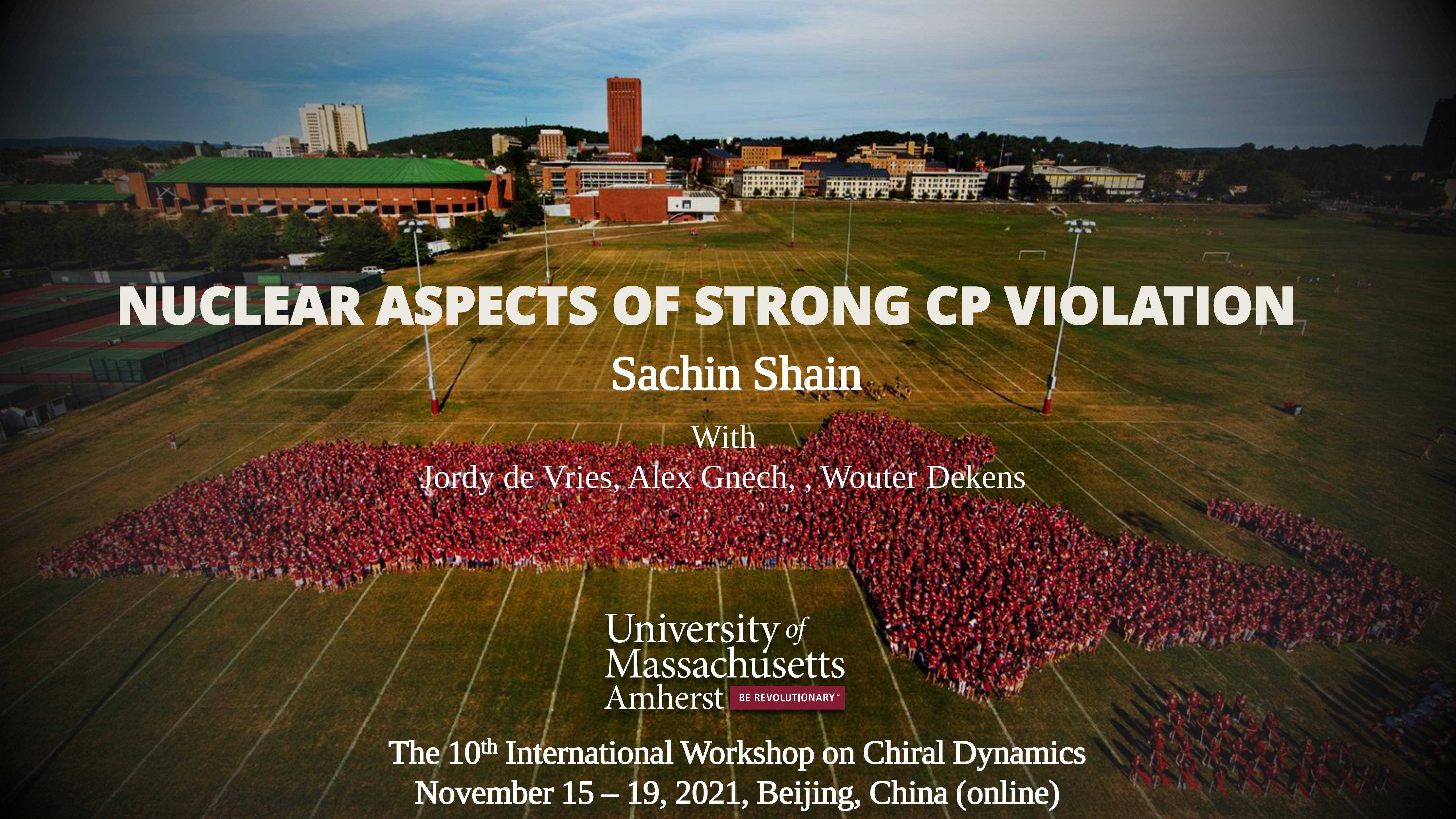

# NUCLEAR ASPECTS OF STRONG CP VIOLATION


Sachin Shain

With

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University of Massachusetts Amherst


The 10th International Workshop on Chiral Dynamics

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# Electric Dipole Moments (EDMs)

- EDMs are great probes for CP violation

$$+d_e(\vec{\sigma}\cdot\vec{E}) = d_e(+\vec{\sigma}\cdot+\vec{E}) \xrightarrow{T\rightarrow -T} d_e(-\vec{\sigma}\cdot+\vec{E}) = -d_e(\vec{\sigma}\cdot\vec{E})$$

CPT Theorem: T Violation $\longleftrightarrow$ CP Violation

- SM sources are phase of the CKM matrix and QCD $\bar{\theta}$ term

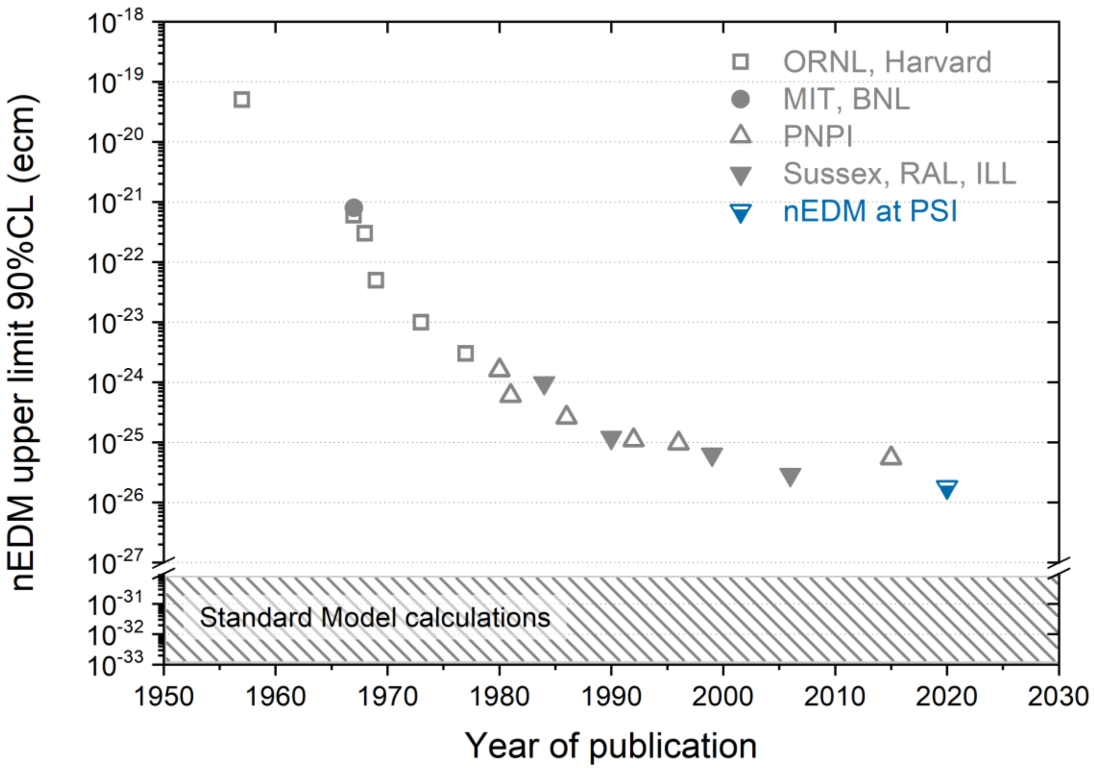
- BSM CP-odd sources

# Electric Dipole Moments (EDMs)

$\boxed{d_n = -1.52(71) \times 10^{-16} \bar{\theta} e \text{ cm}}$ : QCD$\bar{\theta}$ term

Jack Dragos et al ’19

Focus of this talk




www.wikipedia.org

Non-zero EDM measurement

BSM Physics ?

Address it at the end of the talk

$\boxed{d_n \sim 10^{-32} e \text{ cm}}$ : CKM

**Too small!**

Shahida Dar ’00

# Effective CP-odd Lagrangians

E

$\mathcal{L}_{\text{BSM}}$

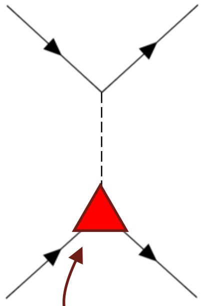
Integrating out the heavy fields

$\Lambda > \text{TeV}$

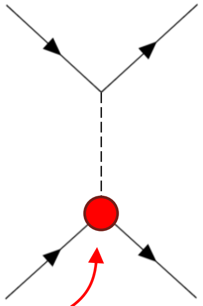
$$\mathcal{L}_{\text{SMEFT}} = i m_* \bar{\theta} \bar{q} \gamma_5 q + \frac{C_i^{(6)}}{\Lambda^2} O^{(6)} + \ldots$$

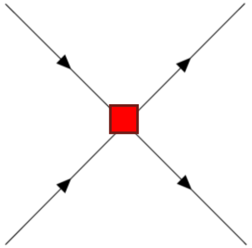
Chiral symmetry

$\Lambda_\chi \sim 1 \text{ GeV}$



$$\mathcal{L}_\chi = \bar{g}_0 \bar{N} \vec{\pi} \cdot \vec{\tau} N + \bar{g}_1 \bar{N} \pi^0 N + \ldots$$



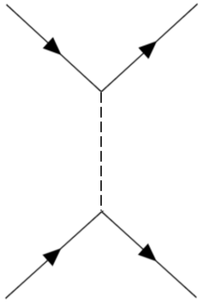


Higher order diagrams

# Hierarchy of CPV nuclear forces

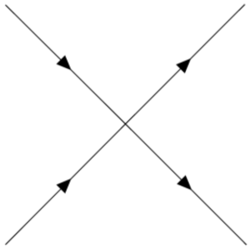
## CP-even potential

$$\frac{g_A}{2F_\pi}\bar{N}(\vec{\sigma}\cdot\boldsymbol{\nabla}\pi^a)\tau^a N$$



LO $\sim \dfrac{(g_A Q)^2}{Q^2} \sim Q^0$

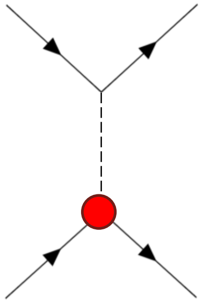
$$\bar{N}N\bar{N}N$$



LO $\sim Q^0$

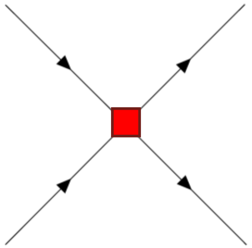
## CP-odd potential

$$\bar{g}_0\bar{N}(\vec{\tau}\cdot\vec{\pi})N$$



LO $\sim \dfrac{(g_A Q)\bar{g}_0}{Q^2} \sim Q^{-1}$

$$\bar{N}N\boldsymbol{\nabla}\left(\bar{N}\vec{\sigma}N\right)$$



N$^2$LO $\sim Q^1$

C. Maekawa et al ’11

# QCD theta term

- General quark mass Lagrangian

$$\bar{m} = \frac{m_u + m_d}{2}$$

$$\varepsilon = \frac{m_u - m_d}{m_u + m_d}$$

$$\mathcal{L} = -\bar{m}\bar{q} - \varepsilon\bar{m}\bar{q}\tau^3 q + i m_* \bar{\theta}\bar{q}\gamma^5 q$$

G. 't Hooft '76
V. Baluni '79

$$m_* = \frac{m_u m_d}{m_u + m_d}$$

- Can be included in $\chi$PT as: $\chi = 2B(\bar{m} + \varepsilon\bar{m}\tau^3) \to 2B(\bar{m} + \varepsilon\bar{m}\tau^3 + i m_* \bar{\theta})$

$$\mathcal{L}_\chi = -\frac{m_\pi^2}{2}\pi^2 - \delta m_N^{\mathrm{str}} \bar{N}\tau^3 N + \bar{g}_0 \bar{N}\vec{\tau}\cdot\vec{\pi}N$$

R. Crewther et al '79

# QCD theta term

- EDMs are great probes for CP violation

$$\bar{m} = \frac{m_u + m_d}{2}$$

$$\varepsilon = \frac{m_u - m_d}{m_u + m_d}$$

$$m_* = \frac{m_u m_d}{m_u + m_d}$$

$$\mathcal{L} = -\bar{m}\bar{q}\boxed{-\,\varepsilon\bar{m}\bar{q}\tau^3 q} + m_*\bar{\theta}\bar{q}i\gamma^5 q$$

G. 't Hooft '76
V. Baluni '79

$$\mathcal{L}_\chi = -\frac{m_\pi^2}{2}\pi^2\boxed{-\,\delta m_N^{\mathrm{str}}\bar{N}\tau^3 N} + \bar{g}_0\bar{N}\vec{\tau}\cdot\vec{\pi}N$$

R. Crewther et al '79

Strong proton-neutron
mass splitting

# QCD theta term

- EDMs are great probes for CP violation

$$\bar{m} = \frac{m_u + m_d}{2}$$

$$\varepsilon = \frac{m_u - m_d}{m_u + m_d}$$

$$m_* = \frac{m_u m_d}{m_u + m_d}$$

$$\mathcal{L} = -\bar{m}\bar{q} - \varepsilon\bar{m}\bar{q}\tau^3 q \boxed{+ m_*\bar{\theta}\bar{q}i\gamma^5 q}$$

G. ‘t Hooft ‘76
V. Baluni ‘79

$$\mathcal{L}_\chi = -\frac{m_\pi^2}{2}\pi^2 - \delta m_N^{\mathrm{str}}\bar{N}\tau^3 N \boxed{+ \bar{g}_0\bar{N}\vec{\tau}\cdot\vec{\pi}N}$$

R. Crewther et al ‘79

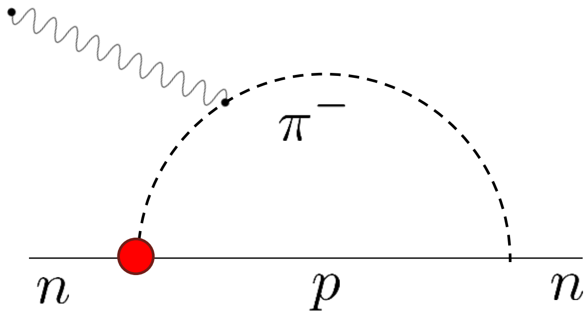
$$\bar{g}_0 = \frac{\delta m_N^{\mathrm{str}}(1-\varepsilon^2)}{4F_\pi\varepsilon}\bar{\theta} = -(14.7 \pm 2.3)\cdot 10^{-3}\bar{\theta}$$

J. De Vries et al ‘15
D. A. Brantley et al ‘16

# EDMs of Light nuclei

- Chiral Lagrangian

$$\mathcal{L}_\chi = \bar{g}_0 \bar{N}\vec{\tau}\cdot\vec{\pi}N + \bar{g}_1 \bar{N}\pi_3 N + \frac{1}{4}\bar{N}(\bar{d}_0 + \bar{d}_1\tau_3)\epsilon^{\mu\nu\alpha\beta}\sigma_{\mu\nu}NF_{\alpha\beta} + \ldots$$




- He EDM in terms of LECs

$$d_{^3\mathrm{He}} = 0.90(1)d_n - 0.03(1)d_p + [0.1191)\bar{g}_0 + 0.14(2)\bar{g}_1]e\ \mathrm{fm}$$ J. Bsaisou et al ‘15

- LEC values

$$\bar{g}_0 = -14.7(2.3)\times 10^{-3}\bar{\theta} \qquad d_n = -0.00125(71)\bar{\theta}e\ \mathrm{fm}$$

$$\bar{g}_1 = -3.4(2.4)\times 10^{-3}\bar{\theta} \qquad d_p = 0.0011(10)\bar{\theta}e\ \mathrm{fm}$$

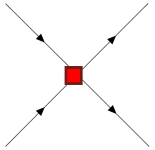
J. De Vries et al ‘15

Jack Dragos et al ‘19

- He EDM

$$\boxed{d_{^3He}(\bar{\theta}) = -2.5(0.8)\times 10^{-3}\bar{\theta}e\ \mathrm{fm}}$$

