Thomas Jefferson Laboratory
Postdoctoral Position: Remote Talk

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CSSM and CoEPP, The University of Adelaide
The stereotypes are true...
Thesis writing inspirations

Theory Football Team: “The Colour Singlets”
SM Physics at Adelaide

- BSc. (First Class Honours) 2008
- PhD with CSSM: 2009 - present
  - Supervisors: Drs. Rod Crewther and Ross Young
- Scope of thesis:
  - $\Delta l = \frac{1}{2}$ rule in K-decays
  - Electroweak corrections to $s \rightarrow d + \gamma$
  - Infrared behaviour of strong running coupling
  - Conformality and dilatons in low-energy QCD
  - $f_0(500)$ phenomenology and construction of chiral-scale perturbation theory.
BSM Physics at Adelaide

- Fulbright scholar 2010: Host UC Berkeley under supervision of Mary K Gaillard
- Developed interest in physics beyond the Standard Model: SUSY and phenomenological string models
- Present: Part-time research associate under Tony Williams and Tony Thomas
  - Major project: Next to Minimal Supersymmetric Standard Model (NMSSM) extension to SOFTSUSY spectrum generator (in collaboration with P. Athron and B. Allanach et al.)
  - Side projects: R-parity violation and LHC collider physics, composite Higgs models
Outline of research topics

- Chiral-scale perturbation theory about an infrared fixed point:
  - Is $f_0(500)$ a pseudo-Goldstone boson?
  - Unitarity corrections to $\eta \rightarrow 3\pi$

- Radiative electroweak corrections for parity violation: QWEAK and Møller scattering in the 12 GeV upgrade

- Hyperon non-leptonic decays and heavy baryon chiral perturbation theory with large-$N_c$
The Scalar-Isoscalar Channel and XPT$_3$

- $J^{PC} = 0^{++}$ channel poses enduring problem for XPT$_3$ expansions

$$A = \{A_{LO} + A_{NLO} + \ldots\} \chi PT_3$$

- Well studied examples include:
  - $\text{BR}(K_L \rightarrow \pi^0\gamma\gamma)$, $\Gamma(\eta \rightarrow 3\pi)$, and $K_{e4}$ decays at NLO
  - $\gamma\gamma \rightarrow \pi^0\pi^0$ with $O(m_K)$ momenta
  - Extreme case: $K_S \rightarrow 2\pi$
    Requires NLO $I=0$ amplitude to be 70 times the expected $\leq 30\%$ correction!

- Additional theoretical input usually required
  (e.g. Inverse Amplitude Method)

Figure: M.R. Pennington (2007)

$\gamma\gamma \rightarrow \pi^0\pi^0$ cross section
The Lowest QCD Resonance

- Dispersive analysis of $\pi\pi$-scattering + precise $K_{e4}$ data on scattering lengths [I. Caprini et al. (2006)] indicates complex pole

\[ \sqrt{s_p} = M - i\Gamma/2 \] on second Riemann sheet:

\[ M_{f_0} = 441^{+16}_{-8} \text{ MeV}, \quad \Gamma_{f_0} = 544^{+18}_{-25} \text{ MeV} \]

- In XPT$_3$ no clear separation of scales between $\{\pi,K,\eta\}$ and the non-Goldstone sector $\{f_0,\rho,...\}$

- Origin of breakdown in XPT$_3$ expansions

GS = Goldstone sector
QCD Infrared Fixed Point and Broken Scale Invariance

- Invariance under scale transformations $x \rightarrow \lambda x$ is anomalous

$$\partial^\mu D_\mu = \theta^\mu_\mu = \frac{\beta(\alpha_s)}{4\alpha_s} G^a_{\mu\nu} G^{a\mu\nu} + (1 + \delta(\alpha_s)) \sum_{u,d,s} m_q \bar{q} q$$

- For low-energies $<< m_{t,b,c}$ and $\alpha_s \leq \alpha_{IR}$ heavy quarks decouple

$$\theta^\mu_\mu |_{\alpha = \alpha_{IR}} = (1 - \delta(\alpha_{IR})) \sum_{u,d,s} m_q \bar{q} q \rightarrow 0 \text{ in } SU(3)_L \times SU(3)_R \text{ limit}$$

- Scale and chiral symmetry spontaneously broken by non-vanishing quark condensate

- Get 9 pseudo-Goldstones $\{\pi,K,\eta\}$ and 0++ QCD dilaton $\sigma$
Chiral-Scale Perturbation Theory About an Infrared Fixed Point

- For expansions in $\alpha_s$ about $\alpha_{\text{IR}}$ construct effective theory $\text{XPT}_\sigma$ of approximate scale and chiral symmetry

\[ L_{\text{str}}[U,U^+,\sigma] = L_{\text{inv}}^{d=4} + L_{\text{anom}}^{d>4} + L_{\text{mass}}^{d<4} \]

- Chiral Lagrangian operators scaled by powers of $\exp(\sigma/F_\sigma)$

\[ K = \frac{F_\sigma^2}{4\pi} \text{Tr}(\partial_\mu U \partial^\mu U^+) \rightarrow K e^{2\sigma/F_\sigma} \] [chiral-scale invariant]

