

相对论核子手征微扰理论的进展与应用

姚德良

湖南大学

物理与微电子科学学院

Part I : Covariant Nucleon Chiral Perturbation Theory

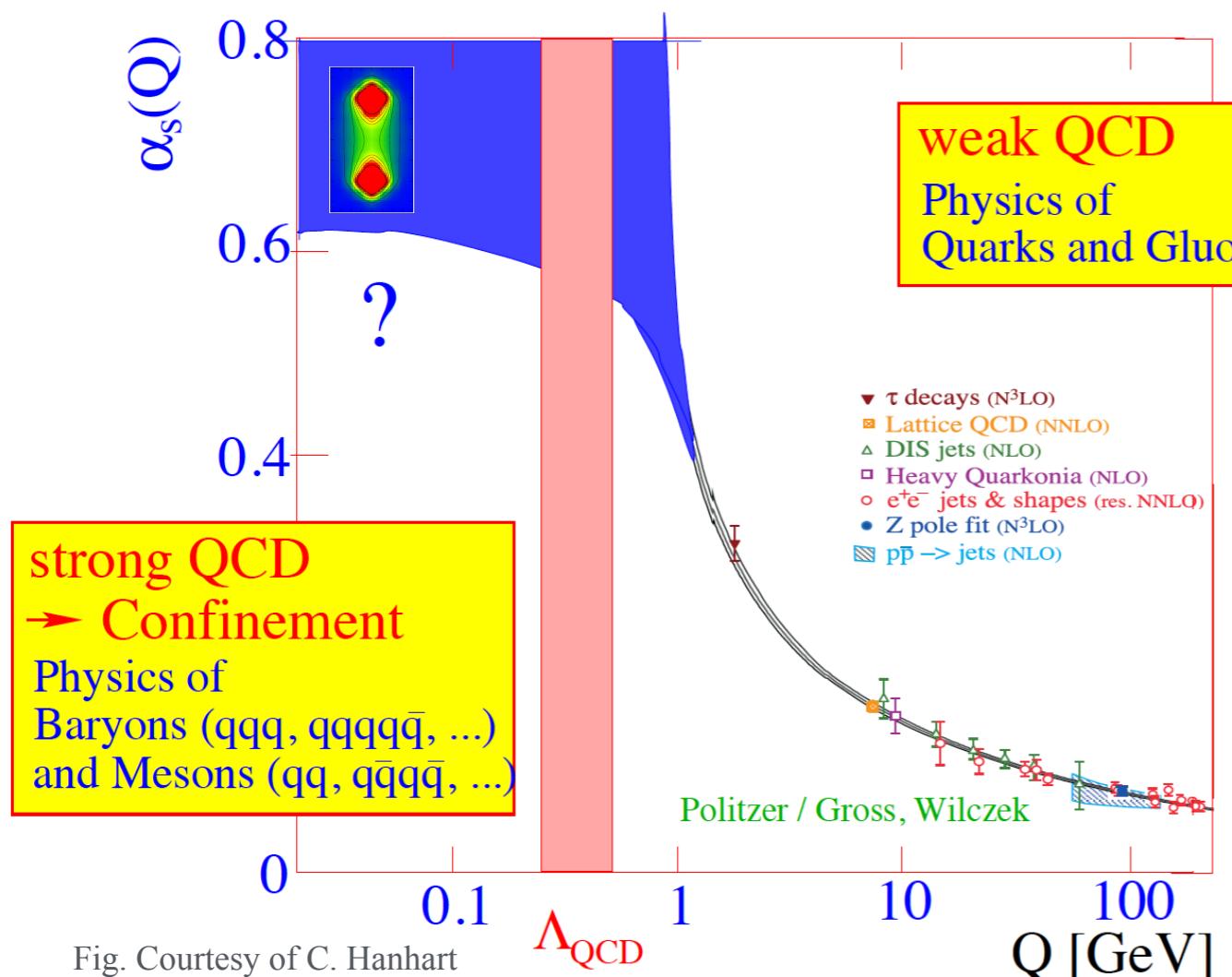
Part II: Applications and Prospects

1. A detailed example: πN scattering
2. Prospect I: Applications in neutrino physics
3. Prospect II: Extensions to heavy flavour physics
4. Prospect III: Combinations with lattice techniques



ChPT: EFT of QCD at low energies

♦ Facets of QCD — Asymptotic Freedom & Color Confinement

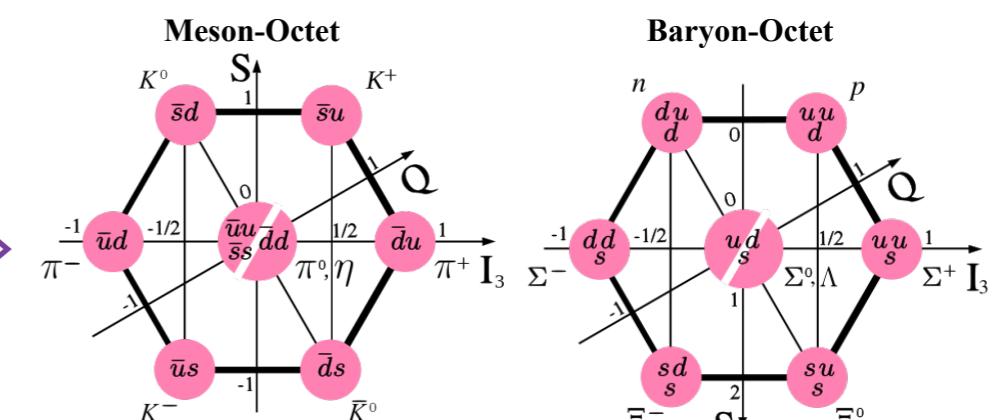


Standard Model of Elementary Particles

three generations of matter (fermions)	
I	II
mass ≈2.4 MeV/c ² charge 2/3 spin 1/2 u up	mass ≈1.275 GeV/c ² charge 2/3 spin 1/2 c charm
III	mass ≈172.44 GeV/c ² charge 2/3 spin 1/2 t top
	mass 0 charge 0 spin 1 g gluon
	mass ≈125.09 GeV/c ² charge 0 spin 0 Higgs

QUARKS	SCALAR BOSONS
mass ≈4.8 MeV/c ² charge -1/3 spin 1/2 d down	mass ≈95 MeV/c ² charge -1/3 spin 1/2 s strange
mass ≈4.511 MeV/c ² charge -1 spin 1/2 e electron	mass ≈105.67 MeV/c ² charge -1 spin 1/2 μ muon
mass ≈2.2 eV/c ² charge 0 spin 1/2 ν _e electron neutrino	mass ≈1.7 MeV/c ² charge 0 spin 1/2 ν _μ muon neutrino
mass ≈15.5 MeV/c ² charge 0 spin 1/2 ν _τ tau neutrino	mass ≈91.19 GeV/c ² charge 0 spin 1 Z Z boson
	mass ≈80.39 GeV/c ² charge ±1 spin 1 W W boson

LEPTONS	GAUGE BOSONS
mass ≈0.511 MeV/c ² charge -1 spin 1/2 e electron	mass ≈1.7768 GeV/c ² charge -1 spin 1/2 τ tau
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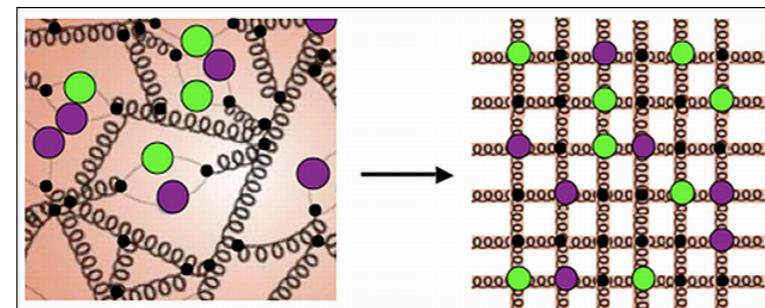
♦ Low-energy region — Quarks are glued together by gluons to form hadrons

Phenomenological Models



- Linear Sigma Model
- Nambu-Jona-Lasinio Model
- Jülich Model
- ...

Lattice QCD



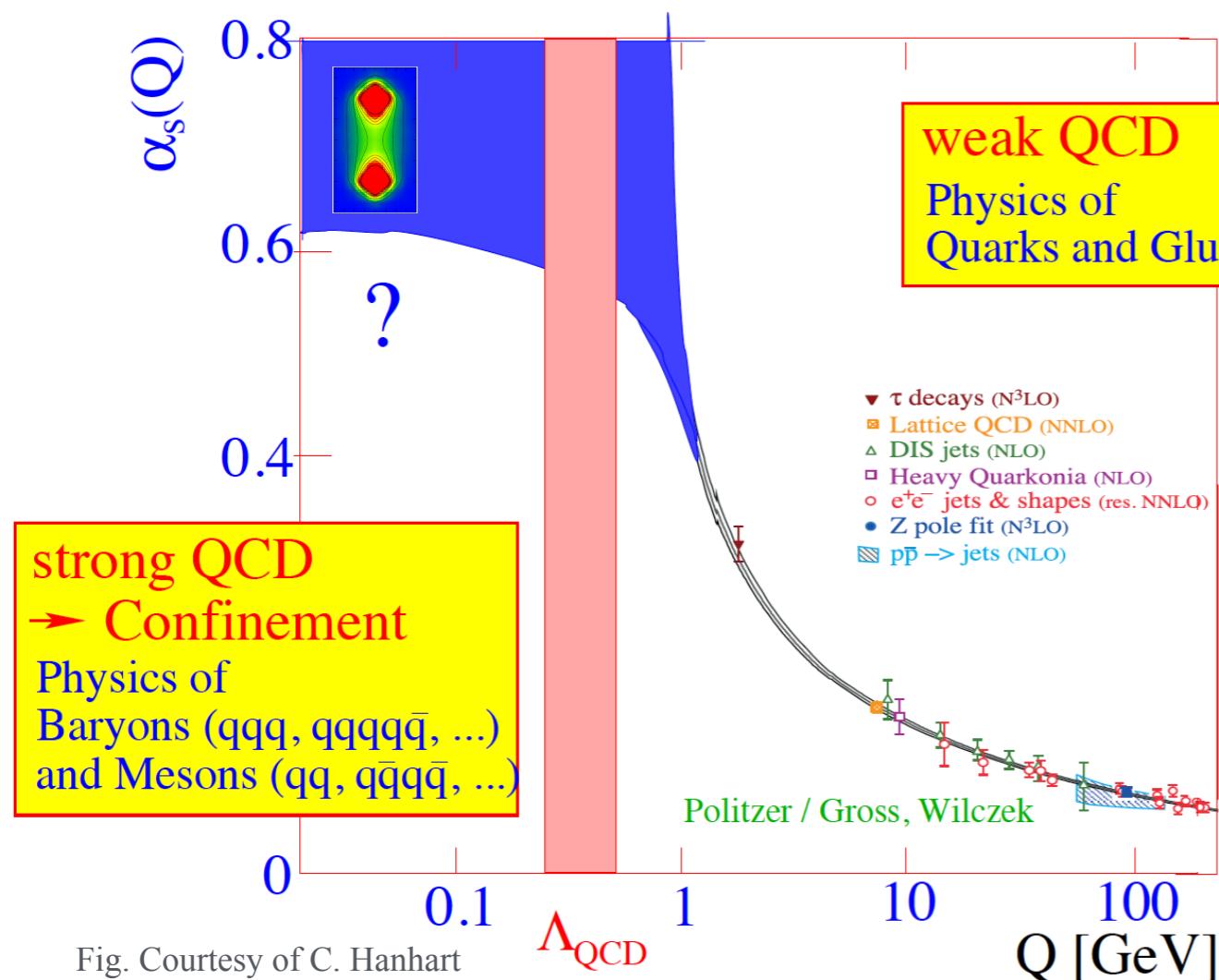
Effective Field Theories



- Chiral Perturbation theory (ChPT)
 - hadron fields as degrees of freedom
 - Expansion in masses and external momenta

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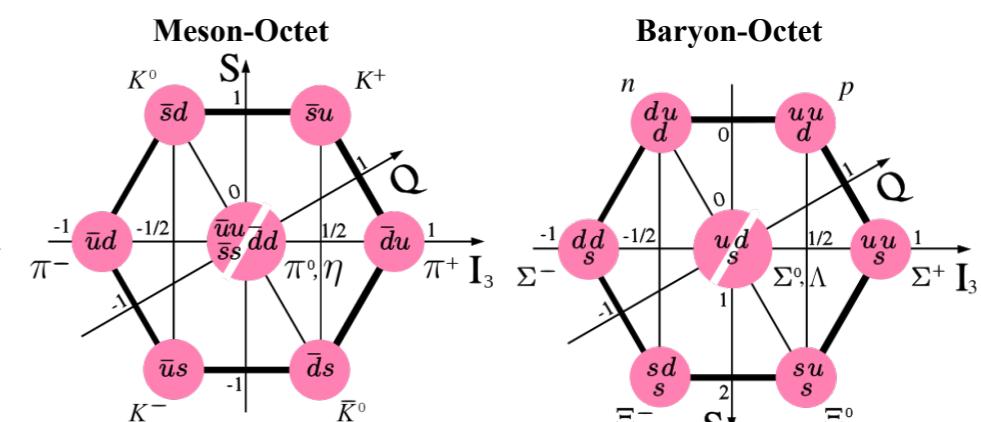
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b down	t top
s strange	g gluon
e electron	γ photon
μ muon	Z boson
τ tau	W boson
ν _e electron neutrino	
ν _μ muon neutrino	
ν _τ tau neutrino	

LEPTONS

SCALAR BOSONS

GAUGE BOSONS



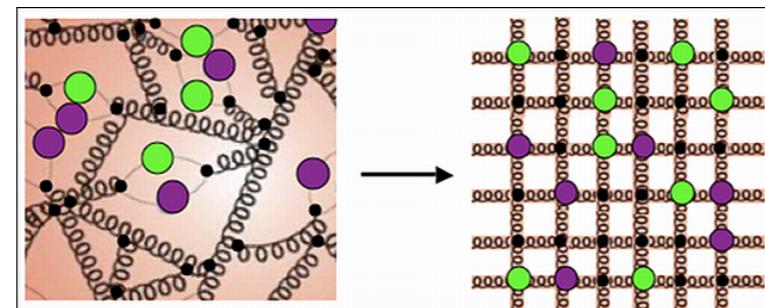
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Effective Field Theories

