Origin of resonances in chiral dynamics

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Resonances in two-body scattering

- Knowledge of interaction (potential)
- Experimental data (cross section, ...)

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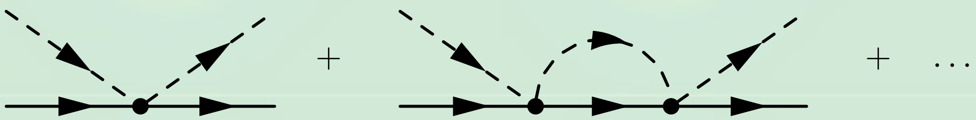

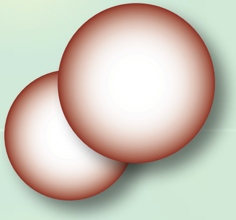

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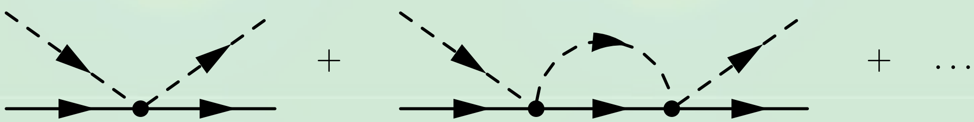

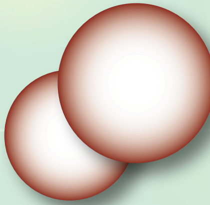

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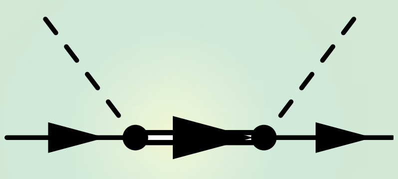
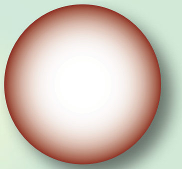




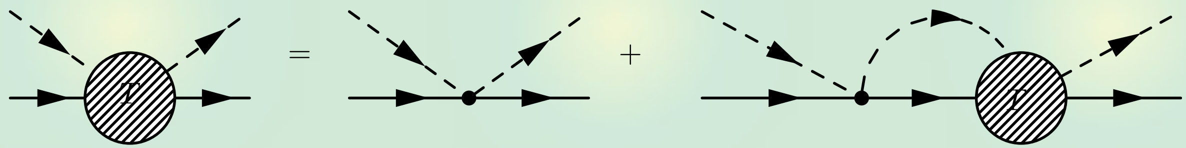
e.g.) J/Ψ in e^+e^-, ...

Chiral unitary approach

Description of meson-baryon scattering, s-wave resonances

- Interaction <-- chiral symmetry
- Amplitude <-- unitarity (coupled channel)

$$T = \frac{1}{V^{-1} - G}$$



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G ~ loop function : subtraction constant (cutoff)

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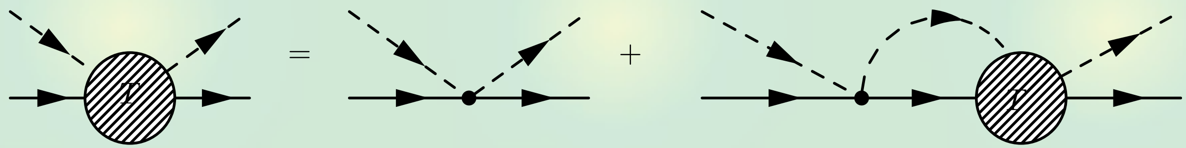

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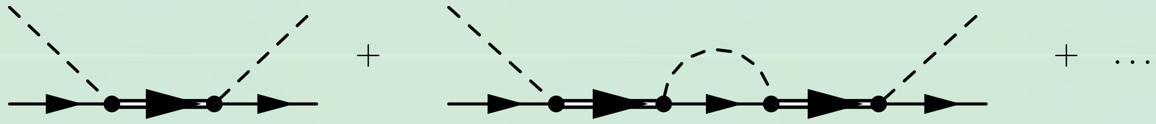
By construction, generated resonances are all dynamical? → **Not always...**

(Known) CDD pole in chiral unitary approach

Explicit resonance field in V (interaction)



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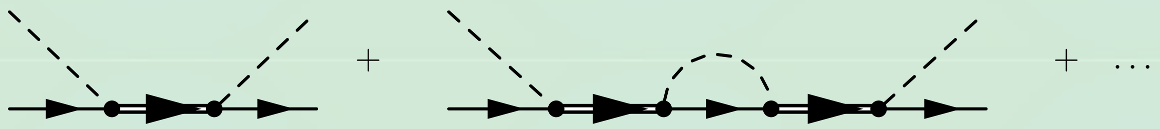

