# Parity violation in $\vec{p}p$ scattering from chiral effective field theory

Jordy de Vries, Institute for Advanced Simulation, Institut für Kernphysik, and Jülich Center for Hadron Physics

In collaboration with: Ulf-G. Meißner, E. Epelbaum, N. Kaiser

# Outline of this talk

- **Part I: Parity-violating interactions**

- Part II: Chiral effective approach

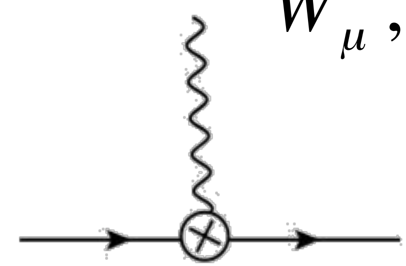
- Part III: The longitudinal asymmetry in pp scattering

# Parity violation in the SM

- Gauge Symmetries of the SM:

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

- After electroweak-symmetry breaking:




$$L = g\,(W_\mu^{+} J_W^{\mu +} + h.c.) + g Z_\mu J_Z^\mu$$

$$J_W^{\mu +} = {}^1\!/\!_{\sqrt{2}}\, \bar{u}_L \gamma^\mu d_L$$

$$J_Z^\mu = {}^1\!/\!_{\cos\theta_W} \left( \bar{u}_L \gamma^\mu u_L [{}^1\!/\!_2 - {}^2\!/\!_3 \sin^2\theta_W] + \bar{u}_R \gamma^\mu u_R [-{}^2\!/\!_3 \sin^2\theta_W] \right)$$

$$+ {}^1\!/\!_{\cos\theta_W} \left( \bar{d}_L \gamma^\mu d_L [-{}^1\!/\!_2 + {}^1\!/\!_3 \sin^2\theta_W] + \bar{d}_R \gamma^\mu d_R [{}^1\!/\!_3 \sin^2\theta_W] \right)$$

+ terms with leptons

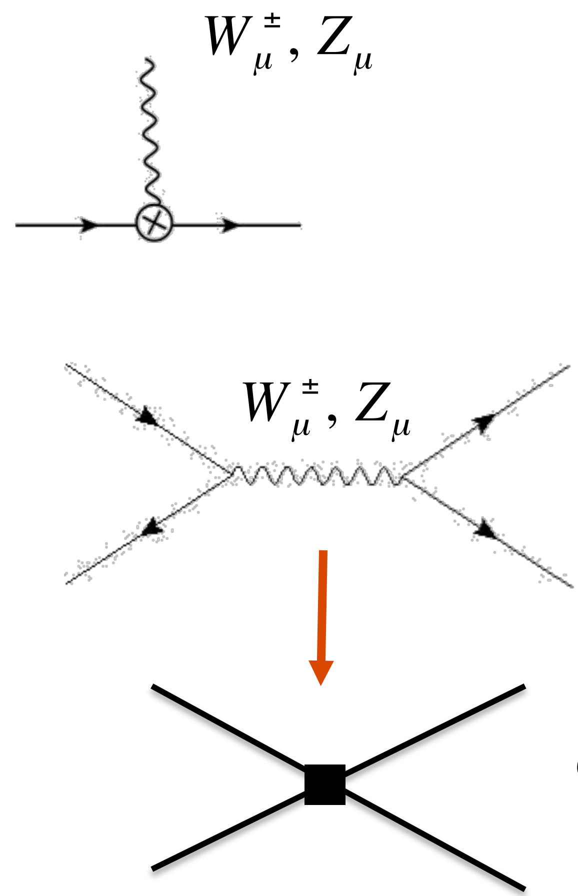
# From high to low energies

**Energy**

**>100 GeV** — Standard Model

$M_{EW}$

**100 GeV** — Integrate out heavy W,Z fields




$$\propto \frac{g^2}{M_{W,Z}^2}$$

**Effective P-odd four-fermion operators**

$M_{QCD}$

**1 GeV**

**Hadronic/nuclear parity violation**

Nuclear and muon beta-decay

Neutrino-nucleon scattering

# Beta decay and P violation



- Beta decay due to **parity-violating four-fermion operators**

$$L = G_F\,(\bar{u}_L \gamma^\mu d_L)(\bar{e}_L \gamma^\mu \nu_L) \qquad G_F \sim g^2 / M_W^2$$

- Wu et al (1957) measured P-violation in decay of $^{60}Co$


# And the four-quark operators ?

- Very similar operators

$$L = F_0\,(\bar{q}\,\gamma^\mu \vec{\boldsymbol{\tau}}\,q)\cdot(\bar{q}\,\gamma^\mu\gamma^5\vec{\boldsymbol{\tau}}\,q)$$

$$+\,F_1\,(\bar{q}\,\gamma^\mu q)(\bar{q}\,\gamma^\mu\gamma^5\boldsymbol{\tau}^3\,q)$$

$$+\,F_2\,(\bar{q}\,\gamma^\mu\boldsymbol{\tau}^3 q)(\bar{q}\,\gamma^\mu\gamma^5\boldsymbol{\tau}^3\,q)\ +$$ strange operators

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

$$F_i \sim G_F$$

- Should manifest in P-odd NN forces

# And the four-quark operators ?

- Very similar operators

$$L = F_0\,(\bar{q}\,\gamma^{\mu}\vec{\tau}\,q)\cdot(\bar{q}\,\gamma^{\mu}\gamma^{5}\vec{\tau}\,q)$$
$$+\,F_1\,(\bar{q}\,\gamma^{\mu}q)(\bar{q}\,\gamma^{\mu}\gamma^{5}\tau^{3}\,q)$$
$$+\,F_2\,(\bar{q}\,\gamma^{\mu}\tau^{3}q)(\bar{q}\,\gamma^{\mu}\gamma^{5}\tau^{3}\,q)\; + \text{ strange operators}$$

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

$$F_i \sim G_F$$

- Should manifest in P-odd NN forces
- **But much harder to measure**

$$\frac{V_{weak}}{V_{strong}} \sim 10^{-6}$$

**Huge strong and electromagnetic background**

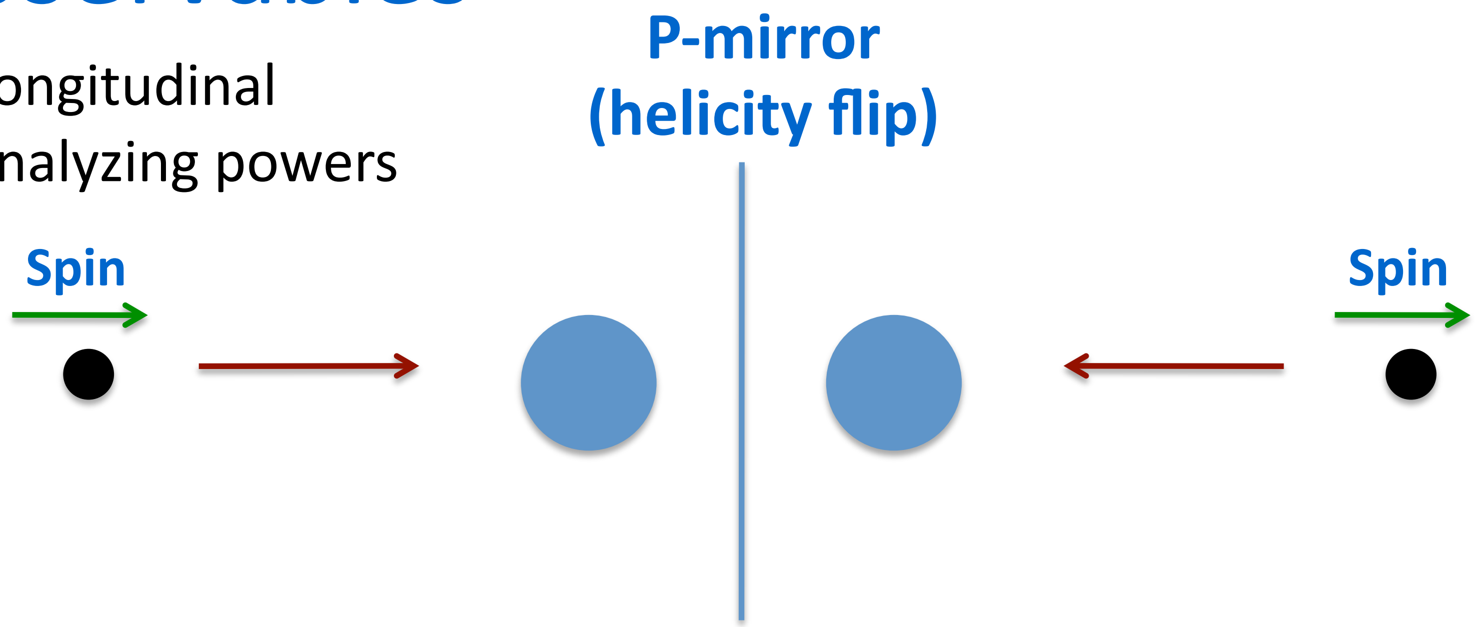
- **and to interpret……**

**Non-perturbativeness of QCD**

# Observables

JÜLICH FORSCHUNGSZENTRUM

Longitudinal analyzing powers



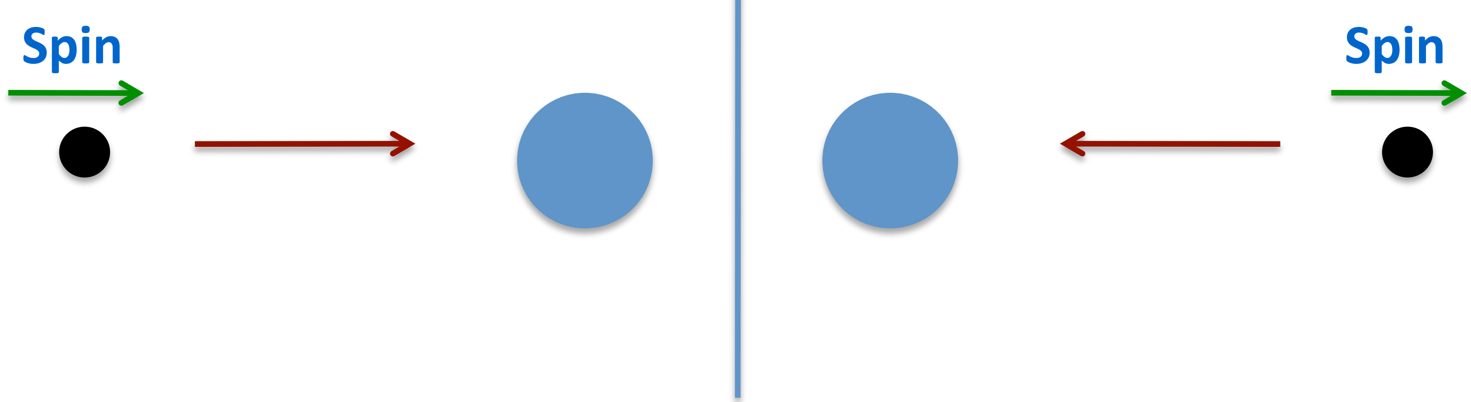

- Observable: $$A_L = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

# Observables



Longitudinal analyzing powers

**P-mirror (helicity flip)**

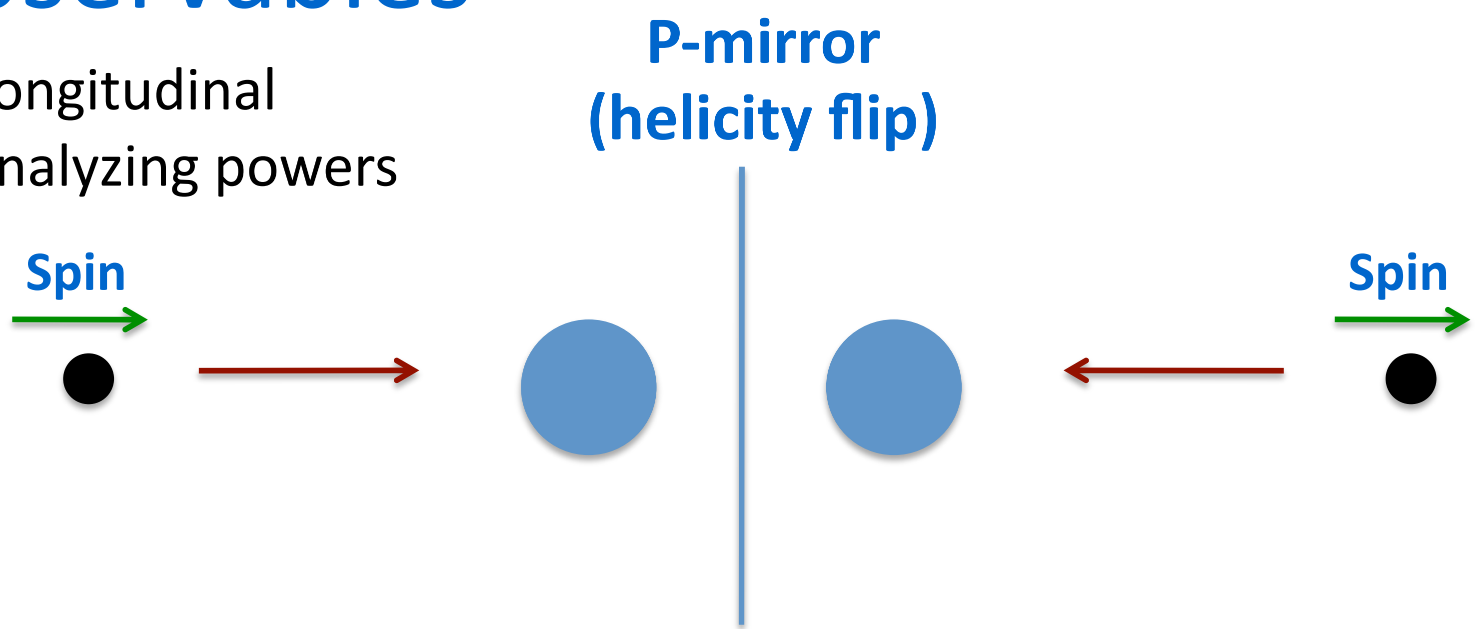



- Observable: $$A_L = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \sim 10^{-6,-7}$$

- **Difficult** measurements: so far signals in: $\vec{p}p \rightarrow pp$, $\vec{p}\alpha \rightarrow p\alpha$

# Observables

Longitudinal analyzing powers




- Observable: $$A_L = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \sim 10^{-6,-7}$$

