Charge Symmetry Breaking in $dd \to {}^4He\ \pi^0$

- Introduction
- The Indiana $dd \to {}^4He\ \pi^0$ experiment.
- Plane wave calculation including heavy meson exchange and π-η meson mixing.
- TRIUMF CSB experiment $np \to d\ \pi^0$

- Anders Gardestig and C. J. Horowitz

Isospin Violation Probes Strongly Interacting Systems

- Determine m_u, m_d: fundamental and poorly known parameters of Standard Model.
- Determine strong interaction phases and amplitudes for CP violation studies.
  - Need two interfering amplitudes for $\not{CP}$. $B \to \rho\rho$ can interfere with $B \to \rho\omega \to \rho\rho$ because of $\rho\omega$ mixing.
  - Extracted $\not{CP}$ parameters such as $\sin 2\alpha$ from other decays can be impacted by isospin violation [S. Gardner].

Determine Weak Interaction Matrix Elements for Standard Model Tests

- Super-allowed β decays give quark mixing V_{ud} after correcting for isospin violation.
  $|V_{ud}|^2 + |V_{us}|^2+|V_{ub}|^2= 1$?
  Brookhaven E865 result for $K^+\rightarrow \pi^0e^+\nu$ branching ratio changes V_{us} and (if true) makes matrix unitary.
- NUTEV Anomaly Sensitive to CSB
  $(<\sigma_{NC}{}^{\nu}>-<\sigma_{NC}{}^{\bar{\nu}}>)/(<\sigma_{CC}{}^{\nu}>-<\sigma_{CC}{}^{\bar{\nu}}>)=1/2-2\sin^2\theta_W$.
- Assumes charge symmetry: $p\rightarrow n$ and $u\rightarrow d$
- Londergan and Thomas find that CSB in $u_v(x)$ in p compared to $d_v(x)$ in n related to np and ud mass differences can explain $\approx$ 1/3 of anomaly.

Separate E+M and Quark Mass Contributions to Isospin Violation

- Two apparently independent sources:
  - E+M makes proton heavier then neutron.
  - $\Delta m \equiv m_d - m_u$ makes n heavier then p.
- $\Delta M \equiv M_n - M_p = 1.29$ MeV one of most basic and important parameters in nuclear astrophysics.
  - If $M_p \approx M_n$ Big Bang makes mostly ^{4}He.
  - If $M_p > M_n$ Big Bang makes ^{4}He and n (stable). H unstable.
  - In either case Universe drastically different.
- How to separate E+M and Δm effects?
  - Use different density dependence.
  - Study isospin violation in π^0-N scattering.

In a high density system

- Kinematics suppresses quark mass effects by large Fermi momentum. $(k_F^2+m^2)^{1/2} \sim k_F + m^2/2k_F$
- E+M effects grow as quarks move closer together. For example Coulomb exchange energy $\sim \alpha\, k_F$.
- In high density limit, isospin violation is dominated by E+M with quark mass terms unimportant. In this limit the proton is heavier then neutron.
  [CJH+J. Piekarewicz, PRC**63**, (2001) 011303]

Isospin Violating π^0-N Scattering (U. van Kolck)

- Chiral sym relates nucleon mass term to π-N scattering.
- Isospin breaking in nucleon mass term (n-p mass difference) related to isospin violating π-N scattering.
- Isospin viol. with symmetries of quark masses: $L_{qm}=\delta m/2[N^\dagger\tau_3 N-2N^\dagger\pi_3\tau\cdot\pi\ N/F_\pi^2]$
- With symmetries of hard photon exchange: $L_{em}=\overline{\delta}m/2[N^\dagger\tau_3 N+2N^\dagger(\pi_3\tau\cdot\pi\ -\pi^2\tau_3)/F_\pi^2]$
- $\Delta M=\delta m+\overline{\delta}m$ and measuring π^0-N scattering can decompose ΔM into quark mass and E+M parts.
- π^0 decay makes π^0 scattering hard. Look at isospin violation in π^0 production instead.

