Exclusive semileptonic b baryon decays from lattice QCD

Stefan Meinel

The University of Arizona

RIKEN BNL Research Center

CKM 2018, University of Heidelberg, September 2018

b (and c) baryon decay form factors from lattice QCD

Early work on $\Lambda_b \to \Lambda_c$ (quenched, focused on Isgur-Wise function):

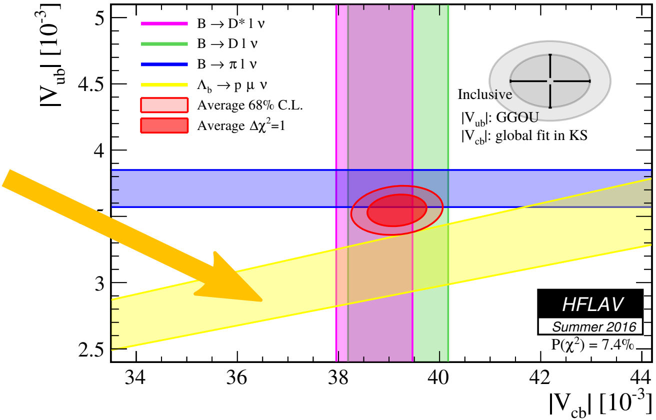
K. C. Boweler *et al.* (UKQCD Collaboration), arXiv:hep-lat/9709028/PRD 1998
S. Gottlieb and S. Tamhankar, arXiv:hep-lat/0301022/Lattice 2002

Our work, using RBC/UKQCD 2 + 1 flavor ensembles:

Transition	m_b	a [fm]	m_π [MeV]	Reference
$\Lambda_b \to \Lambda$	∞	0.11, 0.08	230–360	WD, DL, SM, MW, arXiv:1212.4827/PRD 2013
$\Lambda_b \to p$	∞	0.11, 0.08	230–360	WD, DL, SM, MW, arXiv:1306.0446/PRD 2013
$\Lambda_b \to p$	phys.	0.11, 0.08	230–360	WD, CL, SM, arXiv:1503.01421/PRD 2015
$\Lambda_b \to \Lambda_c$	phys.	0.11, 0.08	230–360	WD, CL, SM, arXiv:1503.01421/PRD 2015; AD, SK, SM, AR, arXiv:1702.02243/JHEP 2017
$\Lambda_b \to \Lambda$	phys.	0.11, 0.08	230–360	WD, SM, arXiv:1602.01399/PRD 2016
$\Lambda_b \to \Lambda^*$	phys.	0.11	340	SM, GR, arXiv:1608.08110/Lattice 2016
$\Lambda_b \to \Lambda_c^*$	phys.	0.11, 0.08	300–430	SM, GR, Later in this talk
$\Lambda_c \to \Lambda$		0.11, 0.08	**140**–360	SM, arXiv:1611.09696/PRL 2017
$\Lambda_c \to p$		0.11, 0.08	230–360	SM, arXiv:1712.05783/PRD 2018

WD = William Detmold
DL = C.-J. David Lin
SM = Stefan Meinel
MW = Matthew Wingate
CL = Christoph Lehner
AD = Alakabha Datta
SK = Saeed Kamali
AR = Ahmed Rashed
GR = Gumaro Rendon (graduate student at U of A)

$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\bar{\nu}$ and $\Lambda_b \to \Lambda_c\mu\bar{\nu}$



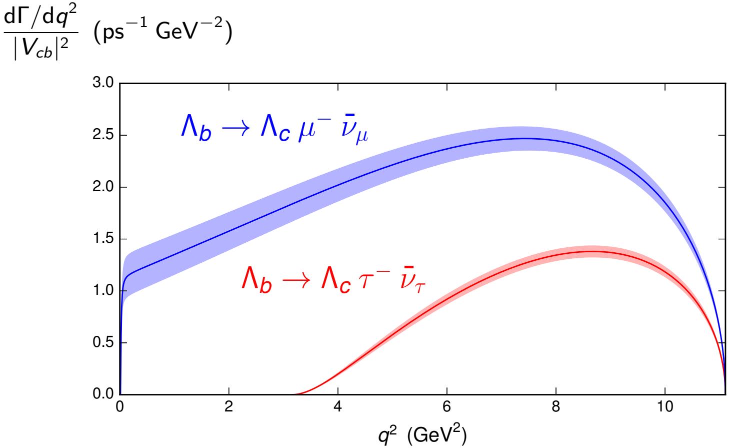
$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.080 \pm 0.004_{\text{ experiment}} \pm 0.004_{\text{ lattice}}$$

[http://www.slac.stanford.edu/xorg/hflav/semi/summer16/html/ExclusiveVub/exclVubVcb.html]

[W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421/PRD 2015]

[LHCb Collaboration, arXiv:1504.01568/Nature Physics 2015]

SM prediction for $R(\Lambda_c)$ from lattice QCD



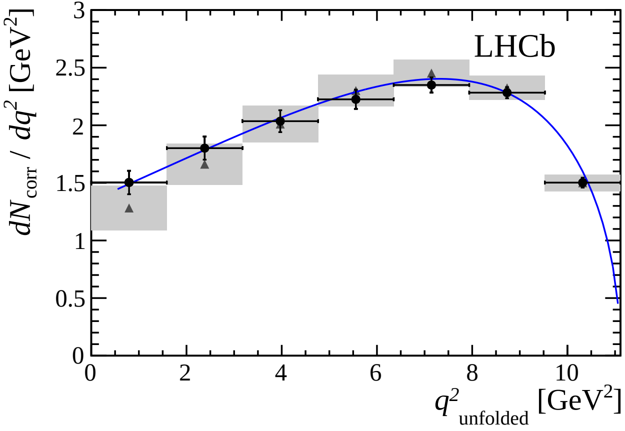
$$R(\Lambda_c) = \frac{\Gamma(\Lambda_b \to \Lambda_c\, \tau^- \bar{\nu}_\tau)}{\Gamma(\Lambda_b \to \Lambda_c\, \mu^- \bar{\nu}_\mu)} = 0.3328 \pm 0.0074_{\text{stat}} \pm 0.0070_{\text{syst}}$$

