Heavy flavors on the lattice

Review on

- ✧ hadron spectroscopy
- ✧ weak transitions between hadrons

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Lattice QCD: brief intro

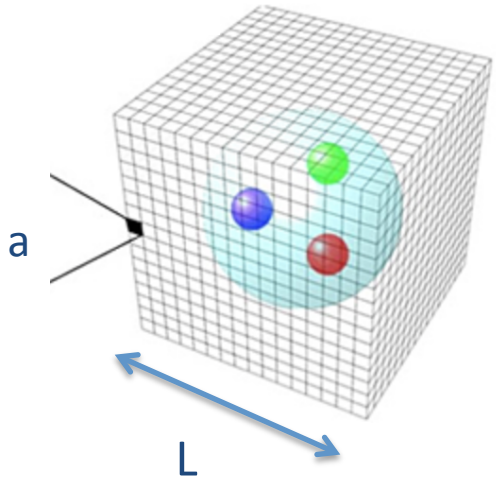
$$L_{QCD} = -\tfrac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \sum_{q=u,d,s,c,b,t} \bar{q} i\gamma_\mu (\partial^\mu + i g_s G^\mu_a T^a) q - m_q \bar{q} q$$

input: g_s , m_q

output: hadron properties

hadron interactions

x,t (Minkovsky) → x, i t (Euclidean)



Numerical evaluation of QFT Feynman path integrals on discretized Eucledian space-time

$$\int DG\, Dq\, D\bar{q}\; e^{-S_{QCD}/\hbar}$$

$$S_{QCD} = \int d^4x\, L_{QCD}[G(x), q(x), \bar{q}(x)]$$

I will concentrate on the recent results on

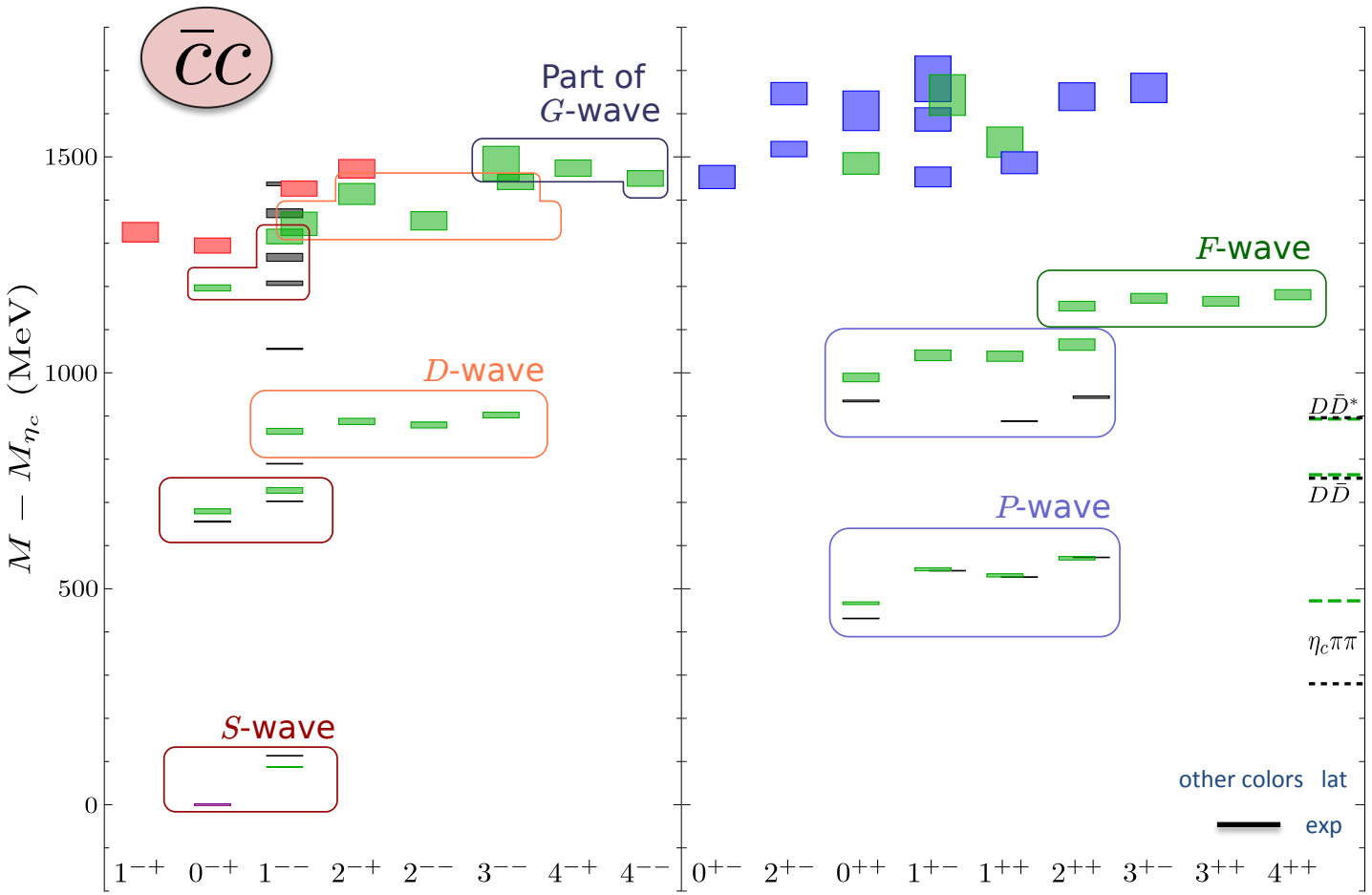
- ✧ hadron spectroscopy
- ✧ weak transitions between hadrons

obtained from lattice summer 2016 (and some older latt. results relevant due to very recent exp. discoveries)

Spectrum

of hadrons containing c, b

Excited cc̄, D, D_s disregarding strong decays and thresholds



HSC, JHEP 2016
1601.01073
m_π=240 MeV
(previously m_π=400 MeV)

states above thresholds treated as strongly stable; effects of thresholds not accounted for on near-threshold states

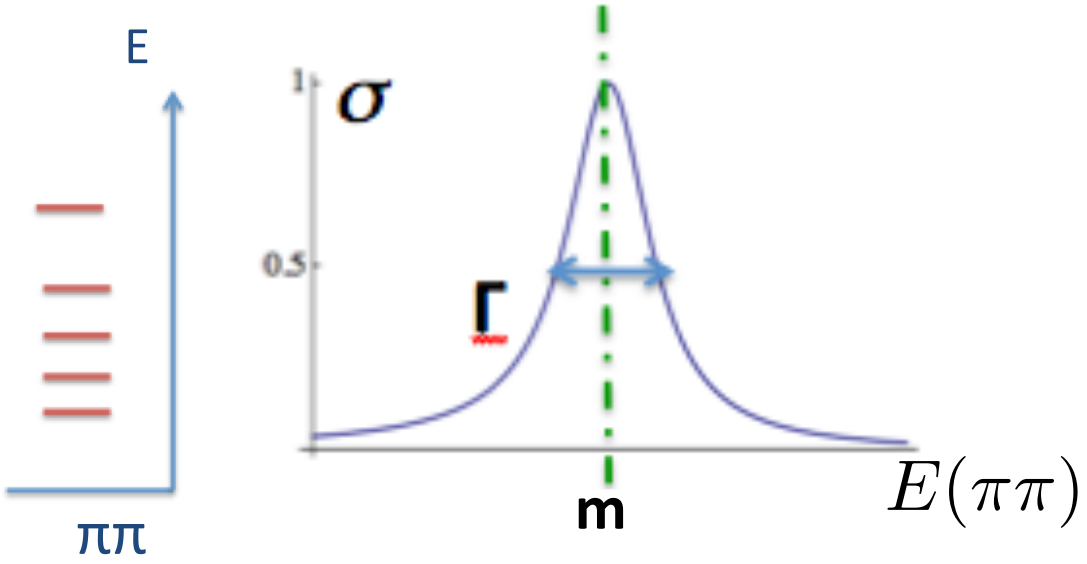
red and blue are candidates for hybrids with excited glue

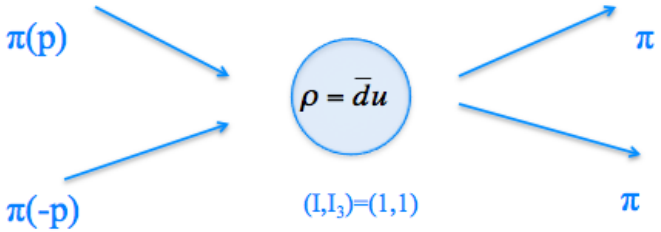
most of these states (J=3,4 or exotic $J^{PC}=1^{-+},2^{+-},..$) yet to be experimentally discovered !!