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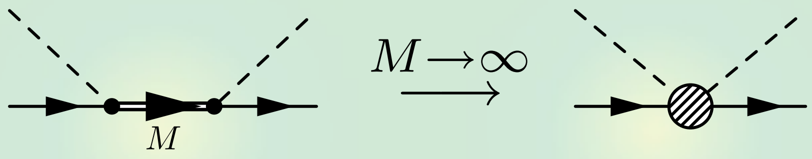

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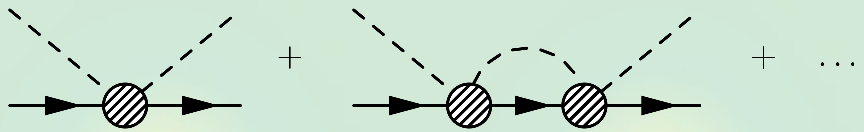

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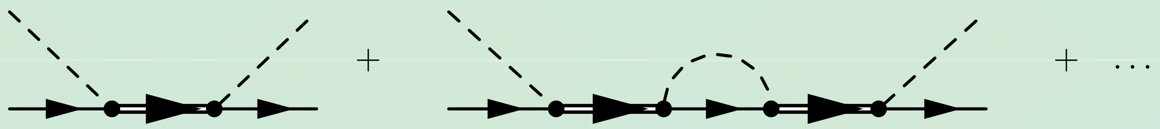

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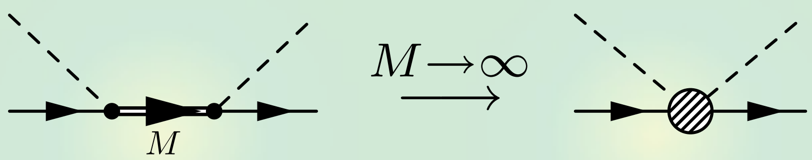

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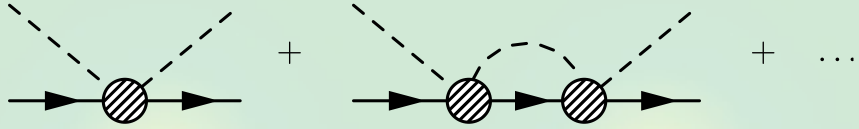

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Is that all? subtraction constant?

CDD pole in subtraction constant?

Phenomenological (standard) scheme

--> V is given, "a" is determined by data

$$T = \frac{1}{(V^{(1)})^{-1} - G(a)}$$

leading order

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next to leading order

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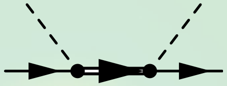
↑pole  **?**

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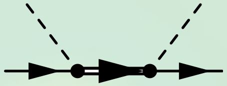
↑pole  **?**

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CDD pole contribution in G?

Natural renormalization scheme

--> fix "a" first, then determine V

to exclude CDD pole contribution from G,
based on theoretical argument.

Natural renormalization condition

Conditions for natural renormalization

- **Loop function G should be negative below threshold.**
- **T matches with V at low energy scale.**

"a" is uniquely determined such that

$$G(\sqrt{s} = M_T) = 0, \quad \Leftrightarrow \quad T(M_T) = V(M_T)$$

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We regard this condition as the exclusion of the CDD pole contribution from G.

Two renormalization schemes

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Same physics (scattering amplitude T)

$$T = \frac{1}{V_{\mathrm{ChPT}}^{-1} - G(a_{\mathrm{pheno}})} = \frac{1}{(V_{\mathrm{natural}})^{-1} - G(a_{\mathrm{natural}})}$$

↑Effective interaction
Origin of the resonance

Pole in the effective interaction

Leading order V : Weinberg-Tomozawa term

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Effective interaction in natural scheme

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There is always a pole for $a_{\mathrm{pheno}} \neq a_{\mathrm{natural}}$

- **small deviation <=> pole at irrelevant energy scale**
- **large deviation <=> pole at relevant energy scale**

Comparison of pole positions

Pole of the full amplitude : physical state

$$z_1^{\Lambda^*} = 1429 - 14i \text{ MeV}, \quad z_2^{\Lambda^*} = 1397 - 73i \text{ MeV}$$

$$z^{N^*} = 1493 - 31i \text{ MeV}$$

two poles for Λ(1405)

