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

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Isospin Symmetry

Two sources of violation:

- Electromagnetic interaction
- Lightest quark mass difference $\mapsto$ Window for probing quark mass ratios

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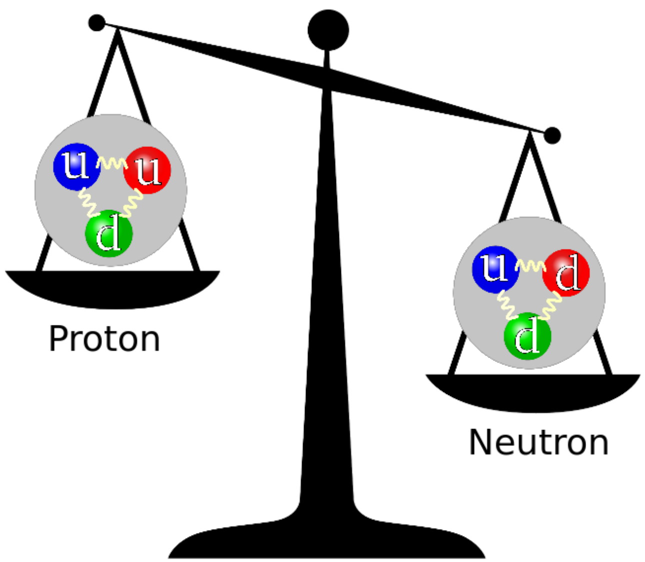

Nucleon mass difference

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

ΔM_{em}: -0.7 ± 0.3 MeV (from QED + dispersion theory)

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

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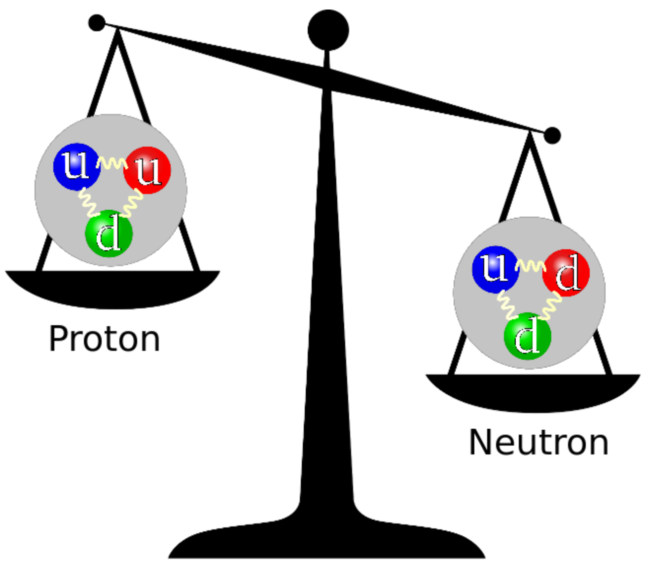

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2.05 ± 0.3 MeV ($\Delta M_{pn} - \Delta M_{em}$)

Access to ΔM_{str} from dynamic ISB 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 $\pi^{\pm} N$

Charge Symmetry Breaking

Isospin Symmetry Breaking

Dominated by pion mass difference Δm_π – e.m. effect

Charge Symmetry (CS) Breaking

Symmetry under the operation of $P_{CS} = e^{-i\tau_2 \pi/2}$ - Δm_π does not contribute

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⇩

Charge Symmetry (CS) Breaking

Symmetry under the operation of $P_{CS} = e^{-i\tau_2 \pi/2}$ - Δm_π does not contribute

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

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

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

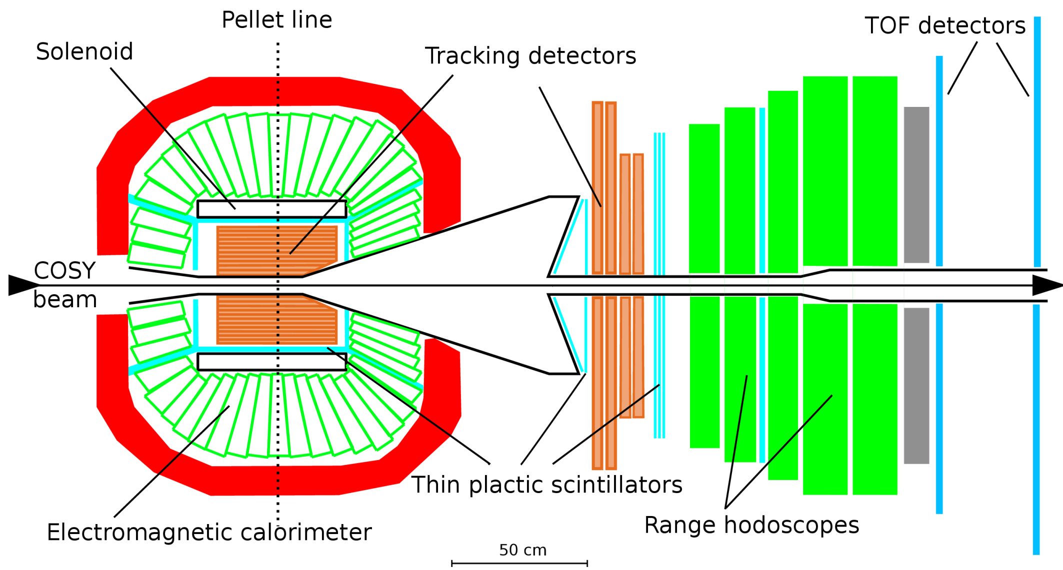
CS ⇒ $\sigma = 0$ ~~CS~~ ⇒ $\sigma \neq 0$, $\sigma \propto |M_{CSB}|^2 = |M_1 + M_2 + \dots|^2$

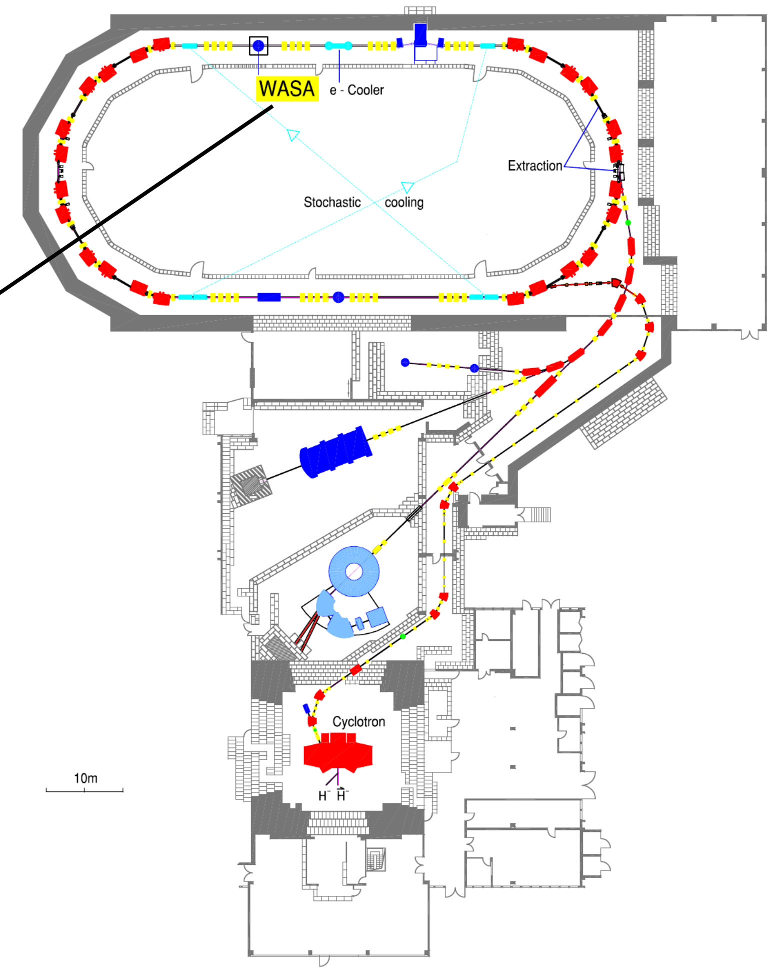
σ_{total} measured at treshold [3] and at Q = 60 MeV [4]

Result at treshold consistent with *s*-wave ⇒ **Chiral Perturbation Theory** ⇒ *p*-wave contribution in $dd \to {}^4He\pi^0$ at higher excess energies needed

[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

WASA-at-COSY experiment





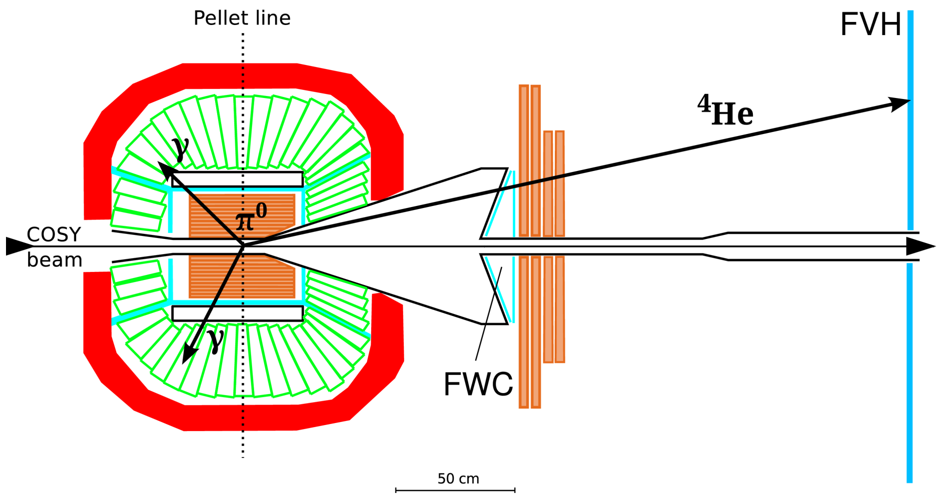
CSB with WASA-at-COSY:

