On the D_s^* and charmonia leptonic decays

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- New Physics searches and extensions of the Higgs sector
- Lattice analysis
- D_s sector
- Charmonia sector
- Outlook

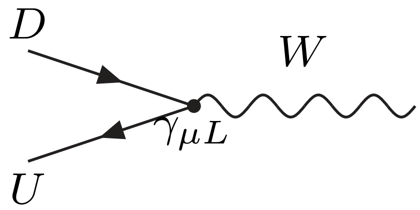
[Work in progress with G. Bailas, J. Heitger, V. Morénas and M. Post]

New Physics searches and extensions of the Higgs sector

Standard Model in the quark sector

3 families of quarks: $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$; strong hierarchy among quark masses

Quarks coupled to charged weak bosons by a left-handed current.



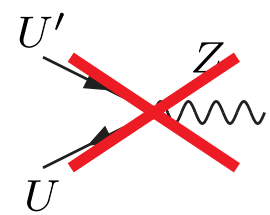
Quark flavour eigenstates $\neq$ quark weak eigenstates; flavour mixing
described by the Cabibbo-Kobayashi-Matrix mechanism, only source of CP violation.

$$\begin{pmatrix} \text{d'} \\ \text{s'} \\ \text{b'} \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} \text{d} \\ \text{s} \\ \text{b} \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} \text{d} \\ \text{s} \\ \text{b} \end{pmatrix}$$

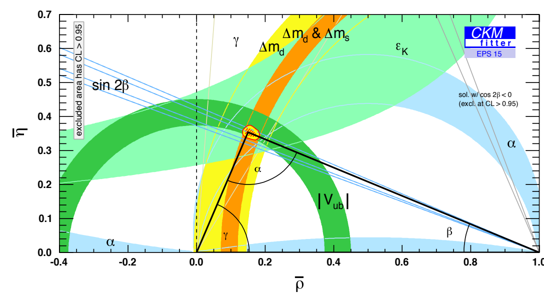
$V_{ij} \sim \mathcal{O}(1)$
$V_{ij} \sim \mathcal{O}(\lambda)$
$V_{ij} \sim \mathcal{O}(\lambda^2)$
$V_{ij} \sim \mathcal{O}(\lambda^3)$

$\lambda \sim 0.22$

Unitarity of the CKM matrix: Glashow - Iliopoulos - Maiani mechanism,
no Flavour Changing Neutral Current at tree level.



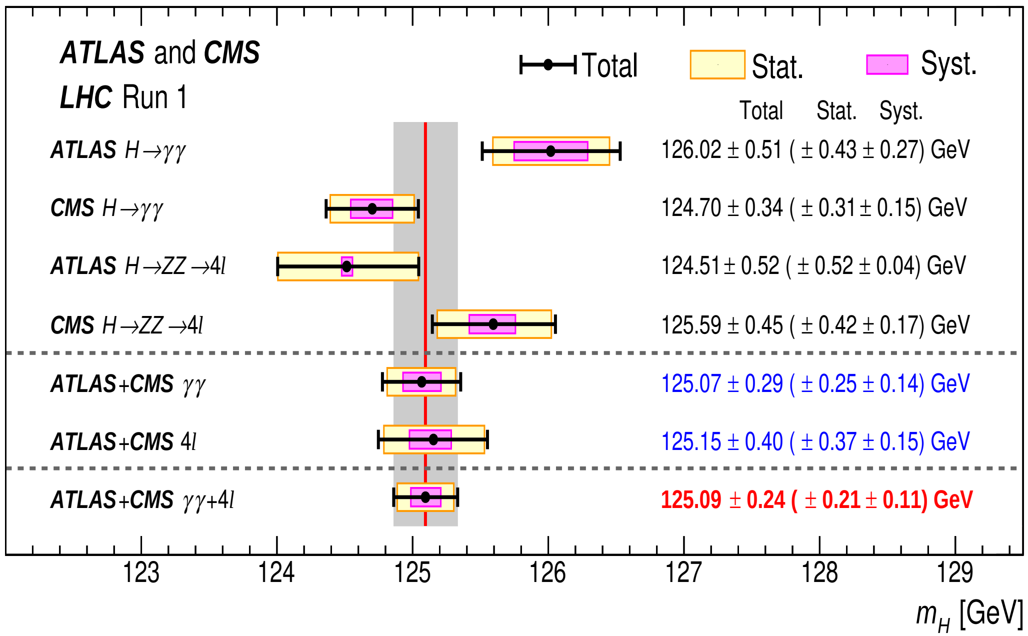
6 unitarity triangles: flavour physics constraints
on sides and angles.



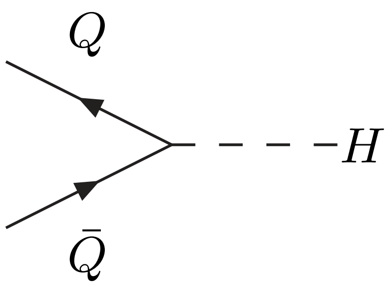
Standard Model in the Higgs sector

Spontaneous symmetric breaking of $SU(2)_{\mathrm{W}} \times U(1)_{\mathrm{Y}}$ in $U(1)_{\mathrm{EM}}$ due to a scalar field with VEV $\neq 0$: Higgs boson H remaining from a complex scalar isodoublet Φ

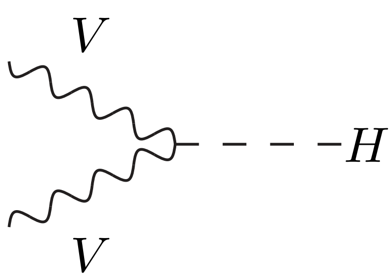
[ATLAS and CMS, ’15]



$$m_H \sim 125.5 \text{ GeV} \quad v = 246 \text{ GeV}$$



$\propto m_Q$



$\propto m_V^2$

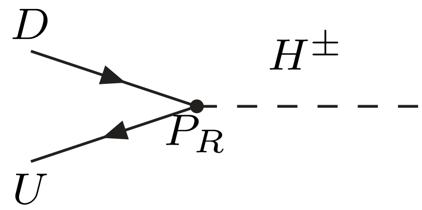
Issue: quartic term of the Higgs potential induces through radiative corrections a quadratic divergence to m_H, "hierarchy" problem

Minimal extension of the Higgs sector

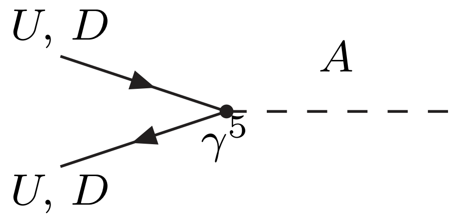
2 complex scalar isodoublets Φ_1 and $\Phi_2 \xrightarrow{\text{EWSB}}$ 5 Higgs bosons: $H^\pm$, h (SM-like, light CP-even), H (heavy CP-even) and A (CP-odd)