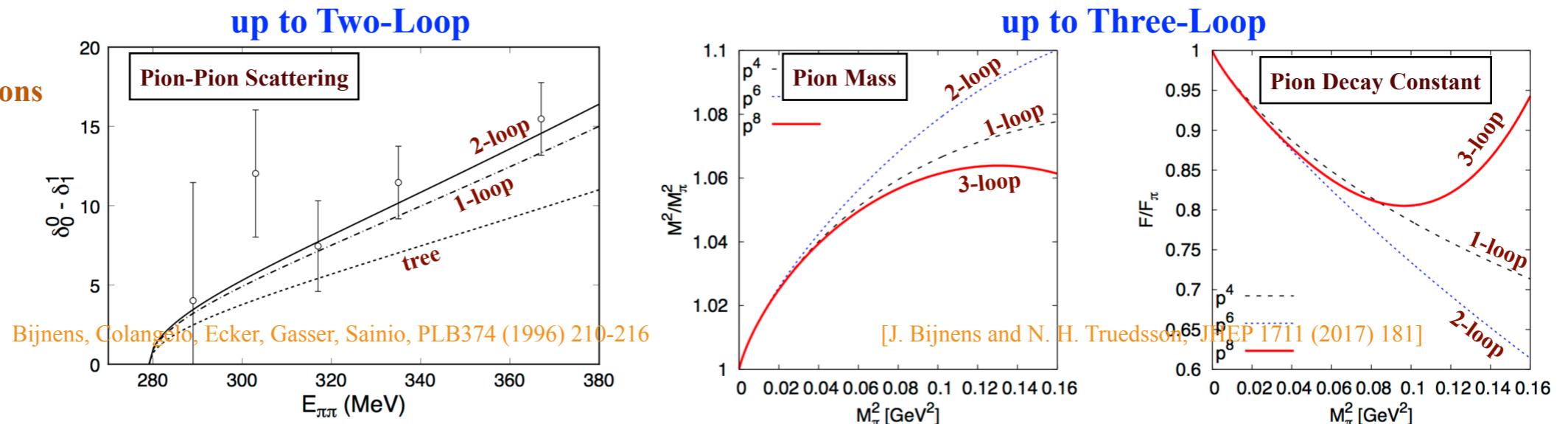


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 - hadron fields as degrees of freedom
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ChPT: Power Counting Breaking (PCB) problem

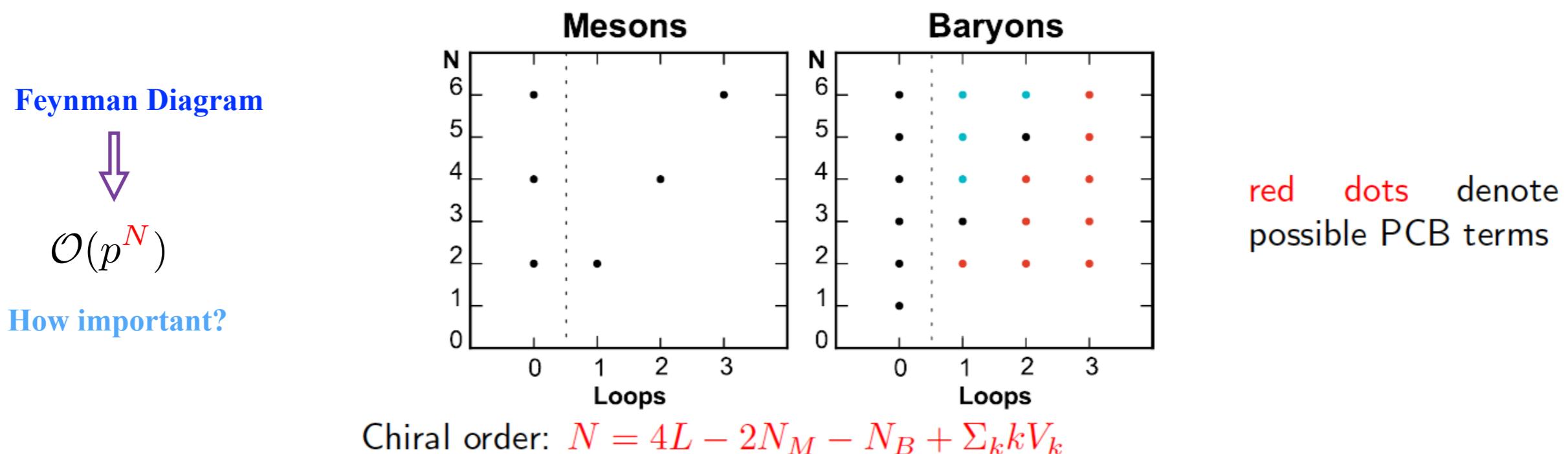
♦ Pure Goldstone Bosons: ChPT has gained great achievements

- High-order calculations become standard
- Fast convergence



♦ Covariant ChPT including matter fields (Baryons, D/B mesons)

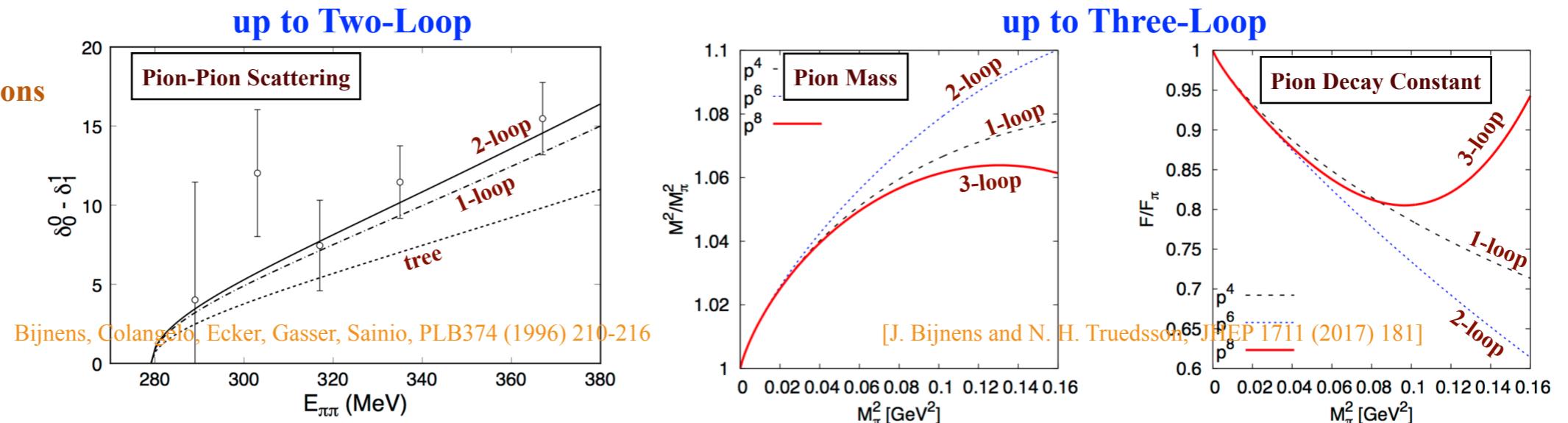
- Dimensional Regularization (DR) with standard MSbar-1 (MS-1) subtraction
- A systematic power counting rule is lost due to the non-zero mass of matter fields in the chiral limit



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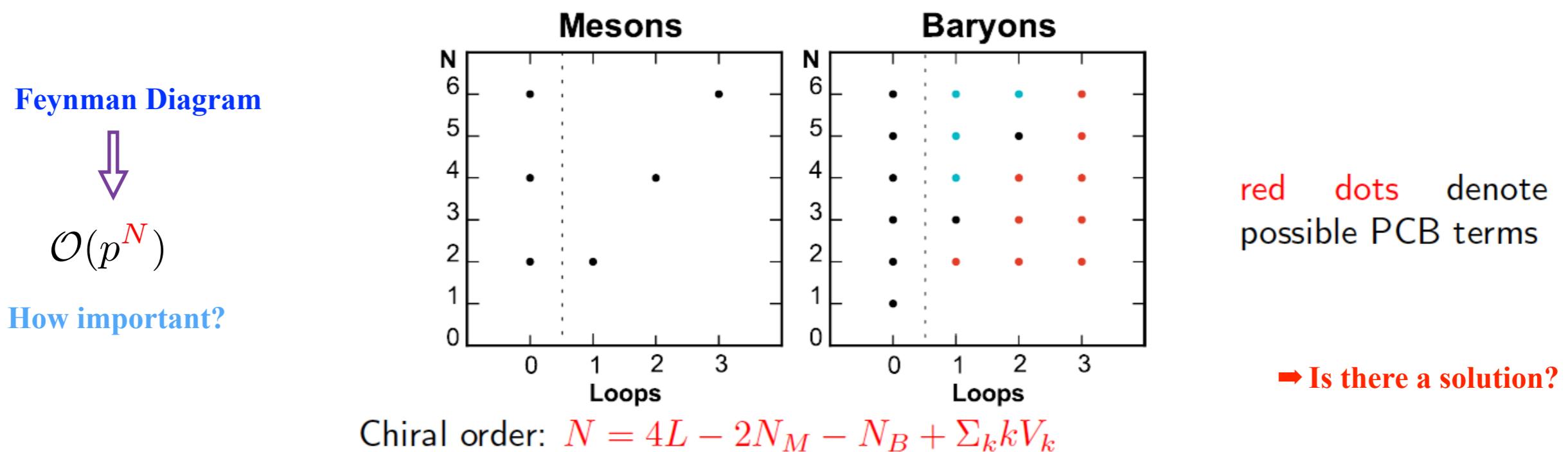
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ChPT: HB approach, IR prescription & EOMS scheme

♦ Heavy Baryon ChPT (HBChPT):

[Jenkins and Manohar,PLB255'91]

A simultaneous expansion in external momenta and $1/m_B$.

- Non-covariant and slowly convergent in the threshold region.

[N.Fettes,Ulf-G.Meissner and S.Steininger, NPA'98],
[M.Mojžiš,Eur.Phys.J.C2'98]

- Even divergent in the sub-threshold region (e.g. scalar form factor).

[V.Bernard,N.Kaiser and Ulf-G.Meissner,Int.J.Mod.Phys.E4'95],
[T.Becher and H.Leutwyler,Eur.Phys.J.C9'99]

♦ Infrared Regularization (IR):

[T.Becher and H.Leutwyler,Eur.Phys.J.C9'99]

The full integral is separated into Infared singular and Regular parts.

- Scale-dependence: amplitude and observables.

[T.Becher and H.Leutwyler,JHEP0106'01]

- Unphysical cuts($u=0$) [J.M.Alarcon,J.Martin Camalich,J.A.Oller and L.Alvarez-Ruso,PRC83'11]

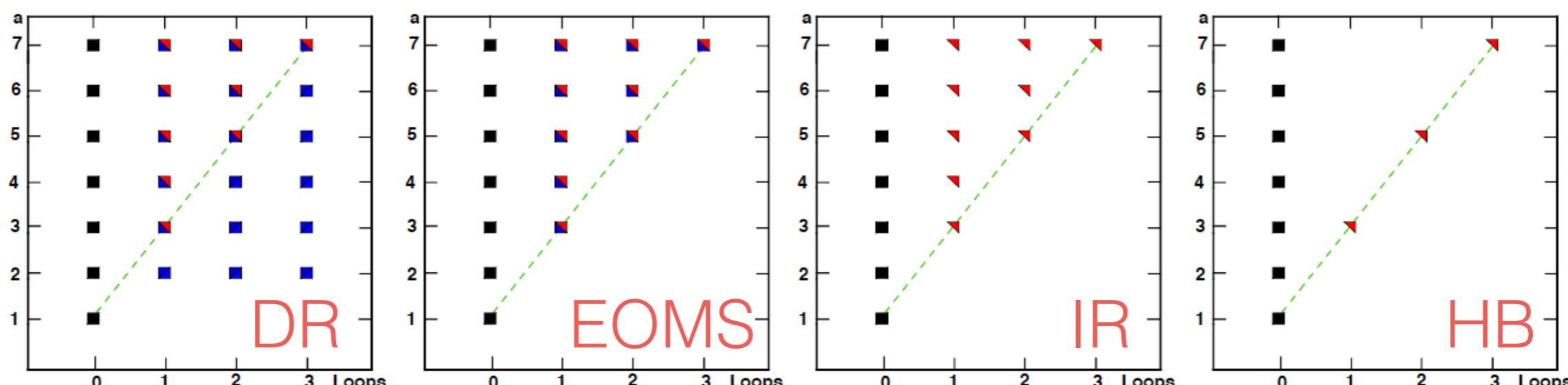
- Bad predictions: e.g., huge Goldberger-Treiman relation violation (20-30%).

[J.M.Alarcon,J.Martin Camalich,J.A.Oller and L.Alvarez-Ruso,PRC83'11]

♦ Extended-on-mass-shell (EOMS):

[T.Fuchs,J.Gegelia,G.Japaridze and S.Scherer,PRD68'03]

Is it an approach to solve the above problems?



Motivation: Why πN scattering? Why explicit Δ 's?

♦ Renewed interest in πN scattering:

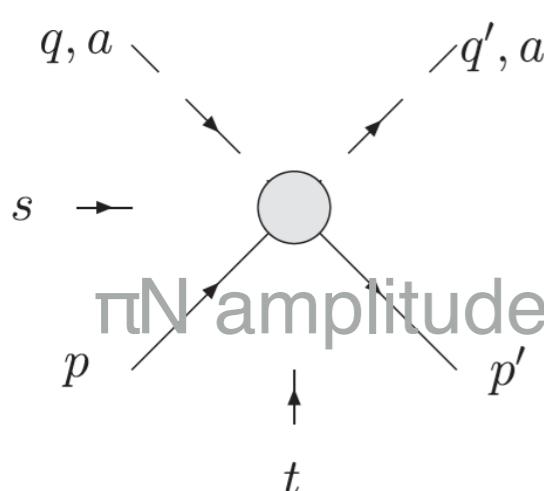
- $\pi N \rightarrow \pi N$ amplitudes e.g. for **σ -term** physics → see talk by Hoferichter, 12:00 PM Monday
- $\bar{N}N \rightarrow \pi\pi$ crossed amplitudes e.g. for **nucleon form factors**

♦ Advantages of covariant πN amplitudes using EOMS:

- Respect original **analyticity, crossing, power counting, etc, suitable for Amplitude analysis**
- Good for matching: e.g. Matching RS to BChPT results e.g. [D.Siemens et al, PLB770 (2017) 27]

♦ Importance of explicit Δ 's:

- Strongly coupled to πN system: $BR(\Delta \rightarrow \pi N) \sim 99.4\%$
- Small mass difference: $\delta = m_\Delta - m_N \sim 300$ MeV



Power counting: $\mathcal{E} : \delta \sim M_\pi \sim \not{p} - m_N \sim q$

Δ incorporated via

Complex Mass Approach

$$T_{\pi N}^{a'a}(s, t, u) = \chi_{N'}^\dagger \left\{ \delta_{a'a} T^+(s, t, u) + \frac{1}{2} [\tau_{a'}, \tau_a] T^-(s, t, u) \right\} \chi_N$$

Isospin struc.

$$T^\pm(s, t, u) = \bar{u}^{(s')}(p') \left\{ D^\pm(s, t, u) - \frac{1}{4m_N} [\not{q}', \not{q}] B^\pm(s, t, u) \right\} u^{(s)}(p)$$

Lorentz struc.

