第十届手征有效场论研讨会

相对论手征核力的新进展

陆俊旭 @ 北京航空航天大学

合作者: 翟擎宇博士，肖杨博士，耿立升教授，梁豪兆副教授

2025年10月 南京

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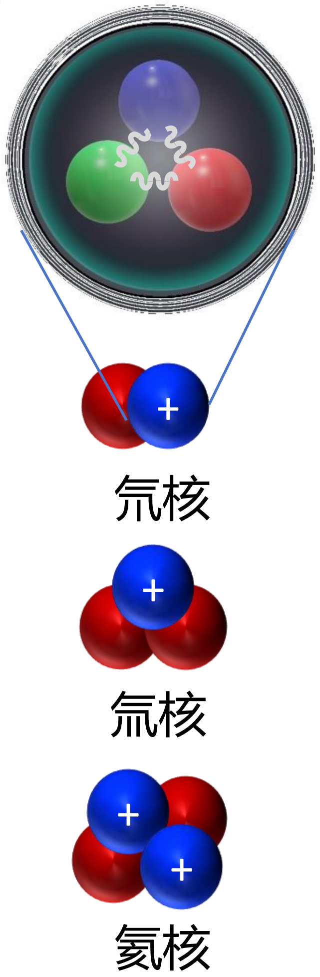
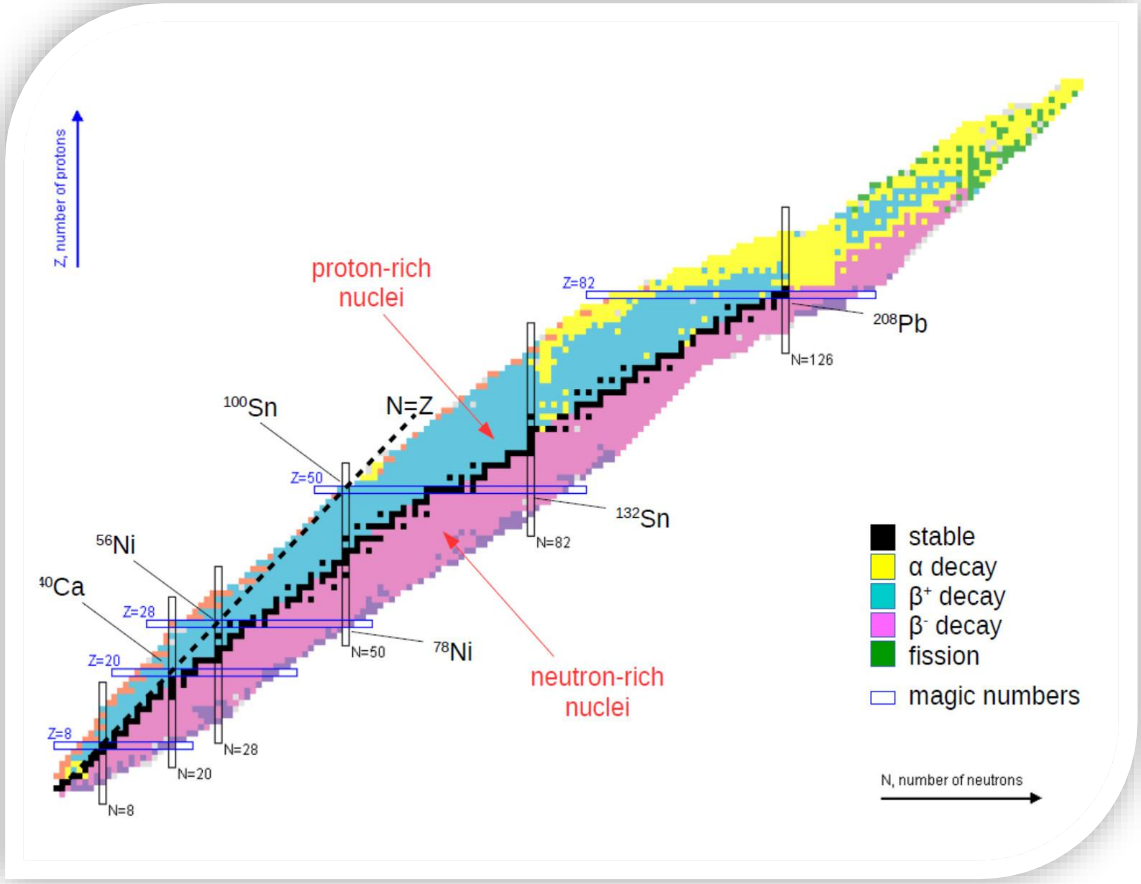
目录

☐ 核物理研究的关键

- 核物质、核反应、核结构、天体物理





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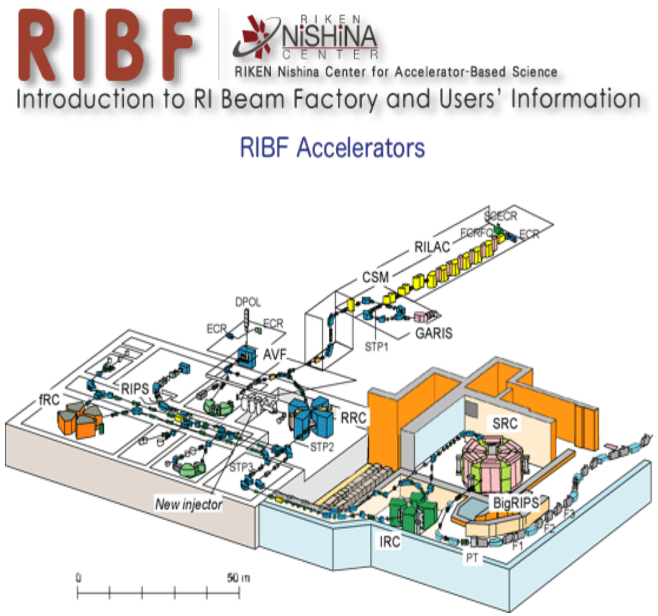
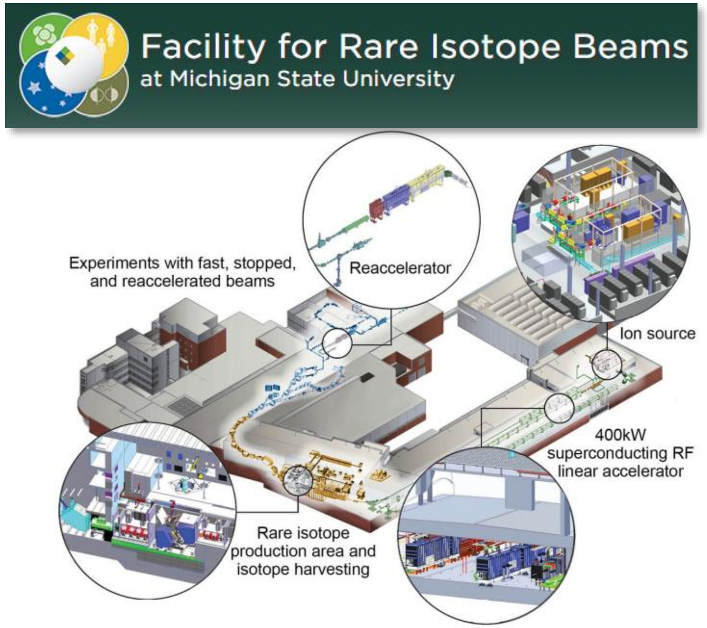
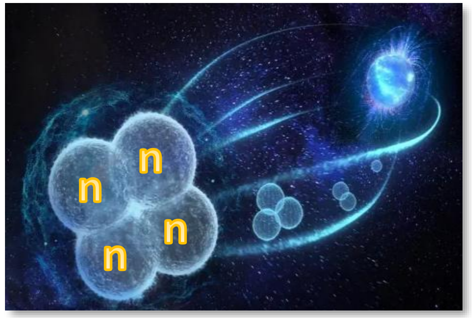
□ 国际大科学装置关注的焦点



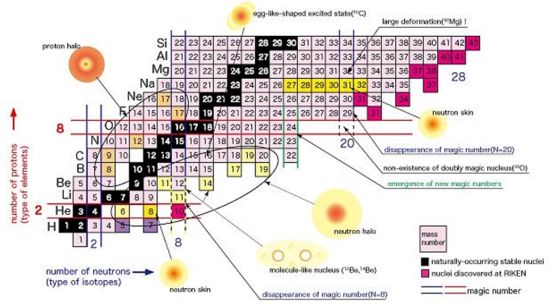


□ “科学发现新时代”----奇特核

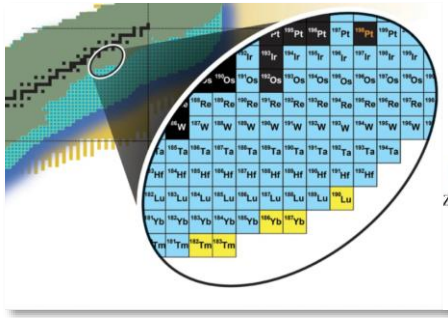
four-neutron system



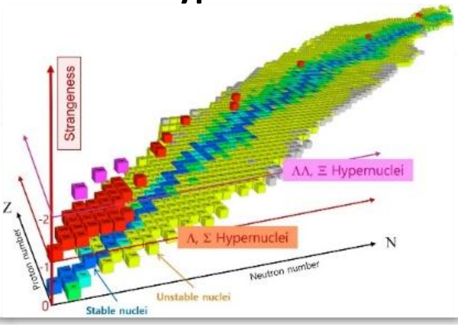
halo nucleus



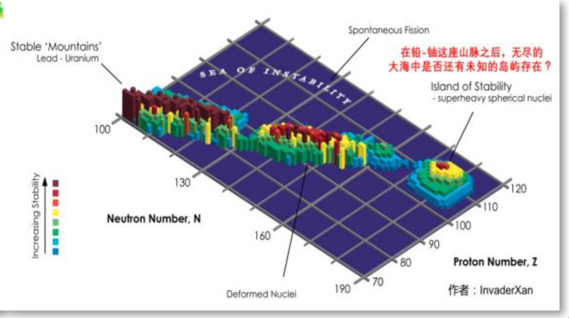
nuclei near drip line



Hyper-nuclei



Super heavy elements

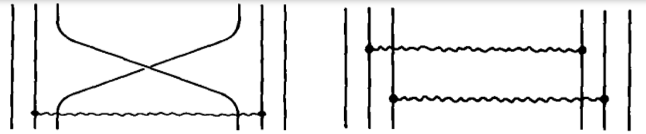


□ 物理学研究中最为困难的问题之一

Hans Bethe **Yukawa**

Nobel Prize 1967/1949

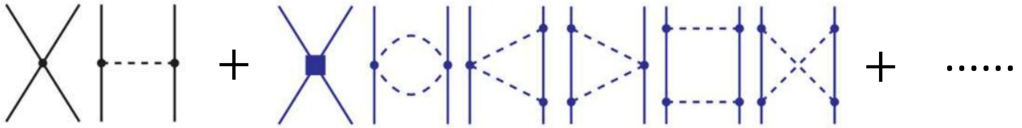
- 1935 Yukawa, Meson theory
- 1950-1960’ One pion exchange, One boson exchange
- 1980’ 夸克模型



- 1990’ Weinberg, **手征有效场论**

S. Weinberg, PLB1990

现代核力

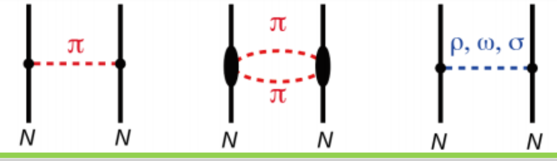


- 1994 **高精度 唯象模型**: **AV18**、**Reid93** （算符因子化）

V. Stoks, PRC1994 R. Wiringa,PRC1994

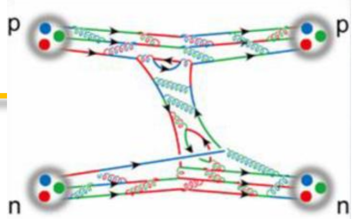
$$V_{NN} = V_c(r)\hat{1} + V_\sigma(r)\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + V_{LS}(r)\, \boldsymbol{L}\cdot\boldsymbol{S} + V_T(r)\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{q}\boldsymbol{\sigma}_2 \cdot \boldsymbol{q} + \cdots\cdots$$

- 2001**高精度 唯象模型**: **CD-Bonn** （介子交换）



R. Machleidt, PRC2001

- 2006完整动力学的**Lattice QCD**



S.R.Beane PRL2006

目录

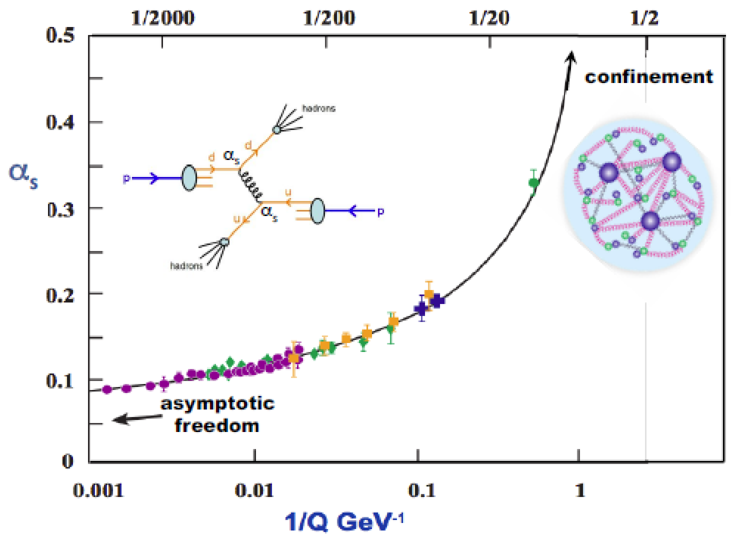
❑ QCD: 渐近自由与色禁闭

➢ 高能区：

- “自由” 夸克

➢ 低能区：

- **非微扰特性**
- **强子** 成为强相互作用自由度

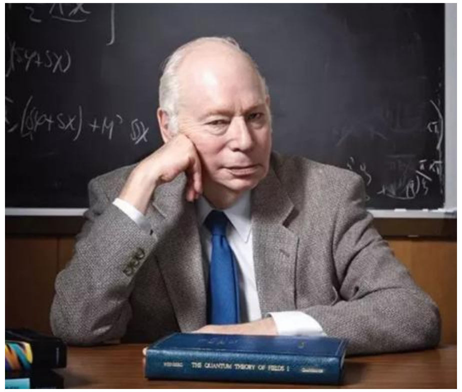


❑ 手征有效场论——QCD低能区近似

➢ 手征对称性及其自发破缺——Goldstone玻色子

➢ 有效场论——低能区相互作用不依赖于高能区相互作用的细节

与QCD紧密相关	基本自由度	构建展开小量
$\mathcal{L}_{QCD} \rightarrow$ $\mathcal{L}_{\chi EFT} = \sum c_i O_i$	夸克 & 胶子 ⬇ **强子**	$Q/\Lambda \ll 1$ **形成计阶规则** • 硬能标 Λ • 软能标 Q



