S-wave π Exchange And Its Implications for Quarkonium Spectroscopy

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Outline

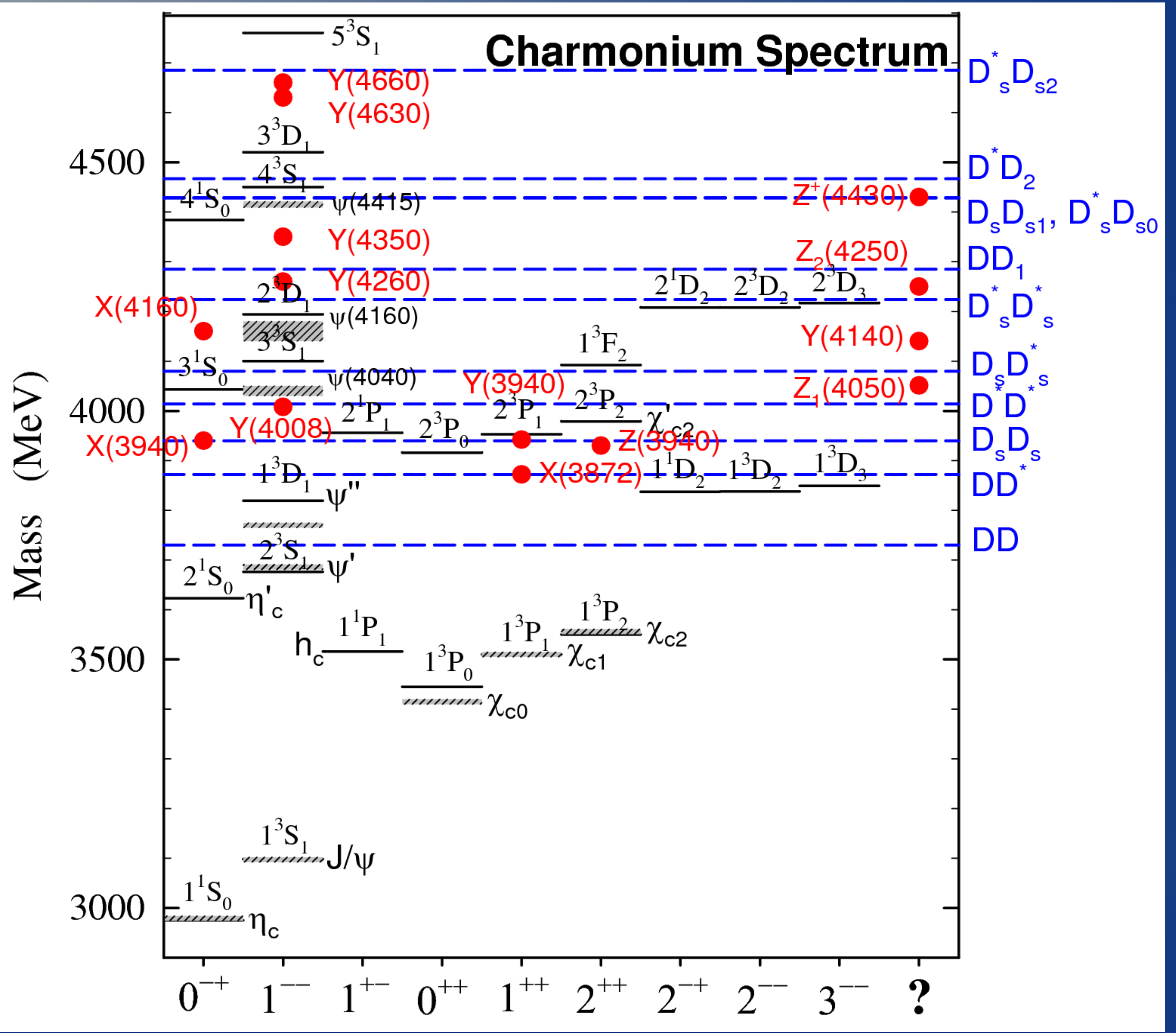
- Review of Charmonium Spectra
- General Phenomenon of S-wave π Exchange
- Application to the D_1D^* System (1^-, I=0)
  - Close, CD, Thomas PRD 81 074033 (2010)
- Generalization to Other Sectors
- Experimental Signature
- Theoretical Uncertainties
  - Filin, *et al.* arXiv:1004.4789
- Summary

States of Interest

- Visha Bhardwaj -- Recent Results on X(3872) at Belle
- Estia Eichten -- Hadronic Transitions in Quarkonium
- Kai Yi -- Quarkonium Spectroscopy Results at CDF
- Kenkichi Miyabayashi -- Other Charmonium and cc-like States at Belle
- Arafat Gabareen Mokhtar -- Babar update on new charmonia in B decays
- Cristoph Hanhart -- Hadron molecules
- Mikhail Voloshin -- Hadroquarkonium
- Chiara Sabelli -- Tetraquarks
- Pierre Artoisenet -- Production of the X(3872) at the Tevatron and the LHC

