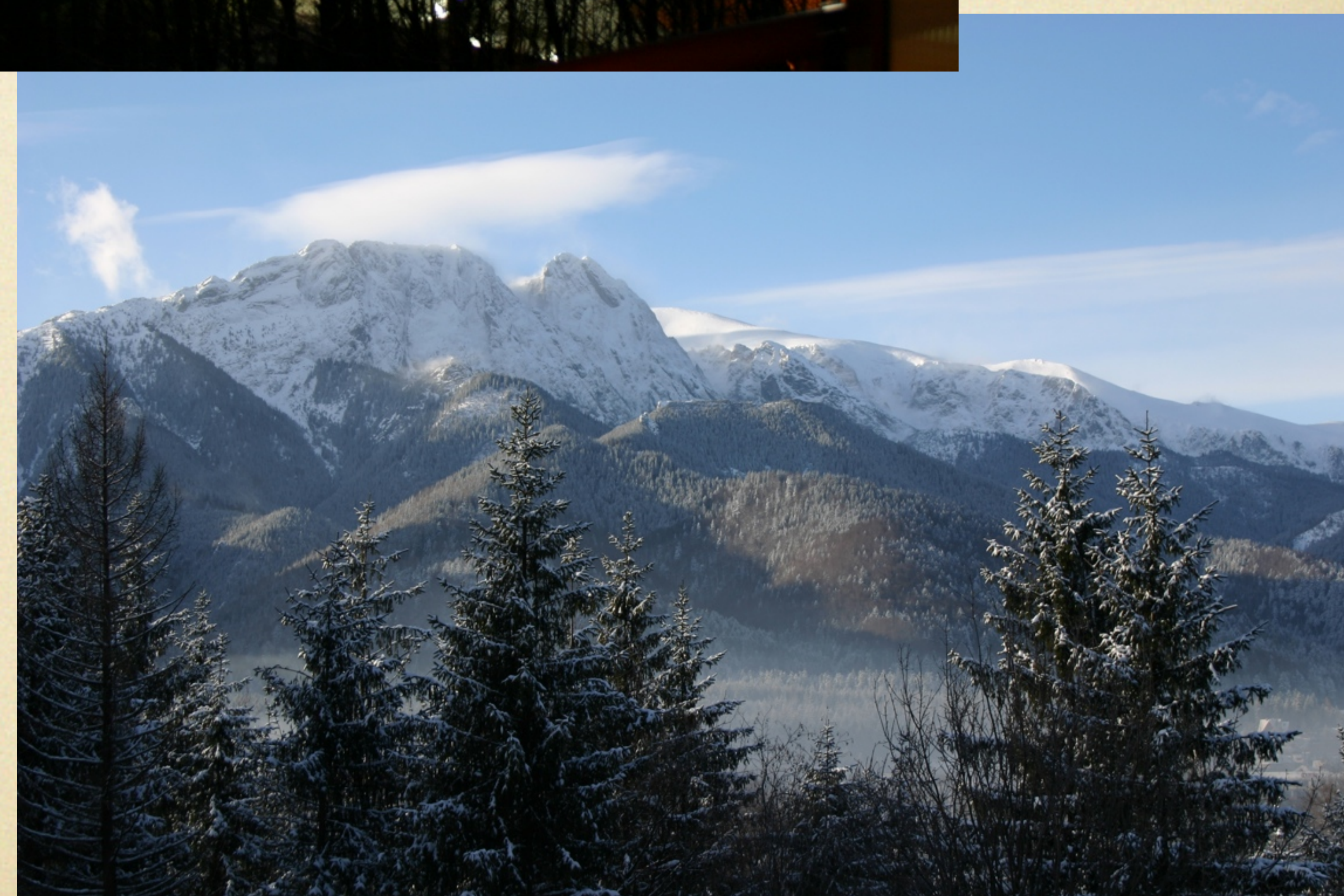
Unquenching and Requenching the Quark Model

Eric Swanson



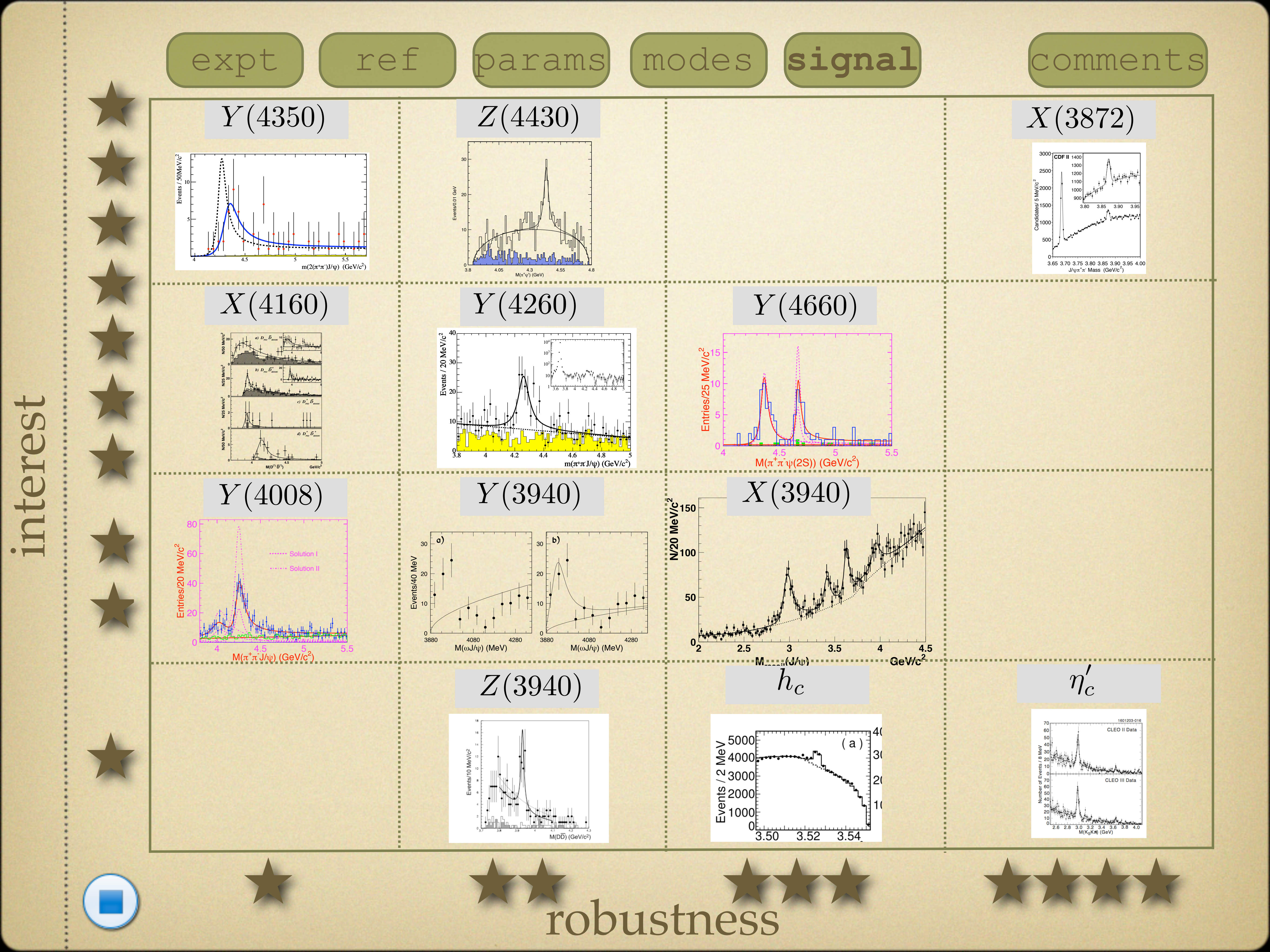


Motivation

- fine structure in the spectrum (esp. near thresholds)
- new and old states :