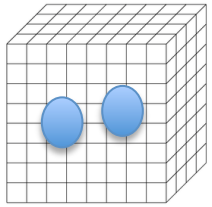
analogous excited spectra for D and D_s : see JHEP 2016

Rigorous treatment of strongly-decaying hadronic resonances

→ simulation of scattering of two-hadrons on the lattice







energy of eigenstate

scattering matrix

cross section

resonance mass and width

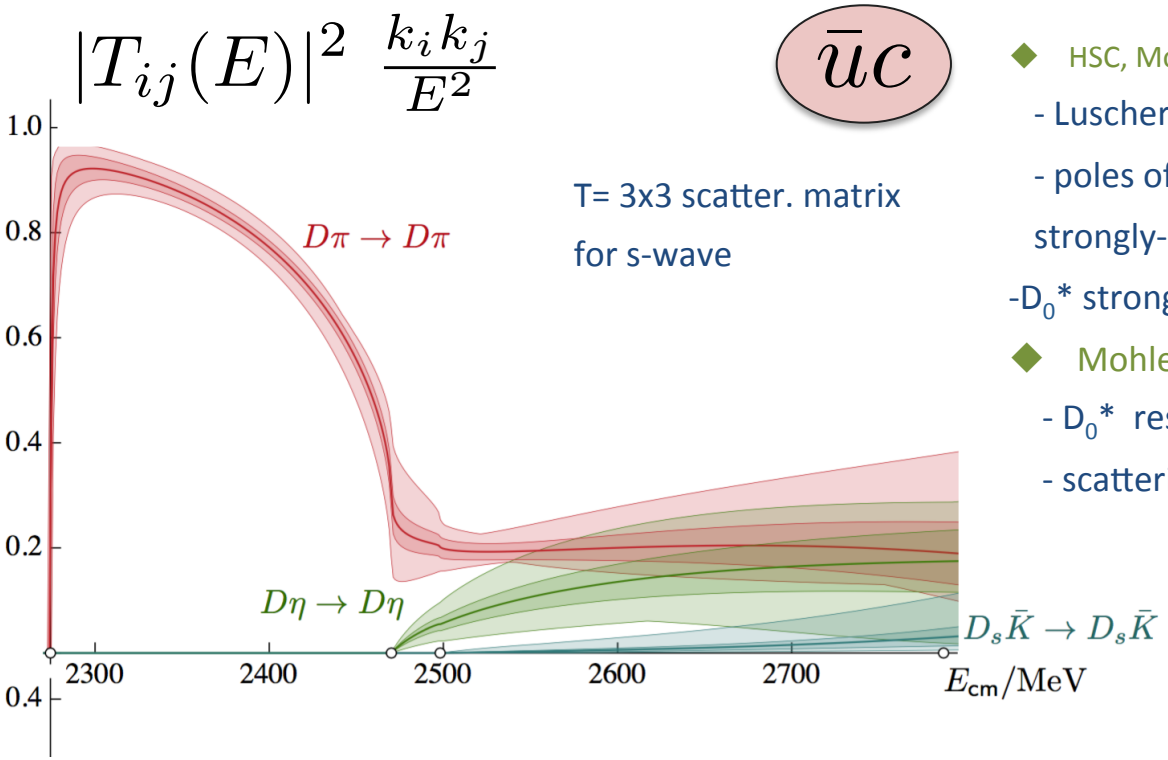
E → $T(E)$ → $\sigma(E) \propto |T(E)|^2$ → m, Γ

ρ, K*,.. verified

[by several lat coll.]

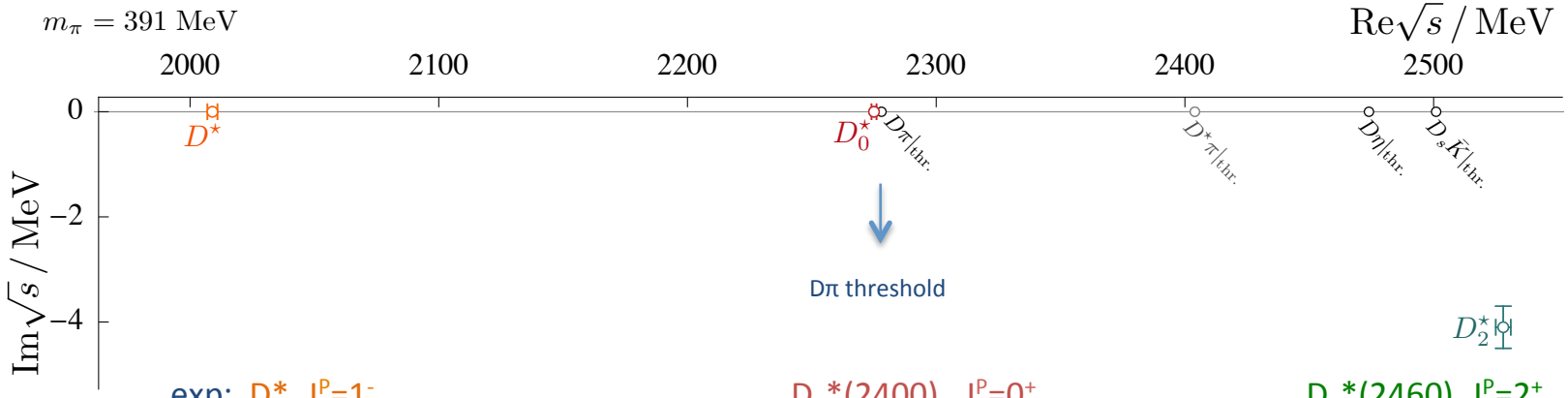
analytic relation:
Luscher 1991

D-meson resonances from Dπ – Dη – D_sK coupled channel scat.



