

The 12th International Workshop on the Physics of Excited Nucleons

Meson-baryon Scattering in Extended-on-mass-shell Scheme at $O(p^3)$

Junxu LU



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Meson-Baryon scattering

- ❑ Introduction and motivation
- ❑ Framework: EOMS ChPT
- ❑ Results and discussion
 - Fit I: a direct fit to elastic phase shifts
 - Convergence
 - Fit II: a combined fit with baryon masses
- ❑ Summary and perspectives

Meson-Baryon scattering

Experimental data

- scattering phase shifts and scattering lengths of πN and KN
WI08 and SP92 solution. W. J. Briscoe et al., SAID on-line program
H. C. Schroder et al., Eur. Phys. J. C 21, 473 (2001).
R. A. Arndt et al, Phys. Rev. C 74, 045205 (2006)
- Cross section and scattering lengths of $\bar{K}N$ channel
 - $K^- p \rightarrow K^- p, \bar{K}^0 n, \pi^+ \Sigma^-, \pi^- \Sigma^+, \pi^0 \Sigma^0, \pi^0 \Lambda, \eta \Lambda$
Phys. Rev. 127 (1962) 1305; J. Phys. G 8 (1982) 13; Phys. Rev. Lett. 19 (1967) 1074;
J. Phys. G 9 (1983) 885; Phys. Lett. 21 (1966) 349; Phys. Rev. 139 (1965) B719.
J. K. Kim, Columbia University Report No. NEVIS-149, 1966.
A. Starostin et al., Phys. Rev. C 64 (2001) 055205.
 - Kaonic hydrogen data
G. Beer et al. [DEAR Collaboration], Phys. Rev. Lett. 94 (2005) 212302
M. Bazzi et al. [SIDDHARTA Collaboration], Phys. Lett. B 704 (2011) 113
- Lattice QCD
 - A. Torok et al, Phys. Rev. D 81, 074506 (2010)
 - W. Detmold and A. Nicholson, Phys. Rev. D 93, 114511 (2016)
- Roy-steiner equation analysis for πN
M. Hoferichter et al. Phys. Rept. 625 (2016) 1

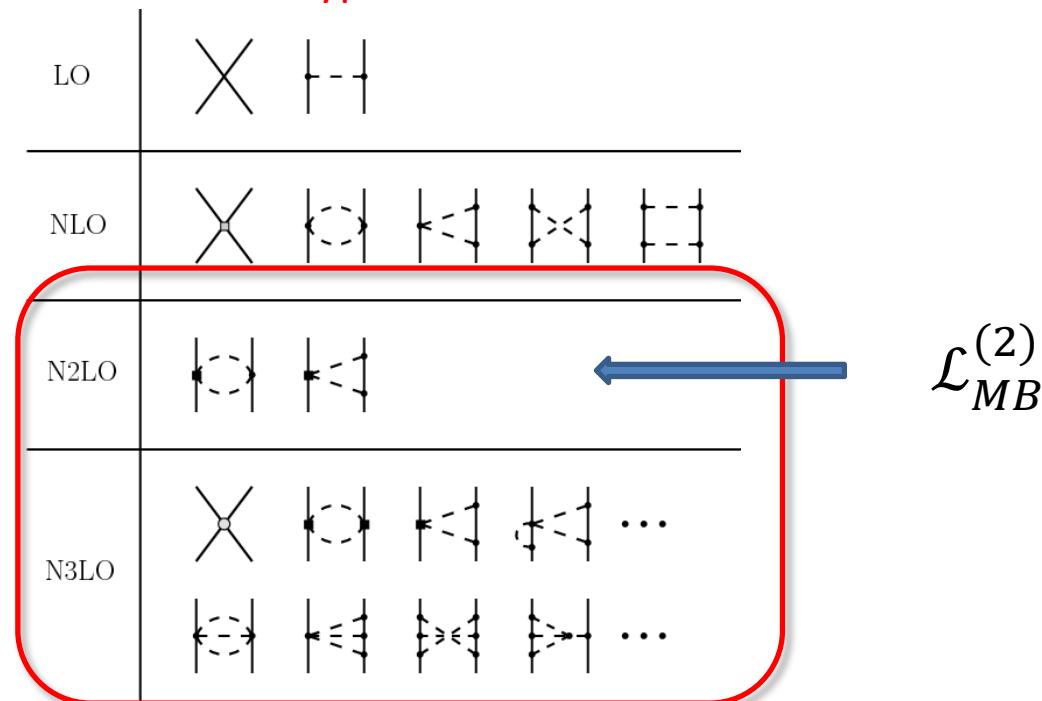
Meson-Baryon scattering

Basic motivation: description of experimental data

- scattering phase shifts and scattering lengths of πN and KN
- Cross section and scattering lengths of $\bar{K}N$ channel

Phenomena related with Meson-baryon scattering

- Baryon-baryon interaction
 - Nucleon-nucleon or hyperon-nucleon interaction



Meson-Baryon scattering

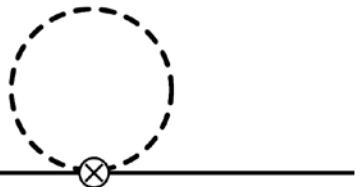
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- Intrinsic properties of baryons
 - Baryon masses and sigma terms

JHEP1212,073; PLB783,7



Tad pole contribution $\mathcal{L}_{MB}^{(2)}$

From baryon masses

$$\sigma_{\pi B} = m_l \langle B(p) | \bar{u}u + \bar{d}d | B(p) \rangle = m_l \frac{\partial M_B}{\partial m_l}$$

$$\sigma_{sB} = m_s \langle B(p) | \bar{s}s | B(p) \rangle = m_s \frac{\partial M_B}{\partial m_s},$$

From MB scattering

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

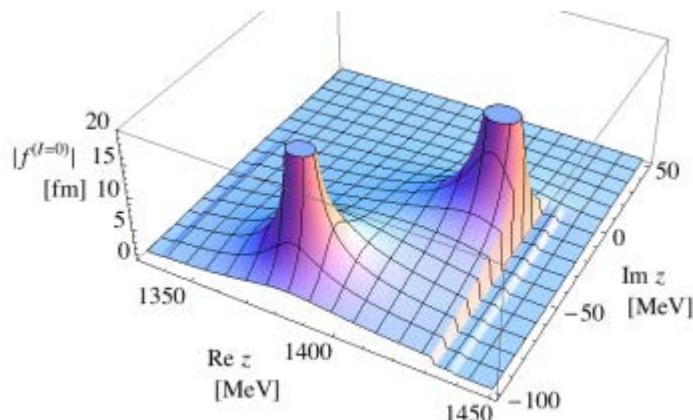
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- Non-perturbation phenomena in Meson-baryon interaction
 - The double-pole structure of $\Lambda(1405)$ in $\bar{K}N$ and its coupled channel



D. Jido et al. *Nucl.Phys. A725 (2003) 181-200*

A.V. Anisovich et al. *arXiv: 1905.05456*

Meson-Baryon scattering

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 - The double-pole structure of $\Lambda(1405)$ in $\bar{K}N$ and its coupled channel
 - In photon-production **CLAS Collaboration; A2 Collaboration**
 - Kaonic cluster $\bar{K}NN$ **J-PARC laboratory**
 - Proton-proton collisions **COSY and HADES Collaboration**

Meson-Baryon scattering

Basic motivation: description of experimental data

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Theoretical progress

- **Elastic scattering**
 - SU(2) up to N3LO, while SU(3) up to NNLO
- **Non-perturbation study of $\bar{K}N$**
 - Stop at NLO

NPA881,98; PRC87,035202; EPJA51,30; NPA881,115; PRC99,035201; NPA954,17

Weinberg's Chiral EFT



- Systematically improve the description
- Estimate theoretical uncertainties

- Power counting rule

First proposed by Steven Weinberg

$$D = 4L + \sum_n n V_n - 2N_M - N_B$$

- D: chiral order of certain diagram
- L: number of loops
- V_n : number of n-th order vertices
- N_M : number of meson propagators
- N_B : number of baryon propagators

$$\mathcal{L}_{EFT} = \mathcal{L}_{MB}^{(1)} + \mathcal{L}_{MB}^{(2)} + \mathcal{L}_{MB}^{(3)} + \dots + \mathcal{L}_{MM}^{(2)} + \dots$$

where the superscripts denote the chiral order

Power counting breaking(PCB) terms

- Non-vanishing baryon mass at chiral limit
- To restore the power counting rules
 - Heavy baryon (HB) E. E. Jenkins and A. V. Manohar, **PLB 255 (1991) 558.**
 - Non-relativistic
 - Modified analytical properties
 - Infrared regularization (IR) T. Becher and H. Leutwyler, **EPJC 9 (1999) 643**
 - Modified analytical properties
 - Extended-on-mass-shell (EOMS) J. Gegelia, T. Fuchs et al. in **PRD60(1999), PRD68 (2003)**
 - Lorentz covariance and analytical properties
 - Converge faster

Baryon masses
JHEP1212,073

Baryon magnetic momentum
EPJC78,489

Pion-Nucleon scattering
PRC94,014620 PRC96,055205

Data

- Phase shifts: WI08/SP92
 - πN channel: $S_{11}, P_{11}, P_{13}, S_{31}, P_{31}, P_{33}$ $L_{2I,2J}$
 - KN channel: $S_{01}, P_{01}, P_{03}, S_{11}, P_{11}, P_{13}$ $L_{I,2J}$
 - Error bar: $err(\delta) = \sqrt{e_s^2 + e_r^2 \delta^2}$ $e_s=0.1^\circ$:systematic error $e_s=2\%$:relative error
- Low energy constants

If we only concentrate on πN and KN elastic scattering, these channels are decoupled

πN	$KN_{I=0}$	$KN_{I=1}$
$b_1 + b_2 + b_3 + 2b_4$	$b_3 - b_4$	$b_1 + b_2 + b_4$
$b_5 + b_6 + b_7 + b_8$	$2b_6 - b_8$	$2b_5 + 2b_7 + b_8$
$c_1 + c_2$	$4c_1 + c_3$	$4c_2 + c_3$
$2b_0 + b_D + b_F$	$b_0 - b_F$	$b_0 + b_D$
d_2	$d_1 + d_2 + d_3$	$d_1 - d_2 - d_3$
d_4	$d_4 + d_5 + d_6$	$d_4 - d_5 + d_6$
$d_8 + d_{10}$	$d_7 - d_8 + d_{10}$	$d_7 + d_8 + d_{10}$
d_{49}	$d_{48} + d_{49} + d_{50}$	$d_{48} + d_{49} - d_{50}$

