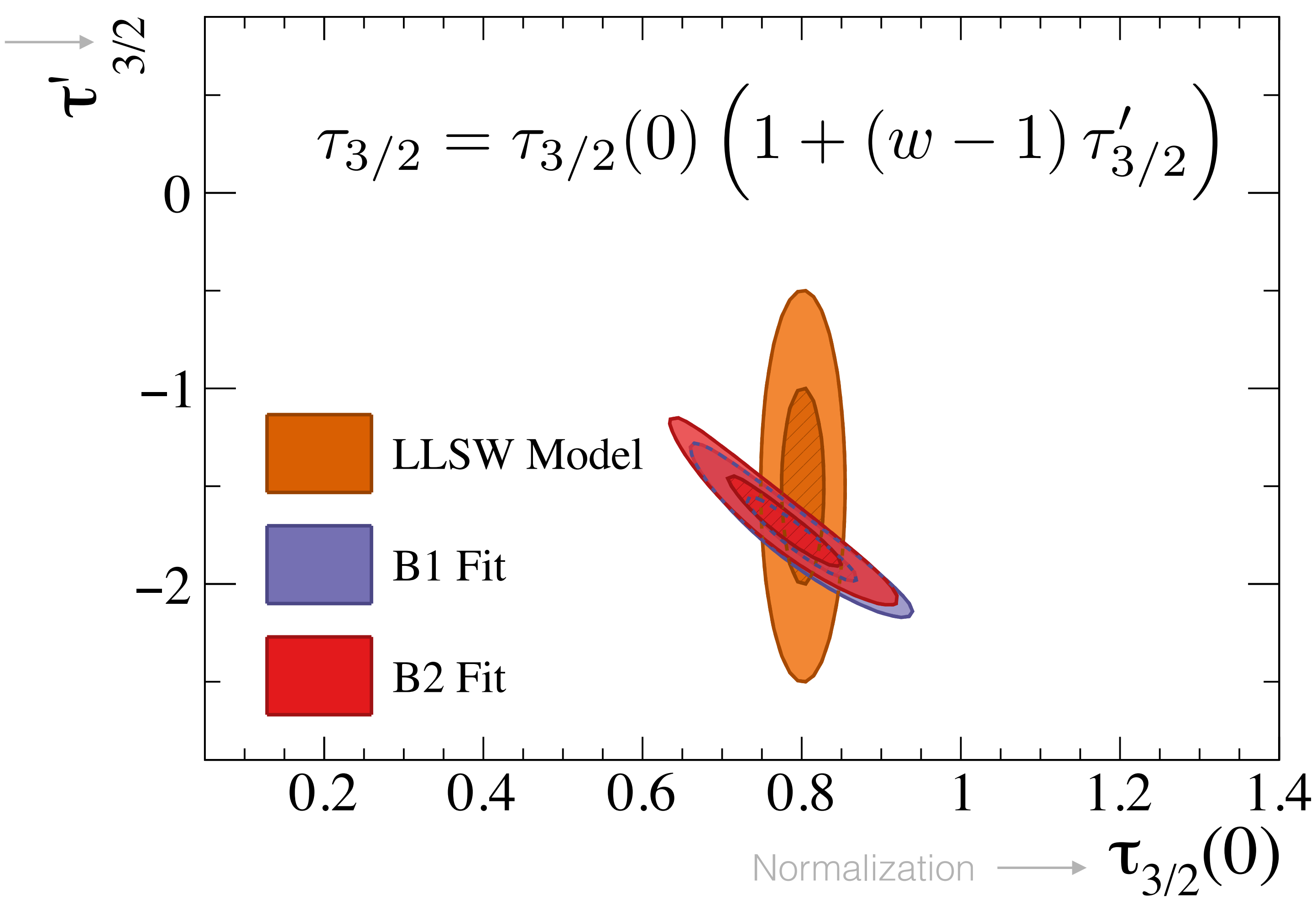
Simultaneous analysis of narrow information

FB & Zoltan Ligeti: manuscript in preparation

- Simultaneous fit of
  - Narrow measured semileptonic BFs
  - Narrow nonleptonic BFs

D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48

- Plot: 68% and 95% confidence regions of
  - LLSW Model, assuming no correlations between slope and normalization.
  - B1 Fit
    - No sub-leading 'IW' functions
  - B2 Fit
    - Sub-leading 'IW' functions proportional to leading 'IW' times mass splitting.



	LLSW [%]	PDG [%]
$B^+ \to D_2^* l\, \nu$	0.40 ± 0.13	0.30 ± 0.04
$B^+ \to D_1 l\, \nu$	0.67 ± 0.18	0.67 ± 0.05
$(B^0 \to D_2^{*-} \pi^+) \times \tau_{+0}$	0.06 ± 0.04	0.064 ± 0.014
$(B^0 \to D_1^- \pi^+) \times \tau_{+0}$	0.13 ± 0.08	0.081 ± 0.018

B^+/B^0 lifetime ratio

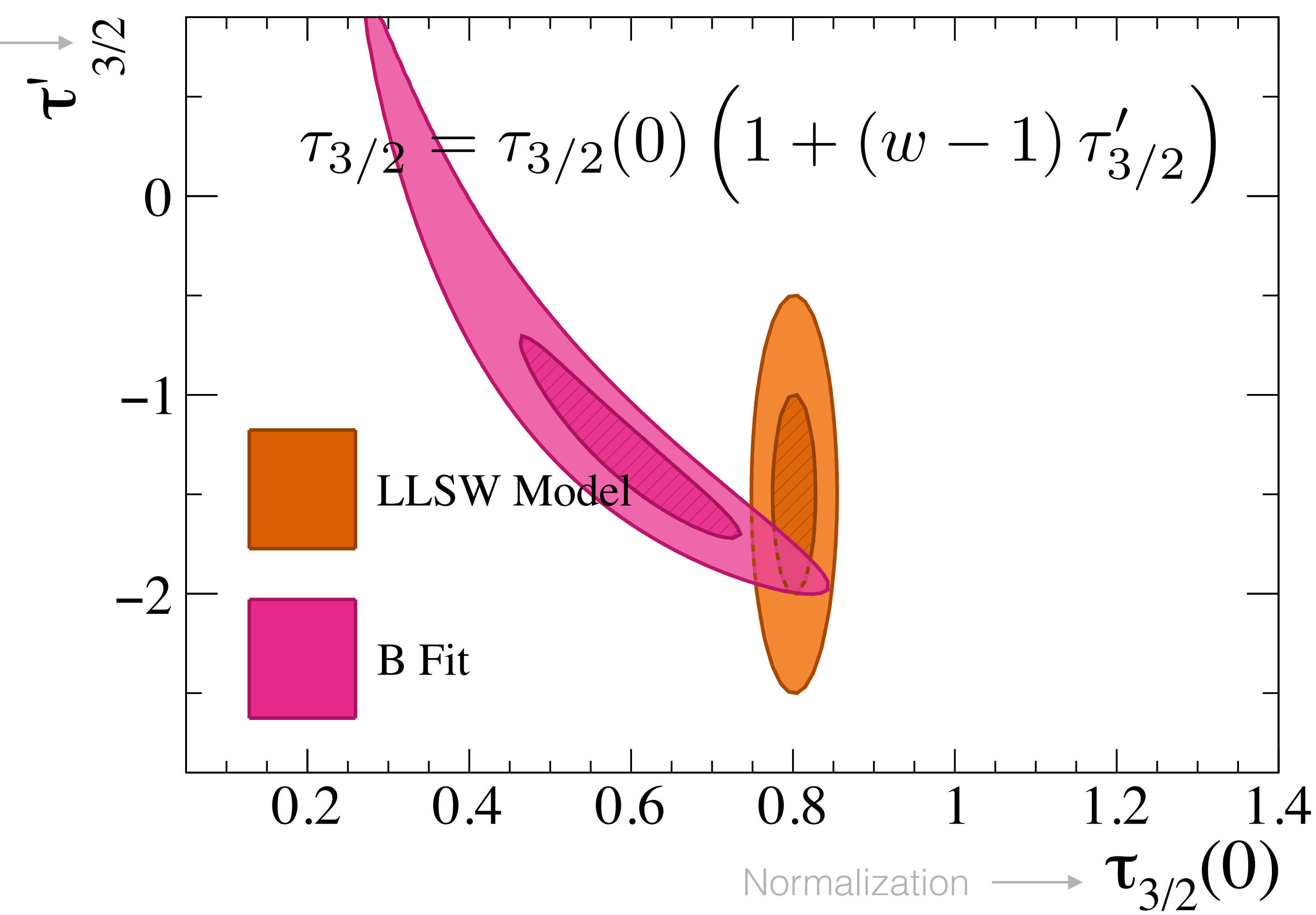
Simultaneous analysis of narrow information