[W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421/PRD 2015]

Shape of the $\Lambda_b \to \Lambda_c \mu \bar{\nu}$ diff. decay rate from LHCb

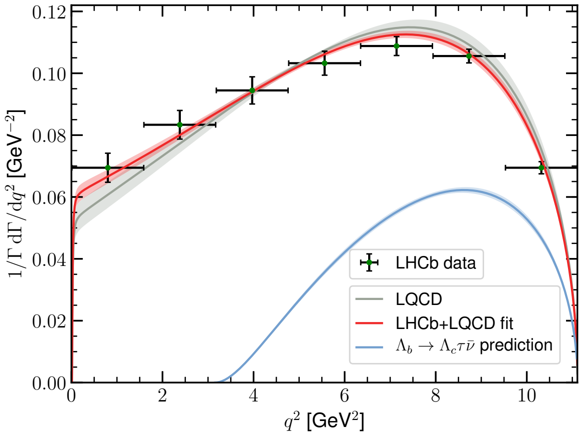
Gray rectangles (triangles = central values): Lattice QCD prediction

Black circles: LHCb



[LHCb Collaboration, arXiv:1709.01920/PRD 2017]

$\Lambda_b \to \Lambda_c \mu \bar{\nu}$ combined HQET fit to LQCD and experiment

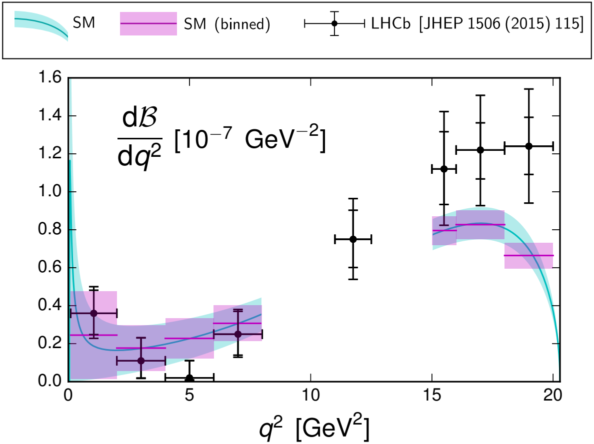


Heavy-quark symmetry provides stronger constraints for $\Lambda_b \to \Lambda_c \ell \bar{\nu}$ than for $B \to D^{(*)} \ell \bar{\nu}$

$\to$ First determination of $\mathcal{O}(\Lambda^2/m_c^2)$ contributions to an exclusive decay

[F. Bernlochner, Z. Ligeti, D. Robinson, W. Sutcliffe, arXiv:1808.09464]

$\Lambda_b \to \Lambda\mu^+\mu^-$ differential branching fraction (2015)

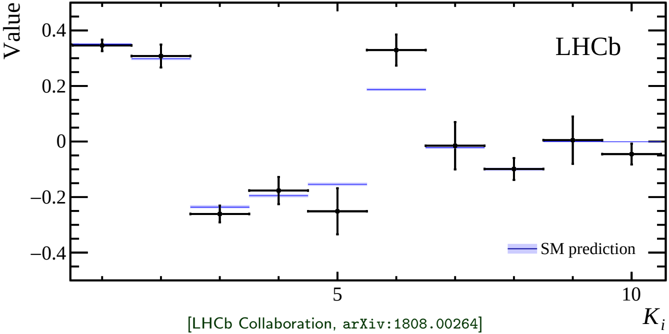


[W. Detmold and S. Meinel, arXiv:1602.01399/PRD 2016]

$\Lambda_b \to \Lambda\mu^+\mu^-$ new angular analysis (2018)

$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2} \sum_i^{34} K_i f_i(\vec{\Omega})$

$15 < q^2 < 20\ \mathrm{GeV}^2$



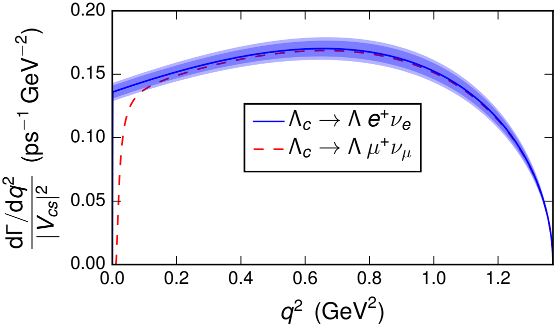
[LHCb Collaboration, arXiv:1808.00264]

$A_{\mathrm{FB}}^{\ell} = \frac{3}{2} K_3, \qquad A_{\mathrm{FB}}^{h} = K_4 + \frac{1}{2} K_5, \qquad A_{\mathrm{FB}}^{\ell h} = \frac{3}{4} K_6$

Note: the 2015 LHCb result for A_{FB}^{ℓ}, which deviated 3.4σ from our SM prediction, was incorrect (it was actually the CP asymmetry in A_{FB}^{ℓ}).

→ Our Wilson coefficient fits [S. Meinel and D. van Dyk, arXiv:1603.02974/PRD 2016] need to be redone.

