Accurate decay constants from lattice QCD for BSM physics

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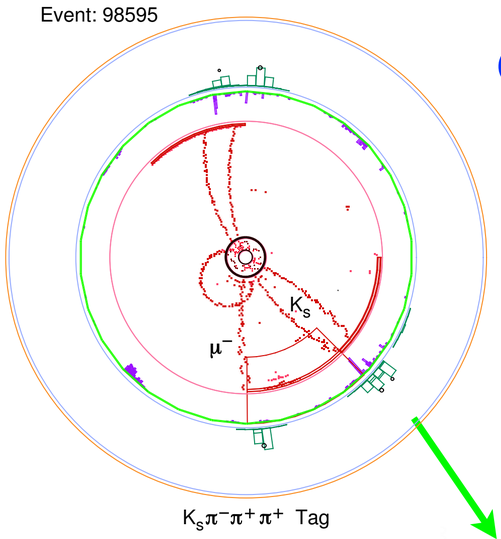
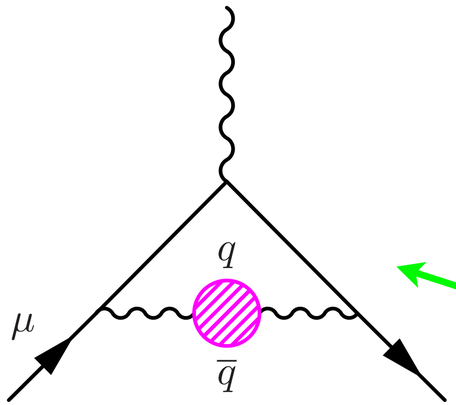
Quarkonium Working group workshop, March 2021

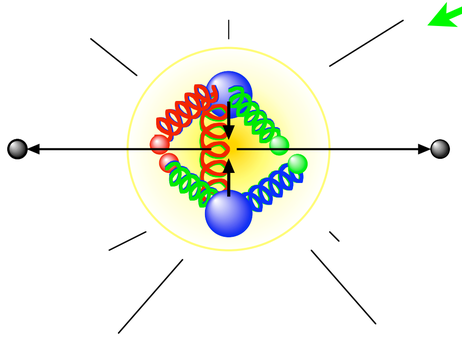
Quark low-energy strong interactions are a major complication in testing the Standard Model/searching for BSM physics



CLEO

$D \to \mu\nu$





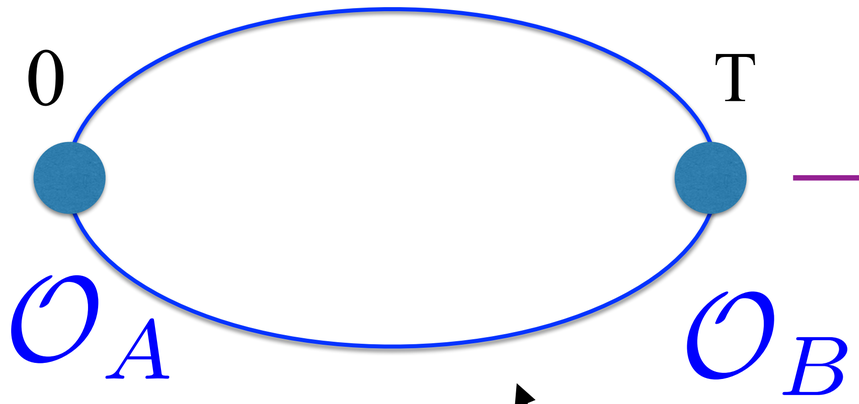
An accurate nonperturbative treatment of QCD - lattice QCD - is key to compare SM and low-energy experimental tests for new physics

At the same time can provide hadronic matrix elements for possible BSM operators or for QCD-like BSM theories.

Concentrate here on decay constants - now determined to ~1% in lattice QCD.

