Relativistic Chiral EFT with baryons: Recent developments and future prospects.

Jose Manuel Alarcón

Helmholtz-Institut für Strahlen- und Kernphysik
University of Bonn

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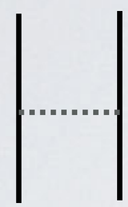
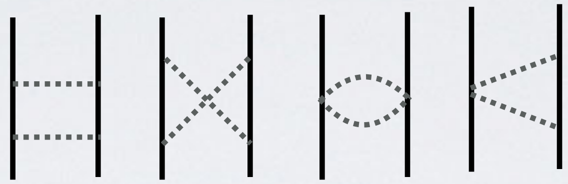
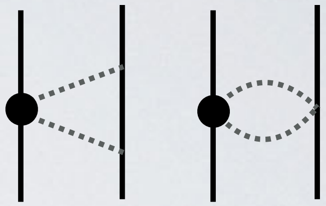
LO:  NLO:  NNLO: 

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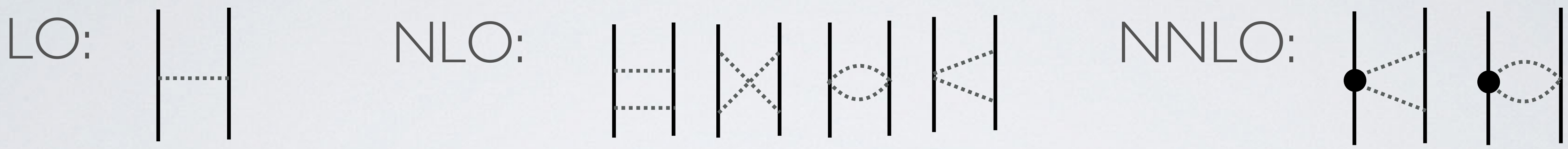

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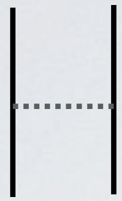
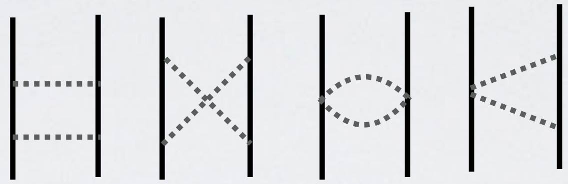
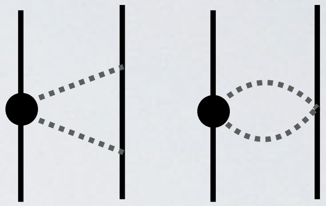
LO:  NLO:  NNLO: 

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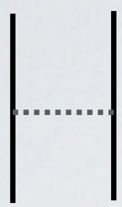
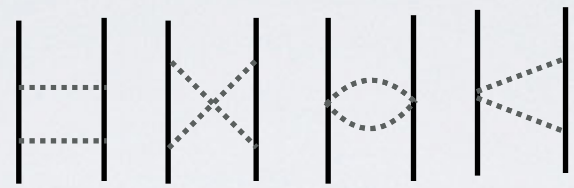
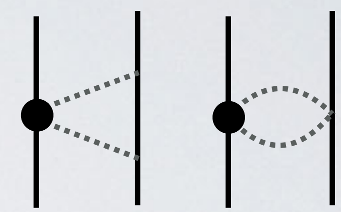
LO:  NLO:  NNLO: 

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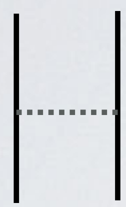
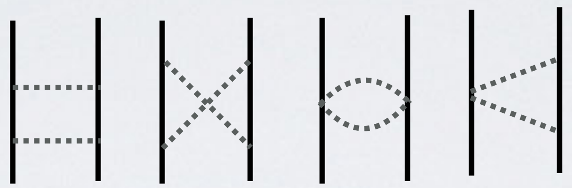
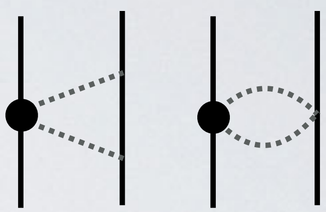
LO:  NLO:  NNLO: 

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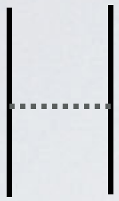
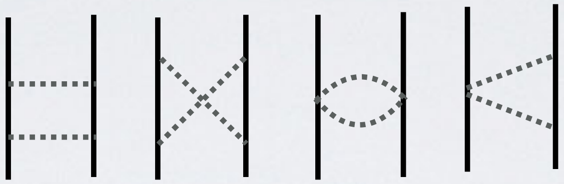
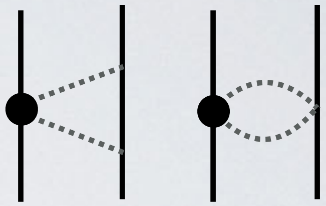
LO:  NLO:  NNLO: 

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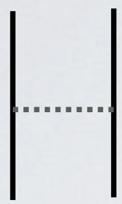
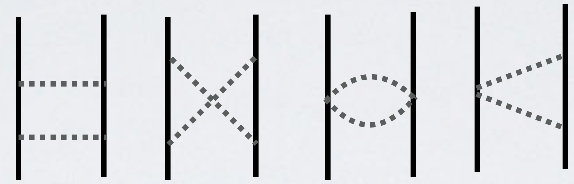
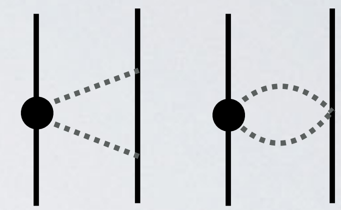
LO:  NLO:  NNLO: 

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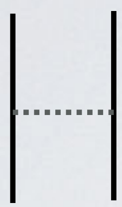
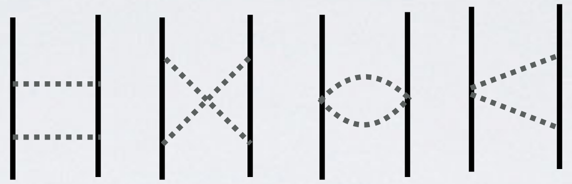
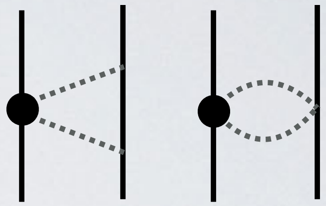
LO:  NLO:  NNLO: 

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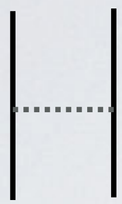
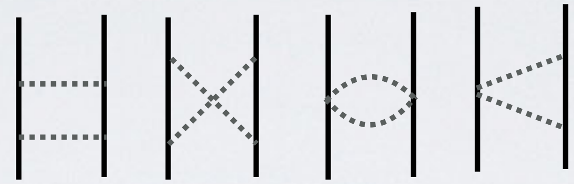
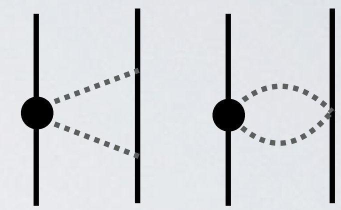
LO:  NLO:  NNLO: 

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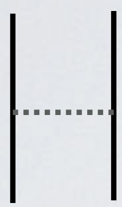
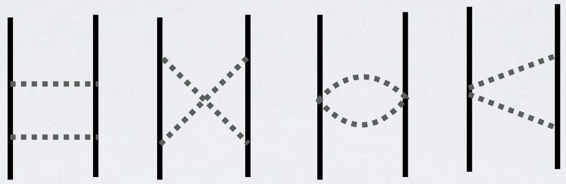
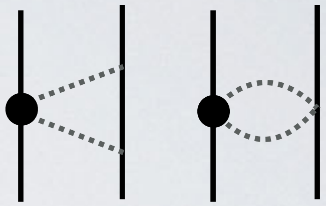
LO: 

NLO: 

NNLO: 

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πN scattering is relevant for hadron and nuclear physics!