Steven Weinberg

Nobel Prize 1979

❑ 手征有效场论的优势

➢ **与QCD紧密关联** ➢ **系统提高描述精度** ➢ **估计理论误差** ➢ **自洽三体力**

相对论手征核力

◻ 相对论理论框架

动力学 & 运动学

- ✓ 洛伦兹协变性
- ✓ 收敛速度快
- ✓ 改善重整化群不变性
- ✓ 可以用于相对论核物理第一性原理研究

手征有效拉氏量: Dirac 旋量 + Clifford 代数

$$u(p,s) = N_p \begin{pmatrix} 1 \\ \frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{E+m} \end{pmatrix} \chi_s$$

	$\mathbb{1}$	γ_5	γ_μ	$\gamma_5\gamma_\mu$	$\sigma_{\mu\nu}$	$\epsilon_{\mu\nu\rho\sigma}$	$\overleftrightarrow{\partial}_\mu$	∂_μ
$\mathcal{O}$	0	1	0	0	0	−	0	1
$\mathcal{P}$	+	−	+	−	+	−	+	+
$\mathcal{C}$	+	+	−	+	−	+	−	+
h.c.	+	−	+	+	+	+	−	+

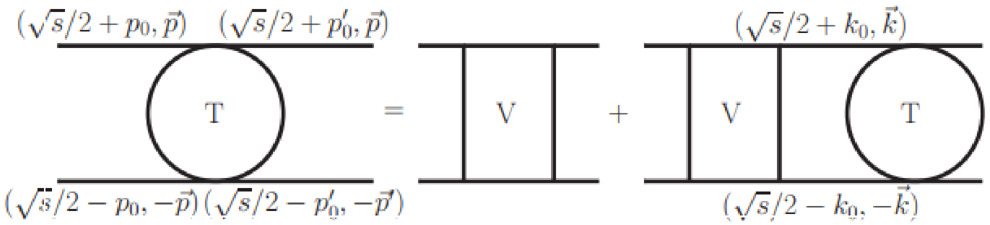
协变计阶规则

Extended-on-mass-shell(EOMS) scheme

$$C_i = C_i^b + C_i^d R + C_i^{\mathrm{PCB}}$$

C_i: LEC C_i^b: the bare value C_i^d: for UV divergence C_i^{PCB}: for PCB terms

非微扰处理: 相对论散射方程 (Blankenbecler-Sugar equation)



$$\mathcal{T}(p',p|W) = \mathcal{A}(p',p|W) + \int \frac{d^4k}{(2\pi^4)} \mathcal{A}(p',k|W)G(k|W)\mathcal{T}(k,p|W),$$

$$\mathcal{T} = \mathcal{V} + \mathcal{V}g\mathcal{T},$$
$$\mathcal{V} = \mathcal{A} + \mathcal{A}(G-g)\mathcal{V}$$

$$g = \frac{\pi i\delta(k^0)\Lambda_+^1(\boldsymbol{k})\Lambda_+^2(-\boldsymbol{k})}{2E_k(E_k^2 - s/4 - i\epsilon)}$$

□现阶段结果-NNLO 2N np 散射

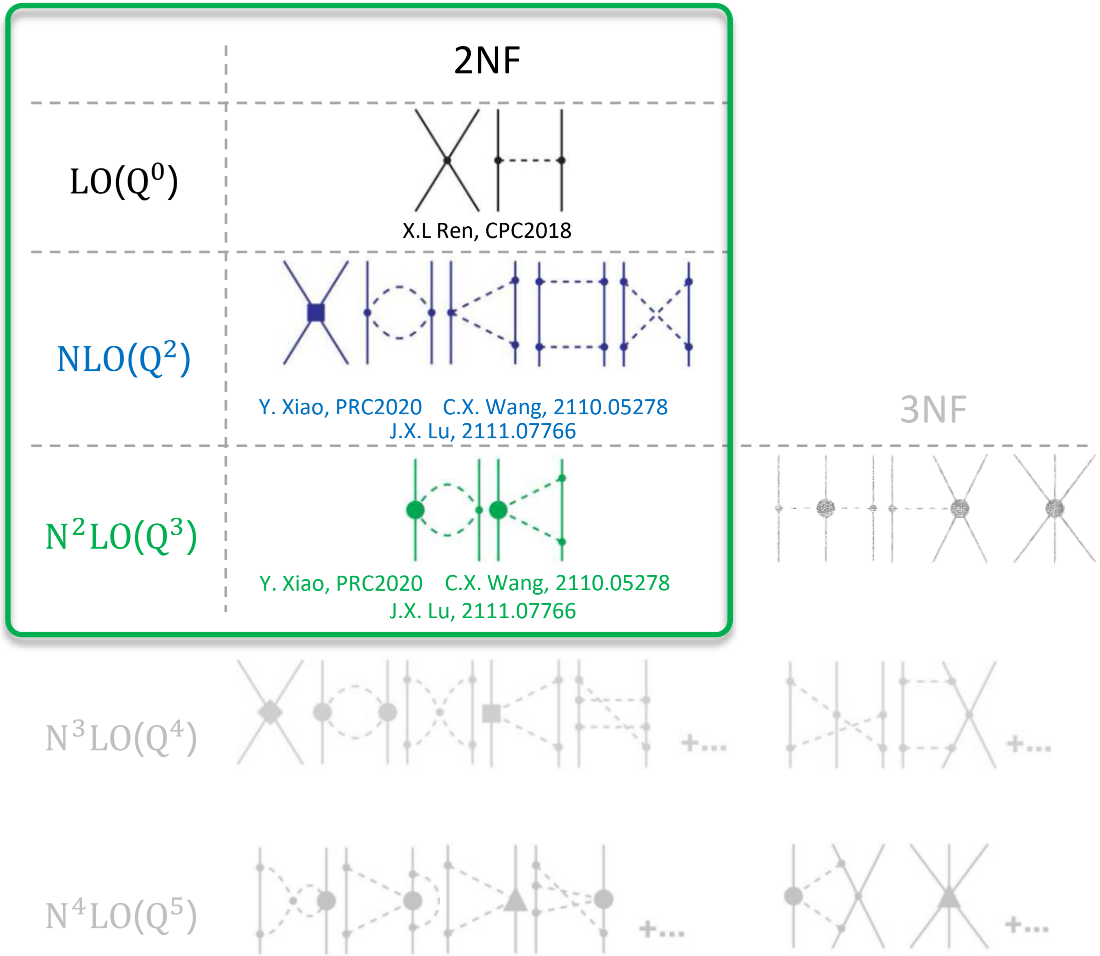
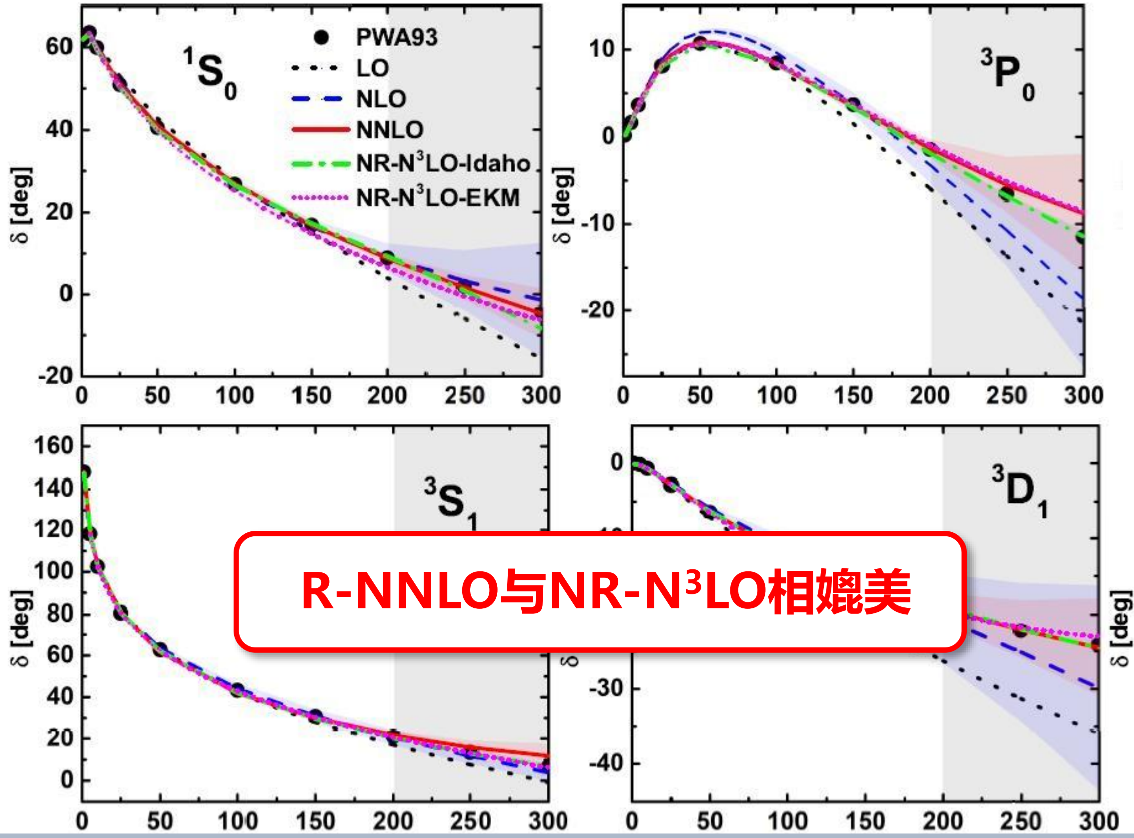


TABLE III. $\tilde{\chi}^2 = \sum_i (\delta^i - \delta^i_{\text{PWA93}})^2$ of different chiral forces for partial waves up to $J \leq 2$.

	Total	$^1S_0$	$^3P_0$	$^1P_1$	$^3P_1$	$^3S_1$	$^3D_1$	ϵ_1	$^1D_2$	$^3D_2$	$^3P_2$	$^3F_2$	ϵ_2
NLO	17.02	1.02	7.04	0.46	0.33	1.80	1.69	0.15	2.18	1.35	0.95	0.01	0.04
NNLO	16.61	0.18	0.30	1.07	1.55	3.36	0.26	0.03	0.01	9.56	0.01	0.27	0.01
NR-N^3LO-Idaho	8.84	1.53	0.30	2.41	0.04	2.33	1.00	0.02	0.57	0.42	0.17	0.03	0.02
NR-N^3LO-EKM	16.08	13.45	0.29	0.34	0.06	0.01	0.13	0.01	0.02	0.43	0.12	1.22	0.00

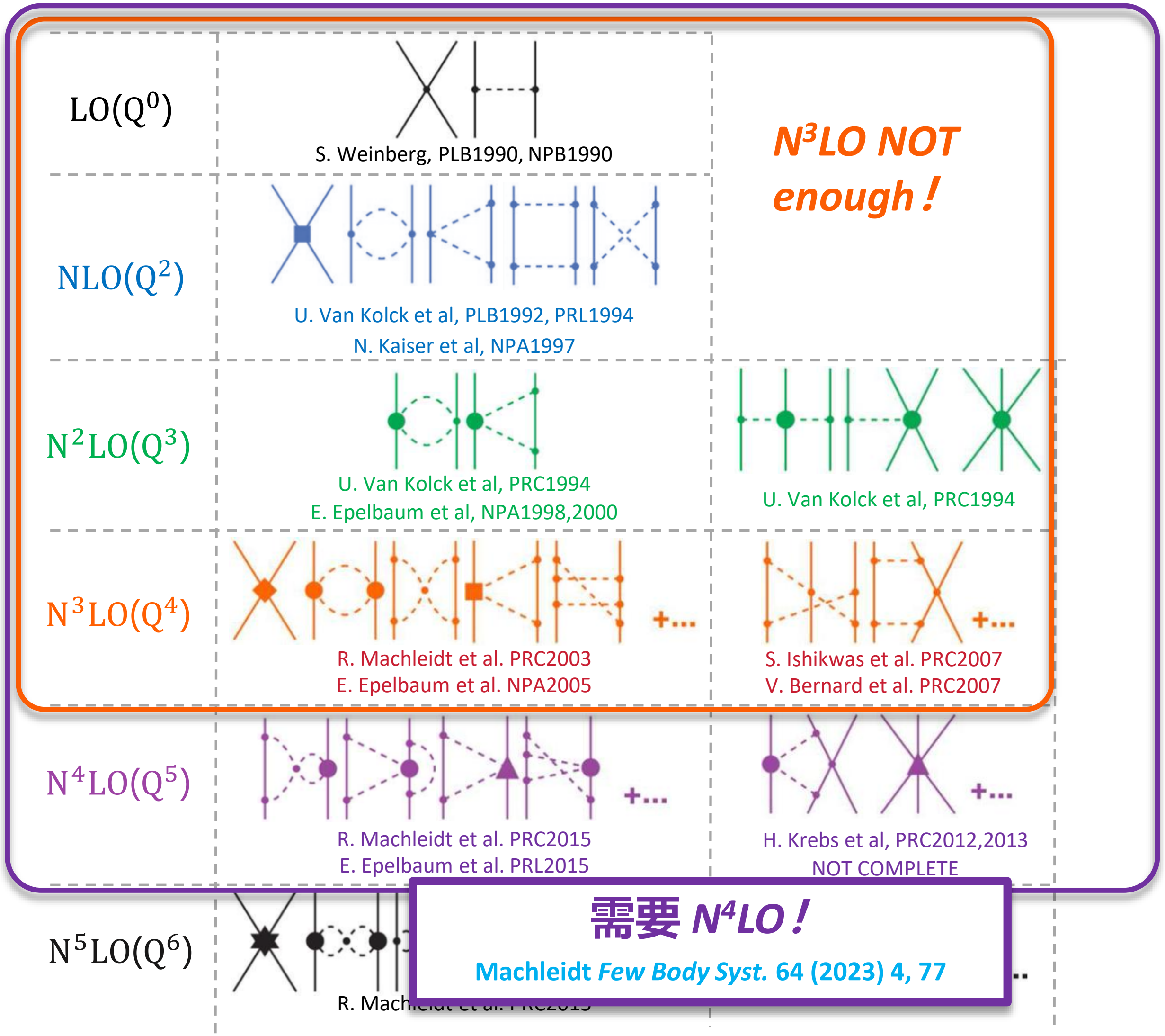
- NLO/NNLO: Phys.Rev.C(2020), Phys.Rev.C(2022), Phys.Rev.Lett.(2022)
- NR-N^3LO-Idaho: R. Machleidt and D. R. Entem, Phys.Rev.C(2003), Phys.Rept.(2011)
- NR-N^3LO-EKM: E. Epelbaum, H. Krebs, and U. G. Meißner, Eur.Phys.J.A(2015), Phys.Rev.Lett. (2015).