Cooler CSB

the search for $d+d \rightarrow \alpha\pi^0$

www.iucf.indiana.edu/~coolcsb

The Cooler-CSB Experiment at the Indiana University Cooler Synchrotron: A Test of Charge Symmetry Breaking and Isospin Conservation via the Reaction d+d $\rightarrow \alpha+\pi^0$

C. Allgower, V. Anferov, A.D. Bacher, G.P.A. Berg, J. Doskow, C.C. Foster, W. Fox, D. Friesel, A. Gardestig, C. Horowitz, C. Lavelle, H. Nann, J. Olmsted, T, Rinckel, E.J. Stephenson, and K. Solberg

Indiana University Cyclotron Facility, Bloomington, IN 47408

M.A. Pickar

Minnesota State University at Mankato, Mankato, MN 56002

B. Chujko, A. Kuznetsov, V. Medvedev, D. Patalakha, A. Prudkoglyad, and P.A. Semenov

Institute for High Energy Physics, Protvino, Moscow Region, Russia 142284

P.V. Pancella

Western Michigan University, Kalamazoo, MI 49001

A. Smith

Hillsdale College, Hillsdale, MI 49242

H.M. Spinka

Argonne National Laboratory, Argonne, IL 60439

S. Shastry

State University of New York, Plattsburgh, NY 12901

J. Rapaport

Ohio University, Athens, OH 45701

G.A. Miller

University of Washington, Seattle, WA 98195

U. van Kolck

California Institute of Technology, Pasadena, CA 91109

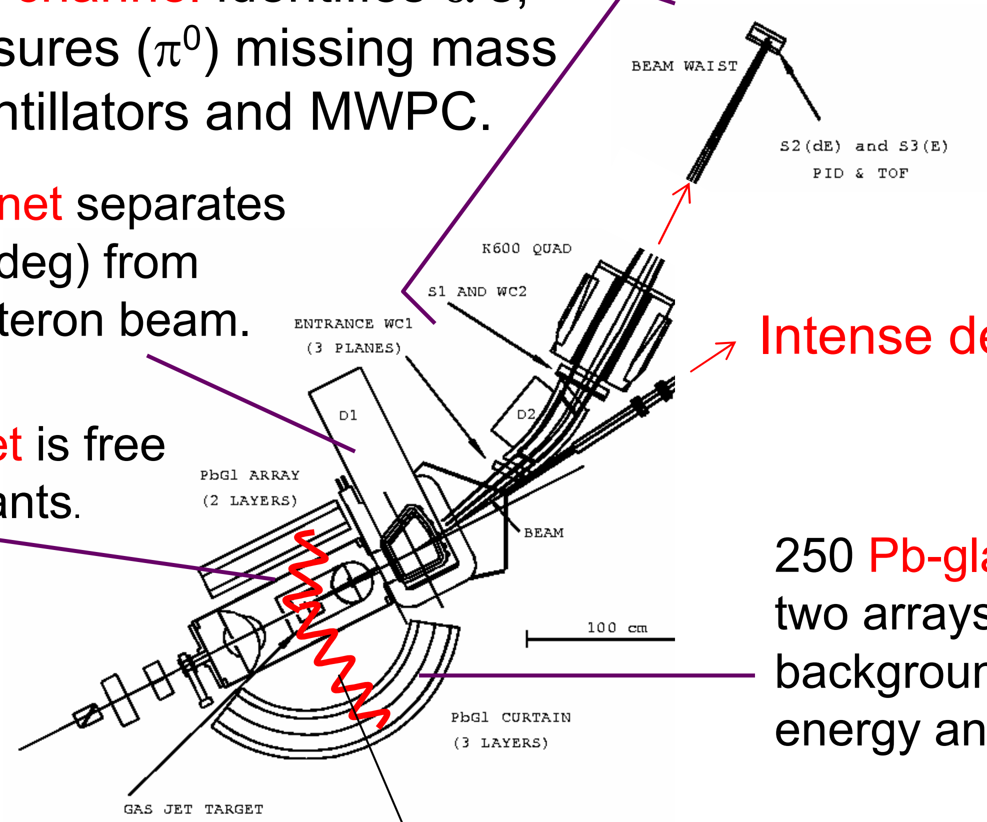
spokesperson for CE-82
spokesperson for Letter of Intent (CE-78)
technical manager
theory

d+d$\rightarrow$ ^{4}He+π^0 at the IUCF Cooler

Magnetic channel identifies α's, and measures (π^0) missing mass using scintillators and MWPC.

