$B \to D$ and $B_s \to D_s^{(*)}$ semileptonic decays on the lattice

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Summary

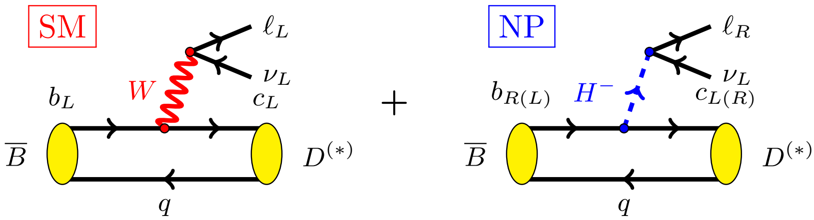
Introduction

1. Physical motivation
2. Lattice QCD for *b*-physics
3. Ratio method

Semileptonic form factors

1. $B_{(s)} \to D_{(s)}$ - based on Eur.Phys.J. C74 (2014)
2. $B_{(s)} \to D^*_{(s)}$ - fresh new for this conference

$B_{(s)} \to D_{(s)}^{(*)}$ semileptonic decays



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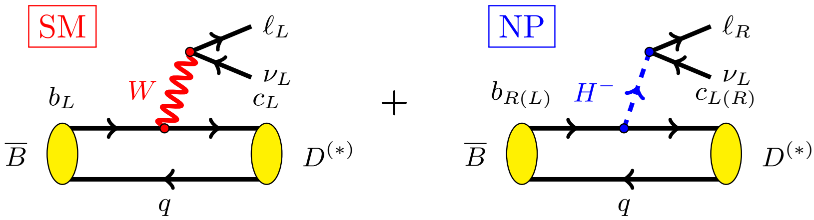

Popular test of New Physics

$$R(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu)}, \qquad R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu)}, \ (\ell = e, \mu)$$

Ratios useful to **cancel/reduce** theoretical uncertainties in V_{cb}/f.f

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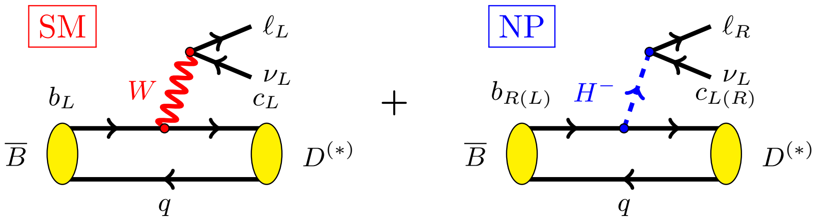

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BaBar ('12)

$$R(D) = 0.440 \pm 0.058 \pm 0.042, \qquad R(D)^{SM} = 0.31 \pm 0.02$$

$$R(D^*) = 0.332 \pm 0.024 \pm 0.018, \qquad R(D^*)^{SM} = 0.252 \pm 0.003$$

- Larger than the SM expectations! **New Physics?**
- Need form factors $f_{+,0,T}^{B \to D}$ to check SM and constraint the NP contribution
- Would be nice to check also the unmeasured $B_s \to D_s\ell\nu$ process (easier on the lattice)

Goal of this research

Form factors relevant for $B_{(s)} \to D_{(s)}$

Embeds the **non-perturbative dynamics** entering $d\Gamma(B_{(s)} \to D_{(s)}\ell\nu_\ell)/dq^2$

- Convenient parameterization (HQET motivated) in terms of $\mathcal{G}(\omega)$ [$\omega = v_B \cdot v_D$ rel.velocity]

$$\frac{1}{\sqrt{m_{B_{(s)}} m_{D_{(s)}}}} \langle D_{(s)}(k) | V_\mu | B_s(p) \rangle \propto \mathcal{G}(\omega) + corr.$$

- $\mathcal{G}$ can be expressed in terms of the standard form factors $f_+(q^2)$ and $f_-(q^2)$
- $\mathcal{G}(1) = 1$ up to radiative and $1/m_h$ corrections, **important** to compute $\mathcal{G}(1)$ on the lattice

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Other form factors

- Scalar form factor f_0: necessary in the SM in the case of **heavy lepton** and to check on a non-zero contribution from the diagram mediated by a **charged Higgs** boson
- Tensor form factor f_T: **leptoquark** scenarios, NP with vector bosons allowing **tensor couplings**
- Need to move away from zero recoil $\omega = 1$ [i.e. $q^2_{max} = (m_{B_{(s)}} - m_{D_{(s)}})^2$]