There are Many Anomalous States

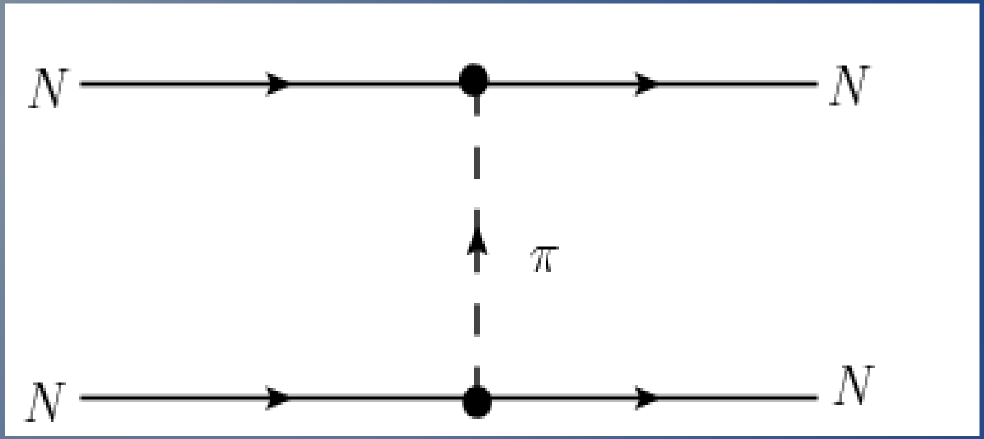
Godfrey Proceedings of DPF-2009



Unique Opportunity to Study QCD Dynamics

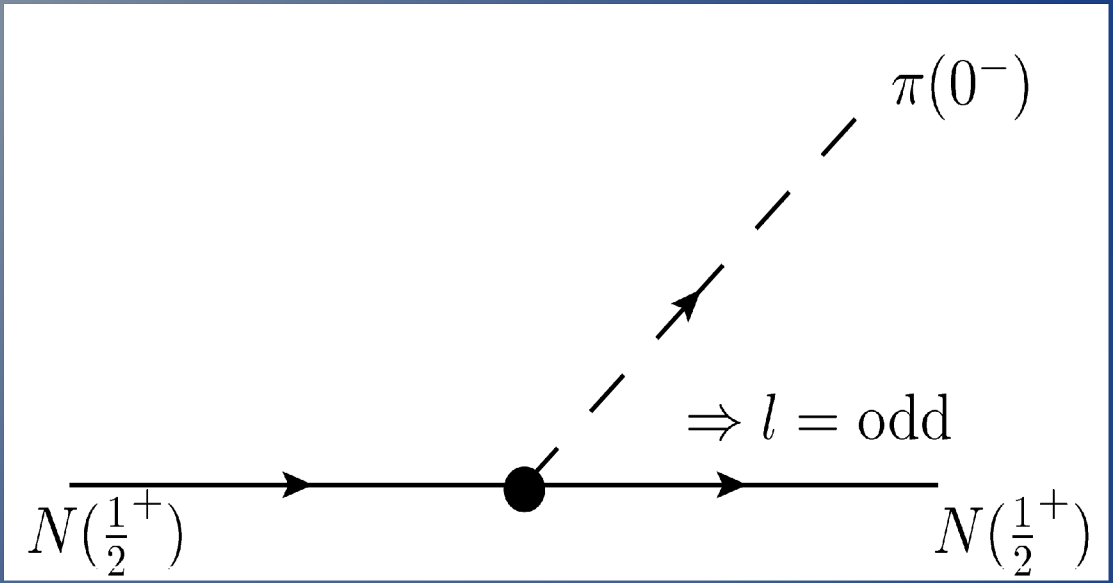
- QCD is very challenging and difficult
- The naïve quark model ($q\bar{q}$) picture of mesons basically worked...
  - Particularly the charm spectrum seemed well understood
- However, many non $q\bar{q}$ states are possible and “predicted”
- Unambiguous identification of these particles will give critical tests of our models.

Historical π Exchange

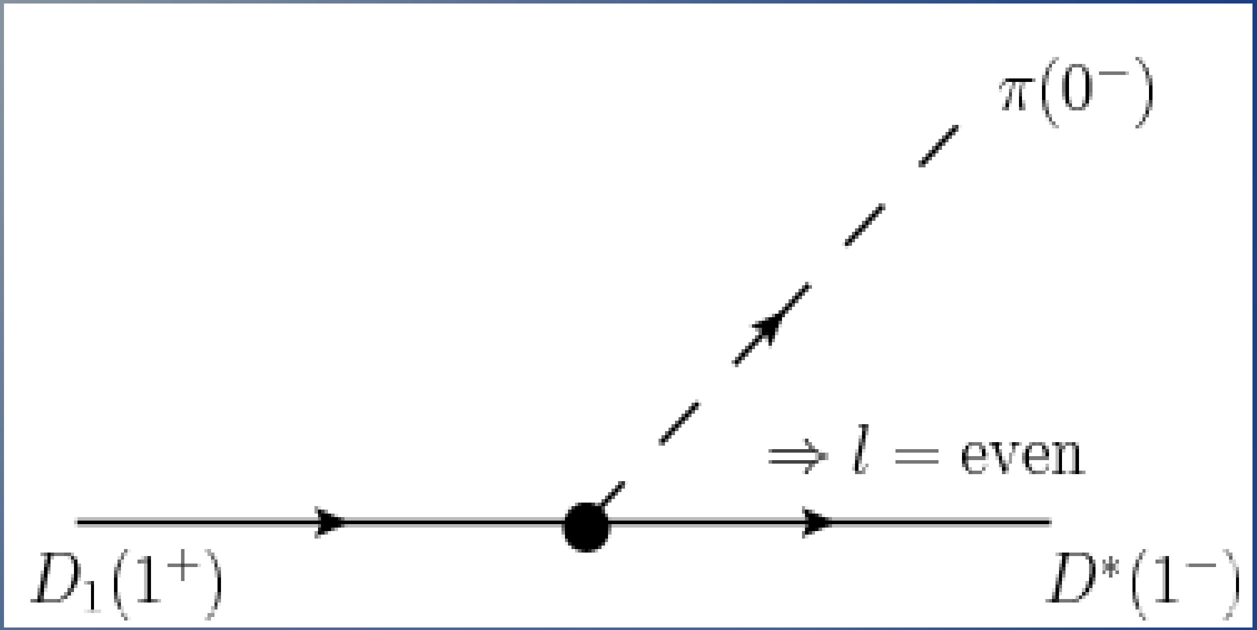


- Familiar from NN Application (Yukawa)
- By Analogy Törnqvist suggested “Deusons”
- Like the NN case Binding Energies were of order 1 MeV
- Discovery of a possible deuson X(3872) led to a great deal of interest in π-bound meson molecules (and other meson exchanges).

