Prospects and challenges for semitauonic decays at LHCb

Lattice results and outlook

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Vector and axial vector form factors:

$$\begin{aligned}
\langle D|\bar{c}\gamma^\mu b|B\rangle &= \left[(p+p')^\mu - \frac{m_B^2 - m_D^2}{q^2} q^\mu\right] f_+(q^2) + \frac{m_B^2 - m_D^2}{q^2} q^\mu f_0(q^2) \\
&= \sqrt{m_B m_D}\left[(v+v')^\mu h_+(w) + (v-v')^\mu h_-(w)\right] \\
\langle D|\bar{c}\gamma^\mu \gamma_5 b|B\rangle &= 0
\end{aligned}$$

$$w = v \cdot v' = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

Note: scalar and pseudoscalar form factors can be obtained using

$$\begin{aligned}\langle ...|\bar{c}b|...\rangle &= \frac{q_\mu}{m_b - m_c}\langle ...|\bar{c}\gamma^\mu b|...\rangle, \\ \langle ...|\bar{c}\gamma_5 b|...\rangle &= -\frac{q_\mu}{m_b + m_c}\langle ...|\bar{c}\gamma^\mu\gamma_5 b|...\rangle\end{aligned}$$

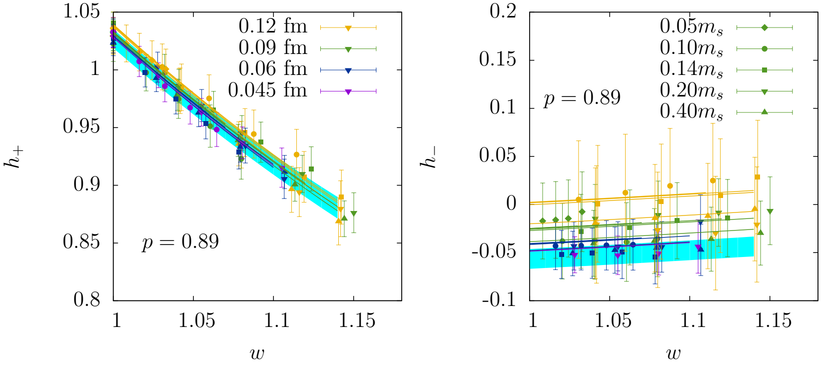
	Fermilab/MILC PRD **92**, 034506 (2015)	HPQCD PRD **92**, 054510 (2015)
u, d, s-quark action	AsqTad	HISQ (val), AsqTad (sea)
c-quark action	clover	HISQ
b-quark action	clover	NRQCD
m_π (MeV)	180 - 560	260 - 480
a (fm)	0.045 - 0.12	0.09 - 0.12
chiral/continuum extrap.	HMχPT	modified[2] BCL[3] z-expansion
fits of q^2-dependence	BGL[1] z-expansion	

[1] [C. G. Boyd, B. Grinstein, R. F. Lebed, PRL **74**, 4603 (1995)]

[2] "modified" = coefficients depend on quark masses and lattice spacing

[3] [C. Bourrely, L. Lellouch, I. Caprini, PRD **79**, 013008 (2009)]

Fermilab/MILC: lattice results and chiral/continuum extrapolation

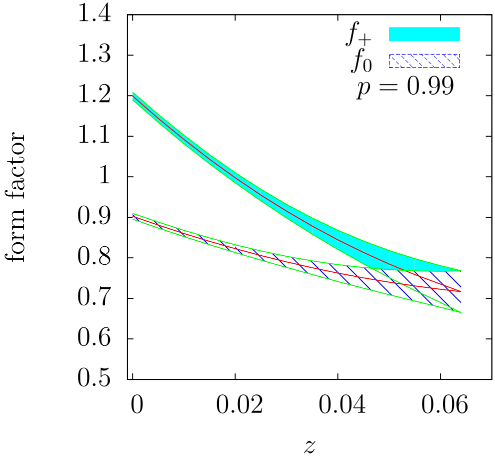


Note: $w(q^2 = 0) \approx 1.59$

[J. A. Bailey *et al.*, PRD **92**, 034506 (2015)]

