Quark mass dependence of light resonances and phase shifts in elastic $\pi\pi$ and πK scattering

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Hadron 2011, Munich
June 13-17, 2011

- Motivation
- Phase shifts M_π dependence in **Standard ChPT**
- Phase shifts M_π dependence in **Unitarized ChPT**
- Comparison of **ChPT and lattice** results
- **Light resonances** dependence on $\hat{m}$
- Summary

Motivation

Lattice: rigorous QCD results with quarks and gluons.
Growing interest in scattering and scalar sector.
Caveat: small, realistic quark masses are difficult to implement.

ChPT: QCD dependence on quark masses as an expansion.

We can compare:

Lattice multi-hadron states calculations $\rightarrow$ phase shifts and scattering lengths	vs.	standard ChPT (model independent) or UChPT (to go higher in $\sqrt{s}$)
Lattice spectrum calculations $\rightarrow$ masses	vs.	UChPT

Standard Chiral Perturbation Theory

Chiral Perturbation Theory Weinberg, Gasser & Leutwyler

Low energy effective theory of QCD with:

- DOF: Pseudo-Goldstone Bosons of the spontaneous chiral symmetry breaking

$$SU(N_f)_L \times SU(N_f)_R \rightarrow SU(N_f)_V$$

  N_f=2 $\rightarrow$ π's
  N_f=3 $\rightarrow$ π's, K's and η

- expansion in masses and momenta

$$\mathcal{L}_{\rm eff} = \mathcal{L}_2 + \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

- parameters: Low Energy Constants (LECs)
  N_f=2 $\rightarrow$ 4 l's (one loop) and 7 r's (two loops)
  N_f=3 $\rightarrow$ 8 L's (one loop)

$\pi\pi$ scattering in SU(2) standard ChPT:

- Already calculated to 1 and 2 loops*, we study the phases dependence on $\hat{m} = \frac{m_u + m_d}{2}$.
- Advantages:
  - SISTEMATIC EXPANSION, MODEL INDEPENDENT
  - some lattice groups already giving results for I=2 phases and scattering lenghts**
- Limitations:
  - only low energy region
  - no resonances.

*J. Bijnens, G. Colangelo, G. Ecker, J. Gasser and M. E. Sainio, Phys. Lett. B **374**, 210 (1996)

** K. Sasaki and N. Ishizuka, Phys. Rev. D **78**, 014511 (2008)

Standard $SU(2)$ ChPT amplitudes with LECs from

G. Colangelo, J. Gasser and H. Leutwyler, Nucl. Phys. B **603**, 125 (2001)

$O(p^4)$ LECs ($\times 10^{-3}$)		$O(p^6)$ LECs($\times 10^{-4}$)	
l_1^r	-3.98 $\pm$ 0.62	r_1^r	-0.60
l_2^r	1.89 $\pm$ 0.23	r_2^r	1.28
l_3	0.82 $\pm$ -3.80	r_3^r	-1.68
l_4^r	6.17 $\pm$ 1.39	r_4^r	-1.00
		r_5^r	1.52 $\pm$ 0.42
		r_6^r	0.40 $\pm$ 0.04

Statistical error, not systematic

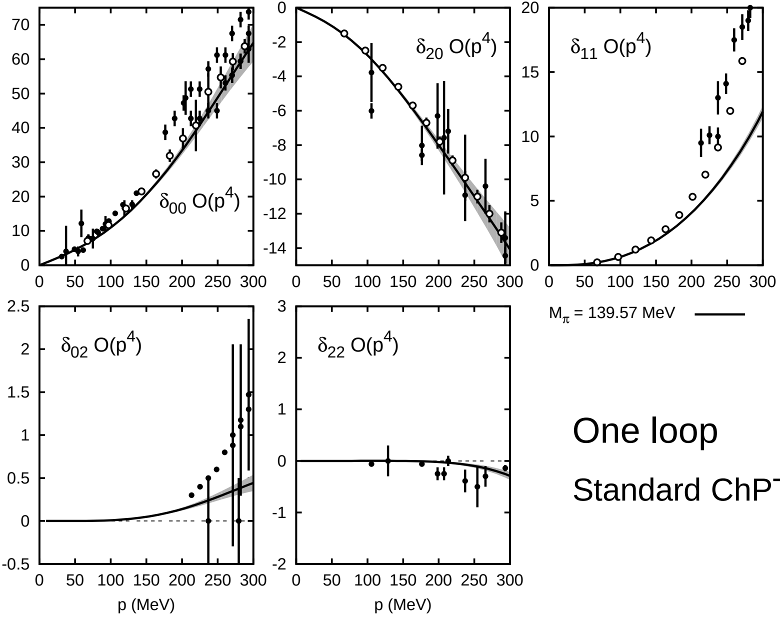
Change $\hat{m}$ $\Rightarrow$ change on $M_\pi^2 = 2\hat{m}B_0$ $\Rightarrow$ change on f_π

(one more $O(p^6)$ parameter: $r_f^r \approx 0 \pm 1.2 \times 10^{-4}$)

Uncertainties in phase shifts: Montecarlo Gaussian Sampling.

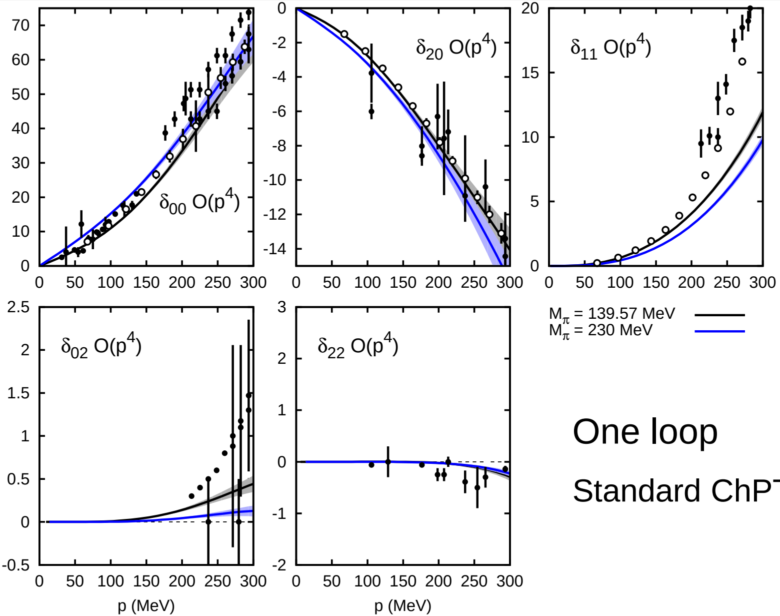
Phase shifts vs. Momentum, increasing M_π

Phases vs. energy $\rightarrow \hat{m}$ dependence from the threshold's shift.
Better to plot phases vs. momentum.



One loop

Standard ChPT



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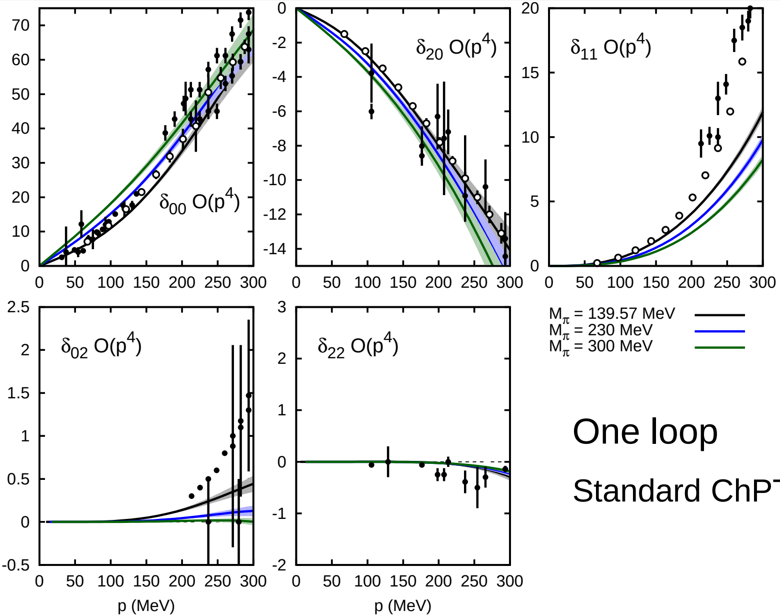

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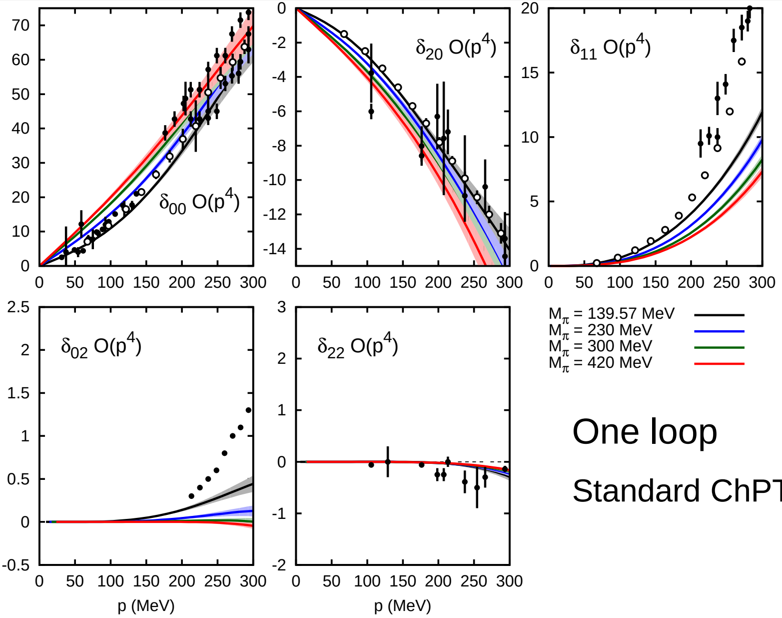

