Hadron-hadron Interactions

- general considerations
- effective approaches
- microscopic approaches
    - OPE methods
    - Dyson-Schwinger
    - constituent quark model
    - chiral symmetry issues

Eric Swanson

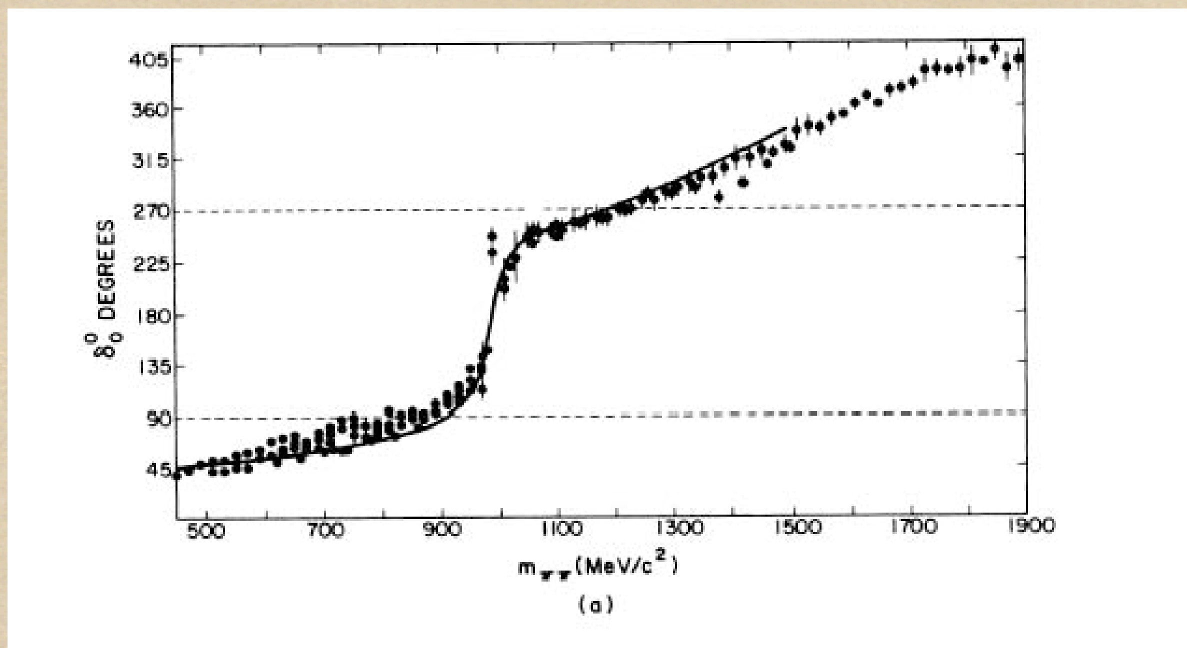

I'M A WAR PRESIDENT!

General Considerations

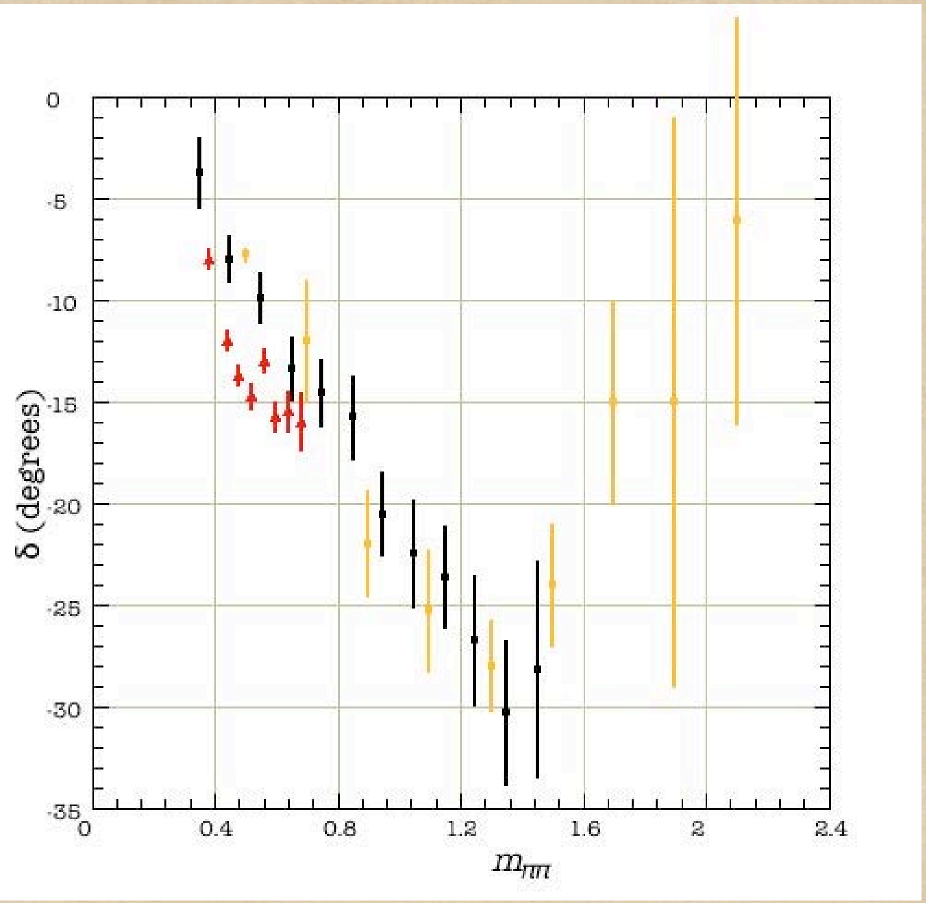
Ubiquitous hadronic interactions

- nuclear physics
- quark-gluon plasma (J/ ψ suppression)
- nuclear astrophysics (EOS)
- high energy physics (g-2, ϵ'/ϵ)
- heavy flavour physics (D- $\pi\pi\pi$, $\Delta I = 1/2$)
- hadronic physics (KK, X(3872), σ, N*,....)

I=0, S-wave ππ Scattering



I=2, S-wave ππ Scattering



Final State Interactions

Electroweak Physics

$$\frac{\epsilon'}{\epsilon} = \frac{\langle \pi\pi_{I=2} | H_{EW} | K_L \rangle}{\sqrt{2}\langle \pi\pi_{I=0} | H_{EW} | K_L \rangle}$$

Final State Interactions

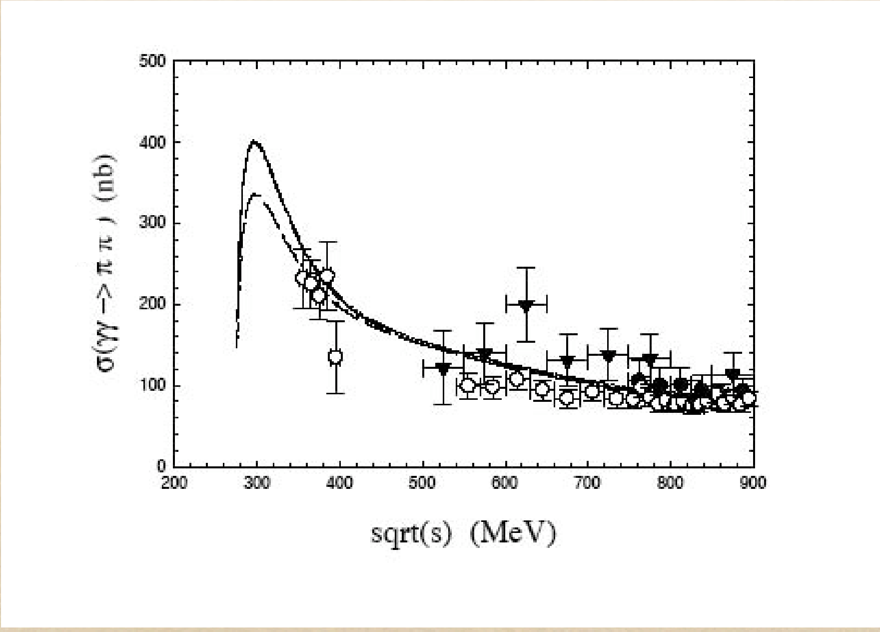
Fermi approximation to FSI

$$T = T_0 F \qquad F = |\frac{\psi(0)}{\psi_0(0)}|$$

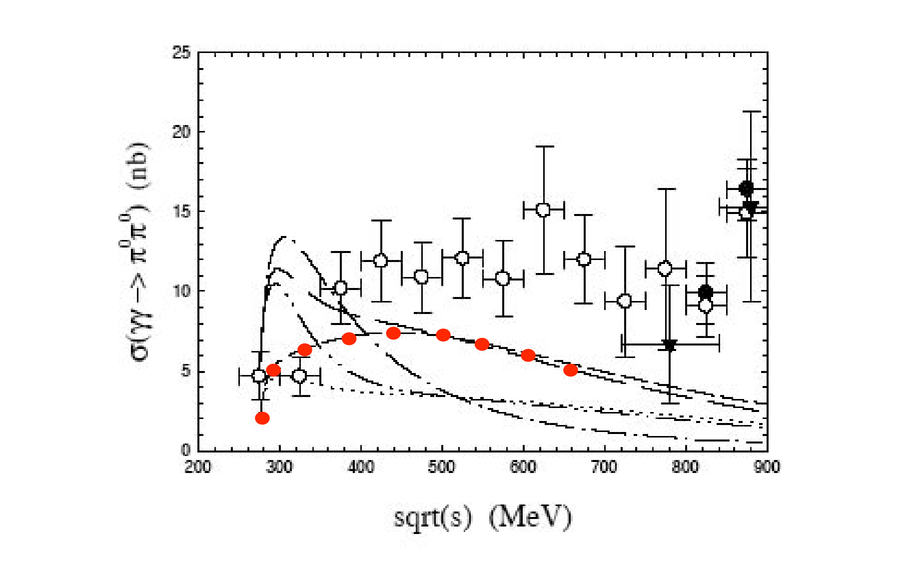
$$\sigma(\gamma\gamma \to \pi^+\pi^-) = \sigma_0 \frac{1}{9}|2F_0 \mathrm{e}^{i\delta_0} + F_2 \mathrm{e}^{i\delta_2}|^2$$

$$\sigma(\gamma\gamma \to \pi^0\pi^0) = \sigma_0 \frac{2}{9}|F_0 \mathrm{e}^{i\delta_0} - F_2 \mathrm{e}^{i\delta_2}|^2$$

$\gamma\gamma \to \pi^+\pi^-$



$\gamma\gamma \rightarrow \pi^0\pi^0$



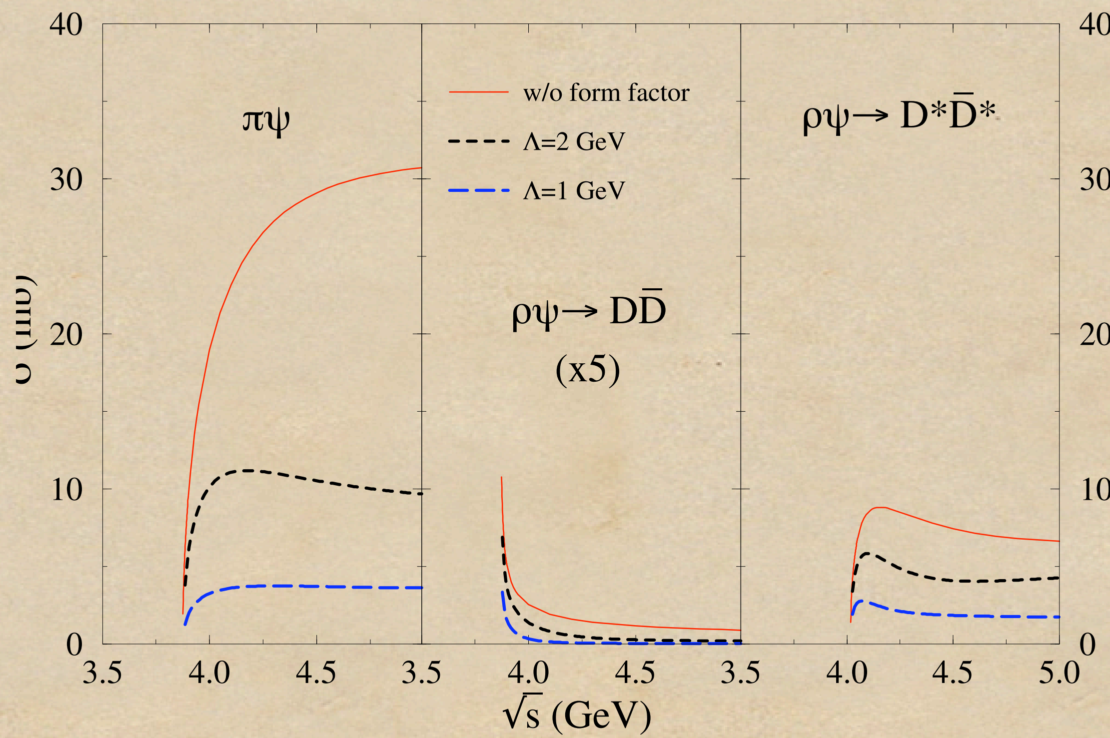
Blundell, Godfrey, Swanson, PRC61, 025203 (2000).

