Charge Symmetry Breaking in the Reaction $dd \to {}^4\mathrm{He}\pi^0$ with WASA-at-COSY

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Isospin Symmetry

Two sources of violation:

- Electromagnetic interaction
- Lightest quark mass difference ↦ Window for probing quark-mass effects

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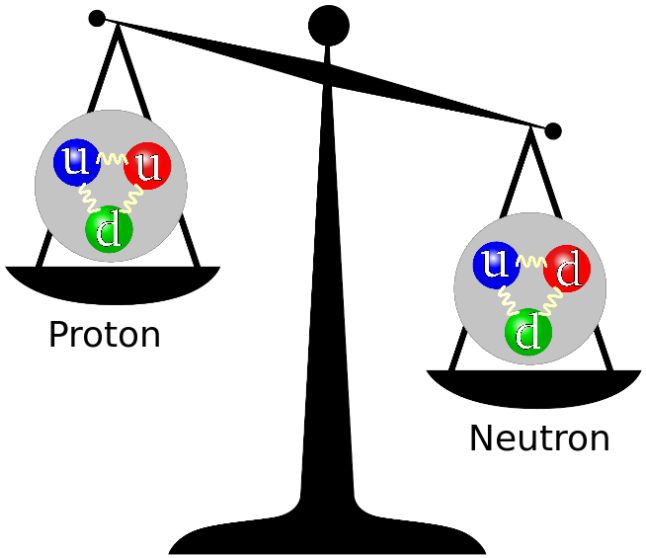

Nucleon mass difference

$$\Delta M_{np} = \Delta M_{em} + \Delta M_{str}$$

-0.7 ± 0.3 MeV
(from QED + dispersion theory)

2.05 ± 0.3 MeV
$(\Delta M_{pn} - \Delta M_{em})$

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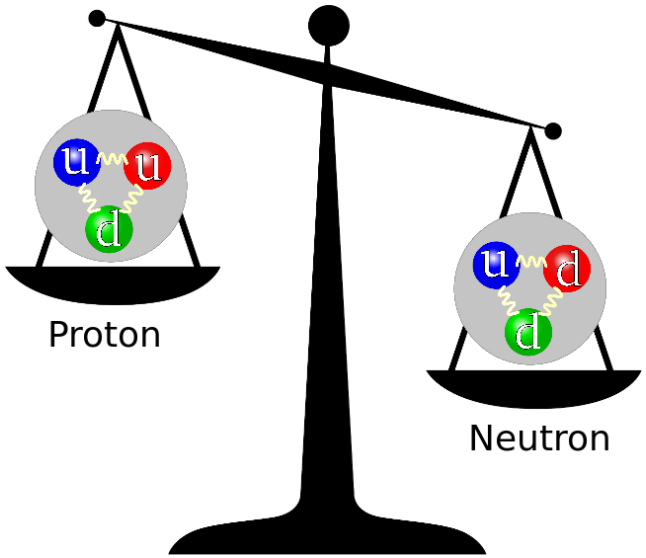

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Link between quark-mass efects and hadronic observables from Chiral Perturbation Theory

πN scattering length, e.g., $a(\pi^0 p) - a(\pi^0 n) = f(\Delta M_{str})$ (Weinberg 1977)

However: – No direct measurement of $\pi^0 N$
– Large e.m. corrections in $\pi^{\pm} N$

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Charge Symmetry Breaking

Isospin Symmetry Breaking

Dominated by pion mass difference Δm_{π} – e.m. effect

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Charge Symmetry (CS) Breaking

Symmetry under the operation of P^{CSB} - Δm_{π} does not contribute

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1. $np \rightarrow d\pi^0$ forward-backward asymmetry A_{fb} [1]

ΔM_{str} = (1.5 ± 0.8 (exp.) ± 0.5 (th.)) MeV (LO) [2]

[1] Opper et al. PRL 91 (2003) 212302

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2. $dd \to {}^4\mathrm{He}\pi^0$

CS ⇒ $\sigma = 0$ ~~CS~~ ⇒ $\sigma \neq 0$, $\sigma \propto |M_{CSB}|^2 = |M_1 + M_2 + \ldots|^2$

σ_{total} measured at treshold [3] – result cosistent with *s*-wave

Chiral Perturbation Theory

Information about higher partial waves in $dd \to {}^4\mathrm{He}\pi^0$ needed

→ Constraint of the contribution from the Δ resonance

[1] Opper et al. PRL 91 (2003) 212302
[2] Filin et al. Phys. Lett. B681 (2009) 423
[3] Stephenson et al. PRL 91 (2003) 142302
[4] Adlarson et al. Phys. Lett. B 739 (2014) 44