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  - Advantage → Keeps the good analytical behavior of the GSS formulation.

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πN scattering with relativistic chiral EFT

- We applied the EOMS approach to the study of πN scattering at low energies for first time in the literature.
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  - Delta-pole is close to the πN threshold → Its inclusion as a dynamical degree of freedom is important for a proper separation of scales.
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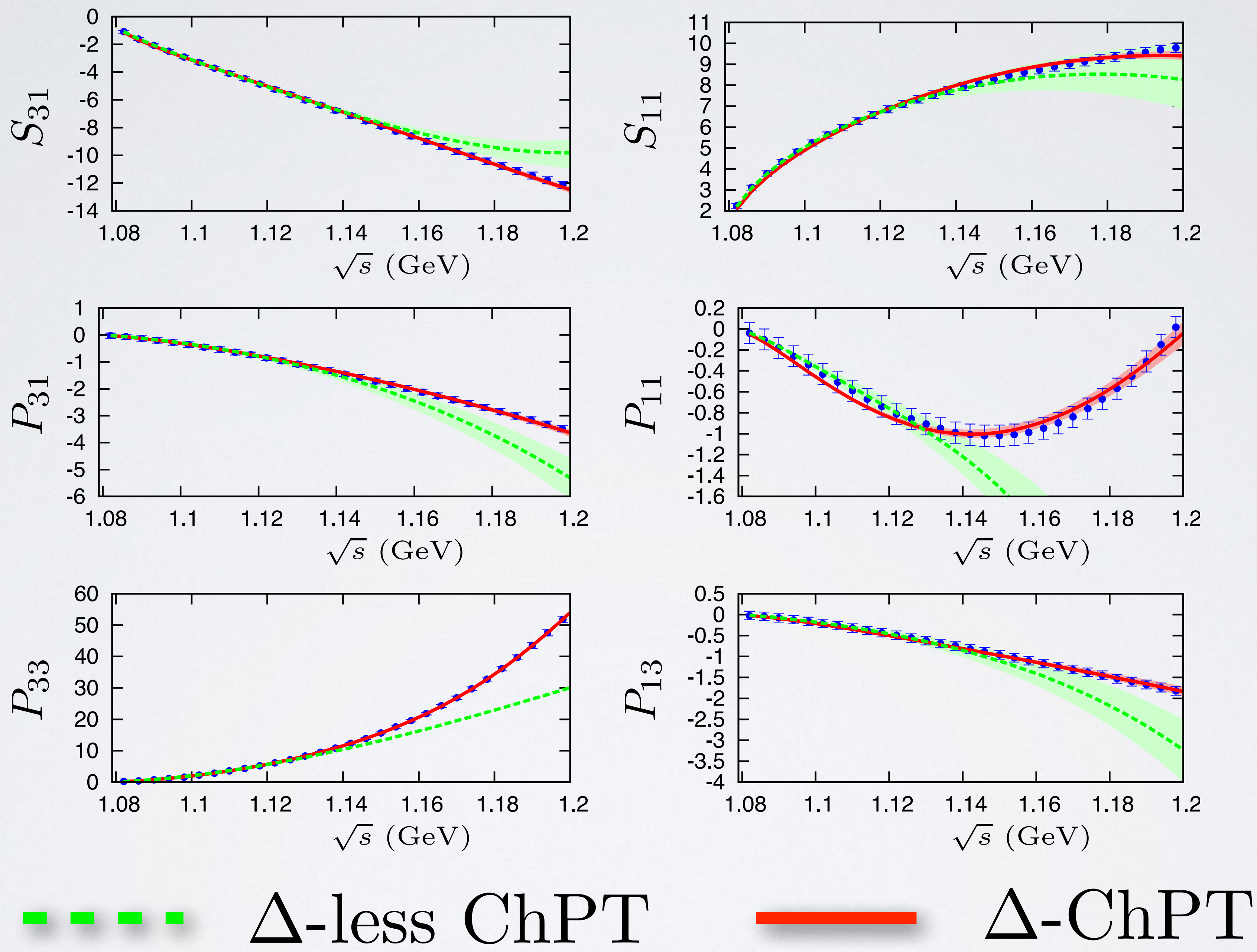
Fits to WI08



[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

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- Threshold parameters:

Partial Wave	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
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a^-_{0+}	8.8(5)	8.33(44)	7.70(8)	9.2	8.83(5)	7.742(61)
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Solves the problem found by Becher and Leutwyler!

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- Tension between the "canonical" value and the updated evaluation:

	Gasser, Leutwyler & Sainio	GWU
$\sigma_{\pi N}$ (MeV)	45(8)	64(7)

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a^+_{0+} $(10^{-3} M_\pi^{-1})$	-11(10)	-1.2(3.3)	2.3(2.0)	-1.0(9)

[1] De Swart, Rentmeester & Timmermans, **πN** Newsletter 13 (1997).
[2] Baru, Hanhart, Hoferichter, Kubis, Nogga & Phillips, NPA 872 (2011)

The pion-nucleon σ-term

- NN scattering and **π**-atoms can provide valuable external information to compare with.
- Goldberger-Treiman violation:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	NN scattering [1]	π-atoms [2]
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	1.9(6)%	1.9(7)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.12(8)	13.12(9)

- Γ_Δ :

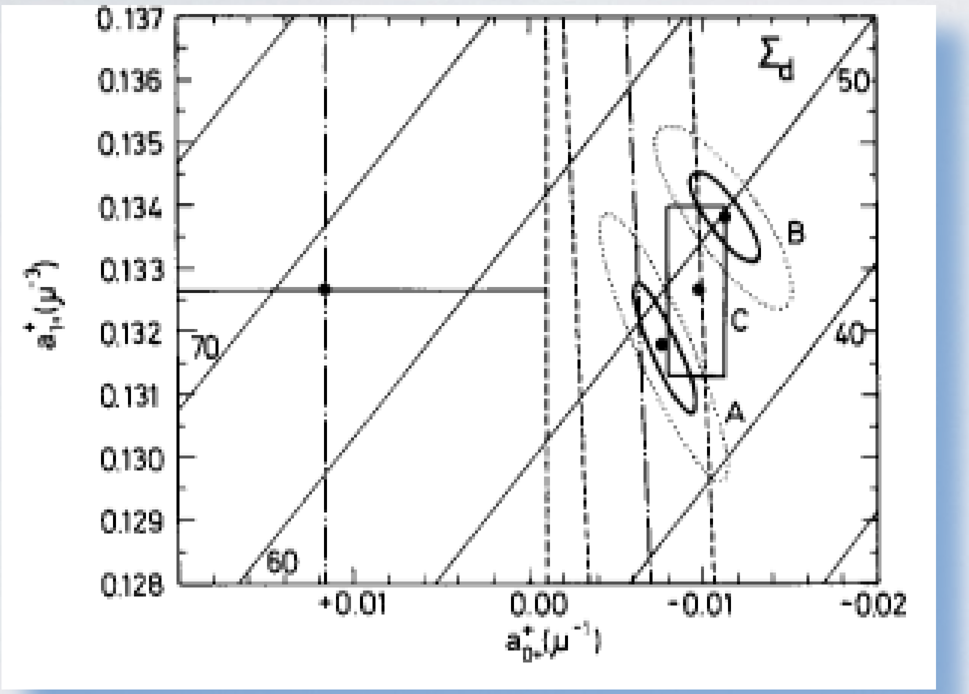
	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	PDG
Γ_Δ (MeV)	128(3)	115(3)	125(2)	117(3)

- a^+_{0+}:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	π-atoms [2] $(\pi^+ p, \pi^- p)$
a^+_{0+} $(10^{-3} M_\pi^{-1})$	-11(10)	-1.2(3.3)	2.3(2.0)	-1.0(9)

[1] De Swart, Rentmeester & Timmermans, **πN** Newsletter 13 (1997).
[2] Baru, Hanhart, Hoferichter, Kubis, Nogga & Phillips, NPA 872 (2011)

- Updating the analysis of Gasser, Leuwyler and Sainio.