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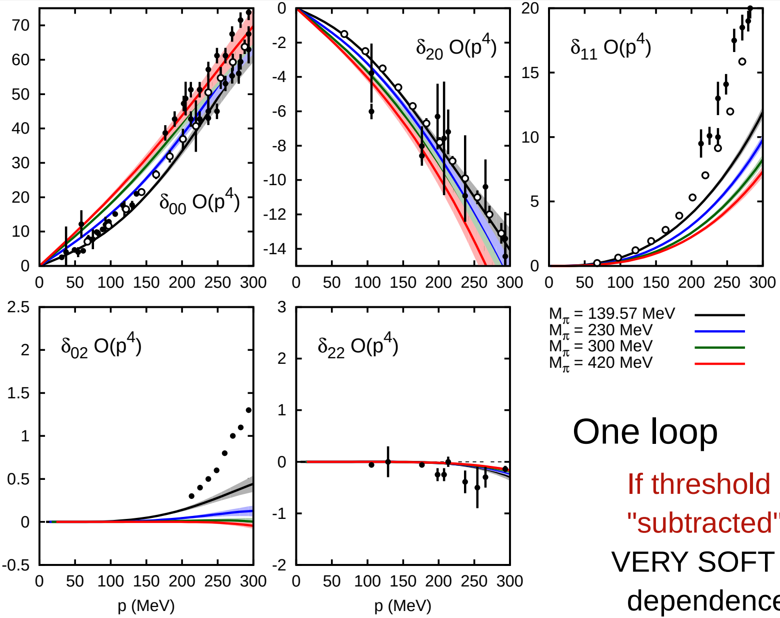
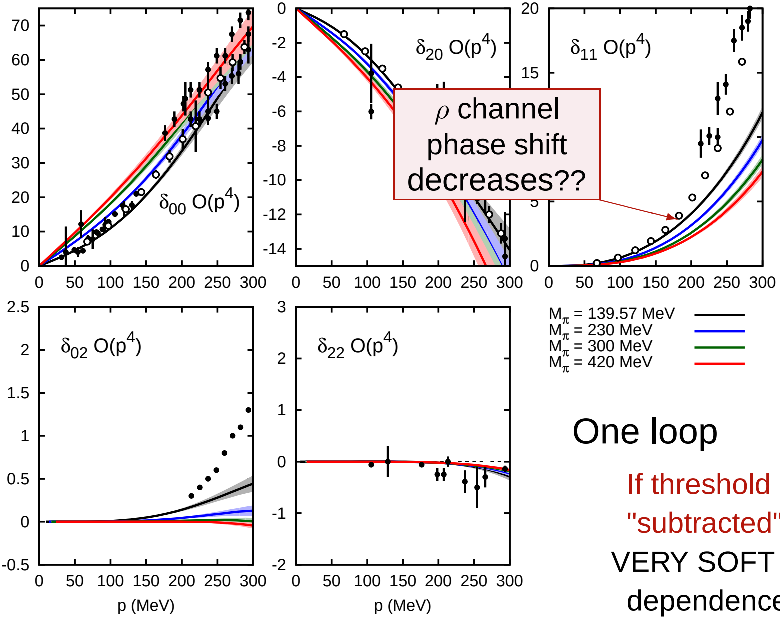


One loop

If threshold is "subtracted": VERY SOFT M_π dependence!



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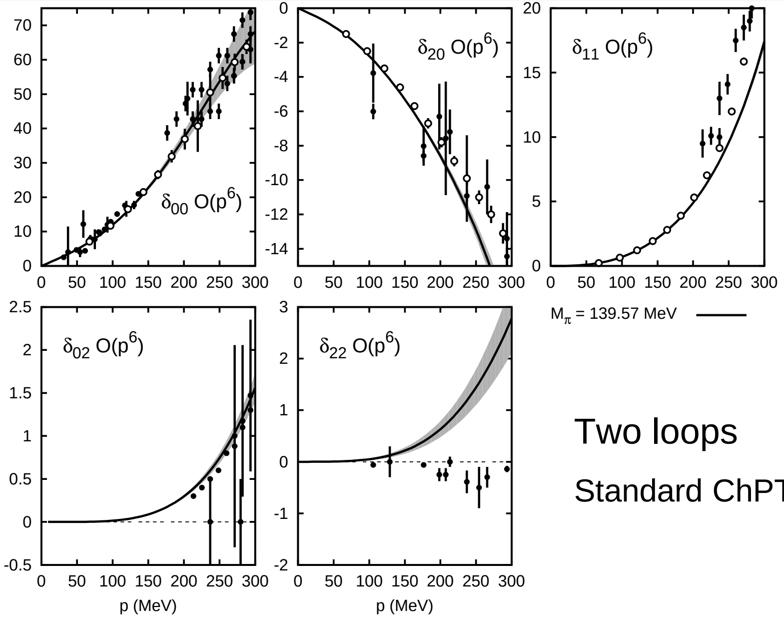
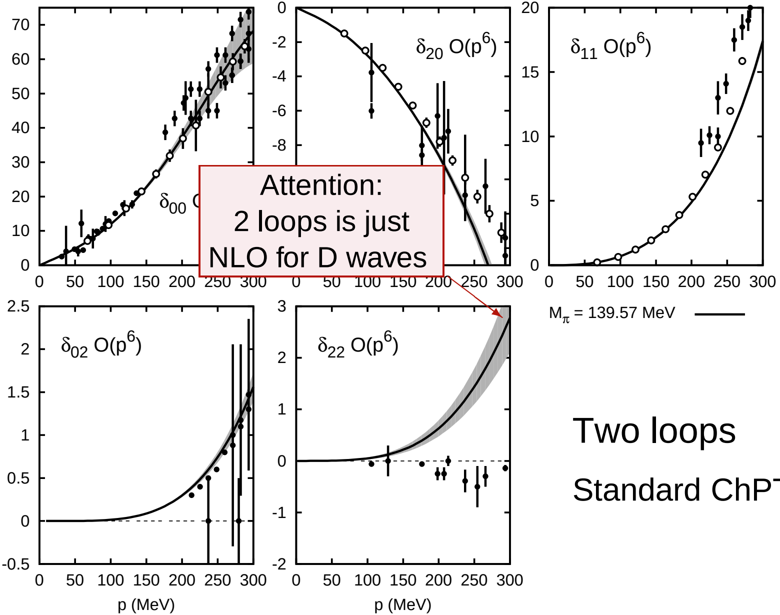


Two loops

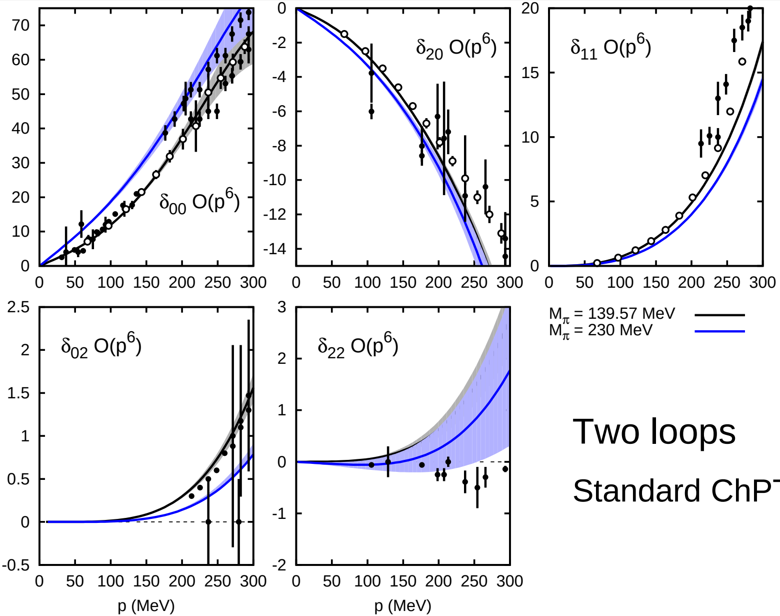
Standard ChPT



Attention:
2 loops is just
NLO for D waves

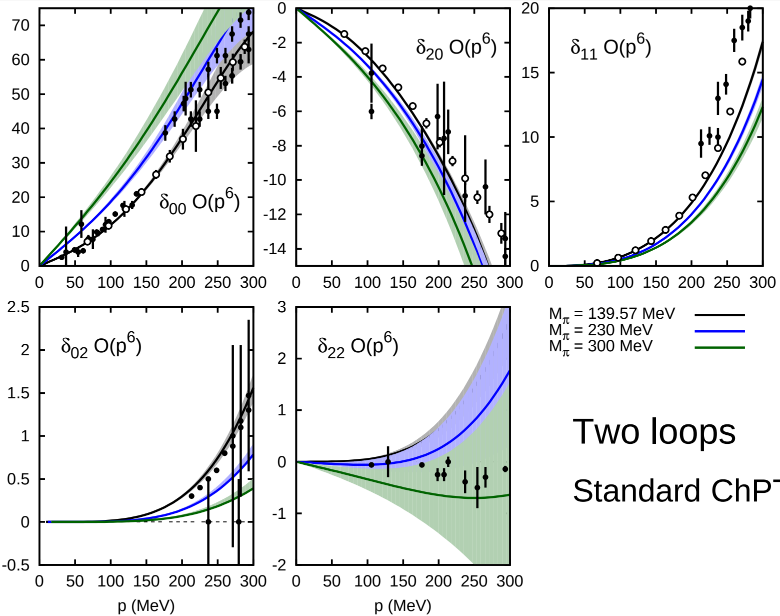
Two loops

Standard ChPT



Two loops

Standard ChPT



Two loops

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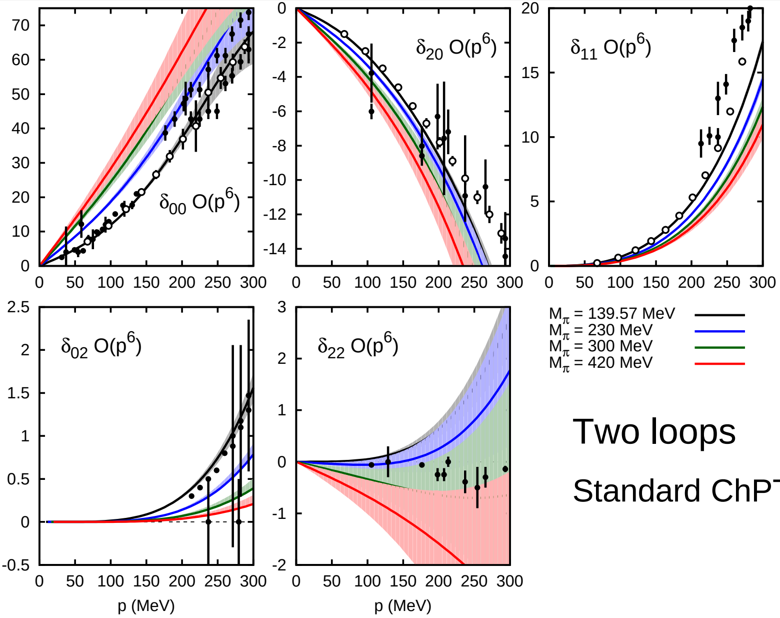

