Hadronic parity violation in chiral effective field theory

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An old story

- Wu et al (1957) measured P-violation in decay of ^{60}Co
- Nobel price awarded same year to Lee and Yang

"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

T.D. Lee

C. N. Yang

Beta decay and P violation

$$^{60}Co \rightarrow {}^{60}Ni + e + \overline{\upsilon}_e + 2\gamma$$

Experimental Test of Parity Conservation in Beta Decay*

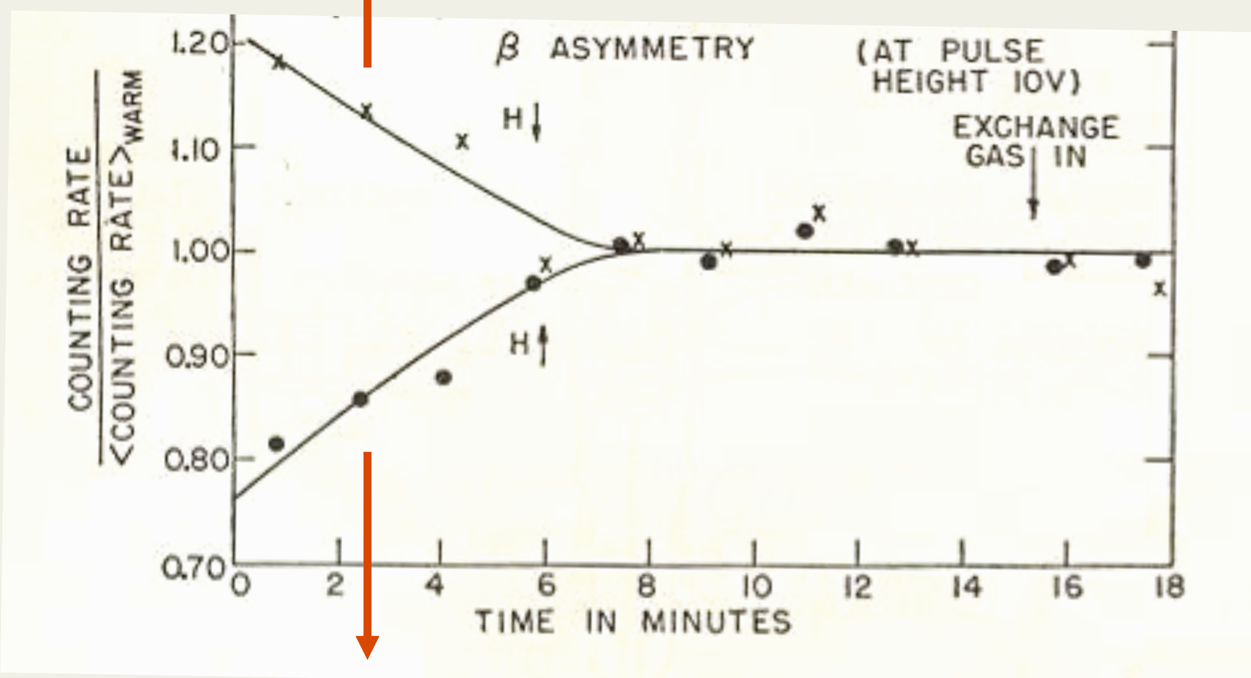
C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

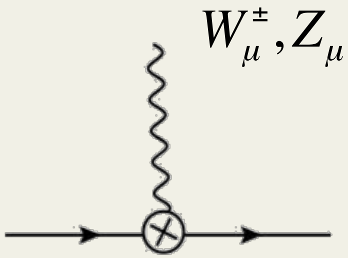
'Backward' rate/unpolarized rate

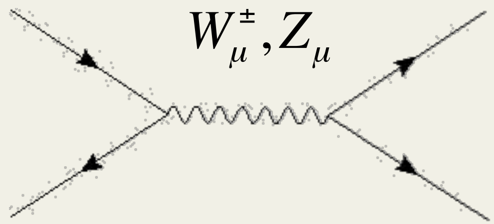


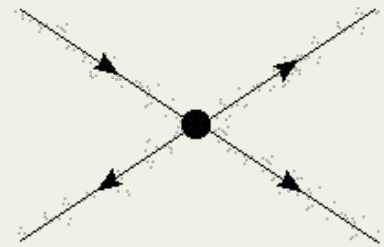
'Forward' rate/unpolarized rate

^{60}Co polarization decreases due to heating of the sample

Parity violation in the SM







$$G_F \propto \frac{g^2}{M_W^2}$$

- PV arises from the gauge symmetries of the SM:

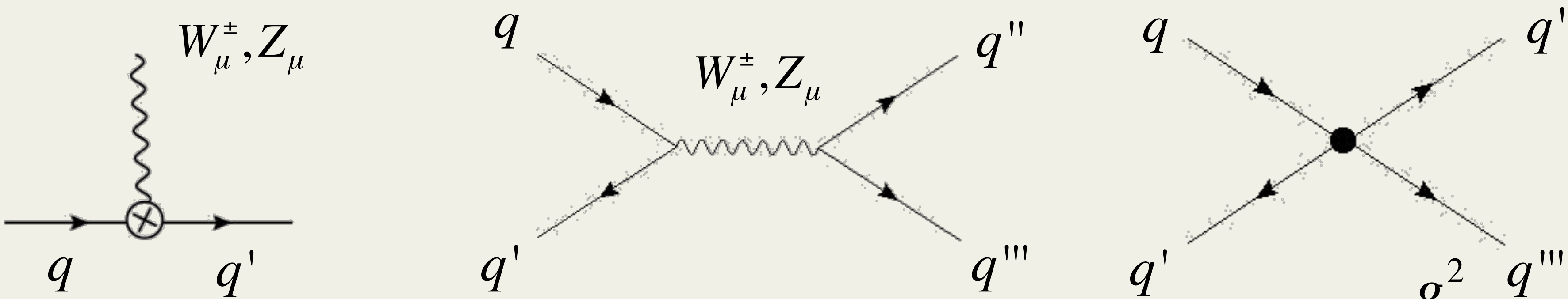
$$SU_C(3) \otimes SU_L(2) \otimes U_Y(1)$$

- PV first measured in beta-decay. Crucial in developing Standard Model

- Learn about W,Z bosons (masses ~ 100 GeV) from very **low-energy** experiments (Q-value ~ MeV)

- Poster child for the power of Effective Field Theories (EFTs)

Parity violation in the SM



$$G_F \propto \frac{g^2}{M_W^2}$$

- For beta-decay there is a clear signal → neutrino's
- HPV is about the PV forces among quarks

$$J_Z^{\mu} = \frac{1}{\cos\theta_W}\left(\bar{u}_L\gamma^{\mu}u_L[\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W] + \bar{u}_R\gamma^{\mu}u_R[-\tfrac{2}{3}\sin^2\theta_W]\right)$$
$$+ \frac{1}{\cos\theta_W}\left(\bar{d}_L\gamma^{\mu}d_L[-\tfrac{1}{2} + \tfrac{1}{3}\sin^2\theta_W] + \bar{d}_R\gamma^{\mu}d_R[\tfrac{1}{3}\sin^2\theta_W]\right)$$

+ terms with strange quarks and leptons + quark charged currents

- Mixing between $SU_L(2)$ and U(1) bosons → PV not maximally violated

$\bar{q} = (\bar{u}\ \bar{d})$

Parity-odd chiral Lagrangians

Kaplan & Savage, NPA '93

$$L = \frac{G_F}{\sqrt{2}}\left[\left(\frac{1}{2} - \frac{1}{3}s_w^2\right)\underbrace{V_\mu \cdot A^\mu}_{\mathbf{F_0}} - \frac{1}{3}s_w^2 \underbrace{I_\mu \cdot A_3^\mu}_{\mathbf{F_1}} - s_w^2 \left(\underbrace{V_3^\mu A_\mu^3 - \frac{1}{3}V_a^\mu A_\mu^a}_{\mathbf{F_2}}\right)\right] + \cdots$$

- They all break P, but have **different** chiral properties

$$V_\mu^a = \bar{q}\gamma^\mu \boldsymbol{\tau}^a q$$

$$A_\mu^a = \bar{q}\gamma^\mu\gamma^5 \boldsymbol{\tau}^a q$$

$$I_\mu = \bar{q}\gamma^\mu q$$

$\mathbf{F_0}$: chiral scalar (conserves chiral symmetry)
$\mathbf{F_1}$: isovector
$\mathbf{F_2}$: isotensor

- All proportional to G_F , but $s_w^2 \cong 1/4$
- Isovector $\mathbf{F_1}$ and isotensor $\mathbf{F_2}$ somewhat **suppressed** compared to $\mathbf{F_0}$

- This should lead to PV nuclear effects
- But very small asymmetries: $\frac{V_{weak}}{V_{strong}} \sim 10^{-6,-7}$
- **Can we probe/understand this ?**

What's the point ?

Kaplan & Savage, NPA '93

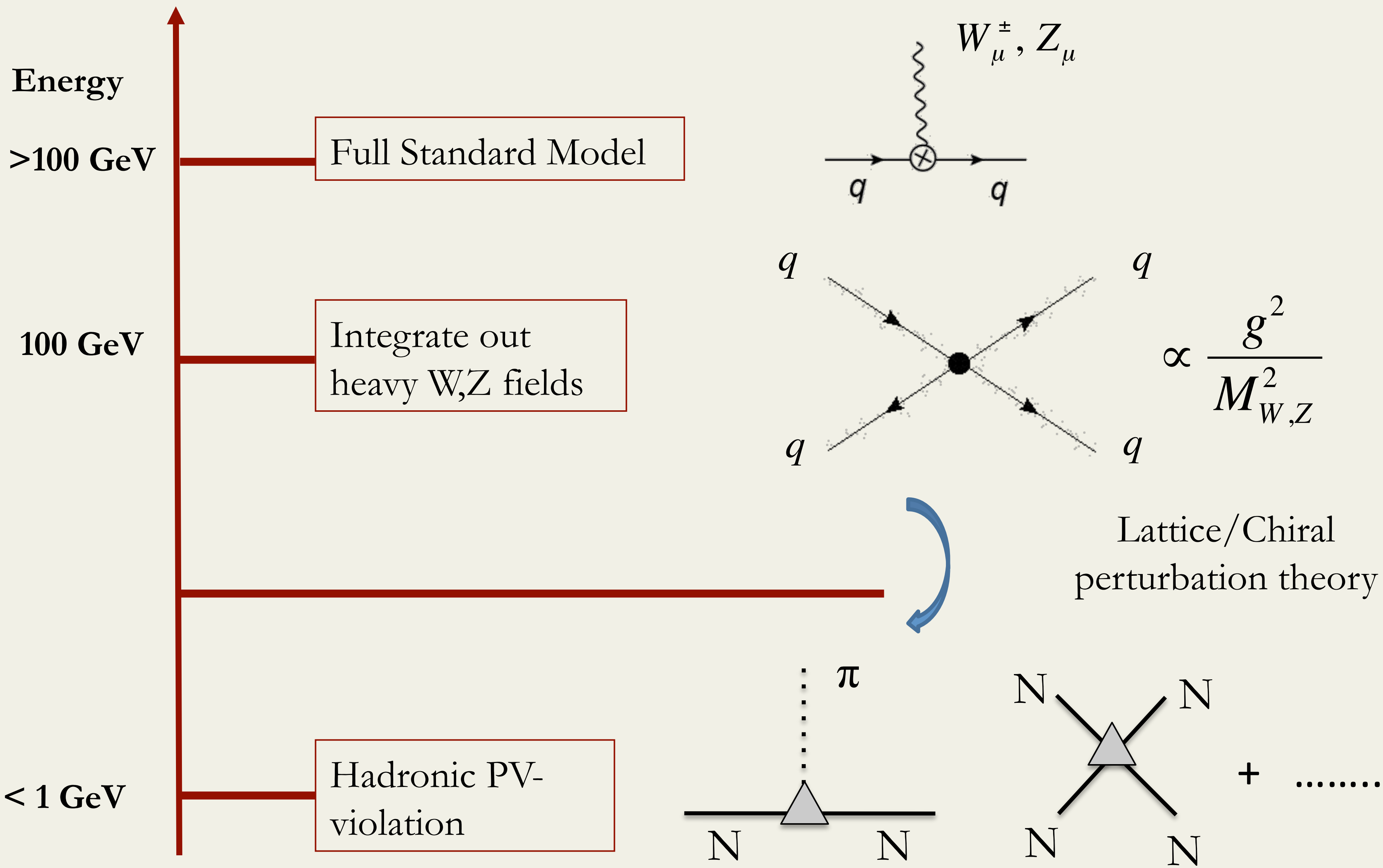
$$L = \frac{G_F}{\sqrt{2}}\left[\left(\frac{1}{2}-\frac{1}{3}s_w^2\right)V_\mu \cdot A^\mu - \frac{1}{3}s_w^2 I_\mu \cdot A_3^\mu - s_w^2\left(V_3^\mu A_\mu^3 - \frac{1}{3}V_a^\mu A_\mu^a\right)\right] + \cdots$$

$$\bar{q} = (\bar{u}\ \bar{d})$$

- **Often-heard question/implied criticism: why bother?**
- We know Parity violation exists ….
- And this not a good method to look for BSM physics....

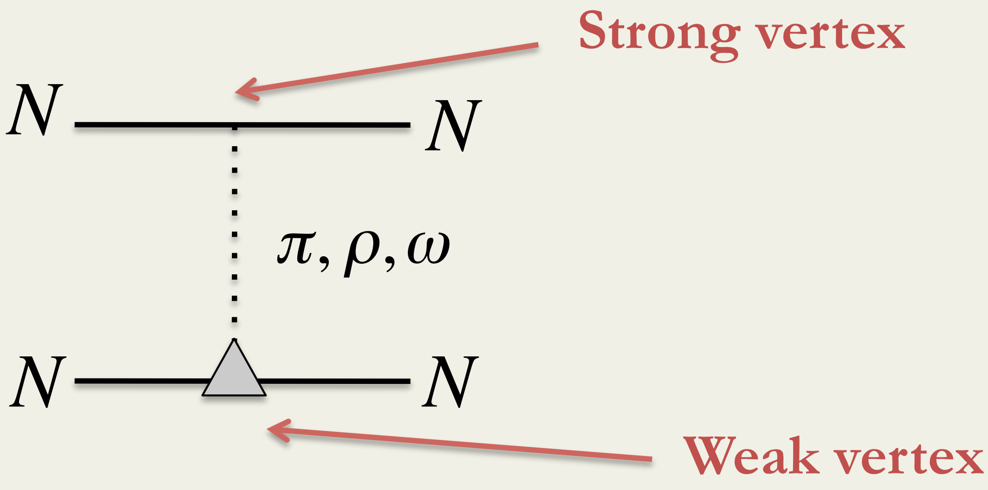
- My point of view:
  1. Interesting probe of low-energy QCD and nuclear forces → Shed light on $\Delta S=1$ processes?
  2. Often assumed we can eventually learn nature of BSM from low-energy precision measurements. **HPV = testing ground !** Here we 'know' the 'symmetry-violating' source !!
  3. Far future: benchmark nuclear theory?