$\Lambda_c \to \Lambda$ form factors from lattice QCD



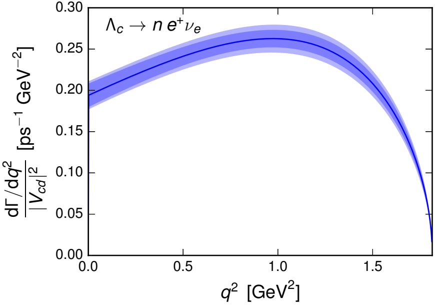
$$\frac{\Gamma(\Lambda_c \to \Lambda \ell^+ \nu_\ell)}{|V_{cs}|^2} = \begin{cases} 0.2007(71)(74)\ \text{ps}^{-1}, & \ell = e, \\ 0.1945(69)(72)\ \text{ps}^{-1}, & \ell = \mu. \end{cases}$$

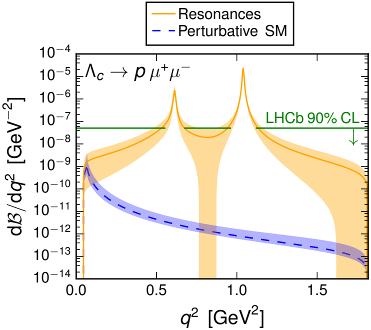
[S. Meinel, arXiv:1611.09696/PRL 2017]

Combined with the BESIII branching fraction measurements [arXiv:1510.02610/PRL 2015; arXiv:1611.04382/PLB 2017] and τ_{Λ_c} from PDG, this gives

$$|V_{cs}| = 0.949 \pm 0.024_{\text{lattice}} \pm 0.051_{\text{experiment}}$$

$\Lambda_c \to N$ form factors from lattice QCD





$$\frac{\Gamma(\Lambda_c \to n \ell^+ \nu_\ell)}{|V_{cd}|^2} = \begin{cases} 0.405(16)(20)\ \text{ps}^{-1}, & \ell = e, \\ 0.396(16)(20)\ \text{ps}^{-1}, & \ell = \mu. \end{cases}$$

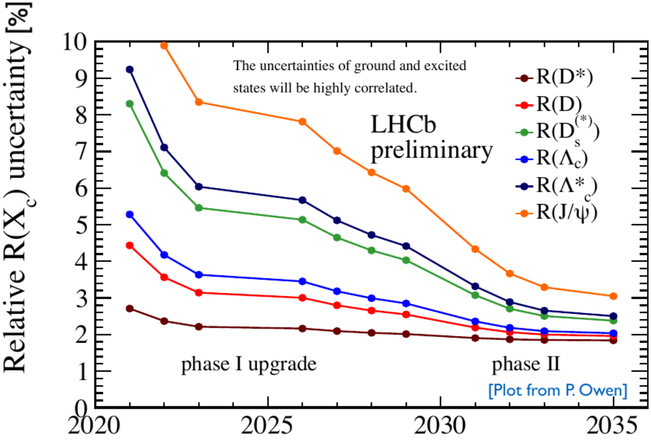
[S. Meinel, arXiv:1712.05783/PRD 2018]

1 Overview

2 $\Lambda_b \to \Lambda_c^*$ form factors

[S. Meinel and G. Rendon, work in progress]

Motivation



[G. Cohan, Talk at 2017 LHCb Implications Workshop]

The Λ_c^* baryons

Name	J^P	Mass [MeV]	Width [MeV]	Strong decay modes
$\Lambda_c^*(2595)$	$\frac{1}{2}^-$	2592.25(28)	2.6(6)	$\Lambda_c\,\pi^+\pi^-$
$\Lambda_c^*(2625)$	$\frac{3}{2}^-$	2628.11(19)	< 0.97	$\Lambda_c\,\pi^+\pi^-$

(decays proceed partly through $\Lambda_c^* \rightarrow \Sigma_c^{(*)}(\rightarrow \Lambda_c\pi)\pi$)

[2017 Review of Particle Physics]

In the following, we will treat the Λ_c^* baryons as if they were stable.

Some notation to define the form factors

$$\langle \Lambda^*_{c\,\frac{1}{2}^-}(\mathbf{p}', s')|\, \bar{c}\Gamma b\, |\Lambda_b(\mathbf{p}, s)\rangle = \bar{u}(m_{\Lambda^*_{c\,\frac{1}{2}^-}}, \mathbf{p}', s')\, \gamma_5\, \mathscr{G}^{(\frac{1}{2}^-)}[\Gamma]\, u(m_{\Lambda_b}, \mathbf{p}, s)$$

$$\langle \Lambda^*_{c\,\frac{3}{2}^-}(\mathbf{p}', s')|\, \bar{c}\Gamma b\, |\Lambda_b(\mathbf{p}, s)\rangle = \bar{u}_\lambda(m_{\Lambda^*_{c\,\frac{3}{2}^-}}, \mathbf{p}', s')\, \mathscr{G}^{\lambda(\frac{3}{2}^-)}[\Gamma]\, u(m_{\Lambda_b}, \mathbf{p}, s)$$

$$\sum_s u(m, \mathbf{p}, s)\bar{u}(m, \mathbf{p}, s) = m + \not{p}$$

$$\sum_{s'} u_\mu(m', \mathbf{p}', s')\bar{u}_\nu(m', \mathbf{p}', s') =$$
$$-(m' + \not{p}')\left(g_{\mu\nu} - \frac{1}{3}\gamma_\mu\gamma_\nu - \frac{2}{3m'^2}p'_\mu p'_\nu - \frac{1}{3m'}(\gamma_\mu p'_\nu - \gamma_\nu p'_\mu)\right)$$

$\frac{1}{2}^+ \to \frac{1}{2}^-$ vector and axial vector form factors

$$\begin{aligned}
\mathscr{G}^{(\frac{1}{2}^-)}[\gamma^\mu] &= f_0^{(\frac{1}{2}^-)}\,(m_{\Lambda_b}+m_{\Lambda_c^*})\frac{q^\mu}{q^2} \\
&+ f_+^{(\frac{1}{2}^-)}\,\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{s_-}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2)\frac{q^\mu}{q^2}\right) \\
&+ f_\perp^{(\frac{1}{2}^-)}\left(\gamma^\mu + \frac{2m_{\Lambda_c^*}}{s_-}p^\mu - \frac{2\,m_{\Lambda_b}}{s_-}p'^\mu\right),
\end{aligned}$$

$$\begin{aligned}
\mathscr{G}^{(\frac{1}{2}^-)}[\gamma^\mu\gamma_5] &= -g_0^{(\frac{1}{2}^-)}\gamma_5\,(m_{\Lambda_b}-m_{\Lambda_c^*})\frac{q^\mu}{q^2} \\
&- g_+^{(\frac{1}{2}^-)}\gamma_5\,\frac{m_{\Lambda_b}+m_{\Lambda_c^*}}{s_+}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2)\frac{q^\mu}{q^2}\right) \\
&- g_\perp^{(\frac{1}{2}^-)}\gamma_5\left(\gamma^\mu - \frac{2m_{\Lambda_c^*}}{s_+}p^\mu - \frac{2\,m_{\Lambda_b}}{s_+}p'^\mu\right),
\end{aligned}$$