- **Experiments planned/ongoing/done**

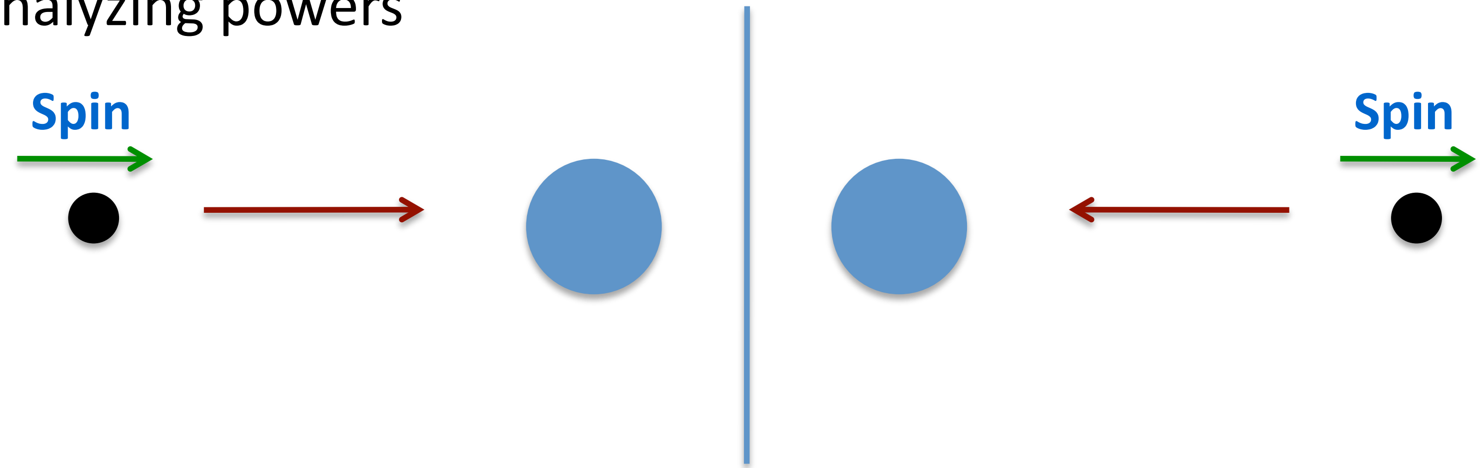
$$\vec{n}p \rightarrow d\gamma$$
$$\vec{n}d \rightarrow t\gamma$$
$$\vec{n}h \rightarrow \vec{n}h$$

**+ Many others**

# Observables

Longitudinal analyzing powers

**P-mirror (helicity flip)**




- Observable: $$A_L = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \sim 10^{-6,-7}$$

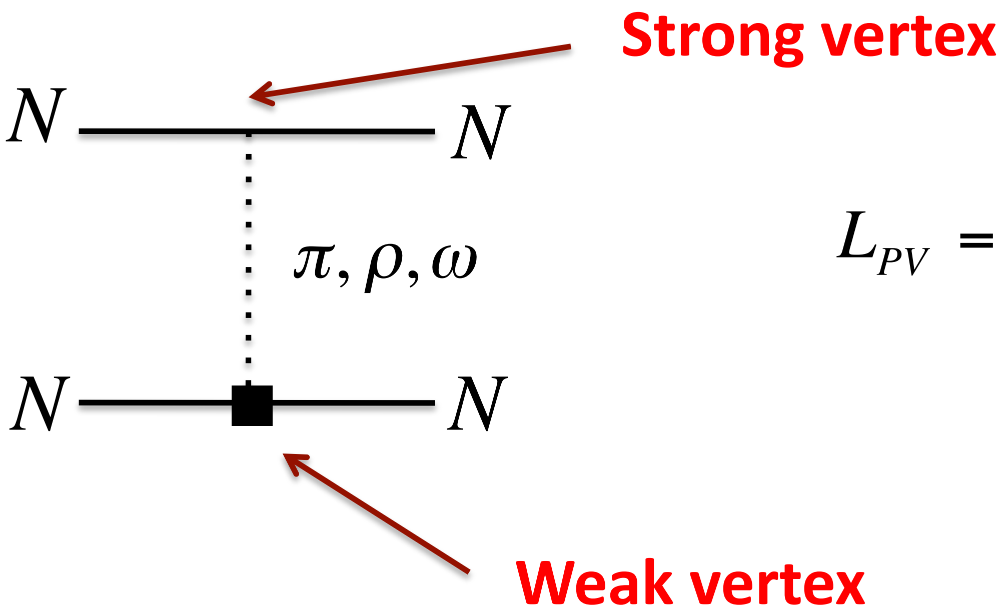
- **Many experiments in heavier nuclei (enhancement factors)**

$$^{18}F,\ ^{19}F,\ ^{133}Cs,\ ^{205}Tl$$

# The one-meson exchange model

- Introduced by **Desplanques, Donoghue, and Holstein (DDH)**

- Hadronic PV captured by one-meson exchange:
  In particular: **pions, rho- and omega-mesons**




$$L_{PV} = \frac{h_\pi}{\sqrt{2}} \overline{N} (\vec{\pi} \times \vec{\tau})^3 N + \cdots$$

Desplanques *et al AP* ’80

# The one-meson exchange model

- Introduced by **Desplanques, Donoghue, and Holstein (DDH)**
- Hadronic PV captured by one-meson exchange:
  In particular: **pions, rho- and omega-mesons**
- Described in terms of **7 coupling constants** estimated by quark model

| | DDH range | 'Best' |
|---|---|---|
| $h_\pi$ | $(6 \pm 6)\cdot 10^{-7}$ | $(4.6)\cdot 10^{-7}$ |
| $h_\rho^{0\,(,1,2)}$ | $(-10 \pm 20)\cdot 10^{-7}$ | $(-11.4)\cdot 10^{-7}$ |
| $h_\omega^{0\,(,1)}$ | $(-2 \pm 8)\cdot 10^{-7}$ | $(5.7)\cdot 10^{-7}$ |
| $h_\rho^{\prime 1}$ | | $(0)\cdot 10^{-7}$ |

Desplanques *et al AP* '80

# The one-meson exchange model

- Introduced by **Desplanques, Donoghue, and Holstein (DDH)**
- Hadronic PV captured by one-meson exchange:
  In particular: **pions, rho- and omega-mesons**
- Described in terms of **7 coupling constants** estimated by quark model

| | **DDH range** | **'Best'** |
|---|---|---|
| $h_\pi$ | $(6 \pm 6)\cdot 10^{-7}$ | $(4.6)\cdot 10^{-7}$ |

Meißner & Weigel *PLB* '99

SU(3) Skyrme calculation $(1.0 \pm 0.3)\cdot 10^{-7}$

First lattice calculation $(1.1 \pm 0.5)\cdot 10^{-7}$

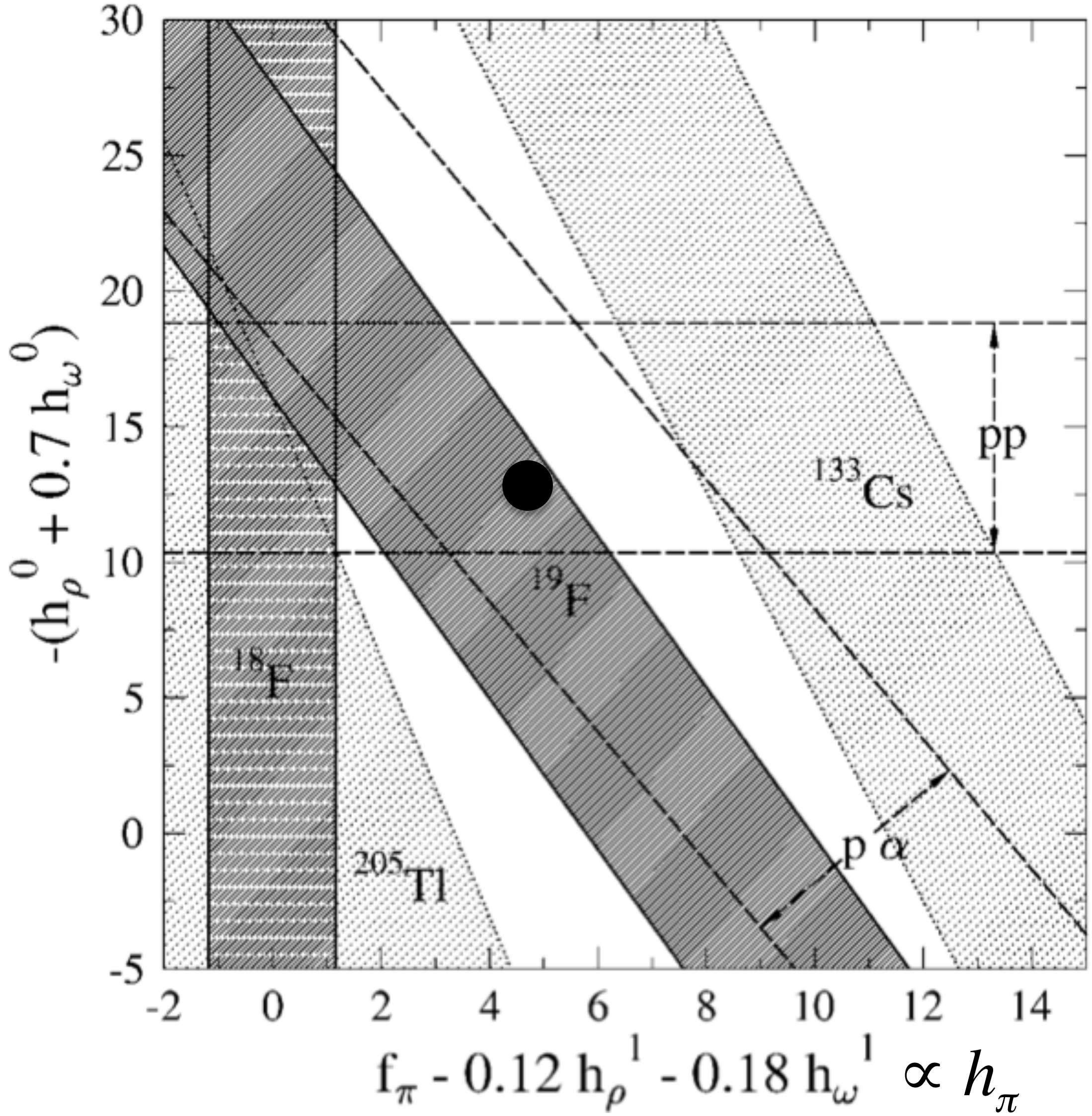
**Small values**

Wasem, PRC '12

**Caveat: large pion mass and no disconnected diagrams**

# Inconsistenties

- Inconsistency in $h_\pi$
- Partly due to anapole Cesium (A=133 ! Much harder for theory)

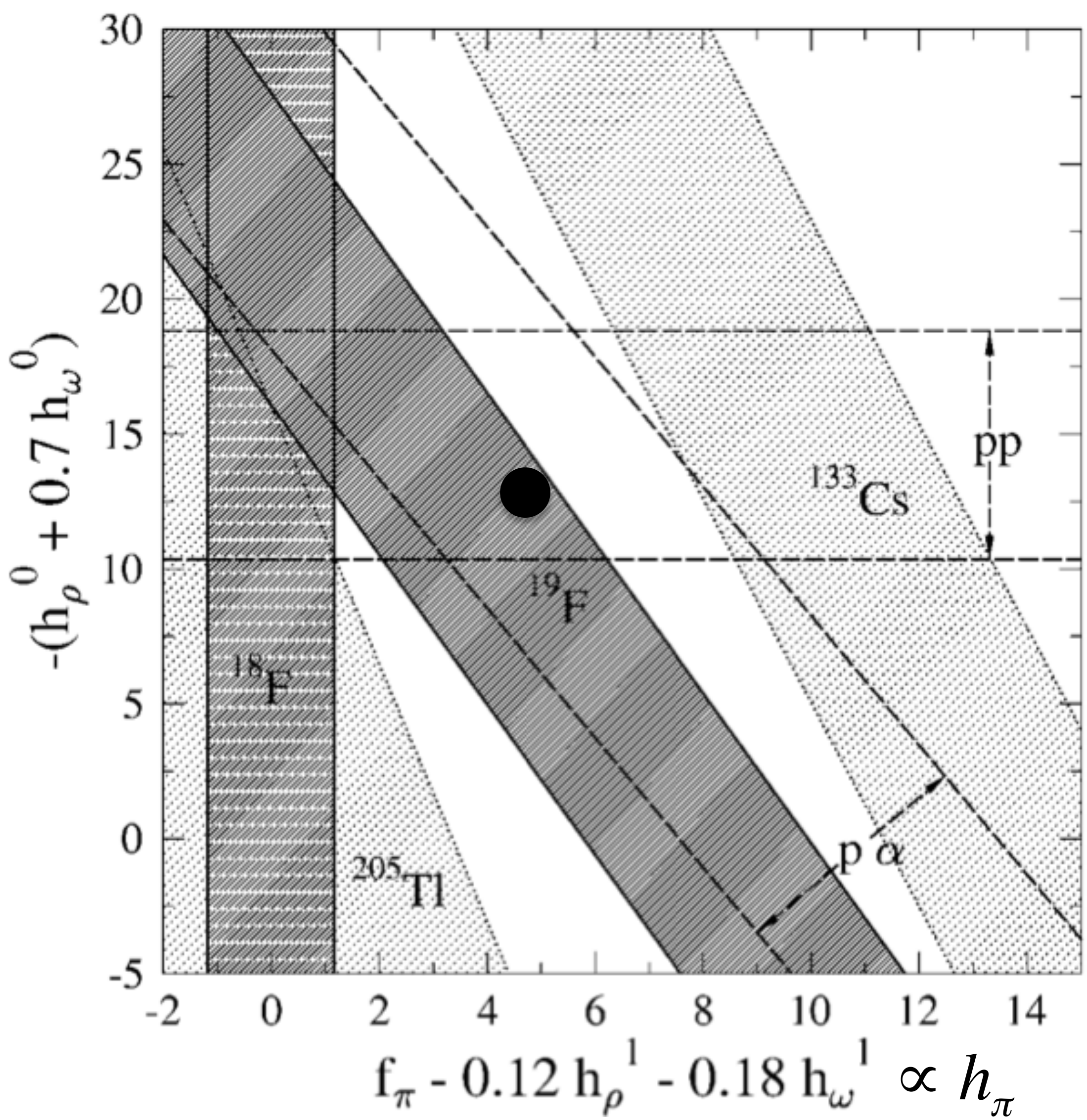



● = DDH best value

Haxton & Wieman, ARNPS ’01

# Inconsistenties

- Inconsistency in $h_\pi$
- Partly due to anapole Cesium (A=133 ! Much harder for theory)




● = **DDH best value**

Consistency of DDH approach? (PV and PC)

Power counting ?

Link to QCD?