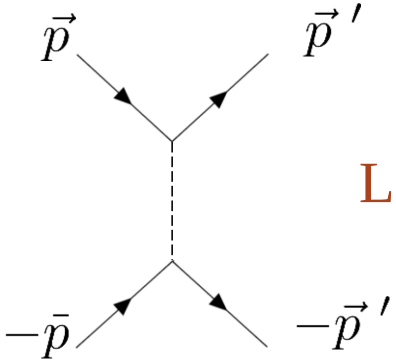
Jack Dragos et al ‘19



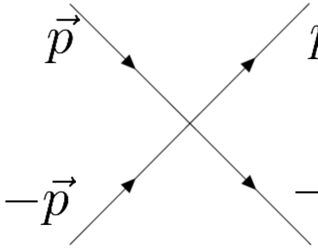
**At LO, OPE is enough?**
**Does short-range interaction play a role in LO?**

# CP-even Chiral Lagrangian

$$V_{\mathrm{str},\pi} = -\frac{1}{(2\pi)^3}\left(\frac{g_A}{2F_\pi}\right)^2 \vec{\tau}_1\cdot\vec{\tau}_2\,\frac{(\vec{\boldsymbol{\sigma}}_1\cdot\vec{\boldsymbol{q}})(\vec{\boldsymbol{\sigma}}_2\cdot\vec{\boldsymbol{q}})}{\vec{\boldsymbol{q}}^2+m_\pi^2} \qquad + \qquad \frac{1}{(2\pi)^3}\left(C_s P_s + C_t P_t\right)$$

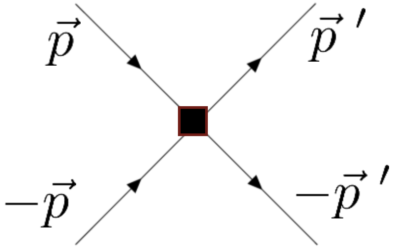



LO




LO

$$+ \qquad \frac{1}{(2\pi)^3}\frac{1}{4} p p' C_P P_p$$




N$^2$LO

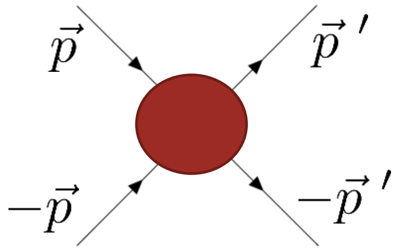
A. Nogga et al'05

# Lippmann-Schwinger (LS) Equation

- LS equation for wave function

$$(H_0 + V)\psi = E\psi \qquad \Longleftrightarrow \qquad \langle p|\psi\rangle = \langle p|\phi\rangle + \langle p|\frac{1}{E - H_0}V|\psi\rangle$$

- LS equation for T-matrix: $\boxed{T_{\mathrm{str}} = V + VG_0T_{\mathrm{str}}}$




$$T^{\alpha'\alpha}_{\mathrm{str}}(p', p, E_{CM}) = V^{\alpha'\alpha}_{\mathrm{str}}(p', p) + \sum_{\alpha''}\int dp''\, p''^2 V^{\alpha'\alpha}_{\mathrm{str}}(p', p'')G_0(p''^2)T^{\alpha''\alpha}_{\mathrm{str}}(p'', p, E_{CM})$$

$$\alpha = \alpha((ls)jm_j, tm_t)$$

# Cut-off Regulator ($\Lambda$)

- To solve LS equation numerically we need to introduce a regulator

$$\boxed{f_\Lambda(p',p) = e^{-(p/\Lambda)^4} e^{-(p'/\Lambda)^4}} \qquad \Rightarrow \qquad V(p',p) \to V(p',p) f_\Lambda(p',p)$$

- **Physics should not depend on the regulator!**

$$T_{\mathrm{str}} = V + V G_0 T_{\mathrm{str}} \qquad \Rightarrow \qquad S(E_{\mathrm{CM}}) = 1 - i\pi m_N^{3/2} E_{\mathrm{CM}}^{1/2} T(p = p' = \sqrt{E_{\mathrm{CM}} m_N})$$

# S-matrix Parameterization

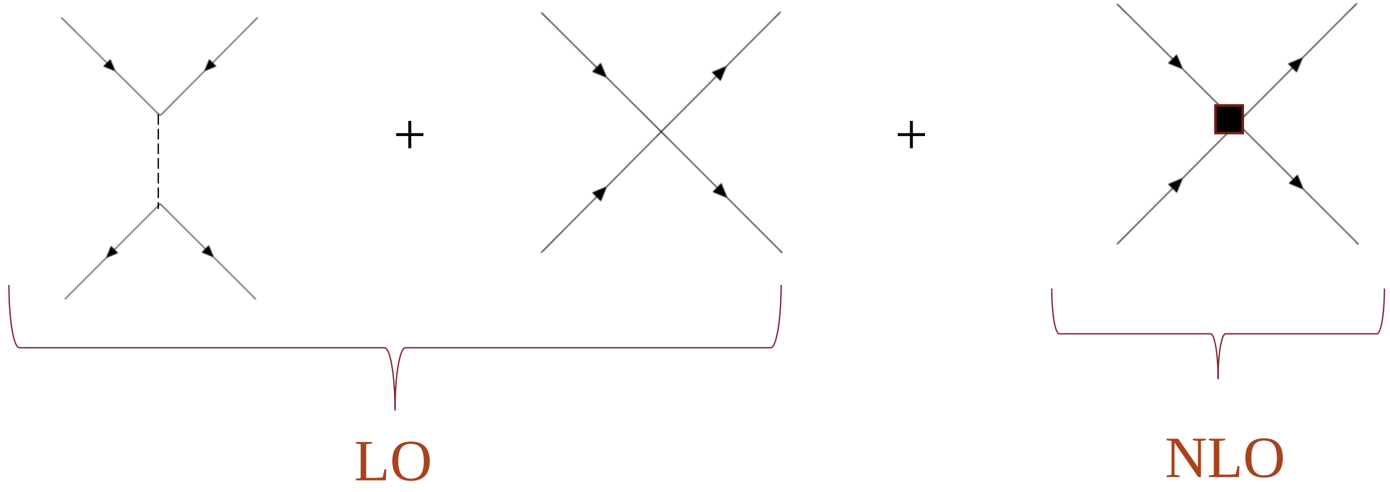
- Uncoupled channel {α}: $S = e^{2i\delta}$

- coupled channel {α$_1$, α$_2$}: $$S = \begin{pmatrix} e^{2i\delta_0}\cos 2\epsilon & ie^{i\delta_0+i\delta_2}\sin 2\epsilon \\ ie^{i\delta_0+i\delta_2}\sin 2\epsilon & e^{2i\delta_2}\cos 2\epsilon \end{pmatrix}$$