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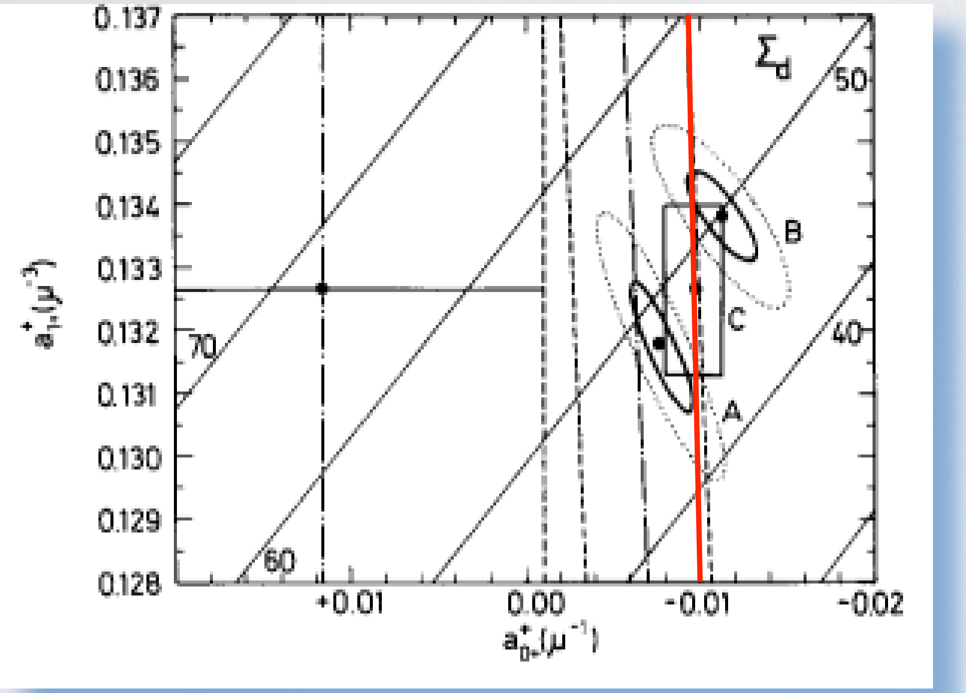

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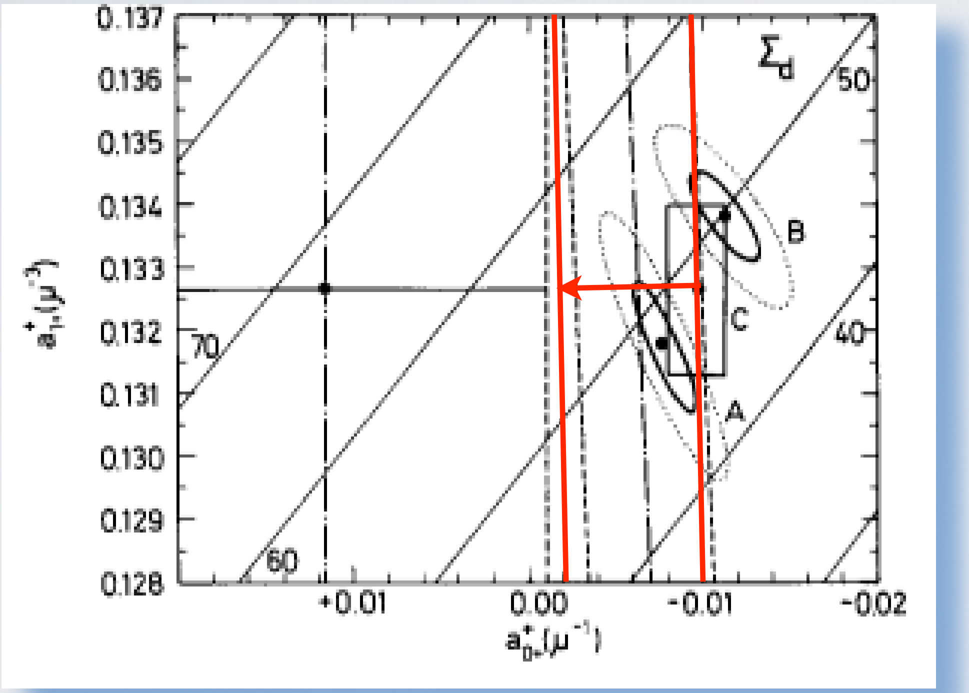

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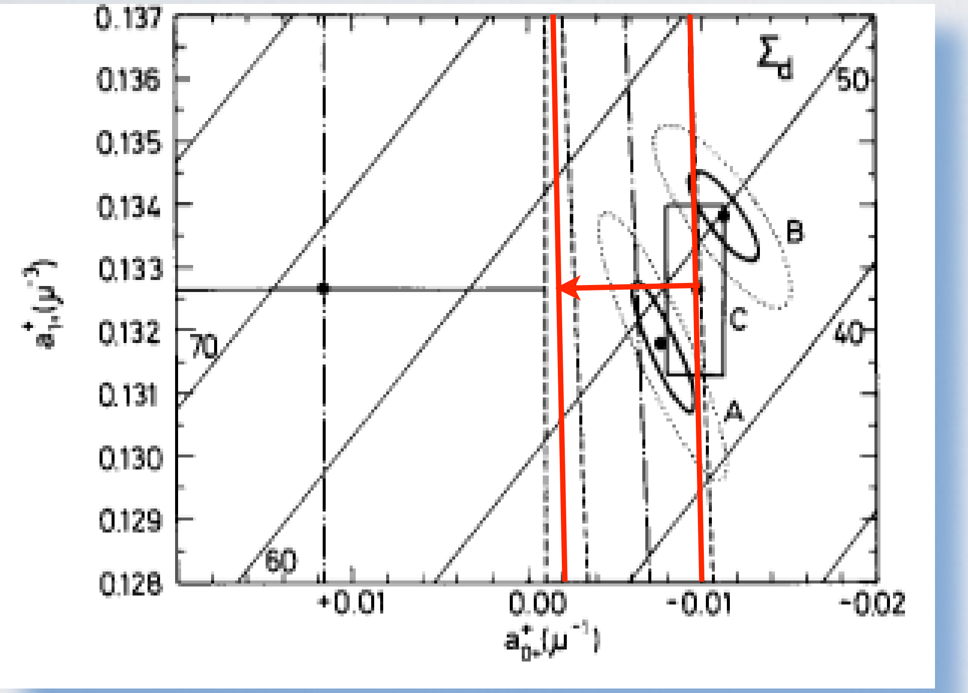