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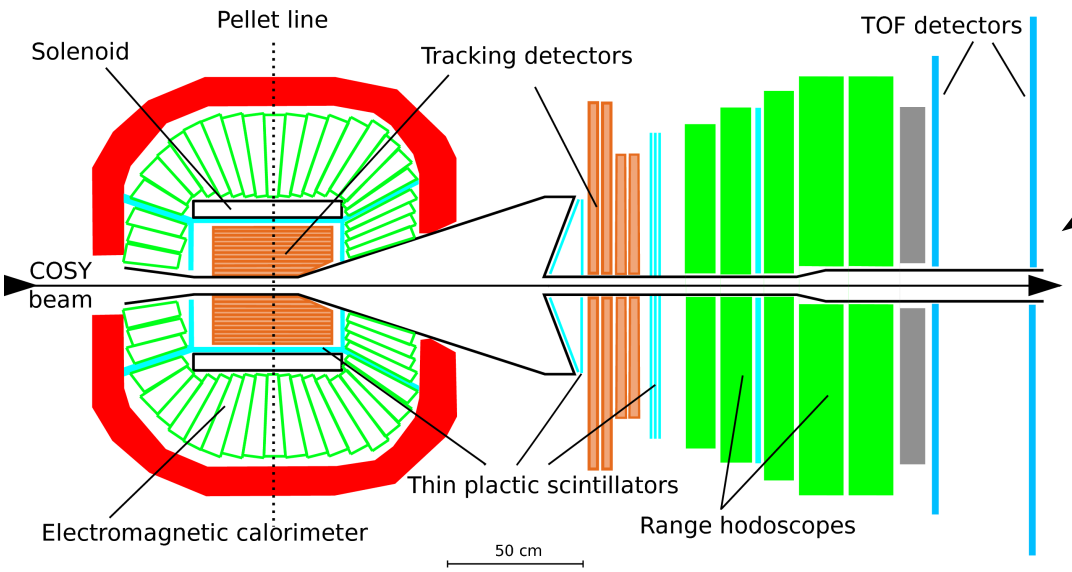
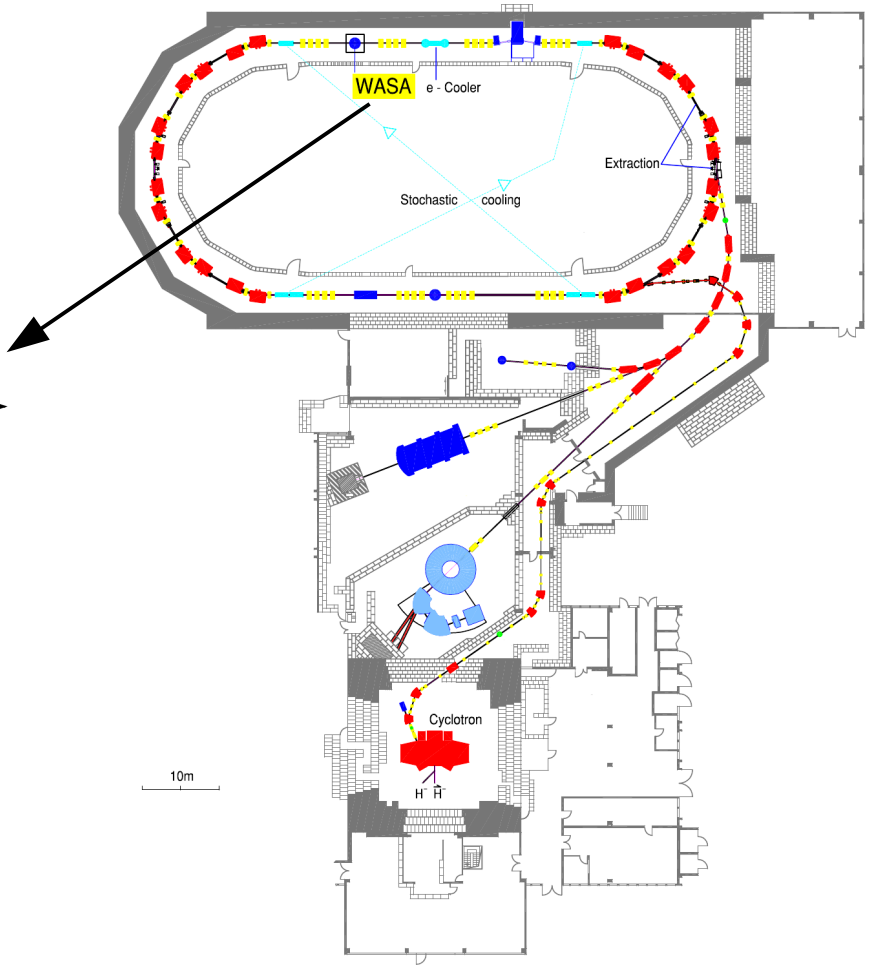
WASA-at-COSY experiment





CSB with WASA-at-COSY:

2007: Measurement of $dd \to {}^3\mathrm{He}\,n\,\pi^0$
goal: description of main background, input for initial-state-interaction calculations

2008: First measurement of $dd \to {}^4\mathrm{He}\,\pi^0$ (2 weeks) @ Q = 60 MeV
goal: σ_{total}

2014: New measurement of $dd \to {}^4\mathrm{He}\,\pi^0$ (10 weeks) @ Q = 60 MeV with modified detector
goal: angular distribution

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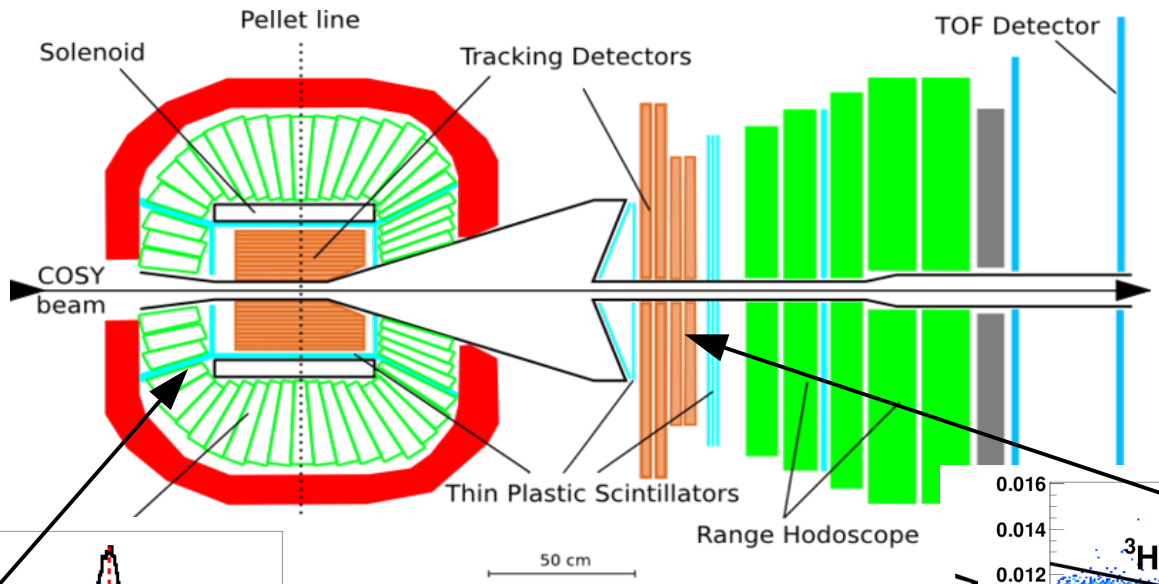
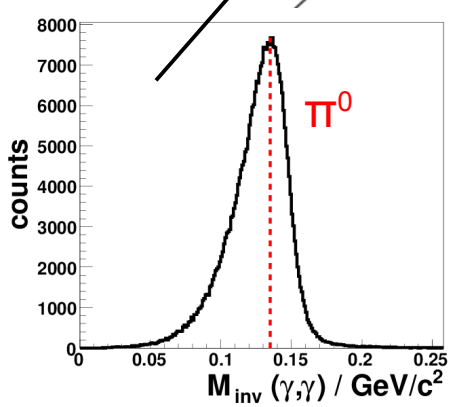
Analysis of $dd \rightarrow {}^3He n \pi^0$