6 degree magnet separates α's (bent 12.5 deg) from circulating deuteron beam.

Gas jet target is free of contaminants.



Intense deuteron beam

250 Pb-glass detectors in two arrays remove trigger background and check π^0 energy and γ coplanarity.

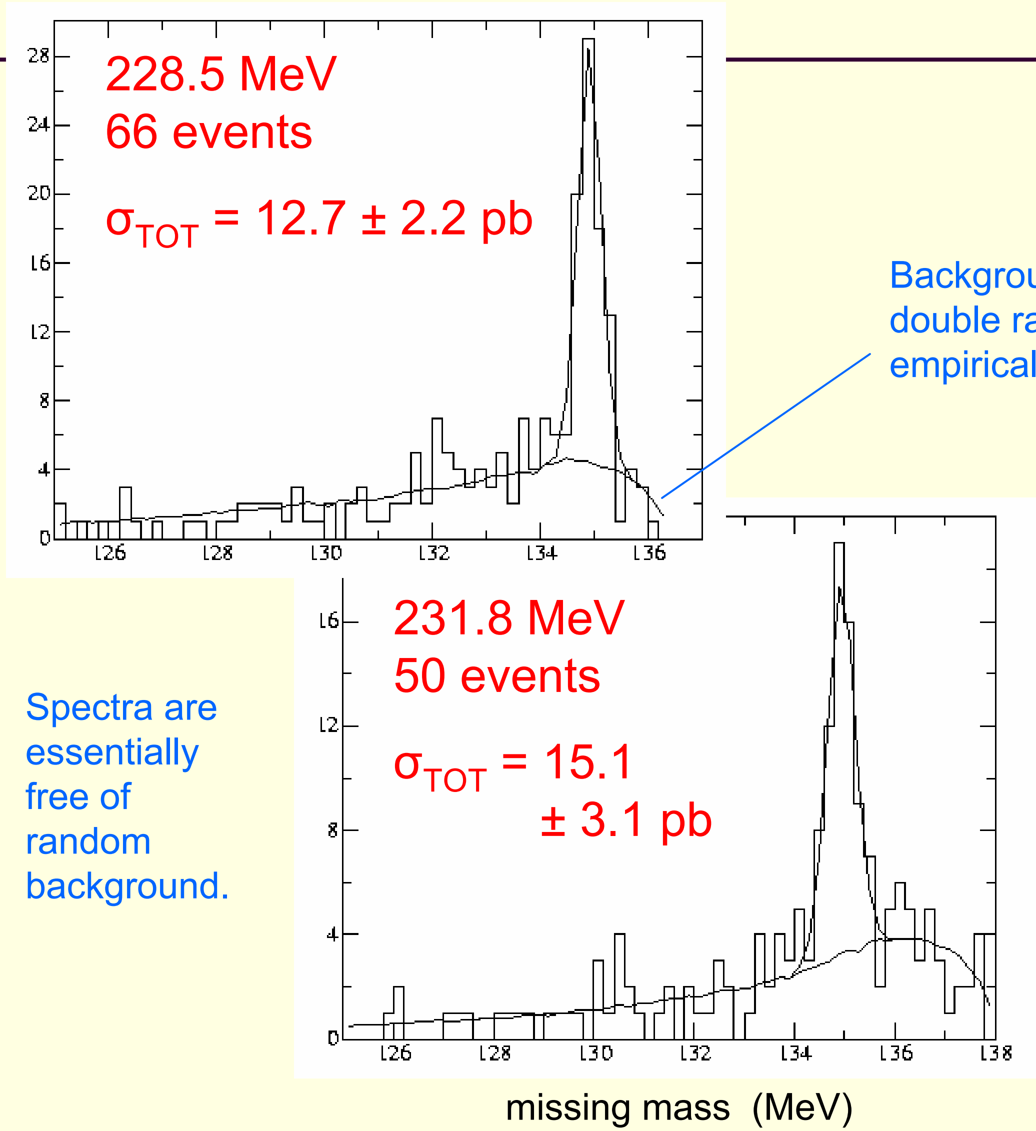
See both γs from π^0 decay

Experimental Results

- Data was taken at two near threshold energies: 228.5 MeV (η_π=0.1434) and 231.8 MeV (η_π=0.209). Also some d+d elastic scattering data taken to help check initial state distortions.
- See a clear pion signal reconstructing to pion mass at both energies while background moves with phase space. Low background for two gamma plus He events.
- Luminosity calibration from dd and pd elastic scattering.

PRELIMINARY RESULTS

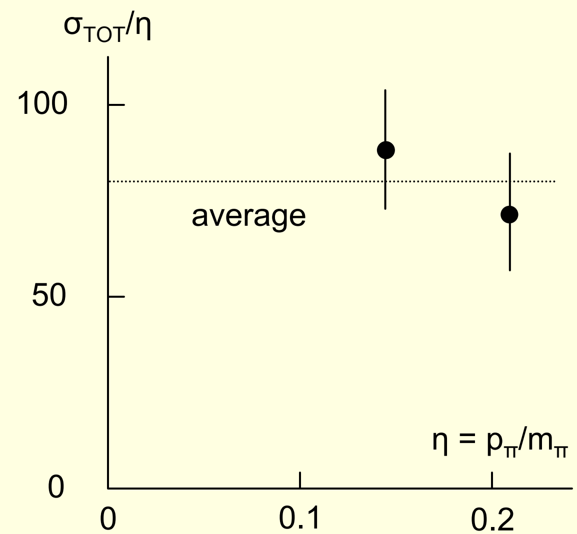
Events in these spectra must satisfy:
- correct pulse height in channel scintillators
- usable wire chamber signals
- good Pb-glass pulse height and timing



Background shape based on calculated double radiative capture, corrected by empirical channel acceptance using ^{4}He.

Spectra are essentially free of random background.

