INVESTIGATIONS OF CHARGE SYMMETRY CONSERVING REACTION $dd \to {}^{3}He n \pi^{0}$ WITH WASA-at-COSY

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CHARGE SYMMETRY BREAKING IN QCD

simplified version of Ch. Hanhart introduction "From QCD to $dd \to \alpha\pi^0$ and back"

$$q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad P_{CS}q = e^{-i\tau_2\pi/2}q = \begin{pmatrix} -d \\ u \end{pmatrix} \qquad P_{CS}\bar{q} = e^{-i\tau_2\pi/2}\bar{q} = \begin{pmatrix} \bar{d} \\ -\bar{u} \end{pmatrix}$$

$$\mathcal{M} = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} = \frac{m_u + m_d}{2} 1 + \frac{m_u - m_d}{2} \tau_3 \qquad \mathcal{Q} = \frac{1}{3} e \begin{pmatrix} 2 & 0 \\ 0 & -1 \end{pmatrix} = \frac{e}{2} 1 + \frac{3e}{2} \tau_3$$

$$q_{R/L} = \frac{1}{2}\left(1 \pm \gamma_5\right) q$$

$$\mathcal{L}_{QCD} = i\bar{q}_L\left(\partial_\mu\gamma^\mu + i\mathcal{Q}\gamma_\mu A^\mu\right)q_L + i\bar{q}_R\left(\partial_\mu\gamma^\mu + i\mathcal{Q}\gamma_\mu A^\mu\right)q_R - \bar{q}_R\mathcal{M}q_L - \bar{q}_L\mathcal{M}q_R + \ldots$$

terms with 1 transform differently than terms with τ_3

$$P_{CS}^{+} 1 P_{CS} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad P_{CS}^{+} \tau_3 P_{CS} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

in QCD charge symmetry is broken by:

up and down quarks mass difference $\sim m_u - m_d$

quark electromagnetic interaction $\sim e^2$

CHARGE SYMMETRY BREAKING FOR HADRONS CHIRAL PERTURBATION THEORY – ChPT

effective Lagrangian for hadrons with the same symmetry as QCD Lagrangian

ChPT Lagrangian structure fixed by symmetries

static isospin violation

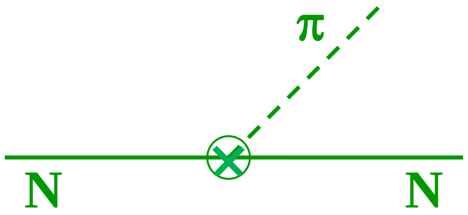
$$m^2_{\pi^\pm} - m^2_{\pi^0} = \frac{2C}{f_\pi^2} e^2$$

$$m_p - m_n = \Delta m_{ud} + \Delta m_{em}$$

$$\begin{cases} \Delta m_{ud} = -4B(m_u - m_d)c_5 = (-2.05 \pm 0.3)\ \mathrm{MeV} \\ \Delta m_{em} = -e^2 f_\pi^2 f_2 = (0.7 \pm 0.3)\ \mathrm{MeV} \end{cases}$$

dynamic isospin violation

πNN vertex



$$V_{\pi NN} = -\delta^{3a} \frac{\beta_1}{f_\pi} \vec{\sigma} \cdot \left(\vec{q} - \frac{m_\pi}{2m_N} (\vec{p} + \vec{p}\,') \right)$$

$$\beta_1 = \frac{m_u - m_d}{m_u + m_d} \left(\frac{m_\pi}{m_N} \right)^2$$

pion mass difference usually dominate isospin symmetry breaking but it does not contribute to charge symmetry breaking ⇒ measure CSB reactions

NULL EXPERIMENTS

$$P_{CS}|d> = |d> \qquad P_{CS}|^4He> = |^4He>$$

$$P_{CS}|\pi^0> = P_{CS}|u\bar{u} - d\bar{d}>/\sqrt{2} = -|d\bar{d} - u\bar{u}>/\sqrt{2} = -|\pi^0>$$

$$P_{CS}|dd> = |dd> \qquad P_{CS}|^4He\pi^0> = -|^4He\pi^0>$$

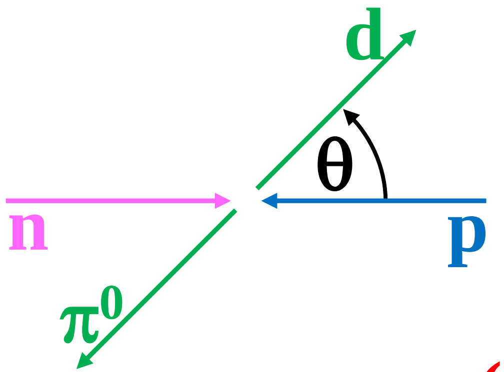
$$\Rightarrow \sigma = 0$$

first observation of $dd \rightarrow {}^4He\pi^0$

Phys. Rev. Lett. 91, 142302 (2003)

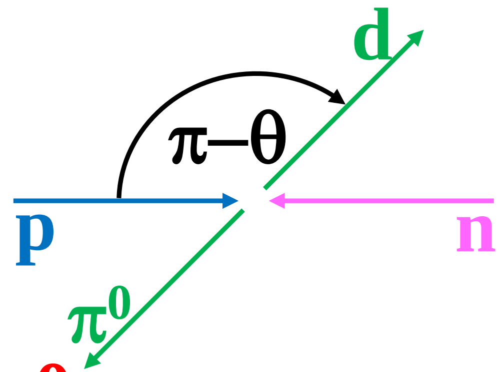
Q = 1.4 MeV, σ = 12.7 ± 2.2 pb and Q = 3.0 MeV, σ = 15.1 ± 3.1 pb

