Towards a unified precision theory of chiral nuclear forces and pion-nucleon dynamics

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in collaboration with

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Outline

- Introduction&Motivation
- Fits to πN scattering
- Recent results for NN scattering
- Summary and Outlook

Introduction

QCD → Chiral Effective Theory → hadron dynamics

Effective Lagrangian: Low Energy Constants (LECs)

$$\mathcal{L}(\Psi_N, U = e^{(i\vec{\tau}\cdot\vec{\pi})/f}, D_\mu) = \mathcal{L}_\pi + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$$

→ The most general S-matrix, consistent with unitarity, analyticity, symmetries

(Weinberg '79)

From QCD to nuclear physics

QCD ⟶ Chiral Perturbation Theory ⟶ hadron dynamics

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- ➔ 2 and more nucleons: **ChPT for nuclear forces** Weinberg '91

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➔ $1/m_N$ expansion: $|\vec{p}_i| \sim M_\pi \ll m_N$ → QM A-body problem

$$\left[\left(\sum_{i=1}^{A} \frac{-\vec{\nabla}_i^2}{2m_N} + \mathcal{O}(m_N^{-3}) \right) + \underbrace{V_{2N} + V_{3N} + V_{4N} + \ldots}_{\text{derived within ChPT}} \right] |\Psi\rangle = E|\Psi\rangle$$

From QCD to nuclear physics

QCD → Chiral Perturbation Theory → hadron dynamics

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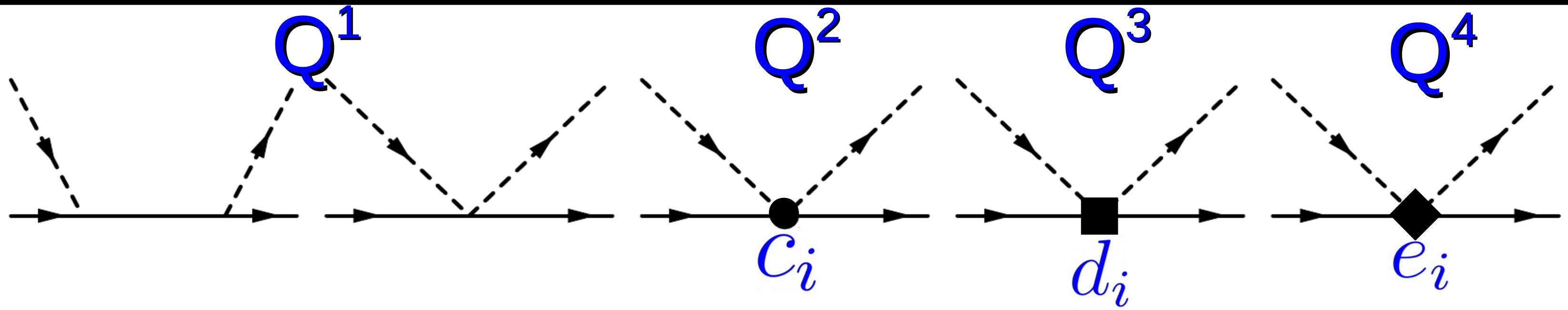
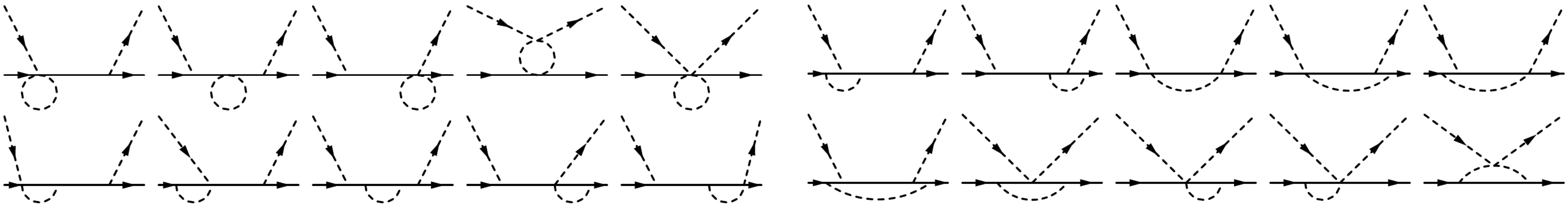
- ➔ unified description of ππ, πN and NN
- ➔ consistent many-body forces
- ➔ systematically improvable

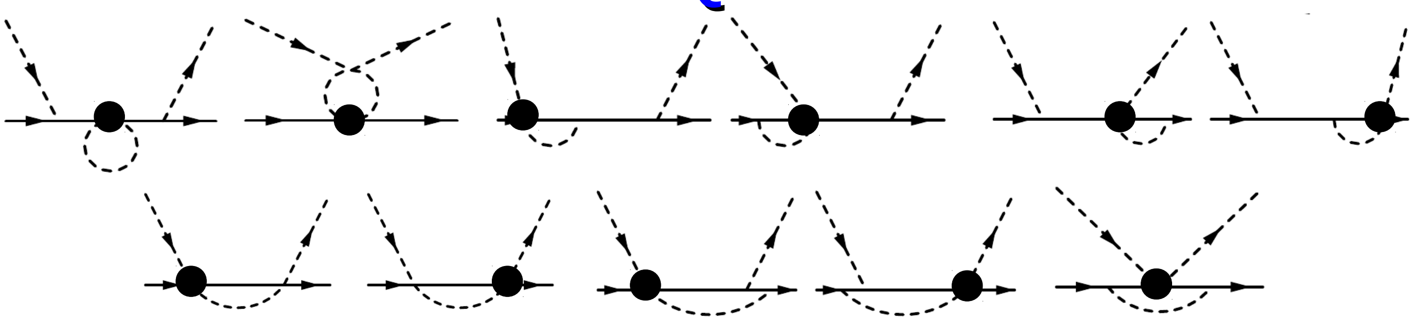
Low energy constants in πN scattering



Q^3



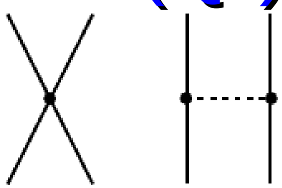
Q^4



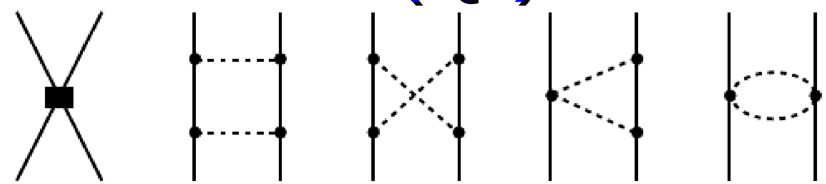
Two-Nucleon Force

Epelbaum, Krebs, Meißner '15

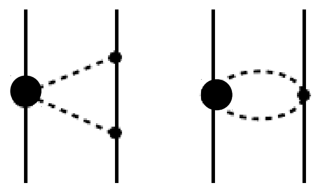
LO(Q^0)