Effective Approaches

hadro-dynamics

- isobar model
- Argonne V18 model
- Fetter-Walecka model
- chiral perturbation theory
- soft collinear effective theory

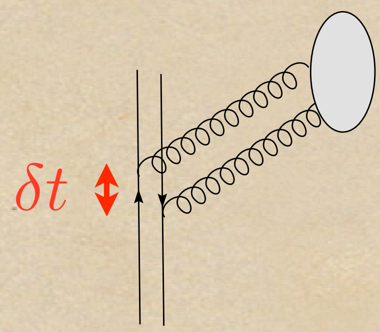
$c\bar{c}$ dissociation (QGP)



Microscopic Approaches

Operator Product Expansion

small hadron interacting with soft gluons



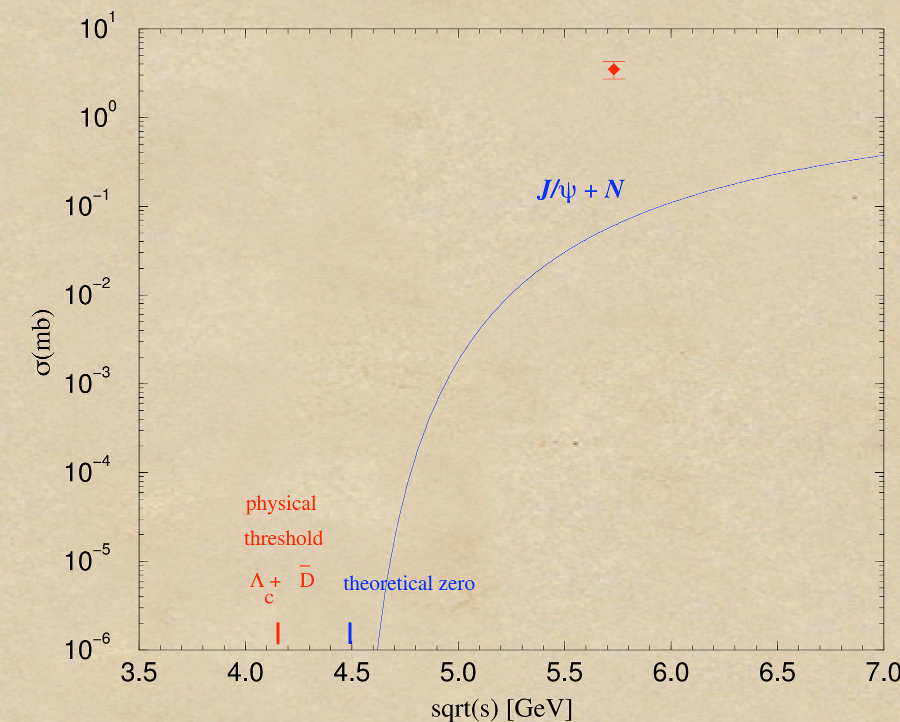
$$\frac{1}{\delta t} \sim E_a - E_\phi \gg \Lambda_{QCD}$$

M. Peskin, NPB156, 365 (1979)

Luke, Manohar, Savage, PLB288, 355 (1992)

Kharzeev & Satz, PLB334, 155 (1994)

Brodsky & Miller, PLB412, 125 (1997)



10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
σ(mb)
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
sqrt(s) [GeV]
$J/\psi + N$
physical
threshold
$\Lambda_c + \bar{D}$
theoretical zero

Operator Product Expansion

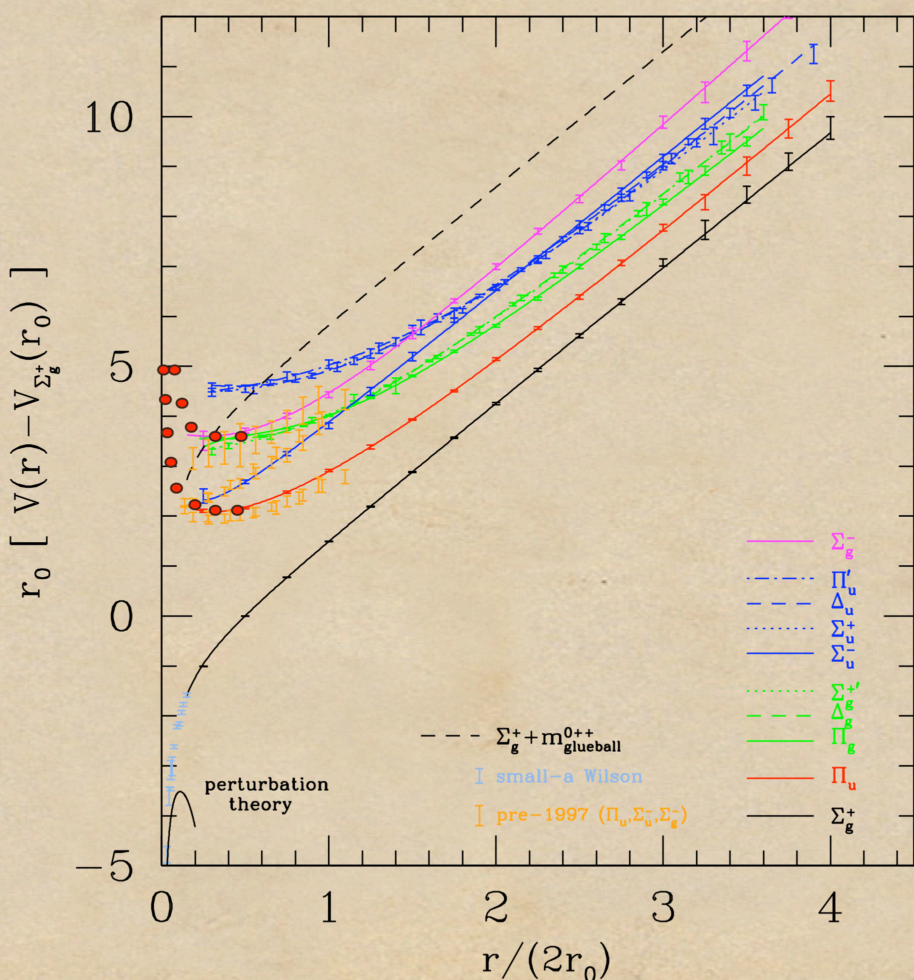
Leutwyler, PLB98, 156 (1981)

$$\delta H = -\mathcal{P}\mathrm{E}\cdot\mathrm{r}\frac{1}{H_a - E_\phi}\mathrm{E}\cdot\mathrm{r}\mathcal{P}$$

$$\delta E_n = \langle\phi_n|\delta H|\phi_n\rangle$$

$$\boxed{\delta E \propto C_E\langle\mathrm{E}^2\rangle}$$

Static Lattice Hybrid Potentials



$$V_a = +\frac{\alpha_S}{6r}$$

Operator Product Expansion

Leutwyler, PLB98, 156 (1981)

$$\delta H = -\mathcal{P}\mathrm{E}\cdot\mathrm{r}\frac{1}{H_a - E_\phi}\mathrm{E}\cdot\mathrm{r}\mathcal{P}$$

$$\delta E_n = \langle\phi_n|\delta H|\phi_n\rangle$$

$$\rightarrow \langle\phi_n;\Sigma_g^+|\delta H|\phi_n;\Sigma_g^+\rangle$$

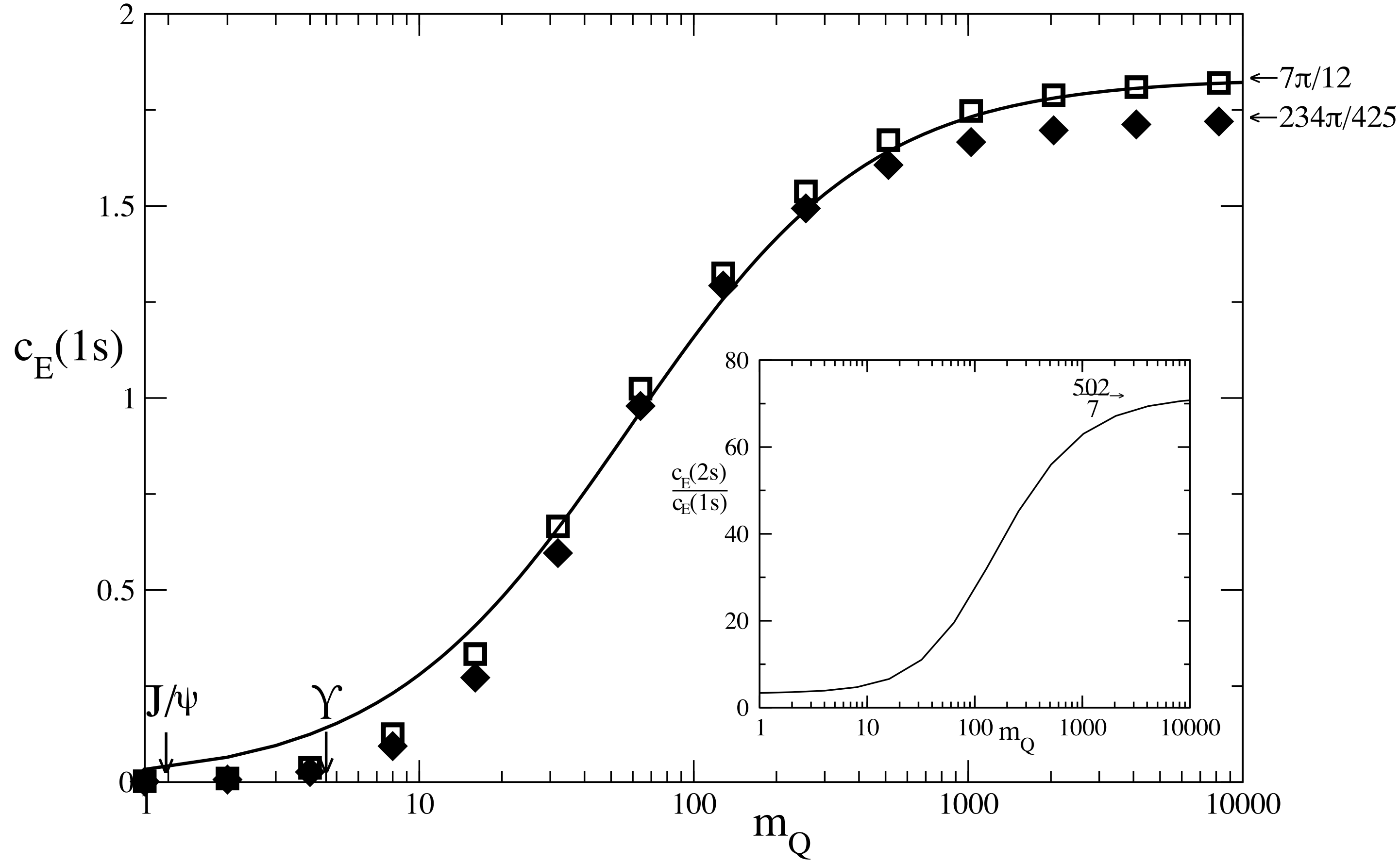
$$= \sum_{h,\Lambda,\eta,Y} \frac{|\langle\phi_n;\Sigma_g^+|\mathbf{E}\cdot\mathrm{r}|h;\Lambda_\eta^Y\rangle|^2}{(E_h(\Lambda_\eta^Y) - E_\phi)}$$

$$= \sum_{h,\Lambda,\eta,Y} \frac{|\langle \phi_n; \Sigma_g^+ | \mathbf{E} \cdot \mathrm{r} | h; \Lambda_\eta^Y \rangle|^2}{(E_h(\Lambda_\eta^Y) - E_\phi)}$$

factorizes

$$\delta E_n = \sum_h \frac{|\langle \phi_n | \mathrm{r} | h \rangle|^2}{(E_h - E_\phi)} \cdot \langle \Sigma_g^+ | \mathrm{E}^2 | \Sigma_g^+ \rangle$$