Haxton & Wieman, ARNPS '01

# Outline of this talk

- Part I: Parity-violating interactions
- **Part II: Chiral effective field theory approach**
- Part III: The longitudinal asymmetry in pp scattering

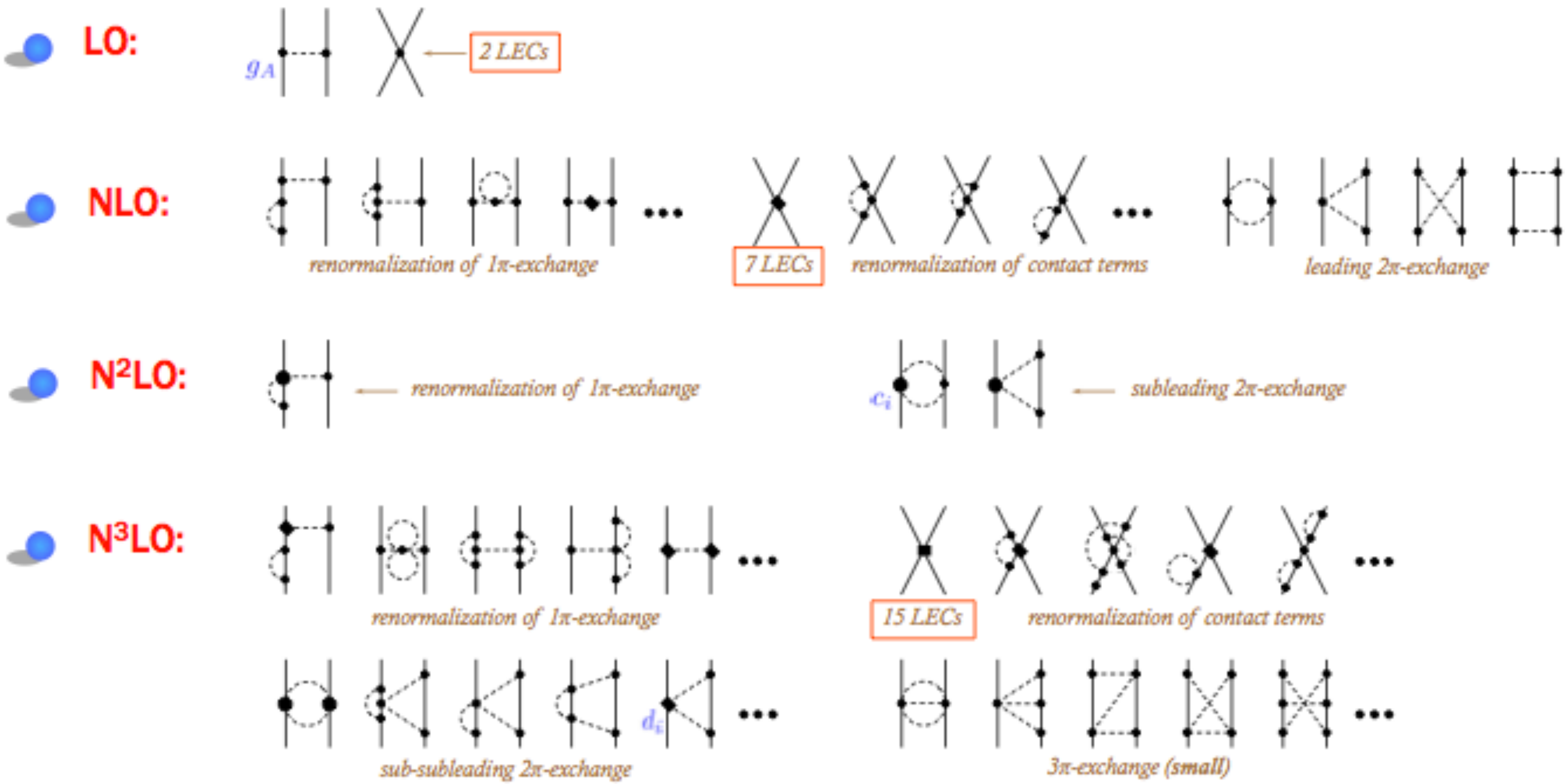
# Updating the DDH framework



- Instead of one-meson exchange use a more **systematic** approach: **effective field theory**
- **Chiral effective field theory** has proven extremely successful in P-conserving NN interactions
- The P-conserving NN potential has been derived up to **next-to-next-to-next-to-leading** order (N3LO)

Ordonez et al. '94; Friar & Coon '94; Kaiser et al. '97; Epelbaum et al. '98,'03; Kaiser '99-'01; Higa et al. '03; ...

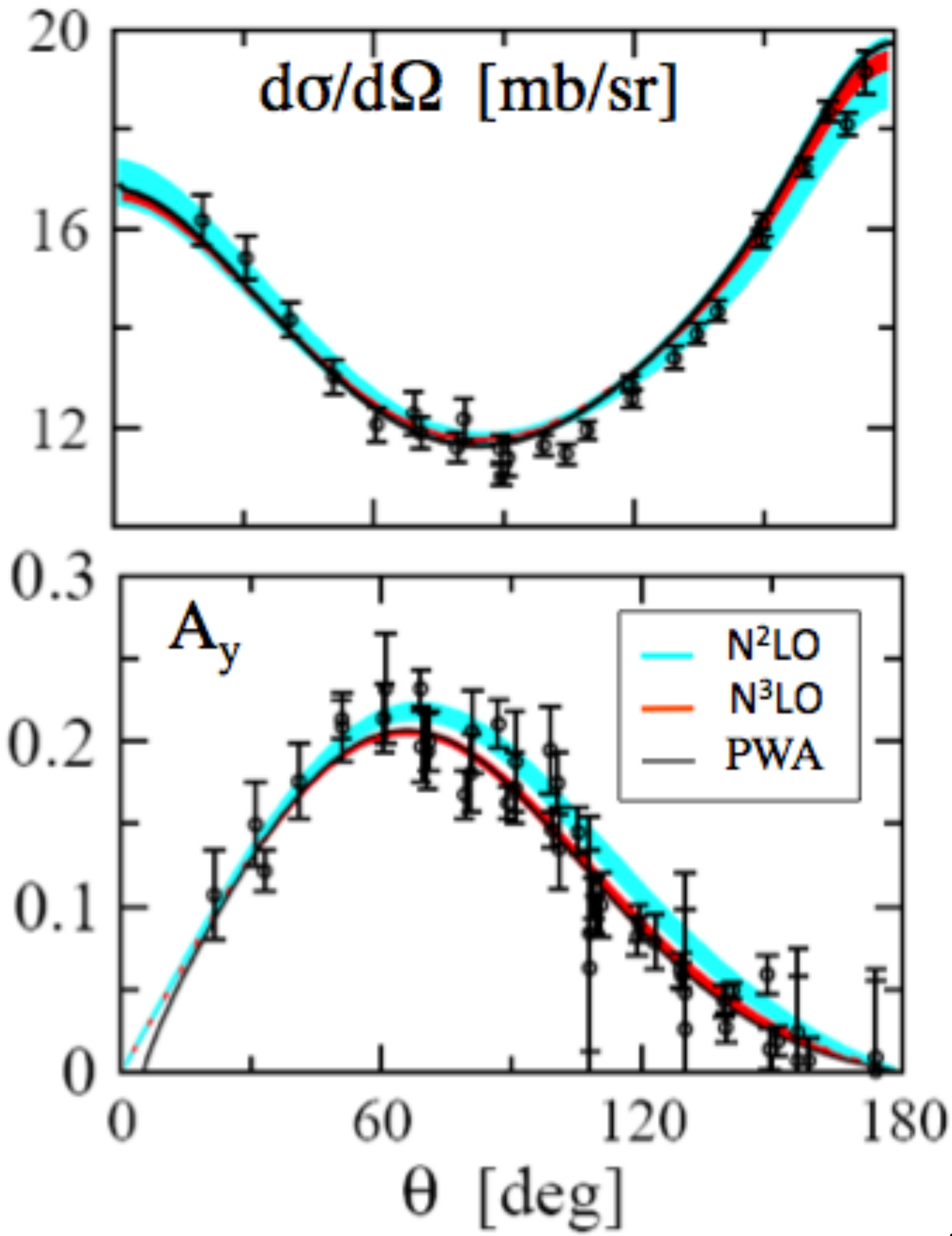
## Chiral expansion for the 2N force: $V_{2N} = V_{2N}^{(0)} + V_{2N}^{(2)} + V_{2N}^{(3)} + V_{2N}^{(4)} + \ldots$




+ 1/m and isospin-breaking corrections…

Slide from H. Krebs

# np scattering at 50 MeV

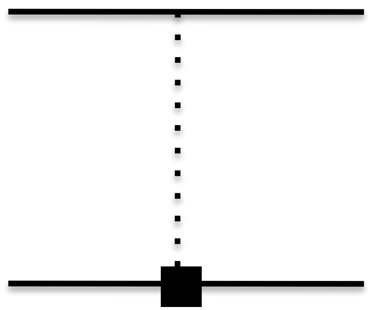



Epelbaum et al, NPA '05

# P-odd chiral NN-potential

Kaplan & Savage, NPA '93

**Leading order**



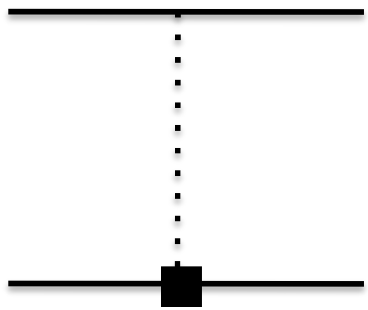
$$-\left(\frac{g_A h_\pi}{2\sqrt{2}F_\pi}\right) i(\vec{\tau}_1 \times \vec{\tau}_2)^3 \frac{(\vec{\sigma}_1 + \vec{\sigma}_2)^3 \cdot \vec{q}}{\vec{q}^{\,2} + m_\pi^2}$$

***One-pion exchange (large uncertainty on coupling constant)***

# P-odd chiral NN-potential

## Leading order

Kaplan & Savage, NPA '93



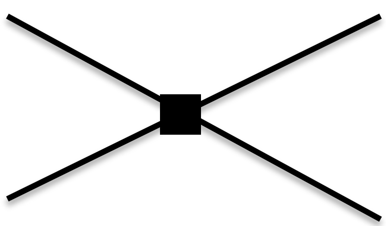
$$-\left(\frac{g_A h_\pi}{2\sqrt{2}F_\pi}\right) i(\vec{\tau}_1 \times \vec{\tau}_2)^3 \frac{(\vec{\sigma}_1 + \vec{\sigma}_2)^3 \cdot \vec{q}}{\vec{q}^{\,2} + m_\pi^2}$$

***One-pion exchange (large uncertainty on coupling constant)***

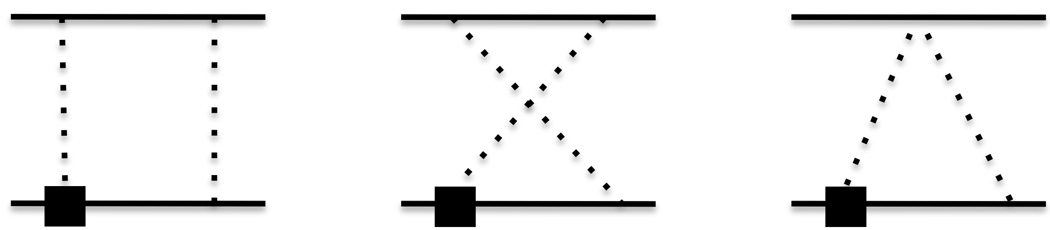
## Next-to-leading order

$$O\left(Q^2/\Lambda_\chi^2\right)$$

Zhu et al, NPA '05
Kaiser, PRC '07
Girlanda, PRC '08



***NN contact terms (5)***



***But also: two-pion exchange!***

***Not in the DDH framework***

# Outline of this talk

- Part I: Parity-violating interactions
- Part II: Chiral effective approach
- **Part III: The longitudinal asymmetry in pp scattering**

# The longitudinal asymmetry

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

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

- (***Only***) three 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 | $A_L(221\ MeV) = +(0.84 \pm 0.34)\cdot 10^{-7}$ | $(\theta_c^\circ - 90^\circ)$ |

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

# Vanishing of one-pion exchange

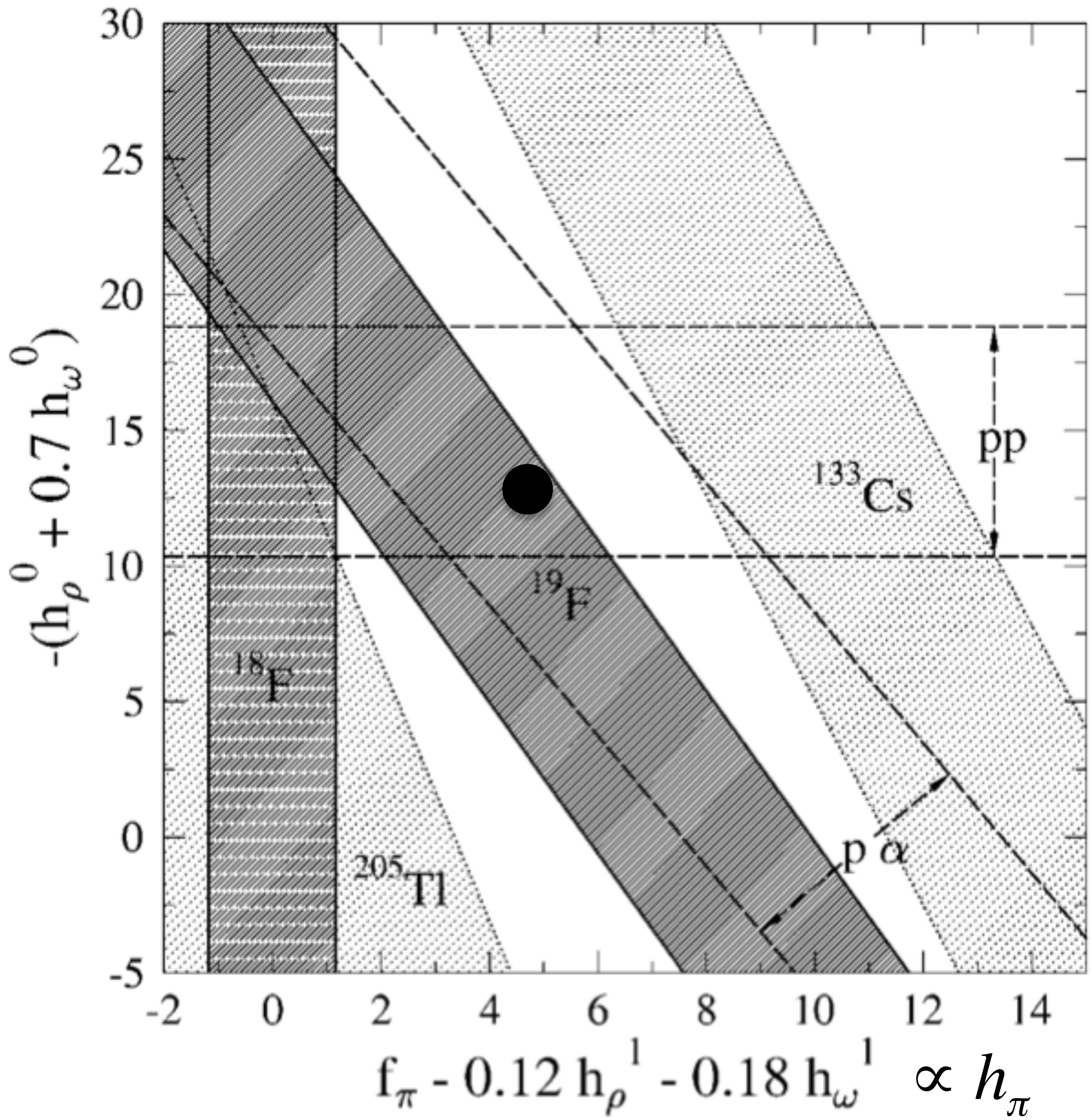
- Consider the P-odd leading order potential

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

- Vanishes between states of equal total isospin.....