R-NNLO与NR-N^3LO相媲美

相对论手征核力——下阶段的发展规划

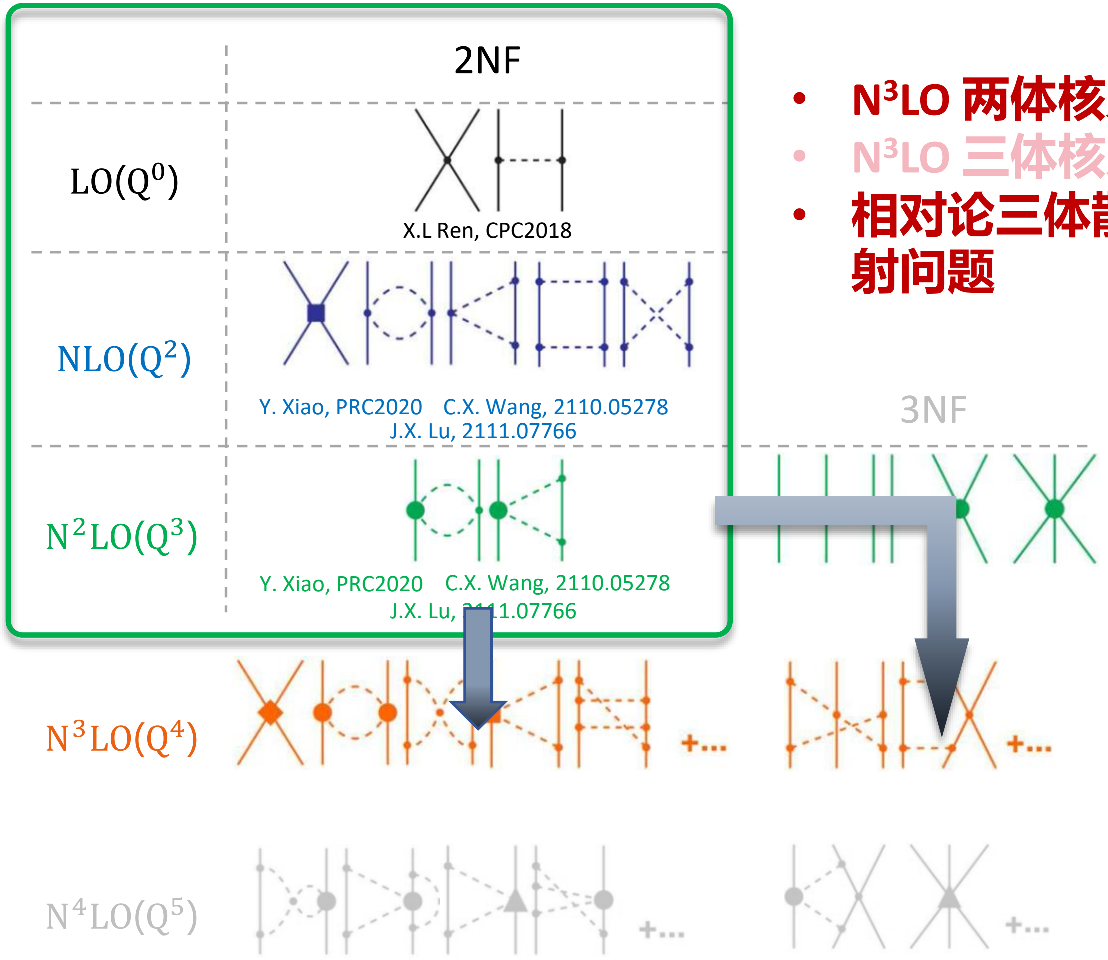
□NR-ChNF: N^3LO 精度不足!



需要 N^4LO!

Machleidt *Few Body Syst.* 64 (2023) 4, 77

□R-ChNF: 下一代（N^3LO）核力



- N^3LO 两体核力
- N^3LO 三体核力
- 相对论三体散射问题

R-ChNF-N^3LO ongoing!

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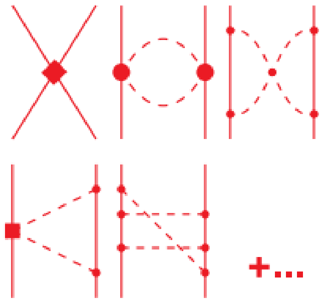
- 核力简介
- 理论框架: 相对论手征核力
- 相对论手征核力新进展
  - $\mathrm{N^3LO}$ 手征核力
  - 相对论三体框架
- 总结与展望

N³LO

$(Q/\Lambda_\chi)^4$



- ✓ Contact term (23 terms)
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- ✓ Three Pion negligible

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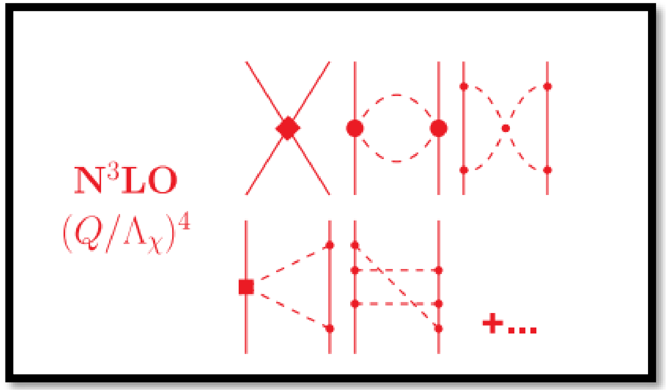
Isospin breaking effect

➢ Contact terms（23项）

$\widetilde{O}_1$	$(\bar\psi\psi)(\bar\psi\psi)$	$\widetilde{O}_{21}$	$\frac{1}{16m^4}\left(\bar\psi i\overleftrightarrow{\partial}^{\mu}\psi\right)\partial^2\partial^\nu\left(\bar\psi\sigma_{\mu\nu}\psi\right)$
$\widetilde{O}_2$	$(\bar\psi\gamma^\mu\psi)(\bar\psi\gamma_\mu\psi)$	$\widetilde{O}_{22}$	$\frac{1}{16m^4}(\bar\psi\sigma^{\mu\alpha}\psi)\partial^2\partial_\alpha\partial^\nu(\bar\psi\sigma_{\mu\nu}\psi)$
$\widetilde{O}_3$	$(\bar\psi\gamma_5\gamma^\mu\psi)(\bar\psi\gamma_5\gamma_\mu\psi)$	$\widetilde{O}_{23}$	$\frac{1}{16m^4}\left(\bar\psi\sigma^{\mu\nu}i\overleftrightarrow{\partial}^{\alpha}\psi\right)\partial^\beta\partial_\nu\left(\bar\psi\sigma_{\alpha\beta}i\overleftrightarrow{\partial}_{\mu}\psi\right)$
$\widetilde{O}_4$	$(\bar\psi\sigma^{\mu\nu}\psi)(\bar\psi\sigma_{\mu\nu}\psi)$	$\widetilde{O}_{24}$	$\frac{1}{16m^4}(\bar\psi\psi)\partial^4(\bar\psi\psi)$
$\widetilde{O}_5$	$(\bar\psi\gamma_5\psi)(\bar\psi\gamma_5\psi)$	$\widetilde{O}_{25}$	$\frac{1}{16m^4}(\bar\psi\gamma^\mu\psi)\partial^4(\bar\psi\gamma_\mu\psi)$
$\widetilde{O}_6$	$\frac{1}{4m^2}\left(\bar\psi\gamma_5\gamma^\mu i\overleftrightarrow{\partial}^{\alpha}\psi\right)\left(\bar\psi\gamma_5\gamma_\alpha i\overleftrightarrow{\partial}_{\mu}\psi\right)$	$\widetilde{O}_{26}$	$\frac{1}{16m^4}(\bar\psi\gamma_5\gamma^\mu\psi)\partial^4(\bar\psi\gamma_5\gamma_\mu\psi)$
$\widetilde{O}_7$	$\frac{1}{4m^2}\left(\bar\psi\sigma^{\mu\nu} i\overleftrightarrow{\partial}^{\alpha}\psi\right)\left(\bar\psi\sigma_{\mu\alpha} i\overleftrightarrow{\partial}_{\nu}\psi\right)$	$\widetilde{O}_{27}$	$\frac{1}{16m^4}(\bar\psi\sigma^{\mu\nu}\psi)\partial^4(\bar\psi\sigma_{\mu\nu}\psi)$
$\widetilde{O}_8$	$\frac{1}{4m^2}\left(\bar\psi i\overleftrightarrow{\partial}^{\mu}\psi\right)\partial^\nu(\bar\psi\sigma_{\mu\nu}\psi)$	$\widetilde{O}_{28}$	$\frac{1}{4m^2}\left(\bar\psi\gamma_5 i\overleftrightarrow{\partial}^{\alpha}\psi\right)\left(\bar\psi\gamma_5 i\overleftrightarrow{\partial}_{\alpha}\psi\right)-\widetilde{O}_5$
$\widetilde{O}_9$	$\frac{1}{4m^2}(\bar\psi\sigma^{\mu\alpha}\psi)\partial_\alpha\partial^\nu(\bar\psi\sigma_{\mu\nu}\psi)$	$\widetilde{O}_{29}$	$\frac{1}{16m^4}\left(\bar\psi\gamma_5\gamma^\mu i\overleftrightarrow{\partial}^{\alpha} i\overleftrightarrow{\partial}^{\beta}\psi\right)\left(\bar\psi\gamma_5\gamma_\alpha i\overleftrightarrow{\partial}_{\mu} i\overleftrightarrow{\partial}_{\beta}\psi\right)-\widetilde{O}_6$
$\widetilde{O}_{10}$	$\frac{1}{4m^2}(\bar\psi\psi)\partial^2(\bar\psi\psi)$	$\widetilde{O}_{30}$	$\frac{1}{16m^4}\left(\bar\psi\sigma^{\mu\nu} i\overleftrightarrow{\partial}^{\alpha} i\overleftrightarrow{\partial}^{\beta}\psi\right)\left(\bar\psi\sigma_{\mu\alpha} i\overleftrightarrow{\partial}_{\nu} i\overleftrightarrow{\partial}_{\beta}\psi\right)-\widetilde{O}_7$
$\widetilde{O}_{11}$	$\frac{1}{4m^2}(\bar\psi\gamma^\mu\psi)\partial^2(\bar\psi\gamma_\mu\psi)$	$\widetilde{O}_{31}$	$\frac{1}{16m^4}\left(\bar\psi i\overleftrightarrow{\partial}^{\mu} i\overleftrightarrow{\partial}^{\beta}\psi\right)\partial^\alpha\left(\bar\psi\sigma_{\mu\alpha} i\overleftrightarrow{\partial}_{\beta}\psi\right)-\widetilde{O}_8$
$\widetilde{O}_{12}$	$\frac{1}{4m^2}(\bar\psi\gamma_5\gamma^\mu\psi)\partial^2(\bar\psi\gamma_5\gamma_\mu\psi)$	$\widetilde{O}_{32}$	$\frac{1}{16m^4}\left(\bar\psi\sigma^{\mu\alpha} i\overleftrightarrow{\partial}^{\beta}\psi\right)\partial_\alpha\partial^\nu\left(\bar\psi\sigma_{\mu\nu} i\overleftrightarrow{\partial}_{\beta}\psi\right)-\widetilde{O}_9$
$\widetilde{O}_{13}$	$\frac{1}{4m^2}(\bar\psi\sigma^{\mu\nu}\psi)\partial^2(\bar\psi\sigma_{\mu\nu}\psi)$	$\widetilde{O}_{33}$	$\frac{1}{16m^4}\left(\bar\psi i\overleftrightarrow{\partial}^{\alpha}\psi\right)\partial^2\left(\bar\psi i\overleftrightarrow{\partial}_{\alpha}\psi\right)-\widetilde{O}_{10}$
$\widetilde{O}_{14}$	$\frac{1}{4m^2}\left(\bar\psi i\overleftrightarrow{\partial}^{\alpha}\psi\right)\left(\bar\psi i\overleftrightarrow{\partial}_{\alpha}\psi\right)-\widetilde{O}_1$	$\widetilde{O}_{34}$	$\frac{1}{16m^4}\left(\bar\psi\gamma^\mu i\overleftrightarrow{\partial}^{\alpha}\psi\right)\partial^2\left(\bar\psi\gamma_\mu i\overleftrightarrow{\partial}_{\alpha}\psi\right)-\widetilde{O}_{11}$
$\widetilde{O}_{15}$	$\frac{1}{4m^2}\left(\bar\psi\gamma^\mu i\overleftrightarrow{\partial}^{\alpha}\psi\right)\left(\bar\psi\gamma_\mu i\overleftrightarrow{\partial}_{\alpha}\psi\right)-\widetilde{O}_2$	$\widetilde{O}_{35}$	$\frac{1}{16m^4}\left(\bar\psi\gamma_5\gamma^\mu i\overleftrightarrow{\partial}^{\alpha}\psi\right)\partial^2\left(\bar\psi\gamma_5\gamma_\mu i\overleftrightarrow{\partial}_{\alpha}\psi\right)-\widetilde{O}_{12}$
$\widetilde{O}_{16}$	$\frac{1}{4m^2}\left(\bar\psi\gamma_5\gamma^\mu i\overleftrightarrow{\partial}^{\alpha}\psi\right)\left(\bar\psi\gamma_5\gamma_\mu i\overleftrightarrow{\partial}_{\alpha}\psi\right)-\widetilde{O}_3$	$\widetilde{O}_{36}$	$\frac{1}{16m^4}\left(\bar\psi\sigma^{\mu\nu} i\overleftrightarrow{\partial}^{\alpha}\psi\right)\partial^2\left(\bar\psi\sigma_{\mu\nu} i\overleftrightarrow{\partial}_{\alpha}\psi\right)-\widetilde{O}_{13}$
$\widetilde{O}_{17}$	$\frac{1}{4m^2}\left(\bar\psi\sigma^{\mu\nu} i\overleftrightarrow{\partial}^{\alpha}\psi\right)\left(\bar\psi\sigma_{\mu\nu} i\overleftrightarrow{\partial}_{\alpha}\psi\right)-\widetilde{O}_4$	$\widetilde{O}_{37}$	$\frac{1}{16m^4}\left(\bar\psi i\overleftrightarrow{\partial}^{\alpha} i\overleftrightarrow{\partial}^{\beta}\psi\right)\left(\bar\psi i\overleftrightarrow{\partial}_{\alpha} i\overleftrightarrow{\partial}_{\beta}\psi\right)-2\widetilde{O}_{14}-\widetilde{O}_1$
$\widetilde{O}_{18}$	$\frac{1}{4m^2}(\bar\psi\gamma_5\psi)\partial^2(\bar\psi\gamma_5\psi)$	$\widetilde{O}_{38}$	$\frac{1}{16m^4}\left(\bar\psi\gamma^\mu i\overleftrightarrow{\partial}^{\alpha} i\overleftrightarrow{\partial}^{\beta}\psi\right)\left(\bar\psi\gamma_\mu i\overleftrightarrow{\partial}_{\alpha} i\overleftrightarrow{\partial}_{\beta}\psi\right)-2\widetilde{O}_{15}-\widetilde{O}_2$
$\widetilde{O}_{19}$	$\frac{1}{16m^4}\left(\bar\psi\gamma_5\gamma^\mu i\overleftrightarrow{\partial}^{\nu}\psi\right)\partial^2\left(\bar\psi\gamma_5\gamma_\nu i\overleftrightarrow{\partial}_{\mu}\psi\right)$	$\widetilde{O}_{39}$	$\frac{1}{16m^4}\left(\bar\psi\gamma_5\gamma^\mu i\overleftrightarrow{\partial}^{\alpha} i\overleftrightarrow{\partial}^{\beta}\psi\right)\left(\bar\psi\gamma_5\gamma_\mu i\overleftrightarrow{\partial}_{\alpha} i\overleftrightarrow{\partial}_{\beta}\psi\right)-2\widetilde{O}_{16}-\widetilde{O}_3$
$\widetilde{O}_{20}$	$\frac{1}{16m^4}\left(\bar\psi\sigma^{\mu\nu} i\overleftrightarrow{\partial}^{\alpha}\psi\right)\partial^2\left(\bar\psi\sigma_{\mu\alpha} i\overleftrightarrow{\partial}_{\nu}\psi\right)$	$\widetilde{O}_{40}$	$\frac{1}{16m^4}\left(\bar\psi\sigma^{\mu\nu} i\overleftrightarrow{\partial}^{\alpha} i\overleftrightarrow{\partial}^{\beta}\psi\right)\left(\bar\psi\sigma_{\mu\nu} i\overleftrightarrow{\partial}_{\alpha} i\overleftrightarrow{\partial}_{\beta}\psi\right)-2\widetilde{O}_{17}-\widetilde{O}_4$