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

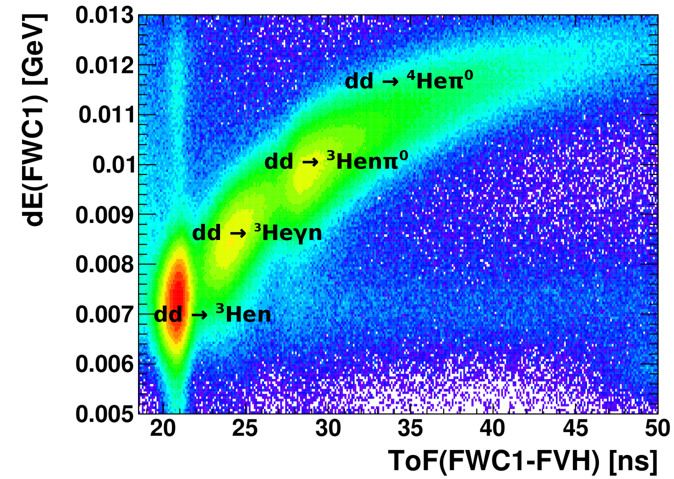
2008: First measurement of $dd \to {}^4\mathrm{He}\pi^0$ (2 weeks) @ Q = 60 MeV
goal: σ_{total}

2014: New measurement of $dd \to {}^4\mathrm{He}\pi^0$ (8 weeks) @ Q = 60 MeV with modified detector
goal: angular distribution

Analysis of *dd* → $^4He\pi^0$

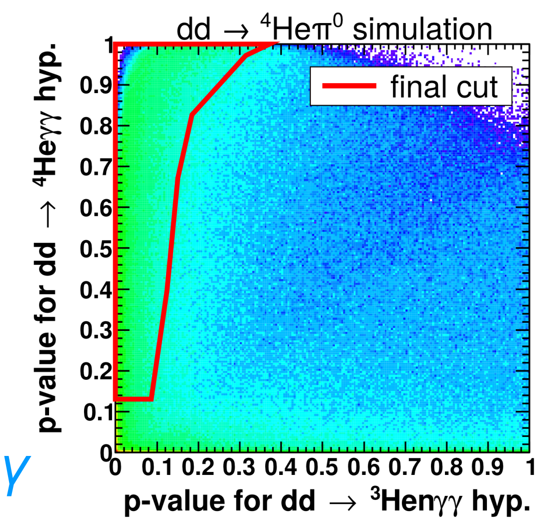


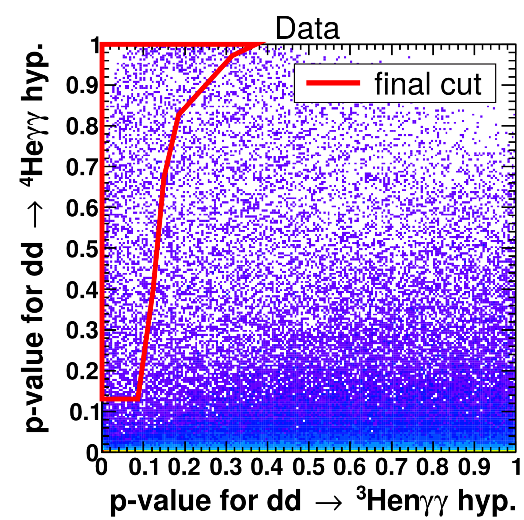
Status after calibration:



Background

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





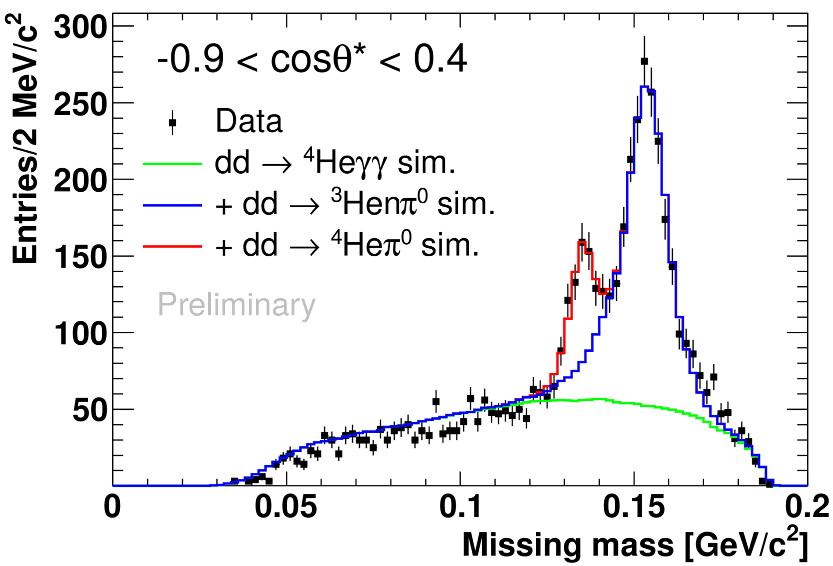
Overall kinematic fit

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

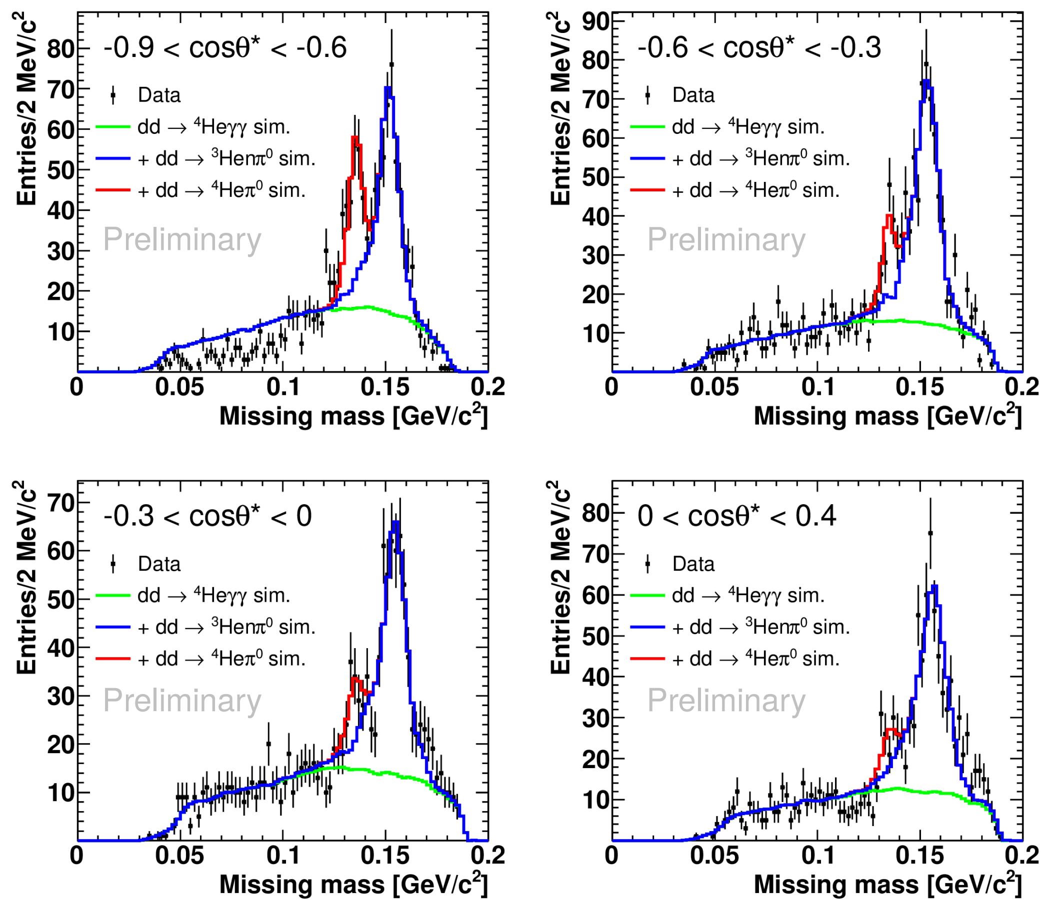
→ Optimized cuts on cumulated probability distribution (p-value)
→ Suppresion of $dd \rightarrow {}^3He n \pi^0$ about 10^4