Fermilab/MILC: fits of kinematic dependence, using

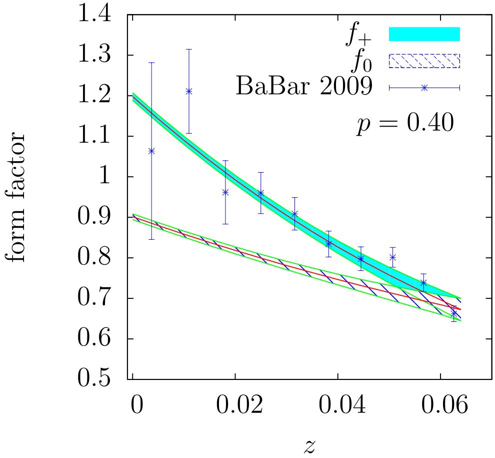
Lattice QCD (synthetic points at $w = 1$, $w = 1.08$, $w = 1.16$)



[J. A. Bailey *et al.*, PRD **92**, 034506 (2015)]

Fermilab/MILC: fits of kinematic dependence using

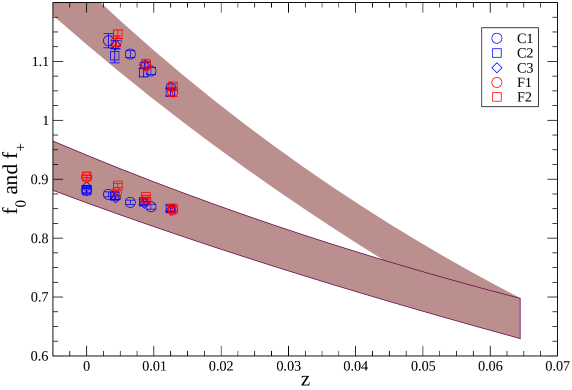
Lattice QCD (synthetic points at $w = 1$, $w = 1.08$, $w = 1.16$) and BaBar data



[J. A. Bailey *et al.*, PRD **92**, 034506 (2015); B. Aubert *et al.* (BaBar), PRL **104**, 011802 (2010)]

HPQCD: combined chiral/continuum/kinematic fit:

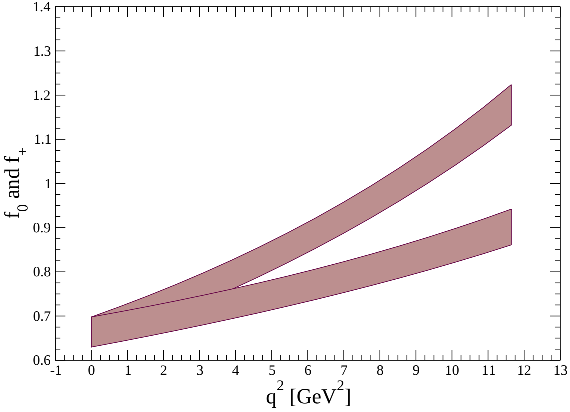
Lattice QCD



[H. Na *et al.*, PRD **92**, 054510 (2015)]

HPQCD: combined chiral/continuum/kinematic fit:

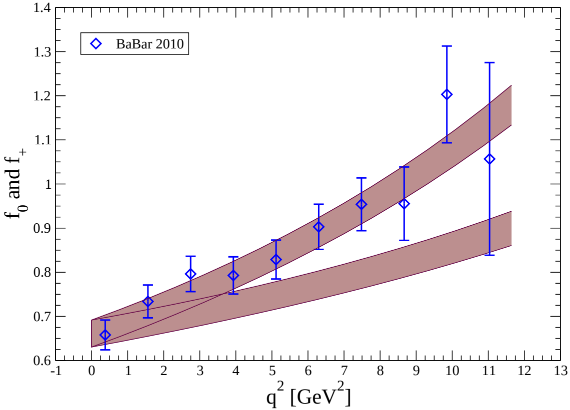
Lattice QCD



[H. Na *et al.*, PRD **92**, 054510 (2015)]

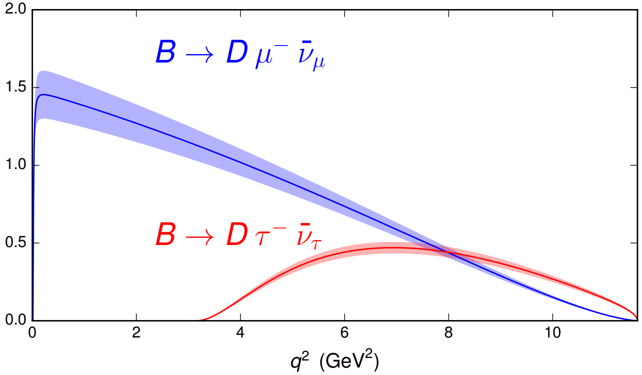
HPQCD: combined chiral/continuum/kinematic fit:

