Current status of Λ(1405) and $\bar{K}N$ interaction

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2015, Jul. 5th

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    Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)
  - **Realistic** $\bar{K}N$ **potential**

    K. Miyahara, T. Hyodo, arXiv:1506.05724 [nucl-th]
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  - K-d -> n πΣ **(c.f. Noumi-san)**

    S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise,
    J. Phys. Conf. Ser. 569, 012077 (2014) + in preprataion

Current status of nuclear force

Phenomenological potentials

- Boson exchange, Av18, quark model, …
- Realistic precision (χ^2/d.o.f. < 1)

Chiral EFT

- Systematic improvement
- Realistic precision (χ^2/d.o.f. < 1)

} Few-body calculations

Lattice QCD

- First principle (fit required for practical use)
- Not yet realistic

$\bar{K}N$ interaction

Requirement for the $\bar{K}N$ system

- large subthreshold extrapolation (~ 100 MeV?)
- accurate description of scattering Data (better than NN?)

Phenomenological potentials: boson (hadron) exchange

S. Shinmura, M. Wada, M. Obu, Y. Akaishi, Prog. Theor. Phys. 124, 125 (2010)
J. Haidenbauer, G. Krein, U.-G. Meissner, L. Tolos, Eur. Phys. J. A 47, 18 (2011)

- not fitted to $\bar{K}N$ data (aiming at unified description)

Lattice?

- more difficult than NN (coupled-channel, quark annihilation)

Chiral coupled-channel approach: This talk

- Systematic improvement with NLO terms
- Realistic precision with $\bar{K}N$ data (χ^2/d.o.f. < 1)

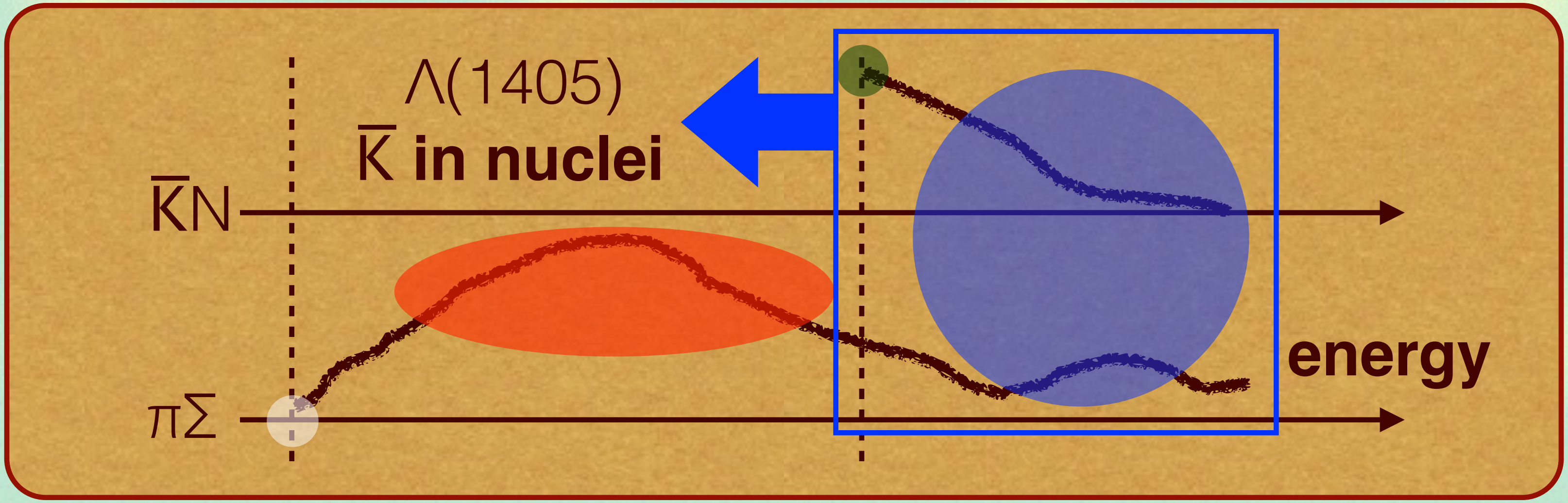
Strategy for $\bar{K}N$ interaction

Above the $\bar{K}N$ threshold:

- K^-p **total cross sections** **(old data)**
- $\bar{K}N$ **threshold branching ratios (old data)**
- K^-p **scattering length (new data: SIDDHARTA)**

Below the $\bar{K}N$ threshold:

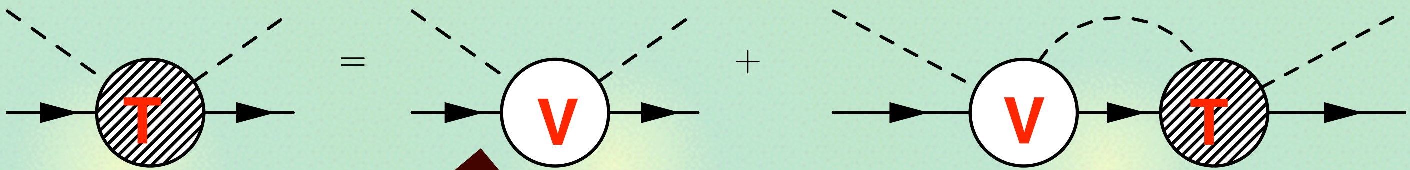
- $\pi\Sigma$ **mass spectra (new data: LEPS, CLAS, c.f. Niiyama-san)**
- $\pi\Sigma$ scattering length **(no data at present)**



Construction of the realistic amplitude

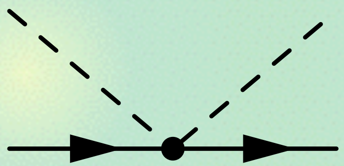
Chiral coupled-channel approach with systematic χ^2 fitting

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B706, 63 (2011); Nucl. Phys. A881 98 (2012)