See J. Koponen (HPQCD) talk, Wednesday (Day 3 morning)

Two-point meson correlation functions are constructed from valence quark propagators



2-point function

av. over gluon fields and fit

Multiple states need to be included in fit

$$C_2 = \sum_n A_n B_n e^{-M_n T}$$

$$\langle 0|\mathcal{O}_A|n\rangle$$

decay constant, if O normalised

Meson mass - Ground-state mass can be very accurate. Use to tune lattice quark mass

For a meson at rest:

$$\langle 0|\overline{\psi}\gamma_0\gamma_5\psi|\mathrm{PS}\rangle = f_{\mathrm{PS}} M_{\mathrm{PS}}$$

$$\langle 0|\overline{\psi}\gamma_i\psi|\mathrm{V}\rangle = f_{\mathrm{V}} M_{\mathrm{V}} \varepsilon_i$$

$$\langle 0|\overline{\psi}\sigma_{0i}\psi|\mathrm{V}\rangle = i f_{\mathrm{T}}^{V}(\mu) M_{\mathrm{V}} \varepsilon_i$$

f_{PS} norm. is fixed from PCAC

Accurate current operator normalisation is critical for f_V and f_T

HPQCD: Work with the Highly Improved Staggered Quark (HISQ) discretisation of the Dirac eq.

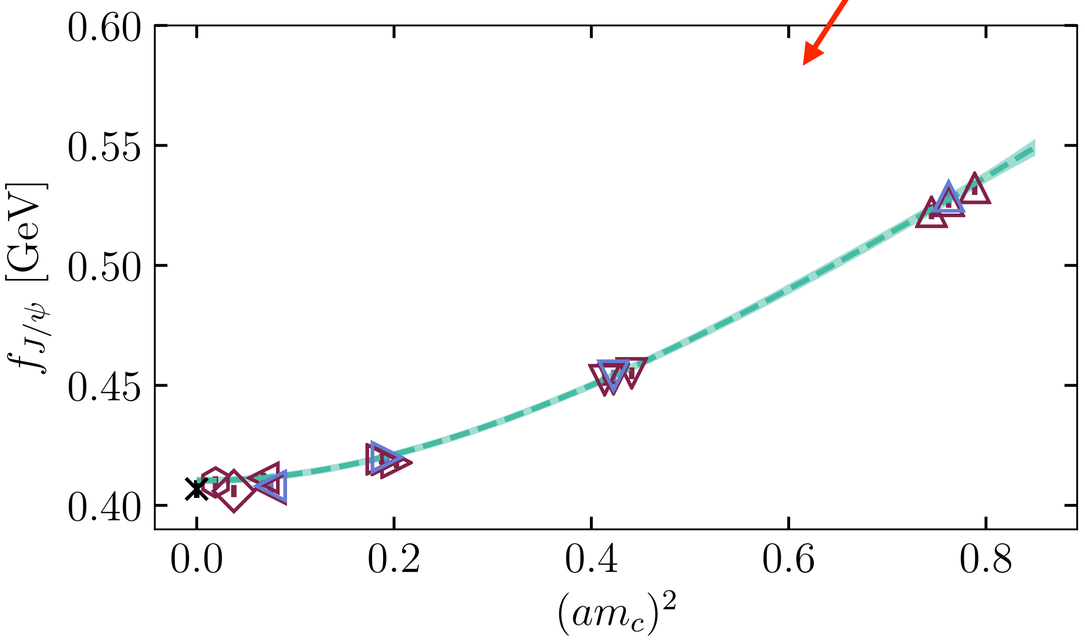
Has good control of discretisation errors (important for c/b quark physics) HPQCD, hep-lat/0610092.

Use MILC gluon field configurations with u, d, s, c HISQ sea quarks and range of lattice spacing values from 0.15 fm to 0.045 fm.