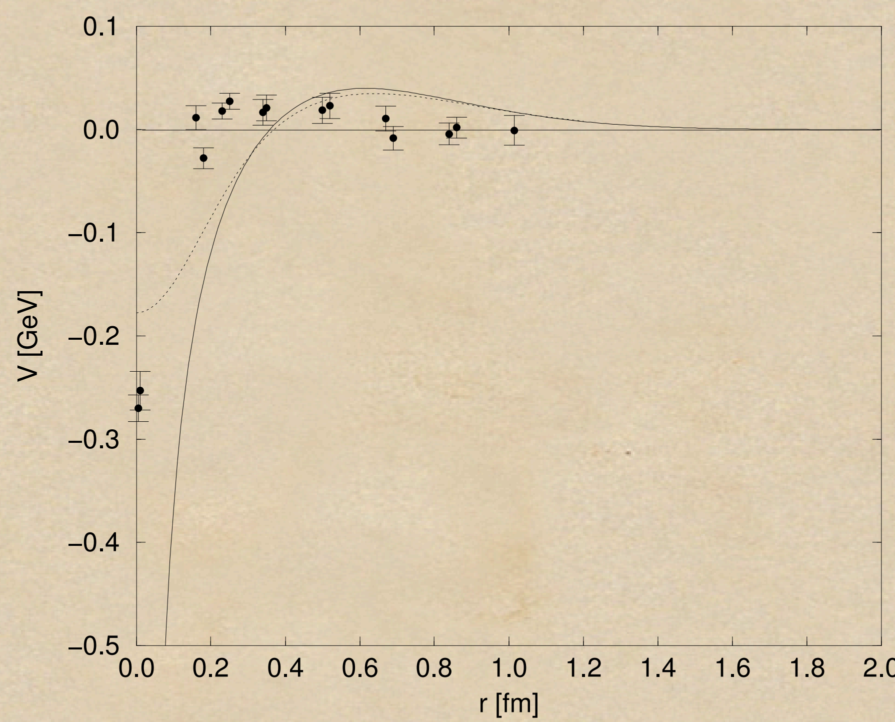
$$\delta E \propto C_E \langle \mathrm{E}^2 \rangle$$



Lakhina and Swanson, PLB582, 167 (2004).

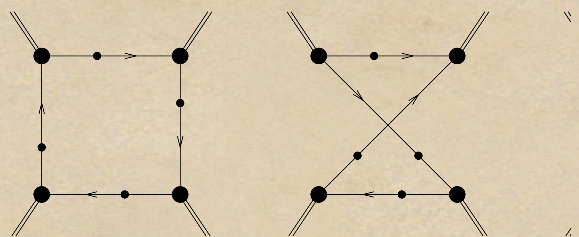
Lattice Gauge Theory

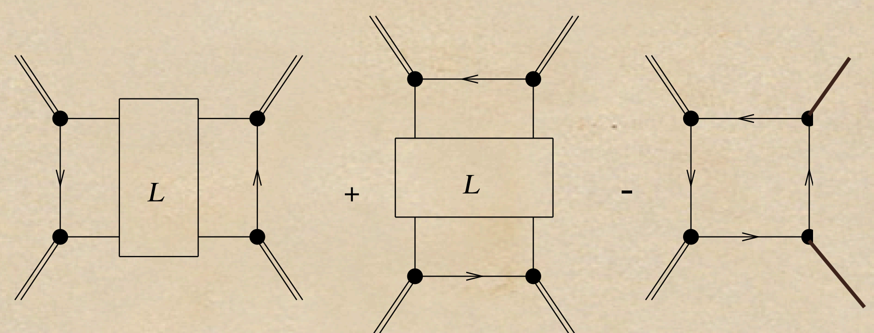
BB Interactions



C. Michael and P. Pennanen (UKQCD Collaboration),
hep-lat/9901007 (Jan. 1999)

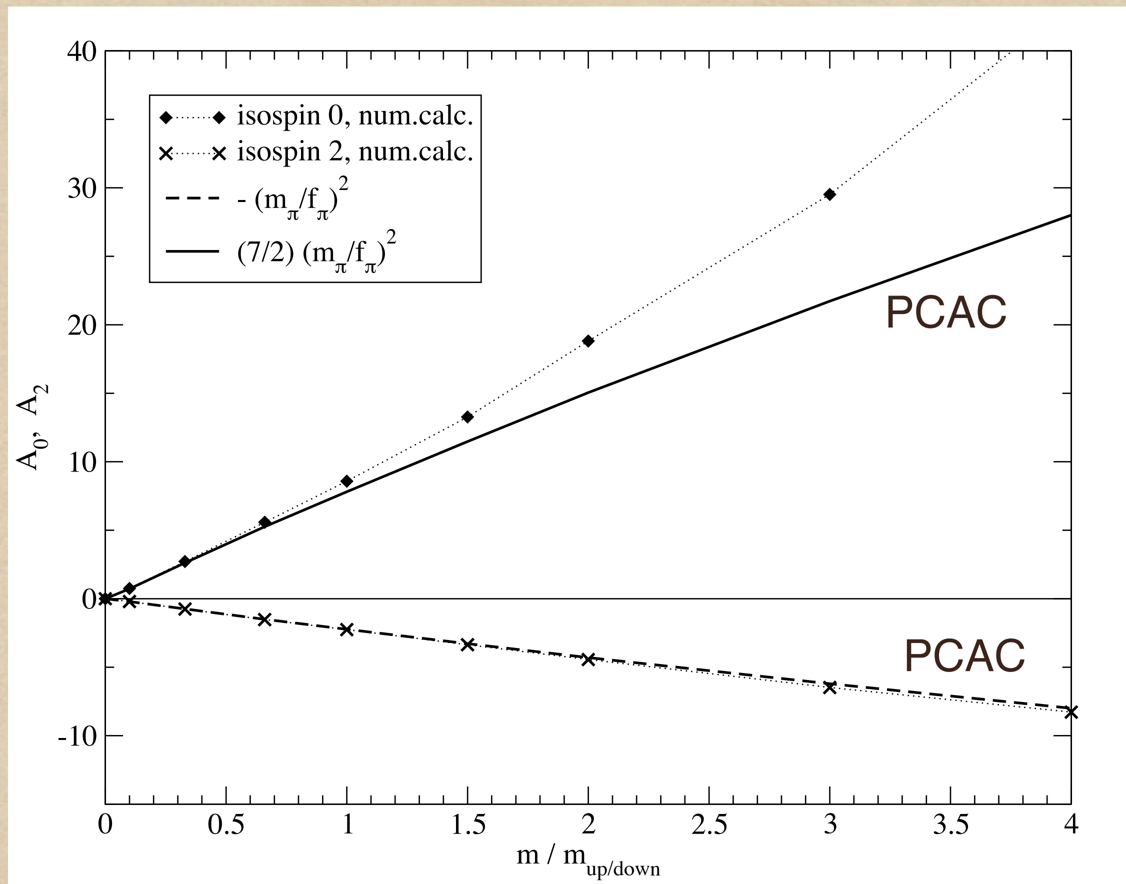
Dyson-Schwinger Equations





Bicudo et al., PRD65, 076008 (2002).

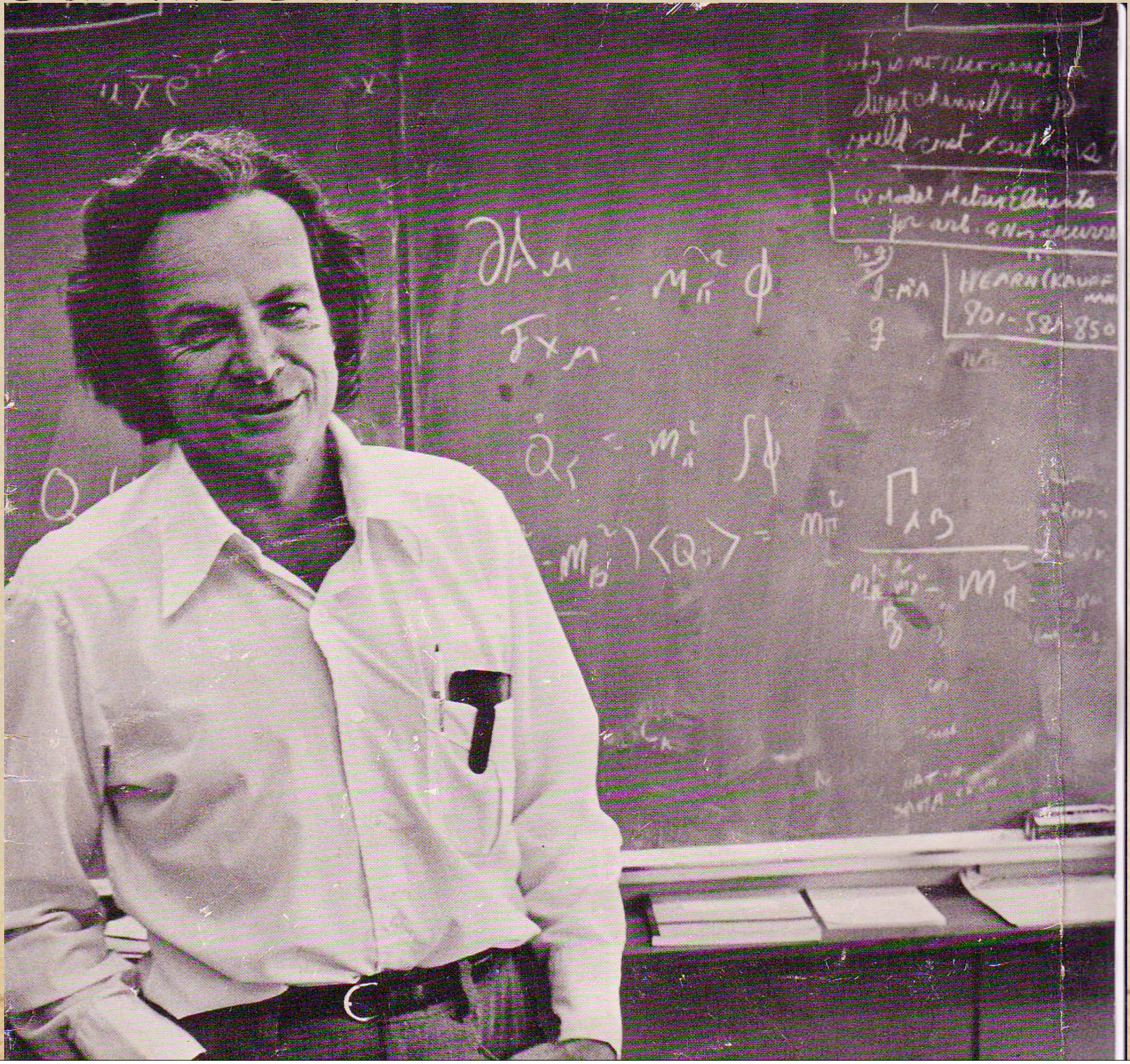
Dyson-Schwinger Equations



Bicudo et al., PRD65, 076008 (2002).