Y. Xiao et al Phys.Rev.C 99,024004

N³LO 两体核力



- ✓ Contact term (23 terms)
- ✓ One Pion Renormalization
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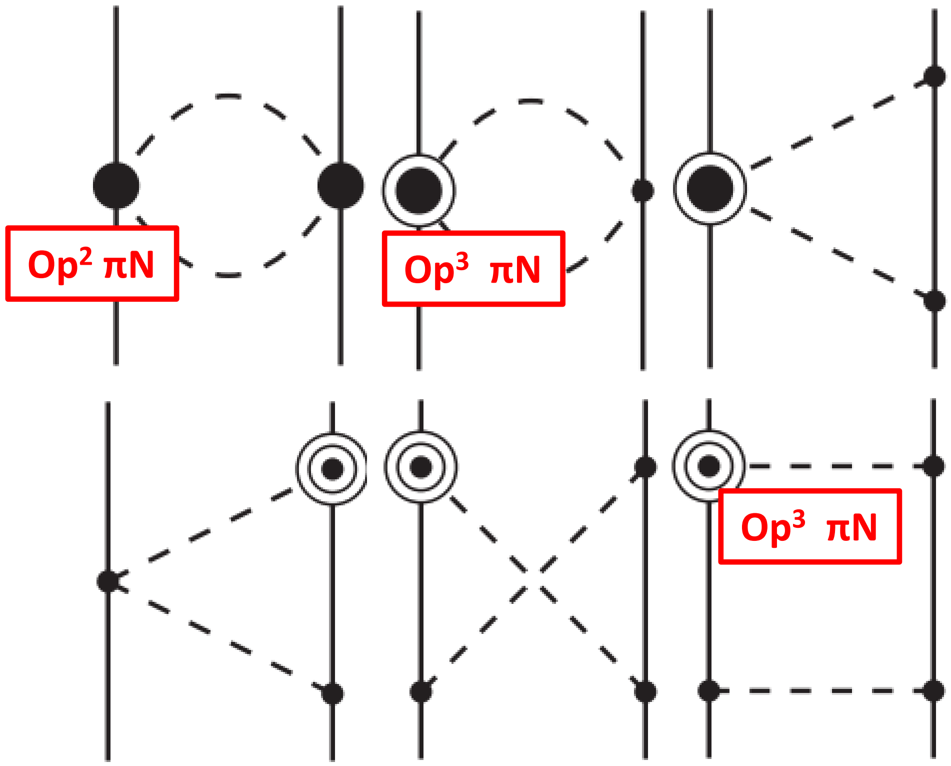
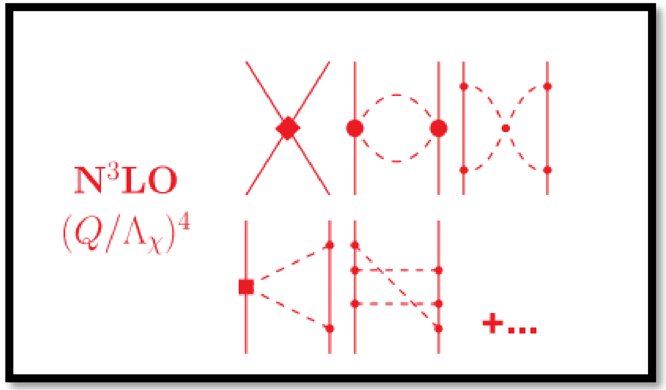
Isospin breaking effect

➢ TPE（One-loop part)





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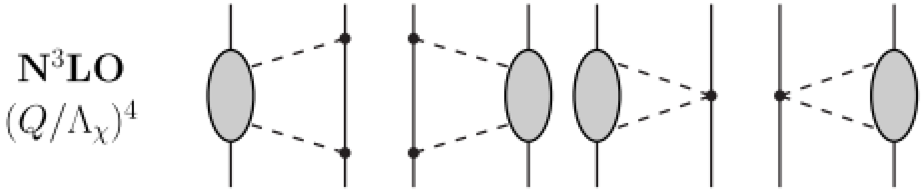
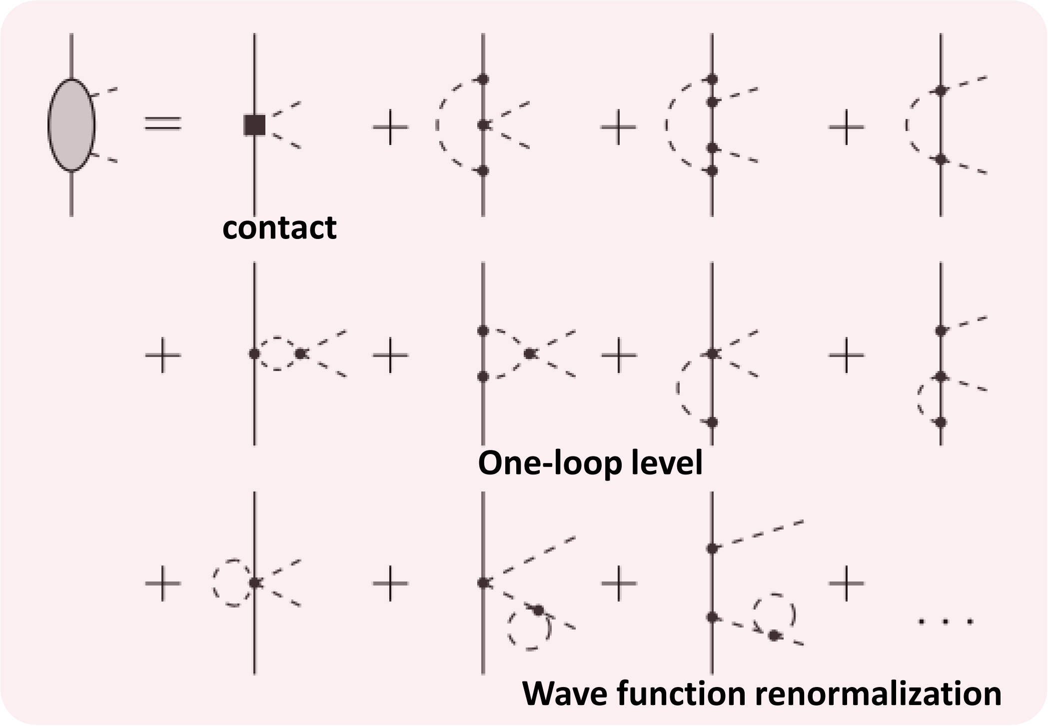
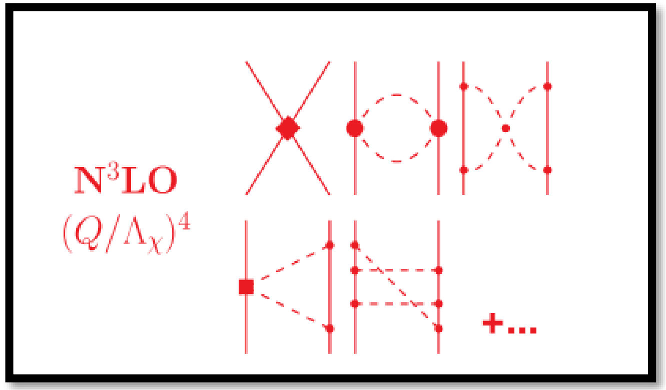
Isospin breaking effect

- TPE (two-loop part)





N³LO 两体核力



- ✓ Contact term (23 terms)
- ✓ One Pion Renormalization
- ✓ Two Pion One + Two loop
- ✓ Three Pion negligible

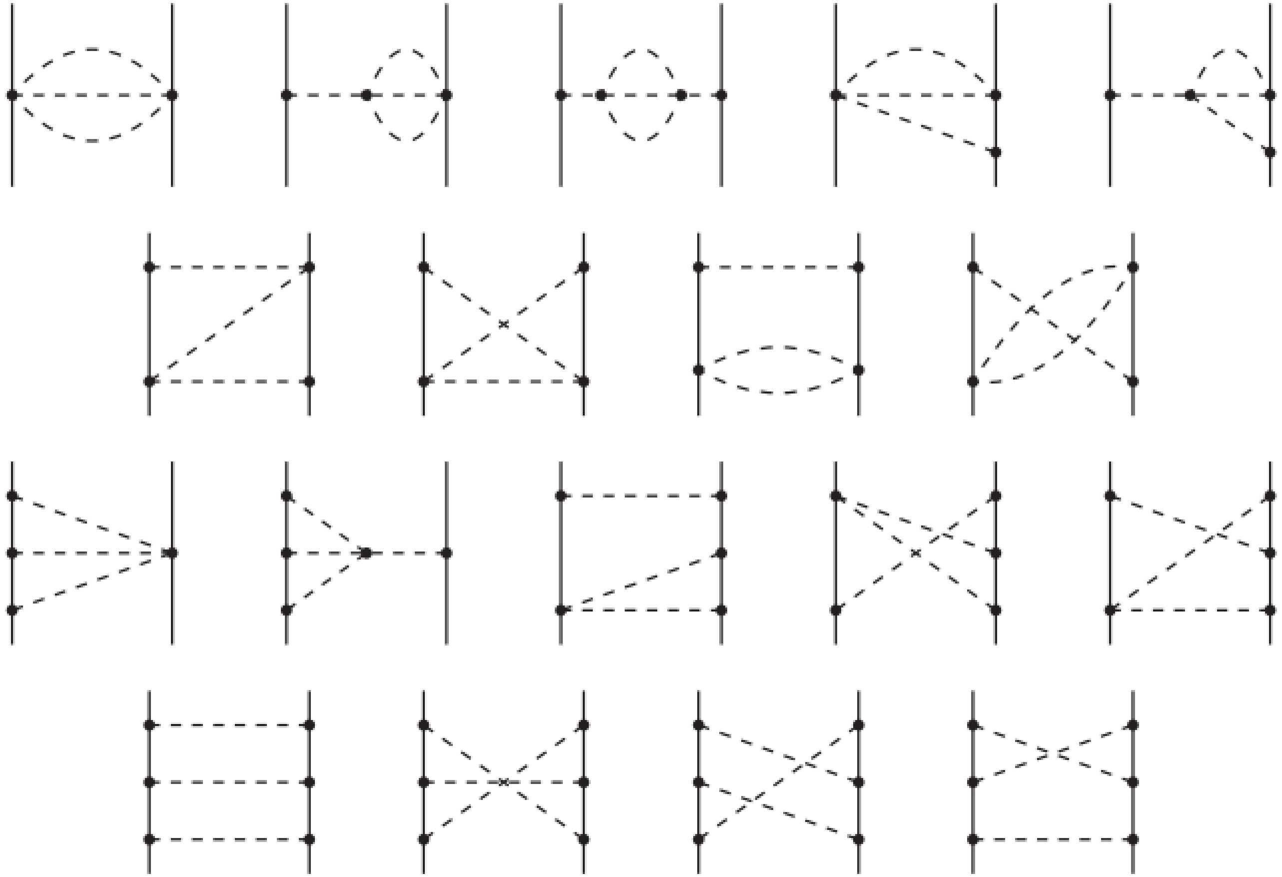
$$V_{1\pi} = V_{1\pi}^{(0)} + V_{1\pi}^{(2)} + V_{1\pi}^{(3)} + V_{1\pi}^{(4)} + \cdots$$

$$V_{2\pi} = V_{2\pi}^{(2)} + V_{2\pi}^{(3)} + V_{2\pi}^{(4)} + \cdots$$

$$V_{3\pi} = V_{3\pi}^{(4)} + \cdots,$$

Isospin breaking effect

- Three Pion Exchange



R. Machleidt, D.R. Entem / Physics Reports 503 (2011) 1–75

两圈图——N³LO 2N核力中最困难的部分

北京航空航天大学 BEIHANG UNIVERSITY

☐ 维数正规化

- 对单圈图，方便直接（FeynCalc、FeynArts、PackageX）
- **完整振幅**----非解析部分 + 解析的多项式部分
- 圈图中 pion介子动量积分至无穷
- 两圈图计算非常复杂，特别是在核力研究中涉及非零质量费米子

目前，核力研究中尚未有采用维数正规化计算两圈图的先例

☐ 谱函数正规化

- **基于解析性质与色散关系——散射振幅的Mandelstam 表示**
- 大多数情况下，**只能得到非解析项**
- 方便对圈图中的pion介子动量进行截断
- 非相对论两圈图可行，**相对论框架下应同样可行**

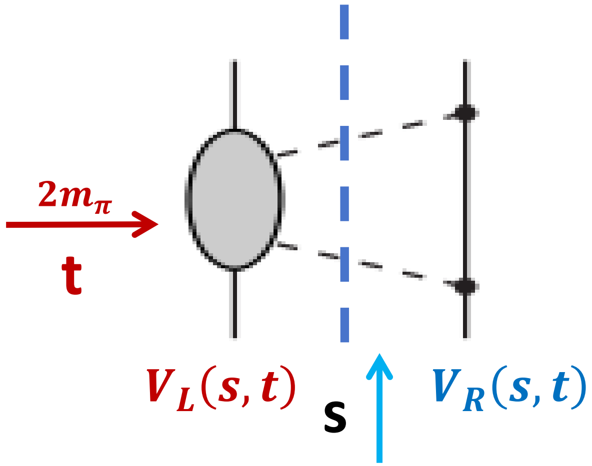
目前已是高阶非相对论手征核力处理多圈图的普遍选择

- **Semi-local N^4LO NR-NF** Reinert et al. *Eur.Phys.J.A* 54, 86 (2018)
- **Local position-space N^3LO NR-NF** Saha et al. *Phys.Rev.C* 107, 034002 (2023)