Manifestation at low-energies



Usual methodology

- One-meson exchange model by **Desplanques, Donoghue, and Holstein (DDH). Parameterization of PV force.**
- Hadronic PV captured by one-meson exchange with handful PV vertices



- More recent: EFT point of view with pionless (review: Springer/Schindler '13) and pionfull EFT (review: JdV/Meißner '15)
- Large N_c considerations (Phillips et al '15, Gardner et al '17)

The DDH couplings

- Hadronic PV captured by one-meson exchange: **pion, rho, omega**
- Described by **7 coupling constants** estimated by quark or soliton model

	DDH '80		Kaiser&Meißner '89
	DDH range	**'Best'**	**'KMW'**
h_π	$(6 \pm 6) \cdot 10^{-7}$	$(4.6) \cdot 10^{-7}$	$(0.3) \cdot 10^{-7}$
$h_\rho^{0\,(,1,2)}$	$(-10 \pm 20) \cdot 10^{-7}$	$(-11.4) \cdot 10^{-7}$	$(-1.9) \cdot 10^{-7}$
$h_\omega^{0\,(,1)}$	$(-2 \pm 8) \cdot 10^{-7}$	$(-1.9) \cdot 10^{-7}$	$(-1.1) \cdot 10^{-7}$
$h_\rho^{\prime 1}$		$(0) \cdot 10^{-7}$	$(-2.2) \cdot 10^{-7}$

- And corresponding phenomenological strong P-even couplings

An ultrashort intro to Chiral EFT

- Use the symmetries of QCD to obtain **chiral Lagrangian**

$$L_{QCD} \rightarrow L_{chiPT} = L_{\pi\pi} + L_{\pi N} + L_{NN} + \cdots$$

- Quark masses = 0 → SU(2)$_L$xSU(2)$_R$ symmetry
  - Spontaneously broken to SU(2)-isospin (pions = Goldstone)
  - Explicit breaking (quark mass) → pion mass

- ChPT has systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$ $\Lambda_\chi \cong 1\,GeV$
  - **Form of interactions fixed by symmetries**
  - Each interactions comes with an unknown constant (LEC)
  - Power counting: **roughly** higher dimension → smaller LEC

- **Extended to include P violation** Kaplan/Savage '93

Weinberg, Gasser, Leutwyler, ….. and many many others

Chiral effective field theory

~ GeV $L = L_{QCD}$ light quarks and gluons

~100 MeV **Chiral limit:** $L_\chi = L_{kin} - m_N \bar{N}N + \frac{g_A}{f_\pi} D_\mu \vec{\pi} \cdot \bar{N}\gamma^\mu \gamma^5 \vec{\tau} N + C_0 \, \bar{N}N\bar{N}N$

- 'LECs' and must be **measured** or **lattice QCD**
- **Pions are gold-stones: only derivative couplings**

$N = (p \;\; n)^T$

Quark masses: $L_m = -\frac{m_\pi^2}{2}\pi^2 - \delta m_N \, \bar{N}\tau^3 N$

Small quark masses → Small pion mass and nucleon mass splitting

Chiral effective field theory

~ GeV $L = L_{QCD} + L_{Fermi}$ light quarks and gluons

~100 MeV **Chiral limit** $L_\chi = L_{kin} - m_N \bar{N}N + \frac{g_A}{f_\pi} D_\mu \vec{\pi} \cdot \bar{N}\gamma^\mu \gamma^5 \vec{\tau} N + C_0 \; \bar{N}N\bar{N}N$

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Small quark masses → Small pion mass and nucleon mass splitting

Parity violation: Add corresponding PV chiral interactions

Parity-odd chiral Lagrangians

$$L = \frac{G_F}{\sqrt{2}}\left[\left(\frac{1}{2}-\frac{1}{3}s_w^2\right)V_\mu \cdot A^\mu - \frac{1}{3}s_w^2 I_\mu \cdot A_3^\mu - s_w^2\left(V_3^\mu A_\mu^3 - \frac{1}{3}V_a^\mu A_\mu^a\right)\right]$$

$\mathbf{F_0}$ ($V_\mu \cdot A^\mu$), $\mathbf{F_1}$ ($I_\mu \cdot A_3^\mu$), $\mathbf{F_2}$ ($V_3^\mu A_\mu^3 - \frac{1}{3}V_a^\mu A_\mu^a$)

- Only $\mathbf{F_1}$ induces a non-derivative pion-nucleon coupling

$$L_{PV} = \frac{h_\pi}{\sqrt{2}}\bar{N}(\vec{\tau}\times\vec{\pi})^3 N = ih_\pi(\bar{p}n\,\pi^+ - \bar{n}p\,\pi^-)$$

- All other P-odd interactions appear at higher order → simple !!
- But: s_w^2 and large-Nc ...... Phillips et al '15, Gardner et al '17

- What about: $\bar{g}_0\bar{N}(\vec{\tau}\cdot\vec{\pi})N + \bar{g}_1\bar{N}(\pi_3)N + \bar{g}_3\bar{N}(\pi_3\tau_3)N$
- These break **P and T** (and thus CP)

The puzzle of the weak pi-N coupling

h_π NDA $h_\pi \propto G_F \Lambda_\chi F_\pi \sim 10^{-6}$

		DDH range	'Best'	
h_π		$(6 \pm 6) \cdot 10^{-7}$	$(4.6) \cdot 10^{-7}$	Desplanques et al' 80
h_π	SU(3) Skyrme calculation		$(1.0 \pm 0.3) \cdot 10^{-7}$	Meißner & Weigel '99 Hyun et al '16
h_π	First lattice calculation		$(1.1 \pm 0.5) \cdot 10^{-7}$	Wasem '12

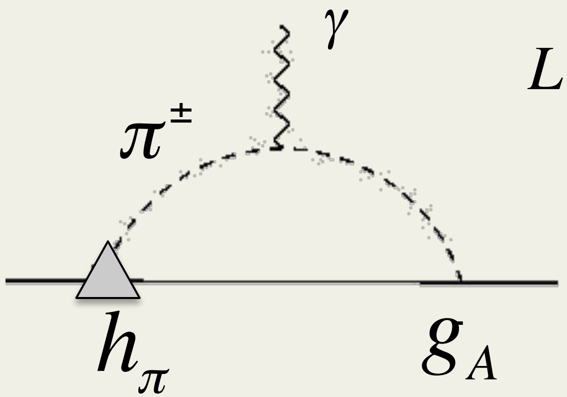
Caveat: large pion mass and no disconnected diagrams

h_π $h_\pi < 1.4 \cdot 10^{-7}$ No PV signal in $^{18}F^*$ decays Haxton '81

h_π $h_\pi \sim 10^{-6}$ ^{133}Cs Anapole moment/p-alpha scatt Liu et al '01, Roser/Simonius '85

Single-nucleon parity violation

- PV pion-nucleon coupling leads to an anapole form factor   Musolf, Holstein '91



$$L = \bar{N}\gamma^{\mu}\gamma^{5}(a_0 + a_3\tau_3)N\,\partial^{\nu}F_{\mu\nu}$$

$$a_0 = e\,\frac{g_A h_\pi}{48\sqrt{2}\pi}\,\frac{m_N^2}{m_\pi f_\pi}$$

$$a_3 = 0$$

- Anapole FF at LO is a prediction (counter terms at NLO)   van Kolck et al '00 '01

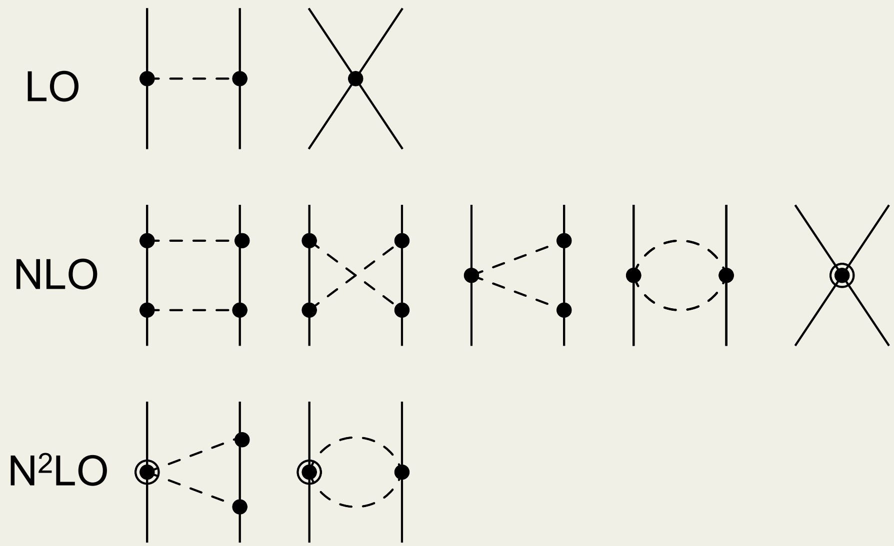
- But anapole vanishes on-shell → $\partial^{\nu}F_{\mu\nu} = 0$
- Adds a contact piece to PV electron-proton scattering
- **Question to audience: at what point is this relevant for Q_{weak} ?**

- Note: contract to EDMs where loops require counter term ! No prediction from chiral perturbation theory

Onwards to nuclear forces

- Single nucleon not good since **anapoles** and also **loop suppression**
- Move towards two (or more nucleons) → **Tree-level contributions !!**

- Chiral EFT: EFT of nuclear forces based on chiral pert. Theory
- Idea: obtain the nucleon-nucleon potential in chiral expansion



Weinberg
Van Kolck et al,
Epelbaum et al,
Machleidt et al,
And many more…

- Potential nowadays known up to N^{4}LO → LECs fitted to pi-N and NN data
- Potential then inserted into a Lippmann-Schwinger/Schrodinger equation

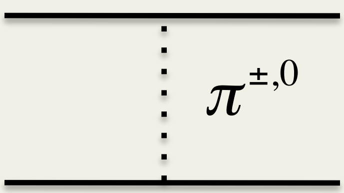
Onwards to nuclear forces

- Leading-order PV NN force is in principle easier !!

P-even

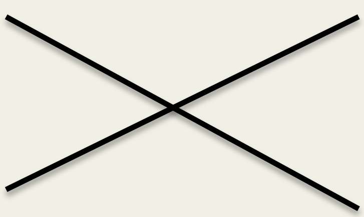
P-odd

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



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

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



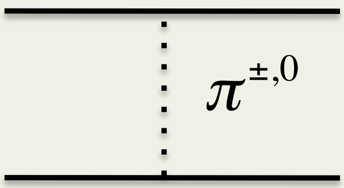
$$\sim Q^0$$

Onwards to nuclear forces

- Leading-order PV NN force is in principle easier !!

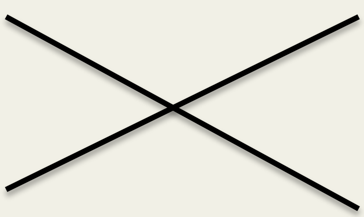
P-even

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



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

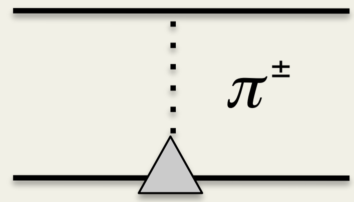
$$\bar{N}N\;\bar{N}N$$



$$\sim Q^0$$

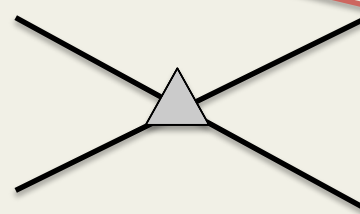
P-odd

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



$$\sim \frac{(g_A Q)h_\pi}{Q^2} \sim Q^{-1}$$

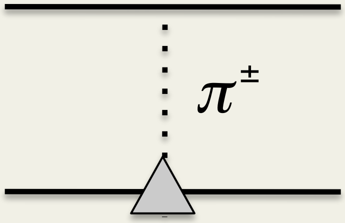
$$\varepsilon^{ijk}\,(\bar{N}\sigma^i N)\,\partial^k(\bar{N}\sigma^j N)$$



$$\sim Q^1$$

PC v PV potential

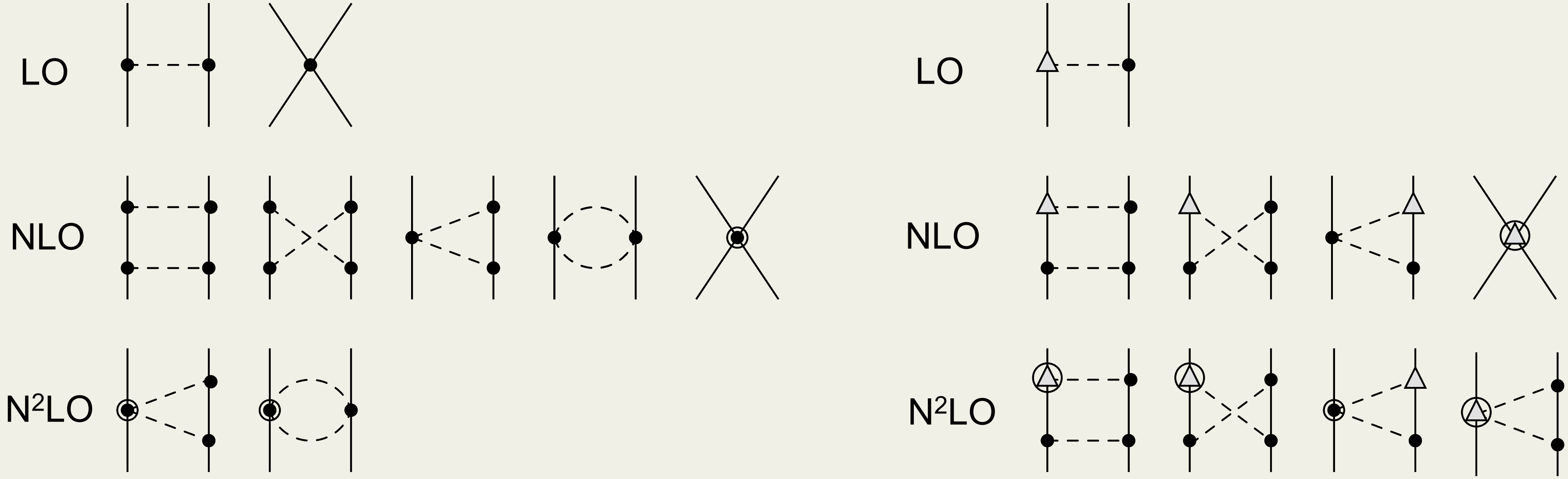
- LO OPE expected to dominate PV forces



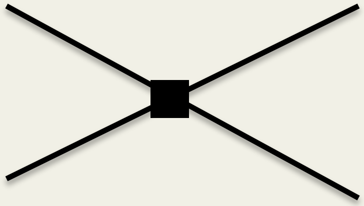
$$-\left(\frac{g_A h_\pi}{2\sqrt{2}F_\pi}\right) i(\vec{\tau}_1 \times \vec{\tau}_2)^3 \frac{(\vec{\sigma}_1 + \vec{\sigma}_2)^3 \cdot \vec{q}}{\vec{q}^{\,2} + m_\pi^2}$$

- Should dominate PV forces, but: Size h_π uncertain
- Total isospin flip: **no contribution** to pp scattering → need higher order

(Zhu et al '05, JdV et al '14 '15, Viviani et al '14)



Interpretation of contact terms



$$C_1\, \varepsilon^{ijk}\, \overline{N}\sigma^i N\, \partial^j (N\sigma^k N)$$ +4 others

NN contact terms (5) (There are 5 $S \leftrightarrow P$ transitions)

