Weak Hyperon Decays from Lattice QCD

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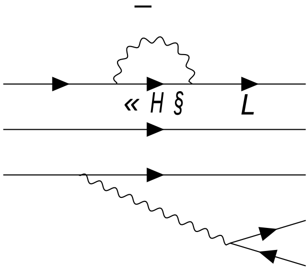
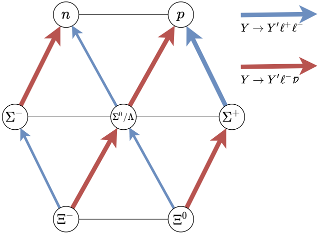
Rare Hyperon Decay

- + ! q`+` is an ! L FCNC process
- Sensitive to new physics
- Baryonic equivalent to the rare kaon decay b ! `+`
  [Felix Erben Fri. 8:30 EDT]

! « Semileptonics

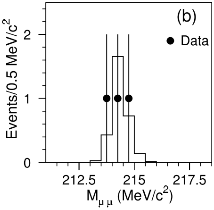
- ! j` et al. are ! « processes
- Alternate measurement of - $_{us}$





! L Motivation: Experiment

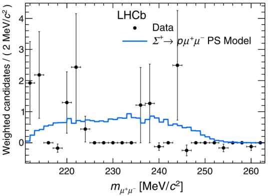
[´q0} Gp r©· ·Us



- Observed 3 events
- $B(\;^{+}\; ! \; q \; ^{+} \;)_{HCP} = 8{:}6^{+6{:}6}_{\;5{:}4} \quad 5{:}5 \quad 10^{\;8}$
- Originally thought this could be signal for a new particle of mass ' 214 $g0$ -

[HyperCP 10.1103/PhysRevLett.94.021801]

d [G@ r©·oPs



- $O(10)$ events
- $B(\;^{+}\; ! \; q \; ^{+} \;)_{LHCb} = 2{:}2^{+1{:}8}_{\;1{:}3} \quad 10^{\;8}$
- No evidence for new particle
- Interest in improving measurement with the latest data, including first measurement of $B(\;^{+}\; ! \; q0^{+}0 \;)$

[LHCb 10.1103/PhysRevLett.120.221803]

! L Motivation: Theory

- SM prediction from combination of experimental input, unitarity cuts, vector meson dominance and Chiral Perturbation Theory

$$1.6 \quad 10^{\ 8} < B(\ ^{+} \ ! \ q \ ^{+} \quad) < 9.0 \quad 10^{\ 8}$$

- Short distance contribution $O(10^{\ 12})$
- Dominated by the long distance contribution

$$^{+} \ ! \ q \quad , \quad ! \quad ^{+}$$

- Large range mainly coming from different types of ChPT

[X. He 10.1103/PhysRevD.72.074003]

[X. He et al. 10.1007/JHEP10(2018)040]

! L Lattice Theory

- Long distance part $^{+}$! q given by amplitude

$$A = hqj ¦ f [_{w} ` gj i$$

- ` : EM current $[_{w}$: ! L effective weak Hamiltonian

$$[_{w}(^{2}) = \frac{W_F}{p\overline{2}} -_{us} -_{ud} [G_1(w_1^u \quad w_1^c) + G_2(w_2^u \quad w_2^c) + :::] + \text{c.c.}$$

with the 4-quark operators

$$w_1^q = (\quad ^{L}L)(x \quad ^{L}x) \qquad w_2^q = (\quad ^{L}x)(x \quad ^{L}L)$$

- Form factor decomposition

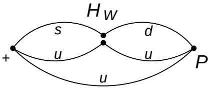
$$A = «_p \quad x^2 \qquad xx \quad (T_1 + X_1 \quad _5) + \qquad x \; (T_2 + X_2 \quad _5) \; «$$

! L Lattice Theory

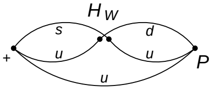
- Can be extracted from the 4pt correlation function

$$G^4 = h \quad _N(\quad §) [\, _w(§_H) ` \quad (§_J) \quad (0) i$$

- Requires computation of diagrams of the type

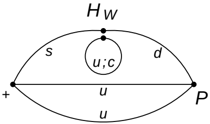


C_{sd}



C_{su}

[github.com/ paboyle/Grid]



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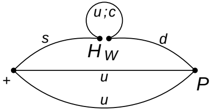


S

[github.com/ aportelli/Hadrons]

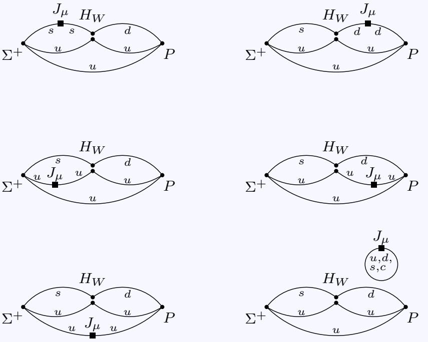
! L Lattice Theory

- Can be extracted from the 4pt correlation function

$$G^4 = h \ {}_N(\ \S) [\ {}_w(\S_H) ` \ (\S_J) \ \ (0) i$$

- Req

Including vector current insertions e.g.



