Investigation of the reaction $dd \to {}^3\mathrm{He}n\pi^0$ at 1.2 GeV/c beam momentum with WASA-at-COSY

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Charge Symmetry Breaking

Use CSB to probe light quarks mass difference – a fundamental parameter of SM

	Symmetry	Probes
General Isospin Symmetry	any rotation in isospin space	quark mass, e.m. interactions
Charge Symmetry	$u \leftrightarrow d$, $\lvert\pi^0\rangle = -\lvert\pi^0\rangle$	quark mass

$dd \rightarrow {}^4He\pi^0$:

Isospin Symmetry Breaking: $0+0 \rightarrow 0+1$

Charge Symmetry breaking: $\sigma_{CS} = 0$, $\sigma_{CSB} \sim |M_{CSB}|^2$ no CSC background

Recent activities

Theory collaboration working on consistent analysis within χPT of:

- forward-backward asymmetry in $np \rightarrow d\pi^0$, Opper et al. PRL91 (2003) 212302
- cross section at threshold for $dd \rightarrow {}^4He\pi^0$, Stephenson et al., PRL 91 (2003) 142302

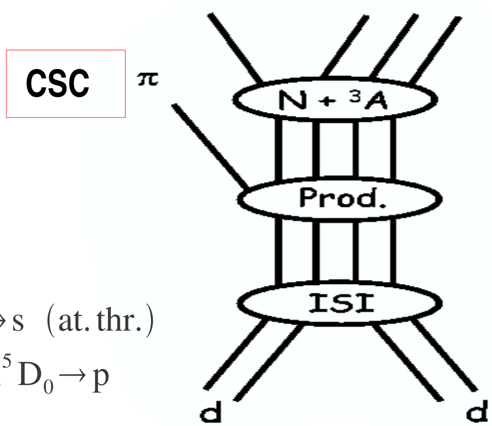
Additional observables needed:

- *p*- wave contribution in $dd \rightarrow {}^4He\pi^0$ at higher energies
- measurement of charge symmetry conserving reaction $dd \rightarrow {}^3He n\pi^0$

Physics Motivation

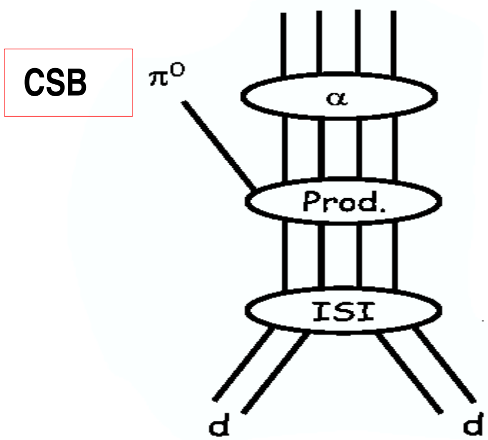
Measurement of d d $\rightarrow$ ^{3}He n π^0 as a first step towards d d $\rightarrow$ ^{4}He π^0

- same initial state as in d d $\rightarrow$ ^{4}He π^0
- study the isospin conserving pion production in 4N system:
  for *s-* and *p-* wave pion production the same partial waves in initial state



$d\,d \rightarrow {}^3He\,n\,\pi^0$: $\;{}^3P_1, {}^3P_0 \rightarrow s$ (at. thr.)

$\;{}^5D_1, {}^5D_2, {}^5D_0 \rightarrow p$

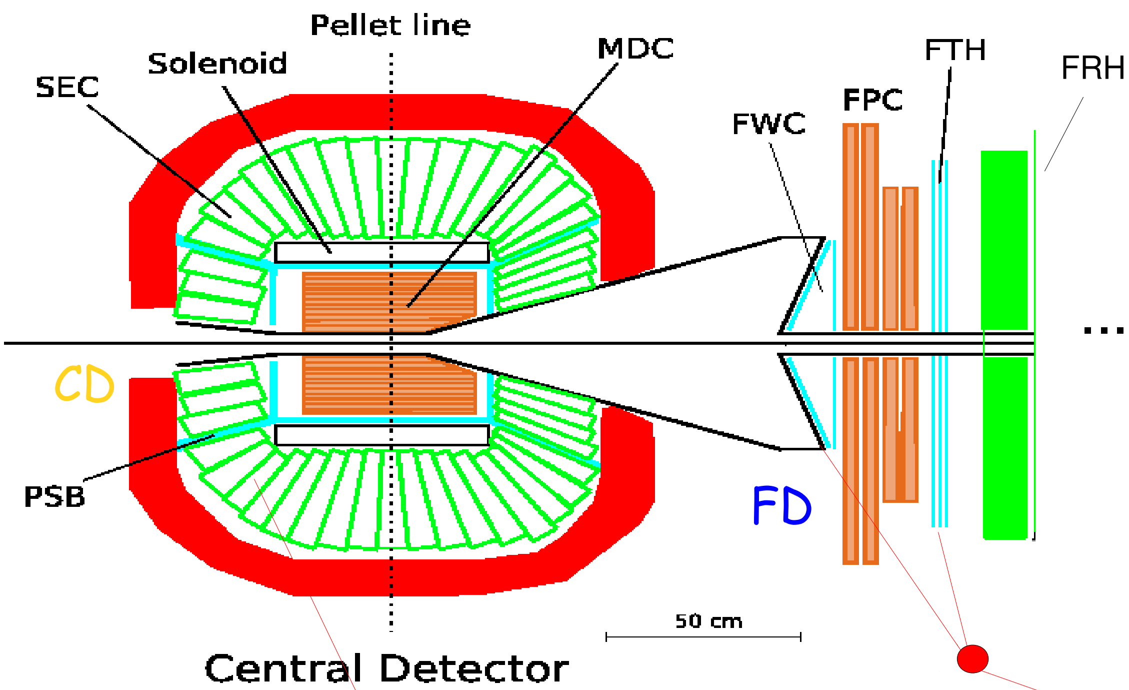


$d\,d \rightarrow \alpha\,\pi^0$: $\;{}^3P_0 \rightarrow s$ (at. thr.)