Two loops

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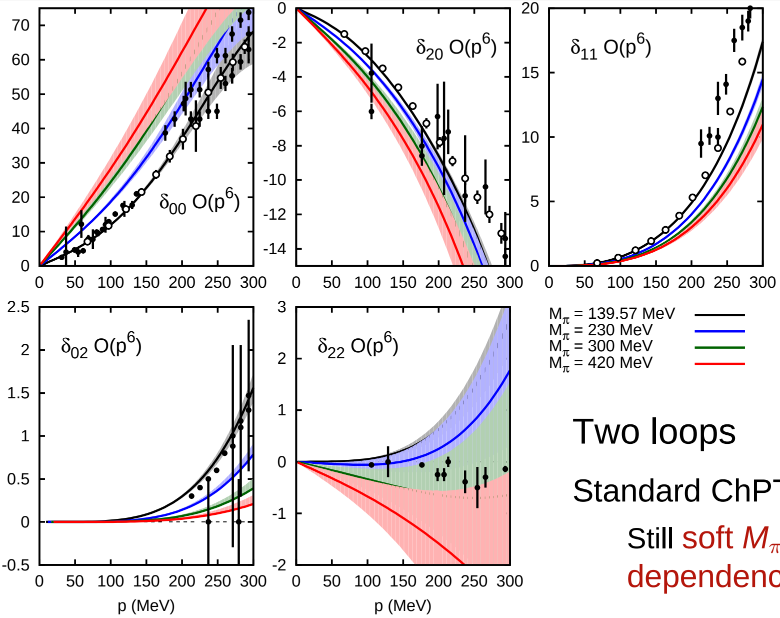
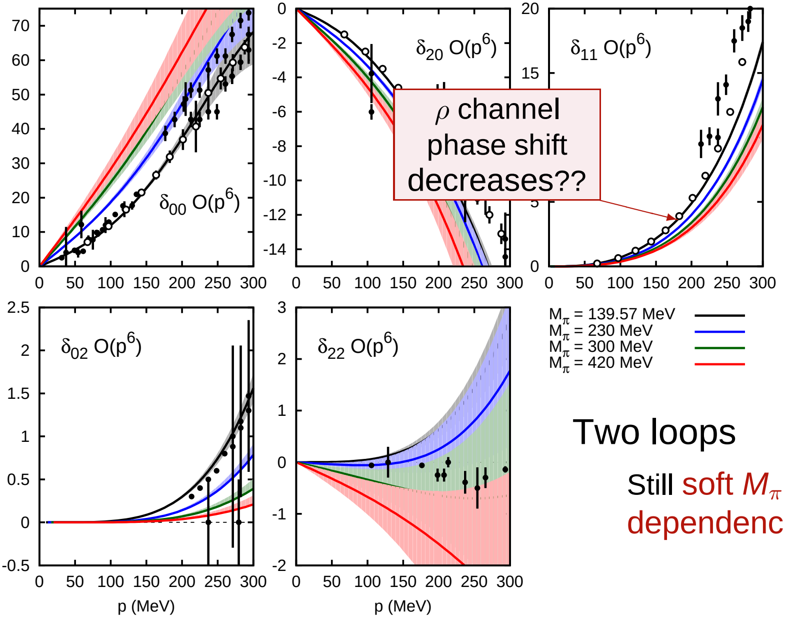


Two loops

Standard ChPT

Still soft M_π dependence



Two loops

Still soft M_π dependence

Unitarized ChPT

Inverse Amplitude Method Truong, Dobado, Herrero, Peláez

Elastic IAM partial waves satisfy exact unitarity

$$\mathbf{S}\mathbf{S}^\dagger = 1 \Rightarrow \text{Im}\, t^{-1} = -\sigma$$

$O(p^4)$ IAM partial waves:

$$t(s) \simeq \frac{t_2^2(s)}{t_2(s) - t_4(s)}$$

It is derived from a dispersion relation:

- exact on the elastic right cut,
- left cut and substraction constants approximated within NLO ChPT,
- fully renormalized,
- no spurious parameters.

Inverse Amplitude Method Truong, Dobado, Herrero, Peláez

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$O(p^6)$ IAM partial waves:

$$t(s) \simeq \frac{t_2^2(s)}{t_2(s) - t_4(s) + \frac{{t_4}^2}{t_2} - t_6}$$

It is derived from a dispersion relation:

- exact on the elastic right cut,
- left cut and substraction constants approximated within NLO ChPT,
- fully renormalized,
- no spurious parameters.

SU(2) Unitarized ChPT phase shifts vs. Momentum

Unitarized SU(2) ChPT amplitudes with LECs:

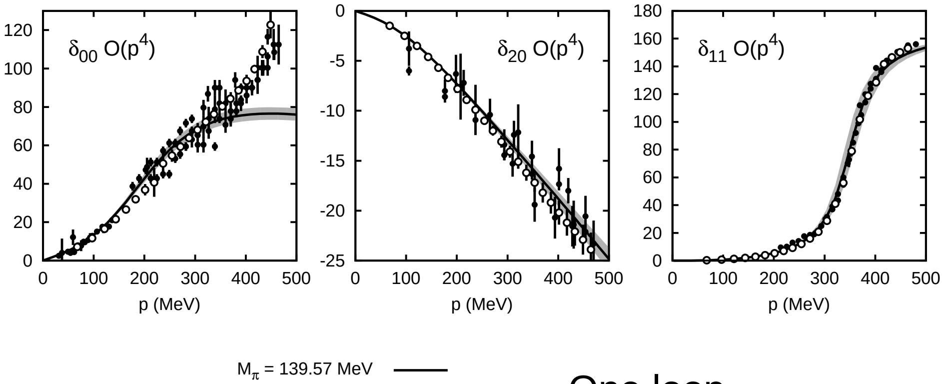
One loop

$O(p^4)$ LECs ($\times 10^{-3}$)	
$l_1^r(\mu)$	-3.7 ± 0.2
$l_2^r(\mu)$	5.0 ± 0.4
$l_3^r(\mu)$	0.8 ± 3.8
$l_4^r(\mu)$	6.2 ± 5.7

Two loops

	Set A	Set D
$O(p^4)$(x10^{-3})		
$l_1^r(\mu)$	-5.0	-4.0
$l_2^r(\mu)$	1.7	1.2
$l_3^r(\mu)$	0.8	0.8
$l_4^r(\mu)$	6.5	6.5
$O(p^6)$(x10^{-4})		
$r_1^r(\mu)$	-0.6	-0.6
$r_2^r(\mu)$	1.3	1.5
$r_3^r(\mu)$	-1.7	-3.3
$r_4^r(\mu)$	2.0	0.9
$r_5^r(\mu)$	2.0	1.7
$r_6^r(\mu)$	-0.6	-0.7
$r_f^r(\mu)$	-1.4	-1.8

Unitarized ChPT



One loop

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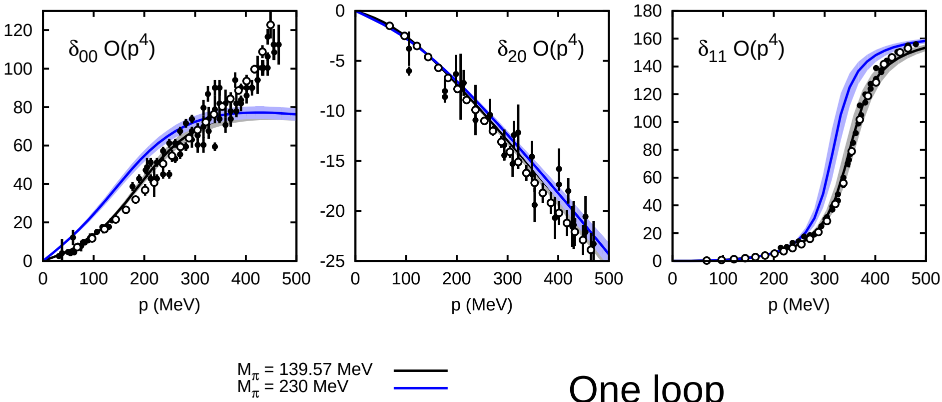

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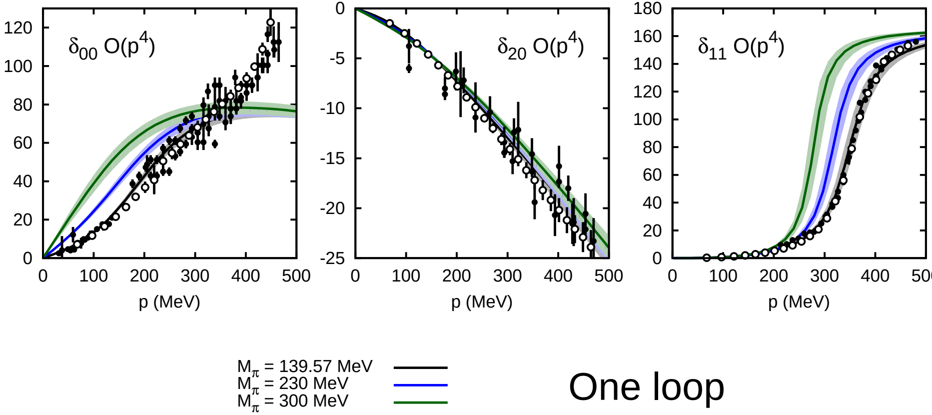

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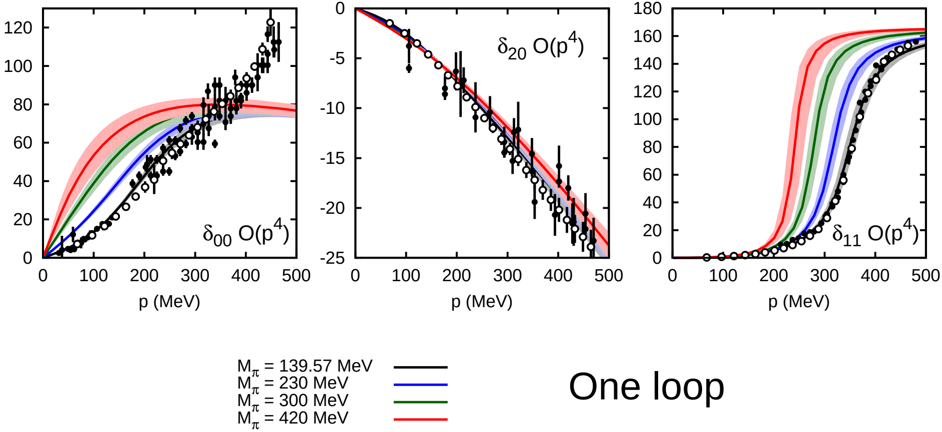
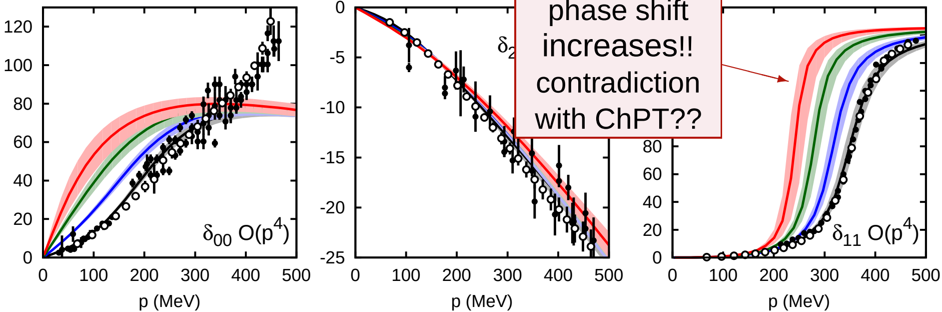


One loop

Unitarized ChPT

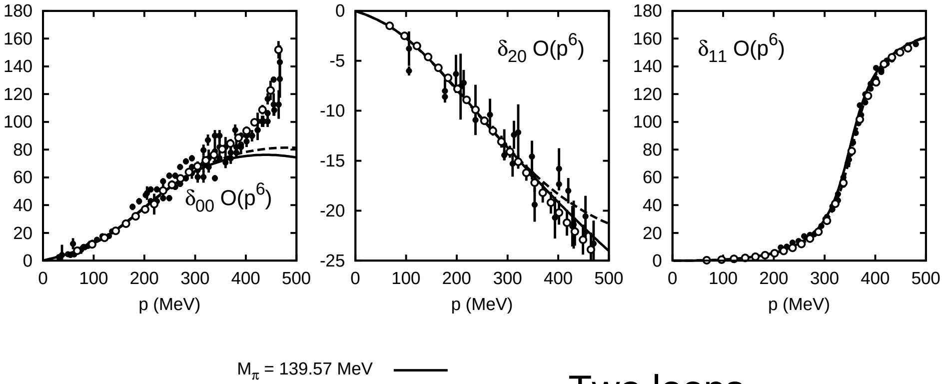
ρ channel phase shift increases!! contradiction with ChPT??