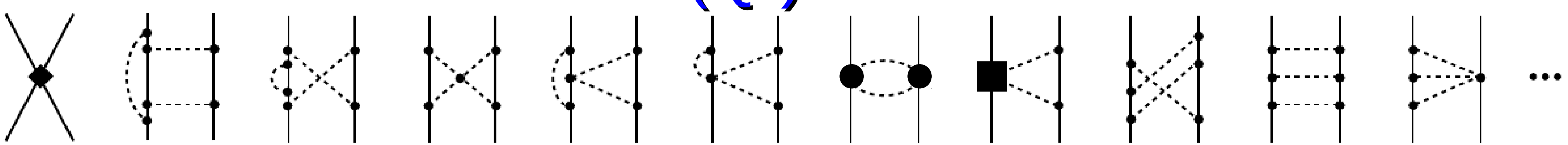
NLO(Q^2)



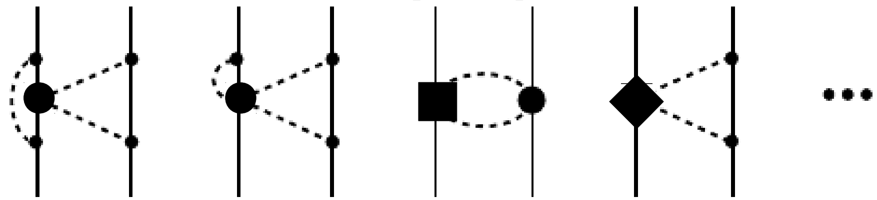
N^{2}LO(Q^3)



N^{3}LO(Q^4)

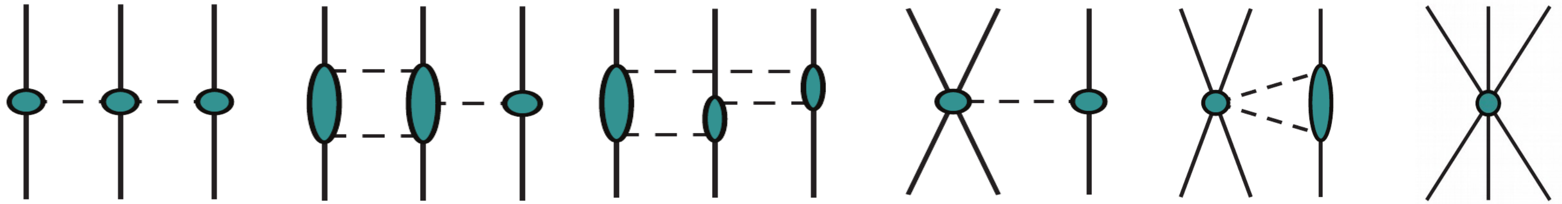


N^{4}LO(Q^5)



3-Nucleon Forces

- Longest-range contributions
- Intermediate-range contributions
- Short-range contributions



2π–exchange | 2π–1π–exchange | ring

3-Nucleon Forces

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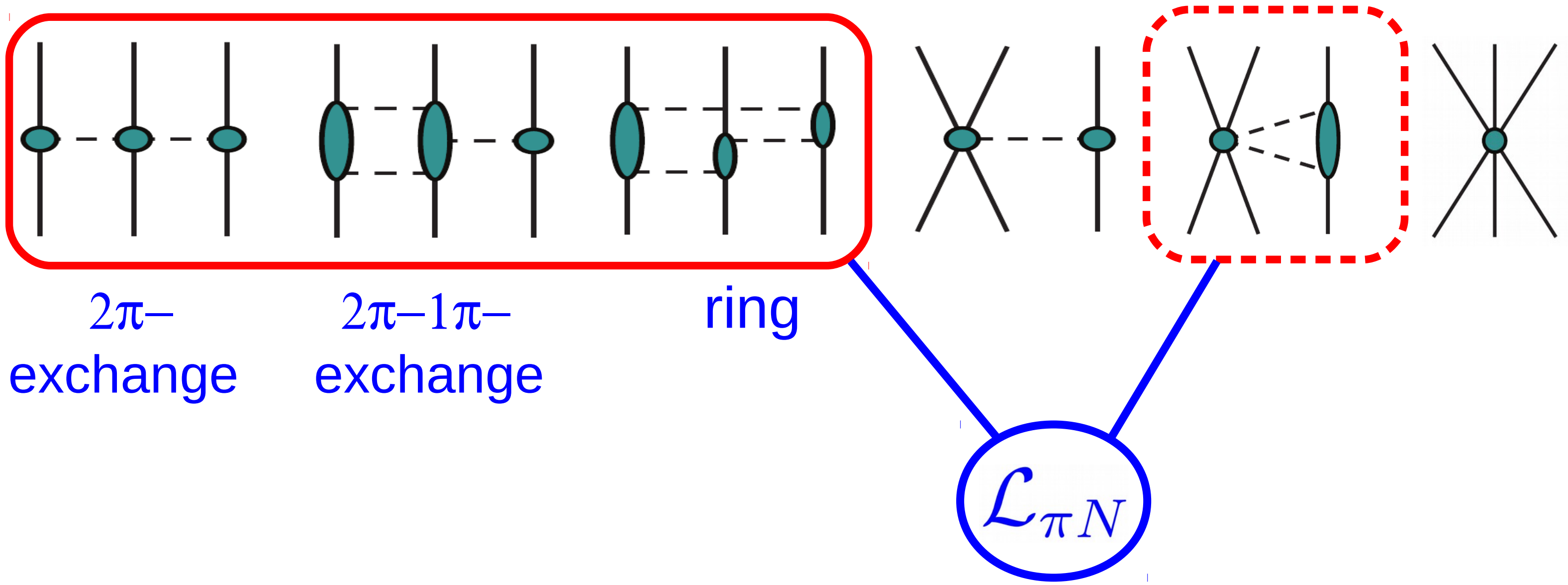
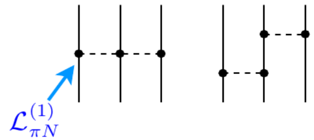
- ➔ Short-range contributions