FB & Zoltan Ligeti: manuscript in preparation

- Simultaneous fit of
  - Narrow measured semileptonic BFs
  - Narrow nonleptonic BFs

D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48

- Plot: 68% and 95% confidence regions of
  - LLSW Model, assuming no correlations between slope and normalization.
  - B Fit
    - Fit leading and sub-leading 'IW' function contributions



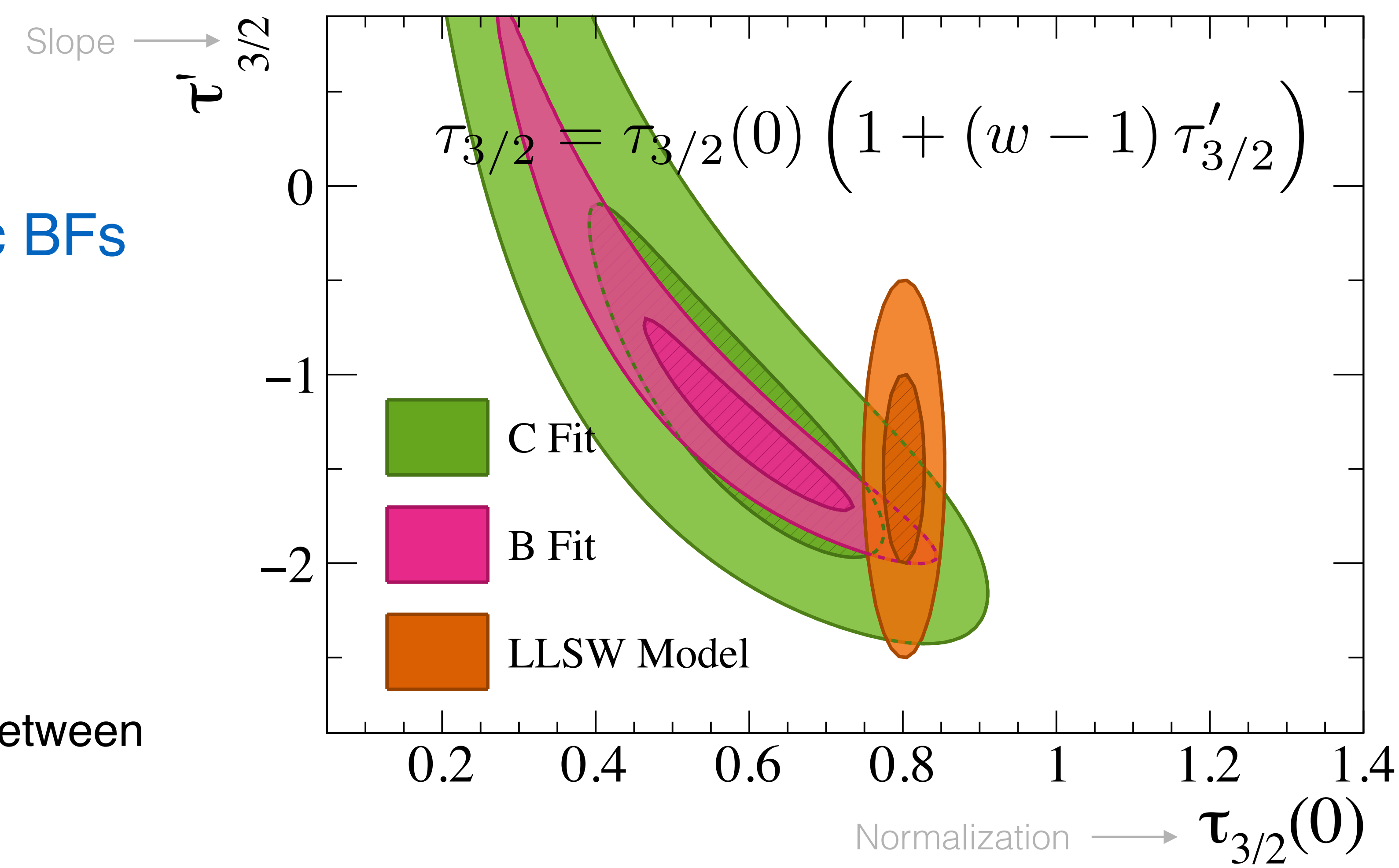
	LLSW [%]	PDG [%]
$B^+ \to D_2^* l\, \nu$	0.40 ± 0.13	0.30 ± 0.04
$B^+ \to D_1\, l\, \nu$	0.67 ± 0.18	0.67 ± 0.05
$(B^0 \to D_2^{*-} \pi^+) x \tau_{+0}$	0.06 ± 0.04	0.064 ± 0.014
$(B^0 \to D_1^- \pi^+) x \tau_{+0}$	0.13 ± 0.08	0.081 ± 0.018

Simultaneous analysis of narrow information

FB & Zoltan Ligeti: manuscript in preparation

- Simultaneous fit of
  - Narrow measured semileptonic BFs
  - Narrow nonleptonic BFs