Cross sections are consistent with S-wave pion production.

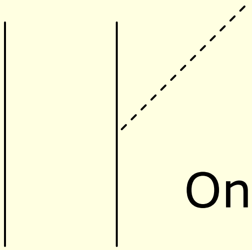


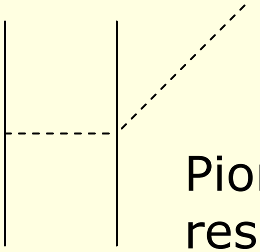
CSB Theory Collaboration

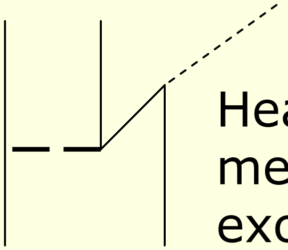
- Antonio Fonseca (dd scattering wave function), Anders Gardestig (plane wave calc.), Chris Hanhart (chiral counting and loops), Chuck Horowitz (CSB operators) , Gerry Miller, Andreas Nogga (^{4}He wave function), Bira van Kolck, … have formed collaboration. Four workshops at Seattle, Albuquerque, Bloomington, and Philly.
- There will be a CSB Workshop in Seattle ~ Oct 20, 2003 and all are welcome.
- We have preliminary plane wave results.
- Full distorted wave calculations with realistic ^{4}He wave function underway.

$pp \rightarrow pp\ \pi^0$ results for s-wave π

- Same $^3P_0 \rightarrow {}^1S_0 s$ quantum numbers!
- Threshold s-wave cross section 5 times larger than one-body contribution.
- Neutral pion rescattering small on-shell.
- Large contributions from sigma and omega heavy meson exchange currents can explain data.
- Convergence of chiral pert theory poor because of large nucleon momenta even at threshold.