P-wave π Emission From Parity Conservation



S-wave π Emission



S-wave π Emission (Cont.)

Chrial Perturbation Theory Model

$$\Gamma(D_1^0 \to D^{*+}\pi^-) = \frac{h^2}{8\pi f_\pi^2}\frac{|\mathbf{q}|m_{D^*}}{m_{D_1}^3}(m_{D_1}^2 - m_{D^*}^2)^2 \times \frac{1}{3}\left(2 + \frac{(m_{D_1}+m_{D^*})^2}{4m_{D_1}^2 m_{D^*}^2}\right)$$

Quark-π Coupling

$$\overline{\psi}\gamma_5\psi \mapsto \sigma \cdot \left(\mathbf{q} + \frac{\omega}{m}\mathbf{p}\right)$$

$^3P_0$ Model

$$H_{^3\mathrm{P}_0} = \gamma \boldsymbol{\sigma}.\vec{p}\,|q\bar{q}\rangle\langle 0|$$

Empirical Support

PDG Live 2009

$P = +$ Meson	Γ[MeV]
$D_1(2430)$	384^{+130}_{-110}
$D_0^*(2400)^0$	261 ± 50
$D_0^*(2400)^\pm$	283 ± 40
$K_1(1400)^\pm$	174 ± 13
$K_0(1430)^\pm$	270 ± 80
$a_1(1260)$	250 to 600
$b_1(1235)$	142 ± 9

D_1D^* Study

Liu *et. al.* PRD77,034003(2008)

– $Z(4430)^+$ as a D_1D^* bound state → Isovector

$$V(r) = \frac{h^2 q_0^2}{8\pi f_\pi^2}\frac{\cos(\mu r)}{r} \approx \frac{h^2 (m_{D_1} - m_{D^*})^2}{8\pi f_\pi^2}\frac{\cos(\mu r)}{r}$$

$$\mu^2 = q_0^2 - m_\pi^2 \approx (m_{D_1} - m_{D^*})^2 - m_\pi^2$$

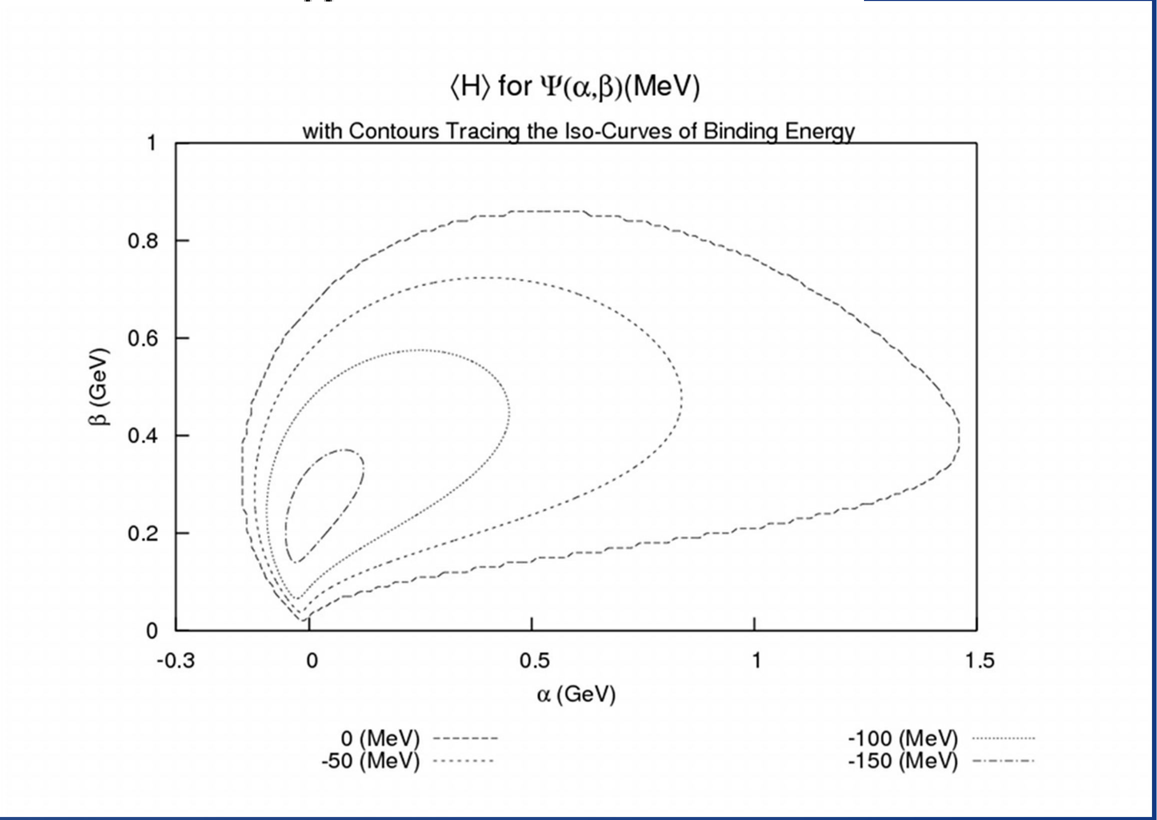
$$\psi(r) = (1 - \alpha r^2)e^{-\beta r^2}$$

Conclusion: No Binding

D_1D^* Study (Cont.)

