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Two-pion exchange contributions to NN interaction in covariant baryon chiral perturbation theory

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OUTLINE

① **Introduction**

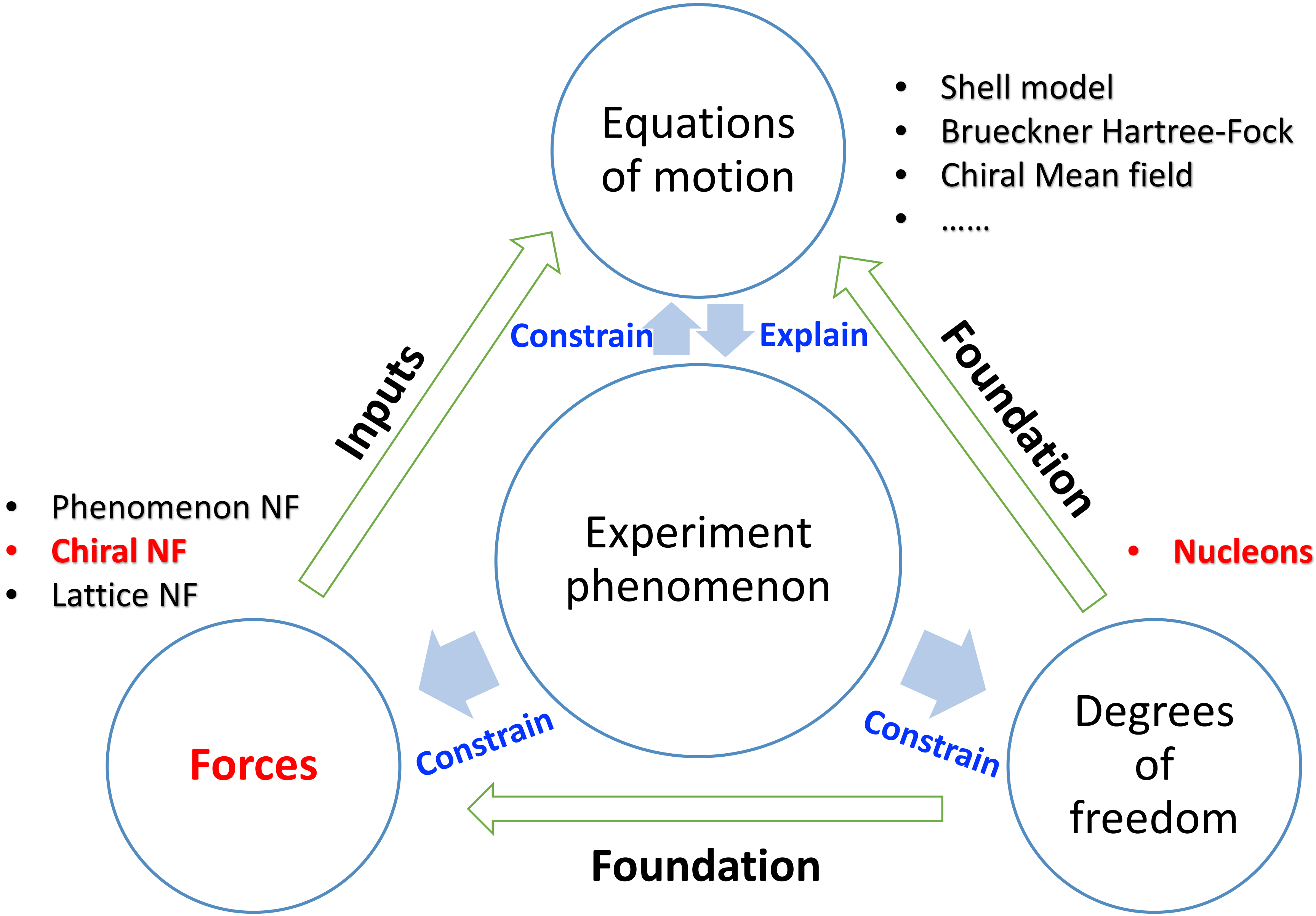
- Why nucleon-nucleon interaction
- Why covariant chiral effective field theory
- Why Two-pion exchange