Chiral perturbation theory

1) TW term

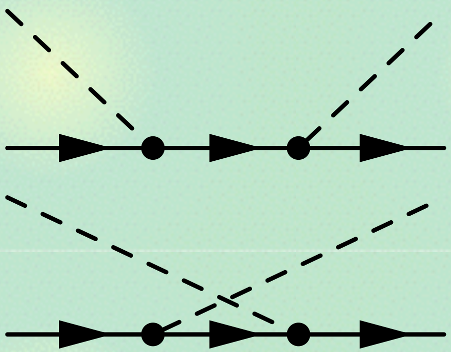


$\mathcal{O}(p)$

6 cutoffs

TW model

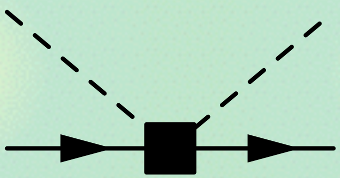
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



$\mathcal{O}(p^2)$

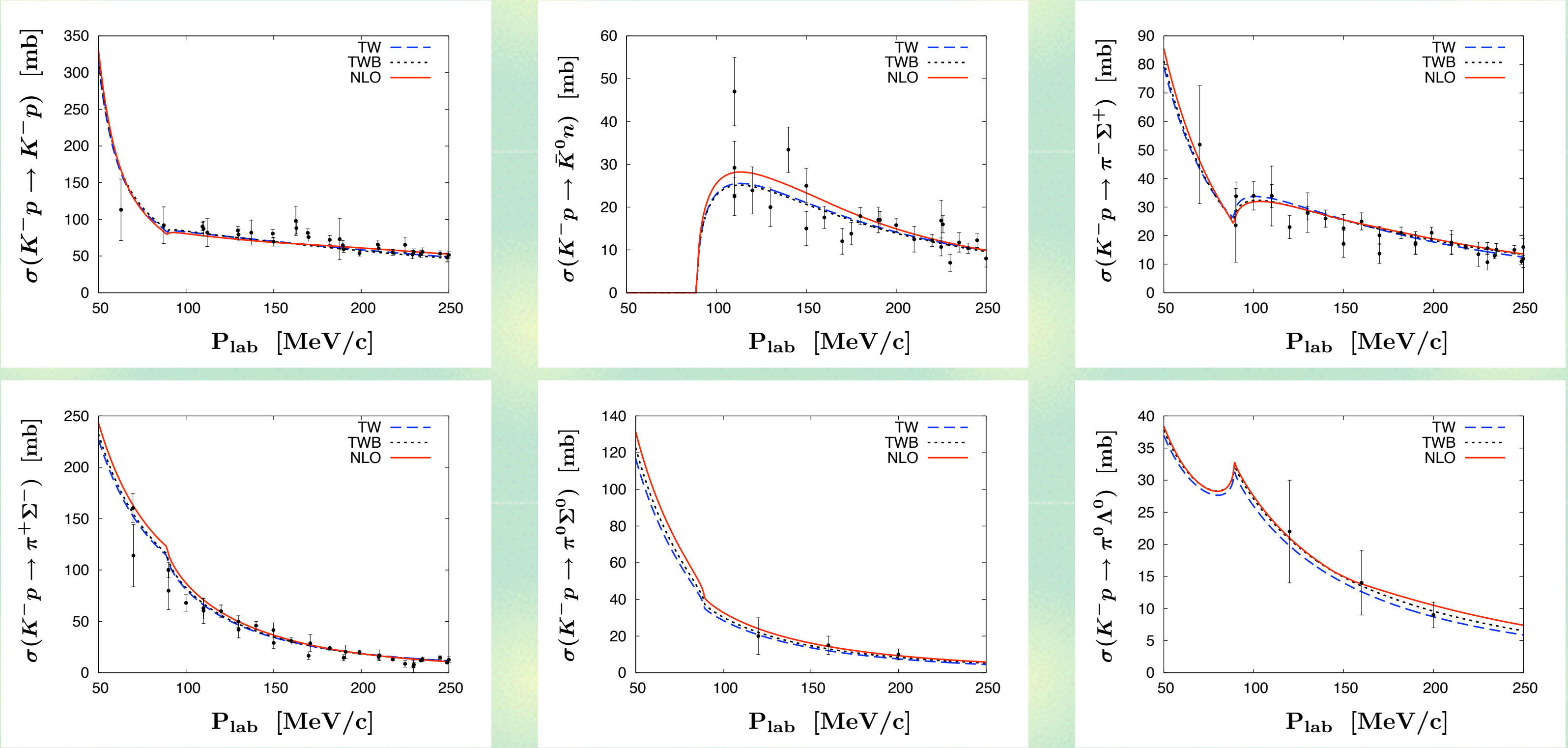
7 LECs

NLO model

Best-fit results

		TW	TWB	NLO	Experiment	
SIDDHARTA	ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[10]
	Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[10]
Branching ratios	γ	2.36	2.36	2.37	2.36 ± 0.04	[11]
	R_n	0.20	0.19	0.19	0.189 ± 0.015	[11]
	R_c	0.66	0.66	0.66	0.664 ± 0.011	[11]
	χ^2/d.o.f	1.12	1.15	0.96		

