# Heavy meson electroweak decays into multi-hadron states

Multi-Hadron Systems from Lattice QCD
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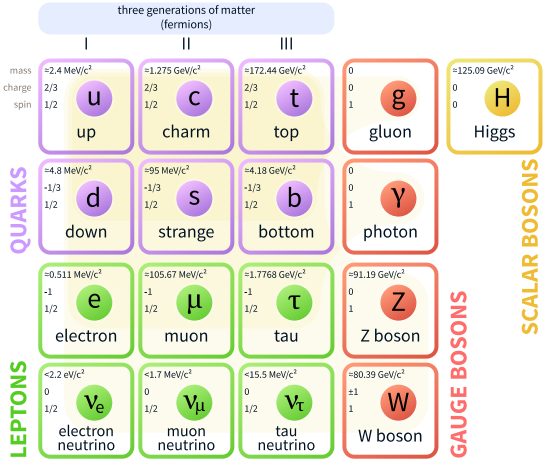
# Motivation

## Standard Model of Elementary Particles




$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- flavor basis
- EW interaction basis

# Motivation

**flavor physics**

*determining the CKM matrix from a combination of Electro-Weak decays*

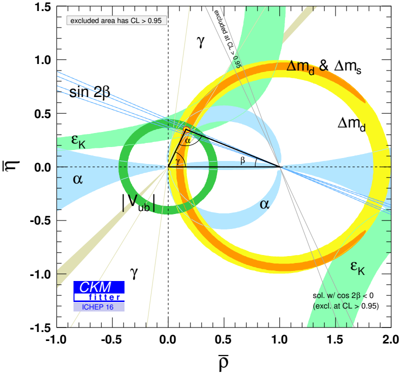
**can we do it?**

- a lot of success (MILC, HPQCD, ETMC, ...)
- "only" involves (QCD)-stable hadrons

**is it done?**

No!

- puzzles!
- new aspects to flavor physics



# Puzzles

## size of CKM elements

- $V_{cb}$
  - $B \to D\, \ell\, \nu\ [V_{cb}^{exc}, R(D)]$
  - $B \to D^*(\to D\pi)\, \ell\, \nu$ $[V_{cb}^{exc}, R(D^*)]$
  - $B \to X_c\, \ell\, \nu\ [V_{cb}^{inc}]$
- $V_u b$
  - $B \to \pi\, \ell\, \nu\ [V_{ub}]$
  - $B \to X_c\, \ell\, \nu$

## phases of CKM

- fully hadronic decays:
  - $B \to K\pi^{\gamma}$ - history
  - $B \to J/\psi K_L^{\beta}$,
  - $B \to \pi\pi^{\alpha}$, $B \to \pi\rho^{\alpha}$, $B \to \rho\rho^{\alpha}$

## rare decays

- $B \to K^*(\to K\pi)\, \ell^+\, \ell^-$
- $B_s \to \phi(\to KK, \rho\pi)\ell^+\ell^-$
- $B \to K\, \ell^+\, \ell^-$

*... and many others ...*

# Puzzles

**flavor point of view**

- properties of the current
- New Physics contribution
- Hadronic effects are a neccessary evil

**hadronic point of view**

- effects of (hadronic) final states
- coupled channel effects
- do decays need to go through resonances?
- how do the resonances behave in these decays?

*Two points of view on the same thing!*

# New aspects?

**what if in addition to going to very high precision on a few decays, we also do reasonable precision on many decays?**

For example: Determine $V_{ub}$ from $B \to \pi \ell \nu$, $\Lambda_b \to p \ell \nu$, $B \to \pi \pi \ell \nu$, and others?

$\to$ More information, more insights and less risk of potentialy harmful systematic effects...

*... and lattice can do many of these things ...*
*((or we're at least close))*

# An Example: $D \to \pi\pi(\to \rho)\ell\nu$

C. Alexandrou, S. Meinel, J.W. Negele, S. Paul, M. Petschlies, A. Pochinsky, G. Rendon, S. Syritsyn

**the final state dictates the complexity of the decay**

$H \to V\ell\nu$, $V \to H_1 H_2$, $H_1', H_2'$

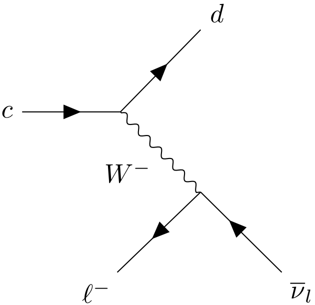
- $3$ angles
- $5$ form factors
- $\ell\nu$ momentum transfer $q^2$
- two-hadron invariant mass $\sqrt{s}$
- $H_1, H_2$, $H_1', H_2'$