2π–exchange 3NF up to N^{4}LO

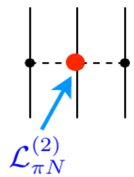
Krebs, Gasparyan, Epelbaum '12

NLO



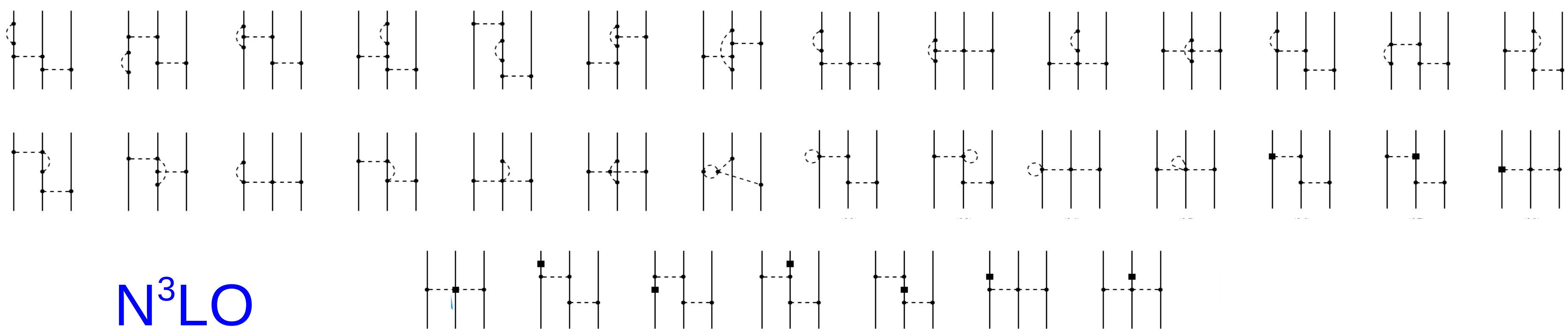
← yield vanishing 3NF contribution

N^{2}LO

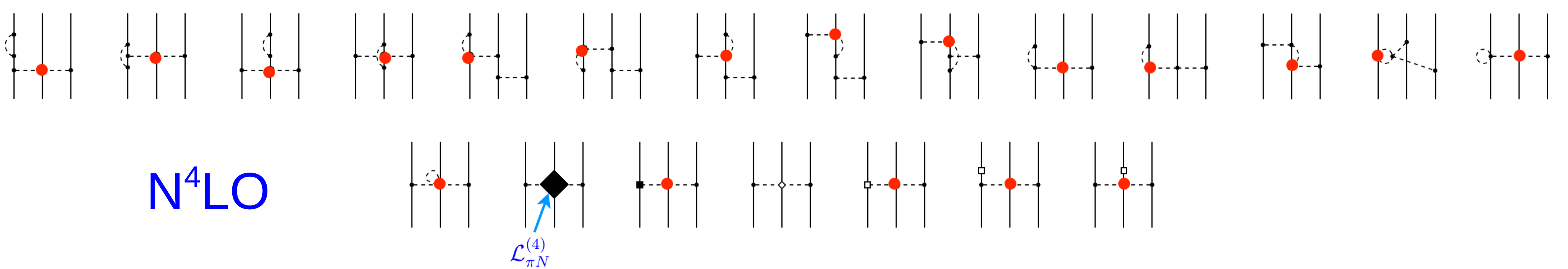


← first non-vanishing 3NF

N^{3}LO

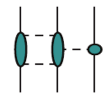


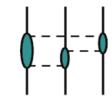
N^{4}LO



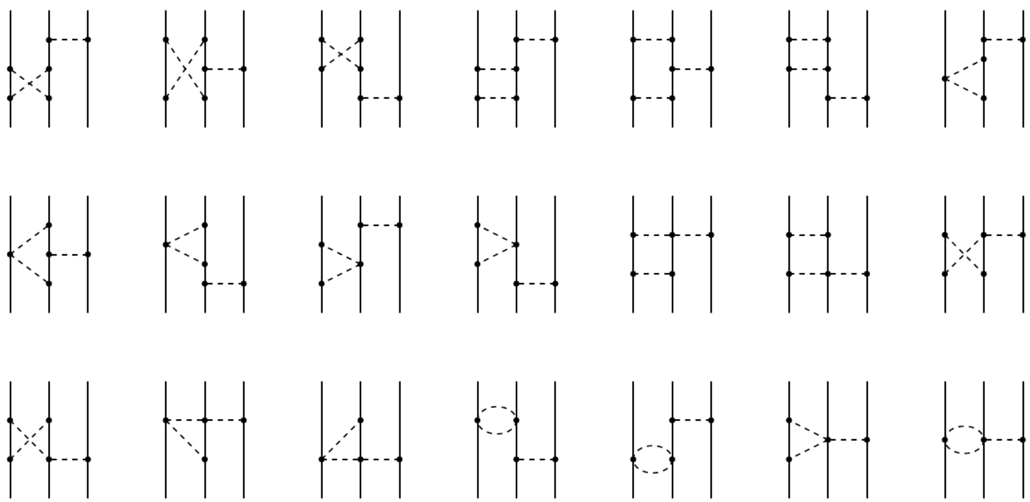
2π–1π and ring diagrams up to N^{4}LO

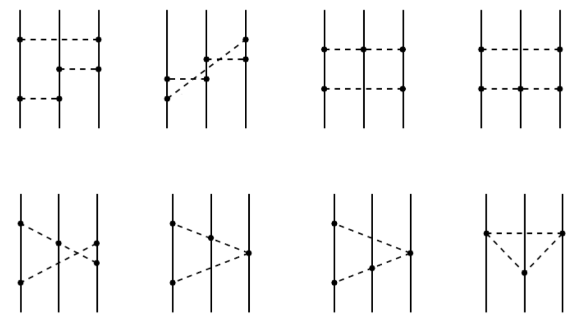
Krebs, Gasparyan, Epelbaum '13

The 2π-1π-exchange 3NF topology 

Ring 3NF diagrams 

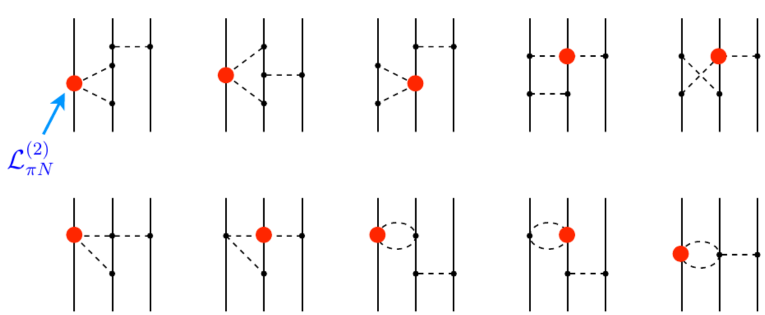
N^{3}LO

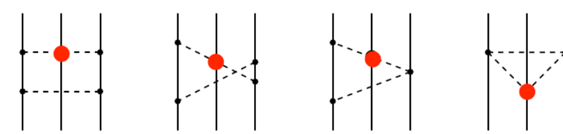




V. Bernard, E. Epelbaum, H. Krebs and U. -G. Meissner PRC 77 (2008) 064004

N^{4}LO





H. Krebs, A. Gasparyan and E. Epelbaum PRC 87 (2013) 054007

πN scattering

Siemens et al. '16

- ➔ Fit to data instead of partial wave analysis   Wendt et al. '14, Carlsson et al. '15
- ➢ Uncertainties of parameters and correlations are better constrained (errors and correlations of the phase shifts are not always well known)