J/ψ vector decay constant

D. Hatton, et al, HPQCD, arXiv:2005.01845

$$f_V(J/\psi) = 410.4(1.7)\,\text{MeV}$$

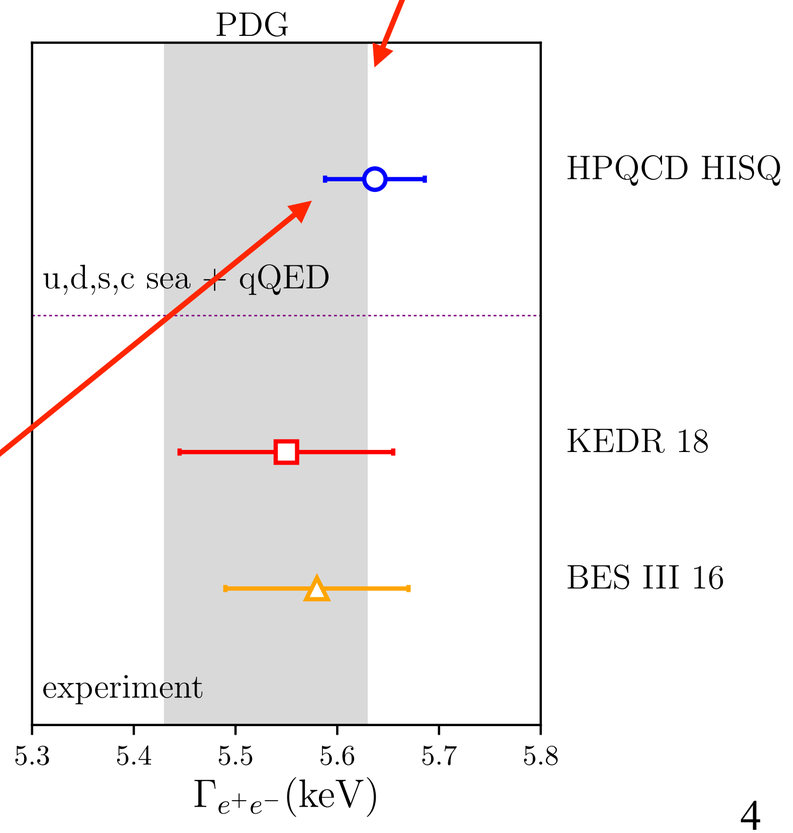


gives

$$\Gamma_{e^+e^-} = \frac{4\pi\alpha^2 Q^2}{3}\frac{f_V^2}{M_V}$$

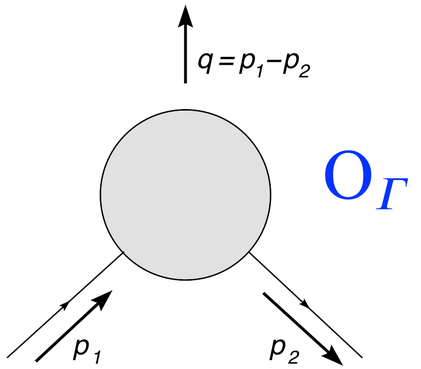
$$\Gamma(J/\psi \to e^+e^-) = 5.637(49)\,\text{keV}$$

Now lattice QCD (+QED) is more accurate than experiment!



Normalisation of vector current used a symmetric momentum-subtraction (RI-SMOM) scheme on the lattice

D. Hatton, et al, HPQCD, arXiv:1909.00756



Mimic what is done in perturbation theory, i.e. impose conditions on Green's functions between off-shell quark states in a fixed gauge on the lattice

$$Z_\Gamma \langle p|O_\Gamma|p\rangle|_{p^2=-\mu^2} = \langle p|O_\Gamma|p\rangle_0,$$

tree-level result

Rome-Southampton hep-lat/9411010

SYMMETRIC

$$p_1^2 = p_2^2 = q^2 = -\mu^2, \ \mu^2 > 0$$

RBC-UKQCD 0901.2599

HPQCD, 1909.00756: this is very accurate in the vector case because Z_V=1 for the conserved vector current

Same technique for the tensor current, BUT:

- contributions appear in Z_T (matching lattice to RI-SMOM) behaving as C/μ^n (condensates)
- Must perturbatively match to MS-bar in the continuum.

HPQCD, 2008.02024: use a physical quantity, e.g. the J/ψ tensor decay constant, to determine and remove condensate effects in Z_T.

Gives value for the J/ψ tensor decay constant to test lepton-flavour violating quarkonium decays.

Hazard and Petrov 1607.00815

Determination of J/ψ tensor decay constant

D. Hatton et al, HPQCD, 2008.02024

$$f_T(J/\psi, \overline{\mathrm{MS}}, 2\,\mathrm{GeV}, \mu, a) = R_T(2\,\mathrm{GeV}) Z_T^{\overline{\mathrm{MS}}/\mathrm{SMOM}} Z_T^{\mathrm{SMOM}}(\mu, a) f_T(J/\psi, \mathrm{latt}, a)$$