- **Short Summary**

only S-channel

$V_{\text{str}} =$



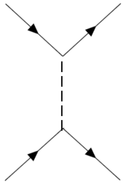

$V(p',p) \to V(p',p) f_\Lambda(p',p)$

# CP-even Phase Shifts : 3S1-3D1

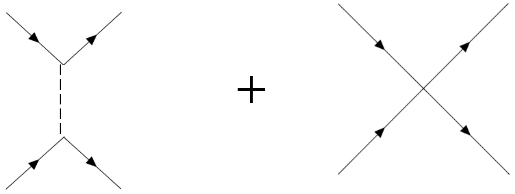
$E_{CM} = 5$ MeV　$E_{CM} = 25$ MeV

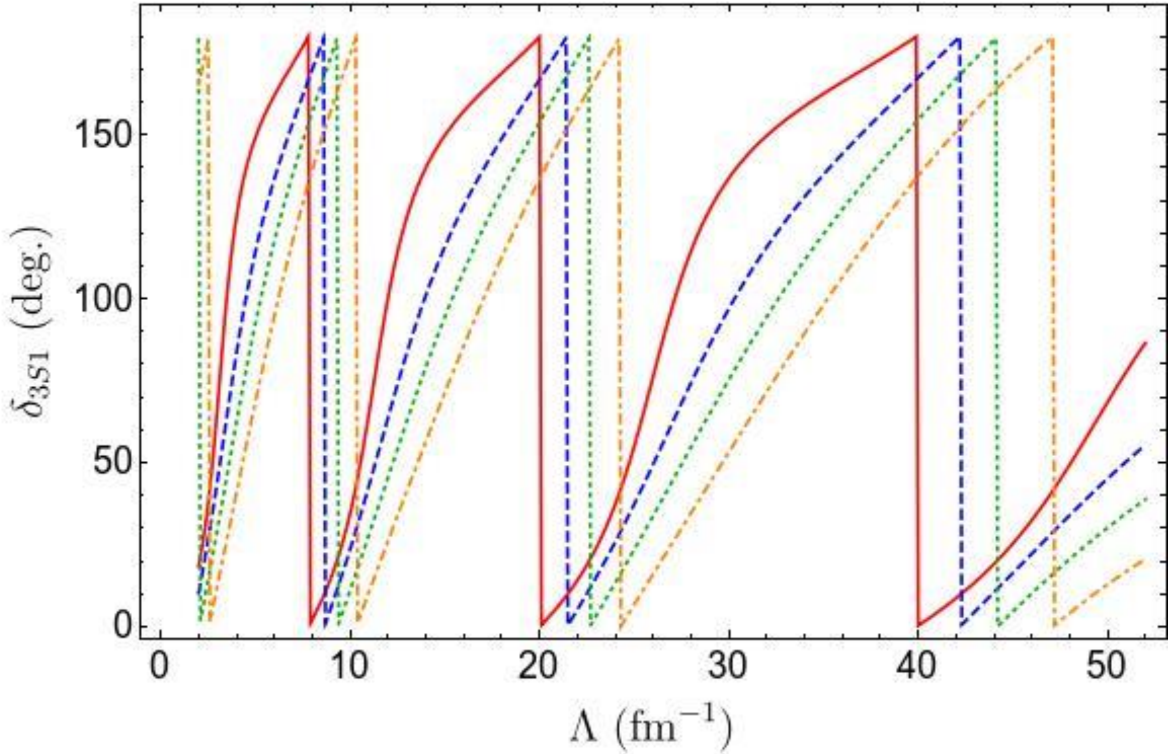
$E_{CM} = 50$ MeV　$E_{CM} = 95$ MeV

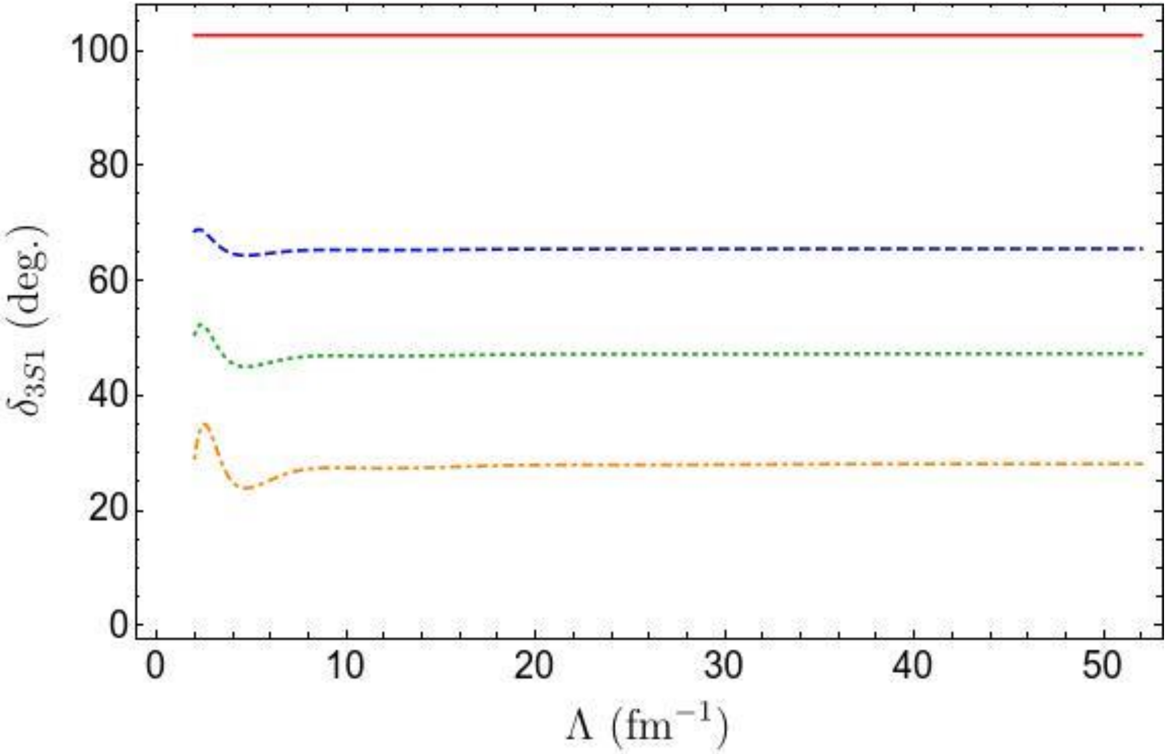
**NDA Works**



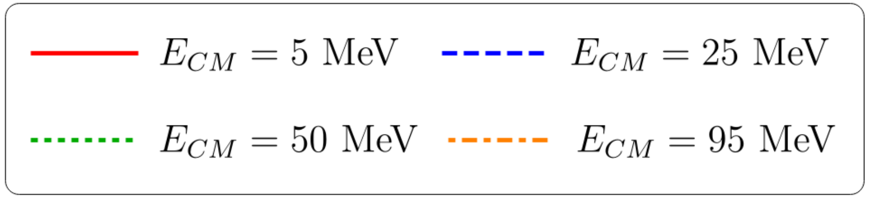
$$V(p',p) \to V(p',p) f_\Lambda(p',p)$$



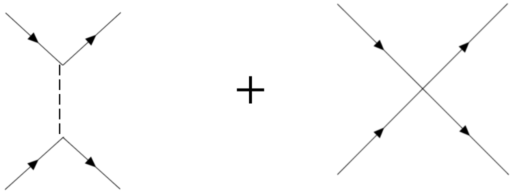



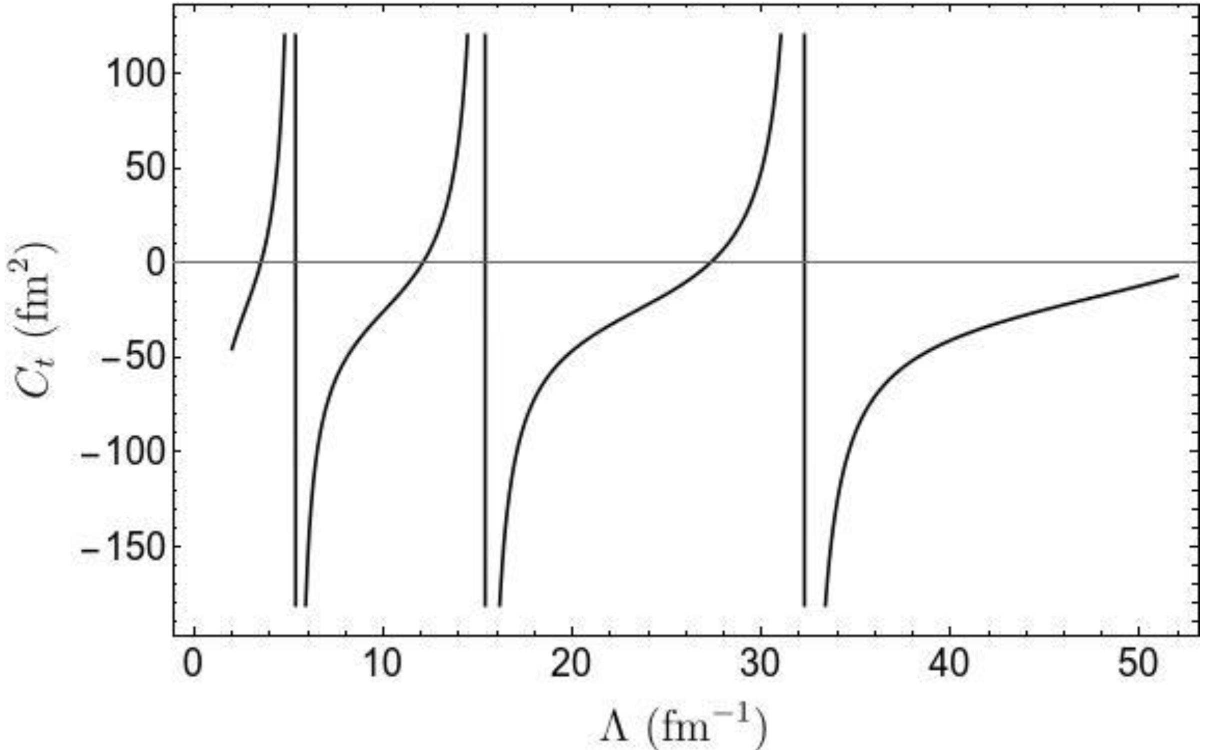



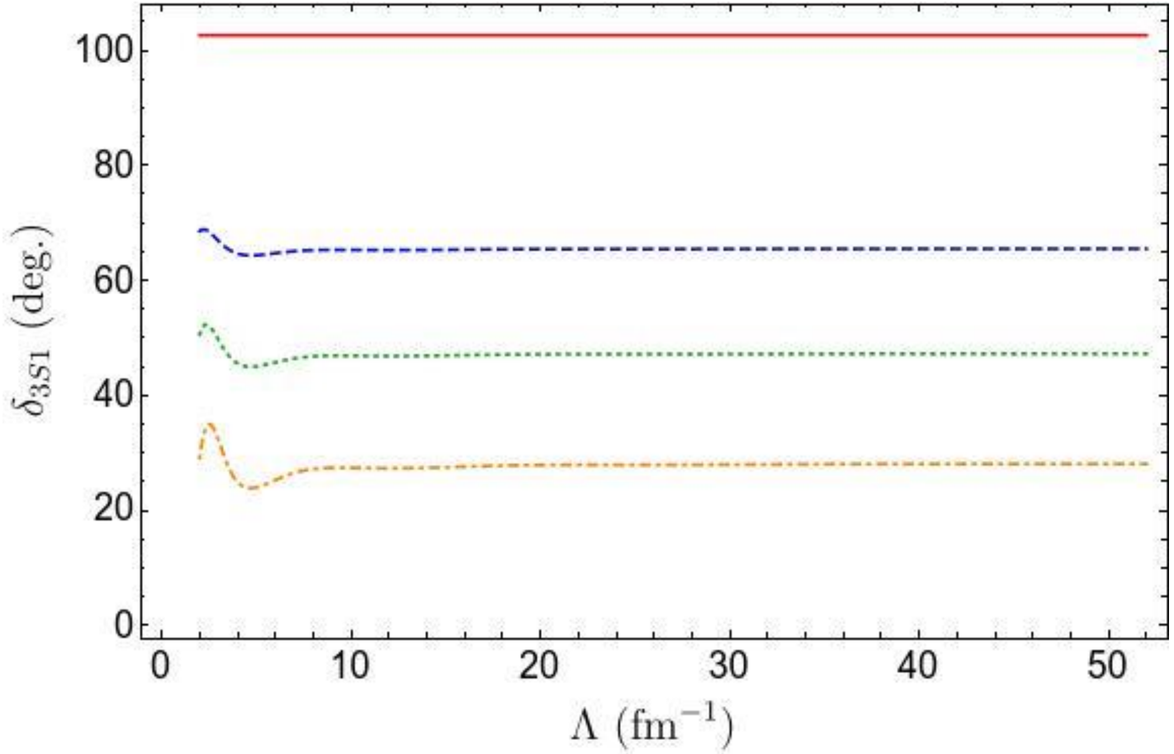
# CP-even Phase Shifts : 3S1-3D1



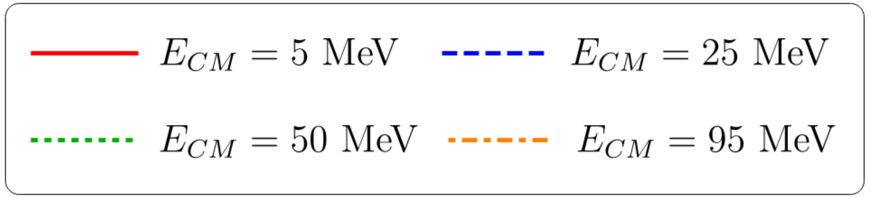

NDA Works



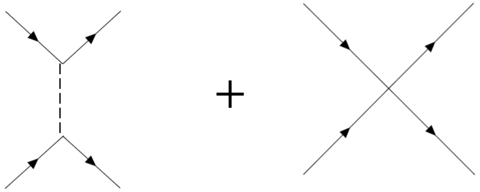



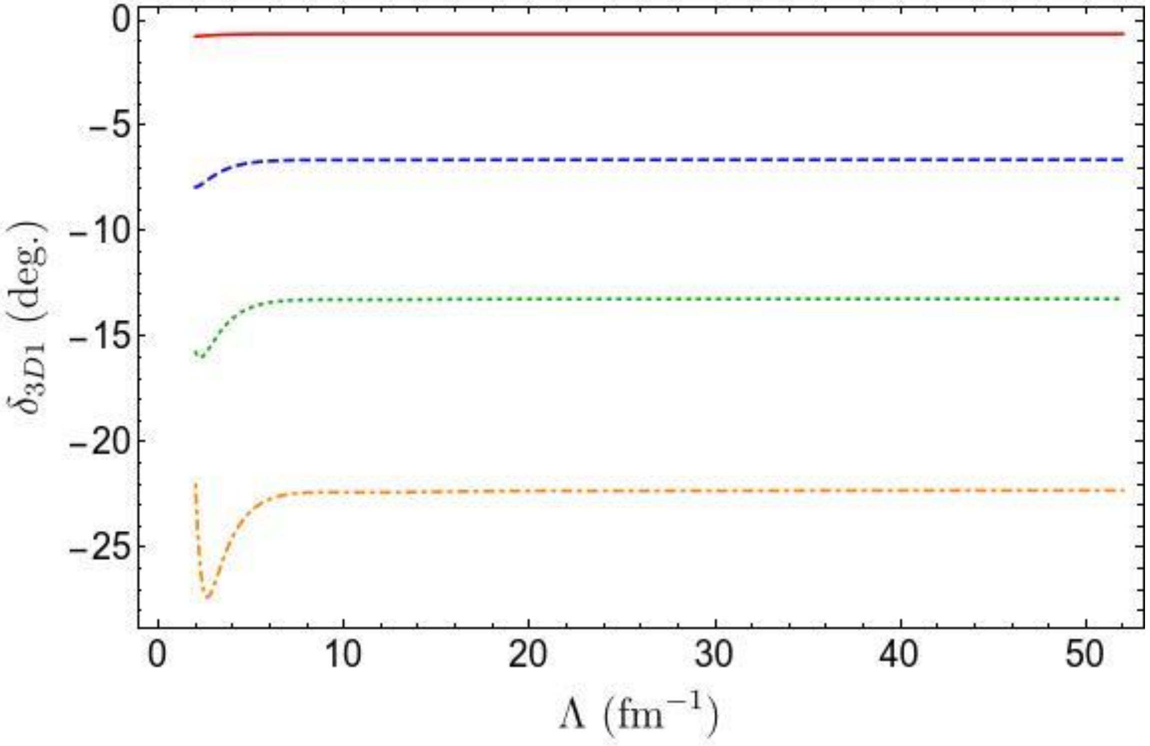



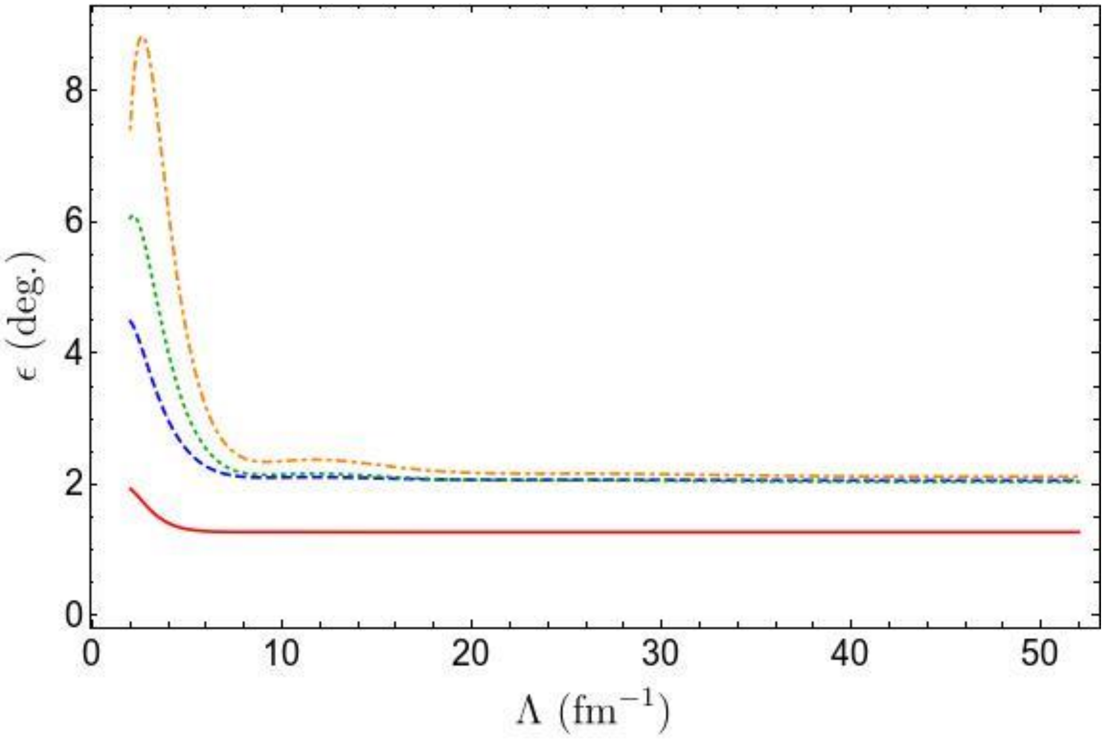
# CP-even Phase Shifts : 3S1-3D1




**NDA Works**

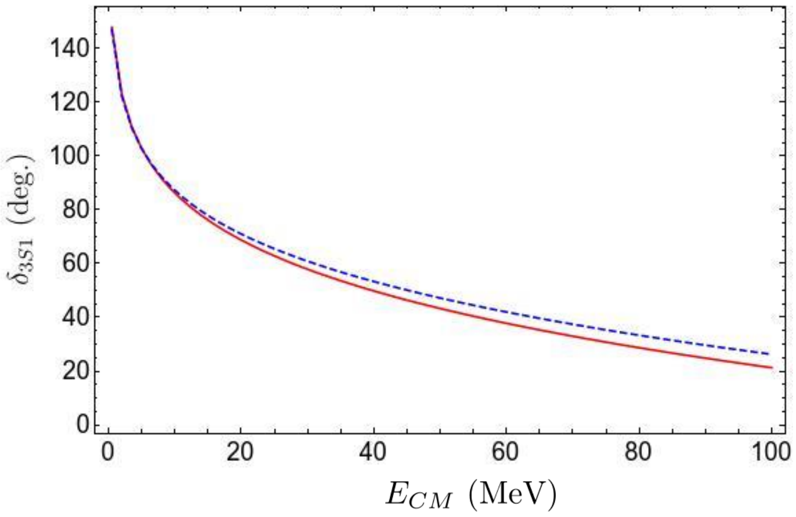


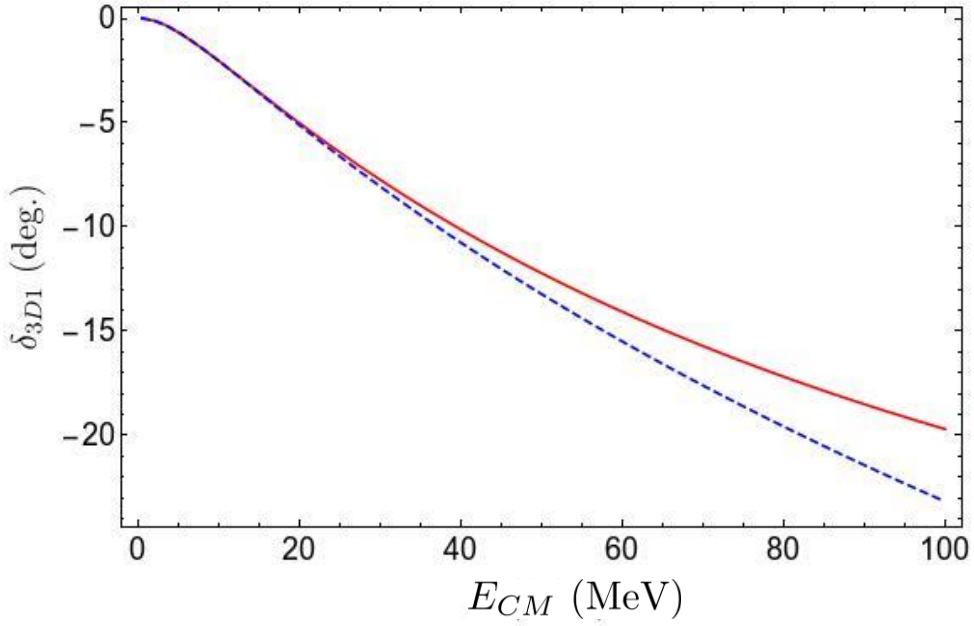



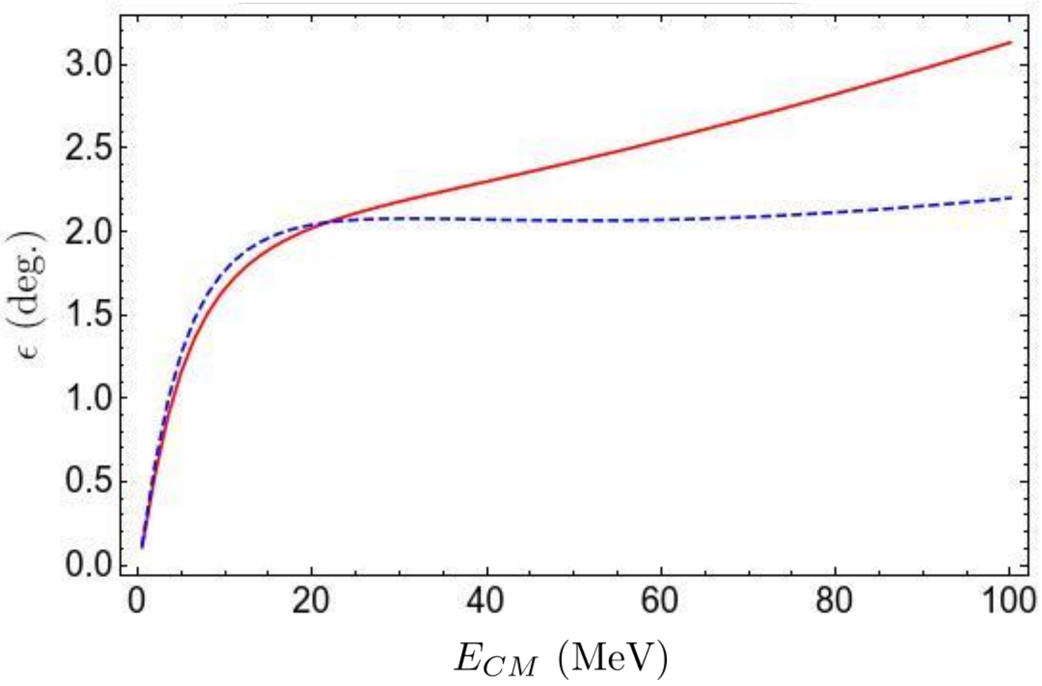
# CP-even Phase Shifts : 3S1-3D1

$\Lambda = 20\ \text{fm}^{-1}$ — Nijmegen PWA

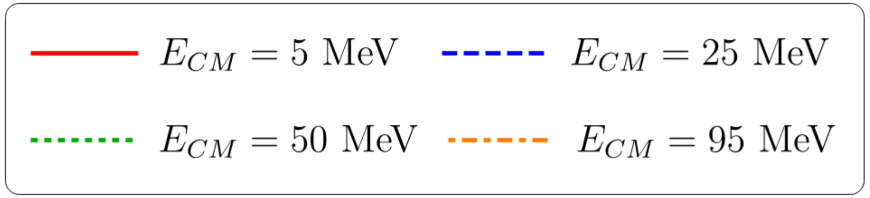


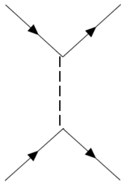

**NDA Works**

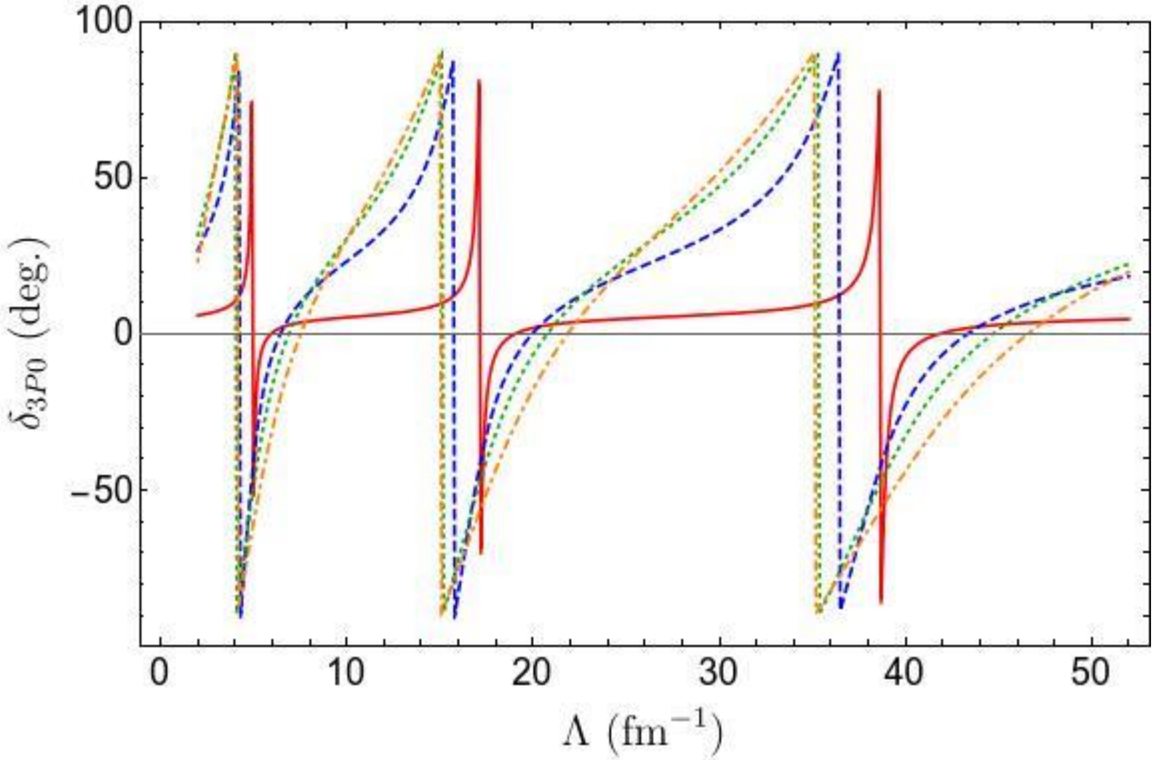


# CP-even Phase Shifts : 3P0






NDA Fails!

# Why NDA fails?

- Consider OPE potential in position basis

$$V_{\mathrm{str},\pi}(\vec{\mathbf{r}}) \sim [-4T(r) + Y(r)(\vec{\boldsymbol{\sigma}}_1 \cdot \vec{\boldsymbol{\sigma}}_2)],$$

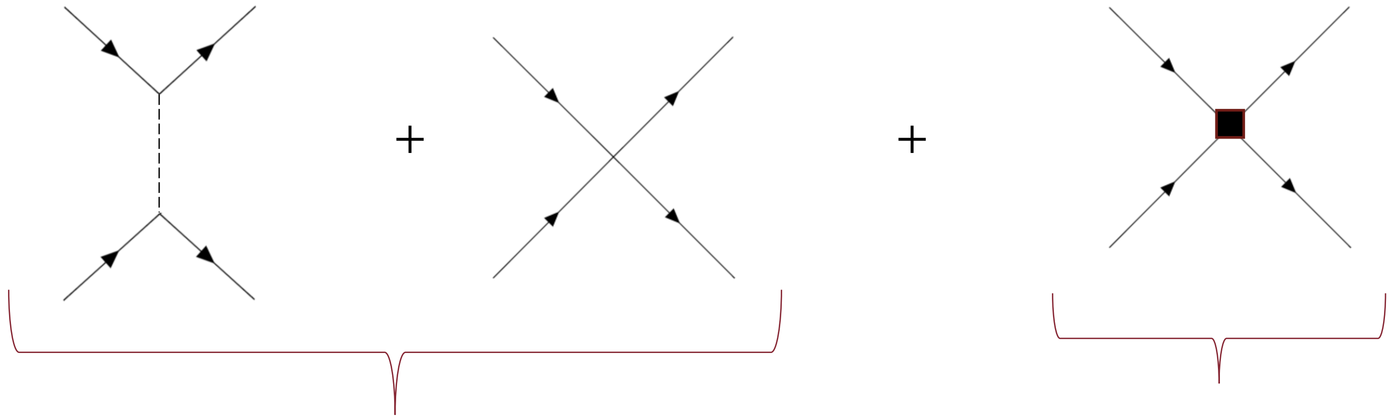
$$T(r) = \frac{e^{-m_\pi r}}{m_\pi r}\left[1 + \frac{3}{m_\pi r} + \frac{3}{(m_\pi r)^2}\right],$$

$$Y(r) = \frac{e^{-m_\pi r}}{m_\pi r}$$

→ Attractive tensor force leads to cut-off dependence

- Solution : promote $N^2LO$ contact potential to LO. A. Nogga et al’05

$$V_{\mathrm{str}} =$$



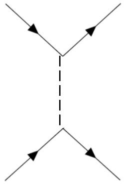
LO

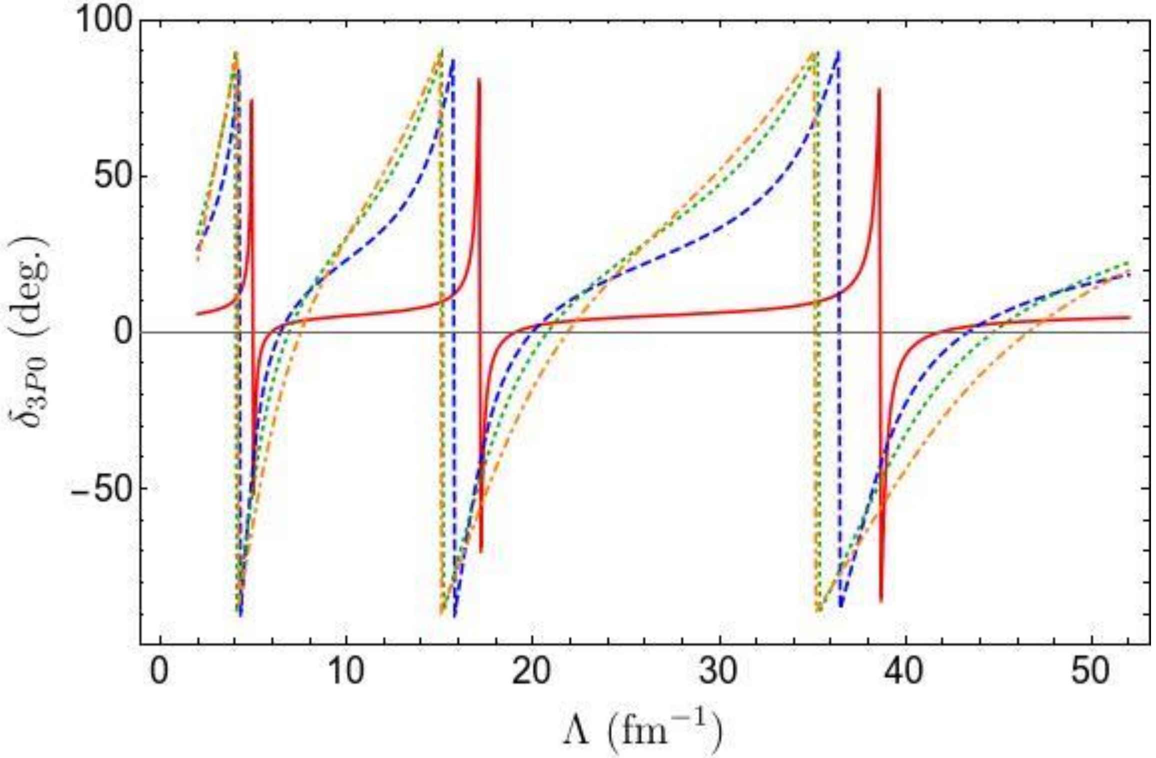
LO (promoted)

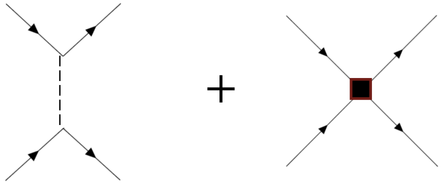
# CP-even Phase Shifts : 3P0

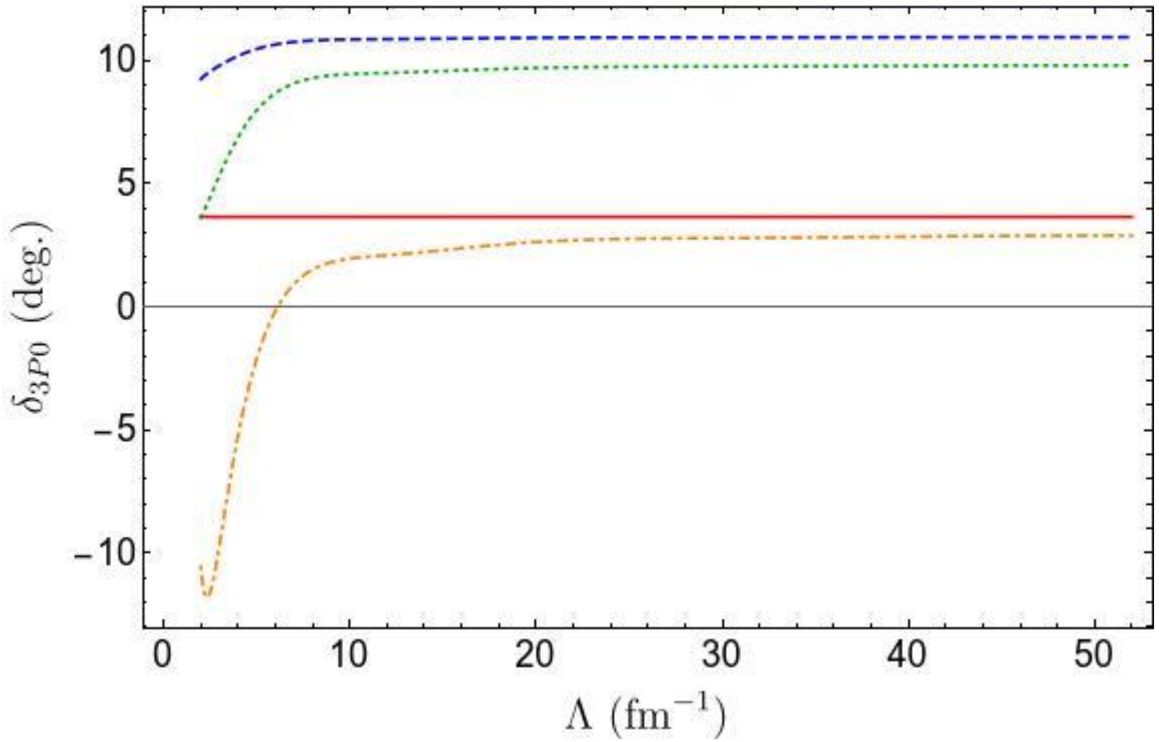