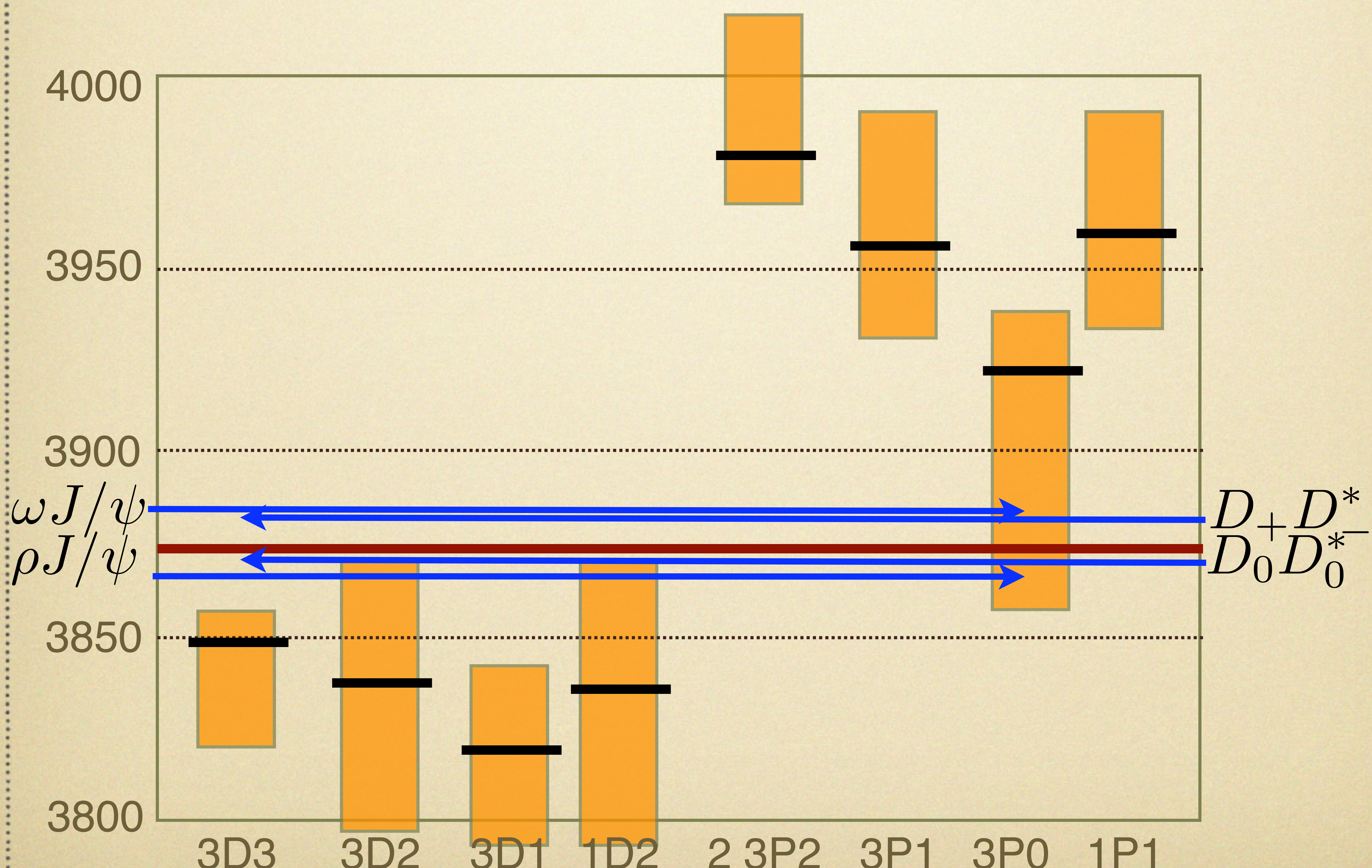
  $f_0(980), \quad f_0(1710), \quad D_{s0}(2317), \quad X(3872), \quad \Lambda(1405)$

- coupled channel effects: form factors, transition amplitudes, leptonic widths, etc
- screened potentials in the quark model?



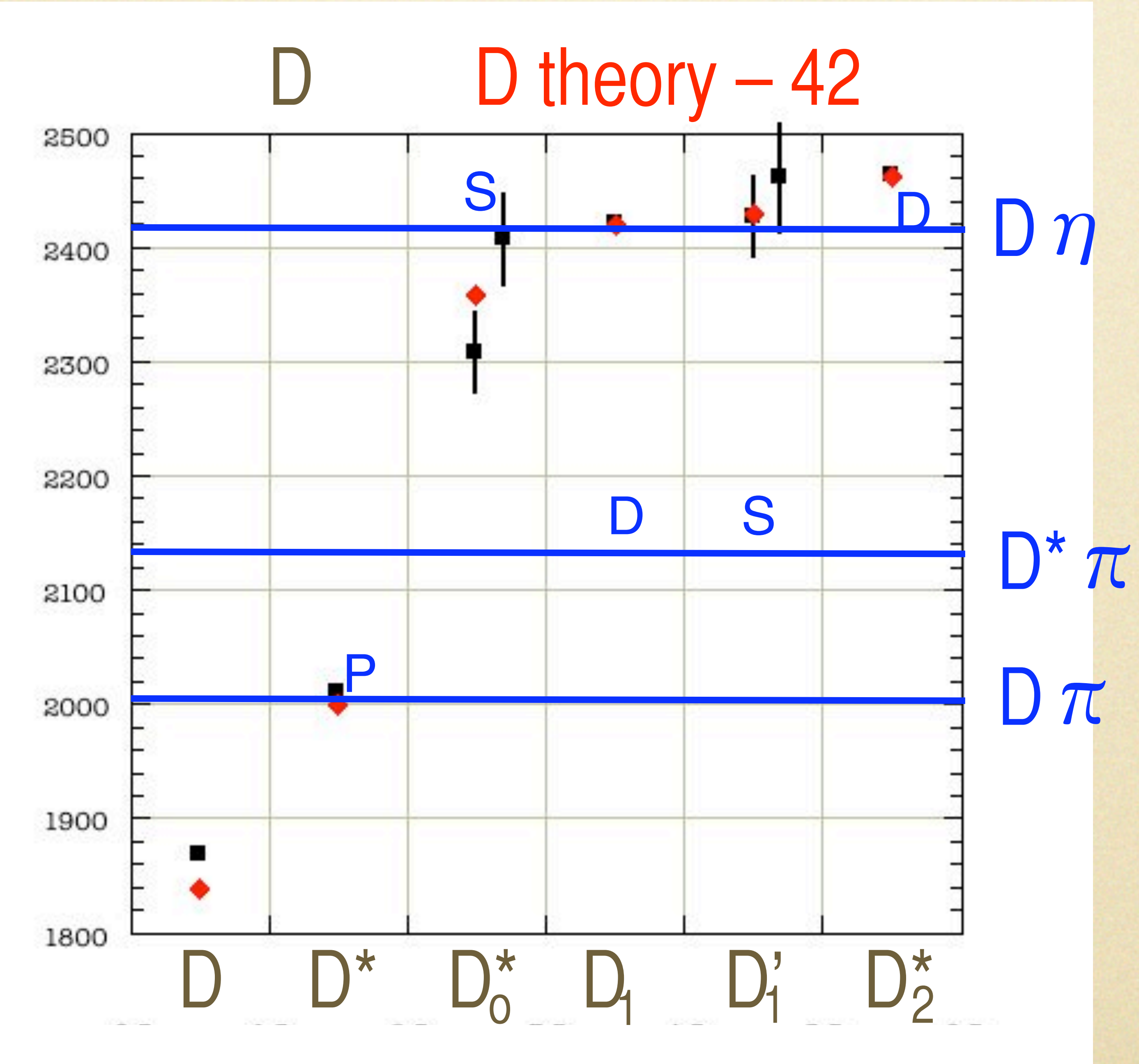
expt
ref
params
modes
signal
comments
interest
robustness
$Y(4350)$
$Z(4430)$
$X(3872)$
$X(4160)$
$Y(4260)$
$Y(4660)$
$Y(4008)$
$Y(3940)$
$X(3940)$
$Z(3940)$
h_c
η_c'

X(3872)

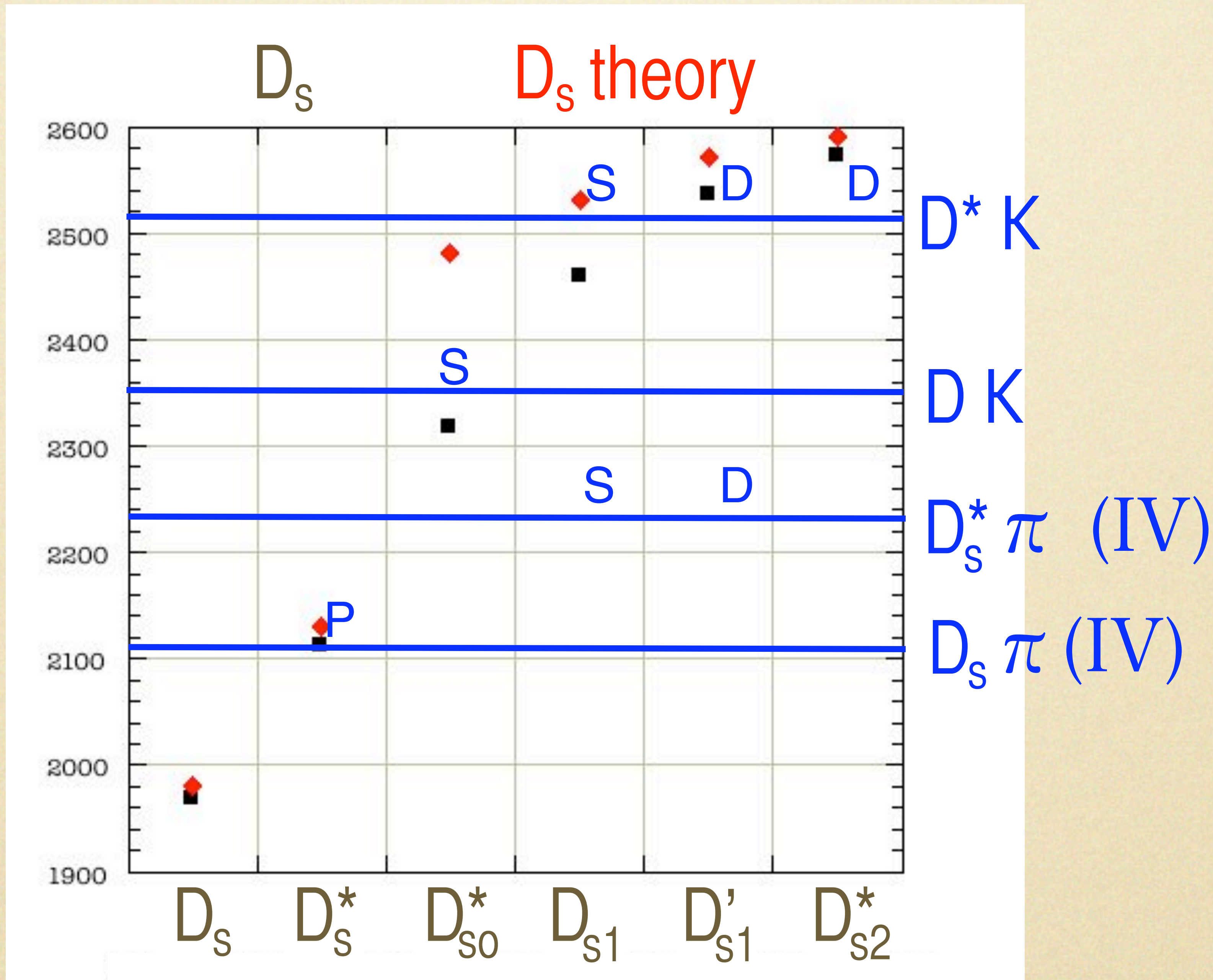


4000
3950
3900
3850
3800
$\omega J/\psi$
$\rho J/\psi$
$D_+ D_-^*$
$D_0 D_0^*$
3D3
3D2
3D1
1D2
2 3P2
3P1
3P0
1P1