πN scattering Basics

◆ Chiral Effective Lagrangian:

LO couplings

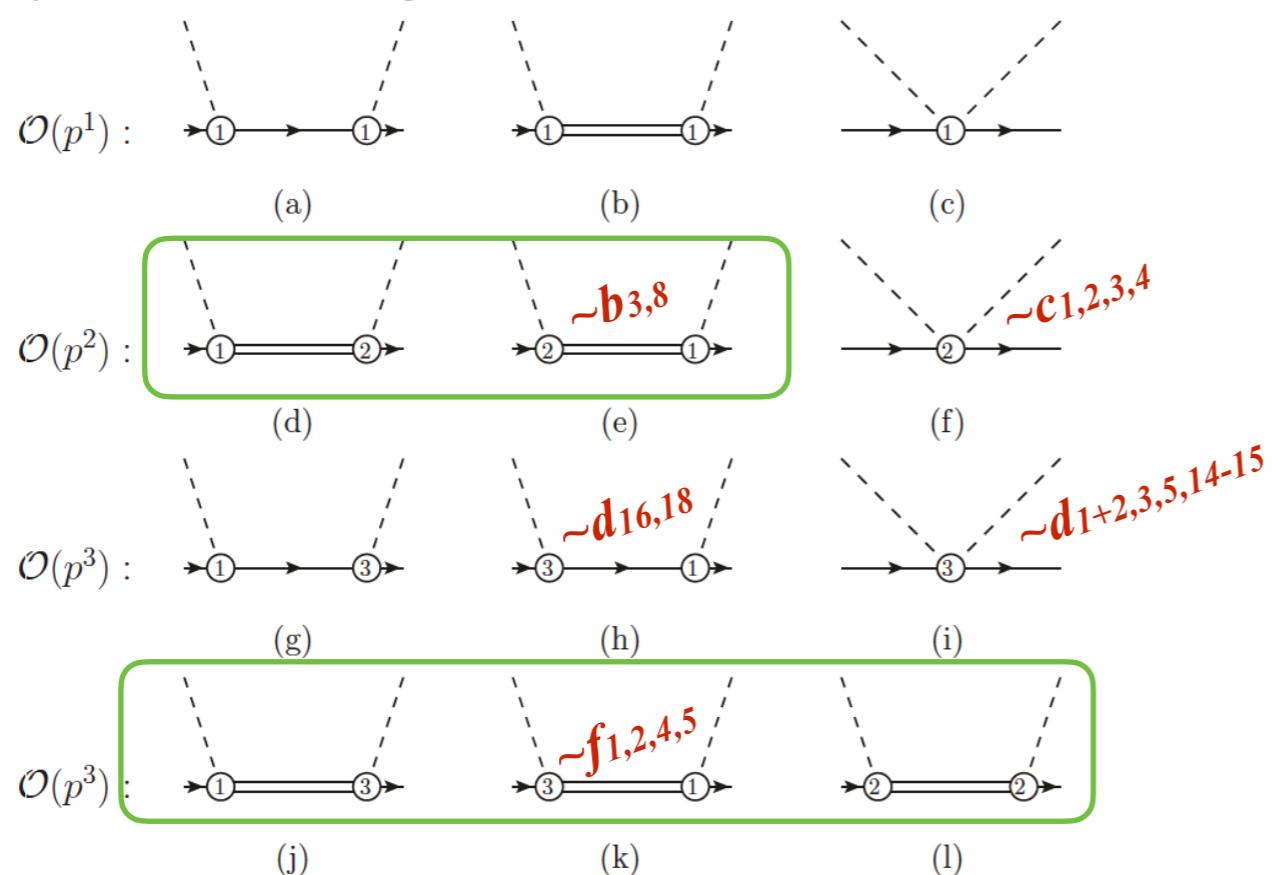
Counter Terms

$$\mathcal{L}_{\text{eff}} = \begin{array}{c|c} \mathcal{L}_{\pi\pi}^{(2)} & + \mathcal{L}_{\pi\pi}^{(4)} \\ + \mathcal{L}_{\pi N}^{(1)} & + \mathcal{L}_{\pi N}^{(2)} + \mathcal{L}_{\pi N}^{(3)} \\ + \mathcal{L}_{\pi\Delta}^{(1)} & + \mathcal{L}_{\pi\Delta}^{(2)} \\ + \mathcal{L}_{\pi N\Delta}^{(1)} & + \boxed{\mathcal{L}_{\pi N\Delta}^{(2)} + \mathcal{L}_{\pi N\Delta}^{(3)}} \end{array}$$

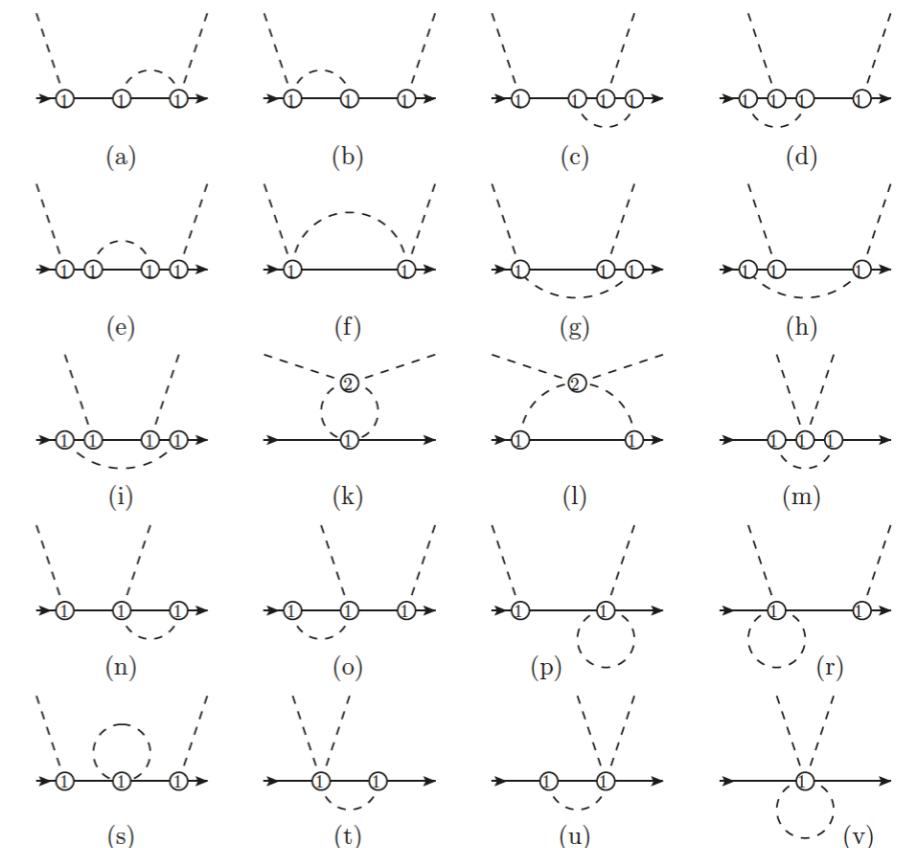
Redundant!

★ Feynman Diagrams:

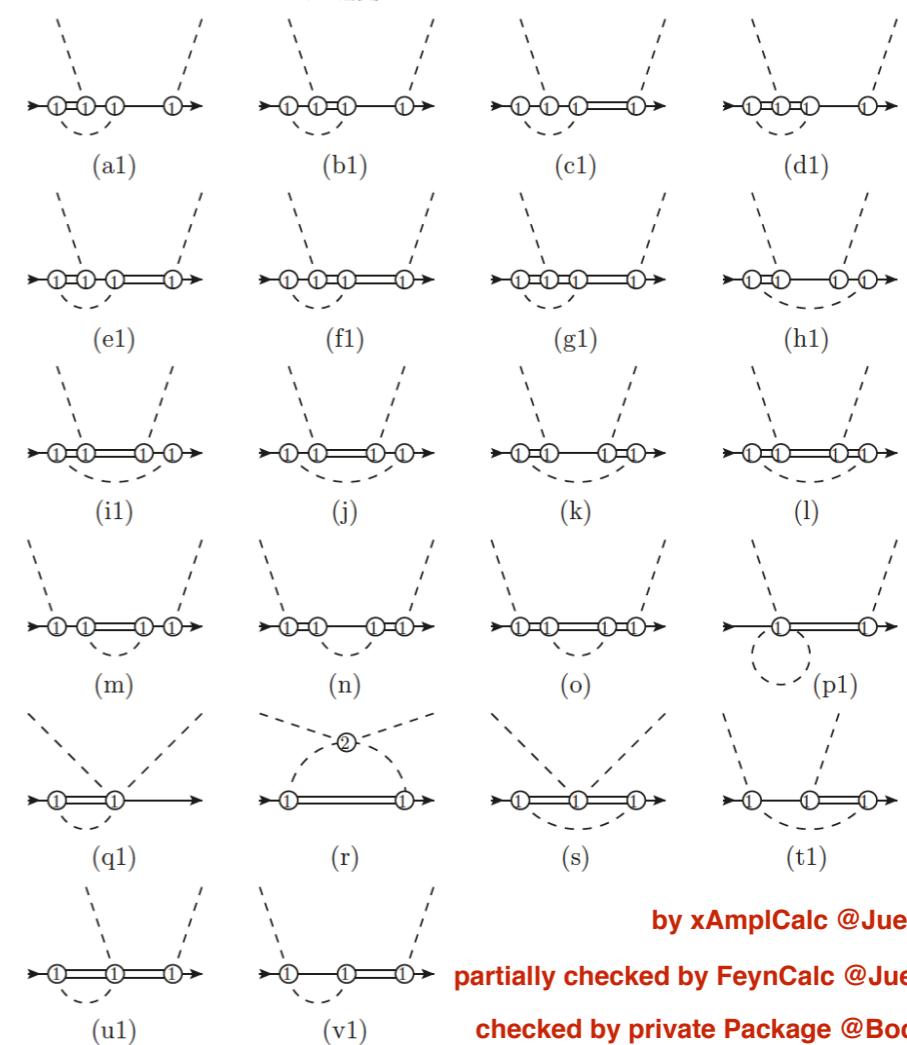
Tree



Loop w/o Δ

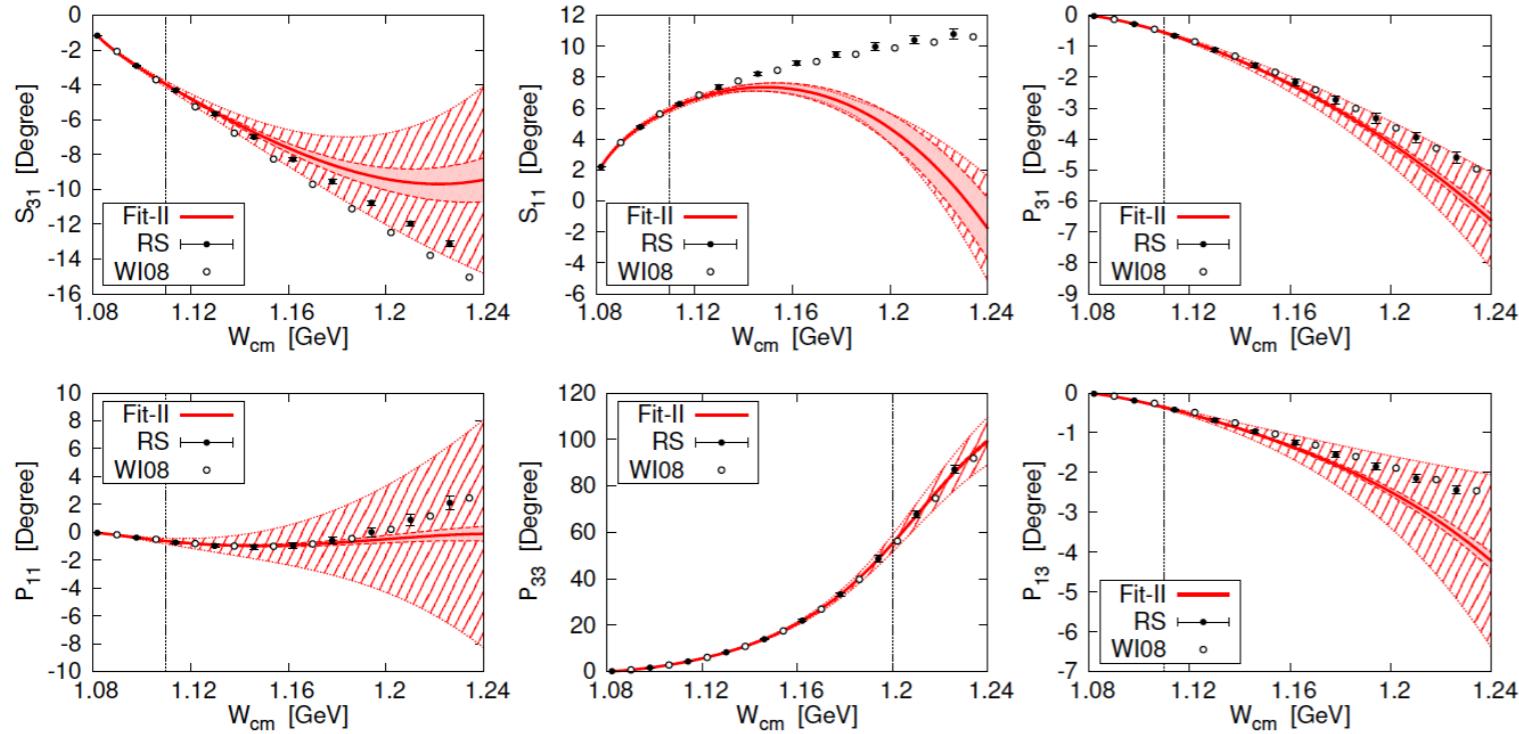


Loop w/ Δ

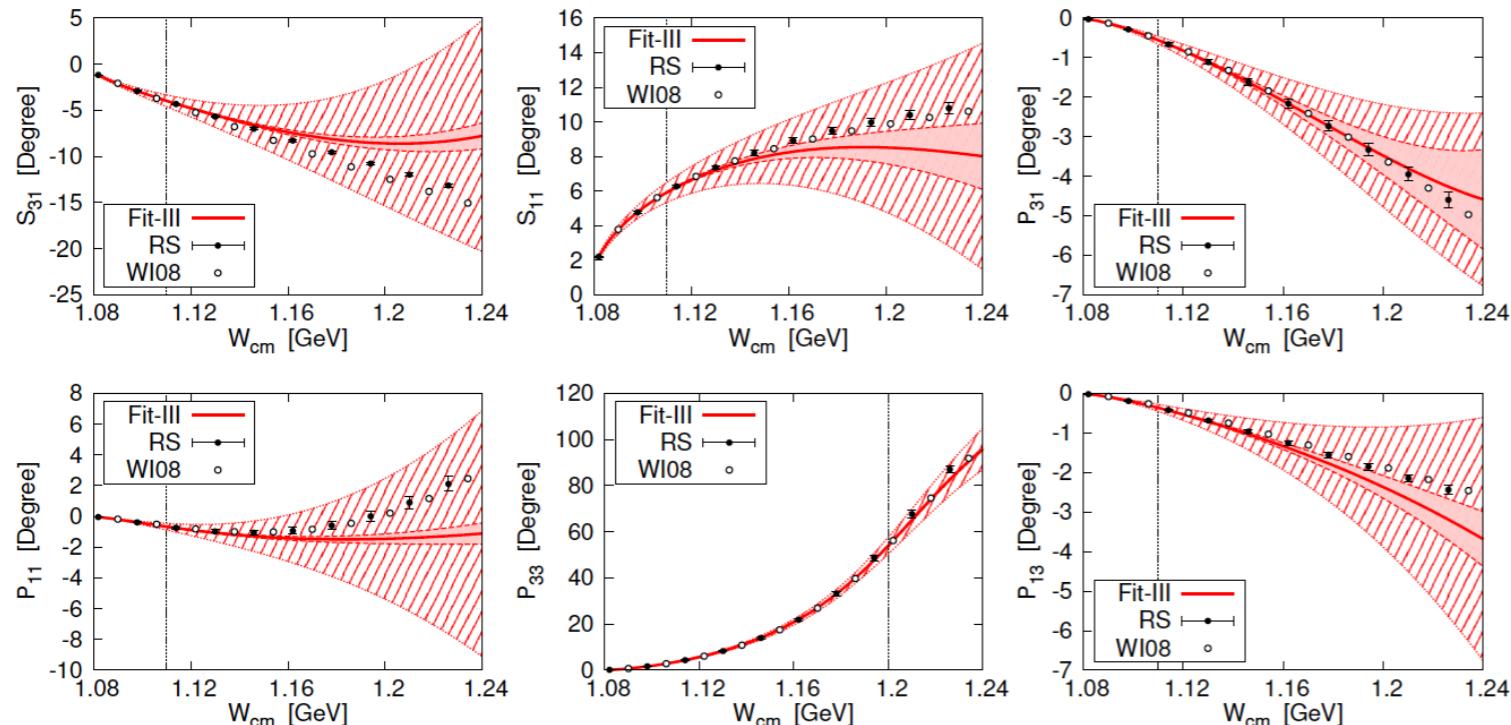


Fitting: S -, P -wave Phase shifts (II)