Benchmark for $^4He\pi^0$:

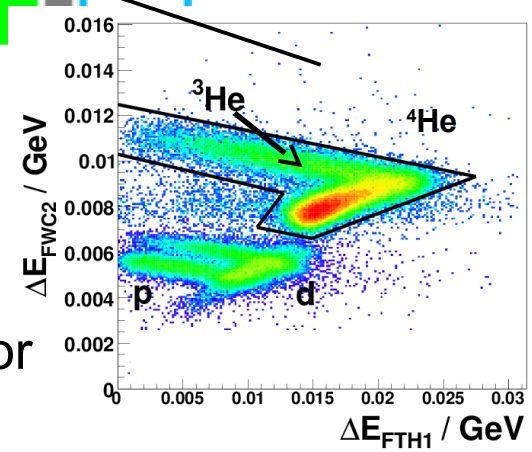
- clean selection of ^3He - π^0 coincidences
- final step: kinematic fit to ensure overall energy and momentum conservation
- 3.4×10^6 fully reconstructed events, nearly full coverage of Dalitz plots





→ 2 coincident photons in calorimeter

→ ^3He in Forward Detector



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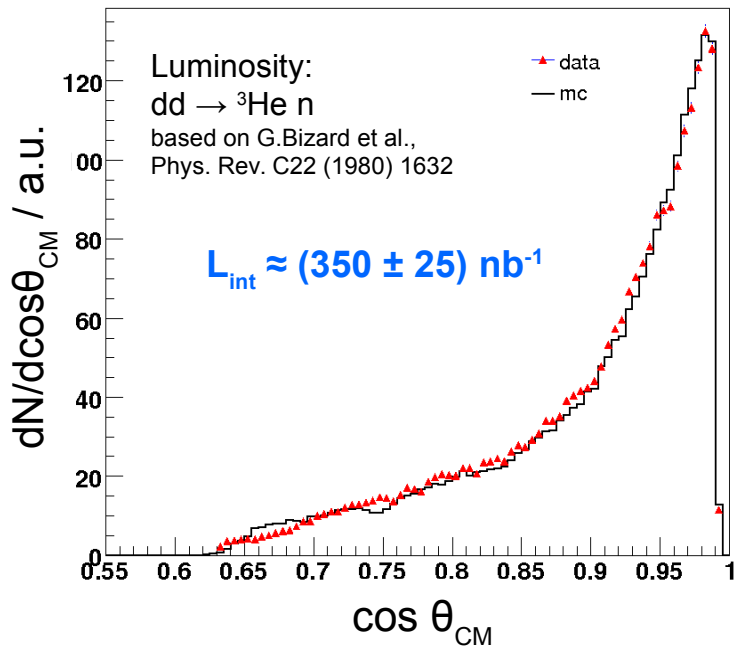


Further analysis

→ **3-body final state, unpolarized:**

9 – 4 – 1 = 4 independent variables

M_{3Hen}, θ_p, θ_q, φ

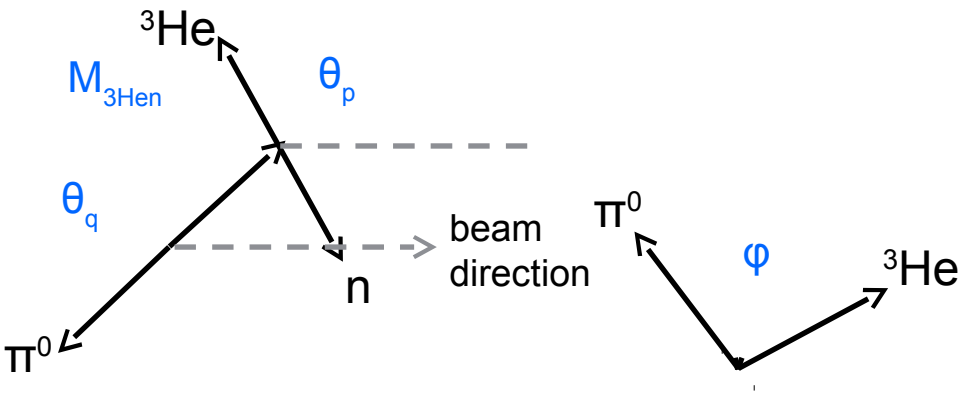
→ **two-fold model ansatz:**

- quasi-free contribution
  $dd \rightarrow {}^3He\pi^0 + n_{spec}$
- partial waves decomposition of the 3-body final state (limited to L≤1)
  full model = incoherent sum

Luminosity determination:

- two-body reaction $dd \rightarrow {}^3Hen$
  interpolated data from
  Bizard et al., PRC22 (1980) 1632:
  perfect match of expected angular distribution

Phys. Rev. C 88 (2013) 014004



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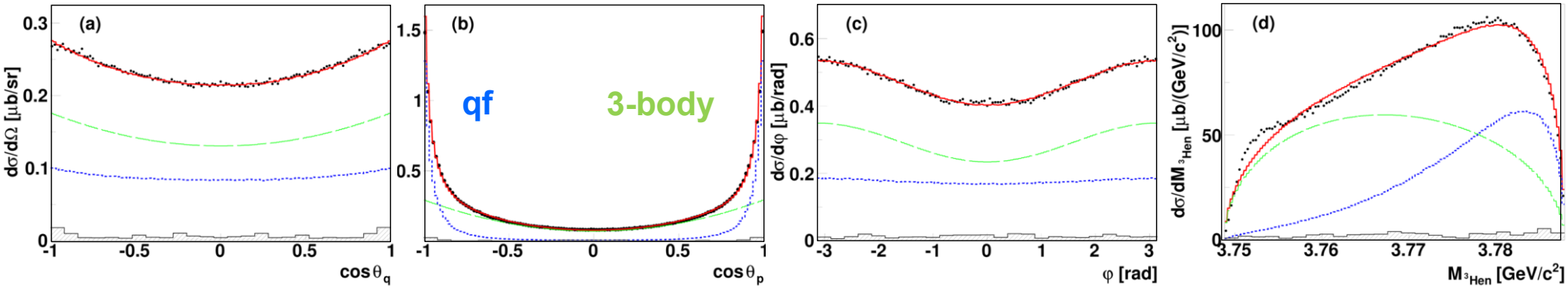
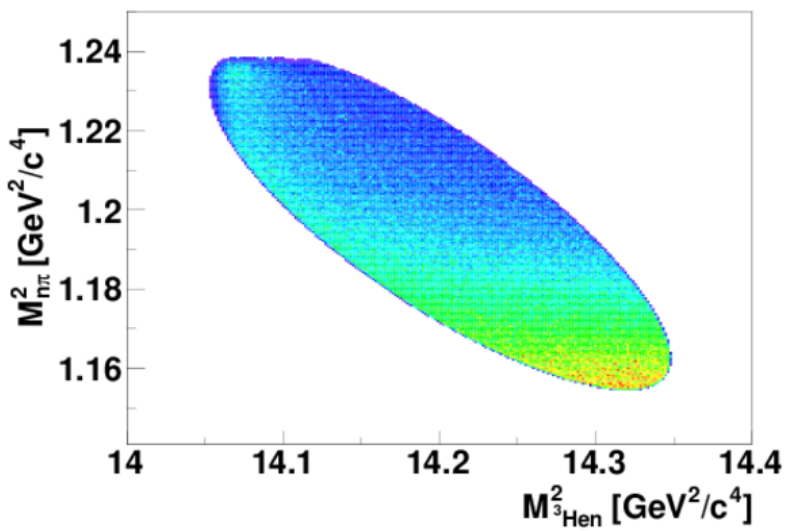
Results





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$\sigma_{tot} = (2.89 \pm 0.01_{stat} \pm 0.06_{sys} \pm 0.29_{norm})$ μb

Model used for simulating the dd → ^{3}Henπ^0 background in the dd → ^{4}Heπ^0 measurement

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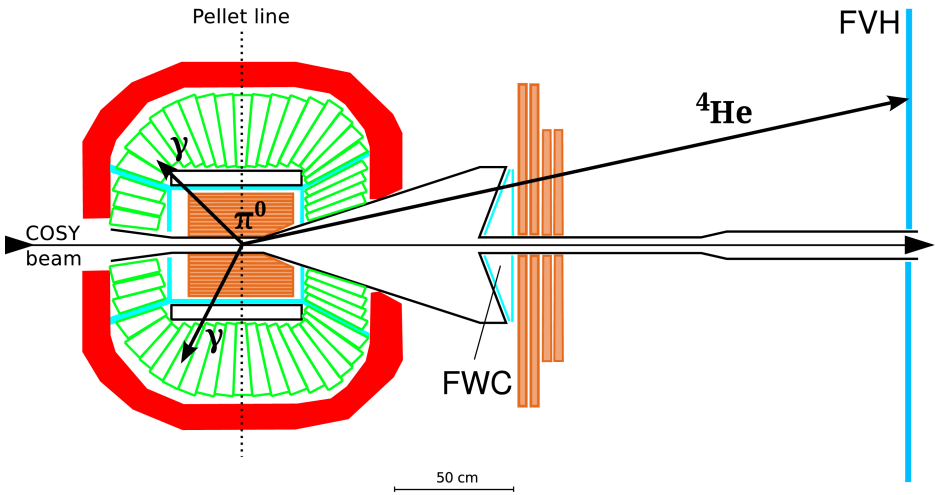
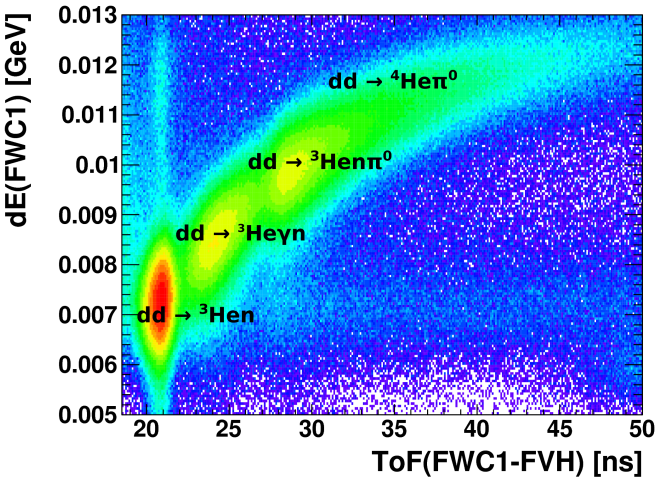
Analysis of $dd \rightarrow {}^4He\pi^0$