Thresholds in D



Thresholds in Ds

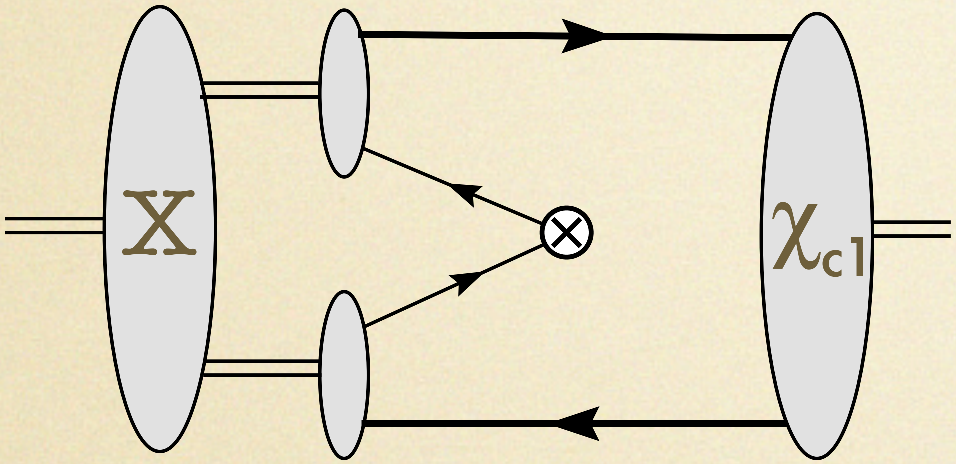


“Oakes-Yang Problem”

R.J. Oakes and C.N. Yang, PRL 11, 174 (63)

Why does the Gell-Mann--
Okubo mass formula work?
Thresholds affect the decuplet
states differently!

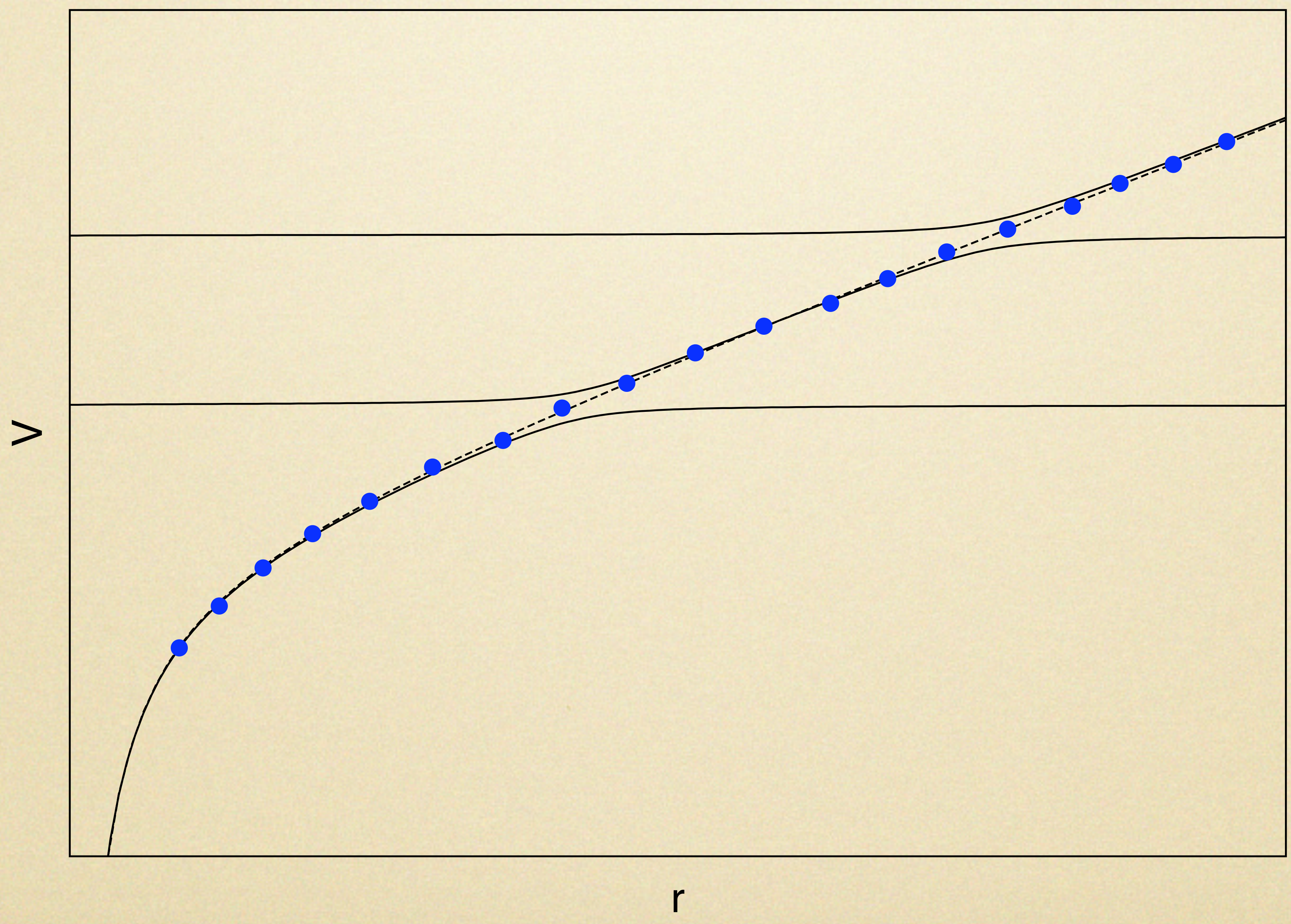
Mixing



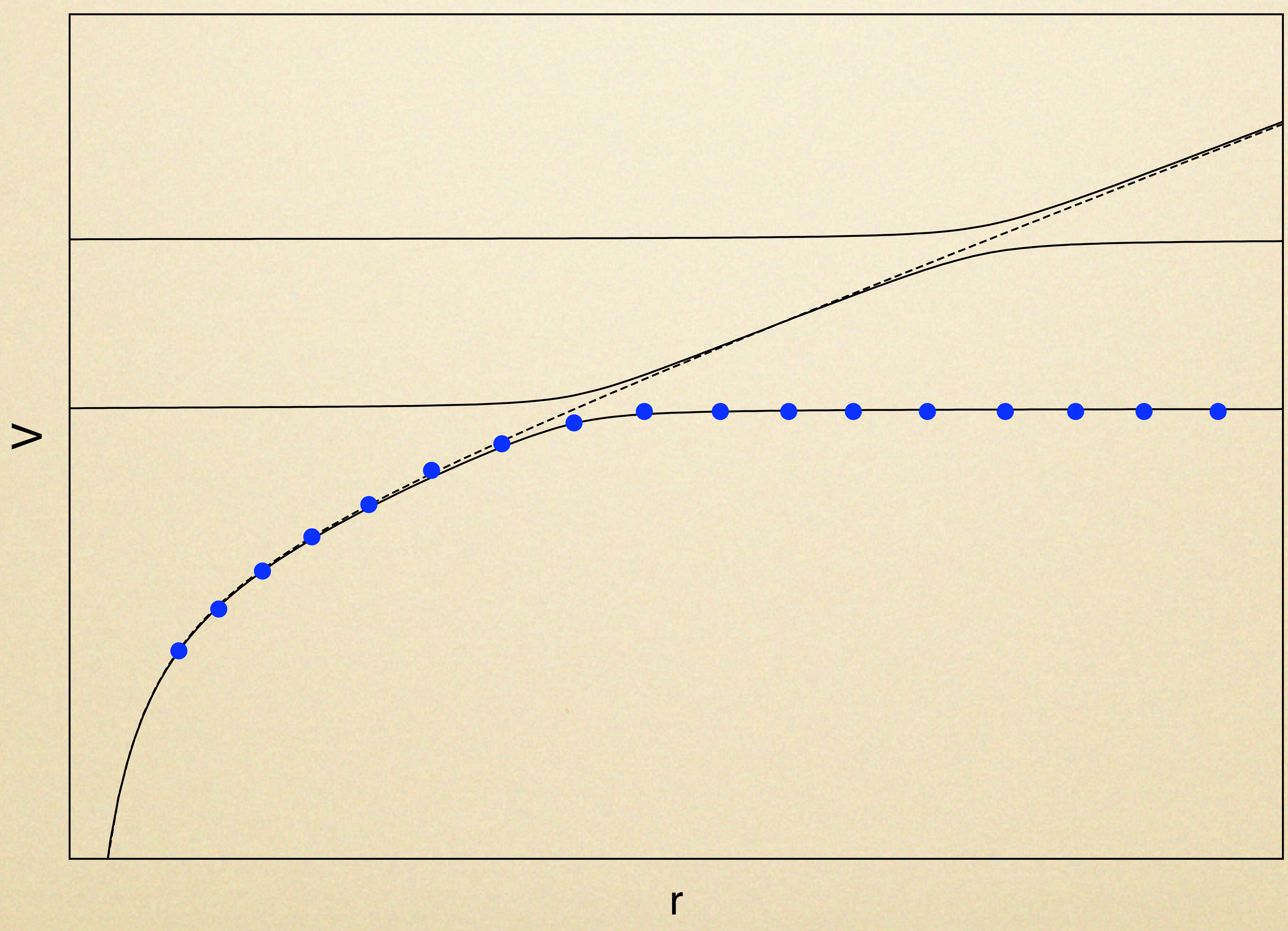
$$a_\chi = \sqrt{2} Z_{00}^{1/2} \int d^3k\, \psi_X(k) \mathcal{A}(-k)$$