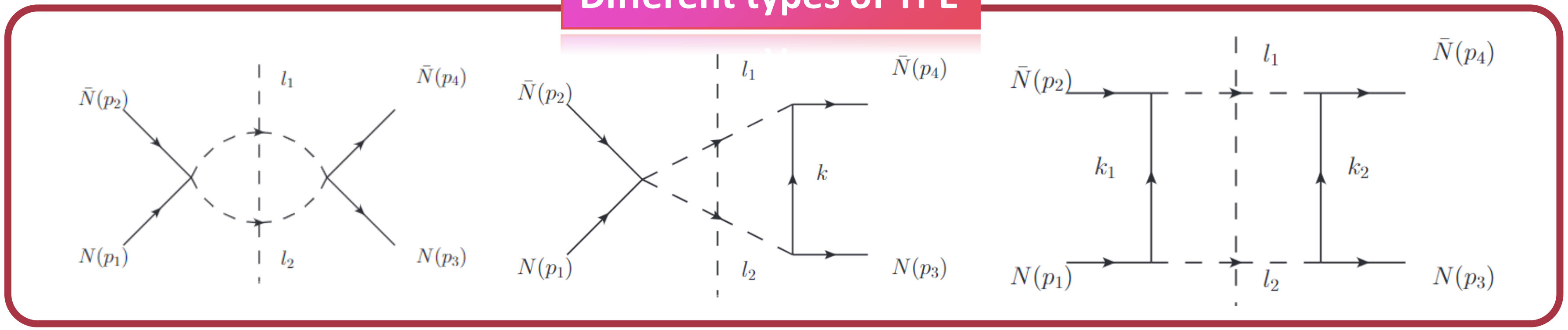
圈图的谱函数正规化

□ 计算TPE的 t 道非连续性——Cutkosky rules

- 等价于 $N\bar{N} \to \pi\pi \to N\bar{N}$ 过程的 s 道非连续性



Different types of TPE



$$\text{Disc}[\mathcal{A}(s,t)] = i\int d^4l\frac{V_L(s,t)V_R(s,t)}{(2\pi)^4}(-2\pi i)^2\delta(l^2-m_\pi^2)\delta((l-q)^2-m_\pi^2)$$

$V_L(s,t)$, $V_R(s,t)$ 为 **πN 振幅** at $\mathcal{O}(p^3)$ or $\mathcal{O}(p^1)$

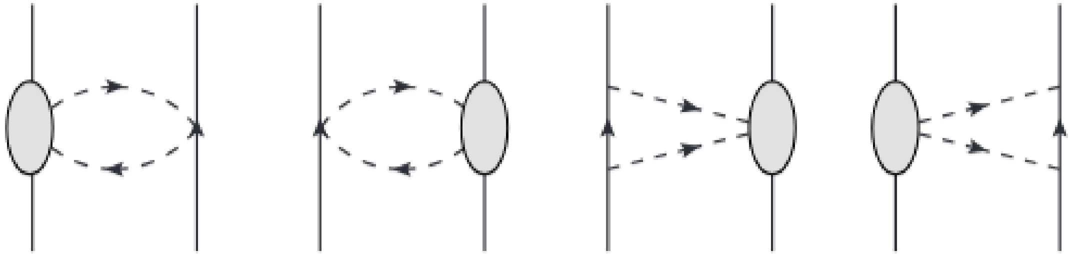
- 利用色散关系，用t道非连续性获得最终振幅

$$\text{Re}[\mathcal{A}(s,t)] = \frac{1}{2\pi i}\int d\mu^2\frac{\text{Disc}[\mathcal{A}(s,\mu^2)]}{\mu^2-t}$$

谱函数

非相对论框架下的两圈图

➢ 非相对论 **πN 振幅**（$\pi^a(q) + N(p) \to \pi^b(q') + N(p')$）: 在重重子近似下非常简洁



$V_L(s,t)$ $V_R(s,t)$

N. Kaiser, Phys.Rev.C64,057001(2001)

$$T^{ba}_{\pi N} = \delta^{ba}\left[g^+(\omega,t) + i\vec{\sigma}\cdot(\vec{q}\,'\times\vec{q})\,h^+(\omega,t)\right] + i\epsilon^{bac}\tau^c\left[g^-(\omega,t) + i\vec{\sigma}\cdot(\vec{q}\,'\times\vec{q})\,h^-(\omega,t)\right]$$

$g^{\pm}(\omega,t)$ isoscalar/isovector non-spin-flip amplitude $h^{\pm}(\omega,t)$ isoscalar/isovector spin-flip amplitude ω the pion cms energy

e.g. $$g^+(\omega,t)_{\rm loop} = \frac{g_A^2}{32\pi F_\pi^4}\left\{-\frac{4\omega^2}{g_A^2}\sqrt{M_\pi^2-\omega^2} + (M_\pi^2-2t)\left[M_\pi + \frac{2M_\pi^2-t}{2\sqrt{-t}}\arctan\frac{\sqrt{-t}}{2M_\pi}\right] + \frac{4g_A^2}{3\omega^2}(2\omega^2+t-2M_\pi^2)\left[(M_\pi^2-\omega^2)^{3/2}-M_\pi^3\right]\right\}$$

Bernard et al. Nucl.Phys.A615,483(1997)

➢ **两圈图NN** 振幅（以中心势部分为例）: 将**πN 振幅作为等效顶点**

$$V_c(q) = -\frac{2q^6}{\pi}\int_{2m_\pi}^{\infty} d\mu\,\frac{\mathrm{Im}\,V_c(i\mu)}{\mu^5(\mu^2+q^2)}$$

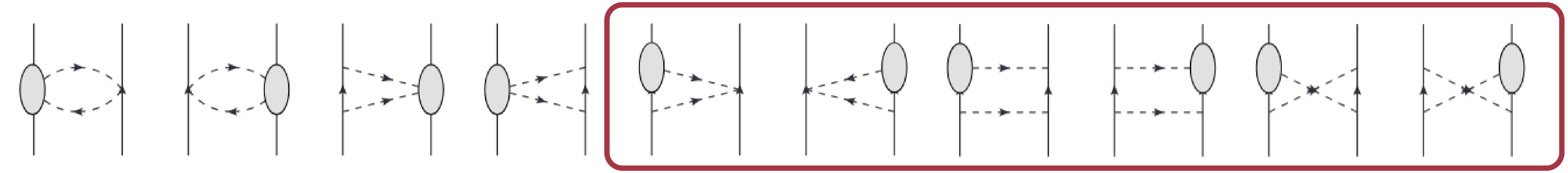
$$\mathrm{Im}\,V_c(i\mu) \propto \mathrm{Re}\,g^+(\omega,t)$$

- **取 $\omega \to 0$ 以及 $t = \mu^2$**

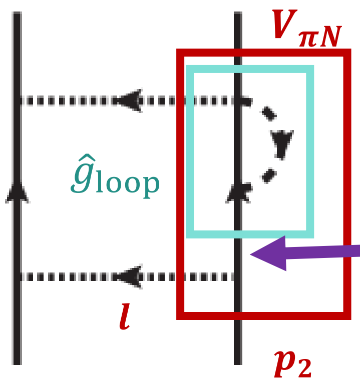
$$\mathrm{Im}\,V_C(i\mu) = \frac{3g_A^4(\mu^2-2m_\pi^2)}{\pi\mu(4f_\pi)^6}\left\{(m_\pi^2-2\mu^2)\left[2m_\pi + \frac{2m_\pi^2-\mu^2}{2\mu}\ln\frac{\mu+2m_\pi}{\mu-2m_\pi}\right] + 4g_A^2 m_\pi(2m_\pi^2-\mu^2)\right\}$$

- 类似可得 $V_{S,T}$ and $W_{C,S,T}$

- 共10类, 88个不同的费曼图



- 相对论 **πN 振幅 仍包含核子传播子**



协变πN振幅

$$V_{\pi \rm N} = \hat{g}_{\rm loop}\frac{1}{(p_2 - l)^2 - m_N^2}$$

重重子近似后的πN振幅

$$p^\mu = m\, v^\mu + k^\mu \qquad v^2 = 1$$

$$(p_2 - l)^2 - m_N^2 \sim 2\, m_N[v\cdot(p_2 - l) - m_N] \sim \omega$$

- **仍然包含类极点的项，无法简单地当作顶点直接计算，同时包含s/t的非连续性**

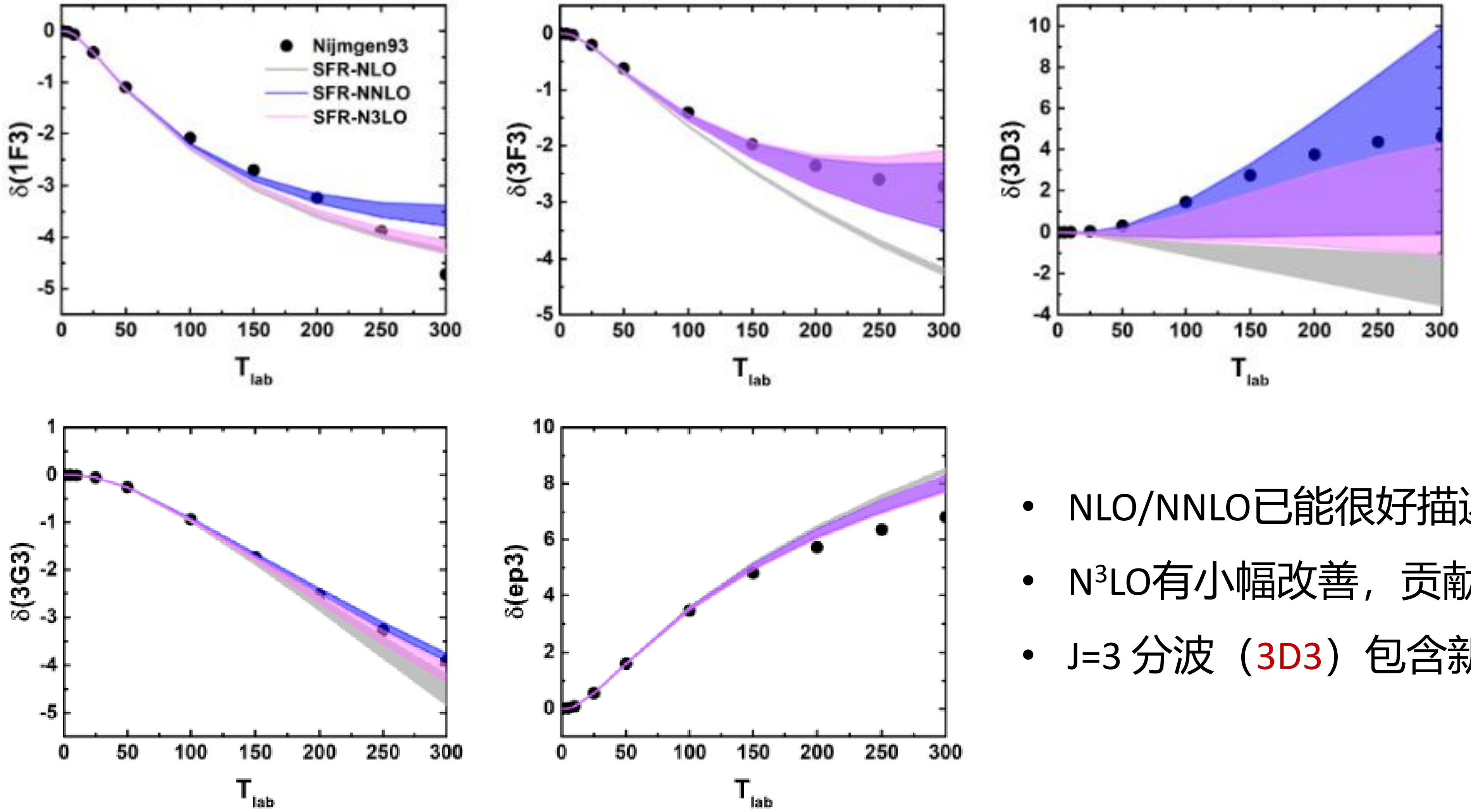
- **谱函数表示下相对论NN振幅的一般形式**

$$\mathcal{A} = \text{Loop integral} \times \text{Bilinear}$$

- Bilinear $\bar{u}_3 u_1 \cdot \bar{u}_4 u_2 \quad \bar{u}_3 \not{p}_i u_1 \cdot \bar{u}_4 u_2$
- Loop integral $\mathrm{Re}[\mathcal{A}(q)] = \frac{1}{2\pi}\int d\mu^2 \frac{\mathrm{Disc}[\mathcal{A}(\mu^2)]}{\mu^2 + q^2}$
- 与非相对论类似，引入对**μ的动量截断**