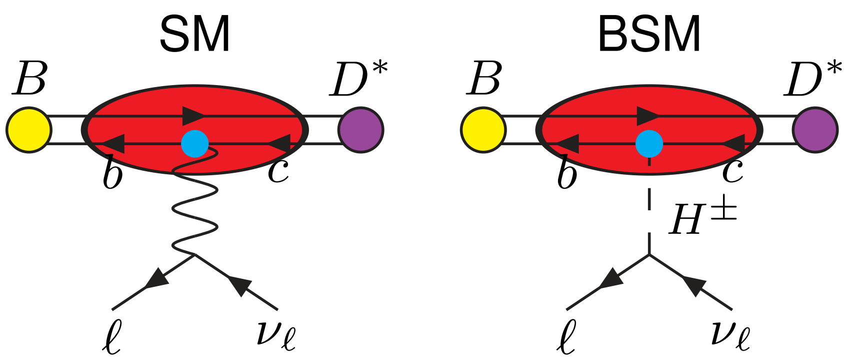
$\tan\beta = v_2/v_1$

Quarks coupled to charged Higgs by a right-handed current.



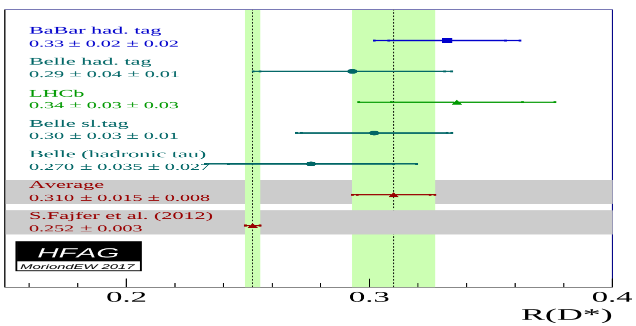
Quarks coupled to neutral extra Higgs as well, in particular with CP-odd A.





Test of lepton flavour universality by measuring $R_{D^*} \equiv \frac{\Gamma(B\to D^*\tau\nu_\tau)}{\Gamma(B\to D^*\ell\nu_\ell)}$, $\ell = e, \mu$

Right-handed contribution helicity suppressed



R_D and R_{D^*} combined: 3.9σ away from SM!

Constraints on NP with extra charged Higgs,

once form factors are determined with enough control

Spectator quark $u, d \to s$: $R_{D_s^{(*)}}$ measured at LHCb, Belle 2?

Form factors of $B_s \to D_s^*$, basic properties of D_s^*: $f_{D_s^*}$

Minimal extension of the Higgs sector

2 complex scalar isodoublets Φ_1 and $\Phi_2 \xrightarrow{\text{EWSB}}$ 5 Higgs bosons: $H^\pm$, h (SM-like, light CP-even), H (heavy CP-even) and A (CP-odd)

$\tan\beta = \langle\Phi_2\rangle / \langle\Phi_1\rangle$

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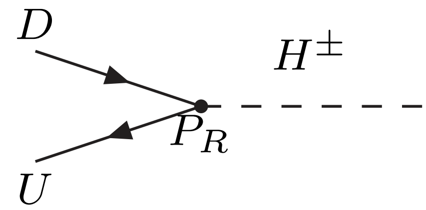
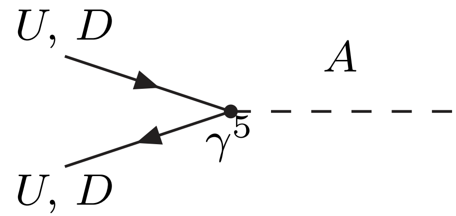
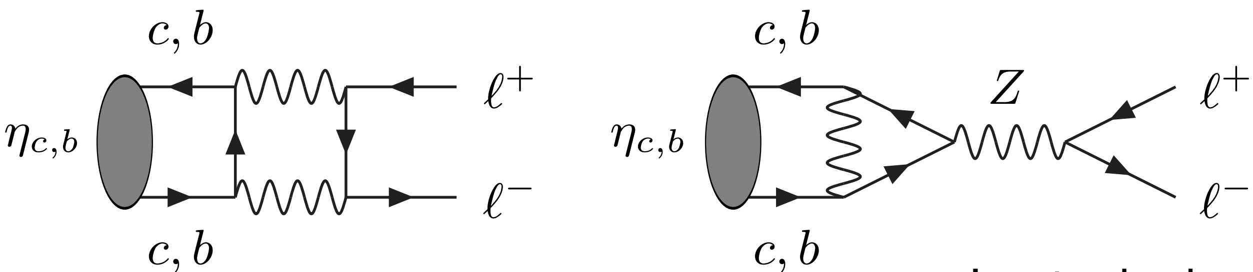


Quarks coupled to neutral extra Higgs as well, in particular with CP-odd A.



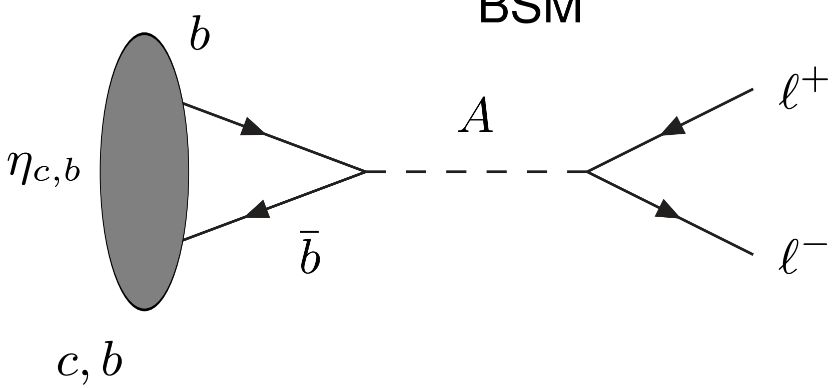
SM



Leptonic decay of charmonia suppressed in SM while enhanced in BSM scenarios with $m_A < 125$ GeV and low $\tan\beta$

A few hadronic inputs required: $f_{\eta_{c,b}}$

BSM



Lattice analysis

Lattice set-up: $\mathcal{O}(a)$ improved Wilson-Clover, $N_f = 2$

CLS based

lattice	β	$L^3 \times T$	$a[\mathrm{fm}]$	$m_\pi[\mathrm{MeV}]$	Lm_π
E5	5.3	$32^3 \times 64$	0.065	440	4.7
F6		$48^3 \times 96$		310	5
F7		$48^3 \times 96$		270	4.3
G8		$64^3 \times 128$		190	4.1
N6	5.5	$48^3 \times 96$	0.048	340	4
O7		$64^3 \times 128$		270	4.2