state	E_B (MeV)	a (fm)	Z_{00}	a_χ (MeV)	prob
χ_{c1}	0.1	14.4	93%	94	5%
	0.5	6.4	83%	120	10%
χ'_{c1}	0.1	14.4	93%	60	100%
	0.5	6.4	83%	80	$>$ 100%

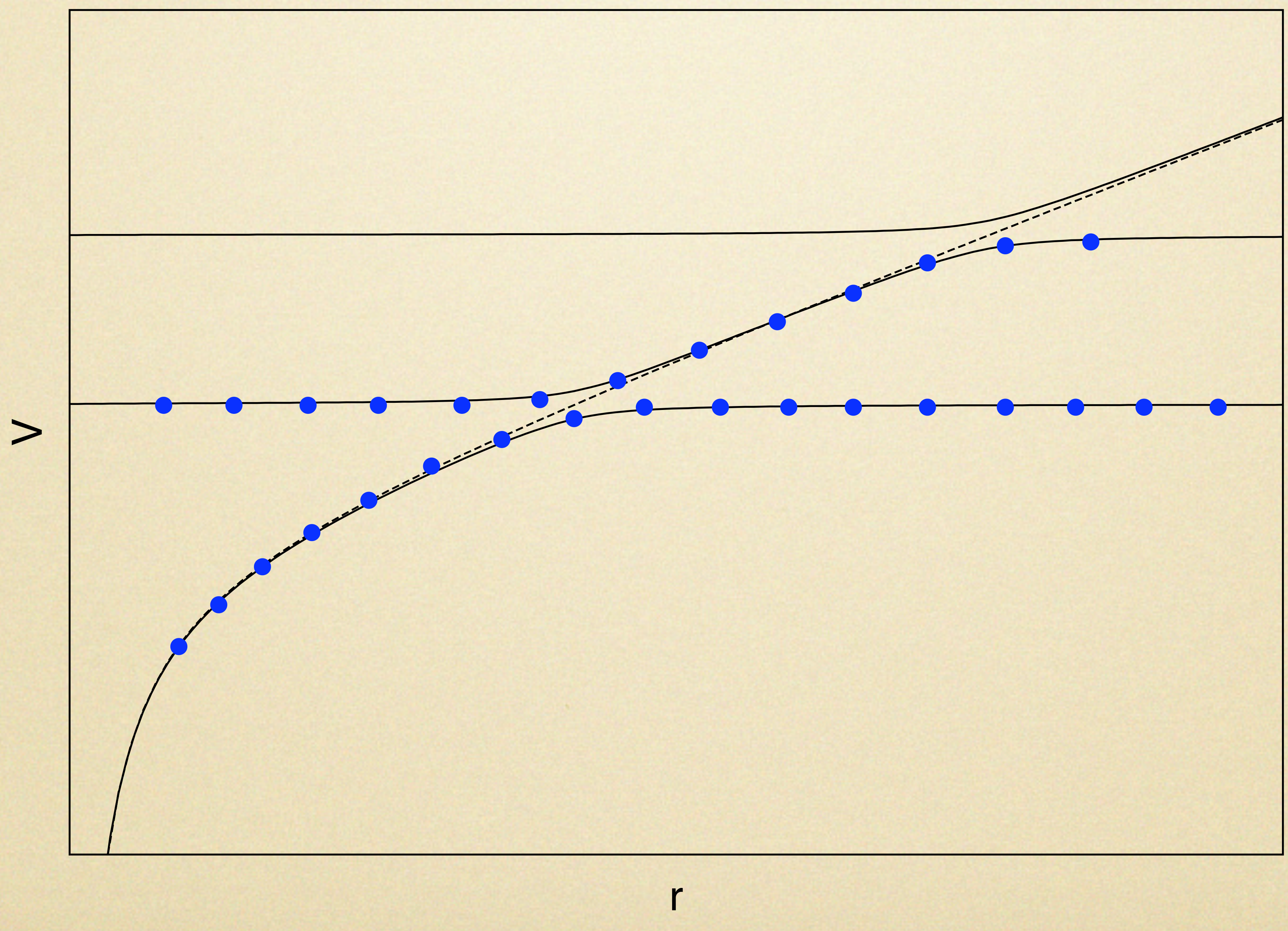
Screened Potentials



Screened Potentials



Screened Potentials

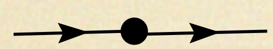


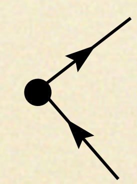
A Simple Model

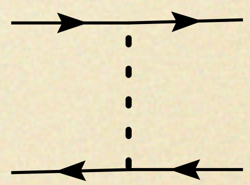
E.S. Swanson, JPG31, 845 (2005)

Non-relativistic Quantum Field Theory

$$\hat{H} = -\int d^3x \hat{\psi}_f^\dagger \tau_3 \left(m_f - \frac{\nabla^2}{2m_f} \right) \hat{\psi}_f + g \int d^3x \hat{\psi}_f^\dagger \tau_1 \hat{\psi}_f + \frac{1}{2} \int d^3x d^3y \hat{\psi}_{f'}^\dagger(x) \hat{\psi}_{f'}(x) V(x-y) \hat{\psi}_f^\dagger(y) \hat{\psi}_f(y).$$







Non-relativistic Quantum Field Theory

$$\hat{H} = -\int d^3x \hat{\psi}_f^\dagger \tau_3 \left(m_f - \frac{\nabla^2}{2m_f} \right) \hat{\psi}_f + g \int d^3x \hat{\psi}_f^\dagger \tau_1 \hat{\psi}_f + \frac{1}{2} \int d^3x d^3y \hat{\psi}_{f'}^\dagger(x) \hat{\psi}_{f'}(x) V(x-y) \hat{\psi}_f^\dagger(y) \hat{\psi}_f(y).$$

$$|\Psi\rangle = \phi_{QQ} |Q\bar{Q}\rangle + \psi |Q\bar{q}q\bar{Q}\rangle$$

$$H_0 \phi_{QQ}(r) + \Omega(r) \psi(\frac{M}{m+M} r) = E \phi_{QQ}(r)$$

$$H_1 \psi(\rho) + (\frac{M}{m+M})^{-3} \Omega(\frac{m+M}{M} \rho) \phi_{QQ}(\frac{m+M}{M} \rho) = E \psi(\rho)$$