Lattice QCD and BaBar data



[H. Na *et al.*, PRD **92**, 054510 (2015); B. Aubert *et al.*, PRL **104**, 011802 (2010)]

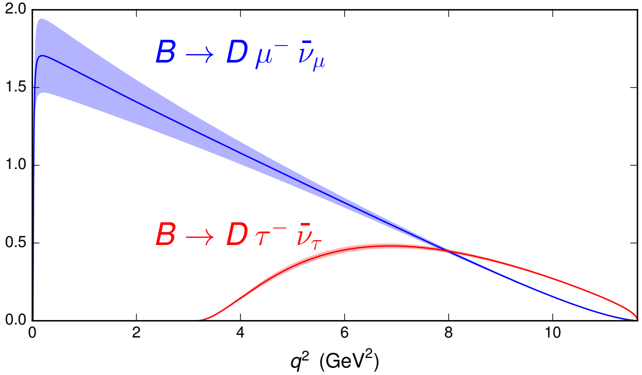
$\frac{d\Gamma/dq^2}{|V_{cb}|^2}$ without EW corrections, in units of ps^{-1} GeV^{-2}



Form factors: HPQCD

[H. Na *et al.*, PRD **92**, 054510 (2015)]

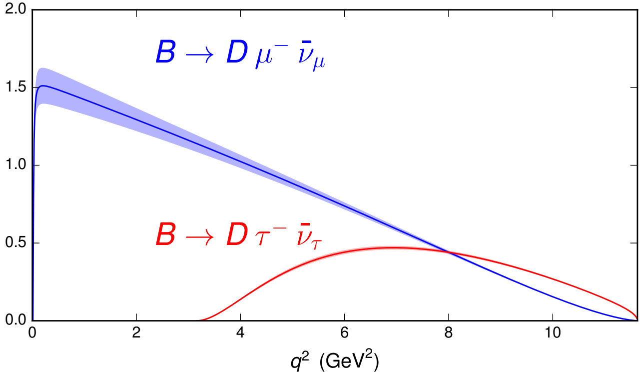
$\frac{d\Gamma/dq^2}{|V_{cb}|^2}$ without EW corrections, in units of ps^{-1} GeV^{-2}



Form factors: Fermilab/MILC

[J. A. Bailey *et al.*, PRD **92**, 034506 (2015)]

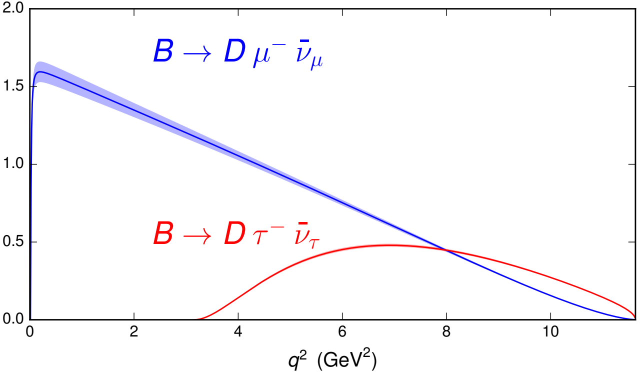
$\frac{d\Gamma/dq^2}{|V_{cb}|^2}$ without EW corrections, in units of ps^{-1} GeV^{-2}



Form factors: Fermilab/MILC + BaBar

[J. A. Bailey *et al.*, PRD **92**, 034506 (2015); B. Aubert *et al.*, PRL **104**, 011802 (2010)]

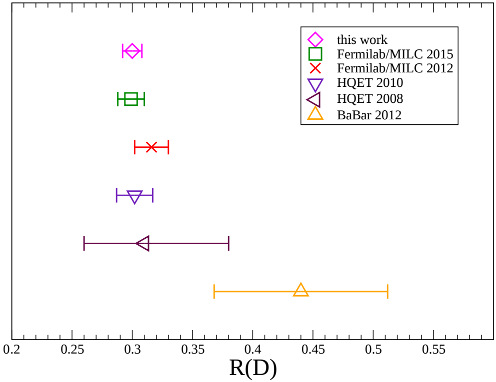
$\frac{d\Gamma/dq^2}{|V_{cb}|^2}$ without EW corrections, in units of ps^{-1} GeV^{-2}



Form factors: Fermilab/MILC + BaBar + Belle

[C. DeTar, priv. comm.; B. Aubert *et al.*, PRL **104**, 011802 (2010); R. Glattauer *et al.*, PRD **93**, 032006 (2016)]

$$R[D] = \frac{\Gamma(B \to D\, \tau^- \bar{\nu}_\tau)}{\Gamma(B \to D\, \mu^- \bar{\nu}_\mu)}$$