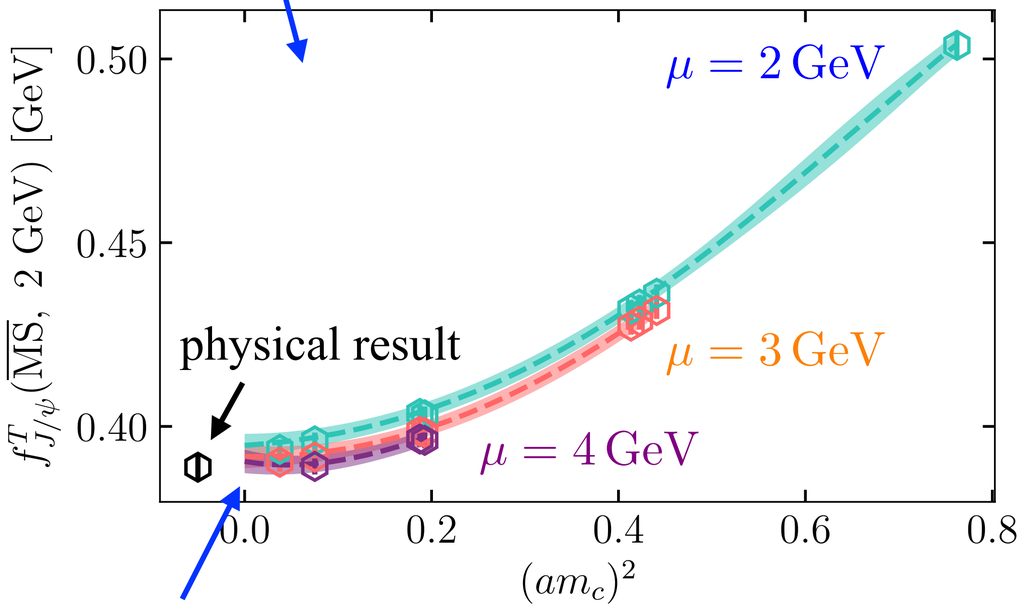
Fit this physical quantity as a function of a, allowing for μ dependence from condensates in Z_T^{SMOM}

Run all the MSbar results to the same scale of 2 GeV using continuum QCD pert. th.

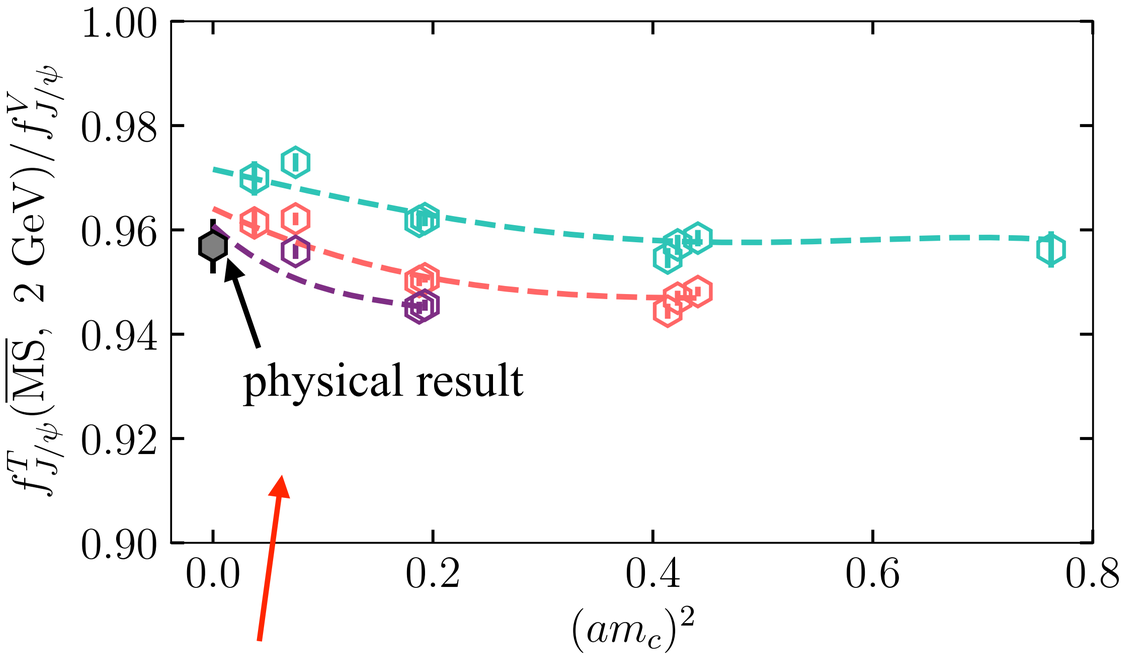
SMOM to MSbar conversion at scale μ from continuum QCD pert. th. through $(\alpha_s)^3$

Lattice to SMOM renormalisation factor, calculated on lattice with scale μ

from amplitudes of lattice correlators on each ensemble



$1/\mu^n$ (n starting at 2) condensates show up at a=0; they must be removed to obtain a physical result.