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

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

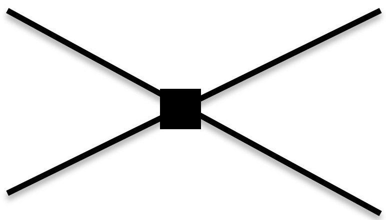


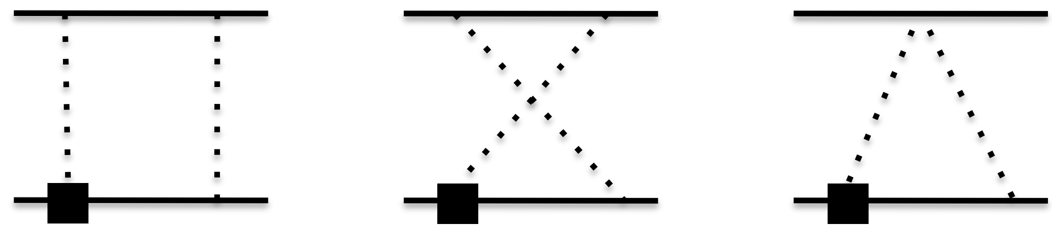

**No dependence on** $h_\pi$

Haxton & Wieman, ARNPS '01

# But two-pion exchange!

- But in an EFT we can go to higher orders





***NN contact term*** ***two-pion exchange!***

$C$ $h_\pi$

- The analyzing power depends now on two unknown couplings

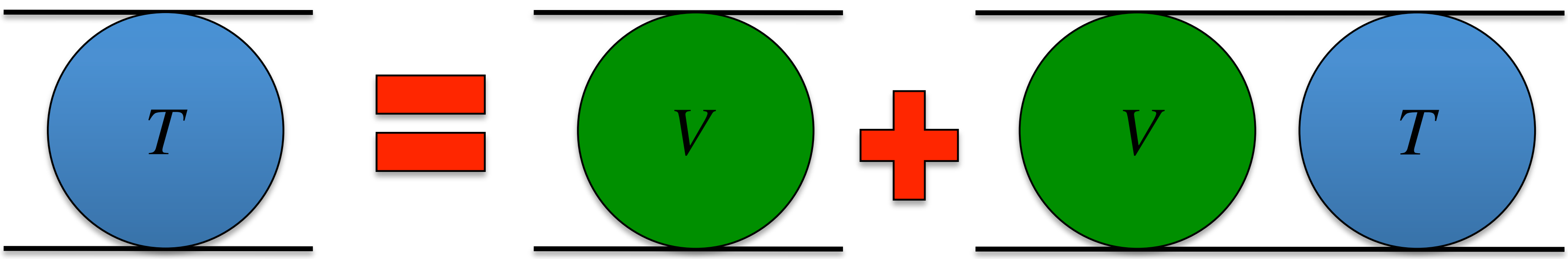
- ***Can we learn something about*** $h_\pi$ ***?***
  ***Are small values of*** $h_\pi$ ***consistent with the data ?***

# The actual calculation

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

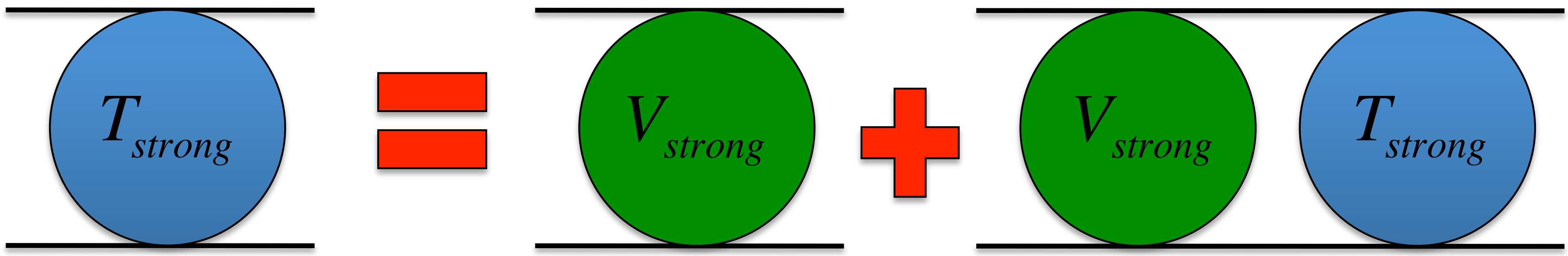
$$T = V + V\,G_0\,T \qquad V = V_{strong} + V_{weak}$$

**Both consistently derived in chiral EFT!**



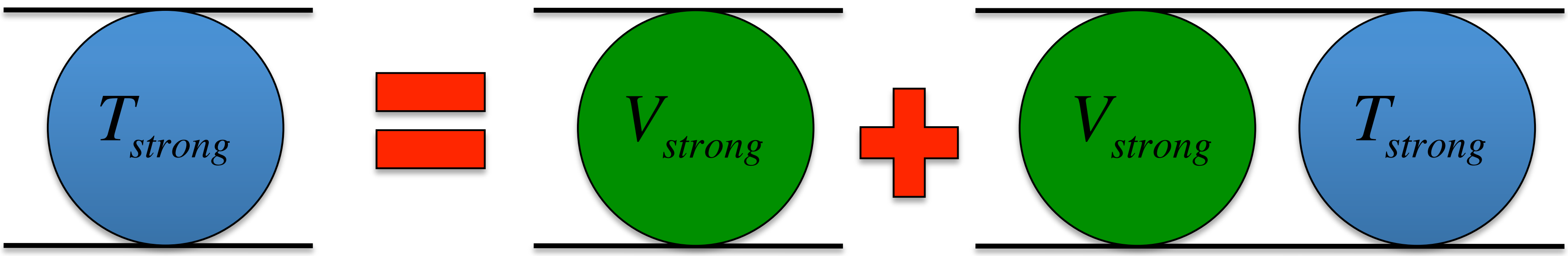
# The actual calculation

- First-order perturbation theory $T = T_{strong} + T_{weak}$

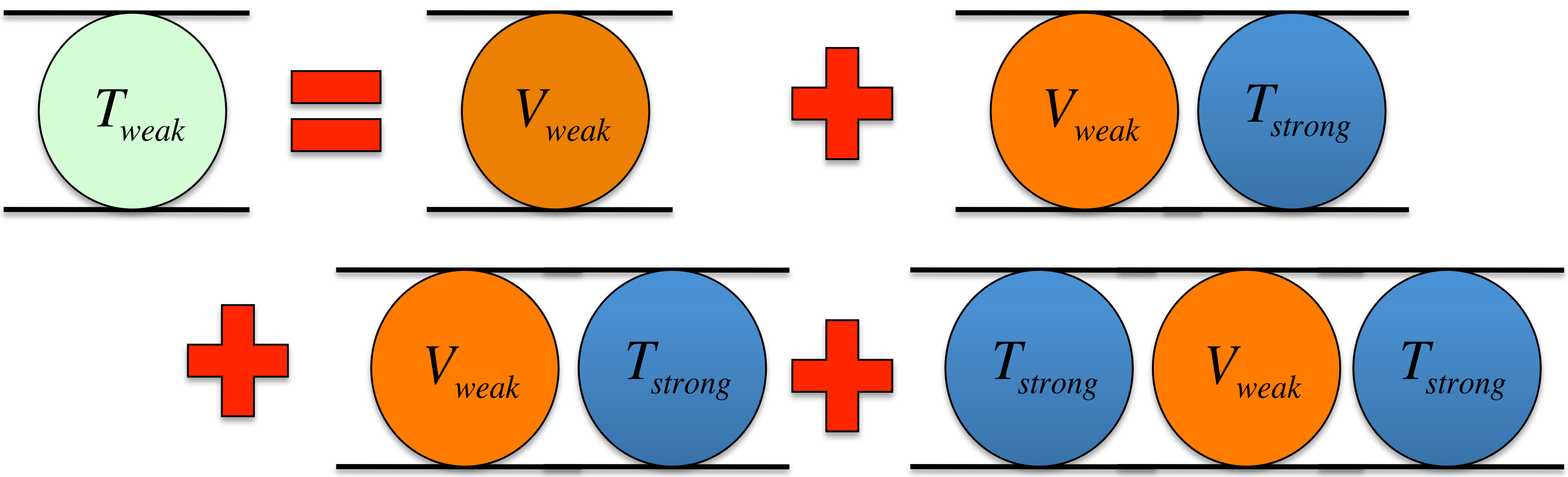


# The actual calculation

- First-order perturbation theory $T = T_{strong} + T_{weak}$

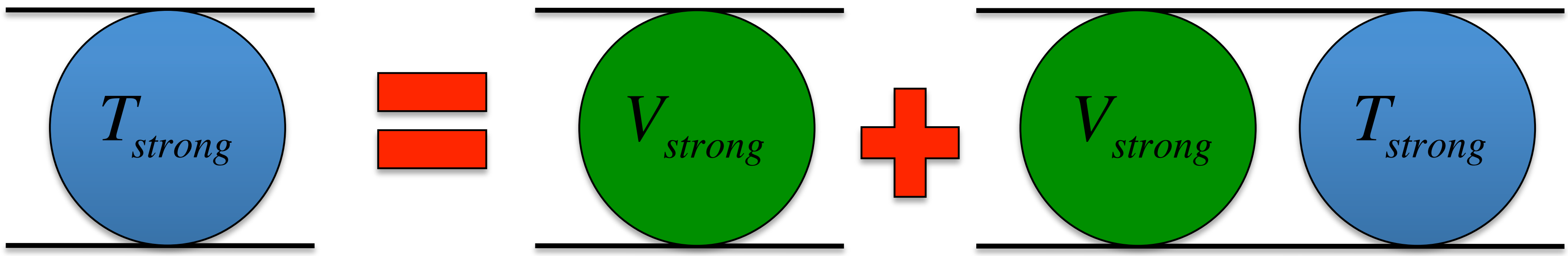



- Perturb with the P-violating potential



# The actual calculation

- First-order perturbation theory $$T = T_{strong} + T_{weak}$$




- **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 (450 – 600 MeV)

# What does P-violation add?



Driscoll & Miller, *PRC '89*
Driscoll & Meißner, *PRC '90*
Carlson *et al, PRC '02*

- More partial waves become coupled

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

$^3S_1 \quad {}^3P_1 \quad {}^1P_1 \quad {}^3D_1$

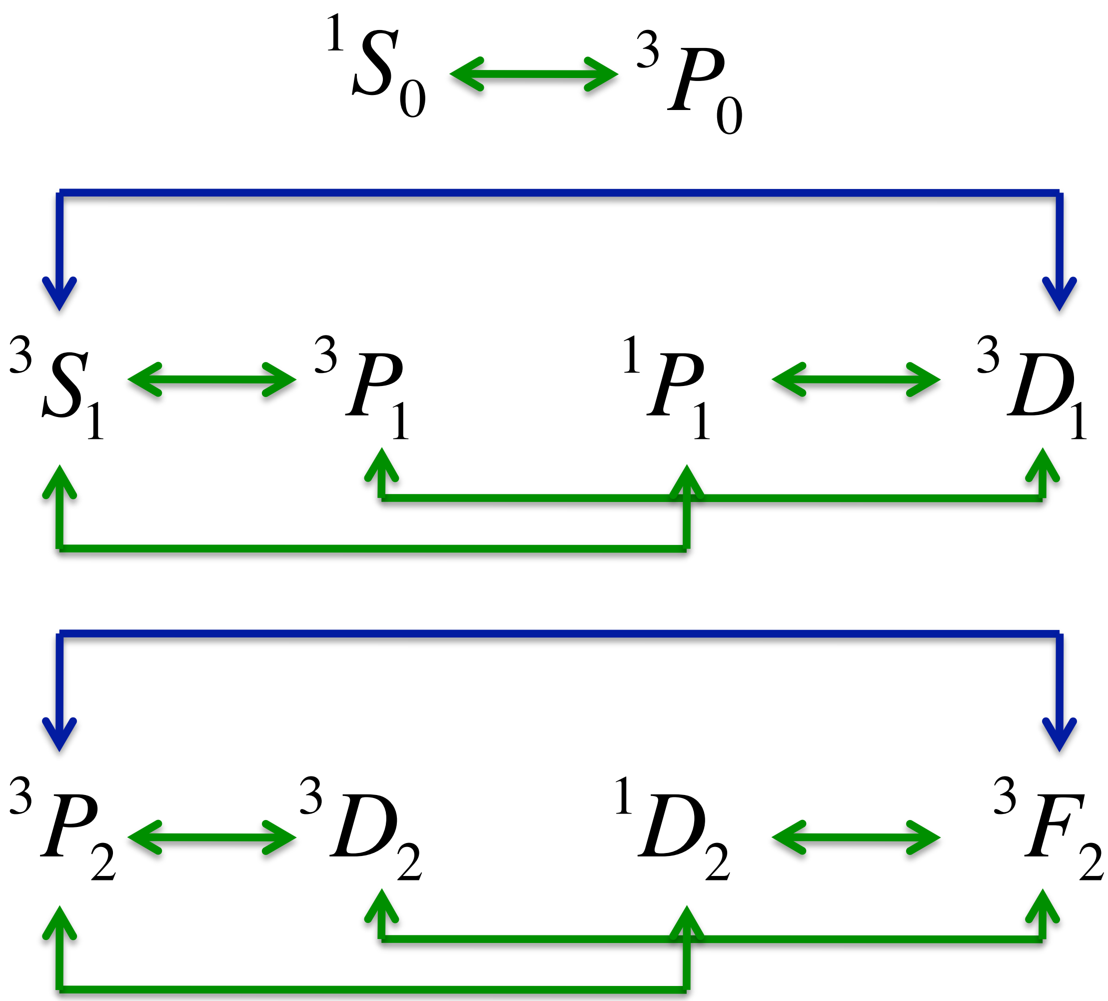
$^3P_2 \quad {}^3D_2 \quad {}^1D_2 \quad {}^3F_2$

# What does P-violation add?

FORSCHUNGSZENTRUM JÜLICH

- More partial waves become coupled

Driscoll & Miller, *PRC '89*
Driscoll & Meißner, *PRC '90*
Carlson *et al*, *PRC '02*

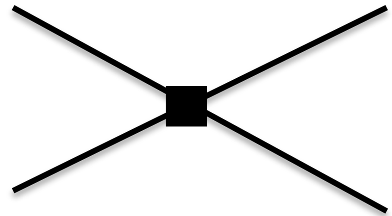


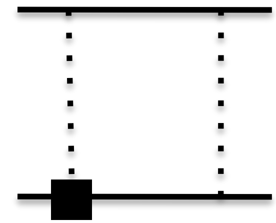
# What does P-violation add?

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

Driscoll & Miller, *PRC '89*
Driscoll & Meißner, *PRC '90*
Carlson *et al, PRC '02*

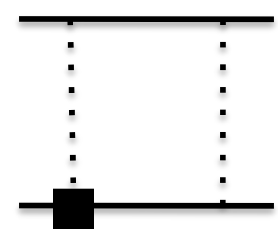
$^1S_0 \longleftrightarrow {^3P_0}$





$^3P_1$

$^3P_2 \qquad {^1D_2} \longleftrightarrow {^3F_2}$

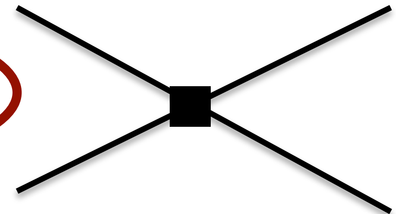


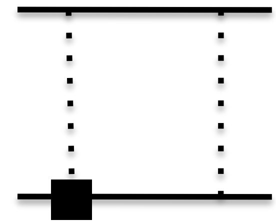
# What does P-violation add?