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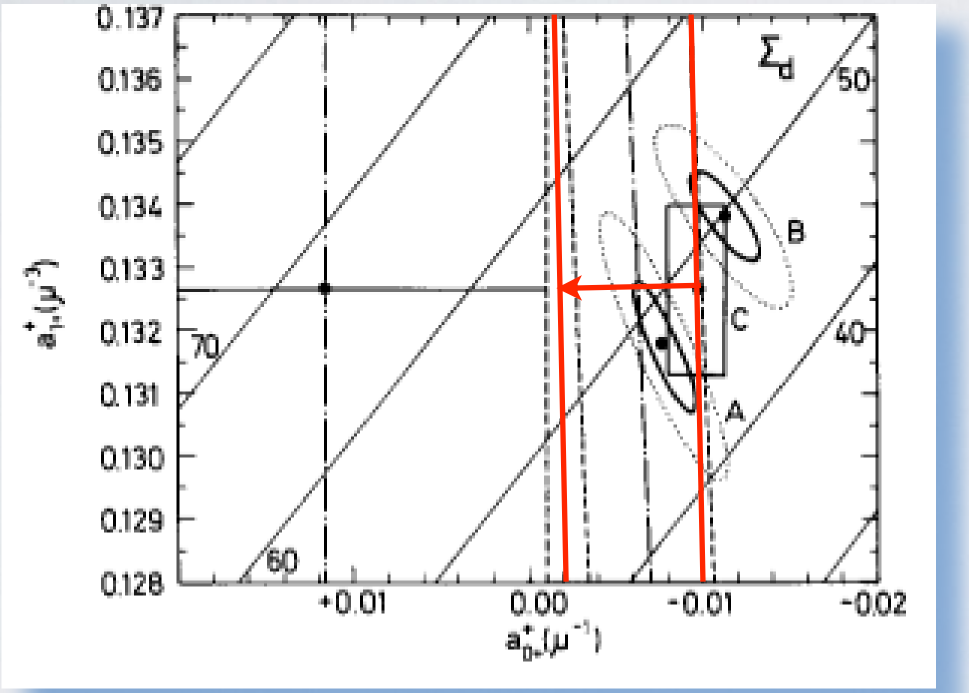

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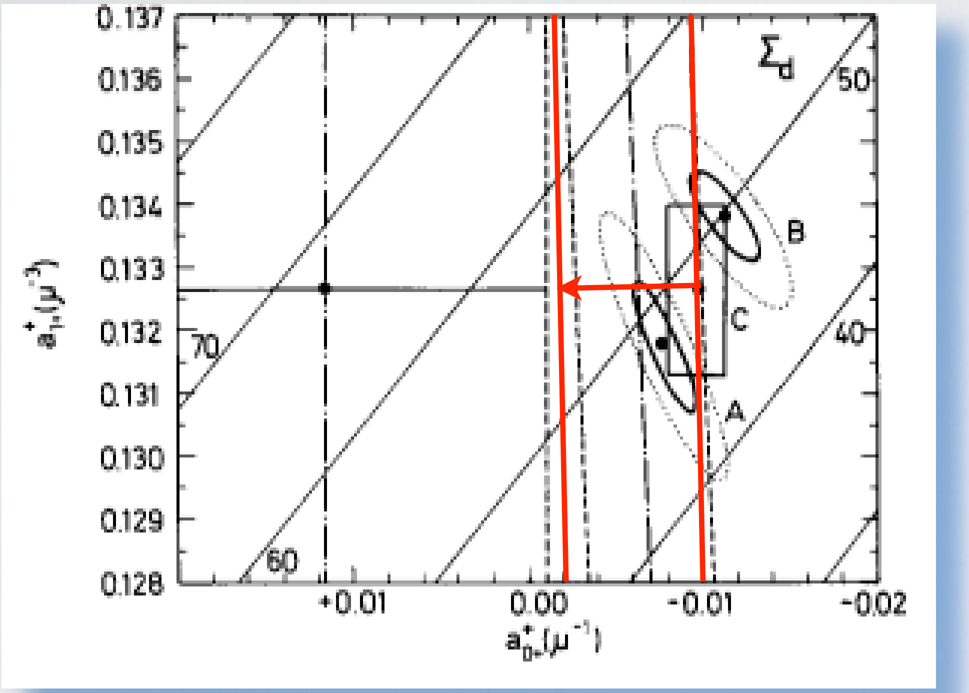

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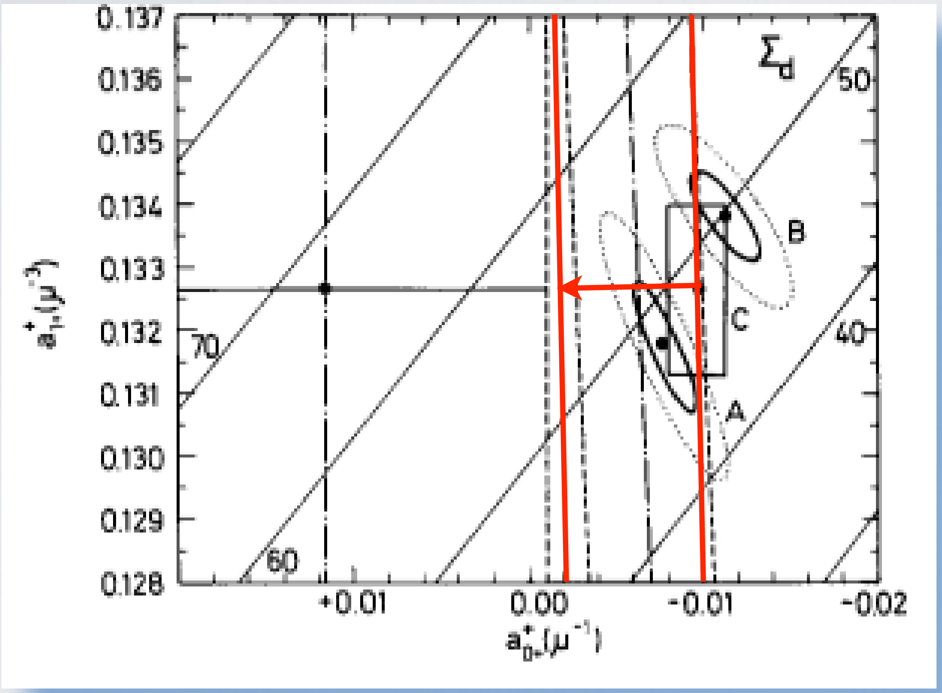

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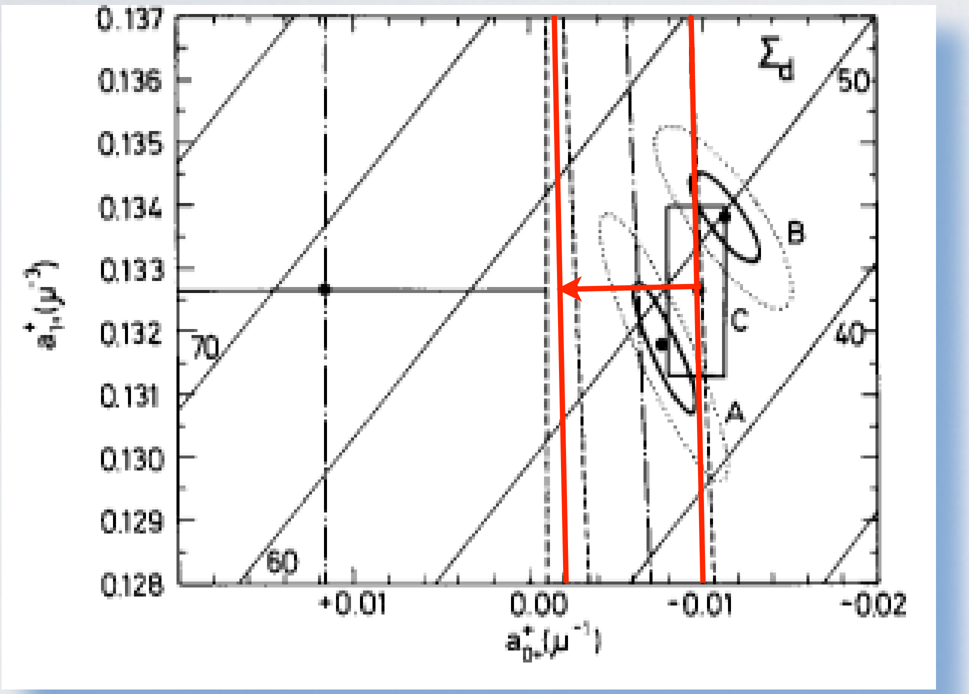