cross sections

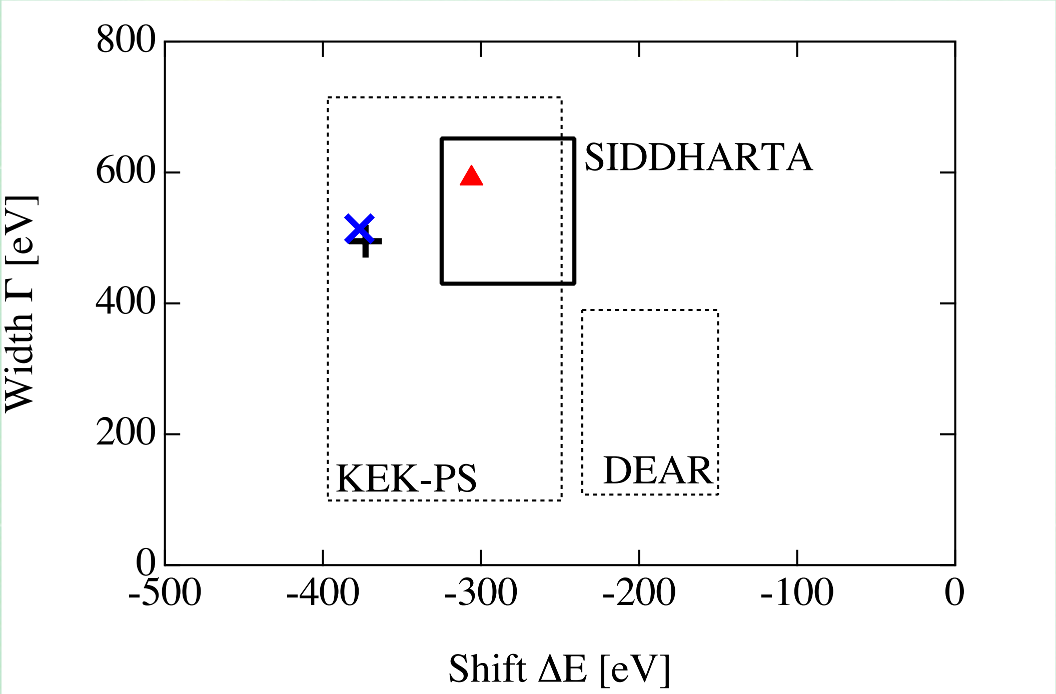


SIDDHARTA is consistent with cross sections

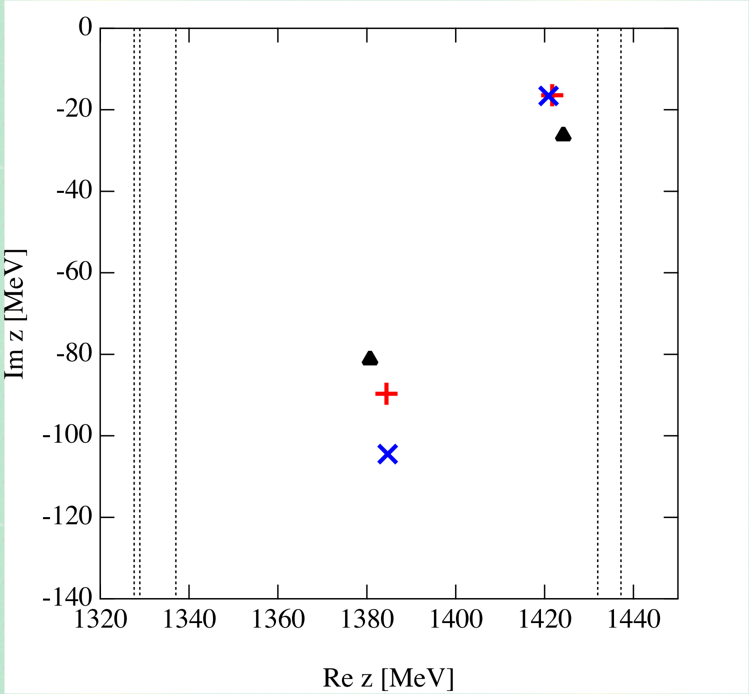
Shift, width, and pole positions

	TW	TWB	NLO
χ^2/d.o.f.	1.12	1.15	0.957

Shift and width



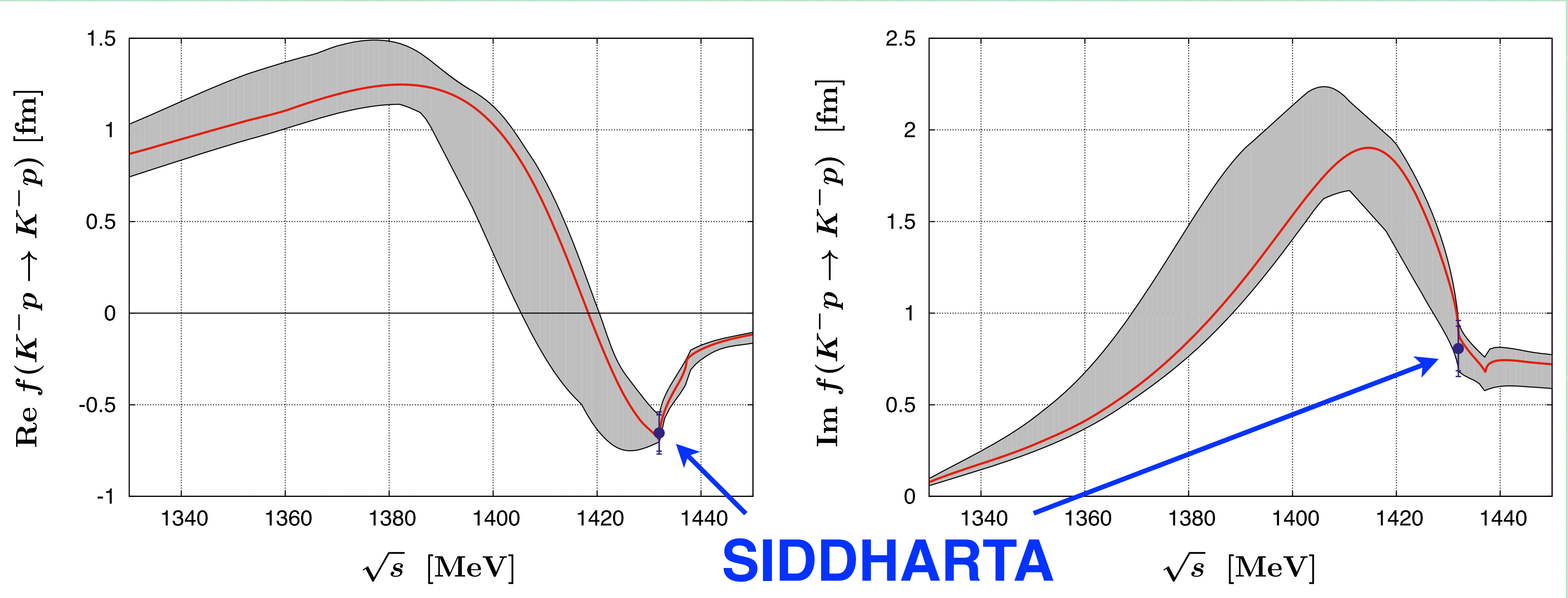
Λ(1405) Pole positions



TW and TWB are reasonable, while best-fit requires NLO.
Systematic error of the pole positions is small.