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

Driscoll & Miller, *PRC '89*
Driscoll & Meißner, *PRC '90*
Carlson *et al, PRC '02*

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



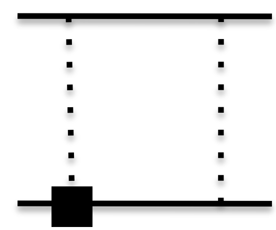


**Dominant contribution**

$^3P_1$

**Starts contributing at E>100 MeV**

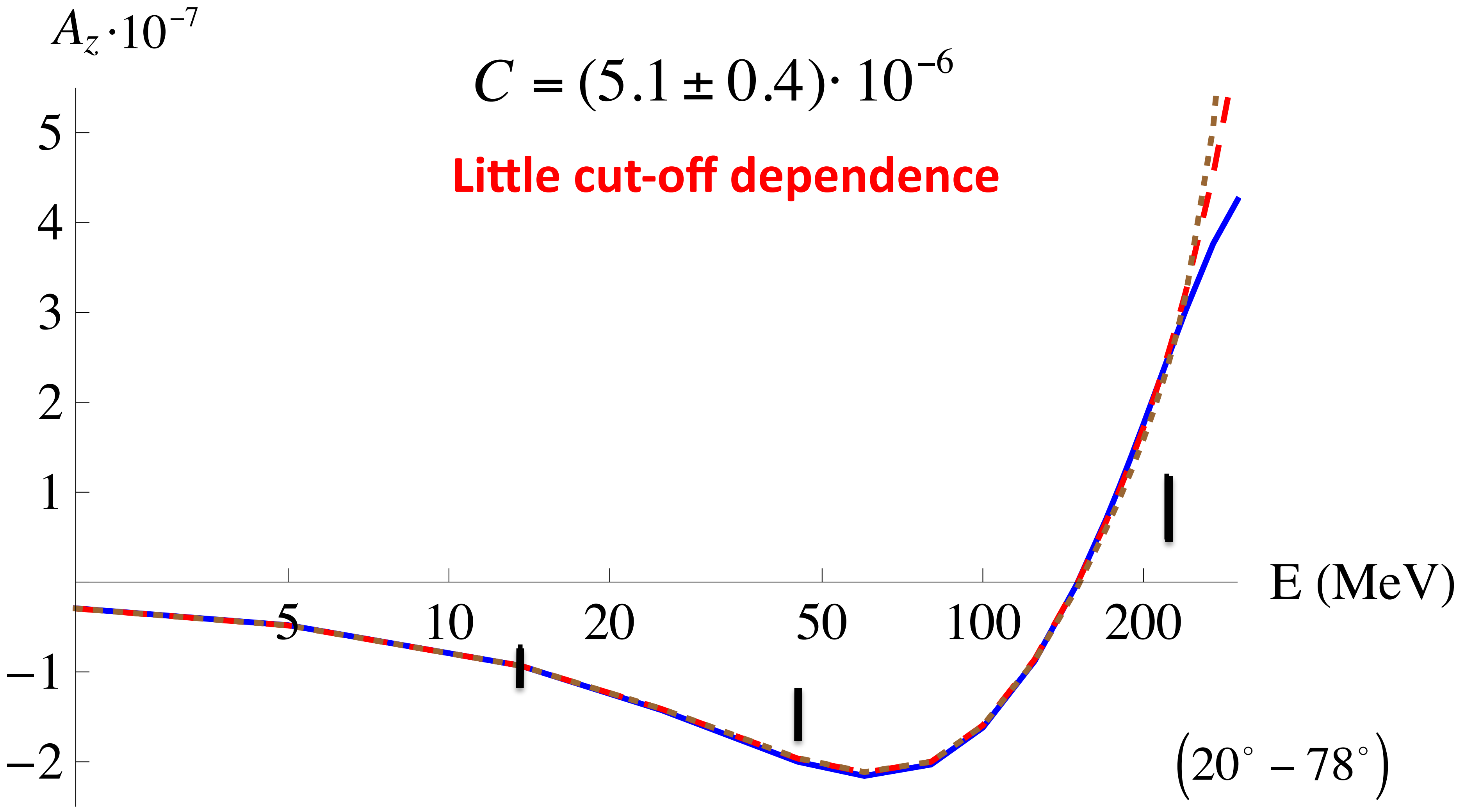
$^3P_2$ $\quad$ $^1D_2 \leftrightarrow {}^3F_2$



# Low-energy data

JdV, Meißner, Epelbaum, Kaiser '13

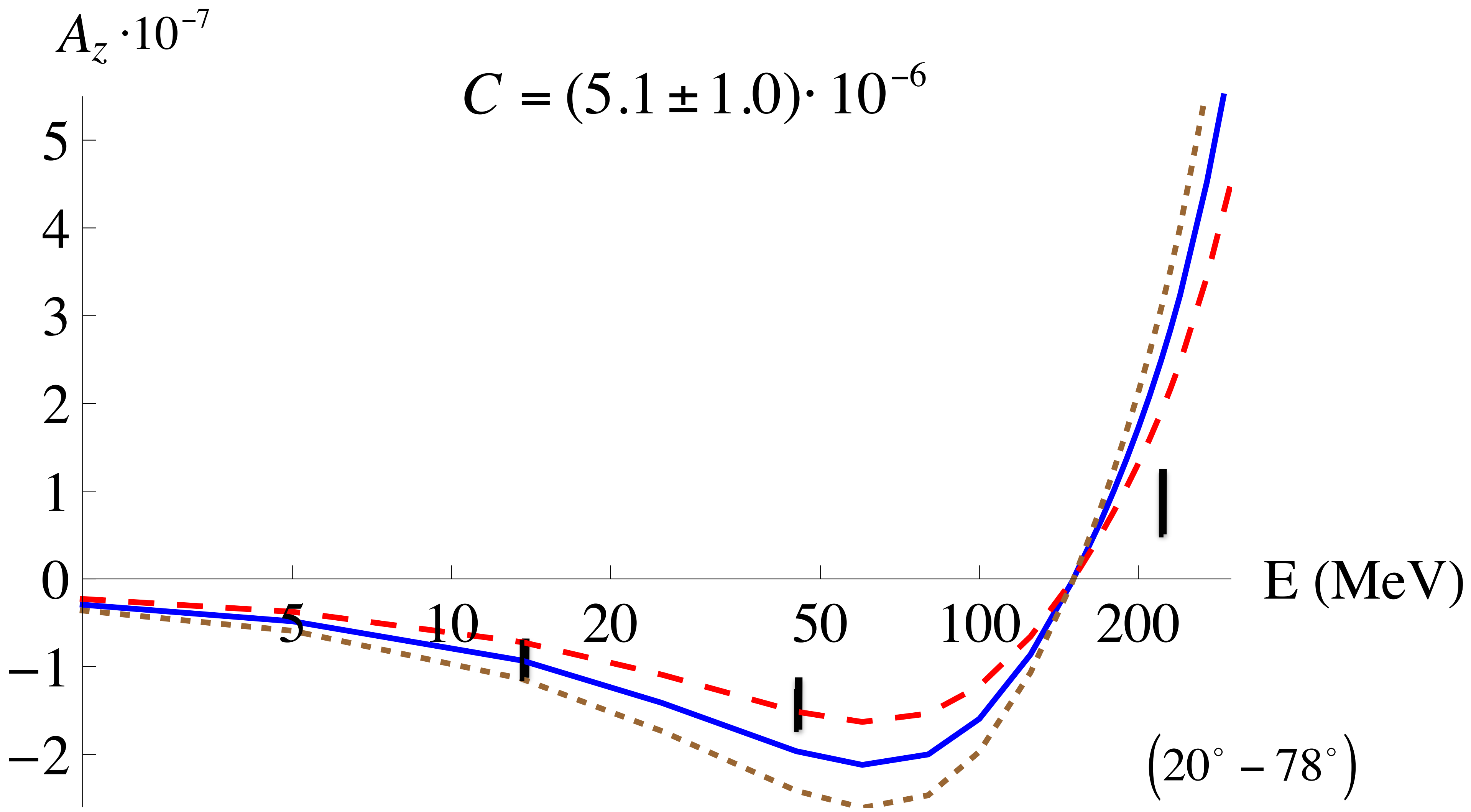
- We first use the DDH 'value' for $h_\pi = (0.46)\cdot 10^{-6}$ and fit counter term.



# Low-energy data

JdV, Meißner, Epelbaum, Kaiser '13

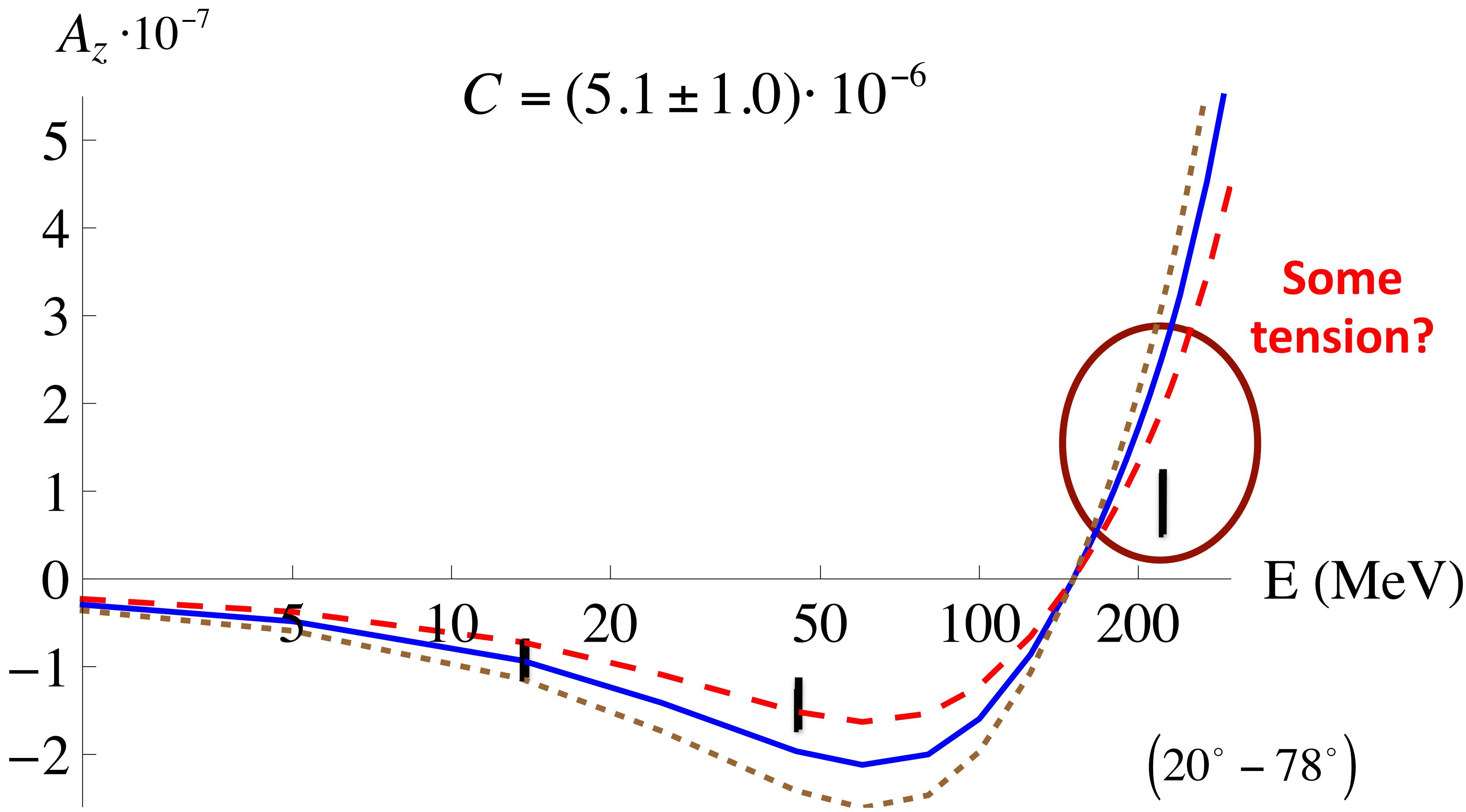
- We first use the DDH 'value' for $h_\pi = (0.46) \cdot 10^{-6}$ and fit counter term.



# Low-energy data

JdV, Meißner, Epelbaum, Kaiser *'13*

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



# Medium-energy data

JdV, Meißner, Epelbaum, Kaiser *'13*

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

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

**Blows up for small opening angles**

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

Driscoll & Miller, *PRC '89*
Carlson *et al, PRC '02*
Partanen *et al, EPJA '12*

# Medium-energy data

JdV, Meißner, Epelbaum, Kaiser *'13*

- 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**

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

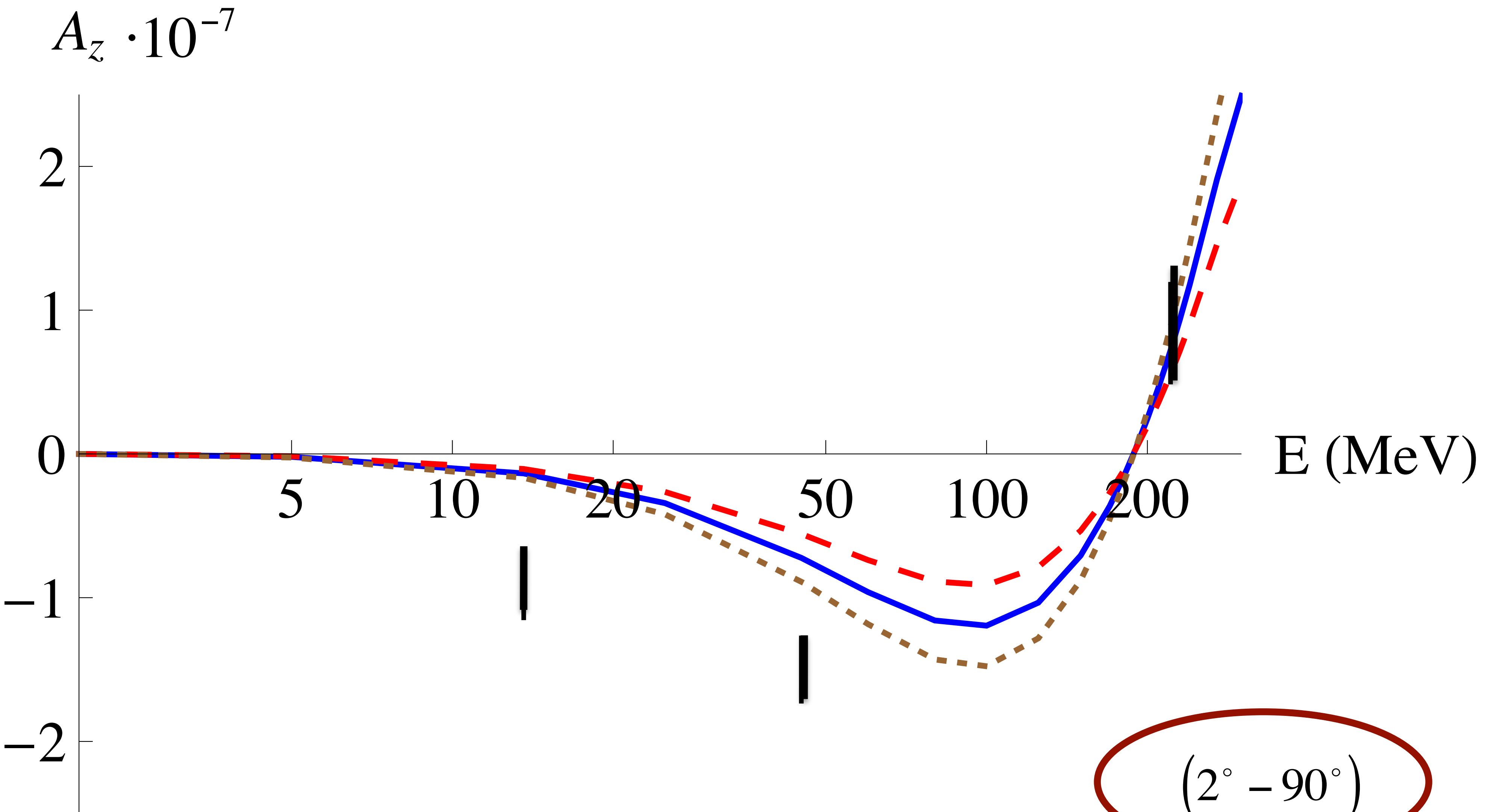
Driscoll & Miller, *PRC '89*
Carlson *et al, PRC '02*
Partanen *et al, EPJA '12*

Mitglied der Helmholtz-Gemeinschaft

# Medium-energy data

JdV, Meißner, Epelbaum, Kaiser '13

- The TRIUMF experiment measures over much smaller angles




Mitglied der Helmholtz-Gemeinschaft

# Large errors……

JdV, Meißner, Epelbaum, Kaiser *'13*

- It seems the DDH value works well, but……
- Uncertainties (mainly lack of data) **too big** to draw conclusion
- Fit to all data points (90% CL):