$E_{CM} = 5$ MeV  $E_{CM} = 25$ MeV
$E_{CM} = 50$ MeV  $E_{CM} = 95$ MeV

**NDA Fails!**





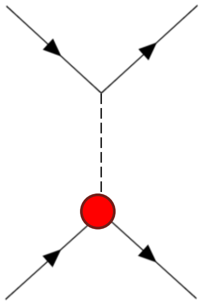



# CP-odd chiral Potentials

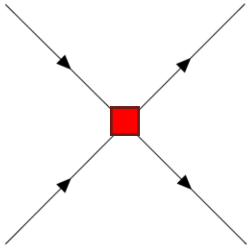
- Cp-odd potential is given by

$$V_{\mathrm{str},\pi} = -\frac{1}{(2\pi)^3}\frac{g_A\bar{g}_0}{2F_\pi}\vec{\tau}_1\cdot\vec{\tau}_2\frac{i(\vec{\boldsymbol{\sigma}}_1-\vec{\boldsymbol{\sigma}}_2)\cdot\vec{\boldsymbol{q}}}{\vec{\boldsymbol{q}}^2+m_\pi^2}$$



LO

$$-\frac{1}{(2\pi)^3}\frac{i\bar{C}_0}{2}\left[\vec{\boldsymbol{q}}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)+\frac{1}{3}\vec{\boldsymbol{q}}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\vec{\tau}_1\cdot\vec{\tau}_2)\right]$$



N$^2$LO

$$\boxed{\bar{g}_0 = \frac{\delta m_N^{\mathrm{str}}(1-\varepsilon^2)}{4F_\pi\varepsilon}\bar{\theta}}$$

Is $\overline{C}_0$ indeed next-to-next-to-leading order?

# T-matrix and S-matrix

- T-matrix:

CP-even calculation

$$T_{\bar{g}_0} = V_{\bar{g}_0} + V_{\bar{g}_0} G_0 T_{\rm str} + T_{\rm str} G_0 V_{\bar{g}_0} + T_{\rm str} G_0 V_{\bar{g}_0} G_0 T_{\rm str}$$

$$T = T_{\rm str} + T_{\bar{g}_0}$$

- S-matrix:

$$\boxed{d_{^3\mathrm{He}} = 0.11(1)\bar{g}_0 e \text{ fm} + \ldots}$$

Bsaisou et al. ’19
A Gnech et al. ’20
Paul Froese et al. ’21

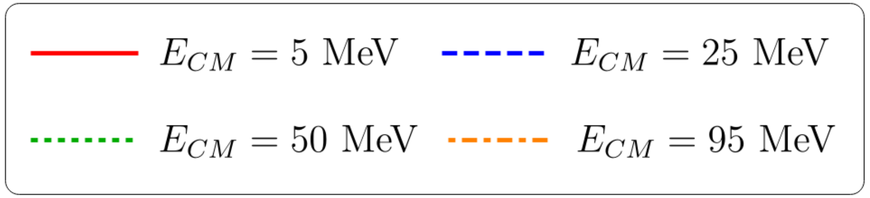
$$S_{j=0} = \begin{pmatrix} e^{2i\delta_{^1S_0}} & \epsilon^0_{\rm SP} e^{i\left[\delta_{^1S_0}+\delta_{^3P_0}\right]} \\ -\epsilon^0_{\rm SP} e^{i\left[\delta_{^1S_0}+\delta_{^3P_0}\right]} & e^{2i\delta_{^3P_0}} \end{pmatrix}$$

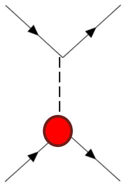
$$S_{j=1} \begin{pmatrix} e^{2i\delta_{^3S_1}} \cos 2\epsilon & ie^{i\left[\delta_{^3S_1}+\delta_{^3D_1}\right]} \sin 2\epsilon & x_{SP} \\ ie^{i\left[\delta_{^3S_1}+\delta_{^3D_1}\right]} \sin 2\epsilon & e^{2i\delta_{^3D_1}} \cos 2\epsilon & x_{DP} \\ -x_{SP} & -x_{DP} & e^{2i\delta_{^1P_1}} \end{pmatrix},$$

$$x_{SP} = \left[\epsilon^1_{\rm SP} + i\epsilon\ \epsilon_{\rm DP}\right] e^{i\left[\delta_{^3S_1}+\delta_{^1P_1}\right]}$$