$\;{}^5D_1 \rightarrow p$

- test full ChPT calculations for CSC case
- control the initial state in d d $\rightarrow$ ^{4}He π^0
- no data available yet

Signature of the reaction



$d\,d \rightarrow {}^3He\; n\; \pi^0\, (\gamma,\gamma)$

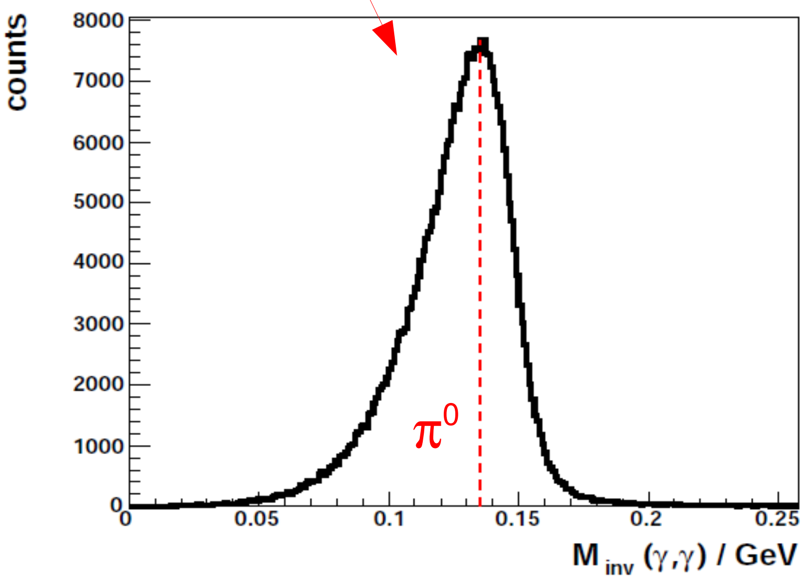
FD — unmeasured — CD

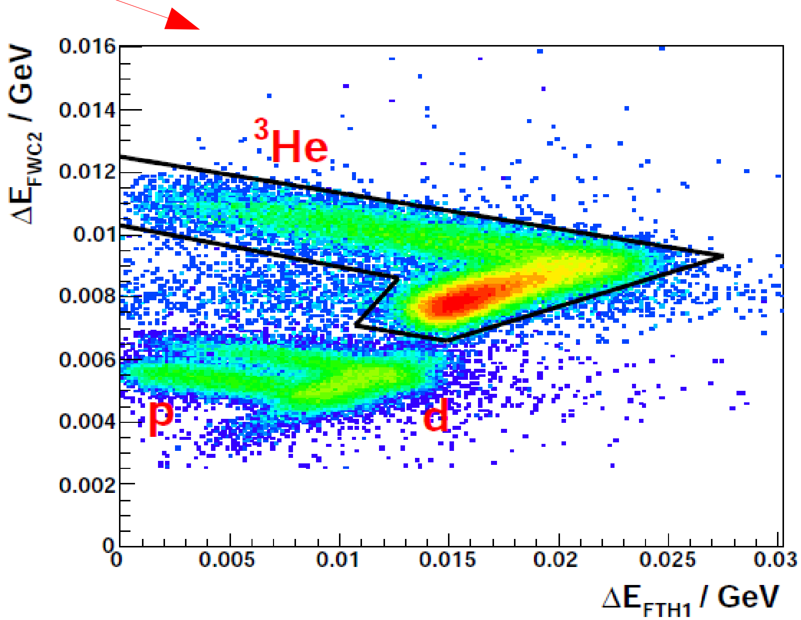
Other open channels:

$dd \rightarrow (dd, pnd, pnpn, tp) + \pi^0$

$dd \rightarrow ({}^3He\; p\; \pi^-, {}^3He\; n)$

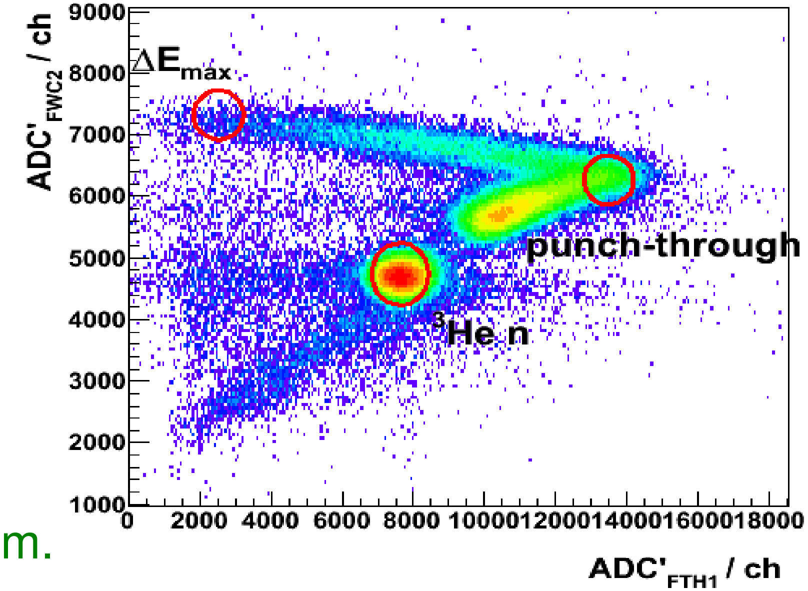
Kinematic fit (${}^3He\; n\; \pi^0$ hypothesis)





Luminosity determination using dd → ^{3}Hen

- clean identification of dd → ^{3}Hen
- using data for dd → ^{3}Hp



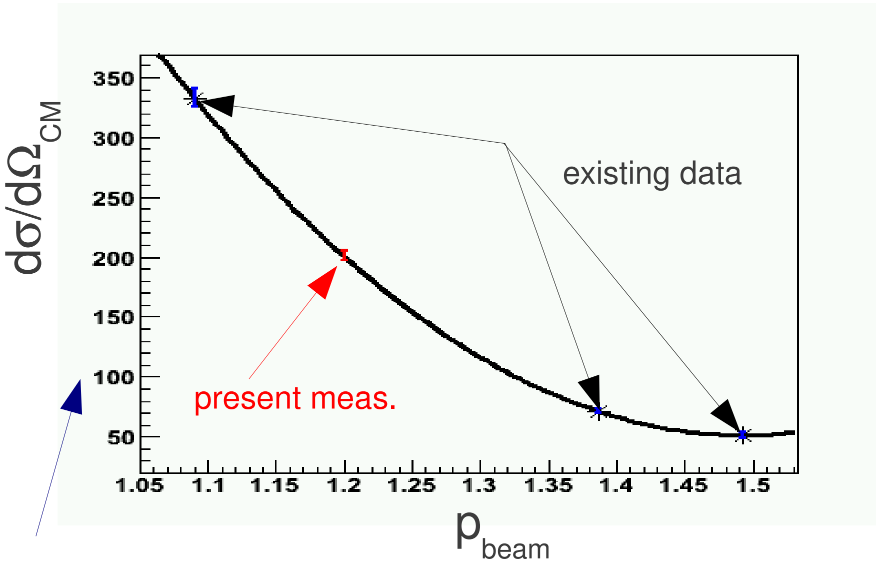
G. Bizhard et.al., Phys. Rev. C 22 (1980)

d d → ^{3}He n p=1.651, 1.89, 1.992, 2.492 (GeV/c)