T= 3x3 scatter. matrix for s-wave

- HSC, Moir et al, 1607.07093, JHEP16, m_π=400 MeV
  - Luscher type method to extract scat. matrix t
  - poles of t-matrix represent strongly-stable (D* and D_0^*) and resonance D_2*
  - D_0* strongly stable (not reson as in exp) due to high m_π
- Mohler, S.P., Woloshyn, 1208.4059, PRD 2012
  - D_0* resonance with m and consistent with exp.
  - scattering mat. extracted in less detail than HSC



locations of poles in T-matrix

Dπ threshold

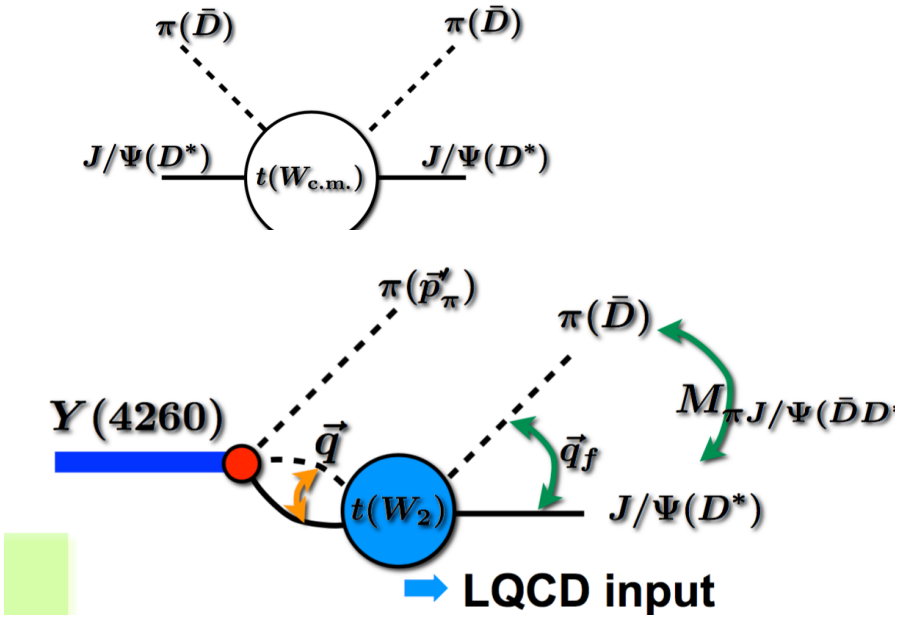
exp: D*, $J^P=1^-$ D_0*(2400) , $J^P=0^+$ D_2*(2460), $J^P=2^+$

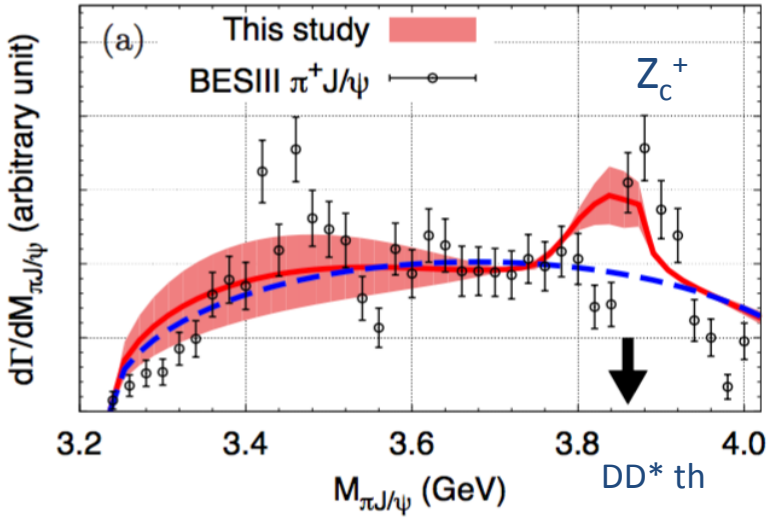
$Z_c^+(3900)$ from coupled $J/\Psi\,\pi^+ - D\bar{D}^* - \eta_c\,\rho$ scattering

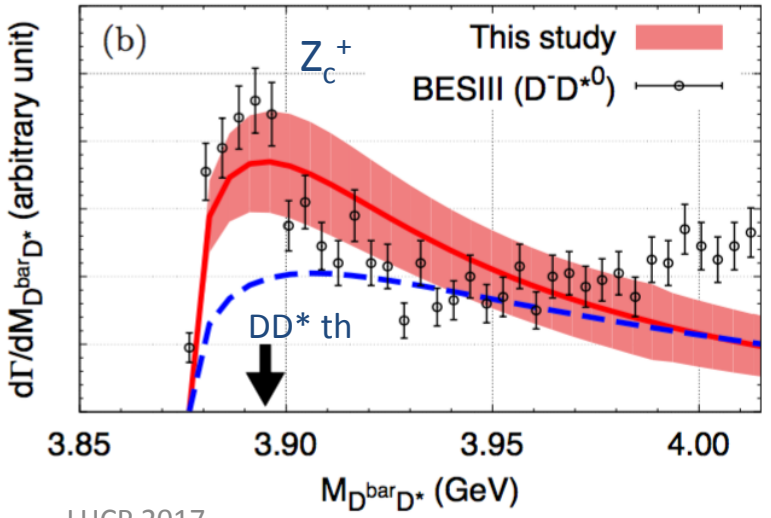
[HALQCD, Ikeda et al, 1602.03465, PRL]

$\bar{c}c\,\bar{d}u$

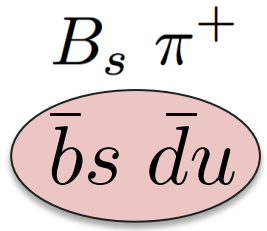
- less rigorous HALQCD method to extract scat. mat. was used which was not verified yet on any conventional resonance
- red line: differential rate from lattice
- blue line: differential rate from lattice if coupling between $J/\Psi\,\pi$ and DD^* channels set to zero by hand
- conclusion $Z_c^*(3900)$ most likely coupled-channel effect, not genuine resonances (i.e. pole on the unphysical sheet)







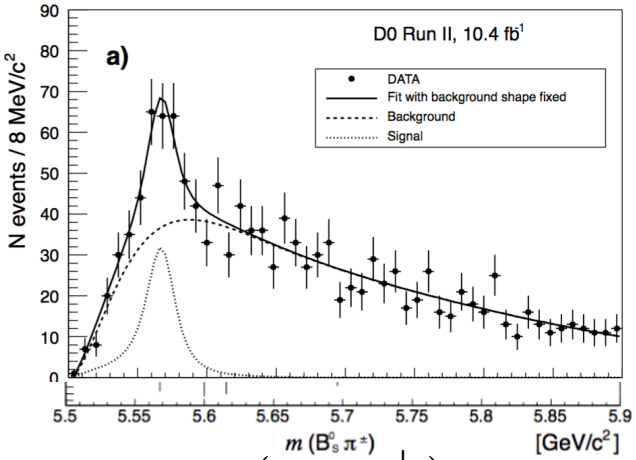
Search for exotic X(5568) in $B_s\ \pi^+$ scattering



D0 collaboration

25. february 2016

1602.07588



$E\ (B_s\pi^+)$

PRL 2016

Lang, Mohler, S.P.

mid march 2016

looking at lattice results of $B_s\ \pi^+$ scattering:

no indication for any resonance ???

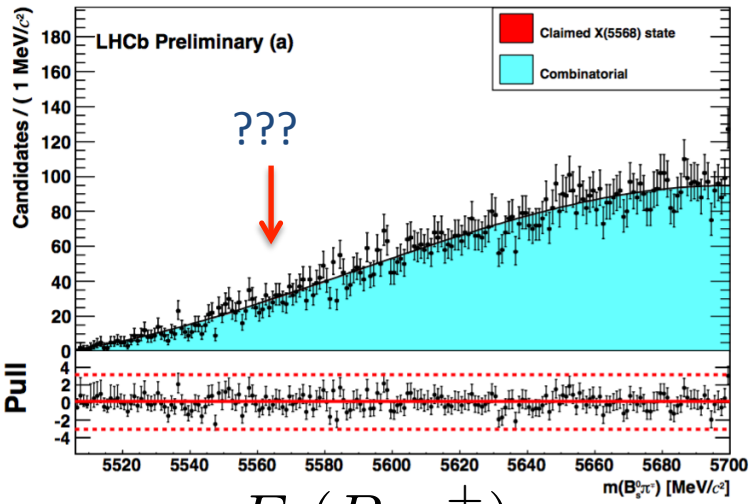
1607.03185

PRD 2016

[only lat. study so far]

LHCb seminar

22. march 2016



$E\ (B_s\pi^+)$

LHCb data published in 1608.00435: PRL 2016

CMS: same conclusion

strongly stable BB^* found with $J^P=1^+$ and isospin=0: search for it !!