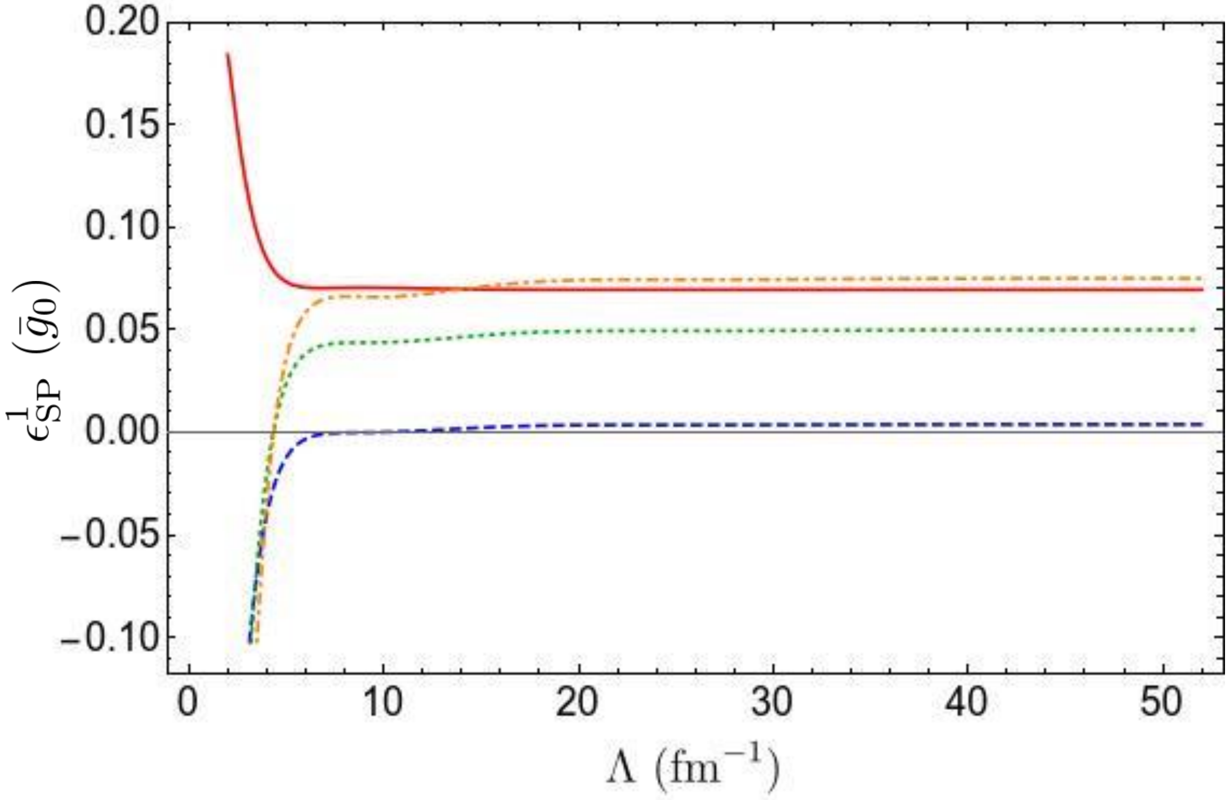
$$x_{DP} = \left[\epsilon_{\rm DP} + i\epsilon\ {\epsilon_{\rm SP}}^1\right] e^{i\left[\delta_{^3D_1}+\delta_{^1P_1}\right]}$$

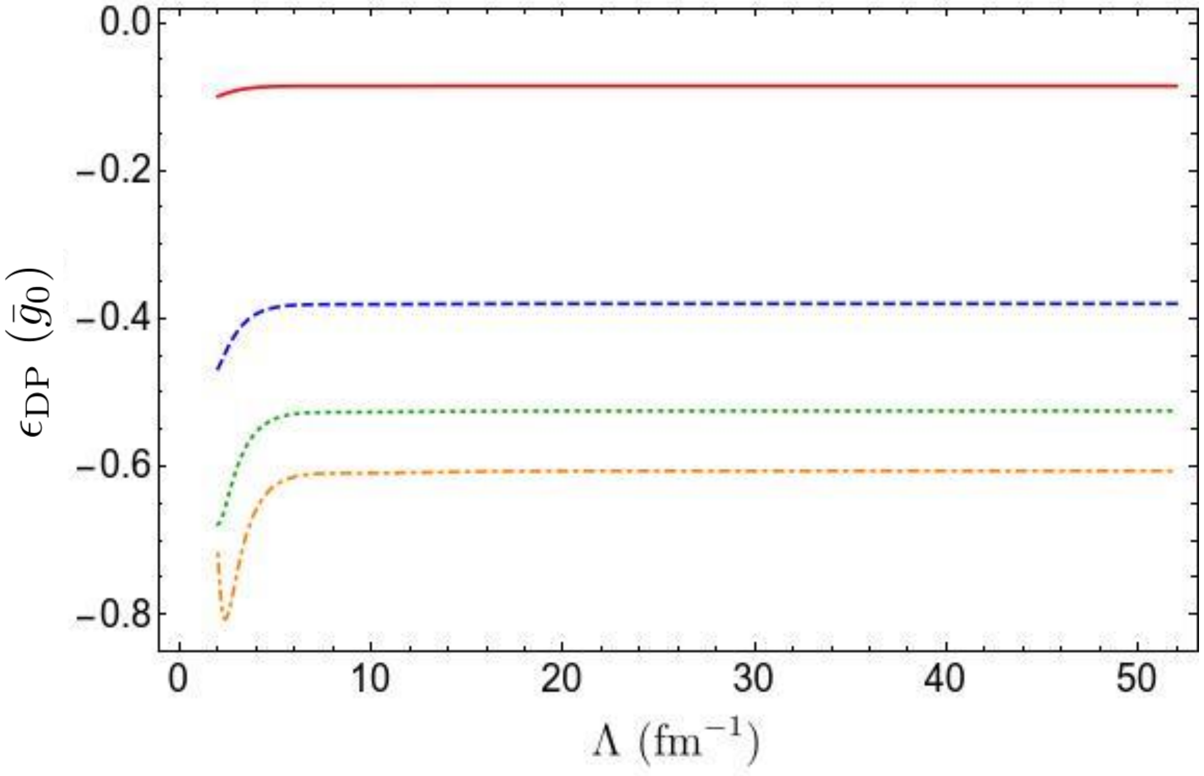
# CP-odd Phase Shifts : j=1



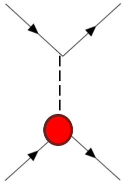
NDA Works!

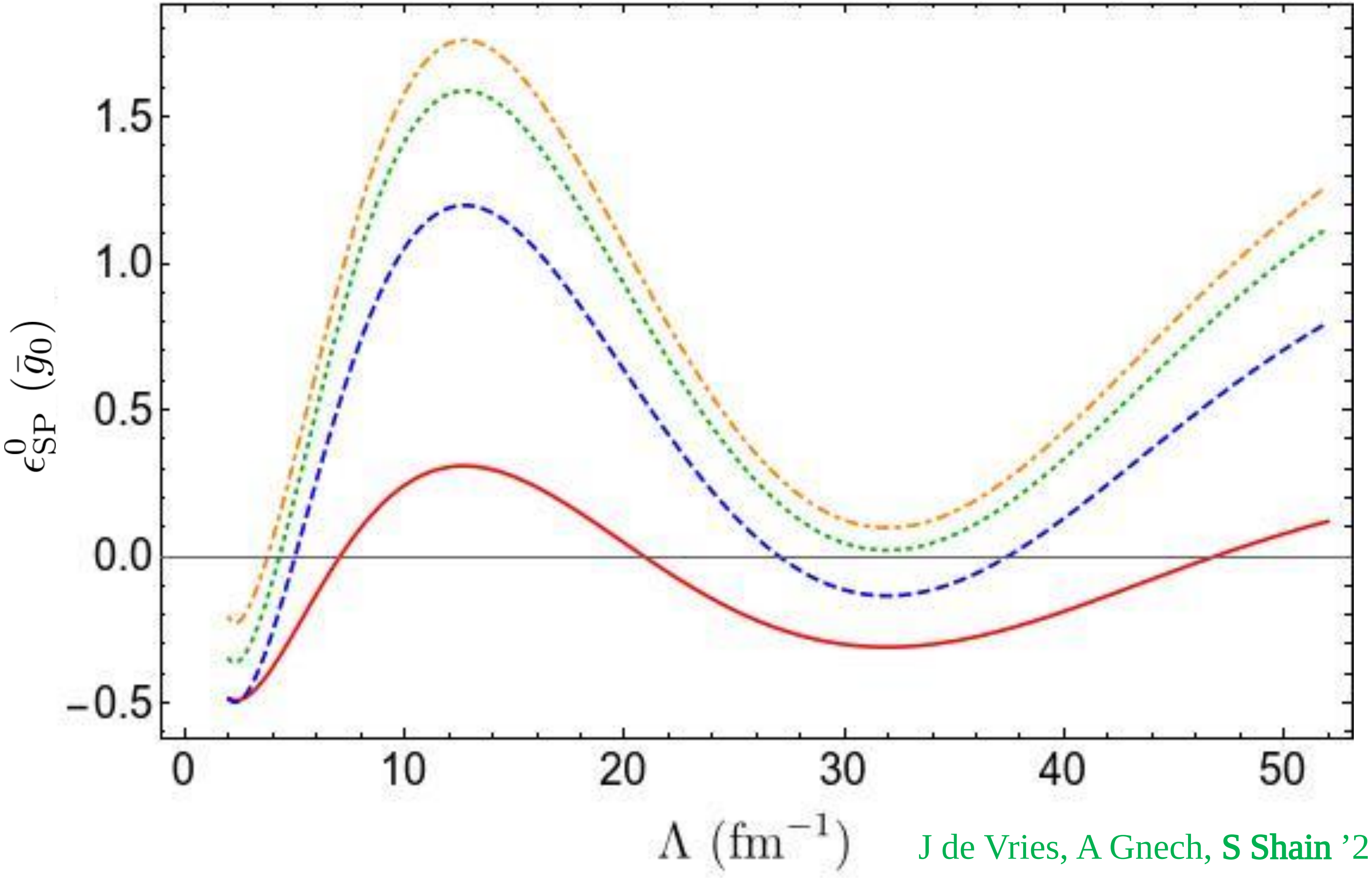


# CP-odd Phase Shifts : j=0

NDA Fails!

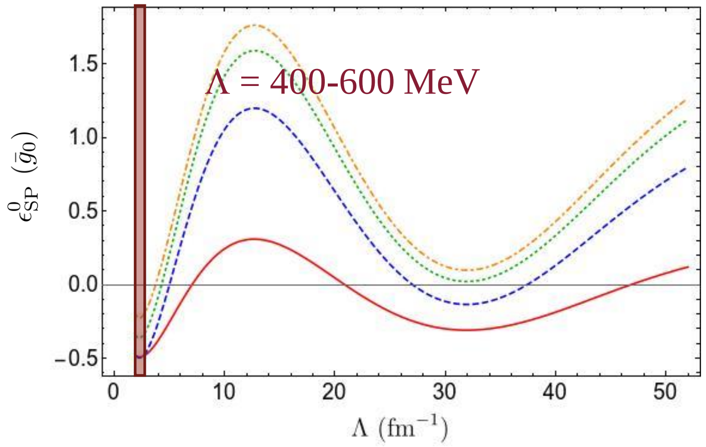





J de Vries, A Gnech, **S Shain** ’21

# Why NDA fails?

- There is no sign of convergence.
- In practice one uses higher order chiral wavefunctions with limited range in Λ.



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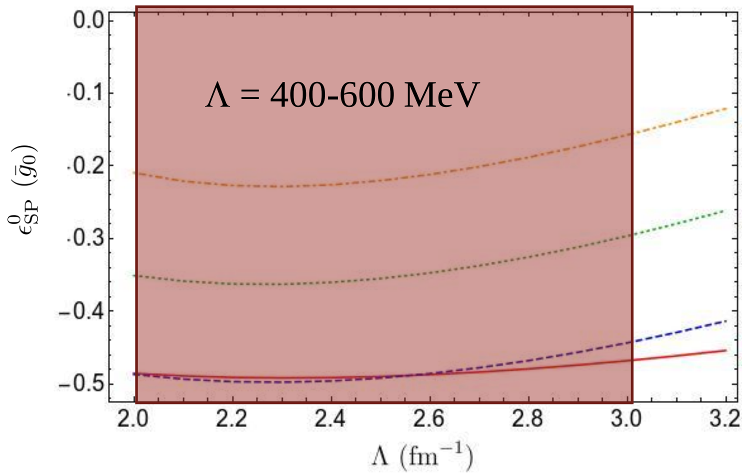
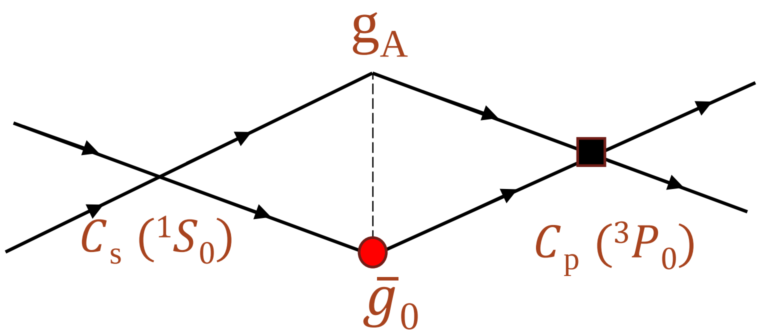
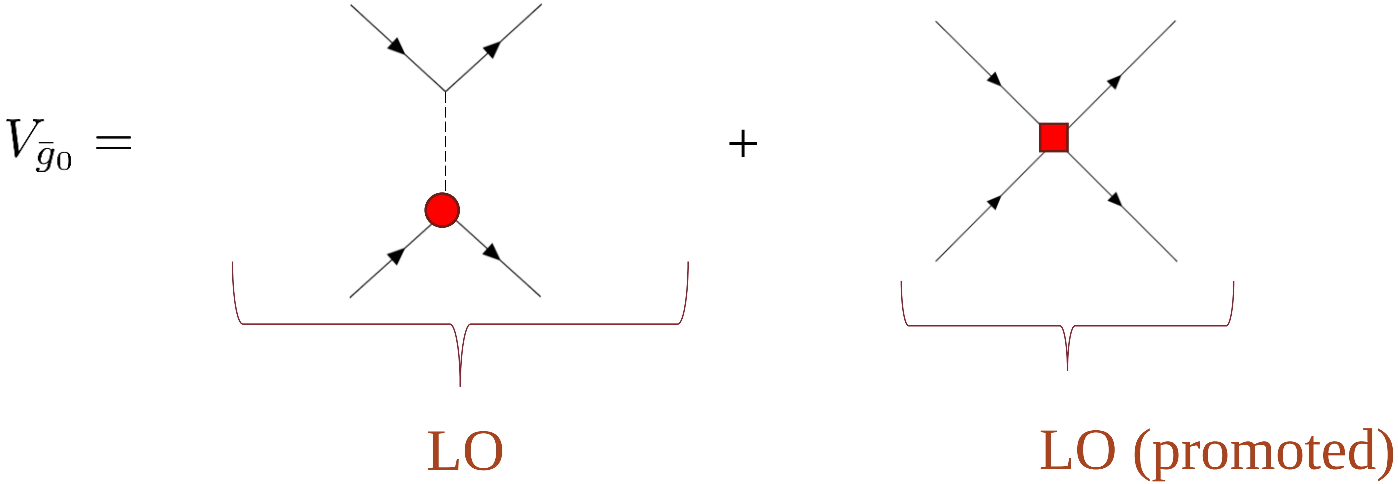



