Semileptonic Charm Decays on the Lattice

Alessandro Barone [1], Felix Erben [2], Jonathan Flynn [3], Andreas Jüttner[2,3]
Justus Tobias Tsang[4], **Aurelia Zuchanke**[4]
[1]PRISMA+, Johannes-Gutenberg-University Mainz [2]Theoretical Physics Department, CERN
[3]School of Physics and Astronomy, University of Southampton [4]Department of Mathematical Sciences, University of Liverpool

DiRAC High Performance Computing Facility
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Chromodynamics and the Lattice

The Standard Model (SM) summarises our current best understanding of particle physics. It is exceptionally accurate, but clearly incomplete.

- No energy frontier colliders likely the next decade(s)
- Indirect detection of new physics best option
- CKM matrix parametrises weak flavour change
- Strictly unitary in SM
- Non unitarity implies new physics
- Use precise results from LHCb, Belle II, BES III
- Future improvements from HL-LHC, FCC-ee
- Requires improved theoretical precision to determine

Quantum Chromodynamics (QCD) is the part of the SM that describes strong force interactions.

- Dominant interaction for hadrons
- Strongly coupled at low energies
- Renders perturbative methods non-viable
- Requires entirely different method

Lattice QCD is an ab initio nonperturbative method for calculating QCD results. It approximates spacetime as a finite discrete set of points. A typical calculation would involve the following steps:

(a) Generate gauge ensemble with size, dimension, fields
(b) Measure observable on each configuration
(c) Extract physical quantities via fitting
(d) Repeat for range of lattice spacings and volumes
(e) Extend to zero-spacing, infinite-volume, physical mass

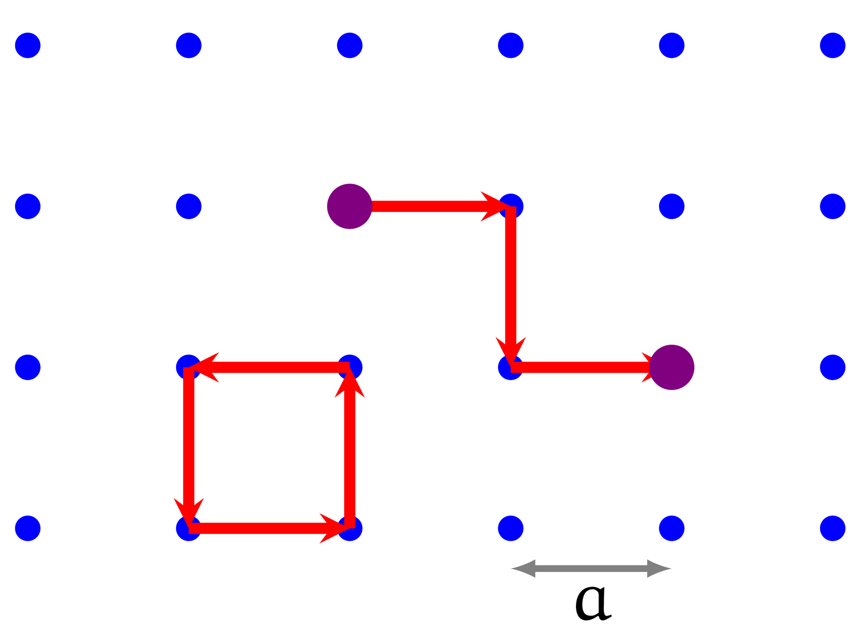


Figure 1: Two dimensional schema of a lattice. Quarks situated on lattice sites, gauge field on links.

Semileptonic Decays

We compute exclusive semileptonic decay rates for range of processes and will address major tension between different lattice results [1].