Can be modeled by the **exchange** of a single **heavy** meson

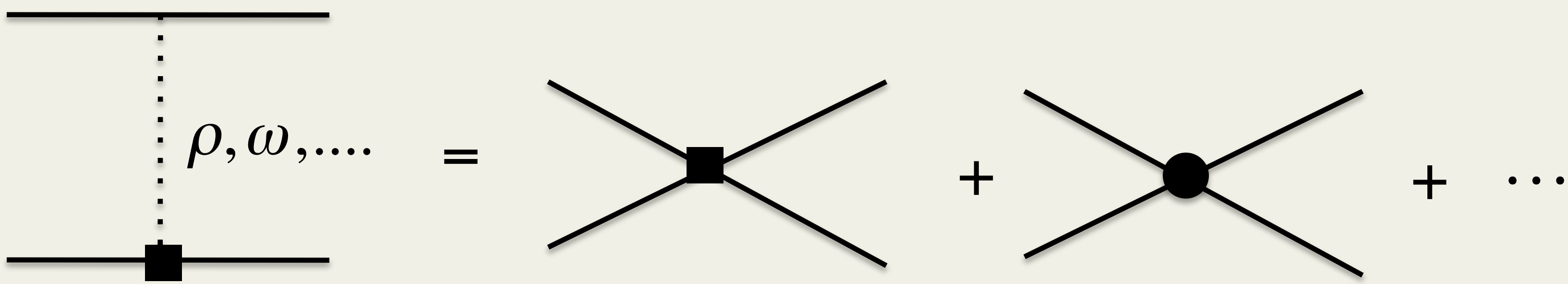
↓

Dictionary between **EFT** and **DDH** model

Interpretation of contact terms

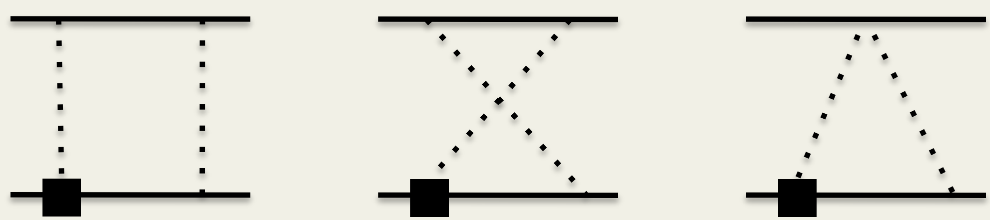
DDH framework

Effective Field Theory



$$\frac{g\bar{g}}{\vec{q}^{\,2}+M^2} = \frac{g\bar{g}}{M^2} - \frac{g\bar{g}}{M^2}\frac{\vec{q}^{\,2}}{M^2} + \cdots$$

Make sure not to 'double count' two-pion exchange



DDH-NN dictionary

- Relation to DDH parameters

$$\frac{C}{F_\pi \Lambda_\chi^2} + \frac{g_A^3 h_\pi}{2\sqrt{2}F_\pi}\frac{8}{(4\pi F_\pi)^2}\frac{s}{\Lambda_S} \simeq$$
$$\frac{1}{m_N}\left[\frac{g_\omega(2+\chi_S)}{m_\omega^2}h_\omega^{pp}c_\omega(0,\Lambda_\omega) + \frac{g_\rho(2+\chi_V)}{m_\rho^2}h_\rho^{pp}c_\rho(0,\Lambda_\rho)\right]$$

JdV et al '14

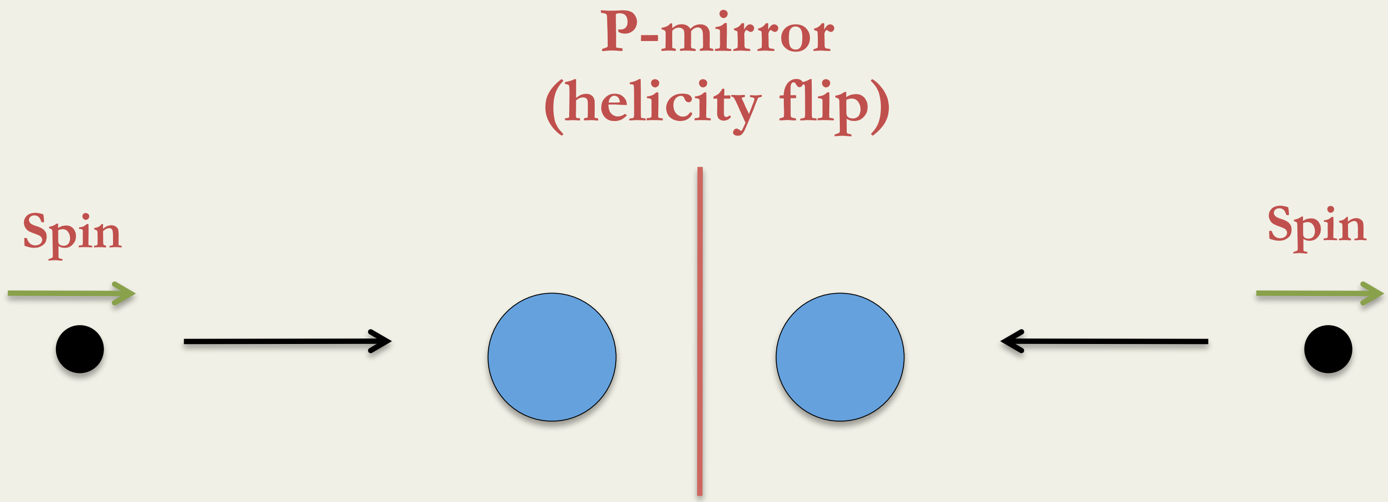
LEC	DDH "best" value	DDH range	KMW
C_0	$4.7 \cdot 10^{-6}$	$(-5.0 \to 13) \cdot 10^{-6}$	$0.89 \cdot 10^{-6}$
C_1	$1.2 \cdot 10^{-6}$	$(-2.5 \to 4.5) \cdot 10^{-6}$	$0.11 \cdot 10^{-6}$
C_2	$-2.2 \cdot 10^{-6}$	$(-5.0 \to -0.2) \cdot 10^{-6}$	$-0.66 \cdot 10^{-6}$
C_3	$1.0 \cdot 10^{-6}$	$(0.8 \to 1.2) \cdot 10^{-6}$	$0.41 \cdot 10^{-6}$
C_4	$0.25 \cdot 10^{-6}$	$(-0.1 \to 0.7) \cdot 10^{-6}$	$-0.049 \cdot 10^{-6}$

- Provides **very rough** estimates of short-distance LECs
- Nevertheless: more accurate than naïve dimensional analysis
- Use it later for some rough estimates

How to measure PV with hadrons?

$$\frac{h_\pi}{g_A} \sim O\left(G_F F_\pi \Lambda_\chi\right) \sim 10^{-6,-7}$$

- Huge **strong (and EM) background** in 'normal' observables.
- Look at observables that filter out PV



- Observable: $A_L = \dfrac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$, **L**ongitudinal **A**nalyzing **P**ower **(LAP)**
- Other observables: spin rotation, photon polarization, …..

The longitudinal asymmetry

- Apply the framework to the asymmetry in $\vec{p}p \rightarrow pp$ scattering

- Three most accurate data points

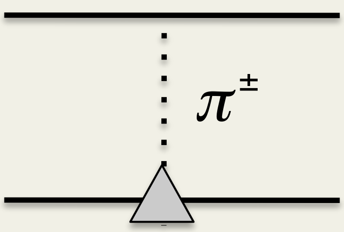
		Angular range
Bonn	$A_L(14\ MeV) = -(0.93 \pm 0.21)\cdot 10^{-7}$	$(20^\circ - 78^\circ)$
PSI	$A_L(45\ MeV) = -(1.50 \pm 0.22)\cdot 10^{-7}$	$(23^\circ - 52^\circ)$
TRIUMF	$A_L(221\ MeV) = +(0.84 \pm 0.34)\cdot 10^{-7}$	$(\theta_c^\circ - 90^\circ)$

- Earlier analysis in Carlson et al '03 and Haxton/Holstein '13 in terms of DDH parameters/Danilov parameters.

Eversheim *et al PLB* '91 Kistryn *et al PRL* '87 Berdoz *et al PRL* '01

Vanishing of one-pion exchange

- Consider the P-odd leading order potential



$$V_{OPE} = -\left(\frac{g_A h_\pi}{2\sqrt{2}F_\pi}\right) i(\vec{\tau}_1 \times \vec{\tau}_2)^3 \frac{(\vec{\sigma}_1 + \vec{\sigma}_2)^3 \cdot \vec{q}}{\vec{q}^{\,2} + m_\pi^2}$$

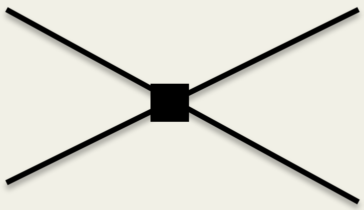
- Vanishes between states of equal total isospin…..

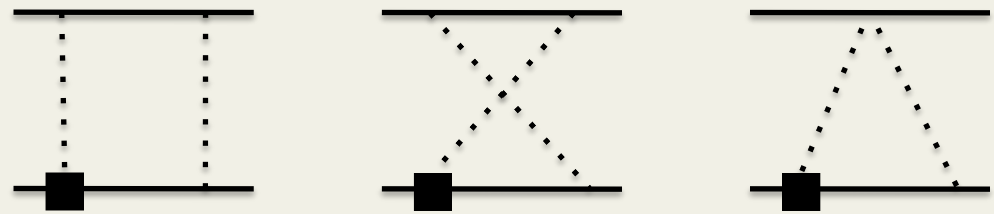
$$< t' || V_{OPE} || t > \sim (t' - t)$$

- **No contribution to proton-proton scattering….**

But two-pion exchange!

- But we do get contributions at higher order





One NN contact term

two-pion exchange!

C $\qquad$ h_π

- The analyzing power depends on **two** unknown couplings

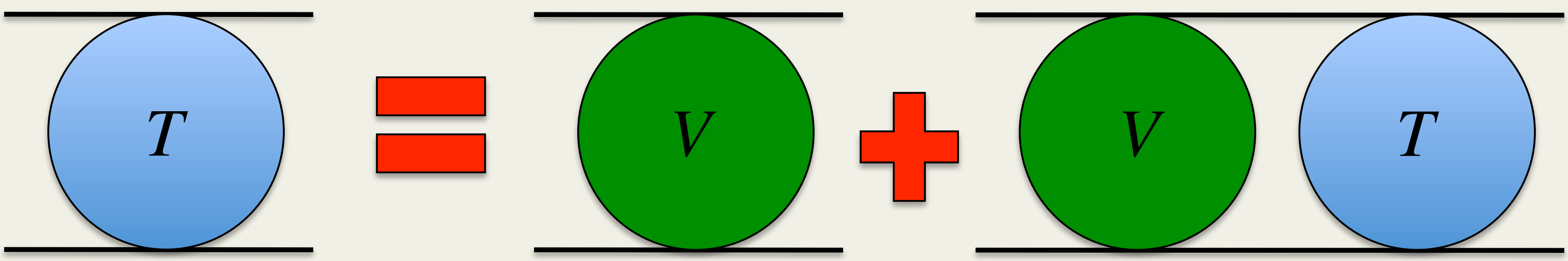
- **Can we learn something about** h_π **? (3 data points …)**

The actual calculation

- Solve the Lippmann-Schwinger equation in presence of P-violation.

$$T = V + V\, G_0\, T \qquad\qquad V = V_{strong} + V_{weak}\ (+V_{Coulomb})$$

Both from chiral EFT



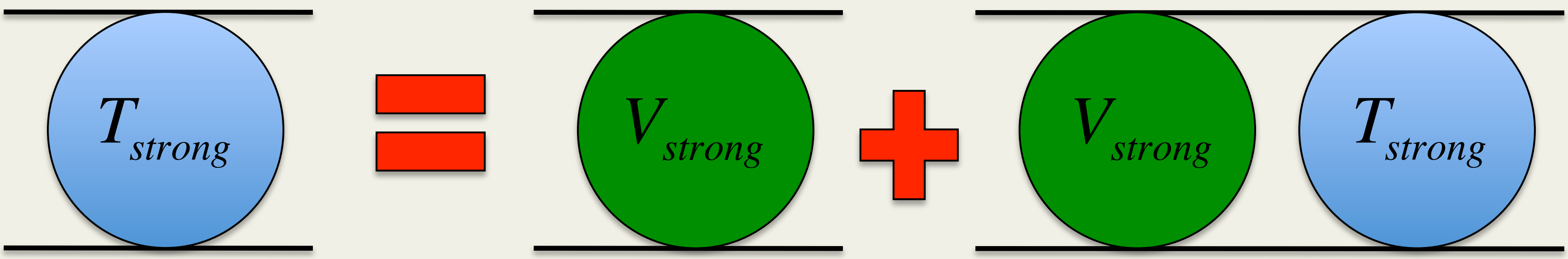
Driscoll, Miller ’89 Driscoll, Meißner ’90 Carlson et al ’02 JdV, Meißner, Epelbaum, Kaiser ‘13