② Theoretical framework

③ Results & discussions

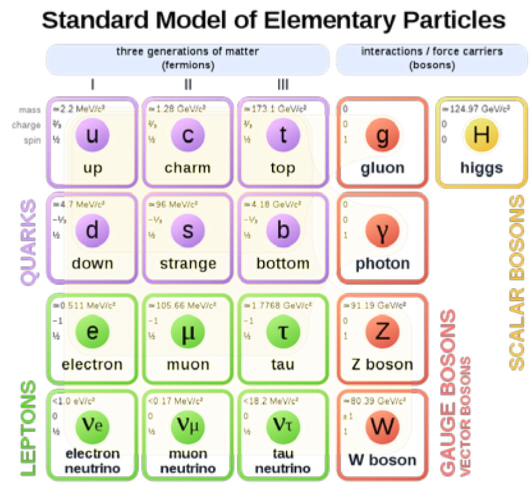
④ Summary & outlook

Nuclear forces (NF) – Basic input in nuclear physics

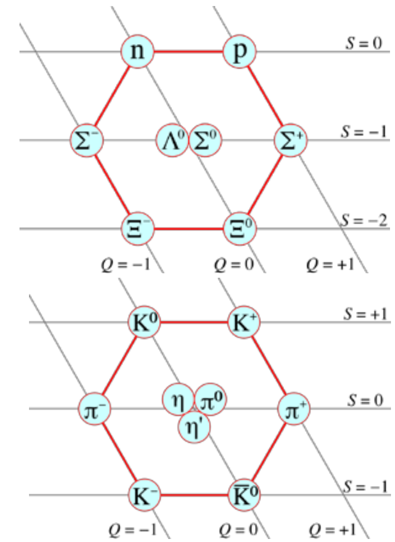


Nuclear force from QCD

quarks

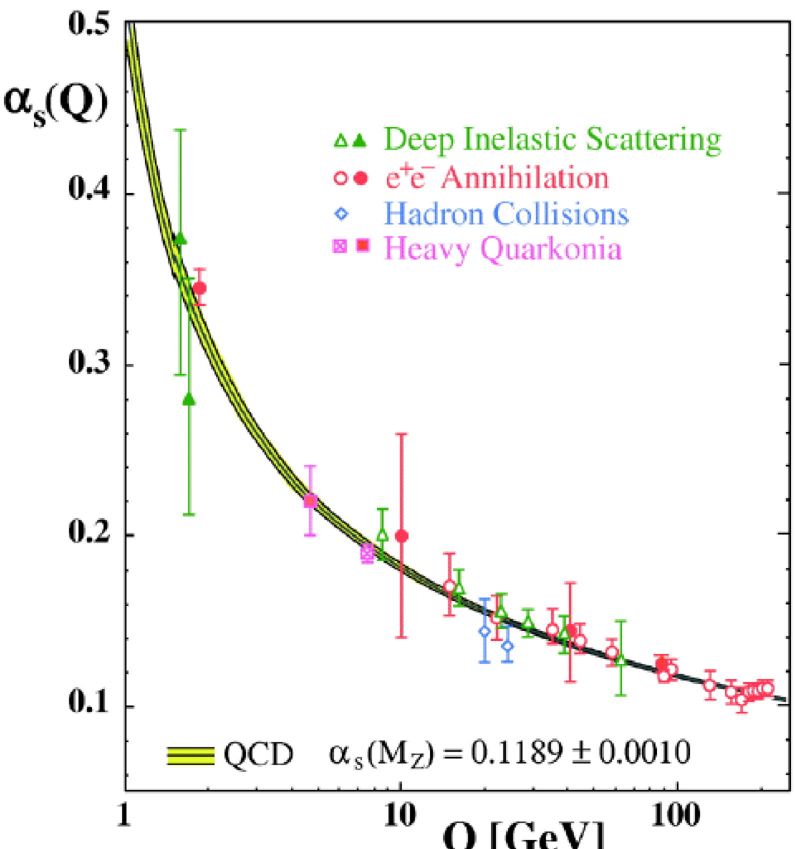


hadrons



➢ **Color confinement**

Quark d.o.f.'s instead of **hadrons**



S.Bethke, PPNP(2013)

➢ **Asymptotic freedom**

Coupling constants $\alpha_s \geq 1$ **(low energy)**

● **Nonperturbative - unsolvable**

- Lattice QCD
- **Effective Field Theory (we prefer)**
- Phenomenological models

Why Chiral Effective Field Theory

Chiral Effective field theory

- **Low energy QCD**
  - $L_{QCD} \rightarrow L_{\chi EFT} \sim \sum_v c_v \times L^v_{\chi EFT}$ (c_v low energy constants, v chiral order)
- **Degree of freedom**
  - quarks → hadrons
- **Power counting scheme (expansion parameter)**
  - $Q \sim M_{lo}/M_{hi}$ ($M_{hi} \sim \Lambda_\chi \sim 1\text{GeV}, M_{lo} \sim \boldsymbol{p}, m_\pi$)

Main advantages of Chiral Nuclear force

- Self-consistently include many-body forces

$$V = V_{2N} + V_{3N} + V_{4N} + \cdots$$

- Systematically improve NF order by order

$$V_{iN} = V_{iN}^{LO} + V_{iN}^{NLO} + V_{iN}^{NNLO} + \cdots$$

- Systematically estimate theoretical uncertainties

$$|V_{iN}^{LO}| > |V_{iN}^{NLO}| > |V_{iN}^{NNLO}| > \cdots$$

Power counting

Chiral NN potential is of high precision

	Phenomenological forces			NR Chiral nuclear force			
	Reid93	CD-Bonn	LO	NLO	N2LO	N3LO	**N4LO**
No. of para.	50	38	2	9	9	24	**24**
χ^2/datum	1.03	1.02	94	36.7	5.28	1.27	**1.10**