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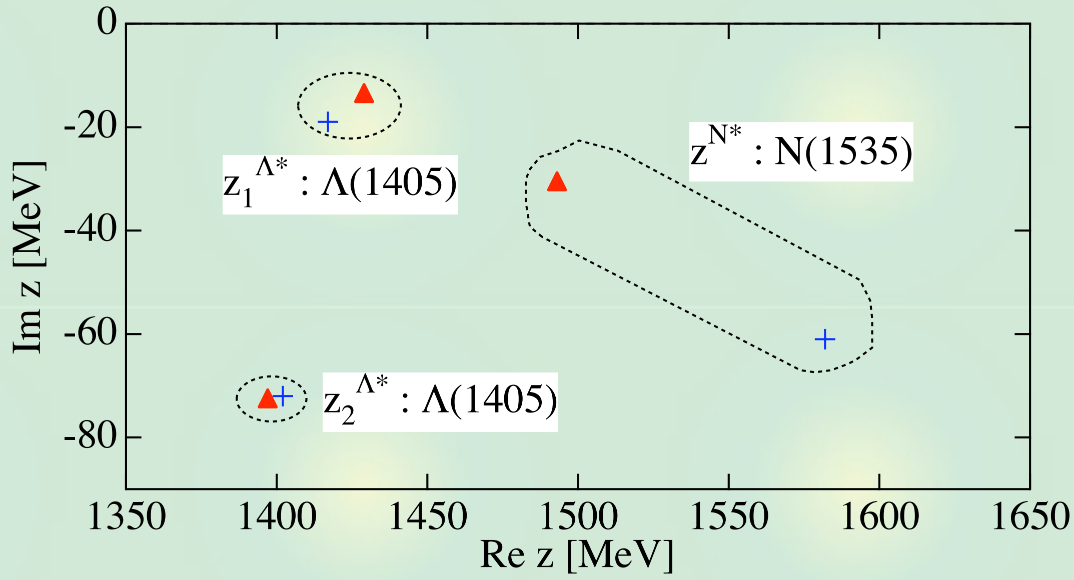

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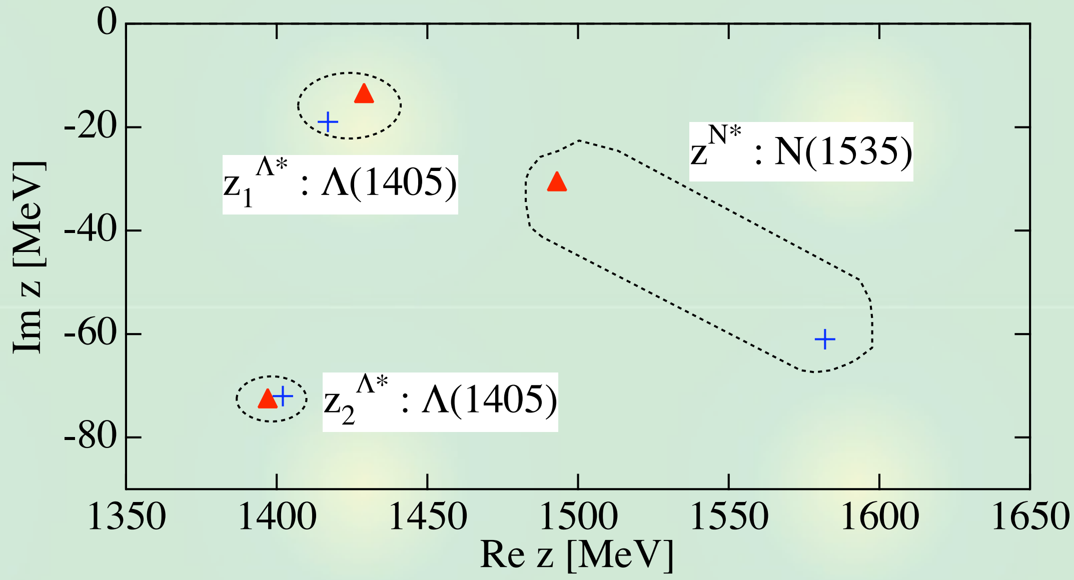