M_π = 139.57 MeV
M_π = 230 MeV
M_π = 300 MeV
M_π = 420 MeV

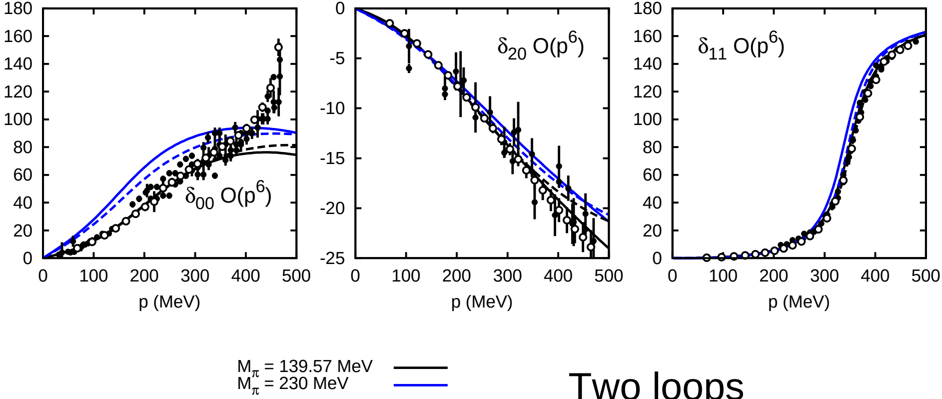
One loop

Unitarized ChPT



Two loops

Unitarized ChPT



Two loops

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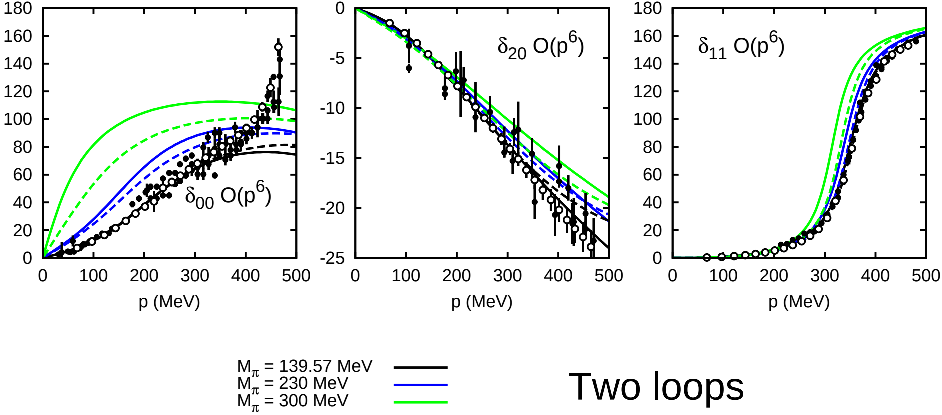

Two loops

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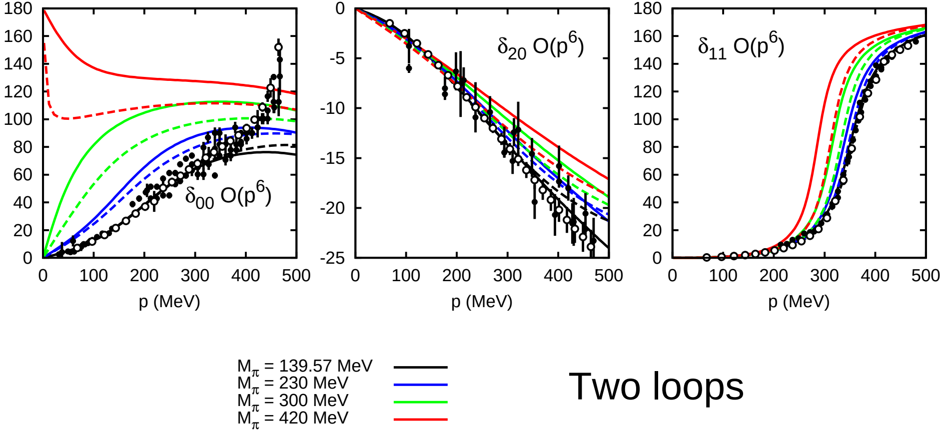
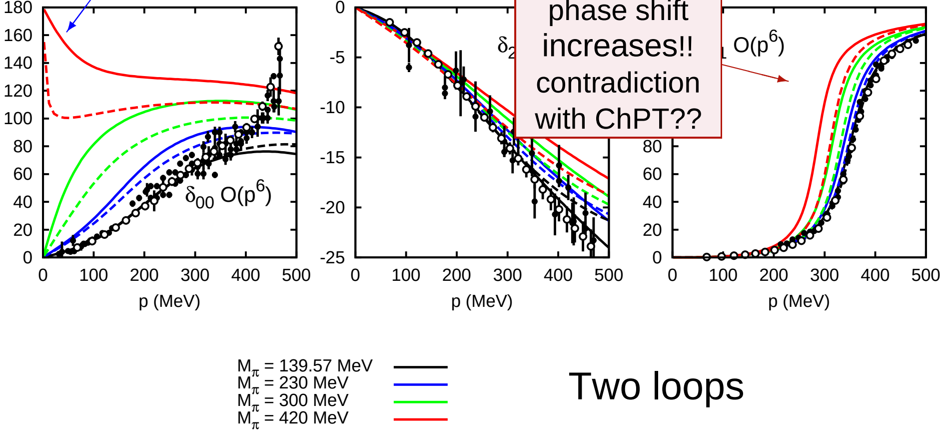


Two loops

Bound state: phase jumps 2π
(Levinson's theorem)

ρ channel phase shift increases!! contradiction with ChPT??



Two loops

Crude, intuitive model of I=1 J=1 channel behavior

For a simple Breit-Wigner parametrization:

$$t(s) = \frac{-\sqrt{s} M\,\Gamma(p)/2p}{s - M^2 + iM\Gamma(p)} \qquad \text{with} \qquad \Gamma(p) = \Gamma_R \left(\frac{p}{p_R}\right)^3$$

we get a positive phase shift derivative:

$$\frac{\partial\delta(p)}{\partial(M_\pi^2)} = -\frac{\partial\delta(p)}{\partial(p_R^2)} = \frac{4M\Gamma(p)}{\left(4p^2 - 4p_R^2\right)^2 + M^2\Gamma(p)^2} > 0.$$

The phase shift grows as the ρ approaches threshold.

Intuitive behavior but opposed to ChPT at low momentum.

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Introducing Blatt-Weisskopf modification:

$$\Gamma(p) = \Gamma_R \left(\frac{p}{p_R}\right)^{2l+1} \frac{D_l(p_R r)}{D_l(pr)} \equiv \tilde{\Gamma}(p)\frac{D_l(p_R r)}{D_l(pr)}$$

the phase shift derivative is given by:

$$\frac{\partial \delta(p)}{\partial (M_\pi^2)} \simeq \frac{1 + p_R^4 (r^2)'}{4 p_R^4} M \tilde{\Gamma}(p)$$

Estimation of r^2 matching LO ChPT at low p:

$$r^2 = \frac{1}{g^2 f_\pi^2} \frac{M}{M_\pi} + O(M_\pi^0) \Rightarrow 1 + p_R^4 (r^2)' = 1 - \frac{M\, p_R^4}{2 g^2 f_\pi^2 M_\pi^3} < 0$$

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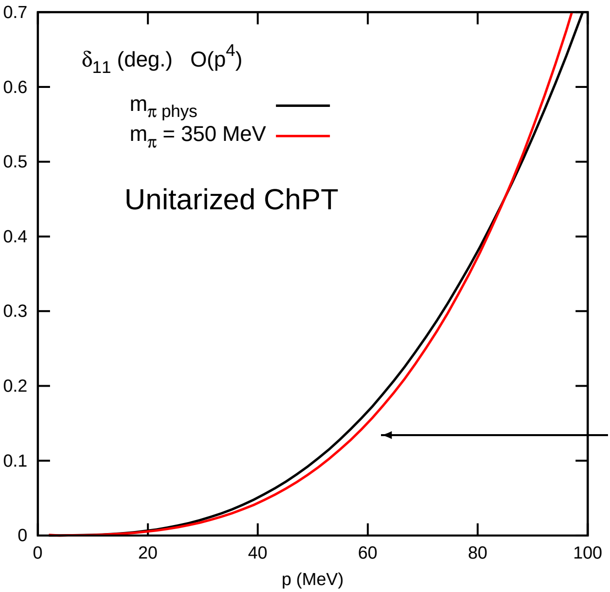
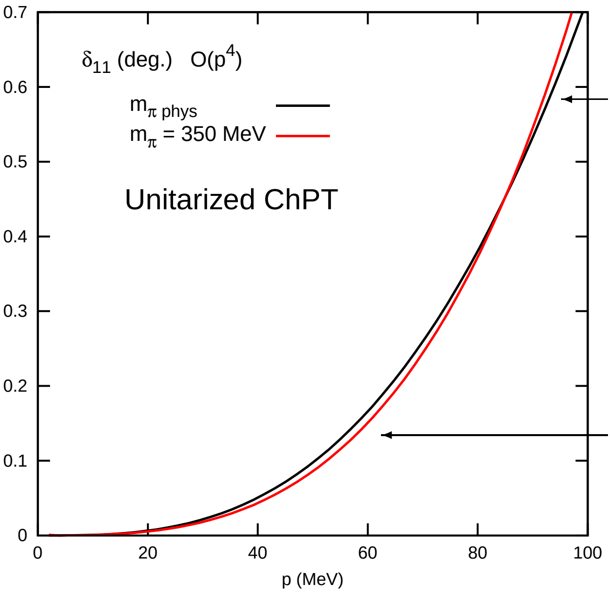
The phase shift goes down for low p and near $M_\pi = M_\pi^{phys}$

Agreement with standard and unitarized ChPT.