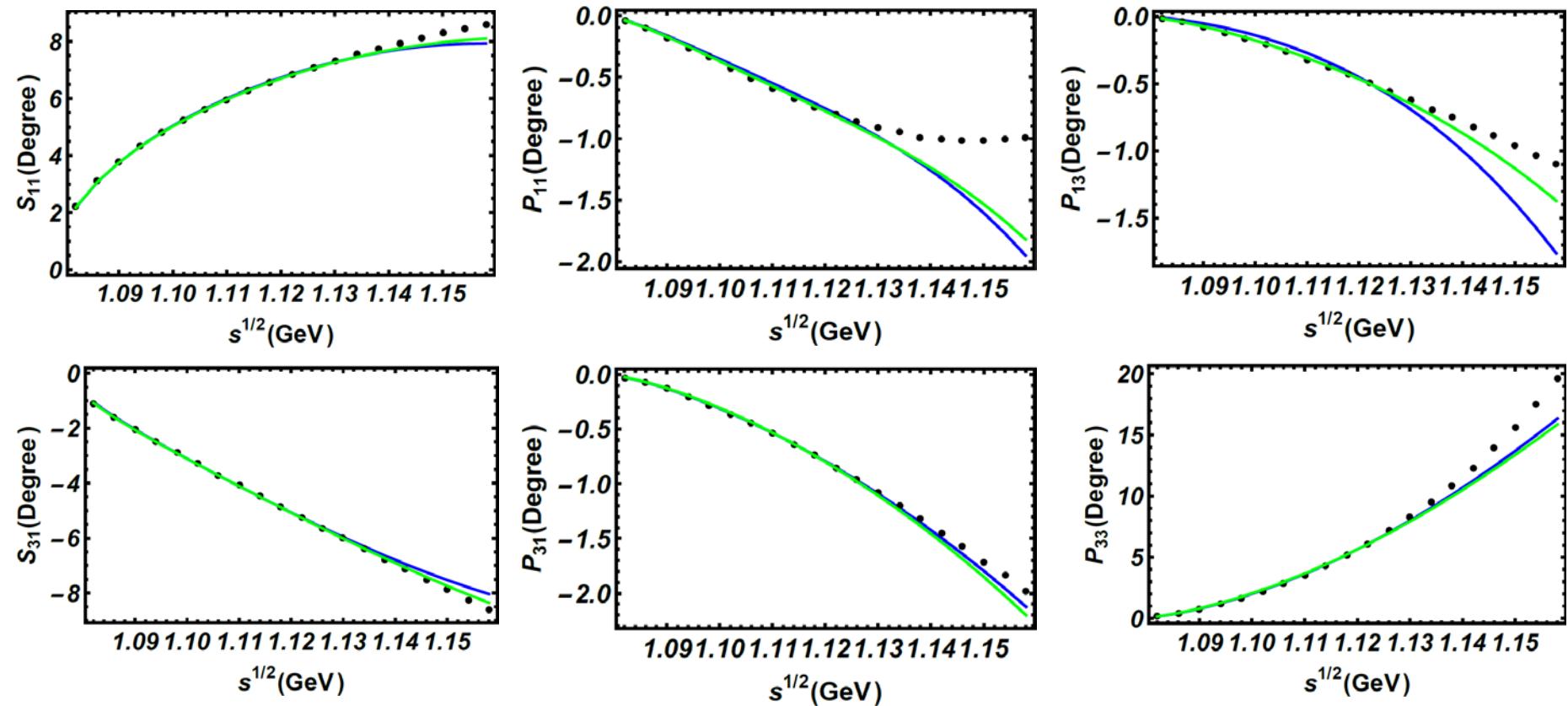
Results and discussions

- Fit I: a direct fit to elastic phase shifts

πN channel: direct fit

The partial wave phase shifts of πN channel.

- $\chi^2/\text{d.o.f} = 0.348$



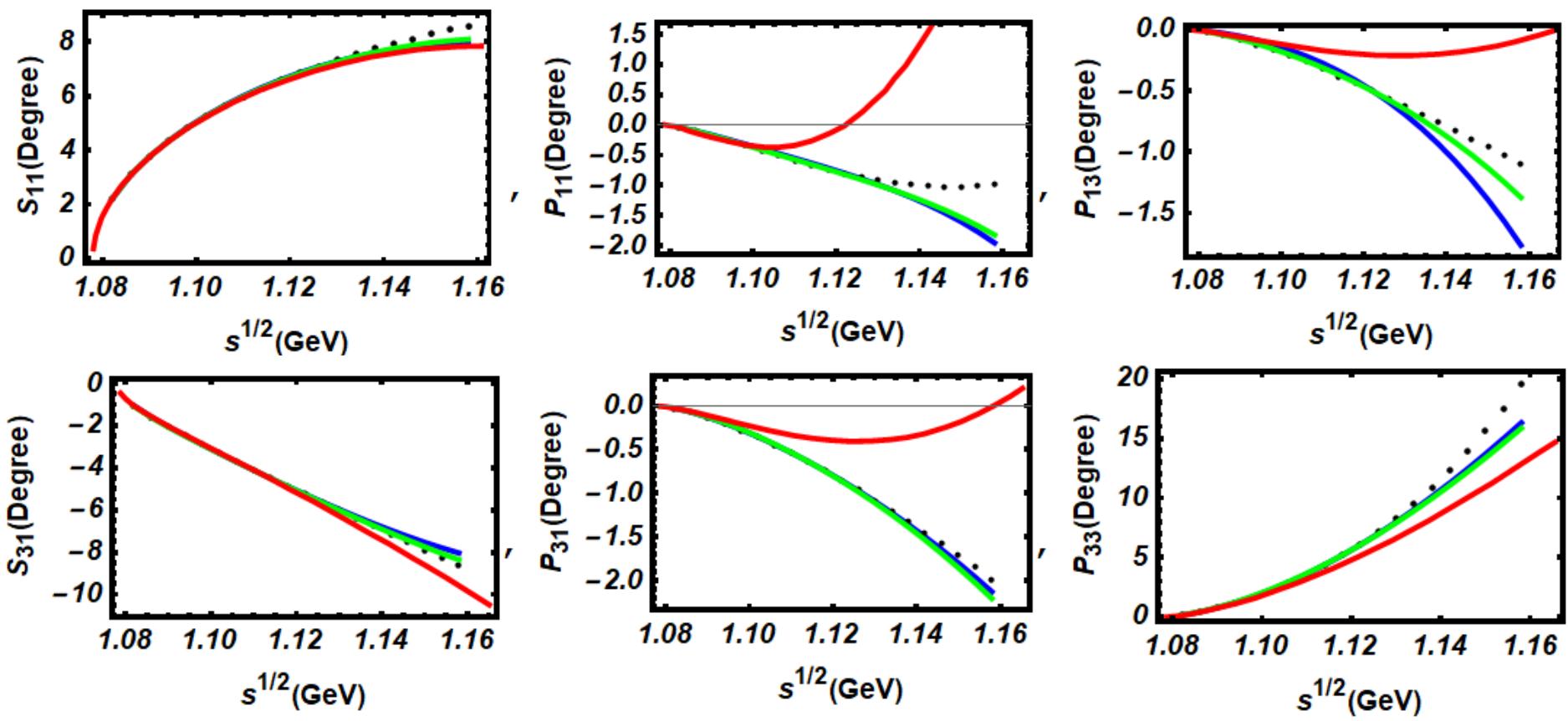
Blue: SU3 EOMS

Green: SU2 EOMS Chen et al. PRD87(2013)054019

Black dot: EXP

πN channel: direct fit

A comparison with **SU(3) heavy baryon ChPT.**



Blue: SU3 EOMS

Green: SU2 EOMS Chen et al. PRD87(2013)054019

Red: SU3 HB Huang et al. PRD96(2017)016021

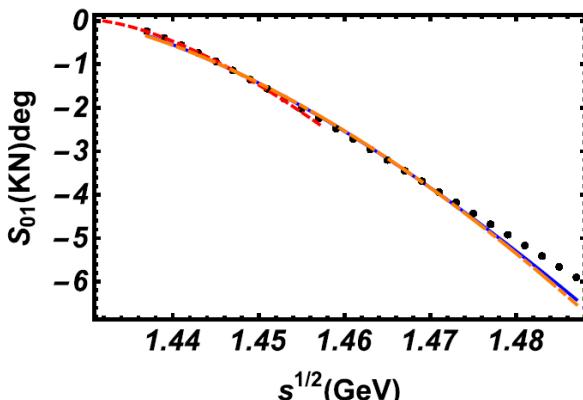
Black dot: EXP

KN channel: direct fit

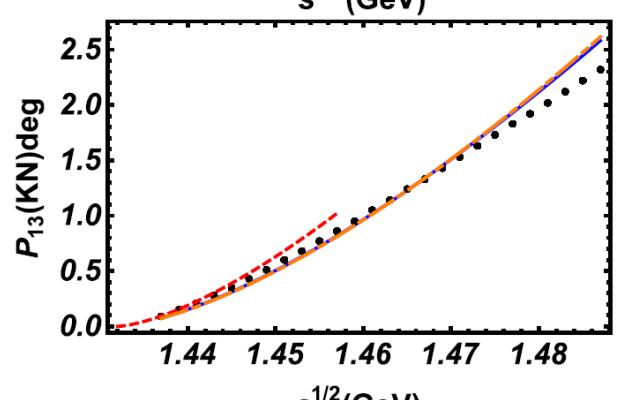
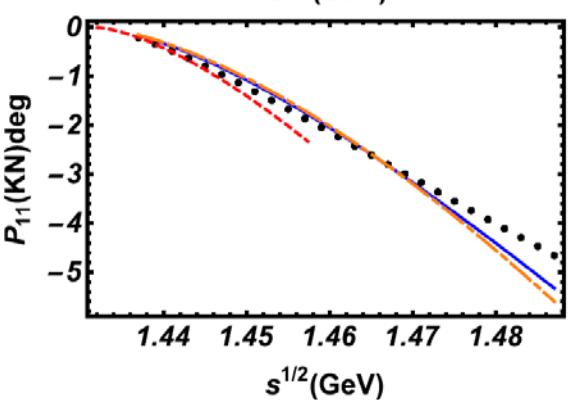
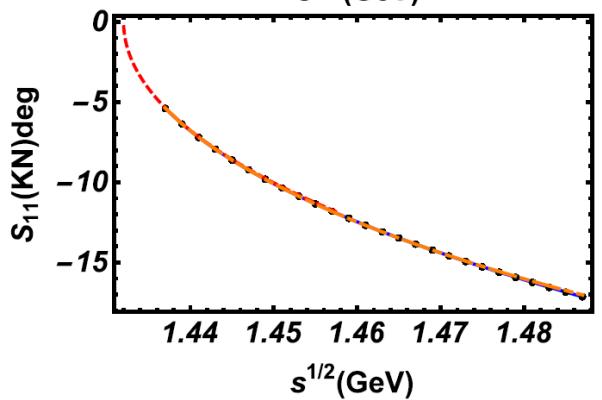
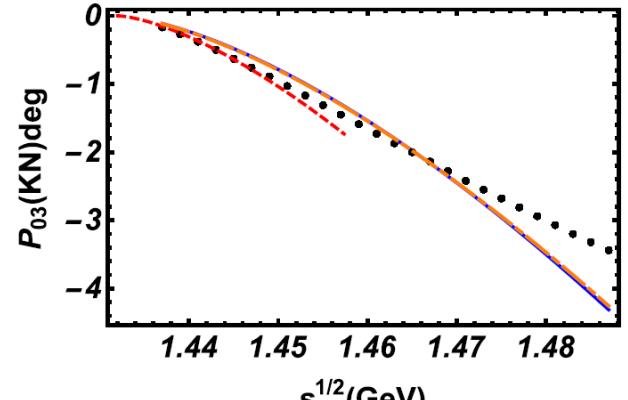
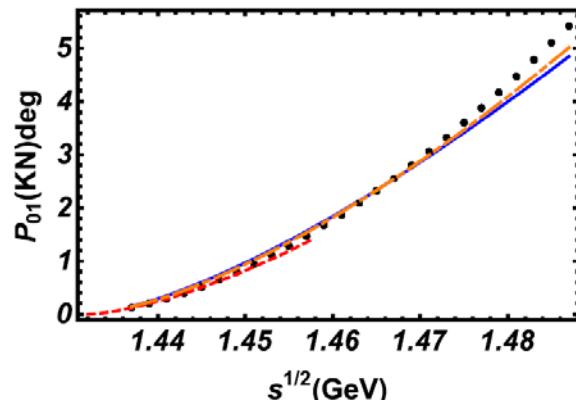
The partial wave phase shifts of KN channel.