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

$\frac{1}{2}^+ \to \frac{1}{2}^-$ tensor form factors

$$\mathscr{G}^{(\frac{1}{2}^-)}[i\sigma^{\mu\nu}q_\nu] = -h_+^{(\frac{1}{2}^-)}\,\frac{q^2}{s_-}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2)\frac{q^\mu}{q^2}\right)$$
$$-h_\perp^{(\frac{1}{2}^-)}\,(m_{\Lambda_b} - m_{\Lambda_c^*})\left(\gamma^\mu + \frac{2\,m_{\Lambda_c^*}}{s_-}\,p^\mu - \frac{2\,m_{\Lambda_b}}{s_-}\,p'^\mu\right)$$

$$\mathscr{G}^{(\frac{1}{2}^-)}[i\sigma^{\mu\nu}\gamma_5 q_\nu] = -\widetilde{h}_+^{(\frac{1}{2}^-)}\gamma_5\,\frac{q^2}{s_+}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2)\frac{q^\mu}{q^2}\right)$$
$$-\widetilde{h}_\perp^{(\frac{1}{2}^-)}\gamma_5\,(m_{\Lambda_b} + m_{\Lambda_c^*})\left(\gamma^\mu - \frac{2m_{\Lambda_c^*}}{s_+}\,p^\mu - \frac{2m_{\Lambda_b}}{s_+}\,p'^\mu\right)$$

$\frac{1}{2}^+ \to \frac{3}{2}^-$ vector and axial vector form factors

$$\begin{aligned}
\mathscr{G}^{\lambda(\frac{3}{2}^-)}[\gamma^\mu] \quad = \quad & f_0^{(\frac{3}{2}^-)} \frac{m_{\Lambda_c^*}}{s_+} \frac{(m_{\Lambda_b} - m_{\Lambda_c^*})\, p^\lambda q^\mu}{q^2} \\
& + f_+^{(\frac{3}{2}^-)} \frac{m_{\Lambda_c^*}}{s_-} \frac{(m_{\Lambda_b} + m_{\Lambda_c^*})\, p^\lambda (q^2 (p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2) q^\mu)}{q^2\, s_+} \\
& + f_\perp^{(\frac{3}{2}^-)} \frac{m_{\Lambda_c^*}}{s_-} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda_c^*} p^\mu)}{s_+} \right) \\
& + f_{\perp'}^{(\frac{3}{2}^-)} \frac{m_{\Lambda_c^*}}{s_-} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda p'^\mu}{m_{\Lambda_c^*}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda_c^*} p^\mu)}{s_+} + \frac{s_-\, g^{\lambda\mu}}{m_{\Lambda_c^*}} \right)
\end{aligned}$$

$$\begin{aligned}
\mathscr{G}^{\lambda(\frac{3}{2}^-)}[\gamma^\mu \gamma_5] \quad = \quad & - g_0^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_-} \frac{(m_{\Lambda_b} + m_{\Lambda_c^*})\, p^\lambda q^\mu}{q^2} \\
& - g_+^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_+} \frac{(m_{\Lambda_b} - m_{\Lambda_c^*})\, p^\lambda (q^2 (p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2) q^\mu)}{q^2\, s_-} \\
& - g_\perp^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_+} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda_c^*} p^\mu)}{s_-} \right) \\
& - g_{\perp'}^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_+} \left(p^\lambda \gamma^\mu + \frac{2\, p^\lambda p'^\mu}{m_{\Lambda_c^*}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda_c^*} p^\mu)}{s_-} - \frac{s_+\, g^{\lambda\mu}}{m_{\Lambda_c^*}} \right)
\end{aligned}$$

$\frac{1}{2}^+ \to \frac{3}{2}^-$ tensor form factors

$$\begin{aligned}
\mathscr{G}^{\lambda(\frac{3}{2}^-)}[i\sigma^{\mu\nu} q_\nu] = & -h_+^{(\frac{3}{2}^-)} \frac{m_{\Lambda_b} m_{\Lambda_c^*}}{s_-} \frac{p^\lambda (q^2(p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2) q^\mu)}{m_{\Lambda_b}\, s_+} \\
& -h_\perp^{(\frac{3}{2}^-)} \frac{m_{\Lambda_b} m_{\Lambda_c^*}}{s_-} \frac{m_{\Lambda_b} + m_{\Lambda_c^*}}{m_{\Lambda_b}} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda_c^*} p^\mu)}{s_+} \right) \\
& -h_{\perp'}^{(\frac{3}{2}^-)} \frac{m_{\Lambda_b} m_{\Lambda_c^*}}{s_-} \frac{m_{\Lambda_b} + m_{\Lambda_c^*}}{m_{\Lambda_b}} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda p'^\mu}{m_{\Lambda_c^*}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda_c^*} p^\mu)}{s_+} + \frac{s_-\, g^{\lambda\mu}}{m_{\Lambda_c^*}} \right)
\end{aligned}$$

$$\begin{aligned}
\mathscr{G}^{\lambda(\frac{3}{2}^-)}[i\sigma^{\mu\nu} q_\nu \gamma_5] = & -\widetilde{h}_+^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_b} m_{\Lambda_c^*}}{s_+} \frac{p^\lambda (q^2(p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2) q^\mu)}{m_{\Lambda_b}\, s_-} \\
& -\widetilde{h}_\perp^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_b} m_{\Lambda_c^*}}{s_+} \frac{m_{\Lambda_b} - m_{\Lambda_c^*}}{m_{\Lambda_b}} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda_c^*} p^\mu)}{s_-} \right) \\
& -\widetilde{h}_{\perp'}^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_b} m_{\Lambda_c^*}}{s_+} \frac{m_{\Lambda_b} - m_{\Lambda_c^*}}{m_{\Lambda_b}} \left(p^\lambda \gamma^\mu + \frac{2\, p^\lambda p'^\mu}{m_{\Lambda_c^*}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda_c^*} p^\mu)}{s_-} - \frac{s_+\, g^{\lambda\mu}}{m_{\Lambda_c^*}} \right)
\end{aligned}$$