==> Λ(1405) is mostly dynamical state

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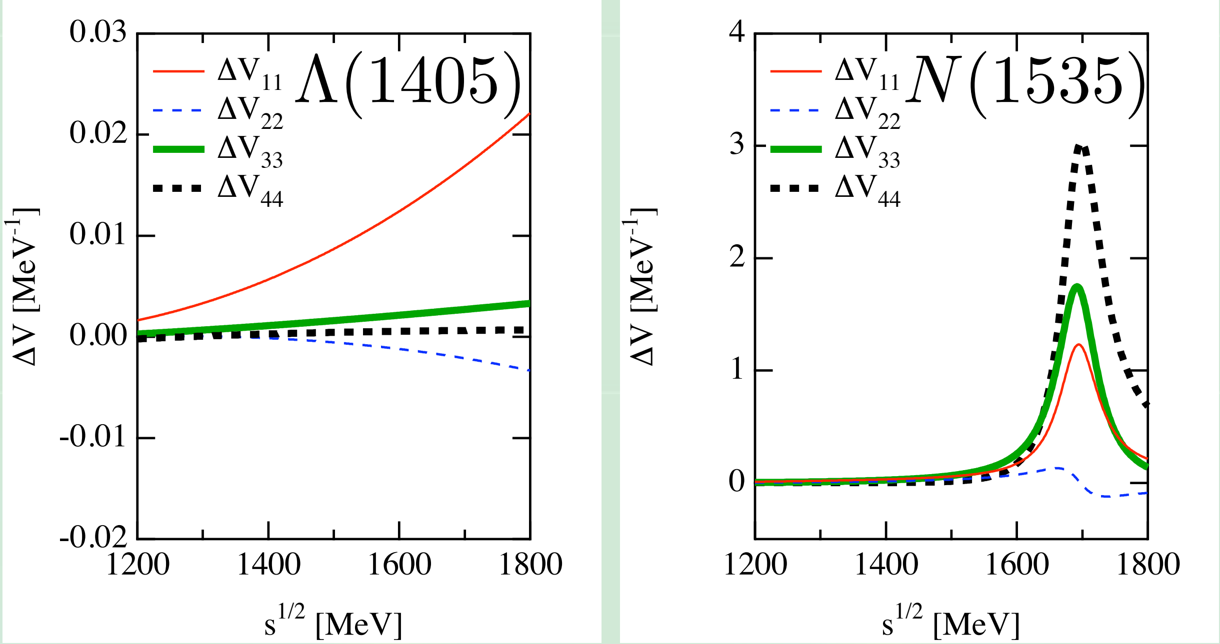

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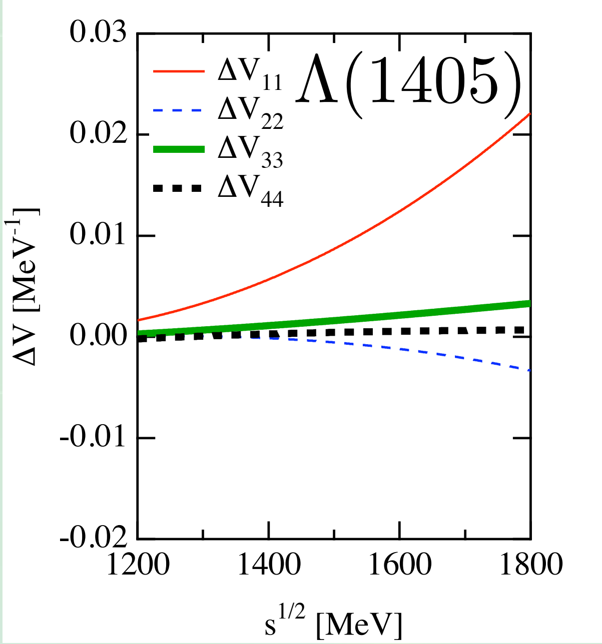
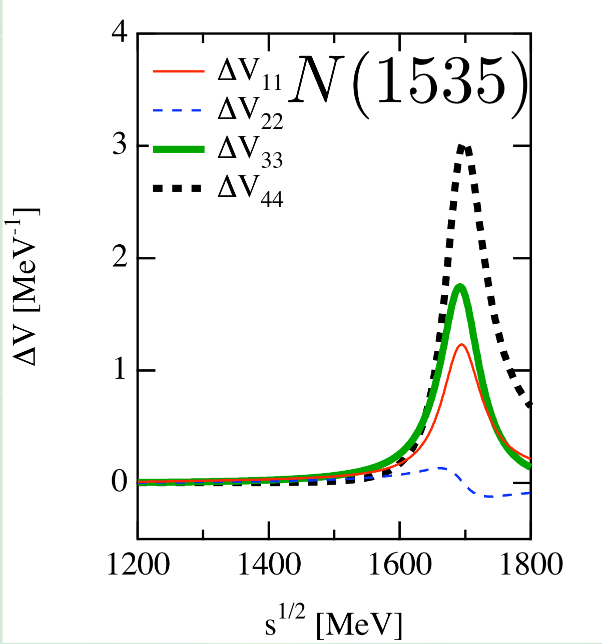




==> Important CDD pole contribution in N(1535)

Summary: formulation

We study the origin (dynamical/CDD) of the resonances in the chiral unitary approach

- Natural renormalization scheme

  Exclude CDD pole contribution from the loop function, consistent with N/D.