Epelbaum et al. '15

- ➔ The novel approach to estimate the theoretical uncertainty

Theoretical errors

(uncertainty from the truncation of the chiral expansion at a given order)

$\mathcal{O}_i$ -observable

$Q = \omega_{CMS}/\Lambda_b$

Λ_b - breakdown scale of the chiral expansion

$$\delta\mathcal{O}_i^{(n)} = \max(|\mathcal{O}_i^{(\mathrm{LO})}|Q^{n-\mathrm{LO}+1}, \{|\mathcal{O}_i^{(k)} - \mathcal{O}_i^{(j)}|Q^{n-j}\}) \qquad \text{with} \qquad j < k \le n$$

$$\delta\mathcal{O}_i^{(n)} \ge \max(\{|\mathcal{O}_i^{(k)} - \mathcal{O}_i^{(j)}|\}) \qquad \text{with} \qquad n \le j < k$$

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$\Lambda_b \sim 600\ \mathrm{MeV}$ - conservative estimation Epelbaum, Krebs, Meißner '15

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Δ–resonance?

Power counting in πN scattering

- ➔ Expansion in $Q = \left\{ \frac{q}{\Lambda_b}, \frac{M_\pi}{\Lambda_b} \right\}$
- ➔ Standard heavy baryon (HB) power counting: $m_N \sim \Lambda_b$ Fettes et al. '98, '00
- ➔ Power counting used in the chiral NN potential: $m_N \sim \Lambda_b^2 / M_\pi$

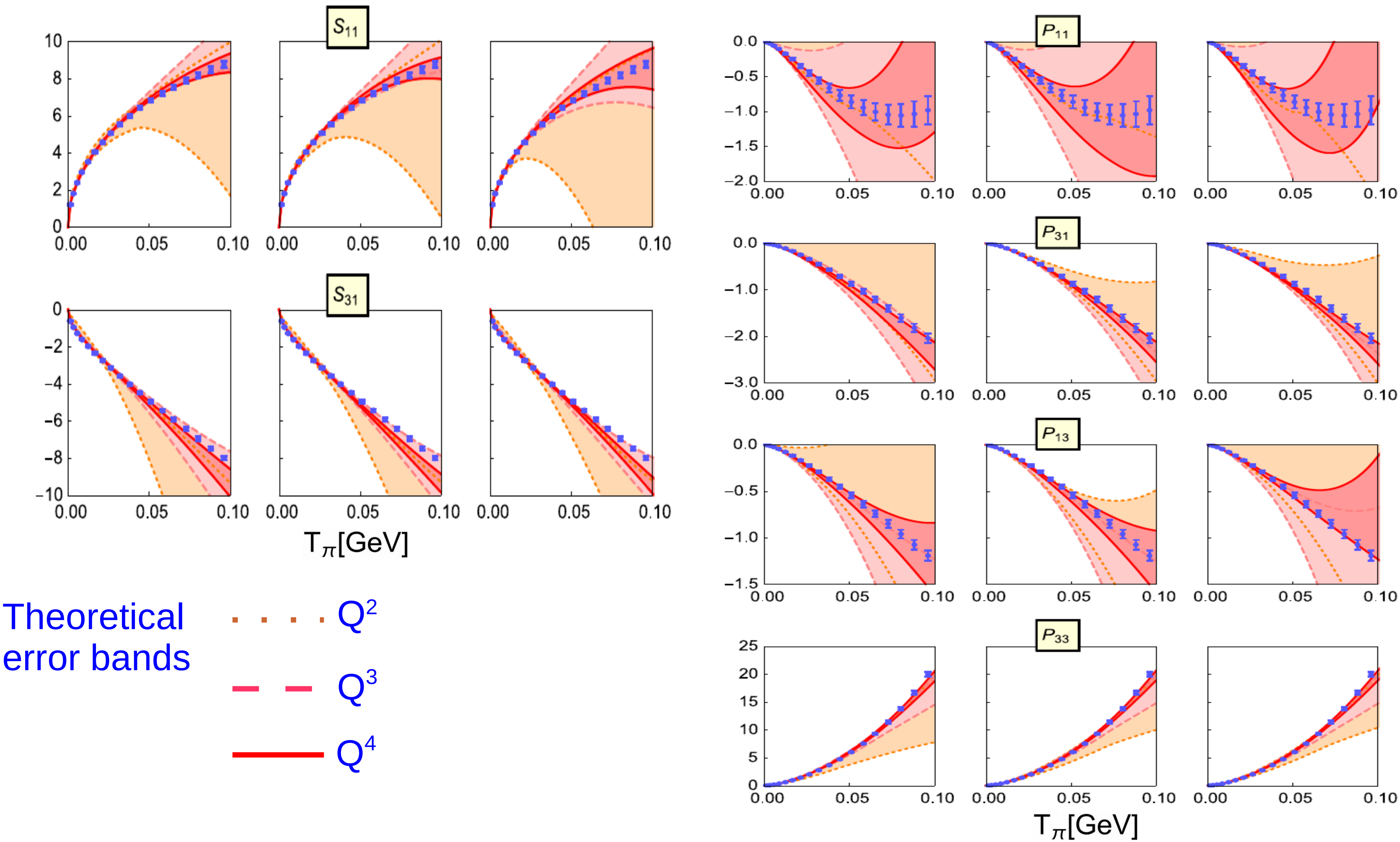
Gegelia, Japaridze '99

- ➔ Modified EOMS (Extended On-Mass-Shell) scheme: $1/m_N$ expansion exactly reproduces HB result.