♦ Fit-II: w/ tree-level Delta

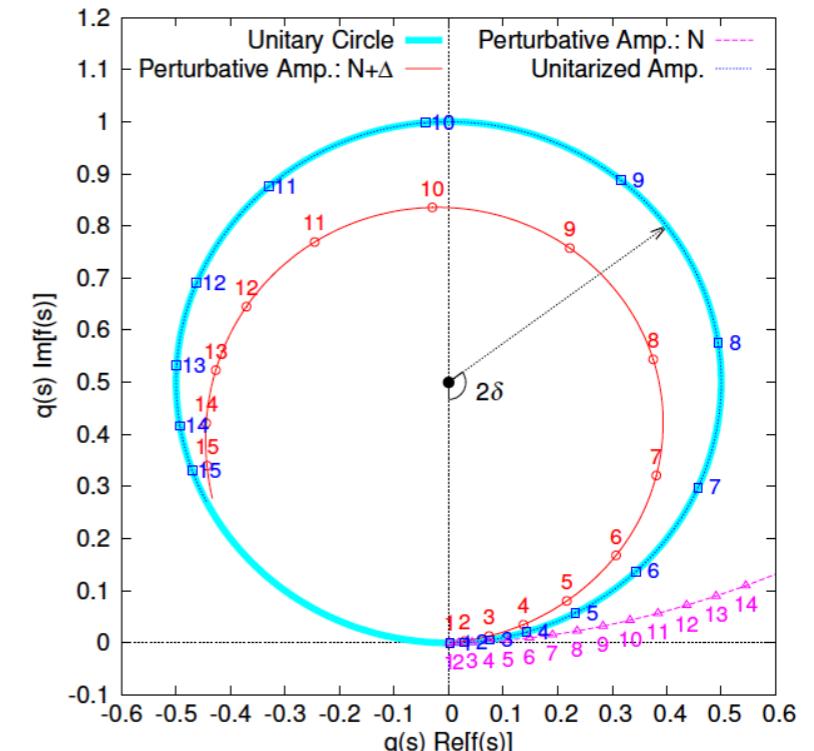


♦ Fit-III: w/ loop-level Delta



LEC	Fit-II	Fit-III
	$N+LO \Delta$	$N+\Delta$
c_1	$-0.99(2)(1)$	$-1.31(2)(1)$
c_2	$1.38(3)(1)$	$0.78(4)(2)$
c_3	$-2.33(3)(1)$	$-2.55(10)(7)$
c_4	$1.71(2)(1)$	$1.20(4)(2)$
d_{1+2}	$0.14(4)(3)$	$4.85(68)(64)$
d_3	$-0.97(8)(15)$	$-0.62(10)(15)$
d_5	$0.39(6)(11)$	$-0.93(11)(15)$
d_{14-15}	$-1.08(8)(3)$	$5.54(2.79)(2.01)$
$g_{\pi N}$	13.12^*	13.12^*
h_A	$1.28(1)(1)$	$1.42(1)(1) - i 0.16(1)(1)$
g_1	—	$-1.21(46)(39)$
χ^2/dof	$\frac{339.8(27.4)}{328-9} = 1.07(9)$	$\frac{373.8(29.9)}{328-10} = 1.18(9)$

Argand plot for P_{33} (Fit-III)



Predictions:

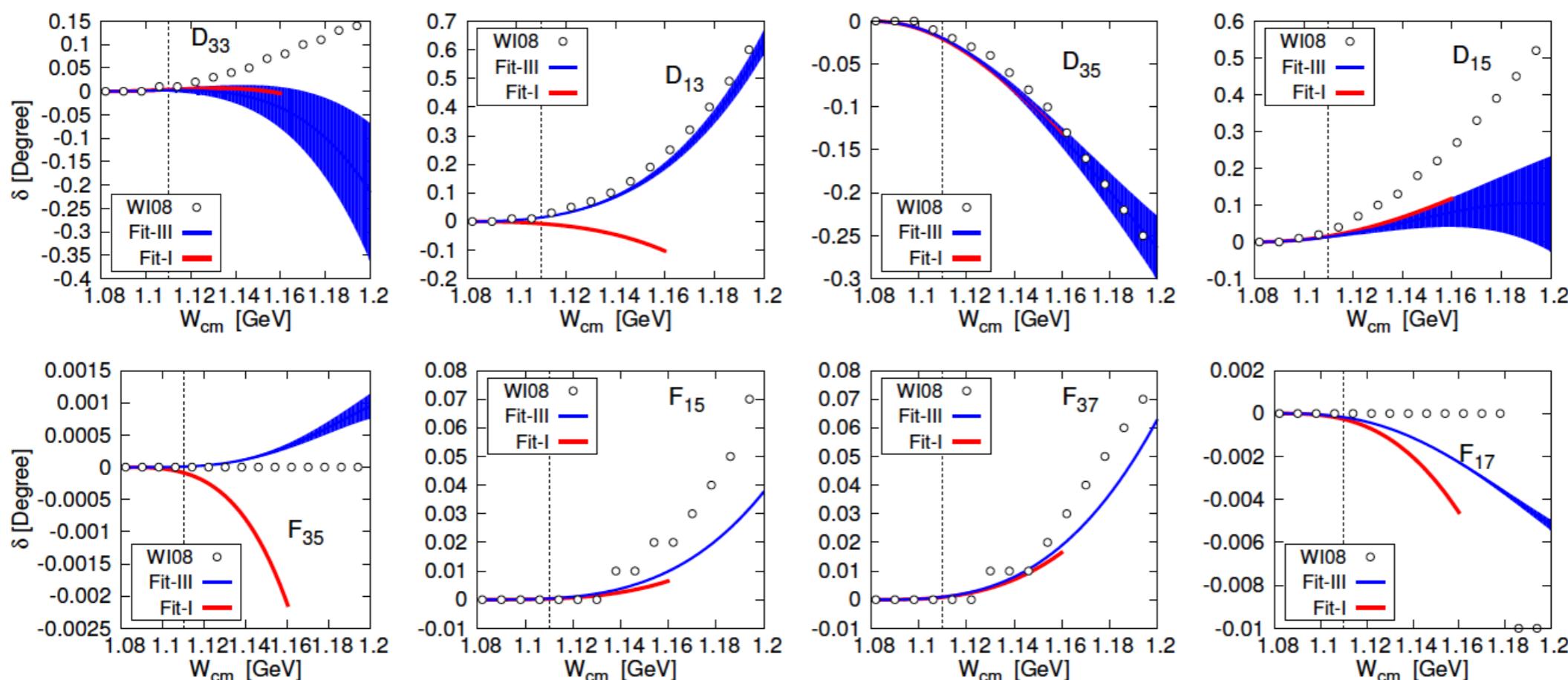
◆ Threshold parameters:

Threshold Para.	Fit-I	Fit-II	Fit-III	RS
$a_{0+}^+ [10^{-3} M_\pi^{-1}]$	-0.6(7)(3.4)	-1.1(7)(3.0)	-0.5(7)(7.1)	-0.9(1.4)
$a_{0+}^- [10^{-3} M_\pi^{-1}]$	85.7(5)(3.3)	85.8(4)(1.1)	85.8(3)(1.0)	85.4(9)
$a_{1-}^+ [10^{-3} M_\pi^{-3}]$	-49.8(1.0)(15.9)	-52.5(4)(4.7)	-51.0(5)(6.7)	-50.9(1.9)
$a_{1-}^- [10^{-3} M_\pi^{-3}]$	-9.7(3)(9.5)	-11.3(3)(3.2)	-9.5(2)(1.7)	-9.9(1.2)
$a_{1+}^+ [10^{-3} M_\pi^{-3}]$	139.9(1.8)(11.6)	131.0(4)(4.0)	131.5(5)(8.8)	131.2(1.7)
$a_{1+}^- [10^{-3} M_\pi^{-3}]$	-84.0(6)(4.0)	-80.3(1)(1.4)	-80.4(2)(2.3)	-80.3(1.1)

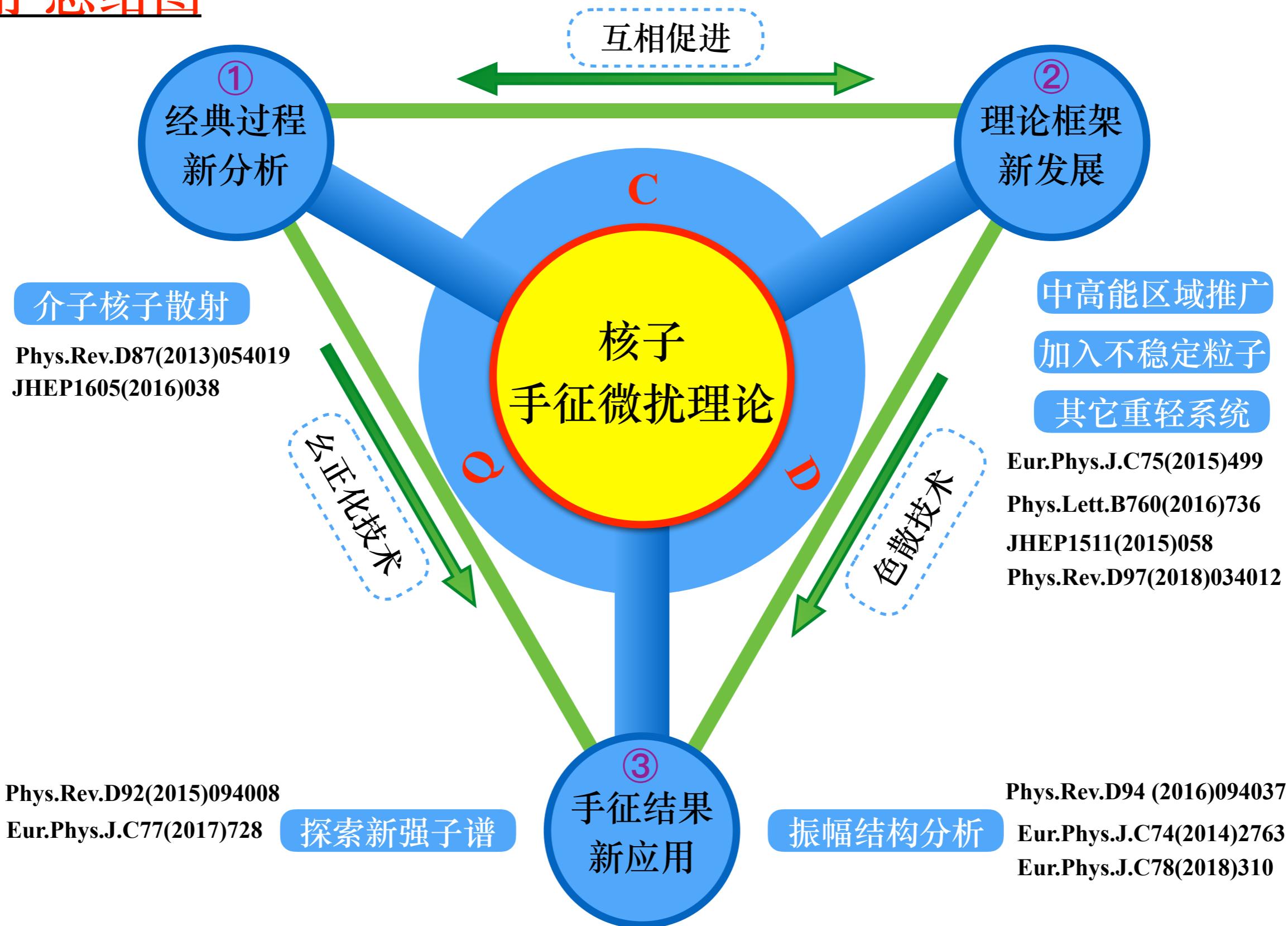
$$a_{\ell\pm}^I = \lim_{|\mathbf{p}| \rightarrow 0} \frac{\tan \delta_{\ell\pm}^I}{|\mathbf{p}|^{2\ell+1}} = \lim_{|\mathbf{p}| \rightarrow 0} \frac{\text{Re} f_{\ell\pm}^I(s)}{|\mathbf{p}|^{2\ell}}$$