- Topology of the diagram responsible for divergence in j=0




- Solution: Promote $N^2LO$ contact term to LO

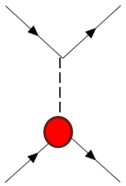


# CP-odd Phase Shifts : j=0

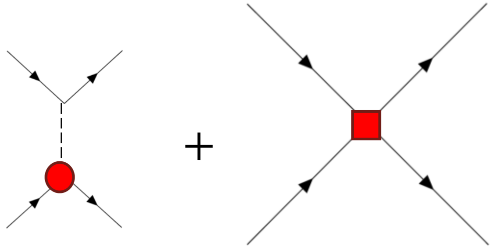
$E_{CM} = 5$ MeV $E_{CM} = 25$ MeV

$E_{CM} = 50$ MeV $E_{CM} = 95$ MeV

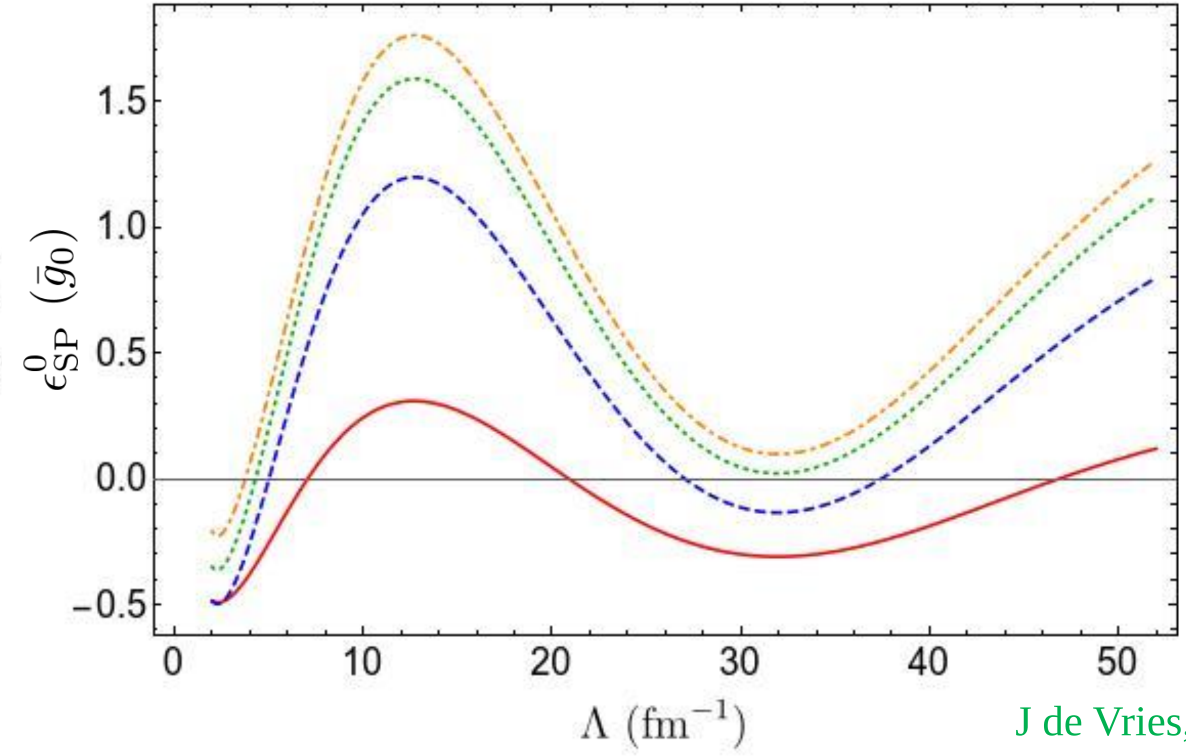
**NDA Fails!**

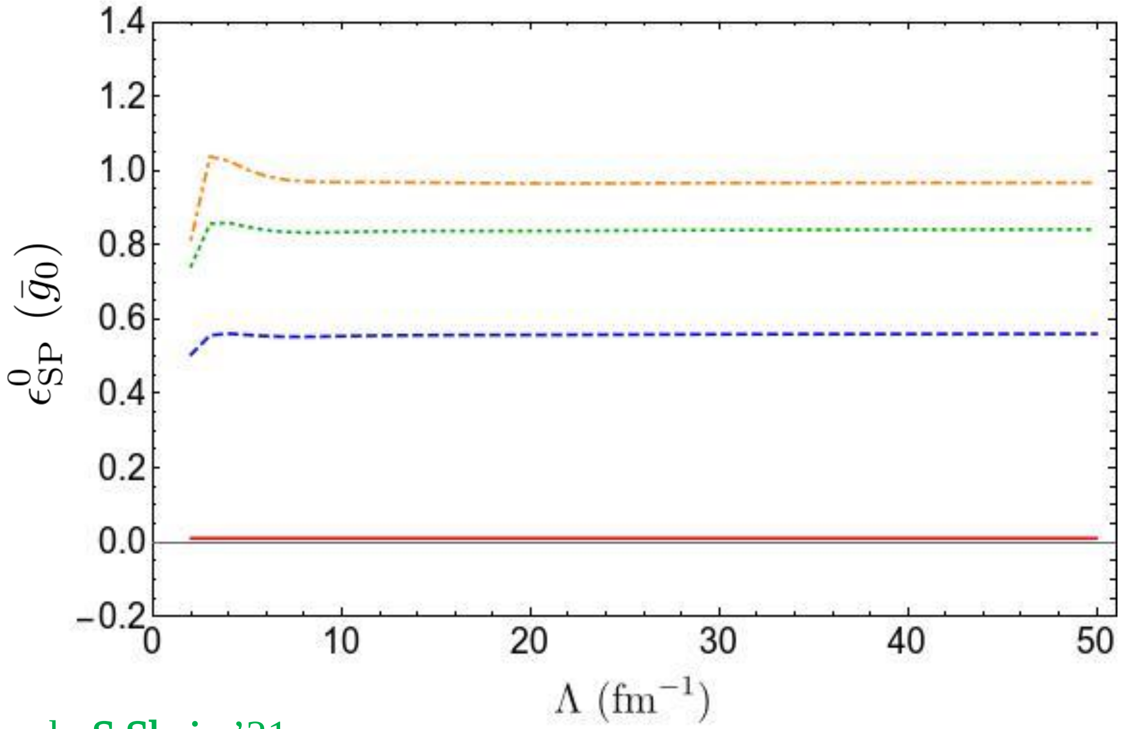


NDA Fails!



$\epsilon^0_{SP} = +0.01\bar{g}_0$

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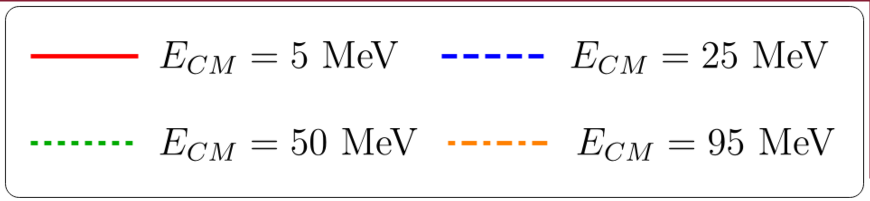
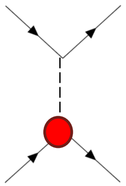
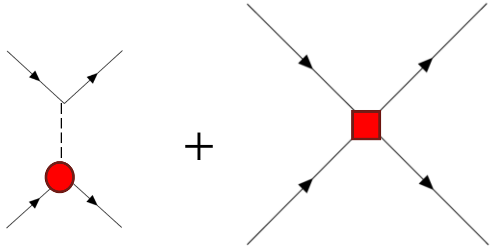


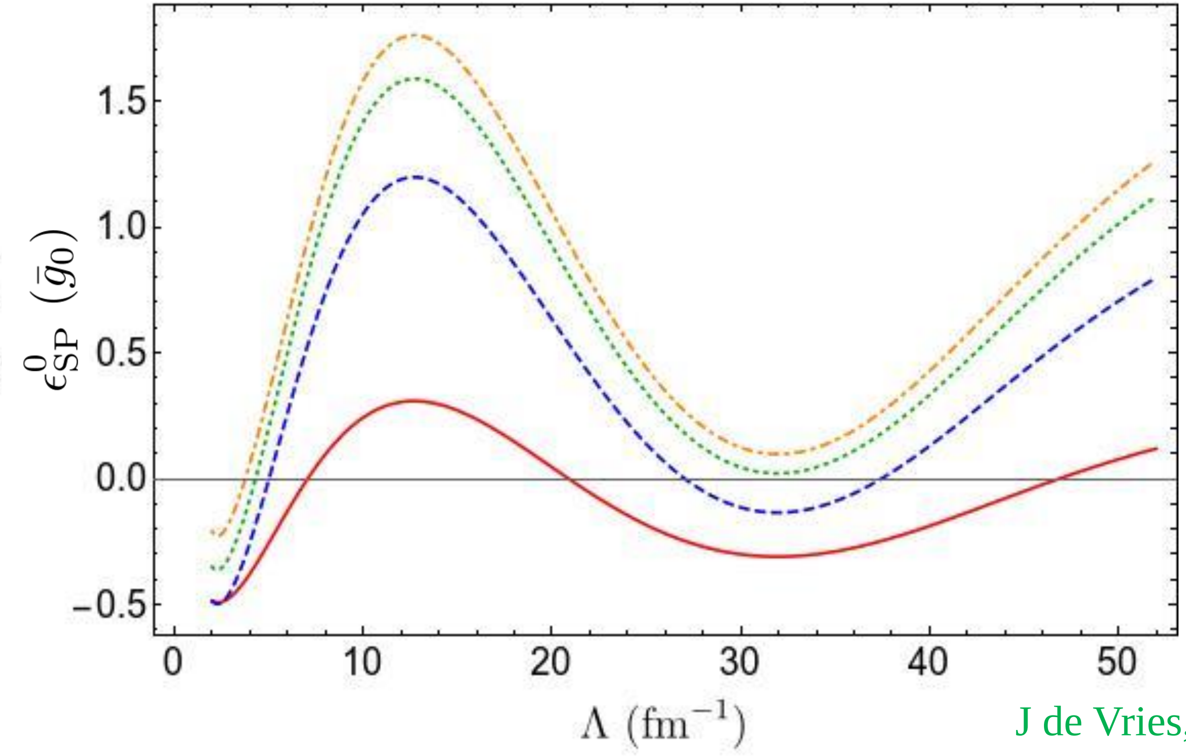

**NDA Fails!**

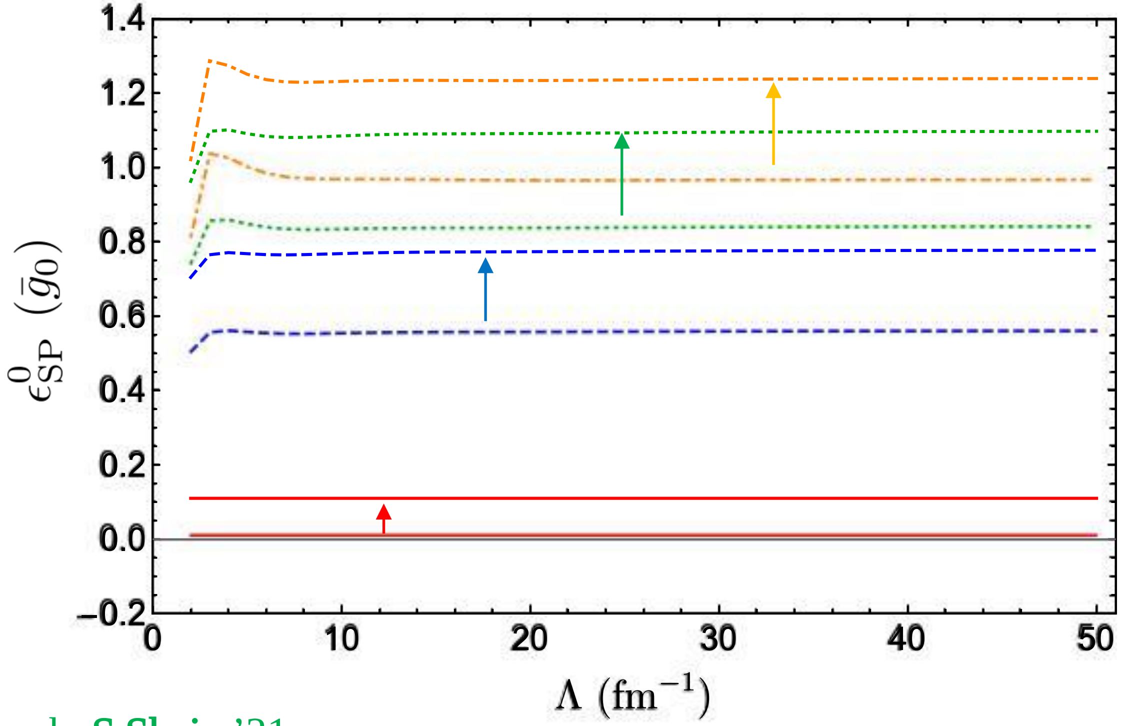


**NDA Fails!**



$\epsilon^0_{SP} = +0.11\bar{g}_0$

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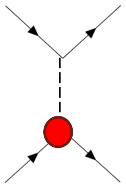
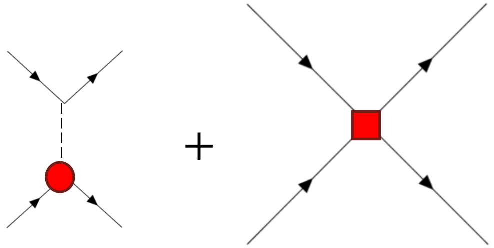
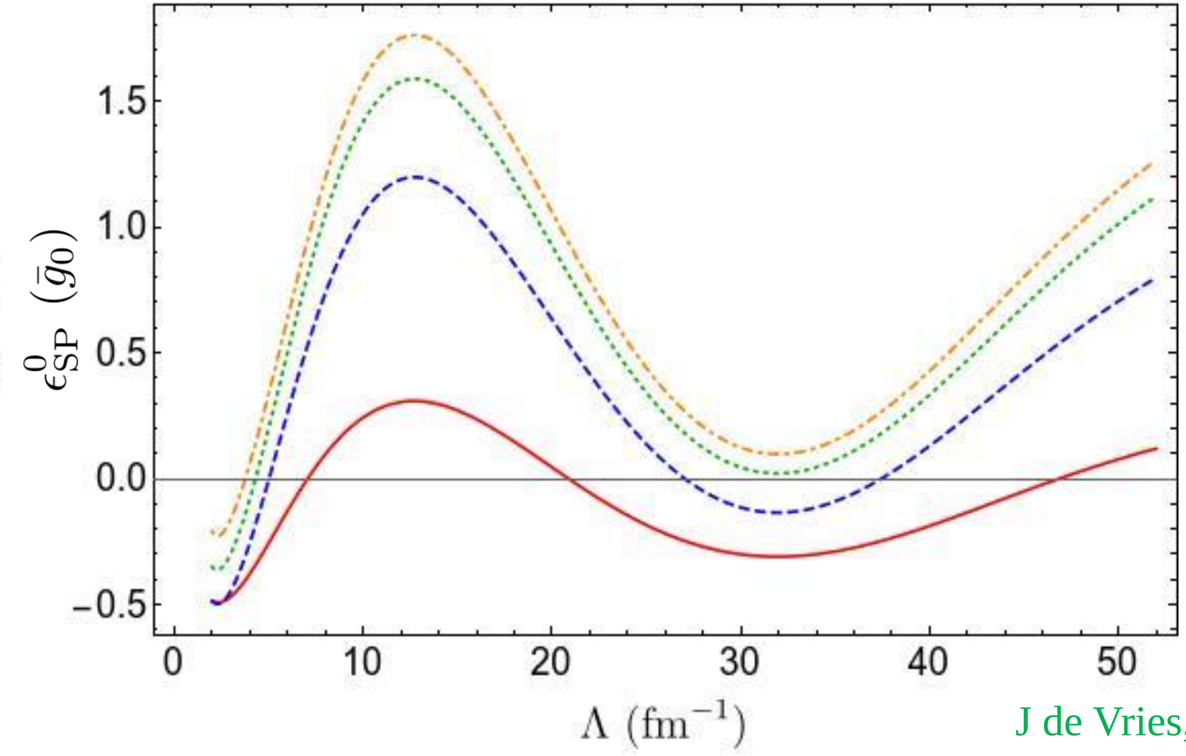
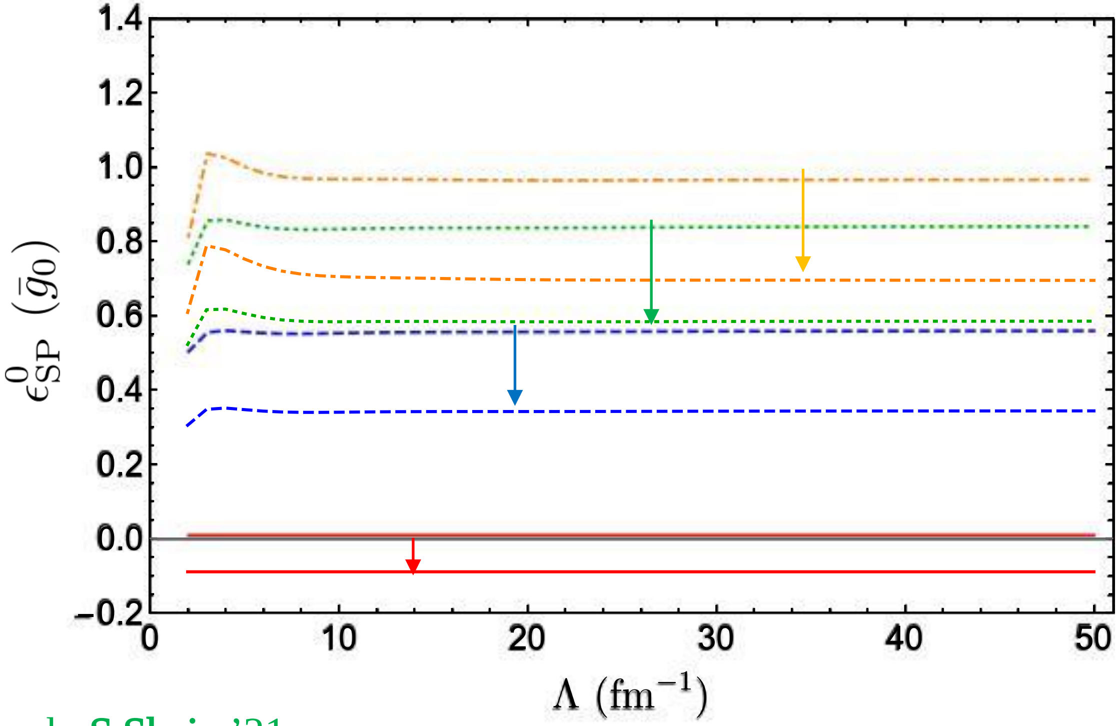