$$\Rightarrow V(r) = -3\frac{h^2(m_{D_1} - m_{D^*})^2}{8\pi f_\pi^2}\frac{\cos(\mu r)}{r}$$

$$\psi(r) = (1 - \alpha r^2)e^{-\beta r^2}$$



Conclusion: No Reason to Expect Isovector Binding
Robust Isoscalar Binding

D_1D^* Study (Cont.) – χ Coupling

$$\Gamma(D_1^0 \to D^{*+}\pi^-) = \frac{h^2}{8\pi f_\pi^2} \frac{|\mathrm{q}| m_{D^*}}{m_{D_1}^3} (m_{D_1}^2 - m_{D^*}^2)^2 \times \frac{1}{3}\left(2 + \frac{(m_{D_1} + m_{D^*})^2}{4 m_{D_1}^2 m_{D^*}^2}\right)$$

$$\Gamma(D_1^0 \to D^*\pi^-) = \frac{2}{3}\Gamma(D_1 \to D^*\pi) \approx \frac{2}{3}\Gamma(D_1) = \frac{2}{3} 384^{+130}_{-110}\ \mathrm{MeV}$$

$$h = 0.80^{+0.20}_{-0.17}$$

$$h \mapsto h\left(1 - \frac{2}{9}\frac{q^2}{\beta^2}\right)\exp\left\{-\frac{p^2}{12\beta^2}\right\}$$

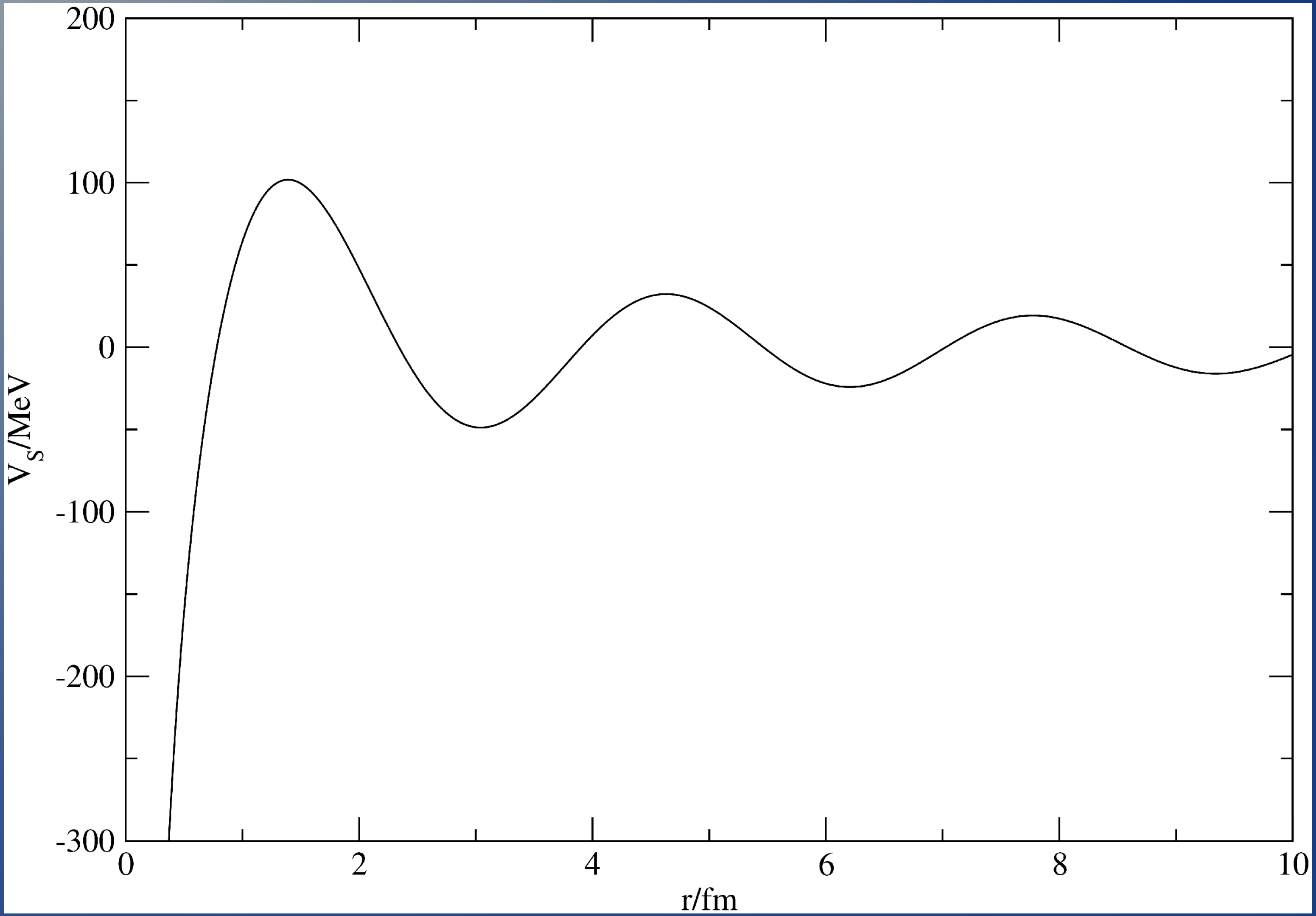
$$h = 1.0^{+0.3}_{-0.2}$$

D_1D^* Study (Cont.) – Schrödinger Eq.

$$\Rightarrow V(r) = -3\frac{h^2(m_{D_1} - m_{D^*})^2}{8\pi f_\pi^2}\frac{\cos(\mu r)}{r}$$

State	Binding Energy / MeV					
	$h = 0.8$	$h = 0.9$	$h = 1.0$	$h = 1.1$	$h = 1.2$	$h = 1.3$
1S $(0,1,2)^{--}$	230	415	680	1000	1500	2100
2S	12	20	29	39	76	210
3S	1.5	3.6	6.7	11	51	65
1P $(0,1,2,3)^{+-}$	8.2	16	25	35	120	260
2P	1	2.8	5.8	22	48	61
3P	–	1	1.5	9.7	15	20
1D $(0,1,2,3,4)^{--}$	1.4	8.3	17	28	40	54
2D	–	1.3	4.1	8.0	13	18
3D	–	–	1	2.6	4.9	7.8