- Retains successful leading order predictions of $\text{XPT}_3$:}

\[ L_{\text{inv}}^{d=4} = \{c_1 K + c_2 K_\sigma + c_3 e^{2\sigma/F_\sigma}\} e^{2\sigma/F_\sigma}, \]
\[ L_{\text{anom}}^{d>4} = \{(1 - c_1) K + (1 - c_2) K_\sigma + c_4 e^{2\sigma/F_\sigma}\} e^{(2 + \beta')\sigma/F_\sigma}, \]
\[ L_{\text{mass}}^{d<4} = \text{Tr}(MU^+ + UM^+) e^{(3 + \delta)\sigma/F_\sigma}. \]
Chiral-Scale Perturbation Theory

- Key results:
  - $\Delta I = \frac{1}{2}$ puzzle explained in leading order by $\sigma$-pole with $K_S-\sigma$ mixing induced through weak vacuum alignment:

$$L_{\text{weak}}^{\text{align}} = Q_8 \sum_n g_{8n} e^{d_{8n} \sigma/F_\sigma} + g_{27} Q_{27} e^{d_{27} \sigma/F_\sigma} + Q_M \{ e^{(3+\delta_\omega) \sigma/F_\sigma} - e^{(3+\delta) \sigma/F_\sigma} \} + h.c.$$  

- Octet dominance no longer required
- Electromagnetic anomaly $\Rightarrow$ nonperturbative estimate for Drell-Yan ratio $R_{\text{IR}} \sim 5$
- NLO analysis of $O(p^4)$ Lagrangian, mass corrections, $K_L \rightarrow \pi^0\gamma\gamma$ underway
Is $f_0(500)$ a pseudo-Goldstone boson?

- Is $f_0(500)$ a quark-antiquark, tetraquark, or gluonic state (or mixture of all three)?

- For unitarized XPT$_2$ with Goldstone sector \{\(\pi^+, \pi^0, \pi^-\)}, large-$N_c$ analysis indicates $f_0(500)$ predominantly not a quark-antiquark state [J. Ruiz de Elvira et al., Phys. Rev. D84, (2011)]

- In leading order of XPT$_\sigma$ dilaton mass given by

\[
m^2_{\sigma}F^2_{\sigma} = F^2_{\pi}(m_K^2 + m_\pi^2/2)(3 + \delta)(1 - \delta) - \beta'(4 + \beta')c_4(m_q)
\]

- Vanishes in chiral limit: smoking gun signal to test on the lattice!
Is $f_0(500)$ a pseudo-Goldstone boson?

- Recent lattice studies of $\pi\pi$-scattering by Z. Fu, Chin. Phys. Lett. 28 (2011); JHEP 1207 (2012):
  \[
  M_{f_0} = 691 \pm 37 \text{ MeV}, \quad \Gamma_{f_0} = 236 \pm 49 \text{ MeV}
  \]


- Examine chiral-scale extrapolations to physical masses

Primakoff effect and $\eta \rightarrow 3\pi$

- GlueX with 12 GeV upgrade to measure low $Q^2$ form factors of $\eta$, $\eta'$ at high precision
- Tests on anomaly structure (especially U(1) problem), $\eta$-$\eta'$ mixing, quark mass ratio $R$

$$R = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

Unitarity corrections to $\eta \rightarrow 3\pi$ in XPT$_{\sigma}$

Electroweak Corrections to $\mathbf{K \rightarrow 2\pi}$

- PhD warm-up problem: investigated $\Delta l = \frac{1}{2}$ enhancement through interference involving $s \rightarrow d + \gamma$
Parity Violation

- Interested in minimising the theoretical error budget for QWEAK and Moller experiments

\[ A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ Q_W(p) + F^p(Q^2, \theta) \right] \]

\[ Q_W(p) = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_{e}] + \square_{WW} + \square_{ZZ} + \square_{\gamma Z}. \]
Parity Violation

$Q_W(p) = [\rho_{NC} + \Delta_e][1 - 4 \sin^2 \hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$.

- $Q_W(p) = 0.0713 \pm 0.0008$ [Erler and Ramsey-Musolf, Phys. Rev. D72 (2005) 073003]

- Dispersive analyses to $\gamma Z$ box reveal varying estimates for theoretical uncertainty [M. Gorchtein et al. 2010-11]

- WW box corrections large $\sim 26\%$ of predicted $Q_W(p)$
  - Reexamine the theoretical uncertainty in existing calculations
Hyperon Non-Leptonic Decays

- Challenge to reconcile $|\Delta S| = 1$ non-leptonic decays

\[
\Sigma \rightarrow n + \pi, \quad \Lambda \rightarrow p + \pi, \quad \Xi \rightarrow \Lambda + \pi
\]

with SU(3) symmetry in baryon (heavy or not) XPT

Hyperon Non-Leptonic Decays

- Mismatch between the S- and P-wave data

Hyperon Non-Leptonic Decays

- Conclude? Baryon XPT is inadequate or (more speculatively!) new physics is responsible for effect

- What about combining with large-$N_c$ expansions?

- Recent applications to baryon masses and axial couplings [A. Calle Cordon and J.L. Goity, arXiv: 1210.2364]

- Can the non-leptonic hyperon decays be finally understood?
Thank you for your attention!