$udb\bar{b}\bar{b}$ **$J^P=1^+$, isospin=0**, mass $m < m_B + m_{B^*}$

- Several collaborations find growing indication that such a strongly stable state exists
- Independent methods for treating b-quarks verify it

binding energy $(m_B+m_{B^*})-m$		
189 ± 10	Francis et al., 1607.05214, PRL 2017 [*]	NRQCD b-quark
90 ± 40	Bicudo et al, 1505.00613, 1612.02758	static b-quark

- such a state would decay weakly, for example [*]

$$udb\bar{b}\bar{b} \to B^+\bar{D}^0$$
$$\to J/\psi\ B^+K^0$$

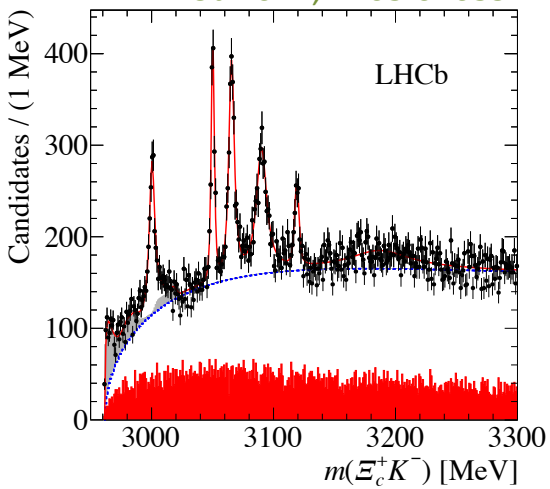
- strongly stable strange partner B_sB^* also predicted [*]

$$usb\bar{b}\bar{b} \to B^+D_s^-,\ J/\psi B_sK^0,\ B_s\bar{D}^0,\ J/\psi B^0\phi$$

Excited Ω_c^*

treated in lattice QCD ignoring their strong decays

LHCb 2017, 1703.04639

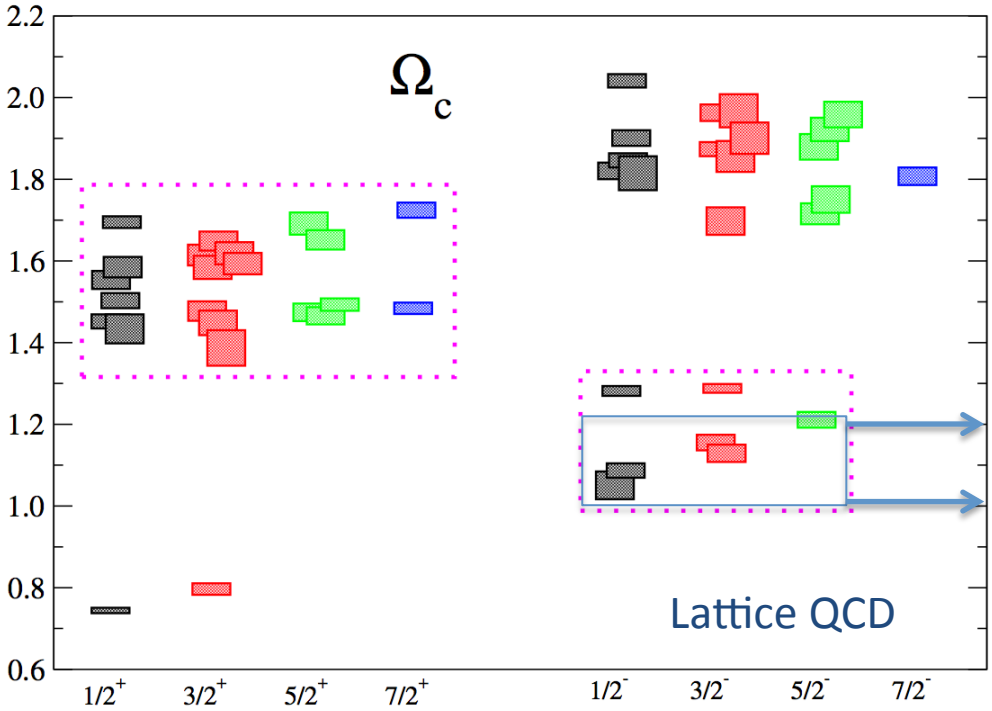


$E(\Xi_c^+ \; K^-) \; [GeV]$

Padmanath et al. 2013

[1311.4806, proc. CHARM2013]

$m - m_{Ds}$ [GeV]



3.2 GeV

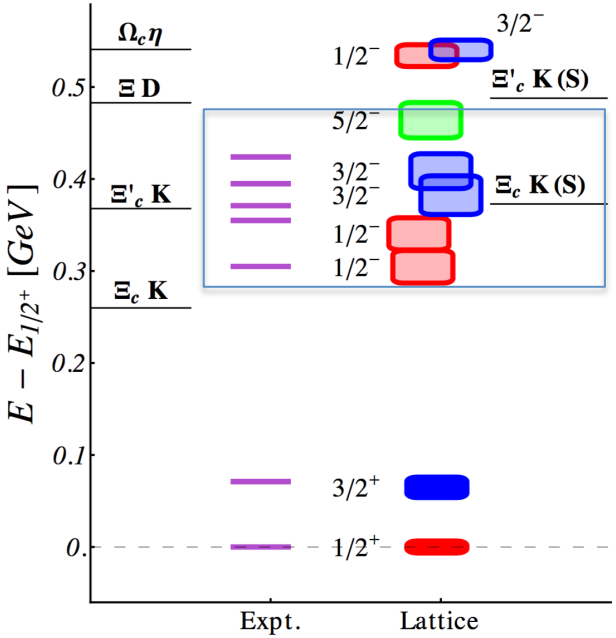
3.0 GeV

1/2- 3/2- 5/2-

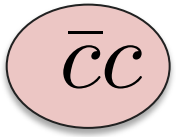
J^P

same results

Padmanath, Mathur, 1704.00259



Scalar $\chi_{c0}(2P)$ and its 2017 observation from Belle in D $\underline{D}$



Belle 1704.01872

Observation of an alternative $\chi_{c0}(2P)$ candidate in $e^+e^- \to J/\psi D\bar{D}$

$m = 3862^{+26}_{-32}{}^{+40}_{-13}$ MeV $\Gamma = 201^{+154}_{-67}{}^{+88}_{-82}$ MeV 0^{++} preferred as quantum number

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Lattice QCD prediction from 2015:

first D $\underline{D}$ simulation on the lattice [Lang, Leskovec, Mohler, S.P., JHEP15, 1503.05363]

- scattering matrix and cross-section determined via Luscher's method
- masses and strong-decay width of the resonance
- s-wave: BW-type fit in resonance region (but more through simulation needed in the future)

m = 3966 ± 20 MeV Γ= 67 ± 18 MeV (note huge errors on exp and th. widths)

Hadro-quarkonium

Alberti et al, 1608.06537, PRD

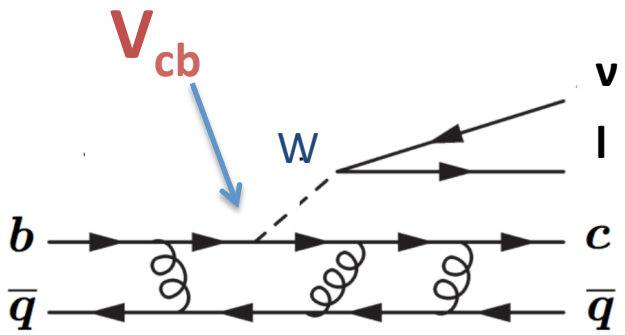
quarkonium ($\underline{Q}Q$)) + a light hadron (meson or baryon)