D_1D^* Study (Cont.) – The Potential

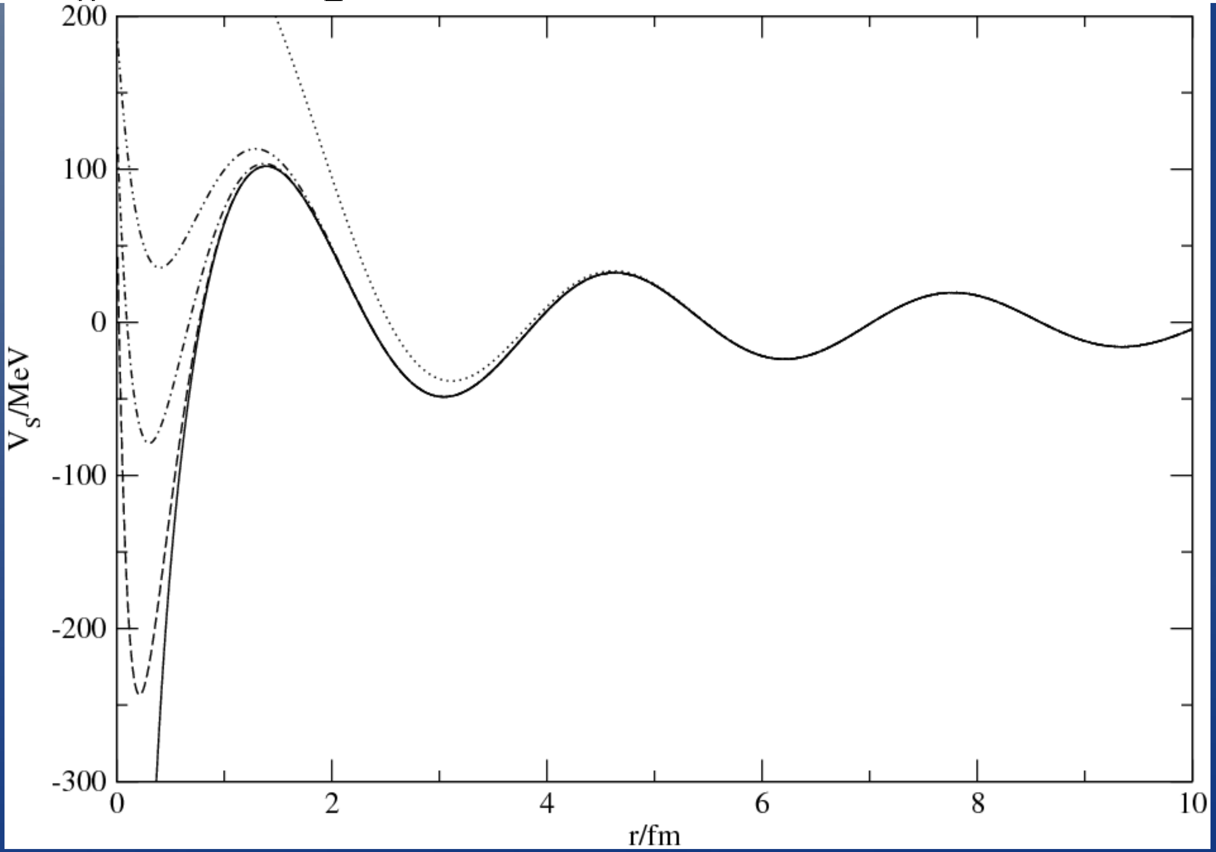


r_{rms} [fm] = 0.6(1S) ; 3(2S); 6.5(3S)