The actual calculation

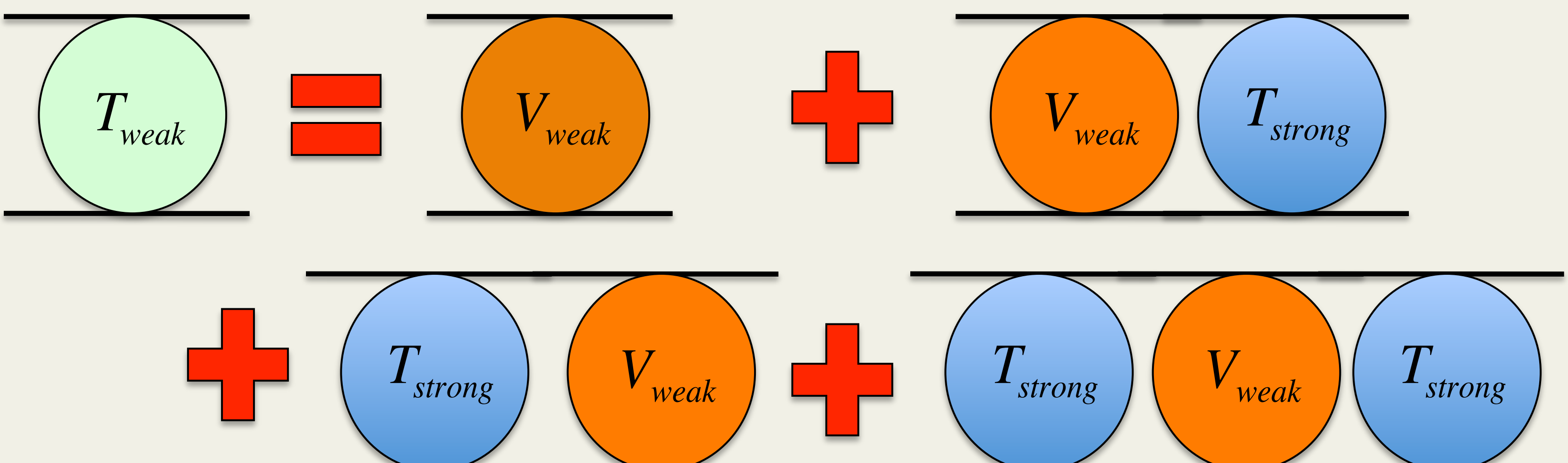
- Solve Lippmann-Schwinger equation

$$T = T_{strong} + T_{weak}$$

$$T_{strong} = V_{strong} + V_{strong}\ G_0\ T_{strong}$$



- Dress with the P-violating potential

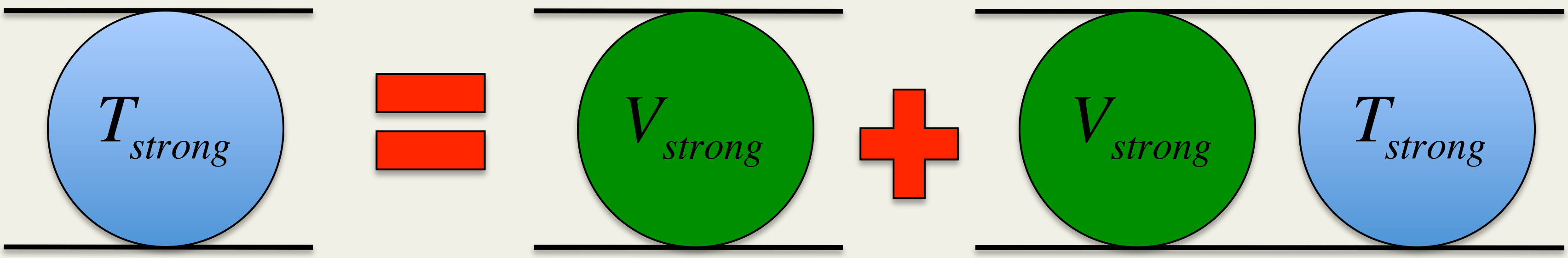


The actual calculation

- Solve Lippmann-Schwinger equation

$$T = T_{strong} + T_{weak}$$

$$T_{strong} = V_{strong} + V_{strong}\, G_0\, T_{strong}$$



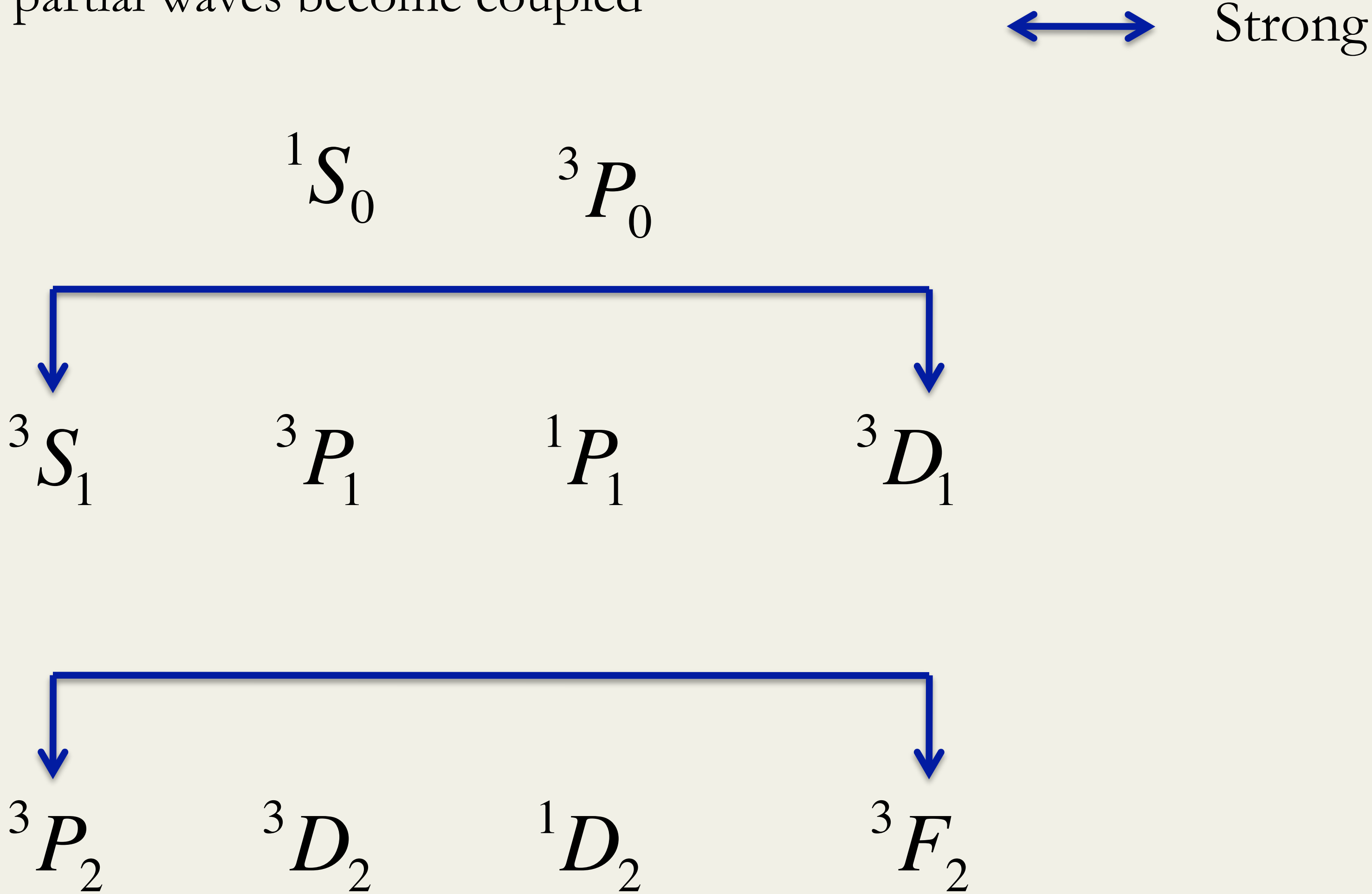
- Cut-off is needed to regularize the integral in the LS equation

$$V \rightarrow e^{-\frac{p^6}{\Lambda^6}}\, V\, e^{-\frac{p'^6}{\Lambda^6}}$$

- Cut-off applied to P-even and P-odd sectors and varied simultaneously (400 – 700 MeV)

What does P-violation add?

- More partial waves become coupled



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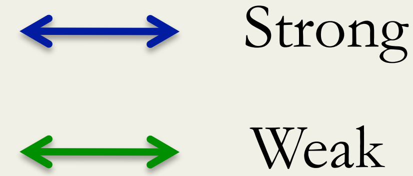
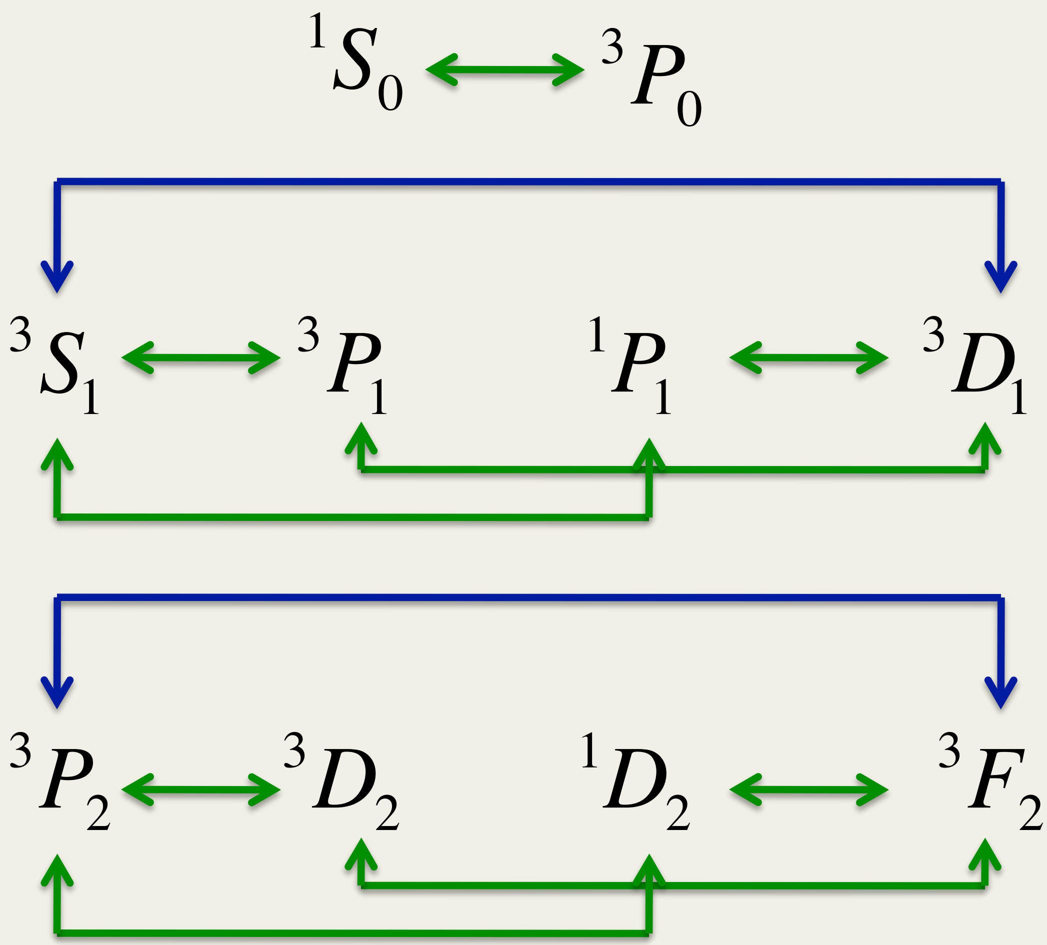
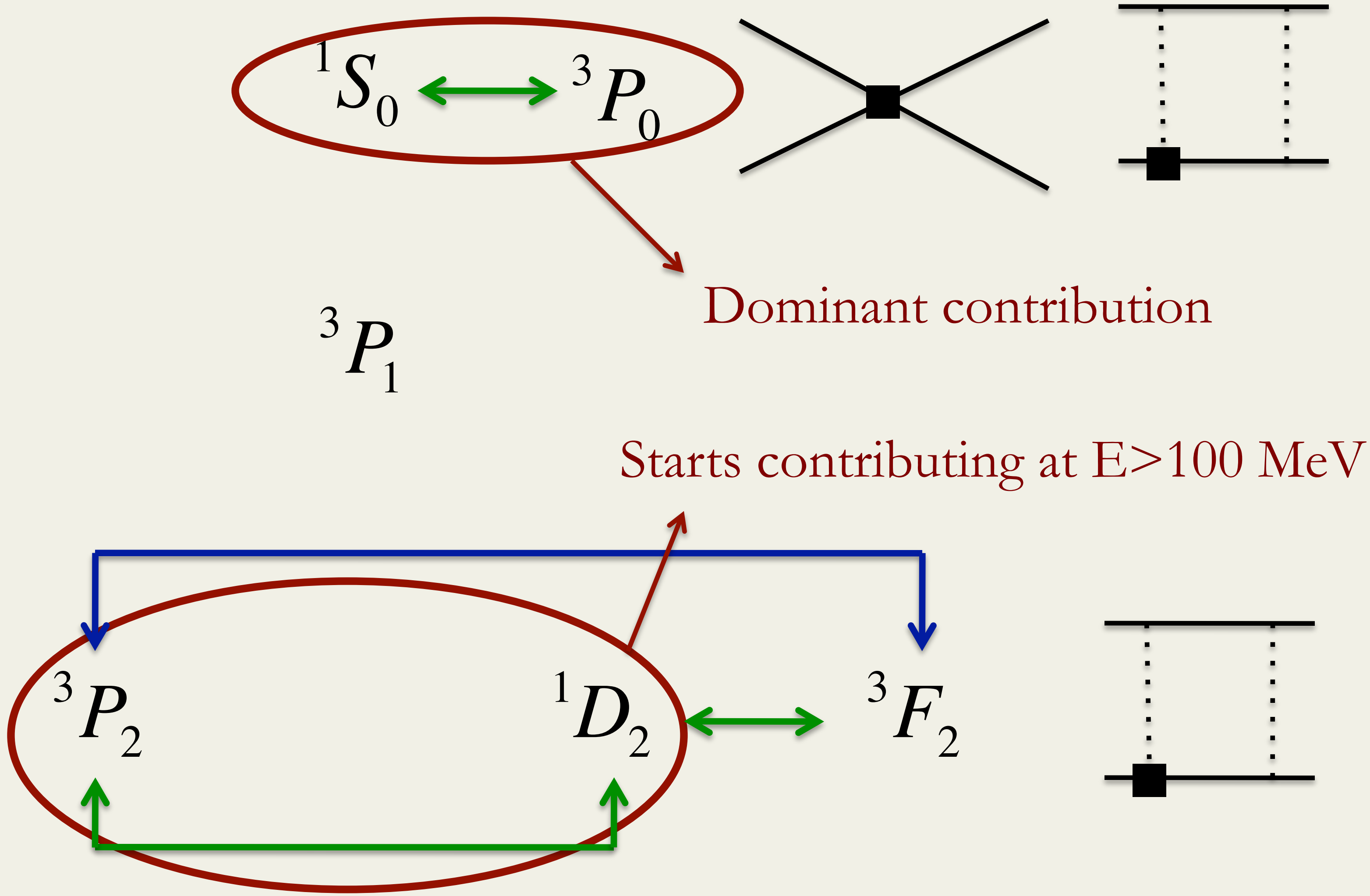




What does P-violation add?

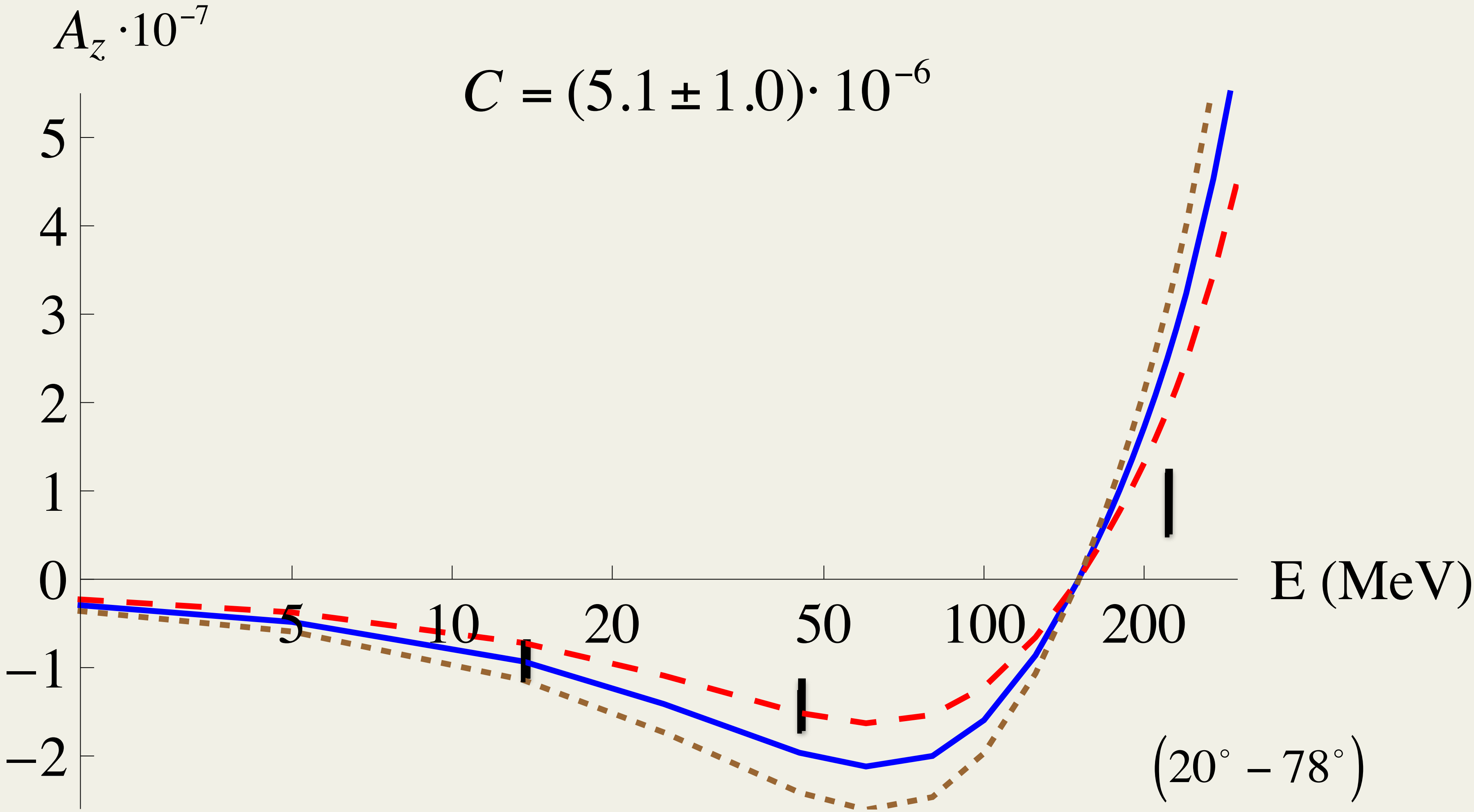
- **But easier in case of proton-proton**