Λ_c^* interpolating fields

We work in the Λ_c^* rest frame to allow exact spin-parity projection. We use

$$
\begin{aligned}
(\Lambda_c^*)_{j\gamma} \quad = \quad & \epsilon^{abc}\,(C\gamma_5)_{\alpha\beta}\,\Big[\tilde{c}^a_\alpha\;\tilde{d}^b_\beta\;(\nabla_j\tilde{u})^c_\gamma - \tilde{c}^a_\alpha\;\tilde{u}^b_\beta\;(\nabla_j\tilde{d})^c_\gamma \\
& + \tilde{u}^a_\alpha\;(\nabla_j\tilde{d})^b_\beta\;\tilde{c}^c_\gamma - \tilde{d}^a_\alpha\;(\nabla_j\tilde{u})^b_\beta\;\tilde{c}^c_\gamma\Big]
\end{aligned}
$$

(˜ denotes Gaussian smearing) [S. Meinel and G. Rendon, arXiv:1608.08110/Lattice2016]

This requires light-quark propagators with derivative sources.

We project to $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$ using

$$
\begin{aligned}
P_{jk}^{(\frac{1}{2}^-)} &= \frac{1}{3}\gamma_j\gamma_k\,\frac{1+\gamma_0}{2}, \\
P_{jk}^{(\frac{3}{2}^-)} &= \left(g_{jk} - \frac{1}{3}\gamma_j\gamma_k\right)\frac{1+\gamma_0}{2}.
\end{aligned}
$$

Lattice methods

- Gauge field configurations generated by the RBC and UKQCD collaborations
  [Y. Aoki *et al.*, arXiv:1011.0892/PRD 2011]

- *u*, *d*, *s* quarks: domain-wall action
  [D. Kaplan, arXiv:hep-lat/9206013/PLB 1992; V. Furman and Y. Shamir, arXiv:hep-lat/9303005/NPB 1995]

- All-mode averaging with 1 exact and 32 sloppy propagators per configuration
  [E. Shintani *et al.*, arXiv:1402.0244/PRD 2015]

- *c*, *b* quarks: anisotropic clover with three parameters, re-tuned more accurately to $D_s^{(*)}$ and $B_s^{(*)}$ dispersion relation and HFS

- "Mostly nonperturbative" renormalization
  [A. El-Khadra *et al.*, hep-ph/0101023/PRD 2001]

- Three-point functions with 9 source-sink separations

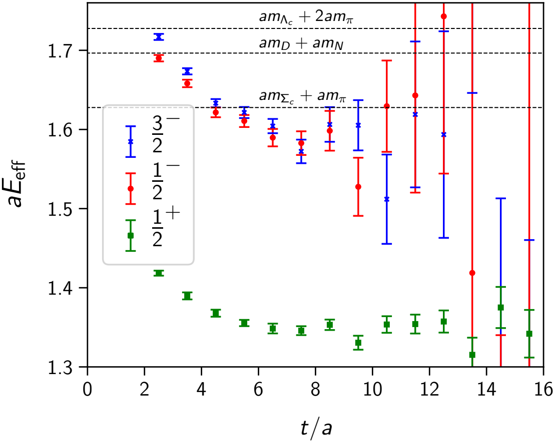
Lattice parameters

Name	$N_s^3 \times N_t$	β	$am_{u,d}$	am_s	a (fm)	m_π (MeV)	Run status
C01	$24^3 \times 64$	2.13	0.01	0.04	≈ 0.111	≈ 430	1/4 cfgs done
C005	$24^3 \times 64$	2.13	0.005	0.04	≈ 0.111	≈ 340	1/4 cfgs done
F004	$32^3 \times 64$	2.25	0.004	0.03	≈ 0.083	≈ 300	1/4 cfgs done

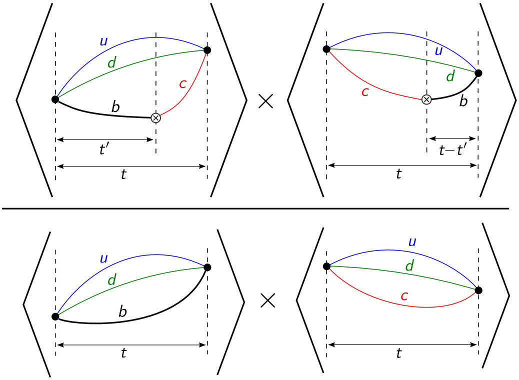
Λ_c^* two-point functions preliminary

Results from $24^3 \times 64$, $am_{u,d} = 0.005$ ensemble, 78 configs $\times$ 32 sources

$a^{-1} = 1.785(5)$ GeV



Extracting the form factors from ratios of 3pt and 2pt functions



t = source-sink separation
t' = current insertion time

We have data for two different Λ_b momenta: $\mathbf{p} = (0,0,2)\frac{2\pi}{L} \approx 0.9$ GeV and $\mathbf{p} = (0,0,3)\frac{2\pi}{L} \approx 1.4$ GeV

Extracting the form factors from ratios of 3pt and 2pt functions

Schematically,

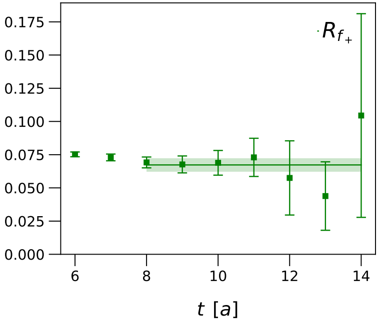
$$R_f(\mathbf{p}, t) \quad = \quad \sqrt{(\text{kinematic factors}) \times (\text{polarization vectors}) \times (\text{ratio at } t' = t/2)}$$