Use $\kappa_{\mathrm{strange}}$ and κ_{charm} determined at each ensemble from m_K [P. Fritzsch *et al*, '12] and m_{D_s} [J. Heitger, G. von Hippel, S. Schaefer and F. Virotta, '13]

Preparatory work to find a good basis of interpolating fields, well isolate the states

Different smearing levels, operators with covariant derivatives $\bar{q}_1 \Gamma \vec{\gamma} \cdot \vec{D} q_2$, operators of the kind $\bar{q}_1 \gamma_0 \Gamma q_2$

GEVP techniques to get spectrum and decay constants

Mix together $\bar{q}\Gamma q$ and $\bar{q}\gamma_0\Gamma q$ in a unique GEVP system [L. Liu *et al*, "12; D. Becirevic and F. Sanfilippo, '12] lets arise questions.

Illustration on $\{P = \bar{q}\gamma_5 q, \quad A_0 = \bar{q}\gamma_0\gamma_5 q\}$: $\langle P(t)P(0)\rangle$ and $\langle A_0(t)A_0(0)\rangle \sim \cosh[E(T/2-t)]$, $\langle P(t)A_0(0)\rangle$ and $\langle A_0(t)P(0)\rangle \sim \sinh[E(T/2-t)]$

$C(t) = \begin{bmatrix} \langle P(t)P(0)\rangle & \langle A_0(t)P(0)\rangle \\ \langle P(t)A_0(0)\rangle & \langle A_0(t)A_0(0)\rangle \end{bmatrix}$ GEVP: $C(t)v_n(t,t_0) = \lambda_n(t,t_0)C(t_0)v_n(t,t_0)$

General case: $C_{ij}(t) = \sum_n Z_n^i Z_n^{*j}[D_{ij}\rho_n^{(1)}(t) + (1-D_{ij})\rho_n^{(2)}(t)]$, $D_{ij} = 0$ or 1, $\rho^{(1),(2)}(t) \sim e^{-Et}$, $\cosh[E(T/2-t)]$, $\sinh[E(T/2-t)]$

Dual vector u_n to $Z's$: $\sum_j Z_m^{*j} u_n^j = \delta_{mn}$

$$\begin{aligned}
\sum_j C_{ij}(t)u_n^j &= \sum_{j,m} Z_m^i Z_m^{*j} u_n^j [D_{ij}\rho_m^{(1)}(t) + (1-D_{ij})\rho_m^{(2)}(t)] \\
&= \sum_m \rho_m^{(2)}(t) Z_m^i \sum_j Z_m^{*j} u_n^j + \sum_m (\rho_m^{(1)}(t) - \rho_m^{(2)}(t)) Z_m^i \sum_j D_{ij} Z_m^{*j} u_n^j \\
&= \rho_n^{(2)}(t) Z_n^i + \sum_m (\rho_m^{(1)}(t) - \rho_m^{(2)}(t)) Z_m^i \sum_j D_{ij} Z_m^{*j} u_n^j
\end{aligned}$$

D_{ij} independent of i, j: $C(t)u_n = \rho(t)Z_n$, $\lambda_n(t,t_0) = \frac{\rho_n(t)}{\rho_n(t_0)}$

Approximate every correlators by sums of exponentials forward in time may face caveats.

A toy model with 3 states in the spectrum to study this issue:

spectrum
1.0
1.25
1.44

Matrix of couplings

$$\begin{bmatrix} 0.6 & 0.25 & 0.08 \\ 0.61 & 0.27 & 0.08 \\ 0.58 & 0.24 & 0.08 \end{bmatrix}$$

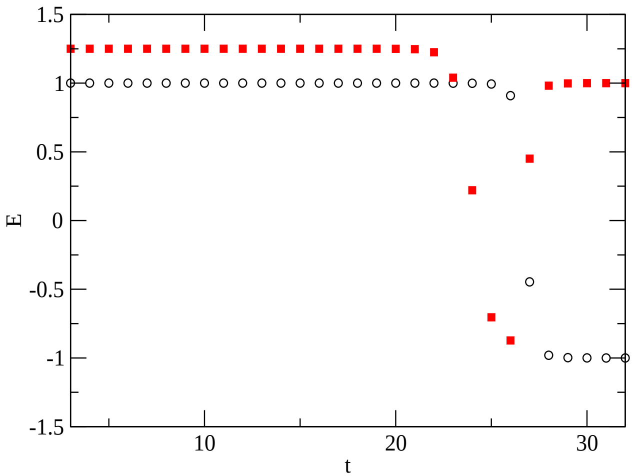
time behaviour of C_{ij}

$$\begin{bmatrix} \cosh & \sinh & \cosh \\ \sinh & \cosh & \sinh \\ \cosh & \sinh & \cosh \end{bmatrix}$$

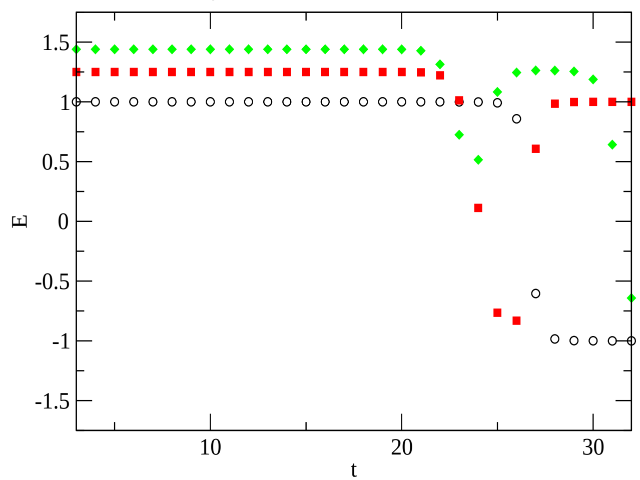
$$E_n = \ln\left(\frac{\lambda_n(t,t_0)}{\lambda_n(t+1,t_0)}\right)$$

$$T = 64 \qquad t_0 = 3$$

subsystem 2×2



system 3×3



Until $t = T/4$ effect not observed. What happens in real data with a dense spectrum?

Build a basis of operators with $\{\bar{q}\Gamma q; \bar{q}\Gamma\vec{\gamma}\cdot\vec{D}q\}$ is an excellent idea...

But life is more complicated, unfortunately.