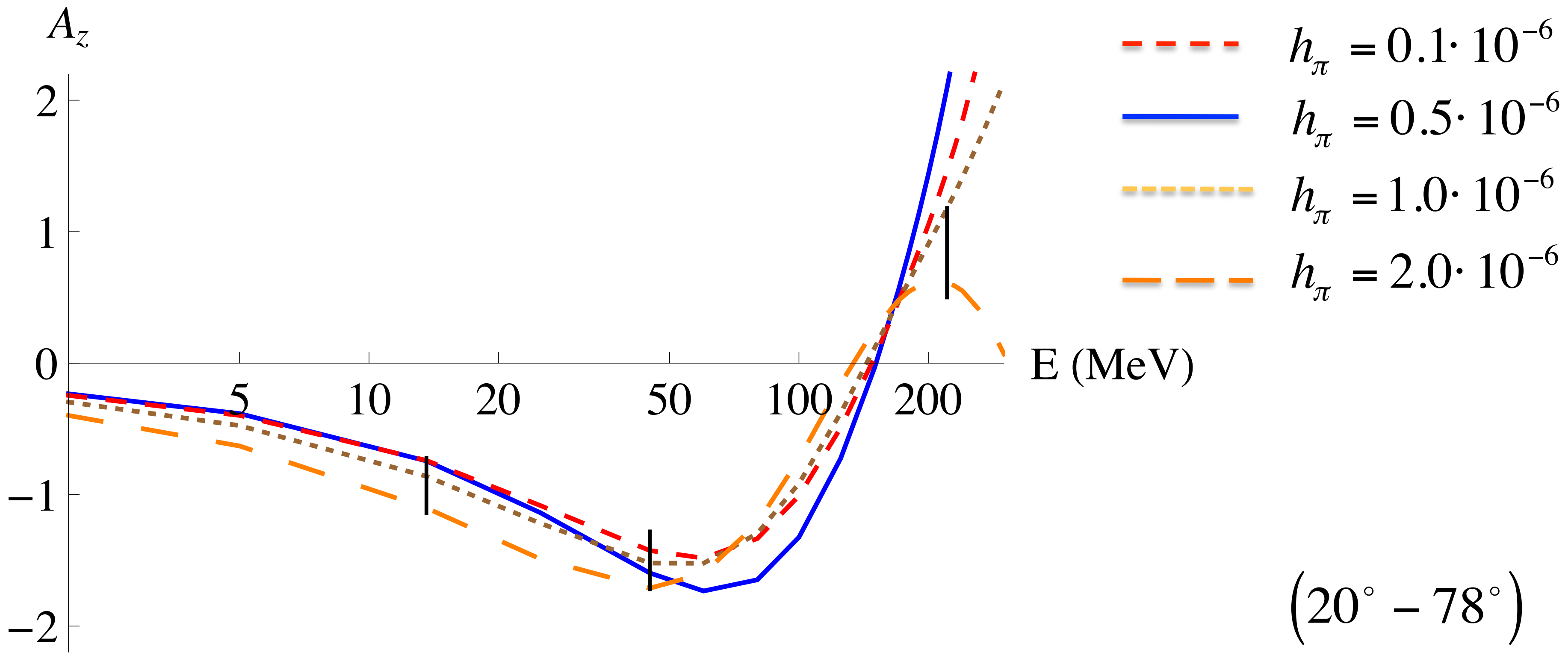
$$h_\pi = (1.1 \pm 2.0)\cdot 10^{-6} \qquad C = (-9.3 \pm 10)\cdot 10^{-6}$$

# Large errors……

JdV, Meißner, Epelbaum, Kaiser *'13*

- It seems the DDH value works well, but……
- Uncertainties (mainly lack of data) **too big** to draw conclusion
- Fit to all data points (90% CL):

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

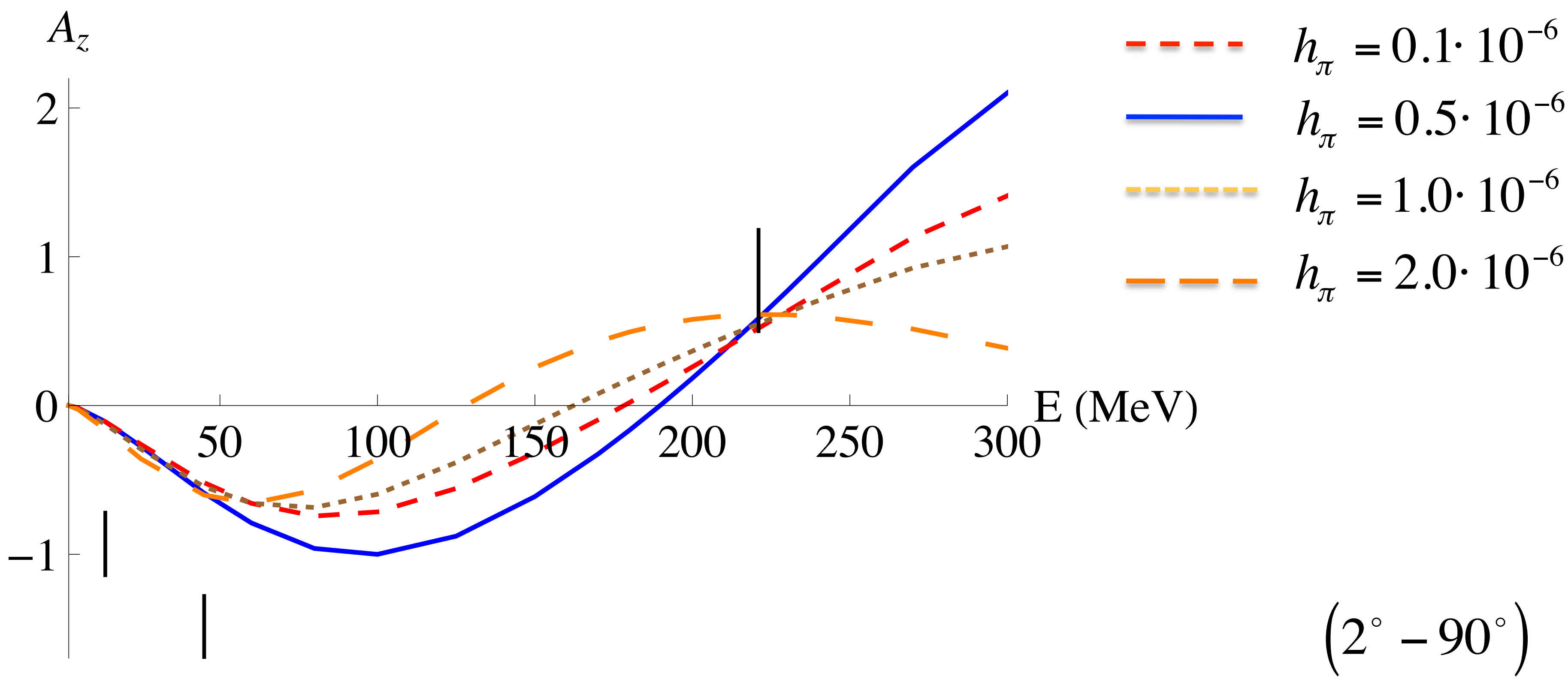


# Large errors……

JdV, Meißner, Epelbaum, Kaiser *'13*

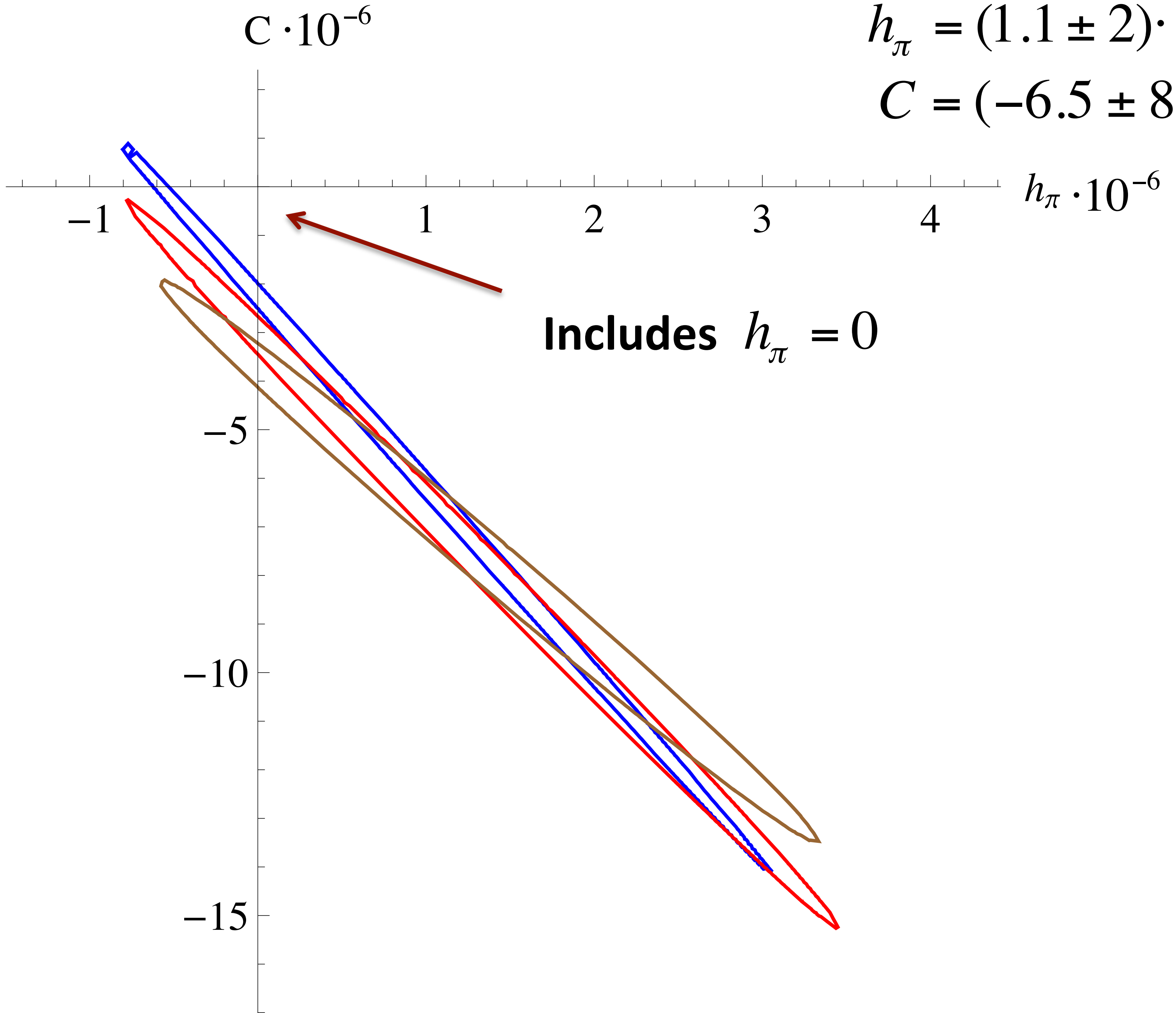
- It seems the DDH value works well, but……
- Uncertainties (mainly lack of data) **too big** to draw conclusion
- Fit to all data points (90% CL):

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



# Fit to all data (90% C.L.)

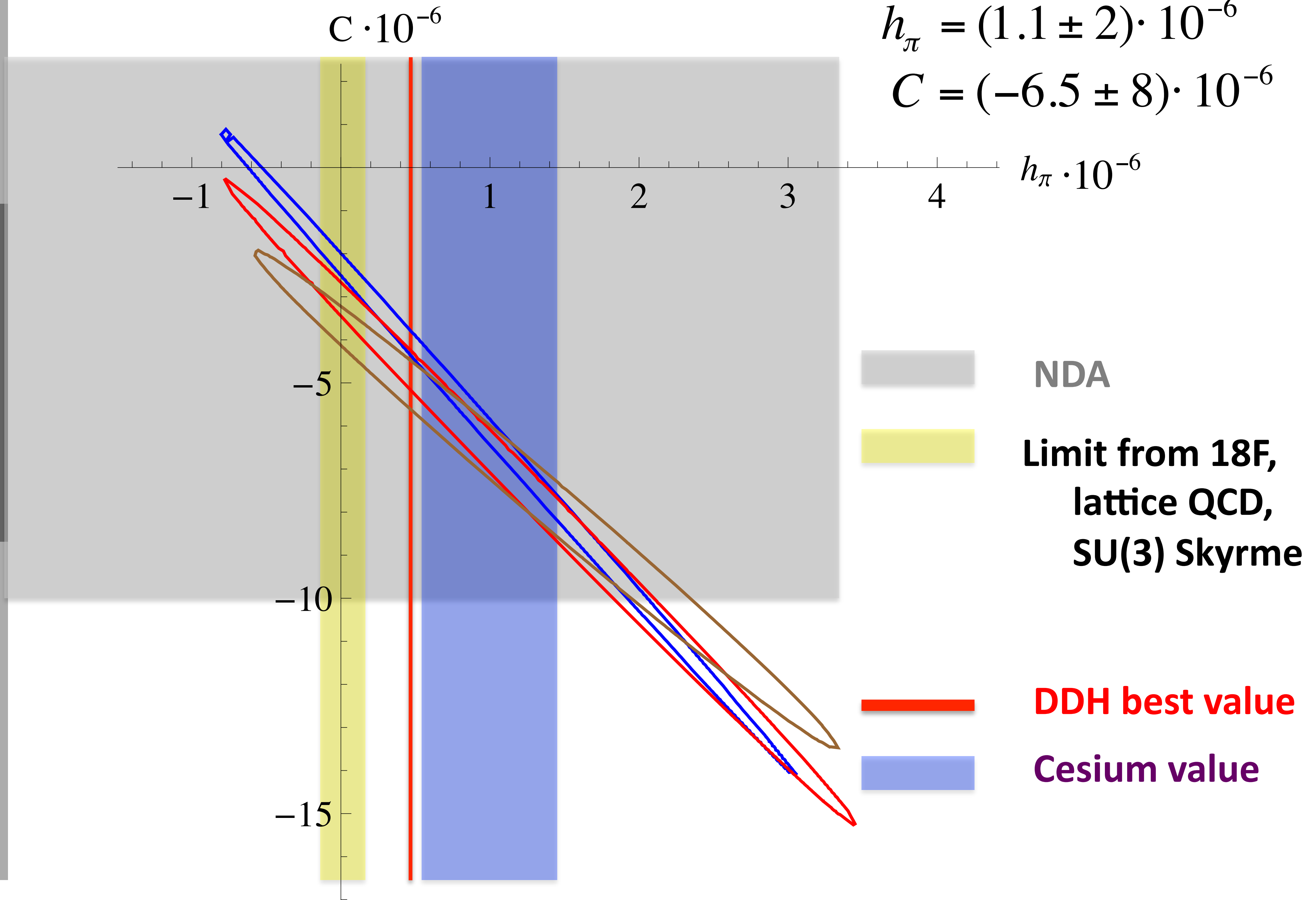
$$h_\pi = (1.1 \pm 2) \cdot 10^{-6}$$
$$C = (-6.5 \pm 8) \cdot 10^{-6}$$




