FORSCHUNGSZENTRUM JÜLICH

Investigations of the charge symmetry breaking reaction dd → ^{4}He π^0 with the WASA-at-COSY experiment

Maria Żurek
Institute of Nuclear Physics
Forschungszentrum Jülich, Germany

on behalf of the WASA-at-COSY collaboration

Physics Motivation

QCD at COSY energies

- Perturbative treatment not possible
- Effective field theory $\mapsto$ Chiral Perturbation Theory

Chiral Perturbation Theory

- Maps all symmetries of QCD
- Symmetry breaking: tests our understanding of QCD
- Extraction of basic QCD parameters

Isospin symmetry

Two sources of violation:

- Electromagnetic interaction
- Lightest quark masses difference $\mapsto$ Experimental window for probing quark mass ratios

Isospin Symmetry Breaking

Static ISB

- pion mass difference: $m(\pi^{\pm}) > m(\pi^{0})$ - e.m. effect
- nucleon mass difference: $m_n > m_p$ – e.m. and strong effect
  - $\Delta M_{em} = (-0.7 \pm 0.3)$ MeV
  - $\Delta M_{str} = (2.05 \pm 0.3)$ MeV

Dynamic ISB

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

  However:
  - no direct measurement of $\pi^0 N$
  - large e.m. corrections in $\pi^{\pm} N$
- πNN production vertex

Charge Symmetry Breaking

ISB – difficulties in access to quark masses:

- Dominated by pion mass difference
- Small signal compared to ISC contribution

↓

Charge Symmetry Breaking observables

- CS - symmetry under the operation of $P_{CS} = e^{-i\tau_2 \pi/2}$
- Symmetry under interchange of u ↔ d quarks
  - Δm_π does not contribute to CS breaking

→ Access to proton-neutron mass difference caused by u-d quark mass difference

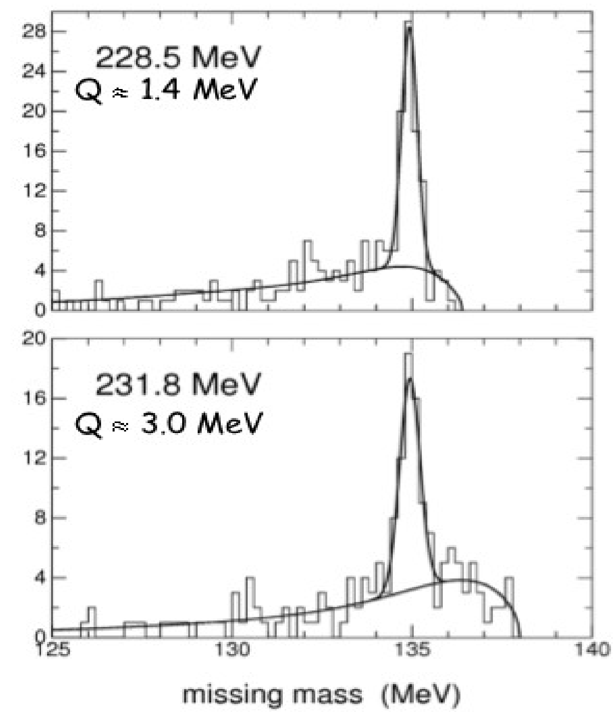
JÜLICH FORSCHUNGSZENTRUM

Charge Symmetry Breaking

Measurements of CSB observables

- **$np \rightarrow d\pi^0$ 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 $dd \rightarrow {}^4He\ \pi^0$**

CSC $\Rightarrow \sigma = 0$

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

Complementary to $np \rightarrow d\pi^0$:

- 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

Next Steps

Theory effort

Theory collaboration working on a consistent analysis of

- forward-backward asymmetry in $np \to d\pi^0$
  $\to \Delta M_{str} = (1.5 \pm 0.8\ (\text{exp.}) \pm 0.5\ (\text{th.}))$ MeV
- cross section at threshold of $dd \to {}^4He\pi^0$