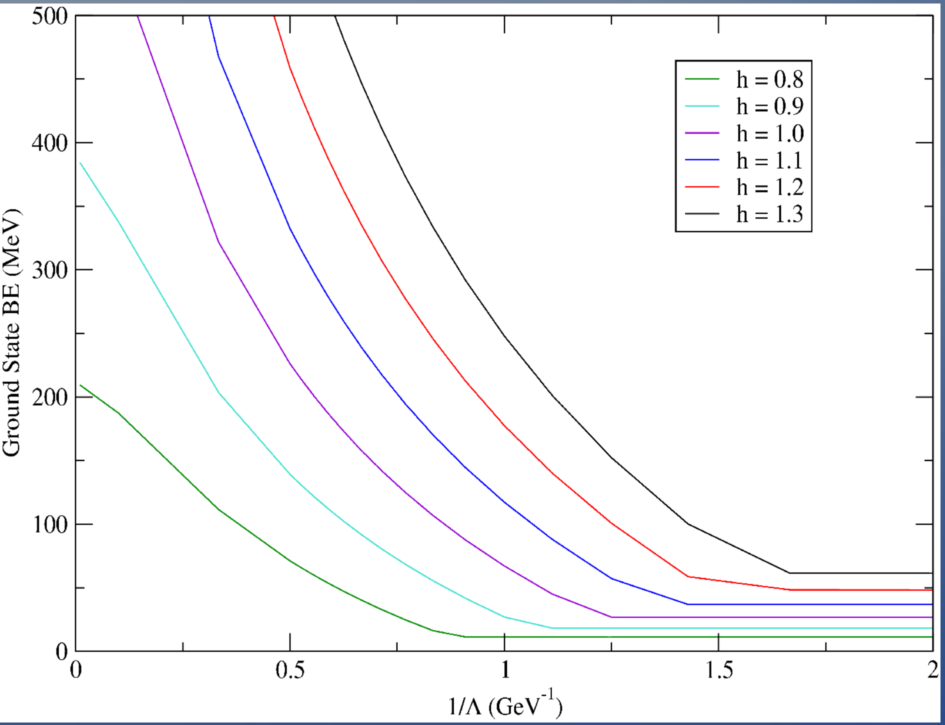
D_1D^* Study (Cont.) – Form Factor

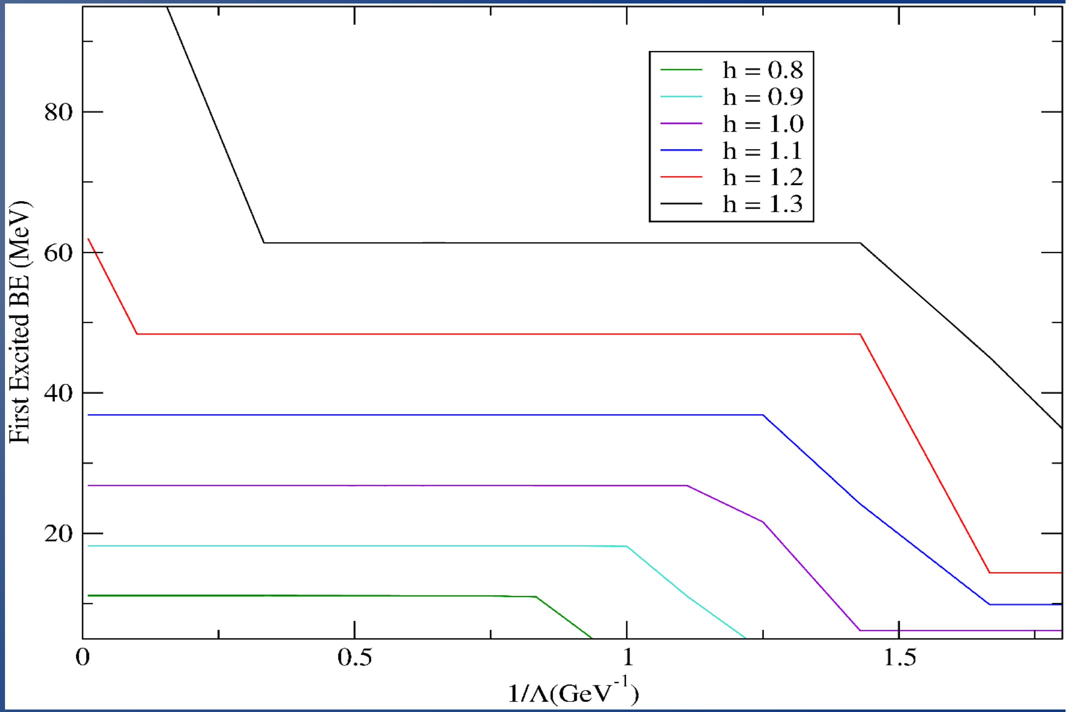
$$\mathcal{F} = \left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - q^2}\right) \approx \left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + \mu^2 - m_\pi^2 + \mathbf{q}^2}\right)$$

$$V_S(r) = \frac{h^2(m_{D_1} - m_{D^*})^2}{8\pi f_\pi^2}\left[\frac{\cos(\mu r)}{r} - \frac{e^{-Xr}}{r} - \frac{(\Lambda^2 - m_\pi^2)}{2X}e^{-Xr}\right](\tau_i \cdot \tau_j)$$