- Exclusive: specific particles in final state
- Flavour changing transitions probe CKM
- Parameterised by form factors depending on q^2

$$q^2 \coloneqq (p^I_\mu - p^F_\mu)^2$$

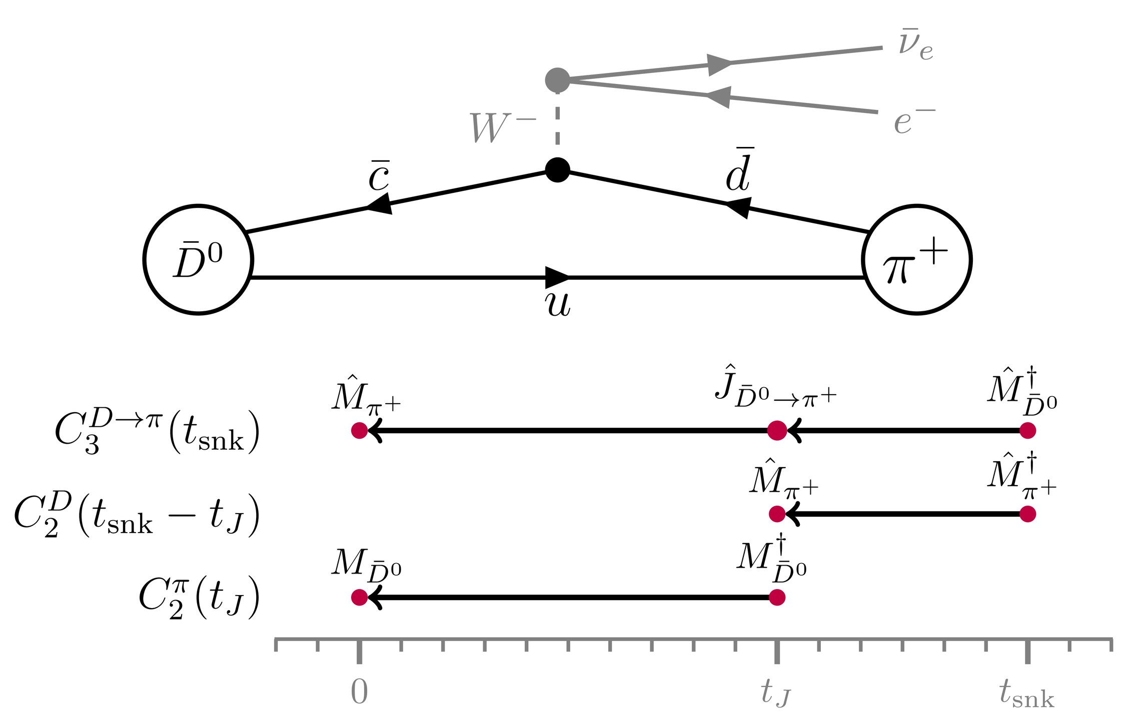
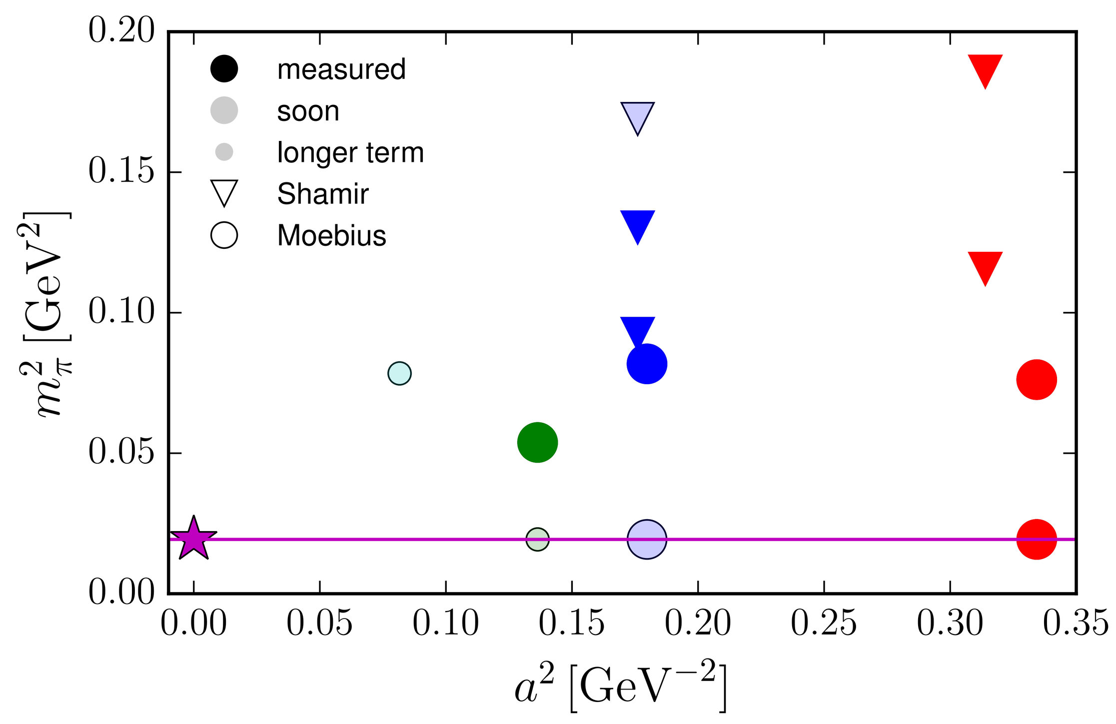