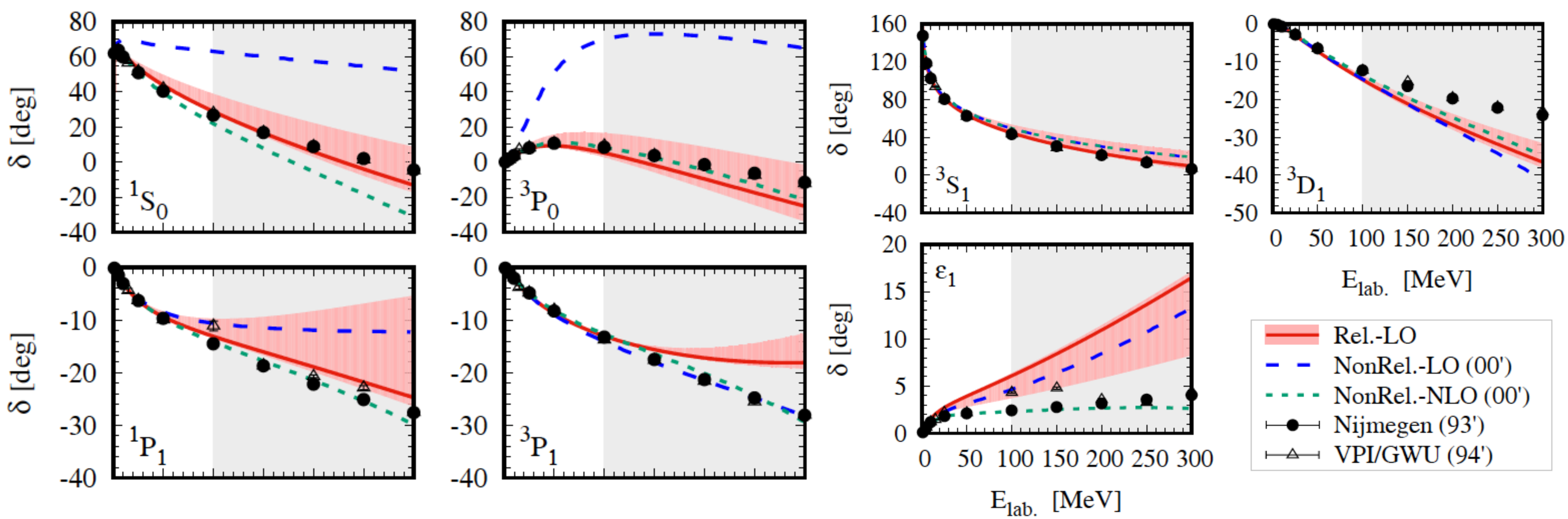
D.Entem, et al., PRC96(2017)024004

Why covariant ?

- **Relativistic** approaches **successful**
  - **Atomic and molecular systems,** why gold is **yellow**
  - **Nuclear system,** spin-orbit splitting, pseudospin symmetry
  - **One-baryon sector,** magnetic moments、masses、sigma terms
- **A critical input** to nuclear reaction/structure calculations in **covariant framework**
  - **Dirac Brueckner Hartree-Fock**
  - **Covariant Chiral MF**
  - **……**

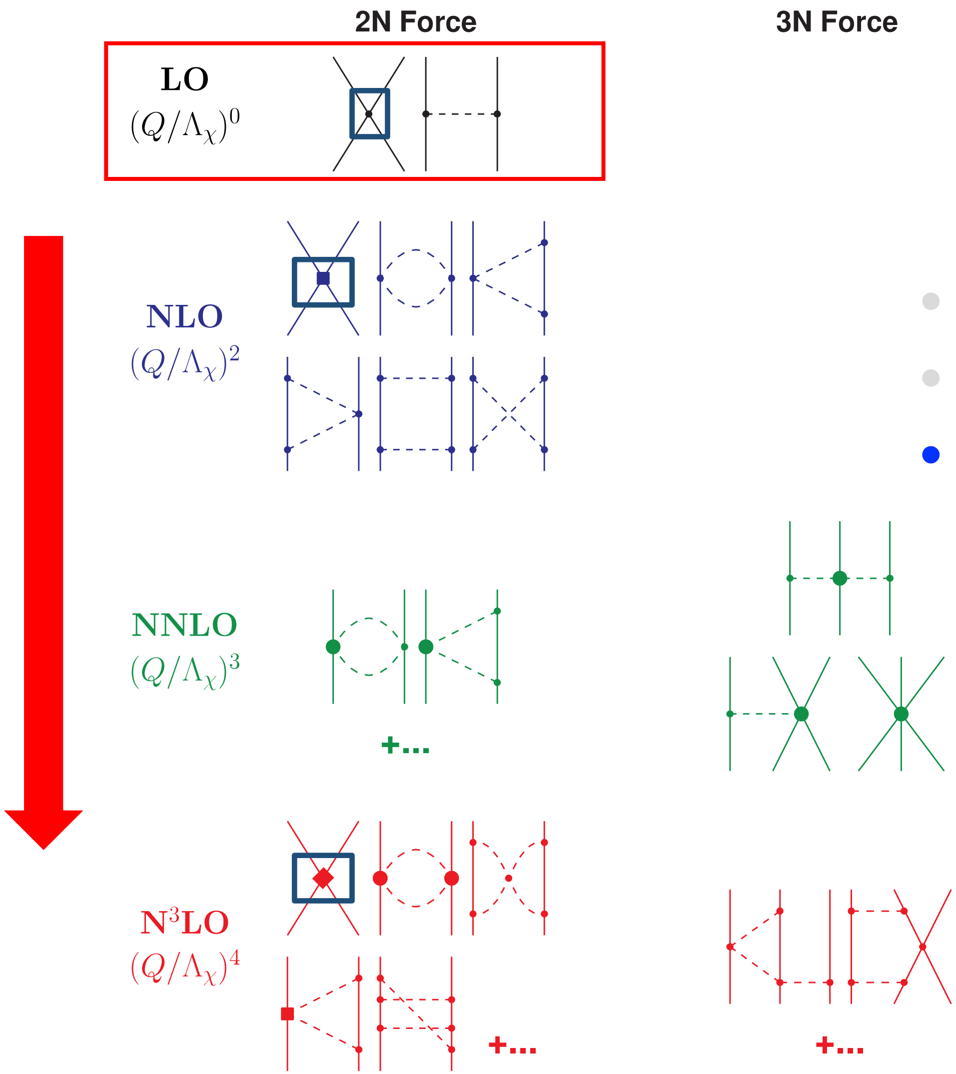
LO covariant Chiral NN force

Xiu-Lei Ren, et.al. CPC42 (2018) 1, 014103



- **LO relativistic ≈ NLO non-relativistic in S & P wave !**
- **Higher order needs to be explored.**