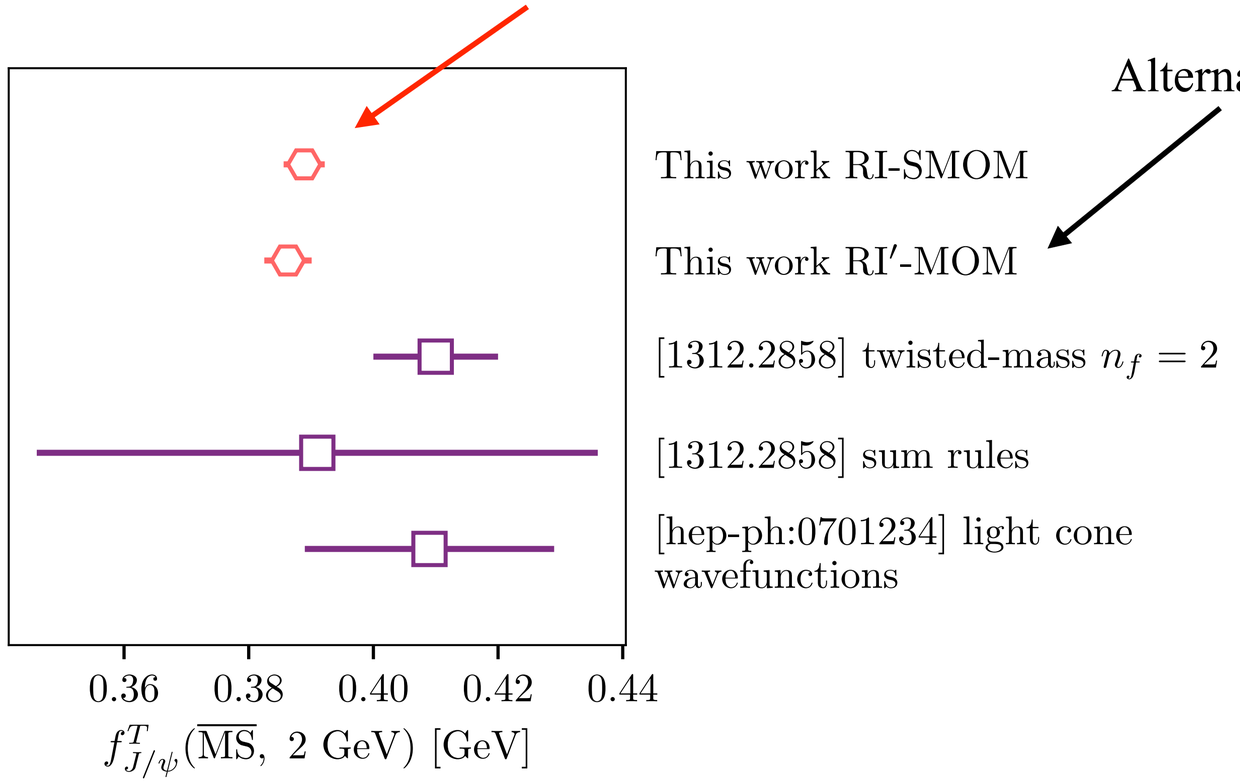


Ratio of tensor (at 2 GeV) to vector clearly < 1 for J/ψ

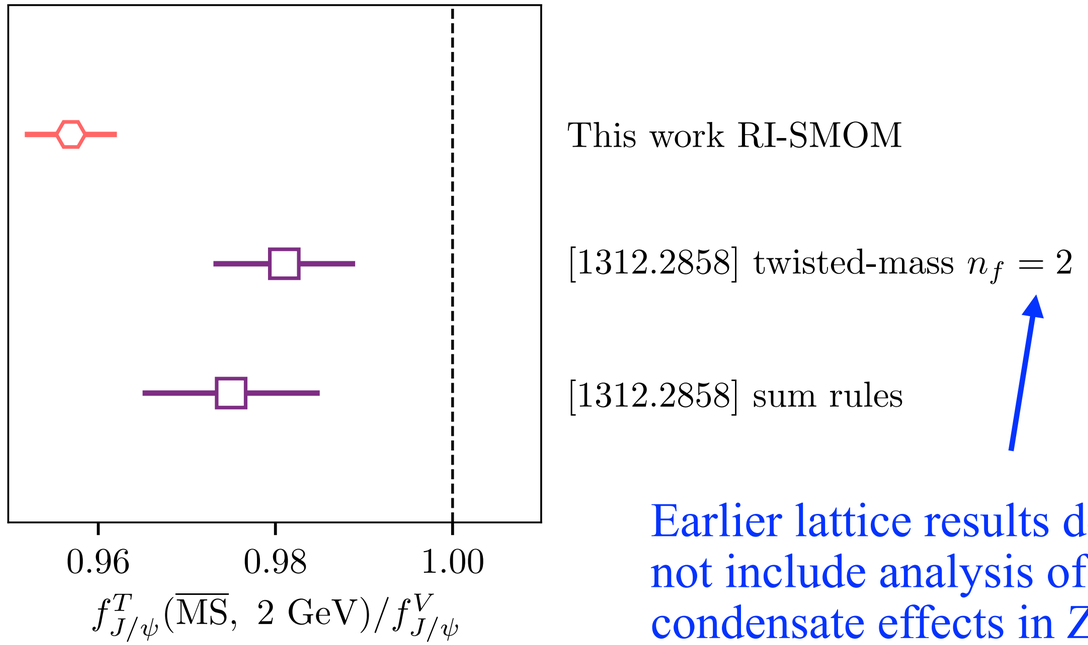
Determination of J/ψ tensor decay constant

D. Hatton et al, HPQCD, 2008.02024

Comparison to earlier results: HPQCD results are much more accurate



Alternative momentum-subtraction scheme