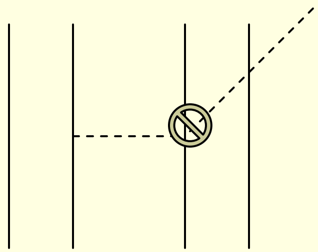






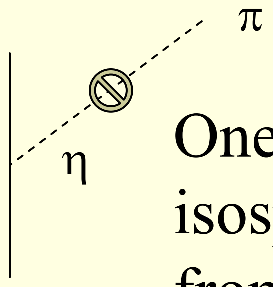
Leading Order Contribution Near Threshold is Pion Rescattering Term.

- Chiral symm relates isospin breaking mass and π^0-nucleon scattering terms
- $L_{qm}=\delta m/2\{N^+\tau_3 N-2N^+\pi_3\pi.\tau N/F_\pi^2\}$,
- $L_{em}=\bar{\delta}m/2\{N^+\tau_3 N+2N^+(\pi_3\pi.\tau-\pi^2\tau_3)N/F_\pi^2\}$,
- $\Delta M=\delta m+\bar{\delta}m$
- Strong isospin dependence of these terms reduces their contribution to $dd\rightarrow {}^4He\ \pi^0$

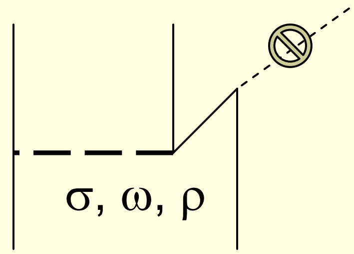


- Not true for CSB in $np\rightarrow d\pi^0$ TRIUMF experiment

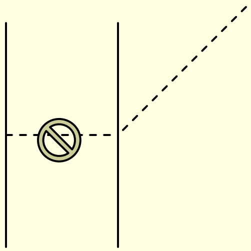
N^2LO Contributions



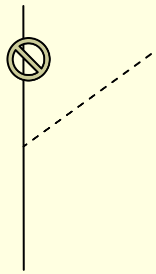
One body with isospin violation from π-η mixing



σ, ω, ρ heavy meson exchange with π-η mixing

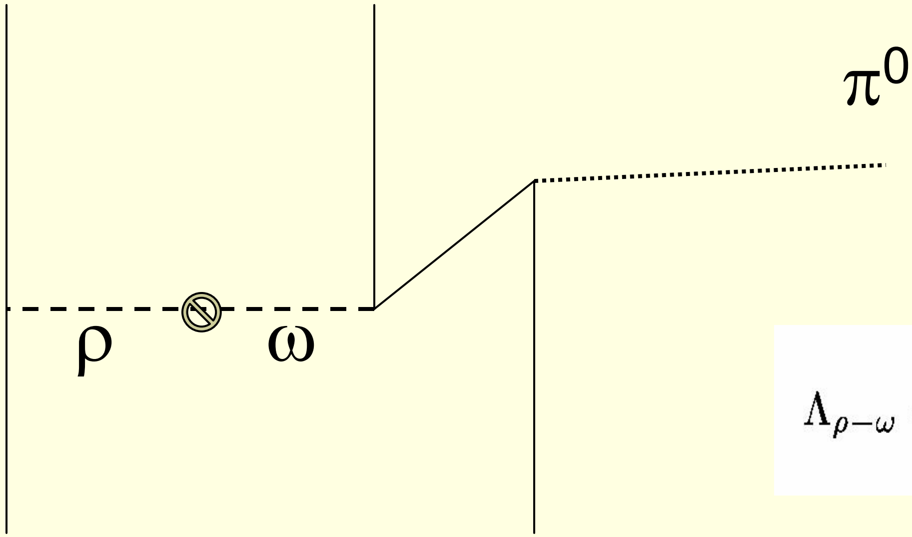


Pion rescattering after π-η mixing



Isospin violation in ^{4}He wave function, very sensitive to difference r_n-r_p

Also Rho-Omega Mixing



$$\Lambda_{\rho-\omega} = \frac{1}{(2m_\pi)^{1/2}} f\left(\frac{<\rho|H\omega>}{m_\omega^2}\right)\frac{1}{M}$$

$$H_{\rho-\omega} = -\Lambda_{\rho-\omega}\left(\frac{g_\rho g_\omega}{4\pi M}\right)\frac{1}{2}\sum_{i\neq j}\left\{(1+\tau_i^3\tau_j^3)\sigma_j\cdot(f_{ij}^\rho p_i + p_i f_{ij}^\rho) + i[1+\tau_i^3\tau_j^3(1+C_\rho)]\sigma_i\wedge\sigma_j\cdot q_j f_{ij}^\rho\right\}$$

