Thomas Jefferson Laboratory Postdoctoral Position: Remote Talk

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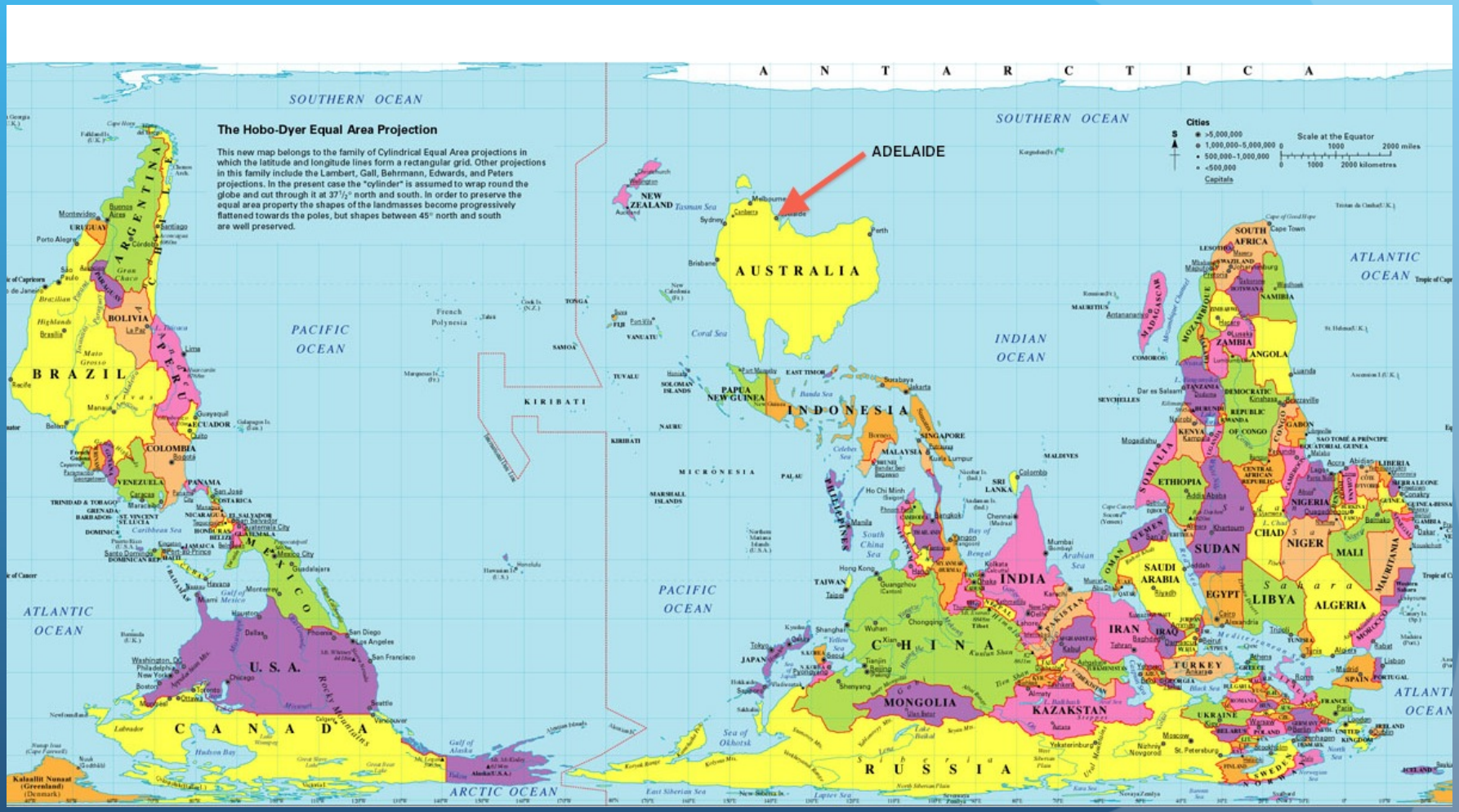
CSSM and CoEPP, The University of Adelaide

Geography as taught in Australia



Source: www.odt.com

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:
  - $\Delta I = ½$ 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.

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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

CoEPP

ARC Centre of Excellence for Particle Physics at the Terascale

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:
  - $BR(K_L \rightarrow \pi^0\gamma\gamma)$, $\Gamma(\eta \rightarrow 3\pi)$, 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 ≤ 30% correction!