Earlier lattice results do not include analysis of condensate effects in Z_T.

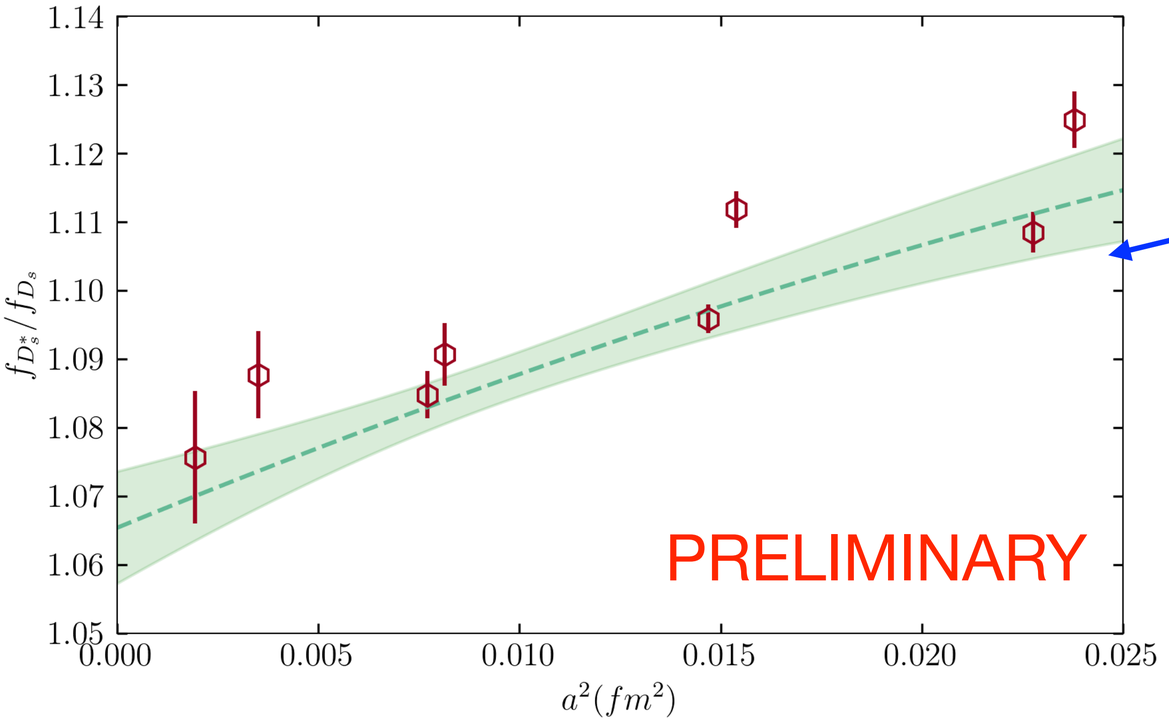
$$f_T(J/\psi, \overline{\rm MS}, 2\,{\rm GeV}) = 0.3899(33)\ {\rm GeV}$$

Uncertainty < 1%

$$\frac{f_T(J/\psi, \overline{\rm MS}, 2\,{\rm GeV})}{f_V(J/\psi)} = 0.9569(52)$$