**NDA Fails!**



$\epsilon^0_{SP} = -0.09\bar{g}_0$

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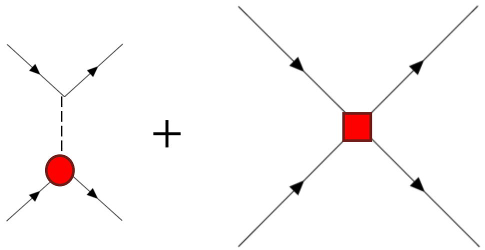
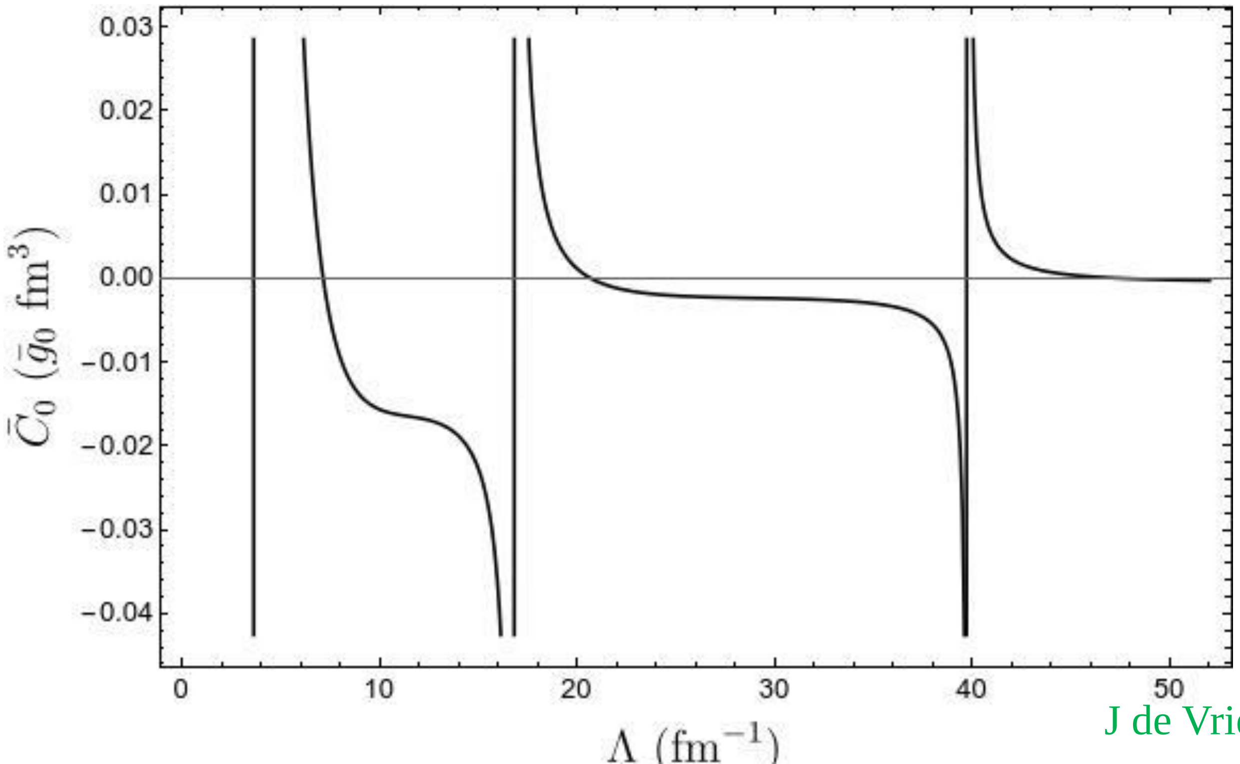
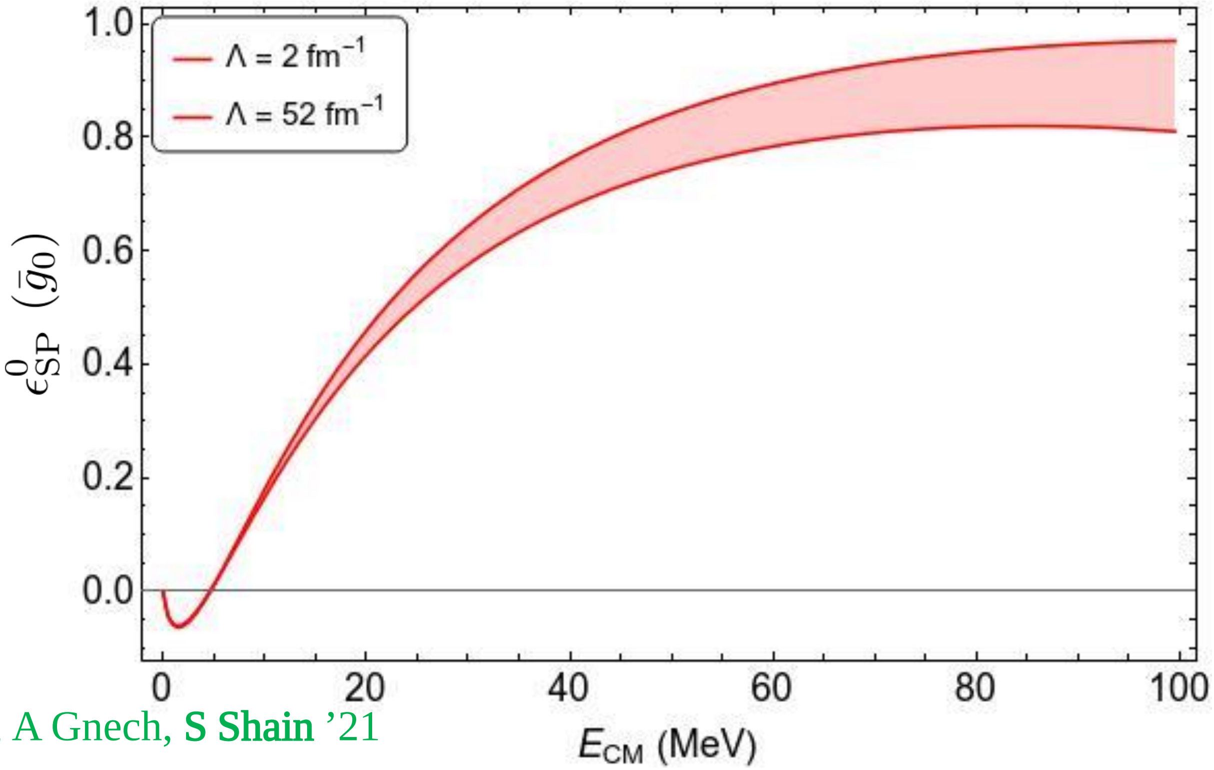
# CP-odd Phase Shifts : j=0



NDA Fails!

$$\epsilon^0_{SP} = +0.01\bar{g}_0$$




J de Vries, A Gnech, **S Shain** ’21

# How to deal with $\bar{C}_0$ ?

- Best way is to fit with the measurement of

  → This is at present not possible!

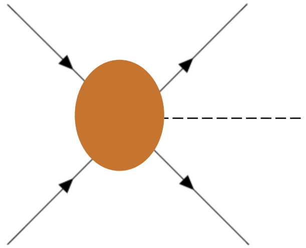
$$-\frac{1}{(2\pi)^3}\frac{i\bar{C}_0}{2}\underbrace{\left[\vec{\boldsymbol{q}}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)+\frac{1}{3}\vec{\boldsymbol{q}}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\vec{\tau}_1\cdot\vec{\tau}_2)\right]}_{=\,0\text{ for }j=1}$$

1. Lattice QCD calculation for NN → NN, in non-zero $\bar{\theta}$ background.
   → Major challenge is to overcome signal-to-noise ratio

J. Dragos et al'19

# How to deal with $\bar{C}_0$ ?

2. Charge-symmetry-breaking (CSB) process: NN → NNπ



$$\mathcal{L}_{NN} = -\frac{iC_0}{8}\mathrm{Tr}[\chi_-]\left[\bar{N}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}N) + \frac{1}{3}\bar{N}\vec{\tau}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}\vec{\tau}N)\right]$$

$$\mathcal{L}_{CSB} = -\frac{\delta m_N^{\mathrm{str}}}{4F_\pi^2}\bar{N}\vec{\tau}\cdot\vec{\pi}\pi^0 N + \frac{C_0 B(m_d - m_u)}{2F_\pi}\pi^0\left[\bar{N}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}N) + \frac{1}{3}\bar{N}\vec{\tau}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}\vec{\tau}N)\right]$$

$$\mathcal{L}_{\bar{g}_0} = \bar{g}_0\bar{N}\vec{\tau}\cdot\vec{\pi}N + \bar{C}_0\left[\bar{N}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}N) + \frac{1}{3}\bar{N}\vec{\tau}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}\vec{\tau}N)\right]$$

$$\boxed{\bar{C}_0 = (Bm_*\bar{\theta})C_0}$$

V. Baru et al ’14
U. van Kolck et al ’00

Simplest process where CSB data is available : $pn \to d\pi^0$ **not sensitive to $C_0$**

**Interested case:** $dd \to \alpha\pi^0$ CSB data can be used to extract $C_0$

WASA-at COSY collab: P. Adlarson et al’14

# More CP-odd operators

Another LO CP-odd chiral Lagrangian (leads to iso-vector potential),

$$\mathcal{L}_{\pi N} = \bar{g}_1 \bar{N} \pi^0 N$$

Similar to $\bar{g}_0$ : **j = 1 there is no regulator dependence**

**j = 0 same regulator dependence as $\bar{g}_0$ (upto an isospin factor)**

J = 0 a LO counter term is needed,

$$\mathcal{L}_{NN} = \bar{C}_1 \overbrace{\left[\bar{\tau}^3 \boldsymbol{\sigma} N \cdot \boldsymbol{\nabla}(\bar{N} N) + \bar{N} \boldsymbol{\sigma} N \cdot \boldsymbol{\nabla}(\bar{N} \tau^3 N)\right]}^{= 0 \text{ for } j = 1}$$

Work in progress

$\Rightarrow \bar{C}_1$ at LO should be included in the **EDM calculations of $^3$He, $^{199}$Hg, $^{225}$Ra**

# P-odd operators

P-odd chiral Lagrangian,

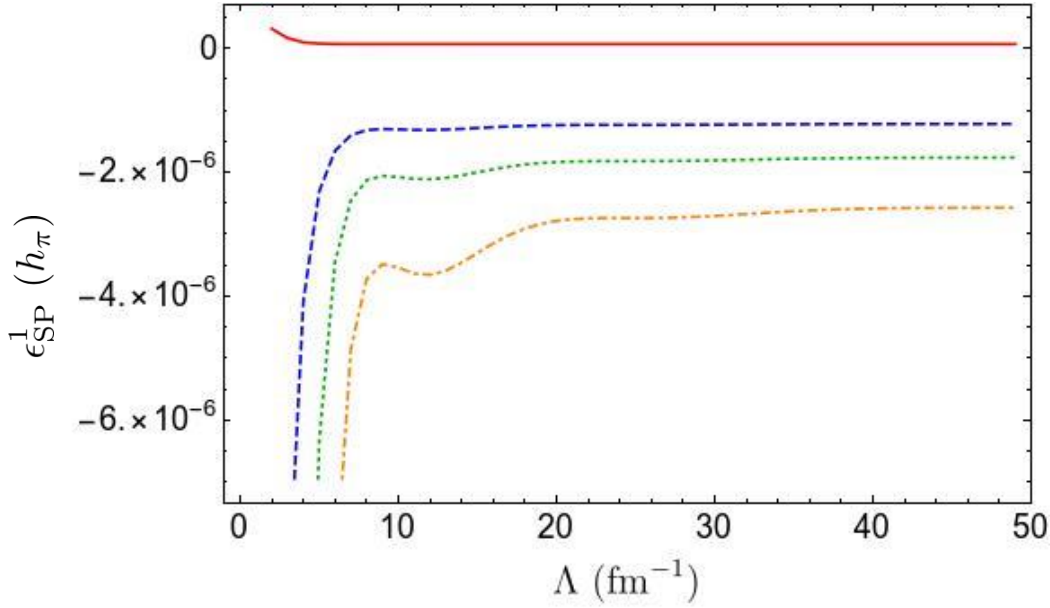
$$\mathcal{L}_{\pi N} = \frac{h_\pi}{\sqrt{2}} \bar{N}(\vec{\pi} \times \vec{\tau})^3 N$$

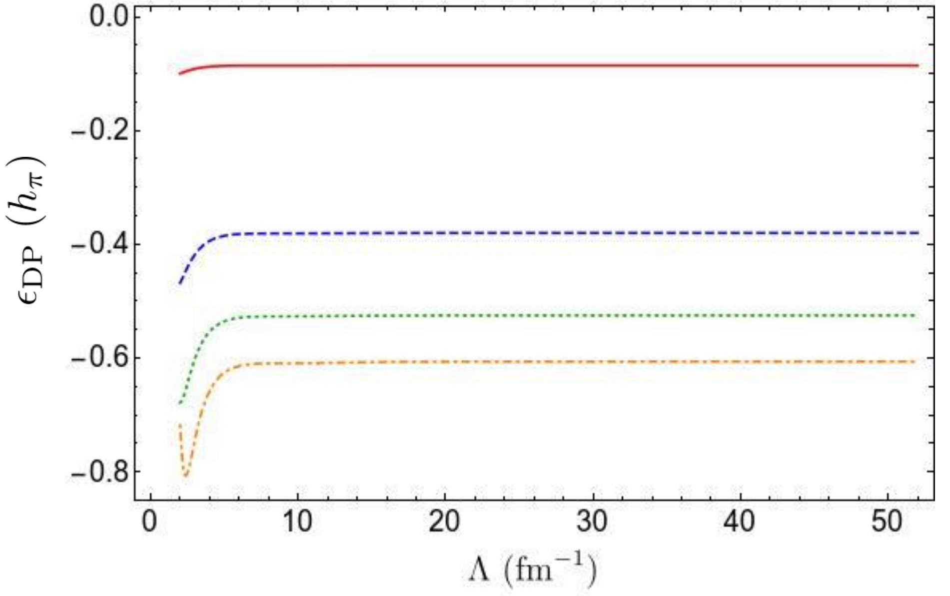
D. B. Kaplan et al'94

**j = 0, 1 there are no regulator dependence**

Value of $h_\pi$ determined from P-odd np → dγ can be used in p-odd observables

D. Blyth et al'18



# Axions

The QCD Lagrangian

$$\mathcal{L} = \overbrace{\bar{q} i \not{D} q - \bar{q}\mathcal{M} q - \bar{\theta} \frac{g_s}{8\pi}\tilde{G}_{\mu\nu}G^{\mu\nu}}^{\text{SM}}$$

$$\underbrace{-\frac{g_s}{2}\bar{q}(i\sigma^{\mu\nu}\gamma_5)\tilde{d}_{CE}t^a q G^a_{\mu\nu} + \ldots}_{\text{LEFT}} + \text{h.c.}$$