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

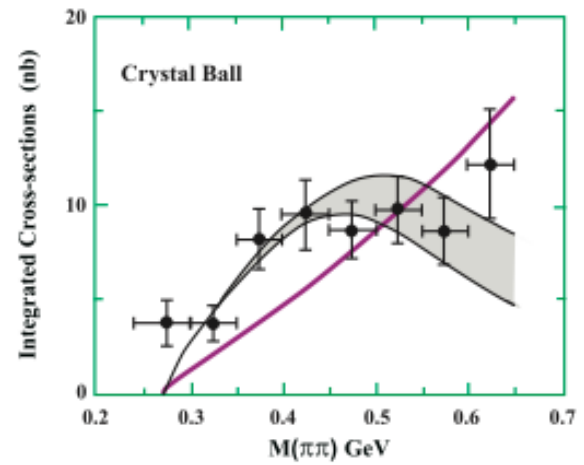


Figure: M.R. Pennington (2007)

$\gamma\gamma \rightarrow \pi^0\pi^0$ cross section

The Lowest QCD Resonance

- Dispersive analysis of ππ-scattering

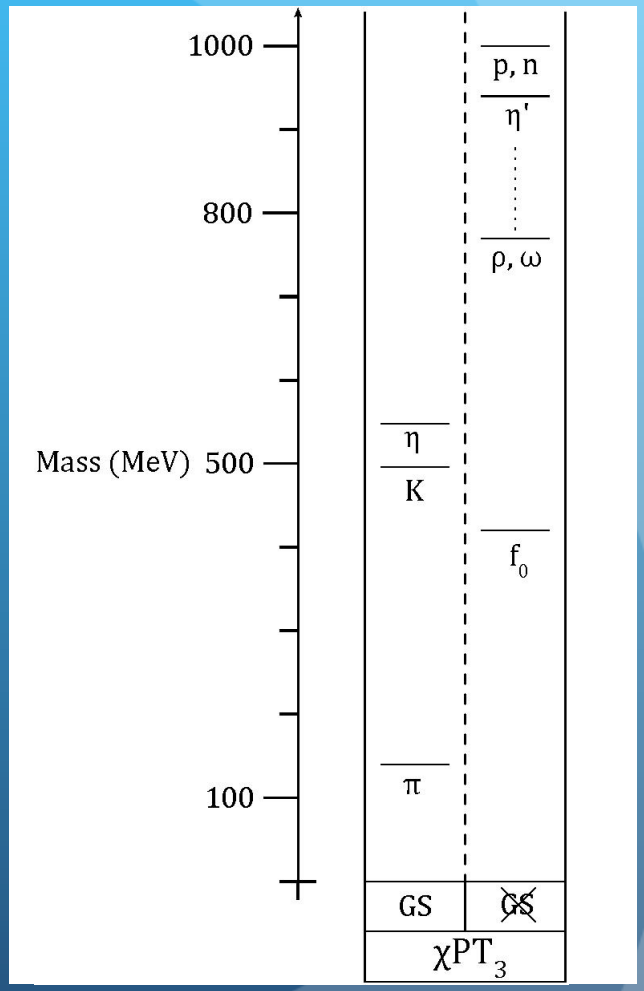
  + precise K_{e4} data on scattering lengths [I. Caprini et al. (2006)] indicates complex pole

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

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

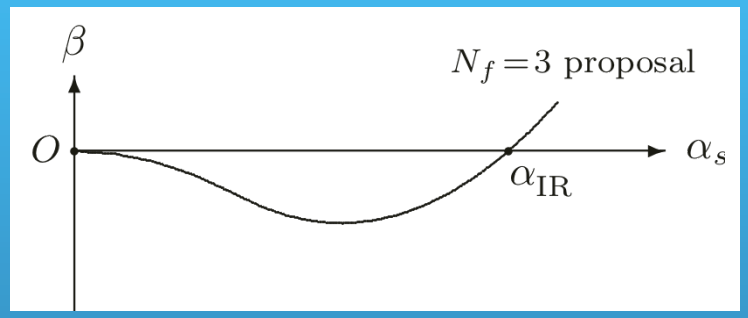
- In χPT_3 no clear separation of scales between {π,K,η} and the non-Goldstone sector $\{f_0,\rho,\ldots\}$

- Origin of breakdown in χPT_3 expansions



GS = Goldstone sector

QCD Infrared Fixed Point and Broken Scale Invariance



- Invariance under scale transformations x → λx 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