For now, we are not considering the tree level at $\mathcal{O}(p^3)$

- Isospin=0, $\chi^2/\text{d.o.f} = 1.046$



- Isospin=1, $\chi^2/\text{d.o.f} = 0.507$



Blue: SU3 EOMS($\mathcal{O}(p^3)$ *)

Red: SU3 HB

Orange: SU3 NLO($\mathcal{O}(p^2)$)

Black dot: EXP

Scattering length

Threshold parameters

$$a_l = \lim_{p \rightarrow 0} \frac{\text{Re} f_{l\pm}}{|p|^{2l}}$$

Channel	Total	Huang(HB) [16]	Mai(IR) [14]	EXP
$a_{\pi N}^{3/2}$	-0.111(16)	-0.110(2)	-0.04(7)	-0.125(3) [73]
$a_{\pi N}^{1/2}$	0.240(22)	0.240(2)	0.07(3)	$0.250^{+0.006}_{-0.004}$ [73]
$a_{KN}^1(\mathcal{O}(p^2))$	-0.327(1)	-0.330(5)	-0.33(32)	-0.33 [59]
$a_{KN}^0(\mathcal{O}(p^2))$	-0.014(2)	0.000(4)	0.02(64)	0.02 [59]
$a_{KN}^1(\mathcal{O}(p^3)^*)$	-0.328(5)	-/-	-/-	-/-
$a_{KN}^0(\mathcal{O}(p^3)^*)$	-0.012(2)	-/-	-/-	-/-

- Both EOMS and HB results are compatible with EXP considering the uncertainties
- Scattering lengths remain almost the same for KN with or without loop level.
- For iso-scalar KN channel, the sign is opposite

Results and discussions

- Convergence

Convergence

- In SU(2), the reasonable convergence has been confirmed PRC94,014620; PRC96,055205

- In SU(3), the convergence turns out to be slow

Expansion parameters:

$$\frac{M_K}{\Lambda_{\chi PT}} \sim \frac{1}{2}$$

□ Threshold parameters

Channel	$\mathcal{O}(p^1)$	$\mathcal{O}(p^2)$	$\mathcal{O}(p^3)$	Total
$a_{\pi N}^{3/2}$	-0.126	0.026(11)	-0.011(8)	-0.111(16)
$a_{\pi N}^{1/2}$	0.212	0.025(10)	0.003(16)	0.240(22)
$a_{KN}^1(\mathcal{O}(p^2))$	-0.476	0.149(1)	-/-	-0.327(1)
$a_{KN}^0(\mathcal{O}(p^2))$	0.043	-0.057(2)	-/-	-0.014(2)
$a_{KN}^1(\mathcal{O}(p^3)^*)$	-0.476	1.067(5)	-0.919	-0.328(5)
$a_{KN}^0(\mathcal{O}(p^3)^*)$	0.043	0.164(2)	-0.219	-0.012(2)

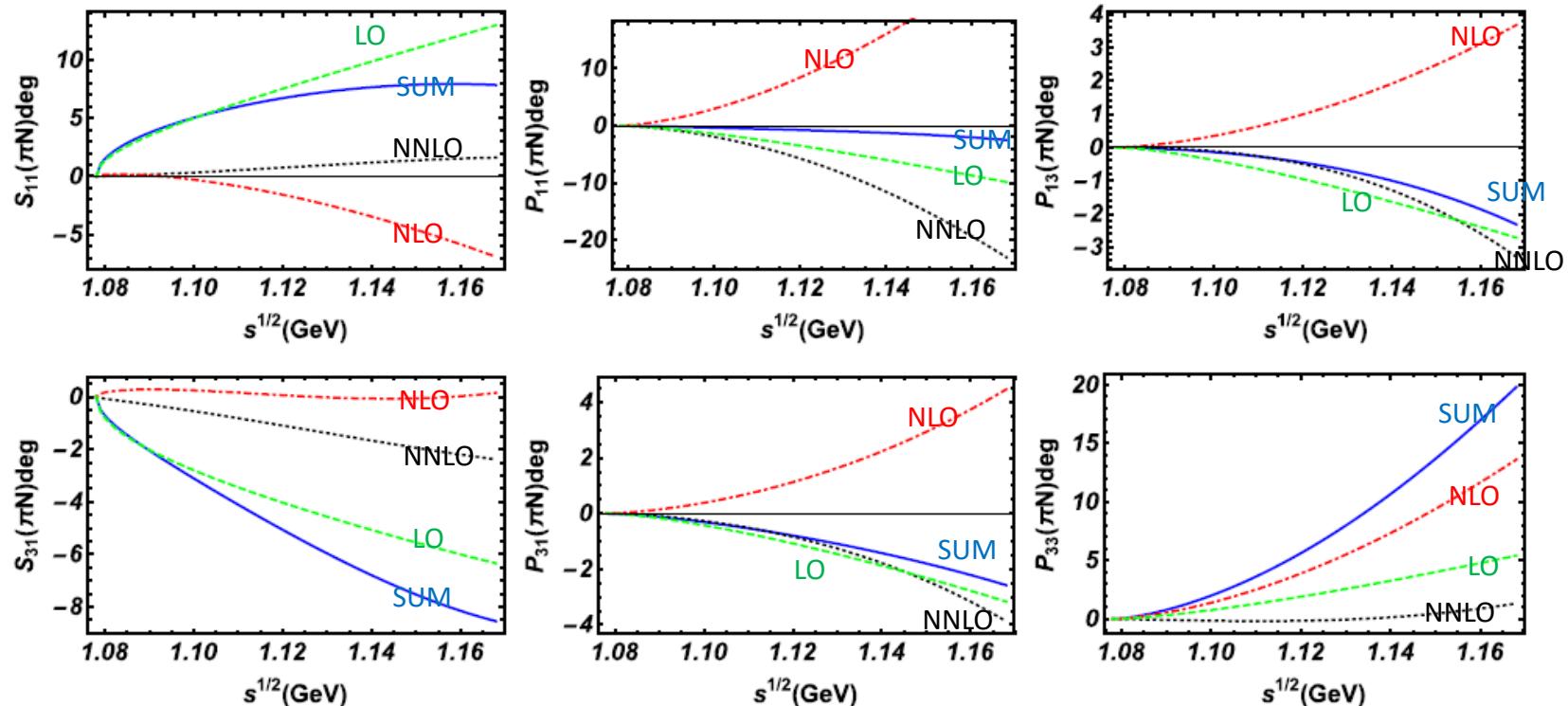
- For πN , the scattering lengths decrease order by order

NNLO tree level not included

- For KN , the LO is smallest
- Large cancellations between NLO and NNLO contributions