Low-energy data

JdV, Meißner, Epelbaum, Kaiser '13

- We first use the DDH 'value' for $h_\pi = (0.46)\cdot 10^{-6}$ and fit C



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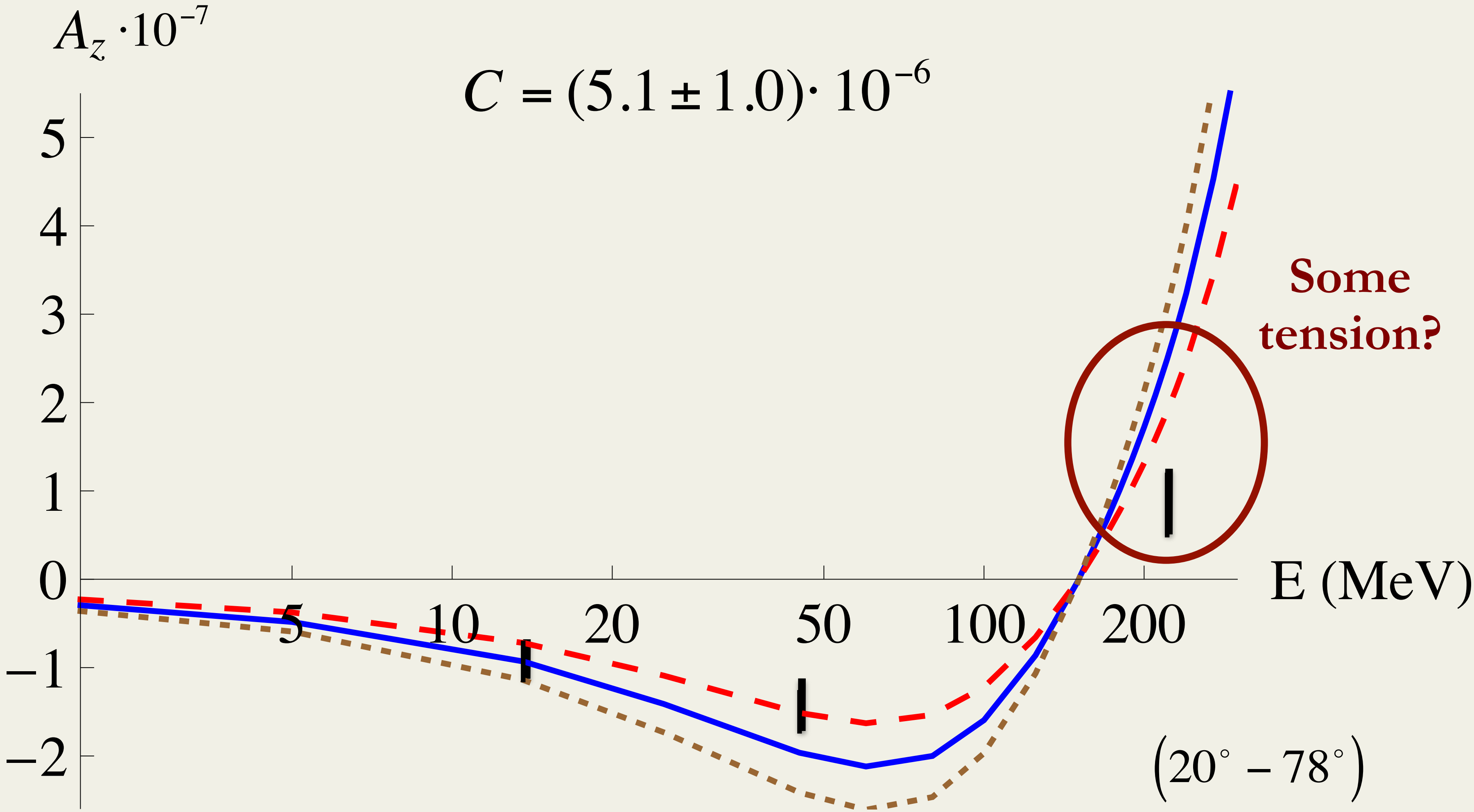


Medium-energy data

- The TRIUMF experiment measures over much smaller angles $\left(2^\circ - 90^\circ\right)$
- Differences due to j=2 transitions **and Coulomb**

$$\sigma_C(E) \propto \frac{\alpha_{em}^2}{E^2}\left(\frac{1}{\sin^2\theta_c} + \cdots\right)$$

But effects diminish for larger energies

Blows up for small opening angles

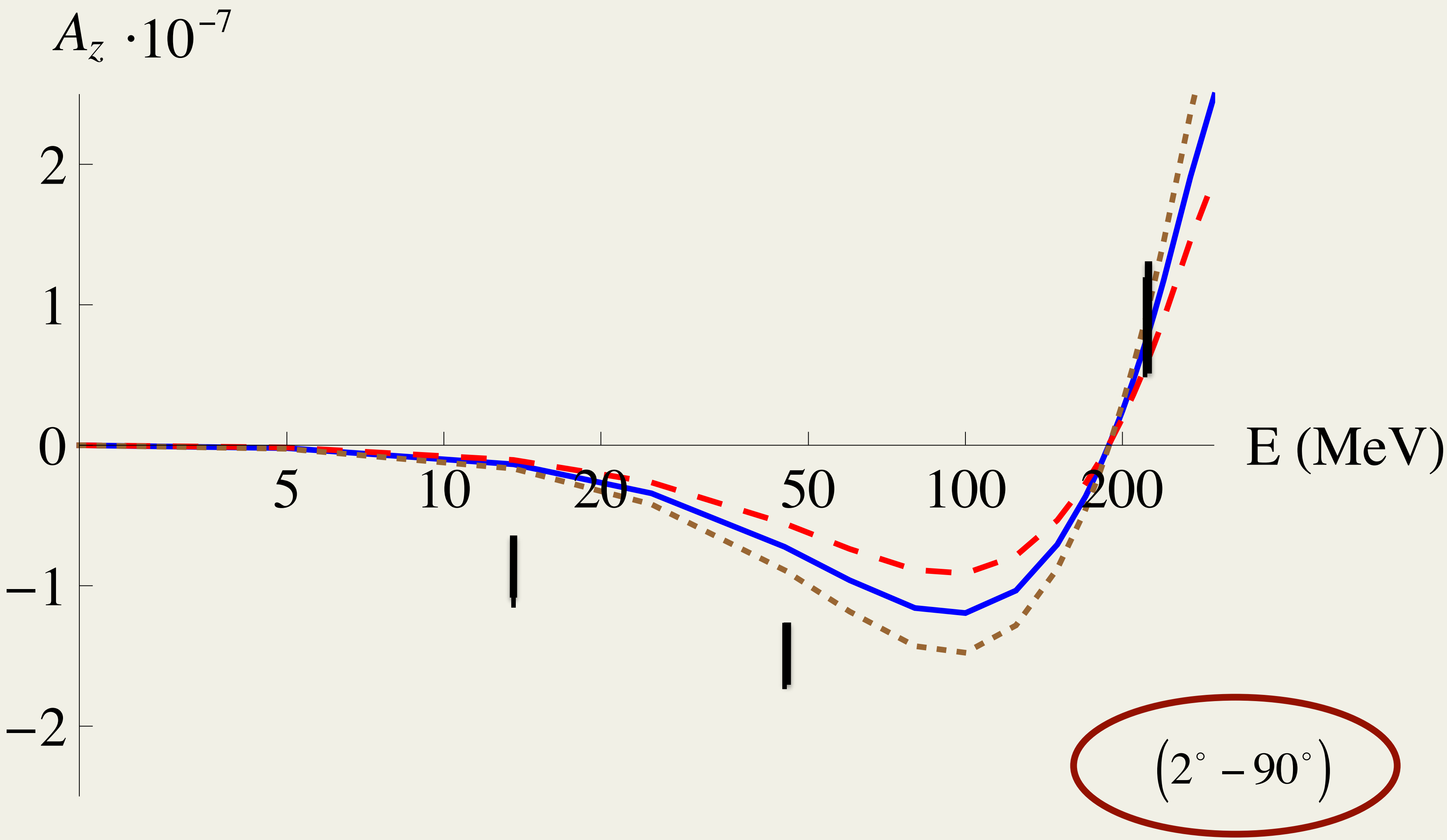
- Coulomb conserves P: so only $(\sigma_L + \sigma_R)$ is affected

$$A_L(\theta_1,\theta_2,E) = \frac{\int d\Omega\,(\sigma_L - \sigma_R)}{\int d\Omega\,(\sigma_L + \sigma_R)}$$

Driscoll & Miller, '89, Driscoll & Meißner '90, Carlson et al '90, JdV et al' 13, Viviani et al '14

Medium-energy data

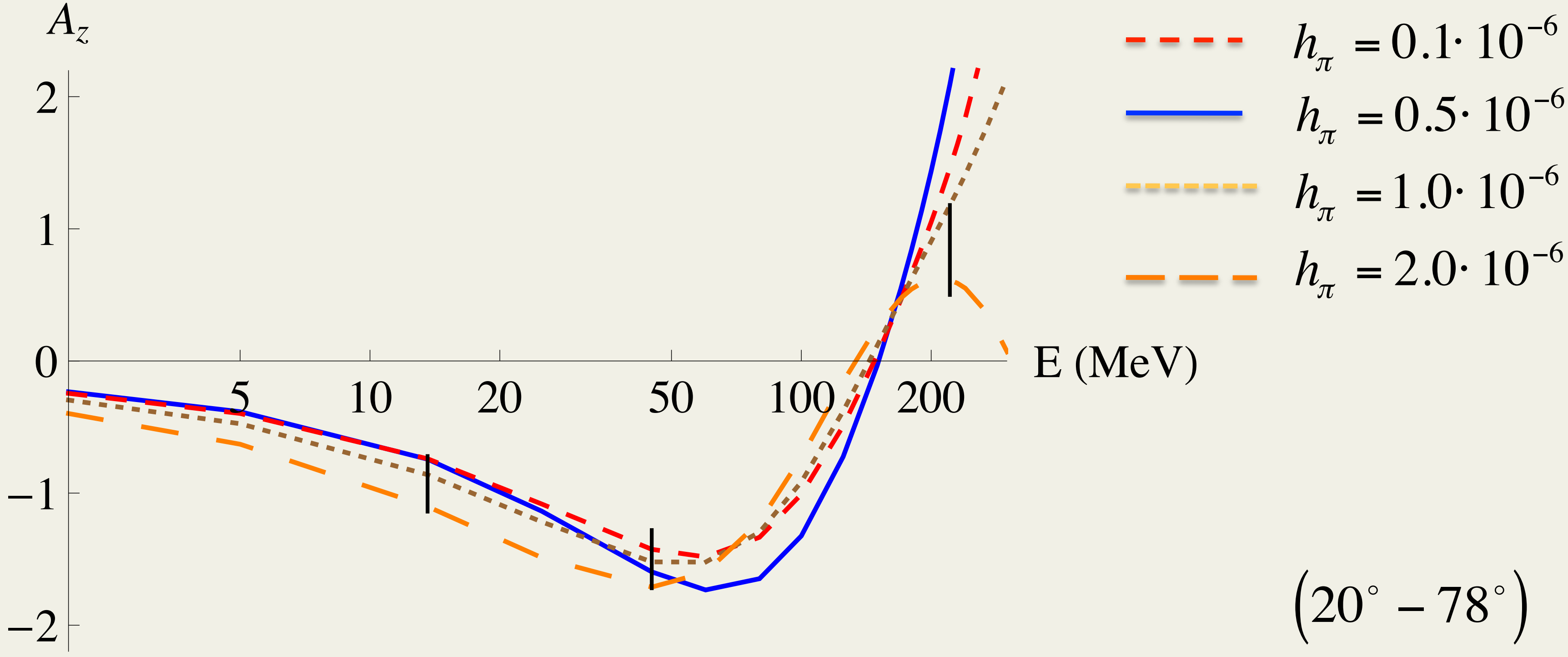
- The TRIUMF experiment measures over much smaller angles



Large errors……

- It seems the DDH value works well, but……
- Uncertainties (mainly lack of data) **too big** to draw conclusion
- Fit to first 2 data points

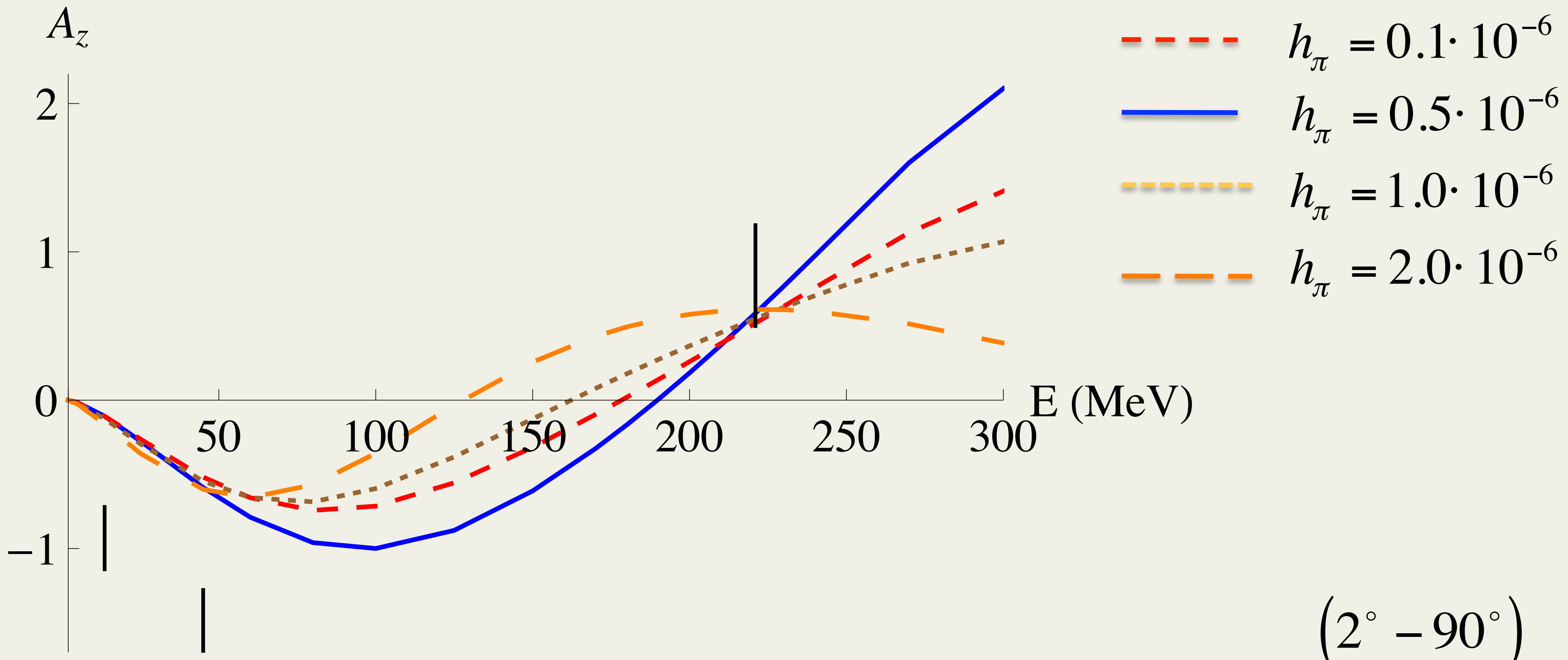
$$h_\pi = (1.1 \pm 2.0) \cdot 10^{-6} \qquad C = (-9.3 \pm 10) \cdot 10^{-6}$$



Large errors……

- It seems the DDH value works well, but……
- Prediction for third data: CROSSING POINT !!??
- **Experiment around 100-150 MeV would help (@CSNS China ?)**