- Comparison with phenomenology --> Pole in the effective interaction

  We extract the CDD pole contribution hiddin in the subtraction constant into effective interaction V_{eff}.

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008)

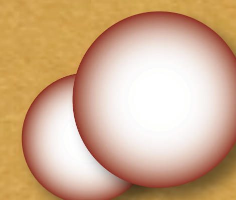
Summary: application to Λ(1405) and N(1535)

Structure of baryon resonances:

- Comparison of natural scheme with phenomenological scheme tells us about the structure of baryon resonance.
- Λ(1405) is mostly dynamical state.

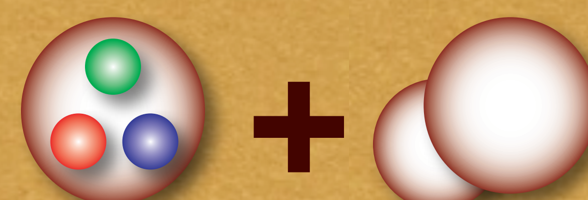
  : consistent with Nc scaling and em size.

  T. Hyodo, D. Jido, R. Loca, Phys. Rev. D77, 056010 (2008)
  R. Loca, T. Hyodo, D. Jido, Nucl. Phys. A809, 65 (2008)
  T. Sekihara, T. Hyodo, D. Jido, Phys. Lett. B669, 133 (2008)



- N(1535) requires CDD pole contribution.

  : a quark origin state?



Backup

Scattering theory : N/D method

Single-channel scattering, masses: M_T and m

G.F. Chew, S. Mandelstam, Phys. Rev. 119, 467 (1960)

$s = W^2$

Divide T into N(umerator) and D(inominator)

unitarity cut --> D, unphysical cut(s) --> N

phase space (optical theorem)

$$T(s) = N(s)/D(s)$$

$$\mathrm{Im}D(s) = \mathrm{Im}[T^{-1}(s)]N(s) = \boxed{\rho(s)}N(s)/2 \quad \text{for } s > s^+$$

$$\mathrm{Im}N(s) = \mathrm{Im}[T(s)]D(s) \quad \text{for } s < s^-$$

Dispersion relation for N and D

--> set of integral equations, input : $\mathrm{Im}[T(s)] \quad \text{for } s < s^-$

General form of the (s-wave) amplitude

Neglect unphysical cut (crossed diagrams), set N=1

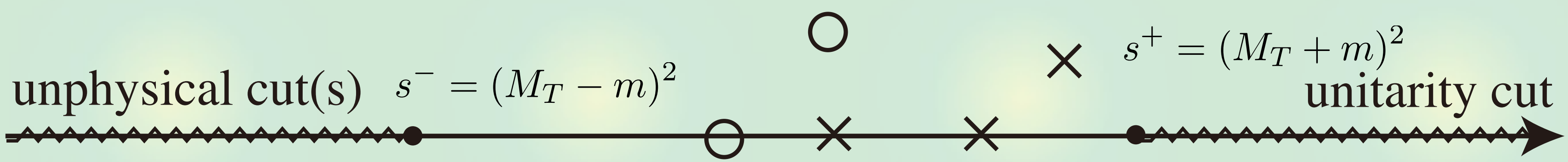
U. G. Meissner, J. A. Oller, Nucl. Phys. A673, 311 (2000)

$$T^{-1}(\sqrt{s}) = \boxed{\tilde{a}(s_0)} + \frac{s-s_0}{2\pi}\int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

subtraction constant, not determined

- **pole (and zero) of the amplitude**

L. Castillejo, R.H. Dalitz, F.J. Dyson, Phys. Rev. 101, 453 (1956)



CDD pole(s), R_i, W_i : not known in advance

$$T^{-1}(\sqrt{s}) = \boxed{\sum_i \frac{R_i}{\sqrt{s}-\sqrt{s_i}}} + \tilde{a}(s_0) + \frac{s-s_0}{2\pi}\int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