very close to threshold, only S wave



$$P_{CS}|np> = -|pn>$$

$$P_{CS}|d\pi^0> = -|d\pi^0>$$



$$\sigma(\theta) = \sigma(\pi-\theta) \Rightarrow A_{fb} = 0$$

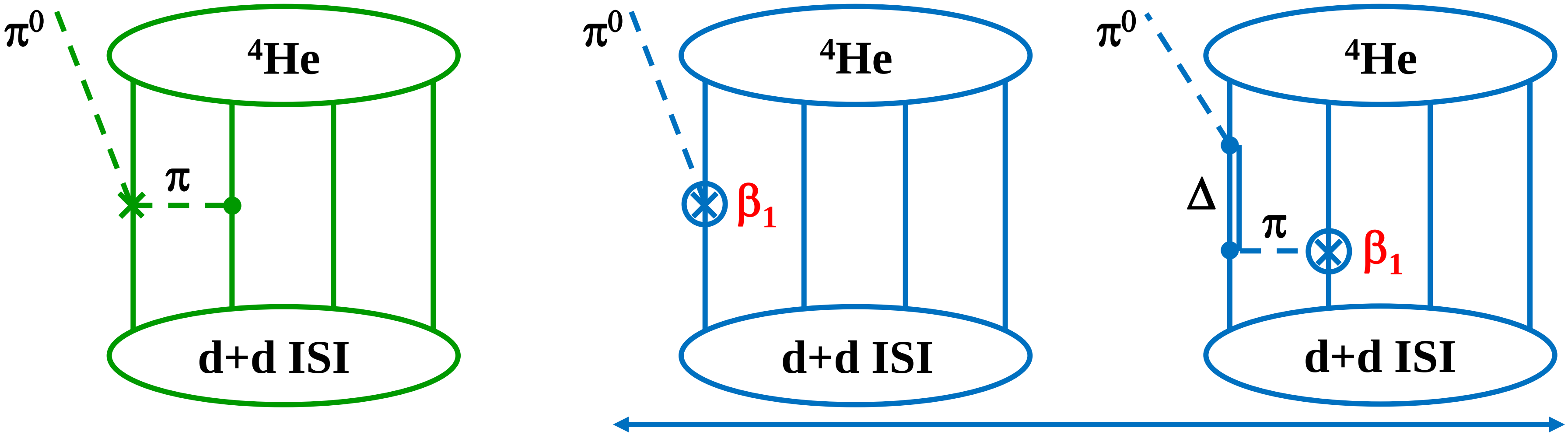
first measurement of non-zero asymmetry in $np \rightarrow d\pi^0$

Phys. Rev. Lett. 91, 212302 (2003)

A_{fb} = [17.2 ± 8.0(stat.) ± 5.5(sys.)] × 10^{-4}

ChPT CALCULATIONS OF dd → ^{4}Heπ^0

- **realistic 2- and 3-nucleon interactions**
- **hybrid ChPT calculations (initial state cannot be treated by ChPT)**



LO

the only one possible for *s*-wave
strongly suppressed due to selection rules in spin and isospin space

NNLO

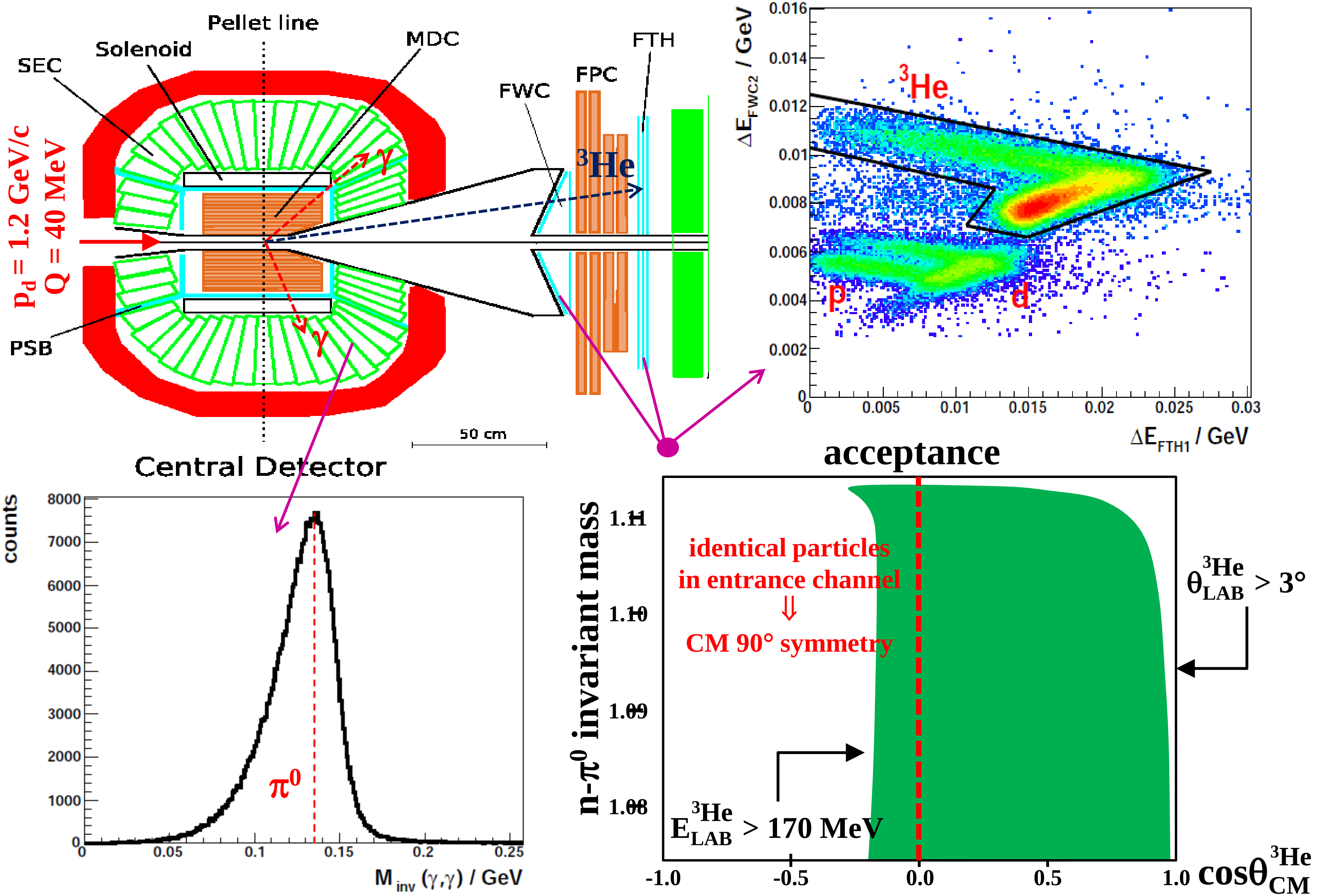
first non-vanishing contributions
important for *p*-wave
(larger energies above threshold)