Plane wave calculation to characterize operators

Anti-symmetrized spin-isospin wave functions

The spin-isospin parts of the wave functions are

$$|\alpha\rangle = \frac{1}{\sqrt{2}}\left([(12)_1(34)_1]_0[(12)_0(34)_0]_0 - [(12)_0(34)_0]_0[(12)_1(34)_1]_0\right)$$

$$|d_1\rangle = (12)_1(12)_0$$

$$|d_2\rangle = (34)_1(34)_0$$

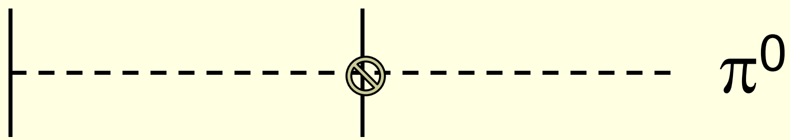
where the first brackets is spin and the second isospin.

π Rescattering is Isospin Disfavored

- Operator has two isospins (τ) but only one spin operator (σ).

$$\mathcal{O}_{i,j} = -\frac{f}{4\pi\mu F_\pi^2\sqrt{2\mu}}[\delta m_N(\boldsymbol{\tau}^{(i)}\cdot\boldsymbol{\tau}^{(j)} + \tau_3^{(i)}\tau_3^{(j)}) - \bar{\delta} m_N(\boldsymbol{\tau}^{(i)}\cdot\boldsymbol{\tau}^{(j)} - \tau_3^{(i)}\tau_3^{(j)})]$$
$$(\boldsymbol{\sigma}^{(i)} - \boldsymbol{\sigma}^{(j)})\cdot(-i\hat{\boldsymbol{r}})\frac{d}{dr}\left(\frac{e^{-\mu r}}{r}\right),$$

- The two τs convert both deuterons to isospin 1 but σ can only convert one of the two deuterons spins to spin 0.
- The s-wave alpha particle is a mixture of spin 0, isospin 1 pairs or spin one, isospin zero pairs.
- Operator gives zero for plane wave initial state. Distortions and or d-waves in ^{4}He or deuterons can change this.



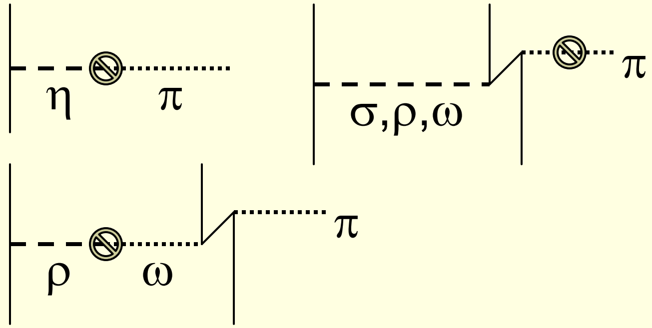
Other Contributions add coherently

- 1-body and sigma are coherent
- Omega involves $-\sigma_3 \cdot p_1$ compared to $\sigma_1 \cdot p_1$ for sigma exchange. For ${}^3P_0 \rightarrow {}^1S_0$, $\sigma_3 \cdot p_1 = -\sigma_1 \cdot p_1$ so omega and sigma add coherently.
- One body + σ + ω HMEC are coherent.
- Should evaluate rho-omega mixing and other HME in $np \rightarrow d\pi^0$.