[github.com/ paboyle/Grid]

[github.com/ aportelli/Hadrons]

! L Computational Approach

- Can use method very similar to the rare Kaon decay b ! `+`
  [Felix Erben Fri. 8:30 EDT] [N. Christ et al. 10.1103/PhysRevD.92.094512] [N. Christ et al. 10.1103/PhysRevD.94.114516]
- Fix EM current position and integrate $\S_H$ in a window around $\S_J$

$$\hat{}(¦_a; ¦_b) = \int_{t_{`} - T_9}^{t_{`} + T_@} L\S_H h \; _N(\; \S) [_w(\S_H) ` \; (\S_J) \quad (0) i$$

- Growing exponential contamination in $¦_a$ from intermediate states i and i with $N < N$
- Can construct and remove i contribution similarly to state in b ! decay [N. Christ et al. 10.1103/PhysRevD.100.114506]
- Understanding of finite volume corrections from i state in progress

3pt Summed Method

Summed method where operator insertion is summed over all time

[L. Maiani et al. 10.1016/0550-3213(87)90078-2]
[C. Bouchard et al. 10.1103/PhysRevD.96.014504]

$$\hat{}^3(\ \S) = \sum_{t=0}^{T} h\ _f(\ \S)\,`(\S)\ _i(0)\,i$$

$$= \sum_{n,m} \text{"}\ \mu^i_{0n}\mu^f_{m0}\,`_{nm}\,\frac{1\quad 0^{\ (E_j\quad E_h)(\ t\ \ 1)}}{0^{E_j\quad E_h}\quad 1}\,0^{\ E_h\ \ t}\ \#$$

$$+ \sum_{n} \text{"}\ \mu^i_{0n}\mu^{fJ}_{n0} + \sum_{l} \frac{\mu^i_{0n}\mu^f_{nl}\,`_{l0}}{0^{E_e}\quad 1}\ \#\ 0^{\ E_j\ \ t}$$

$$+ \sum_{m} \text{"}\ \mu^{iJ}_{0m}\mu^f_{m0} + \sum_{l} \frac{`_{0l}\mu^i_{lm}\mu^f_{m0}}{0^{E_e}\quad 1}\ \#\ 0^{\ E_h\ \ t} + \sum_{k} \mu^i_{0k}\mu^f_{k0}\,`_{00}\,0^{\ E_c\ \ t}$$

- First line gives regular linear $\S$ behaviour for $j = h$ states
- Second and third lines give combination of contact terms ($\S = 0$ and $\S =\ \ \S$) and out of order terms ($\S >\ \ \S$)

4pt Summed Method

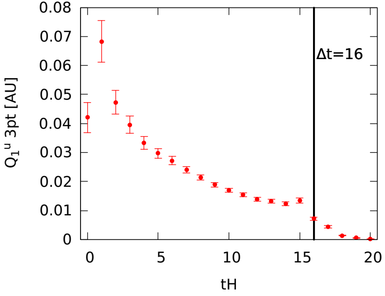
- Can extend the summed method to $^{+} \to q$ 4pt function

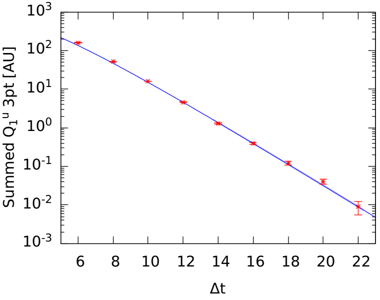
$$\hat{\ }^{4}(\ \tau) = \int_{0}^{T} d\tau_{H} \int_{0}^{T} d\tau_{J} \langle\ _{N}(\ \tau)\, H_{w}(\tau_{H})\, J\ (\tau_{J})\ \ (0)\rangle$$

- Get contamination from intermediate states N, , π , ...
  Can in theory be constructed and removed
- Full understanding of contact and out of order terms in progress
- Investigating practicality of this method
- Could benefit both the rare Hyperon and rare Kaon decays

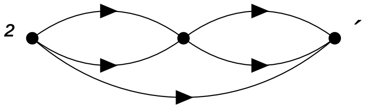
! L Preliminary Results

- Working towards a first exploratory calculation of this matrix element on a larger than physical pion mass ensemble
- RBC UKQCD 2 + 1 flavour 24^3 64 Iwasaki gauge configurations 9 ^{1} = 1780 g0- and h ' 340 g0- using Shamir domain wall fermions
- 3pt correlator h $_N$(§) [$_w$(§$_H$) (0)i using Gaussian smearing without summing (left) and summed (right)