Convergence

□ Phase shifts for πN channel

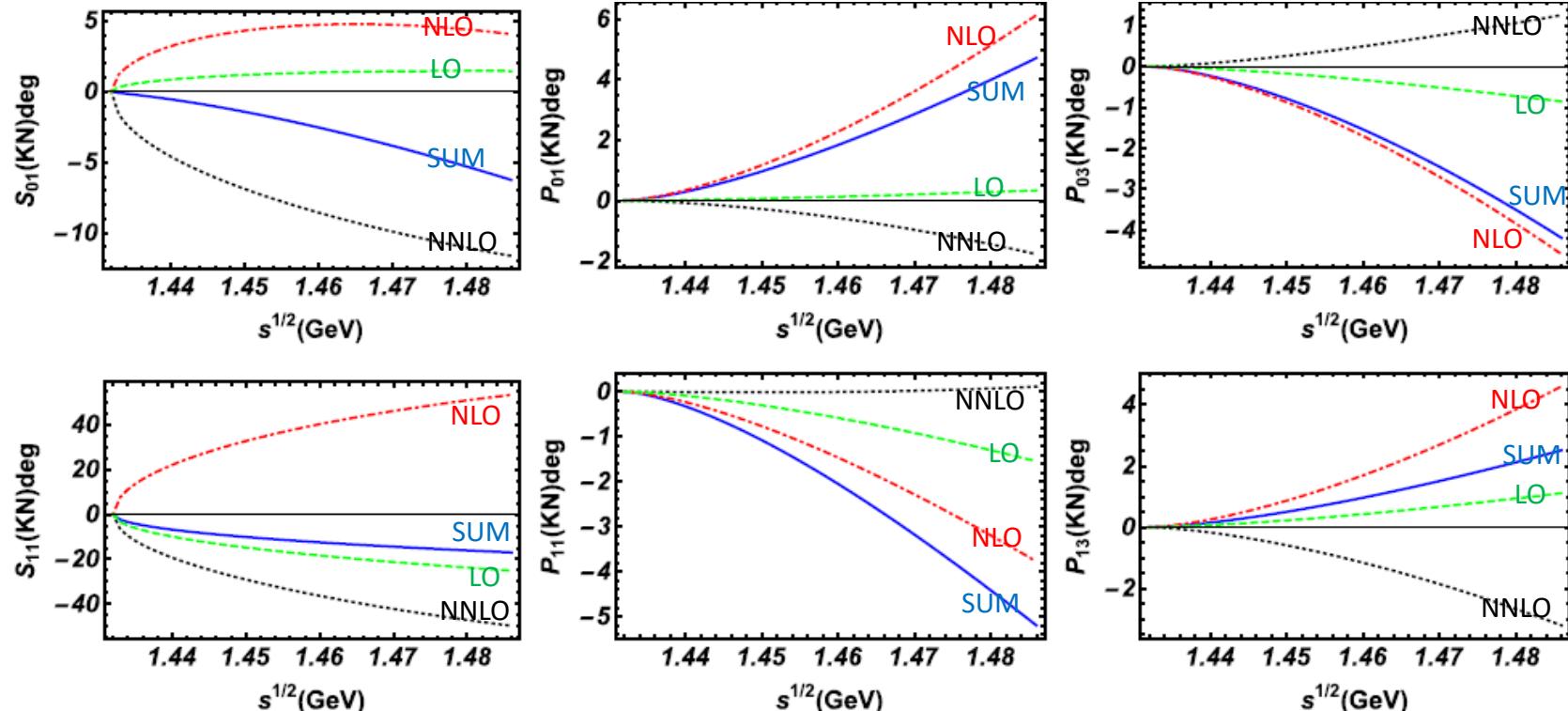


- S-waves, reasonable convergence pattern in low energy
- P-waves, NNLO are in general smaller than NLO in quite a wide region. But in higher region, sizable cancellations appears.

Convergence

- Phase shifts for KN channel

We have not included the NNLO tree level

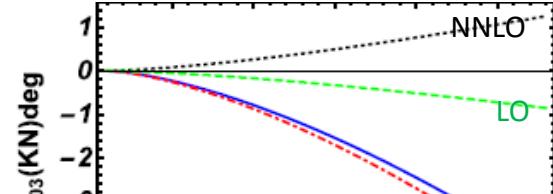
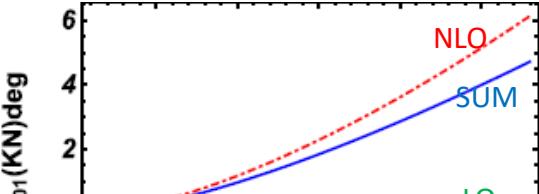
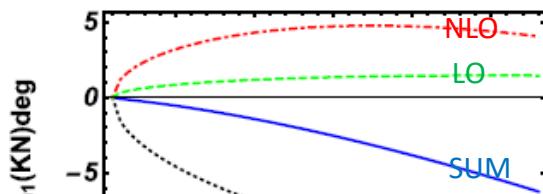


- LO are smallest.
- S-waves, there are obvious cancelations between NLO and NNLO
- Most P-waves, NNLO are significantly smaller than NLO.

Convergence

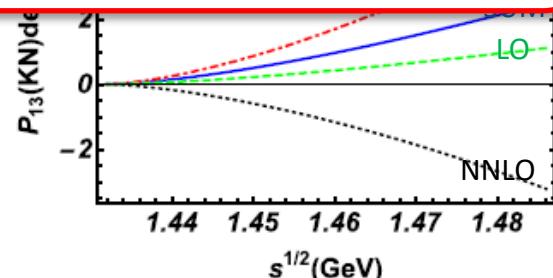
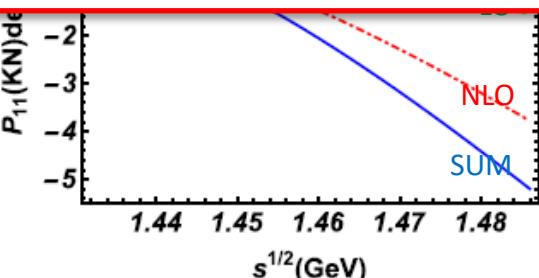
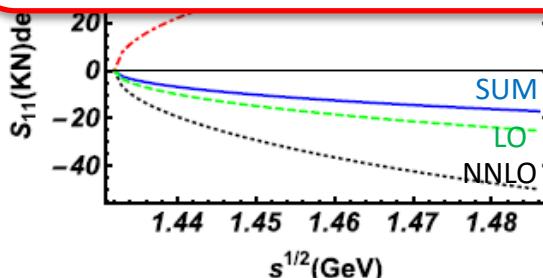
□ Phase shifts for KN channel

We have not included the NNLO tree level



Conclusion:

- Similarly to SU(2) cases: a questionable convergence.
- A significantly smaller NNLO compared with NLO in most partial waves
- The absence of NNLO tree level



- LO are smallest.
- S-waves, there are obvious cancelations between NLO and NNLO
- Most P-waves, NNLO are significantly smaller than NLO.

Results and discussions

- Fit II: a combined fit to baryon masses

Combined fit with baryon masses and scattering

- Baryon masses and MB scattering share one scenario of LECs

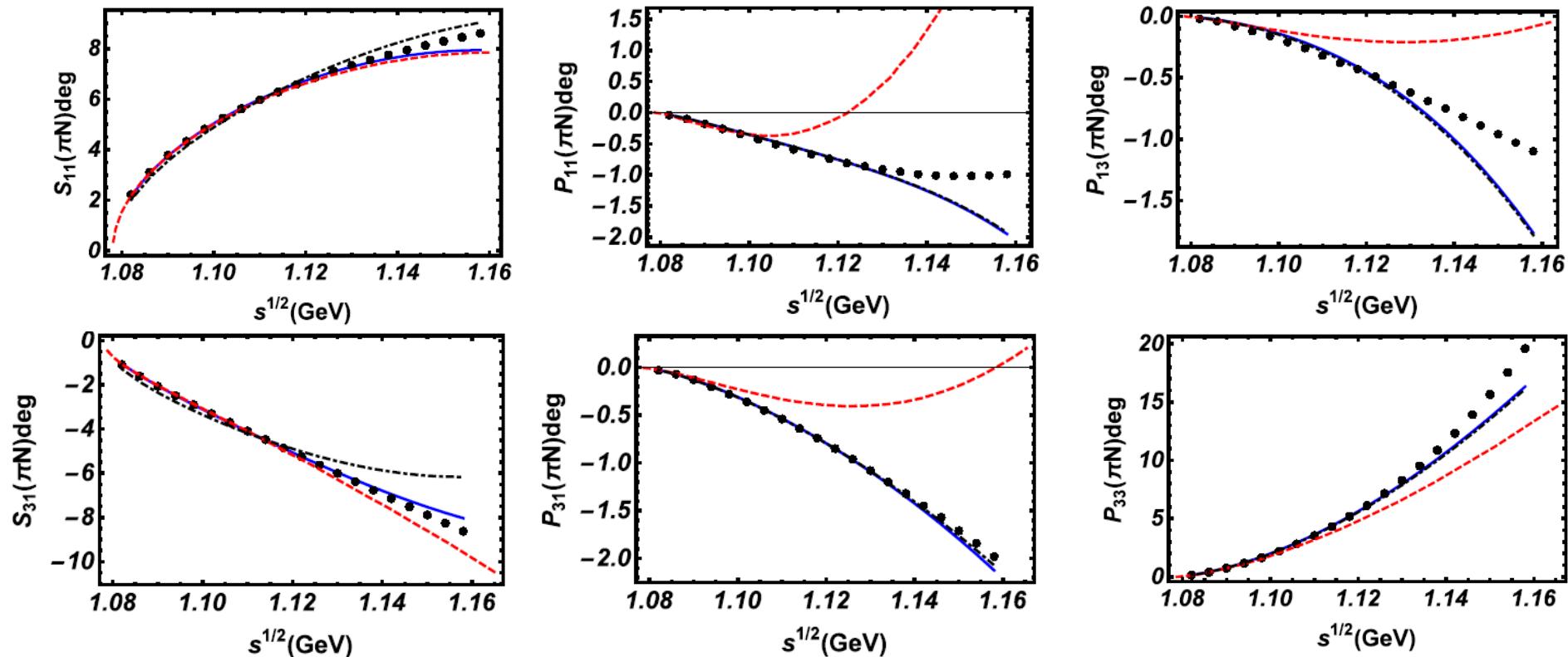
LECs contribute at different orders

	Baryon masses	MB scattering
NLO	NLO LEC: b_0, b_D, b_F	NLO LEC: $b_0, b_D, b_F, b_{1-8}, c_{1-3}$
NNLO		NNLO LEC: d_{1-10}, d_{48-50}
N3LO	NLO LEC: b_0, b_D, b_F, b_{1-8} N3LO LEC: e_{1-5}, e_7, e_8	NLO LEC: $b_0, b_D, b_F, b_{1-8}, c_{1-3}$ All related N3LO LECs

- Up to NNLO, only b_0, b_D, b_F show up in baryon masses, while in scattering amplitudes, there are 21 more LECs.
- The LQCD masses cannot be described well with NNLO baryon masses.
- Up to N3LO, too many parameters compared with experimental data