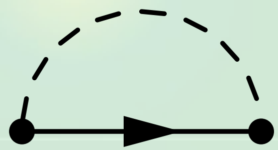
CDD pole contribution --> independent particle

G.F. Chew, S.C. Frautschi, Phys. Rev. 124, 264 (1961)

Order by order matching with ChPT

Identify loop function G, the rest contribution --> V^{-1}

$$T^{-1}(\sqrt{s}) = \sum_i \frac{R_i}{\sqrt{s}-\sqrt{s_i}} + \tilde{a}(s_0) + \frac{s-s_0}{2\pi}\int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

$-$ 

$$= -i\int \frac{d^4q}{(2\pi)^4}\frac{2M_T}{(P-q)^2-M_T^2+i\epsilon}\frac{1}{q^2-m^2+i\epsilon}\Big|_{\text{dim.reg.}}$$

$$= -\frac{2M_T}{(4\pi)^2}\left\{a + \frac{m^2-M_T^2+s}{2s}\ln\frac{m^2}{M_T^2} + \frac{\bar{q}}{\sqrt{s}}\ln\frac{\phi_{++}(s)\,\phi_{+-}(s)}{\phi_{-+}(s)\,\phi_{--}(s)}\right\}$$

$$= -G(\sqrt{s};a)$$

subtraction constant (cutoff)

$$T(\sqrt{s}) = [V^{-1}(\sqrt{s}) - G(\sqrt{s};a)]^{-1}$$

V? chiral expansion of T, (conceptual) matching with ChPT

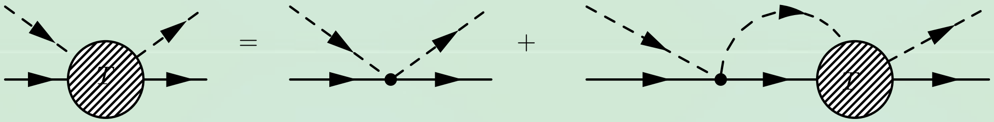
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001)

$$T^{(1)} = V^{(1)}, \quad T^{(2)} = V^{(2)}, \quad T^{(3)} = V^{(3)} - V^{(1)}GV^{(1)}, \dots$$

Summary of chiral unitary appraoch

Scattering amplitude T

$$T(\sqrt{s}) = \frac{1}{V^{-1}(\sqrt{s}) - G(\sqrt{s};a)}$$



$V(\sqrt{s})$: interaction (ChPT at given order)

$G(\sqrt{s};a)$: loop function

a : subtraction constant (cutoff parameter)

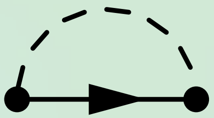
	ChPT	ChU
Unitarity	perturbative	exact
Dynamical resonance	×	○
Crossing symmetry	exact	(perturbative)
Chiral counting	○	×

Nonrenormalizable --> cutoff theory

CDD pole contribution --> V (interaction)

Loop function below threshold

Below threshold, G is real and NEGATIVE
(~ assume no states below threshold)

$$G(\sqrt{s}) =$$  $$\leq 0 \quad (\text{for } \sqrt{s} \leq M_T + m)$$

It is automatically satisfied in 3d cutoff. However, ...

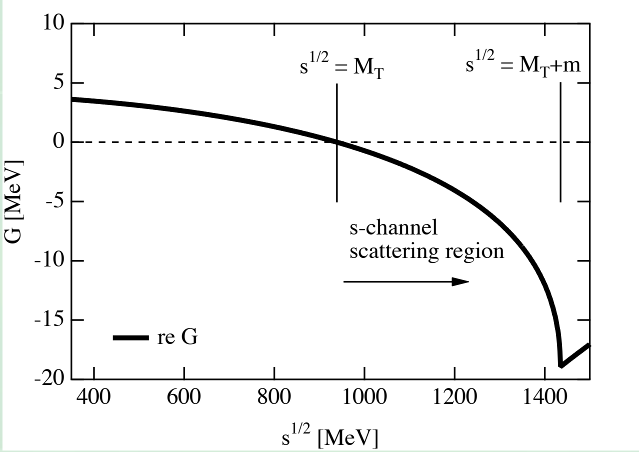
$$G(\sqrt{s}; a) = \frac{2M_T}{(4\pi)^2}\left\{ \underline{a} + \frac{m^2 - M_T^2 + s}{2s} \ln \frac{m^2}{M_T^2} + \frac{\bar{q}}{\sqrt{s}} \ln \frac{\phi_{++}(s)\,\phi_{+-}(s)}{\phi_{-+}(s)\,\phi_{--}(s)} \right\}$$