**Includes** $h_\pi = 0$

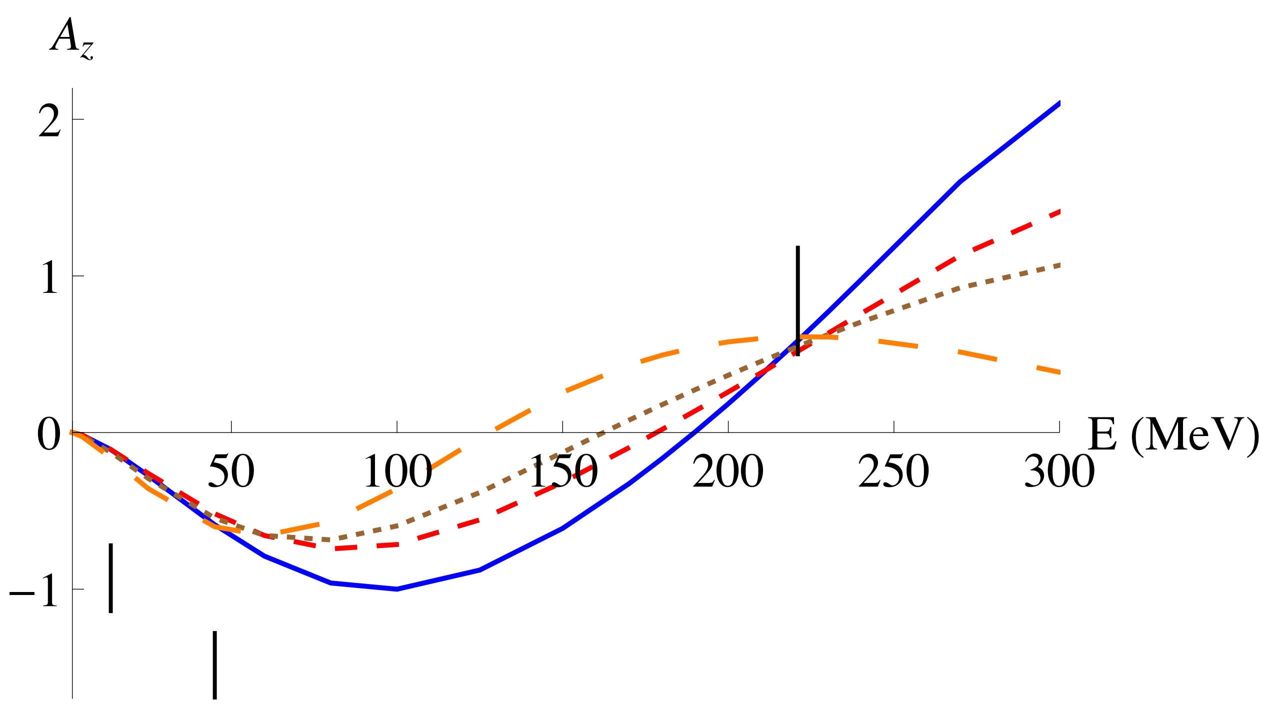
# Fit to all data (90% C.L.)

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



# So….

- Our extracted value of the couplings are consistent with small values of $h_\pi$ (suggested by 18F decay, lattice, soliton model)
- **However, not enough data to say more (only 3 points…)**
- An experiment around 125 MeV could give more information



# So….

- Our extracted value of the couplings are consistent with small values of $h_\pi$ (suggested by 18F decay, lattice, soliton model)
- **However, not enough data to say more (only 3 points…)**
- An experiment around 125 MeV could give more information

- ***We are working on other observables***
- ***Many experiments done/ongoing/planned in few-body systems***

$$\vec{n}p \rightarrow d\gamma$$
$$\vec{\gamma}d \rightarrow np$$
$$\vec{n}p \rightarrow \vec{n}p$$

Proportional to one-pion exchange

→ More sensitive to $h_\pi$

# So….

- Our extracted value of the couplings are consistent with small values of $h_\pi$ (suggested by 18F decay, lattice, soliton model)
- **However, not enough data to say more (only 3 points…)**
- An experiment around 125 MeV could give more information

- ***We are working on other observables***
- ***Many experiments done/ongoing/planned in few-body systems***

$\vec{n}p \to d\gamma$ $\vec{n}d \to t\gamma$ $\vec{p}\alpha \to p\alpha$

$\vec{\gamma}d \to np$ $\vec{n}\,{}^3He \to \vec{n}\,{}^3He$

$\vec{n}p \to \vec{n}p$

**Many others….**

# Summary-Outlook

JÜLICH FORSCHUNGSZENTRUM

- We have calculated the longitudinal analyzing power in pp scattering in chiral EFT
- **Systematic** approach to P-even and -odd interactions
- Although consistent results -> not enough data to say more

**Work in progress** (collaboration with N. Li and S.-L. Zhu)

- **Only first step of the program.** Extend calculations to other observables
- **Calculate P-odd potential up to NNLO** (Important if $h_\pi$ is small).

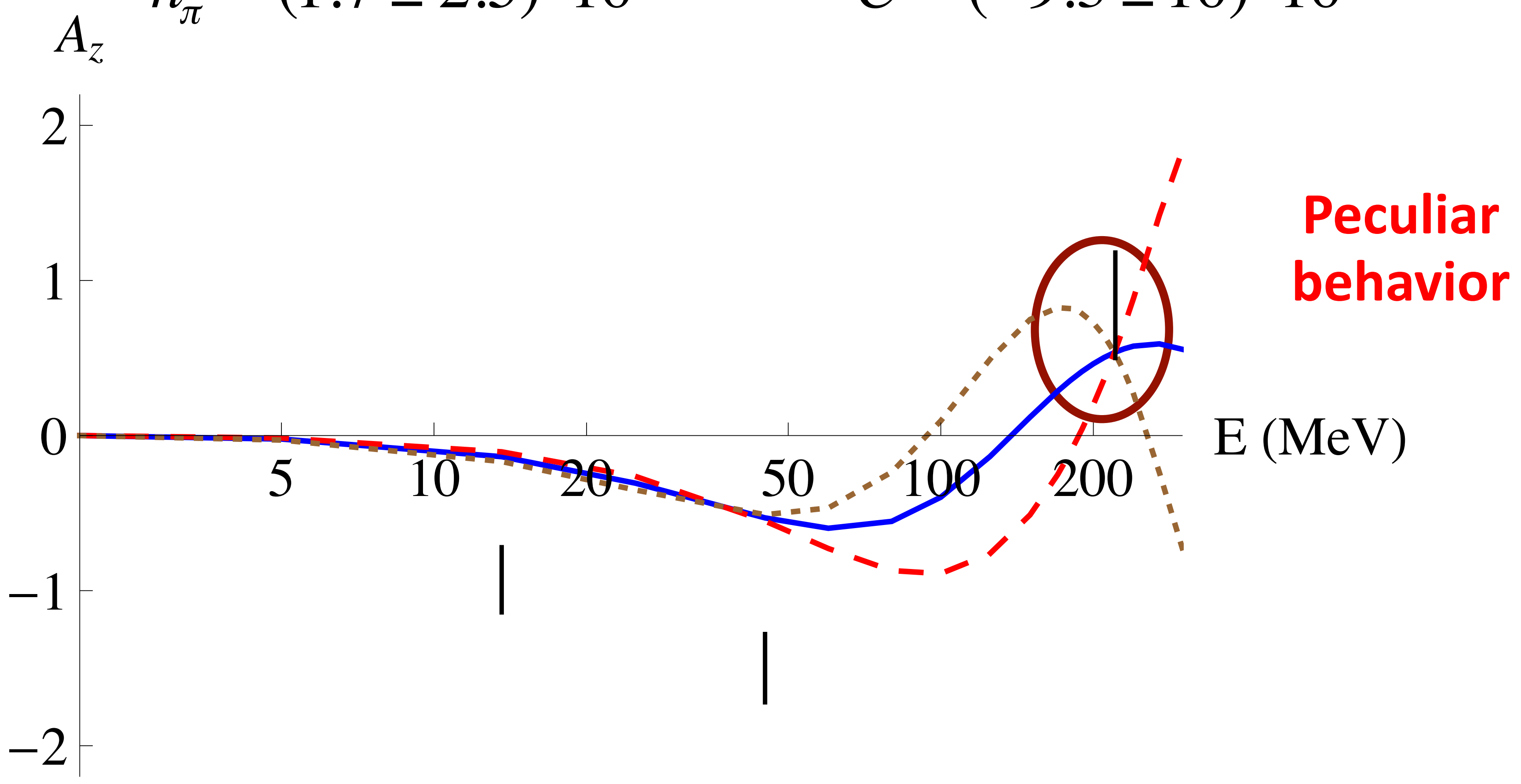
**Goal: Try to establish a consistent framework for hadronic PV**

# Back-up slides

# Large errors……

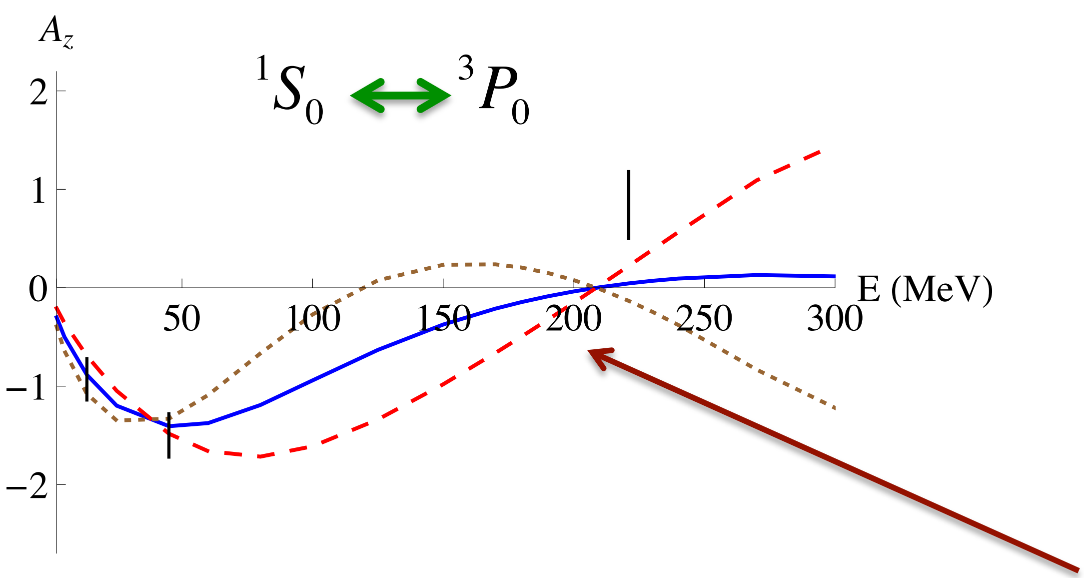
- It seems the DDH value works well, but……
- Experimental errors are **too big** to draw conclusion
- Fit to 2 low-energy points (90% CL):

$$h_\pi = (1.7 \pm 2.5)\cdot 10^{-6} \qquad C = (-9.3 \pm 10)\cdot 10^{-6}$$



# Crossing points

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



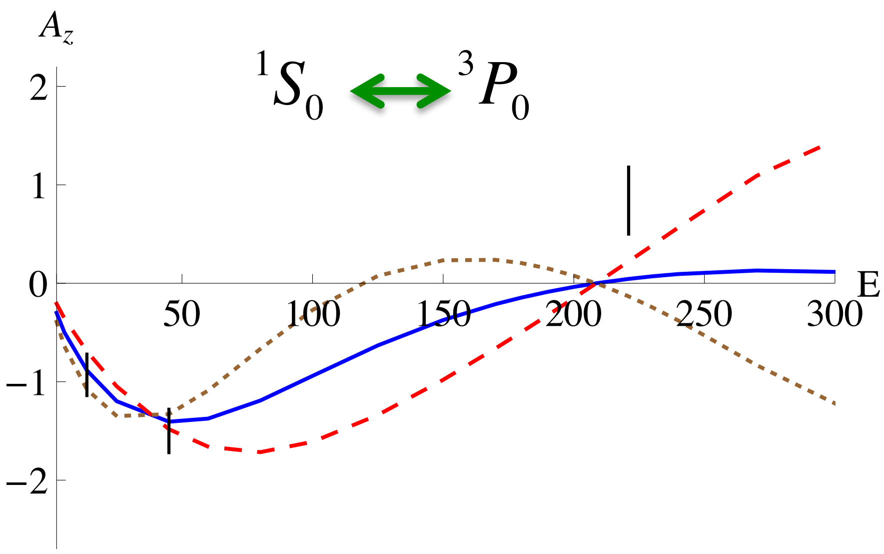

- The j=0 contributions: $\sim \sin\left(\delta_{^1S_0} + \delta_{^3P_0}\right)$ (optical theorem)
- Vanishes at (210 ± 5) MeV → Reason for TRIUMF energy
- Reasoning: Sensitive to different DDH parameters