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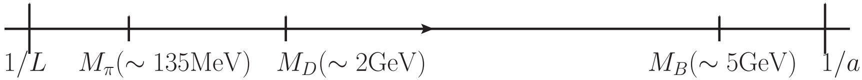
Results of our study

- Central result: form factor for unmeasured $B_s \to D_s\ell\nu$ close to zero recoil, **easier on the lattice**
- Error for $B \to D$ form factor **large: no impact** on V_{cb} with current lattice statistics
- New results at this conference: $B_s \to D_s^*$ axial and tensor form factors at zero recoil
- Results by Fermilab collaboration much more precise but subjects to different systematic errors

Approaching b physics



$M_B/M_\pi \sim 50 \quad \to \quad L/a \gg 50 \quad \to \quad N_{points} \gg 50^4 \quad \to \quad$ too many points!

Moreover: technical problems in going to too-small lattice spacings (breaking of ergodicity?)

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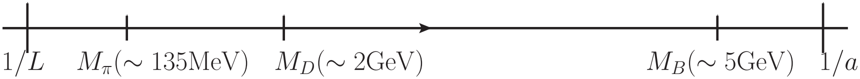

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- Heavy Quark Effective Theory (continuum expansion in $\mathbf{\Lambda_{QCD}/m_b}$): ALPHA coll.
- Propagating Heavy Quarks (reinterpretation in therms of **$\mathbf{1/m_b}$ expansion**): FNAL-MILC coll.

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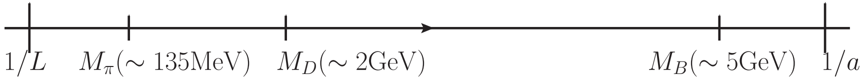

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Separation of scales, Special actions

- Use of step scaling function to **separate various scales** (a, m_b, L): ALPHA coll.
- **Special actions** have been designed to deal with b quarks (HISQ, ...): HPQCD coll.

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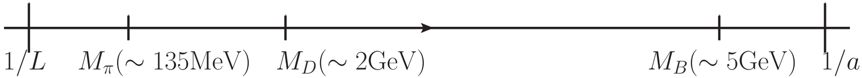

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This Work: Extrapolate results from the charm to the bottom region

- Scaling laws **often known** in effective theories
- Use **exact** information coming from the **static limit**
- Results become more reliable as lattice spacings get smaller

Ratio method [cfr. R.Frezzotti et al., JHEP 1004 (2010)]

Consider a series of masses $m^{(0)} = m_c,\ m^{(1)} = \lambda m_c,\ \dots\ m^{(n)} = \lambda^n m_c$

- Define: $\sigma_i = \frac{\mathcal{G}(1, \lambda m_h, m_c)}{\mathcal{G}(1, m_h, m_c)}$ ratio of form factors at consecutive masses
- Form factor decomposes as: $\mathcal{G}(1,\ m_b,\ m_c) = \sigma_n \sigma_{n-1} ... \sigma_1 \sigma_0 \mathcal{G}\,(1,\ m_c,\ m_c)$ $\rightarrow$ $1\,(\mathrm{charge\,conservation})$
- HQET imposes that in the static h-quark: $\lim_{m_h \to \infty} \sigma(m_h) = 1$

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Reconstructing the form factor at physical b

- Compute $\sigma\left(m_h^{(n)}, \lambda; m_l,\ a\right)$, extrapolate to the continuum & physical m_l
- Fit $\sigma\left(m_h\right)$ enforcing $\lim_{m_h \to \infty} \sigma(m_h) = 1$ constraint
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Advantages of the ratio approach: double constraint

Elastic case constraint

- Requires only to interpolate ratios $\sigma(m_h)$
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HQET constraint

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Home message: we study the scaling toward the static limit taking advantage of **all symmetries**

Lattice setup

Desired features

Continuum: Several lattice spacings to take continuum limit

Renormalization: Non perturbative

b-quark: Work directly with a relativistic b quark at physical mass

Unquenching: Include 2 physical light, strange and charm dynamical quarks

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What we currently have...

Wilson regularization of QCD with twisted mass term (tmQCD)

Continuum: 4 different lattice spacings ($a \in [0.054; 0.100]$ fm)

Renormalization: Non perturbative (RI-MOM), good for non-vector currents

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QCD gauge field configurations produced by ETM collaboration

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Salient features (why are we different from next speaker?)