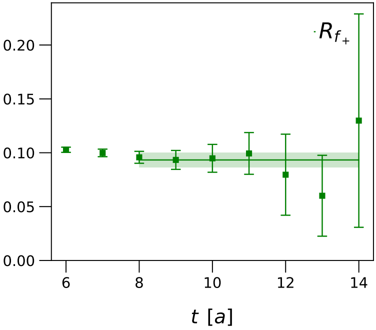
$$\rightarrow \quad f(\mathbf{p}) \quad \text{for large } t$$

Example: R_{f_+} for $\Lambda_b \to \Lambda_c^* \left(\frac{3}{2}^-\right)$ preliminary

Results from $24^3 \times 64$, $am_{u,d} = 0.005$ ensemble, 78 configs $\times$ 32 sources

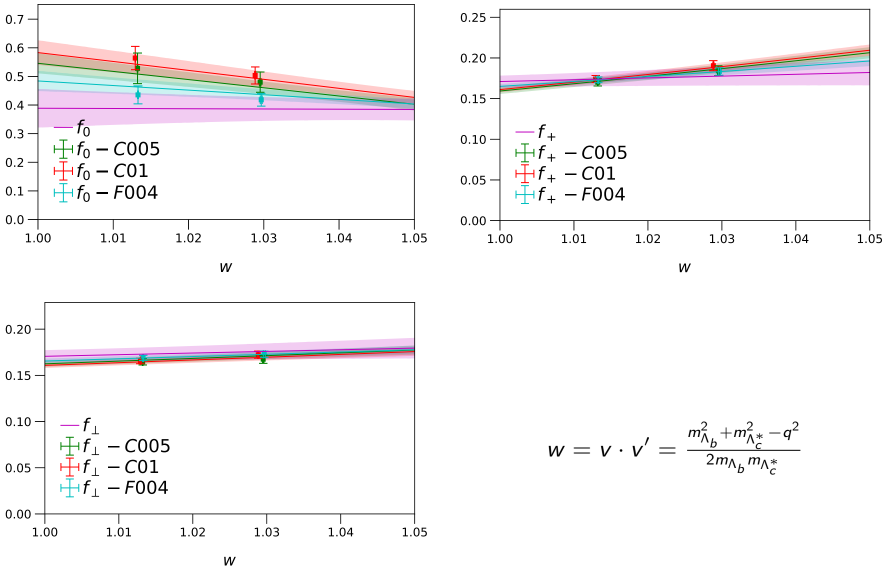
$\mathbf{p} = (0,0,2)\frac{2\pi}{L}$ $\mathbf{p} = (0,0,3)\frac{2\pi}{L}$





$\Lambda_b \to \Lambda_c^* \left(\frac{1}{2}^-\right)$ vector form factors

very preliminary

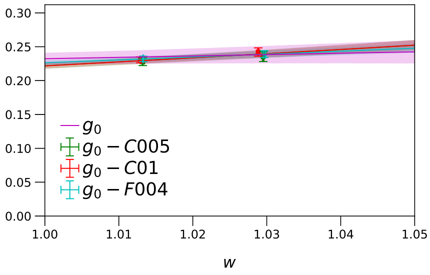


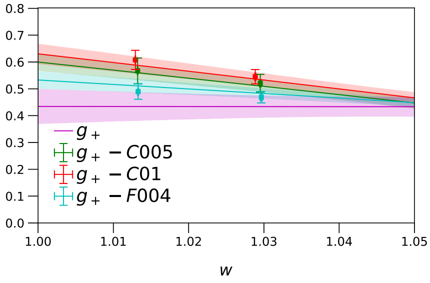
$$w = v \cdot v' = \frac{m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2}{2 m_{\Lambda_b} m_{\Lambda_c^*}}$$

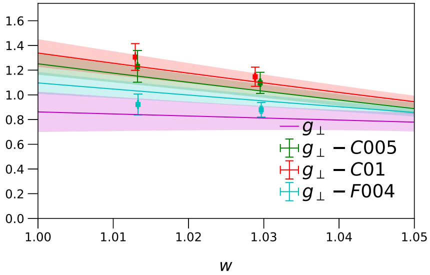
Only the statistical uncertainties are shown.

$\Lambda_b \to \Lambda_c^*\left(\frac{1}{2}^-\right)$ axial vector form factors

very preliminary



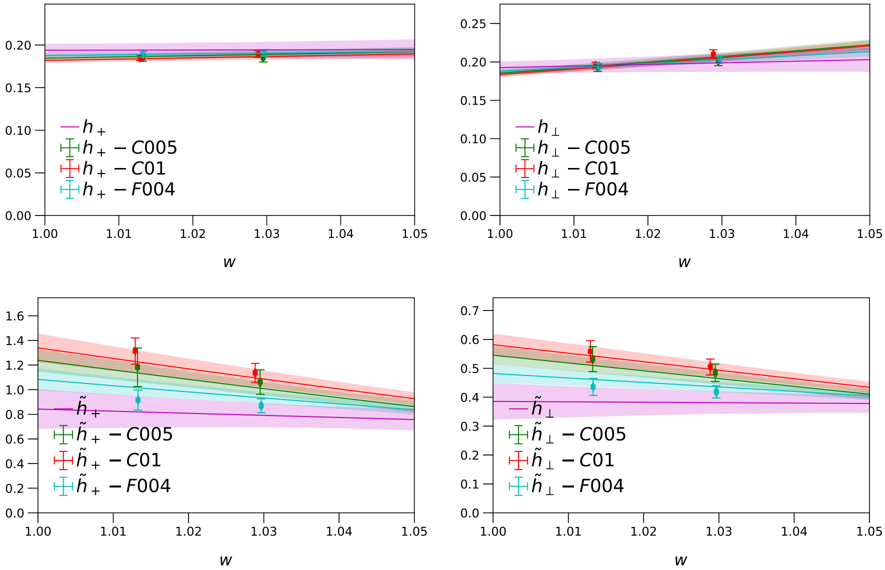




Only the statistical uncertainties are shown.