At low *p* the phase shift **decreases** as in standard ChPT



However at higher *p* the phase shift **grows**

At low *p* the phase shift **decreases** as in standard ChPT

Standard and unitarized ChPT phase shifts vs. lattice results

ChPT

J. Nebreda, J.R. Peláez and G. Ríos, Phys. Rev. D 83: 094011(2011)

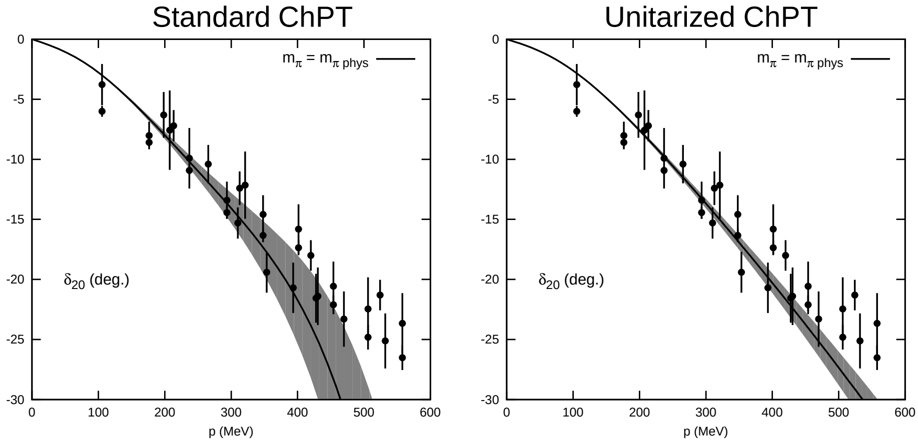
Lattice

J. Dudek et al., Phys.Rev. D 83: 071504 (2011)

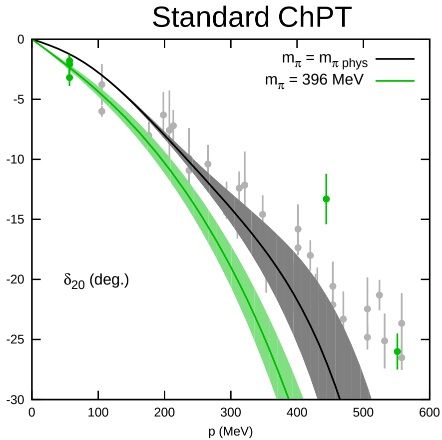
K. Sasaki and N. Ishizuka, Phys. Rev. D 78, 014511 (2008)

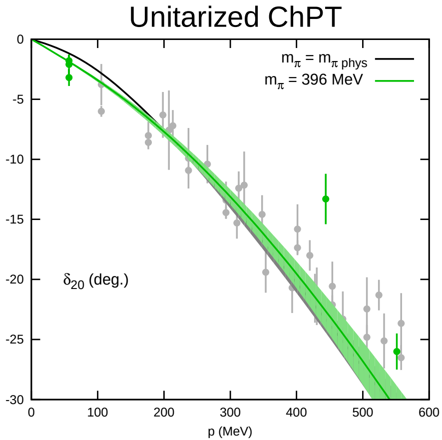
Scalar I=2 wave - one loop

I=2 J=0 phase shift at one loop M_π=139.57 MeV

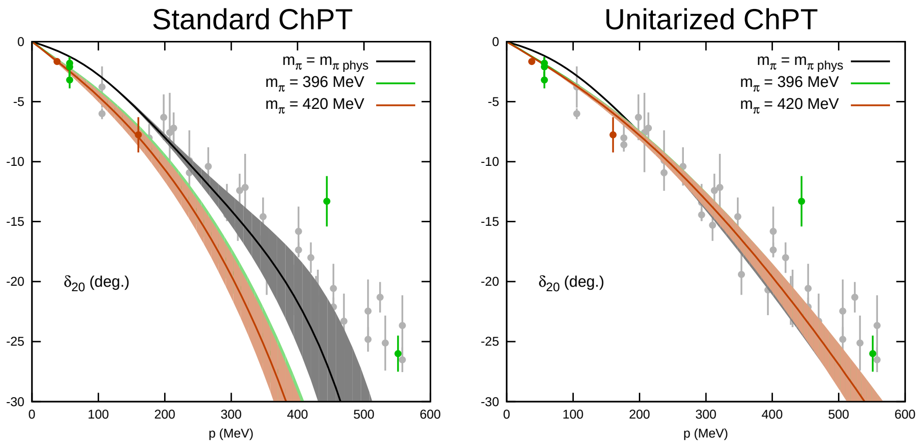


I=2 J=0 phase shift at one loop M_π=396 MeV

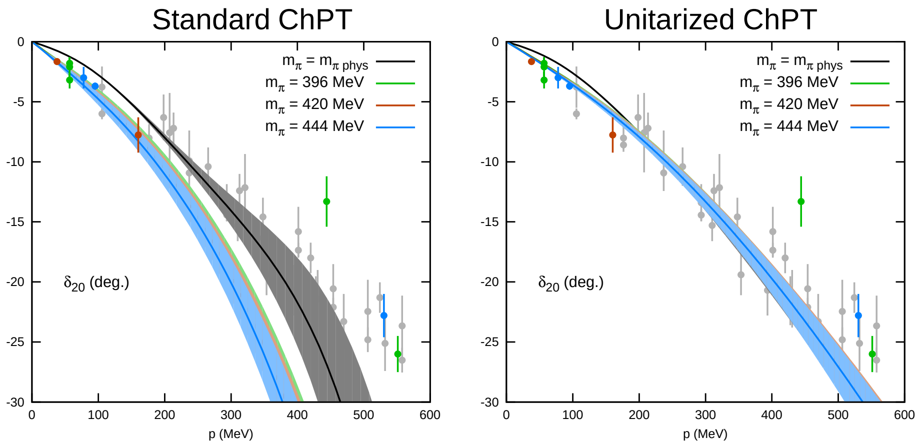




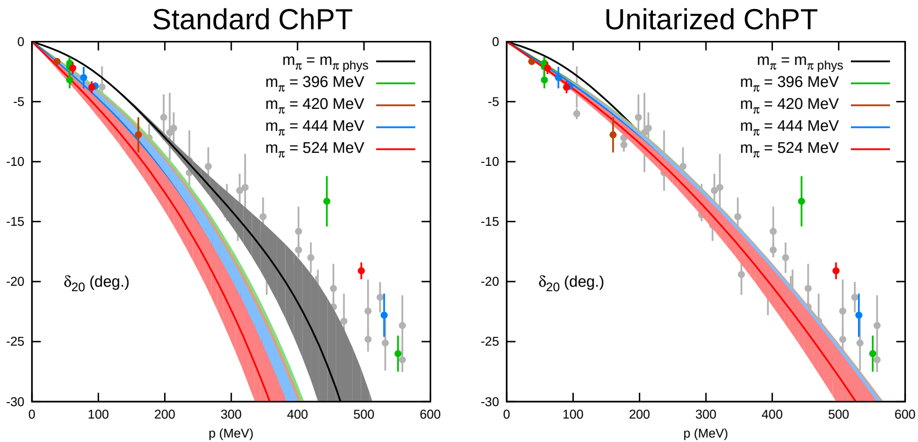
I=2 J=0 phase shift at one loop M_π=420 MeV



I=2 J=0 phase shift at one loop M_π=444 MeV

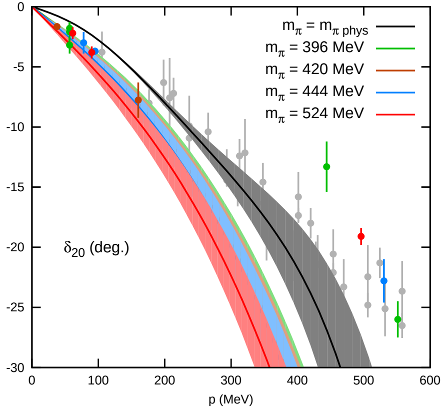


I=2 J=0 phase shift at one loop M_π=524 MeV



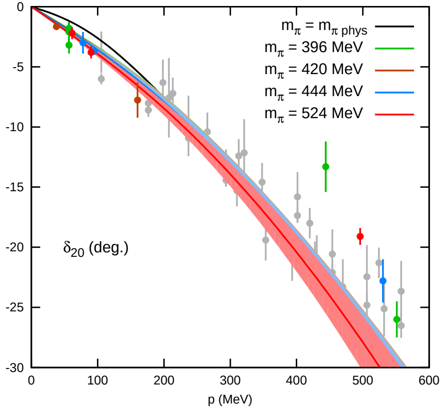
I=2 J=0 phase shift at one loop M_π=524 MeV

Standard ChPT



- Limited to very low momenta

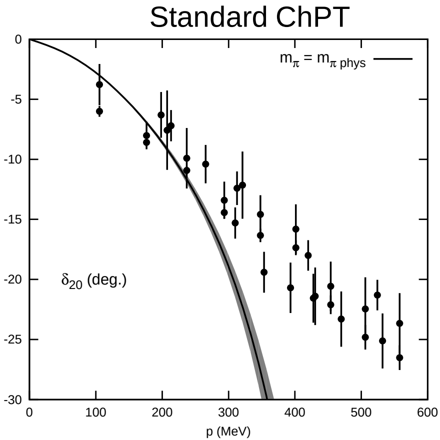
Unitarized ChPT

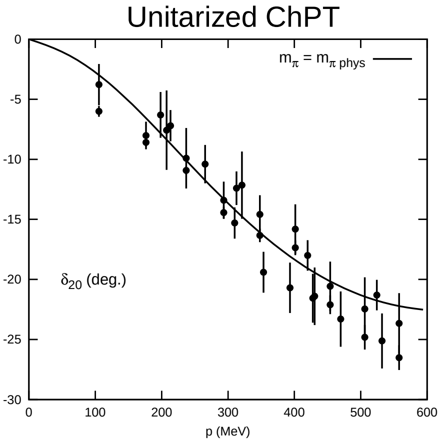


- Improves behavior at higher momenta

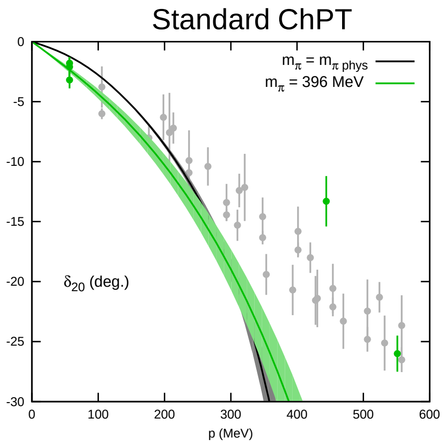
Scalar I=2 wave - two loops

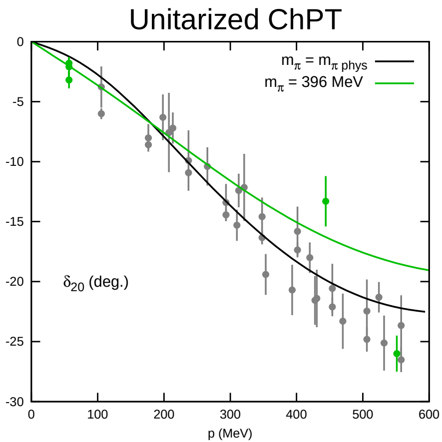
I=2 J=0 phase shift at two loops M_π=139.57 MeV