Constituent Quark Models

"trust your model"



Variational Resonating Group Method

project multiquark system to channels of interest

$$\mathcal{L}(u_L) = \left(\frac{d^2}{dR^2} - \frac{L(L+1)}{R^2} + k^2\right) + \int W^{(L)}(R,R')u_L(R')dR'$$

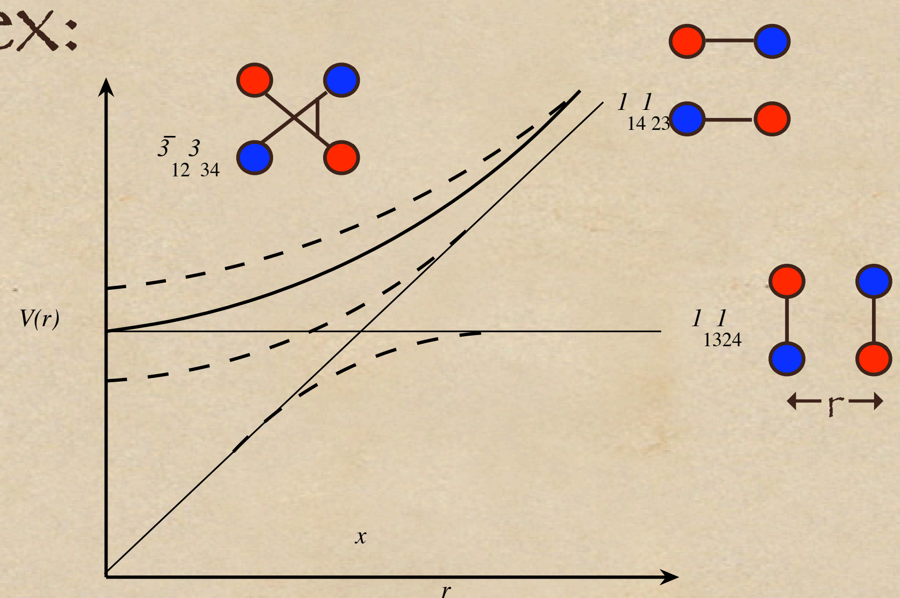
$$\delta \int_0^\infty u_L(R)\mathcal{L}(u_L)dR = 2ik\,\delta S_L$$

$$J[u_L] = S_L + \frac{i}{2k}\int_0^\infty u_L(R)\mathcal{L}(u_L)dR$$

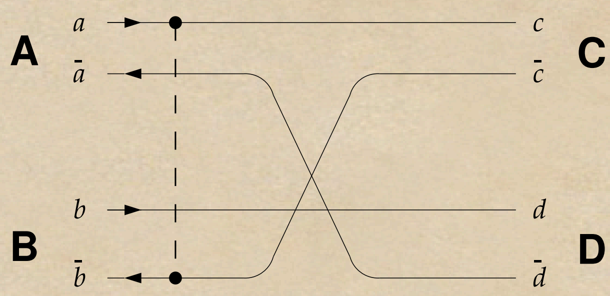
Multiquarks

for the first time, the colour structure becomes important.

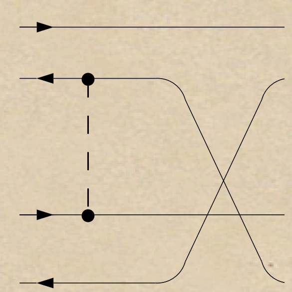
ex:



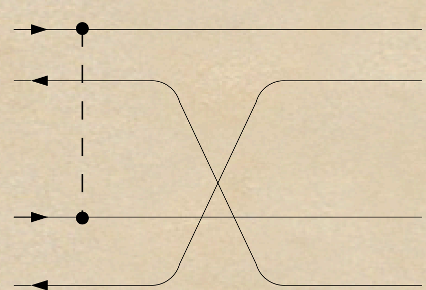
QBDs



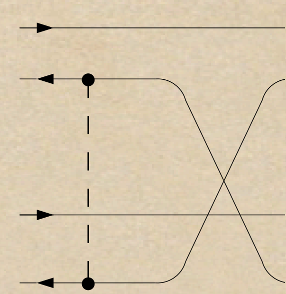
C1



C2



T1

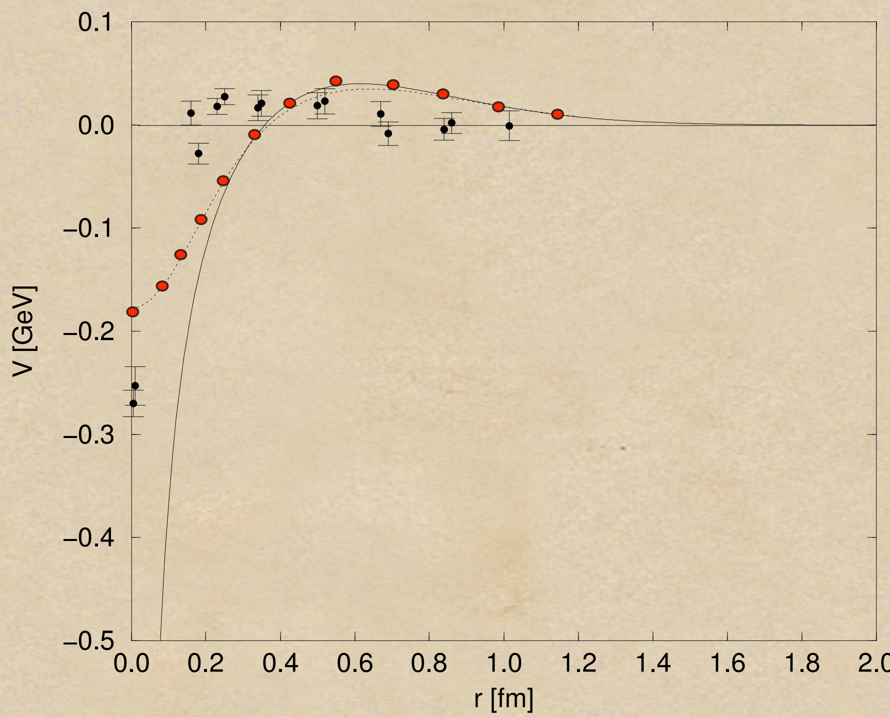


T2

ESS, Ann Phys 220, 73 (1992)

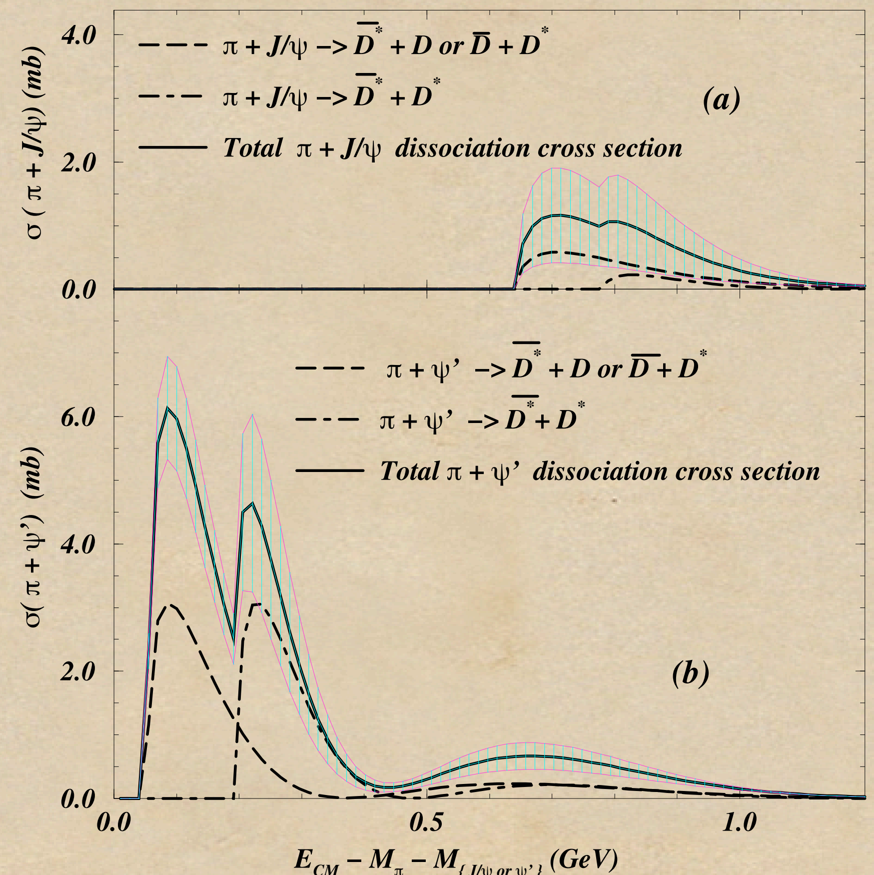
T. Barnes & ESS, PRD46, 131 (1992)

BB Interactions



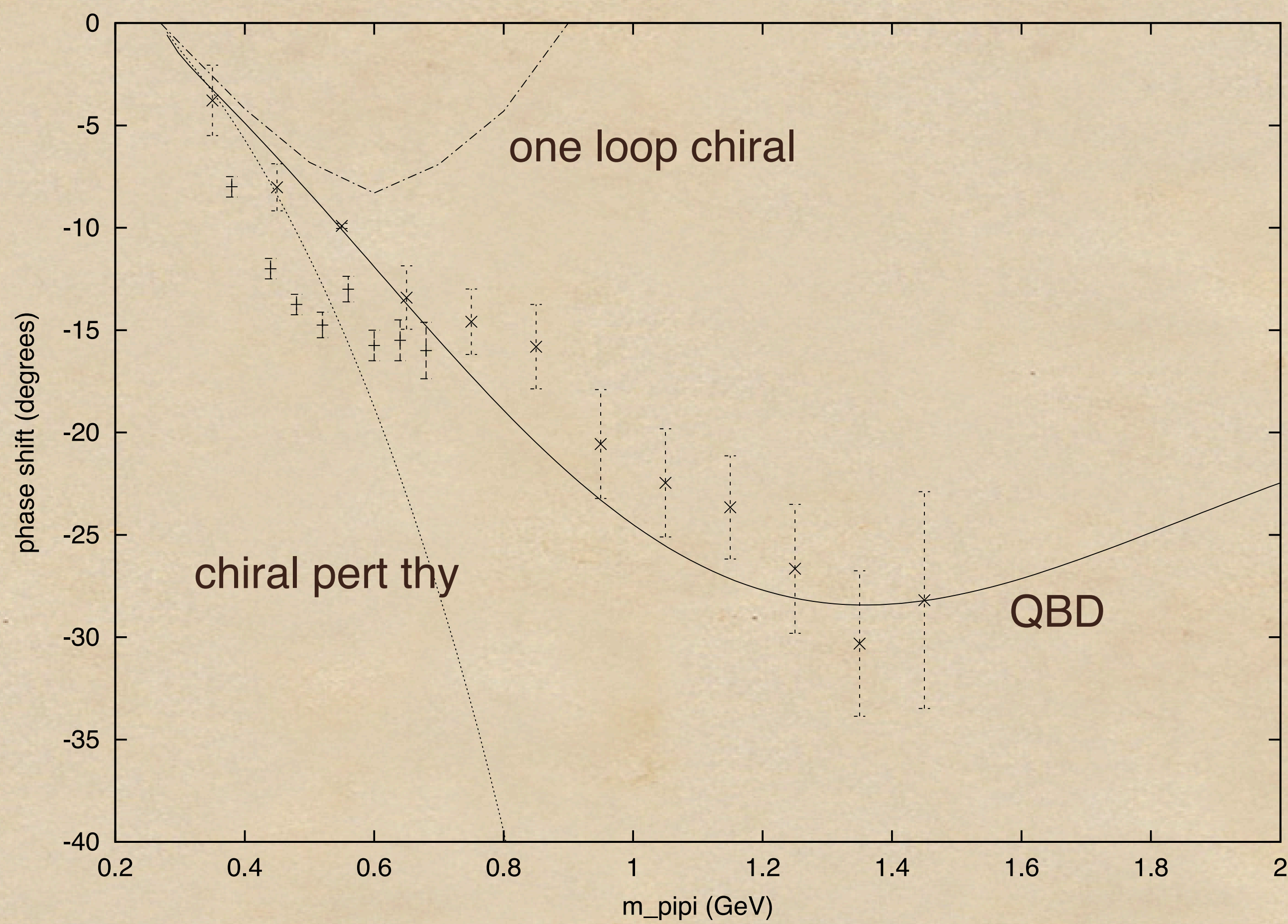
Barnes, Black, Dean, Swanson, PRC60, 045202 (1999).