Let's examine $C(t) = \langle [\bar{c}\gamma^5\vec{\gamma}\cdot\vec{D}c](t)[\bar{c}\gamma^5\vec{\gamma}\cdot\vec{D}c](0)\rangle$

Formalism of quark model, Dirac basis where γ_0 is diagonal, charge conjugation defined by $\mathcal{C} = -\gamma_0\gamma_2$

$$c(\vec{p}_c) = \begin{pmatrix} c_1 \\ c_2 = \frac{\vec{\sigma}\cdot\vec{p}_c}{2m_c}c_1 \end{pmatrix}$$

$$c_c = \mathcal{C}(\bar{c})^T = \gamma_2 c^*, \; \bar{c}_c = c_c^T\gamma_2\gamma_0 = \begin{pmatrix} c_{1c}^T & c_{1c}^T\frac{\vec{\sigma}\cdot\vec{p}_{\bar{c}}}{2m_c} \end{pmatrix}\gamma_2\gamma_0$$

$$\bar{c}_c = -i\begin{pmatrix} c_{1c}^t(\vec{\sigma}\cdot\vec{p}_{\bar{c}}/2m_c)^T\sigma_2 & c_{1c}^T\sigma_2 \end{pmatrix}$$

Meson at rest, $\vec{p}_c = -\vec{p}_{\bar{c}}$, $(\vec{\sigma}\cdot\vec{p}_{\bar{c}})^T\sigma_2 = \sigma_2(\vec{\sigma}\cdot\vec{p}_c)$

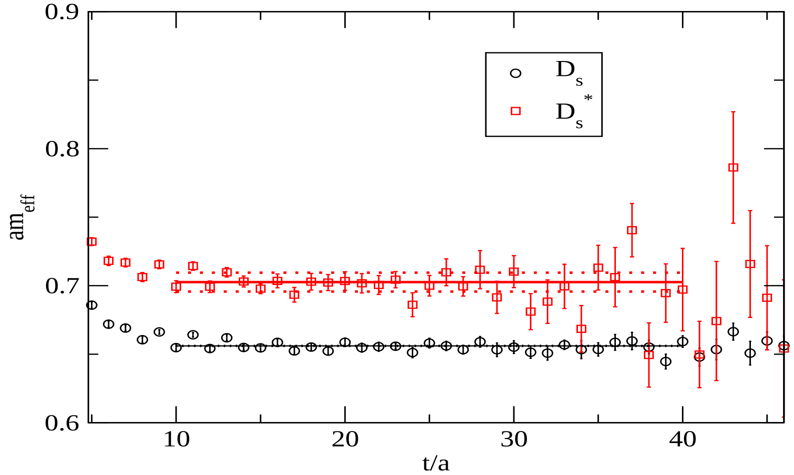
$$\begin{aligned}
\bar{c}_c\gamma_5\vec{\gamma}\cdot\vec{D}c &= -i\begin{pmatrix} c_{1c}^T\frac{(\vec{\sigma}\cdot\vec{p}_{\bar{c}})}{2m_c}\sigma_2 & c_{1c}^T\sigma_2 \end{pmatrix}\begin{pmatrix} -i\sigma_i & 0 \\ 0 & i\sigma_i \end{pmatrix}\begin{pmatrix} 1 \\ \frac{\vec{\sigma}\cdot\vec{p}_c}{2m_c} \end{pmatrix} D_i c_1 \\
&= -ic_{1c}^T\sigma_2\frac{-i\vec{\sigma}\cdot\vec{p}_c\sigma_i + i\sigma_i\vec{\sigma}\cdot\vec{p}_c}{2m_c}D_i c_1 \\
&= -ic_{1c}^T\sigma_2\frac{\sum_{j\neq i} i\sigma_i\sigma_j p_{jc}}{m_c}D_i c_1 \\
&\sim -ic_{1c}^T\sigma_2\frac{\sum_{j\neq i} i\sigma_i\sigma_j p_{ic}p_{jc}}{m_c}c_1 = 0
\end{aligned}$$

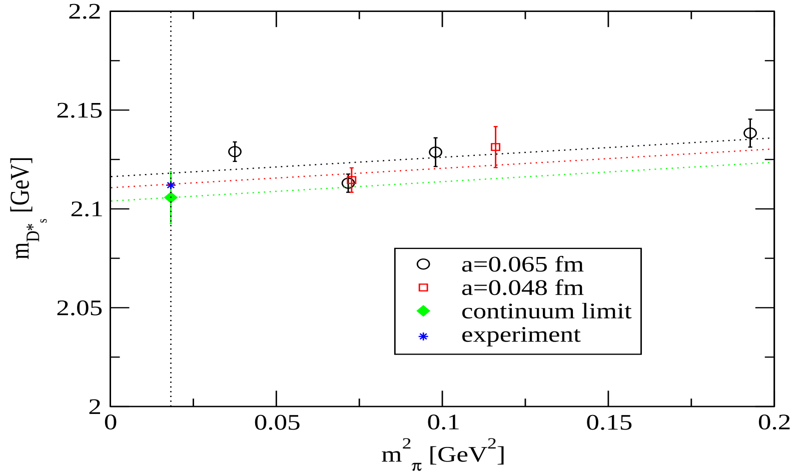
Interpolating fields $\bar{c}\gamma_5\vec{\gamma}\cdot\vec{D}c$ might give very noisy correlators...

D_s sector

4 smearing levels, signal for pseudoscalar and vector D_s mesons clearly seen

$a = 0.065$ fm, $m_\pi = 270$ MeV, $t_0/a = 3$



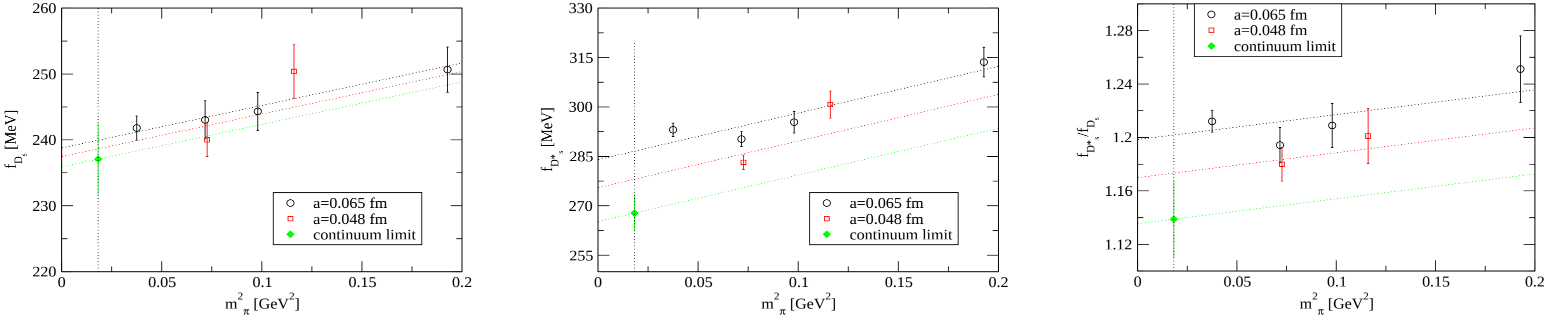


Fit range $[t_{\rm min}, t_{\rm max}]$ fixed such that $\sigma^{\rm sys}(t_{\rm min}) < 0.25\sigma^{\rm stat}(t_{\rm min})$