πN channel in combined fit

- Combine NNLO baryon masses and NNLO MB scattering



- S-waves, visible effect in higher energy regime
- P-waves, tiny differences

Blue: Direct fit

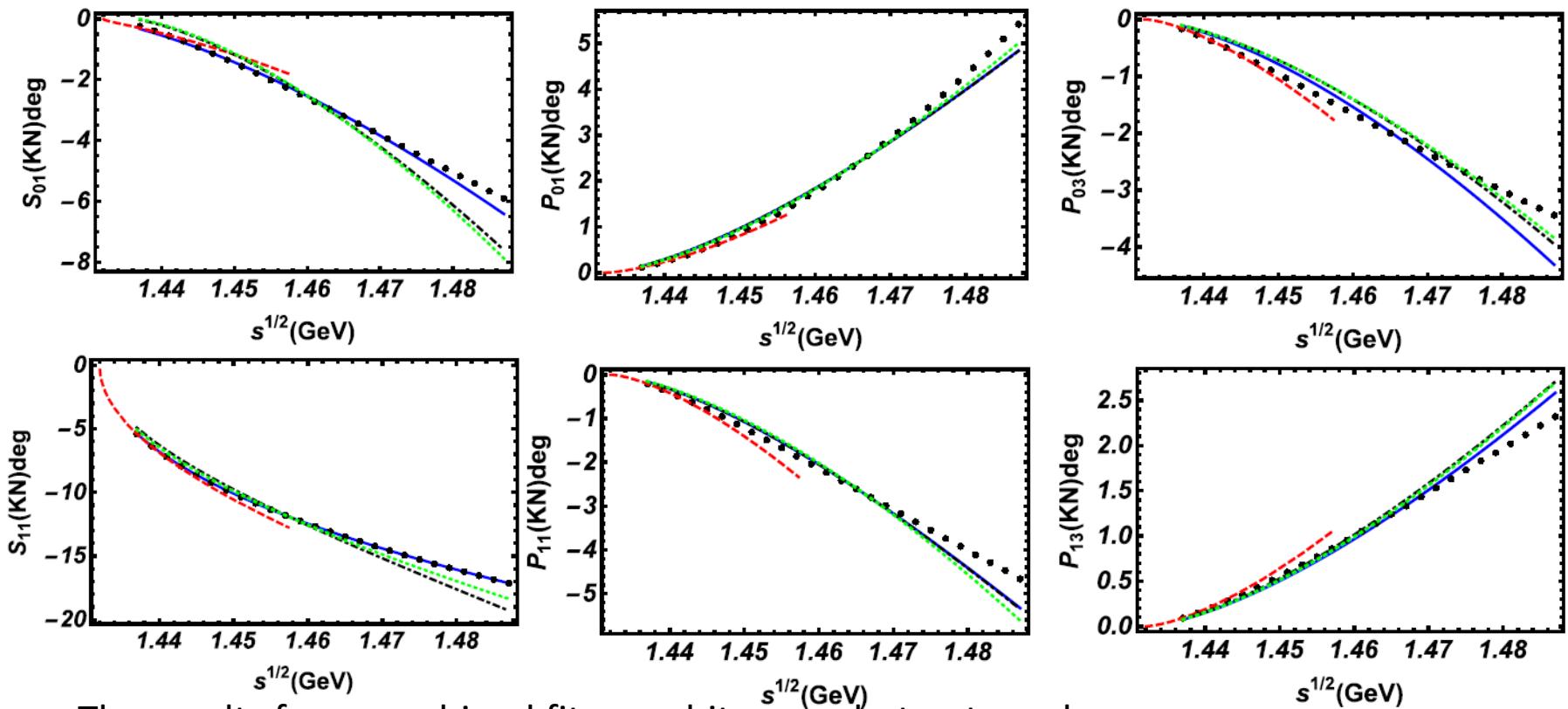
Black :Combined fit

Red: SU3 HB

Black dot: EXP

KN channel in combined fit

- Combine NNLO baryon masses and NNLO MB scattering



- The results from combined fit are a bit worse but not much

Blue: Direct fit

Black :combined fit with loops

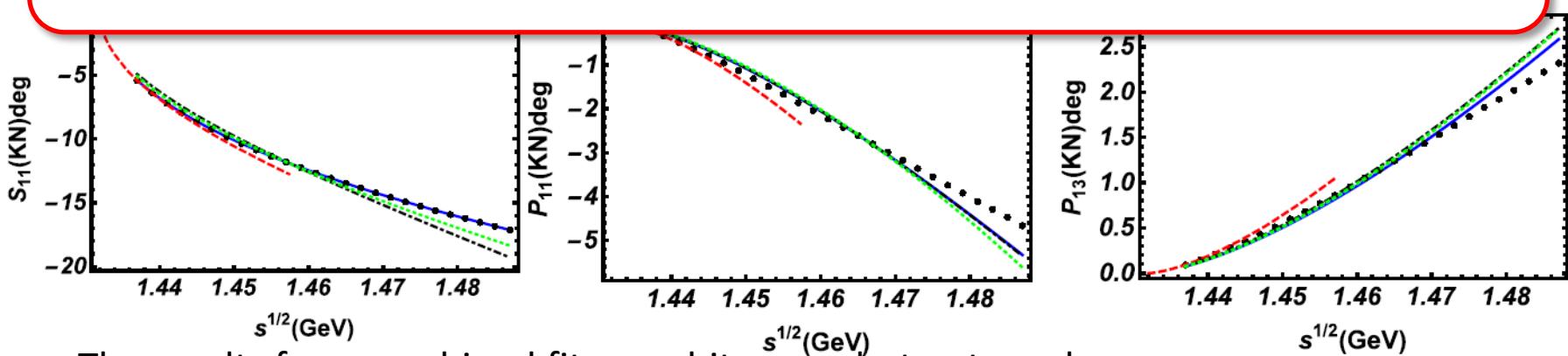
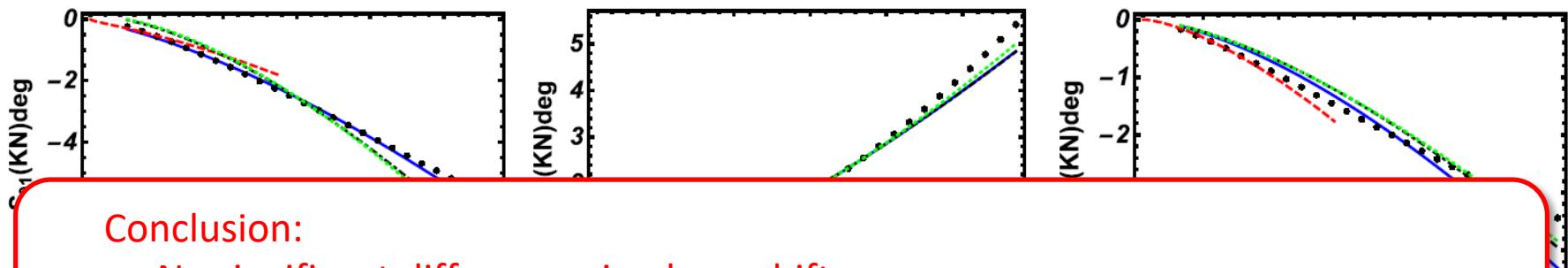
Red: SU3 HB

Green :combined fit without loops

Black dot: EXP

KN channel in combined fit

- Combine NNLO baryon masses and NNLO MB scattering



Blue: Direct fit

Black :combined fit with loops

Red: SU3 HB

Green :combined fit without loops

Black dot: EXP

Summary

We have performed the calculation of Meson-baryon scattering in Extended-on-mass-shell scheme up to NNLO

- A better description for elastic scattering, **especially for πN**
- **Not all LECs involved are determined**
- Convergence
- Combined fit to exam the ability of EOMS ChPT to describe baryon masses and meson-baryon scattering simultaneously

Perspective

- Try to determine all the related NNLO LECs
- $\bar{K}N$ channel and the non-perturbation phenomena there



The 12th International Workshop on the Physics of Excited Nucleons

Thank you for your attention

Lagrangians

$$\mathcal{L}_\phi^{(2)} = \frac{F_\phi^2}{4} \langle D_\mu U (D^\mu U)^\dagger \rangle + \frac{F_\phi^2}{4} \langle \chi U^\dagger + U \chi^\dagger \rangle$$

$$\begin{aligned} \mathcal{L}_{\phi B}^{(1)} &= \langle \bar{B} (i\gamma^\mu D_\mu - m_0) B \rangle + \frac{D/F}{2} \langle \bar{B} \gamma^\mu \gamma_5 [u_\mu, B]_\pm \rangle \\ \mathcal{L}_{\phi B}^{(2)} &= b_D \langle \bar{B} \{\chi_+, B\} \rangle + b_F \langle \bar{B} [\chi_+, B] \rangle + b_0 \langle \bar{B} B \rangle \langle \chi_+ \rangle + \\ &\quad b_1 \langle \bar{B} [u^\mu, [u^\mu, B]] \rangle + b_2 \langle \bar{B} \{u^\mu, \{u^\mu, B\}\} \rangle + \\ &\quad b_3 \langle \bar{B} \{u^\mu, [u^\mu, B]\} \rangle + b_4 \langle \bar{B} B \rangle \langle u^\mu u_\mu \rangle + \\ &\quad i b_5 \left(\langle \bar{B} [u^\mu, [u^\nu, \gamma_\mu D_\nu B]] \rangle - \langle \bar{B} \overleftrightarrow{D}_\nu [u^\nu, [u^\mu, \gamma_\mu B]] \rangle \right) + \\ &\quad i b_6 \left(\langle \bar{B} [u^\mu, \{u^\nu, \gamma_\mu D_\nu B\}] \rangle - \langle \bar{B} \overleftrightarrow{D}_\nu \{u^\nu, [u^\mu, \gamma_\mu B]\} \rangle \right) + \\ &\quad i b_7 \left(\langle \bar{B} \{u^\mu, \{u^\nu, \gamma_\mu D_\nu B\}\} \rangle - \langle \bar{B} \overleftrightarrow{D}_\nu \{u^\nu, \{u^\mu, \gamma_\mu B\}\} \rangle \right) + \\ &\quad i b_8 \left(\langle \bar{B} \gamma_\mu D_\nu B \rangle - \langle \bar{B} \overleftrightarrow{D}_\nu \gamma_\mu B \rangle \right) \langle u^\mu u^\nu \rangle + \\ &\quad i c_1 \langle \bar{B} \{[u^\mu, u^\nu], \sigma_{\mu\nu} B\} \rangle + i c_2 \langle \bar{B} [[u^\mu, u^\nu], \sigma_{\mu\nu} B] \rangle + i c_3 \langle \bar{B} u^\mu \rangle \langle u^\nu \sigma_{\mu\nu} B \rangle \end{aligned}$$