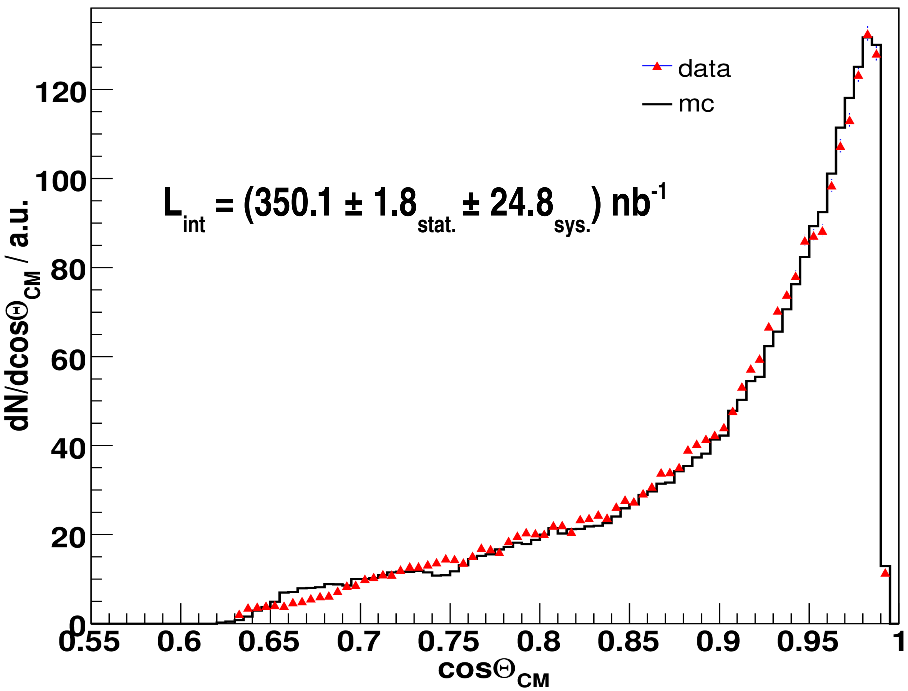
d d → ^{3}H p p=1.109, 1.38, 1.493, 1.651, 1.787 (GeV/c)

Total and differential cross section match at 1.651 GeV/c

- parametrize angular distribution for 3 beam mom.
- for selected angles, interpolation to 1.2 GeV/c

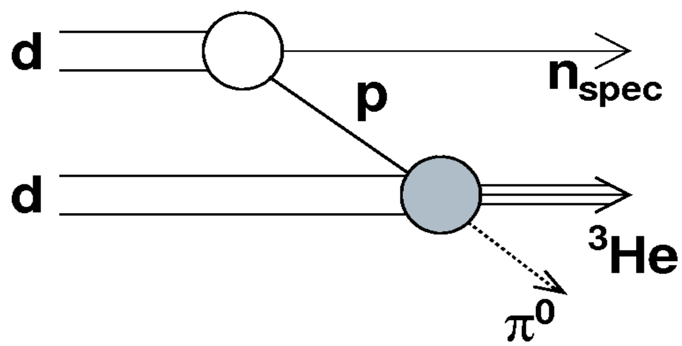


for selected angles interpolation to 1.2 GeV/c



Modelling the dd $\rightarrow$ ^{3}Heπ^0

- 2-body dp $\rightarrow$ ^{3}Heπ^0 (pd$\rightarrow$^{3}Heπ^0) quasi-free reaction (neutron spectator)



Neutron momentum calculated from deuteron wave function (based on Paris potential)

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

N. Nikulin at.al, Phys. Rev. C54 (1996)

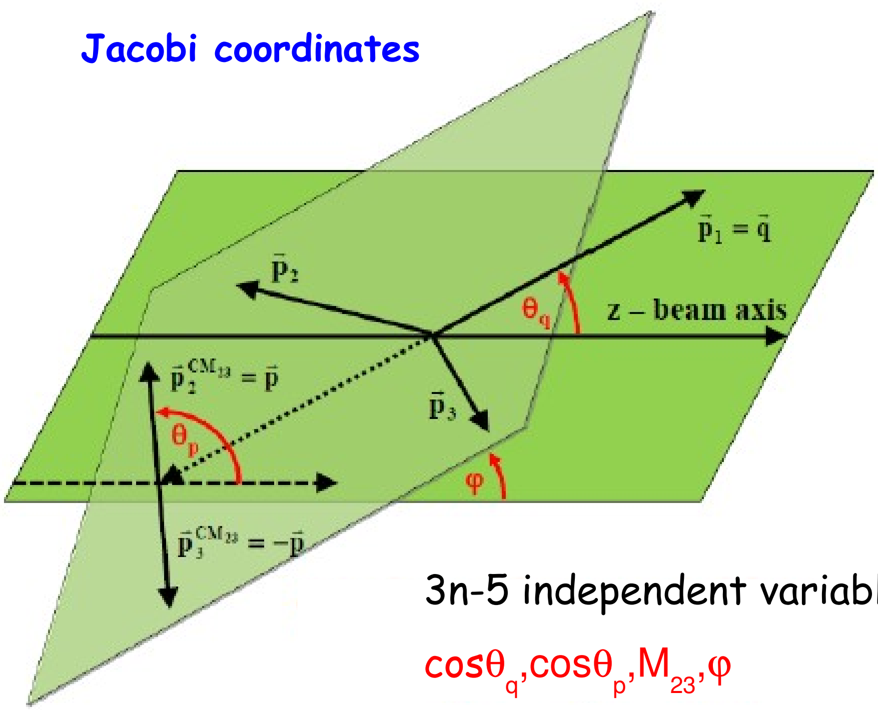
Parametrized total and differential distributions