D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48



- Plot: 68% and 95% confidence regions of
  - LLSW Model, assuming no correlations between slope and normalization.
  - C Fit
    - Fit leading and sub-leading 'IW' function contributions; include chromomagnetic contributions with a prior

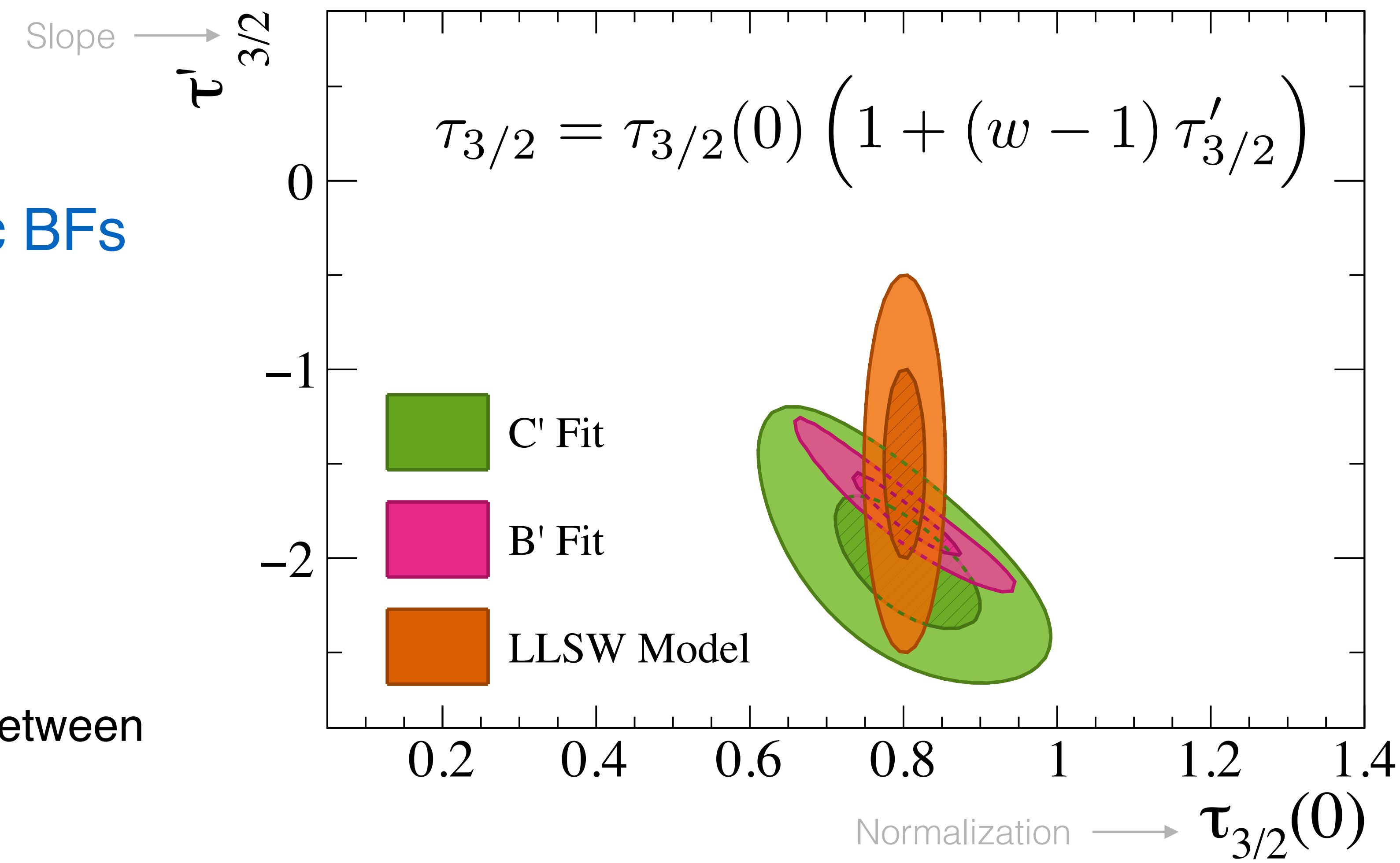
	LLSW [%]	PDG [%]
$B^+ \to D_2^* l\, \nu$	0.40 ± 0.13	0.30 ± 0.04
$B^+ \to D_1\, l\, \nu$	0.67 ± 0.18	0.67 ± 0.05
$(B^0 \to D_2^{*-} \pi^+) \mathrm{x} \tau_{+0}$	0.06 ± 0.04	0.064 ± 0.014
$(B^0 \to D_1^- \pi^+) \mathrm{x} \tau_{+0}$	0.13 ± 0.08	0.081 ± 0.018

Simultaneous analysis of narrow information

FB & Zoltan Ligeti: manuscript in preparation

- Simultaneous fit of
  - Narrow measured semileptonic BFs
  - Narrow nonleptonic BFs