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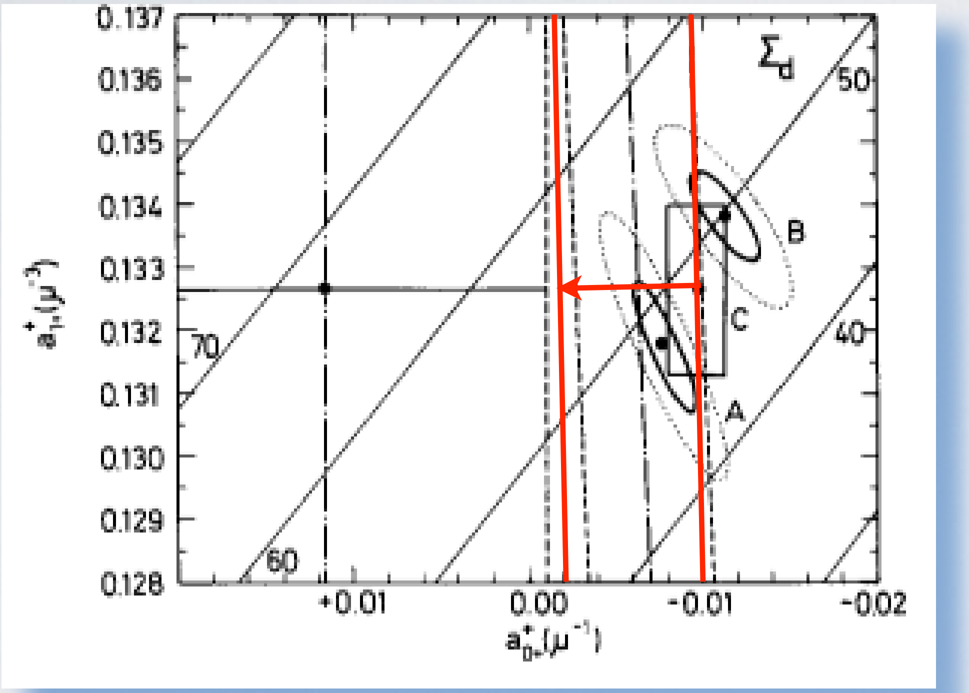

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- Therefore:

$$\sigma_{\pi N} = 59(7)\ \mathrm{MeV}$$

[Alarcón, Martin Camalich and Oller, PRD 85 (2012)]

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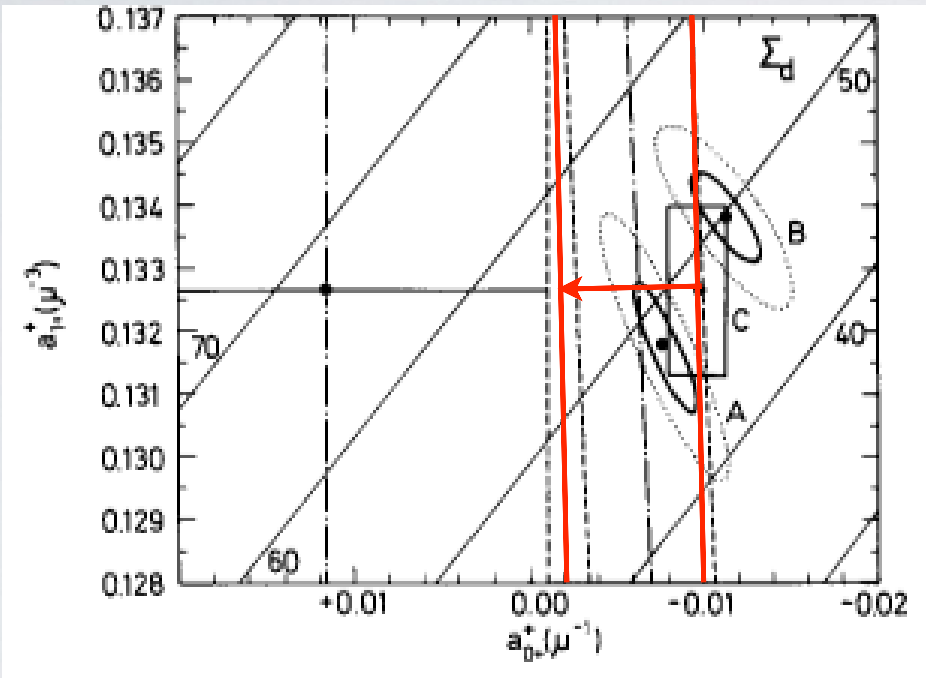

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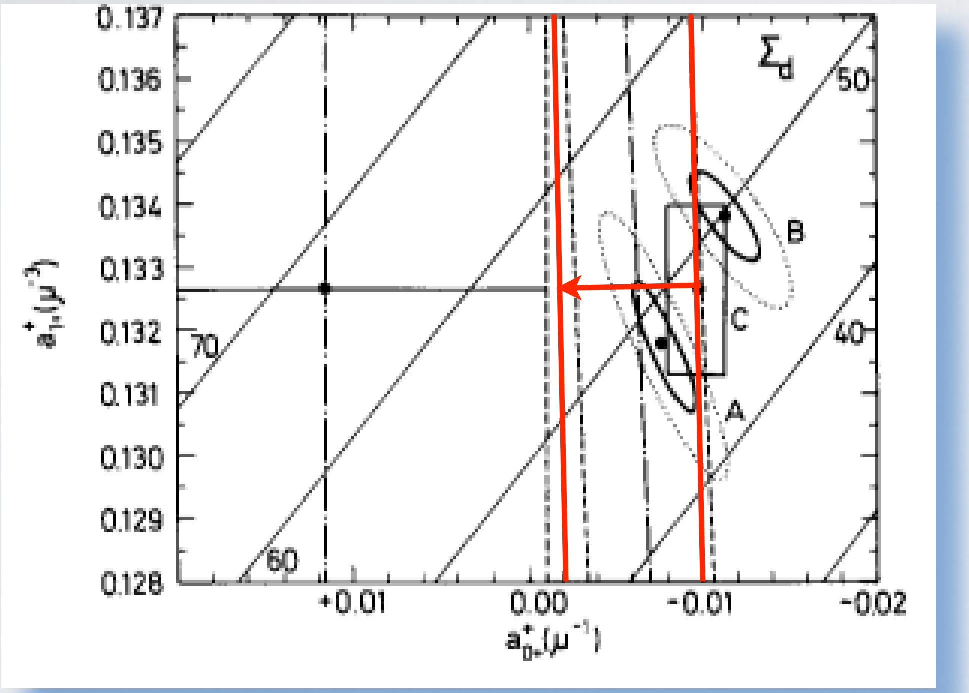

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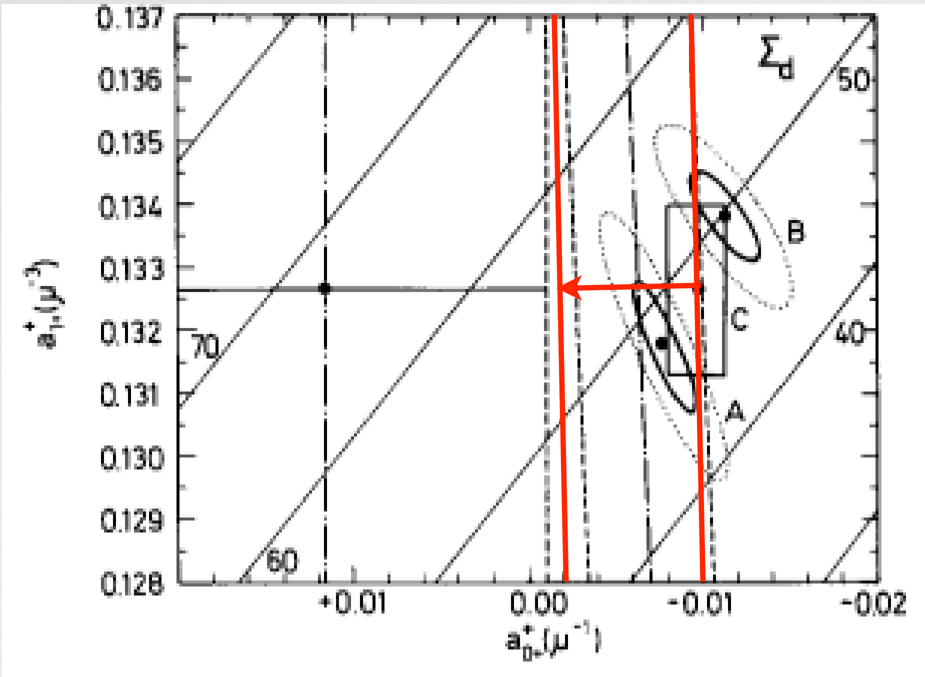