Total cross section for target + beam spectator

σ_{tot} = 0.596 μb + 0.596 μb = 1.192 μb

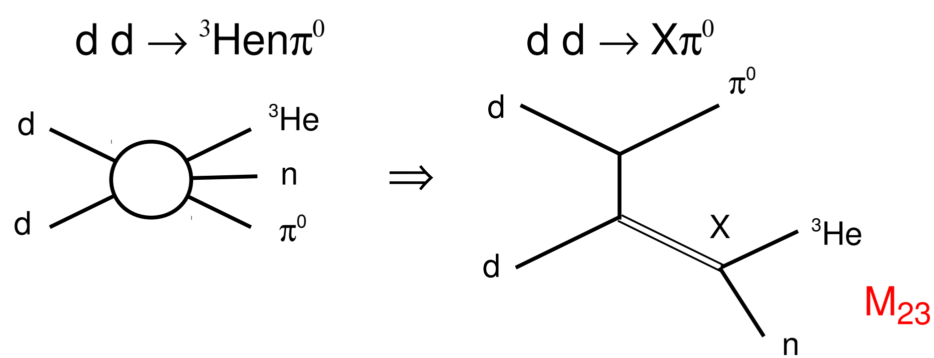
- 3-body partial wave decomposition

Jacobi coordinates



3n-5 independent variables

$\cos\theta_q, \cos\theta_p, M_{23}, \varphi$



Partial wave decomposition: considered contributions $L_\pi + L_{Hen} \leq 1$

dd	$(^3He\ n)\ \pi^0$	s_{3Hen}	L_{3Hen}	j_{3Hen}	L_π	J
$^3P_0$	$(^1S_0)$ s	0	0	0	0	0
$^3P_1$	$(^3S_0)$ s	1	0	1	0	1
$^5D_1$	$(^1S_0)$ p	0	0	0	1	1
$^1S_0$, $^5D_0$		1	0	1	1	0
$^5D_1$	$(^3S_0)$ p	1	0	1	1	1
$^5S_2$, $^5D_2$, $^5G_2$, $^1D_2$		1	0	1	1	2
$^5D_1$	$(^1P_1)$ s	0	1	1	0	1
$^1S_0$, $^5D_0$	$(^3P_0)$ s	1	1	0	0	0
$^5D_1$	$(^3P_1)$ s	1	1	1	0	1
$^5S_2$, $^5D_2$, $^5G_2$, $^1D_2$	$(^3P_2)$ s	1	1	2	0	2

Ss $\rightarrow A_0$

Sp $\rightarrow A_1, A_2$

18 transition amplitude + $(^3He\pi^0)\, n_{spec}$ — large L,J

Ps $\rightarrow A_3, A_4$

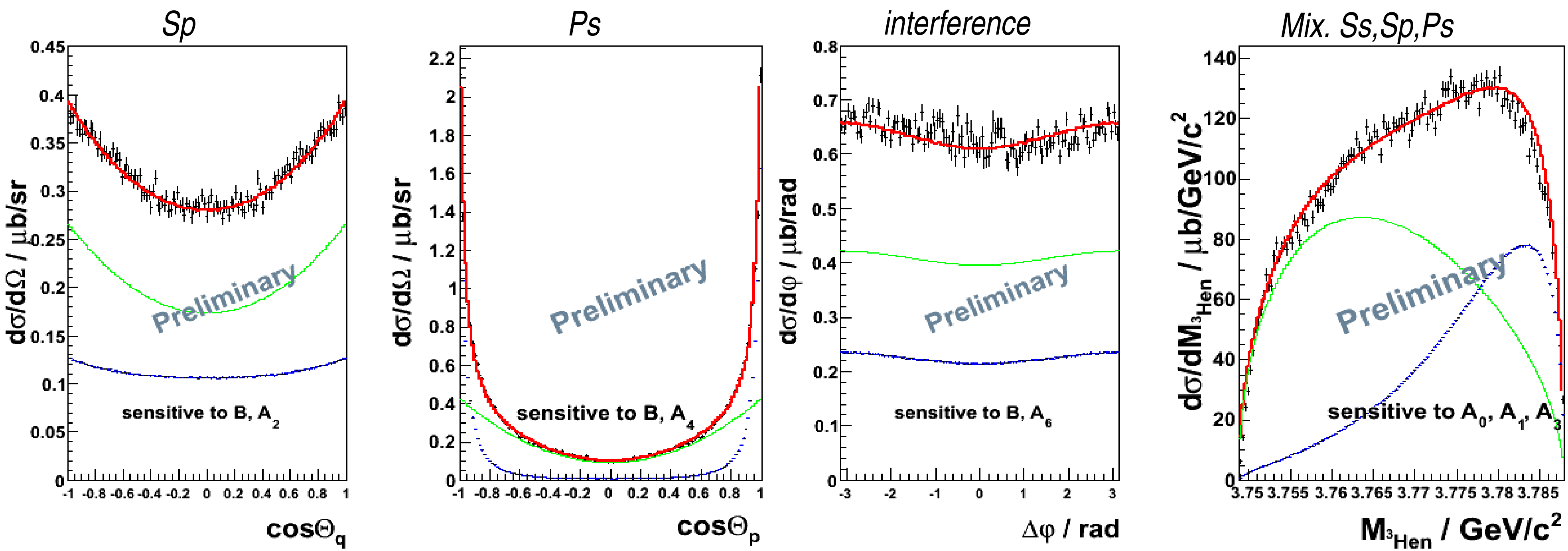
Approx: $\Psi_{pw}(QR) \rightarrow j_L(QR) \propto Q^L$ $\Rightarrow$ amplitudes proportional ~ $q^{L_\pi} p^{L_{Hen}}$

$$\frac{d^4\sigma}{2\pi dM_{23} d\cos\theta_p d\cos\theta_q d\varphi} = \frac{pq}{32(2\pi)^5 s P_a^* (2s_a+1)(2s_b+1)} \Big[A_0 + A_1 q^2 + A_3 p^2 + \frac{1}{4} A_2 q^2 (1 + 3\cos 2\theta_q) + \frac{1}{4} A_4 p^2 (1 + 3\cos 2\theta_p) + A_5 pq \cos\theta_p \cos\theta_q + A_6 pq \sin\theta_p \sin\theta_q \cos\varphi \Big]$$