D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48

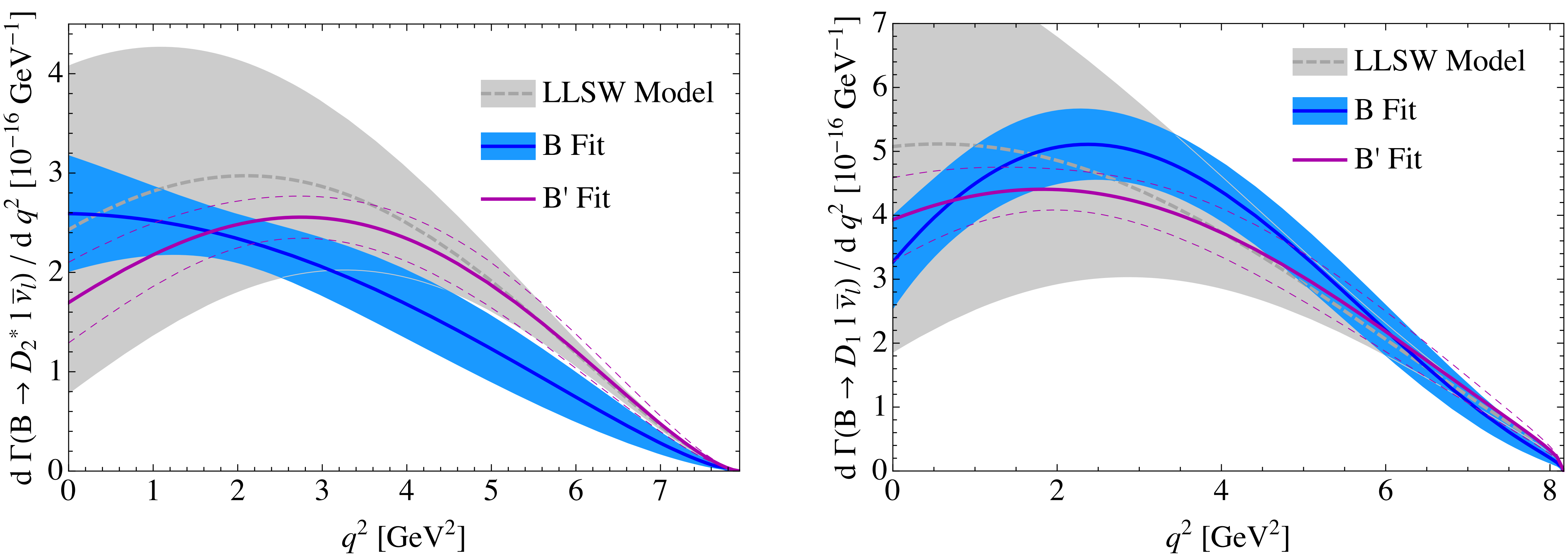


- Plot: 68% and 95% confidence regions of
  - LLSW Model, assuming no correlations between slope and normalization.
  - B' Fit
    - Fit leading 'IW' contributions, constrain sub-leading to LLSW model with prior
  - C' Fit
    - Fit leading 'IW' contributions, constrain sub-leading to LLSW model with prior; add chromomagnetic contributions with a prior

Simultaneous analysis of narrow information

FB & Zoltan Ligeti: manuscript in preparation

- Albeit errors in leading ‘IW’ parameter plane were sizeable
  - Narrow measured semileptonic BFs constrain normalization
  - Narrow nonleptonic BFs constrain $q^2 \sim 0$ GeV^2 point
- Fairly consistent picture, LLSW is doing a good job.
  - Can gain some accuracy by using full experimental information

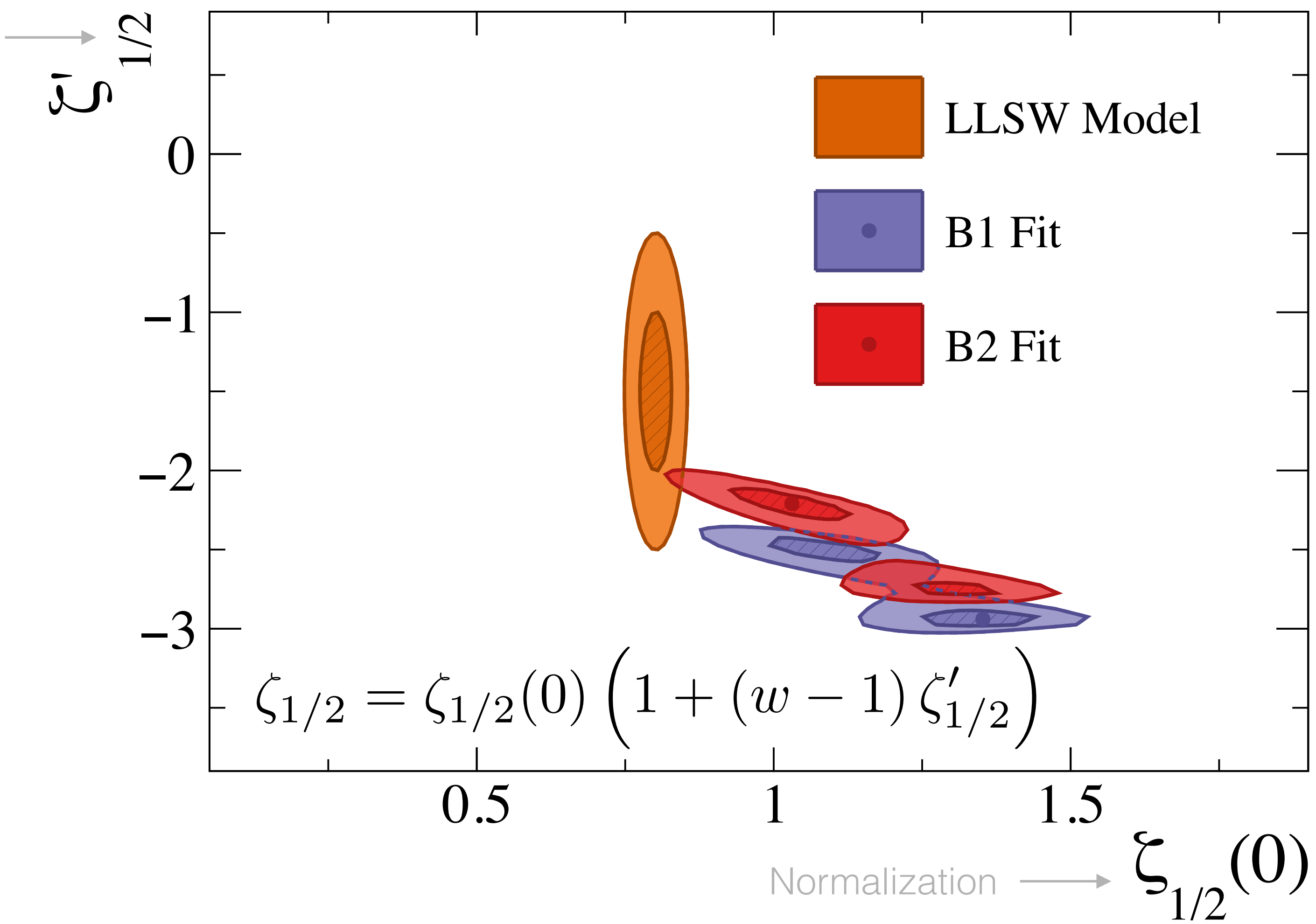


Simultaneous analysis of broad information

FB & Zoltan Ligeti: manuscript in preparation

- Simultaneous fit of
  - Broad measured semileptonic BFs
  - Broad nonleptonic BF

D_0^*	$\frac{1}{2}^+$	0^+	2320	265
D_1^*	$\frac{1}{2}^+$	1^+	2427	384



- Plot: 68% and 95% confidence regions of
  - LLSW Model, assuming no correlations between slope and normalization.
  - B1 Fit
    - No sub-leading 'IW' functions
  - B2 Fit
    - Sub-leading 'IW' functions proportional to leading 'IW' times mass splitting.