Lagrangians

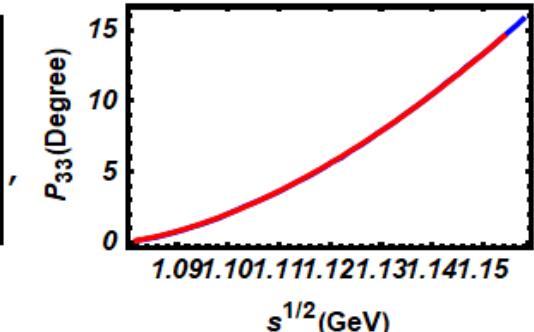
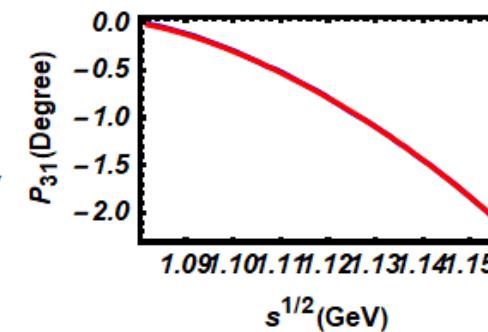
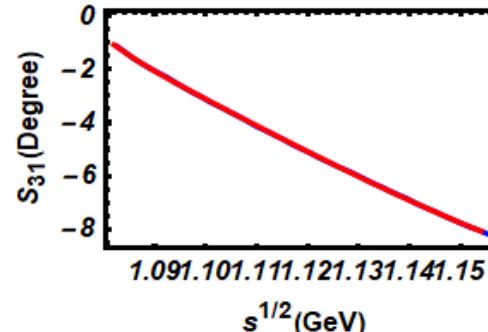
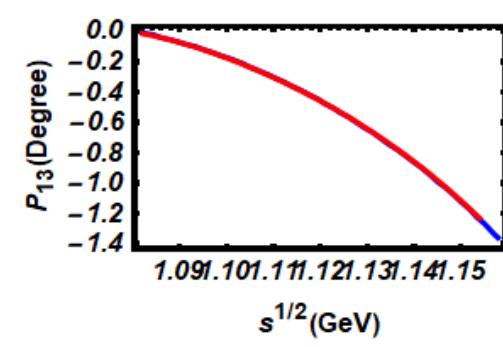
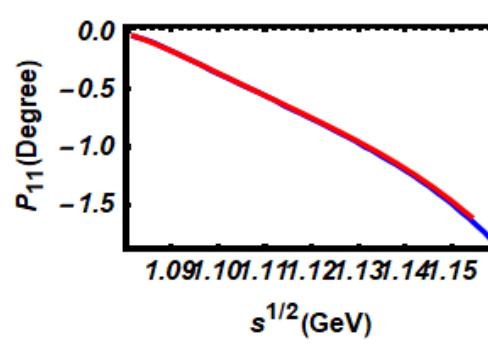
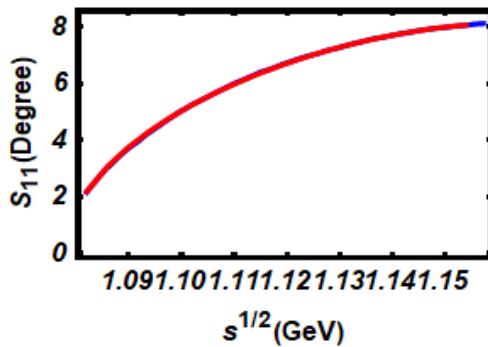
$$\begin{aligned}
 \mathcal{L}_{MB}^3 = & id_1 \left(\langle \bar{B} \gamma_\mu D_{\nu\rho} B [u^\mu, h^{\nu\rho}] \rangle + \langle \bar{B} \overleftarrow{D}_{\nu\rho} \gamma_\mu B [u^\mu, h^{\nu\rho}] \rangle \right) + \\
 & id_2 \left(\langle \bar{B} [u^\mu, h^{\nu\rho}] \gamma_\mu D_{\nu\rho} B \rangle + \langle \bar{B} \overleftarrow{D}_{\nu\rho} [u^\mu, h^{\nu\rho}] \gamma_\mu B \rangle \right) + \\
 & id_3 \left(\langle \bar{B} u^\mu \rangle \langle h^{\nu\rho} \gamma_\mu D_{\nu\rho} B \rangle - \langle \bar{B} \overleftarrow{D}_{\nu\rho} h^{\nu\rho} \rangle \langle u^\mu \gamma_\mu B \rangle \right) + \\
 & id_4 \langle \bar{B} [u^\mu, h^{\mu\nu}] \gamma_\nu B \rangle + id_5 \langle \bar{B} \gamma_\nu B [u^\mu, h^{\mu\nu}] \rangle \\
 & id_6 \left(\langle \bar{B} u^\mu \rangle \langle h^{\mu\nu} \gamma_\nu B \rangle - \langle \bar{B} h^{\mu\nu} \rangle \langle u^\mu \gamma_\nu B \rangle \right) + \\
 & id_7 \left(\langle \bar{B} \sigma_{\mu\nu} D_\rho B \{u^\mu, h^{\nu\rho}\} \rangle - \langle \bar{B} \overleftarrow{D}_\rho \sigma_{\mu\nu} B \{u^\mu, h^{\nu\rho}\} \rangle \right) + \\
 & id_8 \left(\langle \bar{B} \{u^\mu, h^{\nu\rho}\} \sigma_{\mu\nu} D_\rho B \rangle - \langle \bar{B} \overleftarrow{D}_\rho \{u^\mu, h^{\nu\rho}\} \sigma_{\mu\nu} B \rangle \right) + \\
 & id_9 \left(\langle \bar{B} u^\mu \sigma_{\mu\nu} D_\rho B h^{\nu\rho} \rangle - \langle \bar{B} \overleftarrow{D}_\rho u^\mu \sigma_{\mu\nu} B h^{\nu\rho} \rangle \right) + \\
 & id_{10} \left(\langle \bar{B} \sigma_{\mu\nu} D_\rho B \rangle - \langle \bar{B} \overleftarrow{D}_\rho \sigma_{\mu\nu} B \rangle \right) \langle u^\mu h^{\nu\rho} \rangle + \\
 & d_{48} \langle \bar{B} \gamma_\mu B [\chi_-, u^\mu] \rangle + d_{49} \langle \bar{B} [\chi_-, u^\mu] \gamma_\mu B \rangle + \\
 & d_{50} \left(\langle \bar{B} u^\mu \rangle \langle \chi_- \gamma_\mu B \rangle - \langle \bar{B} \chi_- \rangle \langle u^\mu \gamma_\mu B \rangle \right)
 \end{aligned}$$

Data to be fit

πN phase shifts in $S_{11}, P_{11}, P_{13}, S_{31}, P_{31}, P_{33}$ partial waves $L_{2I,2J}$

- Phase shifts: WI08
- Error bar: $err(\delta) = \sqrt{e_s^2 + e_r^2 \delta^2}$ $e_s=0.1^\circ$:systematic error $e_s=2\%$:relative error

Reproduce the SU2 results



LECs

- πN

$b_1 + b_2 + b_3 + 2b_4$	$b_5 + b_6 + b_7 + b_8$	$c_1 + c_2$	$2b_0 + b_D + b_F$	d_2	d_4	$d_8 + d_{10}$	d_{49}
-7.64 ± 0.06	1.42 ± 0.02	1.34 ± 0.01	-1.36 ± 0.06	0.61 ± 0.02	3.25 ± 0.06	1.45 ± 0.03	-0.32 ± 0.12

- $KN(l=1)$

$b_1 + b_2 + b_4$	$2b_5 + 2b_7 + b_8$	$4c_2 + c_3$	$b_0 + b_D$
-0.419 ± 0.002	0.429 ± 0.002	0.616 ± 0.001	-0.090 ± 0.003

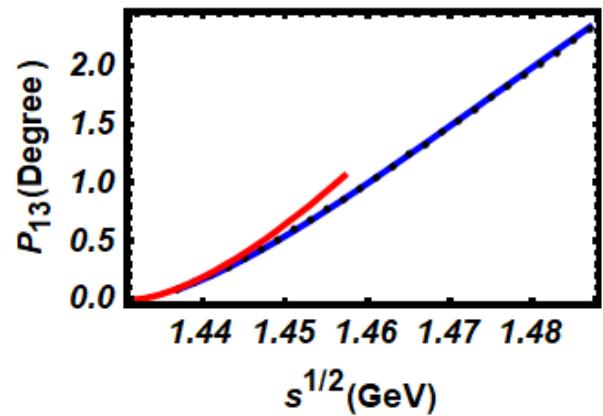
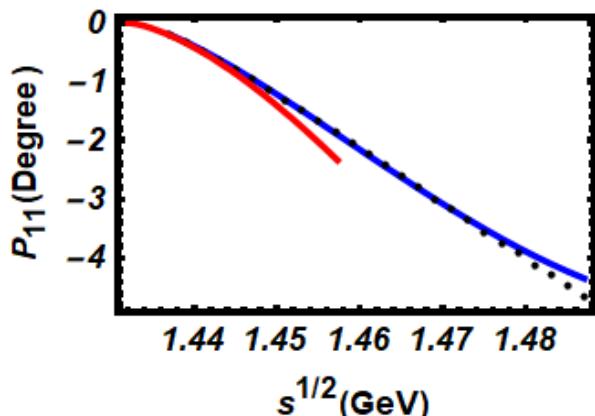
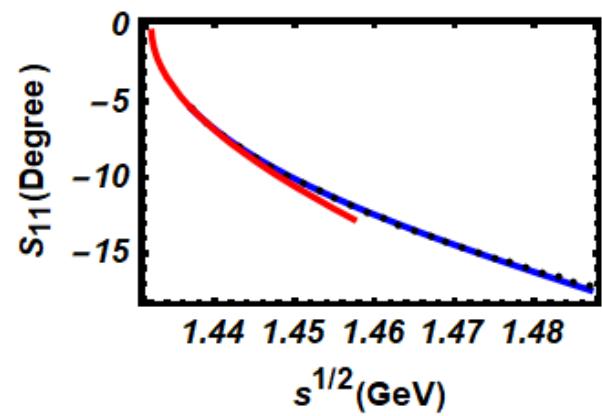
- $KN(l=0)$

$b_3 - b_4$	$2b_6 - b_8$	$4c_1 + c_3$	$b_0 - b_F$
-0.767 ± 0.001	0.126 ± 0.001	0.604 ± 0.003	0.093 ± 0.001

KN($|l|=1$)

This time, we include the tree level at $\mathcal{O}(p^3)$ in KN channel

- $\chi^2/\text{d.o.f} = 0.016$



Combined fit with baryon mass and scattering

- Baryon masses and MB scattering share one scenario of LECs

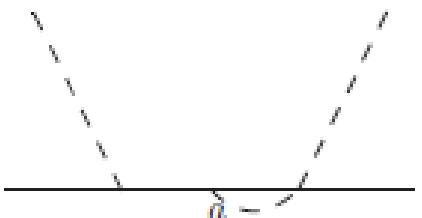
LECs contribute at different orders

	Baryon masses	MB scattering
LO	M_0	
NLO	NLO LEC: b_0, b_D, b_F	NLO LEC: $b_0, b_D, b_F, b_{1-8}, c_{1-3}$
NNLO		NNLO LEC: d_{1-10}, d_{48-50}
N3LO	NLO LEC: b_0, b_D, b_F, b_{1-8} N3LO LEC: e_{1-5}, e_7, e_8	NLO LEC: $b_0, b_D, b_F, b_{1-8}, c_{1-3}$ All related N3LO LECs

- Masses have an extra parameter: M_0
- Up to NNLO, only b_0, b_D, b_F are needed fro baryon masses, while in scattering amplitudes, there are 21 more LECs.
- b_{1-8} start contributing from N3LO masses while they show up in NLO scattering.
- Combine N3LO masses with NNLO scattering is not self-consistent.