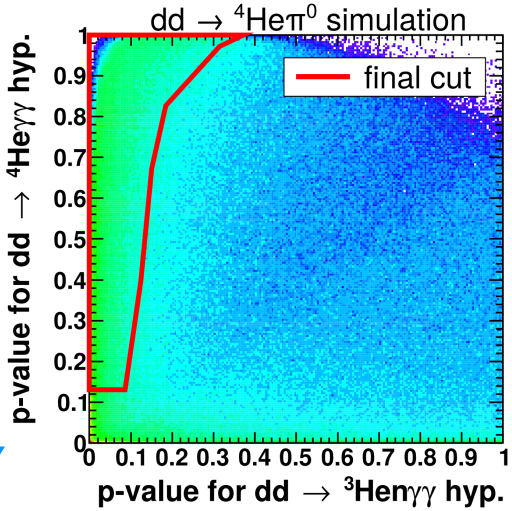


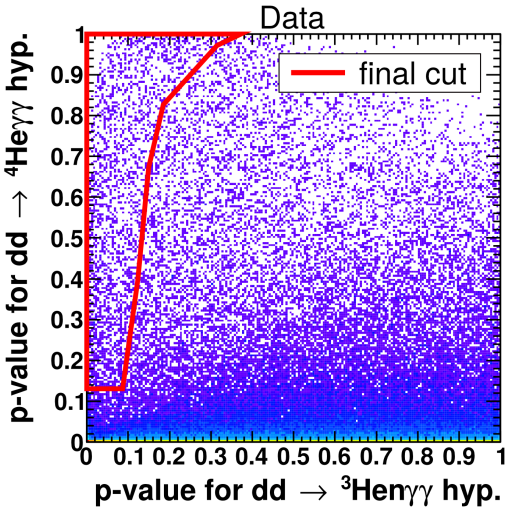
Status after calibration:



Background

- $dd \rightarrow$ (*pnd,pnpn,tp*) + π^0
- $dd \rightarrow {}^3He n \pi^0$ ($3 \cdot 10^5$ higher σ)
- $dd \rightarrow {}^4He\gamma\gamma$ (physics bg)





Overall kinematic fit

→ 2 hypotheses fitted:
$dd \rightarrow {}^4He\gamma\gamma$ and $dd \rightarrow {}^3Hen\gamma\gamma$

→ Optimized cuts on cumulated probability distribution (p-value)
→ Suppresion of $dd \rightarrow {}^3He n \pi^0$ about 10^4

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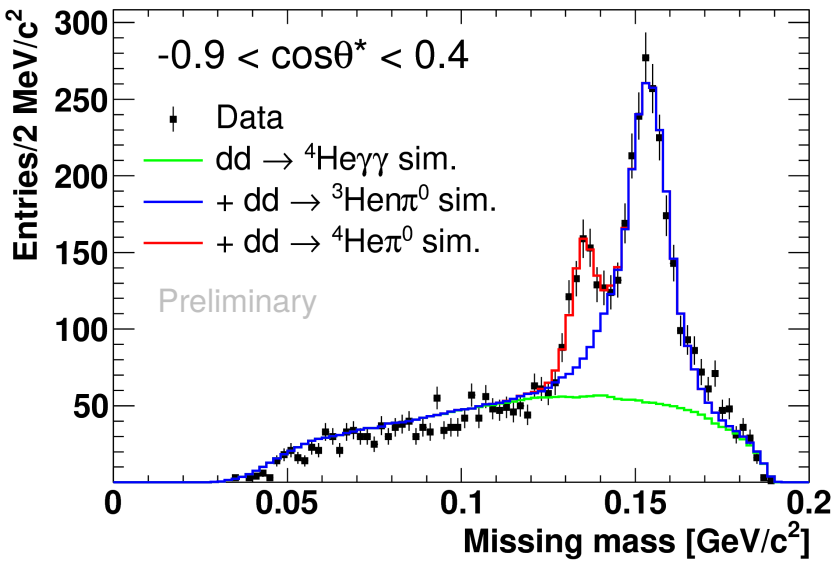
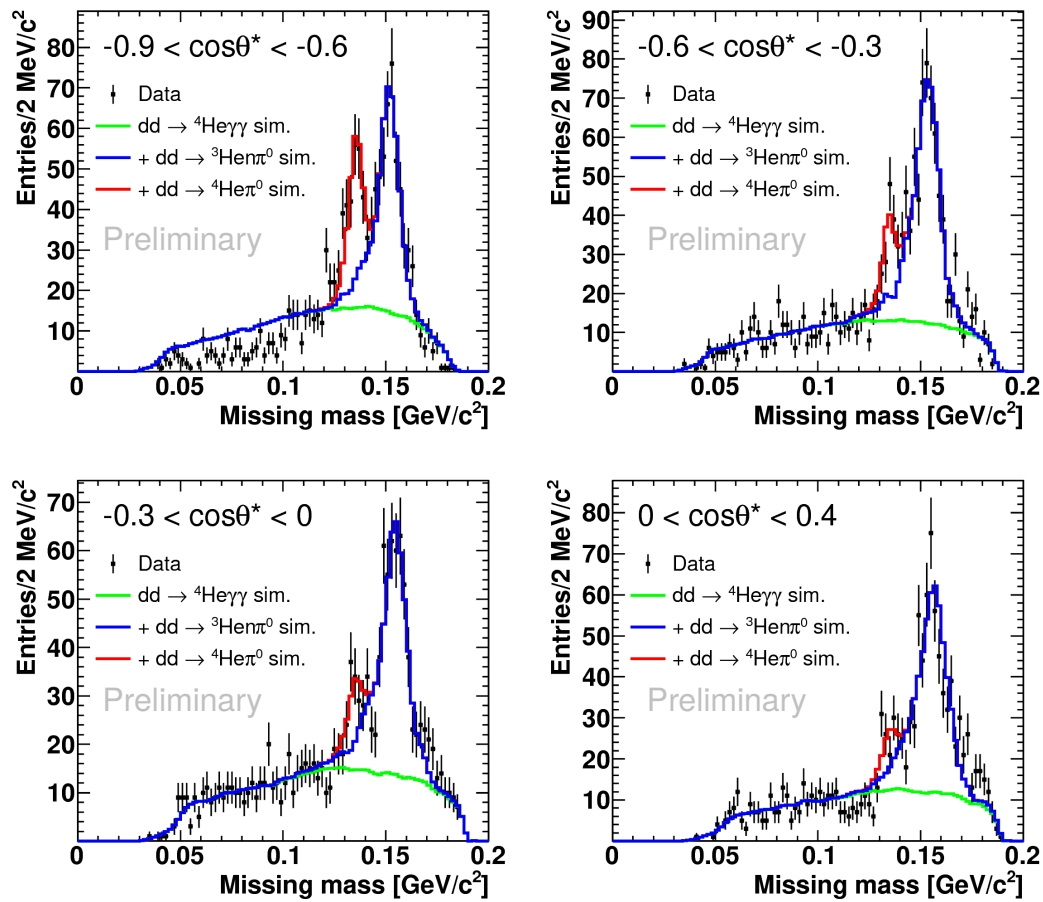
Missing mass of $dd \rightarrow {}^4\mathrm{He}X$