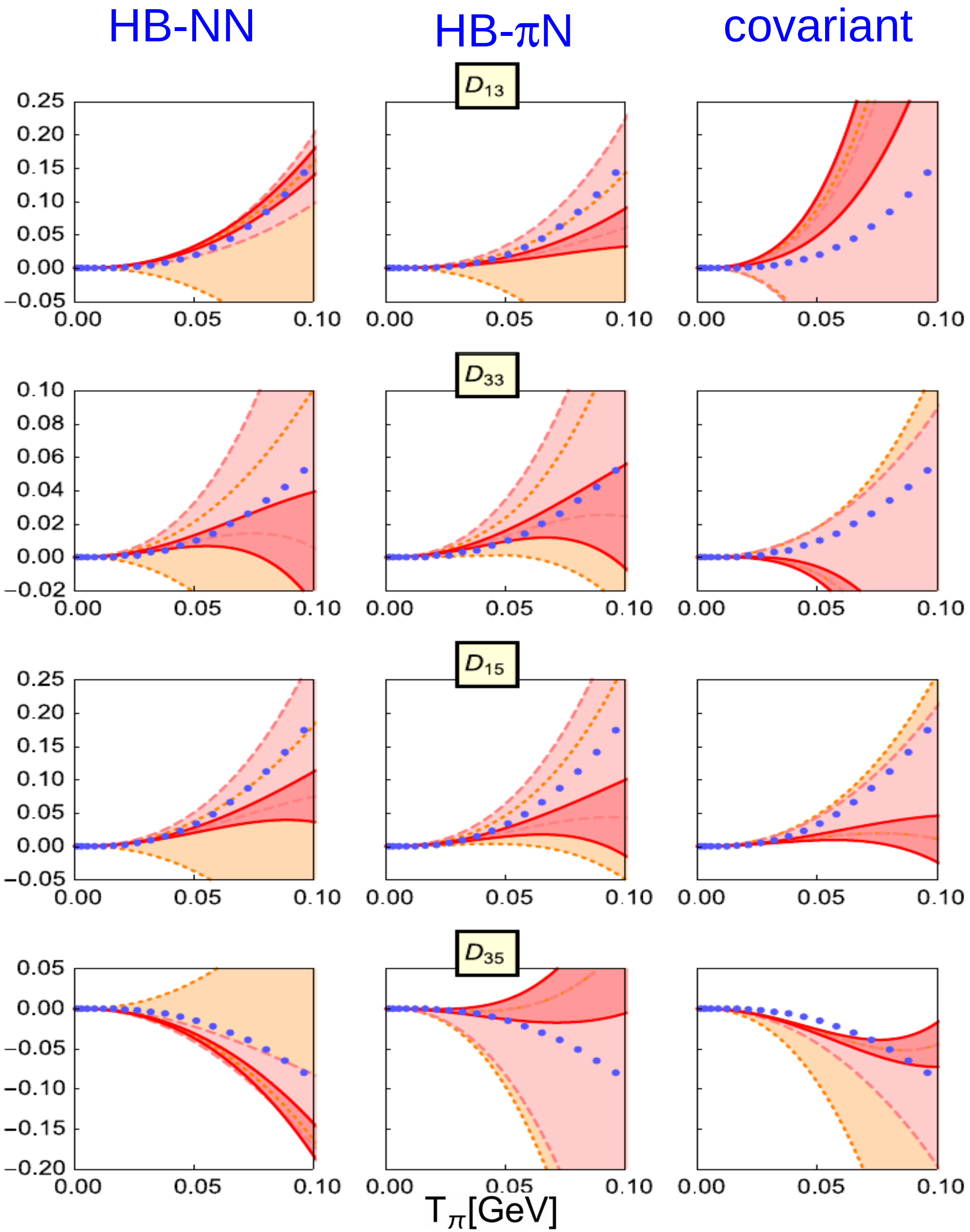
πN phase shifts

(SAID data base)