"This work": H. Na *et al.*, PRD **92**, 054510 (2015) — $R[D] = 0.300(08)$

"Fermilab/MILC 2015": J. A. Bailey *et al.*, PRD **92**, 034506 (2015) — $R[D] = 0.299(11)$

"Fermilab/MILC 2012": J. A. Bailey *et al.*, PRL **109**, 071802 (2012)

"HQET 2010": M. Tanaka and R. Watanabe, PRD **82**, 034027 (2010)

"HQET 2008": U. Nierste, S. Trine, S. Westhoff, PRD **78**, 015006 (2008)

"BaBar 2012": J. P. Lees *et al.*, PRL **109**, 101802 (2012)

1. $B \to D\ell\bar{\nu}$
2. $B \to D^*\ell\bar{\nu}$
3. $\Lambda_b \to \Lambda_c\ell\bar{\nu}$
4. Outlook

$B \to D^* \ell \bar{\nu}$

Vector and axial vector form factors:

$$\frac{\langle D^* | \bar{c}\gamma^\mu b | B \rangle}{\sqrt{m_B m_{D^*}}} = \epsilon^{\mu\nu\alpha\beta} \varepsilon^*_\nu v_\alpha v'_\beta \, h_V(w)$$

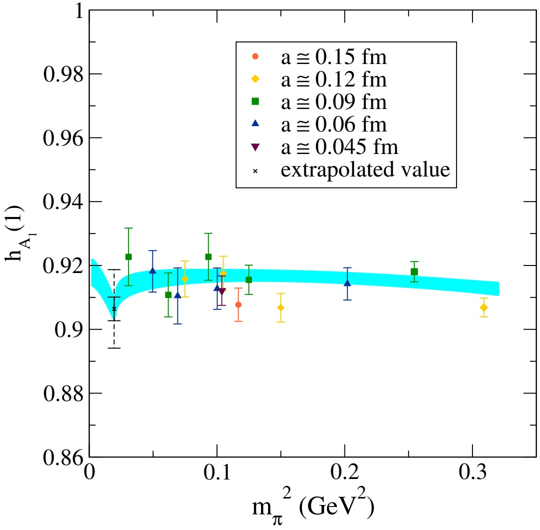
$$\frac{\langle D^* | \bar{c}\gamma^\mu \gamma_5 b | B \rangle}{\sqrt{m_B m_{D^*}}} = i(1+w)\varepsilon^{*\mu} h_{A_1}(w) - i(\varepsilon^* \cdot v) \left[v^\mu h_{A_2}(w) + v'^\mu h_{A_3}(w) \right]$$

In the zero-recoil limit $w \to 1$, the differential decay rate only depends on

$$\mathcal{F}^{B \to D^*}(1) = h_{A_1}(1)$$

	Fermilab/MILC PRD 89, 114504 (2014))
u, d, s-quark action	AsqTad
c-quark action	clover
b-quark action	clover
m_π (MeV)	180 - 560
a (fm)	0.045 - 0.12
chiral/continuum extrap.	HMχPT
fits of q^2-dependence	N/A (zero recoil only)

$B \to D^* \ell \bar{\nu}$



$\mathcal{F}(1) = 0.906(4)(12)$

Uncertainty	$h_{A_1}(1)$
Statistics	0.4%
Scale (r_1) error	0.1%
χPT fits	0.5%
$g_{D^*D\pi}$	0.3%
Discretization errors	1.0%
Perturbation theory	0.4%
Isospin	0.1%
Total	1.4%

[Bailey et al., PRD 89, 114504 (2014)]

	W. Detmold, C. Lehner, S. Meinel PRD **92**, 034503 (2015)
u, d, s-quark action	Domain Wall
c-quark action	RHQ
b-quark action	RHQ
m_π (MeV)	230 - 350
a (fm)	0.085 - 0.11
chiral/continuum/q^2 extrap.	Modified z-expansion

Gauge field configurations from RBC/UKQCD Collaboration [Y. Aoki *et al.*, PRD **83**, 074508 (2011)]