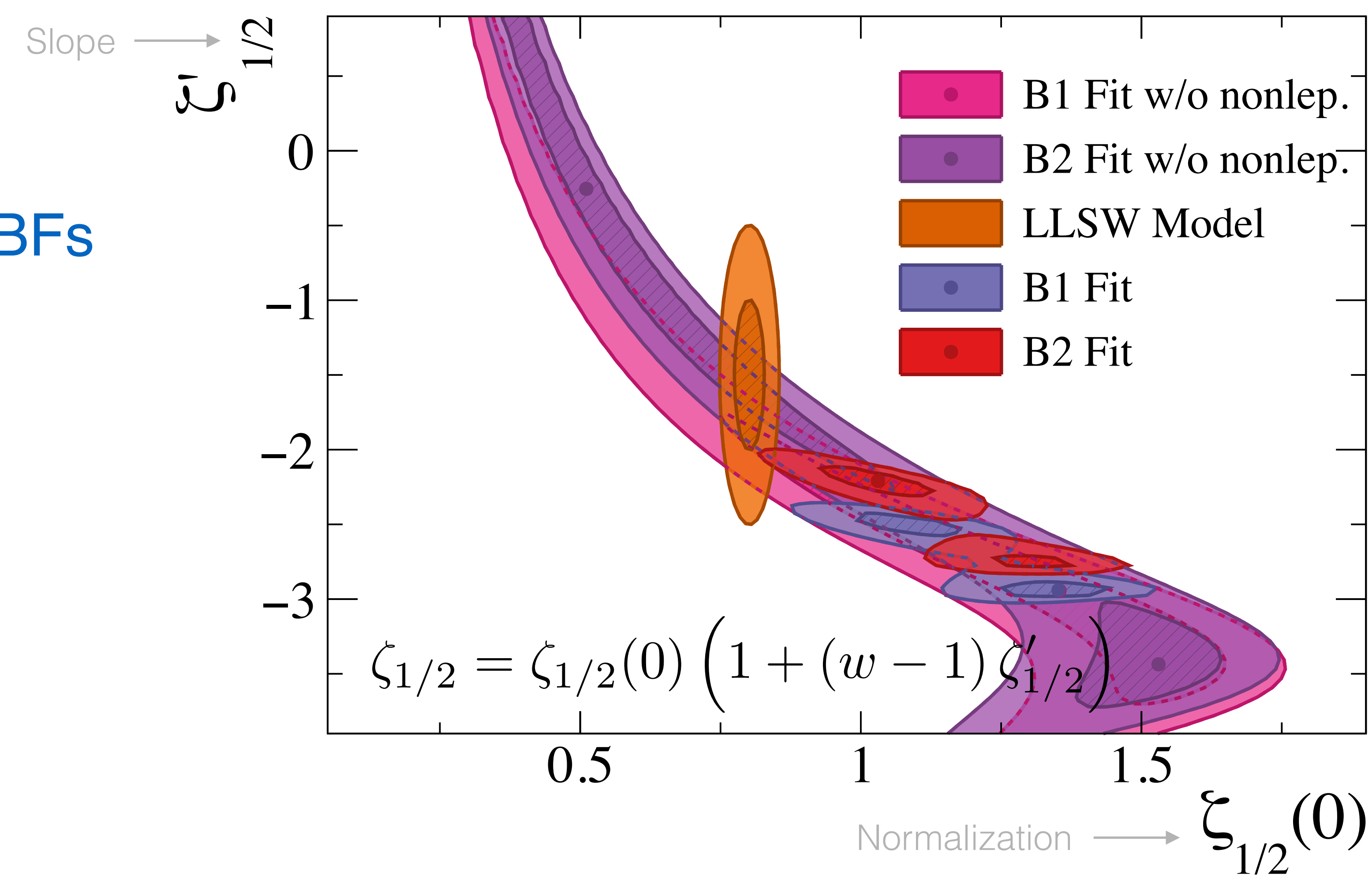
	LLSW [%]	PDG [%]
$B^+ \to D_0^* l\, \nu$	0.56 ± 0.27	0.44 ± 0.08
$B^+ \to D_1^* l\, \nu$	0.20 ± 0.09	0.20 ± 0.05
$(B^0 \to D_0^{*-} \pi^+) \times \tau_{+0}$	0.11 ± 0.08	0.009 ± 0.005

Simultaneous analysis of broad information

FB & Zoltan Ligeti: manuscript in preparation

- Simultaneous fit of
  - Broad measured semileptonic BFs
  - Broad nonleptonic BF

D_0^*	$\frac{1}{2}^+$	0^+	2320	265
D_1^*	$\frac{1}{2}^+$	1^+	2427	384



- Plot: 68% and 95% confidence regions of
  - LLSW Model, assuming no correlations between slope and normalization.
  - B1 Fit
    - No sub-leading 'IW' functions
  - B2 Fit
    - Sub-leading 'IW' functions proportional to leading 'IW' times mass splitting.
- Dropping the nonleptonic constraint reproduces a better agreement with LLSW

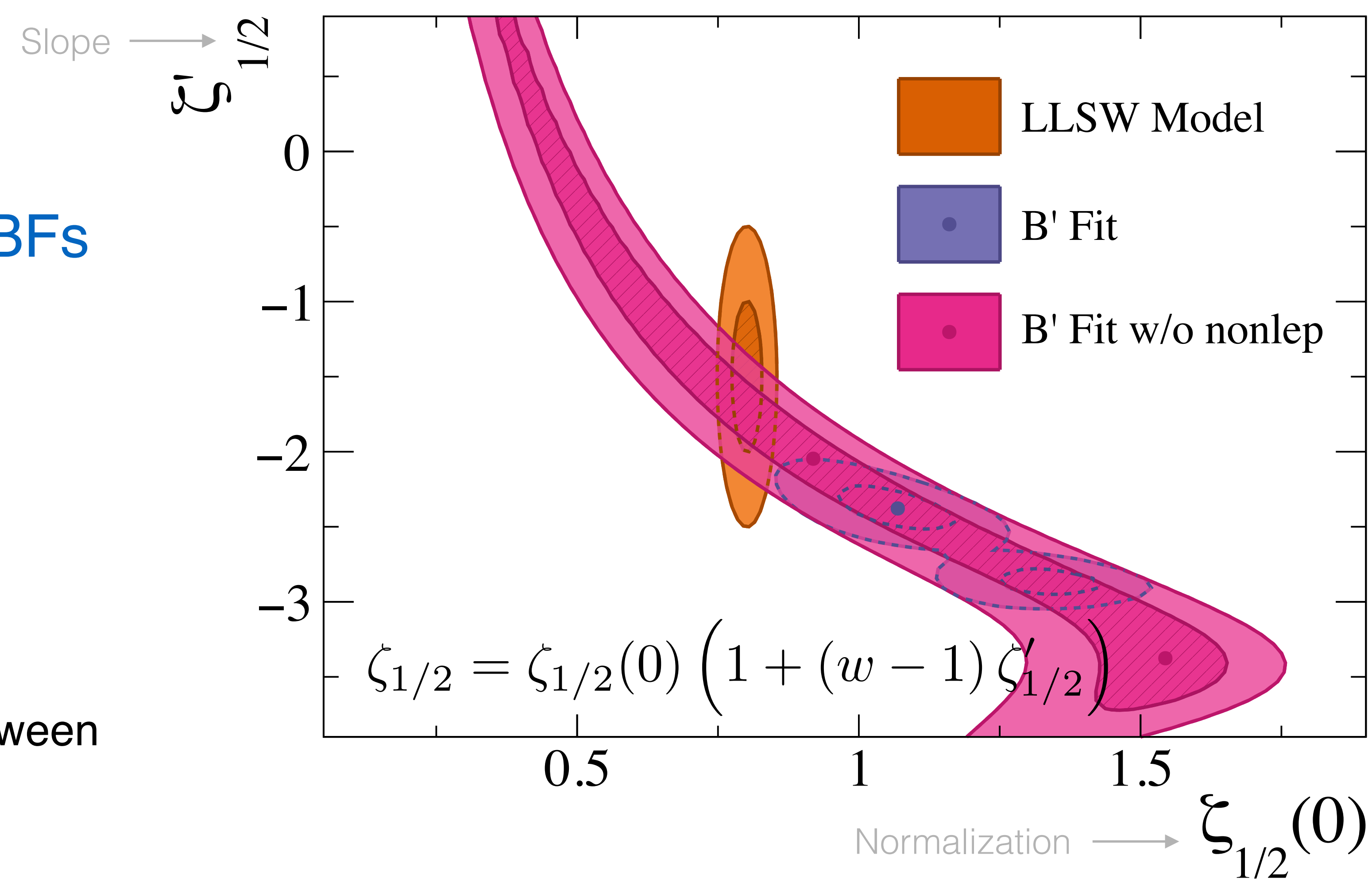
	LLSW [%]	PDG [%]
$B^+ \to D_0^* l \nu$	0.56 ± 0.27	0.44 ± 0.08
$B^+ \to D_1^* l \nu$	0.20 ± 0.09	0.20 ± 0.05
$(B^0 \to D_0^{*-} \pi^+) \times \tau_{+0}$	0.11 ± 0.08	0.009 ± 0.005