additional observables are needed

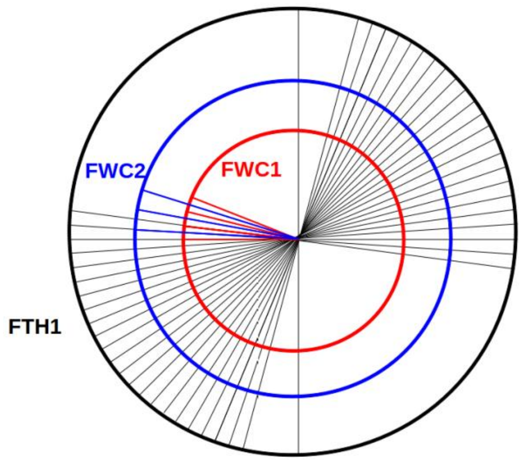
- ***p*-wave in dd → ^{4}Heπ^0 ⇒ $\beta_1 \sim m_u - m_d$ may be extracted**
  (polarization observables allow to disentangle *s*- and *p*-wave contribution)
- **Charge Symmetry Conserving dd → ^{3}ANπ reaction**
  (ChPT with known amplitudes, control of initial state dd → ^{4}Heπ^0)

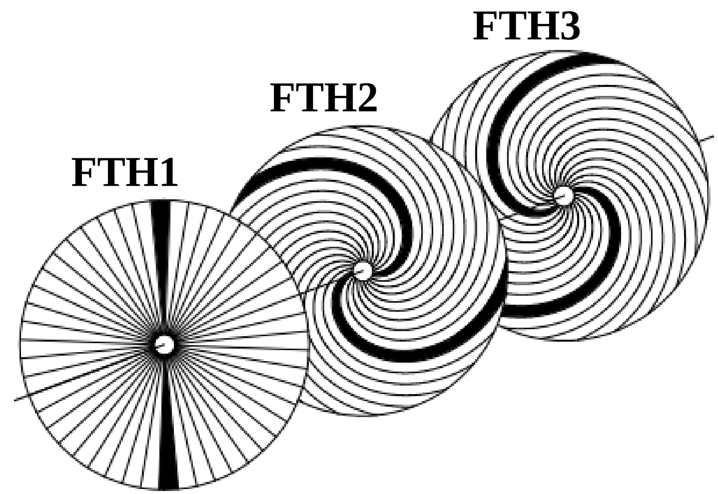
EXPERIMENTAL TECHNIQUE

data analysis
P. Podkopal Ph.D. thesis



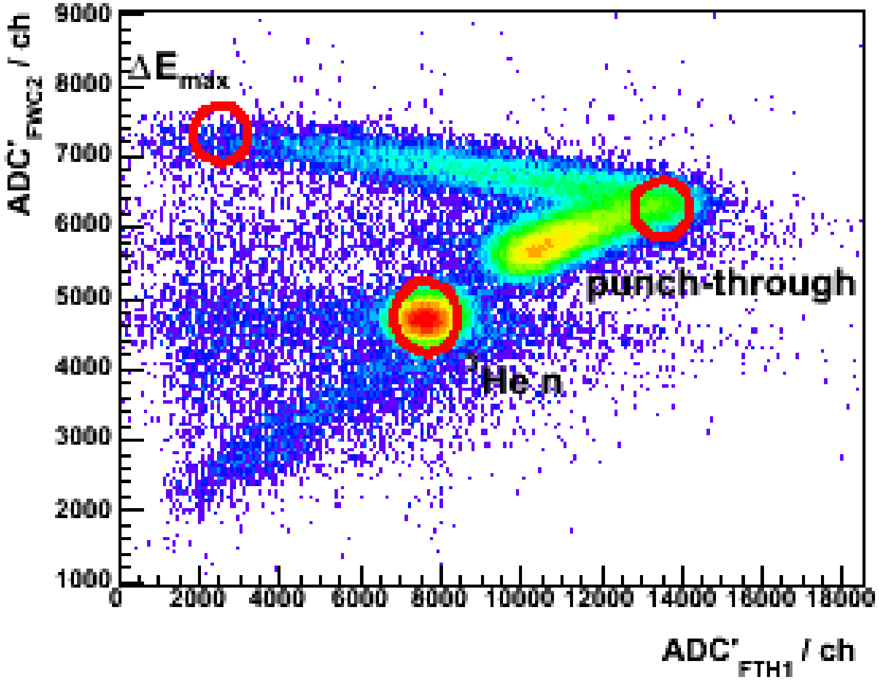
FORWARD DETECTOR CALLIBRATION

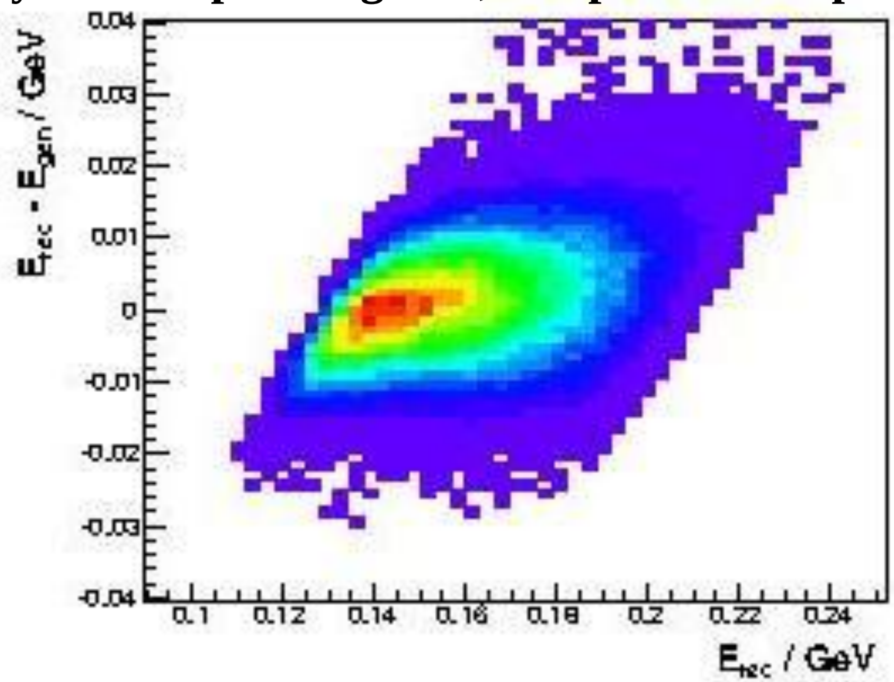




3 layers with 48 detectors each

next layers not operating well, complicated shape





energy resolution σ = 9 MeV improved by kinematical fit

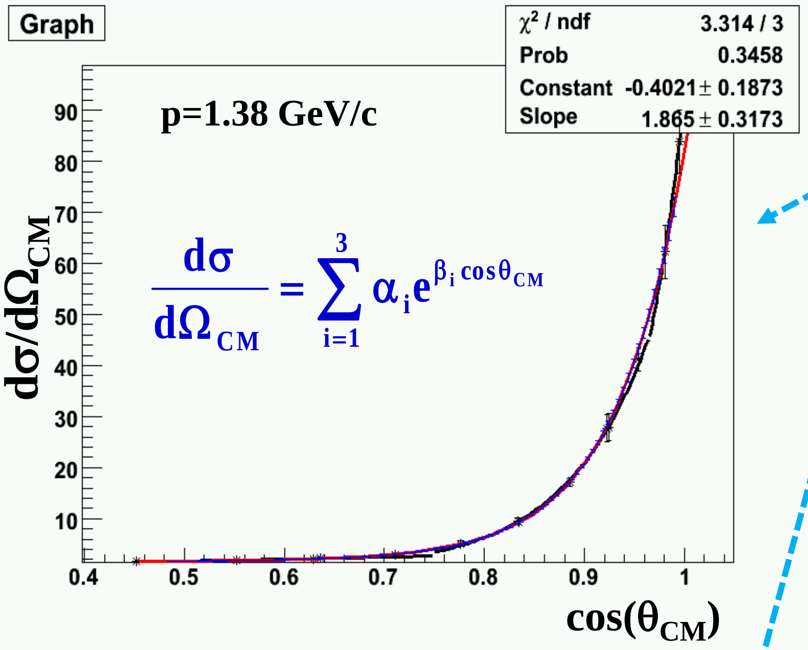
LUMINOSITY DETERMINATION USING dd→^{3}Hen