- Consider smart ratios to **interpolate** relativistic data to m_b^{phys} between m_c and $m_h \to \infty$
- Possible to determine **fully non-perturbatively** form factors different from vector one

Form factor computation

$$\langle H_2(\vec{p}_2)|\, V_\mu \,|H_1(\vec{p}_1)\rangle = p_\mu f_+^{H_1\to H_2}\left(q^2\right) + q_\mu \frac{M_{H_1}^2 - M_{H_2}^2}{q^2} f_0^{H_1\to H_2}\left(q^2\right) \qquad \begin{cases} p = p_1 + p_2 \\ q = p_1 - p_2 \end{cases}$$

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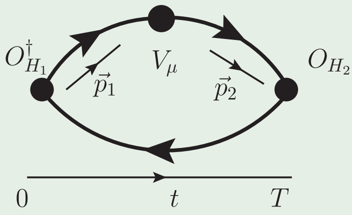
Three point correlation functions

$$C_\mu^{(3)}(t) = \langle \textstyle\sum_{\vec{x},\vec{y}} O_{H_2}^\dagger(\vec{x},\ T)\, e^{-i\vec{p}_2\vec{x}} V_\mu(\vec{y},\ t)\, O_{H_1}(0)\rangle$$

at intermediate times:

$$\overset{0\ll t\ll T}{\simeq} \frac{Z_{H_1} Z_{H_2} \exp[(E_{H_1} - E_{H_2})t]\langle H_1|V_\mu|H_2\rangle}{4E_{H_1}E_{H_2}}$$



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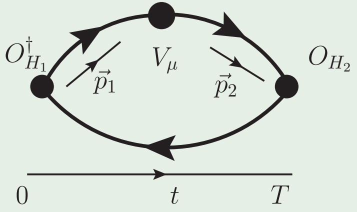
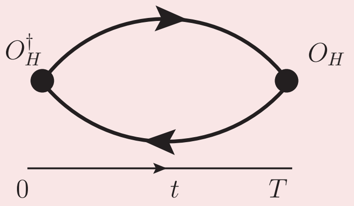


Two points correlation functions: used to remove the sources

$$C^{(2)}(t) = \textstyle\sum_{\vec{x}}\langle O_H(\vec{x},t)\, O_H^\dagger(\vec{0},0)\rangle$$

at large times:

$$\overset{t\to\infty}{\simeq} \frac{{Z_H}^2 \exp(-E_H t)}{2E_H}$$



Correlation functions (two point ones)

Choose a lattice discretization of QCD, in Euclidean space

$$a^4 \mathcal{S}_{lat}^{QCD} = \bar{\psi}_n D_{n,\,m} \psi_m + S_{lat}^{gauge} \underset{a\to 0}{\longrightarrow} S_{cont}^{QCD} = \bar{\psi}\left(\not{D} + m\right)\psi + \frac{1}{4} G_{\mu\nu} G_{\mu\nu}$$

Sample **numerically** (with Monte Carlo methods) the configuration space:

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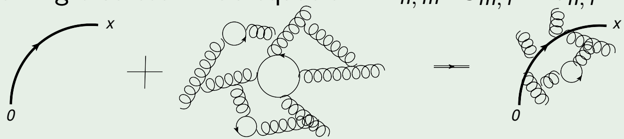
- Compute propagator solving discrete Dirac equation: $D_{n,\,m} \cdot S_{m,\,l} = \delta_{n,\,l}$



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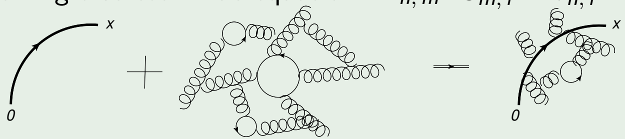