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Confirmed by the Roy-Steiner analysis of *[Hoferichter, et al. arXiv:1506.04142]*

[Alarcón, Martin Camalich and Oller, PRD 85 (2012)]

The strangeness content of the nucleon

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- A new scenario emerges:

	$\sigma_{\pi N}$	σ_0	σ_s	y
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New scenario	59(7)	58(8)	16(80)	0.02(13)

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- Compatible with modern experimental information.
- Compatible with LQCD.

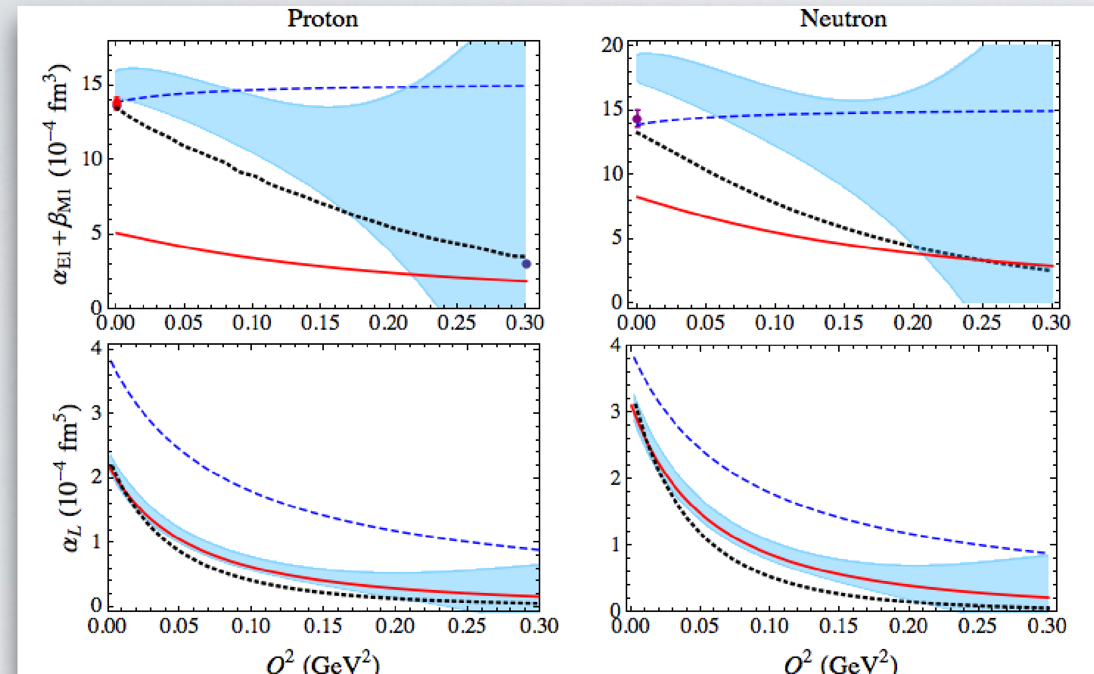
$y = 0.03(2)$ *[Ohki et al. (2008)]*

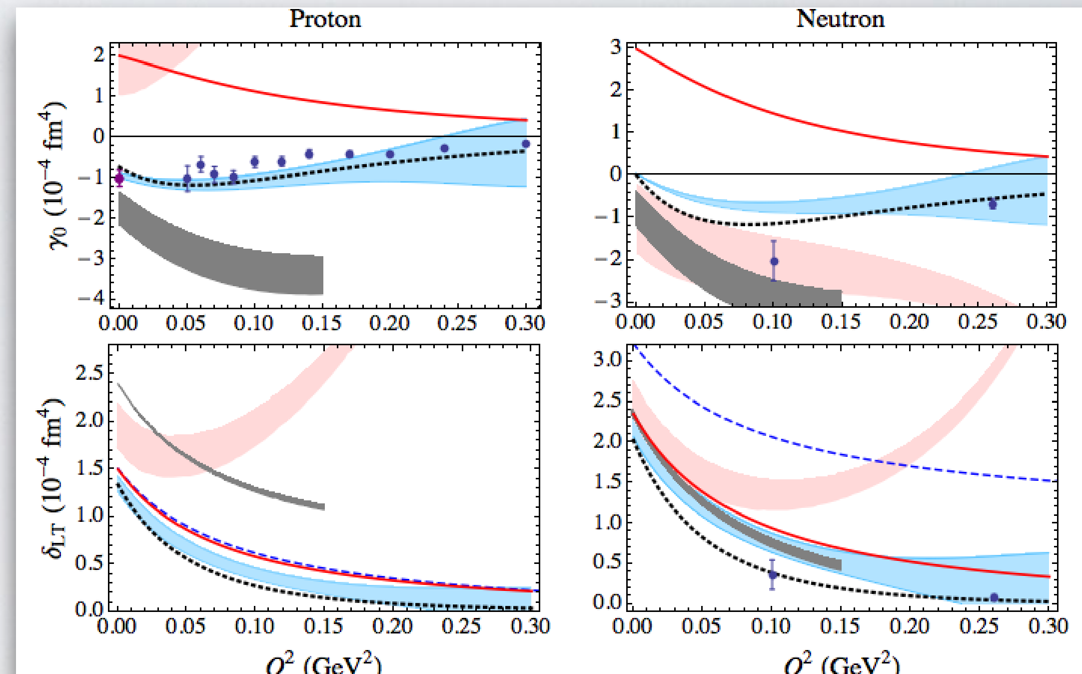
$y = 0.135(46)$ *[Alexandrou et al. (2015)]*

Outreach

Outreach

- After these results:
  - Polarizabilities of the nucleon (VVCS) *[Lensky, Alarcón and Pascalutsa, PRC 90 (2014)]*





  - Polarizability corrections to the μH Lamb shift (Proton Radius Puzzle)

	Heavy Baryon [1]	Relativistic chiral EFT [2]	Dispersive [3]
$\Delta E_{2S}^{(\text{pol})}$	-18.5	$-8.2^{+2.0}_{-2.5}$	-8.5(1.1)

[1] Nevado and Pineda, PRC 77 (2008).
[2] Alarcón, Lensky, Pascalutsa, EPJ C 74 (2014).
[3] Birse and McGovern, EPJ A 48, (2012); Carlson and Vanderhaeghen, PRA 84, (2011).

- π^0-photoproduction *[A.N. Hiller Blin, T. Ledwig, M.J. Vicente Vacas, PLB 747 (2015)]*
- $\pi N \to \pi\pi N$ *[Siemens, Bernard, Epelbaum, Krebs, Meißner, PRC 89 (2014)]*

Summary and Conclusions

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- Chiral EFT with baryons has made important progress in the last years.
- Relativistic formulation + Δ(1232) is crucial to achieve a good convergence in the low energy region.
- Agreement with dispersive analyses in low-energy πN scattering

  → For first time in the literature!
- Extraction of $\sigma_{\pi N}$ from scattering and spectroscopy data.

$$\sigma_{\pi N} = 59(7)\ \mathrm{MeV}$$

- Extraction of the strangeness content of the nucleon.

$$y = 0.02(13)$$

- New picture of σ-terms compatible with LQCD and experiments.
- New πN LECs are expected to improve the convergence of nuclear forces in the chiral EFT formalism → Improved 2N forces.