Simultaneous analysis of broad information

FB & Zoltan Ligeti: manuscript in preparation

- Simultaneous fit of
  - Broad measured semileptonic BFs
  - Broad nonleptonic BF

D_0^*	$\frac{1}{2}^+$	0^+	2320	265
D_1^*	$\frac{1}{2}^+$	1^+	2427	384



- Plot: 68% and 95% confidence regions of
  - LLSW Model, assuming no correlations between slope and normalization.
  - B' Fit
    - Fit leading 'IW' contributions, constrain sub-leading to LLSW model with prior

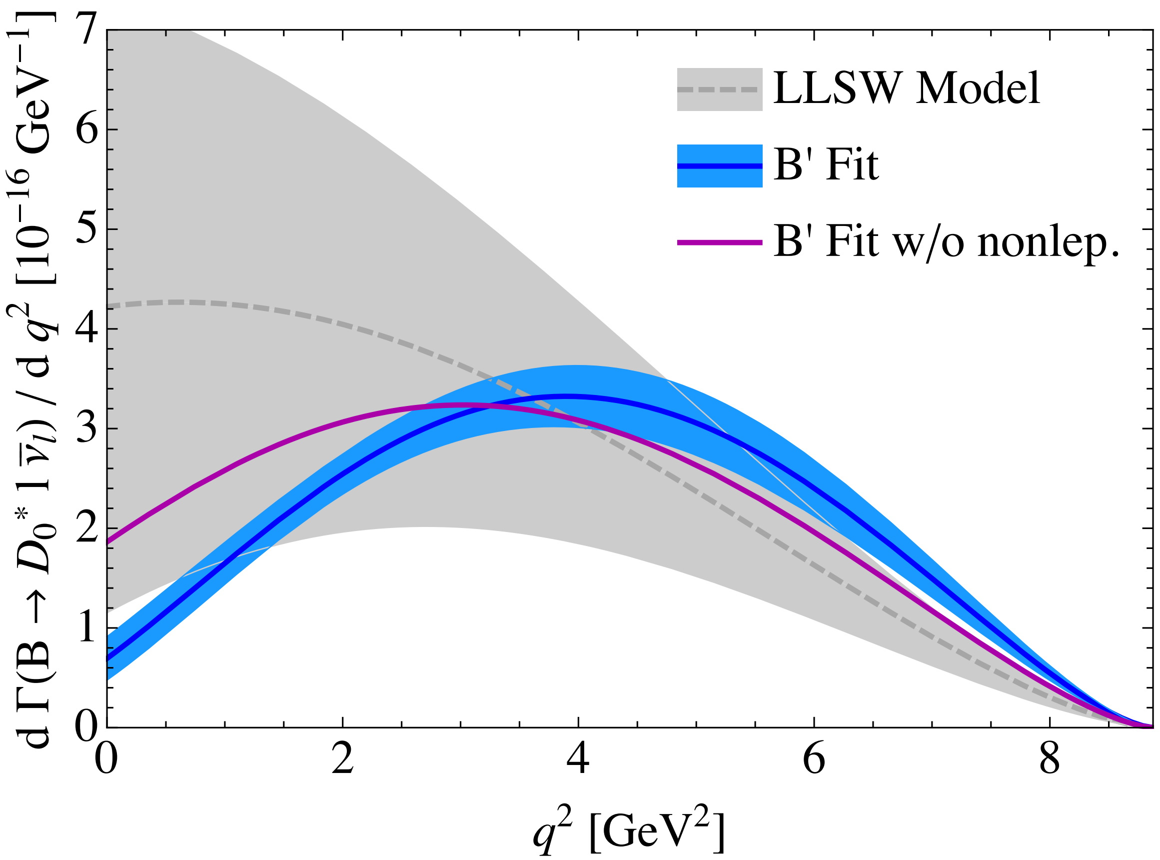
	LLSW [%]	PDG [%]
$B^+ \to D_0^* l\, \nu$	0.56 ± 0.27	0.44 ± 0.08
$B^+ \to D_1^* l\, \nu$	0.20 ± 0.09	0.20 ± 0.05
$(B^0 \to D_0^{*-} \pi^+) \times \tau_{+0}$	0.11 ± 0.08	0.009 ± 0.005