Power counting breaking(PCB) terms

- Non-vanishing baryon mass at chiral limit



Power counting rules

$$D = 4L + \sum_n n V_n - 2N_M - N_B = 3$$

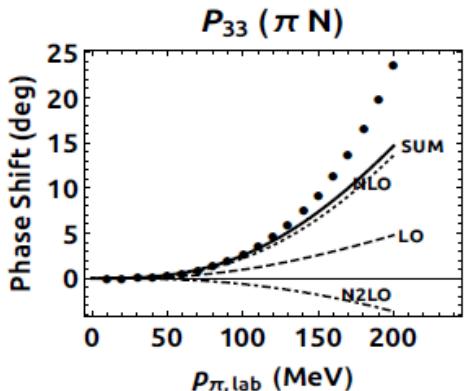
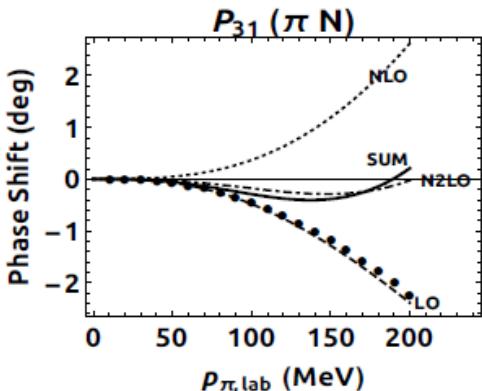
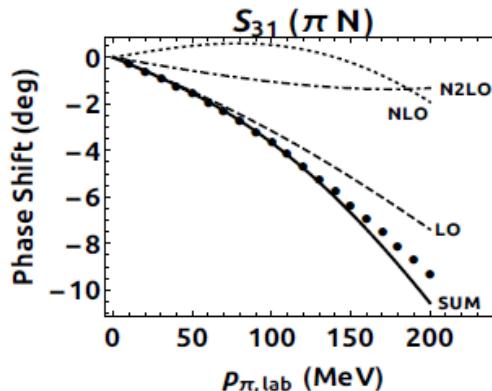
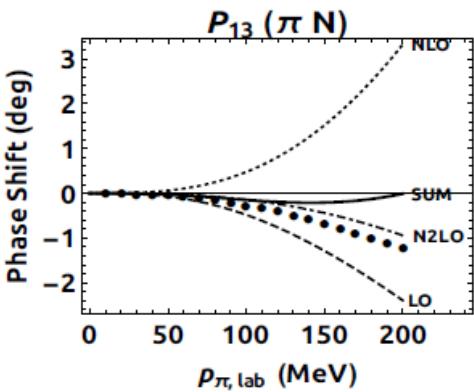
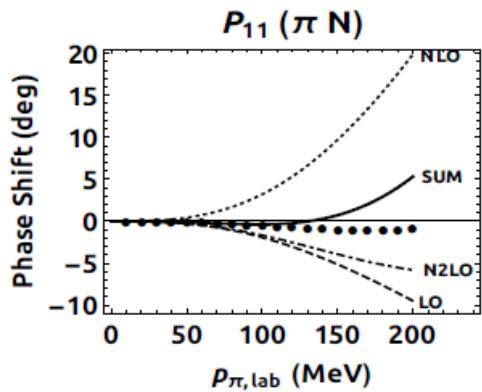
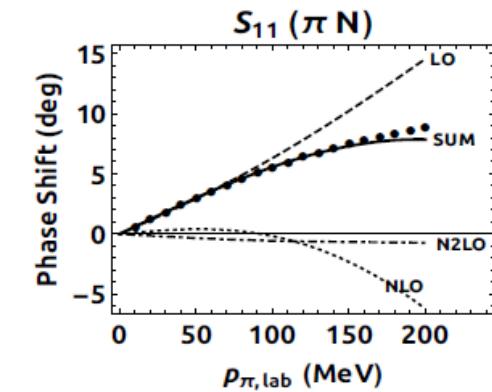
Expected: $A_{loop} = \mathcal{O}(p^3) + \mathcal{O}(p^4) + \dots$

Realistic: $A_{loop} = \mathcal{O}(p^0) + \mathcal{O}(p^3) + \dots$

PCB

Convergence

- Phase shifts for πN channel



Chiral EFT

- Powering counting rule

$$D = 4L + \sum_n n V_n - 2N_M - N_B$$

- D: chiral order of certain diagram
- L: number of loops
- V_n : number of n-th order vertices
- N_M : number of meson propagators
- N_B : number of baryon propagators

$$\mathcal{L}_{EFT} = \mathcal{L}_{MB}^{(1)} + \mathcal{L}_{MB}^{(2)} + \mathcal{L}_{MB}^{(3)} + \dots + \mathcal{L}_{MM}^{(2)} + \dots$$

where the superscripts denote the chiral order

- Small quantities applied for Chiral expansion

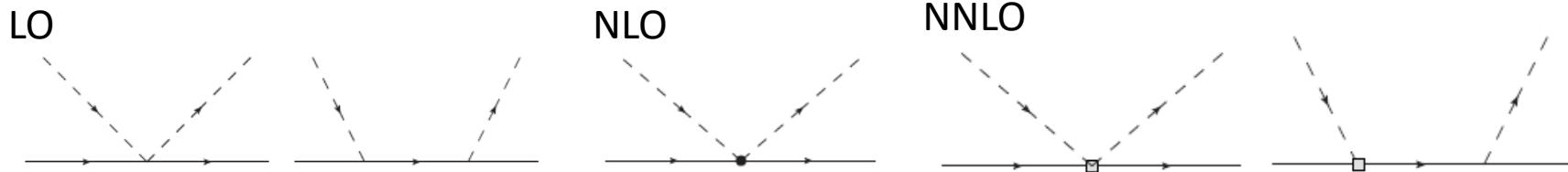
$$s - m^2 \sim \mathcal{O}(p)$$

$$M_{\pi,K,\eta} \sim \mathcal{O}(p)$$

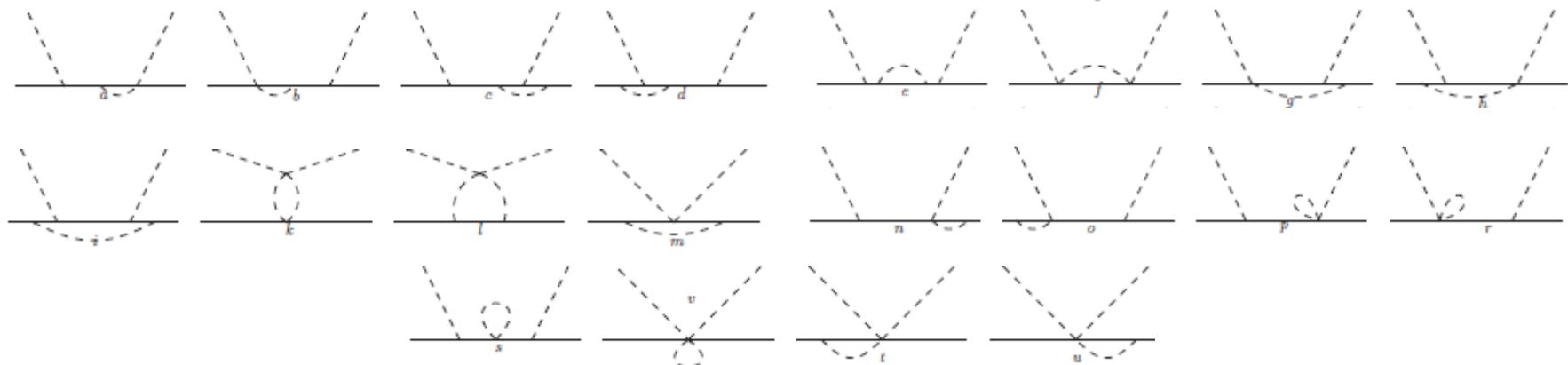
$$t \sim \mathcal{O}(p^2)$$

Diagrams

- Tree level

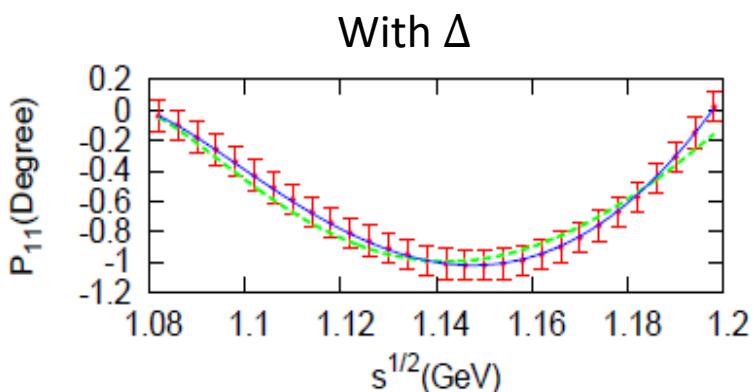
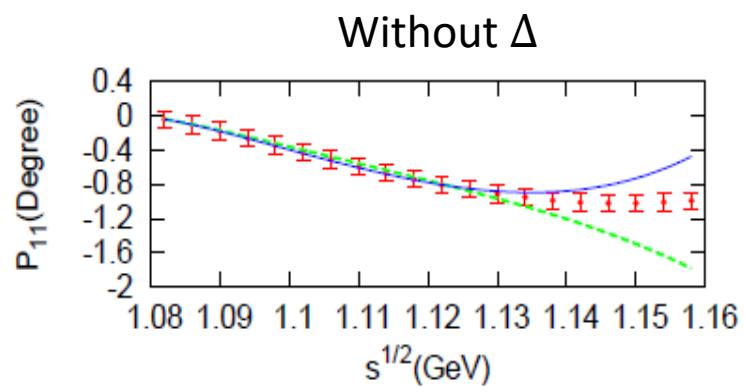
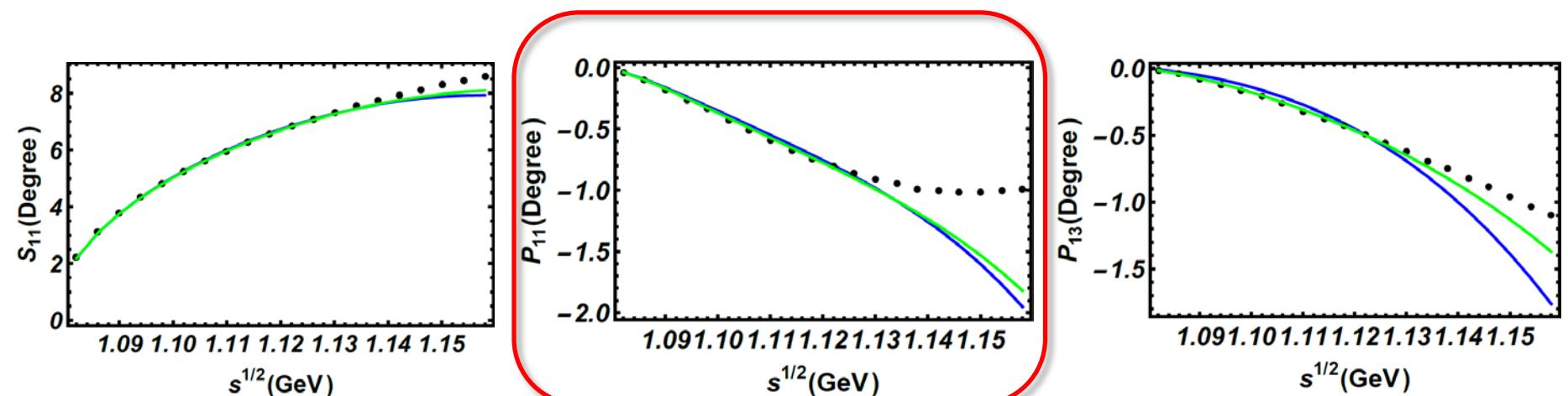