□ 到N³LO J=3 分波 n-p 散射相移

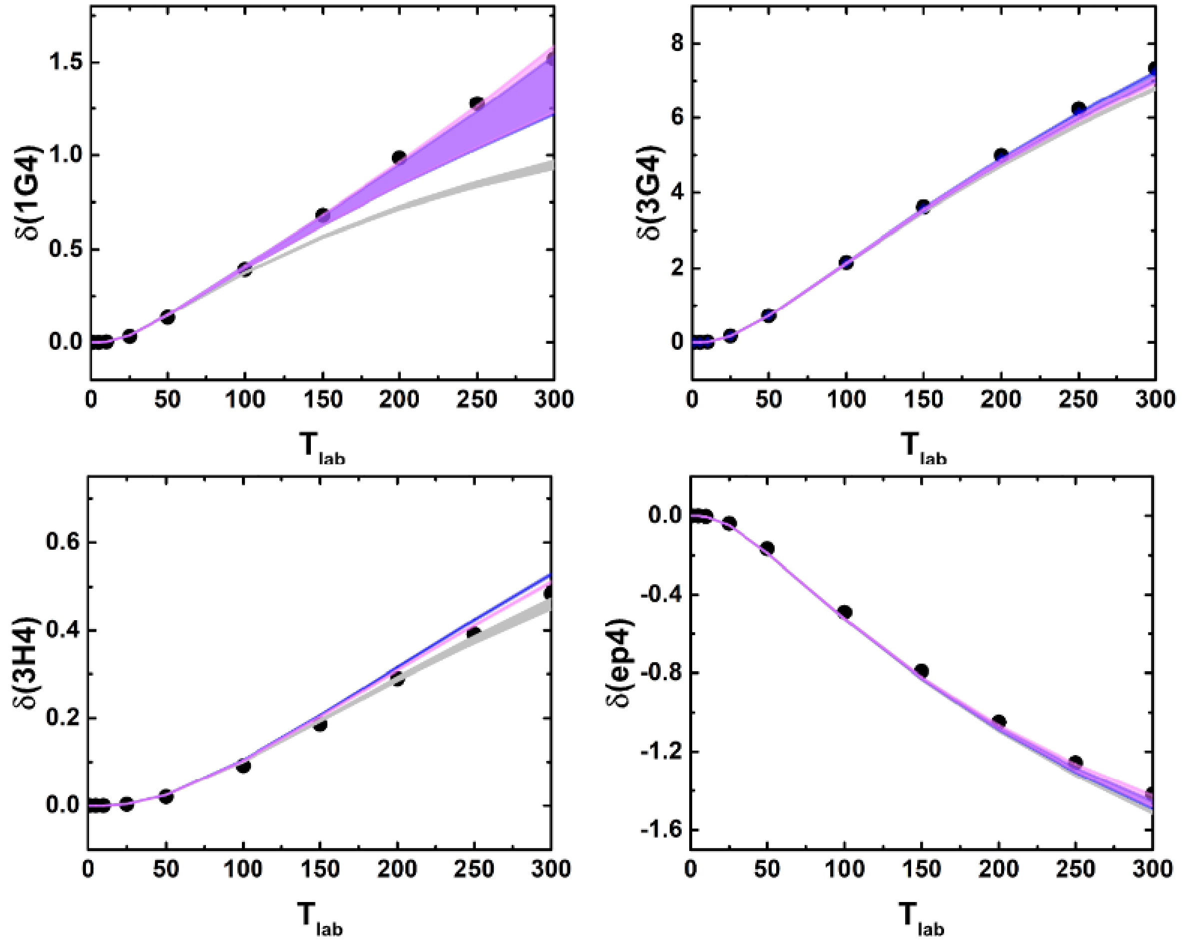
微扰计算

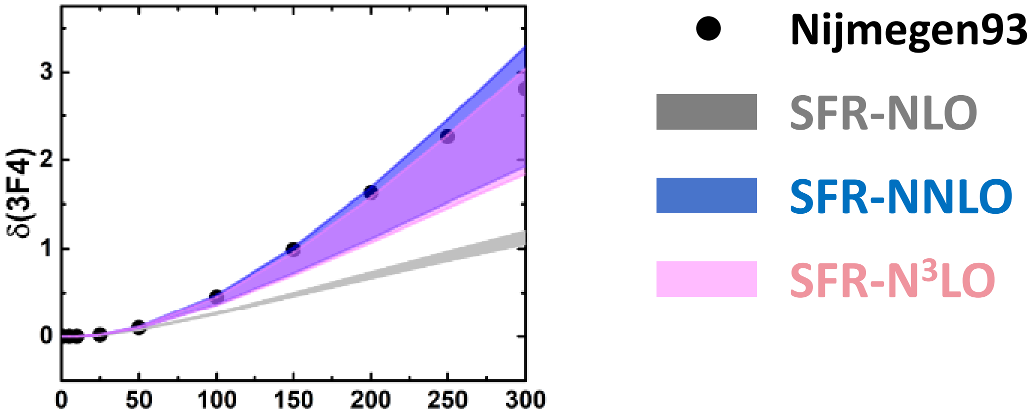


- NLO/NNLO已能很好描述Nijmegen93相移
- N³LO有小幅改善，贡献略小
- J=3 分波（3D3）包含新的接触项贡献

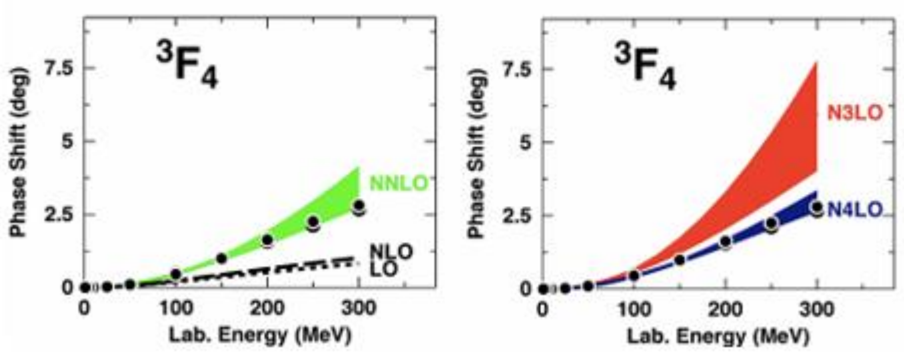
☐ 到N³LO J=4 分波 n-p 散射相移

微扰计算





非相对论N3LO结果



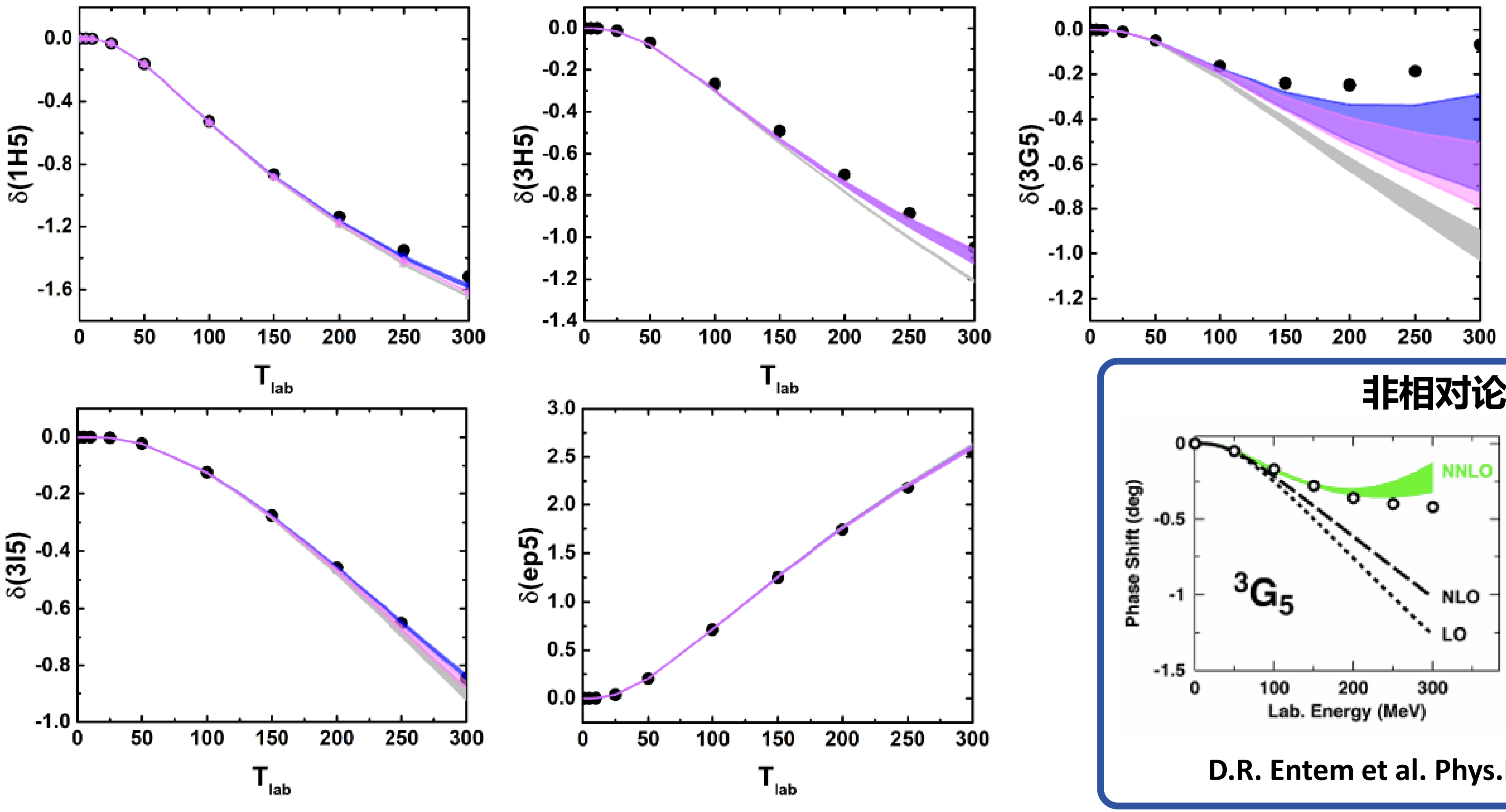
D.R. Entem et al. Phys.Rev.C 91 (2015) 1, 014002

NNLO/N³LO几乎重合：协变框架手征展开收敛速度快

相对论N³LO手征核力结果

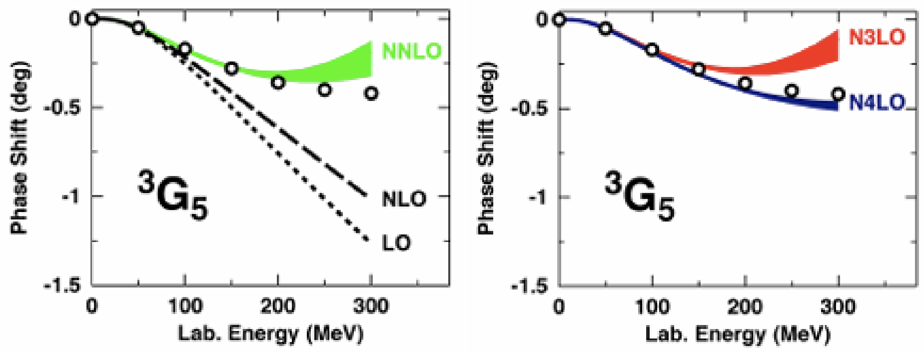
- 到**N³LO J=5** 分波 n-p 散射相移

微扰计算



● Nijmegen93
SFR-NLO
SFR-NNLO
SFR-N³LO

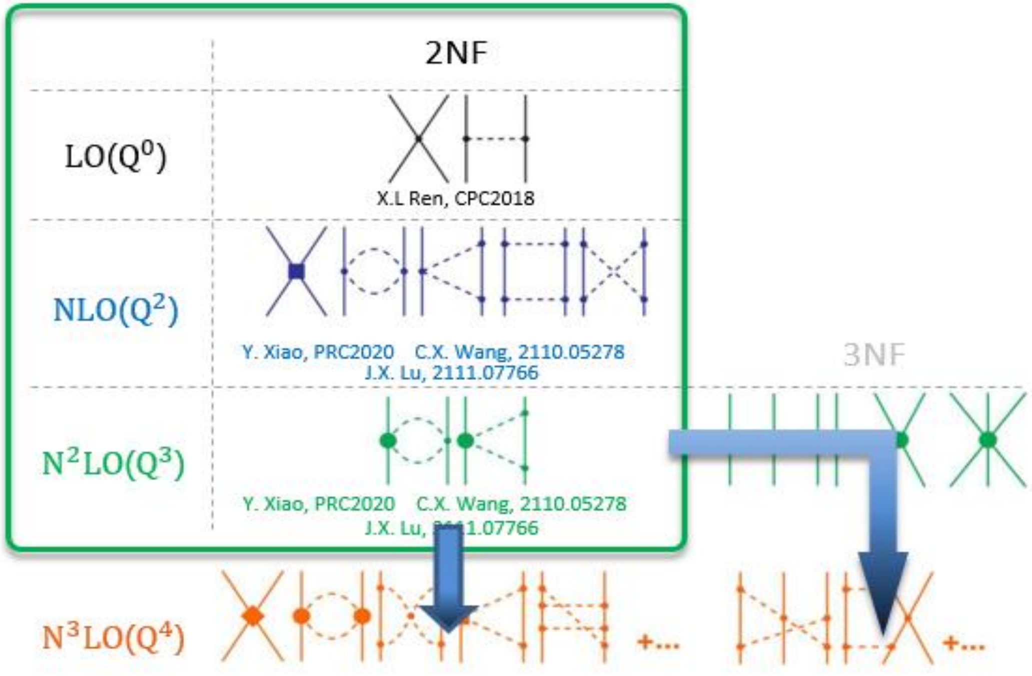
非相对论N3LO结果



D.R. Entem et al. Phys.Rev.C 91 (2015) 1, 014002

NNLO/N³LO几乎重合：协变框架手征展开收敛速度快

R-ChNF-N^3LO ongoing！

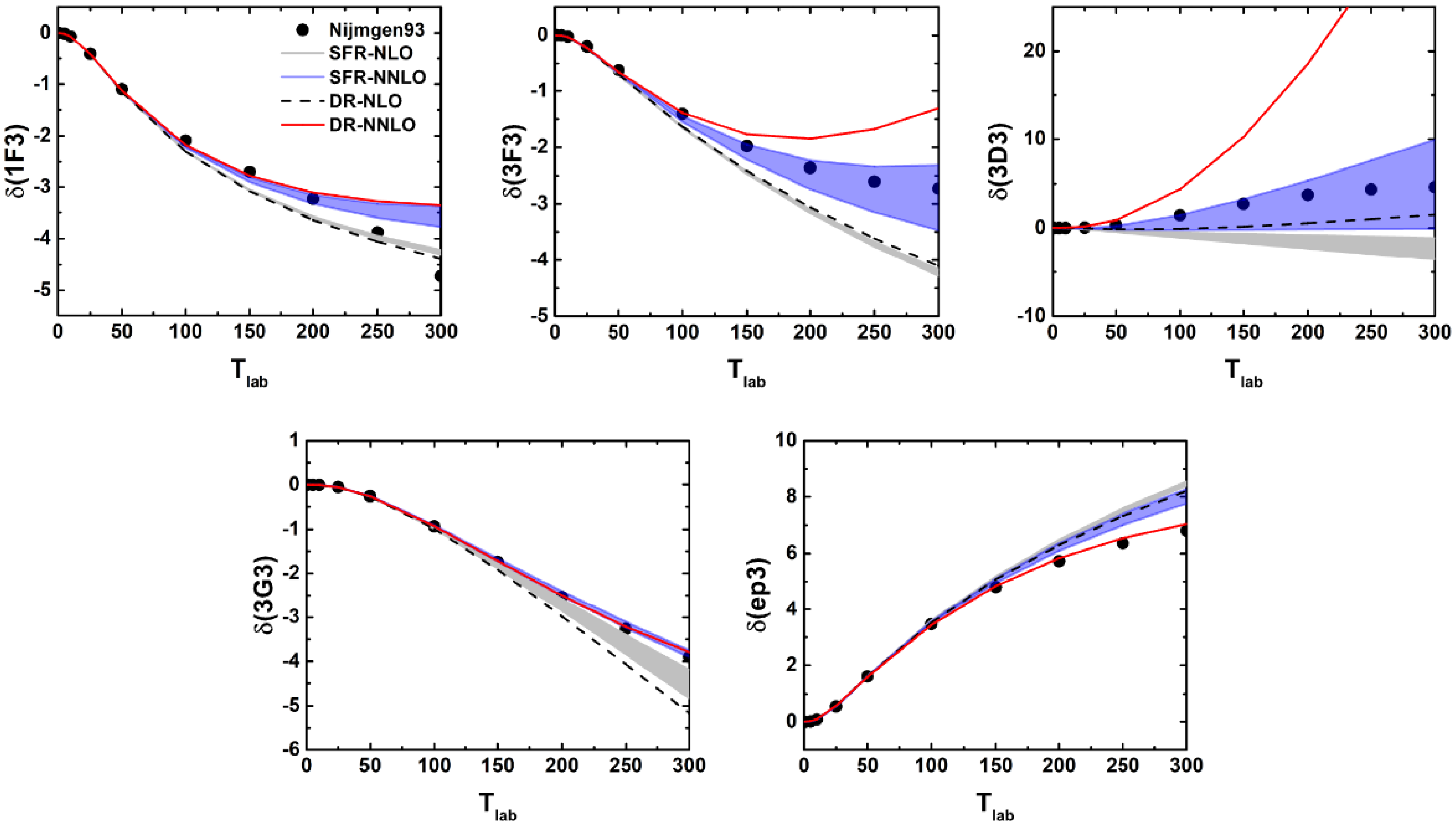


- **N^3LO 两体核力基本构建完成**
  - J≥3 高分波相移与Nijmegen相移符合很好
  - NNLO/N3LO几乎重合
  - 非微扰地描述低分波相移
- **相对论三体框架基本搭建完成**
  - 实现LO相对论两体核力描述三体可观测量
  - NLO/NNLO/N3LO高阶核力
  - 三体力相关问题