$H \to P\ell\nu$, $P$ stable

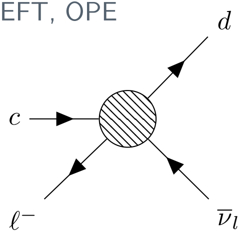
- $2$ angles
- $2$ form factors
- $\ell\nu$ momentum transfer $q^2$

# An Example: $D \to \pi\pi(\to \rho)\ell\nu$

Tree Level SM



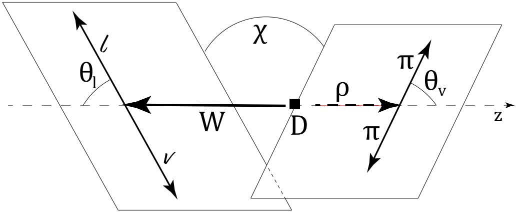

EFT, OPE




$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{cd} \left(\bar{d}\gamma_\mu c - \bar{d}\gamma_5\gamma_\mu c\right) \bar{l}\gamma_\mu(1-\gamma_5)\nu$$

[Feldmann B-Physik Workshop, Siegen 2014]

# An Example: $D \to \pi\pi(\to \rho)\ell\nu$




$$A(\rho \to \pi\pi) = \frac{16\pi\sqrt{s}}{p^*}\frac{\sqrt{s}\Gamma(s)}{s - m_\rho^2 + i\sqrt{s}\Gamma(s)}$$

$$A(H \to \rho\ell\nu)^\mu = V(q^2,\sqrt{s})\varepsilon^{\mu\nu\alpha\beta}\epsilon^{*\nu}p_\rho^\alpha p_H^\beta +$$

$$A_0(q^2,\sqrt{s})\frac{\epsilon^*\cdot q}{q^2}q^\mu + A_1(q^2,\sqrt{s})(\epsilon^{*\mu} - \frac{\epsilon^*\cdot q}{q^2}q^\mu) +$$

$$A_2(q^2,\sqrt{s})\epsilon^*\cdot q((p_\rho + p_H)^\mu - \frac{m_H^2 - m_V^2}{q^2}q^\mu)$$

# An Example: $D \to \pi\pi(\to \rho)\ell\nu$

**leads to very rich differential decay width**

$$H_0(q^2, \sqrt{s}) = \frac{1}{2m_\rho \sqrt{q^2}} \Big( (m_D^2 - m_\rho^2 - q^2)(m_D + m_\rho) A_1(q^2, \sqrt{s}) - 4 \frac{m_D^2 p_\rho^2}{m_D + m_\rho} A_2(q^2, \sqrt{s}) \Big)$$

$$H_\pm(q^2, \sqrt{s}) = (m_D + m_\rho) A_1(q^2, \sqrt{s}) \mp \frac{2 m_D p_\rho}{m_D + m_\rho} V(q^2, \sqrt{s}))$$

$$\frac{d\Gamma(D \to \rho(\to \pi\pi)\ell\nu)}{dq^2 d\cos\Theta_v d\cos\Theta_l d\chi} = \frac{3 G_F^2 |V_{cd}|^2}{8(4\pi)^4} \frac{p_v^2 q^2}{m_D^2} Br(\rho \to \pi\pi) \times$$
$$\times ((1+\cos^2\Theta_l)\sin^2\Theta_v |H_+(q^2,\sqrt{s})|^2 + (1-\cos\Theta_l)^2 \sin^2\Theta_v |H_-(q^2,\sqrt{s})|^2$$
$$+ 4\sin^2\Theta_l \cos^2\Theta_v |H_0(q^2,\sqrt{s})|^2$$
$$+ 4\sin\Theta_l(1+\cos\Theta_l)\sin\Theta_v\cos\Theta_v\cos\chi H_+(q^2,\sqrt{s})H_0(q^2,\sqrt{s})$$
$$- 4\sin\Theta_l(1-\cos\Theta_l)\sin\Theta_v\cos\Theta_v H_-(q^2,\sqrt{s})H_0(q^2,\sqrt{s})$$
$$- 2\sin^2\Theta_l\sin^2\Theta_v\cos 2\chi H_+(q^2,\sqrt{s})H_-(q^2,\sqrt{s})$$