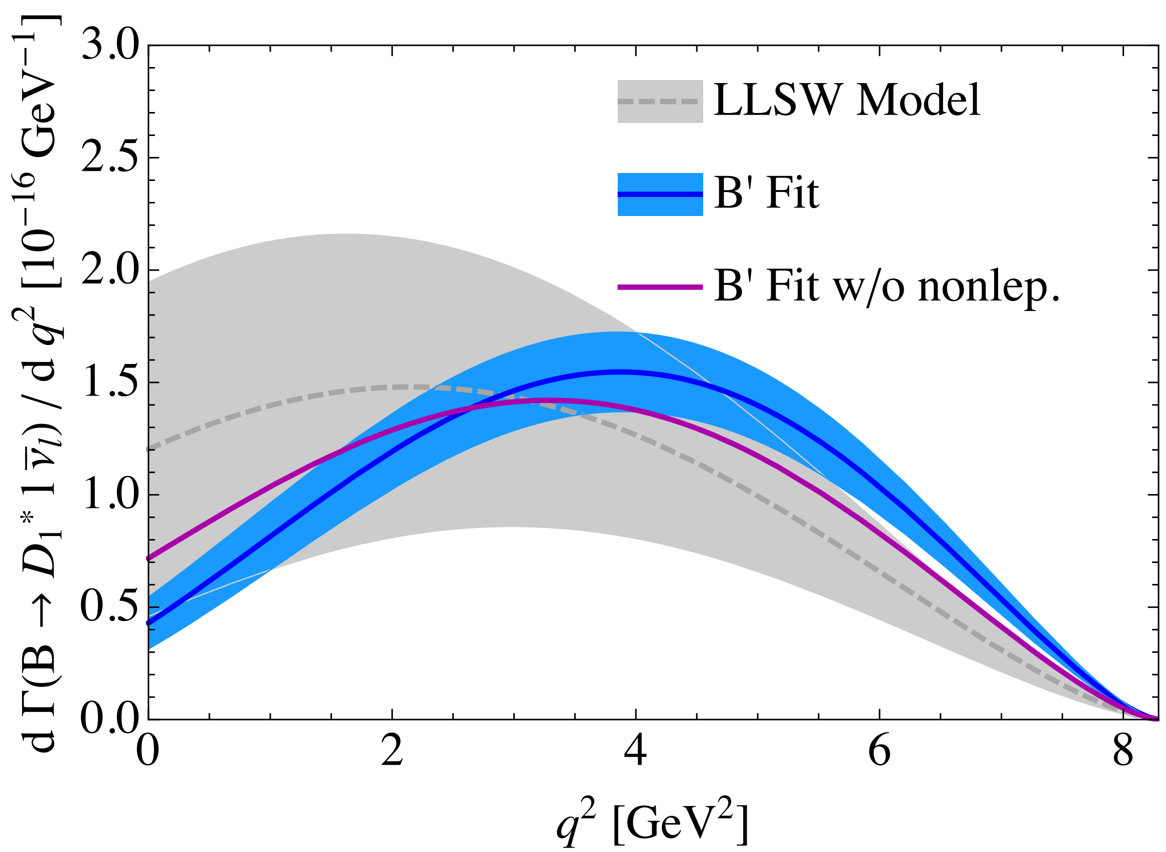
- Still working on C / C' type fits (including chromomagnetic terms)

Simultaneous analysis of all broad information

FB & Zoltan Ligeti: manuscript in preparation

- Poor agreement between LLSW and fits when using nonleptonic information
  - Measured BF implies much lower rate at $q^2 \sim 0$ GeV^2
- Excluding this information results in a better agreement





After the work, some fun!

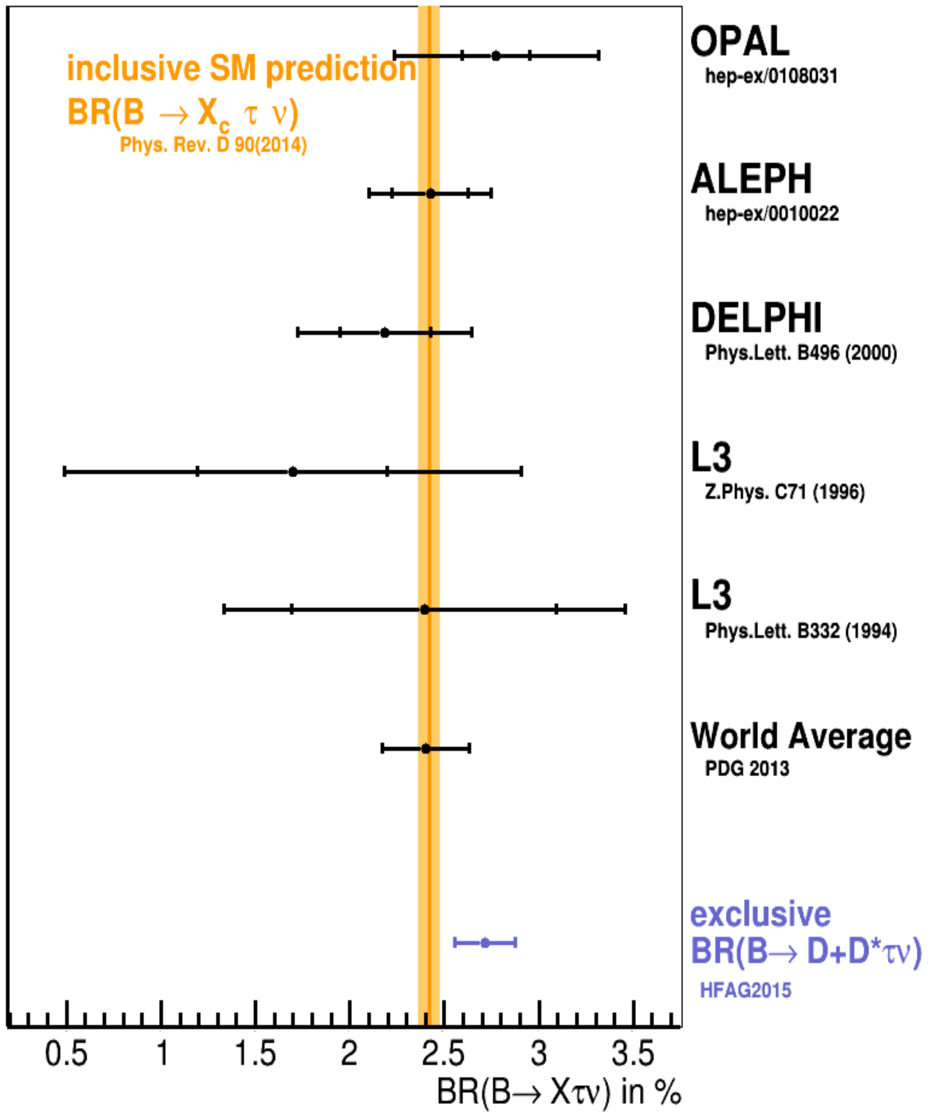
Another angle

Measured R(D) and R(D*) values seem to saturate inclusive $\boldsymbol{B \to X_c\, \tau\nu}$ rate

- Expect O(0.3%) contribution to BF from excited $\boldsymbol{B \to X_c\, \tau\nu}$ in the SM
- If new physics is enhancing the ground states, there also might be a (spin) dependent enhancement of excited states.

Can use extracted leading 'IW' normalization and slope to make predictions for this part.