Figure 2: *top:* Quark flow diagram for $D \to \pi$. *bottom:* Relevant correlation functions on the lattice. Quark component structurally identical for other semileptonic decays.

Our Data



We have a significant amount of data over a range of ensembles and decay processes.

- $N_f = 2+1$ sea domain wall fermions (DWF)
- 3 lattice spacings
- $c \to l, s$ via sequential solves
- l, s and c-quarks use DWF
- Induce definite momenta via Fourier transform
- Include initial state at rest and with momentum
- Allows better q^2 coverage, more currents with signal
- $\mathcal{O}(5)$ source-sink separations in fw and bw direction
- $\mathcal{O}(10)$ final state momenta
- Multiple source positions and all mode averaging

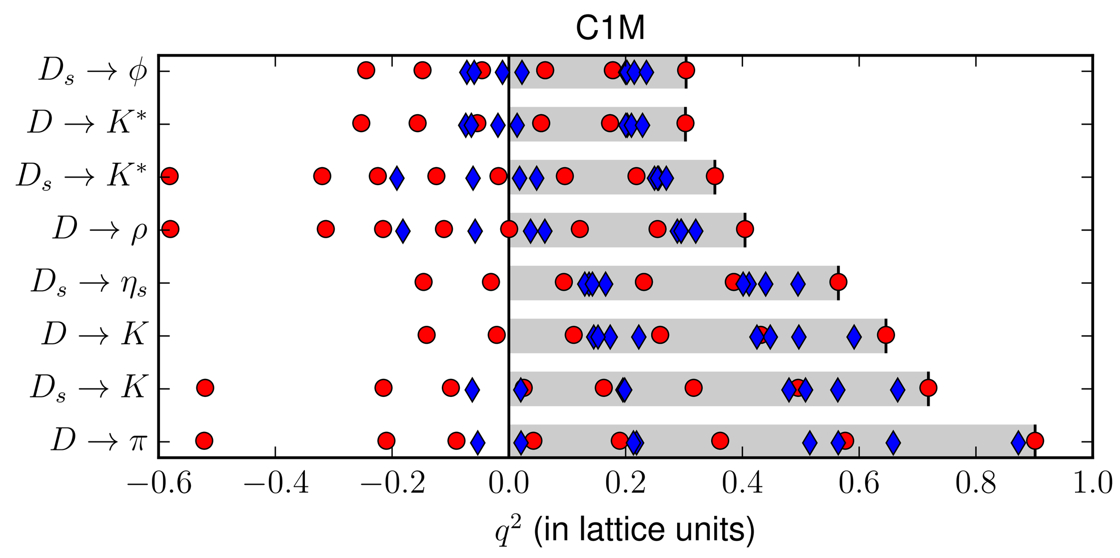


Figure 3: Range of q^2 values covered by dataset. Red circles (blue diamonds) initial state at rest (with momentum).