$\sigma^{\rm sys}(t) = e^{-\Delta E t}$, $\Delta E = E_5 - E_1 \sim 2$ GeV

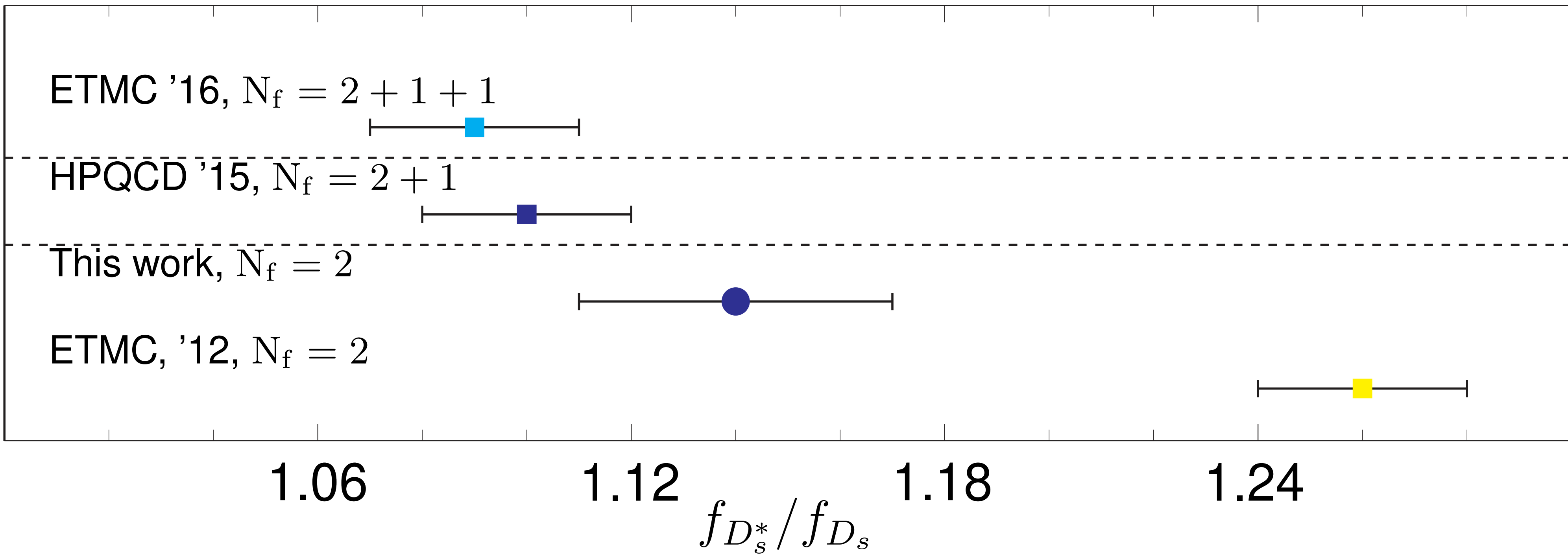
At the physical point, $m_{D_s^*}$ compatible with experiment: $m_{D_s^*} = 2.106(13)(13)$ GeV

f_{D_s} and $f_{D_s^*}$ extracted using non perturbative Z_A and Z_V, improved with perturbative c_A, c_V, b_A, b_V and $m^{AWI} \to m^{VWI}$ matching



Extrapolation of f_{D_s}, $f_{D_s^*}$ and $f_{D_s^*}/f_{D_s}$ to the physical point: linear in m_π^2, cut-off in a^2

$f_{D_s} = 237(5)(2)$ MeV, $f_{D_s^*} = 267(5)(2)$ MeV, $f_{D_s^*}/f_{D_s} = 1.14(3)$ [preliminary]

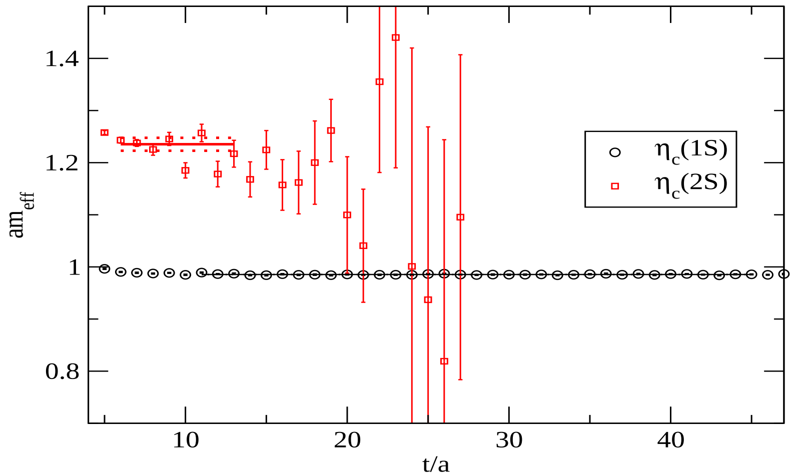


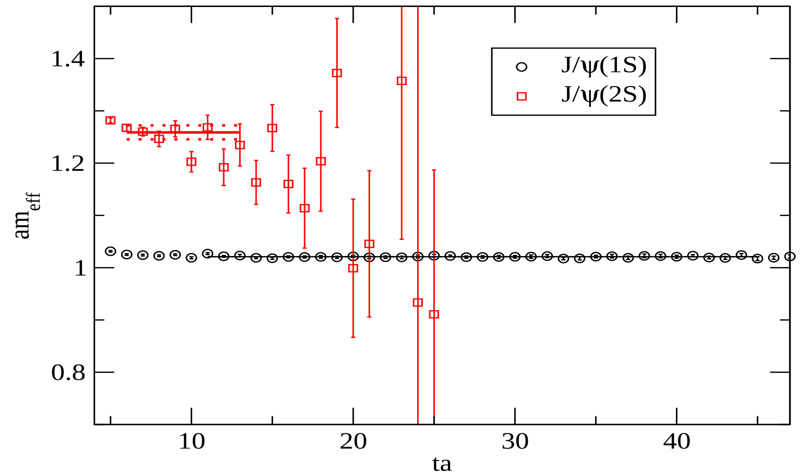
Quenching of the strange quark on $f_{D_s^*}/f_{D_s}$ maybe less pronounced than thought, $\lesssim 10\%$