HB-NN | HB-πN | covariant | HB-NN | HB-πN | covariant

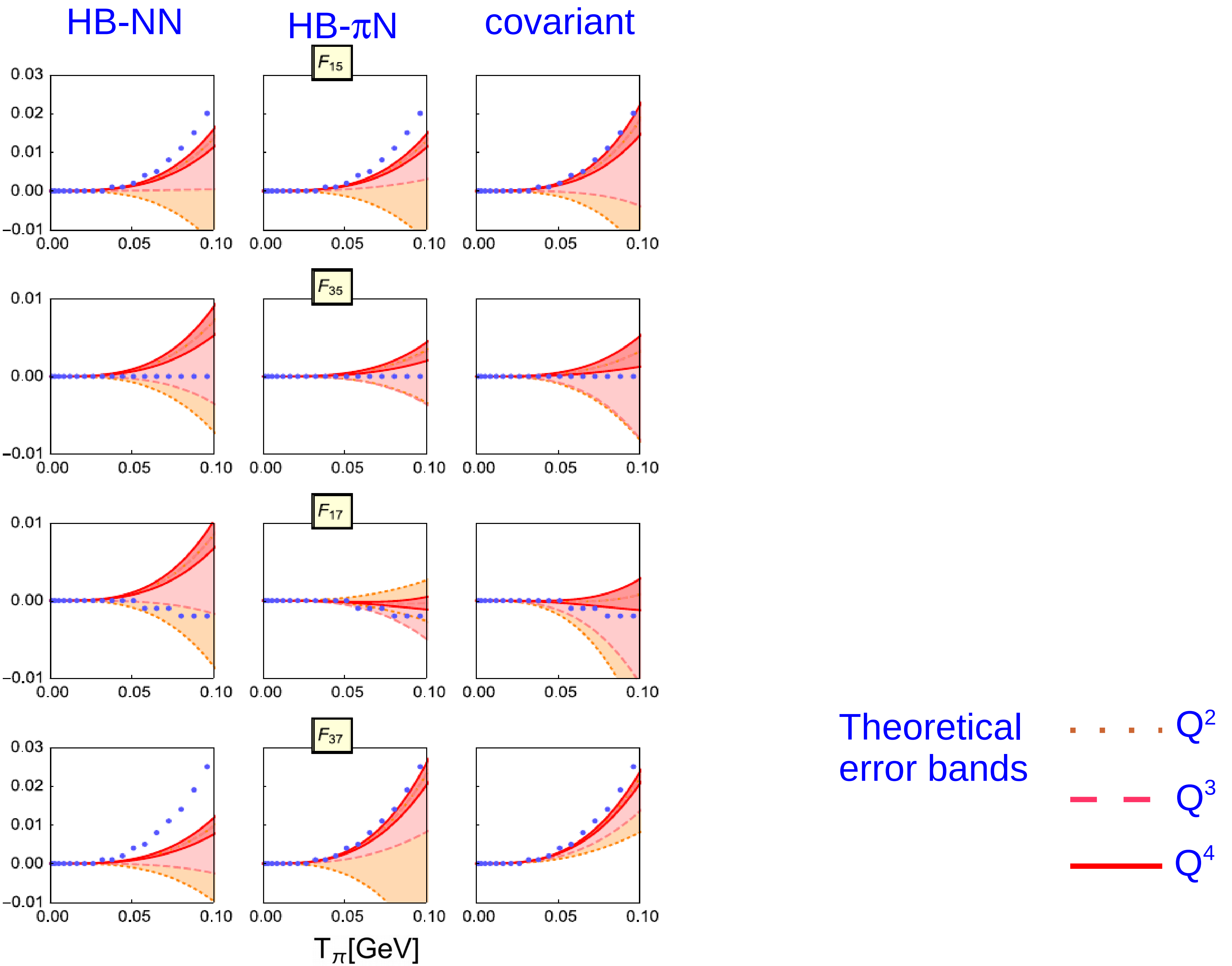


πN phase shifts

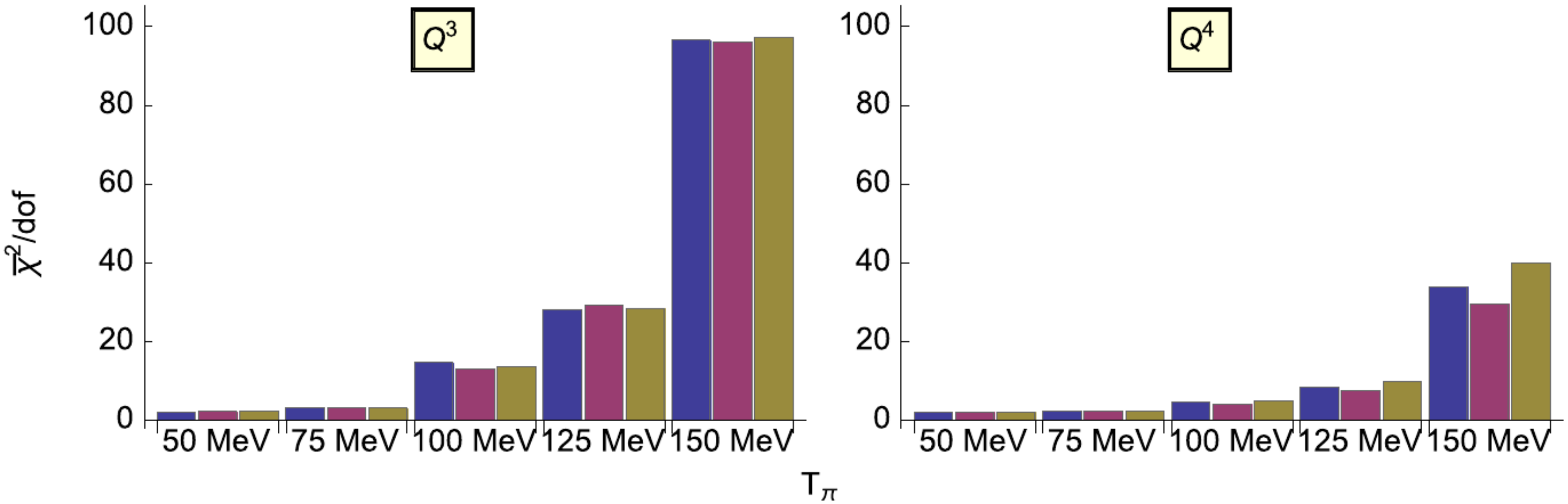


Theoretical error bands

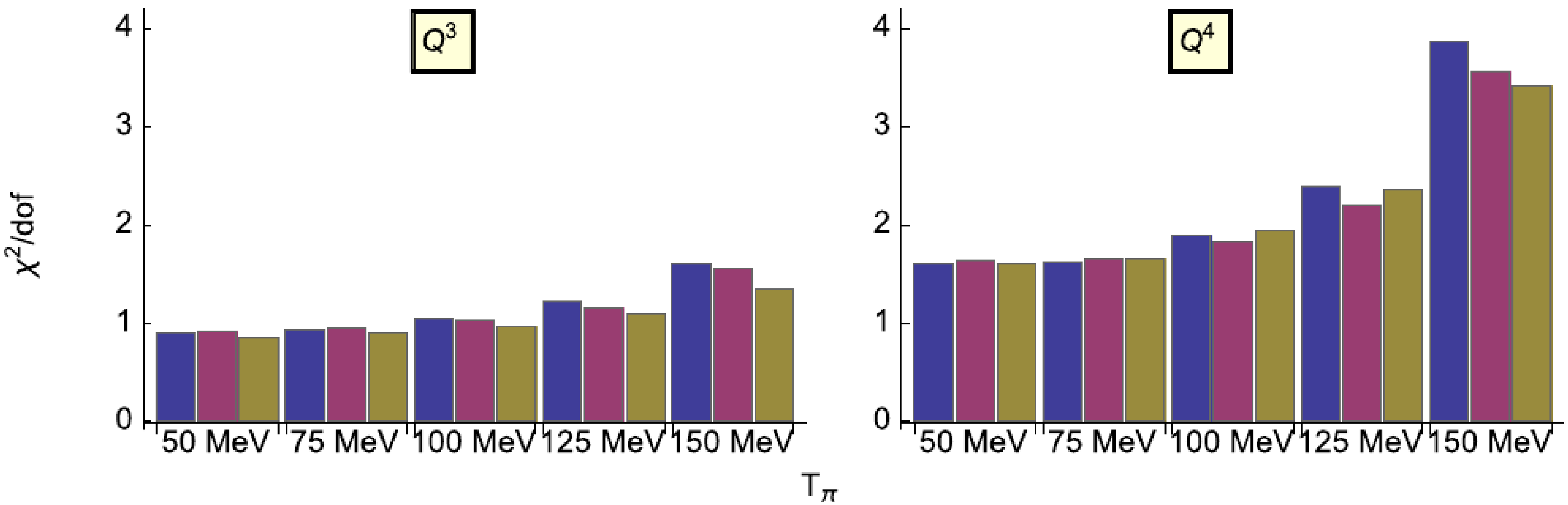
πN phase shifts



Reduced χ^2 (fit up to T_π)