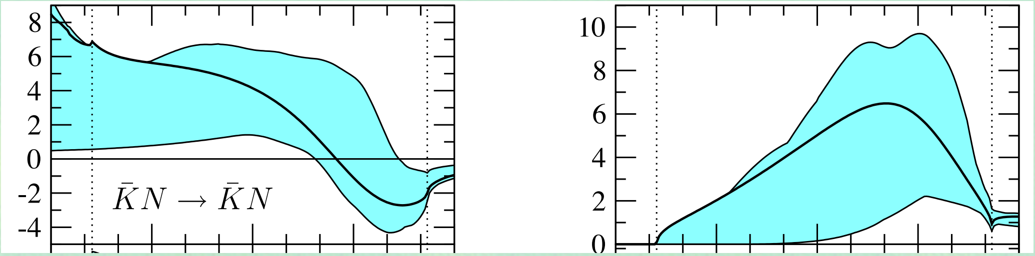
Subthreshold extrapolation

Behavior of K-p —> K-p amplitude below threshold



- c.f. $\bar{K}N$ —> $\bar{K}N$ (I=0) without SIDDHARTA

R. Nissler, Doctoral Thesis (2007)



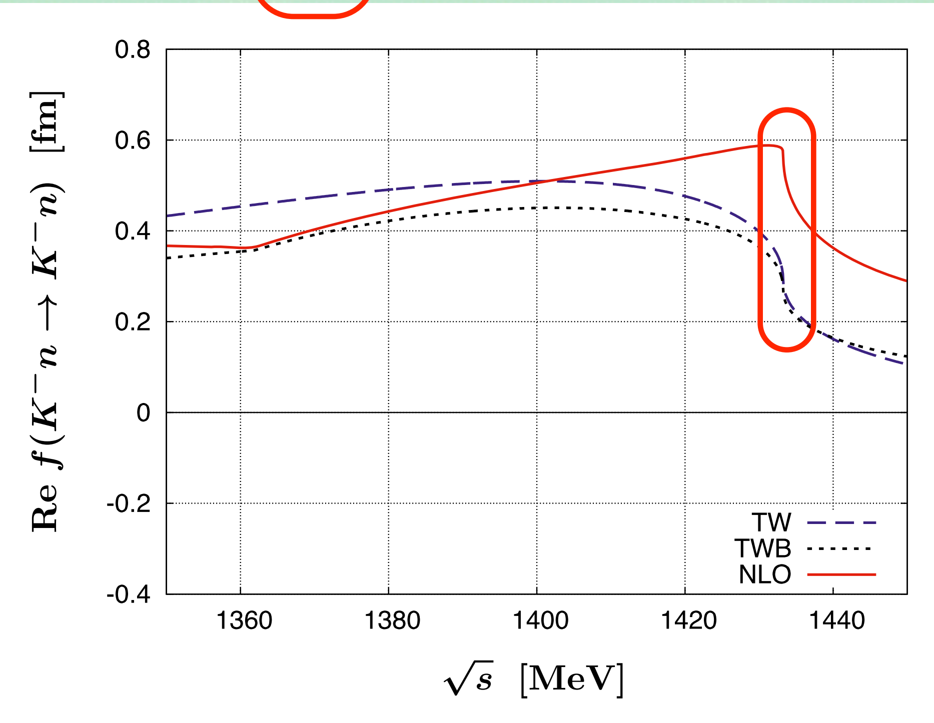
Subthreshold extrapolation is now well controlled.

Remaining ambiguity

For $\bar{K}$-nucleon interaction, we need both K-p and K-n.

$$a(K^-p) = \frac{1}{2}a(I=0) + \frac{1}{2}a(I=1) + \dots, \quad a(K^-n) = a(I=1) + \dots$$

$$a(K^-n) = 0.29 + i0.76 \text{ fm} \quad (\text{TW}) \quad ,$$
$$a(K^-n) = 0.27 + i0.74 \text{ fm} \quad (\text{TWB}) \quad ,$$
$$a(K^-n) = 0.57 + i0.73 \text{ fm} \quad (\text{NLO}) \quad .$$



Some deviation: constraint on K-n (<— kaonic deuterium?)

$\bar{K}N$ potential

Construction of local $\bar{K}N$ potential: few-body application

T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

- Equivalent amplitude on the real axis
- Single-channel, complex, energy-dependent
- SIDDHARTA constraint was not included.
- Pole position was not reproduced.

New realistic $\bar{K}N$ potential

K. Miyahara, T. Hyodo, arXiv:1506.05724 [nucl-th]

- Equivalent amplitude on the complex energy plane (pole)
- Matched with NLO + χ^2 analysis + SIDDHARTA data

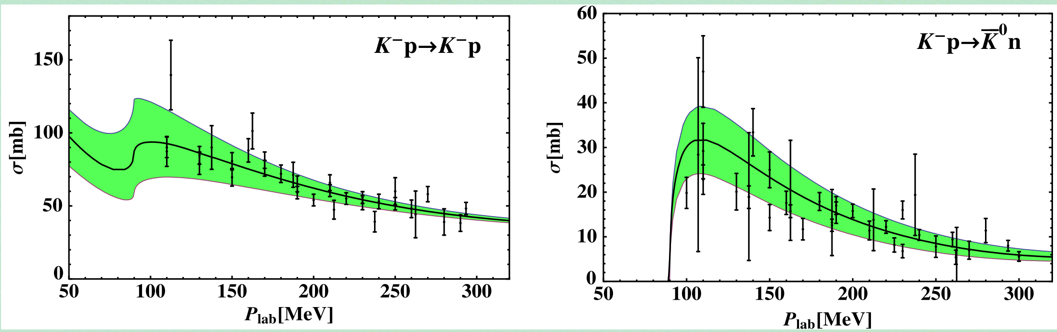
Calculation of $\bar{K}NN$ system: K. Miyahara, S. Ohnishi.