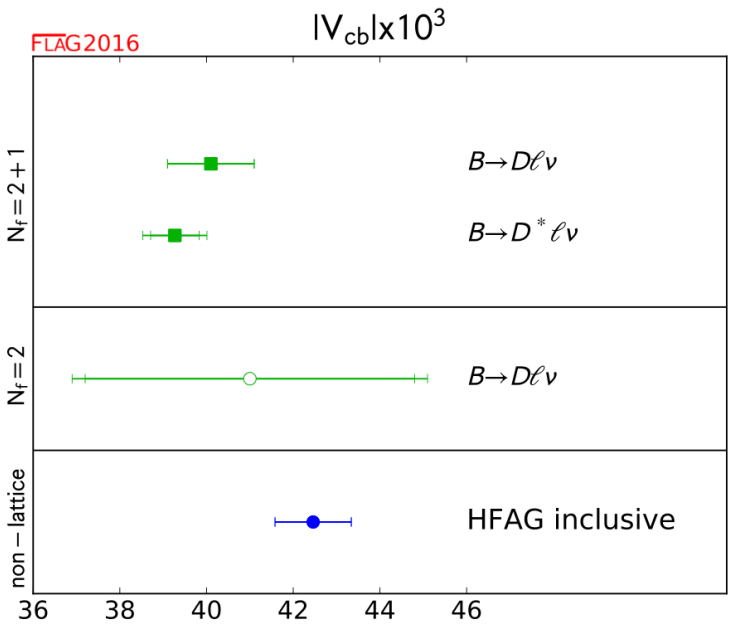
- modification of V(r) between $\underline{Q}Q$ in presence of a light hadron
- modification of $\underline{Q}Q$ binding energy in presence of a light hadron

} - few MeV modifications found
- no new bound states claimed

b→c l ν : exclusive and inclusive

tension between inclusive and exclusive V_{cb}





New preliminary B→D* l ν at zero recoil

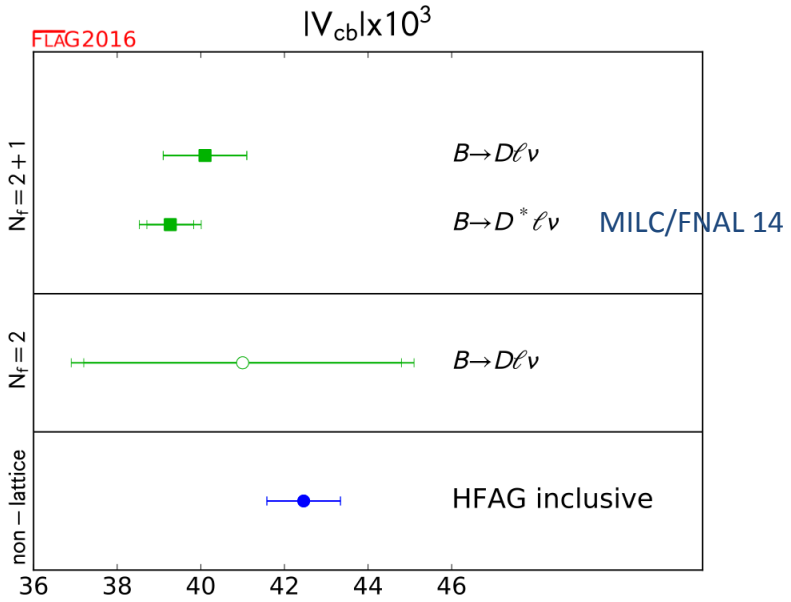
b→c l ν

Motivation:
tension between inclusive and exclusive Vcv

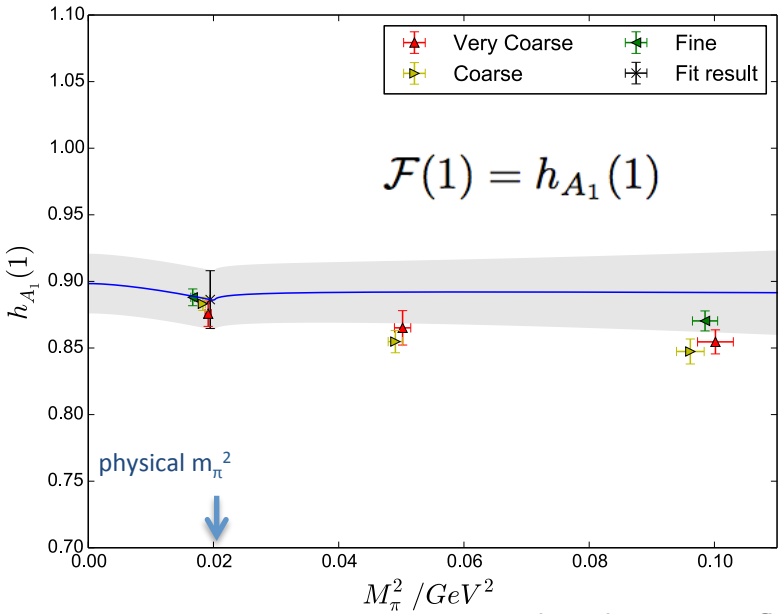
$$\frac{d\Gamma}{dw}(B \to D^* l\bar{\nu}) \propto |V_{cb}|^2 \mathcal{F}(w)^2$$

zero recoil $\vec{p}_B = \vec{p}_{D^*} = \vec{q} = \vec{0}$

$$w = v \cdot v' = 1$$



update on 1612.06716



- existing most precise published value MILC/FNAL 2014 [PRD89 114504]
  - Fermilab action for c and b quarks
  - Vcb: tension with inclusive (resulting value for Vcb taken from PDG 16)

$$\mathcal{F}(1) = 0.906(4)(12) \ \rightarrow \ |V_{cb}| = (38.9 \pm 0.5 \pm 0.5 \pm 0.2) \times 10^{-3}$$

- preliminary value HPQCD [update on 1612.06716 (proceedings of Lattice 16), private communication with Harrison and Wingate]
  - c quark: relativistic HISQ ; b quark: NRQCD ; zero recoil
  - Vcb closer to inclusive value

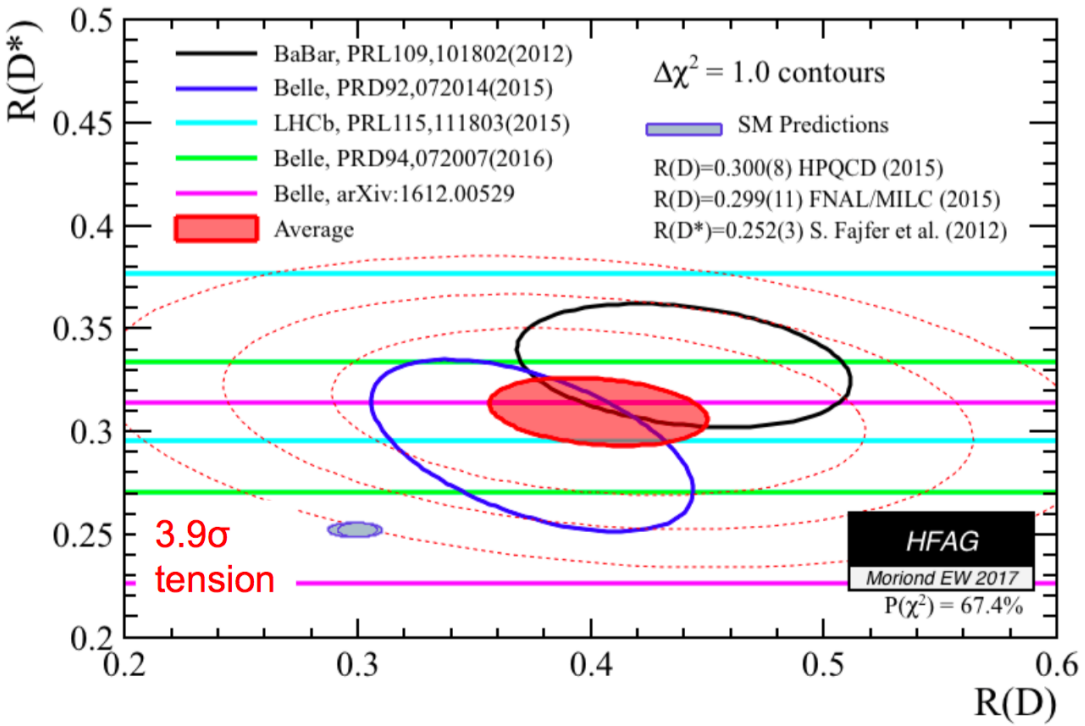
$$\mathcal{F}(1) : \text{left plot} \qquad \rightarrow \ |V_{cb}| = (40 \pm ?) \times 10^{-3} \quad \text{(preliminary)}$$