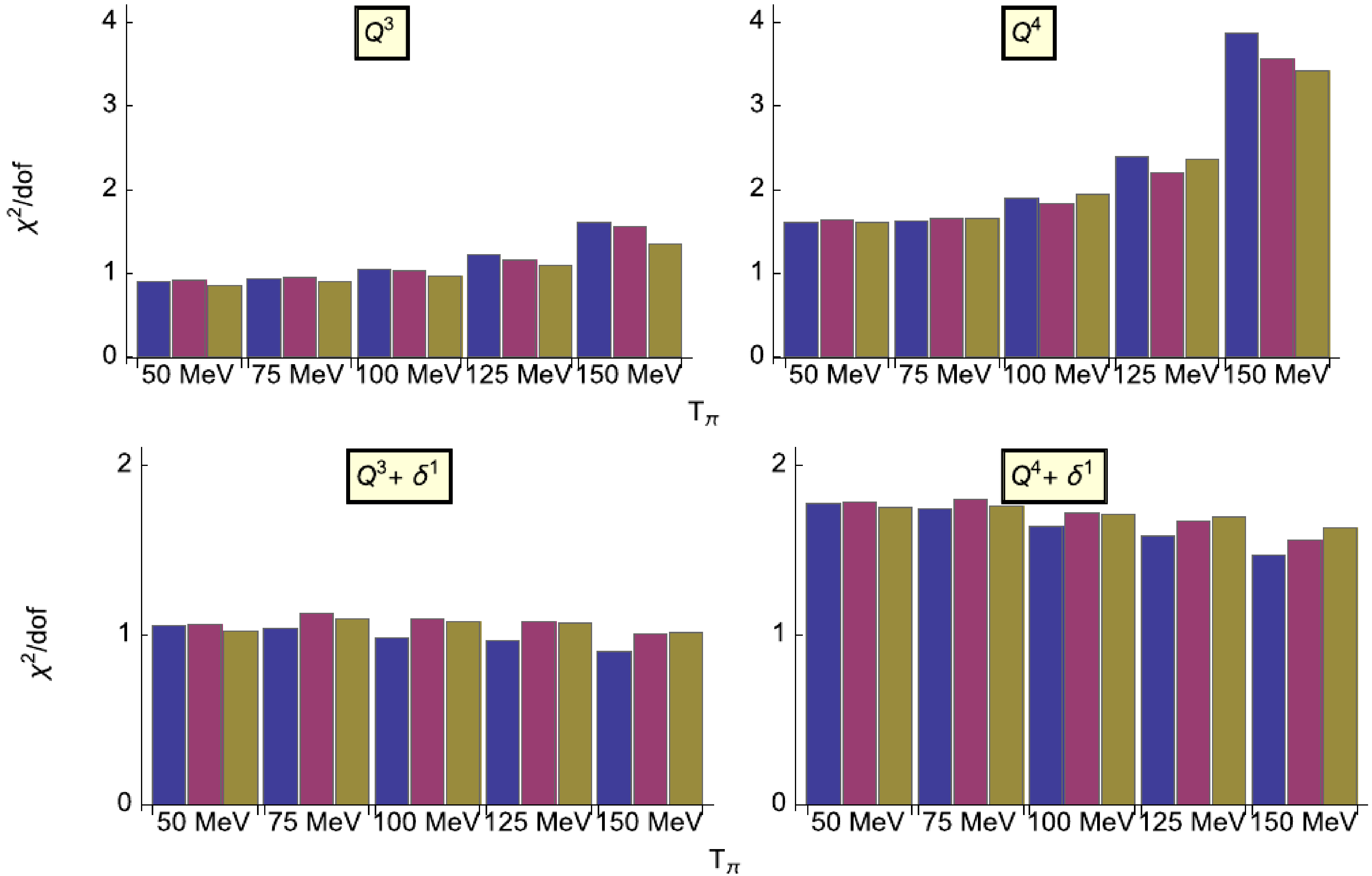


without theoretical errors

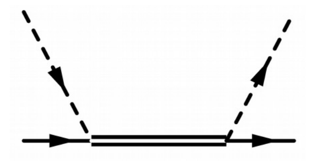


with theoretical errors

Reduced χ^2



Adding Δ–pole diagram



Low energy constants

	c_1	c_2	c_3	c_4	$\bar{d}_1 + \bar{d}_2$	$\bar{d}_3$	$\bar{d}_5$	$\bar{d}_{14} - \bar{d}_{15}$	$\bar{e}_{14}$	$\bar{e}_{15}$	$\bar{e}_{16}$	$\bar{e}_{17}$	$\bar{e}_{18}$
fit to GW	-1.13	3.69	-5.51	3.71	5.57	-5.35	0.02	-10.26	1.75	-5.8	1.76	-0.58	0.96
fit to KH	-0.75	3.49	-4.77	3.34	6.21	-6.83	0.78	-12.02	1.52	-10.41	6.08	-0.37	3.26
fit to data	-1.31	1.88	-4.43	3.24	5.95	-5.64	-0.11	-11.61	0.86	-11.36	10.73	-0.66	4.47
error	0.08	0.23	0.09	0.17	0.09	0.06	0.04	0.09	0.29	0.81	0.95	0.46	0.87