**Strong CP problem**

$$\boxed{\bar{\theta} < 1.2 \times 10^{-10}}$$

C. Abel et al. ’20

Ciaran A J O’Hare et al ’20

# Axions

The QCD Lagrangian

$$\mathcal{L} = \overbrace{\bar{q} i \not{D} q - \bar{q}\mathcal{M} q - \bar{\theta}\frac{g_s}{8\pi}\tilde{G}_{\mu\nu}G^{\mu\nu}}^{\text{SM}} + \overbrace{\frac{1}{2}\partial_\mu a \partial^\mu a - \frac{g_s}{8\pi}\frac{a}{f_a}\tilde{G}_{\mu\nu}G^{\mu\nu}}^{\text{Axion } [\mathrm{U_{PQ}}(1)]}$$

$$\underbrace{-\frac{g_s}{2}\bar{q}(i\sigma^{\mu\nu}\gamma_5)\tilde{d}_{CE}t^a q G^a_{\mu\nu} + \ldots}_{\text{LEFT}} + \text{h.c.}$$

Peccei et al. ’77

By choosing ‘correct’ vacuum expectation value for axion, we can cancel the theta-term

$$\mathcal{L} = -\left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g_s}{8\pi}\tilde{G}_{\mu\nu}G^{\mu\nu} \Rightarrow a \to a + \langle a \rangle \;\; \text{with} \;\; \langle a \rangle = -f_a\bar{\theta}$$

# Axions

We do not want terms in the fom: $\mathcal{L} \sim \bar{q} i \gamma_5 t_3 q \Rightarrow \mathcal{L} \sim \pi^0$

We can remove these by: $q \rightarrow e^{i\alpha_3 t_3 \gamma_5} q \Rightarrow \bar{q}q \rightarrow \alpha_3 \bar{q} i t_3 \gamma_5 q$

But we also have terms like: $\mathcal{L} \sim a \bar{q} i t_3 \gamma_5 q$ Thus $\alpha_3 \sim a$

Since, $q \rightarrow e^{i\alpha_3 t_3 \gamma_5} q \Rightarrow \bar{q} i \gamma_5 q \rightarrow \alpha_3 \bar{q} q$ we can expect axion-(SM CP-even terms)

**If Peccei-Quinn mechanism exists, we expect CP-odd couplings**

**which we can check experimentally!**

# Axion-SM couplings

CP-odd axion-SM terms

Electron, proton, neutron, …

$$\mathcal{L} = -g_s^{\Psi} a\bar{\Psi}\Psi - g_p^{\Psi} a\bar{\Psi}i\gamma_5\Psi$$

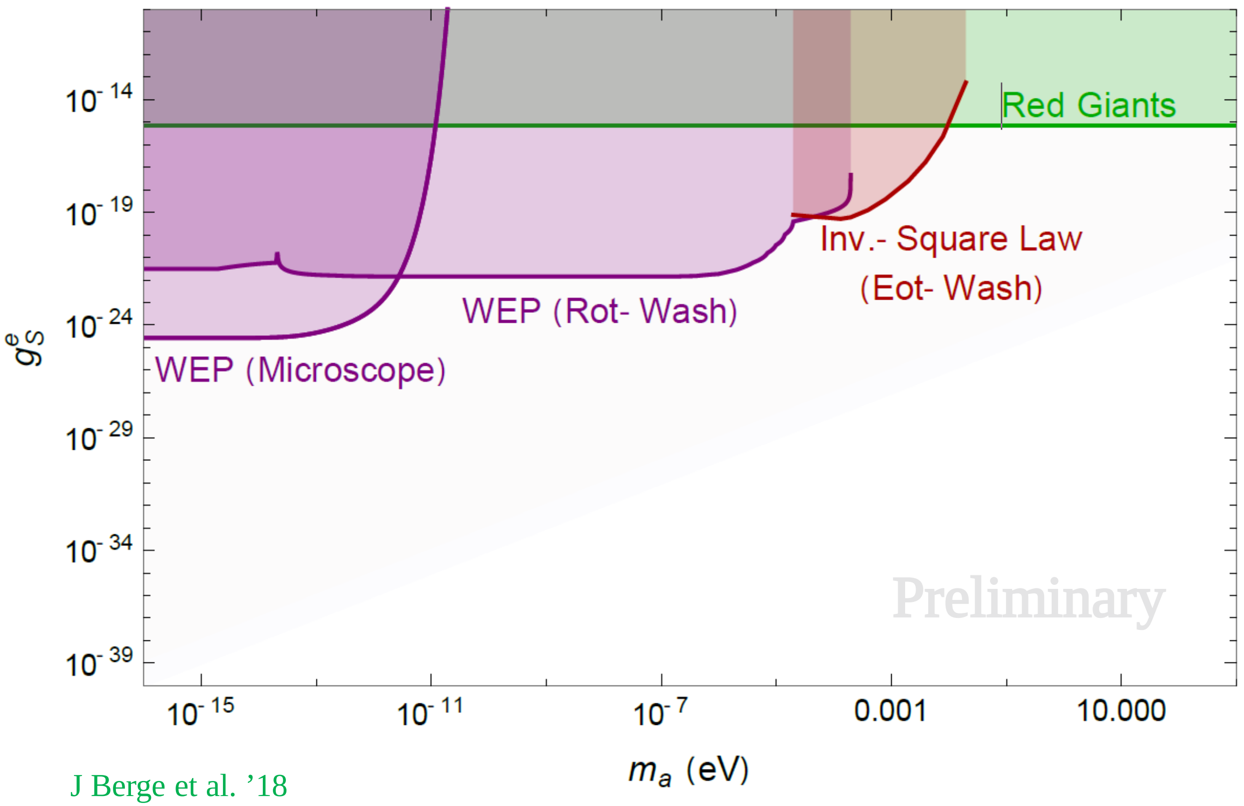
Functions of dim-6 couplings, $f_a$ ($m_a$)

Effect of CPV axion couplings

$$V_{AB} = -\frac{Gm_A m_B}{r}\left(1+\alpha_{AB}e^{-rm_a}\right)$$

Put two test masses in orbit around the Earth
Measure the difference in their acceleration.

J E Moody , F Wilczek '84




J Berge et al. '18
G L smith et al. '00
C D Hoyle et al. '04
E Hardy et al. '17
Ciaran A J O'Hare et al. '20

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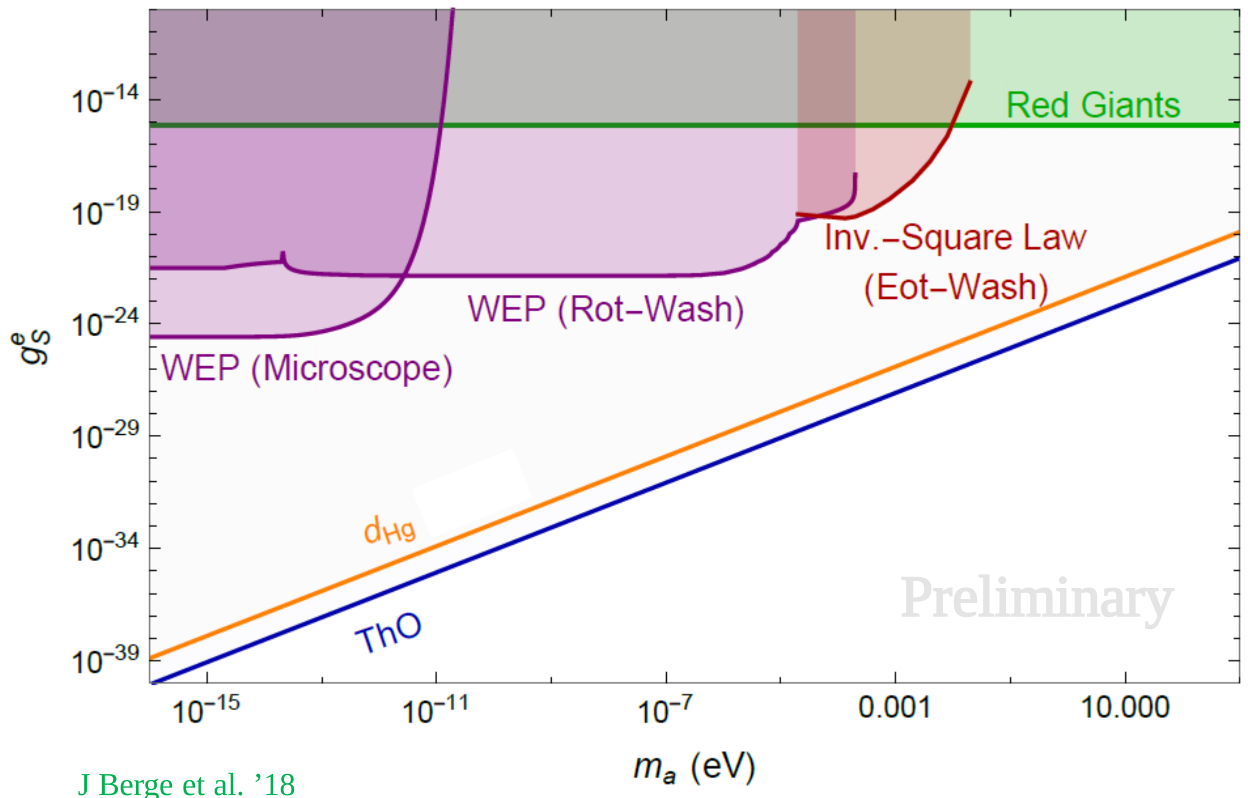
J E Moody , F Wilczek ’84

EDM limits still gives the most stringent constrains




J Berge et al. ’18
G L smith et al. ’00
C D Hoyle et al. ’04
E Hardy et al. ’17
Ciaran A J O’Hare et al. ’20

B Graner et al. ’16
C D panda et al. ’19

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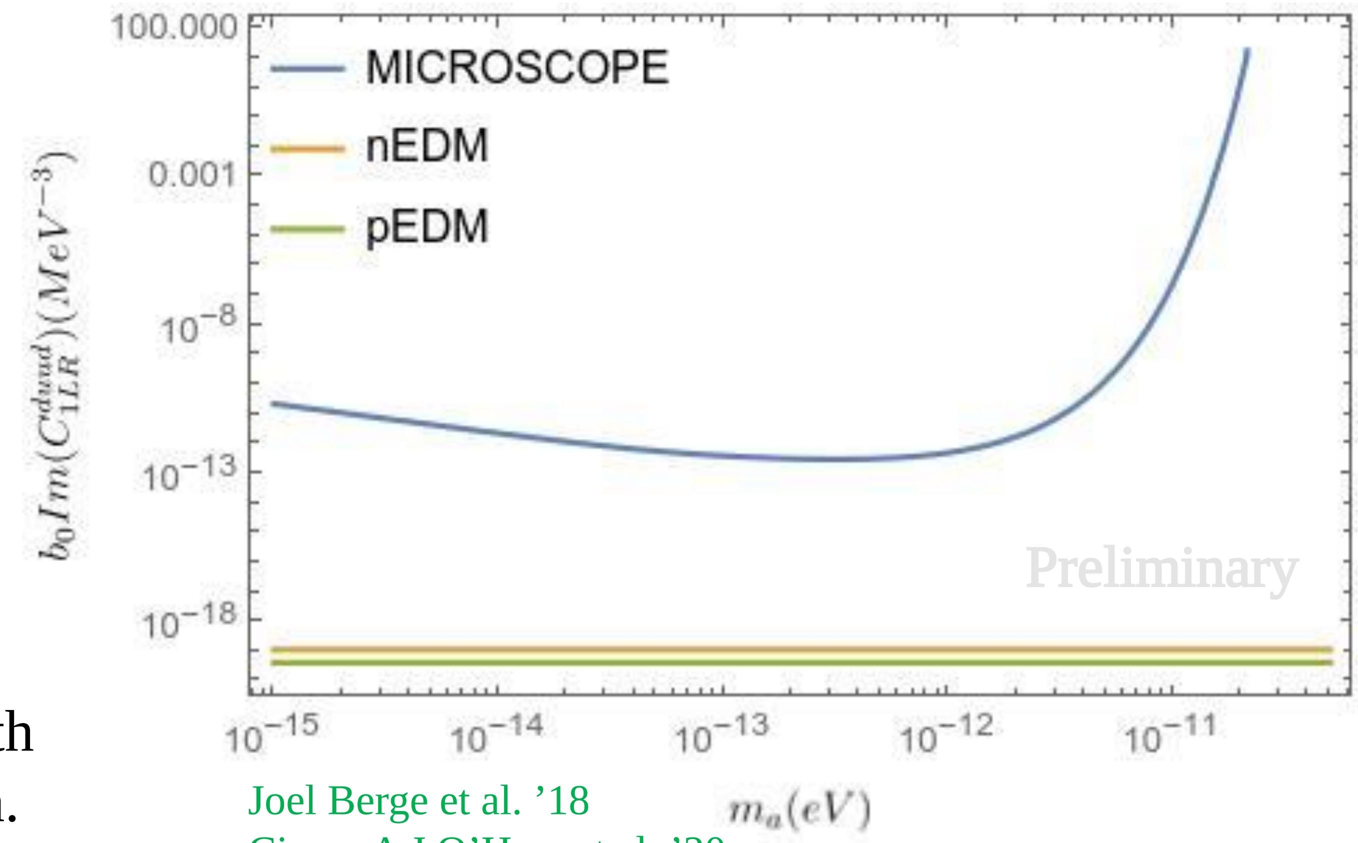
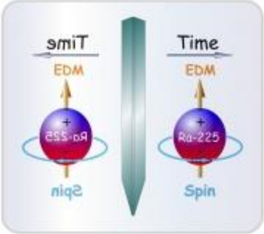



Joel Berge et al. '18
Ciaran A J O'Hare et al. '20

# Summary



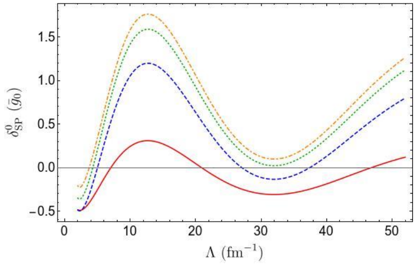

**Our work:** Phys. Rev. C **103**, L012501

- Nuclear EDMs are excellent probes for CP-violation.

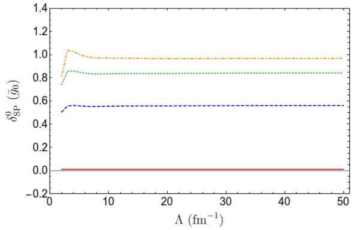
- Nuclear EDMs can be written as linear combination of low energy constants:

$$\boxed{d_{^3\mathrm{He}} = 0.90(1)d_n - 0.03(1)d_p + [0.11(1)\bar{g}_0 + 0.14(2)\bar{g}_1]e \text{ fm}}$$

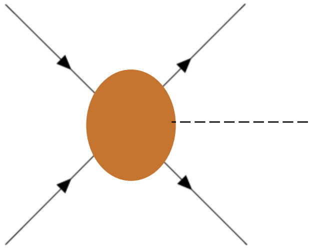
- For j=0 channel, **nucleon-nucleon effects becomes important and should not be neglected as currently done in the literature**.



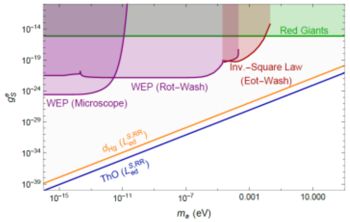

- We done the calculations with intrinsic nucleon-nucleon effects.




- Proposed some strategies to obtain LEC $\bar{C}_0$ : CSB deuteron scattering.



- We created list of all CPV axion-(hadrons, mesons, leptons) interactions using dim-6 LEFT operators.




- EDM limits are more stringent than macroscopic experiments