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

Full angular range
within detector acceptance



Four angular bins

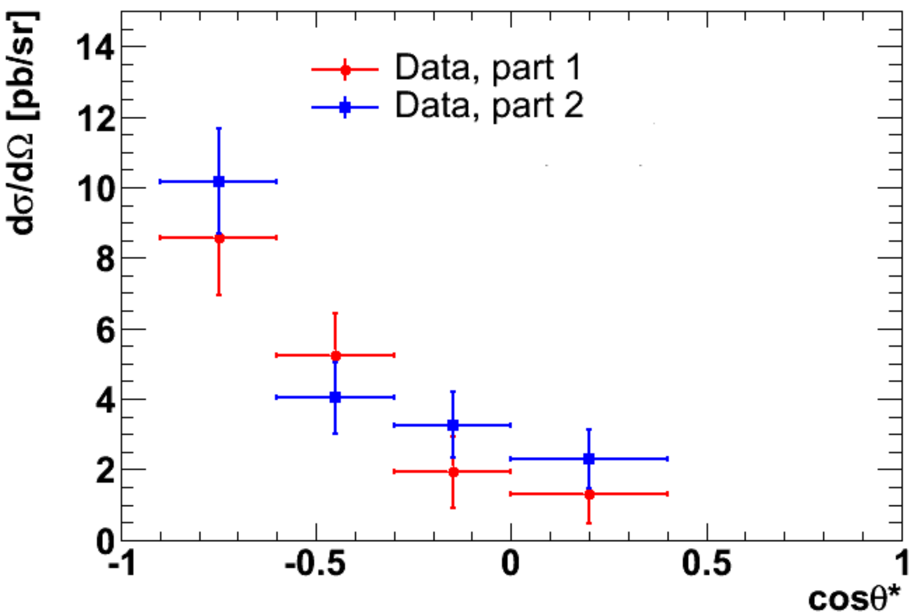


Luminosity determination using $dd \rightarrow {}^3\mathrm{He}n\pi^0$

Total and differential cross section

Unpolarized differential cross section (terms up to order $p^2_{\pi^0}$ to the intensity):

$$\frac{d\sigma}{d\Omega} = \frac{2}{3}\frac{p_{\pi^0}}{p_d}\left(|A_0|^2 - p^2_{\pi^0}\Re\{A_0^* A_2\} + |C|^2 p^2_{\pi^0}\right) + \frac{p_{\pi^0}}{p_d}\left(2p^2_{\pi^0}\Re\{A_0^* A_2\} - \frac{2}{3}|C|^2 p^2_{\pi^0}\right)\cos^2\theta^*$$



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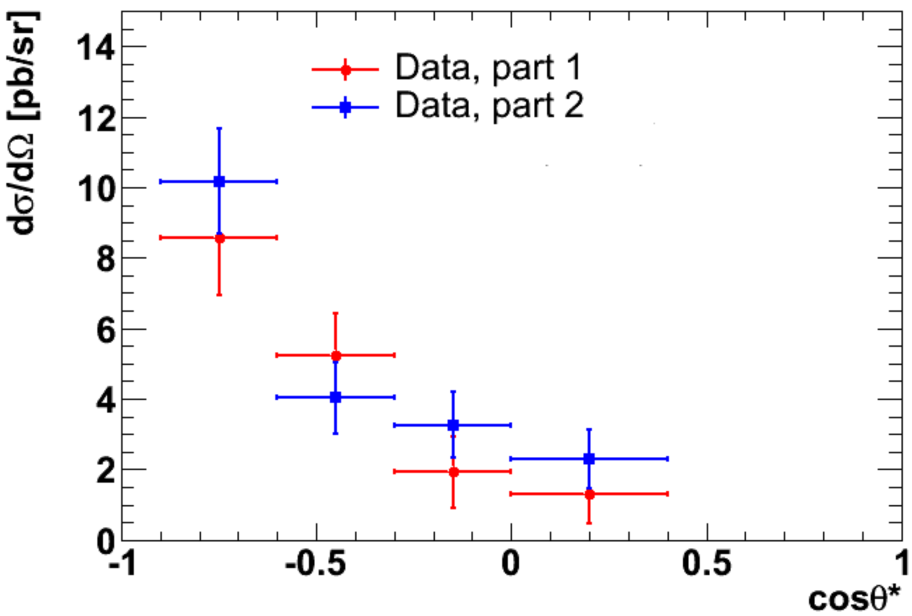
s-wave amplitude



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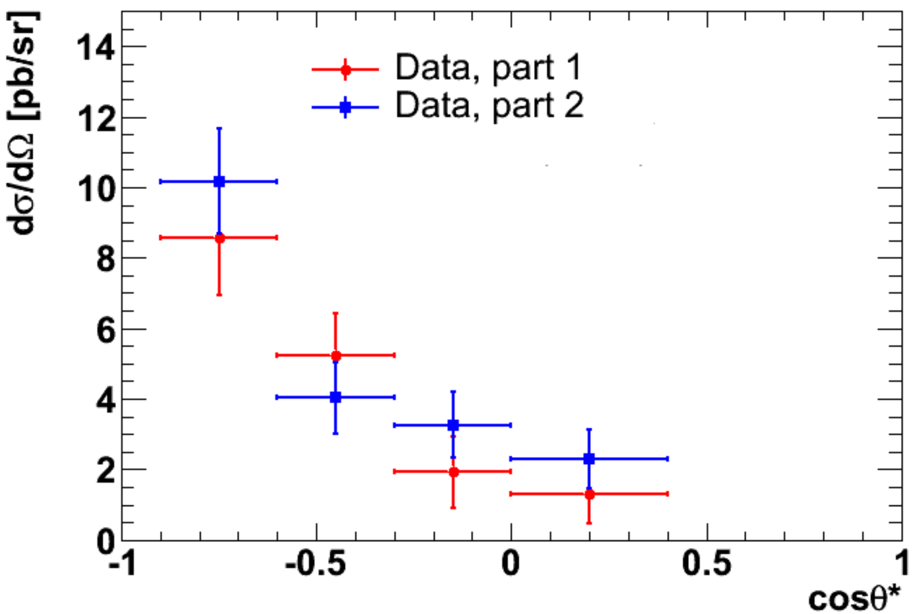
s-wave amplitude

s-*d* interference term



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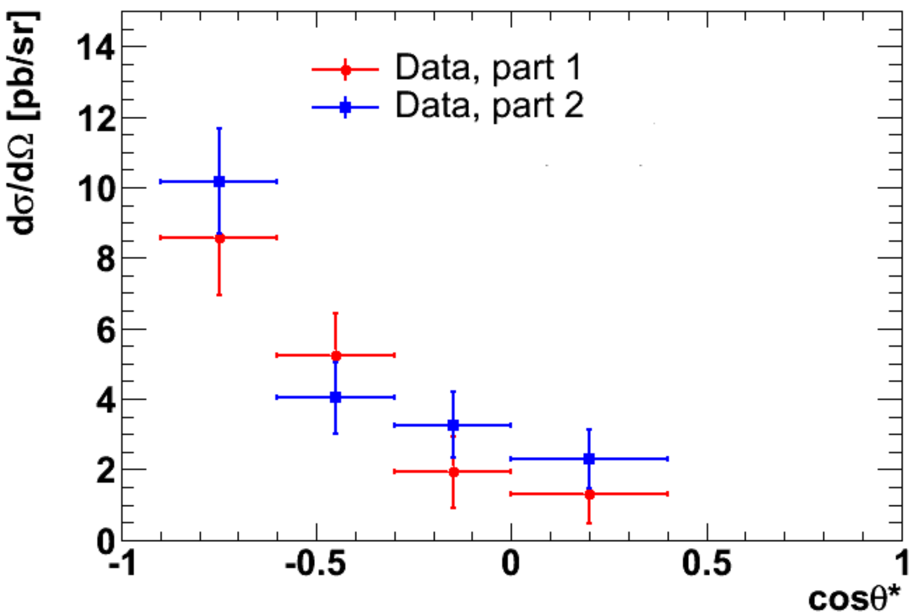
s-wave amplitude

p-wave amplitude

s-*d* interference term



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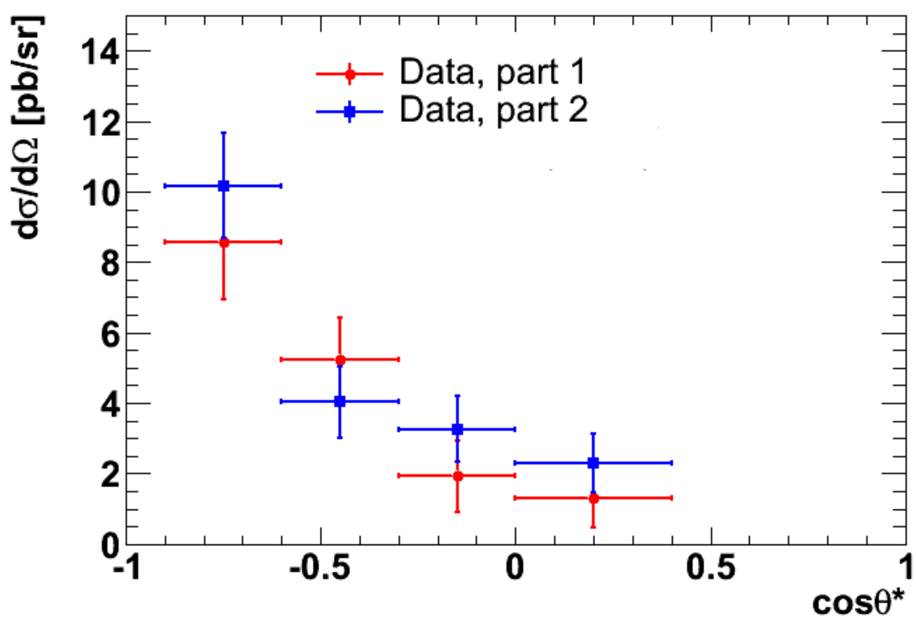
s-wave amplitude *p*-wave amplitude *s*-*d* interference term