GW: Arndt et al. '06

KH: Koch '86

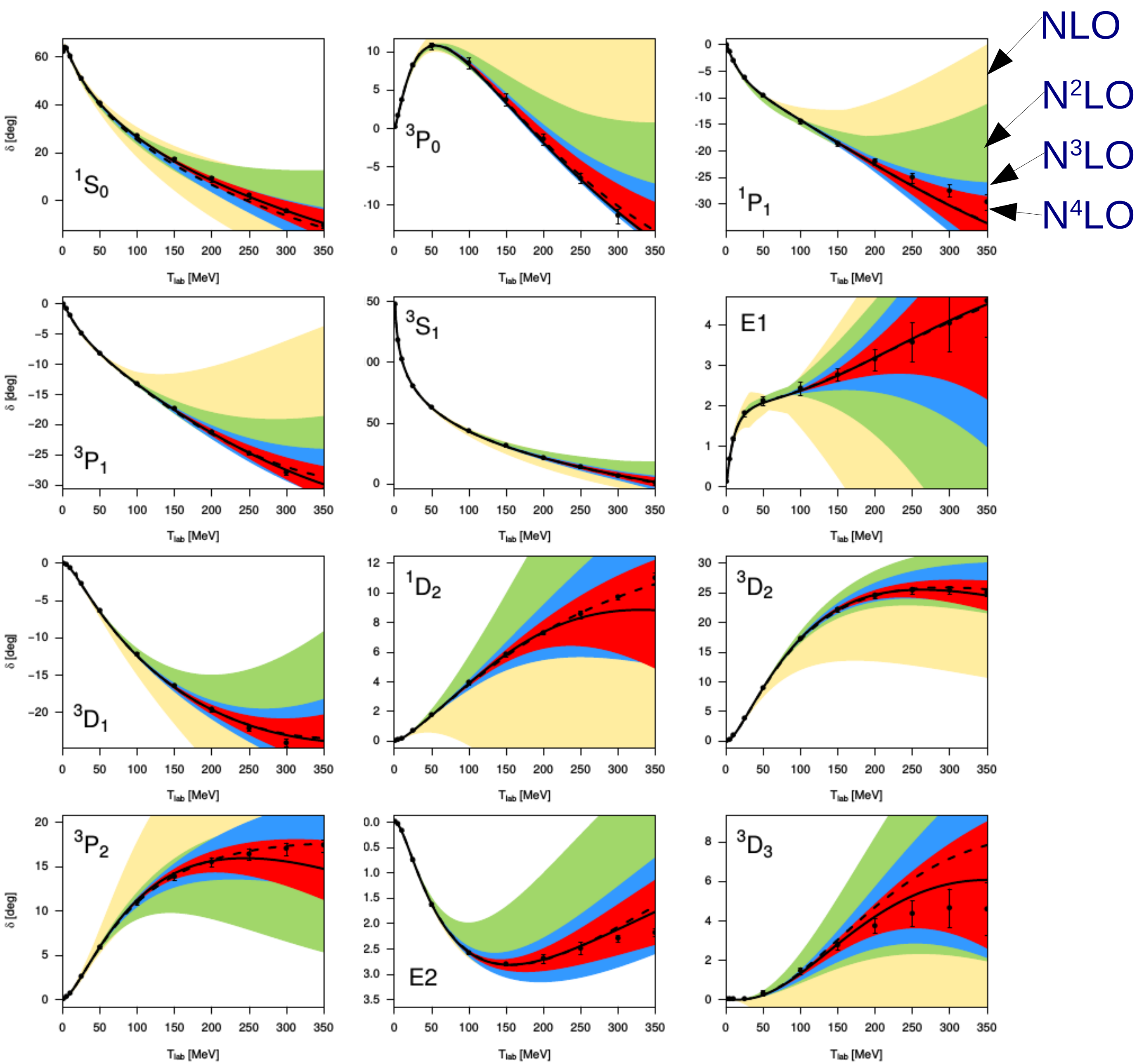
data: GWU-SAID data base

Correlation matrix (x100) NN-counting, Q^4

HB-NN	c_1	c_2	c_3	c_4	d_{1+2}	d_3	d_5	d_{14-15}	e_{14}	e_{15}	e_{16}	e_{17}	e_{18}
c_1		90	12	39	35	-20	-28	-26	-30	38	-78	9	-35
c_2			-31	38	41	-23	-35	-43	-24	58	-94	10	-35
c_3				3	-14	7	16	39	-1	-56	46	-5	1
c_4					94	-61	-65	-55	-29	29	-38	15	-86
d_{1+2}						-68	-66	-56	-26	36	-43	11	-80
d_3							-9	42	23	-24	25	-30	63
d_5								37	15	-27	36	13	45
d_{14-15}									25	-48	50	-42	66
e_{14}										-78	48	-20	31
e_{15}											-81	21	-32
e_{16}												-16	38
e_{17}													-62

np phase shifts

Reinert et al., in preparation



Theoretical error bands, fit to phase shifts

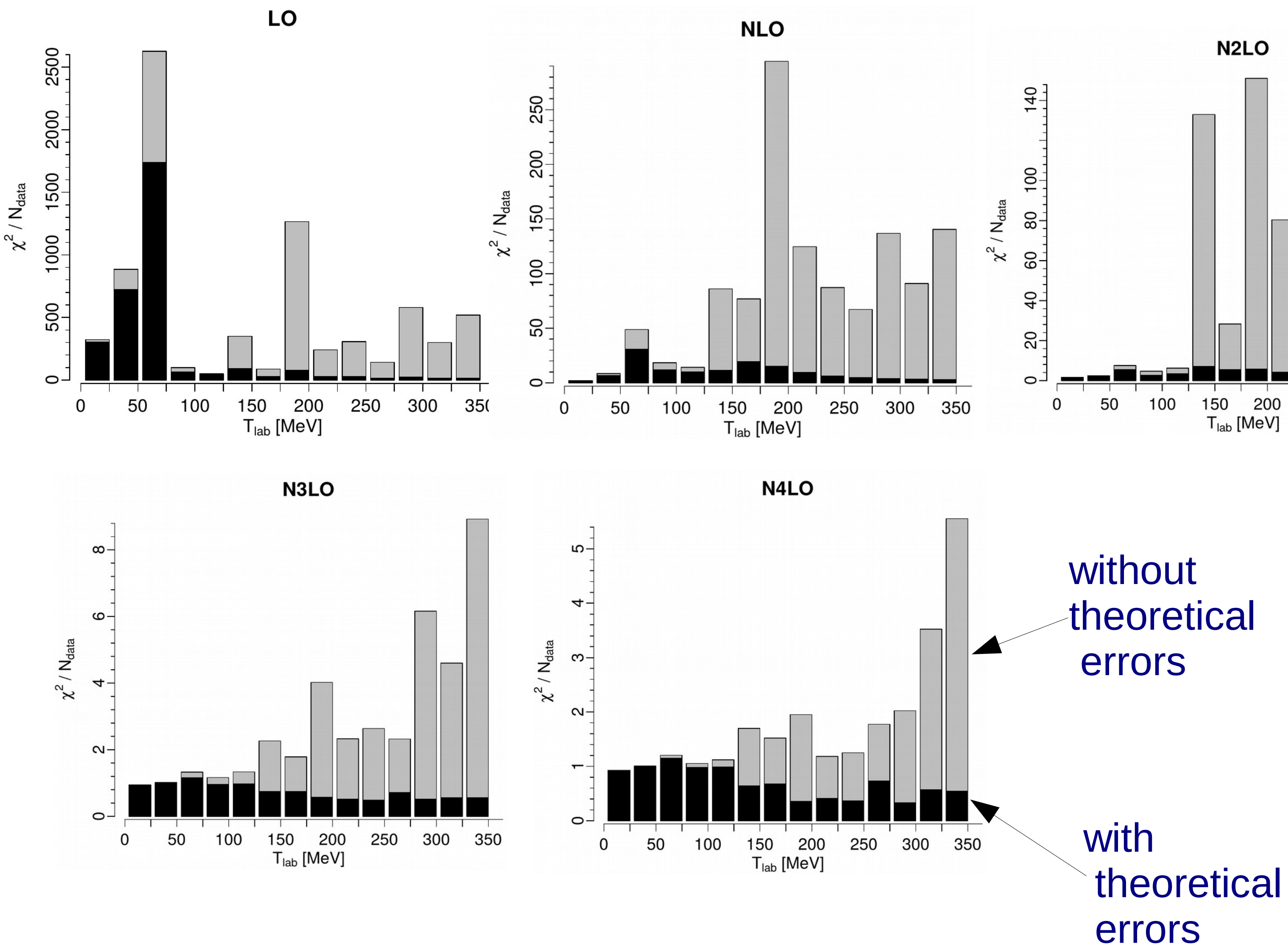
Fit to data:

N³LO

N⁴LO

Data:Nijmegen PWA

NN scatering, fit of chiral potential to data



Summary

- The novel approach to estimate the theoretical uncertainty from the truncation of the chiral expansion is applied to πN scattering
- Direct fits to the low energy πN scattering data are performed using the HB-NN, HB-πN and the covariant versions of χPT
- The extracted LECs are stable and in a reasonably good agreement with the ones reported in the literature
- Preliminary results of direct fits to NN data are presented

Outlook

- Explicit inclusion of Δ–degree of freedom is expected to improve convergence