[Richman, Burchat Rev.Mod.Phys. 67 (1995)]

# An Example: $D \to \pi\pi(\to \rho)\ell\nu$

the lattice: part 1 (preliminary)

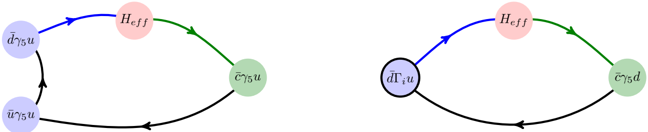
- RHQ charm quarks
  [El-Khadra et al. 1996, Aoki et al. 2001 & 2003, RBC/UKQCD 2012]
- tune $m_{D_s}$ (PS) to experimental value $(1968.3(1)$ MeV)
- relativistic dispersion relation $c^2 = 1$.
- renormalization constant: $Z_{cq} = 1.02054$
- mostly nonperturbative method
  [Hashimoto et al. PRD 61 (1999), El-Khadra et al. PRD 64 (2001)]
- $d_1 = 0.04305$

$$J_\Gamma(y) = Z_{cq}(\bar{q}(y)\Gamma Q(y) + d_1 \bar{q}(y)\Gamma \sum_{i=1}^{3} \gamma_i (\nabla^i Q)(y))$$

# An Example: $D \to \pi\pi(\to \rho)\ell\nu$

the lattice: part 1 (preliminary)

$$C_3^p(t_\rho, t_J, t_D) = \langle O_D(t_D, \vec{p}_D) O_J(t_J, \vec{q}) O^p_{\pi\pi}(t_\rho, \vec{p}_\rho)\rangle$$




optimized three point functions:

$$\Omega_3^n(t_J, \Delta t) = v_p^{(n)} C_3^p(t_J, \Delta t = t_\rho - t_D)$$

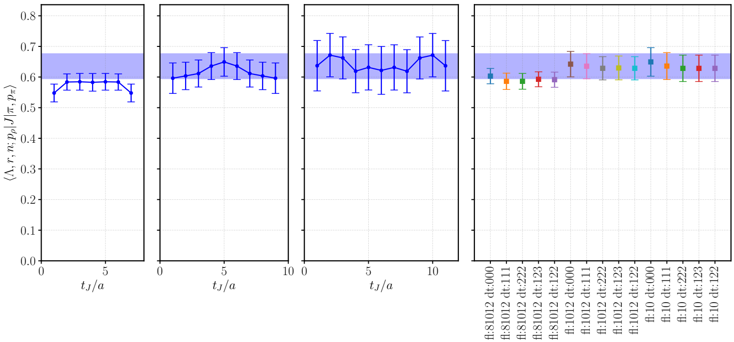
determine (finite volume matrix elements):

$$\langle n, \Lambda, r, \vec{p}_\rho | J_{V,A}(\vec{q}) | \pi, \vec{p}_\pi \rangle$$

# An Example: $D \to \pi\pi(\to \rho)\ell\nu$

## the lattice: part 2 (preliminary)

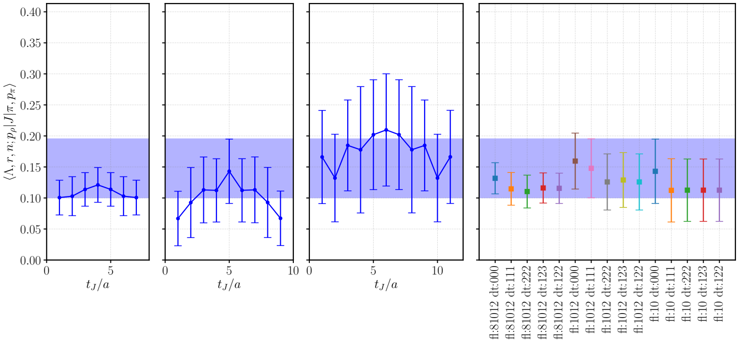
the matrix elements at $(0.43838,\ 0.31339)$ with $(B_2, (0,1,1))$