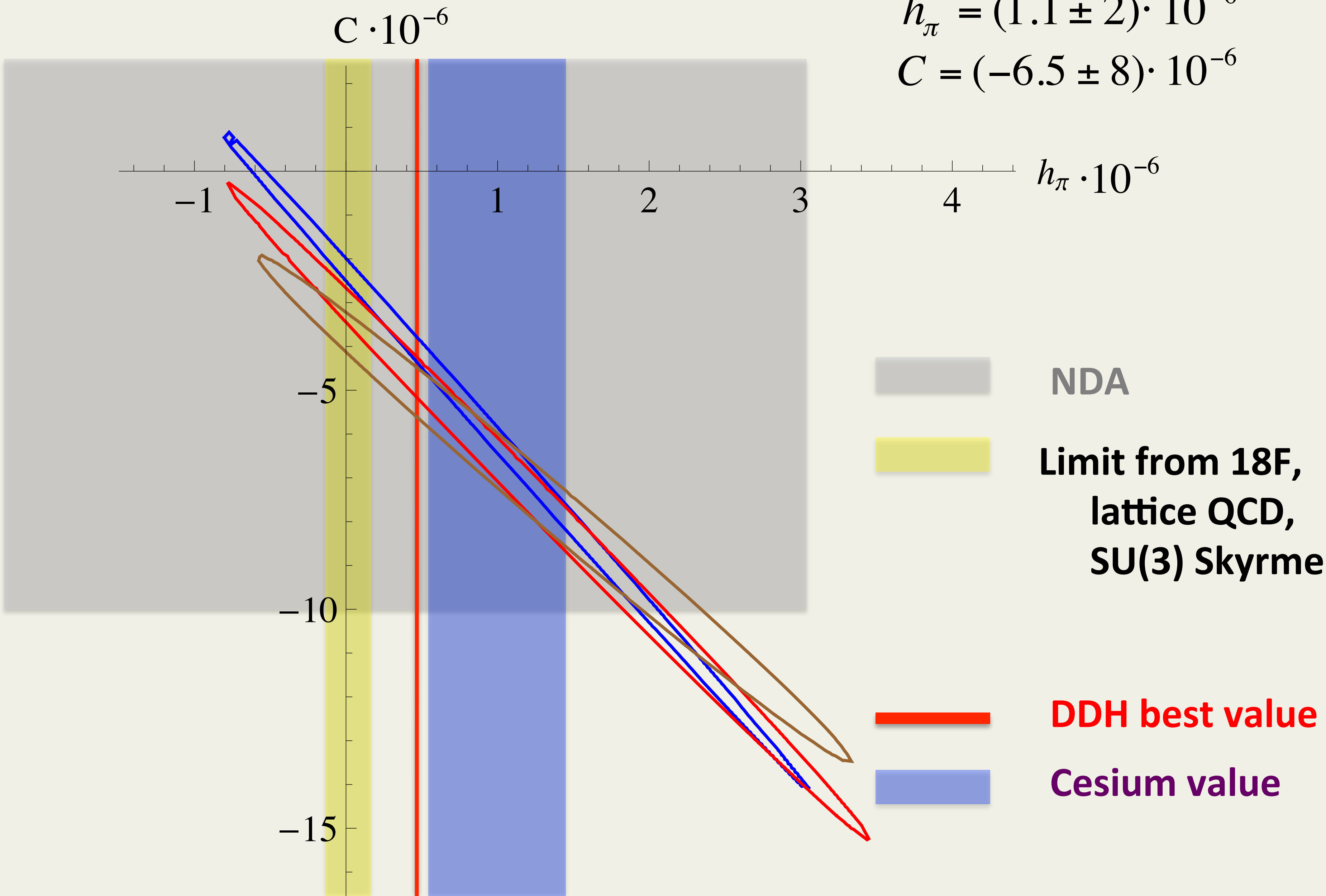
$$h_\pi = (1.1 \pm 2.0)\cdot 10^{-6} \qquad C = (-9.3 \pm 10)\cdot 10^{-6}$$



$(2^\circ - 90^\circ)$

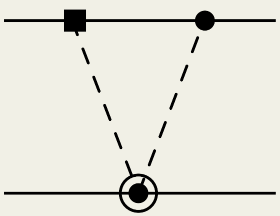
Fit to pp data

$$h_\pi = (1.1 \pm 2) \cdot 10^{-6}$$
$$C = (-6.5 \pm 8) \cdot 10^{-6}$$



Higher-order PV corrections

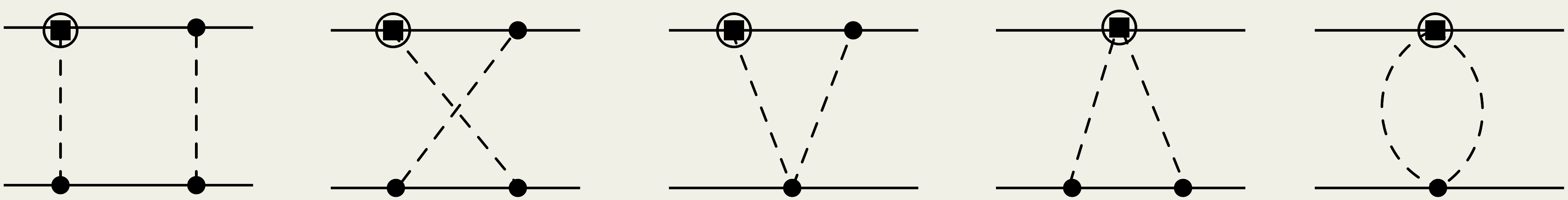
- The NNLO potential contains additional TPE diagrams



prop. to $\pi c_4 h_\pi$

$c_4 = 3.4\ GeV^{-1}$

Rather big: expected to be dominant!

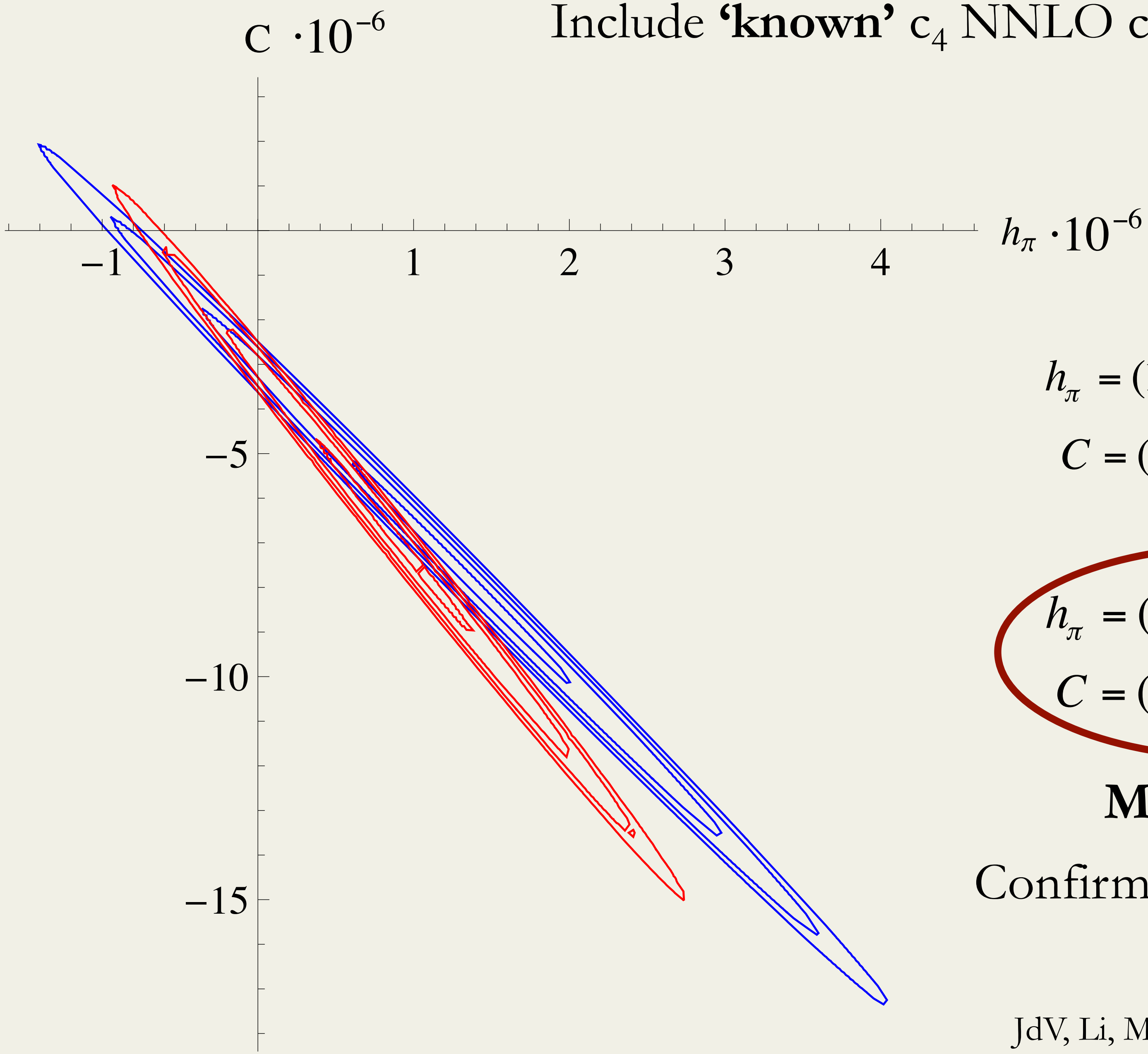


5 New P-odd LECs. One combination appears in pp scattering

JdV, Li, Meißner, Kaiser, Liu, Zhu '14

Refit: sanity check

Include **‘known’** c_4 NNLO contributions



$h_\pi = (1.1 \pm 2) \cdot 10^{-6}$

$C = (-6.5 \pm 8) \cdot 10^{-6}$

$h_\pi = (0.8 \pm 1.5) \cdot 10^{-6}$

$C = (-5.5 \pm 7) \cdot 10^{-6}$

Modified fit

Confirms power counting!

JdV, Li, Meißner, Kaiser, Liu, Zhu ‘14

Theory of the longitudinal asymmetries

$$\vec{n} + p \rightarrow d + \gamma \qquad\qquad \frac{d\sigma}{d\Omega} \sim 1 + A_\gamma \cos\theta$$

- For a long time an upper limit existed $A_\gamma = (1.2 \pm 2) \cdot 10^{-7}$

Gericke et al, PRC '11

- A few years ago there was a preliminary measured that turned out to be 'contaminated' by the 'wrong' Aluminium

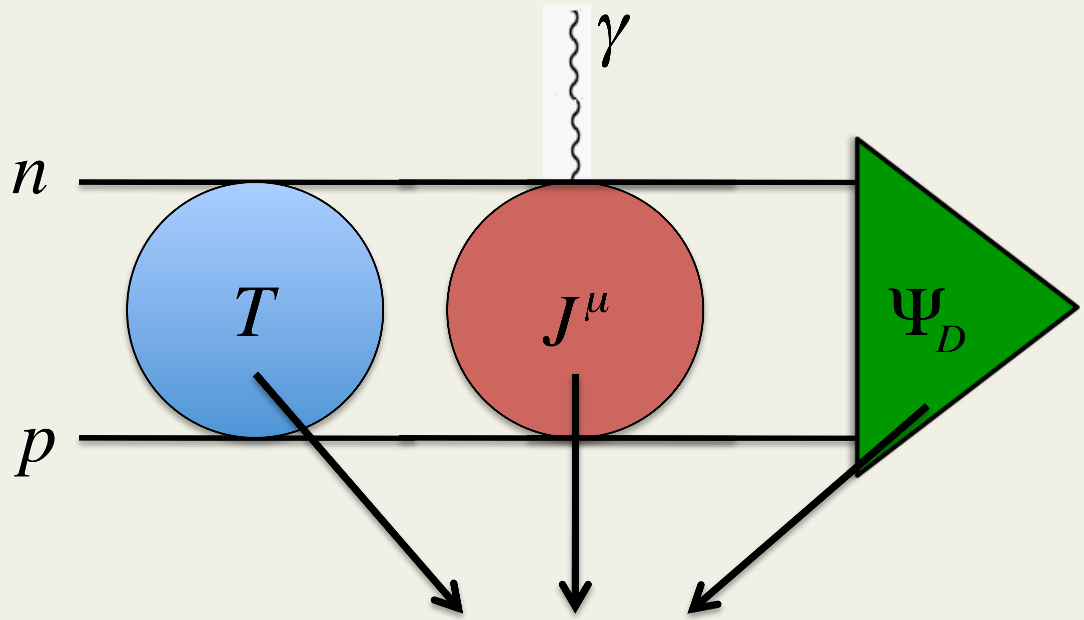
$$A_\gamma = -(0.7 \pm 0.4) \cdot 10^{-7}$$

- But now after an heroic effort from NPDgamma we have:

$$A_\gamma = -(0.31 \pm 0.15) \cdot 10^{-7}$$ (Almost all statistical uncertainty)

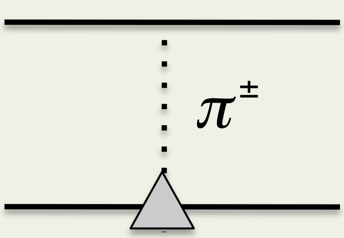
David Blyth, PhD thesis, Arizona State University (2017)

Neutron-Proton fusion



All containing PV components

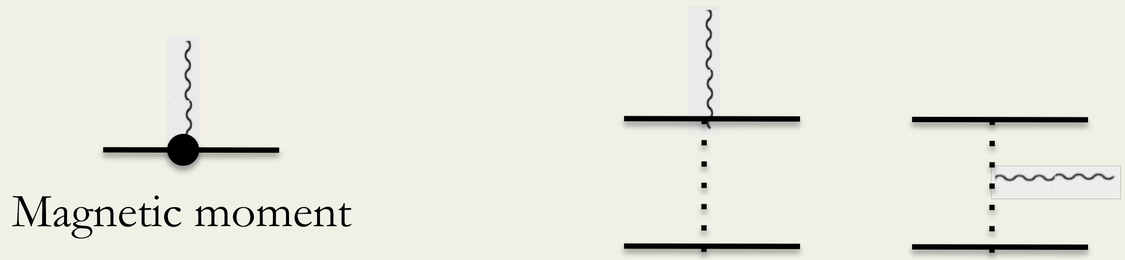
- Get deuteron wave function with same PC + PV potential + regulator
- T-matrix is the same as before but now for neutron-proton



- LO PV potential now contributes !! (unlike in pp)

Neutron-Proton fusion

- First study P-conserving total cross section to 'check' formalism
- The dominant contribution arises from the nucleon magnetic moment
- At NLO we get one-pion-exchange currents



	Isovector magnetic moment	+PC OPE currents	Experimental result
σ_{tot}	305 ± 4	319 ± 5	334.2 ± 0.5

JdV et al' 15

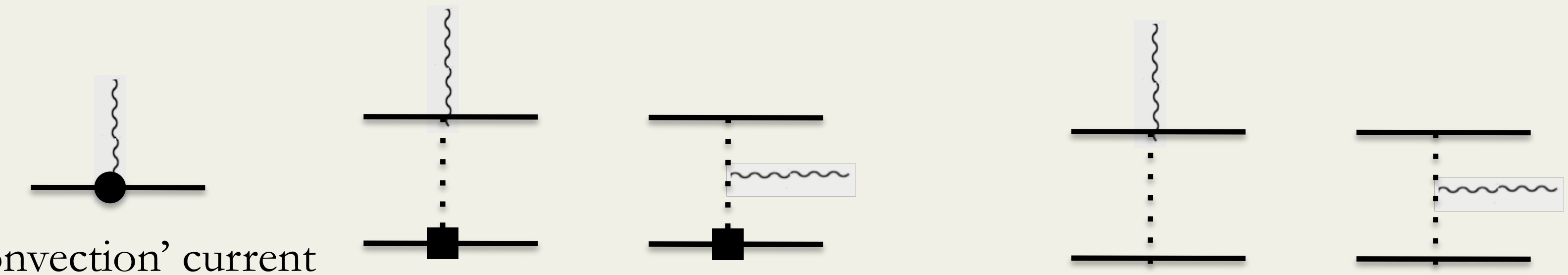
- In principle, we need to add TPE currents + contract currents at N2LO to describe the remaining 3% or so of the cross section
- Not included because PV analogues have not been calculated…
- Phenomenological potentials + OPE currents ~ 320 mb