Full angular range
within detector acceptance



Four angular bins



Luminosity determination using $dd \rightarrow {}^3\mathrm{He}n\pi^0$

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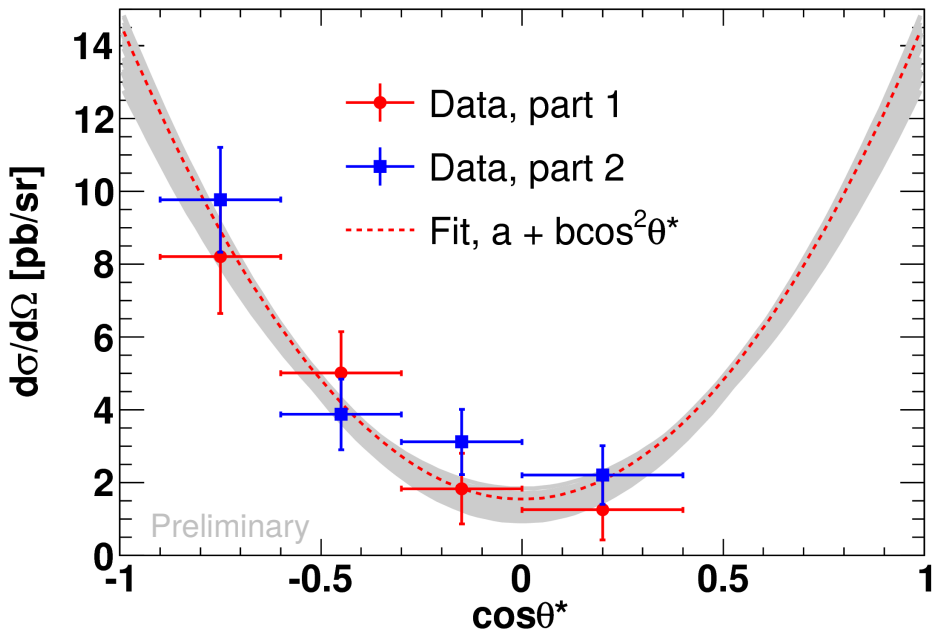
Differential cross section



Identical particles in the initial state
→ forward-backward symmetric cross section
$\mathrm{d}\sigma/\mathrm{d}\Omega = a + b\cos^2\theta^*$ fit result:

$$\mathrm{a} = \left(1.55 \pm 0.46(\mathrm{stat})^{+0.32}_{-0.8}(\mathrm{syst})\right)\ \mathrm{pb/sr}$$

$$\mathrm{b} = \left(13.1 \pm 2.1(\mathrm{stat})^{+1.0}_{-2.7}(\mathrm{syst})\right)\ \mathrm{pb/sr}$$

Common systematic uncertainty of 10% from external normalization

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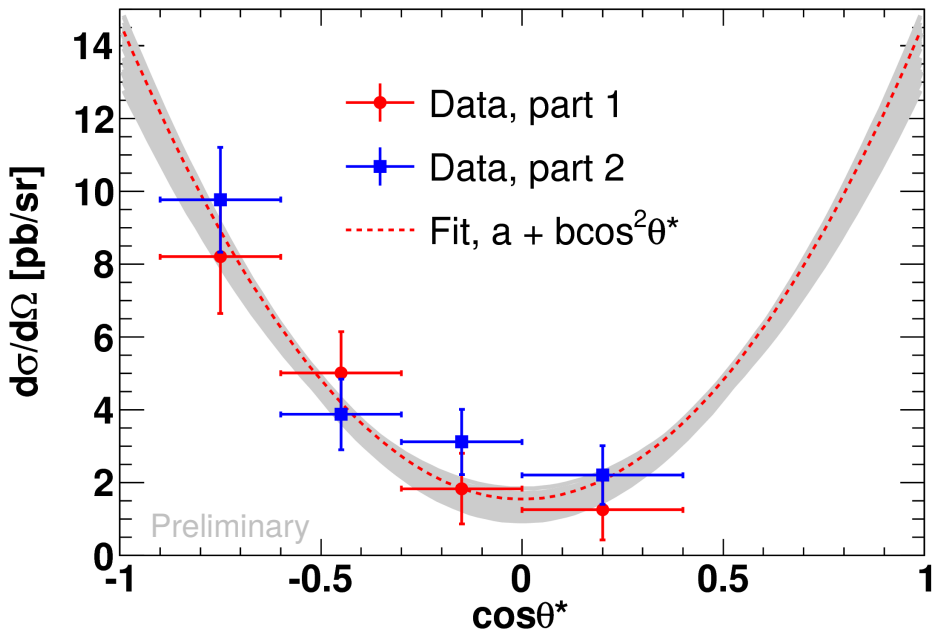