$\Lambda_b \to \Lambda_c^* \left(\frac{1}{2}^-\right)$ tensor form factors

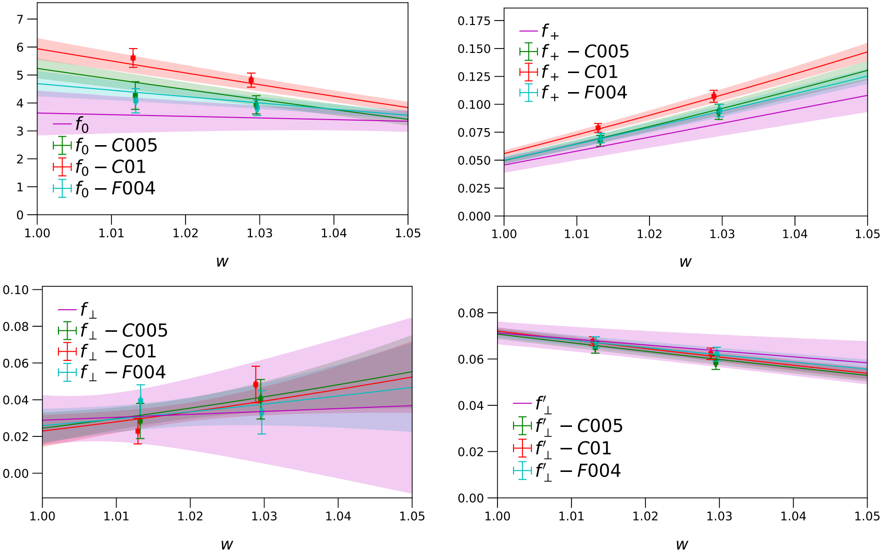
very preliminary



Only the statistical uncertainties are shown.

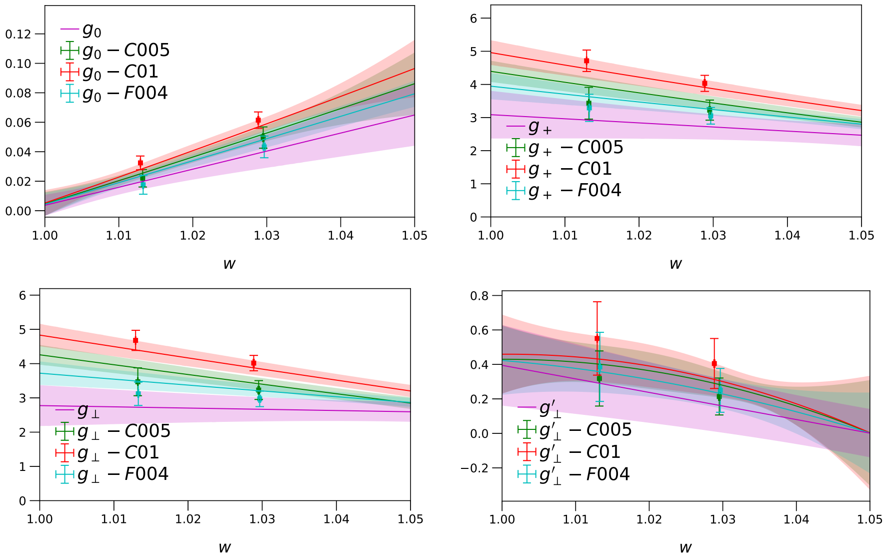
$\Lambda_b \to \Lambda_c^* \left(\frac{3}{2}^-\right)$ vector form factors

very preliminary



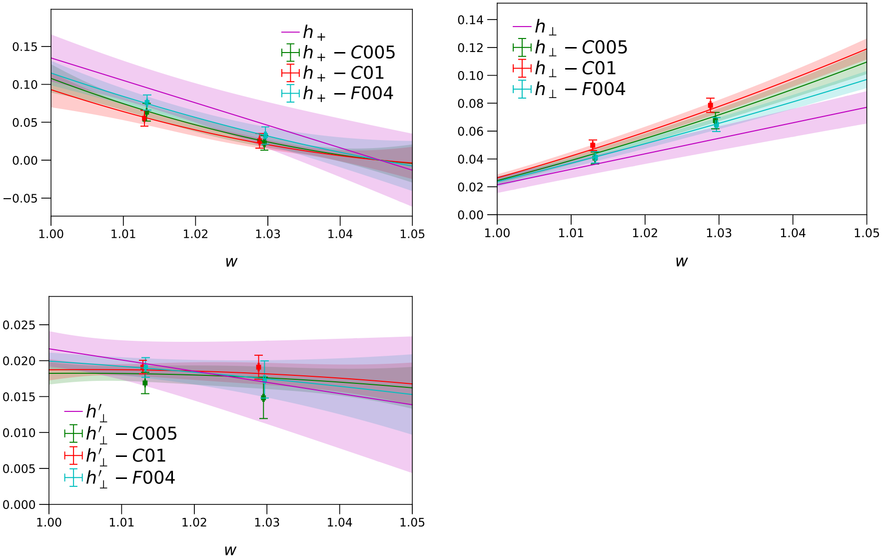
Only the statistical uncertainties are shown.