Charmonia sector

4 smearing fevels, signal for η_c and J/ψ very good, less clear for $\eta_c(2S)$ and $\psi(2S)$

[$a = 0.065$ fm, $m_\pi = 270$ MeV, $t_0 = 3$]





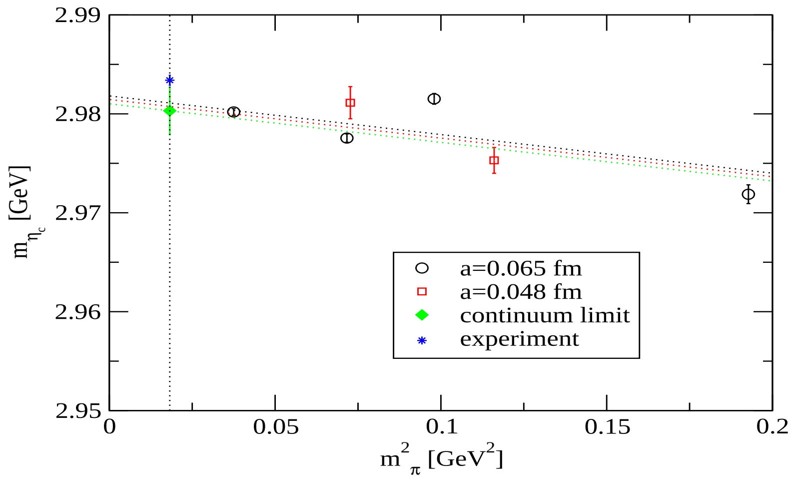
Try to insert correlators of η_c with interpolating field $\bar{c}\gamma_5\vec{\gamma}\cdot\vec{D}c$

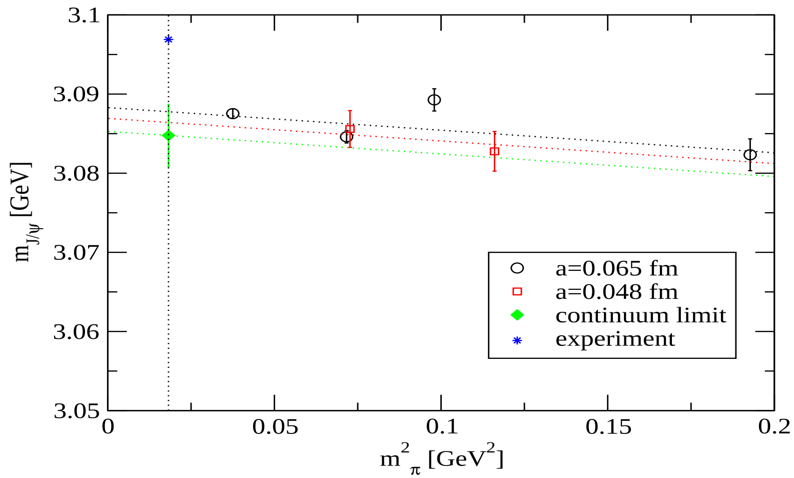
☹ Only noise, numerical compensation between $\sum_i\langle[\bar{c}\gamma_5\gamma_i D_i c](t)[\bar{c}\gamma_5\gamma_i D_i c](0)\rangle$ and $\sum_{i\neq j}\langle[\bar{c}\gamma_5\gamma_i D_i c](t)[\bar{c}\gamma_5\gamma_j D_j c](0)\rangle$

Correlators with interpolating field $\bar{c}\gamma_0\gamma_5\vec{\gamma}\cdot\vec{D}c$: no compensation, nice signal for η_c

Formalism of quark models: $\bar{c}_c\gamma_0\gamma_5\vec{\gamma}\cdot\vec{D}c \sim ic^T_{1c}\sigma_2\frac{\vec{p}_c^{\,2}}{m_c}c_1$

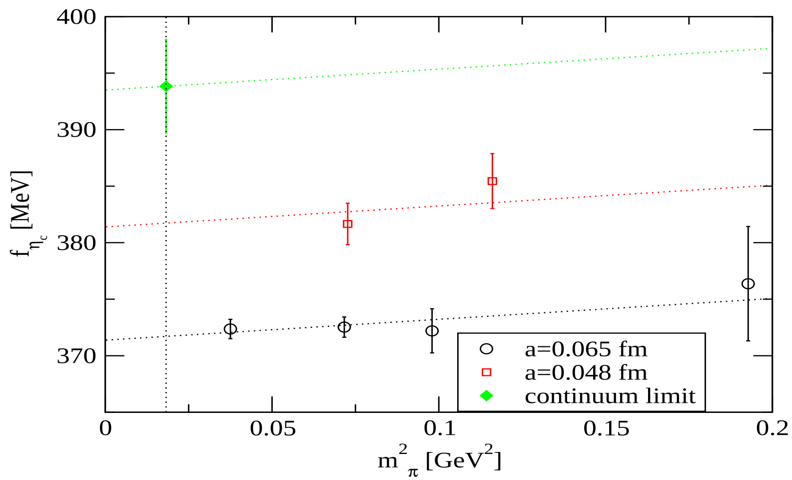
☹ How to analyse with GEVP correlators built with the basis of operators $\{\bar{c}\gamma_5 c,\ \bar{c}\gamma_0\gamma_5\vec{\gamma}\cdot\vec{D}c\}$?

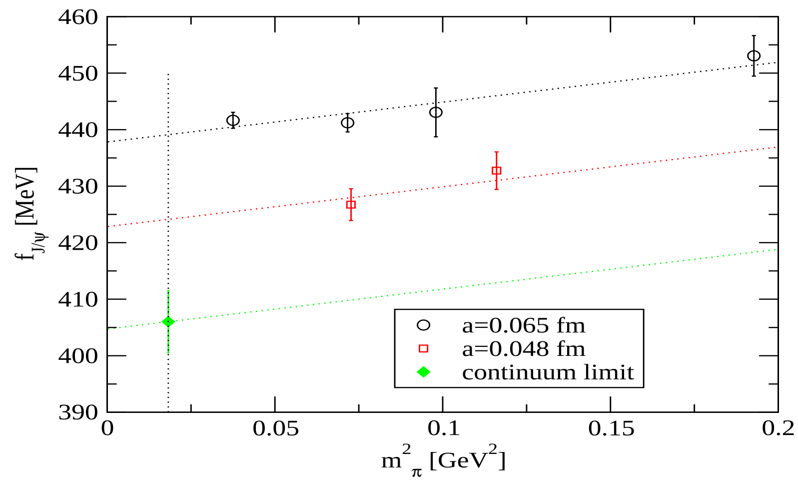




Mild dependence on m_π^2 and a^2 of m_{η_c} and $m_{J/\psi}$, though the non trivial contribution $\neq 2m_c$ difficult to catch