Higher order Feynman diagrams

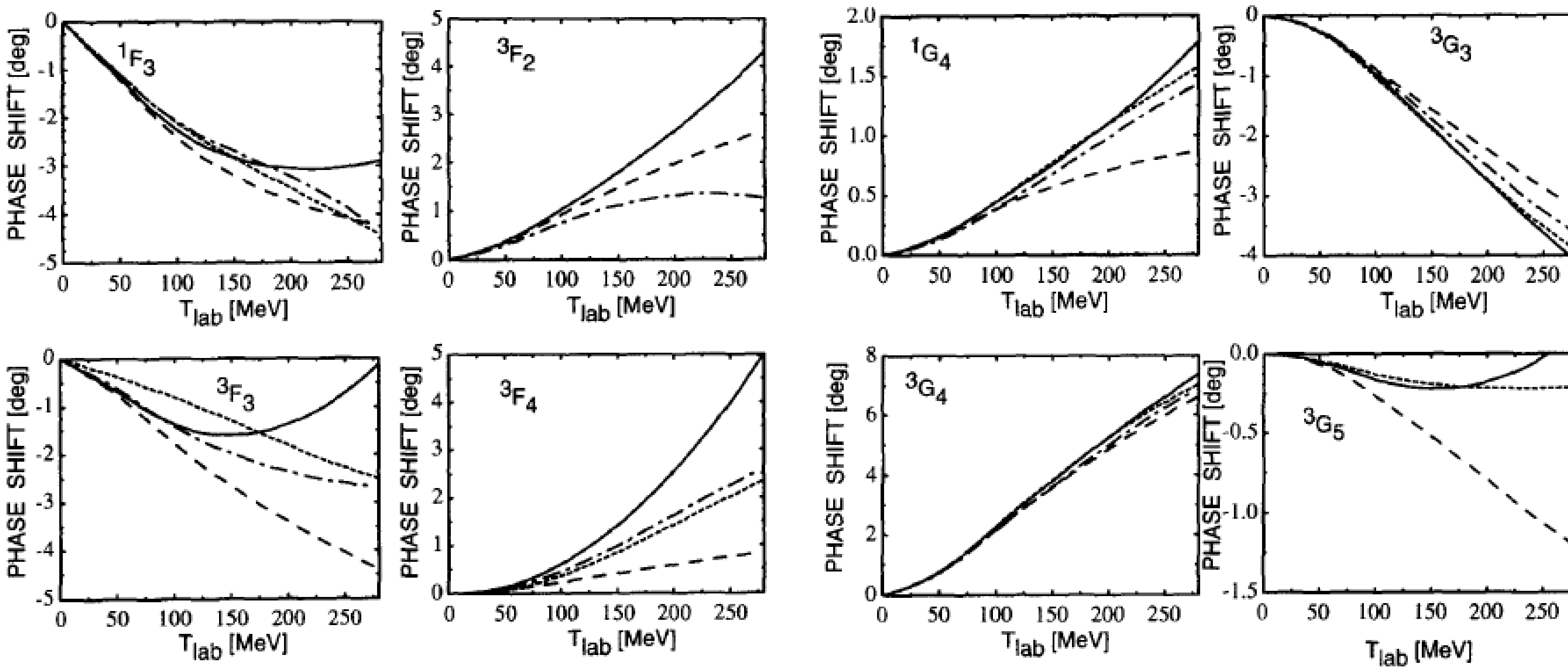


Key inputs

- Four nucleon (baryon) vertices
- Pion-nucleon vertices
- **Two-pion exchanges (TPE)**

Non-relativistic two-pion exchange

Dash: **One pion exchange** (OPE) Full curve: **OPE +TPE** Dot dash: **Data**



Kaiser et, al. NPA 625, 758 (1997).

- **Improved description** for $^1F_3$ & $^3F_3$
- **Good description** for **G** & **higher** partial waves

➢ **TPE important** for **non-relativistic NF**

⇨ **Relativistic TPE ?**

OUTLINE

① Introduction

② **Theoretical framework**

- Two-pion exchange potentials & phaseshifts

③ Results & discussions

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Two-pion exchange up to O(p^3)

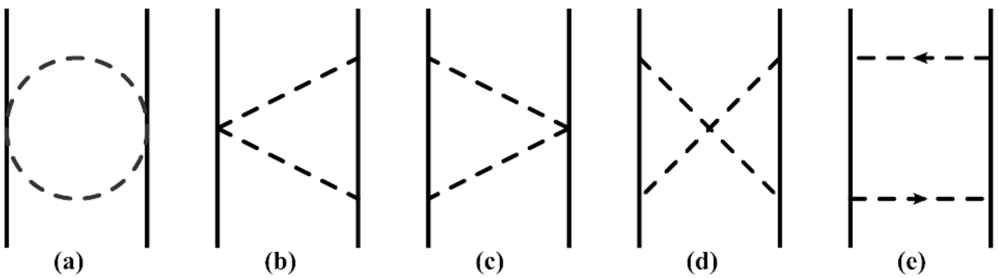
Covariant chiral Lagrangians:

$$\mathcal{L}_{\pi N}^{(1)} = \bar{N}\left(\mathrm{i}\not{D} - m + \frac{g_A}{2}\not{u}\gamma_5\right)N,$$

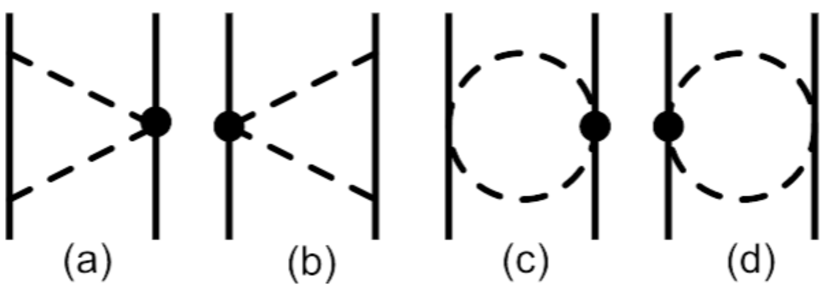
$$\mathcal{L}_{\pi N}^{(2)} = c_1\langle\chi_+\rangle\bar{N}N - \frac{c_2}{4m^2}\langle u^\mu u^\nu\rangle\left(\bar{N}D_\mu D_\nu N + h.c.\right) + \frac{c_3}{2}\langle u^2\rangle\bar{N}N - \frac{c_4}{4}\bar{N}\gamma^\mu\gamma^\nu\left[u_\mu, u_\nu\right]N,$$