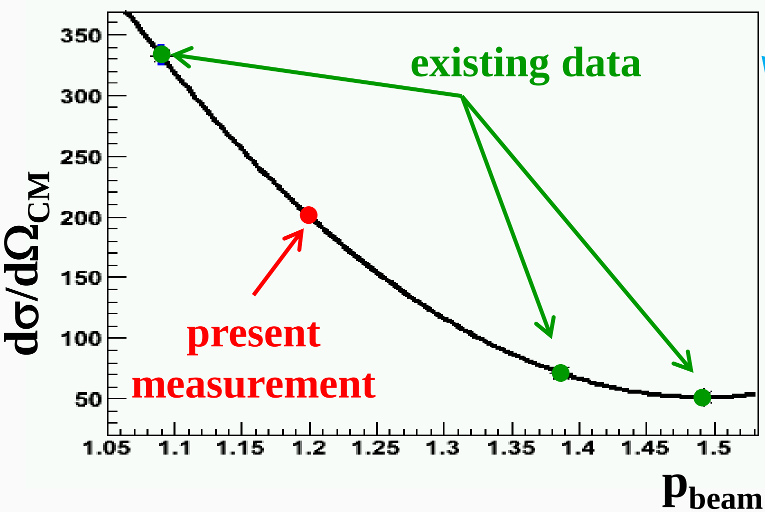
Phys. Rev. C22 (1980) 1632

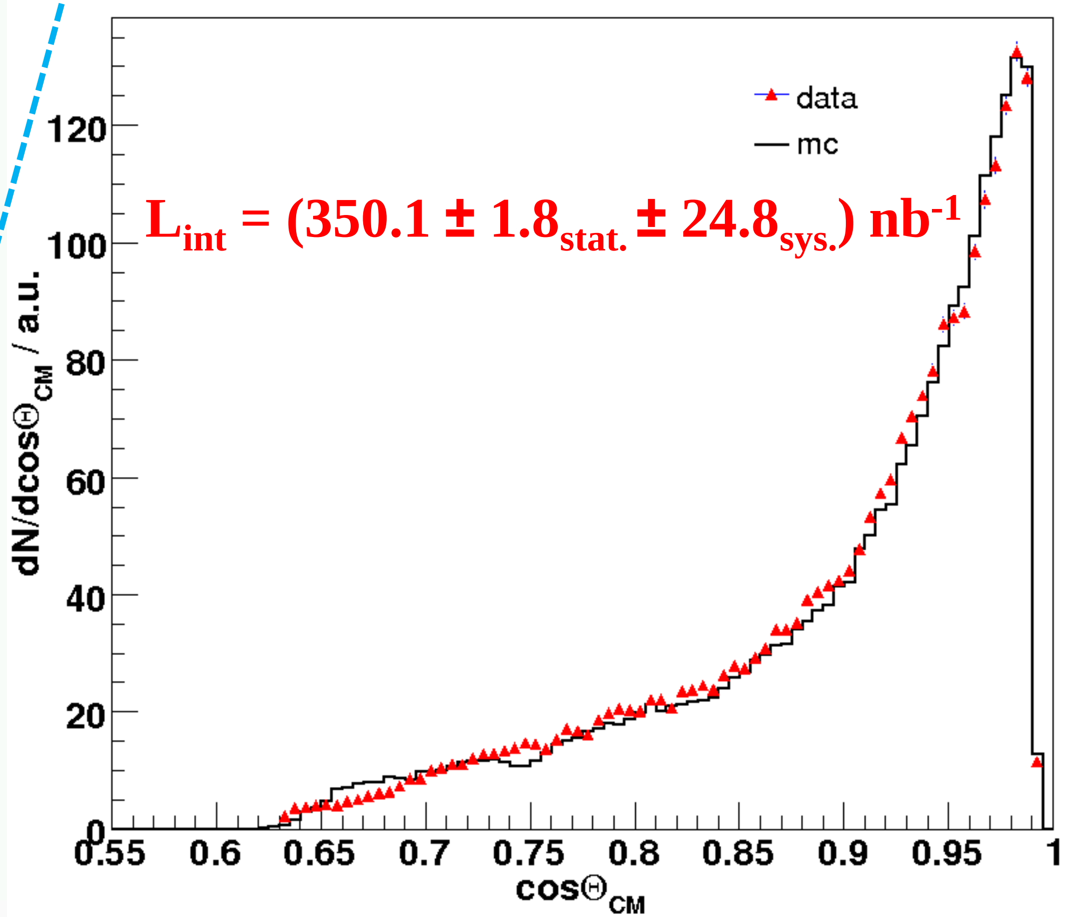
dd→^{3}Hen – p_{beam} = 1.651, 1.890, 1.992, 2.492 GeV/c

dd→^{3}Hp – p_{beam} = 1.109, 1.380, 1.493, 1.651, 1.787 GeV/c

- parameterization for 3 beam momenta
- for each angle interpolation for 1.2 GeV/c







CHOICE OF INDEPENDENT VARIABLES