  → Many-body nuclear interactions with NLEFT

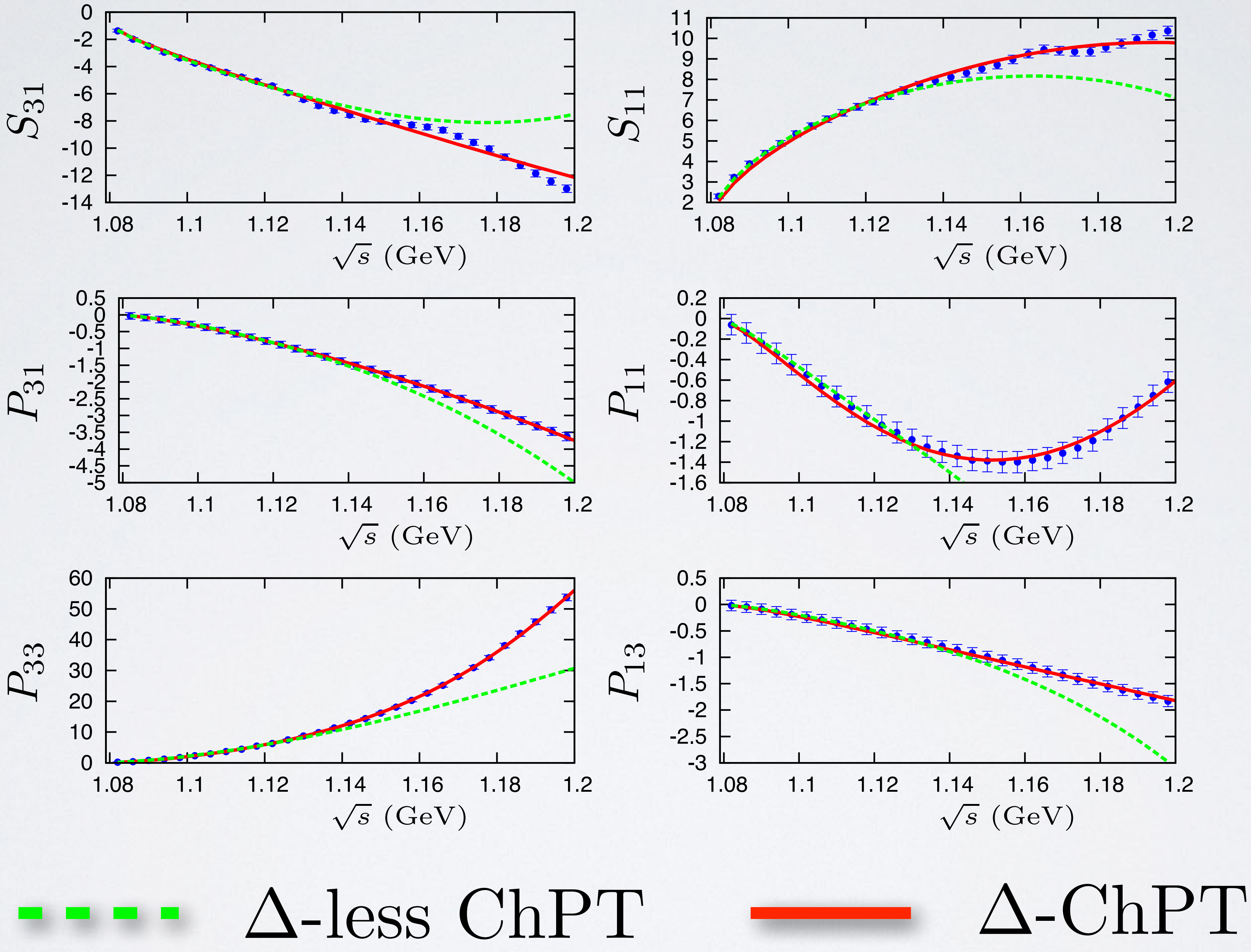
FIN

Spares

Fits to PWAs

Fits to PWAs

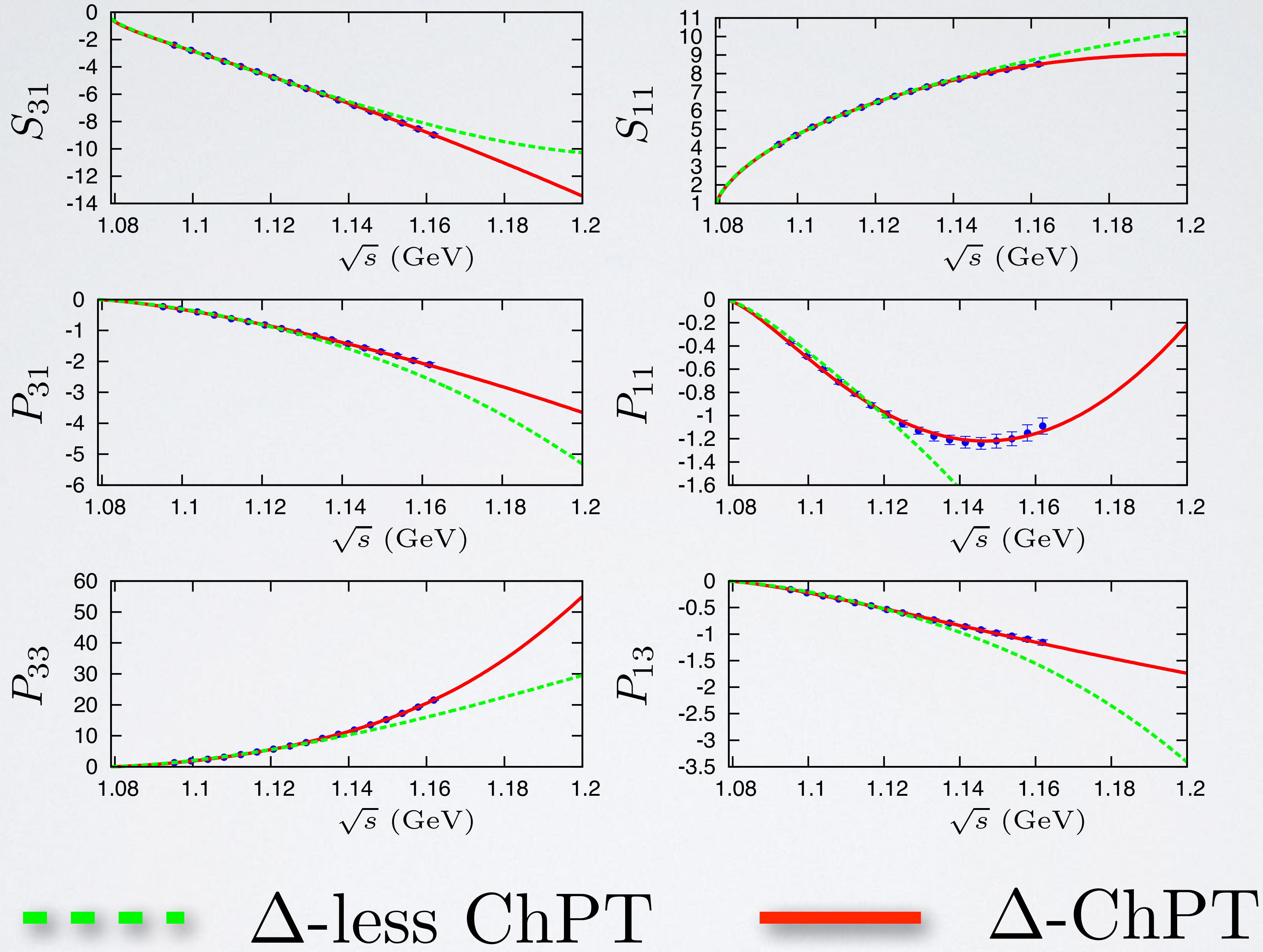
Fits to KA85



[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

Fits to PWAs

Fits to EM06



[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

LECs

LECs

LEC	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT
c_1	−0.80(6)	−1.00(4)	−1.00(1)
c_2	1.12(13)	1.01(4)	0.58(3)
c_3	−2.96(15)	−3.04(2)	−2.51(4)
c_4	2.00(7)	2.02(1)	1.77(2)
$d_1 + d_2$	−0.15(21)	0.15(20)	−0.36(6)
d_3	−0.21(26)	−0.23(27)	0.28(4)
d_5	0.82(14)	0.47(7)	0.20(3)
$d_{14} - d_{15}$	−0.11(44)	−0.5(5)	0.35(9)
d_{18}	−1.53(27)	−0.2(8)	−0.53(12)
h_A	3.02(4)	2.87(4)	2.99(2)
$\chi^2_{\text{d.o.f.}}$	0.77	0.24	0.11

Subthreshold expansion

Subthreshold expansion

- The disagreement found by Becher and Leutwyler is related to the disagreement in the subthreshold expansion.

$$T(\nu,t) = \bar{u}\Big(D(\nu,t) - \frac{1}{4m_N}B(\nu,t)[\not{q},\not{q}']\Big)u \qquad \nu \equiv \frac{s-u}{4m_N}$$

$$\bar{D}^+(\nu,t) = \bar{d}^+_{00} + \bar{d}^+_{01}t + \bar{d}^+_{10}\nu^2 + \bar{d}^+_{02}t^2 + \dots \qquad \bar{B}^+(\nu,t) = \bar{b}^+_{00}\nu + \dots$$

$$\bar{D}^-(\nu,t) = \bar{d}^-_{00}\nu + \bar{d}^-_{01}\nu\, t + \bar{d}^-_{10}\nu^3 + \dots \qquad \bar{B}^-(\nu,t) = \bar{b}^-_{00} + \dots$$

	KA85 $\not{\Delta}$-ChPT	WI08 $\not{\Delta}$-ChPT	EM06 $\not{\Delta}$-ChPT	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85 [50]	WI08 [4]
d^+_{00} (M_π^{-1})	−2.02(41)	−1.65(28)	−1.56(5)	−1.48(15)	−1.20(13)	−0.98(4)	−1.46	−1.30
d^+_{01} (M_π^{-3})	1.73(19)	1.70(18)	1.64(4)	1.21(10)	1.20(9)	1.09(4)	1.14	1.19