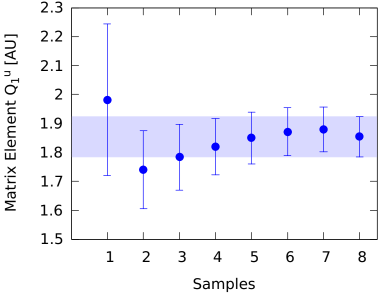


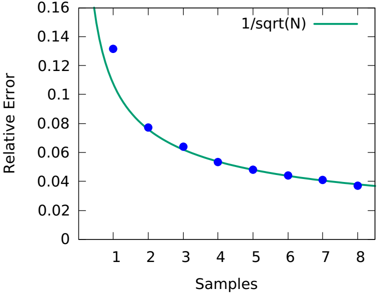
Source-Sink Sampling



- Positions ² and ´ fixed in solves
- Volume sum for momentum projection requires 14,000 solves on 24^3 64 lattice

- Approximate with sum over N random position samples
- Could get up to $1/i$ error scaling [Y. Li et al. 10.1103/PhysRevD.103.014514]
- Only observe approx. $1/\sqrt{i}$ scaling for this quantity





! « Motivation

- Currently best -$_{us}$ measurement from (semi)leptonic Kaon decays b ! ` and $b$ ! ` : j -$_{us}j$ = 0:2243(4)

  E8 j L}0° ³njX ¦\«}u o©l©· NK¦F [Particle Data Group 10.1093/ptep/ptaa104]

- Gives a 2 tension with first row CKM unitarity

- Semileptonic Hyperon octet transitions can give alternative determination of j -$_{us}j$ from the experimental measurements and theory prediction of form factors
- From ~^{a} (3)$_F$ symmetry : j -$_{us}j$ = 0:2250(27)(?)$_{SU(3)}$

  [N. Cabibbo 10.1103/PhysRevLett.92.251803]

- ~^{a} (3)$_F$ breaking required for improved precision

! « Theory

- ³ ! ³′\` hadronic amplitude $A = h\,³\,'j\,\grave{}\,^{s\,!\,u}j\,³\,i$
  where $\grave{}\,^{s\,!\,u} = « \quad (1 \qquad {}_5)$
- Form factor decomposition

$$
\begin{aligned}
A \quad &= «' \;\; T_1 \qquad + T_2 \frac{x}{g \; + \; g\,'} + T_3 \frac{x}{g \; + \; g\,'} \\
&\qquad + X_1 \qquad {}_5 + X_2 \frac{x \quad {}_5}{g \; + \; g\,'} + X_3 \frac{x \quad {}_5}{g \; + \; g\,'} \quad «
\end{aligned}
$$

- T_1 subject to at most second order SU(3) breaking
- T_3 and $X_2 = 0$ in the SU(3) limit
- T_3 and X_3 terms suppressed in the full amplitude by the charged lepton mass $h\,\grave{}$. Therefore negligible in electronic decays but relevant for muonic decays

- Using RBC UKQCD 2 + 1 flavour 48^3 96 Iwasaki gauge configurations and Möbius domain wall fermions. 9 ^{1} = 1730 g0- and h ' 140 g0-
- Using generalised summed method to reduce cost and improve signal

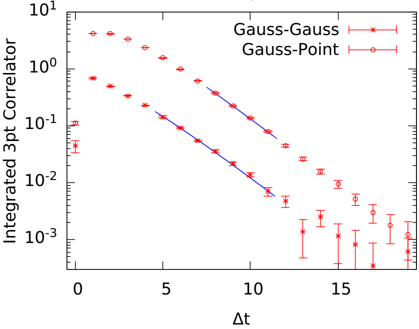
$$^{(3)}(\S) = \sum_t h \; _{Y'}(\S) \; `^{s\,!\,u}(\S) \; _Y(0) i$$

- Twisted boundary conditions on the strange quark to achieve $x^2 = 0$ point for the ! i and ! decays

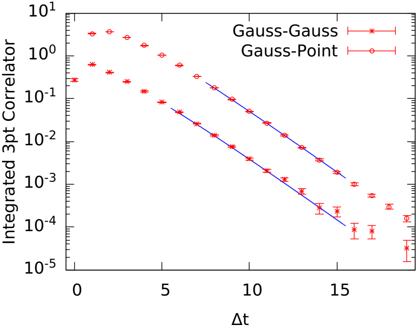
! « Preliminary Results

- Example integrated 3pt correlators of the temporal component of the current $\hat{}^{(3)}_{0}($ §$)$ [arbitrary units]

! j



0 ! +



Summary / Outlook

Summary

- SM prediction of + ! q`+` is a quantity of interest
- Have a method to compute on the lattice and working towards a calculation at larger than physical pion mass
- Also working on ! « hyperon transitions at the physical point

Future outlook

- Compute ! « hyperon transitions with second lattice spacing
- Compute + ! q`+` decay at the physical point

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