Non-relativistic Quantum Field Theory

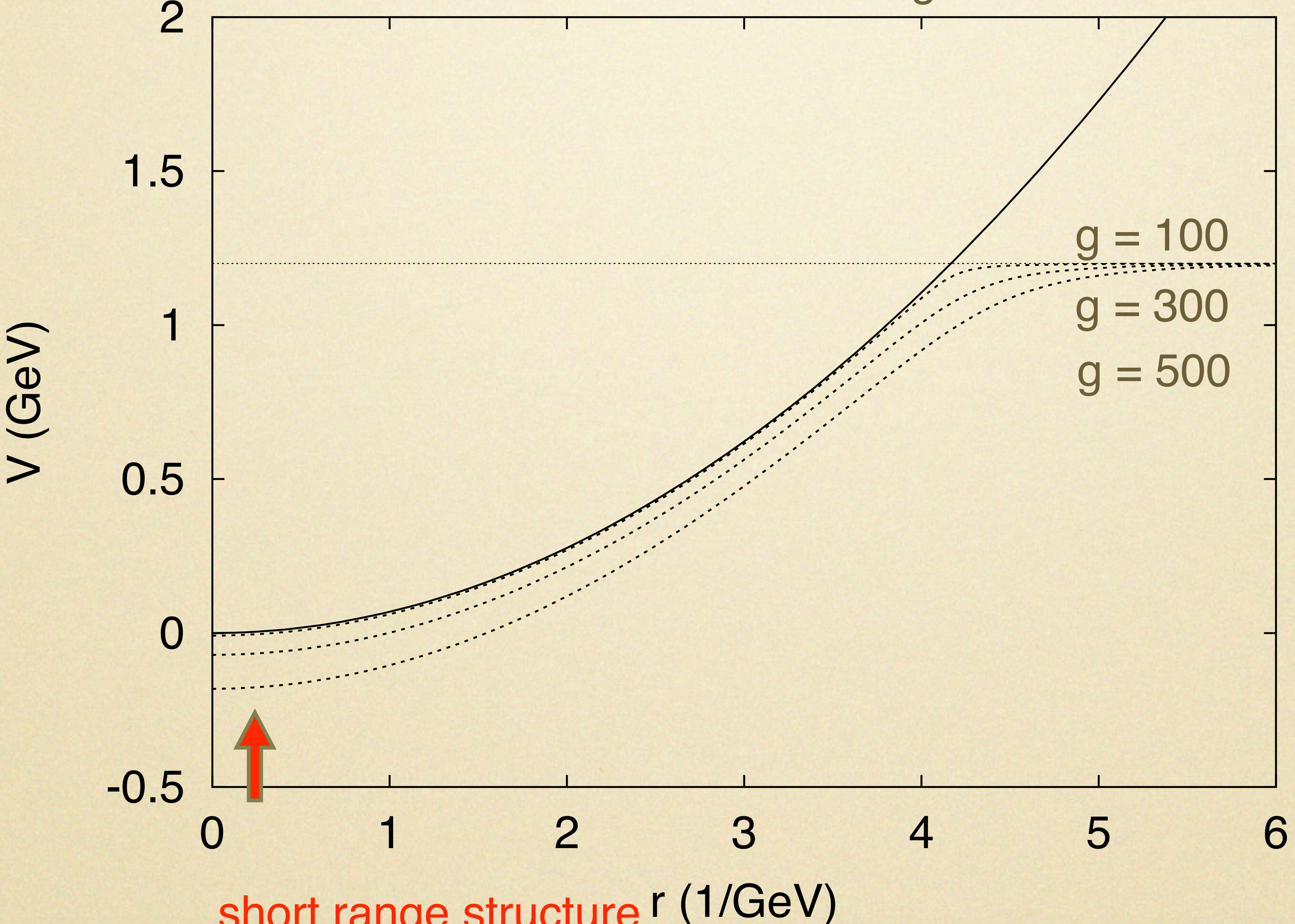
$$H_0\phi_{QQ}(r) + \Omega(r)\psi(\frac{M}{m+M}r) = E\phi_{QQ}(r)$$

$$H_1\psi(\rho) + (\frac{M}{m+M})^{-3}\Omega(\frac{m+M}{M}\rho)\phi_{QQ}(\frac{m+M}{M}\rho) = E\psi(\rho)$$

$$\Omega(r) = g\int d^3x\,\phi_{Qq}(r/2-x)\phi_{Qq}(r/2+x)$$

Adiabatic Potentials

diagonalise in the heavy quark limit



short range structure

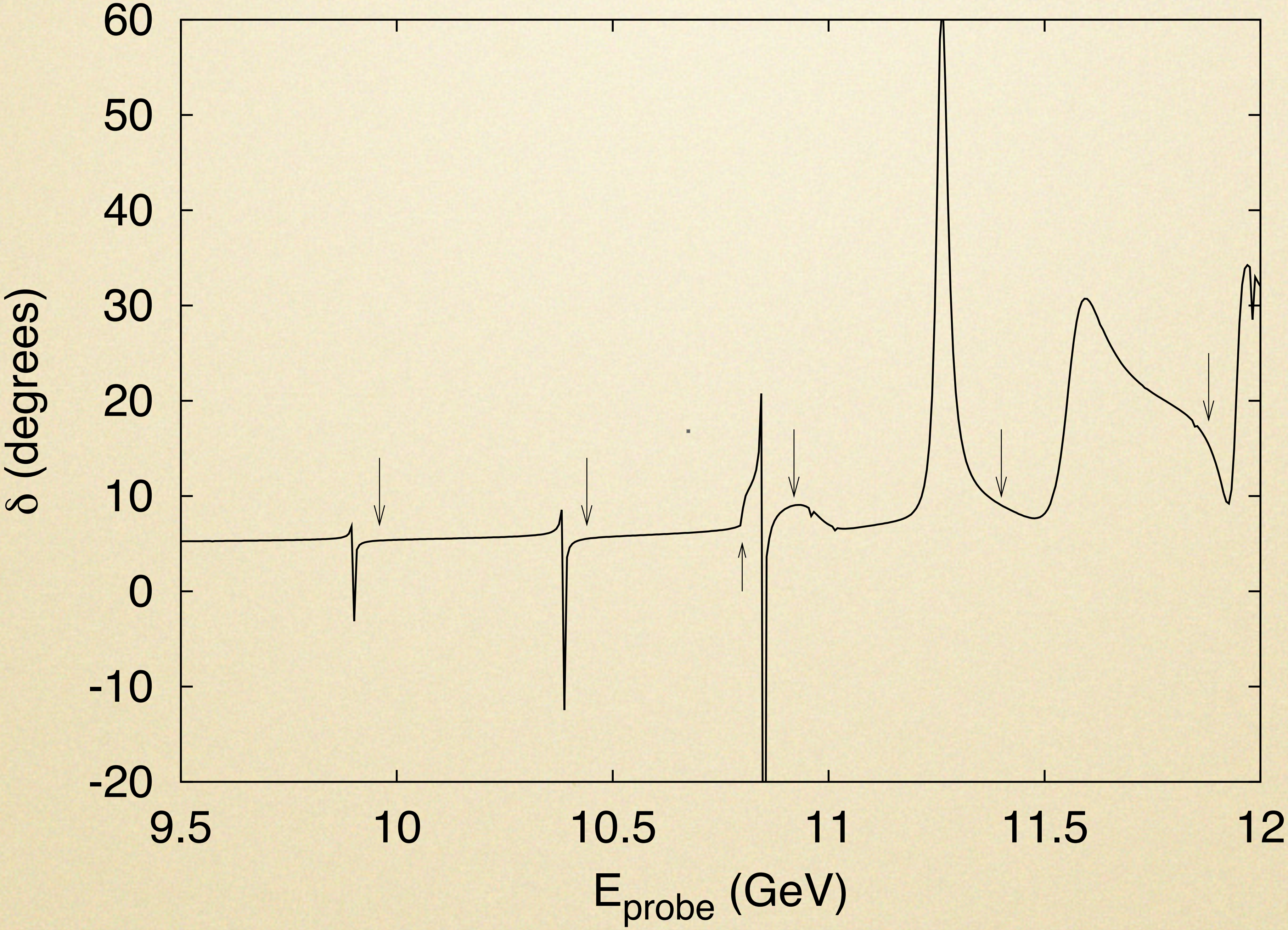
Coupled Channel Bethe-Heitler Equation

$$T(k,k') = V_{eff}(k,k') + \int d^3q\, V_{eff}(k,q) G_E(q) T(q,k')$$

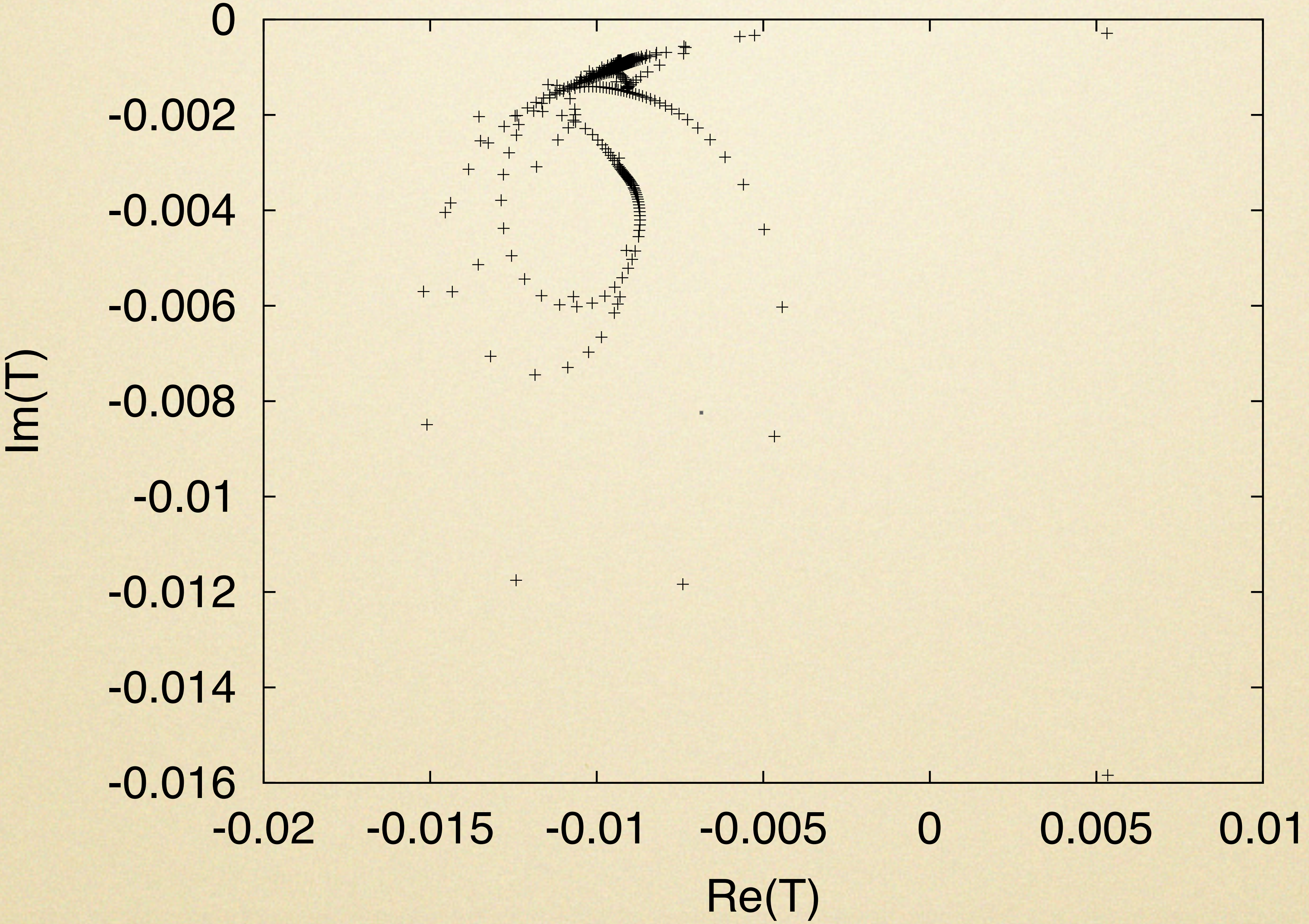
$$\langle k|V_{eff}|k'\rangle = 2\pi^2 \sum_i \frac{\omega_i^*(k)\omega_i(k')}{E - E_i}$$