in good agreement with RS determinations

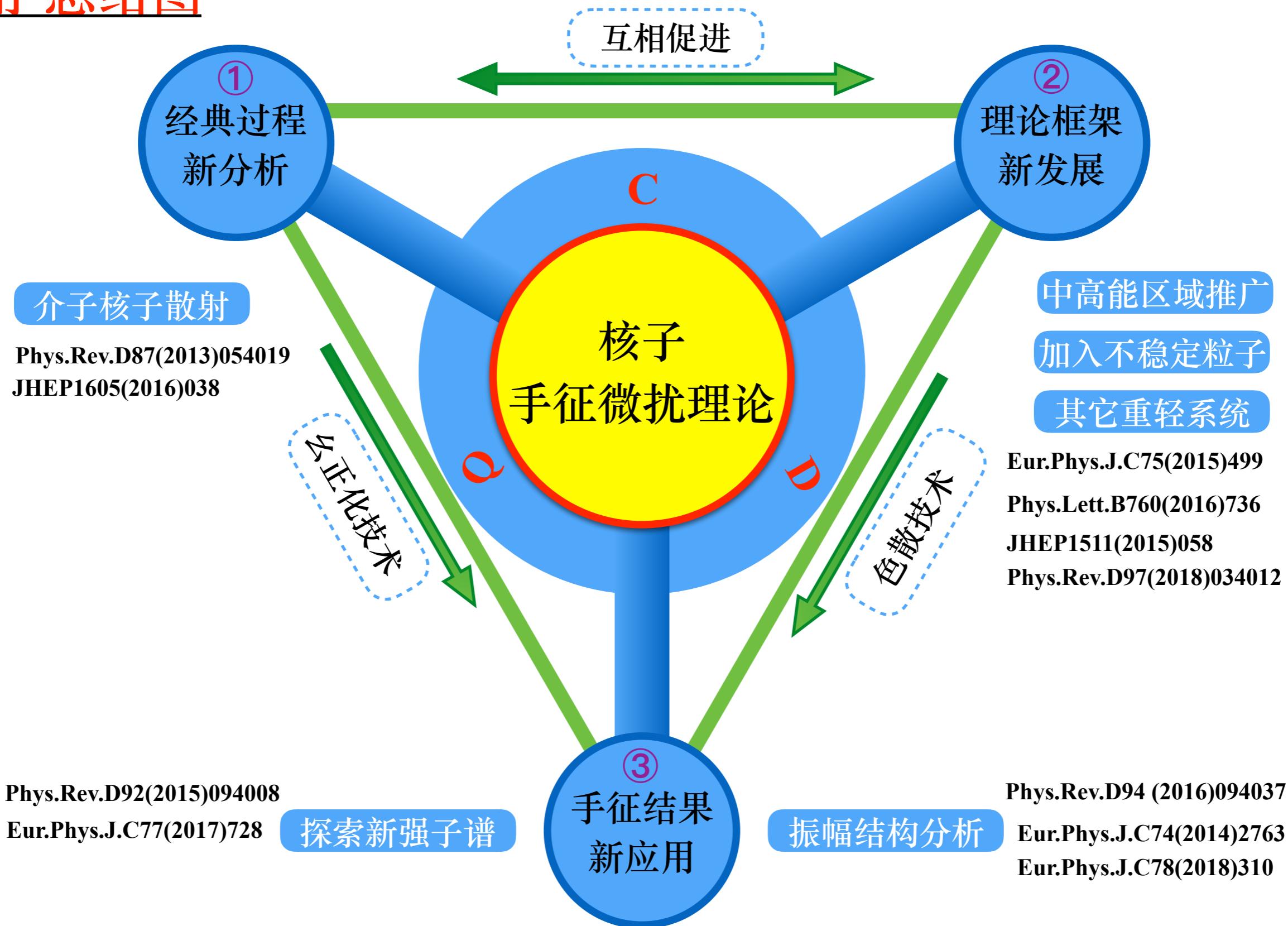
◆ D -, F -wave Phase shifts:



应用-总结图



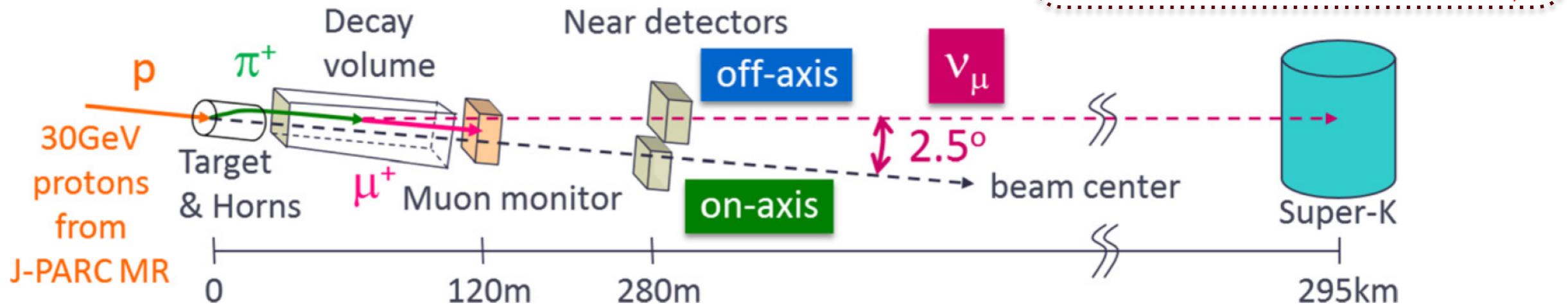
应用-总结图



What more can we do with Baryon Chiral Perturbation Theory?

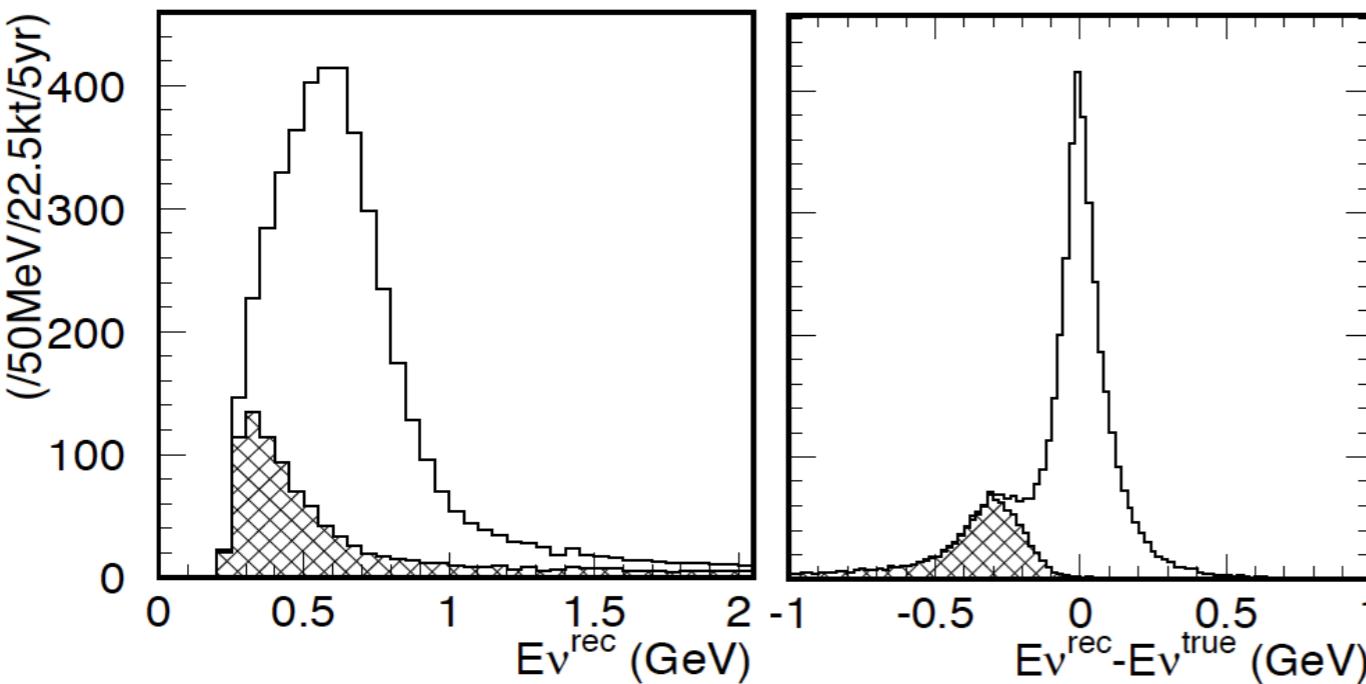
Prospect I: Applications in neutrino physics

♦ Oscillation experiments (e.g T2K)



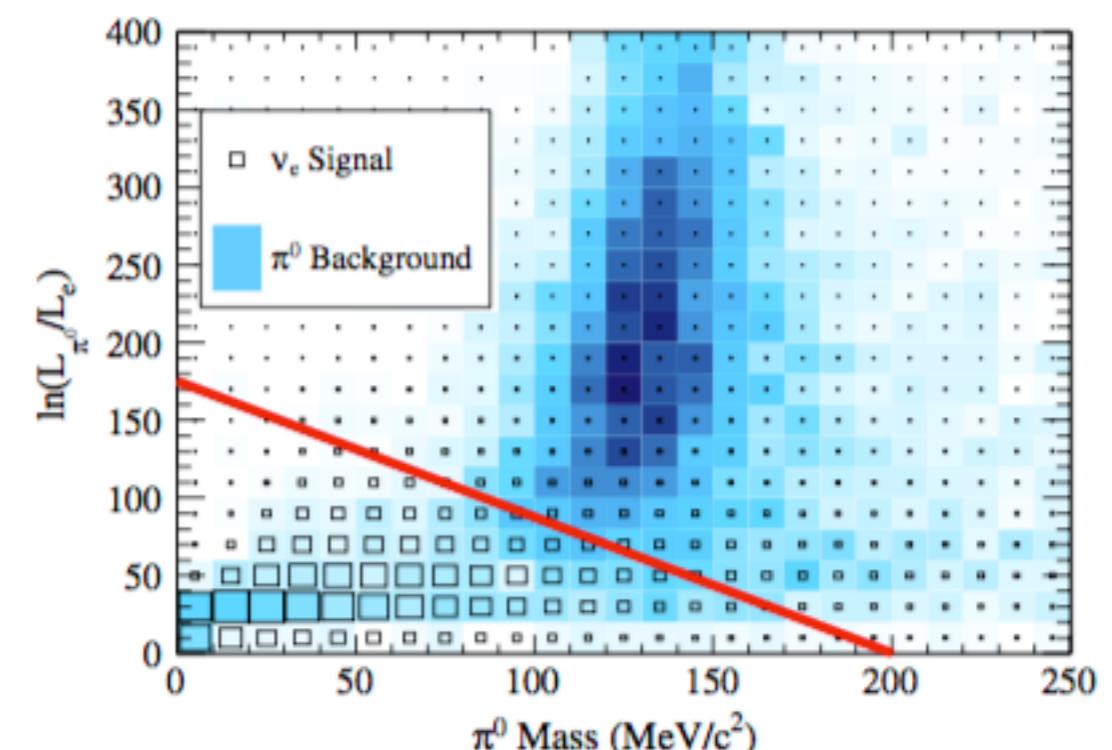
♦ CC1 π :

- Source of CCQE-like events
→ Misidentification of pion
- to be subtracted for a good $E\nu$ reconstruction



♦ NC1 π :

- e-like background to $\nu_\mu \rightarrow \nu_e$ searches
- Improved at T2K with a π^0 rejection cut

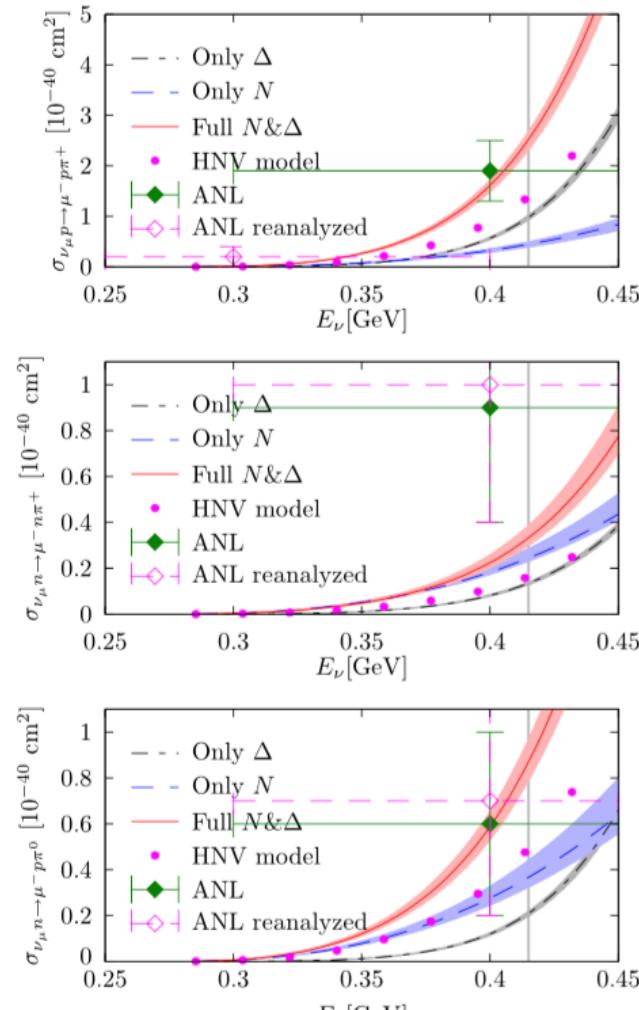


Prospect I: Applications in neutrino physics

[DLY, Alvarez-Ruso and Vicente-Vacas, PRD794(2019)109]