Still no dynamical results on B→D* l ν beyond zero-recoil

b →c l ν

That would be valuable to confirm the Standard Model prediction for

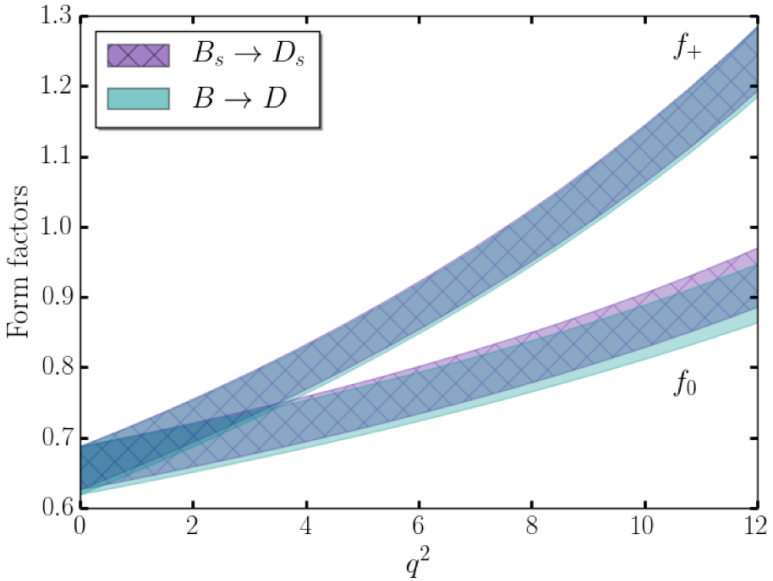
$$R(D^*) = \frac{Br(B \to D^* \tau \bar{\nu})}{Br(B \to D^* \mu \bar{\nu})}$$



$B_s \to D_s\, l\, \underline{\nu}$ in whole q^2 region

[HPQCD, 1703.09728]

$b \to c\, l\, \underline{\nu}$



PDG quotes only $B_s \to D_s\, l\, \underline{\nu}$ + anything

c-quark : relativistic HISQ
b-quark: NRQCD

results agree with only existing previous result
[Atoui et al, EPJC74 2861 (4014)]

compared to B→D [HPQCD, PRD 2015]

Fragmentation functions f_s/f_d needed in $B_s \to \mu\mu$

[HPQCD, 1703.09728]

$$\mathcal{B}(B_s \to \mu^+\mu^-) = \mathcal{B}(B_q \to X)\frac{f_q}{f_s}\frac{\epsilon_X}{\epsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}$$

$$\frac{f_0^{B_s\to D_s}(M_\pi^2)}{f_0^{B\to D}(M_K^2)} = 1.000(62), \quad \longrightarrow \quad \frac{f_s}{f_d} = 0.310(30)_{\rm stat.}(21)_{\rm syst.}(6)_{theor.}(38)_{\rm latt.}$$

$$\frac{\mathcal{B}(\overline{B}_s^0 \to D_s^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^+K^-)}$$

exp. ratio of nonleptonic decays

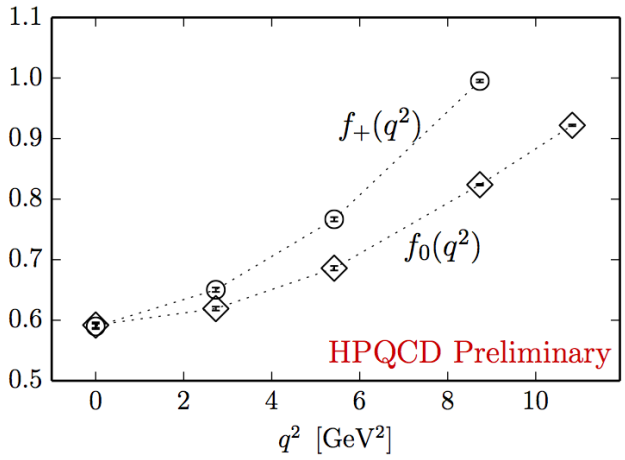
+ factorization [Fleischer et a. 2010]

First dynamical calculation of $B_c \to$ charmonium l $\underline{\nu}$

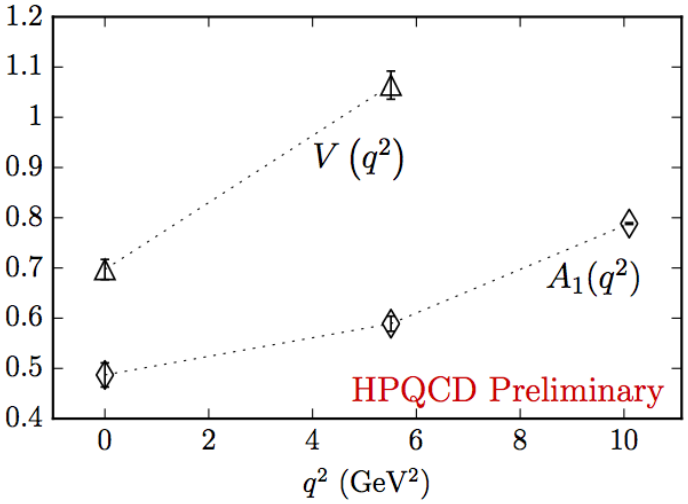
[HPQCD, proceedings of Lattice 2016, 1611.01987]

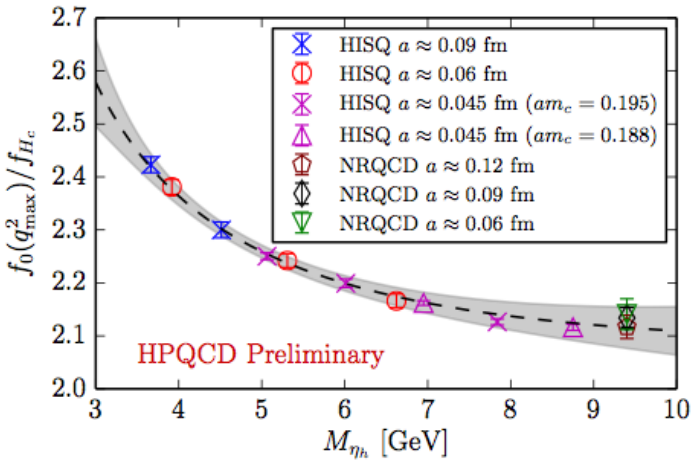
$b \to c$ l $\underline{\nu}$

$B_c \to \eta_c$ l $\underline{\nu}$



$B_c \to J/\Psi$ l $\underline{\nu}$





heavy quark treatment:

c quark: relativistic HISQ

b quark: (1) relativistic HISQ for range of m_Q

(2) NRQCD at $m_Q = m_b$

(1) and (2) lead to consistent results (left Fig.): good !