Experimental input

- reaction dynamics of $dd \to {}^3Hen\pi^0$ (CSC)

In $dd \to {}^4He\pi^0$: A. Nogga et al., Phys. Lett. B 639 (2006) 465

- Wienberg term is suppressed (NNLO & NNNLO calculations needed)
- Once the parameters are fixed the *p*-waves can be predicted
  parameter free to LO and NLO

↓

- *p*-wave contribution in $dd \to {}^4He\pi^0$ at higher excess energies
  → NLO calculation → expected uncertainty 20% - 30%

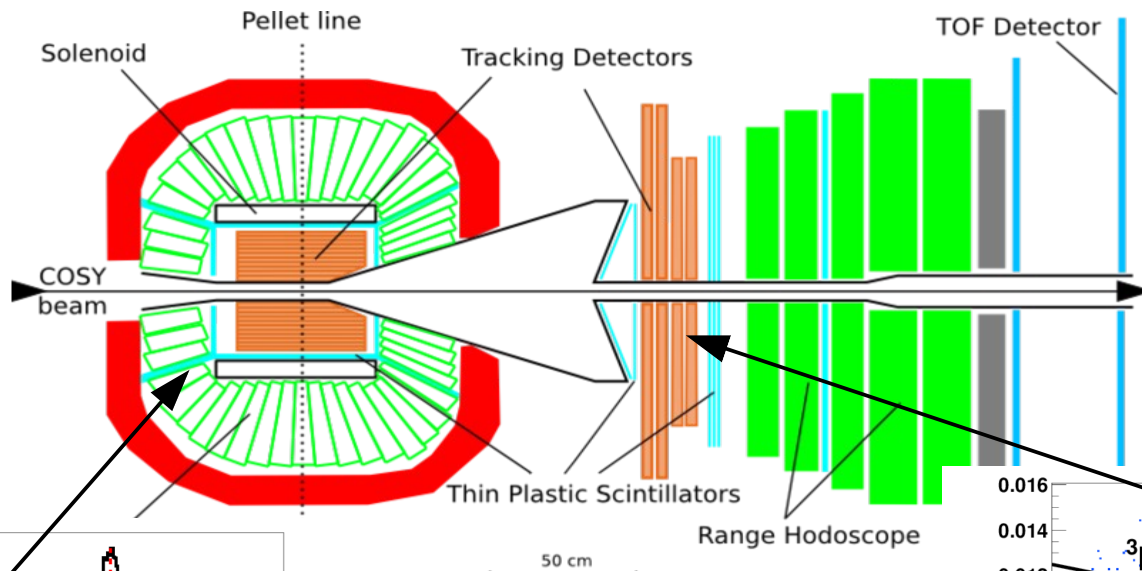
Mitglied der Helmholtz-Gemeinschaft

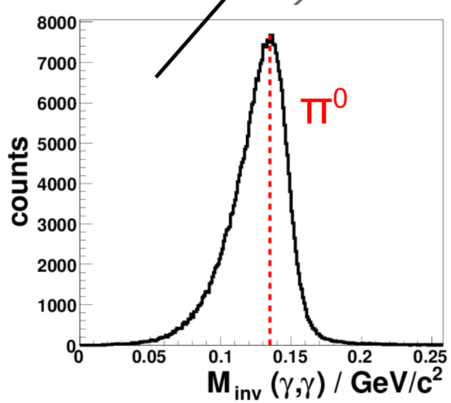
The reaction $dd \rightarrow {}^3\mathrm{He} n \pi^0$ at p_d = 1.2 GeV/c