interference terms A_5, A_6

Differential distributions for dd → $^3He n \pi^0$

Data described by incoherent sum of 3 body + quasi free



- Total cross: σ_{tot} = (3.98 ± 0.01$_{stat.}$ ± 0.55$_{sys.}$) μb

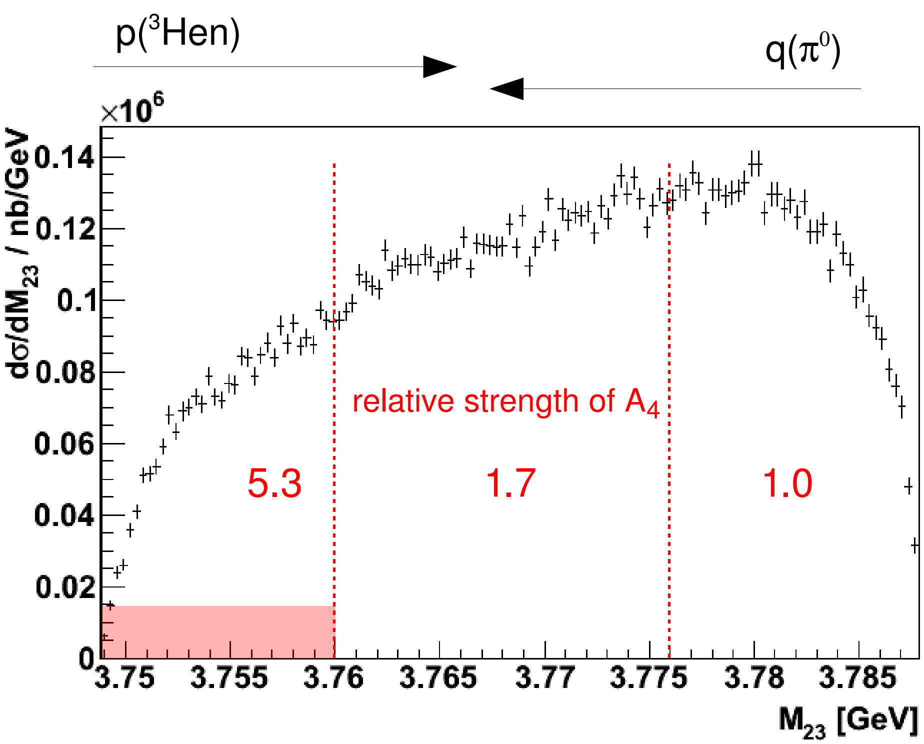
  Models reproduce data fairly well:

  - about 1/3 quasi-free (matches model calculation)

  - pS and sP of similar strength

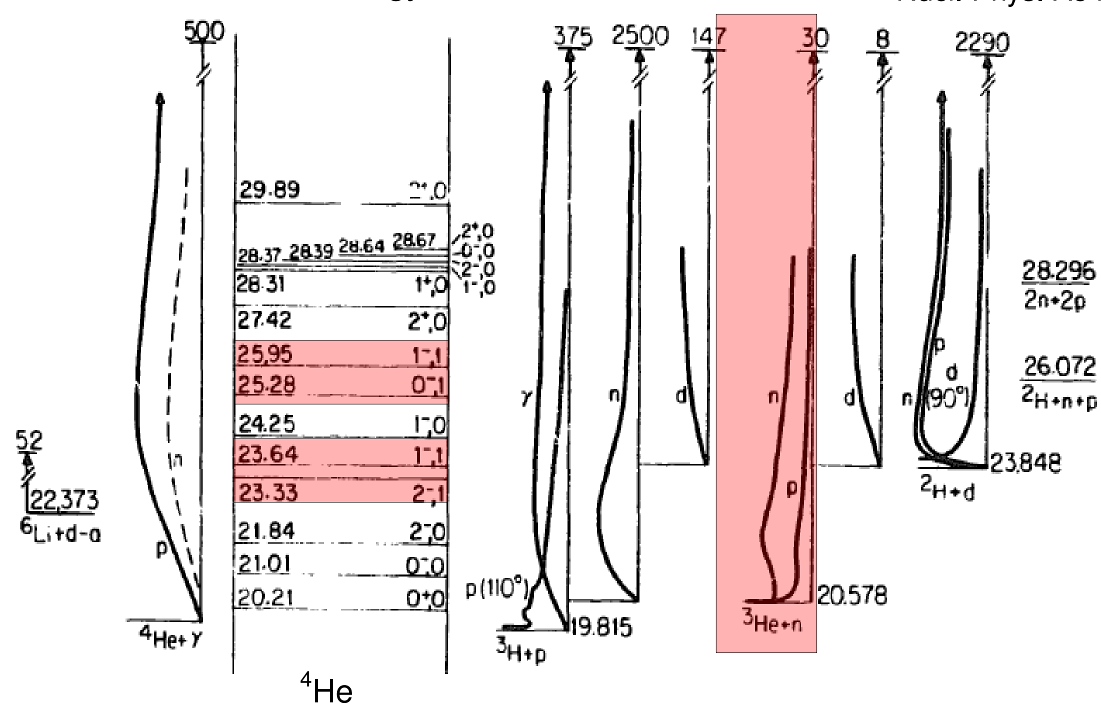
preliminary

Momentum dependence of partial waves



Energy levels of ^{4}He

D.R.Tilley et al.,
Nucl. Phys. A541



A_4 sensitive to *p*- wave in ^{3}He-n system

Possible point of interest:
4 isospin=1 states in the ^{3}He-n
Spectrum L=1, J=0,1,2

Summary

- The differential and total cross section for $d\,d \to {}^3He\,n\,\pi^0$ measured at beam momentum 1.2 GeV/c (Q=40 MeV) have been evaluated:

$\sigma_{tot} = (3.98 \pm 0.01_{stat.} \pm 0.55_{sys.})\ \mu b$ **preliminary**

- Differential cross section described by sum of quasi-free pion production and 3-body partial wave decomposition