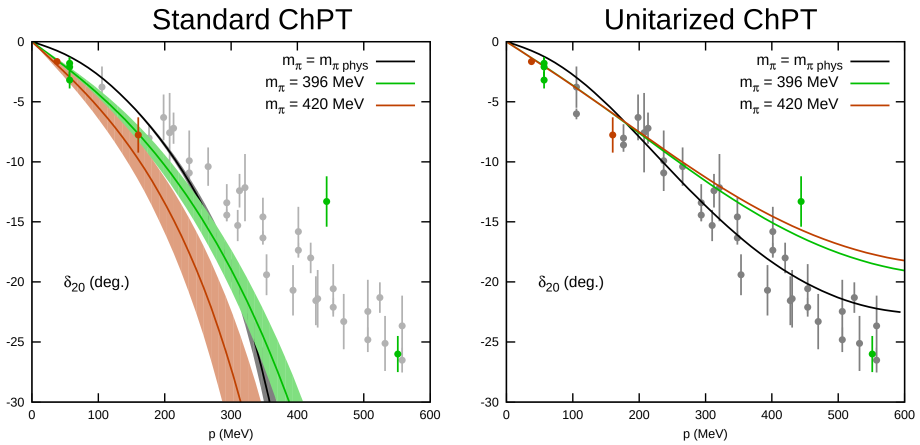


I=2 J=0 phase shift at two loops M_π=396 MeV

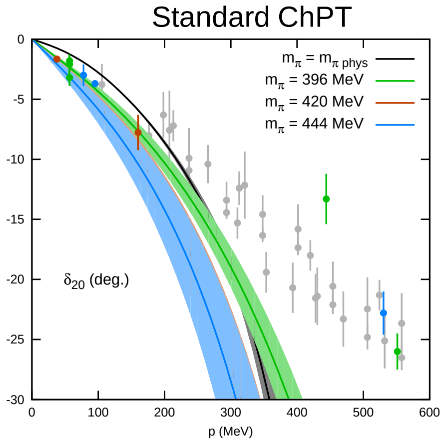


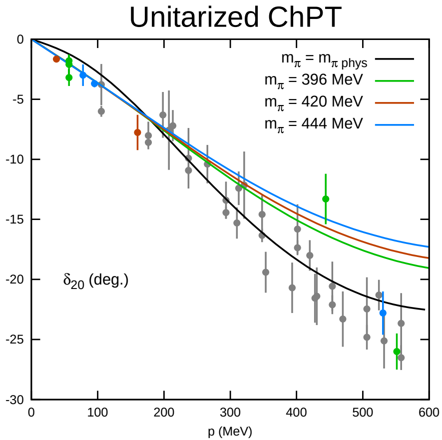


I=2 J=0 phase shift at two loops M_π=420 MeV

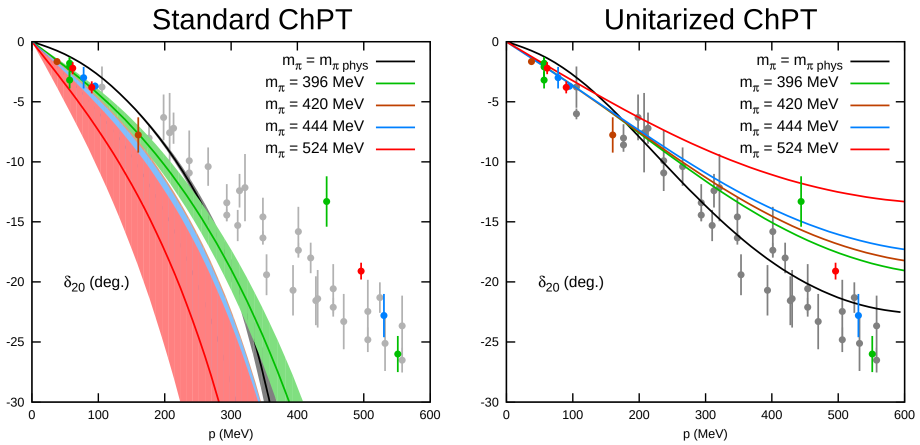


I=2 J=0 phase shift at two loops M_π=444 MeV



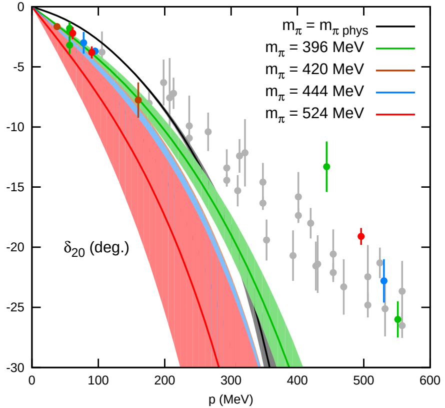


I=2 J=0 phase shift at two loops M_π=524 MeV



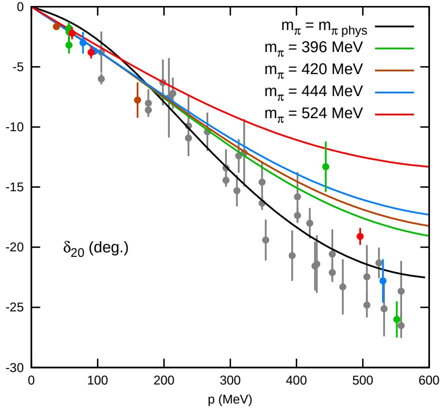
I=2 J=0 phase shift at two loops M_π=524 MeV

Standard ChPT



- Bends down faster than 1 loop
- No improvement

Unitarized ChPT



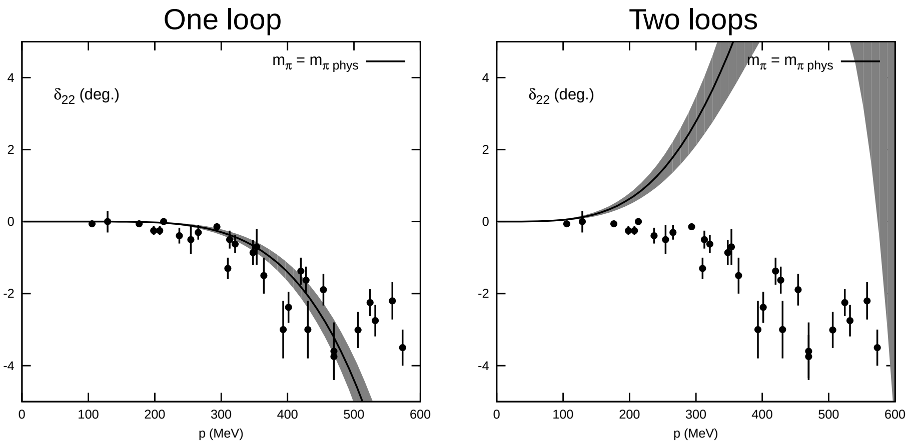
- Works better than Standard ChPT at high *p*
- No clear improvement either

Tensor I=2 wave

D waves are zero at tree level:

- IAM cannot be applied at one or two loops
- one and two-loops amplitudes are only LO and NLO

I=2 J=2 phase shift in standard ChPT M_π=139.57 MeV



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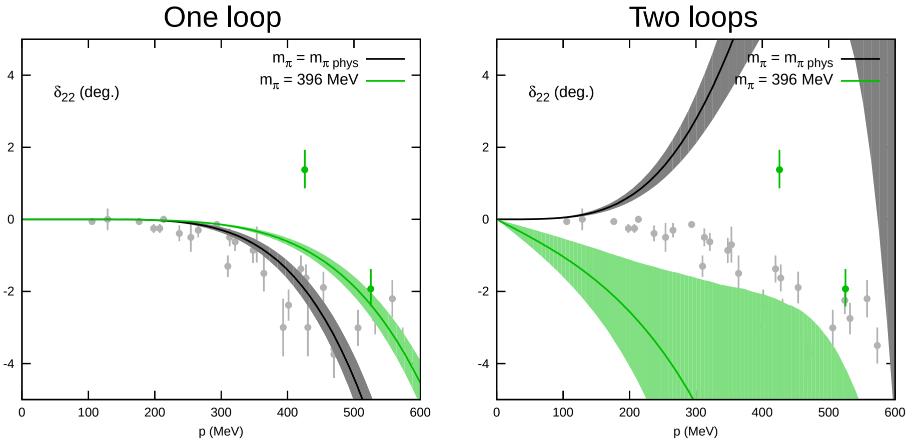
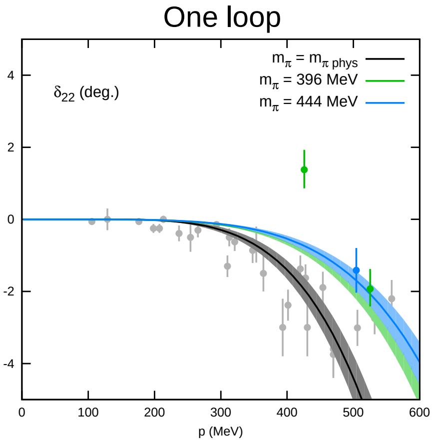
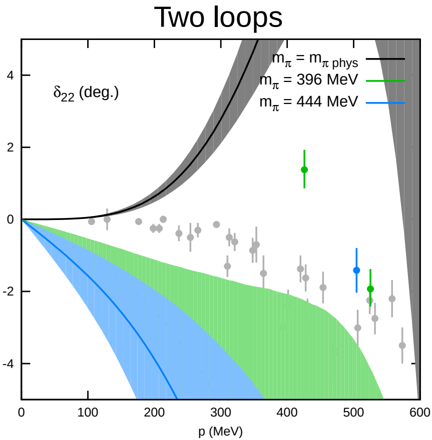


I=2 J=2 phase shift in standard ChPT M_π=444 MeV





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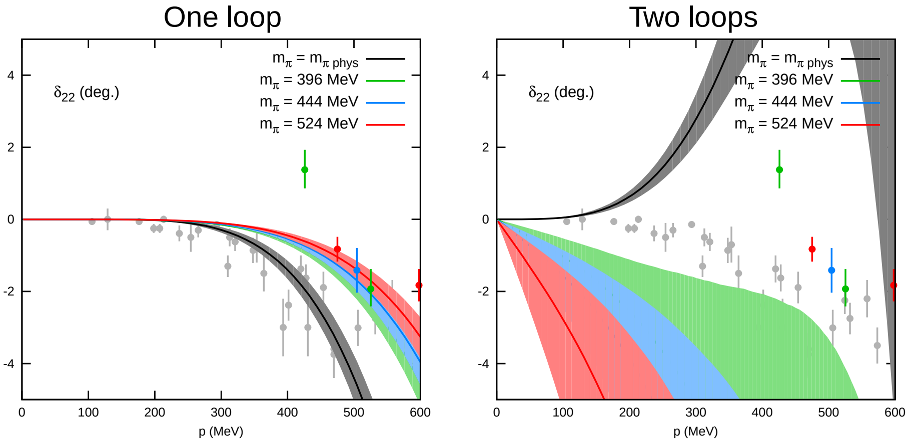

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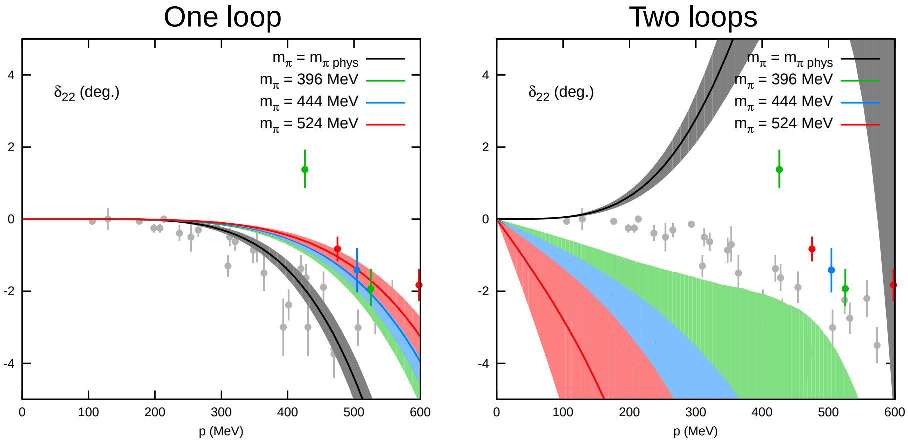


- Works up to higher *p*
- No improvement

Scalar and vector mesons dependence on M_π

Quark mass dependence

Generalization to $SU(3)$ of previous work on $SU(2)$*.