Mitglied der Helmholtz-Gemeinschaft

Total and differential cross section

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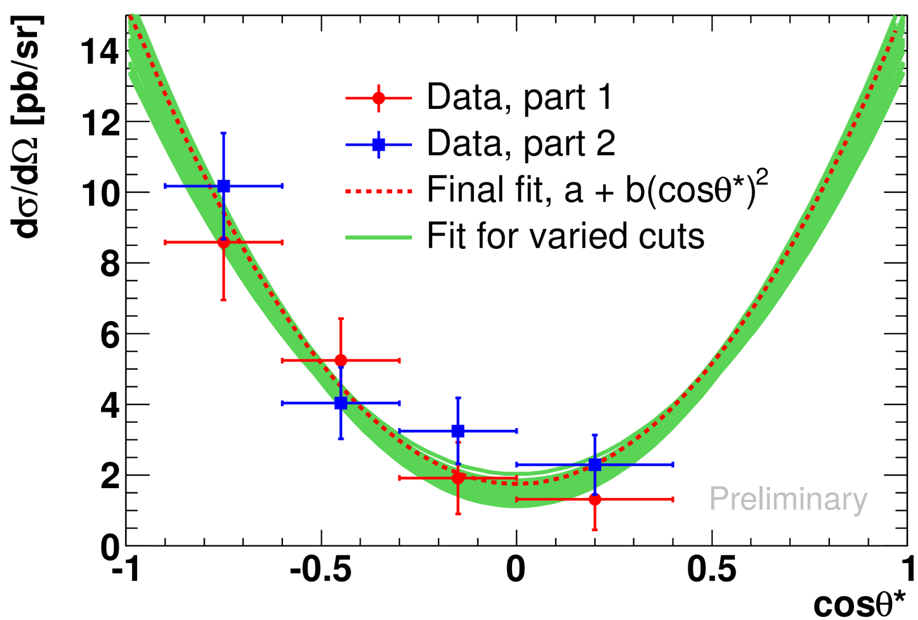


$$a = \left(1.75 \pm 0.46(\text{stat.})^{+0.31}_{-0.8}(\text{syst.})\right)\ \text{pb/sr}$$

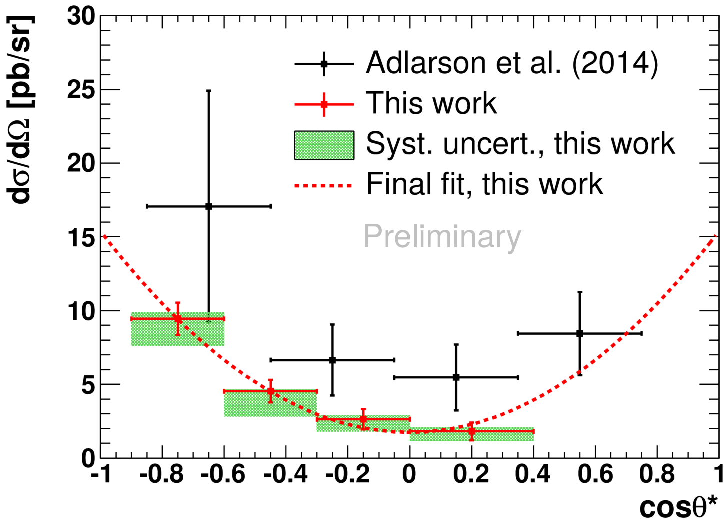
$$b = \left(13.6 \pm 2.2(\text{stat.})^{+0.9}_{-2.7}(\text{syst.})\right)\ \text{pb/sr}$$

common systematic uncertainties
10% - external normalization
2% - luminosity determination

→ Requires higher partial waves

$$\sigma_{\text{tot}} = \left(79.1 \pm 7.3(\text{stat.})^{+1.2}_{-10.5}(\text{syst.}) \pm 8.1(\text{norm.}) \pm 2.0(\text{lumi. syst.})\right)\ \text{pb}$$

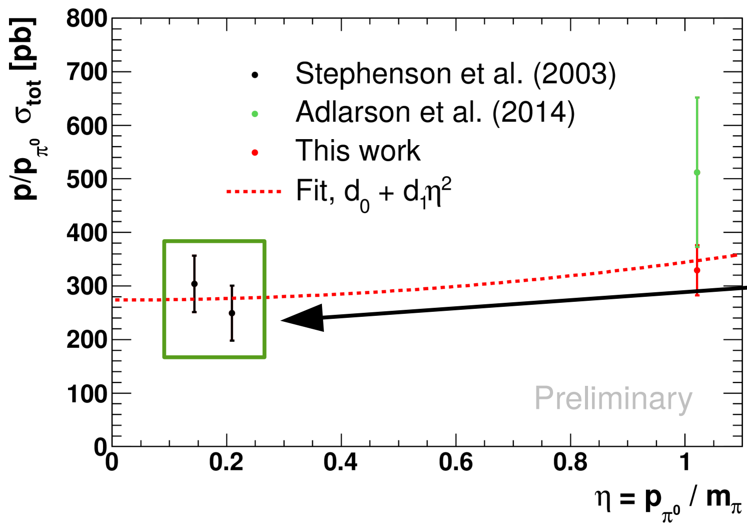
Comparison with other measurements



$$\sigma_{tot} = \left(79.1 \pm 7.3(\text{stat.})^{+1.2}_{-10.5}(\text{syst.}) \pm \pm 8.1(\text{norm.}) \pm 2.0(\text{lumi. syst.})\right) \text{pb}$$

$$\sigma^{prev}_{tot} = (123 \pm 30(\text{stat.}) \pm 12(\text{norm.}) \pm 8.6(\text{ext.}))\,\text{pb}$$

From energy dependence of total cross section we can obtain *s*-wave amplitude $|A_0|^2$



(Neglecting initial and final state interactions)

$$\frac{p}{p_{\pi^0}}\sigma_{tot} = \frac{8\pi}{3}|A_0|^2 + \frac{16\pi}{9}m^2_{\pi^0}|C|^2\eta^2$$

Defined mostly by measurement close to threshold

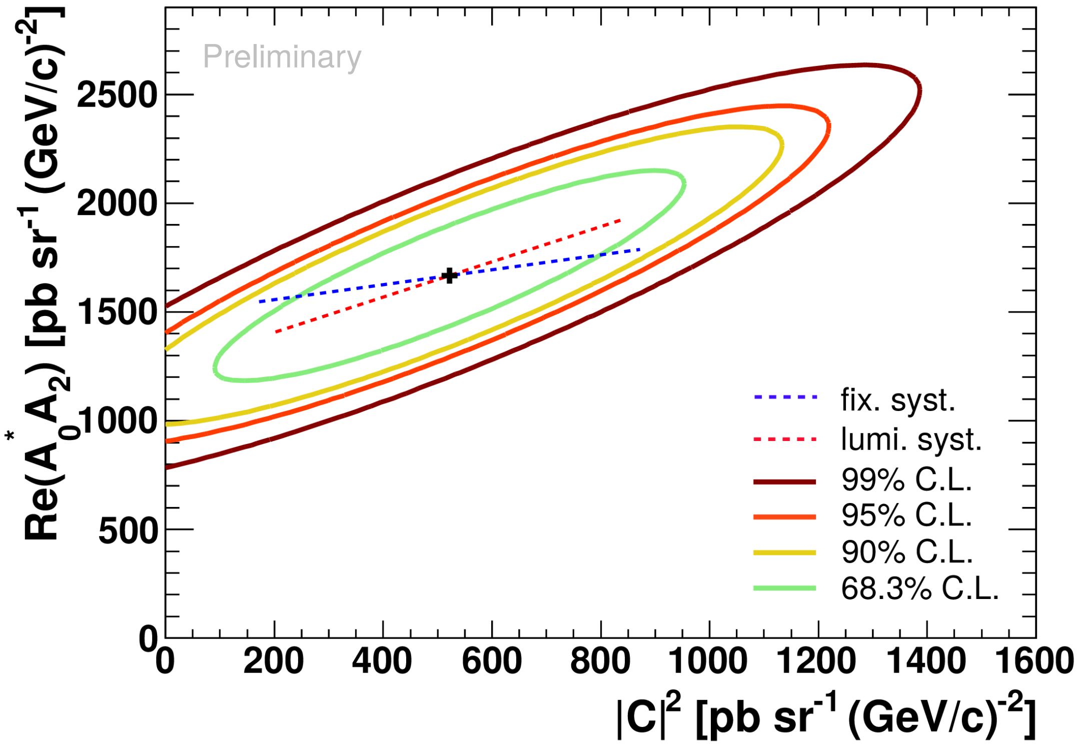
$$|A_0|^2 = (32.7 \pm 4.5)\ \text{pb/sr}$$