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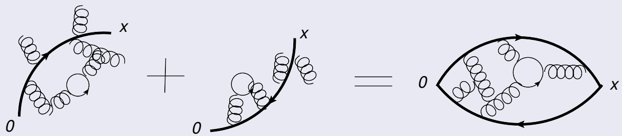
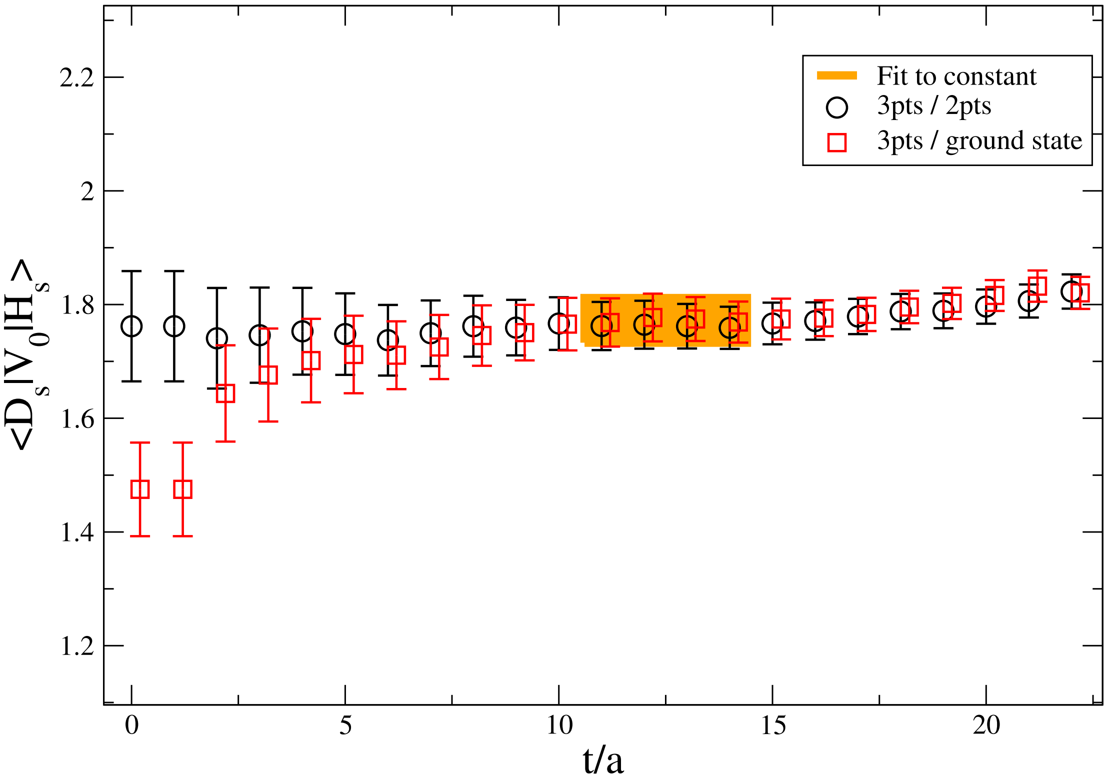
Combine 2 propagators with suitable Dirac structures

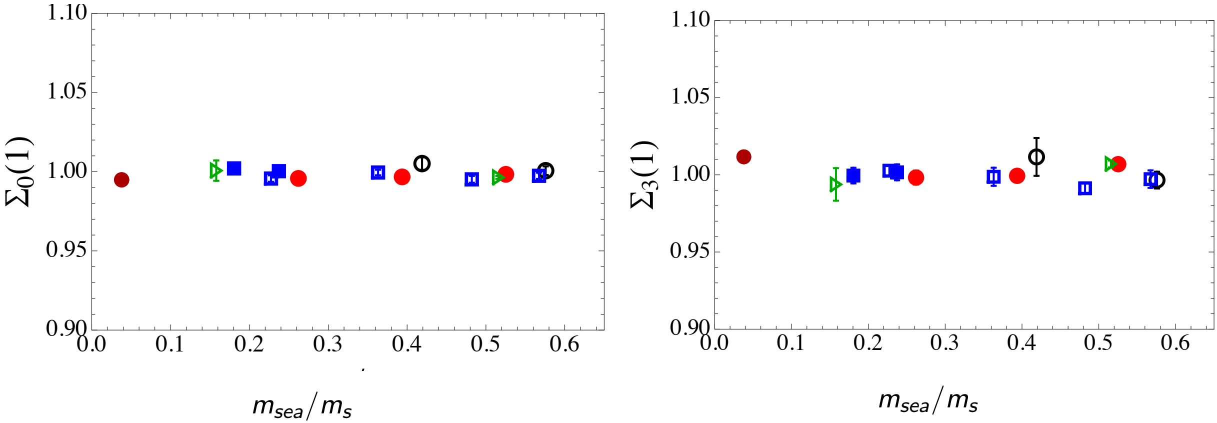


$\langle \bar{\psi}(0)\Gamma_1\psi(0) \cdot \bar{\psi}(x)\Gamma_2\psi(x)\rangle \rightarrow$ Fully non-perturbative correlation function