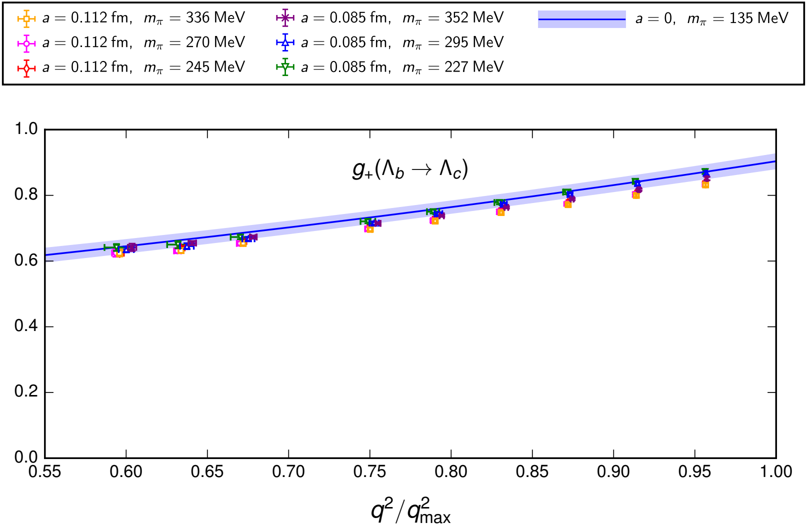
Vector and axial vector form factors:

$$\begin{aligned}
\langle \Lambda_c | \overline{c} \gamma^\mu b | \Lambda_b \rangle \quad = \quad & \overline{u}_{\Lambda_c} \Bigg[(m_{\Lambda_b} - m_{\Lambda_c}) \frac{q^\mu}{q^2} \, f_0(q^2) \\
& + \frac{m_{\Lambda_b} + m_{\Lambda_c}}{s_+} \left(p^\mu + p'^\mu - (m^2_{\Lambda_b} - m^2_{\Lambda_c}) \frac{q^\mu}{q^2} \right) f_+(q^2) \\
& + \left(\gamma^\mu - \frac{2 m_{\Lambda_c}}{s_+} p^\mu - \frac{2 m_{\Lambda_b}}{s_+} p'^\mu \right) f_\perp(q^2) \Bigg] u_{\Lambda_b},
\end{aligned}$$

$$\begin{aligned}
\langle \Lambda_c | \overline{c} \gamma^\mu \gamma_5 b | \Lambda_b \rangle \quad = \quad & -\overline{u}_{\Lambda_c} \, \gamma_5 \Bigg[(m_{\Lambda_b} + m_{\Lambda_c}) \frac{q^\mu}{q^2} \, g_0(q^2) \\
& + \frac{m_{\Lambda_b} - m_{\Lambda_c}}{s_-} \left(p^\mu + p'^\mu - (m^2_{\Lambda_b} - m^2_{\Lambda_c}) \frac{q^\mu}{q^2} \right) g_+(q^2) \\
& + \left(\gamma^\mu + \frac{2 m_{\Lambda_c}}{s_-} p^\mu - \frac{2 m_{\Lambda_b}}{s_-} p'^\mu \right) g_\perp(q^2) \Bigg] u_{\Lambda_b},
\end{aligned}$$

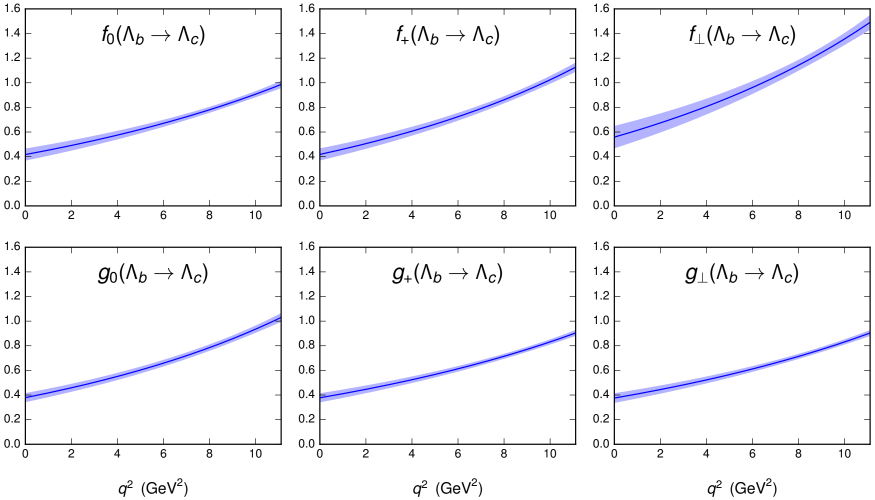
where $s_\pm = (m_{\Lambda_b} \pm m_{\Lambda_c})^2 - q^2$