With fixed $|A_0|^2$ we can determine $|C|^2$ and $\Re\{A_0^* A_2\}$ from the fit:

$$\frac{p_d}{p_{\pi^0}}\frac{d\sigma}{d\Omega} = \frac{2}{3}\left(|A_0|^2 - p^2_{\pi^0}\Re\{A_0^*A_2\} + |C|^2 p^2_{\pi^0}\right) + \left(2p^2_{\pi^0}\Re\{A_0^*A_2\} - \frac{2}{3}|C|^2 p^2_{\pi^0}\right)\cos^2\theta^*$$

fixed

Combined interpretation



***p*-wave amplitude**
small and consistent with zero within uncertainties

***s-d* interference term**
significantly different from zero

Direct contribution from $|A_2|^2$
Subtracted in σ_{tot} by factor $1/p_{\pi^0}^2 \approx 50$
(it is of order of $p_{\pi^0}^4$)

$$\Re\{A_0^* A_2\} = \left(1670 \pm 320(\text{stat.})^{+80}_{-430}(\text{syst.})\right)\ \text{pb}/\left(\text{sr}\cdot(\text{GeV}/c)^2\right)$$

$$|C|^2 = \left(520 \pm 290(\text{stat.})^{+50}_{-430}(\text{syst.})\right)\ \text{pb}/\left(\text{sr}\cdot(\text{GeV}/c)^2\right)$$

Common (correlated) systematic uncertainties:

- From luminosity determination
- From fixed $|A_0|^2$

Summary

- Charge Symmetry Breaking used to access quark mass effects. Theoretical tool: Chiral Perturbation Theory.

- Higher partial wave contributions in $dd \rightarrow {}^4\mathrm{He}\pi^0$ needed.

- Data from the new measurement of $dd \rightarrow {}^4\mathrm{He}\pi^0$ at Q = 60 MeV in 2014 with WASA analyzed. Total and differential cross section obtained.

- **Results show that any theoretical attempt to describe the reaction had to include, in addition to *p*-waves, also *d*-wave contributions.**

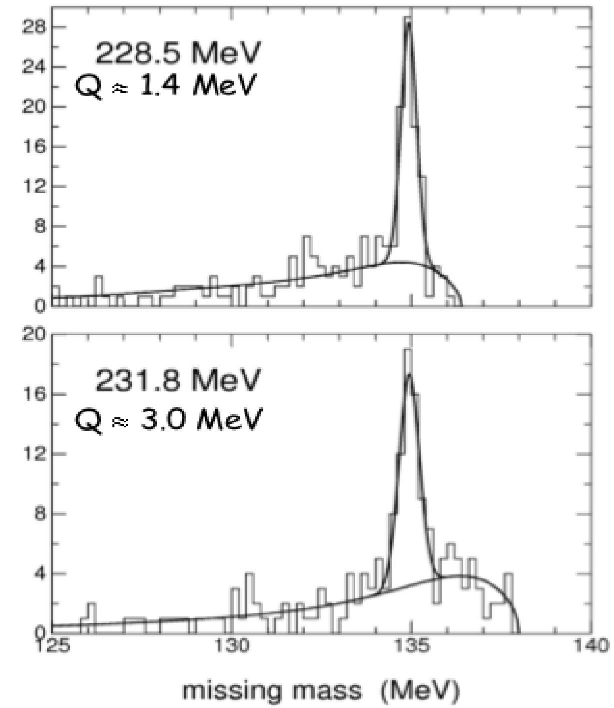
Backup

Charge Symmetry Breaking

Measurements of CSB observables

- **np→dπ⁰ forward-backward asymmetry A_{fb}**
  - leading CSB term: πN rescattering
  - Opper et al., $A_{fb} = (17.2 \pm 8.0 \pm 5.5) \cdot 10^{-3}$

    (PRL 91 (2003) 212302)



- **Pion production in dd→⁴He π⁰**

CSC ⇒ $\sigma = 0$

CSB ⇒ $\sigma \neq 0$, $\sigma \propto |M_{CSB}|^2$

Complementary to np→dπ⁰:

  - different strength of CSB terms
  - dd initial state more demanding

Result: Stephenson et al.

(PRL 91 (142302) 2003)

σ_{tot} (Q=1.4 MeV) = 12.7 ± 2.2 pb

σ_{tot} (Q=3.0 MeV) = 15.1 ± 3.1 pb

Result consistent with s-wave production

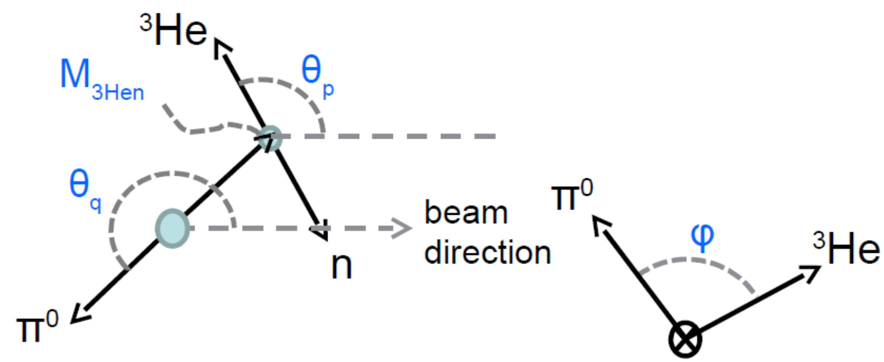
dd→^{3}He*n*π^0 reaction measurement

Two-fold model ansatz:

- Quasi-free contribution: dd → ^{3}Heπ^0 + n_{spec}
- Partial waves decomposition of the 3-body final state (limited to L≤1)

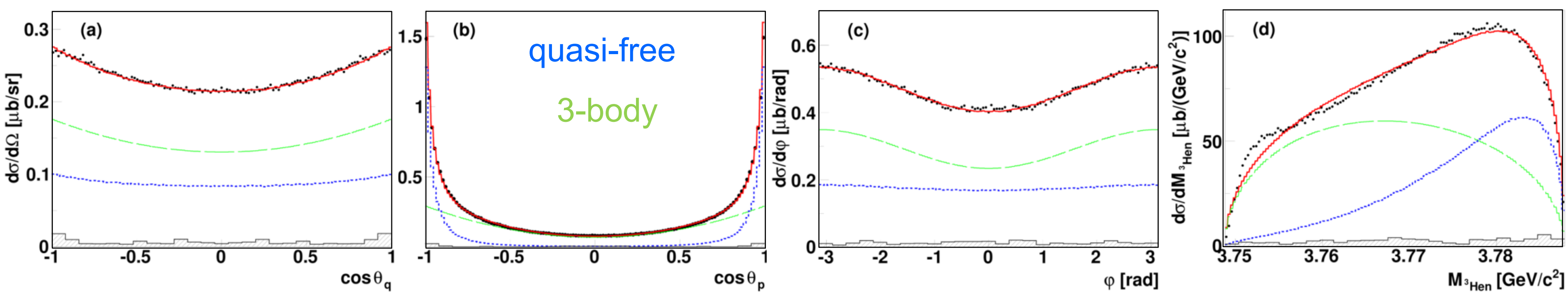
full model
incoherent sum

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



Model used for **simulating** the *dd* → ^{3}He*n*π^0 background and for **normalization**

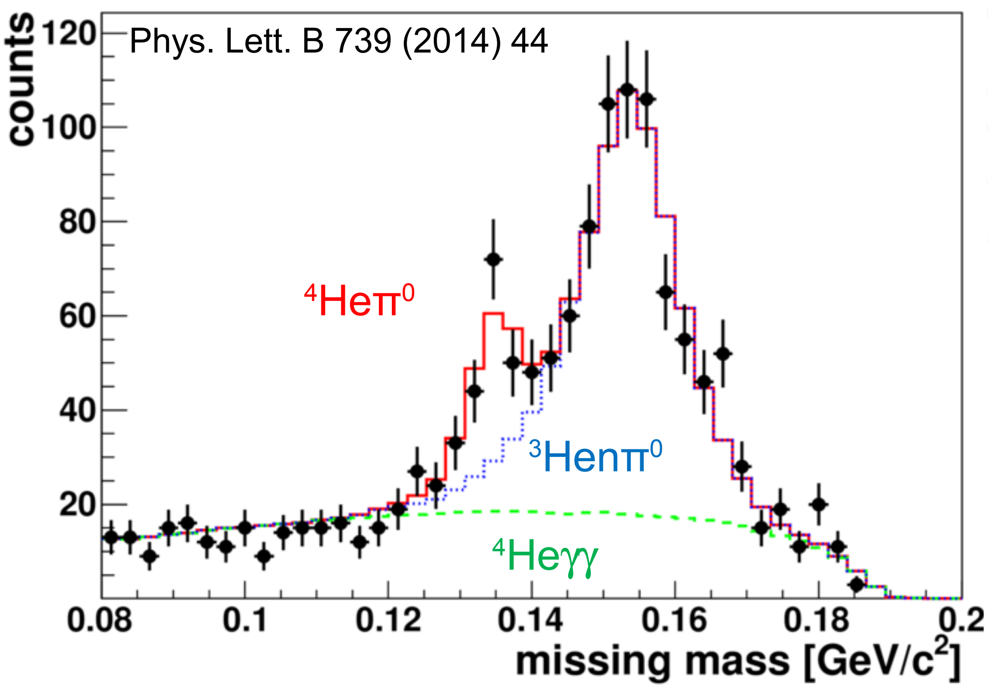
4 independent variables M_{3Hen}, θ_p, θ_q, φ