Carlson et al '98 '03
Hyun et al '01 '05

PV in proton-neutron fusion

$$\vec{n} + p \rightarrow d + \gamma \qquad \frac{d\sigma}{d\Omega} \sim 1 + A_\gamma \cos\theta$$

- For LAP need interference between E1 and M1 currents. LO requires:



'convection' current

- Contribution 1: PV in wave functions + PC one-body current
- Contribution 2: PV in wave functions + PC OPE currents
- Contribution 3: PC wave functions + PV OPE currents

	Part 1	Part 2	Part 3	Total
a_γ / h_π	-0.27 ± 0.03	-0.53 ± 0.02	0.72 ± 0.03	-0.11 ± 0.05

- Cancellations between contributions causes **theoretical uncertainty**
- **Should be possible to improve**

JdV, Li, Meißner, Epelbaum, Kaiser, Nogga et al' 15

PV in proton-neutron fusion

$$\vec{n} + p \rightarrow d + \gamma \qquad \frac{d\sigma}{d\Omega} \sim 1 + A_\gamma \cos\theta$$

- For LAP need interference between E1 and M1 currents. LO requires:

- At NLO there appear PV contact terms and currents:

$$A_\gamma (10^{-8}\ MeV) = -(0.11 \pm 0.04)\, h_\pi + (0.055 \pm 0.025)\, C_4$$

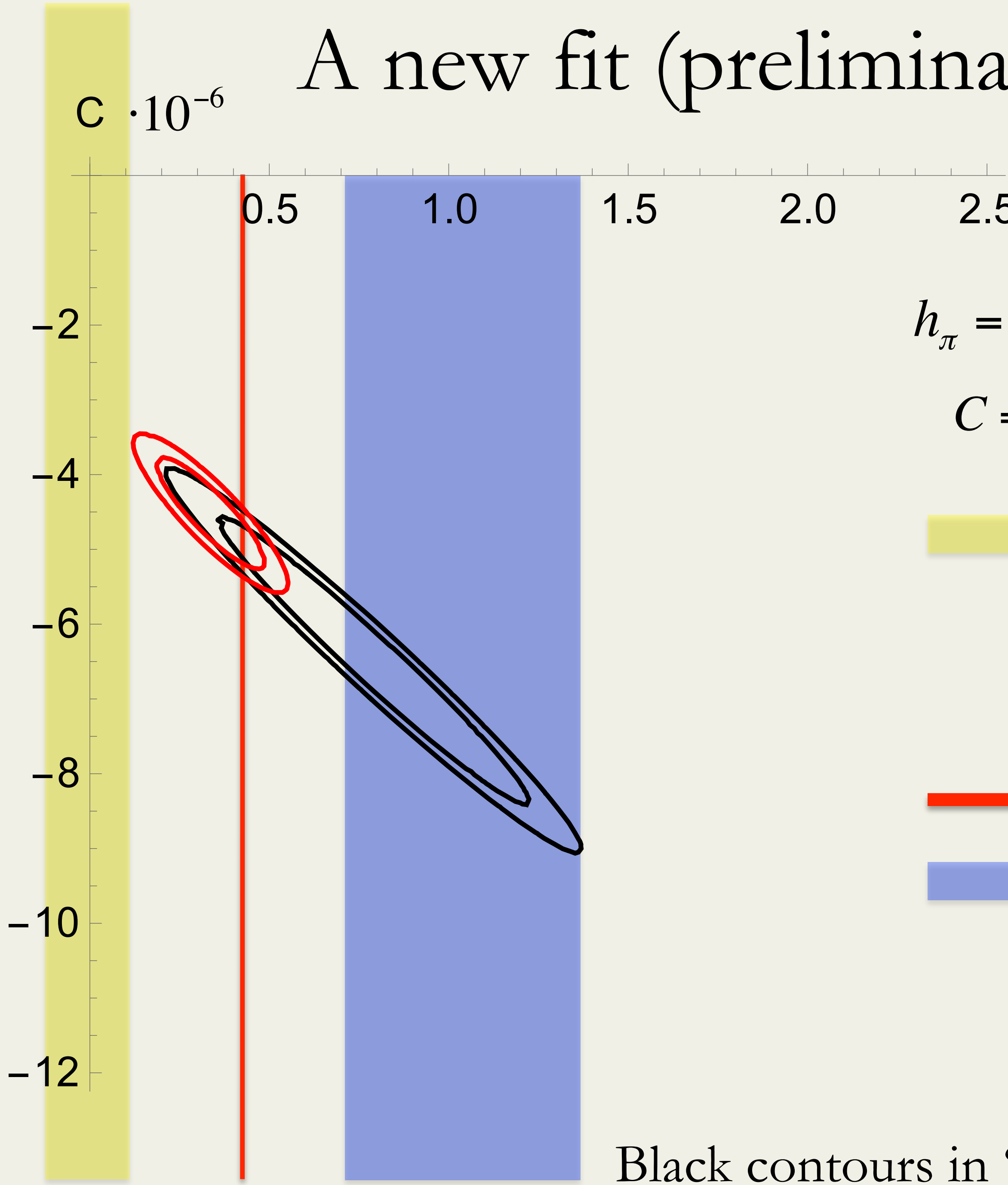
- C_4 should be NLO ! But if $h_\pi \sim 0$….
- Estimate by resonance factorization + parameter estimates

$$C_4 = \frac{F_\pi \Lambda_\chi^2}{2m_N}\left[\frac{g_\omega h_\omega^1}{m_\omega^2} + \frac{g_\rho (h_\rho^{1\prime} - h_\rho^1)}{m_\rho^2}\right] \qquad A_\gamma = -(0.11 \pm 0.04)\, h_\pi + (0.5 \pm 0.5) \cdot 10^{-8}$$

- Contact term seems small, but who knows…

JdV, Li, Meißner, Epelbaum, Kaiser, Nogga et al' 15

A new fit (preliminary…)



$$h_\pi = (0.40 \pm 0.25) \cdot 10^{-6}$$

$$C = (-5 \pm 2) \cdot 10^{-6}$$

Limit from 18F, lattice QCD, SU(3) Skyrme

DDH best value

Cesium value

Black contours in ‘15 paper (wrong data)

Framework can (has been) extended

- Pisa group has performed chiral-EFT calculations for spin-rotation measurements in n-p, n-^{2}H, n-^{3}He,
- And on the LAP in n + ^{3}He → p + ^{3}H

Viviani et al, PRC '14

$$A_L = -(0.14 \pm 0.01)h_\pi + (0.017 \pm 0.003)C_0 - (0.007 \pm 0.001)C_1 + (0.008 \pm 0.001)C_2 + (0.018 \pm 0.002)C_4.$$

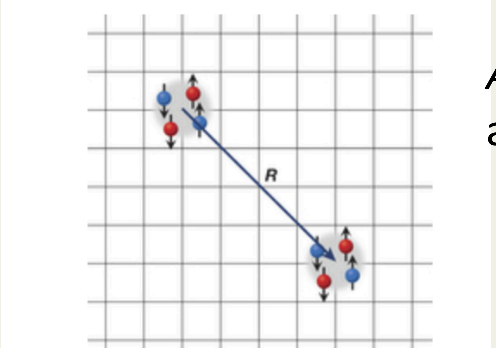
- Goal is to measure this at 2*10^{-8} level (Gericke, HPV workshop KITP)

- Larger systems difficult in chiral EFT (^{18}F, Cs) but clearly ^{18}F is crucial…
- Nonzero measurement was reported in proton-4He scattering

$$A_L(46\ MeV) = -(3.3 \pm 0.9) \cdot 10^{-7}$$

- Something for Nuclear lattice-EFT ?

D. Lee et al Nature '15



Ab initio alpha–alpha scattering

Summary-Outlook

- A chiral EFT approach to hadronic PV has been developed
- **Systematic** approach to P-even and -odd interactions
- So far: applied to pp and np→ dgamma + fits to data
- **Evidence for sizeable weak pion-nucleon coupling**

However…

- The evidence is still weak…
- Inconsistent PV in Fluoride decays... (but not so easy in our framework)
- **More observables** can and should be included
- **Theoretical accuracy** of np→d gamma should be improved
- Work in progress....

A new Lattice idea

Chien-Yeah Seng et al, PRL '18

- Direct lattice calculation of h_π difficult (pion-nucleon state…)

- Trick: chiral symmetry connects operators with different P
- Used to 'understand' the theta term +dim-6 CPV

Crewther et al, 79
Pospelov '03
JdV et al '15' 16

$$\bar{\theta}\,\bar{m}\,\bar{q}i\gamma^5 q \quad \longleftrightarrow \quad (m_u - m_d)\,\bar{q}\boldsymbol{\tau}^3 q$$

$SU_A(2)$

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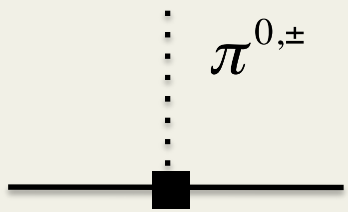
$SU_A(2)$

$\pi^{0,\pm}$



$\bar g_0$

δm_N

CP-odd pion-nucleon coupling ⟷ **Strong proton-neutron mass splitting**

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

Use **lattice** for mass splitting

Walker-Loud '14, Borsanyi '14, Aoki (FLAG) '13

$$g_0 = \delta m_N \frac{1-\varepsilon^2}{2\varepsilon}\bar\theta = (15.5 \pm 2.5)\cdot 10^{-3}\ \bar\theta$$

A new Lattice idea

Feng, Guo, Seng, PRL '18

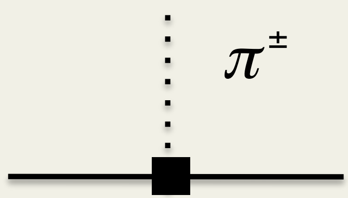
- Direct lattice calculation of h_π difficult (pion-nucleon state…)

- Trick: chiral symmetry connects operators with different P
- Apply it for hadronic PV

Crewther et al, 79
Pospelov '03
JdV et al '15' 16

$$\bar{q}\gamma^\mu q\ \bar{q}\gamma_\mu\gamma_5\boldsymbol{\tau}^3 q \longleftrightarrow \bar{q}\gamma^\mu q\ \bar{q}\gamma_\mu\boldsymbol{\tau}^3 q$$

$SU_A(2)$



h_π $\qquad$ $(\delta m_N)_{4q}$

P-odd pion-nucleon coupling ⟷ **'EW' proton-neutron mass splitting**

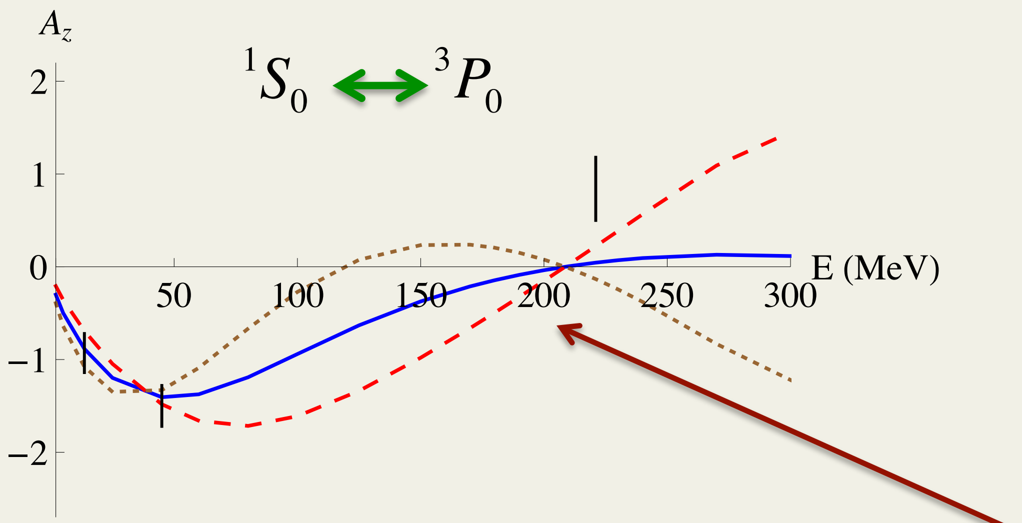
Idea: Use again **lattice** for mass splitting →simpler
Relation stable against N^2LO corrections!!

$$h_\pi = \frac{(\delta m_N)_{4q}}{\sqrt{2} f_\pi}$$

Can these relations be studied in large N_c ??

Crossing points

- Crossing points can be qualitatively understood by dissecting the partial-wave contributions. First ignore Coulomb.

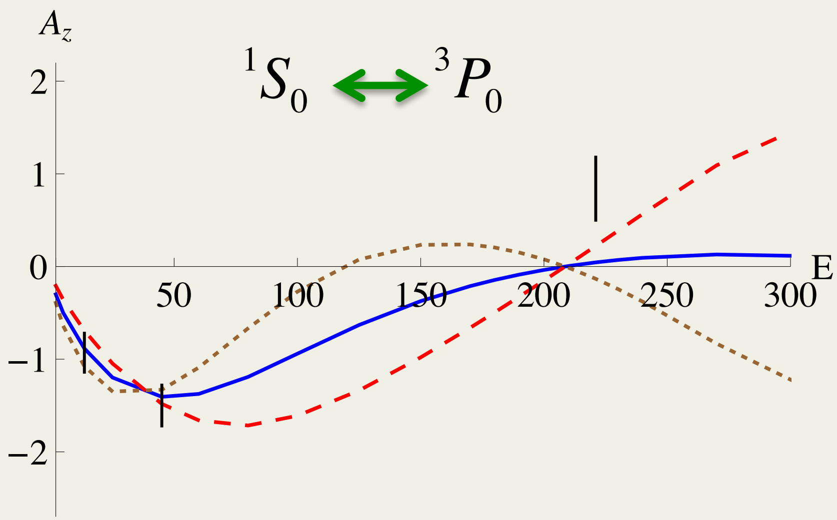


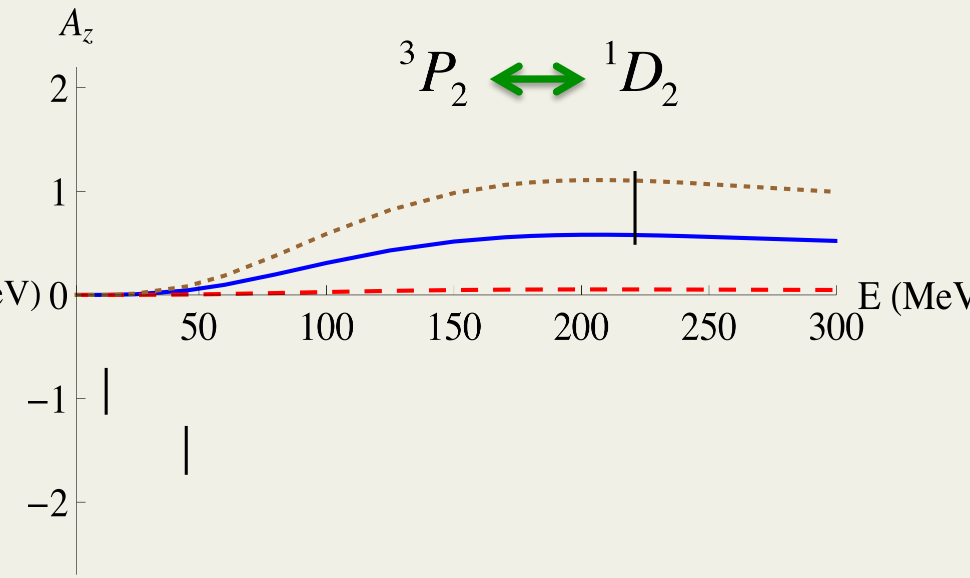
- The j=0 contributions: $\sim \sin\left(\delta_{^1S_0} + \delta_{^3P_0}\right)$ (optical theorem)
- Vanishes at (210 ± 5) MeV → Reason for TRIUMF energy
- Reasoning: Sensitive to different DDH parameters

(to j=2 transitions)

Crossing points

- Crossing points can be qualitatively understood by dissecting the partial-wave contributions. First ignore Coulomb.