Feynman diagrams

$(Q/\Lambda)^2$

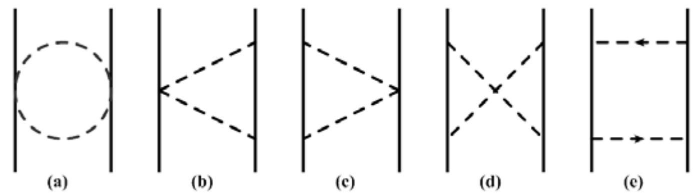


$(Q/\Lambda)^3$



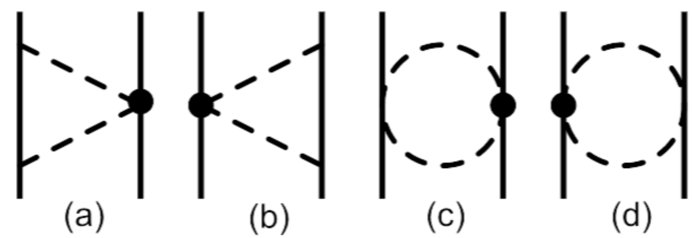
Covariant chiral potentials

$$V_{NN}^{(2)} = \bar{u}_1 \bar{u}_2 \{$$



$$\} u_1 u_2$$

$$V_{NN}^{(3)} = \bar{u}_1 \bar{u}_2 \{$$



$$\} u_1 u_2$$

$$u(\boldsymbol{p}, s) = N \begin{pmatrix} 1 \\ \dfrac{\boldsymbol{\sigma} \cdot \boldsymbol{p}}{E + m_n} \end{pmatrix} \chi_s, \qquad N = \sqrt{\frac{E + m_n}{m_n}}$$

T matrix & phase shifts

- **On-shell *T* matrix**: **in first order perturbation theory**

$$T_{NN} = V_{NN}$$

- ***T* matrix** to **phase shifts**

$$\delta_{LSJ} = -\frac{m_n^2|\boldsymbol{p}|}{16\pi^2 E}\,\mathrm{Re}\langle LSJ|\mathcal{T}_{NN}|LSJ\rangle,$$

$$\epsilon_J = \frac{m_n^2|\boldsymbol{p}|}{16\pi^2 E}\,\mathrm{Re}\langle J-1,1,J|\mathcal{T}_{NN}|J+1,1,J\rangle.$$

⇨ **Perfect check** of **relativistic corrections** (**No free parameters**)

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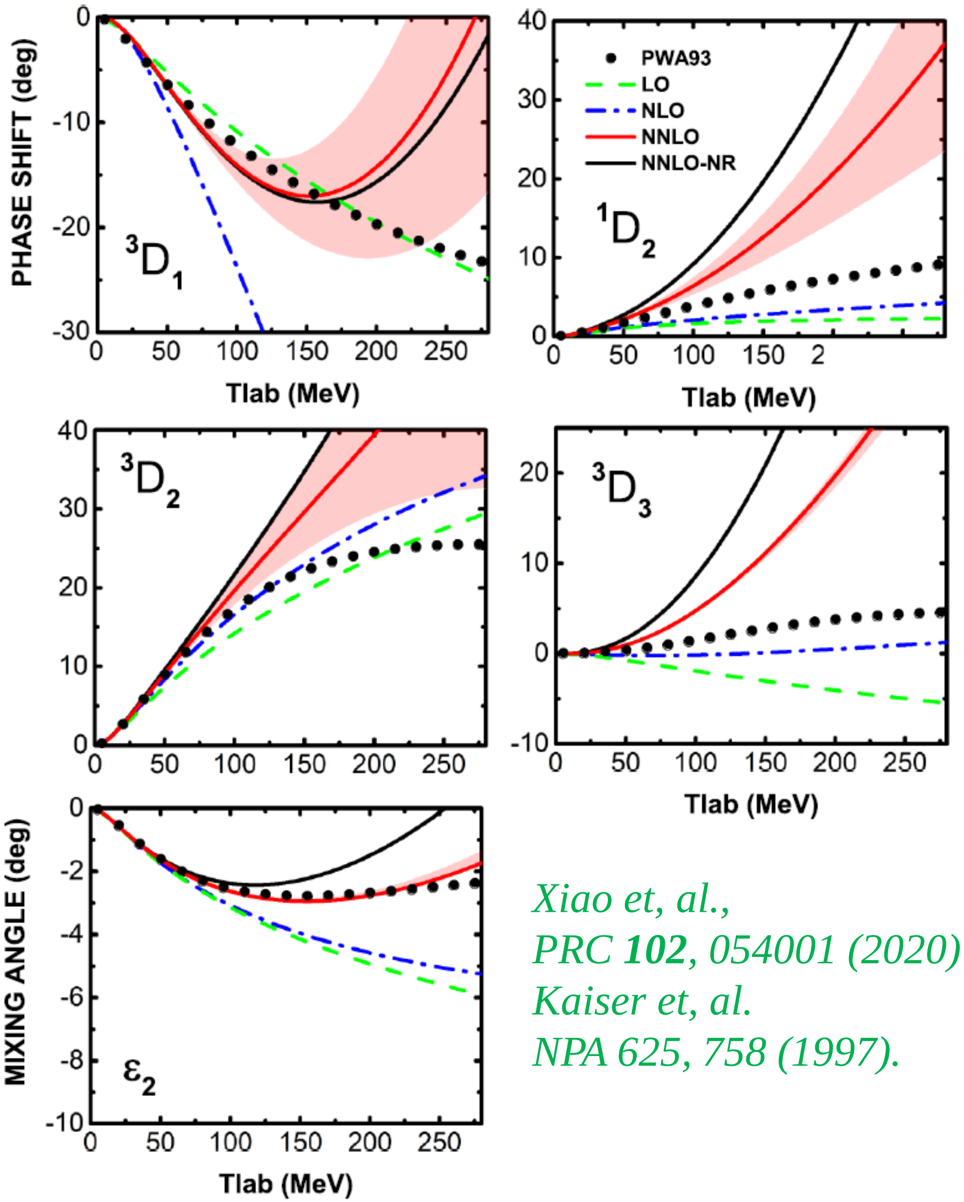
- *NN* phase shifts for $L, J \geq 2$