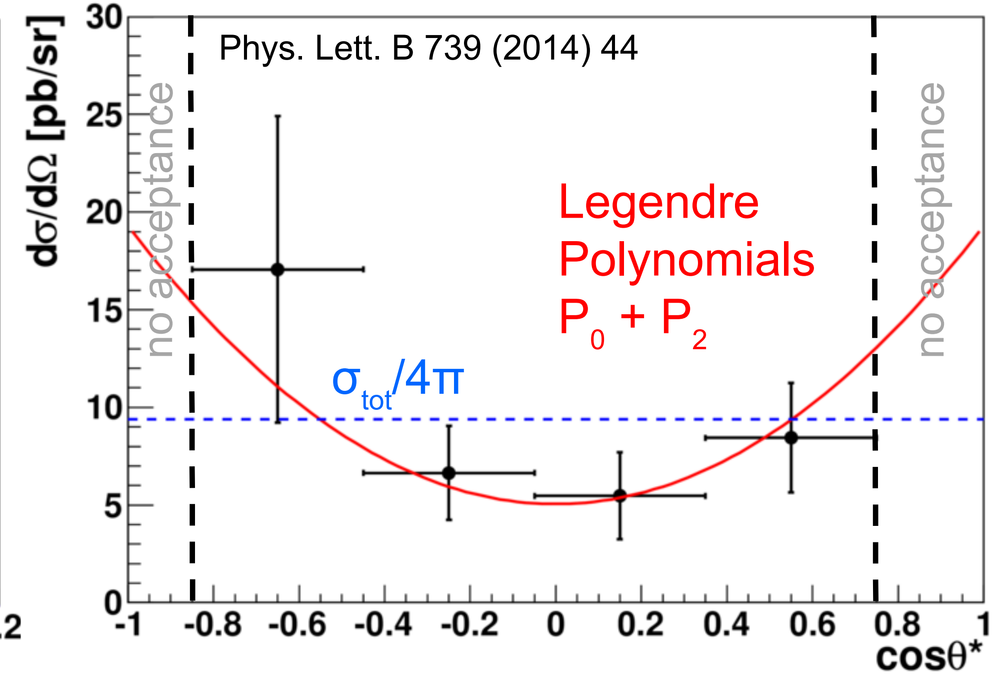


Phys. Rev. C 88 (2013) 014004

First dd→^{4}Heπ^0 measurement with WASA

Results:





Total cross section:

^{4}Heπ^0: $\sigma = (118 \pm 18_{stat} \pm 13_{sys} \pm 8_{ext})$ pb

^{4}Heγγ: $\sigma = (920 \pm 70_{stat} \pm 100_{sys} \pm 70_{ext})$ pb

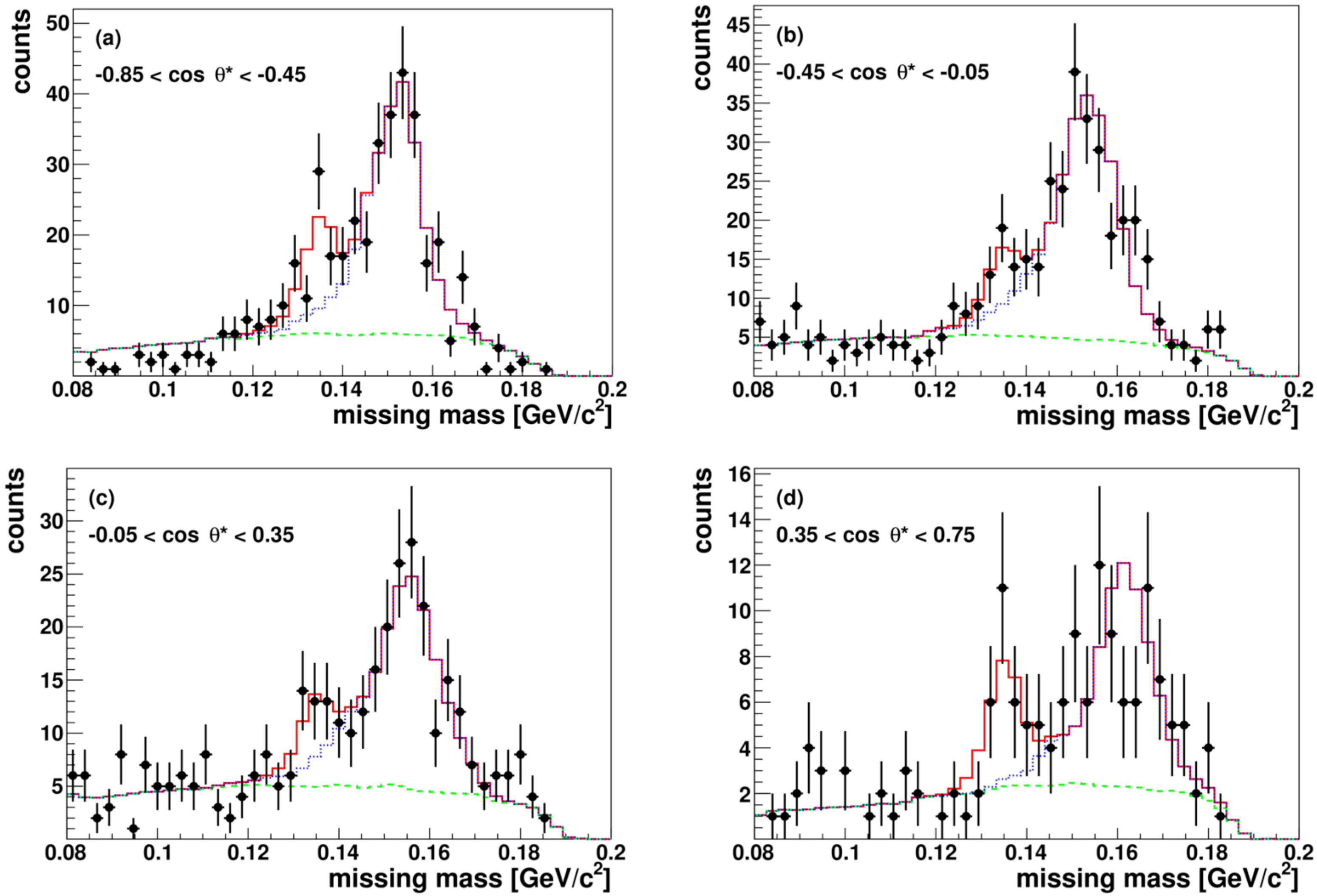
Fit including *p*-wave:

$$d\sigma/d\Omega = (9.8 \pm 2.6)\ \text{pb/sr} \cdot P_0(\cos\theta^*) + (9.5 \pm 7.4)\ \text{pb/sr} \cdot P_2(\cos\theta^*)$$

consistent with *s*-wave only

However: not decisive due to limited statistics

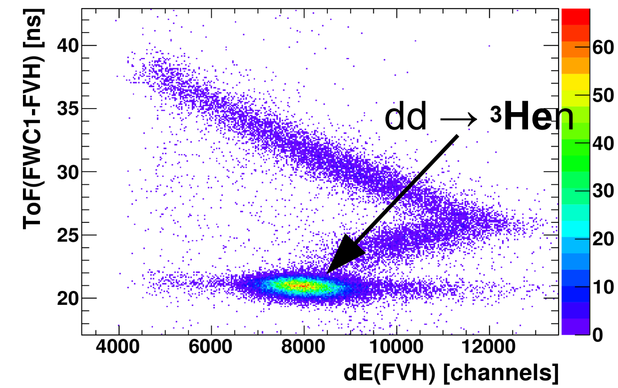
Results – angular distribution



Detector Calibration

ToF Calibration

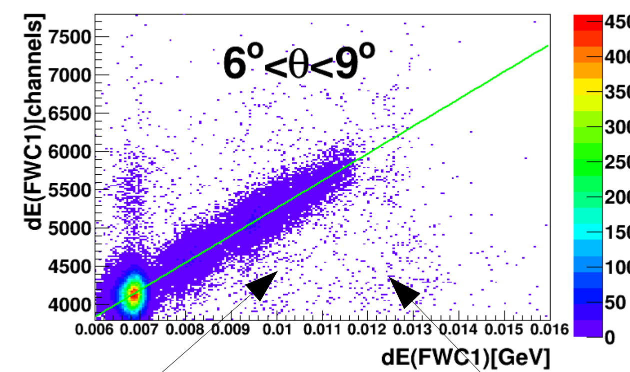
- dd → ³Hen time peak position used
- Calibrate the data to the MC values for every detector element as a function of θ



dE Calibration

- Based on ToF
- **MC:** dE [GeV] vs ToF [ns] → $\mathbf{dE_{GeV}(ToF)}$
- **Data:** dE [channels] vs ToF [ns] → $\mathbf{dE_{ch}(ToF)}$