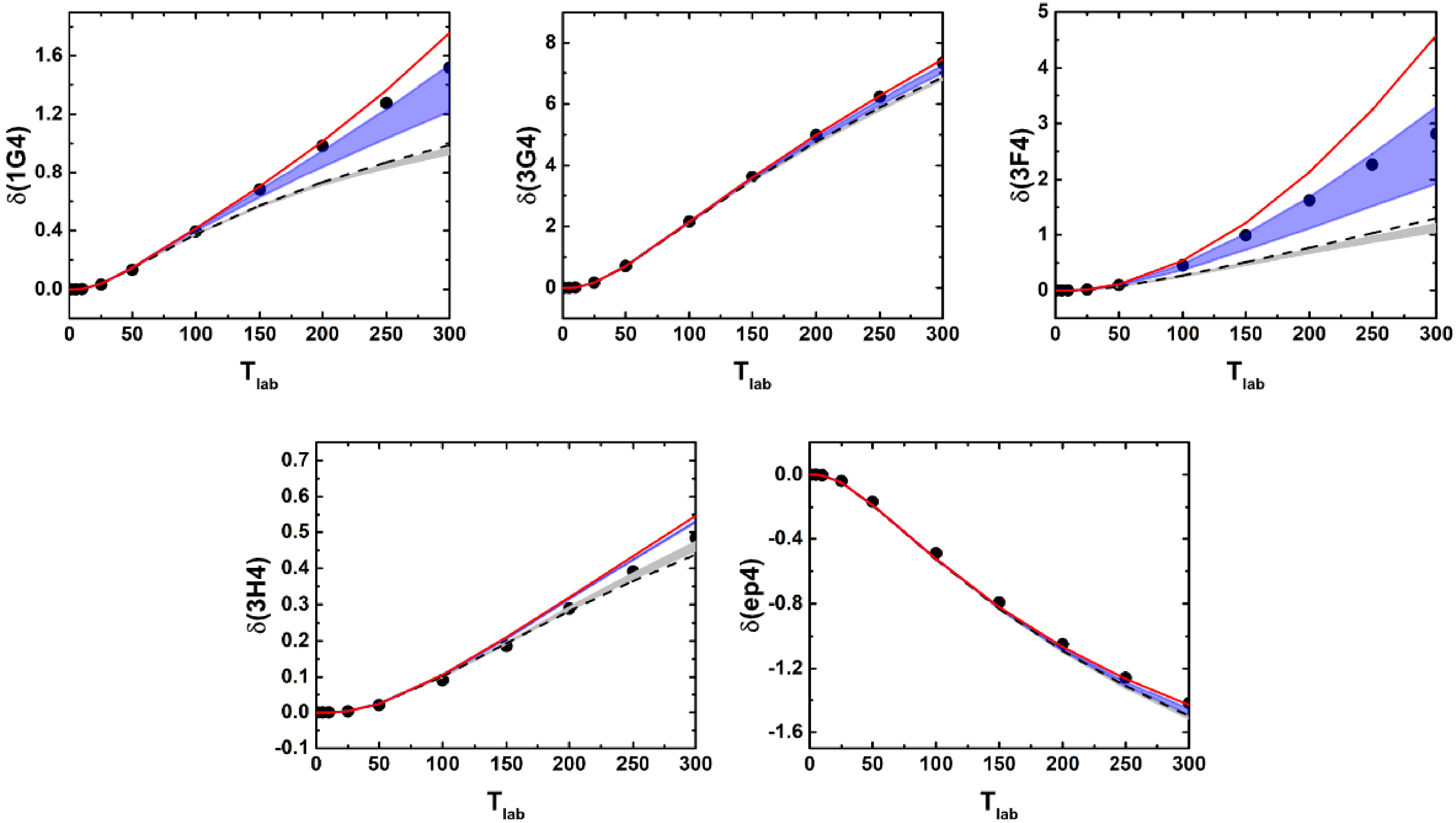
Thanks for your attention

Back up

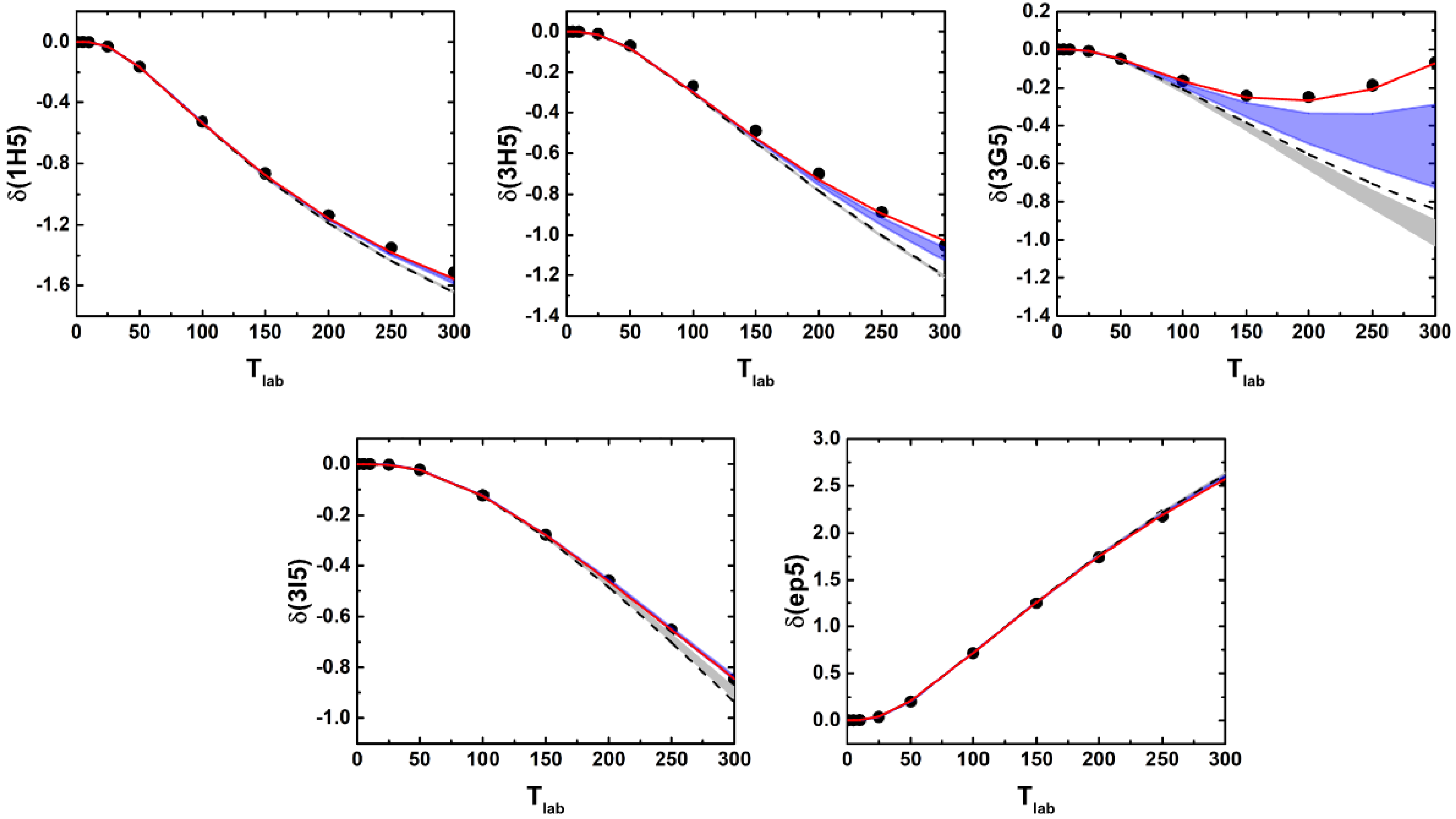
□维数正规化方法与谱函数正规化方法



□维数正规化方法与谱函数正规化方法

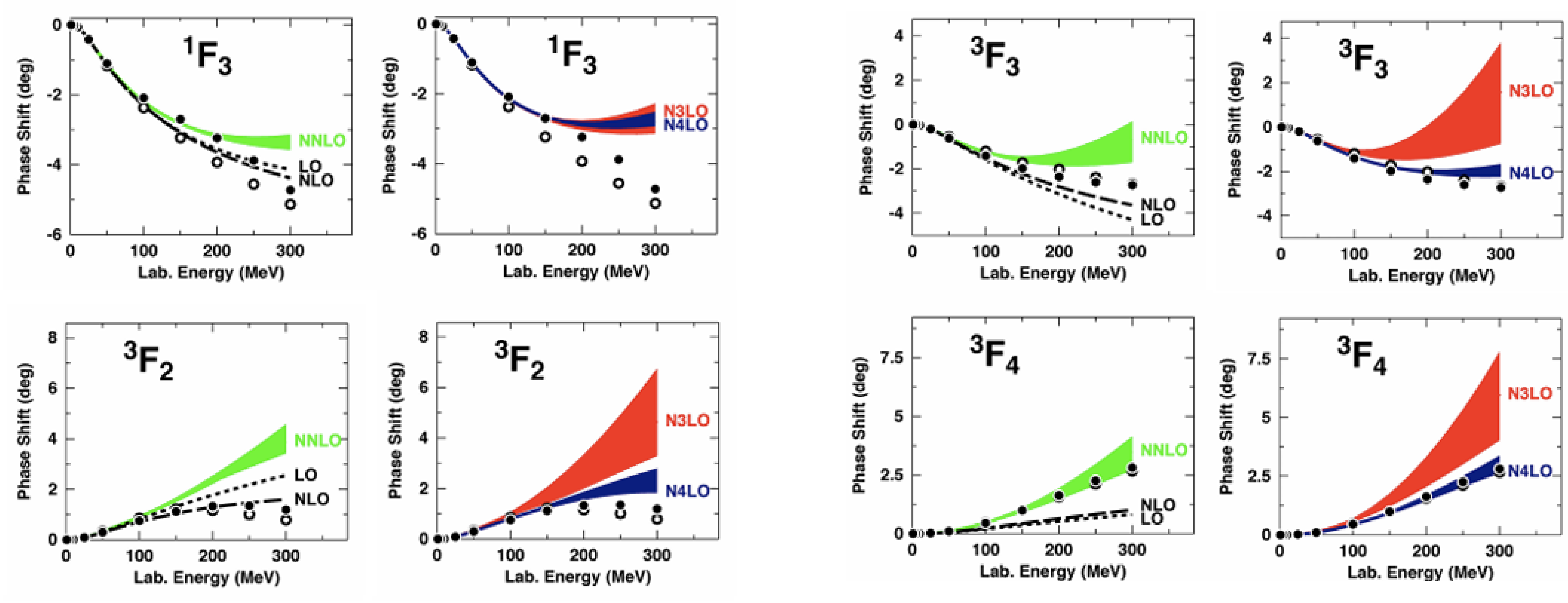


□维数正规化方法与谱函数正规化方法



□非相对论N3LO/N4LO

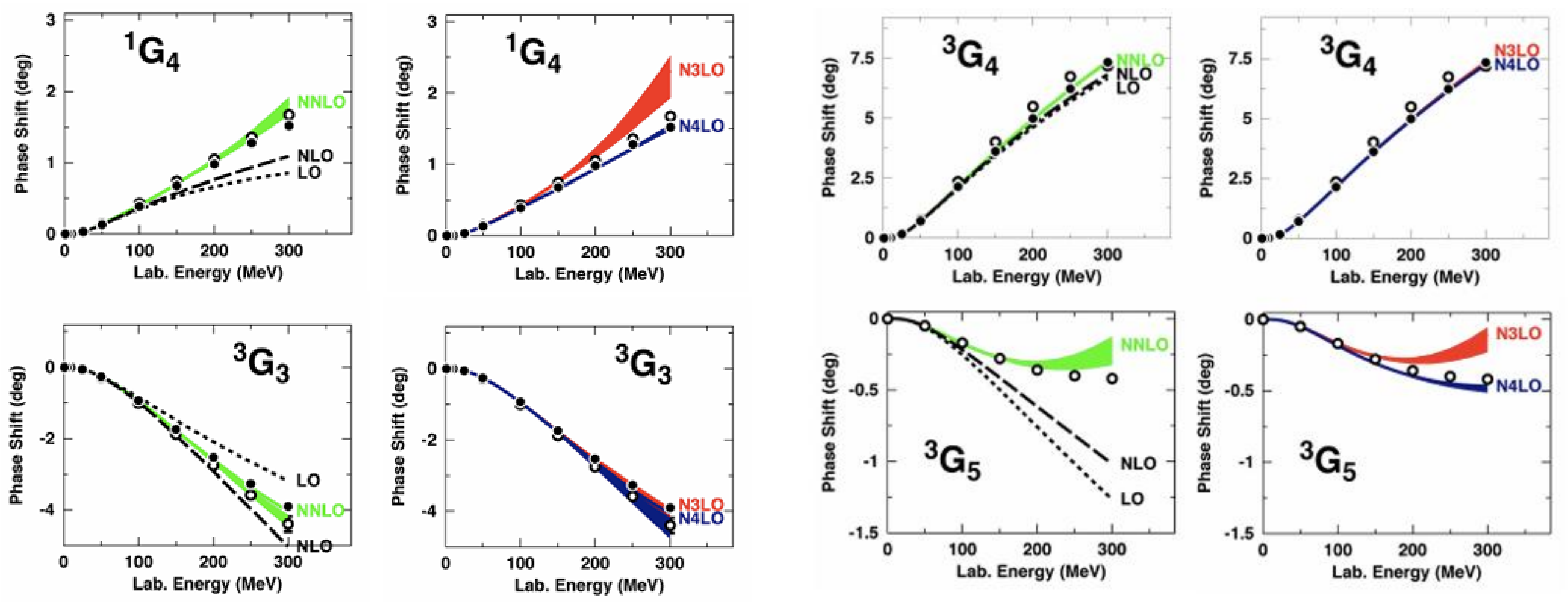
D.R. Entem et al. Phys.Rev.C 91 (2015) 1, 014002