④ Summary & outlook

Phase shifts-D wave



Xiao et, al.,
*PRC **102**, 054001 (2020)*
Kaiser et, al.
NPA 625, 758 (1997).

- No contact terms
- No S & P wave

  Contact terms dominate

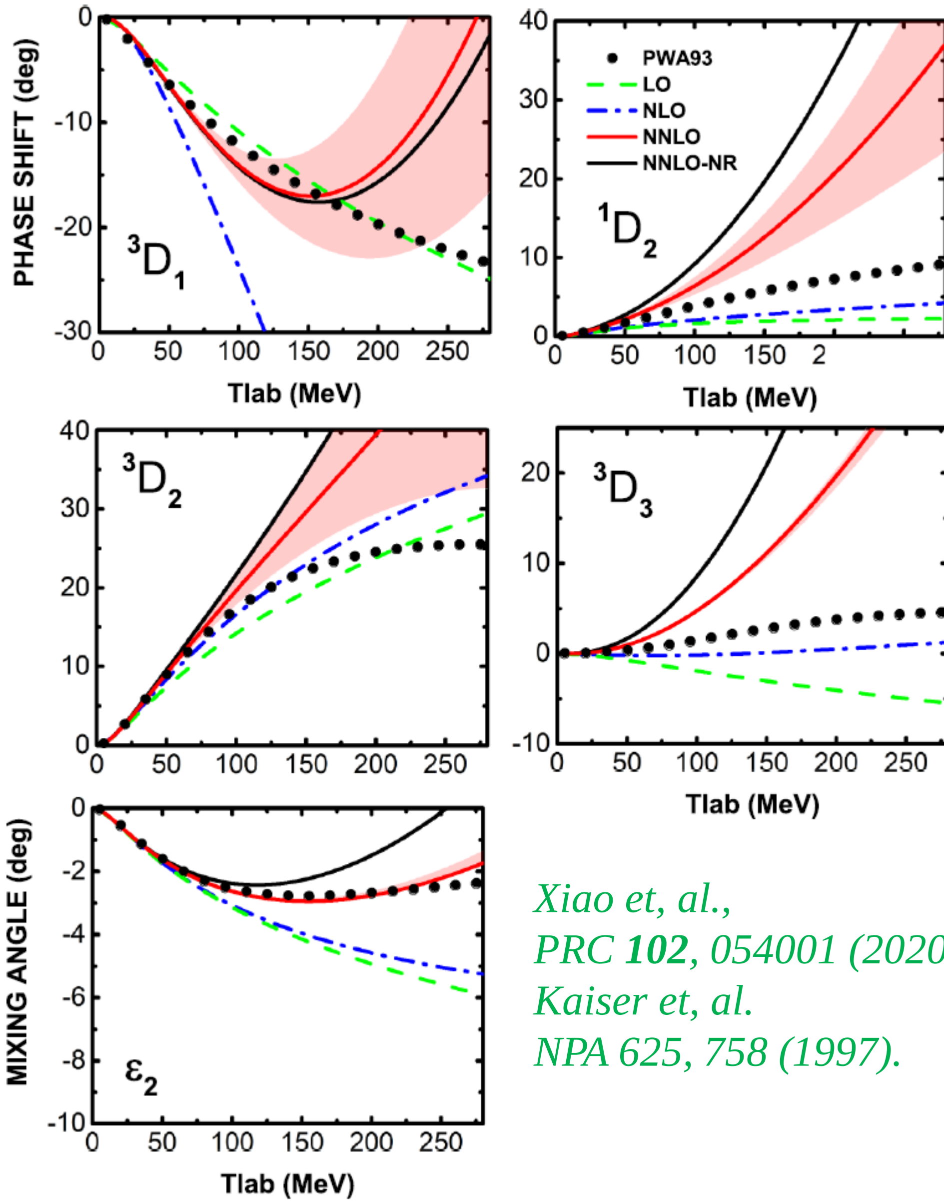
- **Red bands:**

  renormalization scale 0.5 ~ 1.5GeV

✓ Quantitatively better

✓ ϵ_2 much improved

Phase shifts-D wave



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- ➢ **No contact terms**
- ➢ **No S & P wave**