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Common systematic uncertainty of 10% from external normalization

Considering only ***s*- and *p*-waves** [1]: $b = -\frac{p_{\pi^0}}{p}\frac{2}{3}\underbrace{\boxed{|C|^2}}_{p\text{-wave}}p_{\pi^0}^2$

- *p*-waves contribute with a **negative** sign → maximum at 90° in angular distribution
- **Observed minimum** at 90° → explained only with **d-waves** in the final state

Data establish for the first time presence of sizable contribution of d-waves

[1] A. Wronska et al., Eur. Phys. J. A26, 421 (2005).

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Quantitative results

Including *d*-waves, terms up to fourth order in pion momentum has to be considered:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{p_{\pi^0}}{p}\frac{2}{3}\Big(|A_0|^2 + 2\,\mathrm{Re}(A_0^* A_2)P_2(\cos\theta^*)p_{\pi^0}^2 + |A_2|^2 P_2^2(\cos\theta^*)p_{\pi^0}^4 + |C|^2\sin^2\theta^* p_{\pi^0}^2 + |B|^2\sin^2\theta^*\cos^2\theta^* p_{\pi^0}^4\Big)$$

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d-wave

$$+ \boxed{|B|^2}\sin^2\theta^*\cos^2\theta^* p_{\pi^0}^4\Big)$$

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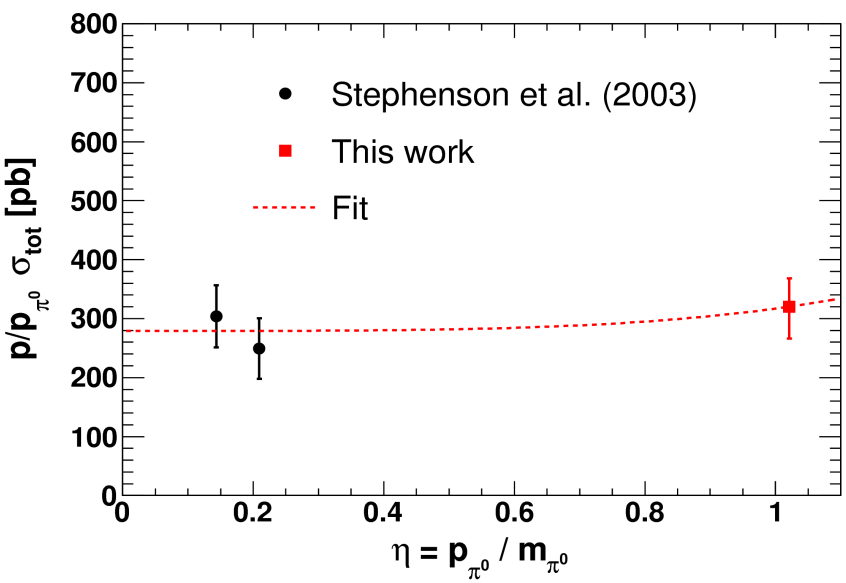
Assuming that amplitudes do not carry any momentum dependence

→ simultaneous fit of **angular distribution** and **momentum dependence of total cross section**

$$\sigma_{\mathrm{tot}} = \frac{p_{\pi^0}}{p}\frac{8\pi}{3}\left(|A_0|^2 + \frac{2}{3}|C|^2 p_{\pi^0}^2 + \frac{1}{5}|A_2|^2 p_{\pi^0}^4 + \frac{2}{15}|B|^2 p_{\pi^0}^4\right)$$



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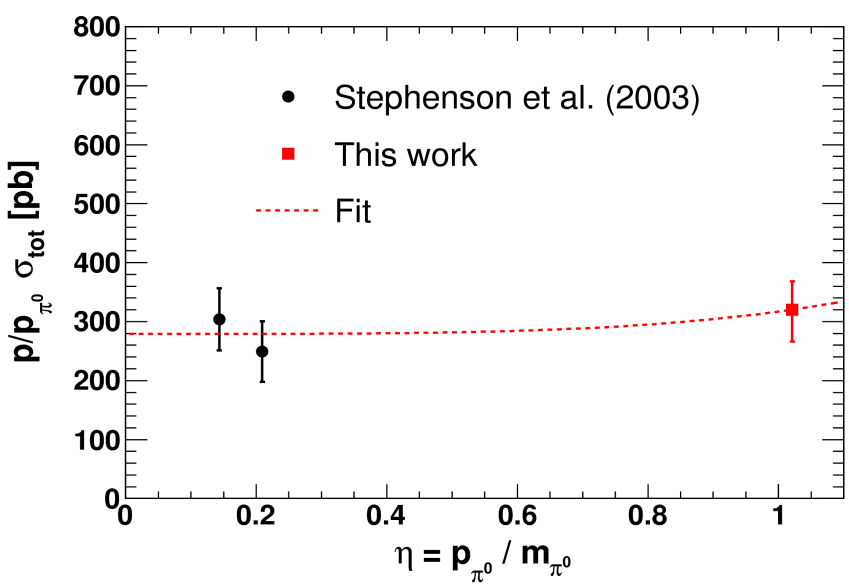

Systematic check of the fit:

- $|B|^2$ – consistent with 0 within the fit error
- $|C|^2$ – consistent with 0 within the fit error
- Other parameters: stable within the fit error