相对论手征核力

□非相对论N3LO/N4LO

D.R. Entem et al. Phys.Rev.C 91 (2015) 1, 014002



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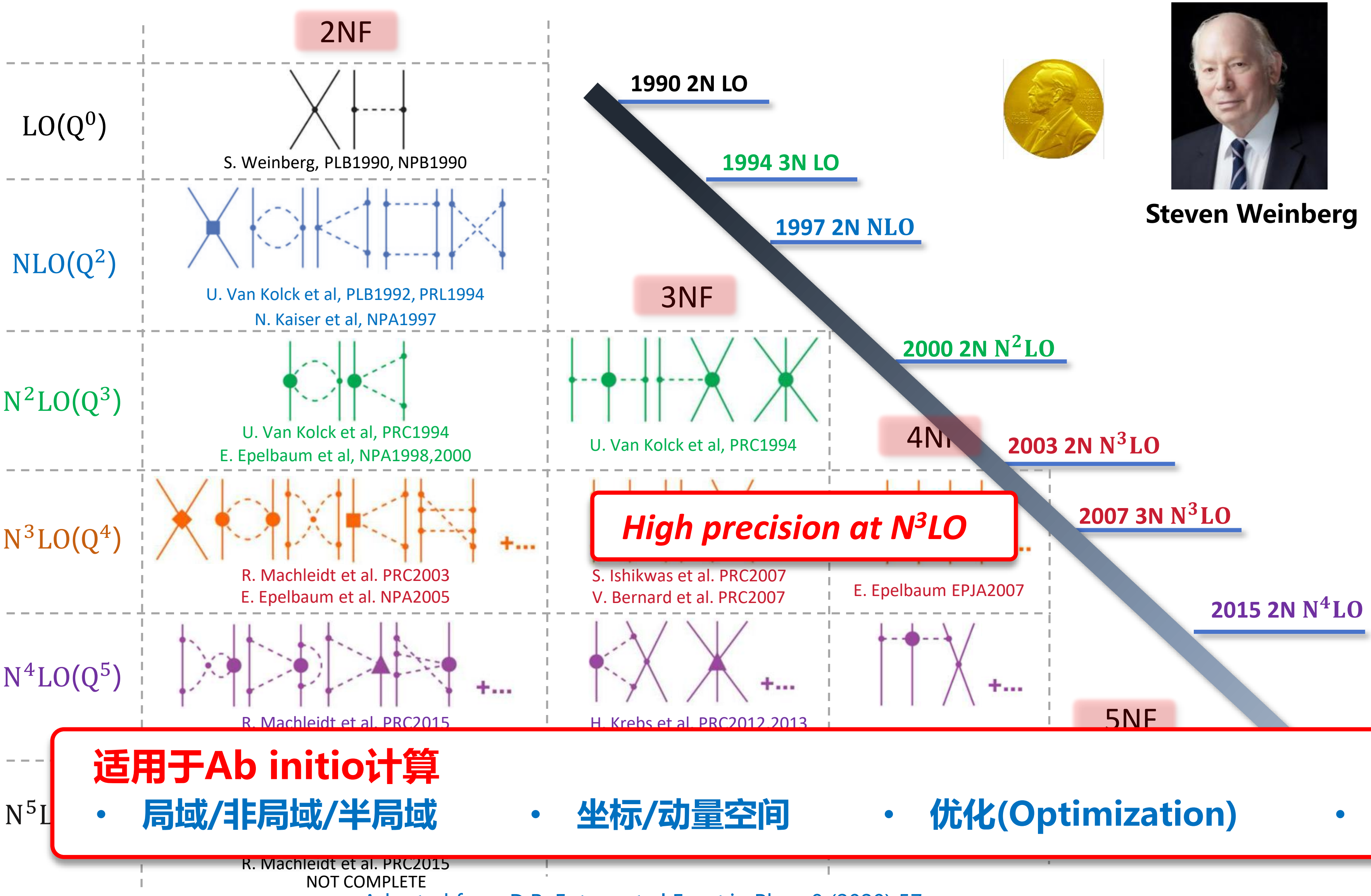
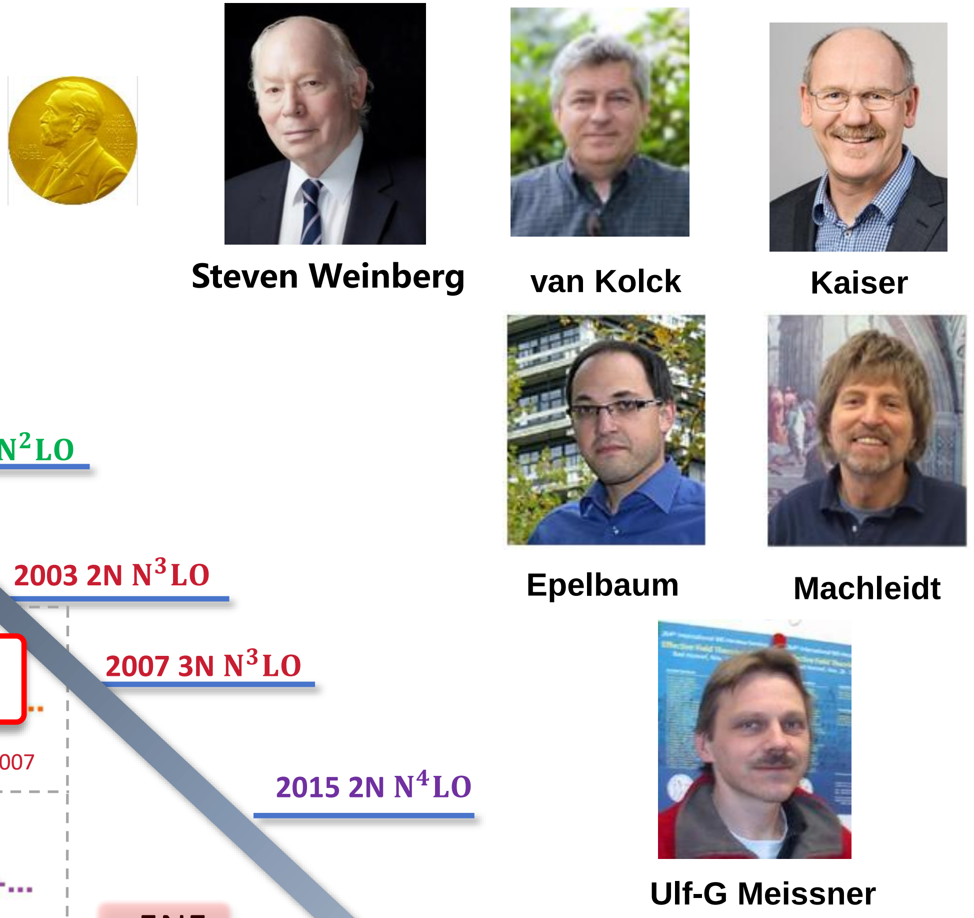
◻ 非相对论手征核力研究现状





适用于Ab initio计算

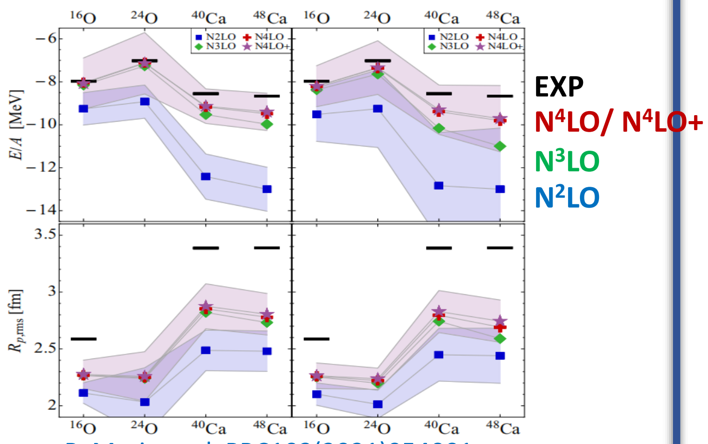
- 局域/非局域/半局域
- 坐标/动量空间
- 优化(Optimization)
- 软化(SRG)

Adopted from D.R. Entem et al Front.in Phys. 8 (2020) 57

□ 非相对论手征核力取得了巨大的成功，但仍不尽人意

收敛速度慢

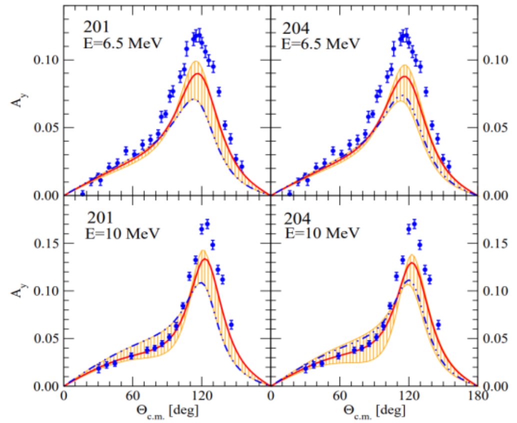
至少需要 N^4LO:
实现理想精度



P. Maris et al. PRC103(2021)054001

n-d散射的Ay疑难

自洽 N^3LO:
2N+3N
仍不能解决实验、理论之间的偏差

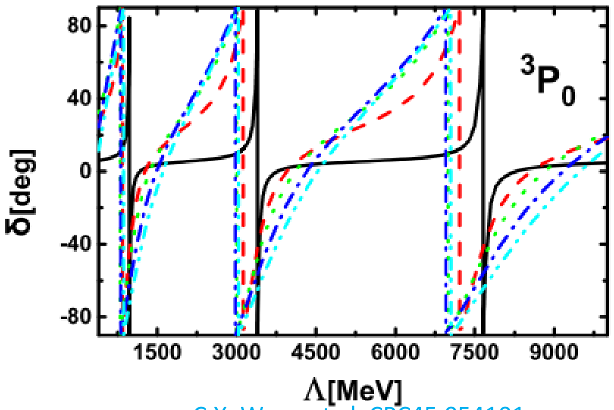


L. Girlanda et al. PRC2019 J. Golak et al. EPJA50,177

Red: N3LO chiral NN potential
Blue: N3LO chiral NN + full 3N potential

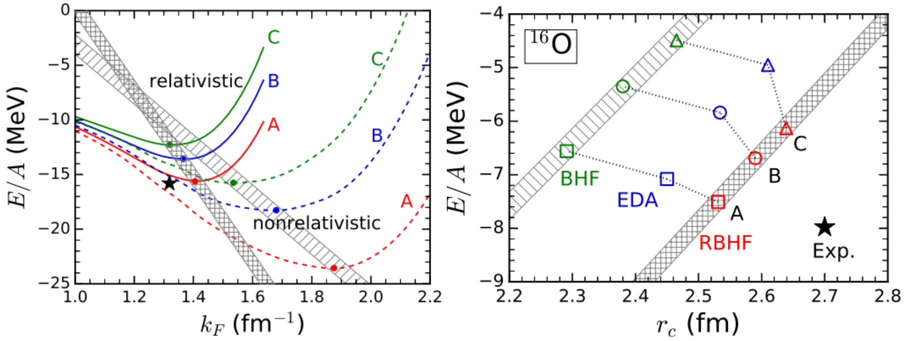
重整化群不变性

当截断到手征展开某一阶时，LS方程是不可重整的



C.X. Wang et al. CPC45,054101

相对论核物理第一性原理计算已展现出显著优势



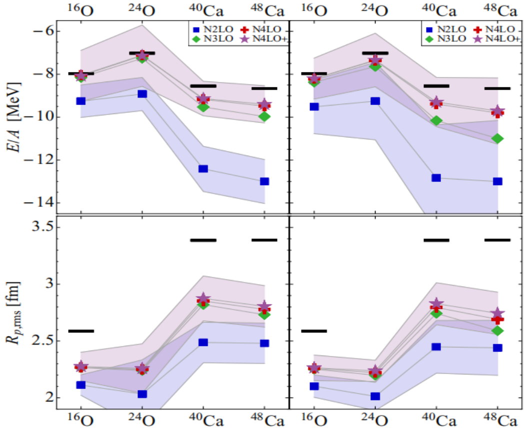
核物质状态方程　　每核子结合能

S.H. Shen et al. PPNP109,103713

□ 非相对论手征核力取得了巨大的成功，但仍不尽人意

收敛速度慢

至少需要 N^{4}LO:
实现理想精度



P. Maris et al. PRC103(2021)054001

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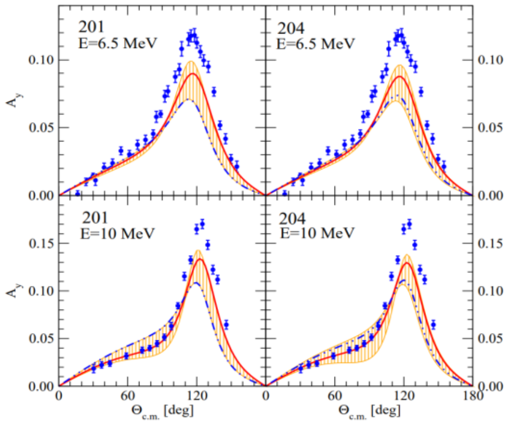

Red: N3LO chiral NN potential
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L. Girlanda et al. PRC2019 J. Golak et al. EPJA50,177

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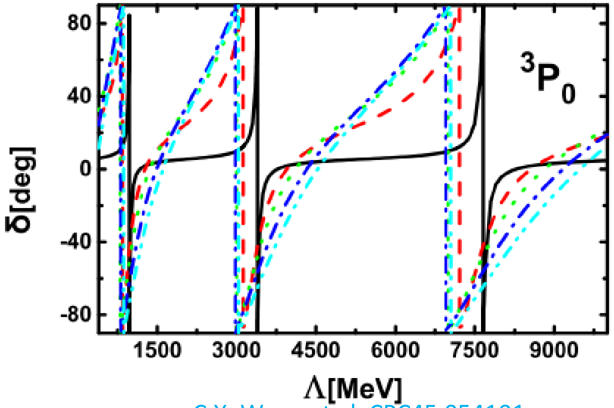
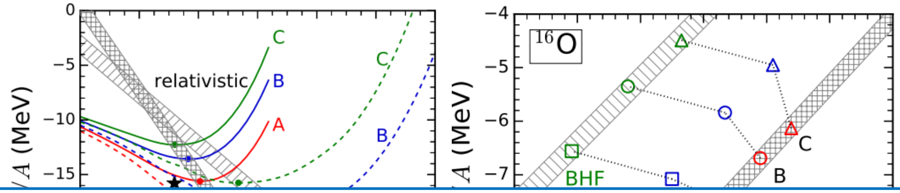


C.X. Wang et al. CPC45,054101

相对论核物理第一性原理计算已展现出显著优势



然而目前，相对论第一性原理计算可用的核力仍然是
唯象的Bonn势
亟须相对论框架下的微观核力

S.H. Shen et al. PPNP109,103713

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❑ 低能区强相互作用的微扰处理(Q/Λ)

➢ 手征阶数：外场动量、轻夸克质量的幂次——记阶规则（power counting rule）

$$p_i \to \alpha\, p_i \qquad m_q \to \alpha^2\, m_q$$

$$\mathcal{A}(\alpha p_i, \alpha^2 m_q) = \alpha^D \mathcal{A}(p_i, m_q)$$

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

- D: 手征阶数
- L : 圈个数
- N_M: 介子传播子的个数
- N_B: 重子传播子的个数
- V_n: n阶顶点的个数

❑ 手征有效场论的优势

➢ 与QCD紧密关联 ➢ 系统提高描述精度 ➢ 估计理论误差 ➢ 自洽三体力

❑ 重子系统—— 记阶规则破坏(PCB)

➢ 手征极限下重子质量不为0

Heavy baryon (HB)
- 重重子近似，**非相对论性**

Jenkins and Manohar, **PLB** 255 (1991) 558.

Infrared regularization (IR)
- 协变，破坏解析性

Becher and Leutwyler, EPJC 9 (1999) 643

Extended-on-mass-shell (EOMS)
- 协变，收敛快

Gegelia, Fuchs et al. in **PRD60**(1999), **PRD68** (2003)