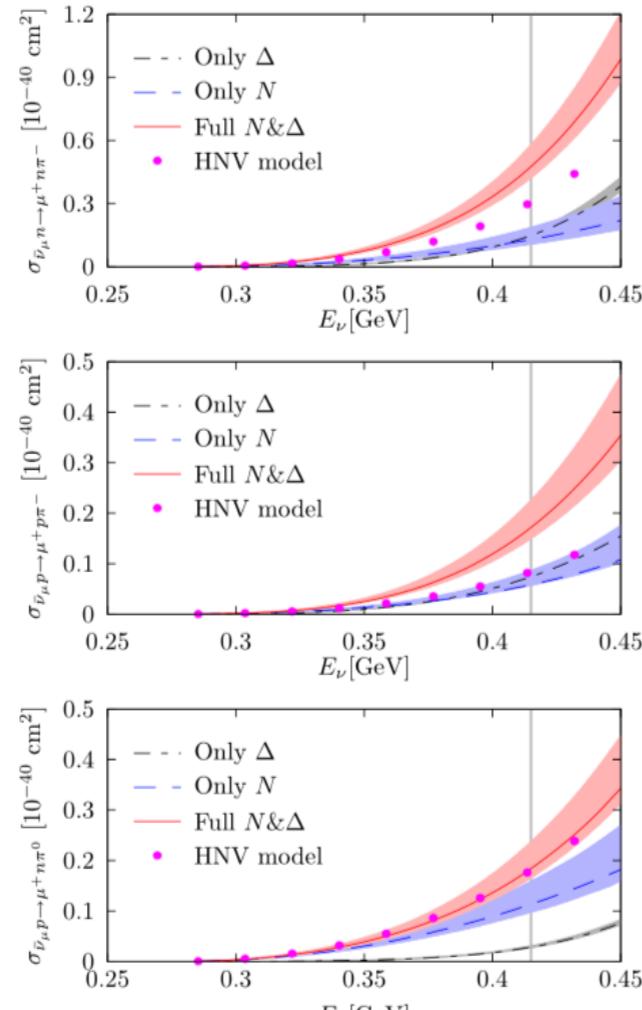
♦ First results from BChPT

v-CC1 π

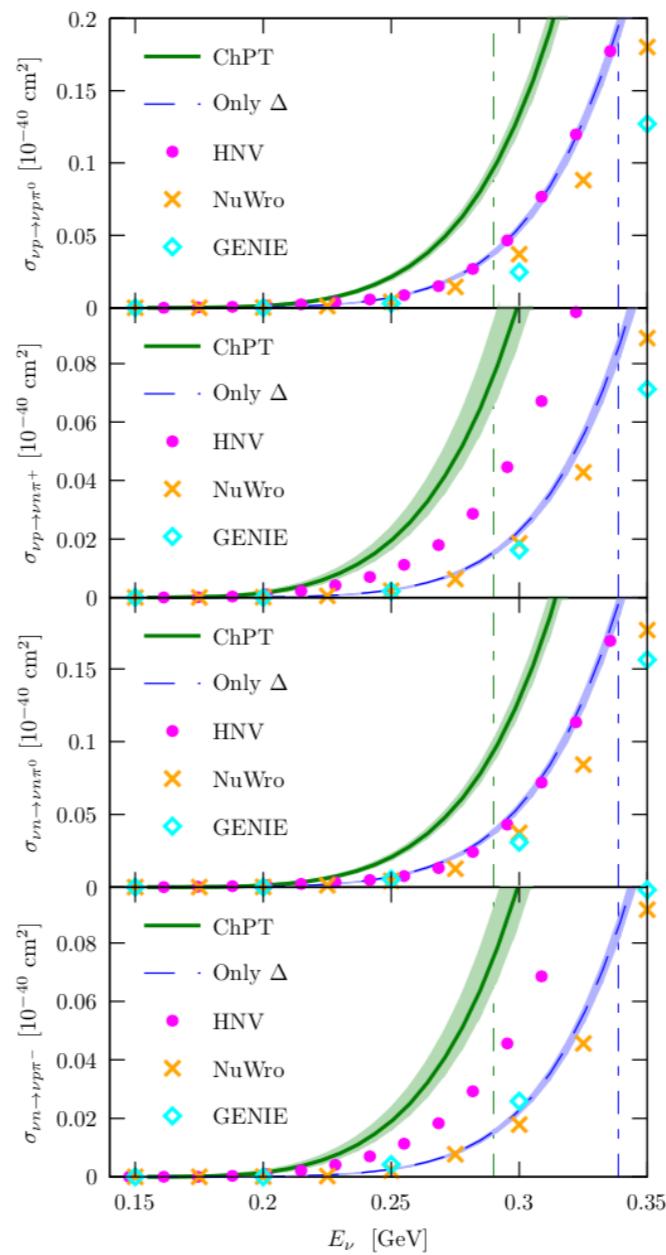


[DLY, Alvarez-Ruso, Hiller-Blin and Vicente-Vacas, PRD98(2018)076004]

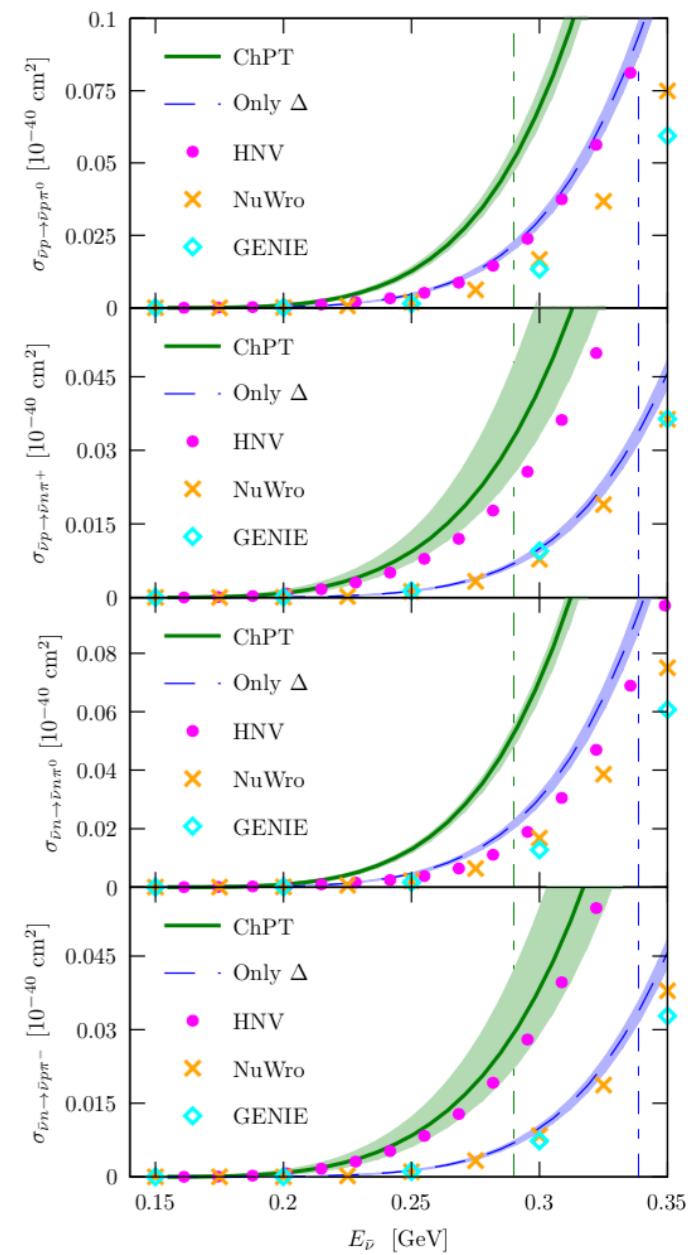
anti-v-CC1 π



v-NC1 π

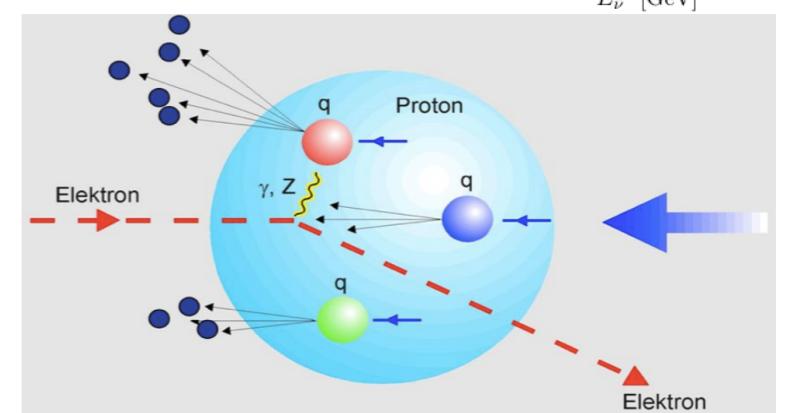


anti-v-NC1 π



♦ More outcomes from BChPT:

- Extended to intermediate energies.
- Multi pion productions & Coherent pion productions (nuclear effects)
- Production of pseudo-scalar with strangeness
- The same game can be played for neutrinoless beta decays?
- Electron-Ion Collider



Prospect II: Extensions in heavy flavour physics

◆ Chiral potentials for charmed meson interactions from ChPT & Unitarization

✓ **NLO:** [Kolomeitsev & Lutz
PLB582 (2004) 39]

[Guo, et al,
PLB641 (2006) 278]

[Liu, et al,
PRD87, 014508 (2013)]

[Altenbuchinger, et al,
PRD89, 014026 (2014)]

✓ **NNLO:** [Geng, et al, PRD82, 054022 (2010)] [Du, Guo, Meissner & Yao, JHEP11(2015)058 & Arxiv:1703.10836]

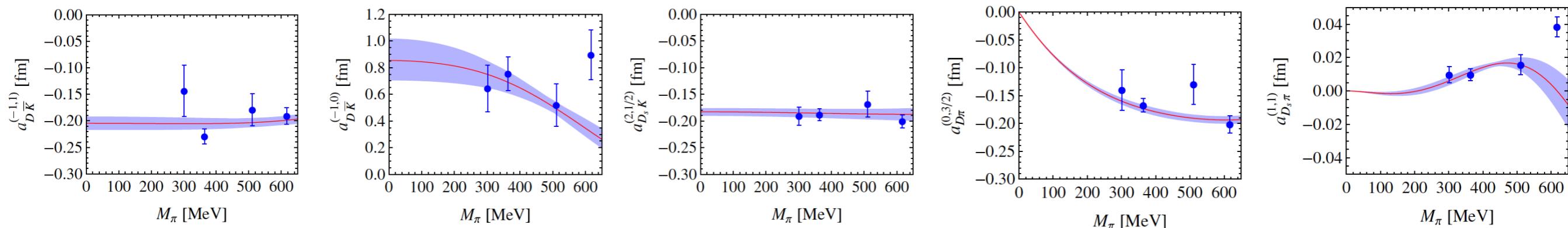
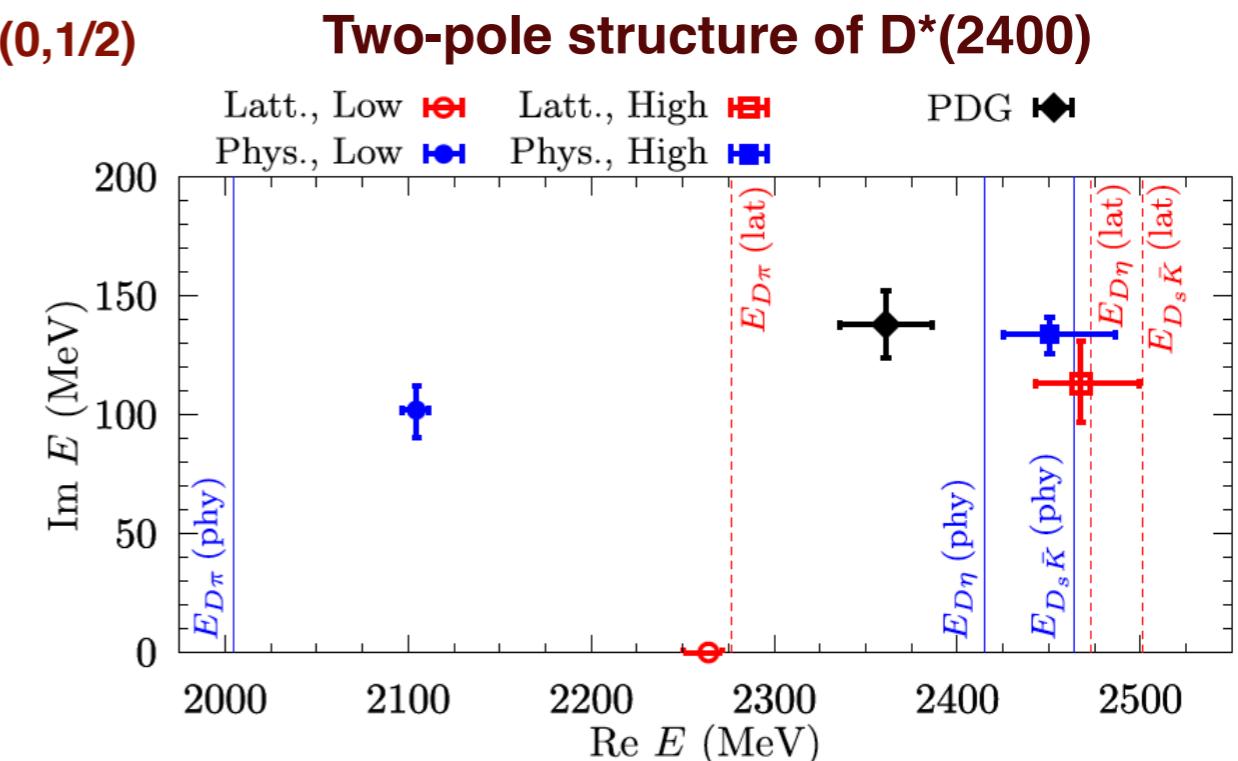
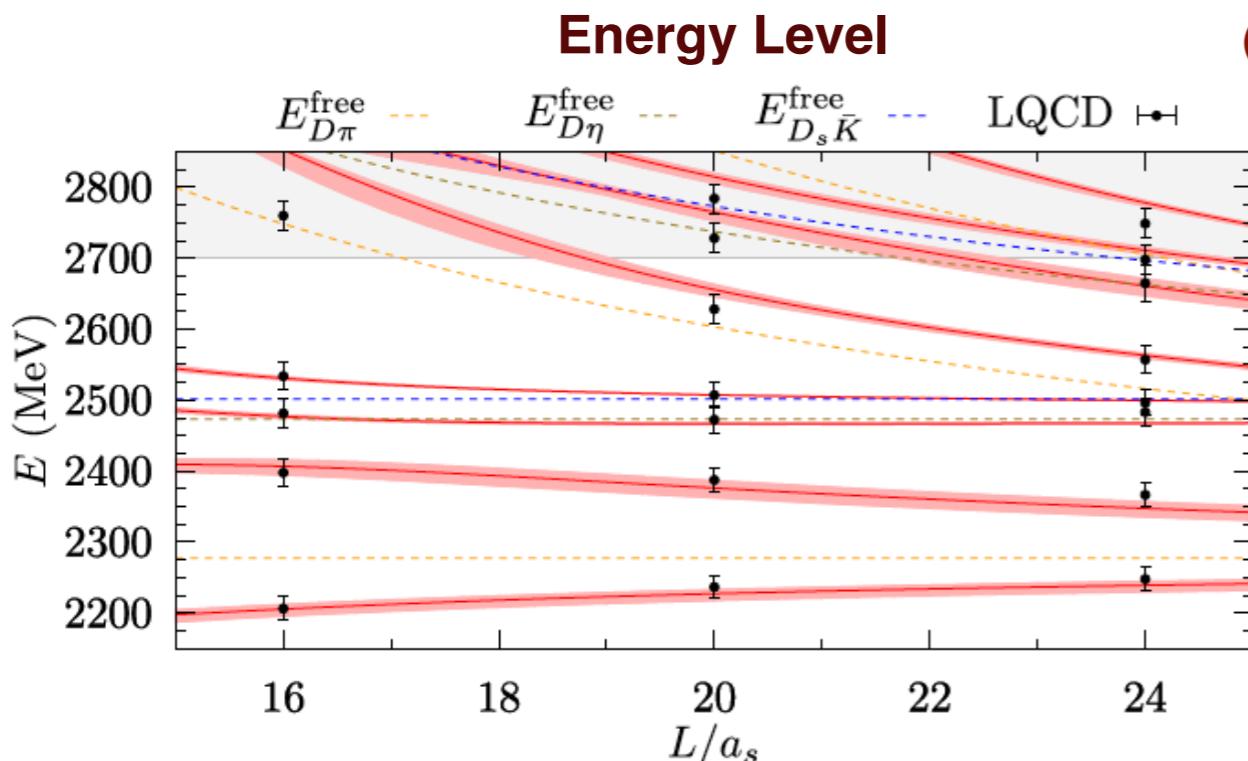