Elastic channels:

- $\pi\pi \to \pi\pi$: resonances ρ and σ (comparison to $SU(2)$ results)
- $\pi K \to \pi K$: resonances $K^*(892)$ and κ.

Change of $\hat{m} = \frac{m_u+m_d}{2}$ and $m_s \Rightarrow$

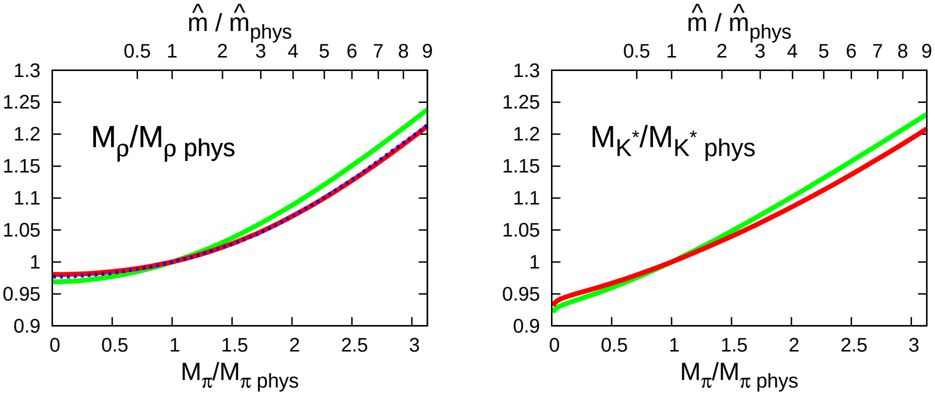
$$\text{change of } M_\pi^2, M_K^2, M_\eta^2, f_\pi, f_K, f_\eta.$$

Applicability in $SU(3)$: $0 < M_\pi \lesssim 400$ MeV $\Rightarrow M_K \lesssim 600$ MeV (Being optimistic!)

* C. Hanhart, J.R. Pelaez and G. Rios, Phys. Rev. Lett. **100**, 152001 (2008)

Light vector mesons: ρ and $K^*(892)$

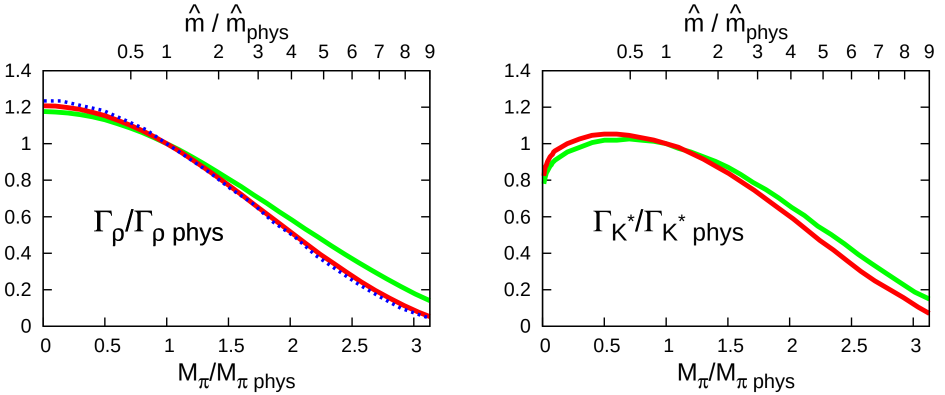
$\hat{m}$ dependence - Light vector mesons - Mass



- Both masses increase slower than M_π
- Agreement with SU(2) analysis (blue line)*

* C. Hanhart, J.R. Pelaez and G. Rios, Phys. Rev. Lett. **100**, 152001 (2008)

$\hat{m}$ dependence - Light vector mesons - Width



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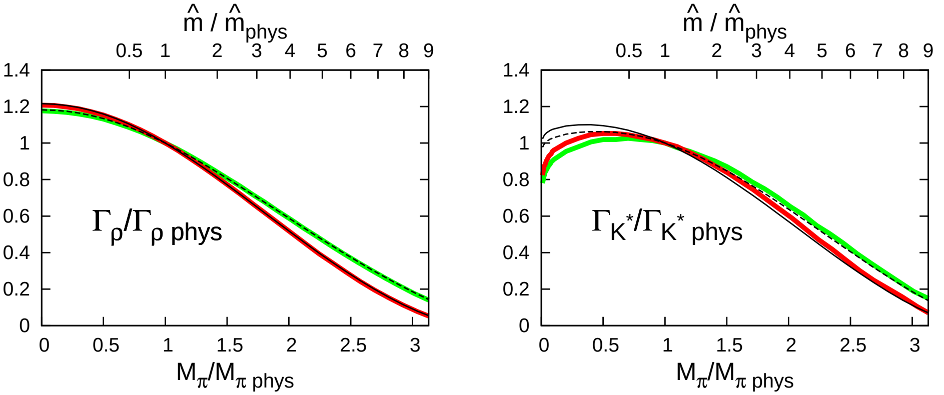
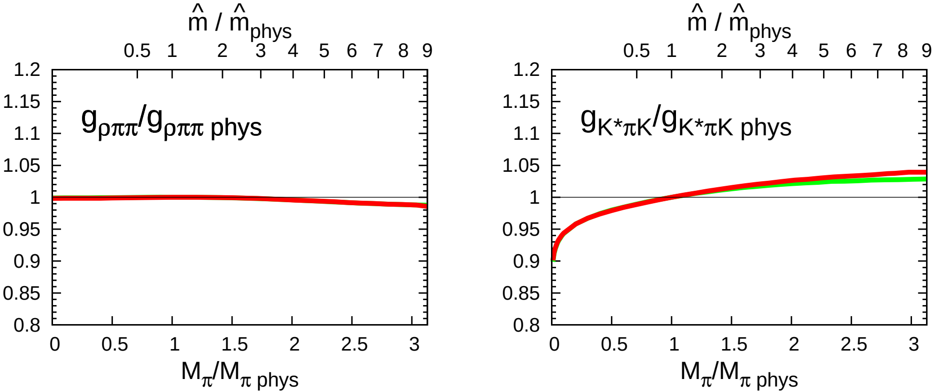


- Width decrease in accordance with phase space reduction:

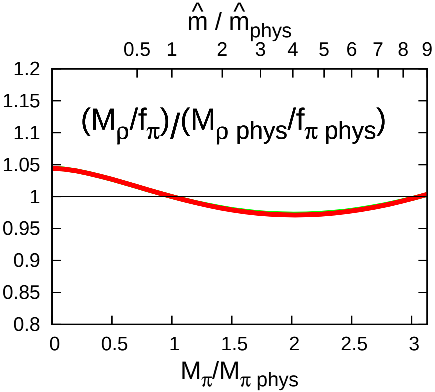
$$\Gamma_V = g^2 \frac{1}{8\pi} \frac{|\mathbf{p}|^3}{M_V^2} \qquad \text{(black lines)}$$

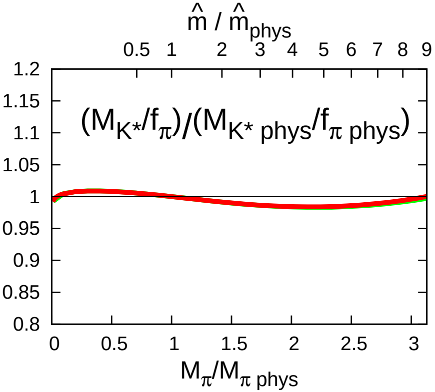
$\hat{m}$ dependence - Light vector mesons - Coupling



- Coupling to two mesons independent of $\hat{m}$ (assumption in some lattice works)

$\hat{m}$ dependence - Light vector mesons - KSFR



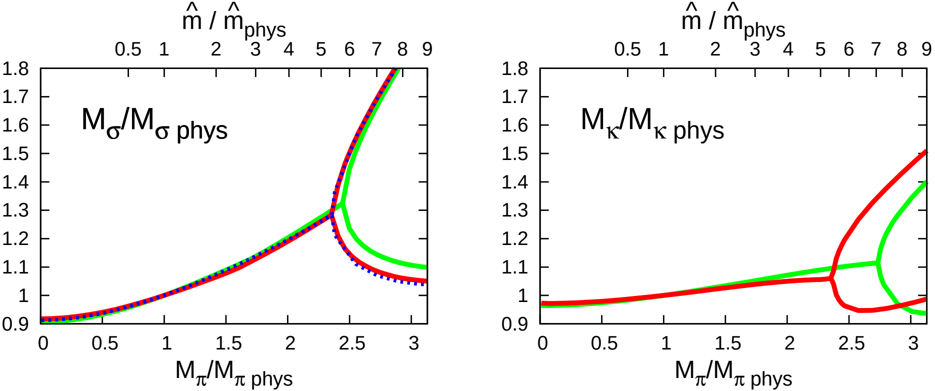


- Fulfill the KSFR relation for different $\hat{m}$:

$$g \simeq M_V/2\sqrt{2}f_\pi$$

Light scalar mesons: σ and κ

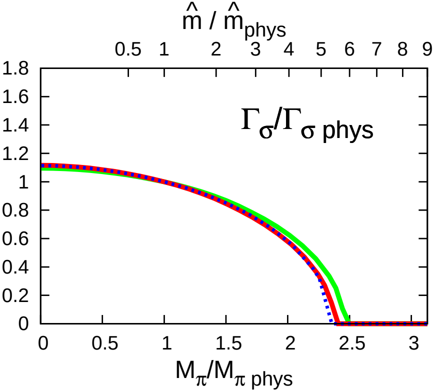
$\hat{m}$ dependence - Light scalar mesons - Mass

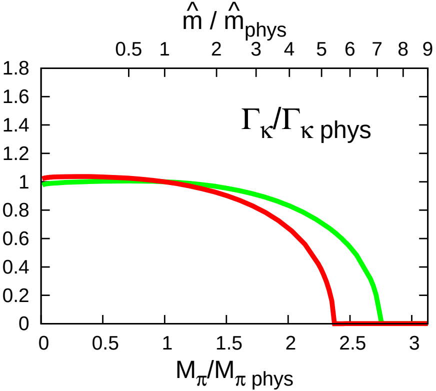


- Mass split into two branches
- Agreement with SU(2) analysis

* C. Hanhart, J.R. Pelaez and G. Rios, Phys. Rev. Lett. **100**, 152001 (2008)