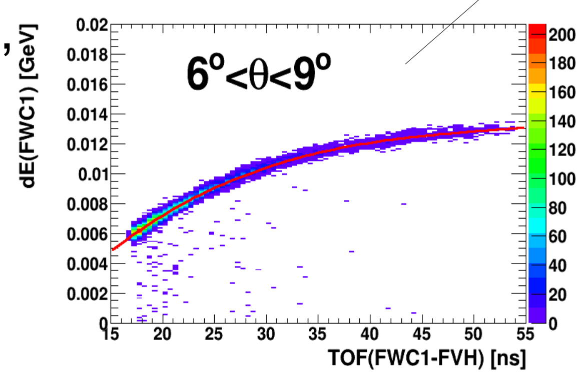
→ Run-wise correction, θ-dependency correction

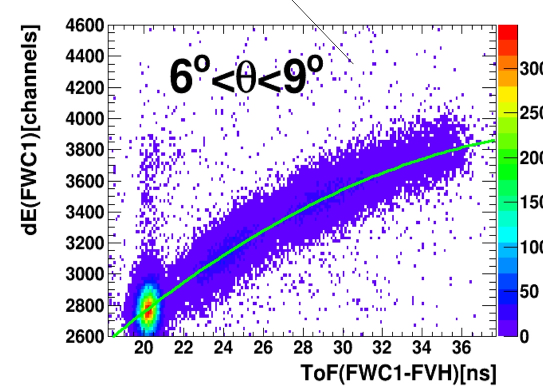


$dE_{GeV}(ToF)$

Kinetic Energy Reconstruction

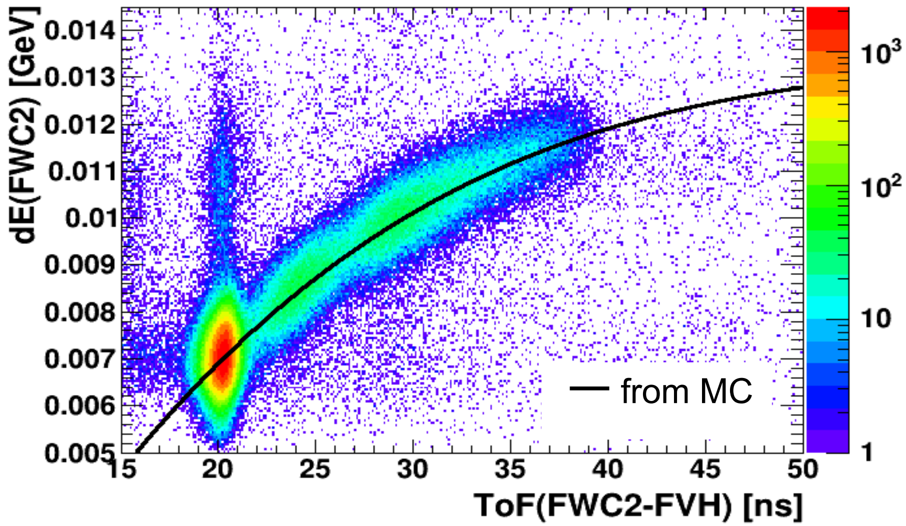
- Based on $E_{kin}(ToF_1)$, $E_{kin}(ToF_2)$, $E_{kin}(dE_{FWC1})$, $E_{kin}(dE_{FWC2})$
- χ^2 fit used to obtain the best matching E_{kin}



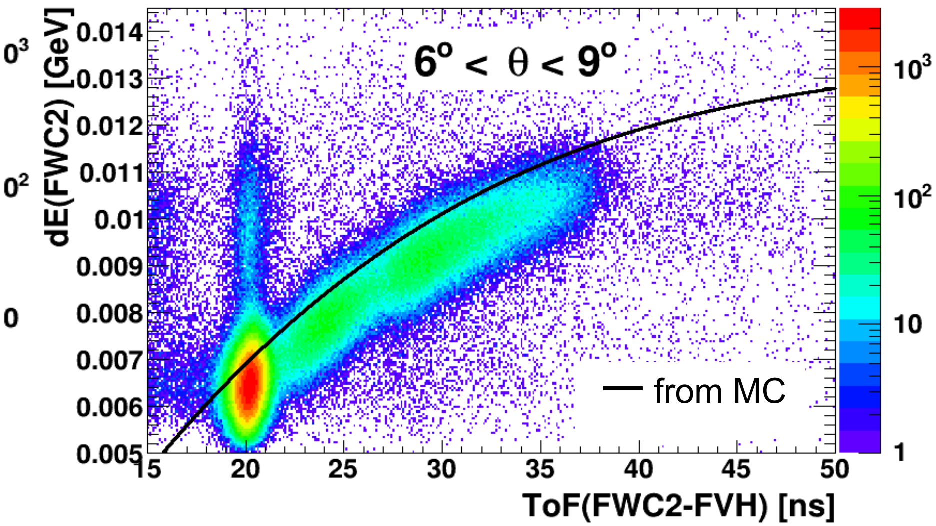


Energy losses calibration in FWC

JÜLICH
FORSCHUNGSZENTRUM

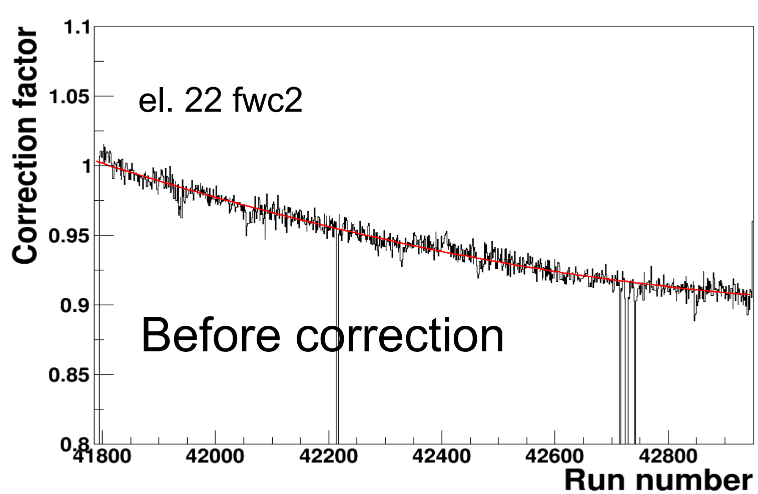


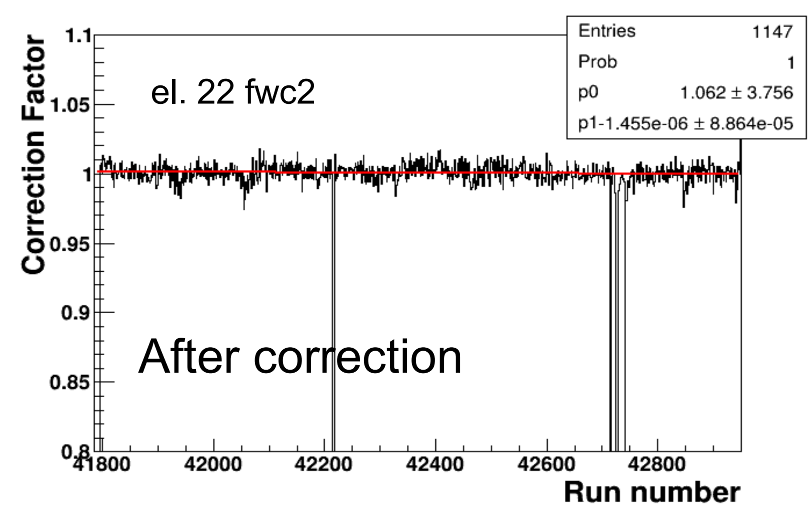
beginning of the beamtime



830 runs after beginning of the beamtime (about ¼ of all runs)

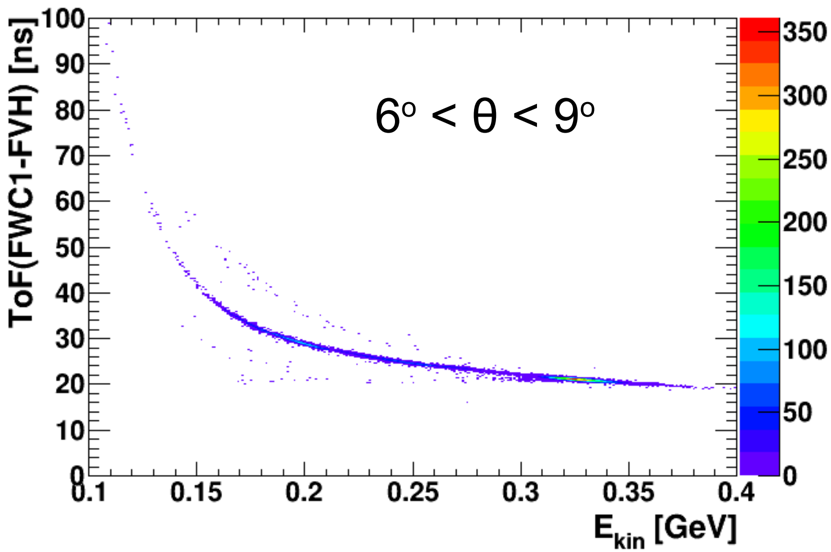
→ Run correction to dE calibration for every FWC1 and FWC2 element need
→ Separate calibration for 2nd part of the beamtime