Jacobi coordinates

$$\vec{P} = \vec{p}_1 + \vec{p}_2 + \vec{p}_3 = 0$$

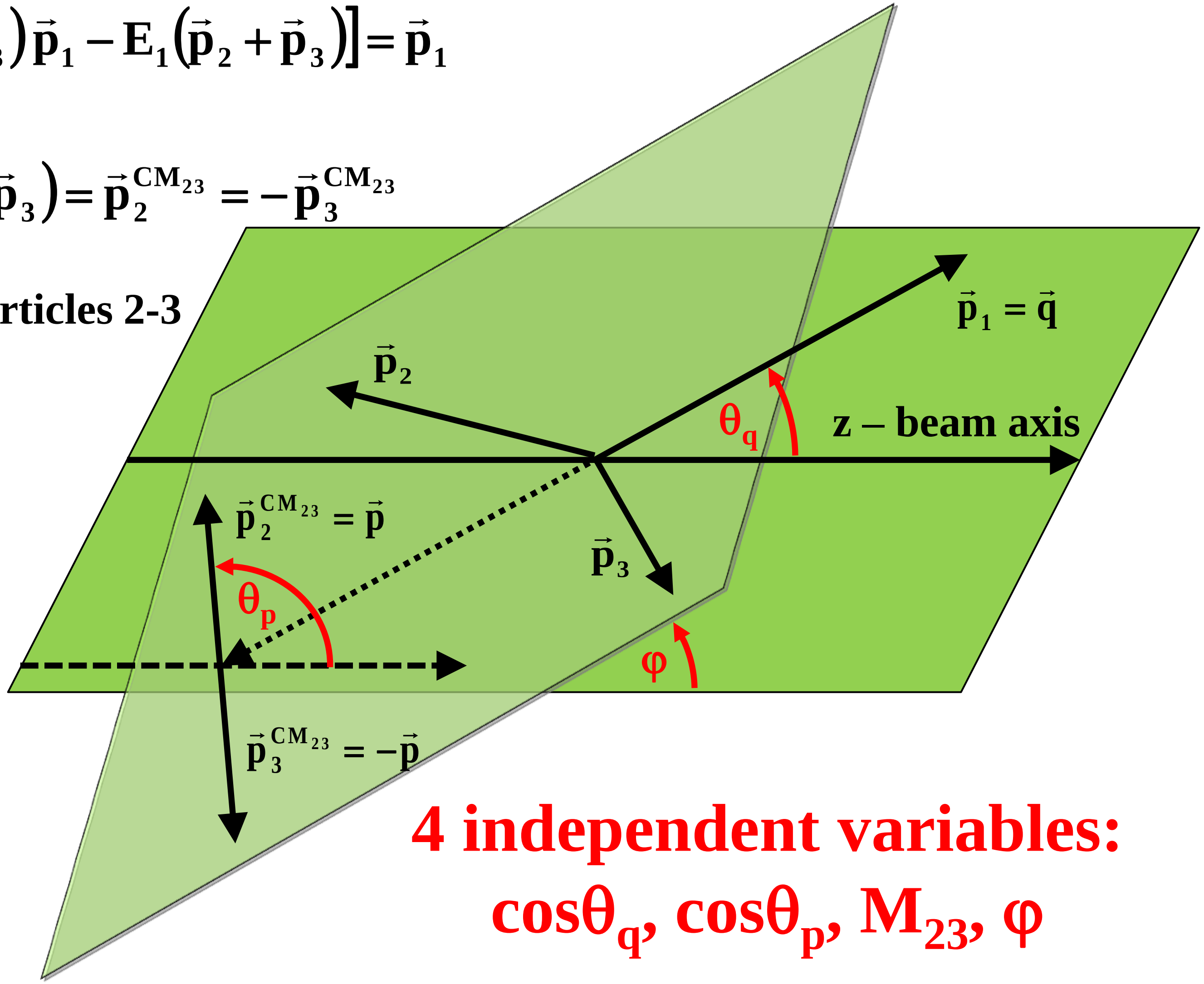
$$\vec{q} = \frac{1}{E_1 + E_2 + E_3}\left[\left(E_2 + E_3\right)\vec{p}_1 - E_1\left(\vec{p}_2 + \vec{p}_3\right)\right] = \vec{p}_1$$

$$\vec{p} = \frac{1}{E_2 + E_3}\left(E_3\vec{p}_2 - E_2\vec{p}_3\right) = \vec{p}_2^{\,CM_{23}} = -\vec{p}_3^{\,CM_{23}}$$