d^+_{10} (M_π^{-3})	1.81(16)	1.60(18)	1.532(45)	0.99(14)	0.82(9)	0.631(42)	1.12(2)	–
b^+_{00} (M_π^{-3})	−6.5(2.4)	−7.4(2.3)	−7.01(1.1)	−5.1(1.7)	−5.1(1.7)	−4.5(9)	−3.54(6)	–
d^-_{00} (M_π^{-2})	1.81(24)	1.68(16)	1.495(28)	1.63(9)	1.53(8)	1.379(8)	1.53(2)	–
d^-_{01} (M_π^{-4})	−0.17(6)	−0.20(5)	−0.199(7)	−0.112(25)	−0.115(24)	−0.0923(11)	−0.134(5)	–
d^-_{10} (M_π^{-4})	−0.35(10)	−0.33(10)	−0.267(14)	−0.18(5)	−0.16(5)	−0.0892(41)	−0.167(5)	–
b^-_{00} (M_π^{-2})	17(7)	17(7)	16.8(7)	9.63(30)	9.755(42)	8.67(8)	10.36(10)	–

- Remarkable agreement of Δ-ChPT with dispersive results.
- Never achieved before with Chiral EFT.
- Solves the problems found by Becher and Leutwyler.

The Cheng-Dashen Theorem

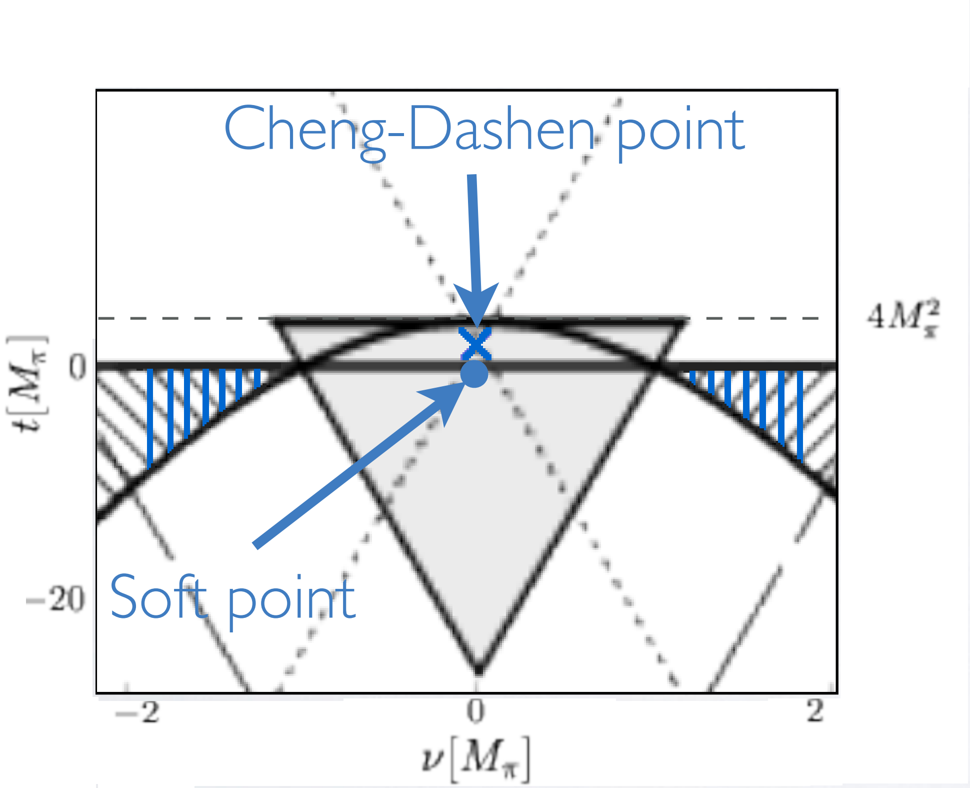
The pion-nucleon σ-term

- Traditionally, the sigma-term has been extracted using the Cheng-Dashen Theorem:

t-channel

$$\Sigma \equiv f_\pi^2 \bar{D}^+(0, 2M_\pi^2) = \sigma(t = 2M_\pi^2) + \Delta_R = \sigma_{\pi N} + \Delta_\sigma + \Delta_R$$

~15 MeV



$$\Sigma = \underbrace{f_\pi^2(\bar{d}_{00}^+ + \bar{d}_{01}^+ 2M_\pi^2)}_{\Sigma_d} + \underbrace{f_\pi^2(\bar{d}_{02}^+ 4M_\pi^4 + \dots)}_{\Delta_D}$$

$$\sigma_{\pi N} = \Sigma_d + \Delta_D - \Delta_\sigma$$

$$\Delta_D - \Delta_\sigma \approx 3(1)\ \text{MeV}$$

$$\Delta_D^{(3)} - \Delta_\sigma^{(3)} \approx 3.5(2.0)\ \text{MeV}$$

[Gasser, Leutwyler & Sainio, PLB 253 (1991)]

[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

We recover the dispersive result !

- Smart way to suppress "contamination" from the t-channel.

Different scenarios for the **σ**-*terms*

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