[T. Feldmann and M. Yip, PRD **85**, 014035 (2012)]



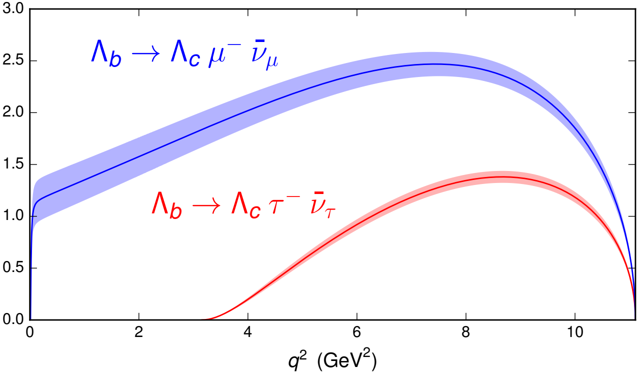
[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

Vector and axial vector form factors:



[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

$$\frac{d\Gamma/dq^2}{|V_{cb}|^2} \ (\mathrm{ps}^{-1}\ \mathrm{GeV}^{-2})$$



[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

$$R[\Lambda_c] = \frac{\Gamma(\Lambda_b \to \Lambda_c\, \tau^- \bar{\nu}_\tau)}{\Gamma(\Lambda_b \to \Lambda_c\, \mu^- \bar{\nu}_\mu)} = 0.3328 \pm 0.0074_{\,\mathrm{stat}} \pm 0.0070_{\,\mathrm{syst}}$$

(3% uncertainty)

[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

Also: $b \to u$

$$R[p] = \frac{\Gamma(\Lambda_b \to p\,\tau^-\bar{\nu}_\tau)}{\Gamma(\Lambda_b \to p\,\mu^-\bar{\nu}_\mu)} = 0.689 \pm 0.058_{\rm stat} \pm 0.064_{\rm syst}$$

(12% uncertainty)

Using form factors from [W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

Another ratio, useful as a normalization factor in the LHCb measurement of $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$:

$$R = \frac{\Gamma(\Lambda_b^0 \to \Lambda_c^+ \, \mu^- \bar{\nu}_\mu)}{\Gamma(\bar{B}^0 \to D^+ \mu^- \bar{\nu}_\mu)}$$

Input	R
DLM+HPQCD	2.47 ± 0.26
DLM+Fermilab/MILC	2.30 ± 0.23
DLM+Fermilab/MILC+BaBar	2.45 ± 0.19
DLM+Fermilab/MILC+BaBar+Belle	2.37 ± 0.16

[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

[J. A. Bailey *et al.*, PRD **92**, 034506 (2015)]

[H. Na *et al.*, PRD **92**, 054510 (2015)]

[B. Aubert *et al.* (BaBar), PRL **104**, 011802 (2010)]

[R. Glattauer *et al.* (Belle), PRD **93**, 032006 (2016)]

[C. DeTar, private communication]

New-physics sensitivity of $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ studied in:

S. Shivashankara, W. Wu, A. Datta, PRD **91**, 115003 (2015)

R. Dutta, PRD **93**, 054003 (2016)

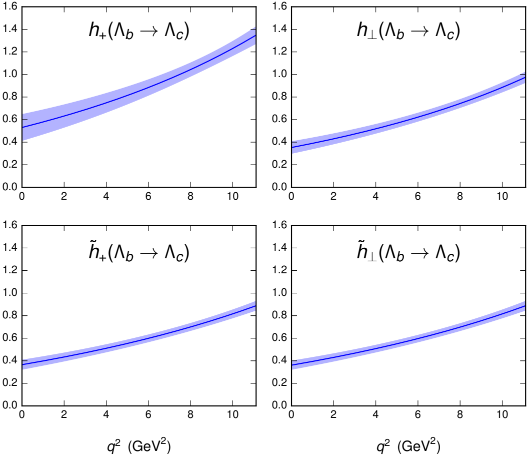
R. M. Woloshyn, PoS **Hadron 2013**, 203 $\to$ large effects from tensor coupling?