M_{23} – invariant mass of particles 2-3

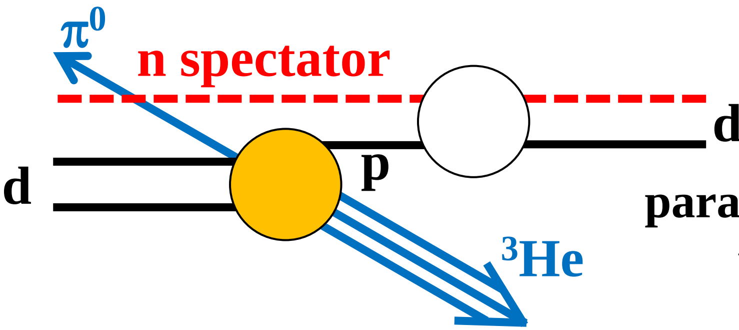
$$q = \frac{\sqrt{\lambda\left(s, M_1^2, M_{23}^2\right)}}{2\sqrt{s}}$$

$$p = \frac{\sqrt{\lambda\left(M_{23}^2, M_2^2, M_3^2\right)}}{2M_{23}}$$



4 independent variables:
$\cos\theta_q$, $\cos\theta_p$, M_{23}, φ

QUASI-FREE REACTION



Phys. Rev. C54 (1996) 1732

$$\vec{d}p \rightarrow {}^3He\pi^0$$

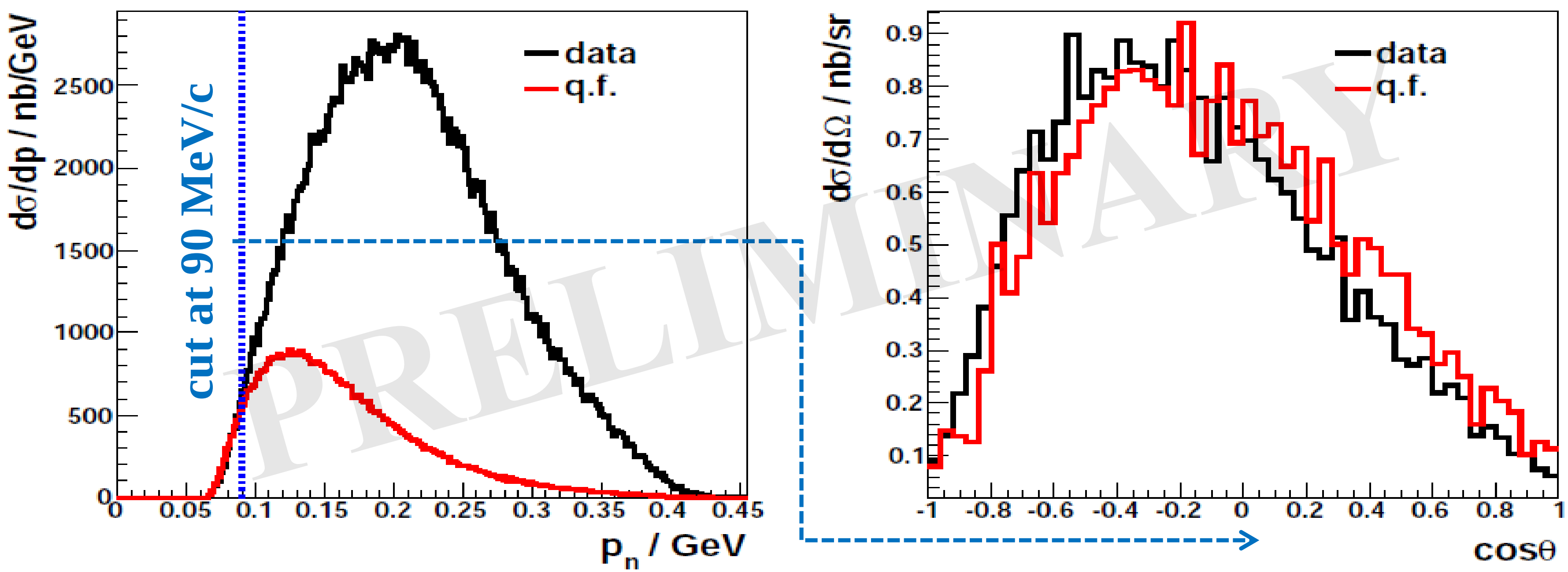
parameterized total cross section and angular distributions for 20 beam energies in the range of 397-429 MeV

neutron momentum from deuteron wave function calculated with Paris potential

total cross section for target + beam spectator

σ = 0.58 μb + 0.58 μb = 1.16 μb

present data and the model are absolutely normalized



PARTIAL WAVE DECOMPOSITION

No.	s_i	L_i	L_1	j_1	s_{23}	L_{23}	j_{23}	J	transition	
1	1	1	0	1/2	1/2	0	1/2	0	$^3P_0 \to {}^1S_1\,{}^1S_1$	sS
2	1	1	0	1/2	1/2	0	1/2	1	$^3P_1 \to {}^1S_1\,{}^1S_1$	
3	0	0	0	1/2	1/2	1	1/2	0	$^1S_0 \to {}^1S_1\,{}^1P_1$	sP
…	…	…	…	…	…	…	…	…	…	
10	2	4	0	1/2	1/2	1	3/2	2	$^5G_2 \to {}^1S_1\,{}^1P_3$	
11	0	0	1	1/2	1/2	0	1/2	0	$^1S_0 \to {}^1P_1\,{}^1S_1$	pS
…	…	…	…	…	…	…	…	…	…	
18	2	4	1	3/2	1/2	0	1/2	2	$^5G_2 \to {}^1P_3\,{}^1S_1$	