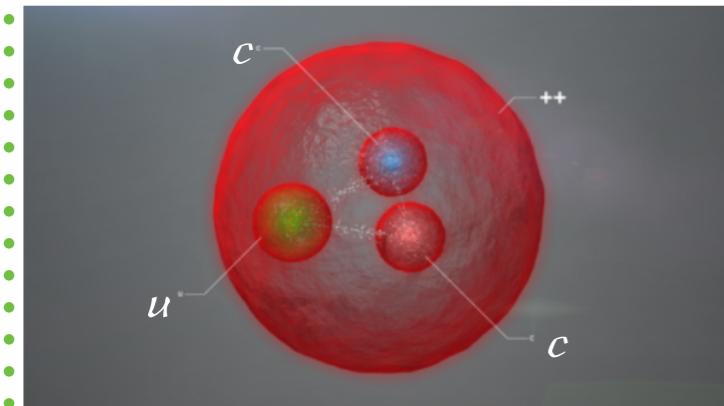
Fig from [Liu, et al, PRD87, 014508 (2013)]

◆ Applications of NLO potentials by Liu, et al



Prospect II: Extensions in heavy flavour physics

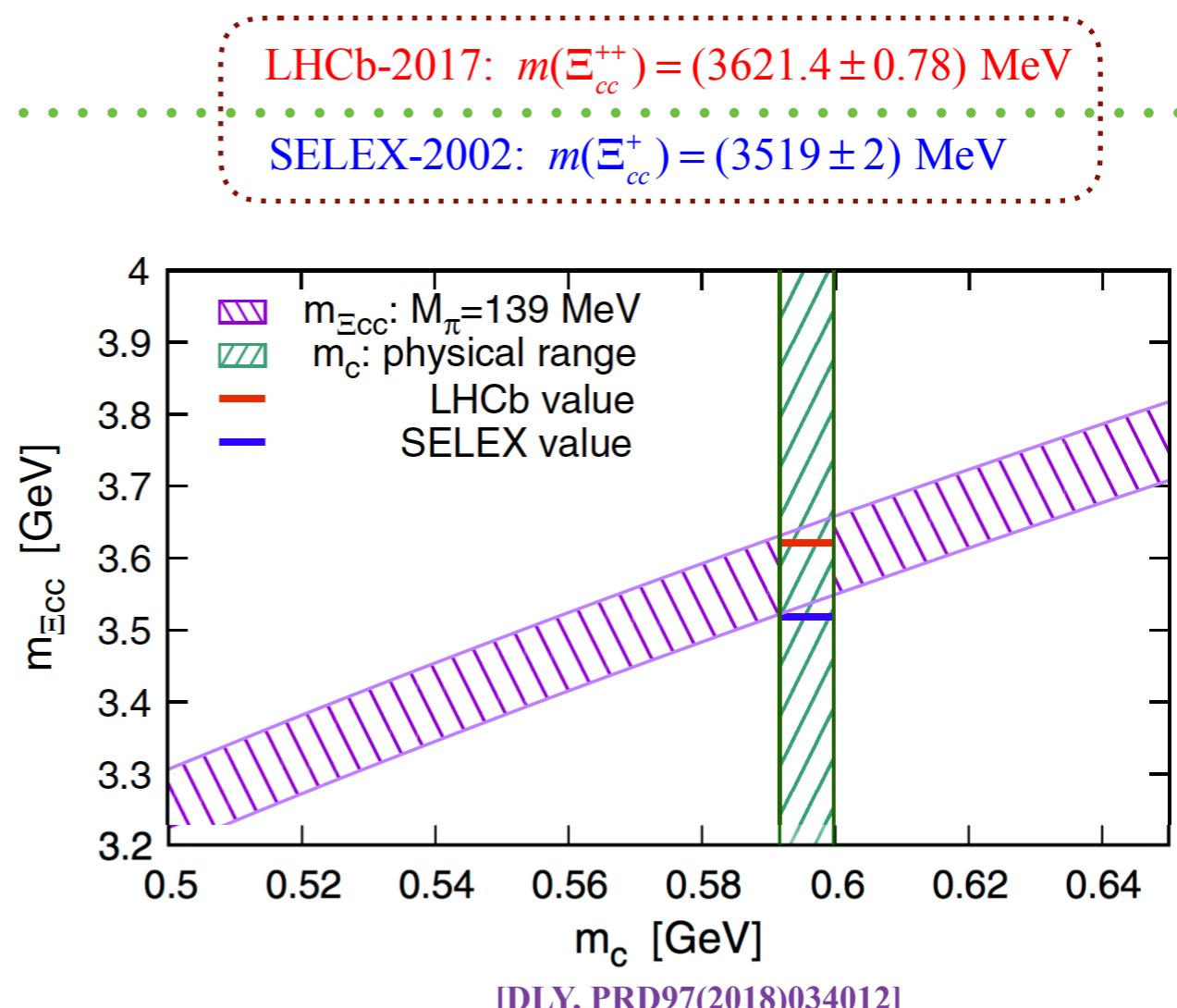
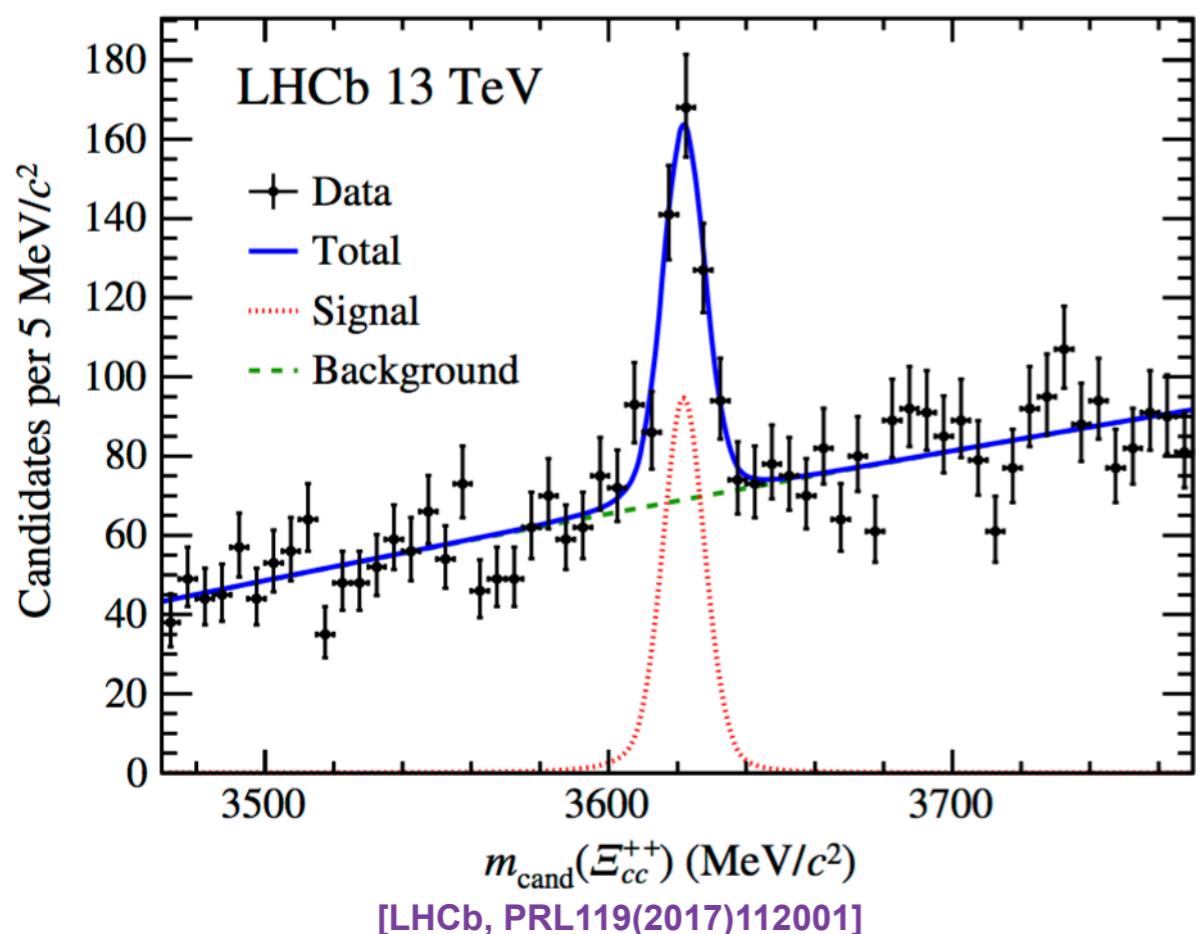
♦ Time to study doubly charmed baryons (DCB)



LHCb announces a charming new particle

The LHCb experiment has reported the observation of a baryon containing two charm quarks and one up quark

News | Experiments | 06 July, 2017



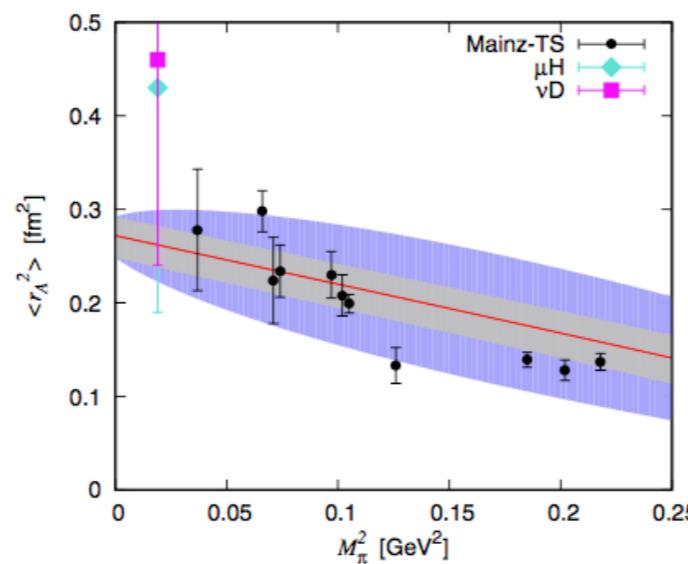
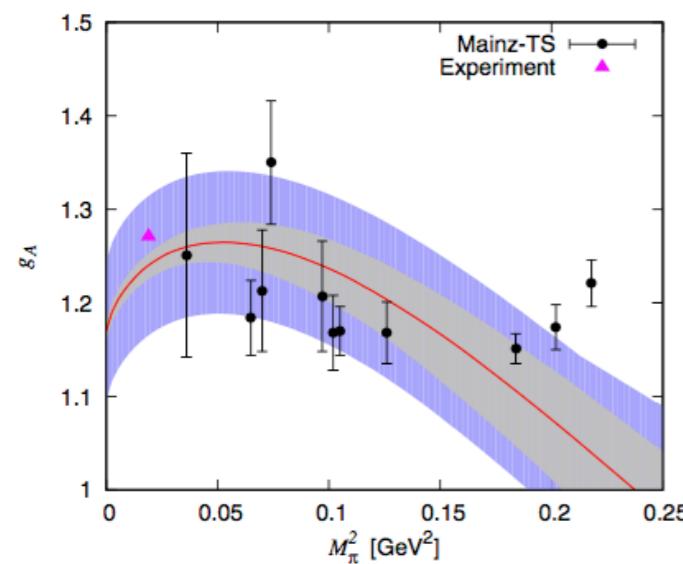
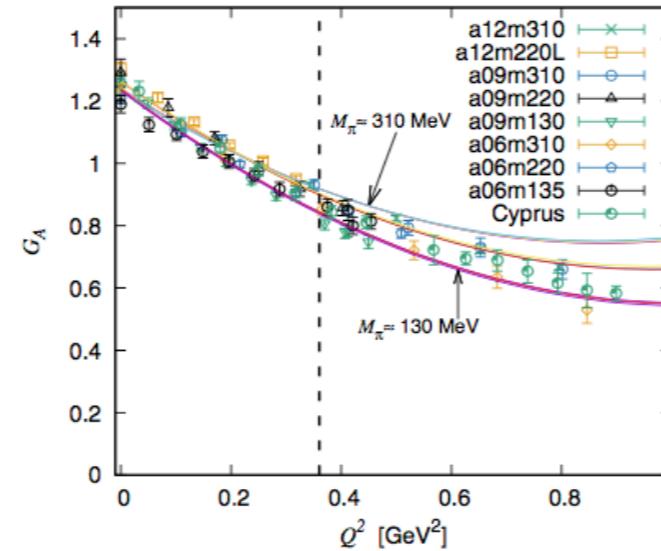
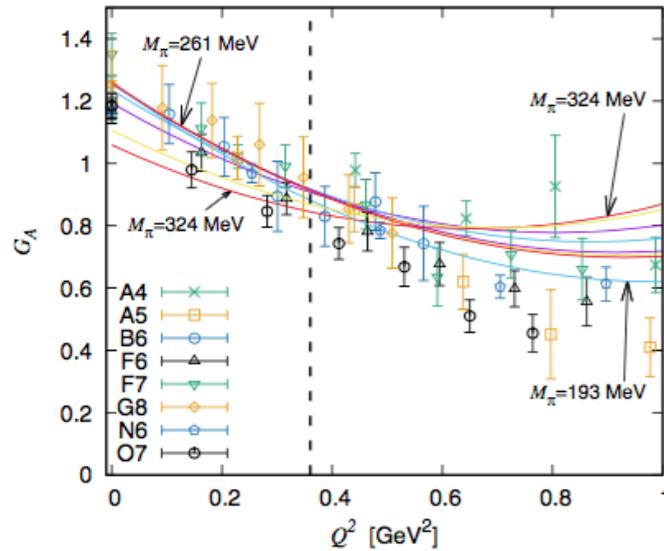
♦ Towards a new paradigm for negative-parity doubly charmed baryons?