- The j=2 contributions are fairly constant around 220 MeV

Crossing points

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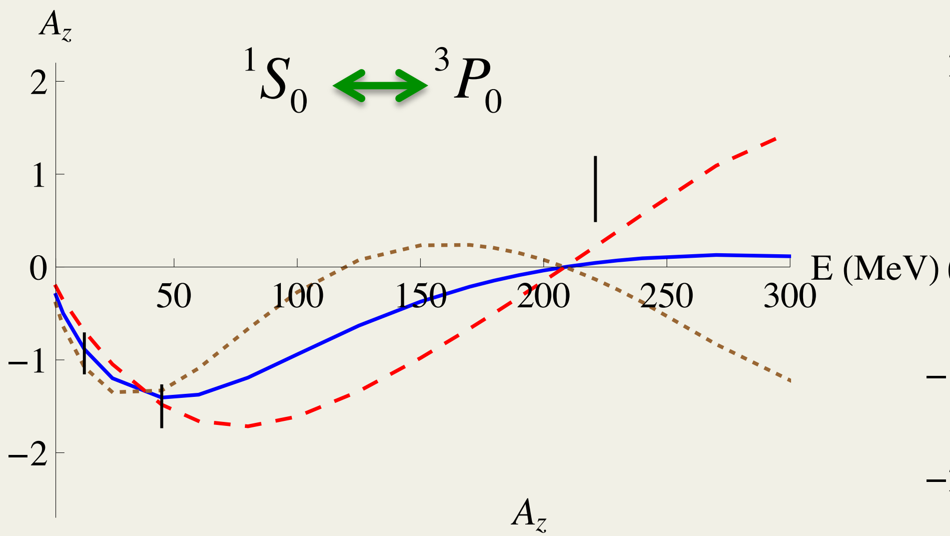
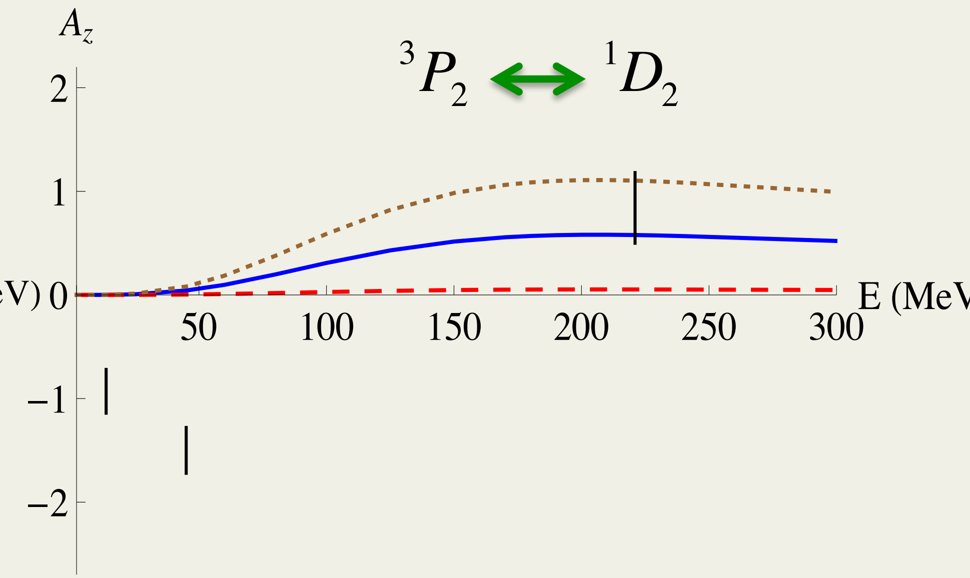
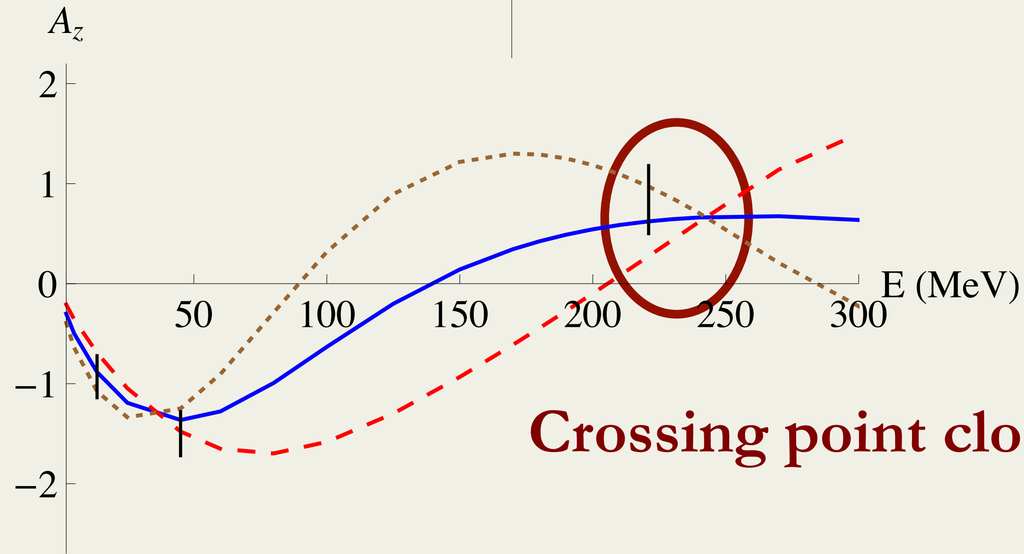




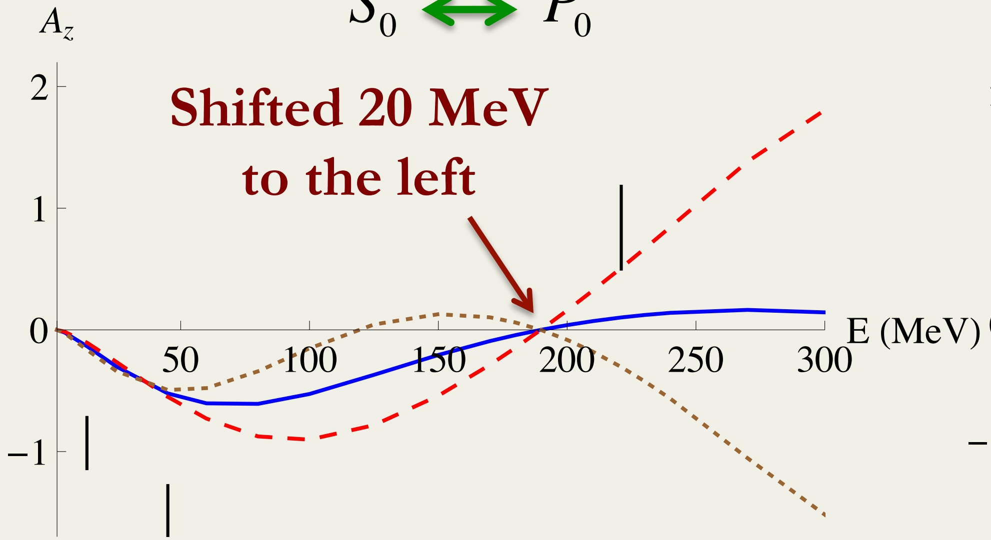


Crossing point close to 220 MeV

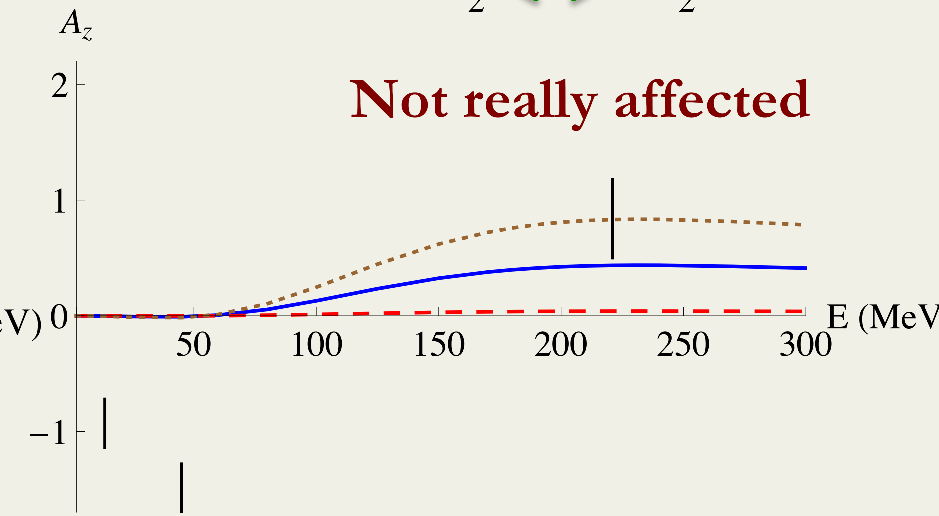
Crossing points

- Now add the Coulomb amplitude

$^1S_0 \longleftrightarrow {}^3P_0$



$^3P_2 \longleftrightarrow {}^1D_2$



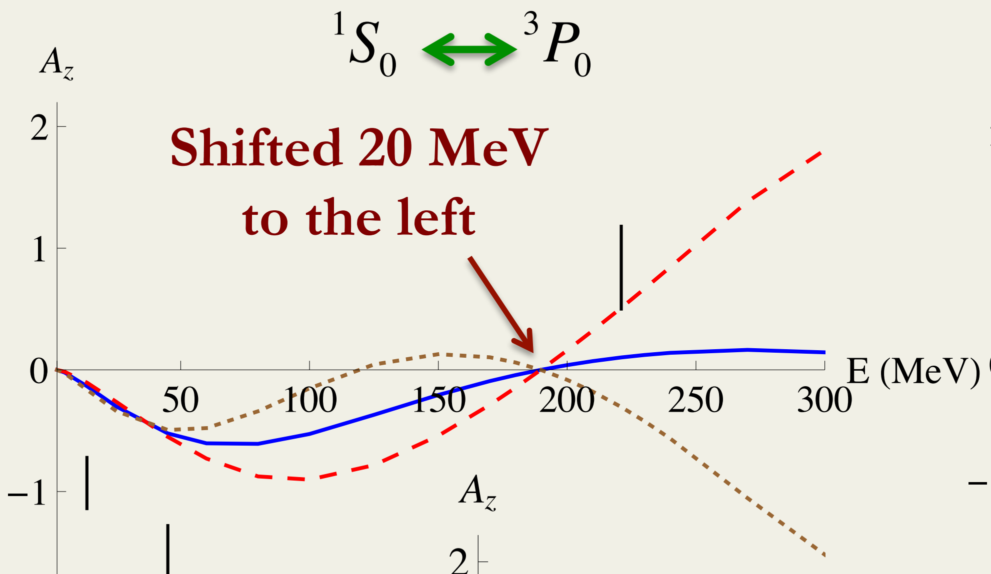
- The j=0 contributions: $\sim \sin\left(\delta_{^1S_0} + \delta_{^3P_0} + \phi_{em}\right)$

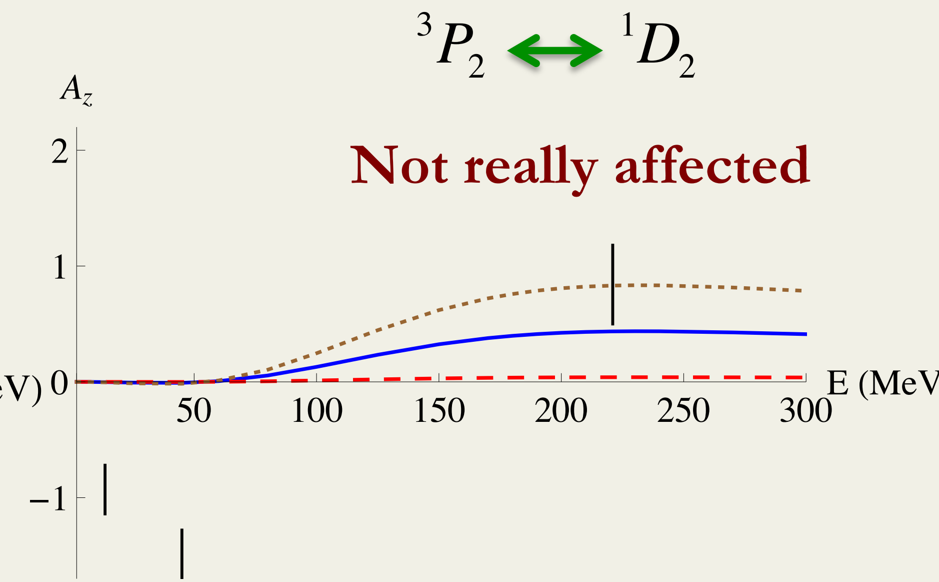
$$\phi_{em} \propto m_p \frac{\alpha_{em}}{\sqrt{E}} \ln(\sin\frac{\theta_c}{2}) \approx 4^\circ$$

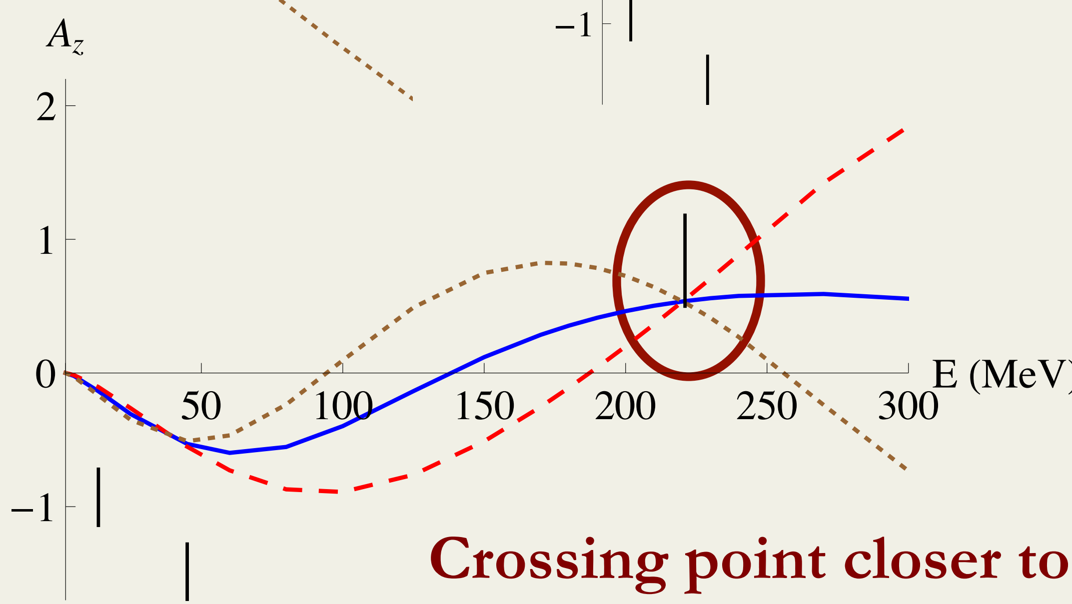
- New phase relatively small but….. **Important** for zero-crossing

Crossing points

- Now add the Coulomb amplitude







Crossing point closer to 220 MeV...

Chiral EFT → DDH translation