πψ Scattering



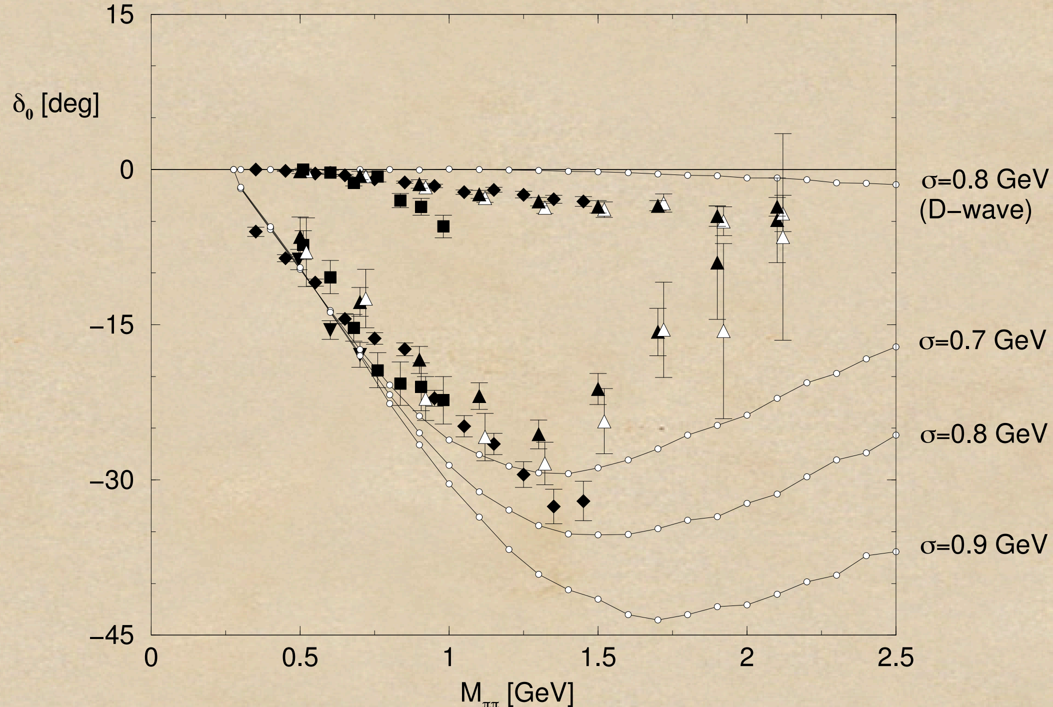
Wong, Swanson, Barnes, PRC62, 04520 (2000).

ππ Interactions

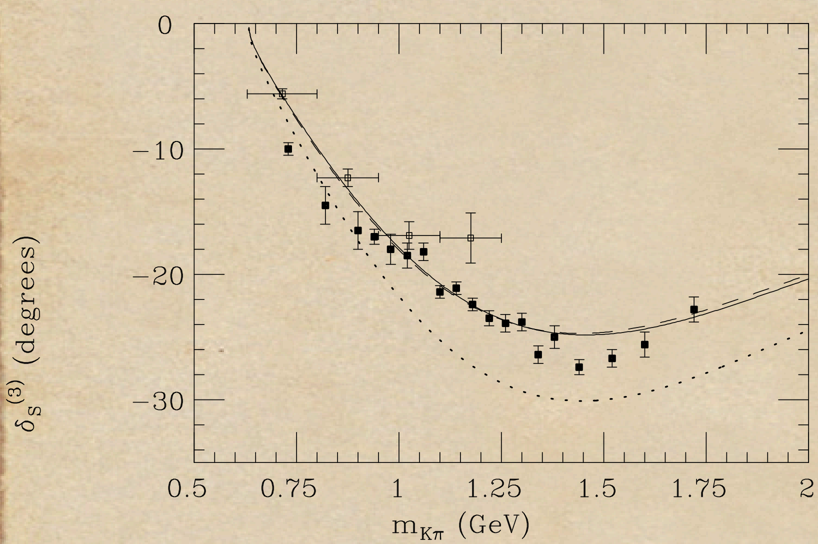


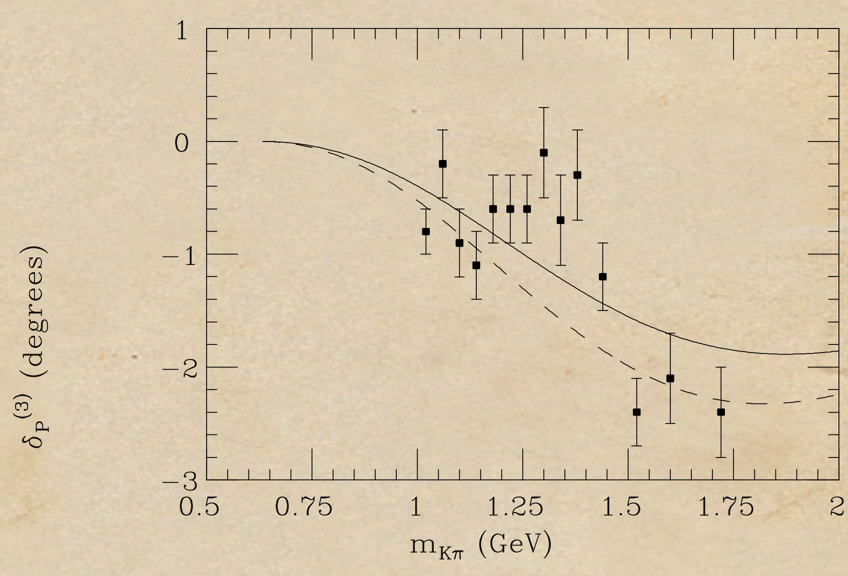
T. Barnes & ESS, PRD46, 131 (1992)

ππ Interactions



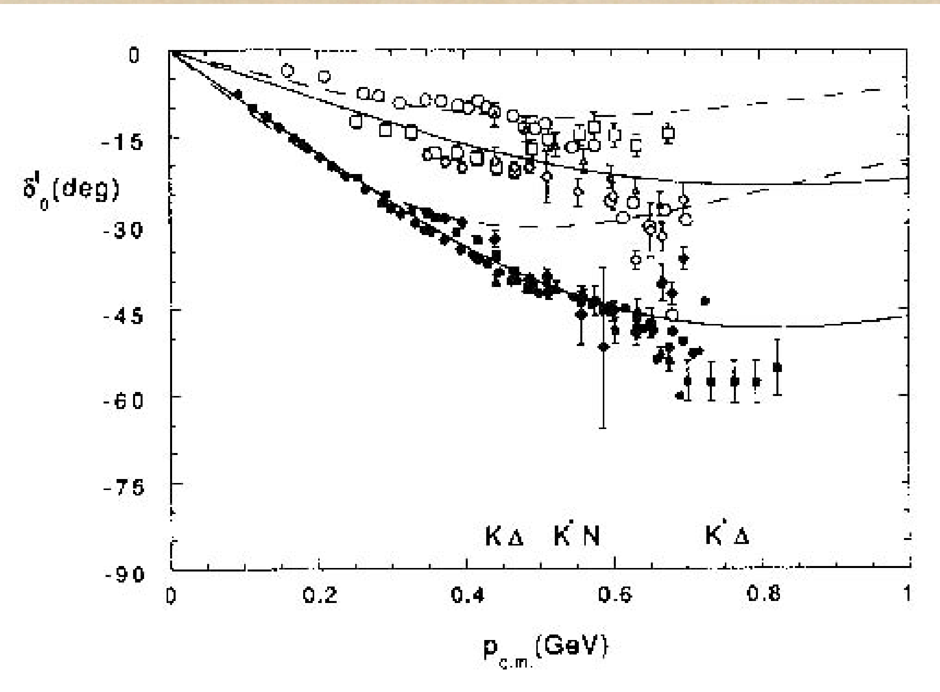
K π Scattering





Barnes, Swanson, Weinstein, PRD46, 4868 (1992).