Determination of Ds* decay constants

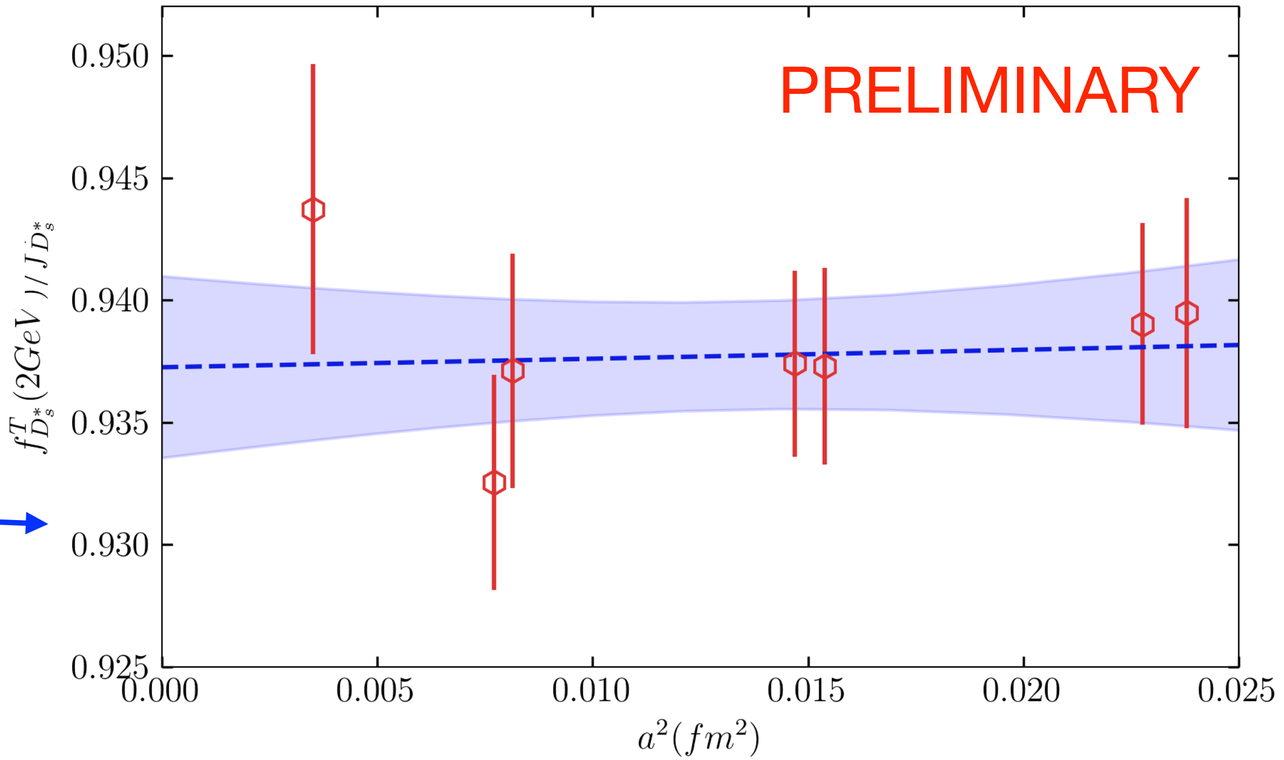
A. Smecca, J. Harrison, et al, HPQCD, in preparation