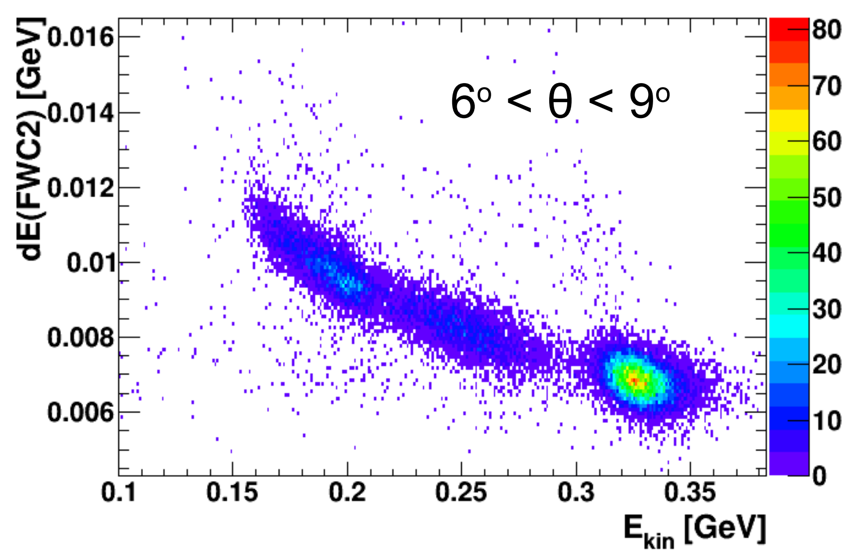




Kinetic energy calibration

- Minimization of χ² : $\chi^2 = \sum_{i=1}^{n} \frac{(dE_i^{meas} - dE(E_{kin})_i)^2}{\sigma_i^2} + \sum_{j=1}^{m} \frac{(\mathrm{TOF}_j^{meas} - \mathrm{TOF}(E_{kin})_j)^2}{\sigma_j^2}$
- $E_{kin}(ToF_1)$, $E_{kin}(ToF_2)$, $E_{kin}(dE_{FWC1})$, $E_{kin}(dE_{FWC2})$ dependency from MC
- Data based uncertainties of ToF(dE) as a function of ToF(dE) (first ineration)





Obtained partial-waves contributions

$$\frac{p}{p_{\pi^0}}\frac{d\sigma}{d\Omega} = \left(\frac{2}{3}|A_0|^2_{\text{fixed}} - \frac{2}{3}p^2_{\pi^0}\Re\{A_0^*A_2\} + \frac{2}{3}|C|^2p^2_{\pi^0}\right) + \left(2p^2_{\pi^0}\Re\{A_0^*A_2\} - \frac{2}{3}|C|^2p^2_{\pi^0}\right)\cos^2\theta^*$$

$\frac{2}{3}|A_0|^2_{\text{fixed}}$ → ≈ 22 pb/sr

$\frac{2}{3}p^2_{\pi^0}\Re\{A_0^*A_2\}$ → ≈ 21 pb/sr

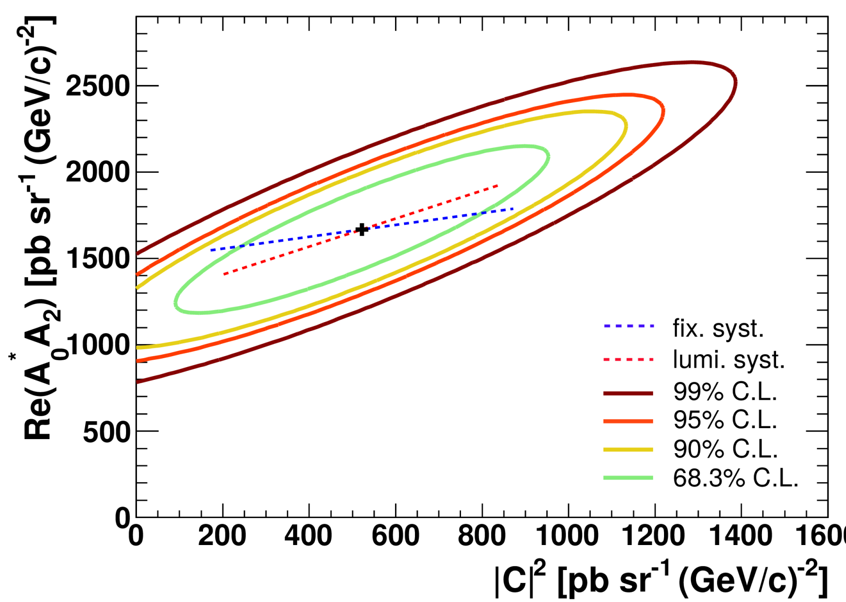
$\frac{2}{3}|C|^2p^2_{\pi^0}$ → ≈ 6.6 pb/sr

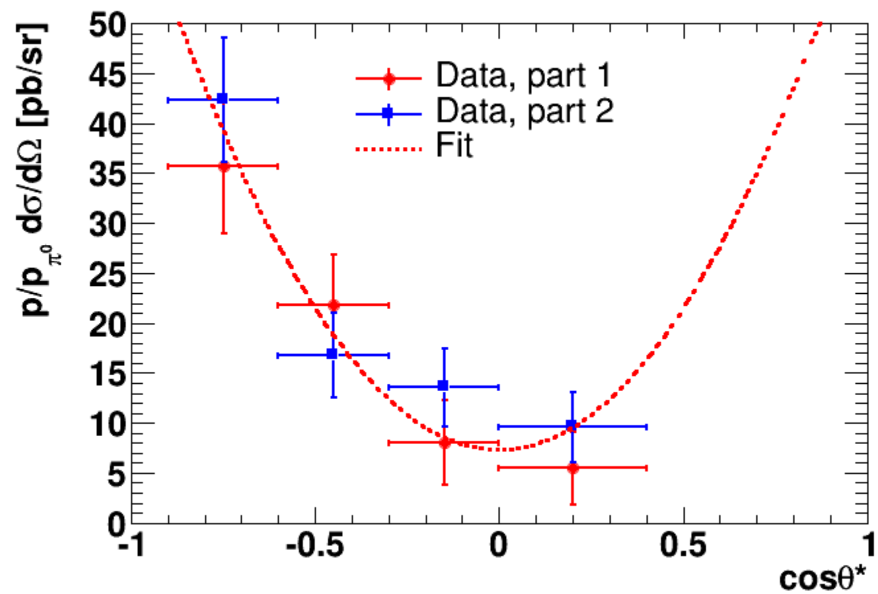
$2p^2_{\pi^0}\Re\{A_0^*A_2\}$ → ≈ 64 pb/sr

$\frac{2}{3}|C|^2p^2_{\pi^0}$ → ≈ 6.6 pb/sr

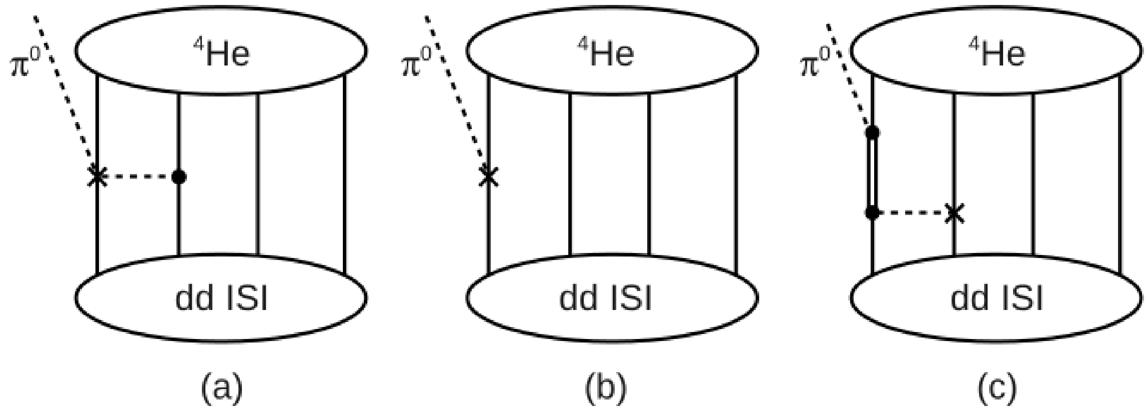
$$\Re\{A_0^*A_2\} = \left(1670 \pm 320(\text{stat.})^{+80}_{-430}(\text{syst.})\right)\ \text{pb}/\left(\text{sr}\cdot(\text{GeV}/c)^2\right)$$

$$|C|^2 = \left(520 \pm 290(\text{stat.})^{+50}_{-430}(\text{syst.})\right)\ \text{pb}/\left(\text{sr}\cdot(\text{GeV}/c)^2\right)$$

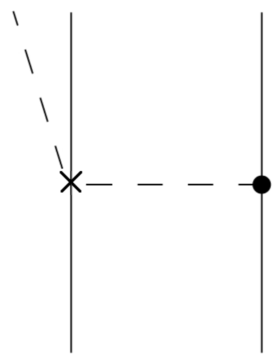




Leading diagrams of CSB reactions



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



- cross – occurrence of CSB
- dot – leading order charge invariant vertex
- dashed line – pions
- single solid line – nucleons
- double solid line – Δ

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