Example of determination of $\langle D_s | V_0 | H_s(\sim 2m_c) \rangle$



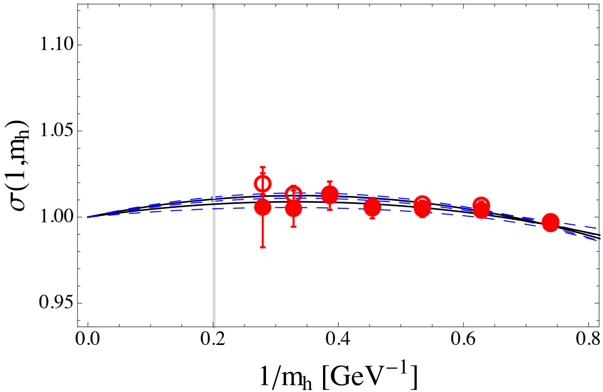
Chiral and continuum limit extrapolation for ratios



Chiral continuum extrapolation

- Fit ansatz: $\Sigma_k(1) = \alpha_k + \beta_k \frac{m_{sea}}{m_s} + \gamma_k a^2$
- Very smooth continuum extrapolation
- Negligible dependance in m_{sea} (perfectly fitted if $\beta_k = 0$)
  (expected since m_{sea} dependance occurs only through loop effects)
- Chiral logarithms cancel between numerator and denominator of the ratios

Interpolation to b quark mass



$B_s \to D_s$ vector form factor

- Final Results: $\mathcal{G}^{B_s \to D_s}(1) = 1.052(46)$. If no chiral extrapolation included: 1.073(17)
  M.Atoui, V.Morénas, D.Bečirevic, FS, Eur.Phys.J. C74 (2014)
- De Divitiis et al. (Phys.Lett.B '07): $\mathcal{G}^{B \to D}(1) = 1.026(17)$ ✓ Step scaling method ✗ Quenched
- MILC+Fermilab: 1.074(24), Preliminary results at Lattice '04

Other form factors (first computation of f_T) near zero recoil

$$f_0\left(q_0^2\right)/f_+\left(q_0^2\right) = 0.77(2), \qquad f_T\left(q_0^2\right)/f_+\left(q_0^2\right) = 1.08(7) \qquad \text{at } q_0^2 = 11.5\,\mathrm{GeV}^2$$

The case of $B_s \to D_s^* \ell \nu$ (new results)

Non-perturbative quantities [hadronic matrix elements]

- Possible currents inducing this process: $T_{\mu\nu} = \bar{c}\sigma_{\mu\nu} b$, $A = \bar{c}\gamma_\mu\gamma_5 b$, $V = \bar{c}\gamma_\mu b$
- In total 7 form factors: Axial (A_1, A_2, A_3), Tensor (T_1, T_2, T_3) and Vector (V)
- At zero recoil only A_1 and T_2 contribute

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Form factors determination

- In Standard Model only A_1 contributes at zero recoil $\omega = 1$ [or $q^2 = (m_{B_{(s)}} - m_{D^*_{(s)}})^2$]
- In $B_s \to D_s^*$ case we consider $\mathcal{F}(1)$ form factor related to A_1
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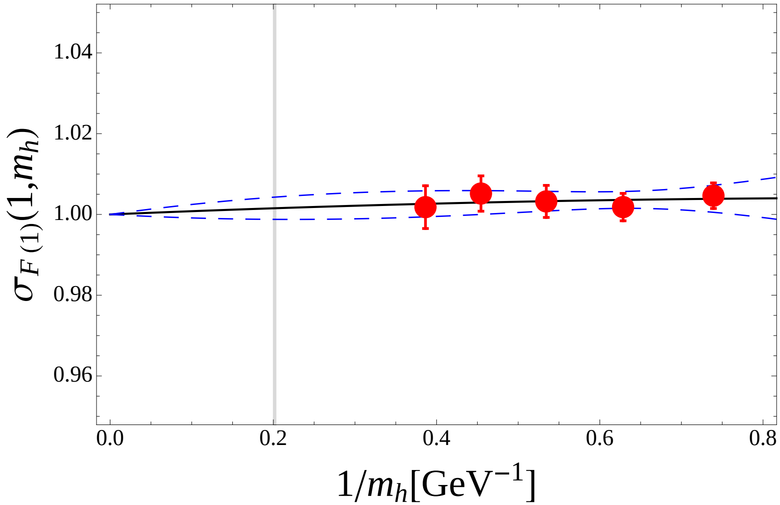
Ratio of Tensor/Axial form factor