D_1D^* Study (Cont.) – Parameter Flexibility

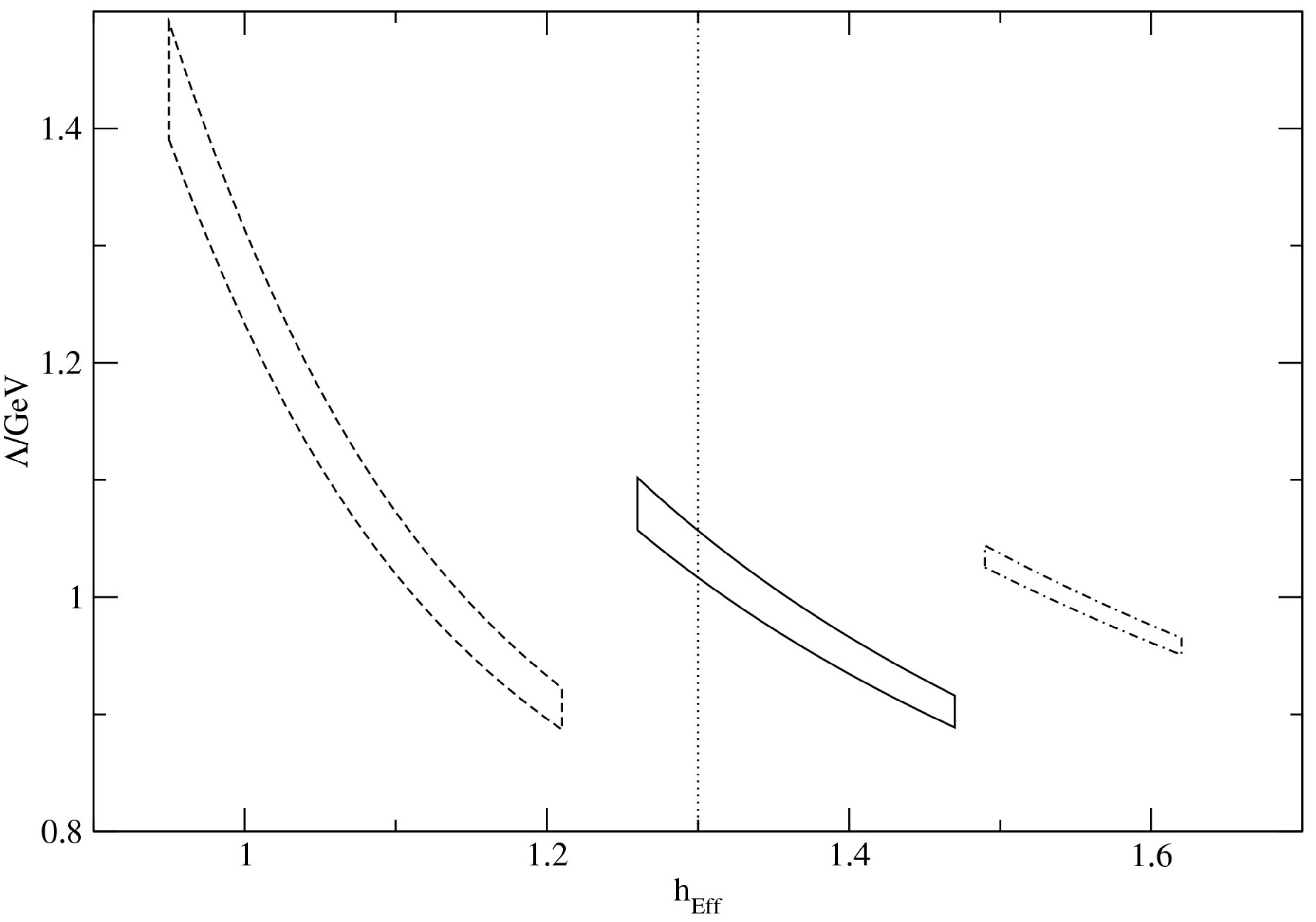




D_1D^* Study (Cont.) – More Sensible Results (Λ = 1 GeV)

	Binding Energy / MeV					
State	$h = 0.8$	$h = 0.9$	$h = 1.0$	$h = 1.1$	$h = 1.2$	$h = 1.3$
1S $(0, 1, 2)^{--}$	12	20	29	60	106	160
2S	1.5	3.6	23	39	51	65
3S	– –	– –	6.7	11	15	21
1P $(0, 1, 2, 3)^{+-}$	8.2	16	25	35	48	61
2P	1	2.8	5.8	9.7	15	20
3P	–	– –	1.5	3.3	6	8.6
1D $(0, 1, 2, 3, 4)^{--}$	1.4	8.3	17	28	40	54
2D	–	1.3	4.1	8.0	13	18
3D	–	–	1	2.6	4.9	7.8

D_1D^* Study (Cont.) – Tune to Fit Y(4260) and Y(4360)



D_1D^* Study (Cont.) – Generalize (Other C/I Channels; Λ= 1 GeV)

State	Isospin	Binding Energy / MeV $h = 0.8$	$h = 0.9$	$h = 1.0$	$h = 1.1$	$h = 1.2$	$h = 1.3$
1S $(0,1,2)^{--}$	0	12	20	29	60	110	160
2S		1.6	3.6	23	39	57	65
3S		–	0.6	6.7	11	15	21
1S $(0,1,2)^{--}$	1	4.2	8.8	15	21	29	38
2S		0.0	0.0	0.2	0.7	1.5	2.8
3S		–	–	–	–	0.0	0.2
1S $(0,1,2)^{-+}$	0	47	67	90	120	150	180
2S		4.2	8.1	13	19	27	35
3S		0.5	1.7	3.5	6.1	10	14
1S $(0,1,2)^{-+}$	1	0.1	0.5	1.6	3.4	5.9	8.9
2S		–	–	–	0.1	0.4	0.9

Theoretical Uncertainty

Pretend S-wave π is the only thing...

Make a static approximation to q_0

$$\mu^2 = q_0^2 - m_\pi^2 \approx (m_{D_1} - m_{D^*})^2 - m_\pi^2$$

Normal Yukawa Process...

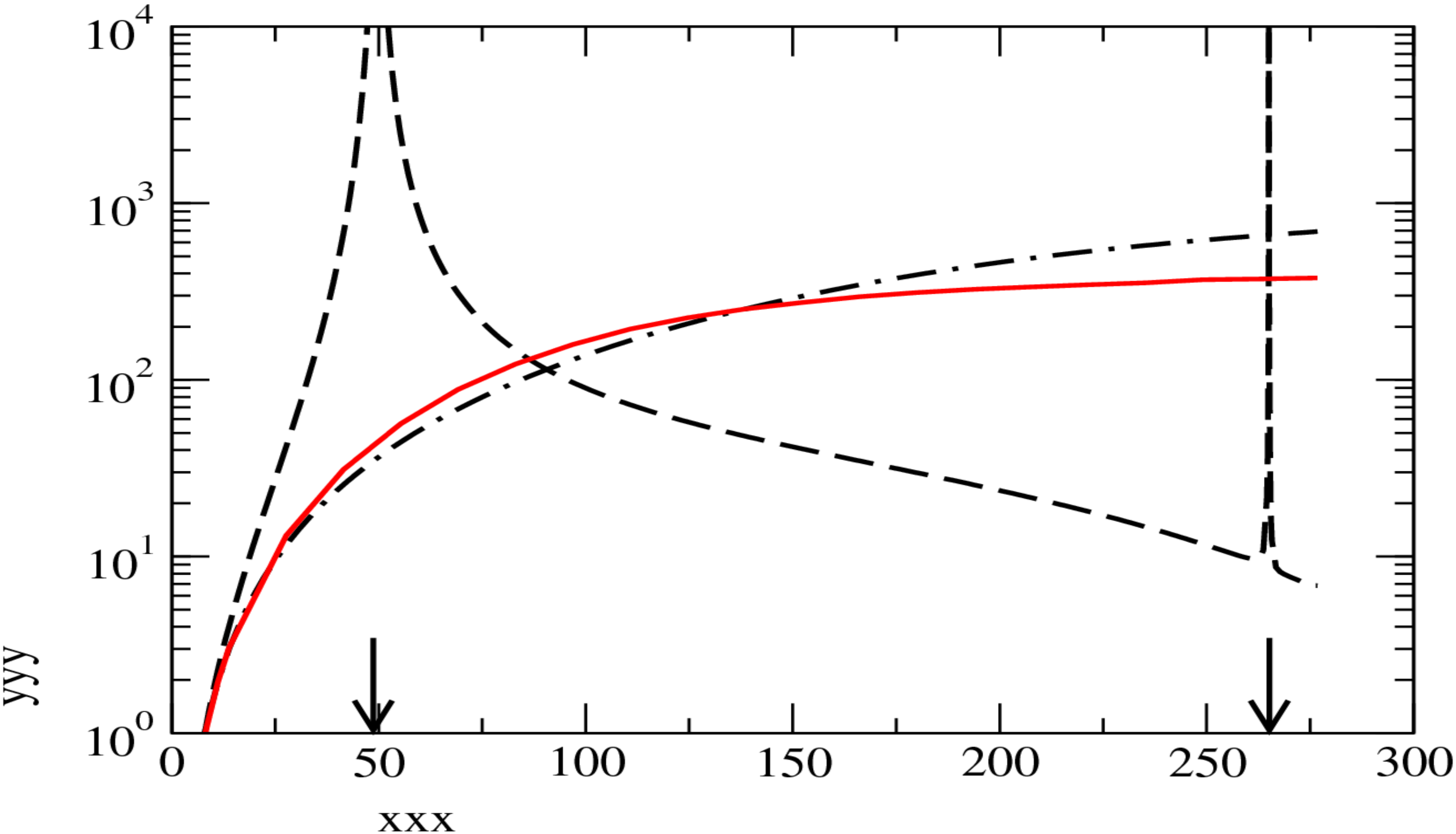
$$V(q) \propto \frac{1}{q^2+m^2+i\epsilon} \rightarrow V(r) \propto \frac{e^{-mr}}{r}$$