- Full mass dependence make the nice rate equations a bit more ugly

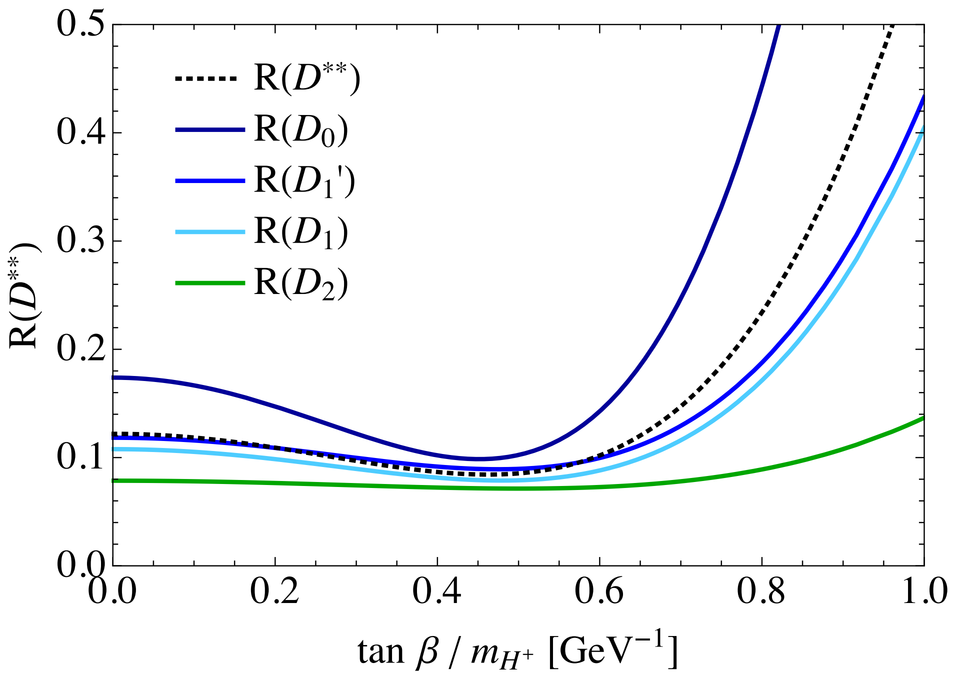


Another angle

FB & Zoltan Ligeti: manuscript in preparation

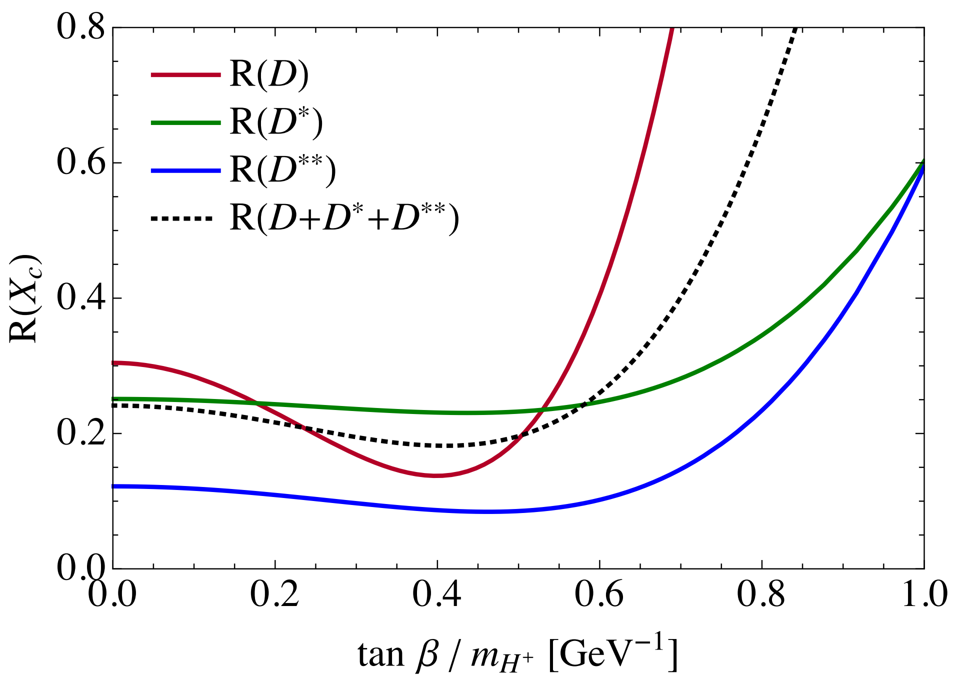
Measured R(D) and R(D*) values seem to saturate inclusive ***B* → *X_c* *τν*** rate

- Expect O(0.3%) contribution to BF from excited $\boldsymbol{B \to X_c \tau \nu}$ in the SM
- If new physics is enhancing the ground states, there also might be a (spin) dependent enhancement of excited states.



Can use extracted leading ‘IW’ normalization and slope to make predictions.

- Full mass dependence make the nice rate equations a bit more ugly

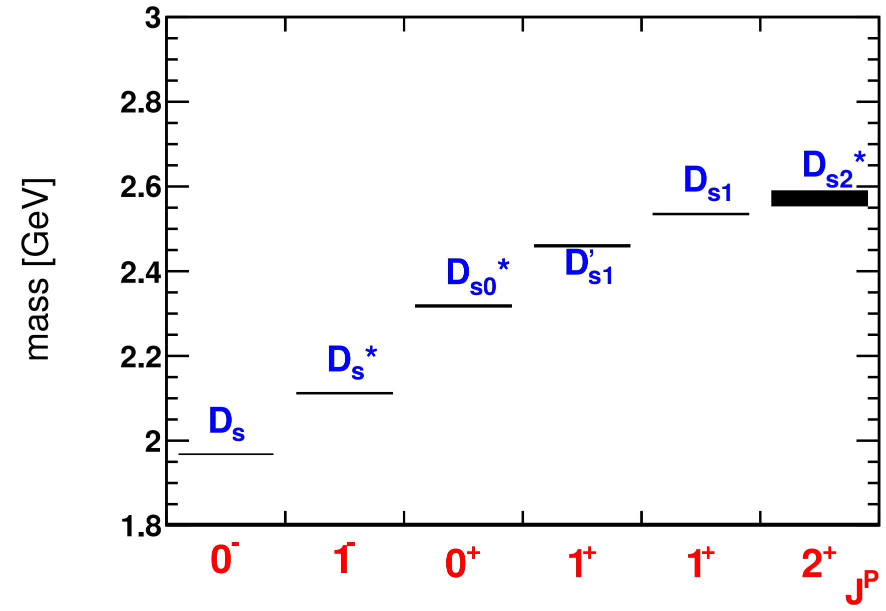


So how can we improve our understanding of these states?

More measurements, D_s, input from lattice

D_s might hold part of the answer or open the door to complementary questions

- No broad states as mass below DK threshold
- Challenging for LHCb though as decays happen electromagnetic or via π^0
- SU(3) symmetry relates form factors



D^{**} of the B-Factories only used partial data; no down feed from D(*)$\pi\pi$ considered in the past

- Nonleptonic measurements of broad states very useful (only have one measurement here from Belle)
- Differential measurements in w for narrow and broad states could further clarify situation; separation maybe via helicity information rather than via mass spectrum (Idea of M. Rotondo)

Can the lattice do the narrow states?

- Would be very useful input.
- Broad states might be very difficult