Tensor form factors:

$$
\begin{aligned}
q_\nu \langle \Lambda_c | \bar{c} i \sigma^{\mu\nu} b | \Lambda_b \rangle &= -\bar{u}_{\Lambda_c} \left[\frac{q^2}{s_+} \left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c}^2) \frac{q^\mu}{q^2} \right) h_+(q^2) \right. \\
&\quad \left. + (m_{\Lambda_b} + m_{\Lambda_c}) \left(\gamma^\mu - \frac{2 m_{\Lambda_c}}{s_+} p^\mu - \frac{2 m_{\Lambda_b}}{s_+} p'^\mu \right) h_\perp(q^2) \right] u_{\Lambda_b}, \\
q_\nu \langle \Lambda_c | \bar{c} i \sigma^{\mu\nu} \gamma_5 b | \Lambda_b \rangle &= -\bar{u}_{\Lambda_c} \gamma_5 \left[\frac{q^2}{s_-} \left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c}^2) \frac{q^\mu}{q^2} \right) \widetilde{h}_+(q^2) \right. \\
&\quad \left. + (m_{\Lambda_b} - m_{\Lambda_c}) \left(\gamma^\mu + \frac{2 m_{\Lambda_c}}{s_-} p^\mu - \frac{2 m_{\Lambda_b}}{s_-} p'^\mu \right) \widetilde{h}_\perp(q^2) \right] u_{\Lambda_b}
\end{aligned}
$$

[T. Feldmann and M. Yip, PRD **85**, 014035 (2012)]

Tensor form factors:



[S. Meinel, unpublished]

1. $B \to D\ell\bar{\nu}$
2. $B \to D^*\ell\bar{\nu}$
3. $\Lambda_b \to \Lambda_c\ell\bar{\nu}$
4. Outlook

Other form factors:

- $B_s \to D_s$ at nonzero recoil (easier than $B \to D$)
- $B \to D^*$ at nonzero recoil (easier than $B \to K^*$)
- $B \to$ (excited D)? Which states are you interested in?
- $\Lambda_b \to$ (excited Λ_c)? Which states are you interested in?
- Other wishes?

Resonances in final state:

- Naive single-hadron treatment is very accurate for D^*
- Broader resonances require multi-hadron methods on the lattice

QED corrections:

- Successfully implemented lattice QCD + QED simulations for hadron masses
- Leptonic and semileptonic decays require more complicated treatment of IR divergences

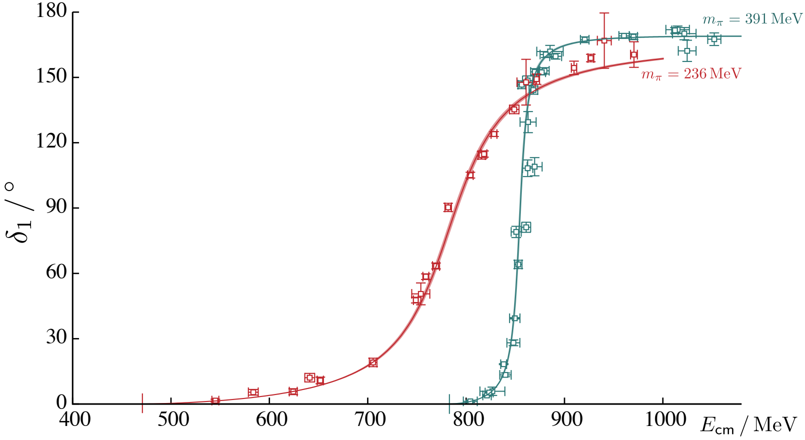
February 2015 workshop

www.bnl.gov/mnme2015/

(slides and videos available under "Agenda")

Coupled $\pi\pi$, $K\bar{K}$ scattering in P wave and the ρ resonance from latticeQCD

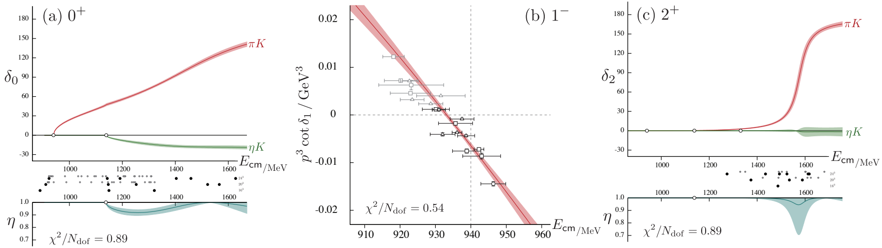
D. Wilson, R. Briceno, J. Dudek, R. Edwards, C. Thomas, PRD **92**, 094502 (2015)