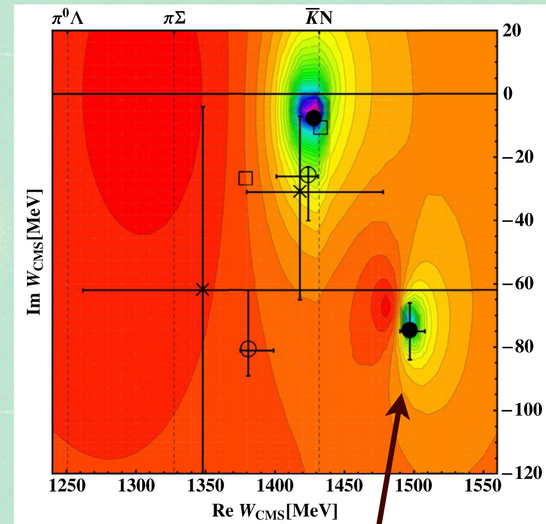
Analyses by other groups

Other models with NLO + χ^2 analysis + SIDDHARTA data

- Bonn group

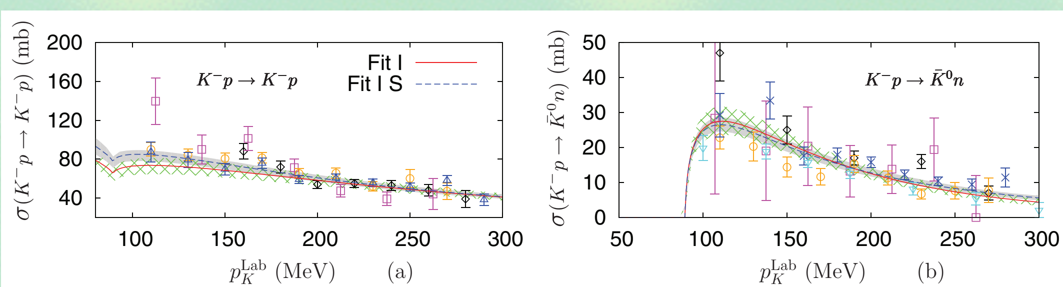
M. Mai, U.-G. Meissner, Nucl. Phys. A900, 51 (2013)





- Murcia group

Z.H. Guo, J.A. Oller, Phys. Rev. C87, 035202 (2013)



~13 parameters —> several local minima

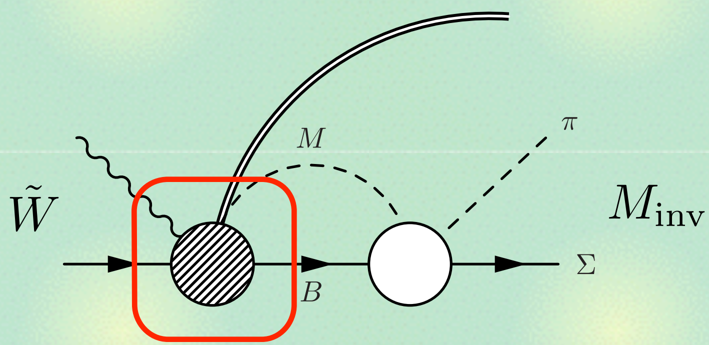
"exotic" solution by Bonn group (second pole above $\bar{K}N$)?

Constraints from the $\pi\Sigma$ spectrum

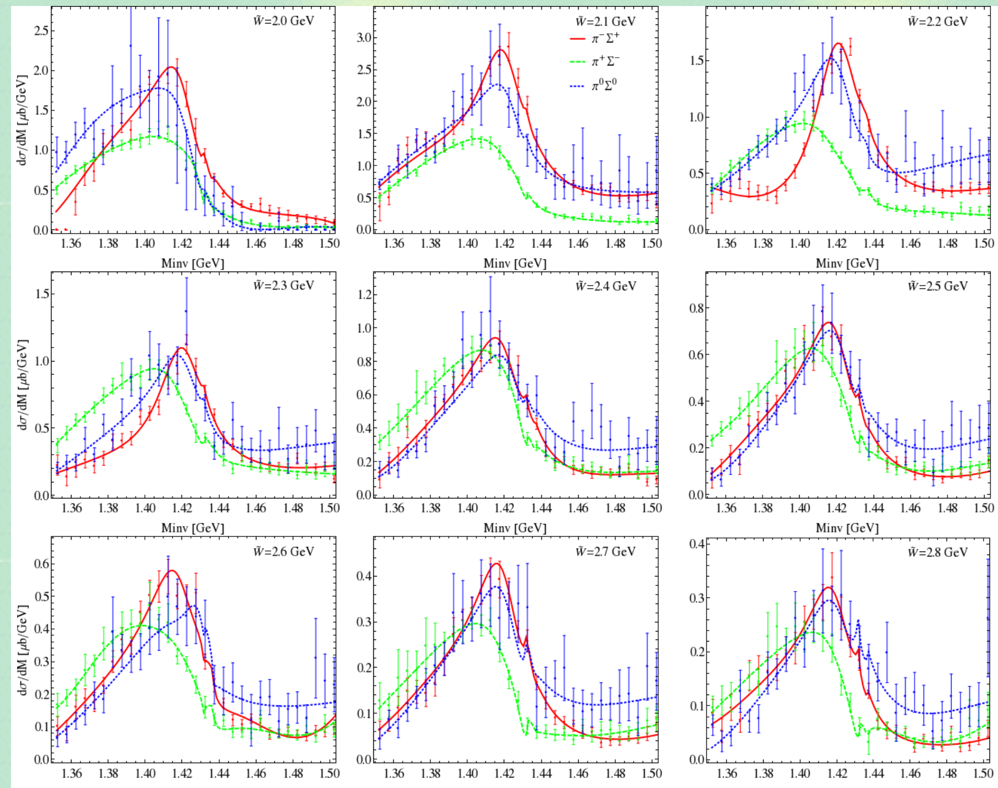
Combined analysis of scattering data + $\pi\Sigma$ spectrum