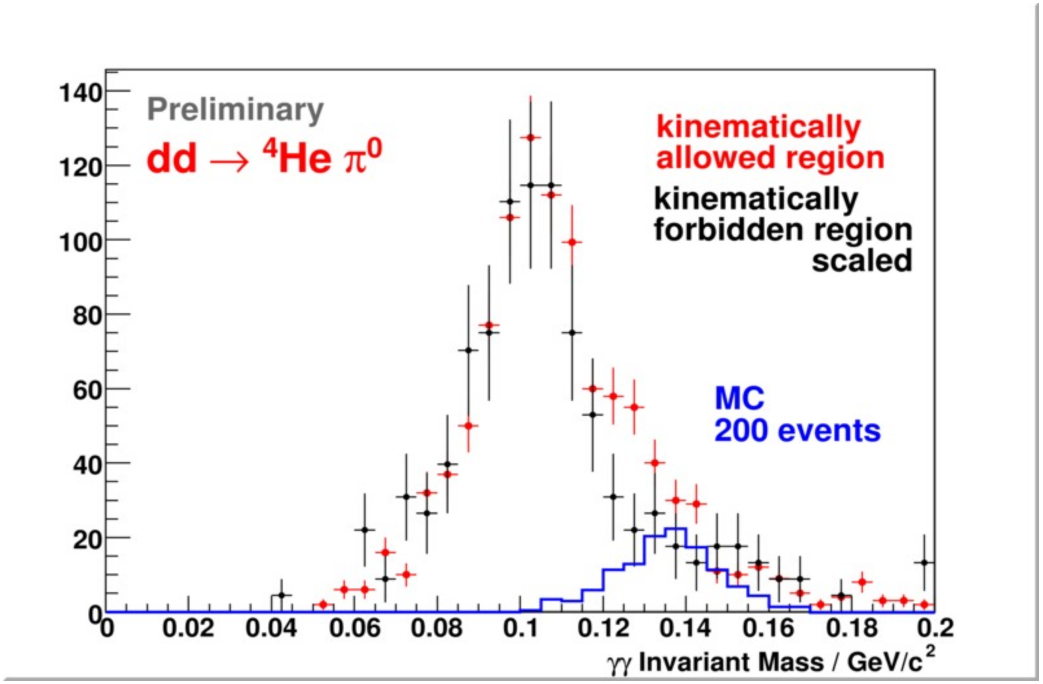
- Models can serve as a guidance for microscopic description within ChpT
    - 30% of cross section can be reproduced by quasi-free mechanism
    - important *p*- wave contributions
    - pS and sP of similar strength
    - results are being finalized

preliminary

Outlook

Outlook:

- 2-week pilot measurement of d d $\rightarrow$ $^4He\ \pi^0$ at p_b = 1.2 GeV/c
- indication of d d $\rightarrow$ $^4He\ \pi^0$ signal (first analysis)
- consistent with estimated cross section σ=75 pb



Challenges:

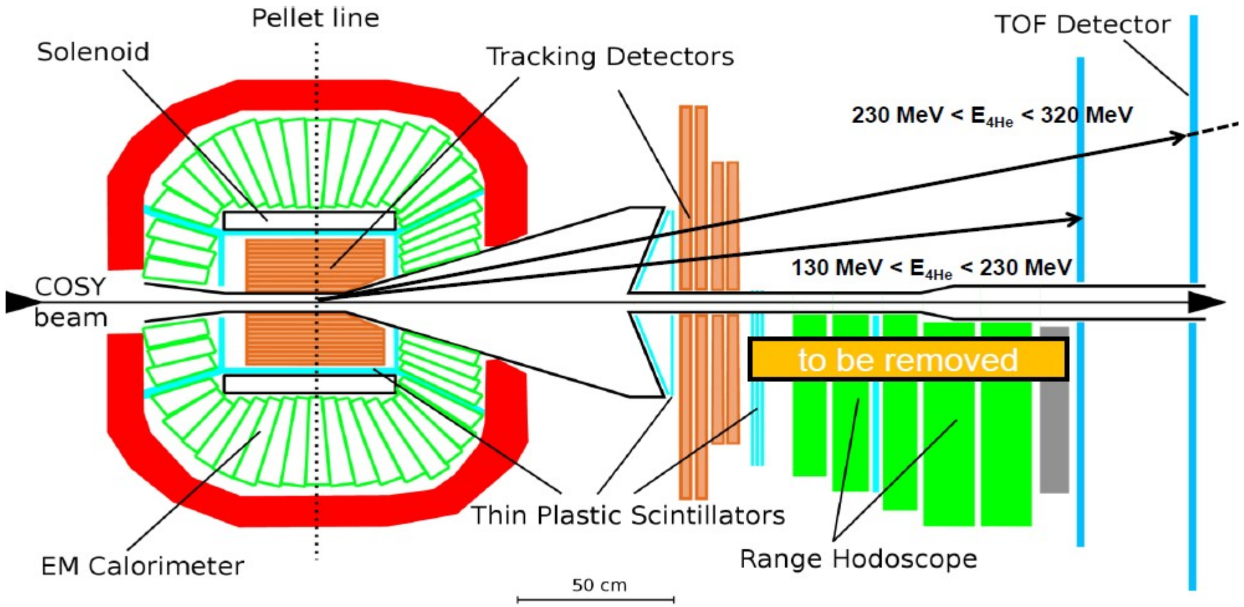
- Separation between $^4He/^3He$
- Background supression

- to be finalized: total cross section / upper limit

Outlook I

Future perspectives:

- High statistics measurements of d d $\rightarrow$ ^{4}He π^0 with optimized detection setup
  - one block of beam time with modified detector setup
    use TOF – better background suppression and energy reconstruction



  - several energies (e.g. 350MeV, 450MeV, 560MeV), extract energy dependence of cross section
  - highest energy: use d d $\rightarrow$ ^{4}He $\pi^0 \pi^0$ as a reference for ^{4}He reconstruction

Partial wave decomposition

$$\sigma = \frac{1}{2\sqrt{\lambda(s, M_a^2, M_b^2)}(2\pi)^5}\int \prod_{i=1}^{3}\frac{d^3p_i}{2E_i}\delta^4\left(P_a + P_b - \sum_{j=1}^{3} P_j\right)|T|^2 \xrightarrow{\text{integration}} \frac{d^4\sigma}{2\pi dM_{23} d\cos\theta_q d\cos\theta_p d\varphi} = \frac{1}{32(2\pi)^5 sP_a^*} pq|T|^2$$

$$|T|^2 = \frac{1}{(2s_a+1)(2s_b+1)}\sum_{\substack{m_a,m_b,\\ m_1,m_2,m_3}} |T^{m_a,m_b}_{m_1,m_2,m_3}|^2$$

$$\begin{aligned} T^{m_a,m_b}_{m_1,m_2,m_3} = \sum_{\substack{s_i,L_i,s_{23},j_{23},\\ L_{23},L_1,j_1,J}} & \langle s_a, m_a, s_b, m_b | s_i, m_a+m_b\rangle \langle L_i, 0, s_i, m_a+m_b | J, m_a+m_b\rangle \\ & \langle s_2, m_2, s_3, m_3 | s_{23}, m_2+m_3\rangle \langle s_1, m_1, L_1, m_{L_1} | j_1, m_{j_1}\rangle \\ & \langle s_{23}, m_2+m_3, L_{23}, m_{L_{23}} | j_{23}, m_{j_{23}}\rangle \langle j_1, m_{j_1}, j_{23}, m_{j_{23}} | J, m_a+m_b\rangle \\ & \delta_{\Pi_i,\Pi_f}\delta_{\text{identity}} a_{s_i,L_i,s_{23},j_{23},L_{23},L_1,j_1,J}\sqrt{2L_i+1}\, Y^{m_{L_{23}}}_{L_{23}}(\hat{p}) Y^{m_{L_1}}_{L_1}(\hat{q}) \end{aligned}$$