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

- Scale *and* chiral symmetry spontaneously broken by non-vanishing quark condensate
  - Get **9** pseudo-Goldstones {π,K,η} and 0^{++} QCD dilaton σ

Chiral-Scale Perturbation Theory About an Infrared Fixed Point

- For expansions in α_s about α_{IR} construct effective theory XPT_σ of approximate scale and chiral symmetry

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

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

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

- Retains successful leading order predictions of XPT_3:

$$\begin{aligned} L_{inv}^{d=4} &= \{c_1 K + c_2 K_\sigma + c_3 e^{2\sigma/F_\sigma}\} e^{2\sigma/F_\sigma}, \\ L_{anom}^{d>4} &= \{(1-c_1)K + (1-c_2)K_\sigma + c_4 e^{2\sigma/F_\sigma}\} e^{(2+\beta')\sigma/F_\sigma}, \\ L_{mass}^{d<4} &= Tr(MU^+ + UM^+) e^{(3+\delta)\sigma/F_\sigma}. \end{aligned}$$

Chiral-Scale Perturbation Theory

- Key results:
  - $\Delta I = ½$ puzzle explained in *leading order* by σ-pole with K_S-σ mixing induced through weak vacuum alignment:

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

  - Octet dominance no longer required
  - Electromagnetic anomaly => nonperturbative estimate for Drell-Yan ratio R_{IR} ~ 5

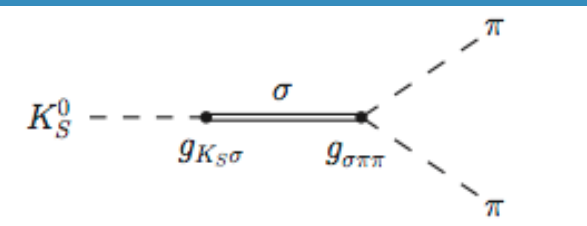


FIG. 2. Role of a QCD dilaton in $K_S \to \pi\pi$.

- NLO analysis of $O(p^4)$ Lagrangian, mass corrections, $K_L \to \pi^0\gamma\gamma$ 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_σ dilaton mass given by

$$m_\sigma^2 F_\sigma^2 = F_\pi^2 (m_K^2 + m_\pi^2/2)(3+\delta)(1-\delta) - \beta'(4+\beta')c_4(m_q)$$

- Vanishes in chiral limit: smoking gun signal to test on the lattice!

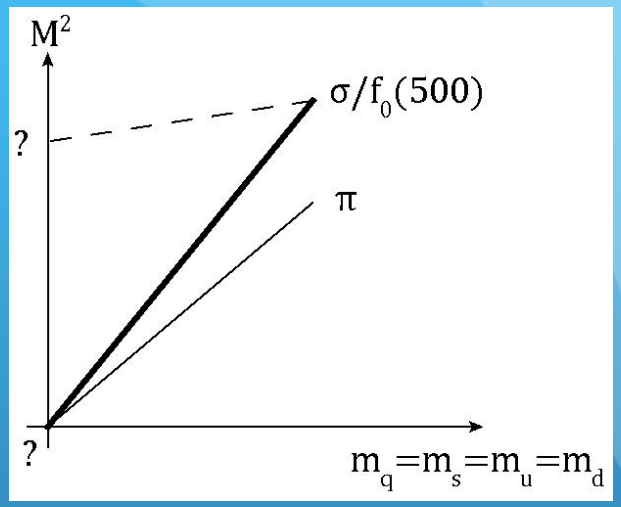
Is $f_0(500)$ a pseudo-Goldstone boson?

- Recent lattice studies of ππ-scattering by Z. Fu, Chin. Phys. Lett. 28 (2011); JHEP 1207 (2012):

$$M_{f_0} = 691 \pm 37 \text{ MeV}, \quad \Gamma_{f_0} = 236 \pm 49 \text{ MeV}$$

- Complement existing JLab interest in isoscalar meson spectroscopy [J. Dudek *et al., Phys.Rev. D83 (2011) 111502]*