Large (positive) “a” can make G positive.
Avoid this for s-channel region (> M_T),

$$a \leq a_{\max}(M_T, m)$$

or equivalently
(G: decreasing),

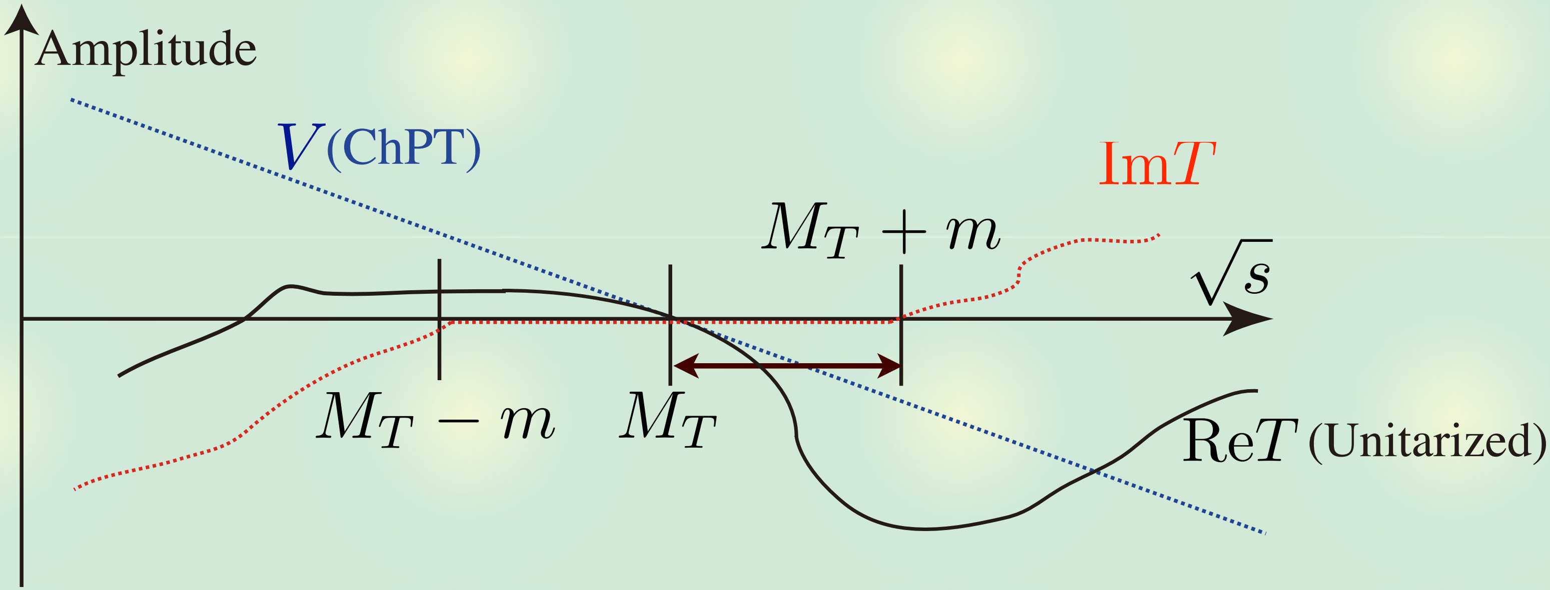
$$G(\sqrt{s} = M_T) \leq 0$$



(Explicit) matching with ChPT

V is given by ChPT.
At a "low energy", T should be matched with V:

$$G(\sqrt{s}=\mu_m)=0, \quad \Leftrightarrow \quad T(\mu_m)=V(\mu_m)$$



matching in s-channel region, subtraction constant is real

$$\Rightarrow \quad M_T \leq \mu_m \leq M_T + m$$

consistent with "low energy" requirement

$$\sqrt{s}=M_T+m \;\Rightarrow\; \boldsymbol{p}=0, \quad \sqrt{s}=M_T \;\Rightarrow\; \omega\sim 0$$