M. Mai, U.-G. Meissner, Eur. Phys. J. A 51, 30 (2015)

- **a simple model for the photoproduction** $\gamma p \rightarrow K^+(\pi\Sigma)^0$
- **CLAS data of the** $\pi\Sigma$ **spectrum**



$$= \sum_{i=1}^{10} C^i(\tilde{W}) G^i(M_{\rm inv}) f_{0+}^{i,\pi\Sigma}(M_{\rm inv})$$



—> The "exotic" solution is excluded.

Pole positions of Λ(1405)

Mini-review prepared for PDG2015

Pole structure of the Λ(1405)

Ulf-G. Meißner, Tetsuo Hyodo

February 4, 2015

The Λ(1405) resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the archetype of

[11,12] Ikeda-Hyodo-Weise, [14] Murcia, [15] Bonn (updated)

approach	pole 1 [MeV]	pole 2 [MeV]
Ref. [11, 12] NLO	$1424^{+7}_{-23} - i26^{+3}_{-14}$	$1381^{+18}_{-6} - i81^{+19}_{-8}$
Ref. [14] Fit I	$1417^{+4}_{-4} - i24^{+7}_{-4}$	$1436^{+14}_{-10} - i126^{+24}_{-28}$
Ref. [14] Fit II	$1421^{+3}_{-2} - i19^{+8}_{-5}$	$1388^{+9}_{-9} - i114^{+24}_{-25}$
Ref. [15] solution #2	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$	$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
Ref. [15] solution #4	$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

well convergence (pole 1) **still some deviations** (pole 2)

Summary: chiral SU(3) dynamics

We perform systematic χ^2 analysis for the $\bar{K}N$-$\pi\Sigma$ interaction in chiral coupled-channel approach.

- **With the accurate SIDDHARTA data, we can construct realistic $\bar{K}N$-$\pi\Sigma$ interaction. Ambiguity in the subthreshold extrapolation for Λ(1405) energy region is significantly reduced.**
- **Pole position of Λ(1405):**

$$z_1 = (1424^{+7}_{-23} - i26^{+3}_{-14}) \text{ MeV}, \quad z_2 = (1381^{+18}_{-6} - i81^{+19}_{-8}) \text{ MeV}$$

- **Remaining ambiguity: I=1 channel <— kaonic deuterium measurement.**

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)

Summary of current status of Λ(1405)

- **Fitting data above $\bar{K}N$ threshold, the (main) pole of Λ(1405) appears at ~1420-20i MeV, not at 1405 MeV.**

- **Consistency with πΣ spectra is important to constrain the amplitude far below threshold.**

- **Future direction:**

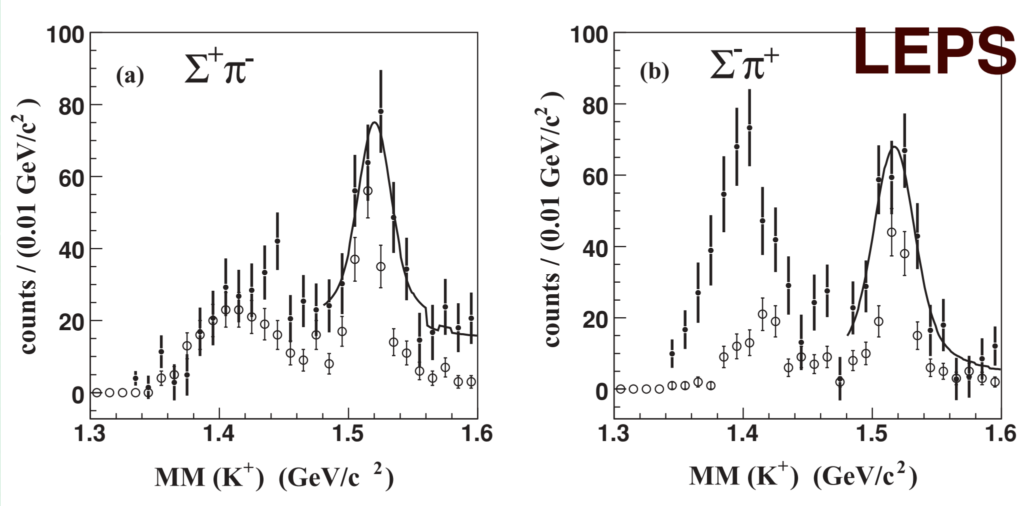
NLO chiral interaction χ^2 **error analysis** **reliable reaction model**	→	$\bar{K}N$ **scattering data** K-p **scattering length** πΣ **spectrum**

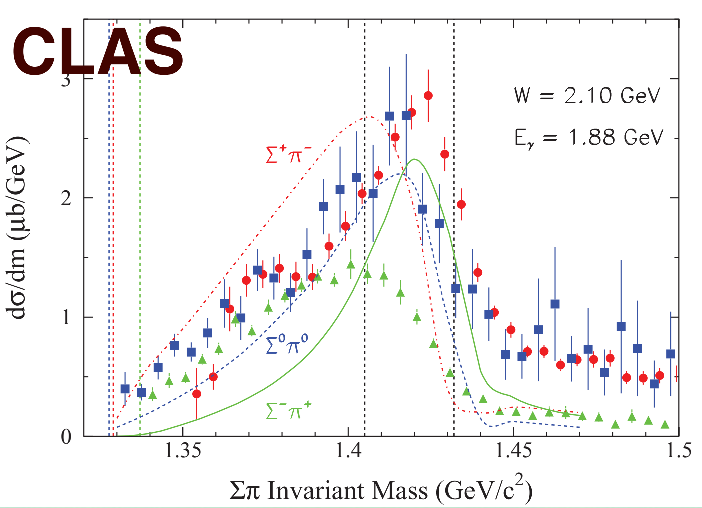
New πΣ spectra

Photoproduction experiments: γp -> K⁺(πΣ)⁰

- **LEPS@**1.5 < Eγ < 2.4 **GeV, CLAS@**1.56 < Eγ < 3.83 **GeV**

M. Niiyama, *et al.*, Phys. Rev. C78, 035202 (2008);
K. Moriya, *et al.*, Phys. Rev. C87, 035206 (2013)





Hadron-induced reactions:

- **HADES:** pp -> K⁺p(πΣ)⁰

G. Agakishiev, *et al.*, Phys. Rev. C87, 025201 (2013)

- **J-PARC E31 (to be available):** K-d -> n(πΣ)⁰

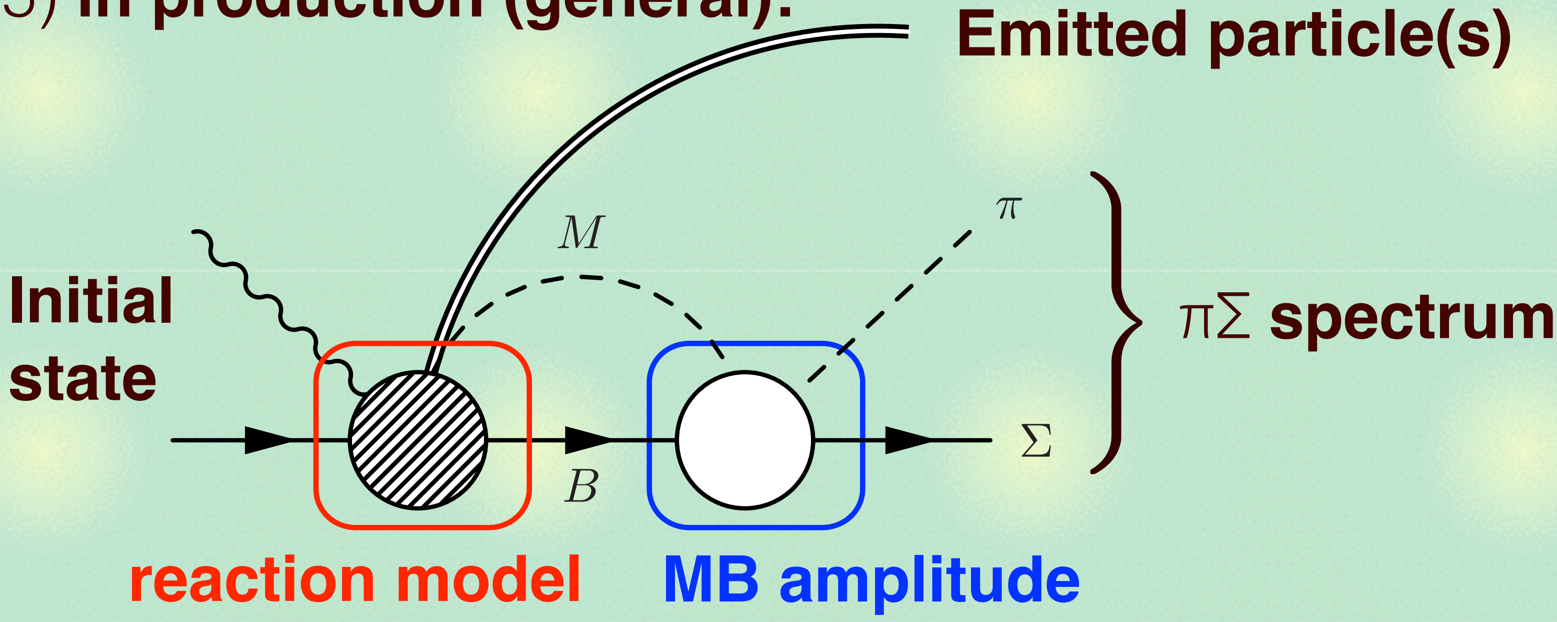
New and precise spectra are being available.

πΣ spectra and $\bar{K}N$ interaction

Can spectra constrain the MB amplitude ($\bar{K}N$ interaction)?

- Not directly.

Λ(1405) in production (general):



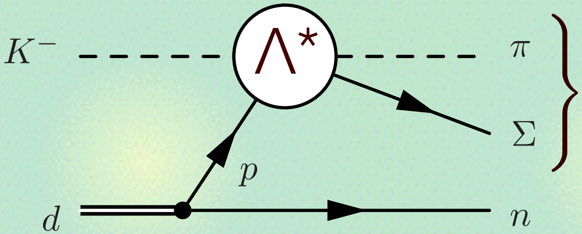
- Spectra depend on the reaction (ratio of $\bar{K}N$/πΣ in the intermediate state, interference with I=1,...).

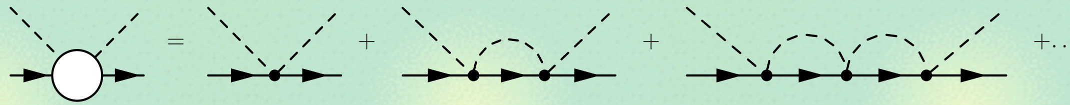
—> Detailed model analysis for each reaction

Faddeev approach for K-d **reaction**

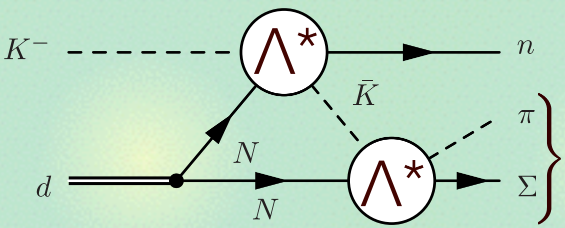
Diagrams for K-d -> πΣn **: J-PARC E31 (~1 GeV** K-**)**