- Examine chiral-scale extrapolations to physical masses



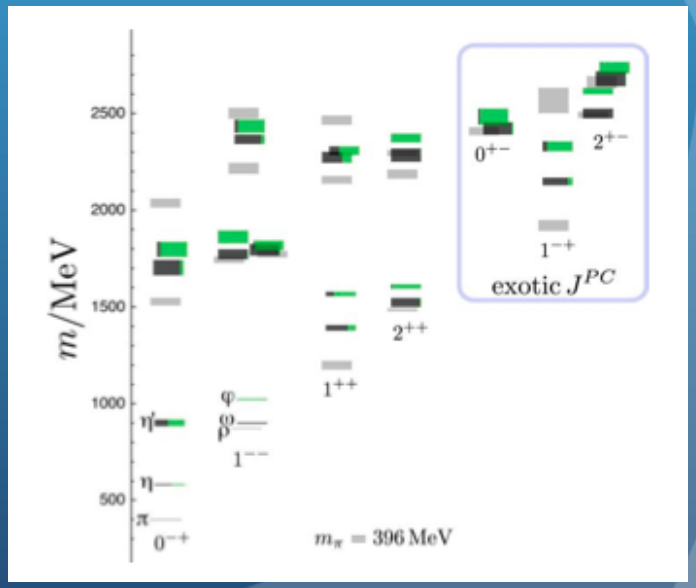
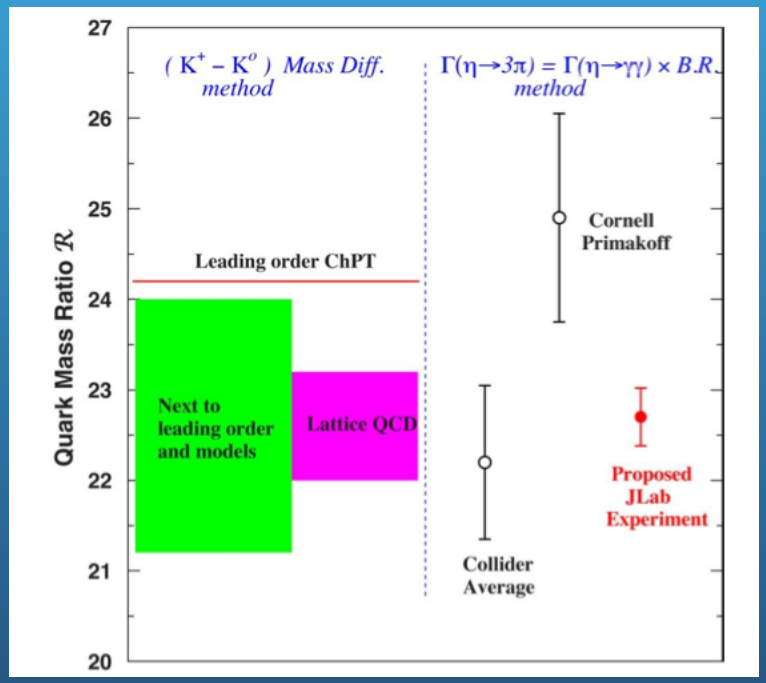


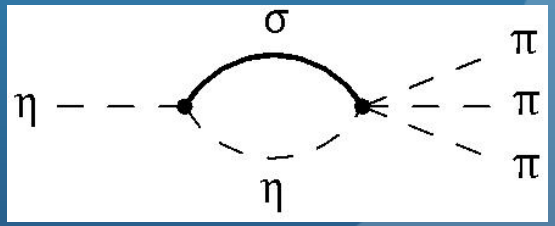
Fig: J. Dudek *et al.*, Eur. Phys. J. A48 (2012) 187