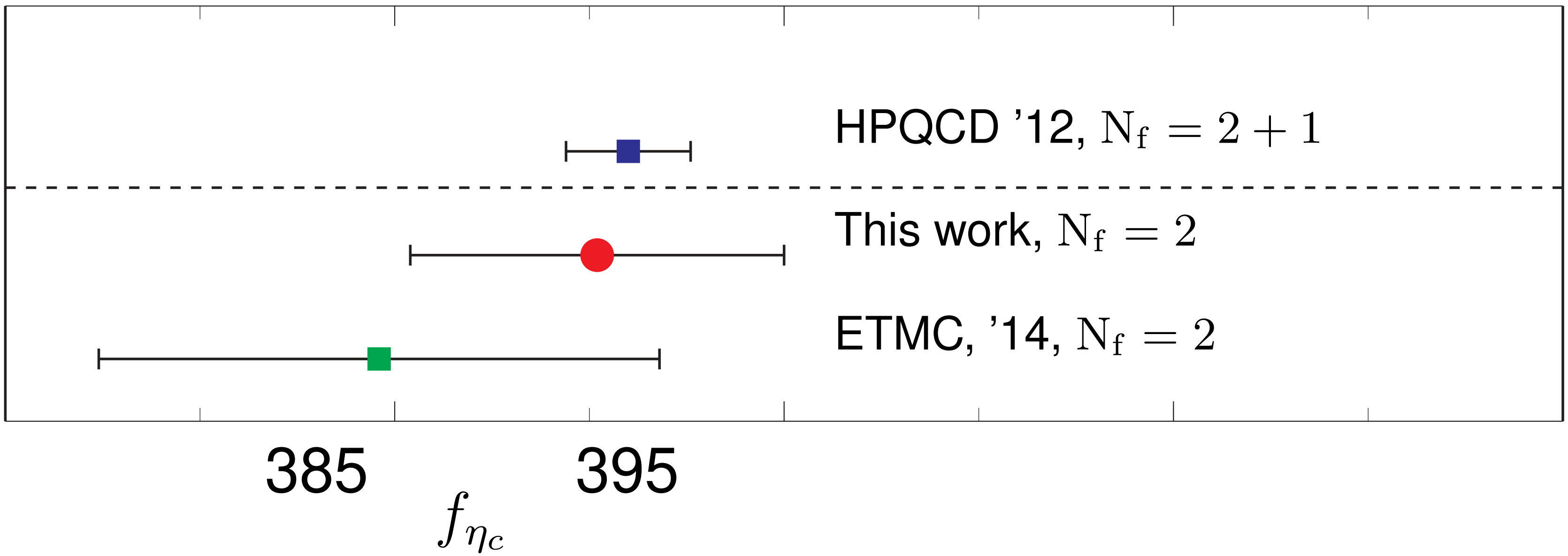
$m_{\eta_c} = 2.980(2)(18)$ GeV, $m_{J/\psi} = 3.085(4)(19)$ GeV

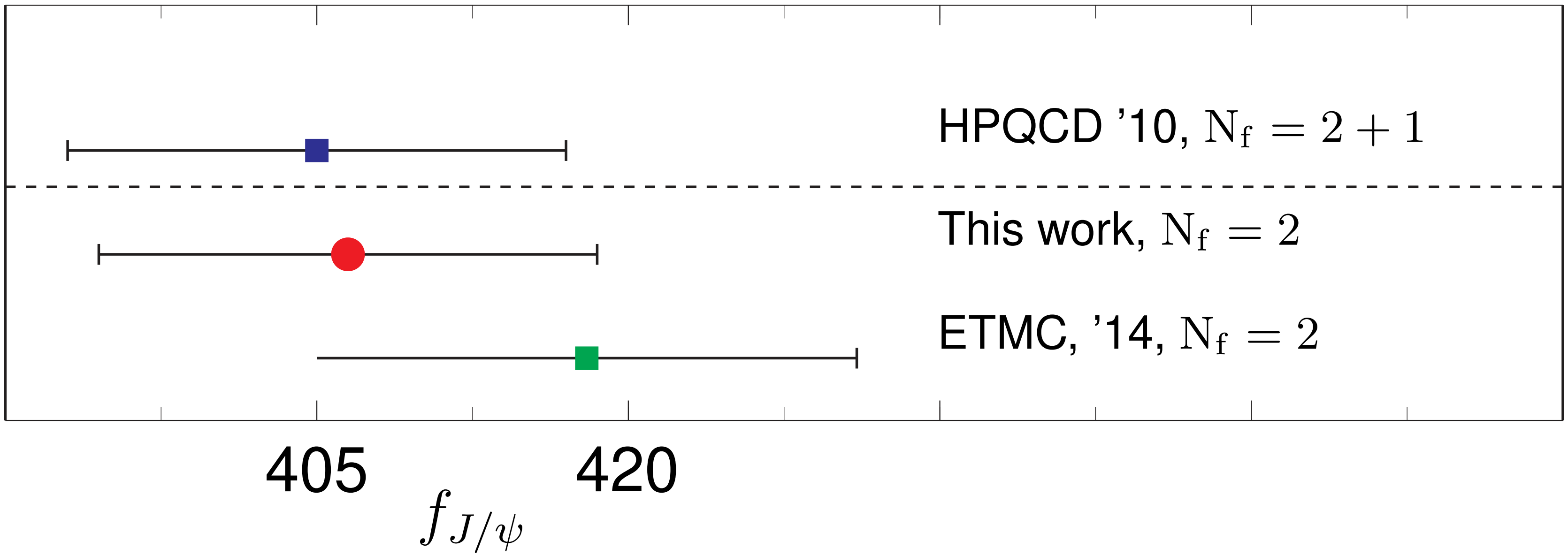




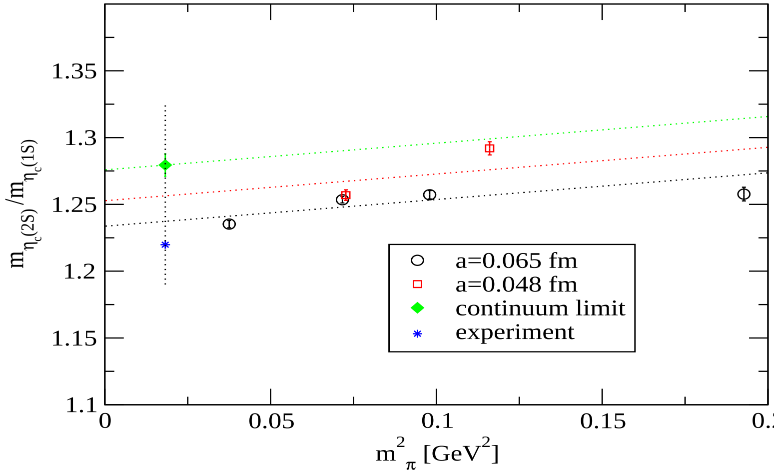
Smooth dependence on m_π^2 and a^2 of f_{η_c} and $f_{J/\psi}$