$$\omega_i(k) = \langle \phi_{QQ}^{(i)}|\hat{\Omega}|k\rangle$$

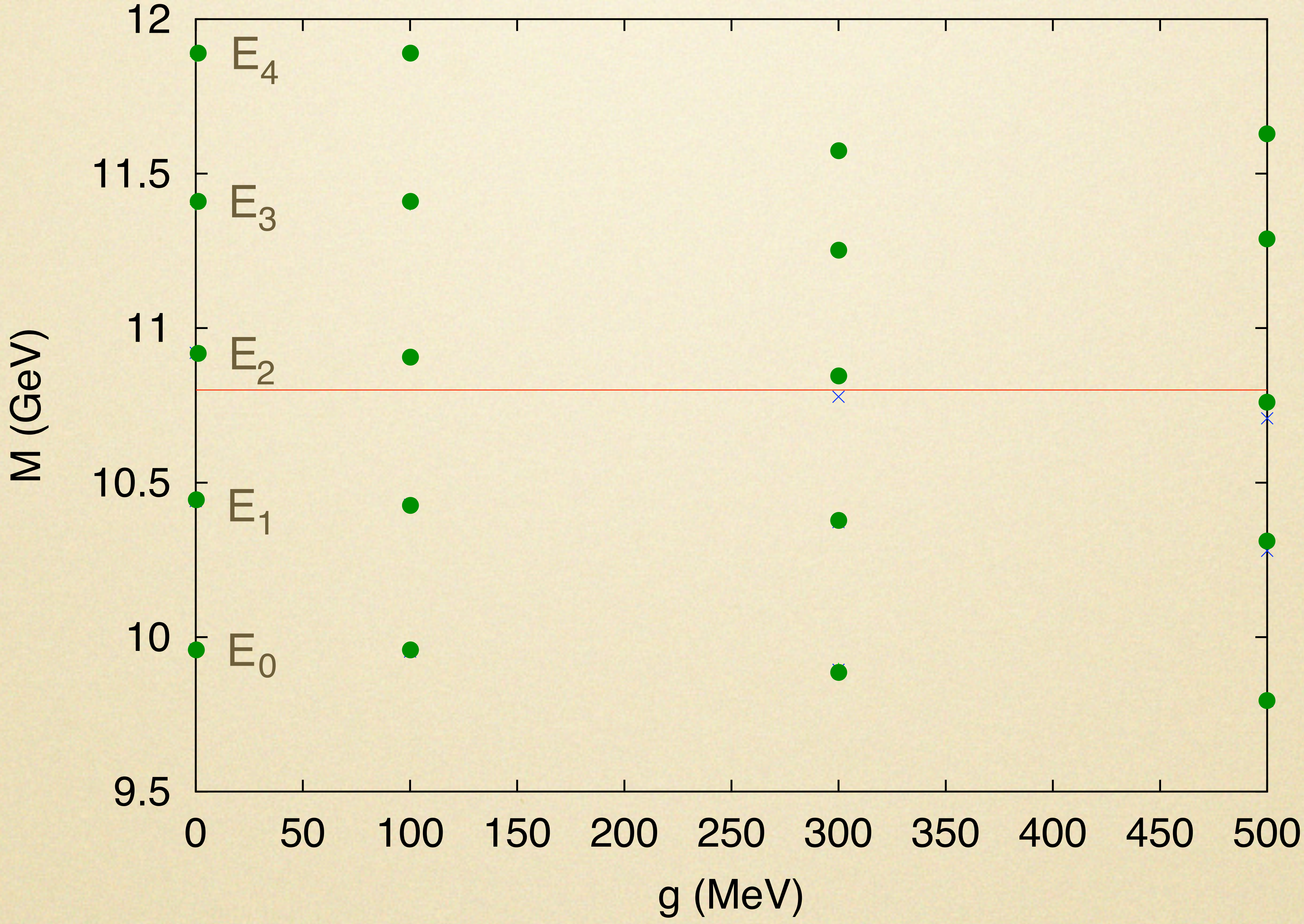
Couple to a Probe Channel



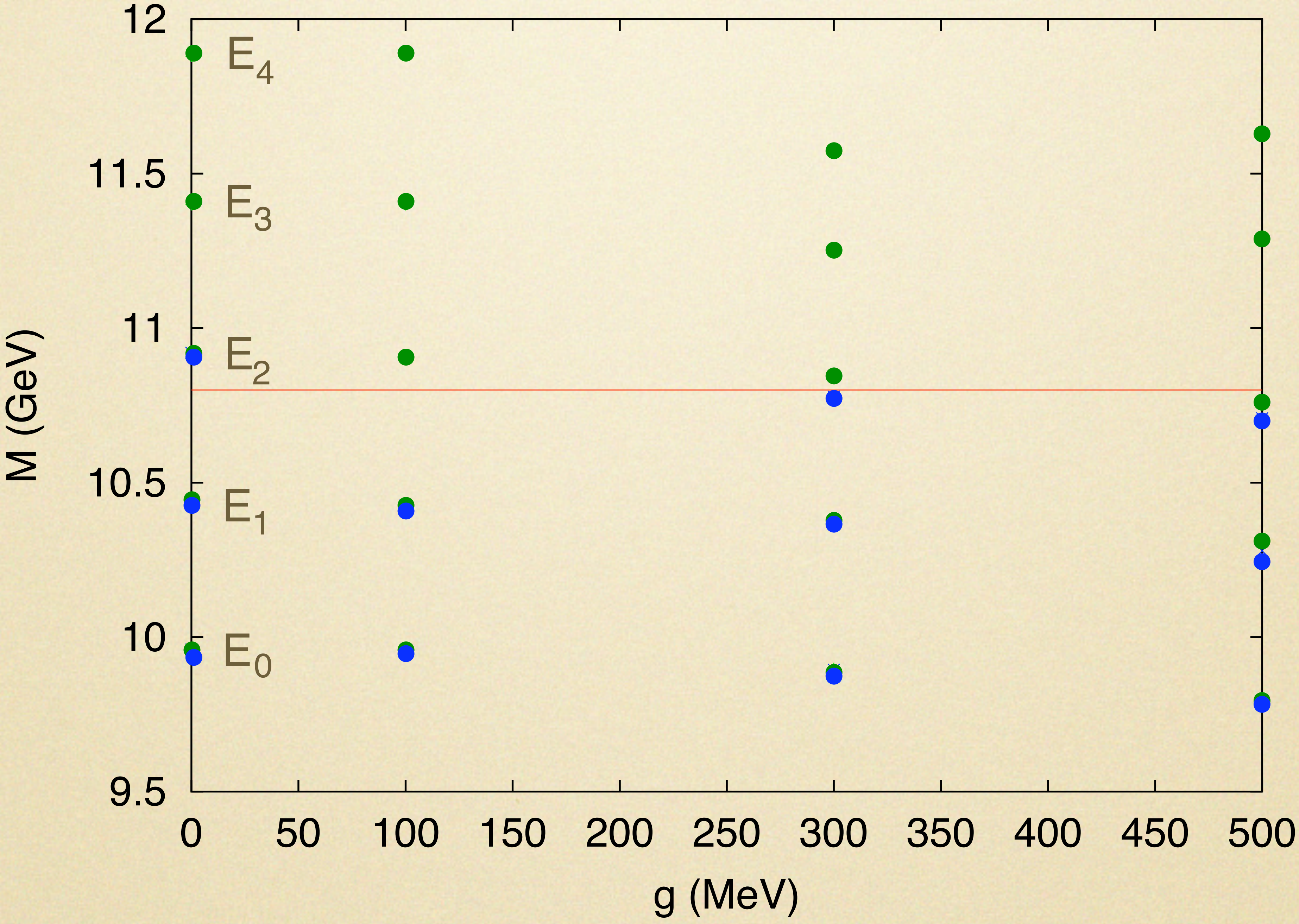
Argand Diagram



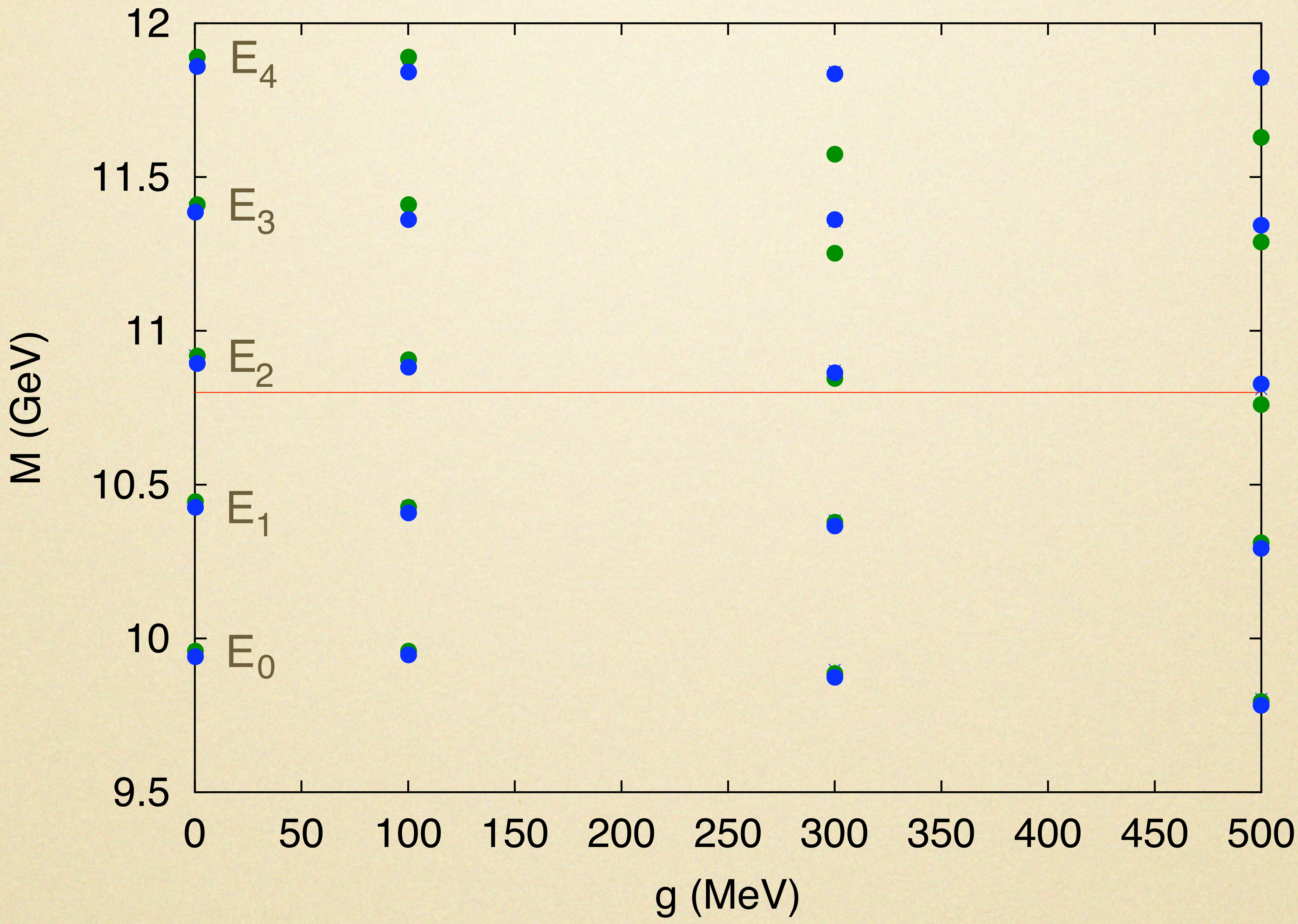
Full Spectrum



Screened Spectrum



Renormalised Spectrum



Some Loop Theorems

T. Barnes and E.S. Swanson, PRC77, 055206, (2008)

for a general class of decay models mixing via degenerate multiplets of states...

- Loop mass shifts are identical for all states in an N,L multiplet
- these states have the same open flavour decay widths
- loop-induced valence configuration mixing vanishes if $L_i <> L_f$ or $S_i <> S_f$