$\Lambda_b \to \Lambda_c^* \left(\frac{3}{2}^-\right)$ axial vector form factors very preliminary



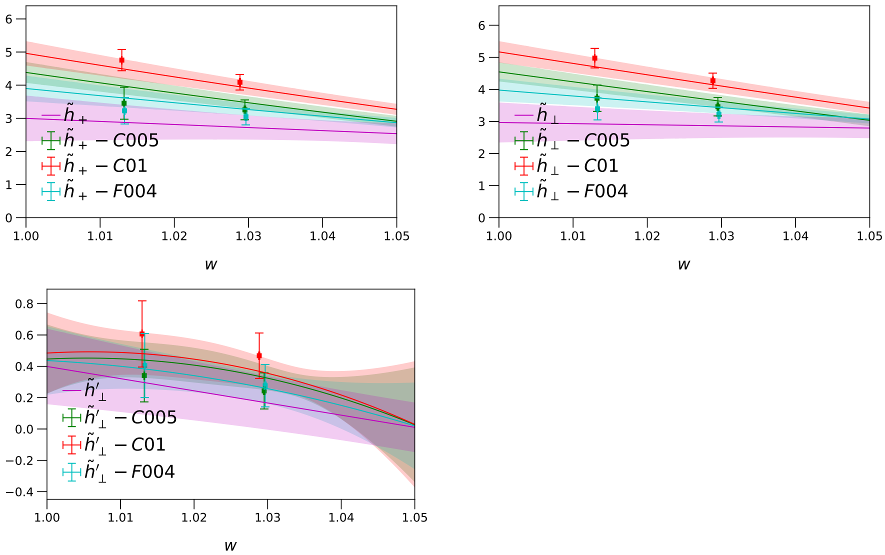
Only the statistical uncertainties are shown.

$\Lambda_b \to \Lambda_c^*\left(\frac{3}{2}^-\right)$ tensor form factors part 1 very preliminary



Only the statistical uncertainties are shown.

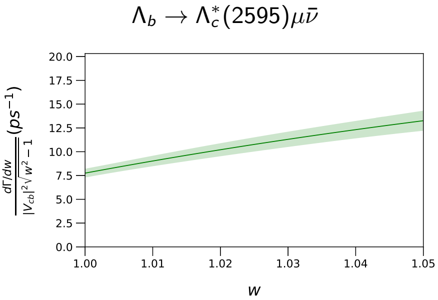
$\Lambda_b \to \Lambda_c^* \left(\frac{3}{2}^-\right)$ tensor form factors part 2 very preliminary

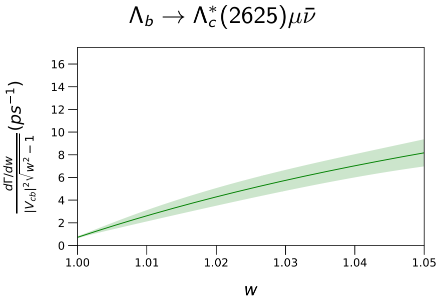


Only the statistical uncertainties are shown.

$\Lambda_b \to \Lambda_c^*\,\mu\bar{\nu}$ differential decay rates

very preliminary





Only the statistical uncertainties are shown.

To predict $R(\Lambda_c^*)$, we will combine the lattice QCD form factors (which are limited to low recoil) with experimental data for the shapes of the $\Lambda_b \to \Lambda_c^*\mu\bar{\nu}$ differential decay rates, making use of HQET.

[P. Boer, M. Bordone, E. Graverini, P. Owen, M. Rotondo, and D. Van Dyk, arXiv:1801.08367]

Outlook

$\Lambda_b \to p\ell\bar{\nu}$, $\Lambda_b \to \Lambda_c\ell\bar{\nu}$

- A higher-precision lattice QCD calculation of the form factors is underway (extra slide).
- LHCb measurement of $R(\Lambda_c)$?

$\Lambda_b \to \Lambda\ell^+\ell^-$

- To Do: New fit of Wilson coefficients using the 2018 LHCb angular analysis.
- Can the differential branching be measured more precisely? (Limited by normalization mode $\Lambda_b \to J/\psi\,\Lambda$?)

$\Lambda_b \to \Lambda_c^*(2595)\ell\bar{\nu}$ and $\Lambda_b \to \Lambda_c^*(2625)\ell\bar{\nu}$

- A first lattice QCD calculation at high q^2 is underway.
- Need to combine with experimental data for the shape of the $\Lambda_b \to \Lambda_c^*\mu\bar{\nu}$ decay rates to predict $R(\Lambda_c^*)$.

$\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$

- A first lattice QCD calculation at high q^2 is underway.
- Can LHCb isolate the $\Lambda^*(1520)$ contribution to $\Lambda_b \to pK\ell^+\ell^-$?

Forthcoming improved calculation of $\Lambda_b \to p, \Lambda, \Lambda_c$ form factors

- Remove data sets with $m_{u,d}^{(\text{val})} < m_{u,d}^{(\text{sea})}$, add two new ensembles
- For $\Lambda_b \to \Lambda$: physical $m_s^{(\text{val})}$
- More accurate tuning of charm and bottom actions
- All-mode-averaging for higher statistics
- Better source smearing

$N_s^3 \times N_t$	β	$am_{u,d}^{(\text{sea})}$	$am_{u,d}^{(\text{val})}$	$am_s^{(\text{sea})}$	a (fm)	$m_\pi^{(\text{sea})}$ (MeV)	$m_\pi^{(\text{val})}$ (MeV)	Status
$24^3 \times 64$	2.13	0.005	0.005	0.04	≈ 0.111	≈ 340	≈ 340	done
~~$24^3 \times 64$~~	~~2.13~~	~~0.005~~	~~0.002~~	~~0.04~~	~~≈ 0.111~~	~~≈ 340~~	~~≈ 270~~	
~~$24^3 \times 64$~~	~~2.13~~	~~0.005~~	~~0.001~~	~~0.04~~	~~≈ 0.111~~	~~≈ 340~~	~~≈ 250~~	
$48^3 \times 96$	2.13	0.00078	0.00078	0.0362	≈ 0.114	≈ 140	≈ 140	done
$32^3 \times 64$	2.25	0.006	0.006	0.03	≈ 0.083	≈ 360	≈ 360	done
$32^3 \times 64$	2.25	0.004	0.004	0.03	≈ 0.083	≈ 300	≈ 300	done
~~$32^3 \times 64$~~	~~2.25~~	~~0.004~~	~~0.002~~	~~0.03~~	~~≈ 0.083~~	~~≈ 300~~	~~≈ 230~~	
$48^3 \times 96$	2.31	0.002144	0.002144	0.02144	≈ 0.071	≈ 230	≈ 230	planned

Expected completion: 2020. Hope to reduce total uncertainties by factor of 2.