Preliminary results with gaussian He and d and plane wave dd initial state

- Pure s-wave π at lower E=228.5 MeV
- One body π-η mixing alone σ=4.8 pb [0.8 pb].
- Total cross section $\sigma_{1+\sigma+\omega+\rho+\rho-\omega}$=37.7 pb [8.7 pb]
- Experiment= 12.7$\pm$ 2.2 pb
- Based on <πHη>=-4200 MeV^2, $g_\eta{}^2/4\pi$=3.68 [0.6] and <ρHω>=-4500MeV^2.

Heavy Meson Exc. Amplitude	Comp. to 1-Body
σ	0.62
ω	0.66
ρ	0.17
ρ-ω	0.36



Coherent Pion Bremstrahlung

- Can arrange spin one deuterons so axial charges of all 4 nucleons contribute coherently.
- We find heavy meson exchange currents increase cross section because all pairs contribute with same sign and add coherently to one-body.
- Plane wave calculations with heavy meson exchange and isospin violation from reasonable π-η mixing parameters can explain large observed cross section.
- Important to include dd distortions and full ^{4}He wave function and to calculate Weinberg terms with correlations! Calculations underway.

CSB in $np \to d\pi^0$ (A. K. Opper)

- Forward, backward asymmetry violates CS
  $A_{fb}(\theta)=(\sigma(\theta)-\sigma(\pi-\theta))/(\sigma(\theta)+\sigma(\theta))$
- TRIUMF exp at 279.5 MeV detects both forward and backward d in same spectrometer setting. Result angle integrated:
  $A_{fb}=+17.2 \pm 8(\text{stat}) \pm 5.5(\text{sys}) \times 10^{-4}$
  based on careful simulation of spectrometer acceptance.

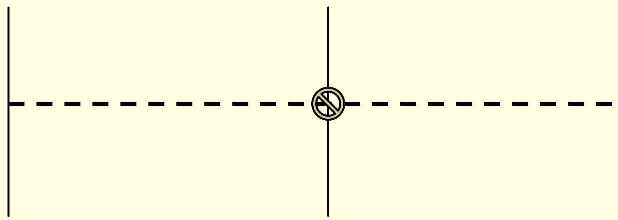
$np \rightarrow d\pi^0$ Theory (Niskanen)

- A_{fb} depends on interference of s+p waves and CSB and CS amplitudes. This increases uncertainty. No isospin cancellations for δ m, $\bar{\delta}$ m terms:

$$A_{fb} = -28\{ g_{\eta NN}/(4\pi(3.68))^{1/2} \langle\pi H\eta\rangle/(-5900\ \mathrm{MeV}^2) - 0.87/\mathrm{MeV}(\delta m-\bar{\delta} m/2) \} \times 10^{-4}.$$

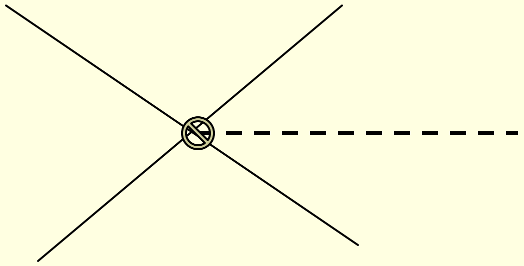
  This is – for $\pi\eta$ mixing, + for δ m.
- Positive exp result may be evidence for δ m terms.
- Different isospin dependence makes $np\rightarrow d\pi^0$ and $dd\rightarrow {}^4He\pi^0$ sensitive to different combinations of CSB operators.
- Important to improve calculation of A_{fb}, including HME for example, and assess theoretical uncert.

CSB Operators in Chiral Pert Theory



Leading order: $(\sigma_1 - \sigma_2)\cdot q\ \tau_1\ \tau_2$

Contributes to $np \to d\pi^0$, isospin suppressed for $dd \to {}^4He\ \pi^0$



Contact term: down by $m_\pi/M \sim 1/7$

Important for $dd \to {}^4He\ \pi^0$, should be calculated for $np \to d\pi^0$

$\sigma_1 \cdot p$ for σ, ω HMEC or $\sigma_1 \times \sigma_2 \cdot q\tau_1\tau_2$ for ρ-ω