- there is thus some hope that the constituent quark model is robust (thereby resolving the Oakes-Yang problem)

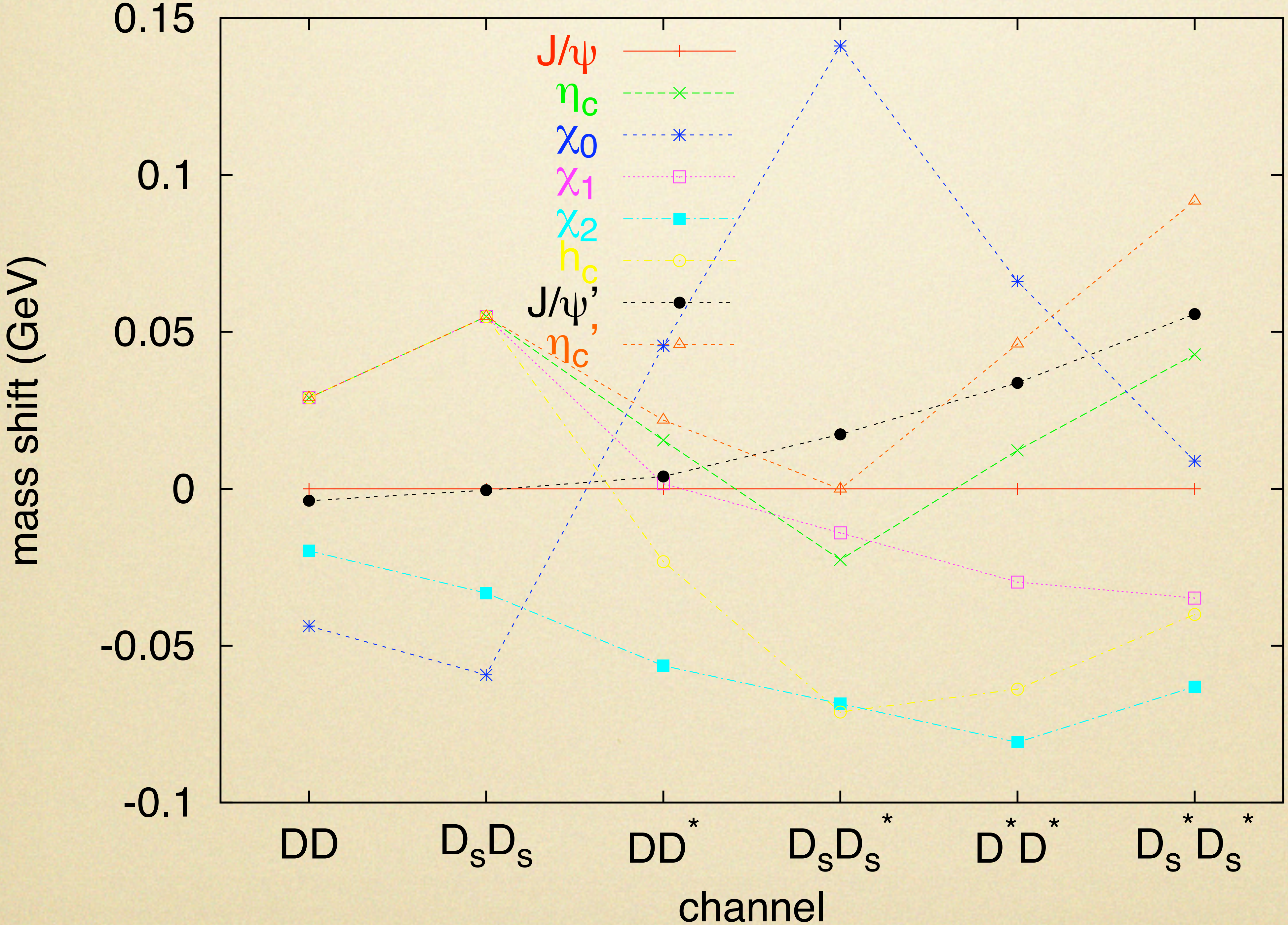
$$\langle J_{\mathrm{A}}[Lj_{\mathrm{BC}}];j_{\mathrm{BC}}[j_{\mathrm{B}}j_{\mathrm{C}}];j_{\mathrm{B}}[s_{\mathrm{B}}\ell\ _B]\,j_{\mathrm{C}}[s_{\mathrm{C}}\ell_{\mathrm{C}}]|\sigma\psi|J_{\mathrm{A}}[s_{\mathrm{A}}\ell_{\mathrm{A}}]\rangle =$$

$$\sum_{s_{\mathrm{BC}}\ell_{\mathrm{BC}}L_f} (-)^{\eta}\hat{1}\hat{L}_f\hat{s}_{\mathrm{BC}}\hat{\ell}_{\mathrm{BC}}\hat{j}_{\mathrm{B}}\hat{j}_{\mathrm{C}}\hat{j}_{\mathrm{BC}}\hat{s}_{\mathrm{A}}\hat{s}_{\mathrm{B}}\hat{s}_{\mathrm{C}}\hat{s}_{\mathrm{BC}}\cdot mber$$