K N Scattering



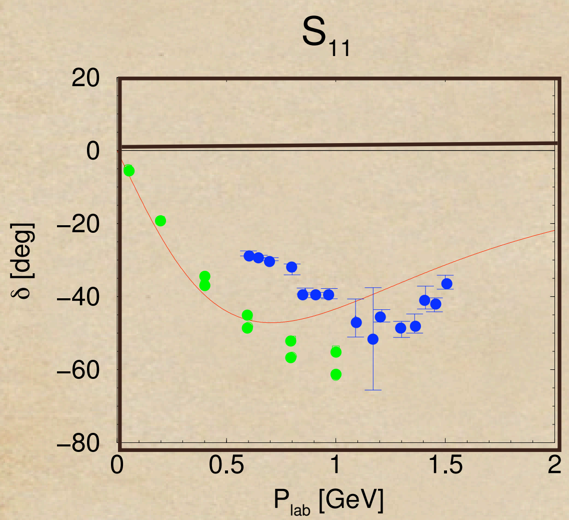
I=0

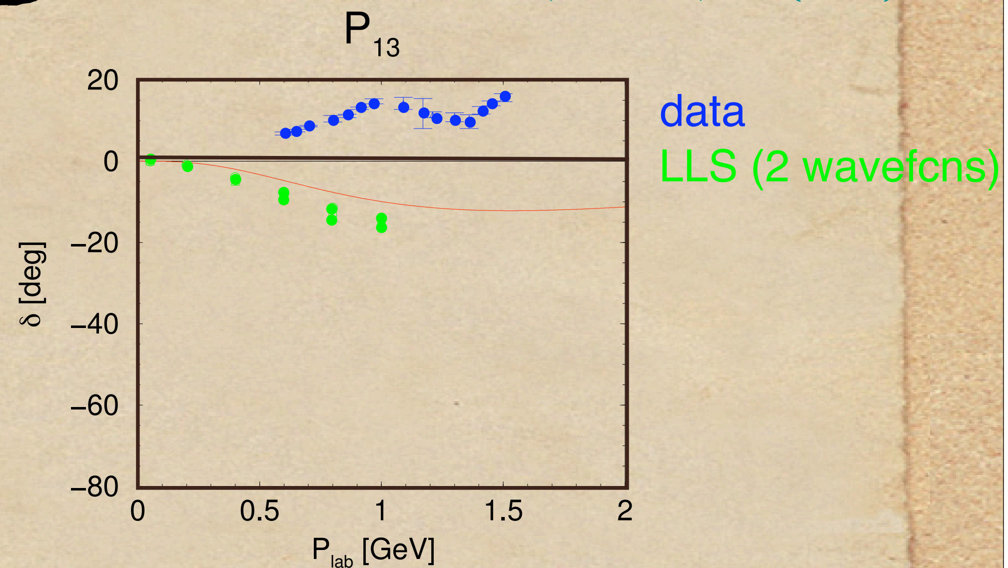
I=1

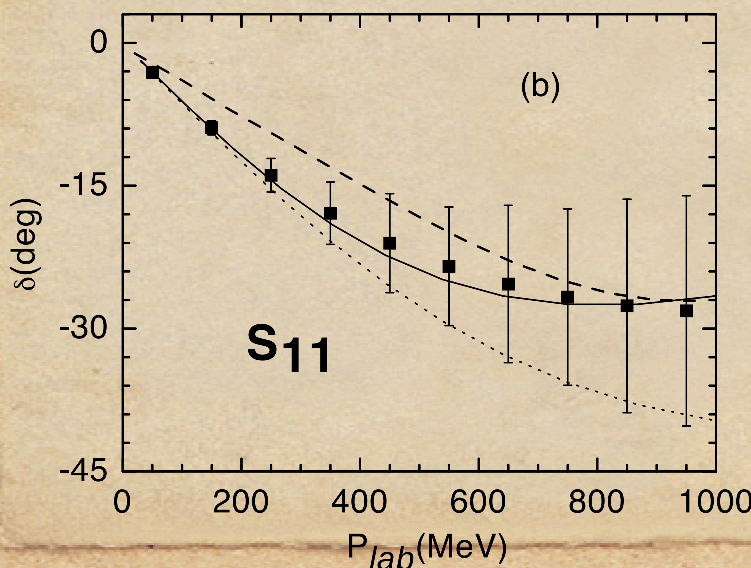
Barnes & Swanson, PRC49, 1166 (1994).

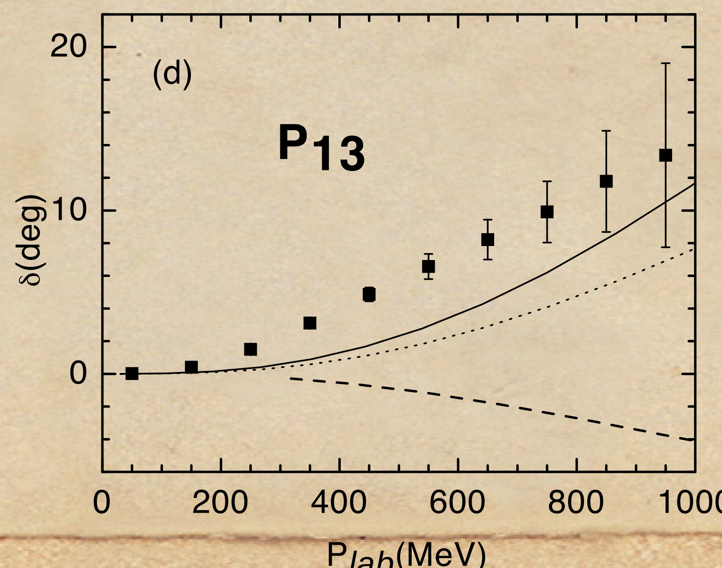
K N Scattering

Black, JPG28, 1953 (2002).
Lemaire, Labarsoque, Silvestre-Brac, NPA656, 497 (2001).









Wang, Yang, Su, hep-ph/0410376

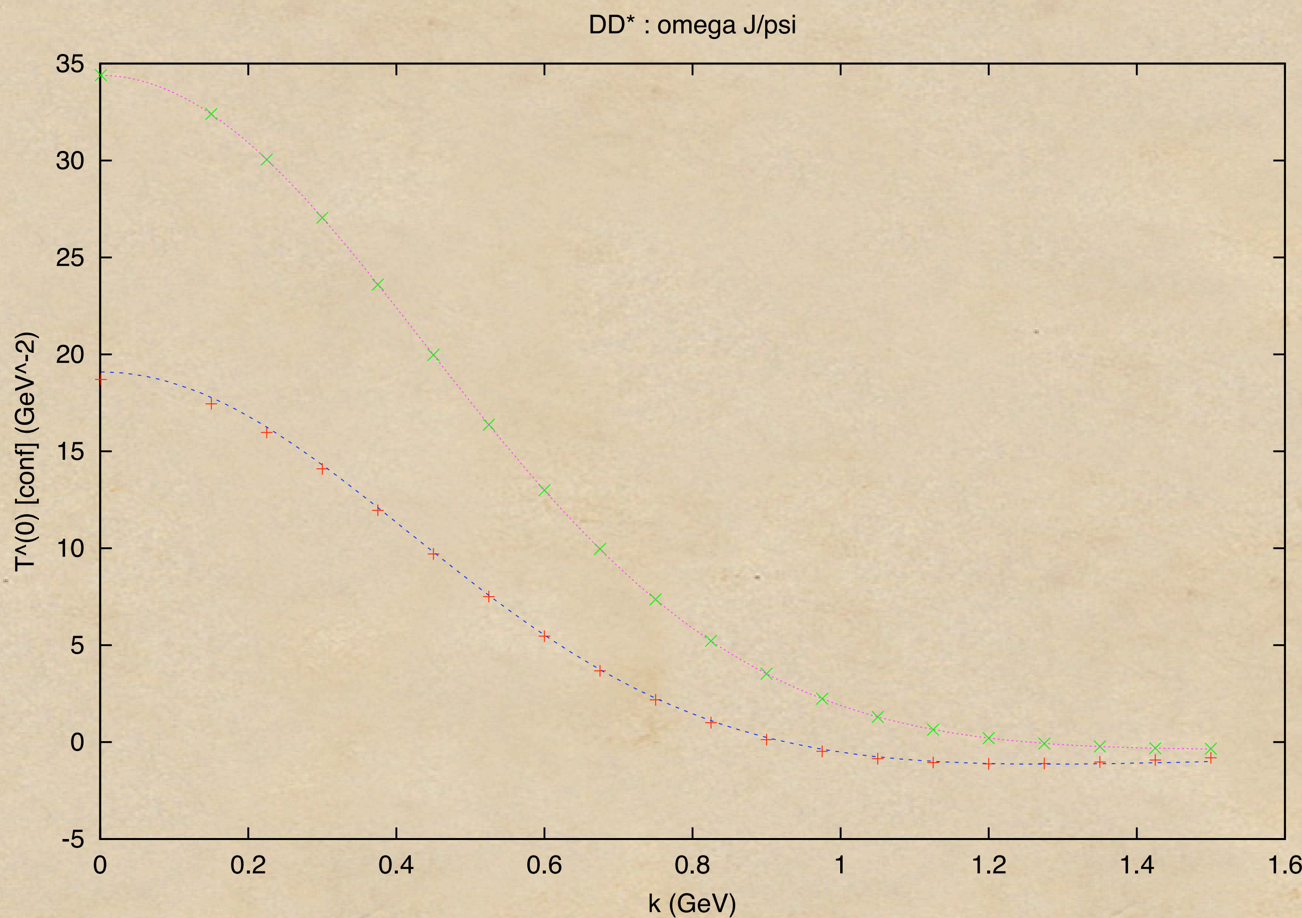
X(3872)

Swanson, PLB588, 189 (2004)

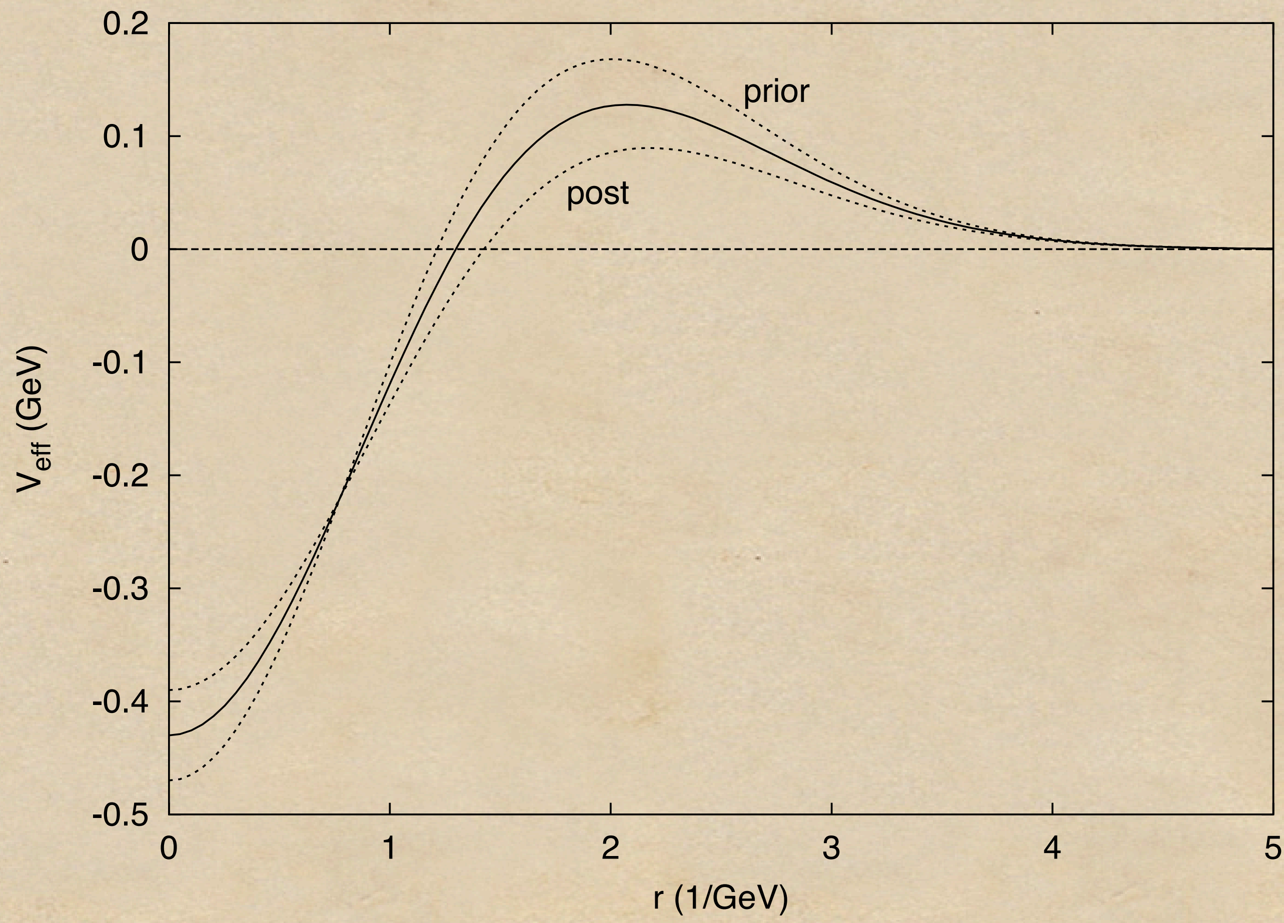
V	$\rho\psi$	$D^0\bar{D}^{0*}$	D^+D^{-*}	$\omega\psi$
$\rho\psi$	–	V_q	V_q	–
$D^0\bar{D}^{0*}$		V_π	V_π	V_q
D^+D^{-*}			V_π	V_q
$\omega\psi$				–