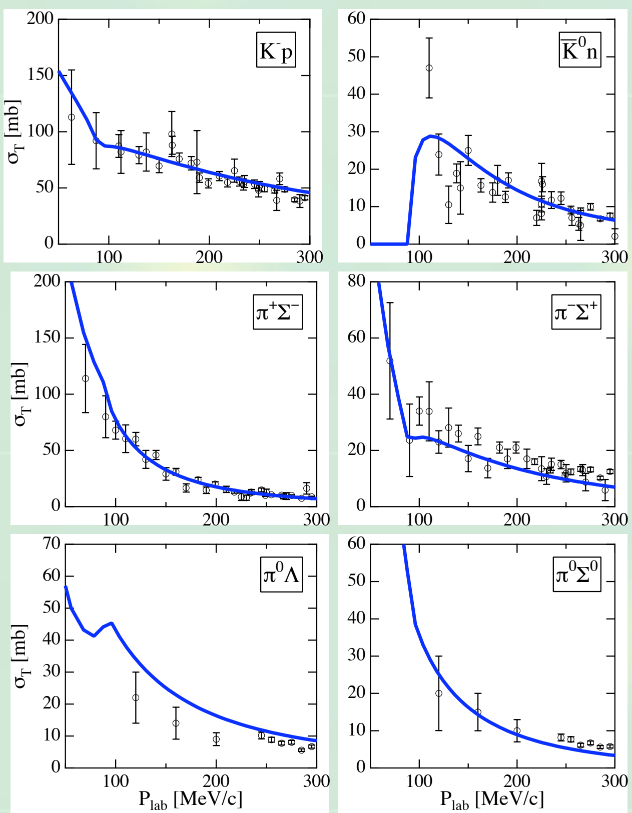
Application: Λ(1405) and N(1535)

S=-1 and S=0 meson-baryon scatterings

Models for the Meson-baryon scattering :

E. Oset, A. Ramos, C. Bennhold, Phys. Lett. B527, 99 (2002),
T. Inoue, E. Oset, M.J. Vicente Vacas, Phys. Rev. C. 65, 035204 (2002)
T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, Phys. Rev. C. 68, 018201 (2003)
T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, Prog. Thor. Phys. 112, 73 (2004)

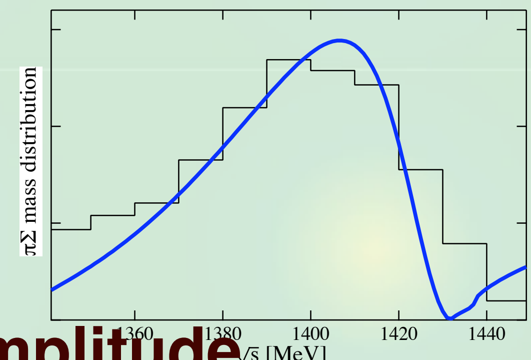
K-p total cross sections



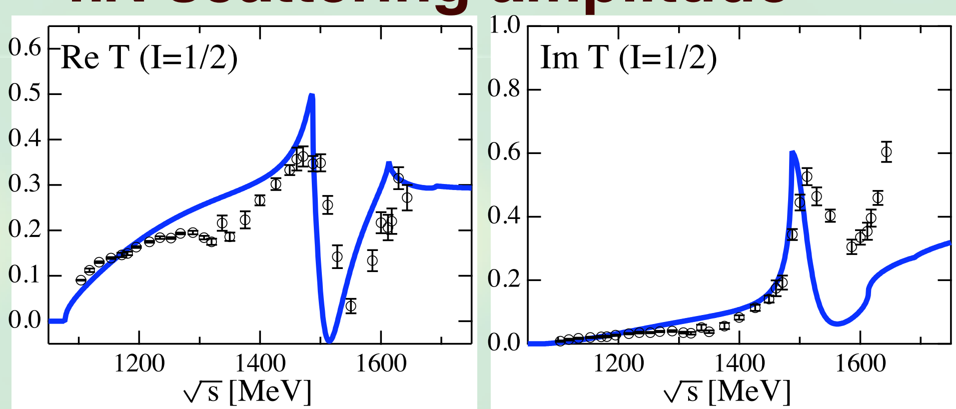
threshold ratios

	γ	R_c	R_n
exp.	2.36	0.664	0.189
theo.	1.80	0.624	0.225

πΣ spectrum



πN scattering amplitude



N(1535) coupling strengths

Residues of the pole --> coupling strengths

$$T_{ij}(\sqrt{s}) \sim \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2}$$

pole in	property	πN	ηN	KΛ	KΣ
full T	physical	0.949	1.64	1.45	2.96
$V_{natural}$	CDD	4.67	2.15	5.71	7.44
WT+natural	Dynamical	0.353	2.11	1.71	2.93

Coupling properties of the physical pole is similar with those of dynamical pole.

Dynamical nature (on top of CDD pole) is also important?