Blinding

To reduce bias 3pt data was blinded by applying

$$C^{I\to F}_{3,\text{blind}} = \left(1 + \alpha_{I\to F} + \beta_{I\to F}(\vec{p}_i^{\,2} + \vec{p}_f^{\,2})\right) C_3^{I\to F},$$

where $\alpha_{I\to F}$ and $\beta_{I\to F}$ are blinding factors, for the process I decaying to F.

- α between -0.5 and 0.5
- β between -1.0 and 1.0
- Different for each decay channel
- Momentum factor blinds q^2 dependence of form factor
- Allows partial unblinding for $q^2_{\max}$ benchmark result

Excited States and Laplace Filtering

On the lattice we produce two and three-point functions.

$$C_2(t) = \sum_n A_n^2 e^{-E_n t}$$

$$C_3^{I\to F}(t_J, t_{snk}) = \sum_{n,m} A_n^F \langle F_n | J | I_m \rangle A_m^I e^{-E_n^F t_J - E_m^I (t_{src} - t_J)}$$

- Operators induce 'all' excitations, get tower of states
- Analysis often limited by excited state contributions
- Laplace filtering mitigates this [2]:
  - Preserves exponential modes
  - Can tune to remove/suppress low excited states
  - Linear transform of mode amplitudes

$$D_\lambda C(t) = -C(t-1) + (2+\lambda^2)C(t) - C(t+1)$$

$$D_\lambda C_2(t) = \sum_n (\lambda^2 - \tilde{E}_n^2) A_n^2 e^{-E_n t}$$

Analysis

Effective mass flatness is a proxy for ground state dominance. Laplace filter improves the onset to the plateau.

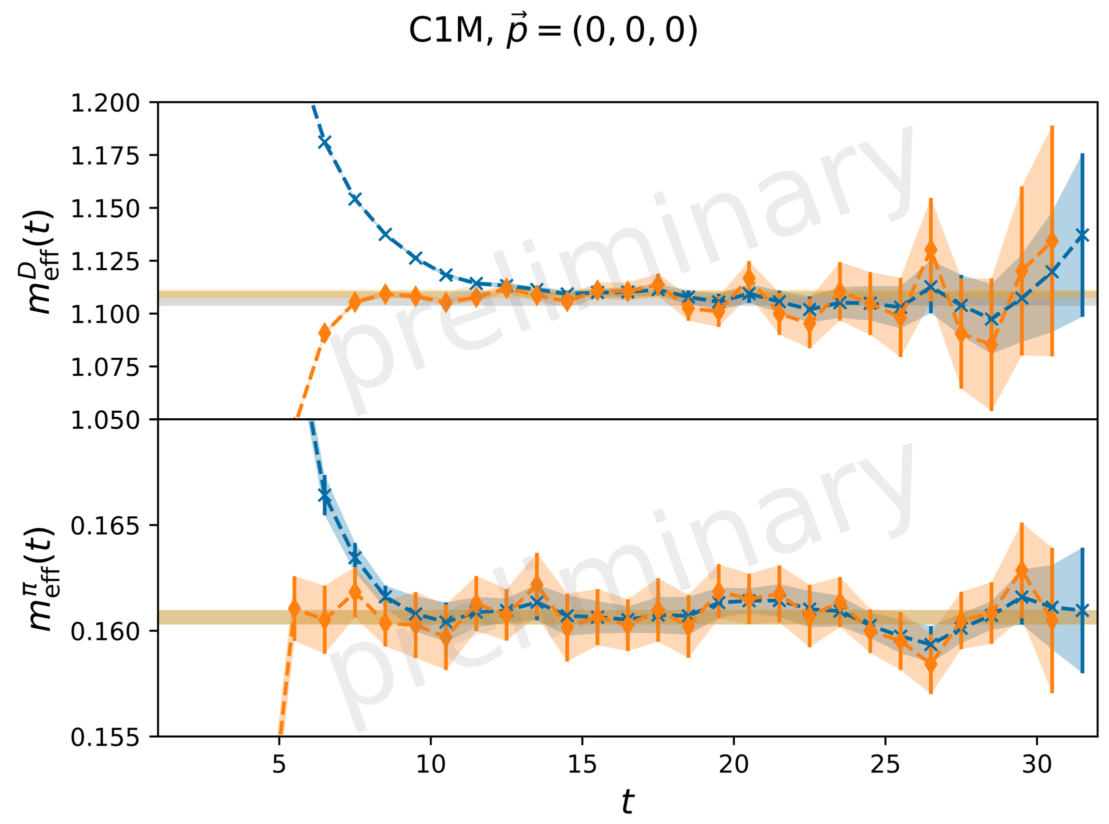


Figure 4: Effective masses for two-point functions. Original: blue crosses, Laplace filtered: orange diamonds.