$$\frac{d^4\sigma}{2\pi dM_{23} d\cos\theta_p d\cos\theta_q d\varphi} \propto A_0 + A_1 q^2 + A_3 p^2 + \frac{1}{4} A_2 q^2 (1 + 3\cos 2\theta_q) +$$
$$+ \frac{1}{4} A_4 p^2 (1 + 3\cos 2\theta_p) + A_5 pq \cos\theta_p \cos\theta_q + A_6 pq \sin\theta_p \sin\theta_q \cos\varphi$$

$$\Psi_{PW}(QR) \to j_L(QR) \propto Q^L$$

approximation: amplitudes proportional to $q^{L_1} p^{L_{23}}$

A_0	$\to$	sS – wave	$\vec{L}_1 = 0, \vec{L}_{23} = 0$
A_1, A_2	$\to$	pS – wave	$\vec{L}_1 = 1, \vec{L}_{23} = 0$
A_3, A_4	$\to$	sP – wave	$\vec{L}_1 = 0, \vec{L}_{23} = 1$
A_5, A_6	$\to$	sP and pS interference	

FORMULAE FOR DIFFERENTIAL DISTRIBUTIONS

$$I_{sS} = \int_{(M_2+M_3)^2}^{(\sqrt{s}-M_1)^2} pq \, dM_{23} \qquad I_{pS} = \int_{(M_2+M_3)^2}^{(\sqrt{s}-M_1)^2} pq^3 \, dM_{23} \qquad I_{sP} = \int_{(M_2+M_3)^2}^{(\sqrt{s}-M_1)^2} p^3 q \, dM_{23} \qquad I_{pS+sP} = \int_{(M_2+M_3)^2}^{(\sqrt{s}-M_1)^2} p^2 q^2 \, dM_{23}$$

$$B = A_0 I_{sS} + A_1 I_{pS} + A_3 I_{sP}$$

$$\frac{d\sigma}{2\pi d\cos\theta_p} = 4\pi C\left[B + \frac{1}{4} A_4 \left(1 + 3\cos 2\theta_p\right) I_{sP}\right]$$

$$\frac{d\sigma}{2\pi d\cos\theta_q} = 4\pi C\left[B + \frac{1}{4} A_2 \left(1 + 3\cos 2\theta_q\right) I_{pS}\right]$$

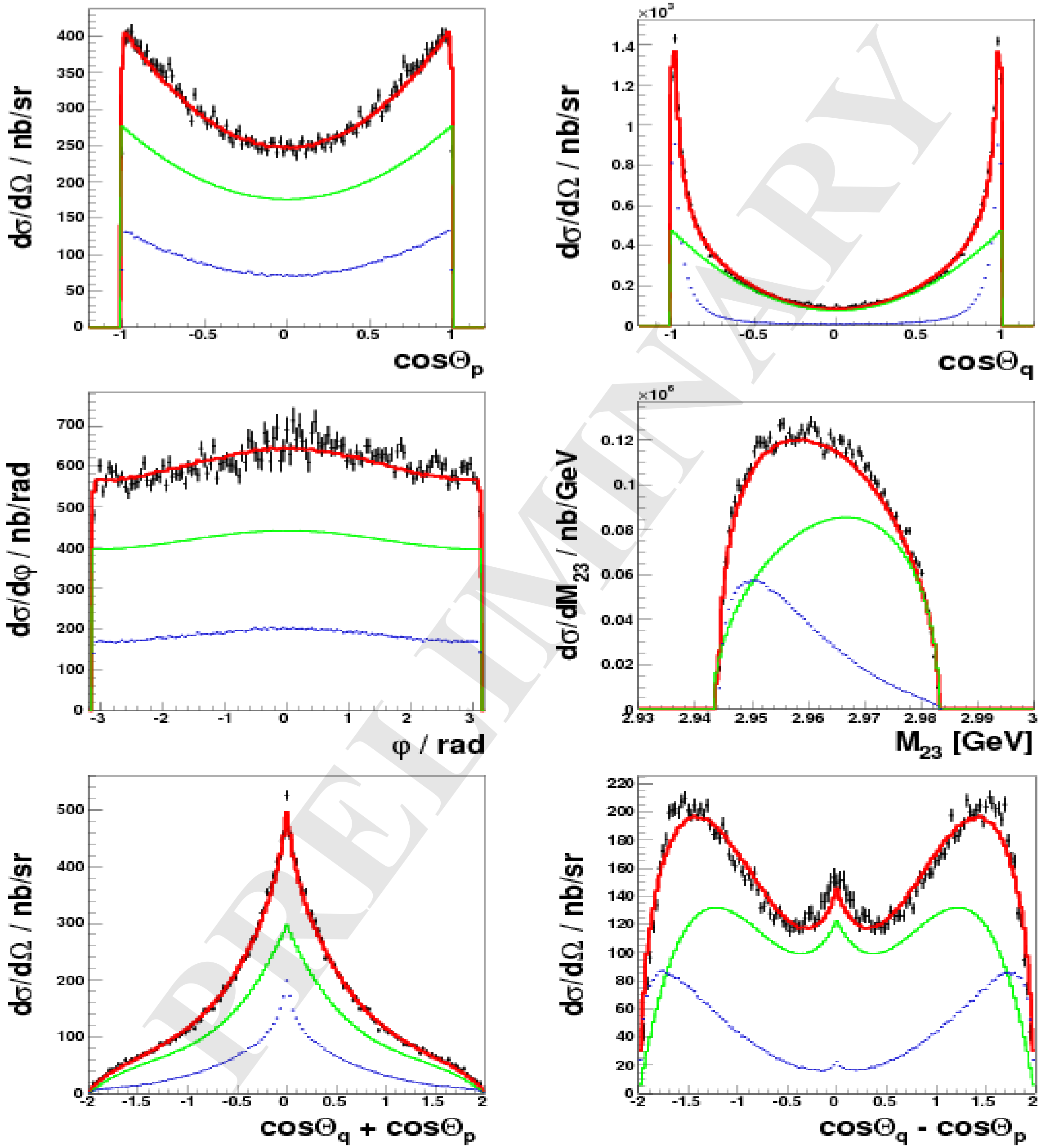
$$\frac{d\sigma}{d\varphi} = 8\pi C\left[B + \frac{\pi^2}{16} A_6 I_{pS+sP} \cos\varphi\right]$$