Towards inclusive semileptonic decays

S. Hashimoto, 1703.01881

$B \to X_c\, l\bar{\nu}$

b →c l ν

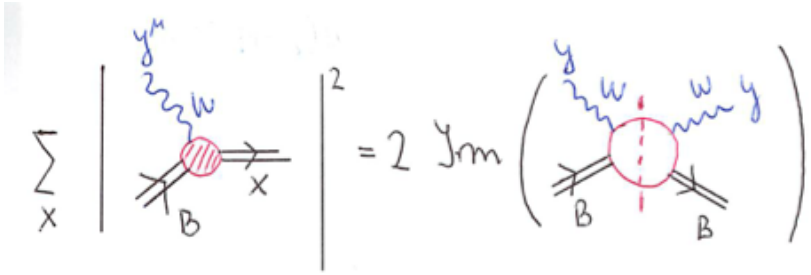
$$H = V_{cb}\frac{G_f}{\sqrt{2}}\,\bar{l}\gamma_\mu(1-\gamma_5)\nu\;\underbrace{\bar{c}\gamma^\mu(1-\gamma_5)b}_{J^\mu=V^\mu-A^\mu}$$

$$|\mathcal{M}|^2 = |V_{cb}|^2 G_F^2 M_B\; l^{\mu\nu}\; W_{\mu\nu}$$

$$W_{\mu\nu} = \sum_{X=D,D^*,..} (2\pi)^3\delta^4(p_B - q - p_x)\frac{1}{2M_B}\,\langle B(p_B)|J_\mu^\dagger(0)|X\rangle\,\langle X|J_\nu(0)|B(p_B)\rangle$$

$$W = -\frac{1}{\pi}\,\mathrm{Im}T$$

optical theorem



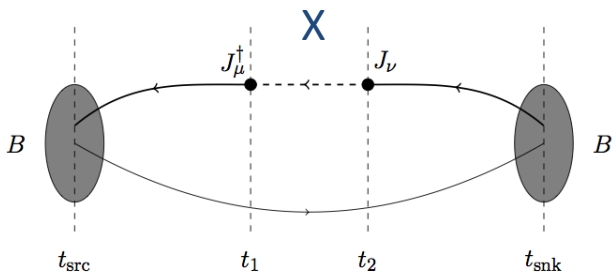
$$T^{\mu\nu} = i\int d^4x\; e^{-iqx}\frac{1}{2M_B}\langle B|T\{J_\mu^\dagger(x)J_\nu(0)\}|B\rangle$$

$$T^{JJ}_{\mu\nu}(\omega,\vec{q}) \propto \int_0^\infty dt\; e^{\omega t}\int d^3x\; e^{i\vec{q}\vec{x}}\;\langle 0|B(\vec{p}_B{=}\vec{0},t_{snk})\;J_\mu^\dagger(\vec{x},t_2)\;J_\nu(0,t_1)\;B^\dagger(\vec{0},t_{src})|0\rangle$$

on the Lattice T is computed from 4-point function

q=momentum of state X

ω = energy of state X



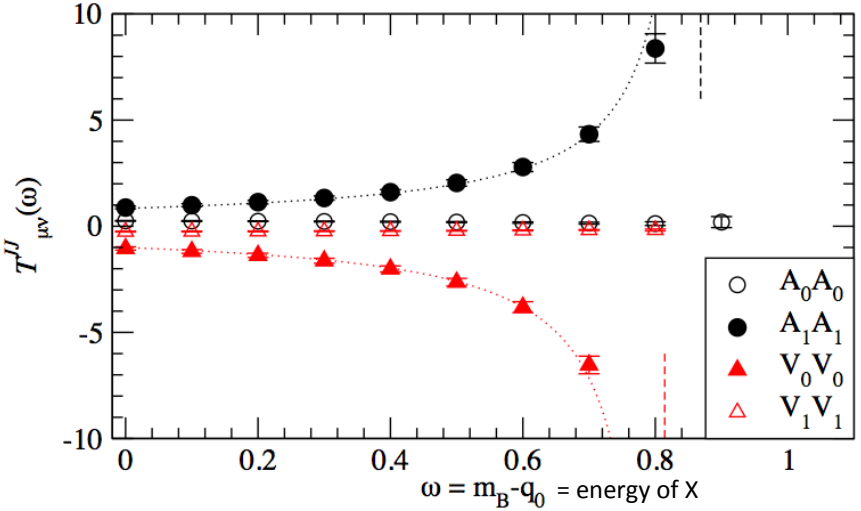
Lattice study of inclusive semileptonic decays

S. Hashimoto, 1703.01881

$B_s \to X_c\, l\bar{\nu}$ $\quad H = V_{cb}\frac{G_f}{\sqrt{2}}\,\bar{l}\gamma_\mu(1-\gamma_5)\nu\;\bar{c}\gamma^\mu(1-\gamma_5)b$ $\quad X_c=D_s, D_s^*,\ldots$

$J^\mu=V^\mu-A^\mu$

- spectator quark is s
- zero recoil: $\vec{q}=\vec{0}$



V_0V_0 dominated by $X=D_s$ pole (red dashed)

A_1A_1 dominated by $X=D_s^*$ pole (black dashed)

$$T_{00}^{VV}(\omega,\vec{0}) = \frac{|h_+(1)|^2}{M_{D_s}-\omega} \qquad T_{11}^{AA}(\omega,\vec{0}) = \frac{|h_{A_1}(1)|^2}{M_{D_s^*}-\omega}$$

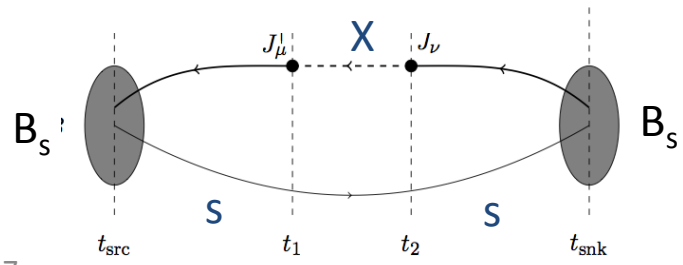
- HQET form factors determined in this way

agree with direct computation but have larger errors

- V_1V_1 and A_0A_0 contain X with other quantum num.

$$T^{JJ}_{\mu\nu}(\omega,\vec{q}=0) \propto \int_0^\infty dt\, e^{\omega t} \int d^3x\, \langle 0|B_s(\vec{p}_B{=}\vec{0},t_{snk})\, J^\dagger_\mu(\vec{x},t_2)\, J_\nu(0,t_1)\, B_s^\dagger(\vec{0},t_{src})|0\rangle$$

- on the Lattice T is computed from 4-point function
- will allow access to further understanding of tension between inclusive and exclusive V_{cb} and V_{ub}



news on $q \to q' \, l \, \bar{\nu}$ and $q \to q' \, l^+ \, l^-$ in exclusive baryon decays