Vector to pseudoscalar ratio > 1

Update of HPQCD:1312.5264

Ratio of Tensor (at 2 GeV) to Vector < 1 and smaller than ratio for J/ψ



Results for other heavy-light mesons in progress, Bs* …

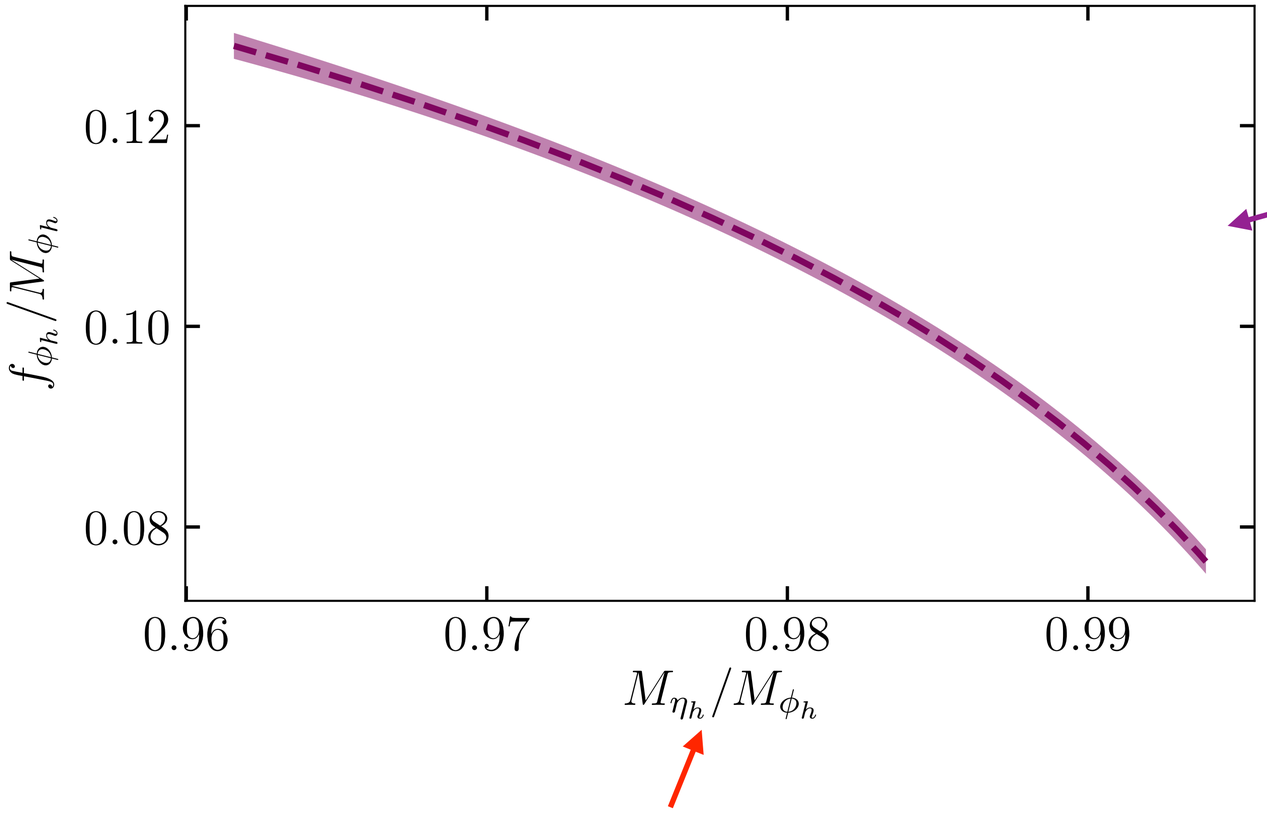
Mapping out decay constants as a function of meson mass

D. Hatton et al, HPQCD, 2101.08103

Increase mass from c to b to determine properties of bottomonium. Extrapolation to zero lattice spacing then gives the physical dependence of decay constants on meson masses from c to b.

Can provide constraints for QCD-like composite theories for BSM physics

DeGrand and Neill:1910.08561



Ratio of pseudoscalar to vector heavy quarkonium masses. Tends to 1 at large mass

Ratio of decay constant to mass of vector quarkonium can be used to constrain coupling of 'dark ρ' to 'dark photon'.

Note: ratio falls fast at high masses.

Curve must connect smoothly to lighter masses e.g. at $M_{PS}/M_V = 0.673$ (strange quark):

$$\frac{f_V}{M_V} = 0.233(3)$$

HPQCD:1703.05552

Conclusions

HPQCD:1909.00756; 2005.01845; 2008.02024; 2101.08103
D. Hatton, CD, B. Galloway, J. Koponen, P. Lepage, A. Lytle

• Meson decay constants are now very accurately calculable in Lattice QCD, with uncertainties < 1%.

• This includes vector and tensor decay constants for vector mesons, following HPQCD work to pin down renormalisation constants. For tensor decay constants this requires fitting and removing condensate contributions from Z_T renormalisation factors in intermediate momentum-subtraction schemes, calculated on the lattice.

• Tensor decay constants calculated for J/ψ and Ds* - others underway. All a few percent smaller (at 2 GeV) than corresponding vector decay constants.

• Can also map out quarkonium decay constants as a function of meson mass, to constrain QCD-like BSM theories

Future

• Determining further matrix elements of tensor currents such as form factors for $B \to K\ell^+\ell^-$