$$\frac{d\sigma}{dM_{23}} = 16\pi^2 C pq\left[A_0 + A_1 q^2 + A_3 p^2\right]$$

$$\frac{d\sigma}{2\pi d(\cos\theta_p \pm \cos\theta_p)} = 4\pi C\left[B \mp \frac{1}{3} A_5 I_{pS+sP} - \frac{1}{2}\left(A_0 I_{sS} + A_1 I_{pS} + A_3 I_{sP} + A_2 I_{pS} + A_4 I_{sP} \pm A_5 I_{pS+sP}\right)\left|\cos\theta_p - \cos\theta_q\right| + \right.$$

$$\left. + \frac{3}{4}\left(A_2 I_{pS} + A_4 I_{sP}\right)\left|\cos\theta_p - \cos\theta_q\right|^2 + \frac{1}{4} A_4 \left(1 + 3\cos 2\theta_p\right) I_{sP} - \frac{1}{4}\left(A_2 I_{pS} + A_4 I_{sP} \mp A_5 I_{pS+sP}\right)\left|\cos\theta_p - \cos\theta_q\right|^3\right]$$

dd→^{3}Henπ^0 DIFFERENTIAL DISTRIBUTIONS



SUMMARY

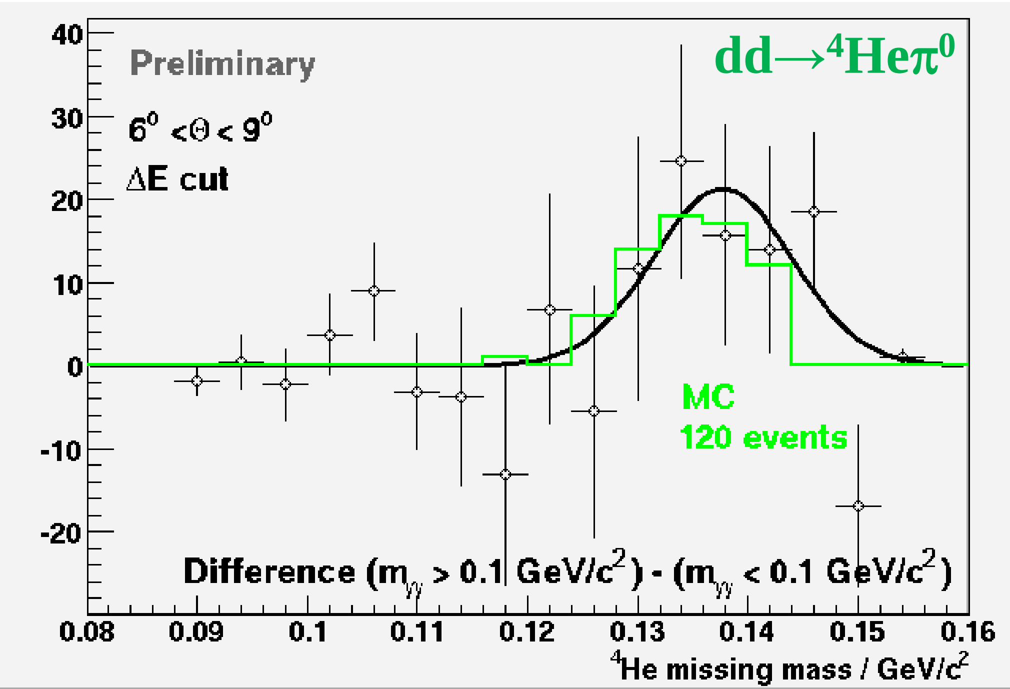
- **total and differential cross section was measured for the first time for $dd \rightarrow {}^3He n \pi^0$ reaction at beam momentum 1.2 GeV/c (Q = 40 MeV)**

$$\sigma_{tot} = (3.81 \pm 0.01_{stat.} \pm 0.42_{sys.})\ \mu b$$

- **30% contribution of quasi-free reaction**
- **important *p*-wave contribution**
- **in the quasi-free contribution higher partial waves are involved**
- ***pS* and *sP* interference important in specific distributions**
- **waiting for microscopic calculations**

OUTLOOK

V. Hejny for the WASA-at-COSY Collaboration
at MESON2010 conference



modifications of WASA-at-COSY are necessary
measure angular distribution
anisotropy → *p*-wave

use of spin selectivity
for $dd\to{}^4He\pi^0$ reaction
to disentangle *s*- and *p*-wave

$$\sigma(\theta) \propto \frac{1}{3} a_0^2 + \frac{9}{10} a_1^2 \sin^2\theta$$

$$T_{20}(\theta)\sigma(\theta) \propto \frac{1}{3\sqrt{2}} a_0^2 - \frac{9}{20\sqrt{2}} a_1^2 \sin^2\theta$$

$$T_{22}(\theta)\sigma(\theta) \propto \frac{9\sqrt{3}}{40} a_1^2 \sin^2\theta$$

$$iT_{11}(\theta)\sigma(\theta) \propto \frac{3}{2\sqrt{10}} \mathrm{Im}(a_0 a_1^*) \sin\theta$$

Charge Symmetry Breaking in $dd\to dd\pi^0$

dd – different spin-isospin symmetries than ^{4}He ⇒ { LO not suppressed; larger cross section?? }