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

Approximation: Amplitudes proportional to:

$$q^{L_1} p^{L_2}$$

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

$$\frac{d^4\sigma}{2\pi dM_{23} d\cos\theta_p d\cos\theta_q d\varphi} = \frac{pq}{32(2\pi)^5 sP_a^*(2s_a+1)(2s_b+1)}\Big[A_0 + A_1 q^2 + A_3 p^2 + \frac{1}{4}A_2 q^2(1+3\cos 2\theta_q) + \frac{1}{4}A_4 p^2(1+3\cos 2\theta_p) + A_5 pq\cos\theta_p\cos\theta_q + A_6 pq\sin\theta_p\sin\theta_q\cos\varphi \Big]$$

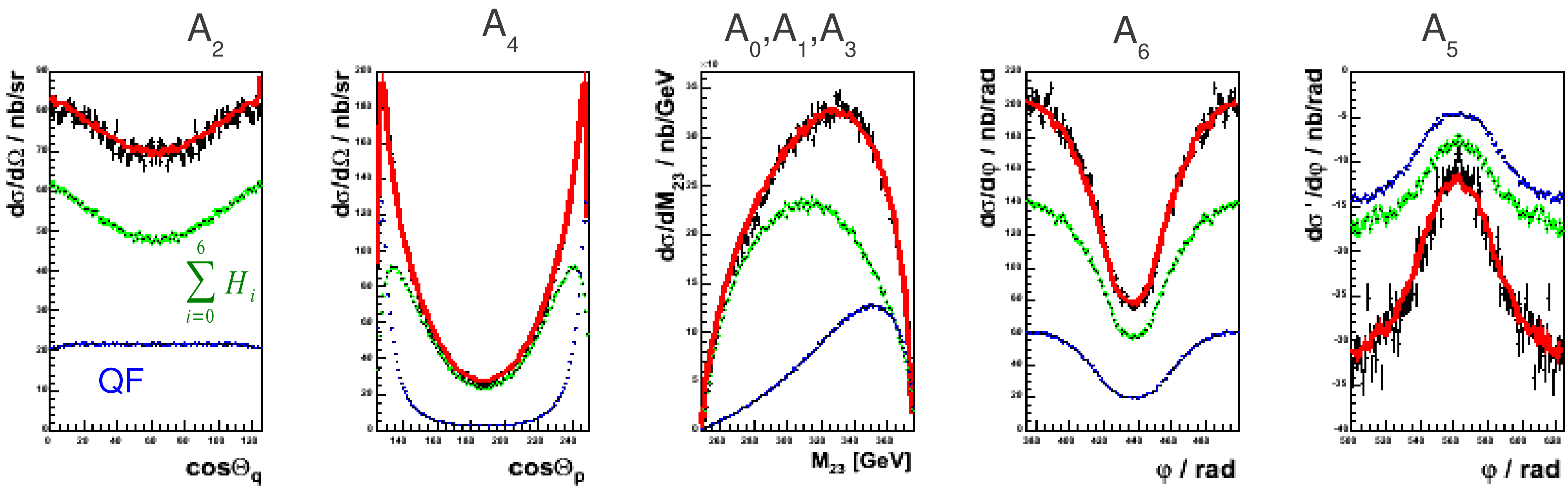
Differential distributions before acceptance correction

$$d^4\sigma \propto \text{ph.sp.}\left[A_0\cdot 1 + A_1\cdot q^2 + A_3\cdot p^2 + \frac{1}{4}A_2\cdot q^2\left(1+3\cos 2\theta_q\right) + \frac{1}{4}A_4\cdot p^2\left(1+3\cos 2\theta_p\right) + A_5\cdot pq\cos\theta_p\cos\theta_q + A_6\cdot q\sin\theta_p\sin\theta_q\cos\varphi\right]$$

H_0 H_1 H_2 H_3 H_4 H_5 H_6

- MC simulation of individual terms
- fitting data D

$$D = \sum_{i=0}^{6} H_i + Q.F.$$



- fit results used for acceptance corrections

Differential distributions for dd → $^3He n \pi^0$

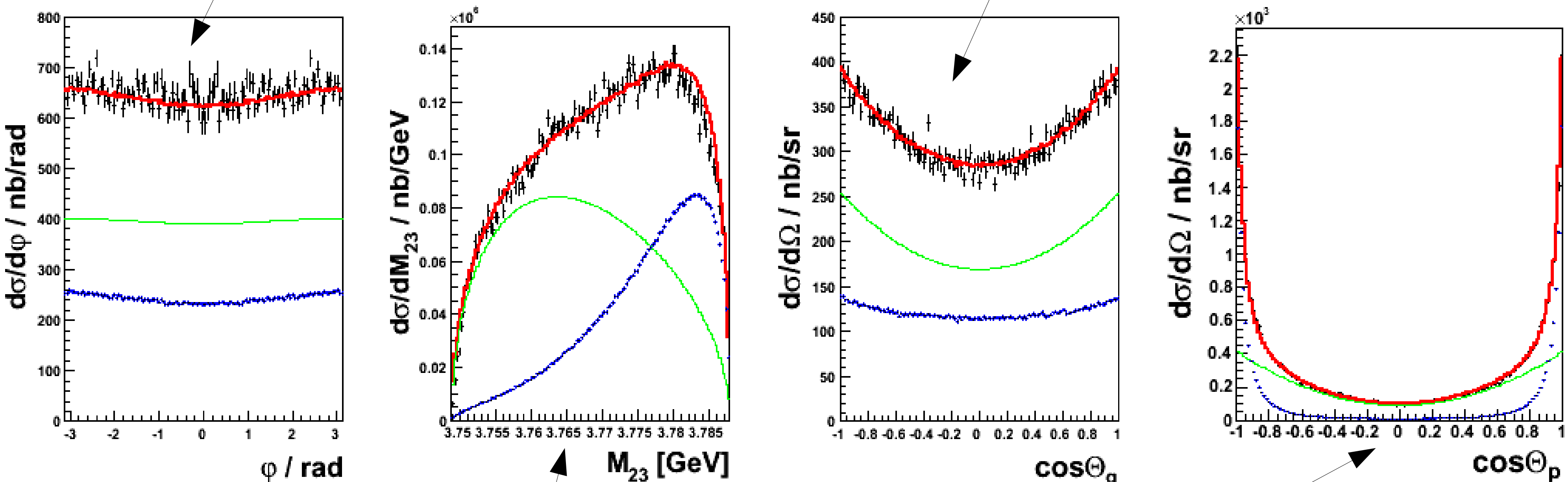
- Data after acceptance corrections using parameters from the fit before acc. corrections