Primakoff effect and η → 3π

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



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

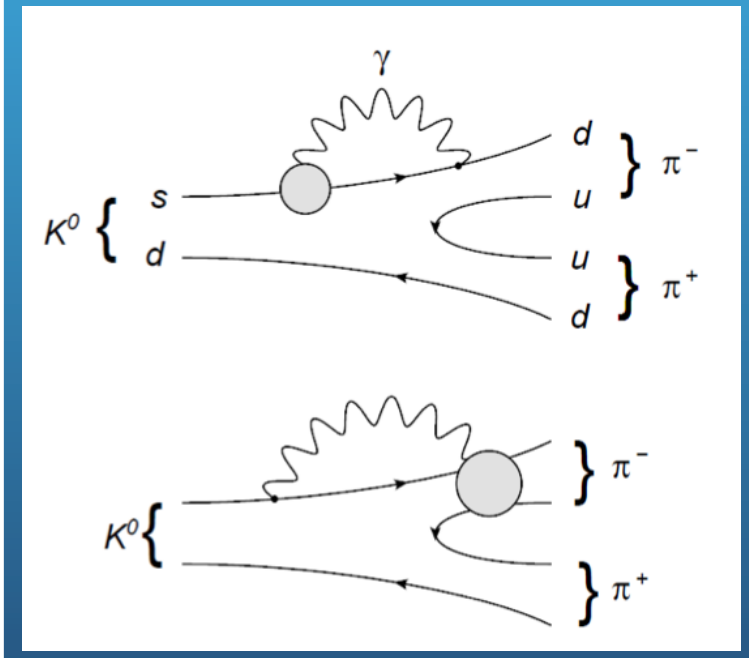


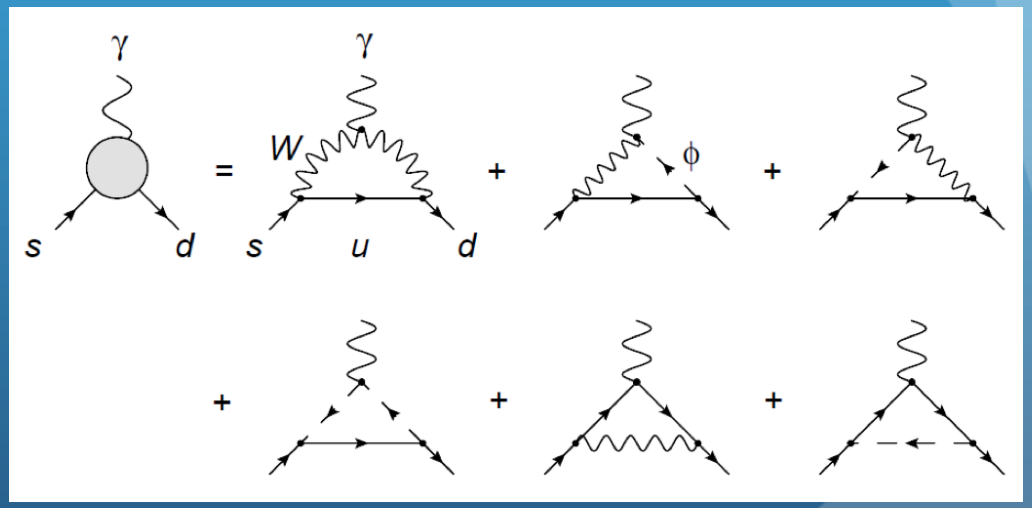
Unitarity corrections to η → 3π in XPT_σ

J. Dudek *et al.*, Eur. Phys. J. A48 (2012) 187

Electroweak Corrections to K → 2π

- PhD warm-up problem: investigated ΔI = ½ enhancement through interference involving s → d + γ



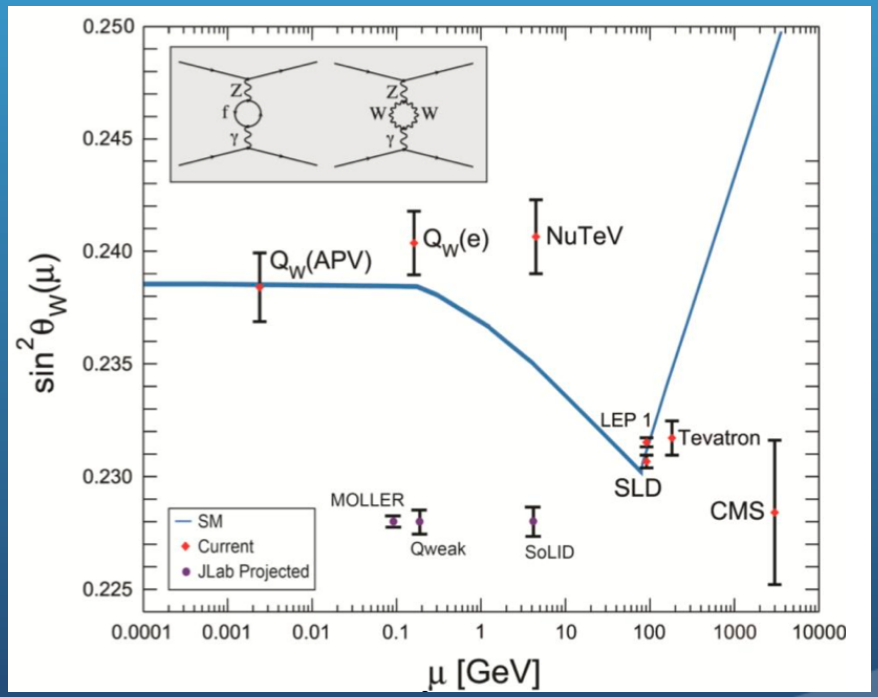


Parity Violation

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

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

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



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 γZ box reveal varying estimates for theoretical uncertainty [M. Gorchtein *et al*. 2010-11]
- WW box corrections large ~ 26% of predicted $Q_W(p)$
  - Reexamine the theoretical uncertainty in existing calculations