Construct a suitable ratio which asymptotes to ground state matrix element.

$$R^{I\to F}(t_J, t_{snk}) \coloneqq \frac{C_3^{I\to F}(t_J, t_{snk})}{C_2^F(t_J) C_2^I(t_{snk} - t_J)}$$

Filtering the two-point functions which enter the ratio improves approach to the ground state.

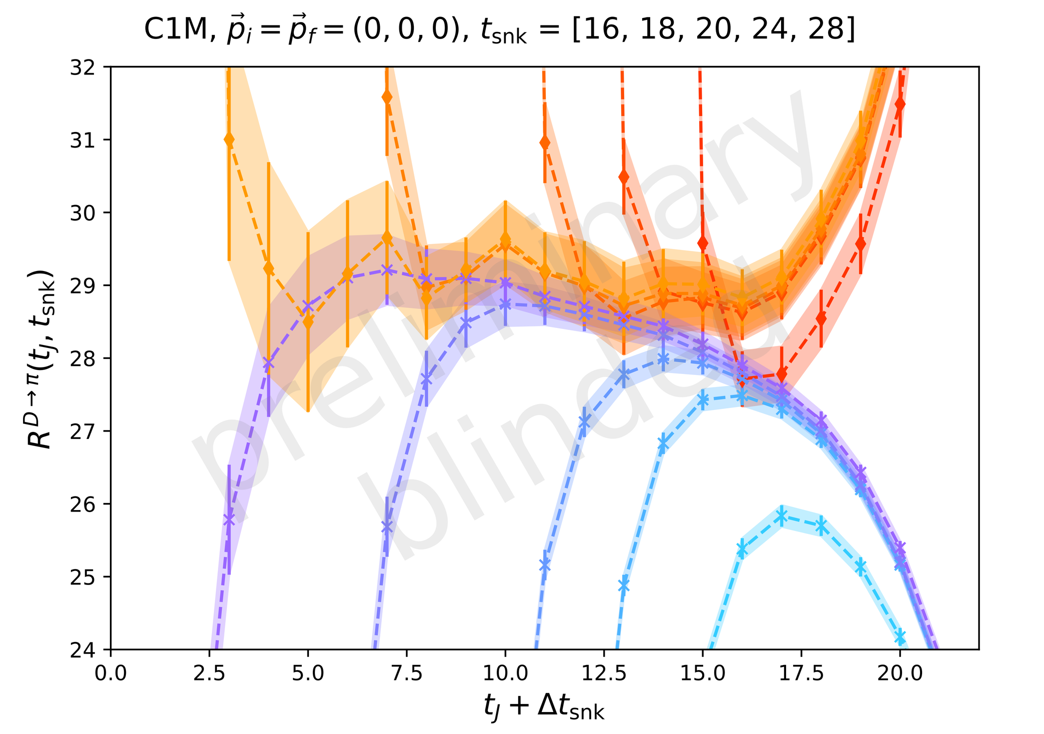


Figure 5: Ratios of three-point and two-point functions, corresponds to matrix element. Original data purple-blue crosses, Laplace filtered yellow-orange diamond.

Future Work

Many threads and people working in parallel, on multiple aspects and targets.

- Advance/systematise fitting via unified analysis code
- perform $a \to 0, L \to \infty, m_q \to m_q^{\text{phys}}$
- Calculation of $q^2_{\max}$ as benchmark quantity [3].
- Full q^2-dependence and determination of CKM.
- Extend analysis to vector final states
- $b \to l, s, c$ using RHQ b-quarks (data exists)

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