- strongest attraction: I=0 1^{++}
- find a single bound state
- isospin symmetry violation is natural in weakly bound molecules

DD* →ω J/ψ T-Matrix



Effective Potential



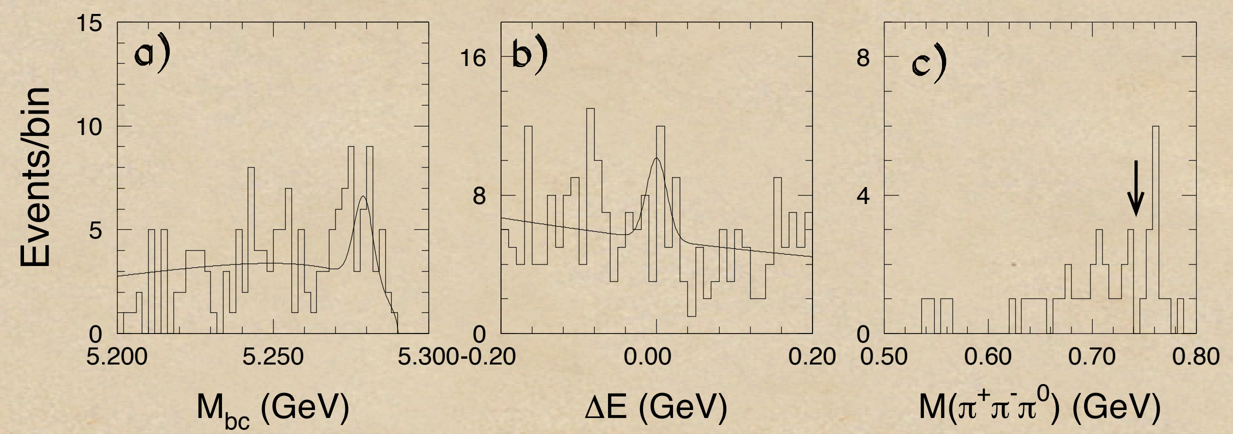
X(3872): decays

weak binding → use free space decay widths to estimate dissociation decay modes

	D^{0*}	D^{0*}	D^{-*}	D^{-*}	D^{-*}	ρ	ρ/ω	ω	ρ/ω
B_E (MeV)	$D^0\bar{D}^0\pi^0$	$D^0\bar{D}^0\gamma$	$D^+D^-\pi^0$	$(D^+\bar{D}^0\pi^-+\text{c.c})/\sqrt{2}$	$D^+D^-\gamma$	$\pi^+\pi^-J/\psi$	$\pi^+\pi^-\gamma J/\psi$	$\pi^+\pi^-\pi^0 J/\psi$	$\pi^0\gamma J/\psi$
0.7	67	38	5.1	4.7	0.2	1290	12.9	720	70
1.0	66	36	6.4	5.8	0.3	1215	12.1	820	80
2.0	57	32	9.5	8.6	0.4	975	9.8	1040	100
3.8	52	28	12.5	11.4	0.6	690	6.9	1190	115
6.1	46	26	15.0	13.6	0.7	450	4.5	1270	120
9.0	43	24	16.9	15.3	0.8	285	2.9	1280	125
12.7	38	22	18.5	16.7	0.9	180	1.8	1240	120

$$\frac{\Gamma(\hat{\chi} \to \pi\pi\pi J/\psi)}{\Gamma(\hat{\chi} \to \pi\pi J/\psi)} = 0.56$$

X(3872): decays



$$\frac{\Gamma(X \to \omega J/\psi)}{\Gamma(X \to \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3(stat) \pm 0.1(sys)$$

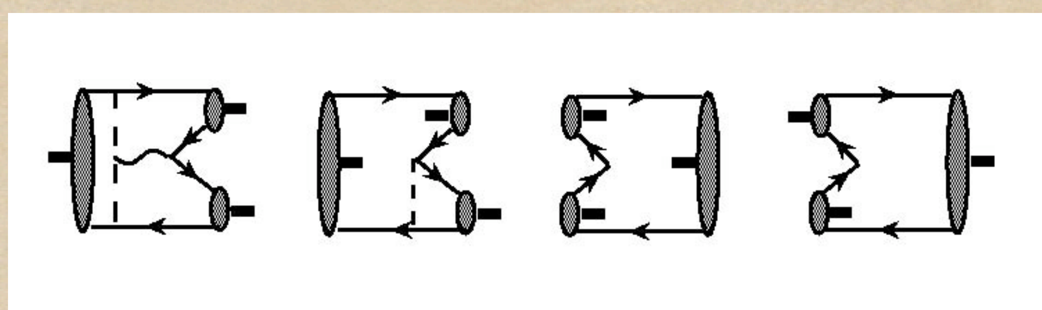
K. Abe et al [Belle], hep-ex/0408116

Coupled Channels

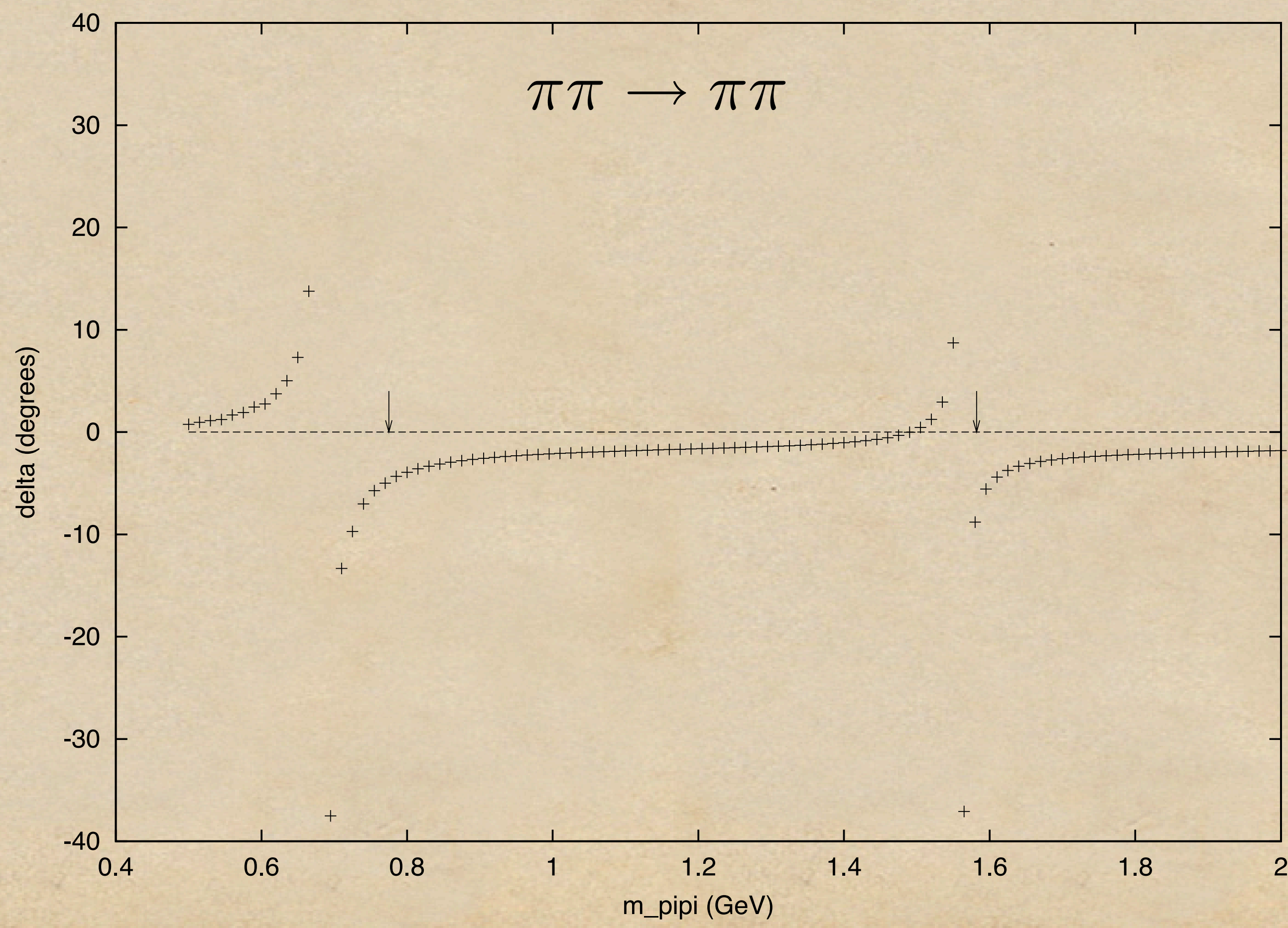
- c.c. effects are clearly important to almost all hadronic interactions
- microscopic models require an understanding of nonperturbative gluodynamics