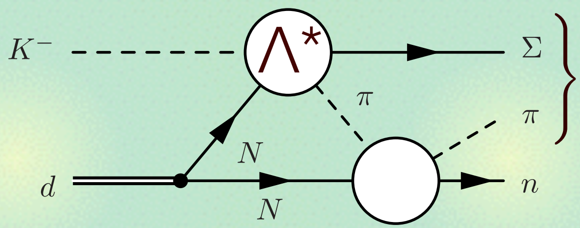
- one-step process

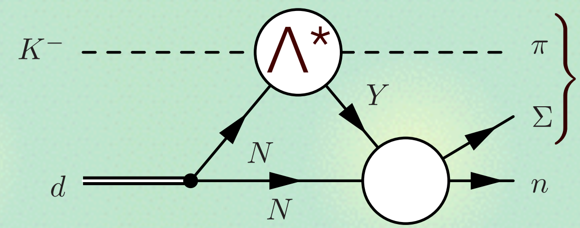




- two-step processes

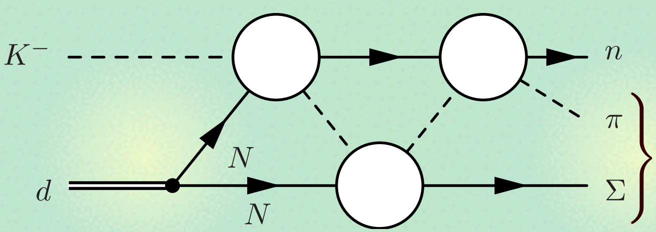






(non-resonant background)

- three-step processes,…



+ infinitely many diagrams

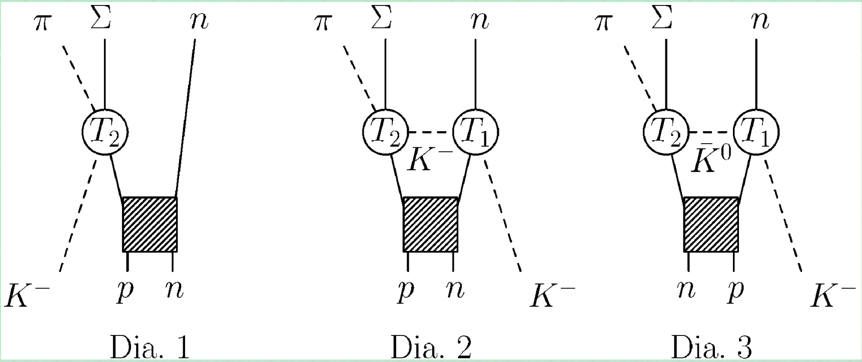
Faddeev equation sums all diagrams nonperturbatively.

Previous attempts for K-d reaction

Two-step approaches

D. Jido, E. Oset, T. Sekihara, Eur. Phys. J. A42, 257 (2009);
J. Esmaili, Y. Akaishi, T. Yamazaki, Phys. Rev. C83, 055207 (2011);
D. Jido, E. Oset, T. Sekihara, Eur. Phys. J. A47, 42 (2011);
K. Miyagawa, J. Haidenbauer, Phys. Rev. C85, 065201 (2012);
J. Yamagata-Sekihara, T. Sekihara, D. Jido, PTEP 043D02 (2013)

- **Perturbative: full three-body dynamics is not included.**



Faddeev(AGS) approach for stopped K

J. Revai, Few-Body Syst. 54, 1865 (2013)

- πΛN **channel is not included.**
- **relative s-wave to spectator (valid at low energy)**
- **nonrelativistic kinematics (valid at low energy)**

Strategy for in-flight K-d reaction

Framework of K-d -> πΣn for J-PARC E31 (~1 GeV K-)

S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise,
J. Phys. Conf. Ser. 569, 012077 (2014)

- **Faddeev(AGS)** **amplitude: full three-body dynamics**
- **Inclusion of the** πΛN **channel: proper** I=1 **contribution**
- **Inclusion of relative** L > 0 **with spectator (two-body interaction is s-wave only)**
- **MB interaction: energy-dep. and energy-indep. interactions (fitted to cross sections, to be constrained by SIDDAHRTA)**

Y. Ikeda, H. Kamano, T. Sato, Prog. Theor. Phys. 124, 533 (2010)

Recent improvements:

S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise, in preparation

- **Relativistic kinematics (1 GeV incident momentum)**
- **Inclusion of** πN, YN **final state interaction**

πΣ spectra with various charge combinations

πΣ spectra @ P_{K^-} = 1 GeV, angle integrated

<u>**S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise, in preparation**</u>

See the forthcoming preprint

Difference of energy-dep. / energy-indep. (shape, magnitude)

- distinction of subthreshold $\bar{K}N$ amplitude

$\pi\Sigma$ spectra with various charge combinations

$\pi\Sigma$ spectra @ P_{K^-} = 1 GeV, forward neutron

S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise, in preparation

See the forthcoming preprint

Difference of $\pi^-\Sigma^+$ and $\pi^+\Sigma^-$ spectra

- **large interference effect with I=1 components**

$$|\,\bar{K}[NN]_{I=0}\,\rangle_{I=1/2} = -\frac{1}{2}|\,[\bar{K}N]_{I=0}N\,\rangle_{I=1/2} + \frac{\sqrt{3}}{2}|\,[\bar{K}N]_{I=1}N\,\rangle_{I=1/2}$$

Summary: production reaction

We study the K-d -> πΣn reaction for J-PARC E31

- We employ the Faddeev(AGS) amplitude with πΛN channel, relative L to spectator, all final state interactions and relativistic kinematics are included.
- Deviation of different charged πΣ states indicates the large interference with I=1.
- Lineshape and the magnitude of πΣ spectra are sensitive to subthreshold $\bar{K}N$ interaction.

S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise,
J. Phys. Conf. Ser. 569, 012077 (2014) + in preparation