Parity Changing π Exchange Prop...

$$V(q) \propto \frac{1}{q^2-\mu^2+i\epsilon} \rightarrow V(r) \propto \frac{e^{-i|\mu|r}}{r} \propto \frac{\cos(|\mu|r)-i\sin(|\mu|r)}{r}$$

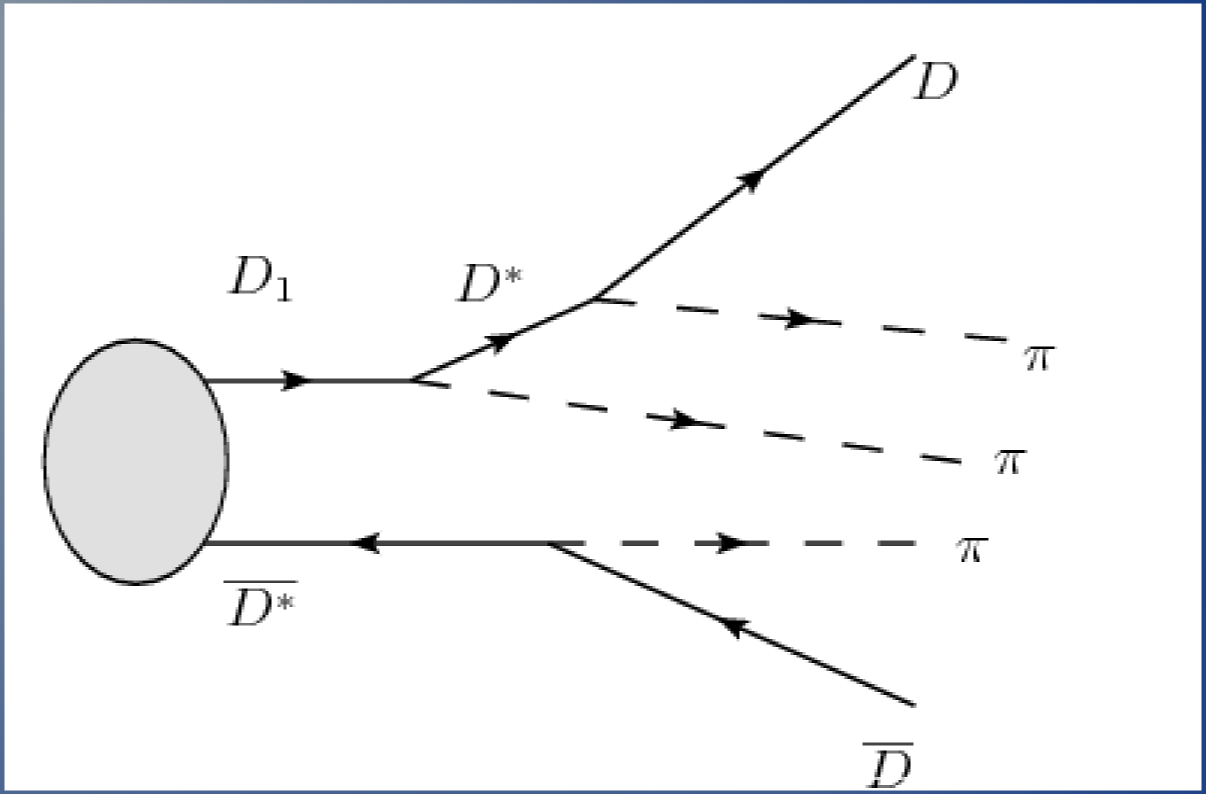
$$E_n \mapsto \tilde{E}_n + i\frac{\Gamma}{2}$$

Recent Developments
Filin, *et al.* arXiv:1004.4789



Conclusion: Our States Do Not Exist

Experimental Searches



- A deeply bound D1D* system requires strength in the DD3π channel.
- We recommended looking in Y(4260) and Y(4360) decays

Summary

- S-wave π Exchange as an interaction has general applicability (D_1D^*, DD_0, B_1B^*, K_1K^*, K_0K, $a_1\rho$, $b_1\omega$, etc...)
- Uncertainties of OBE Molecular Models are large → Study patterns and unique decay channels.
  - $Y(4260) \rightarrow DD3\pi$
- Filin *et al.* find that the states are, at best, too broad to be observed. We should confirm.
- Is there a pair of mesons with suitable masses for S-wave π Exchange to work well?