Vertex Models

Cornell , $^3P_0$, $^3S_1$, one gluon exchange

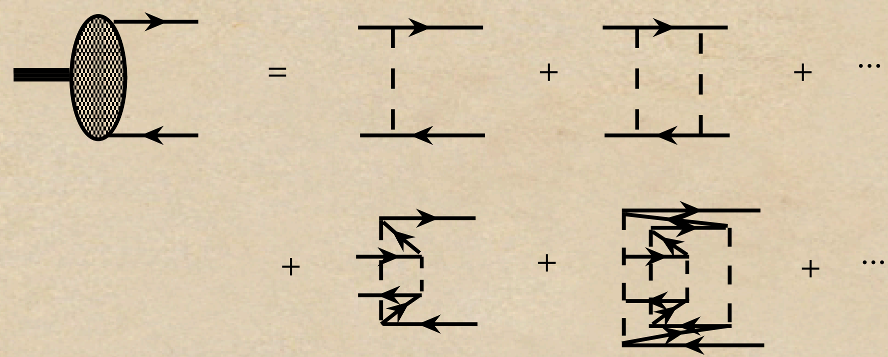


coupled channel CQM

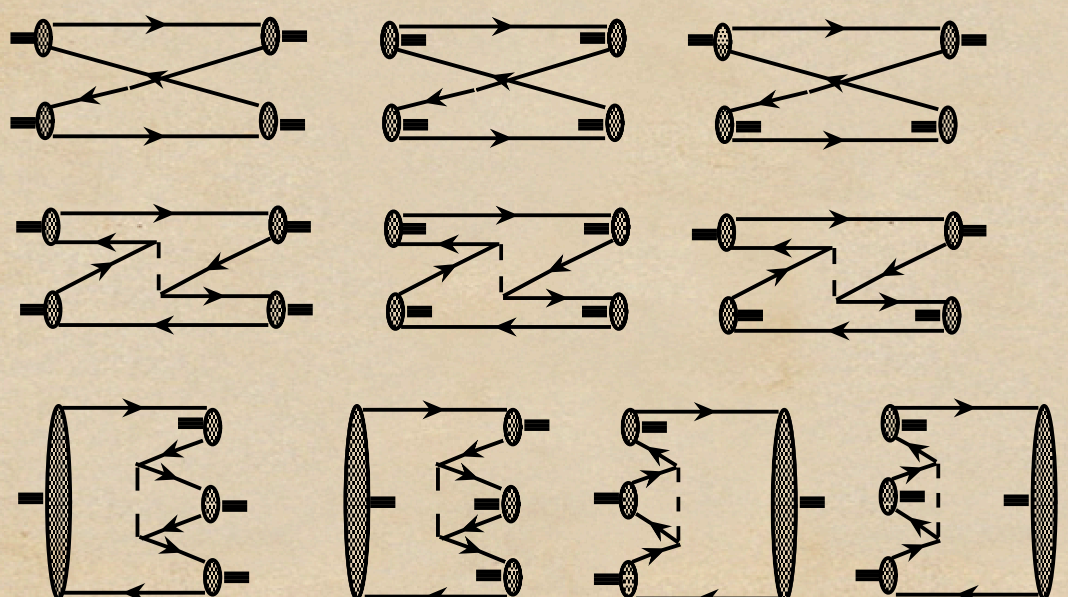


the trouble with pions

- chiral pions



π RPA equation

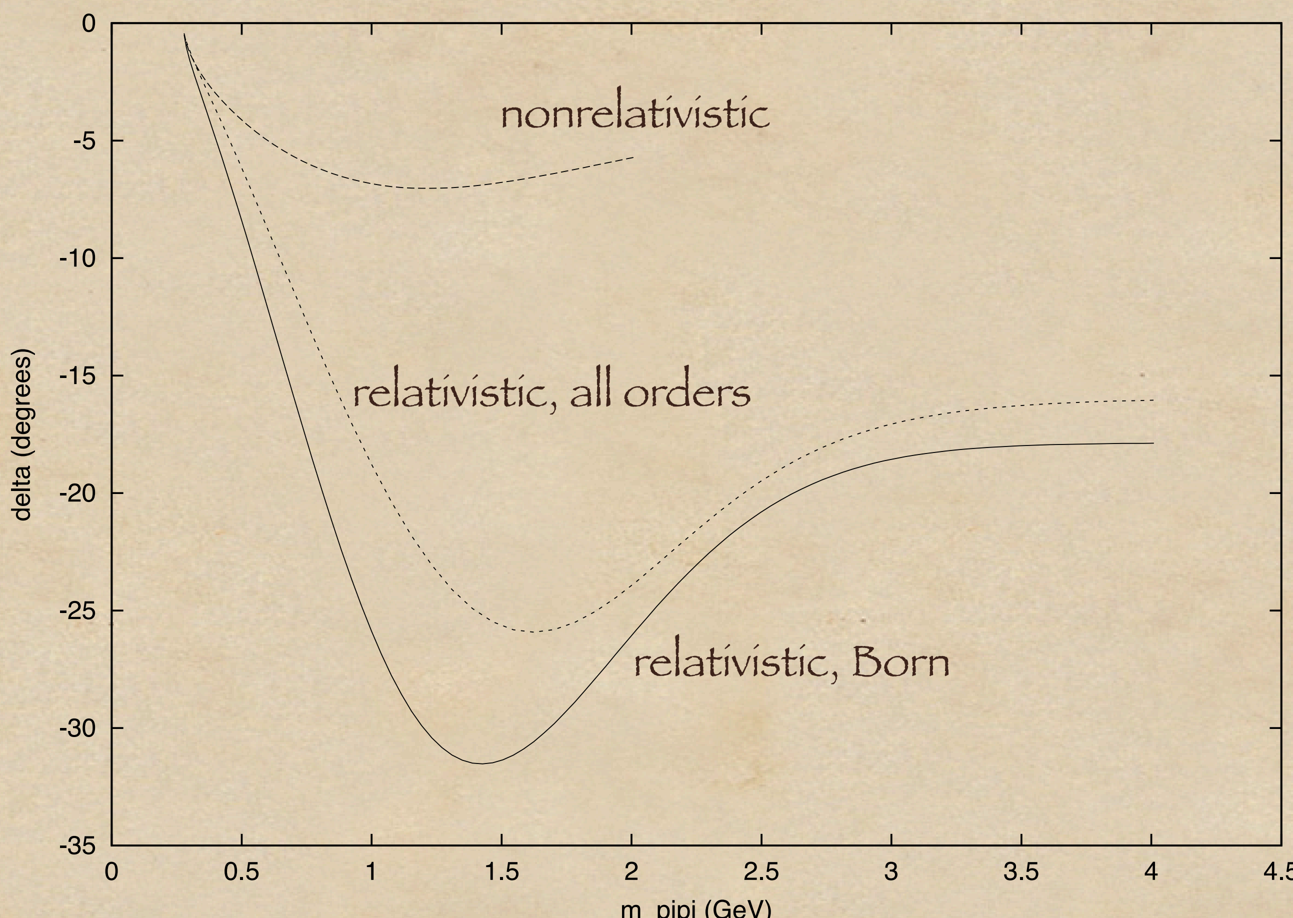


RPA ππ scattering

the trouble with pions

- chiral pions
- light pions

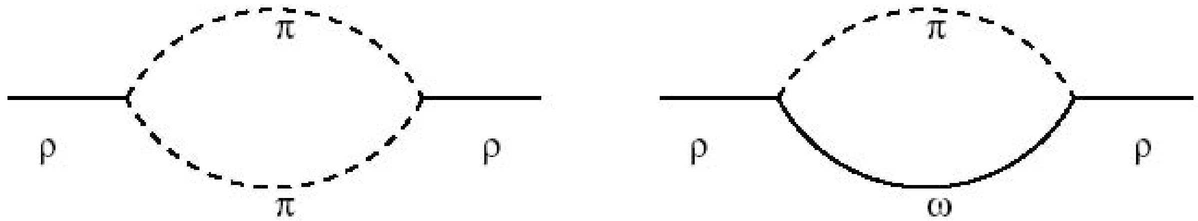
ππ I=2 L=0 scattering

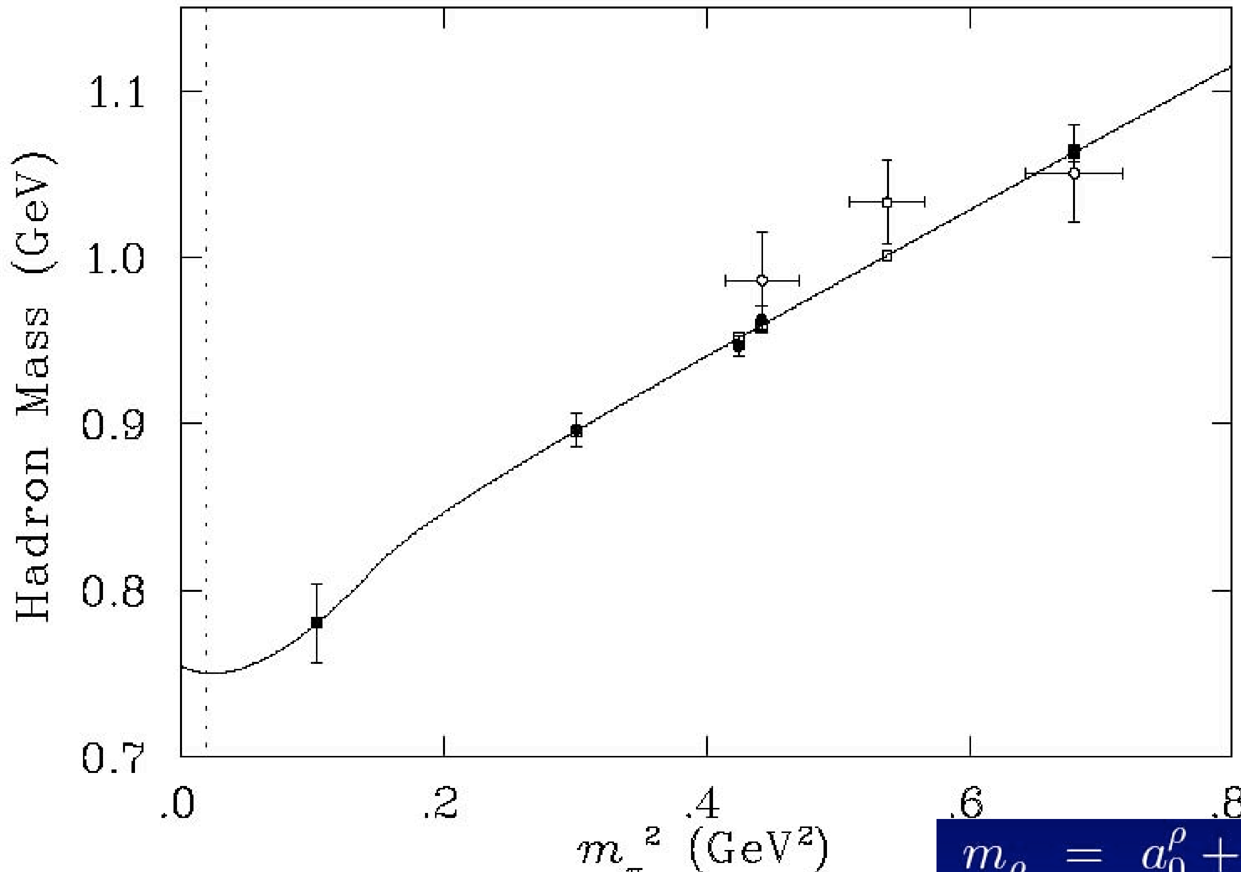


the trouble with pions

- chiral pions
- light pions
- pion clouds

rho mass extrapolation on the lattice



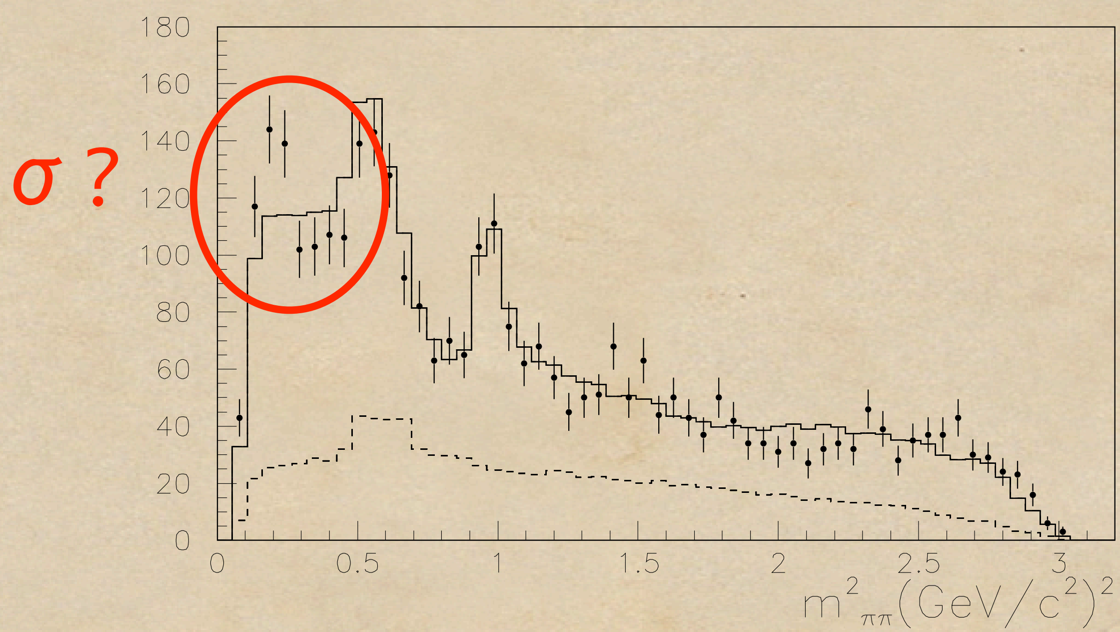


$$
\begin{aligned}
m_\rho &= a_0^\rho + a_2^\rho m_\pi^2 + a_4^\rho m_\pi^4 \\
&\quad + \sigma_{\omega\pi}(m_\pi, \Lambda_\rho) + \sigma_{\pi\pi}(m_\pi, \Lambda_\rho)
\end{aligned}
$$

the trouble with pions

- chiral pions
- light pions
- pion clouds
- pions in the final state (σ)

$$D^+ \rightarrow \pi^- \pi^+ \pi^+$$



Conclusions

- hadron-hadron interactions are everywhere and are important
- LGT: H-H is its most difficult regime
- DS: Euclidean space and analytic structure
- naive application of the CQM is reasonably successful -- BUT

  details depend on $1/m^2$ structure

  coupled channels matter

  relativistic kinematics can matter

  chiral dynamics matter

+ ÆRIC MEC HEHT GEWYRCAN