- Same external fields that couple to B_s and D_s^*
- Determine T_2/A_1 directly from ratio of correlators, together with $Z_T(\mu)/Z_A$

$$\frac{T_2}{A_1} = \frac{Z_T}{Z_A} \frac{C^T_{3pts}(t)}{C^A_{3pts}(t)}$$

- Allow **high precision** determination of T_2/A_1

Interpolation of $B_s \to D_s^*$ to b quark mass

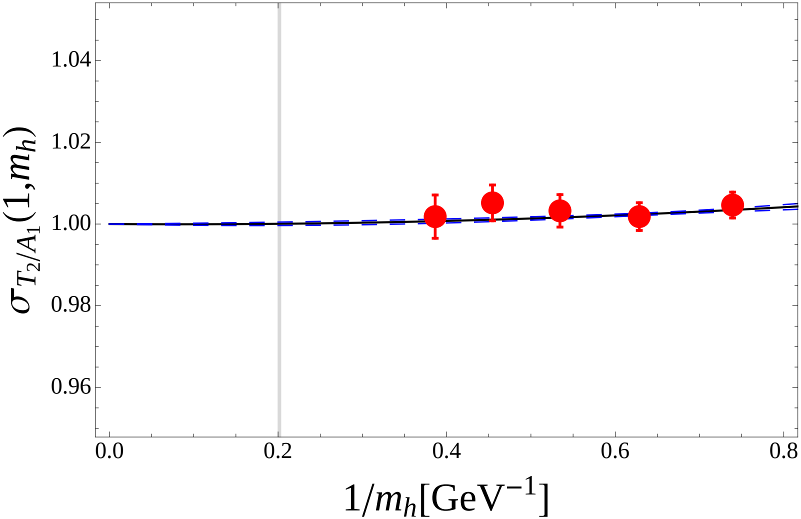


$B_s \to D_s^*$ axial form factor

- PRELIMINARY Result: $\mathcal{F}^{B_s \to D_s^*}(1) = 0.953(35)$
- Very recently Fermilab + MILC reported: $\mathcal{F}^{B \to D^*}(1) = 0.906(4)(12)$, PRD 89 114504 (2014)

(see next talk for more info!)

Tensor to axial form factor ratio



Considerations

- In HQET static limit the matrix element of Tensor and Axial currents are equal
- $1/M_h^2$ corrections to the relation could be large in the charm region
- It turns out they are instead VERY small!!!
- $T_2^{B_s \to D_s^*}/A_1^{B_s \to D_s^*}(\omega = 1; \mu = 2\mathrm{GeV}) = 1.073(5)$ (PRELIMINARY!)

Conclusions & future perspectives

$B_s \to D_s$ near zero recoil

- First unquenched determination of $\mathcal{G}^{B_s \to D_s}(1) = 1.052(46)$: compatible with previous results
- Determination of f_T/f_+ and f_0/f_+ important to constraint BSM low energy couplings
- So far statistics does not allow to study $B \to D$ at the precision needed to have impact on V_{cb}

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$B_s \to D_s^*$ at zero recoil

- Determination of $\mathcal{F}^{B_s\to D_s^*}(1) = 0.953(35)$
- The first computation of the ratio T_2/A_1 at zero recoil: very close to 1 (at $\mu = 2$ GeV)
  - important to constraint new physics models from $B_s \to D_s^* \ell\nu$
  - reveal the smallness of $1/M_h^2$-corrections to the static limit provided the QCD renormalization scale is $\mu \sim 2\,\mathrm{GeV}$

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Non-strange decay

- $B_s \to D_s^{(*)} \ell\nu$ decays still to be measured
- Invitation to experimentalists to measure these processes
- Strategy presented here can also be used to study the non-strange case
- Commitment to improve statistics and get a more accurate valued of $B \to D^{(*)} \ell \nu_\ell$ form factors

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Stay tuned!