# An Example: $D \to \pi\pi(\to \rho)\ell\nu$

the lattice: part 2 (preliminary)

the matrix elements at $(0.48269,\ 0.195071)$ with $(A_2, (1,1,1))$

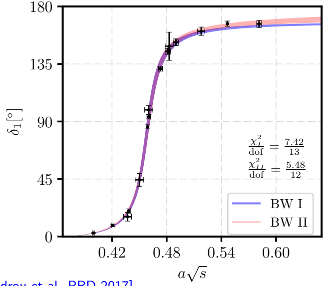


# An Example: $D \to \pi\pi(\to \rho)\ell\nu$
## the lattice: part 3 (preliminary)

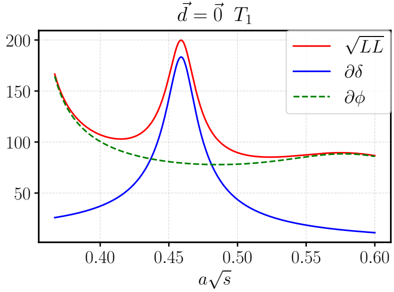
map the matrix elements from FV to IV

[Lellouch & Lüscher 2001, ..., Briceño, Hansen & Walker-Loud 2014, Feng, Christ, Martinelli & Sachrajda 2015]

$$\frac{|\langle n,\Lambda,r,\vec{p}_\rho|J^\mu,\vec{q}|D,\vec{p}_D\rangle(q^2,\sqrt{s})|^2_{IV}}{|\langle n,\Lambda,r,\vec{p}_\rho|J^\mu,\vec{q}|D,\vec{p}_D\rangle|^2_{FV}} = \frac{32\pi E_D\sqrt{s}}{k}\left[\frac{\partial\delta_1(\sqrt{s})}{\partial E_{\pi\pi}} + \frac{\partial\phi_1^{\vec{d}}(k)}{\partial E_{\pi\pi}}\right]$$

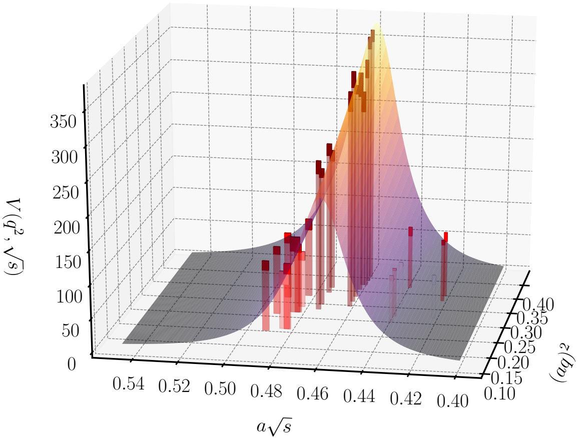



[Alexandrou et al. PRD 2017]



# An Example: $D \to \pi\pi(\to \rho)\ell\nu$

## the lattice: part 4 (preliminary)




[$z$-expansion(1-pole) + BW + some residual $\sqrt{s}$ dependence]

# An Example: $D \to \pi\pi(\to \rho)\ell\nu$

- known very well experimentally [FOCUS, hep-ex/0509027]
- maybe we can chime in on the one-pole vs two-pole discussion [Fajfer & Kamenik, hep-ph/0601028]
- use as a check of the methodology ($V_{cd}$ known very well)
- (potential interplay with experiment?)
- crucial: cannot treat $\rho$ as stable

# Other decays

(from M. Neubert Moriond 2017)

- $B \to K\pi(\to K^*(892))\ell^+\ell^-$
  $P_5'$: (2-3 $\sigma$), $R_{K^*}$: (2.5 $\sigma$)
- $B \to D^*\tau\nu$
  $\frac{d\Gamma}{dq^2}$: (3.5 $\sigma$)
- $B_s \to \phi\mu^+\mu^-$
  rate: (suppressed at $3.5\ \sigma$)
- $3\ \sigma$ tension in $V_{ub}$ exclusive vs. inclusive
- $3\ \sigma$ tension in $V_{cb}$ exclusive vs. inclusive
- (and $\mu\ g-2$, $K$ physics)

Is it New Physics? Maybe. But ...

Maybe the Standard Model has some surprises for us?

# Conclusions

- multi-hadron system represent a whole new opportunity in electroweak decay studies
- a plethora of decays to investigate with QCD
- still issues though: long-distance effects in general
- also issues: sometimes resonances couple to three particles

- it can provide additional observables that can be compared to experiment
- (better control of systematics)

- semileptonic decays can be done
- rare decays can be done
- fully hadronic? a bit harder

Thank you :)