Hyperon Non-Leptonic Decays

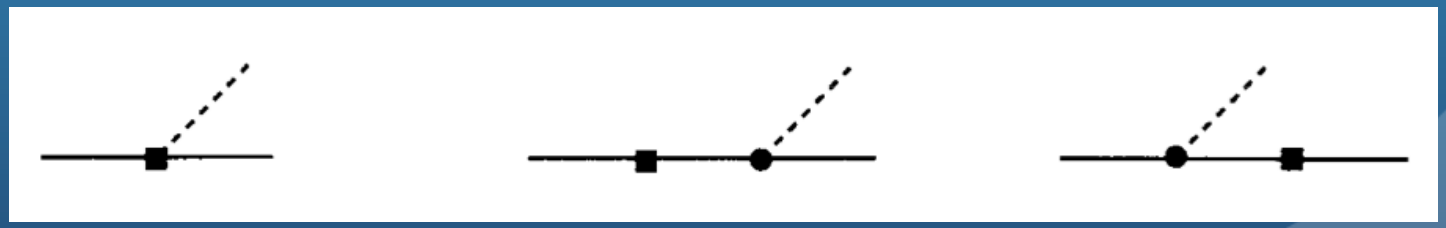
- Challenge to reconcile $|\Delta S| = 1$ non-leptonic decays

$$\Sigma \rightarrow n + \pi, \qquad \Lambda \rightarrow p + \pi, \qquad \Xi \rightarrow \Lambda + \pi$$

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

$$L_v^{\Delta S=1} = h_{\mathrm{D}}\ \mathrm{Tr}\ \bar{B}_v\{\xi^\dagger h \xi,\ B_v\} + h_{\mathrm{F}}\ \mathrm{Tr}\ \bar{B}_v[\xi^\dagger h \xi,\ B_v]$$

$$+ h_{\mathrm{C}} \bar{T}_v^\mu (\xi^\dagger h \xi) T_{v\mu} + h_\pi \frac{f^2}{4} \mathrm{Tr}\ h \partial_\mu \Sigma \partial^\mu \Sigma^\dagger,$$



Ref: E. Jenkins, Nucl. Phys. B 375 (1992)

Hyperon Non-Leptonic Decays

- Mismatch between the S- and P-wave data

Decay	s_{expt}	s_{theory}	s_{tree}	Δs_{loop}	Δs_{octet}	Δs_{decup}
$\Sigma^+ \to n\pi^+$	0.06	−0.09	0.00	−0.09	0.13	−0.22
$\Sigma^+ \to p\pi^0$	−1.43	−1.41	−0.85	−0.55	−0.04	−0.51
$\Sigma^- \to n\pi^-$	1.88	1.90	1.21	0.69	0.18	0.51
$\Lambda \to p\pi^-$	1.42	1.44	0.91	0.53	0.16	0.37
$\Lambda \to n\pi^0$	−1.04	−1.02	−0.64	−0.37	−0.11	−0.27
$\Xi^- \to \Lambda\pi^-$	−1.98	−2.04	−1.19	−0.84	−0.14	−0.71
$\Xi^0 \to \Lambda\pi^0$	1.52	1.44	0.84	0.60	0.10	0.50

Decay	p_{expt}	p_{theory}	p_{tree}	Δp_{loop}	Δp_{octet}	Δp_{decup}
$\Sigma^+ \to n\pi^+$	1.81	0.82	−0.06	0.89	0.16	0.72
$\Sigma^+ \to p\pi^0$	1.17	0.36	−0.13	0.49	−0.06	0.55
$\Sigma^- \to n\pi^-$	−0.06	0.34	0.13	0.21	0.26	−0.05
$\Lambda \to p\pi^-$	0.52	−0.52	−0.28	−0.24	−0.31	0.08
$\Lambda \to n\pi^0$	−0.39	0.38	0.21	0.17	0.23	−0.05
$\Xi^- \to \Lambda\pi^-$	0.48	0.35	0.11	0.24	0.30	−0.07
$\Xi^0 \to \Lambda\pi^0$	−0.33	−0.24	−0.07	−0.16	−0.21	0.05

Ref: E. Jenkins, Nucl. Phys. B 375 (1992)

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!