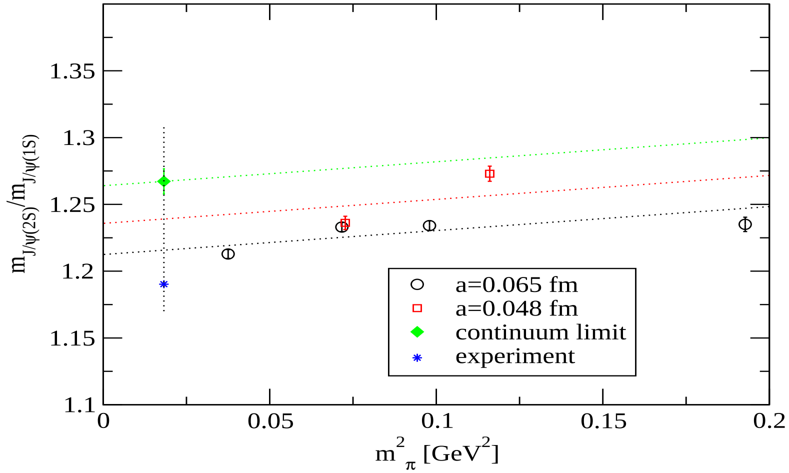
$f_{\eta_c} = 394(4)(2)$ MeV, $f_{J/\psi} = 406(5)(3)$ MeV [preliminary]



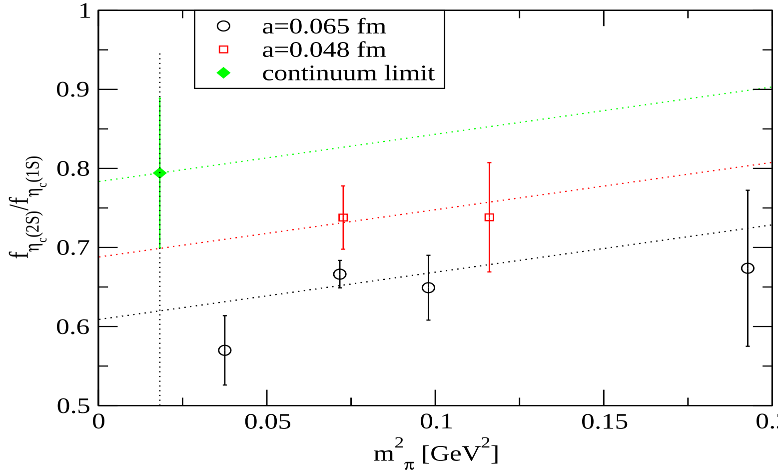


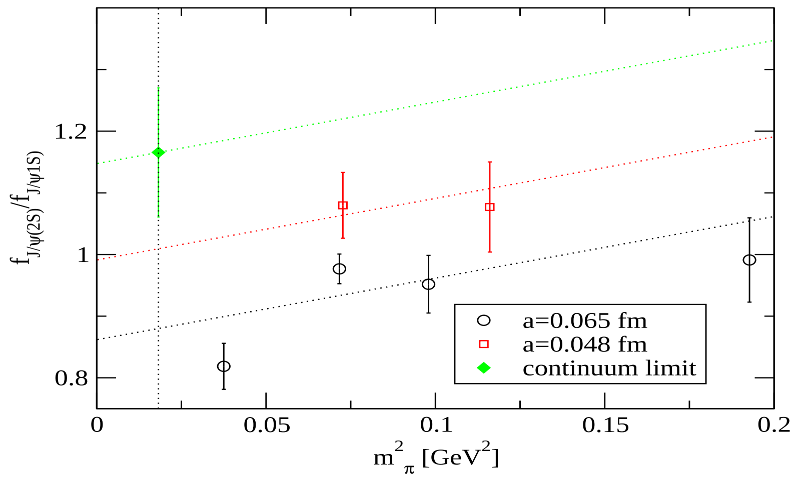
Remark: from $\Gamma(J/\psi \to e^+e^-) = \frac{4\pi}{3}\frac{4}{9}\alpha_{\mathrm{em}}(m_c^2)\frac{f_{J/\psi}^2}{m_{J/\psi}^2}$, measurement of J/ψ mass and width, and $\alpha_{\mathrm{em}}(m_c^2) = 1/134$, $f_{J/\psi}^{\text{"exp"}} = 407(6)$ MeV





Both $m_{\eta_c(2S)}/m_{\eta_c} \gg (m_{\eta_c(2S)}/m_{\eta_c})^{\rm exp}$ and $m_{\psi(2S)}/m_{J/\psi} \gg (m_{\psi(2S)}/m_{J/\psi})^{\rm exp}$, lack of control on data





Situation very confusing for $f_{\eta_c(2S)}/f_{\eta_c}(< 1)$ and $f_{\psi(2S)}/f_{J/\psi}(> 1)$

Using experimental widths $\Gamma(J/\psi \to e^+e^-)$ and $\Gamma(\psi(2S) \to e^+e^-)$: $f_{\psi(2S)}/f_{J/\psi} \sim 0.7$

Outlook

- For the moment not many hints of New Physics; violation of lepton flavour universality observed in $B \to D^{(*)}$ semileptonic decays, very exciting to look at $B_s \to D_s^{(*)}$ transitions, control on the lattice of D_s^* hadronic properties

- Observables useful to constrain NP with extensions of the Higgs sector: leptonic widths of $\eta_{c,b}$ sensitive to couplings with a hypothetic CP-odd Higgs.

- Explore what can be done for D_s and charmonia physics with $N_f = 2$ Wilson-Clover fermions: no issue with chiral extrapolation, GEVP useful to guarantee the signal of ground states.

- Confident in the extraction of $f_{D_s^*}/f_{D_s}$, f_{η_c} and $f_{J/\psi}$, cut-off effect under good control

- Much more tricky as far as radial excitations are concerned, still need to work and understand the literature

- Further steps: exploration of step scaling in mass methods to extrapolate in heavy mass up to m_b, dispersion relation to assess the reliability of any form factors computation