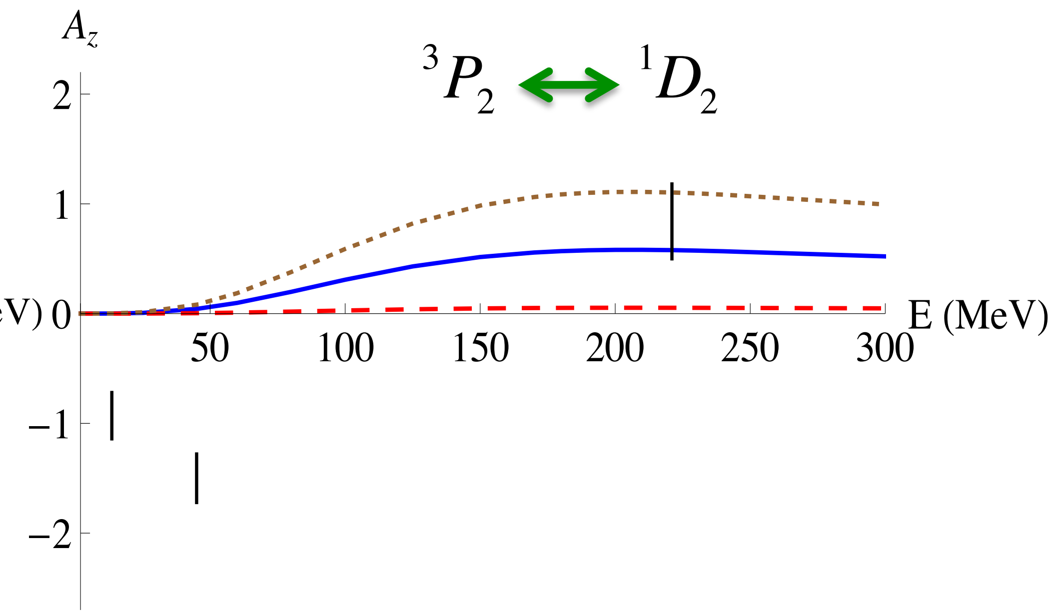
  *(to j=2 transitions)*

# Crossing points



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

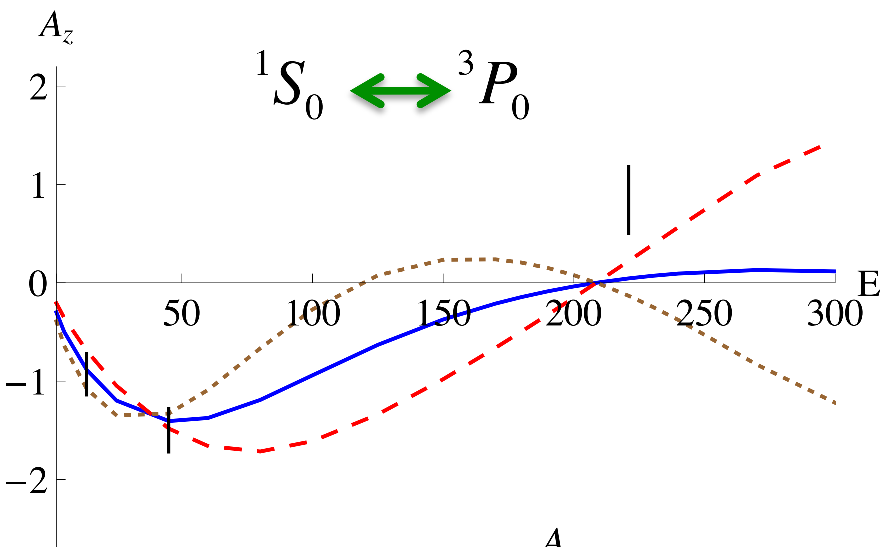


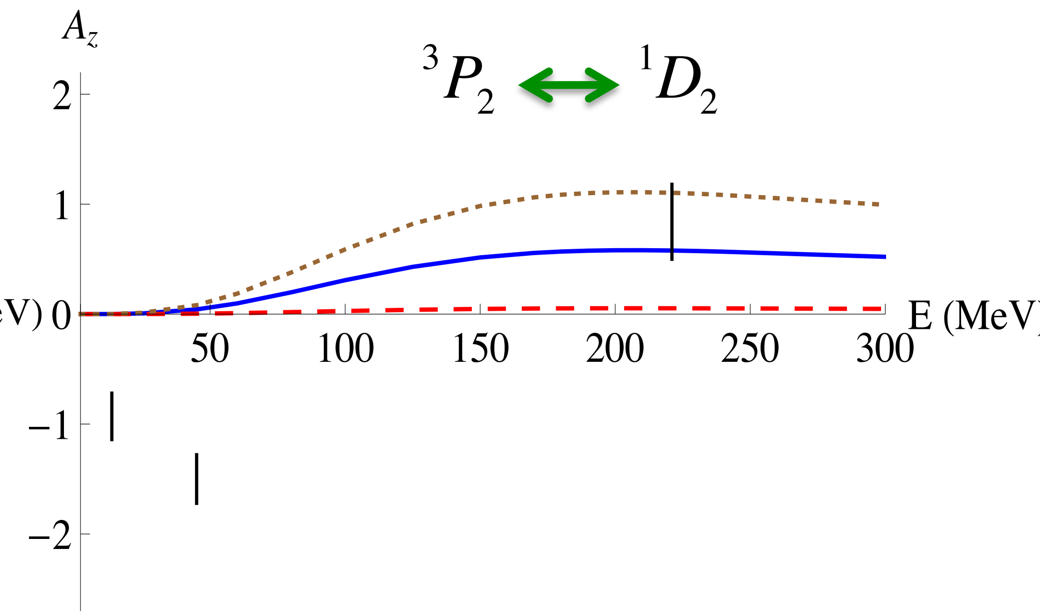



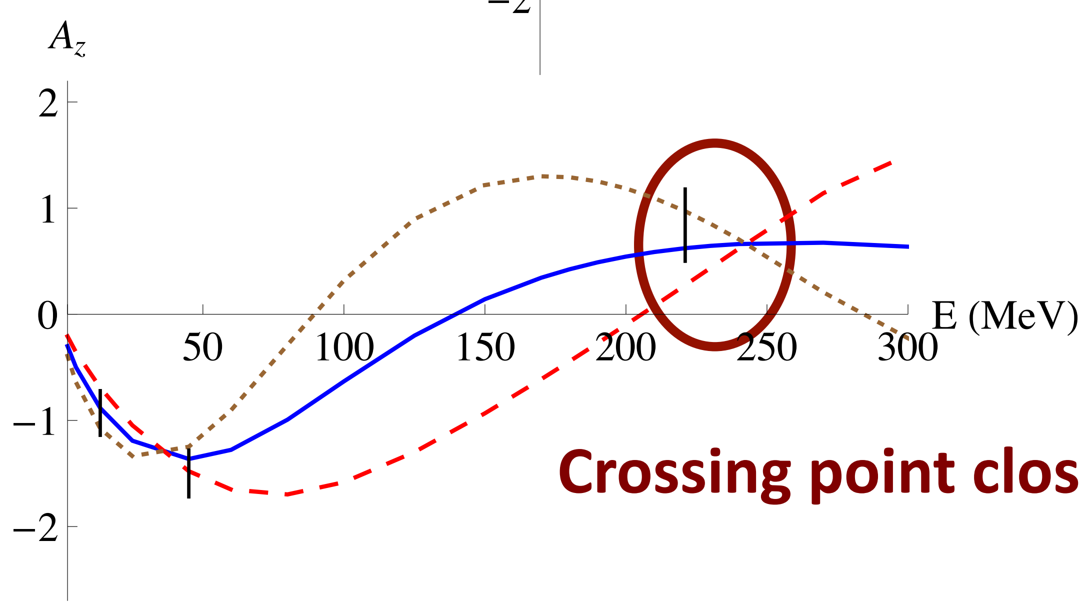

- The j=2 contributions are fairly constant around 220 MeV

# Crossing points

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



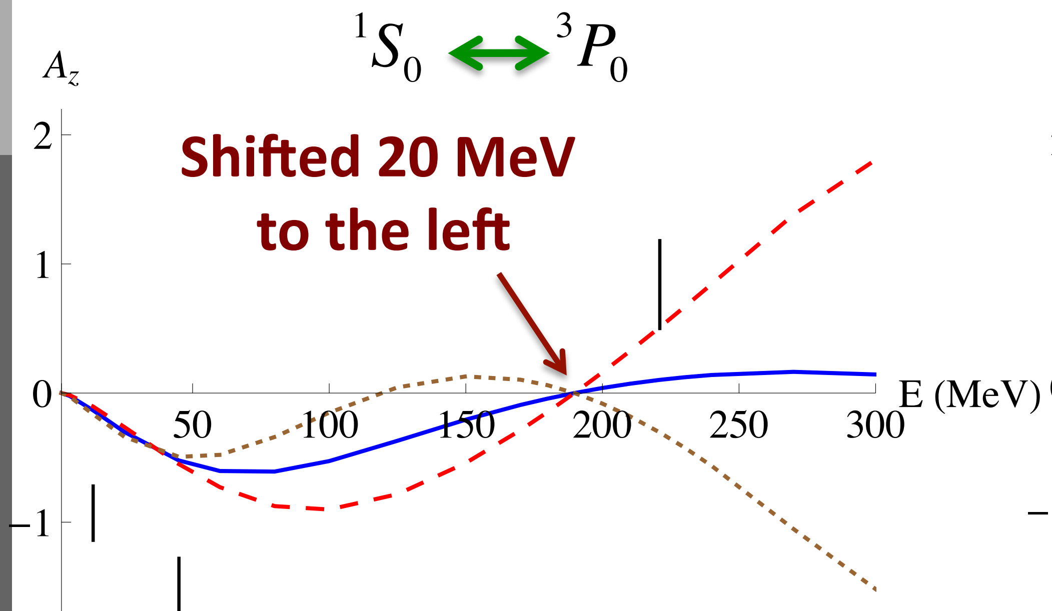



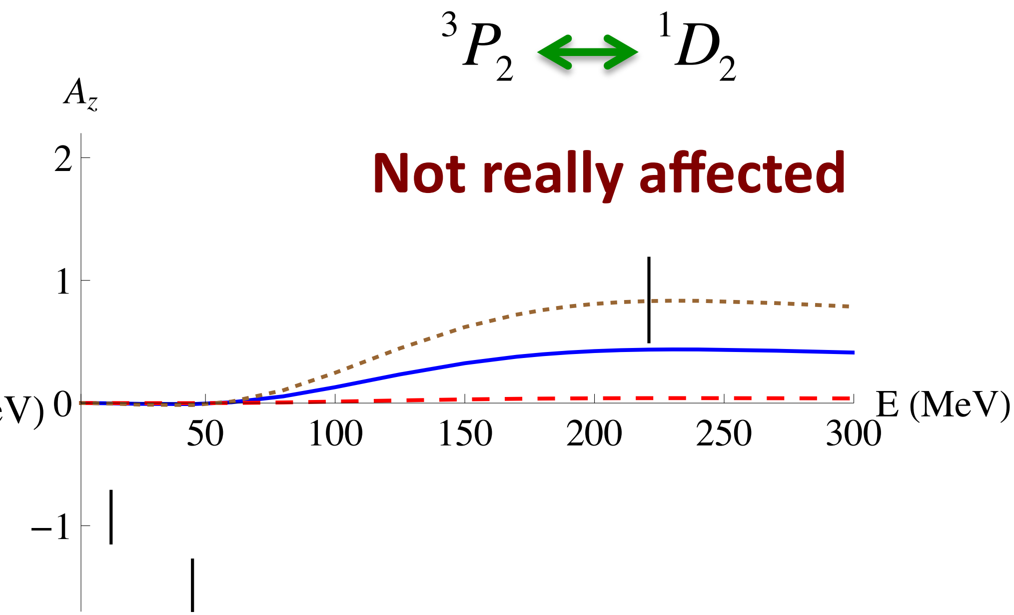




**Crossing point close to 220 MeV**

# Crossing points

- Now add the Coulomb amplitude



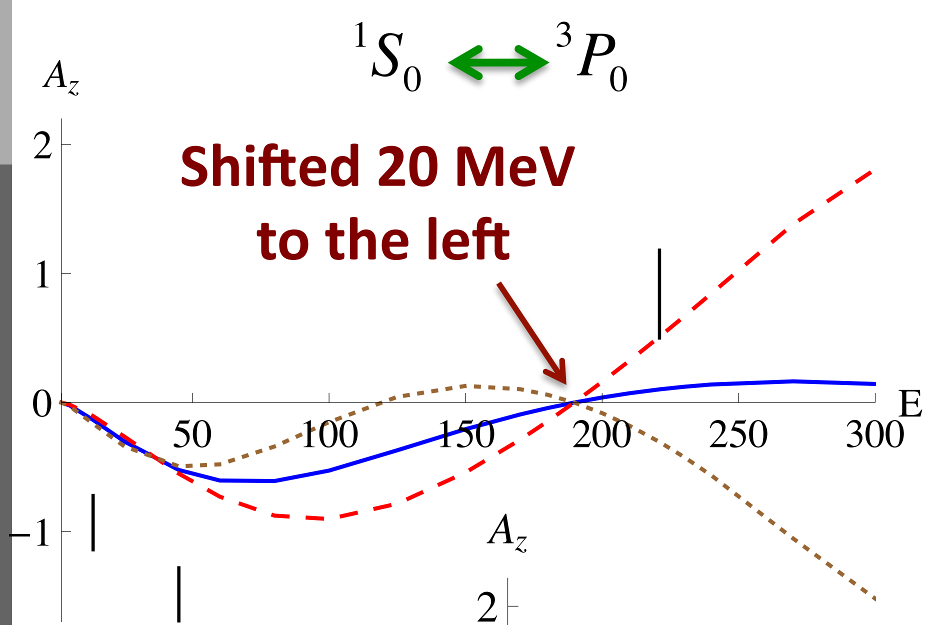

- The j=0 contributions: $\sim \sin\left(\delta_{^1S_0} + \delta_{^3P_0} + \phi_{em}\right)$

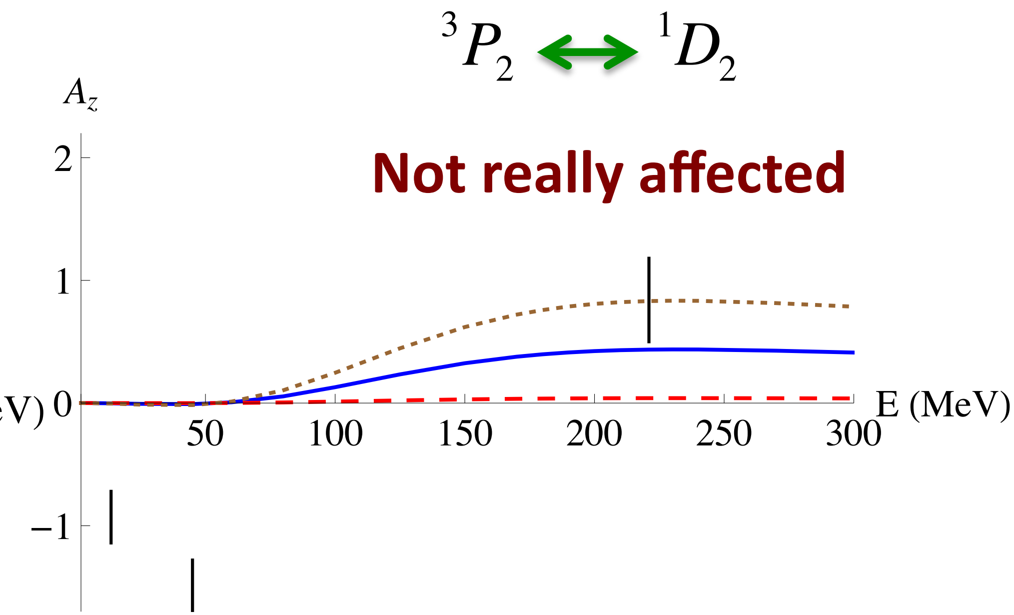
$$\phi_{em} \propto m_p \frac{\alpha_{em}}{\sqrt{E}} \ln(\sin\frac{\theta_c}{2}) \approx 4^\circ$$

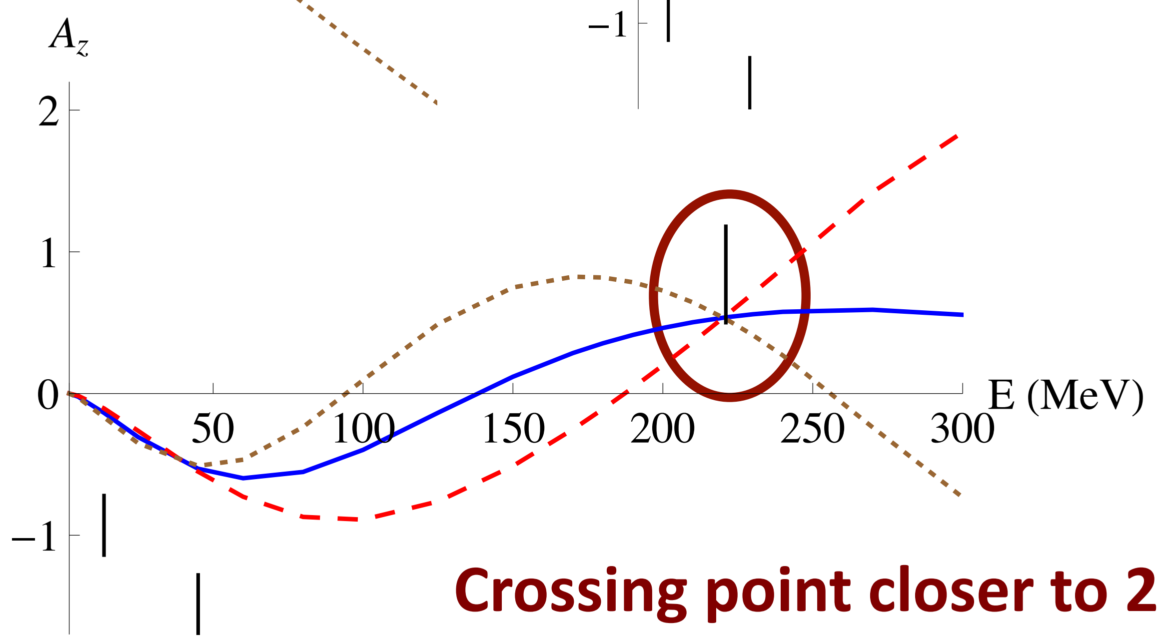
- New phase relatively small but..... **Important** for zero-crossing

# Crossing points

- Now add the Coulomb amplitude




Crossing point closer to 220 MeV...