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

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

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

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



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

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

Luminosity determination using dd → ^{3}Hen

- clean identification of dd → ^{3}Hen
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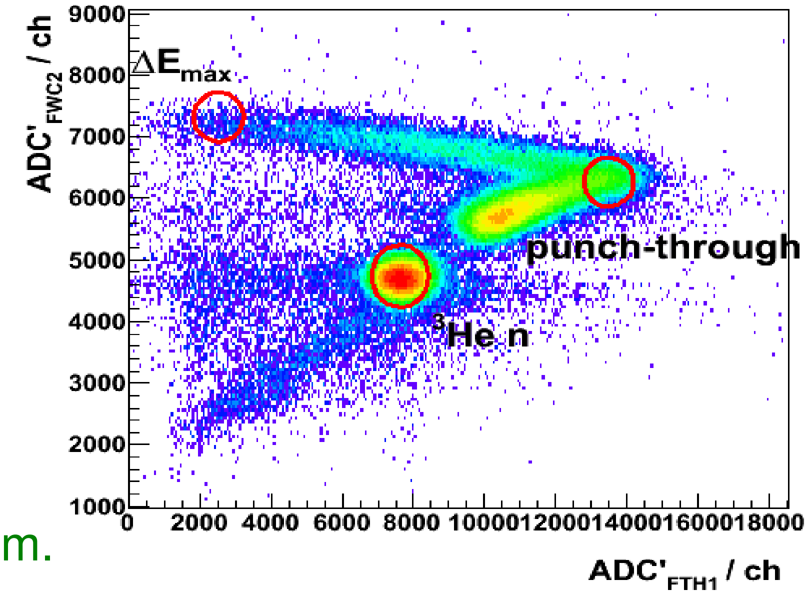

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Total and differential cross section match

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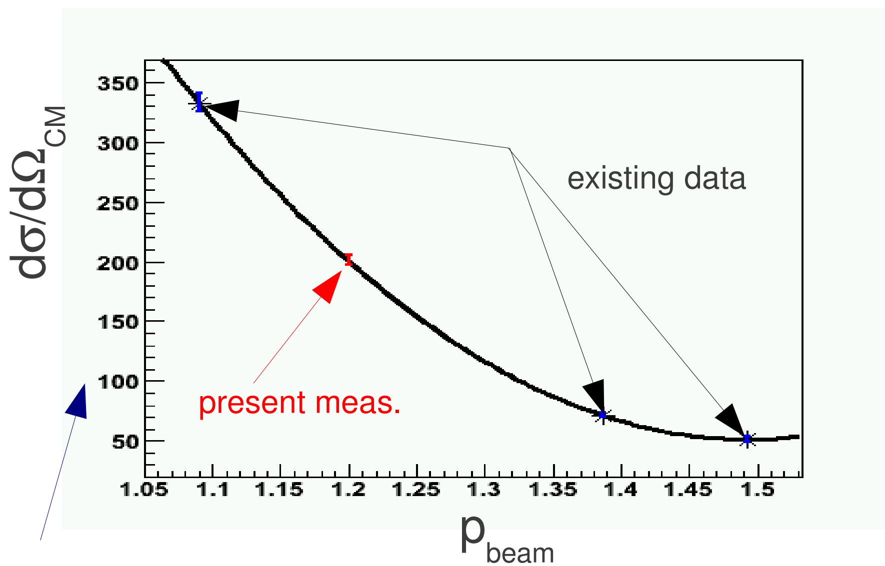
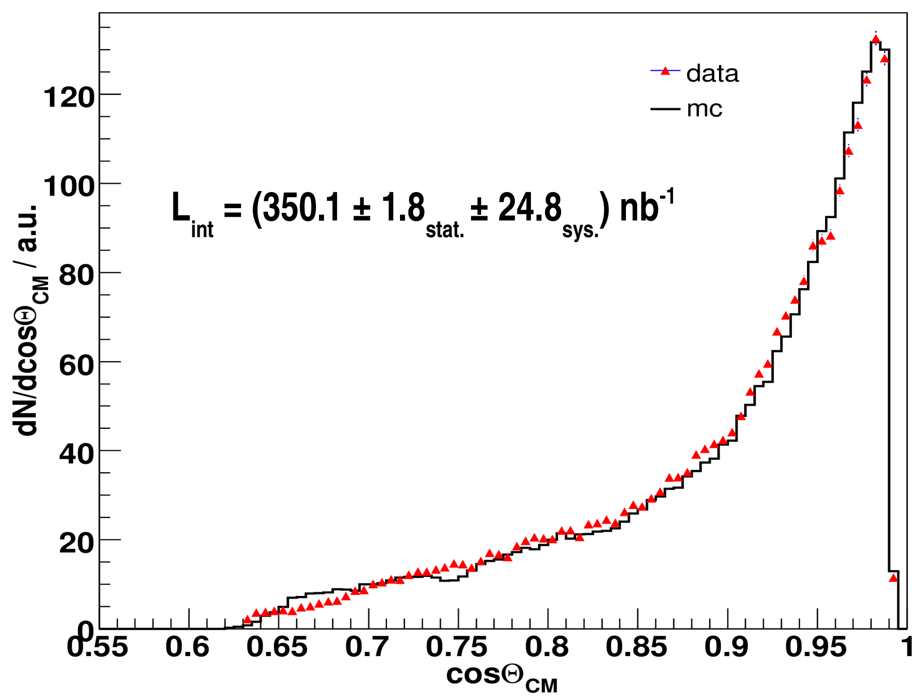
- for selected angles, interpolation to 1.2 GeV/c





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