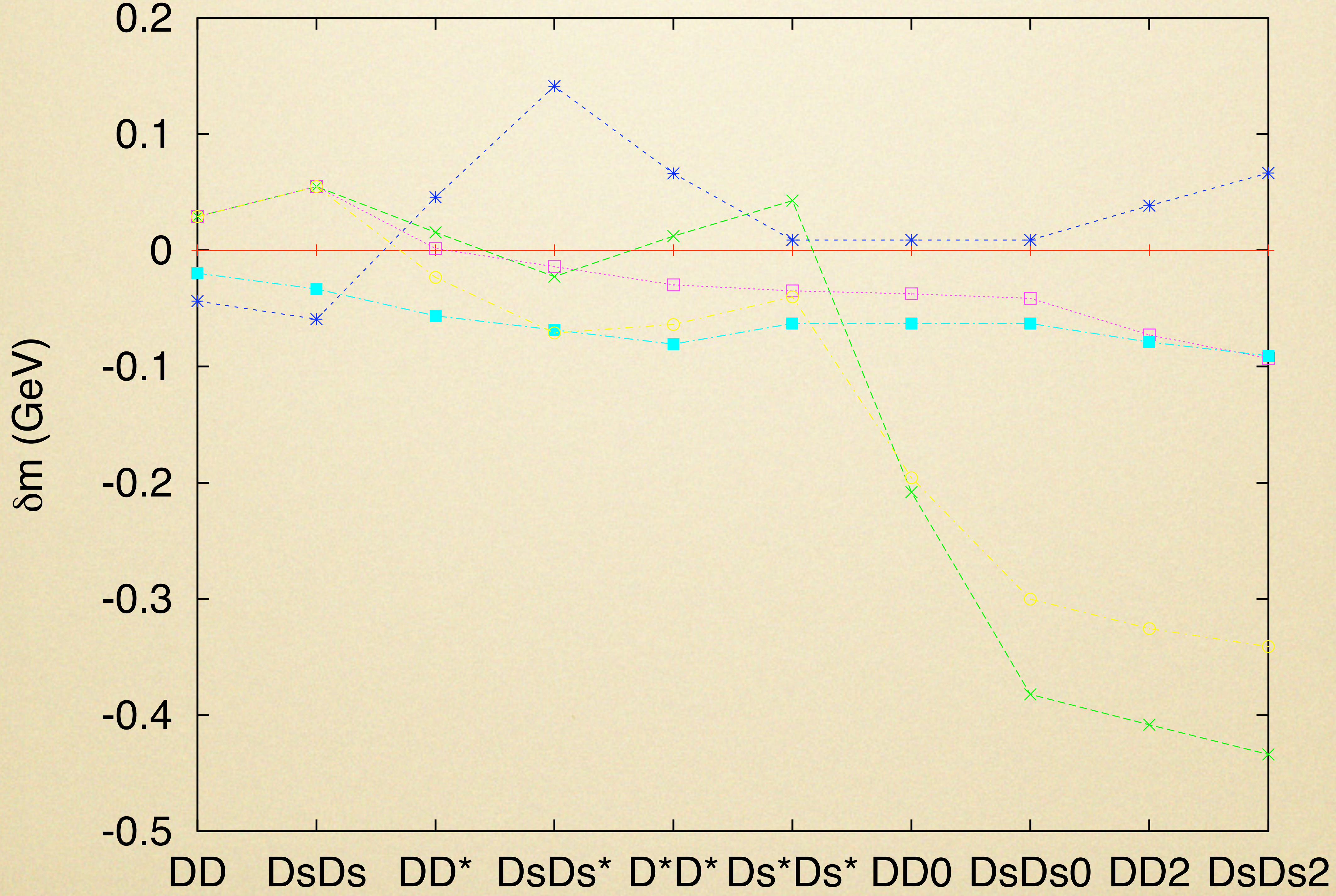
$$\langle L_f[\text{Ł}\ell_{\mathrm{BC}}];\ell_{\mathrm{BC}}[\ell_{\mathrm{B}}\ell_{\mathrm{C}}]||\underline{\mathrm{m}}\psi||\ell_{\mathrm{A}}\rangle\cdot$$

$$\left\{\begin{array}{ccc} s_{\mathrm{B}} & \ell_{\mathrm{B}} & j_{\mathrm{B}} \\ s_{\mathrm{C}} & \ell_{\mathrm{C}} & j_{\mathrm{C}} \\ s_{\mathrm{BC}} & \ell_{\mathrm{BC}} & j_{\mathrm{BC}} \end{array}\right\}\left\{\begin{array}{ccc} 1/2 & 1/2 & s_{\mathrm{B}} \\ 1/2 & 1/2 & s_{\mathrm{C}} \\ s_A & 1 & s_{\mathrm{BC}} \end{array}\right\}\cdot$$

$$\left\{\begin{array}{ccc} s_{\mathrm{BC}} & \ell_{\mathrm{BC}} & j_{\mathrm{BC}} \\ \text{Ł} & j_{\mathrm{A}} & L_f \end{array}\right\}\left\{\begin{array}{ccc} s_{\mathrm{BC}} & s_{\mathrm{A}} & 1 \\ \ell_{\mathrm{A}} & L_f & j_{\mathrm{A}} \end{array}\right\}$$



J/ψ
η_c
χ_0
χ_1
χ_2
h_c
J/ψ'
η_c'
0.15
0.1
0.05
0
-0.05
-0.1
mass shift (GeV)
DD
D_sD_s
DD^*
$D_sD_s^*$
D^*D^*
$D_s^*D_s^*$
channel


0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
δm (GeV)
DD
DsDs
DD*
DsDs*
D*D*
Ds*Ds*
DD0
DsDs0
DD2
DsDs2

Requenching

derive the effective theory that removes continuum effects

E.S. Swanson, in progress

Another nonrelativistic Field Theory

$$T \qquad\qquad V$$

$$\begin{aligned} H &= \sum_k \epsilon_k (b_k^\dagger b_k + d_k^\dagger d_k) + \sum_{pqk} v_q^{(M)} b_{k+q}^\dagger d_{p-q}^\dagger d_p b_k \\ &+ \frac{1}{2} \sum_{pqk} V_q^{(B)} b_{k+q}^\dagger b_{p-q}^\dagger b_p b_k + \sum_k (b_k^\dagger \gamma_k d_{-k}^\dagger + \text{H.c.}) \end{aligned}$$

$$\Gamma$$

Requench...

$$\psi = \mathrm{e}^{-iS}\psi'$$
$$H' = \mathrm{e}^{iS} H \mathrm{e}^{-iS}$$

$$[iS_1, H_0] = -\Gamma$$

$$V' + \Gamma' = T + [iS_1, V + \Gamma] + \frac{1}{2}[iS_1, [iS_1, H_0]]$$

S_2 is determined by $[iS_2, H_0] = -\Gamma'$. One finds

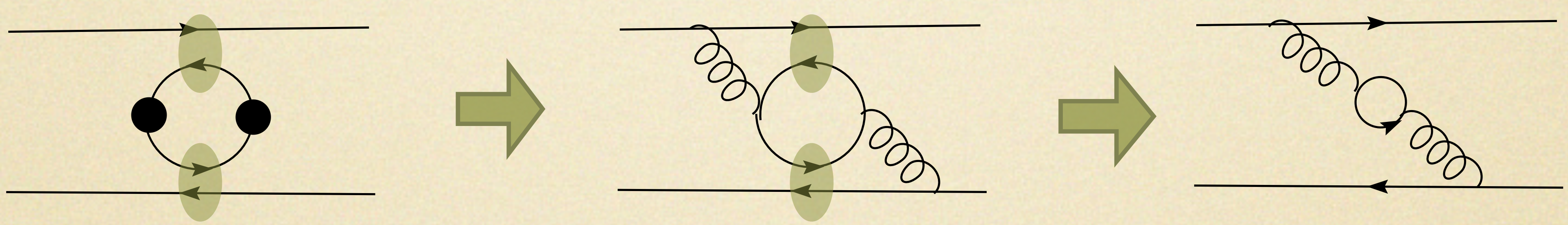
$$\begin{aligned} V' &= T + \frac{1}{2}[iS_1, \Gamma] = T + T' \\ \Gamma' &= [iS_1, V] \end{aligned}$$

$$
\begin{aligned}
V'' + \Gamma'' &= [iS_2, V] + [iS_2, \Gamma] + [iS_1, T] + \frac{1}{2}[iS_1, [iS_2, H_0]] \\
&\quad + \frac{1}{2}[iS_2[iS_1, H_0]] + \frac{1}{2}[iS_1, [iS_1, V]] + \frac{1}{2}[iS_1, [iS_1, \Gamma]] \\
&\quad + \frac{1}{6}[iS_1, [iS_1, [iS_1, H_0]]] \\
&= [iS_2, V] + \frac{1}{2}[iS_2, \Gamma] + [iS_1, T] + \frac{2}{3}[iS_1, T']
\end{aligned}
$$

$$
\begin{aligned}
H_{\text{eff}} = H'' \quad = \quad & \sum_k (m^* + \gamma^2 m^* + \frac{k^2}{2m^*})(b_k^\dagger b_k + d_k^\dagger d_k) \\
& + \sum_{pkq} V_q^{(M)} b_{k+q}^\dagger d_{p-q}^\dagger d_p b_k \left[1 - \frac{1}{8m^2}\gamma^2(p^2 + (p-q)^2 + k^2 + (k-q)^2)\right] \\
& + \frac{1}{2}\sum_{pkq} V_q^{(B)} b_{k+q}^\dagger b_{p-q}^\dagger b_p b_k + \frac{1}{8m^2}\sum_{pkq} V_q^{(M)} \left[b_{k+q}^\dagger b_{p-q}^\dagger \gamma_{p-q}\gamma_p b_p b_k + \text{H.c.}\right] \quad (1)
\end{aligned}
$$

Issues

Renormalisation



$$q^2 < \Lambda^2 \approx 1\text{GeV}^2$$

$$1\text{GeV}^2 < q^2 < \Lambda^2 \approx 4\text{GeV}^2$$

$$4\text{GeV}^2 < q^2 < \Lambda^2 \to \infty$$

- nonperturbative gluodynamics
- multipion intermediate states
- chiral restoration
- emergence of the string regime

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