→ Assumption about $|A_0|^2$ momentum independence reasonable

→ Relative phase δ between A_0 and A_2: 0 with a statistical uncertainty in the range ±(1.0 – 1.6) rad

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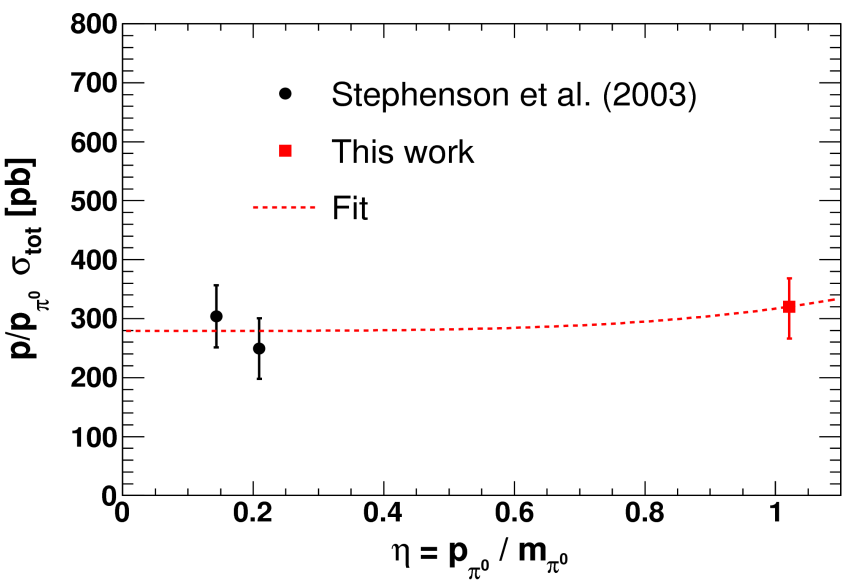

Final result of the simultaneous fit:
B – fixed to 0, phase *δ* – fixed to 0

$$|A_0| = \left(5.77 \pm 0.35(\mathrm{stat})^{+0.08}_{-0.33}(\mathrm{syst})^{+0.01}_{-0.19}(\mathrm{norm})\right)(\mathrm{pb/sr})^{1/2}$$

$$|A_2| = \left(255 \pm 59(\mathrm{stat})^{+48}_{-38}(\mathrm{syst})^{+37}_{-12}(\mathrm{norm})\right)\frac{(\mathrm{pb/sr})^{1/2}}{(\mathrm{GeV}/c)^2}$$

$$|C| = \left(4 \pm 38(\mathrm{stat})^{+9}_{-10}(\mathrm{syst})^{+10}_{-5}(\mathrm{norm})\right)\frac{(\mathrm{pb/sr})^{1/2}}{\mathrm{GeV}/c}$$

Obtained total cross section:

$$\sigma_{\mathrm{tot}} = \left(76.9 \pm 7.8(\mathrm{stat})^{+1.9}_{-8.8}(\mathrm{syst})^{+8.3}_{-5.7}(\mathrm{norm})\right)\mathrm{pb}.$$

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Conclusions

- **First measurement of contributions of higher partial waves** in the charge symmetry breaking reaction dd → ^{4}Heπ^0
- Angular distribution with a minimum at $\theta^* = 90^o$ can be understood only by the presence of a **significant *d*-wave contribution** in the final state
- Data are consistent with **vanishing *p*-wave** contribution

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Role of the Δ isobar ?

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- Deep insights not only into the dynamics of the nucleon-nucleon interaction but also the role of **quark masses in hadron dynamic**

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Backup

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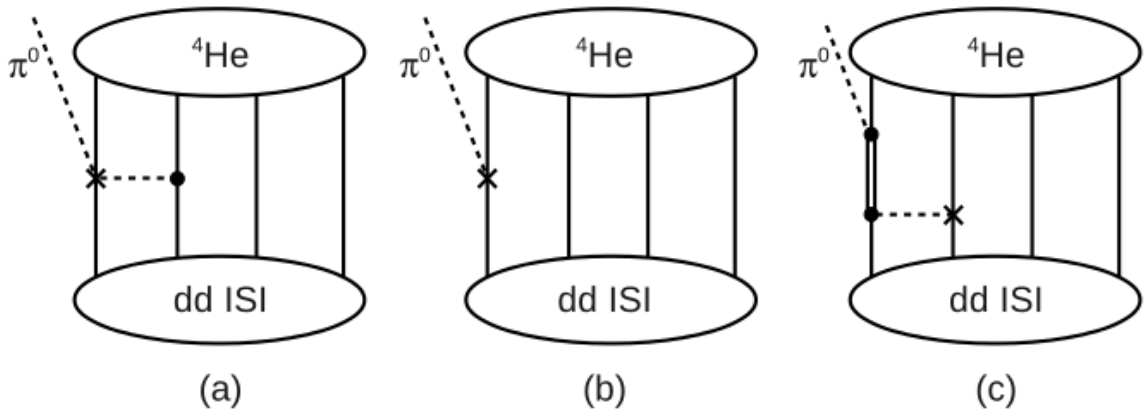
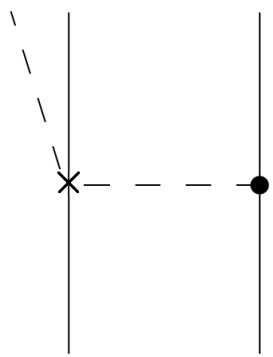
Leading diagrams of CSB reactions



Formally leading operators for *p*-wave pion production in $dd \to {}^4\mathrm{He}\pi^0$.



x – occurrence of CSB
• – LO charge invariant vertex
- - - - - – π
——— – nucleons
═══ – Δ

Leading order diagram for the CSB *s*-wave amplitudes of the $np \to d\pi^0$ reaction

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