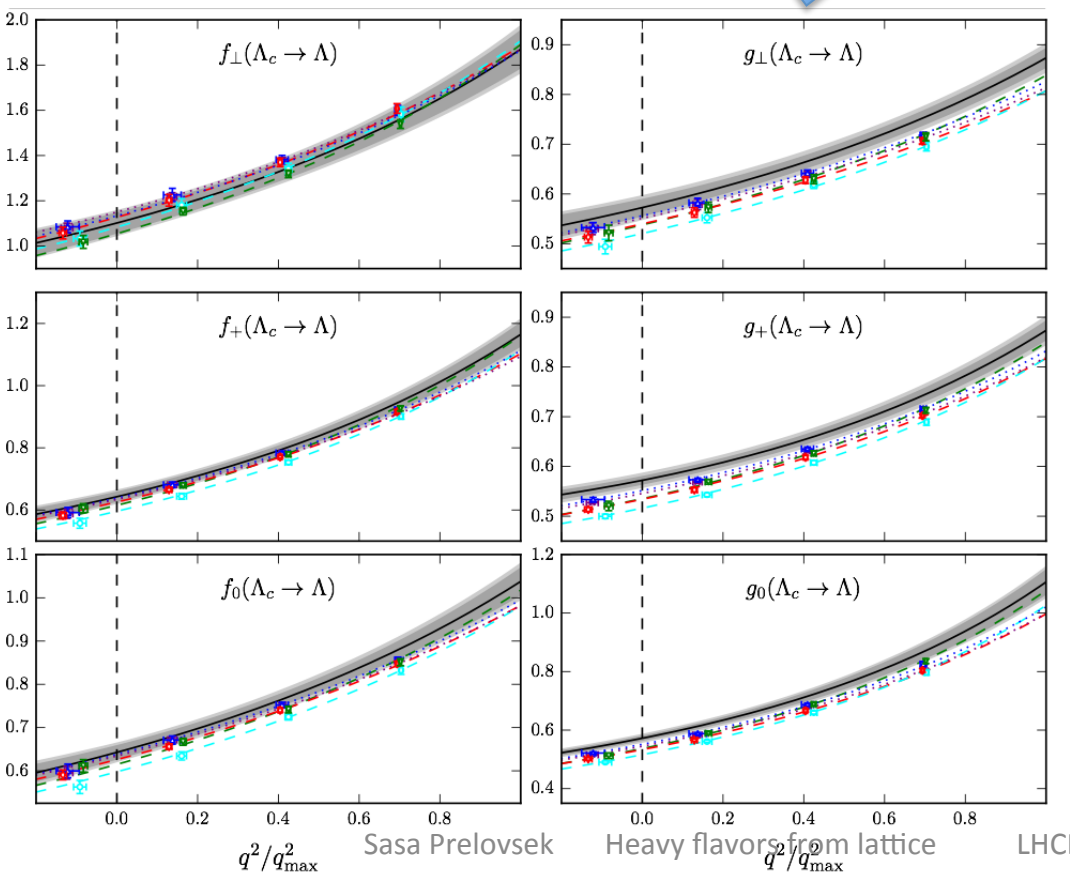
c→s l ν & first determination of $\Lambda_c \to \Lambda$ l ν form factors

$$|V_{cs}| = \begin{cases} 1.008(5)(16) & \text{from } D_s \to \ell^+\nu_\ell \text{ [5, 6]}, \\ 0.975(25)(7) & \text{from } D \to K\ell^+\nu_\ell \text{ [6, 7]}, \\ 0.97344(15) & \text{indirect, CKM unitarity} \end{cases}$$

V_{cs} from $\Lambda_c \to \Lambda$ l ν

$$|V_{cs}| = \begin{cases} 0.951(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(56)_{\mathcal{B}}, & \ell = e, \\ 0.947(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(72)_{\mathcal{B}}, & \ell = \mu, \\ 0.949(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(49)_{\mathcal{B}}, & \ell = e, \mu, \end{cases}$$

[Meinel, 1611.09696, PRL 2017]: lattice form factors



$$\mathcal{B}(\Lambda_c \to \Lambda\ell^+\nu_\ell) = \begin{cases} 0.0363(38)(20), & \ell = e, \\ 0.0349(46)(27), & \ell = \mu. \end{cases}$$

[BESIII, PRL, 2015]

motivations:

- determination of V_{cs}
- given V_{cs} : test of lattice studies of heavy baryon approach
- this channel useful for normalization modes

	Probes all Dirac structures	Final hadron QCD-stable	Charged hadrons from b-decay vertex	LQCD Refs.
$B^+ \to K^+\ell^+\ell^-$	×	✓	✓	[6, 7, 8, 9]
$B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$	✓	×	✓	[10, 11, 12]
$B_s \to \phi(\to K^+K^-)\ell^+\ell^-$	✓	×	✓	[10, 11, 12]
$\Lambda_b^0 \to \Lambda^0(\to p^+\pi^-)\ell^+\ell^-$	✓	✓	×	[13, 14, 15]
$\Lambda_b^0 \to \Lambda^{*0}(\to p^+K^-)\ell^+\ell^-$	✓	×	✓	This work

Table 1: Comparison of exclusive $b \to s\ell^+\ell^-$ decay channels.

[6] C. Bouchard *et al.* (HPQCD Collaboration), Phys. Rev. D **88**, 054509 (2013).
[7] C. Bouchard *et al.* (HPQCD Collaboration), Phys. Rev. Lett. **111**, 162002 (2013).
[8] J. A. Bailey *et al.* (Fermilab Lattice and MILC Collaborations), Phys. Rev. D **93**, 025026 (2016).
[9] D. Du *et al.* (Fermilab Lattice and MILC Collaborations), Phys. Rev. D **93**, 034005 (2016).
[10] R. R. Horgan, Z. Liu, S. Meinel, and M. Wingate, Phys. Rev. D **89**, 094501 (2014).
[11] R. R. Horgan, Z. Liu, S. Meinel, and M. Wingate, Phys. Rev. Lett. **112**, 212003 (2014).
[12] J. Flynn, A. Jüttner, T. Kawanai, E. Lizarazo, and O. Witzel (RBC and UKQCD Collaborations), PoS LATTICE **2015**, 345 (2016).
[13] W. Detmold, C.-J. D. Lin, S. Meinel, and M. Wingate, Phys. Rev. D **87**, 074502 (2013).
[14] W. Detmold and S. Meinel, Phys. Rev. D **93**, 074501 (2016).
[15] S. Meinel and D. van Dyk, Phys. Rev. D **94**, 013007 (2016).

$$R(K^*) = \frac{Br(B \to K^*\mu^+\mu^-)}{Br(B \to K^*e^+e^-)}$$

no new lattice results concerning $B \to K^* l^+l^-$ since summer 2016

$b \to s\ l^+l^-$ & towards $\Lambda_b \to \Lambda^*(1520)\ l^+l^-$ form factors

Meinel & Rendon [1608.08110, Lattice 2016 proceedings]

Experimental drawback with $\Lambda_b \to \Lambda\ l^+l^-$: ground state Λ is electrically neutral and long-lived

→ worth experimentally exploring decays to Λ^* resonances which can immediately decay into charged particles and produce tracks that originate from b-decay vertex

→ many Λ^* resonances exist: **narrow $\Lambda^*(1520)$** with $J^P=3/2^+$ strikes out : $\Gamma \approx 15$ MeV, decays to $NK, \Sigma\pi, \Sigma\pi$

→ $\Lambda^*(1520)$ treated as strongly stable in the lattice simulation

→ preliminary lattice results for 14 form factors

Conclusions for the time being

Thanks to experimentalists for providing lots of puzzling hadrons ...

Theoretical study requires non-perturbative treatment of strong interaction → lattice QCD

- **Strongly stable hadrons** B, D, K, N,.. ...
  - masses ✔✔✔✔

  - exclusive weak and EM transitions between them: increasing precision, variety of transitions ✔✔✔

  - inclusive semileptonic decays ✔

- **Lattice QCD can extract scattering matrix and cross-section for scattering of two hadrons**

  this gives access to conventional and exotic **strongly decaying hadron resonances:**
  - in one-channel scattering ✔✔
  - in two or three channel scattering ✔ : most of exotic exp. candidates fall in this category

- **Lots of exciting and challenging problems remain to be attacked**