Resonances in coupled $K\pi$, $K\eta$ scattering from lattice QCD

J. Dudek, R. Edwards, C. Thomas, D. Wilson, PRL **113**, 182001 (2014),

J. Dudek, R. Edwards, C. Thomas, D. Wilson, PRD **91**, 054008 (2015)

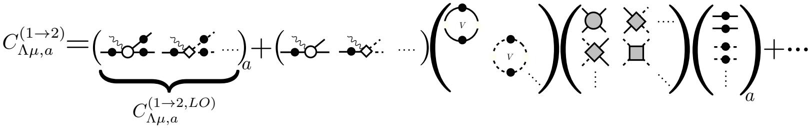


Rigorous method for computing $0 \to 2$, $1 \to 2$ and $2 \to 2$ hadronic matrix elements in lattice QCD

R. Briceno, M. Hansen, A. Walker-Loud, PRD **91**, 034501 (2015),

R. Briceno, M. Hansen, PRD **92**, 074509 (2015),

R. Briceno, M. Hansen, arXiv:1509.08507



$$|\langle \mathbf{2}|\widetilde{\mathcal{J}}_A|\mathbf{1}\rangle| = \sqrt{\frac{1}{2E_1}}\sqrt{\mathcal{H}_A^{\rm in}\ \mathcal{R}\ \mathcal{H}_A^{\rm out}}$$

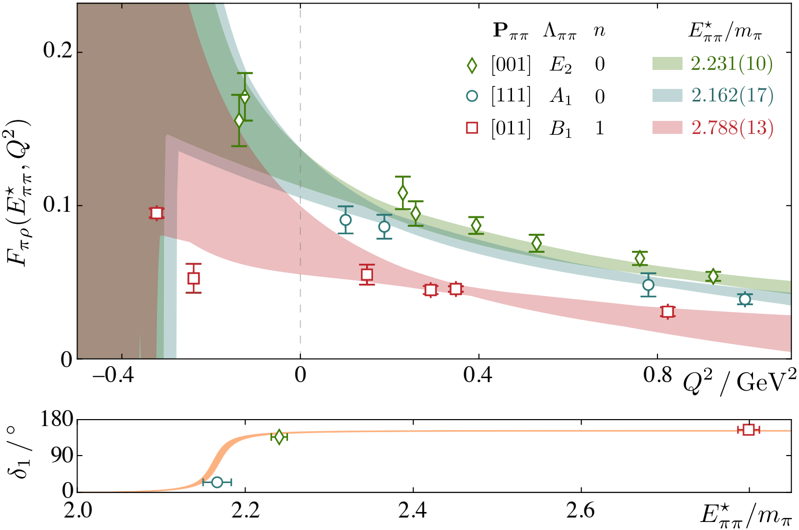
infinite volume transition amplitude

known finite volume function

finite volume matrix element

The resonant $\pi\gamma \to \pi\pi$ amplitude from lattice QCD

R. Briceno, J. Dudek, R. Edwards, C. Shultz, C. Thomas, D. Wilson, PRL **115**, 242001 (2015)



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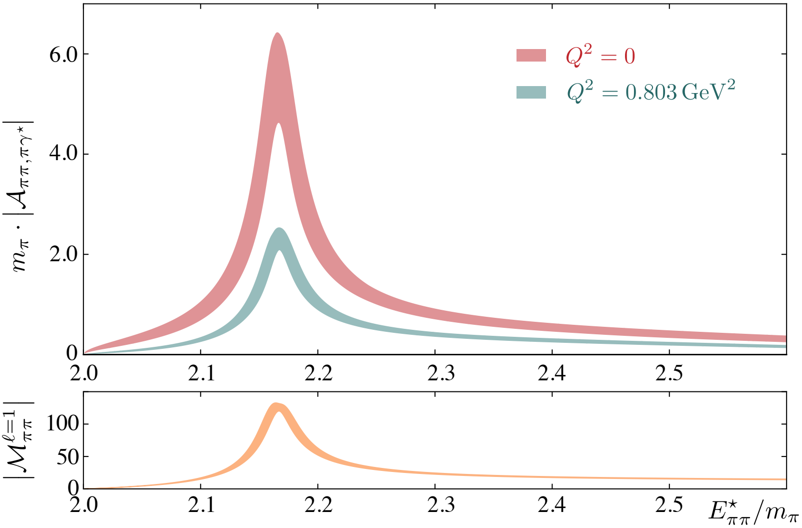
R. Briceno, J. Dudek, R. Edwards, C. Shultz, C. Thomas, D. Wilson, PRL **115**, 242001 (2015)



QED corrections to weak decays from lattice QCD

C. Sachrajda, talk at MNME 2015; N. Carrasco *et al.*, PRD 91, 074506 (2015)