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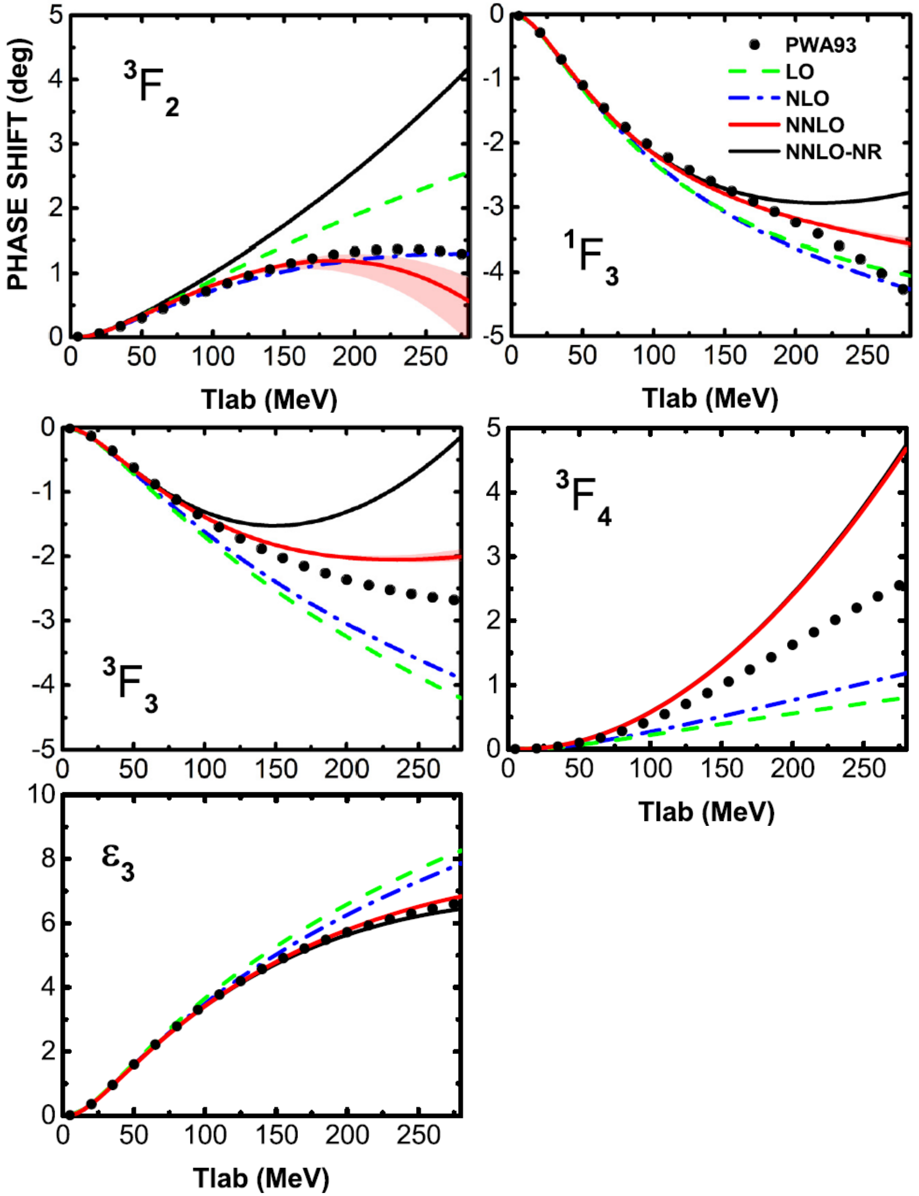
  renormalization scale 0.5 ~ 1.5GeV