→ Interactions between Goldstone Bosons and DCB

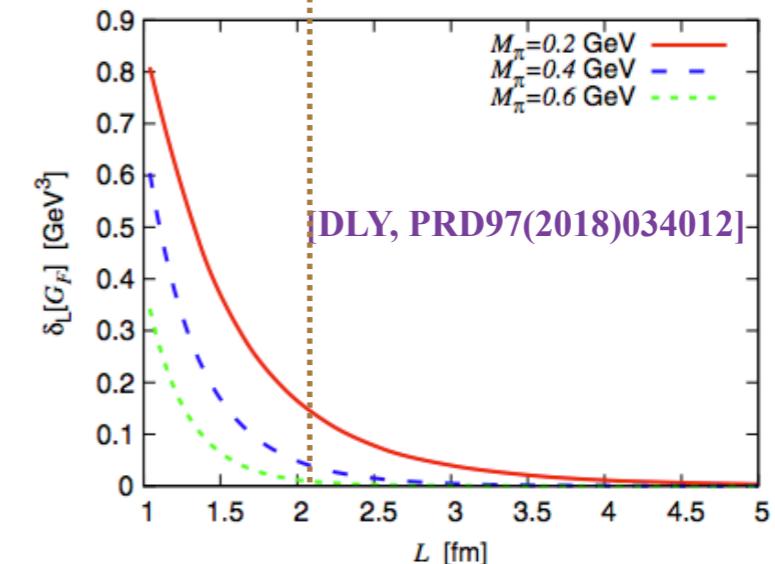
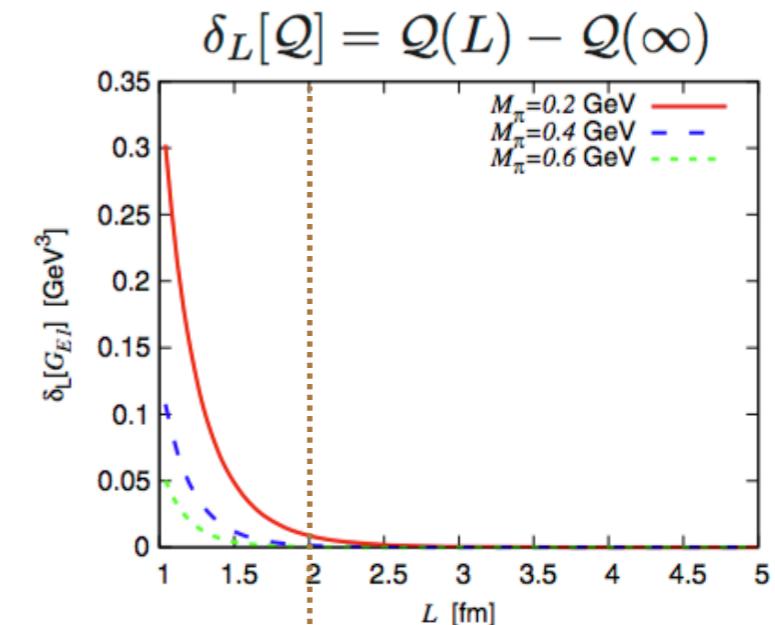
Prospect III: Combinations with Lattice techniques

♦ Chiral Extrapolation & Finite volume correction...

[DLY, Alvarez-Ruso and Vicente-Vacas PRD96(2017)116022]



Axial coupling and radius of the nucleon

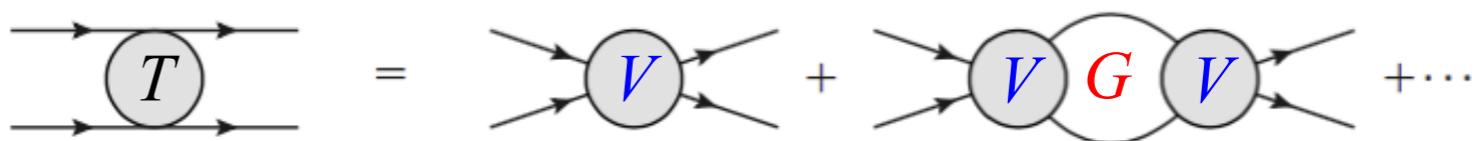


Lattice-size (L) dependence

♦ Unitarized ChPT in a finite volume

$$T = V \cdot (1 - V \cdot G)^{-1}$$

[Doring, Meissner, Oset and Rusetsky, EPJA(2011)139]

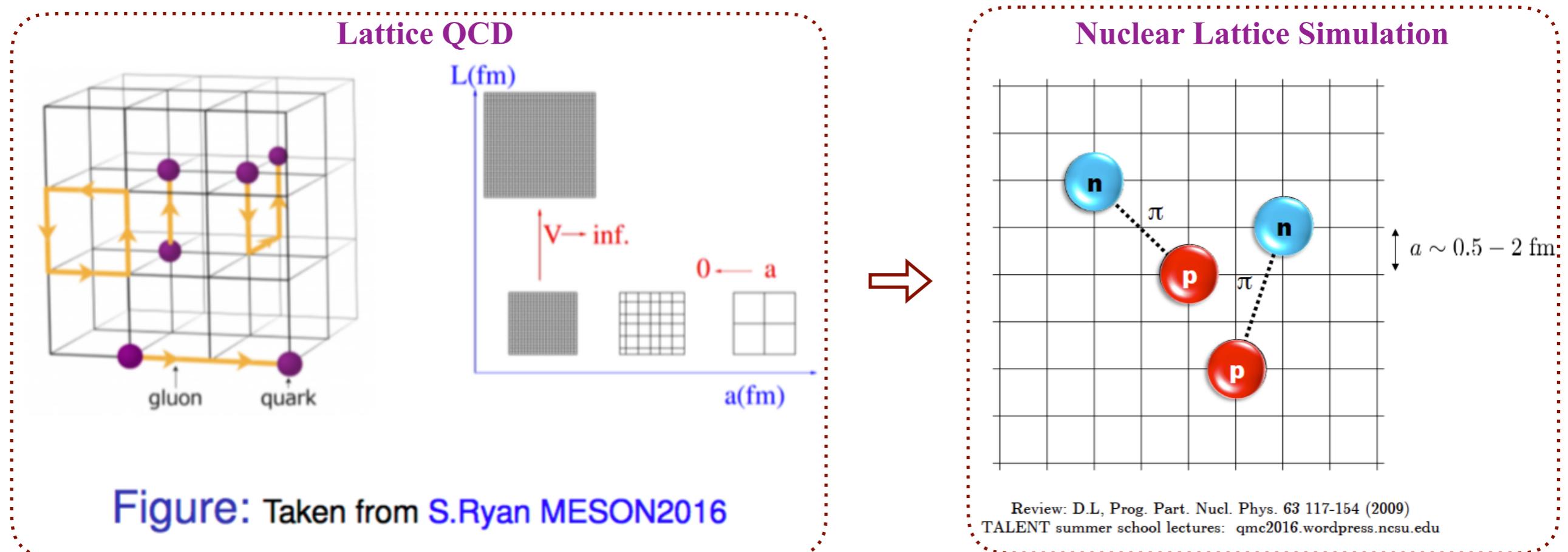


ChPT

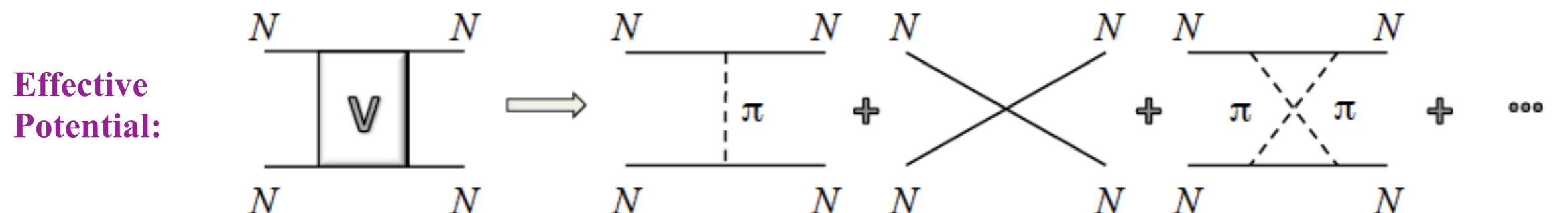
Discretization

Prospect III: Combinations with Lattice techniques

♦ Nuclear Lattice Chiral Effective Field Theory (NLEFT)



♦ Inputs: chiral effective Lagrangians



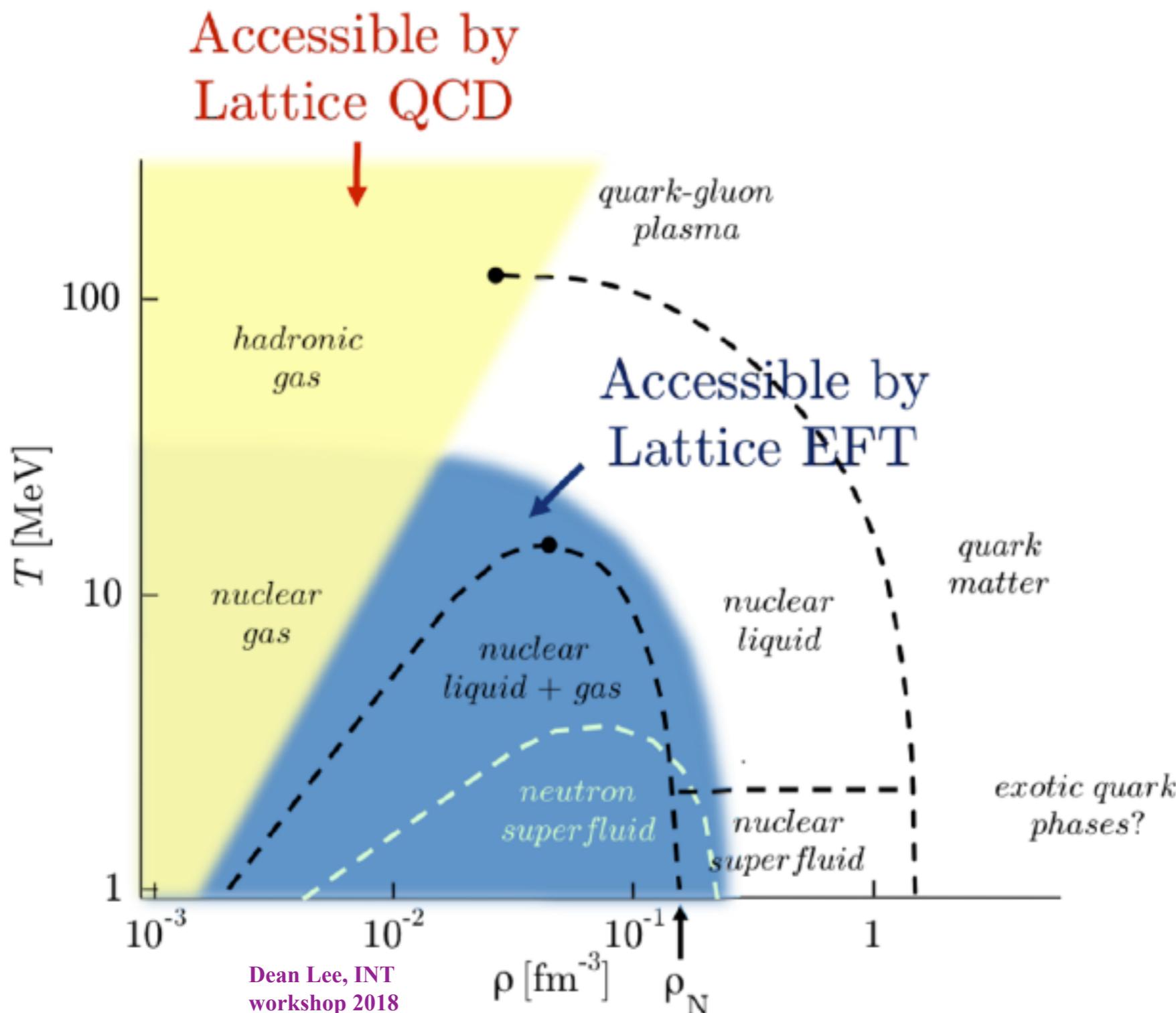
→ πN scatterings are sub-processes

→ one-nucleon sector to two- or multi-nucleon sectors

→ study also strangeness?...

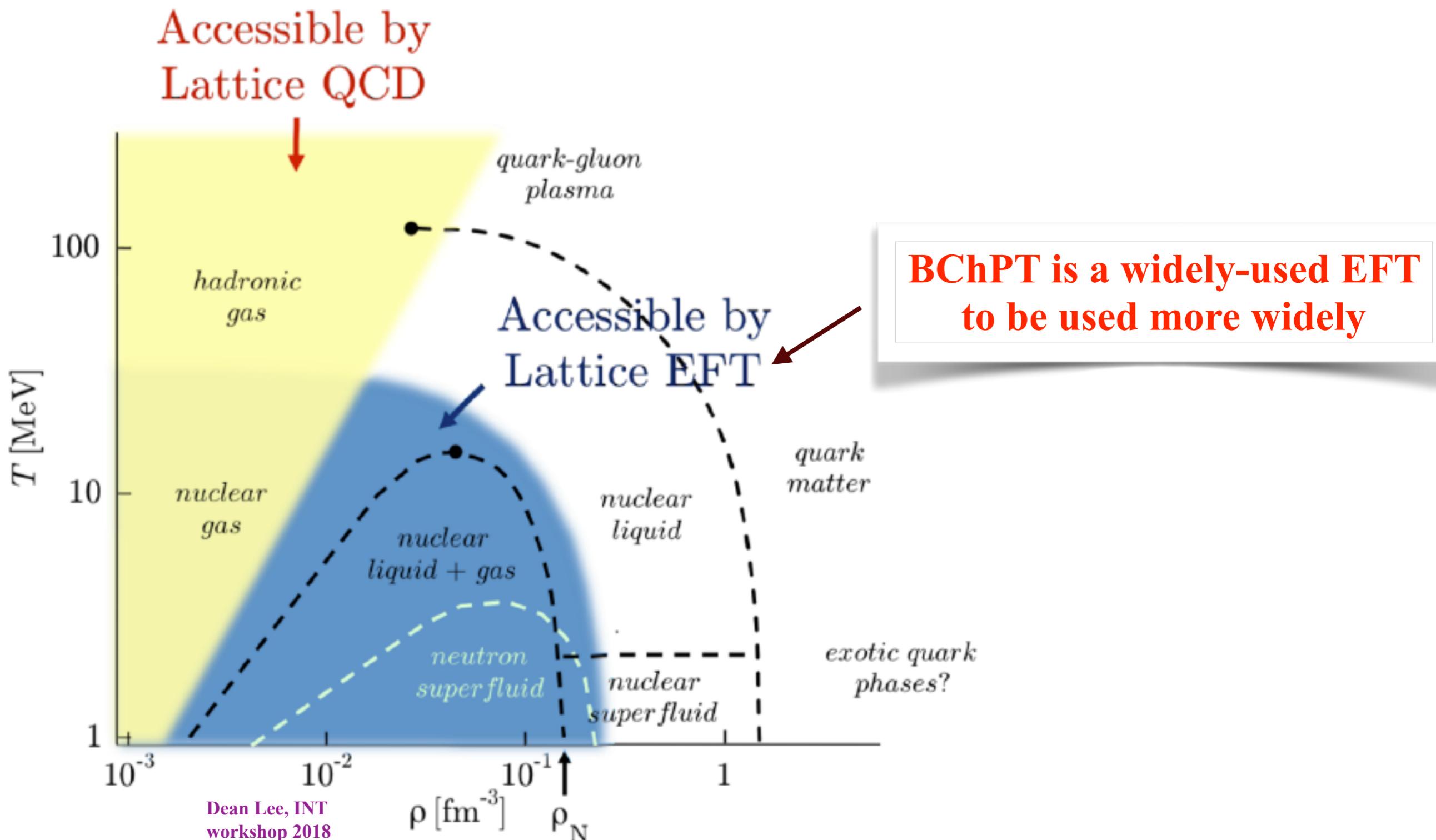
Prospect III: Combinations with Lattice techniques

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Thank you for your attention!