- Loop level



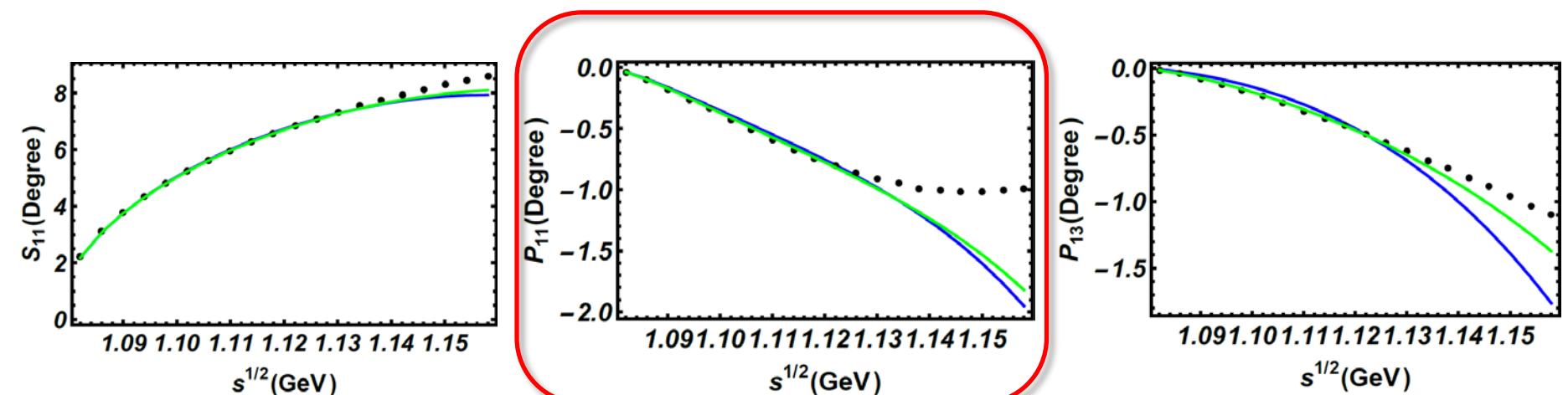
πN channel: direct fit

The partial wave phase shifts of πN channel.



πN channel: direct fit

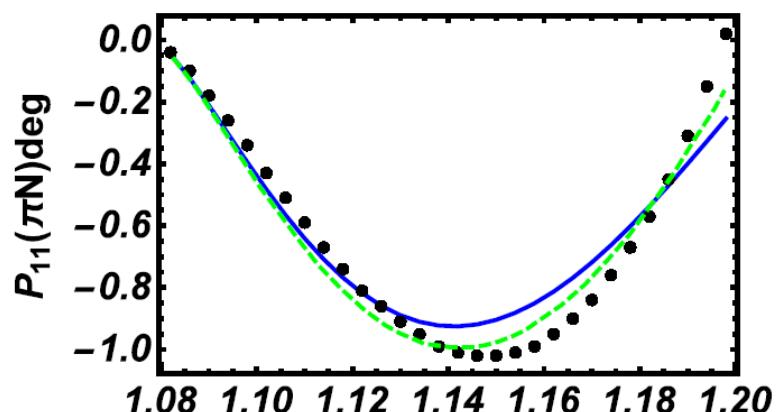
The partial wave phase shifts of πN channel.



Blue: SU3 EOMS

Green: SU2 EOMS Chen et al. PRD87(2013)054019

Black dot: EXP



- Decuplets included

Renormalization

Rewrite the **bare values** of C , m_B , f in Lagrangians with their **physical values**

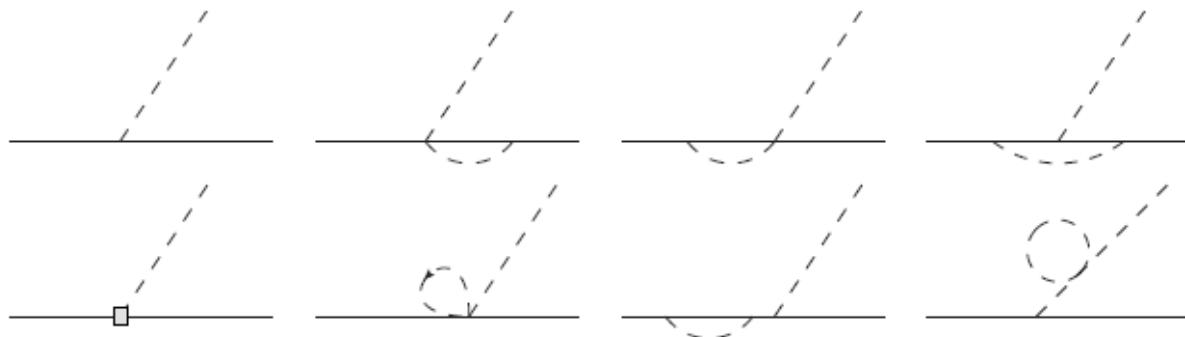
- C :coupling constants
- m_B :baryon masses
- f :decay constants

- m_B :baryon masses

$$m_{ph} = m_{bare} + \Sigma_{O(p^2)} + \Sigma_{O(p^3)}$$



- C :coupling constants $C_{ph}\gamma^5\rlap{/}q_f = C_{bare}\gamma^5\rlap{/}q_f + C_{ph}\gamma^5\rlap{/}q_f Z + C_{ph}\gamma^5\mathcal{A}_{loop}(s) + C_{ph}\gamma^5\rlap{/}q_f \Delta_F$



Convergence

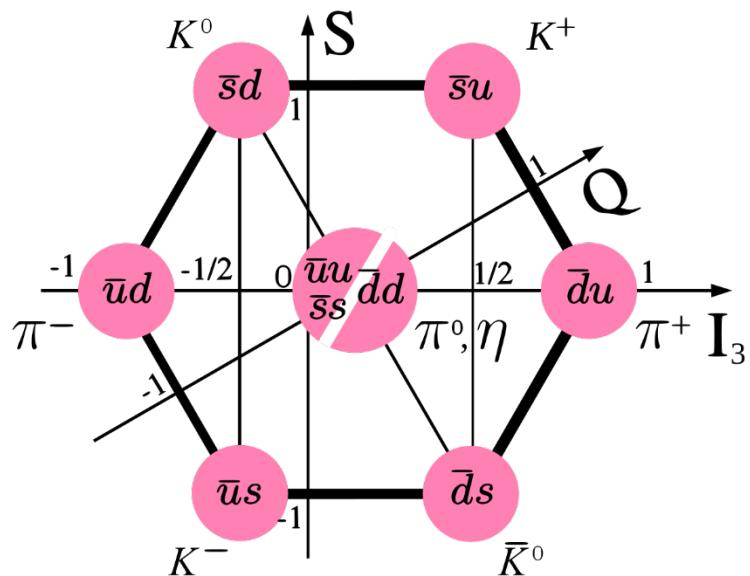
- In SU(2), the reasonable convergence has been confirmed

- HB scheme, threshold parameters. Mojziz, EPJC 2, 181
 - HB scheme, up to NNLO.
 - Converge at lower energies but large cancellations appear in higher regime Fettes et al NPA640, 199
 - HB scheme, up to NNNLO
 - Relatively smaller NNNLO contribution Fettes et al NPA676, 311
 - EOMS scheme, up to NNLO
 - Questionable without Δ but reasonable with Δ Alarcon et al Annals Phys. 336, 413
 - EOMS scheme, up to NNNLO
 - Converge even without Δ Chen et al PRD87, 054019
 - EOMS scheme, up to NNLO with explicit Δ Yao et al JHEP 1605, 038
- ✓ Detailed comparison between HB and EOMS Siemens et al, PRC94,014620; PRC96,055205
 - Visible improvements in a covariant scheme

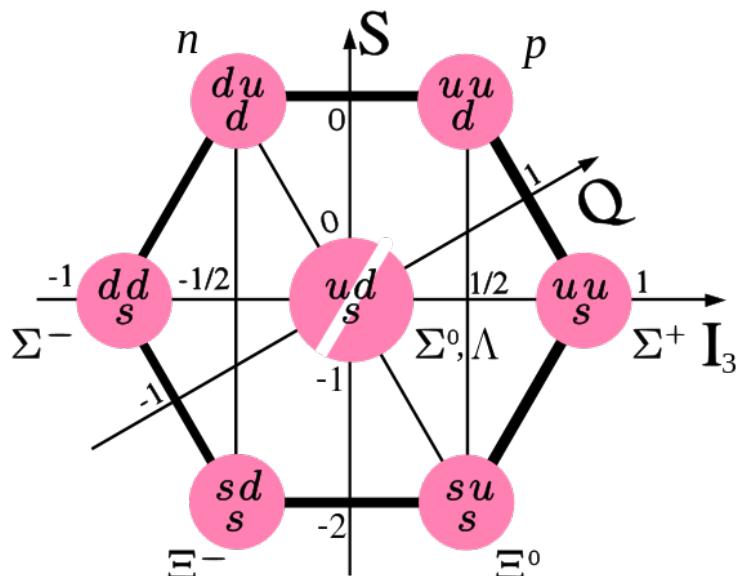
Meson-Baryon scattering

Characterized by

- Charge Q
- Strangeness S
- Third component of isospin I_3



Meson Octet



Baryon Octet