✓**Quantitatively better**

✓ϵ_2 much improved

➢**Contact terms** needed

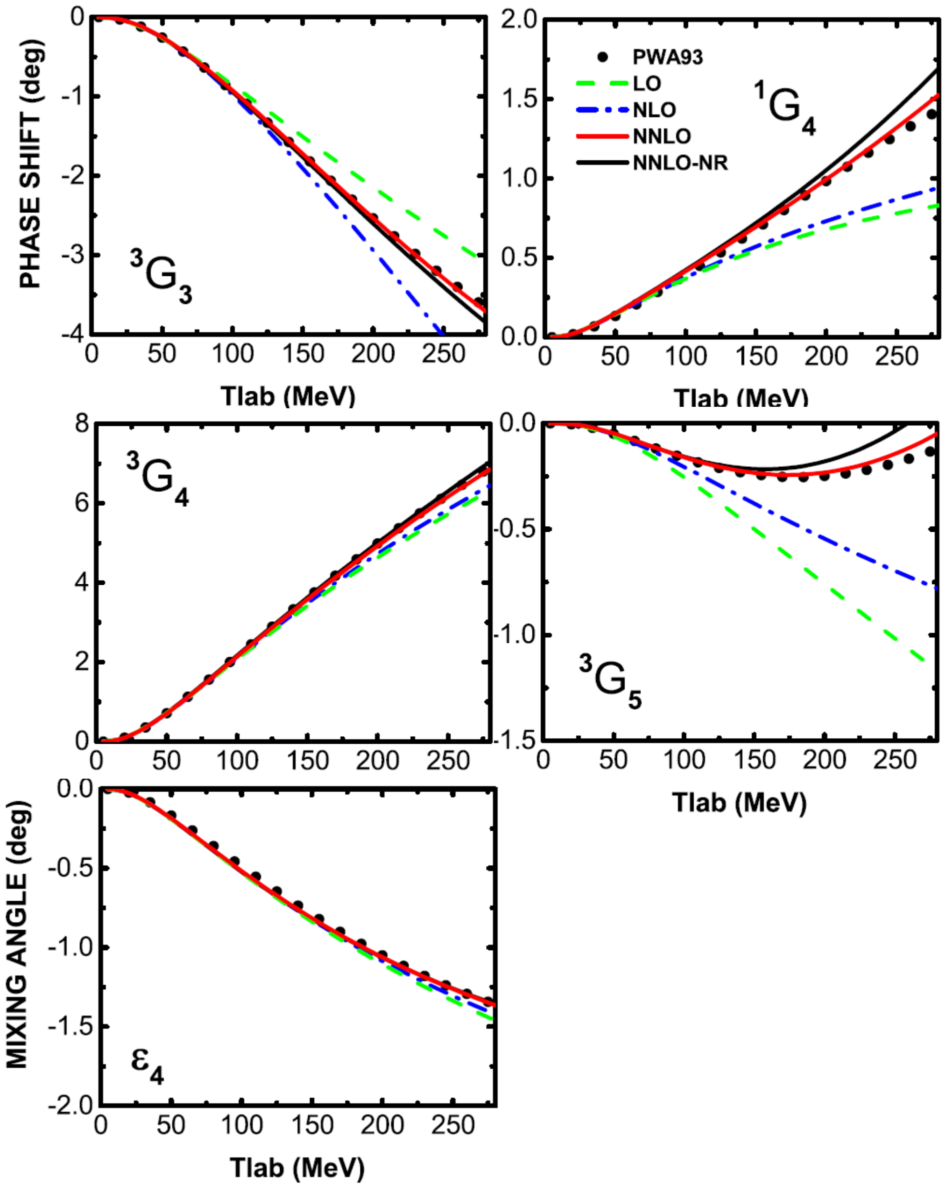
Phase shifts-F wave



✓**Improved description** for $^3F_2$, $^1F_3$ & $^3F_3$

✓**Relativistic corrections sizeable !**

Phase shifts-G wave

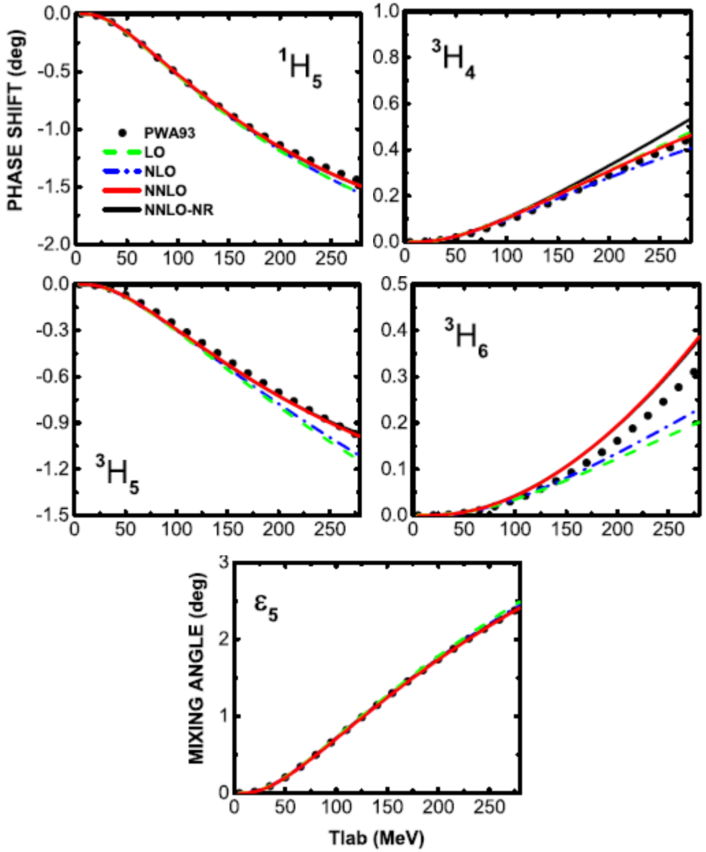


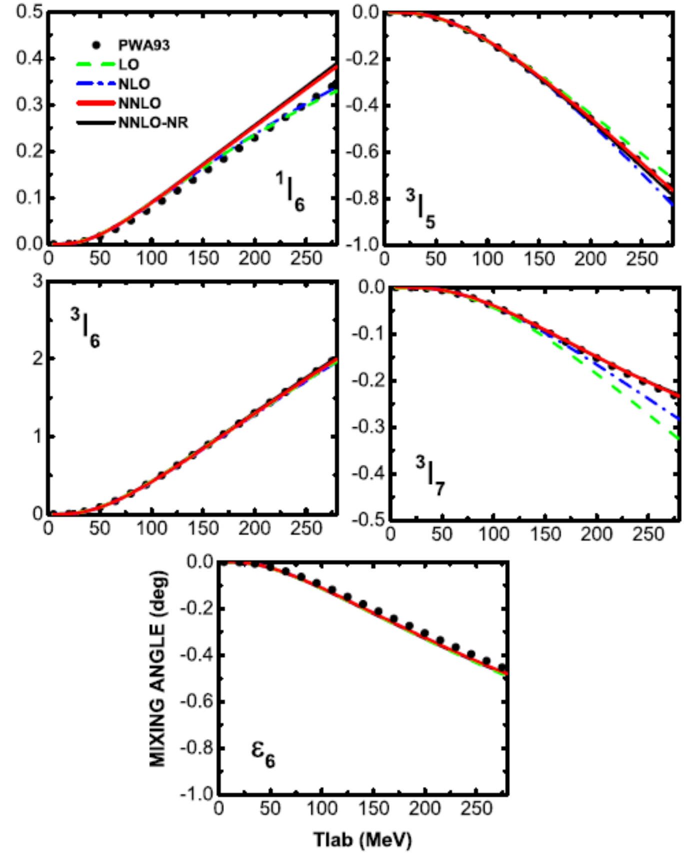
✓**Independent** of **renormalization scale**

✓**Quantitatively** better

✓**Relativistic effects small**

Phase shifts-H wave & I wave





✓**High partial wave: Two-pion exchange insignificant!**

OUTLINE

Summary & outlook

☐ Summary

- ✓ Calculate **two-pion exchange** contributions in **covariant BChPT**
- ✓ **Quantitatively better** description is achieved especially for **F wave**

☐ Outlook

- ✓ The role of **nucleon resonance**
  - $\Delta(1232)$
  - **Roper resonance**

Thank you very much for your attention