$\hat{m}$ dependence - Light scalar mesons - Width





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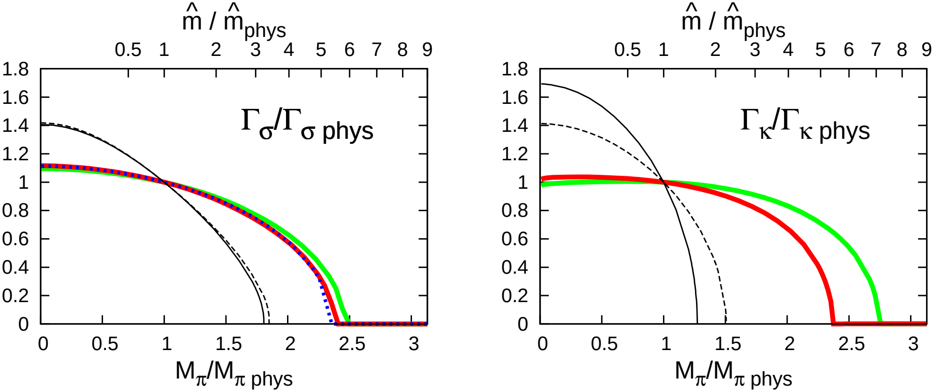
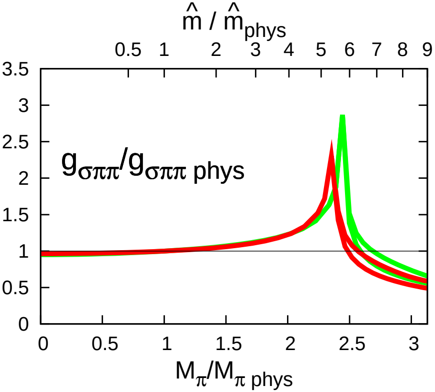
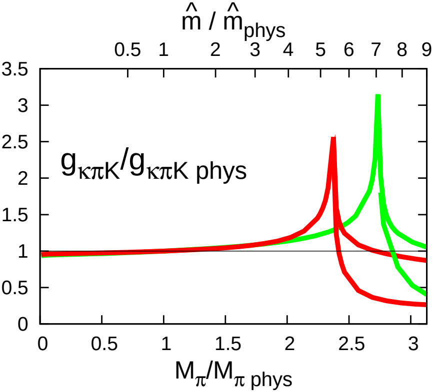


- Width decrease not explained by phase space reduction:

$$\Gamma_S = g^2 \frac{1}{8\pi} \frac{|\mathbf{p}|}{M_S^2}$$

$\hat{m}$ dependence - Light scalar mesons - Coupling





- Strong $\hat{m}$ dependence of coupling to two mesons

Summary

Summary

Chiral extrapolation of the parameters of the σ ($f_0(600)$), $\kappa(800)$, $\rho(770)$ and $K^*(892)$ resonances increasing $\hat{m}$.

Vector mesons

Scalar mesons

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Summary

We have presented recent results for the phase shifts M_π dependence :

Standard ChPT

Unitarized ChPT

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m_s dependence of σ, ρ, κ and $K^*(892)$

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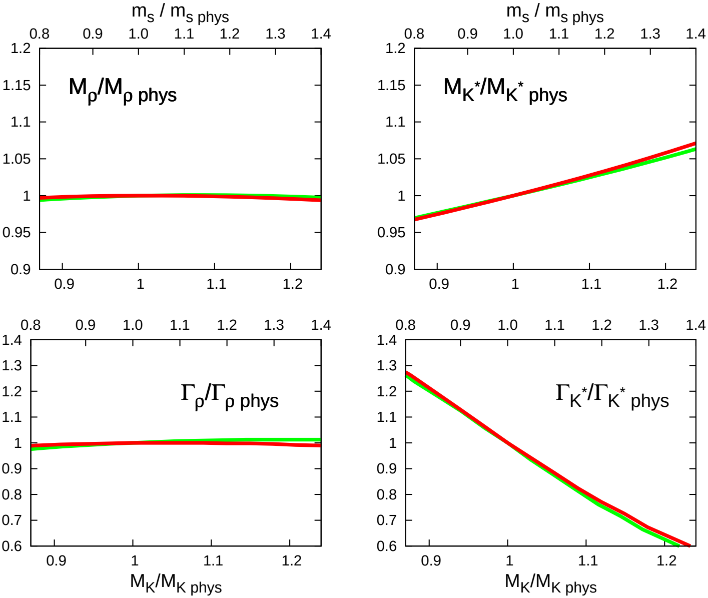
m_s dependence - Light vector mesons - Mass & Width



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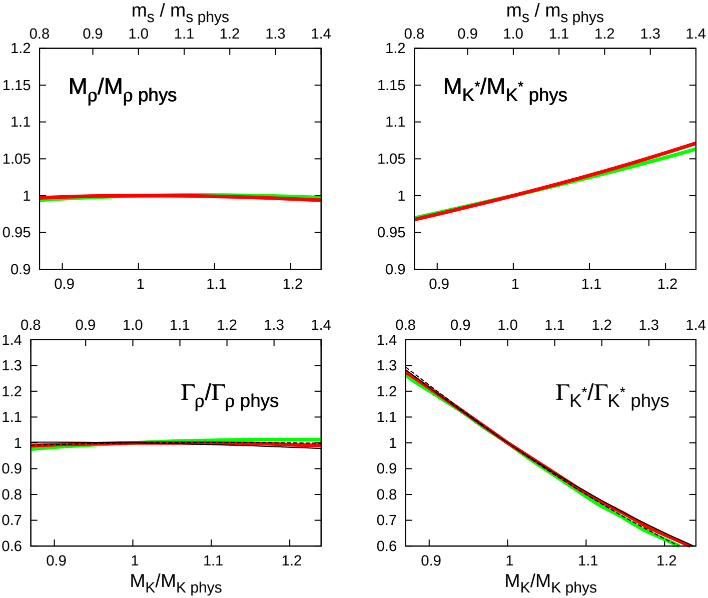
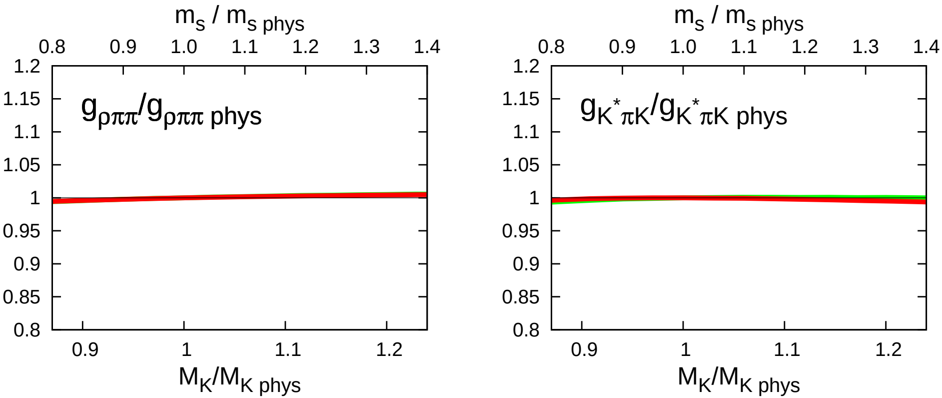
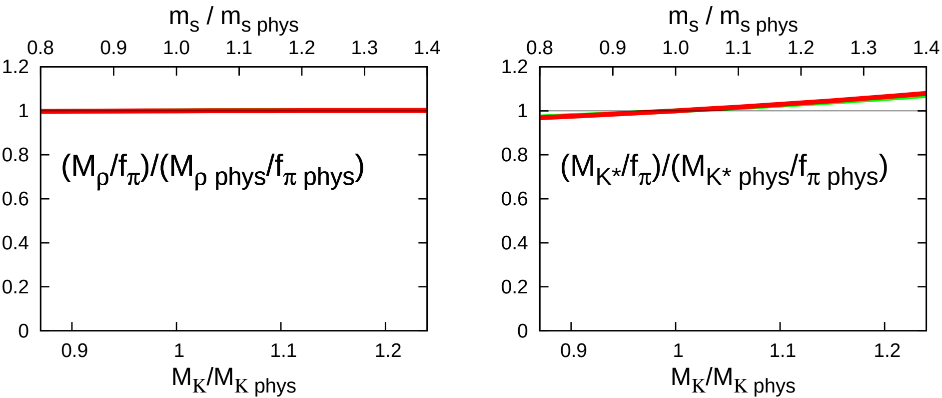


m_s dependence - Light vector mesons - Coupling



- Coupling to two mesons constant

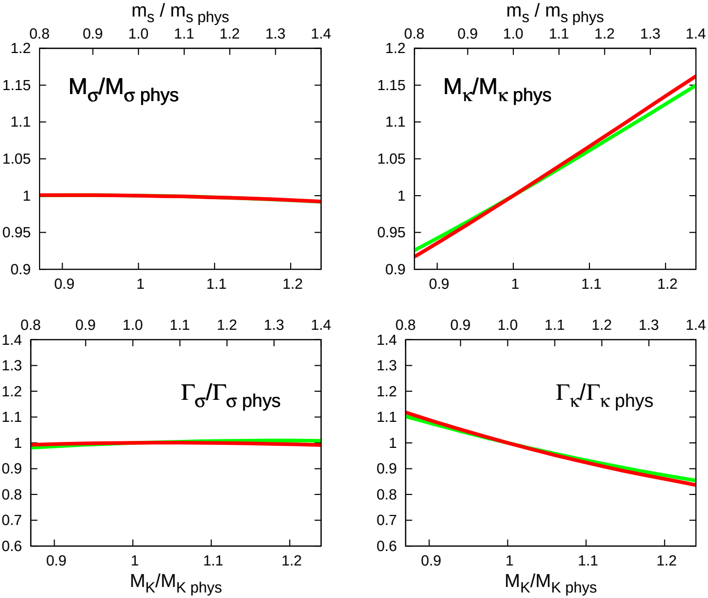
m_s dependence - Light vector mesons - KSFR



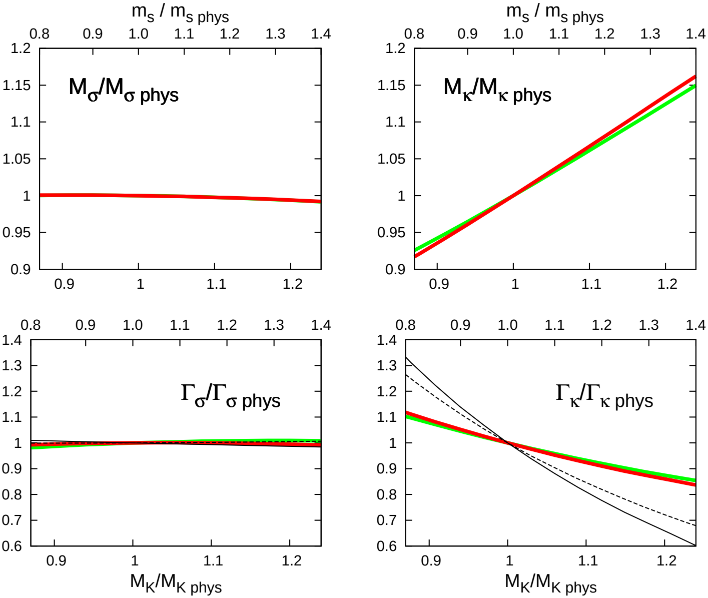
- KSFR relation well satisfied for different m_s

Light scalar mesons: σ and κ

m_s dependence - Light scalar mesons - Mass & Width



m_s dependence - Light scalar mesons - Mass & Width



m_s dependence - Light scalar mesons - Coupling