Data Analysis

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

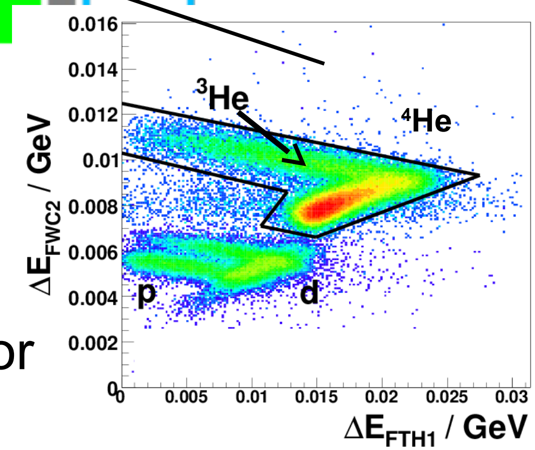
- clean selection of ^3He - π^0 coincidences
- final step: kinematic fit to ensure overall energy and momentum conservation
- 3.4 x 10^6 fully reconstructed events, nearly full coverage of Dalitz plots



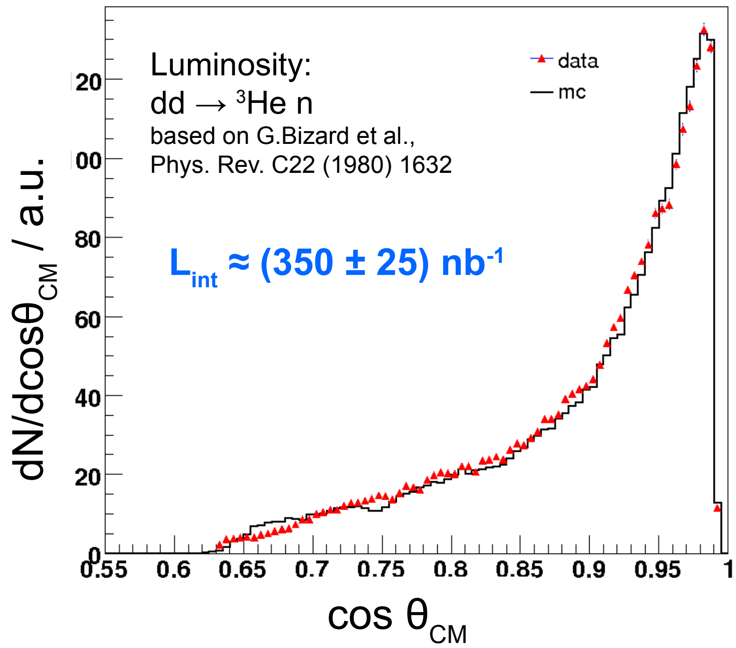


→ 2 coincident photons in calorimeter

→ ^{3}He in Forward Detector



Data Analysis



Further analysis

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

9 – 4 – 1 = 4 independent variables

M_{3Hen}, θ_p, θ_q, φ

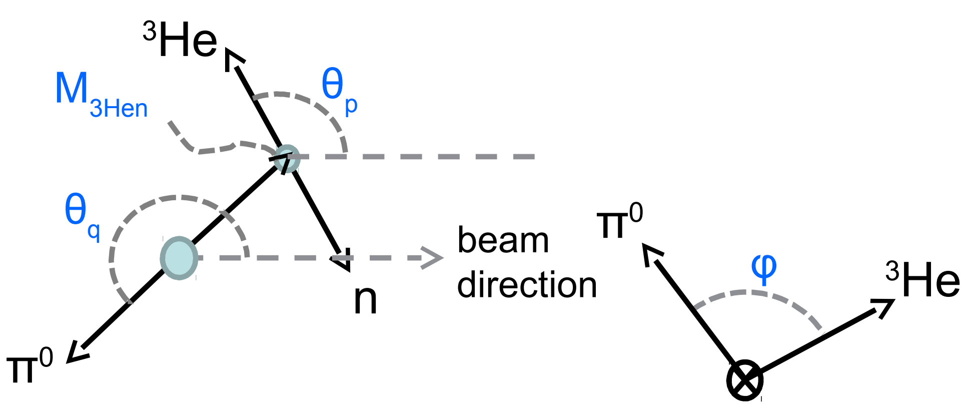
→ **two-fold model ansatz:**

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

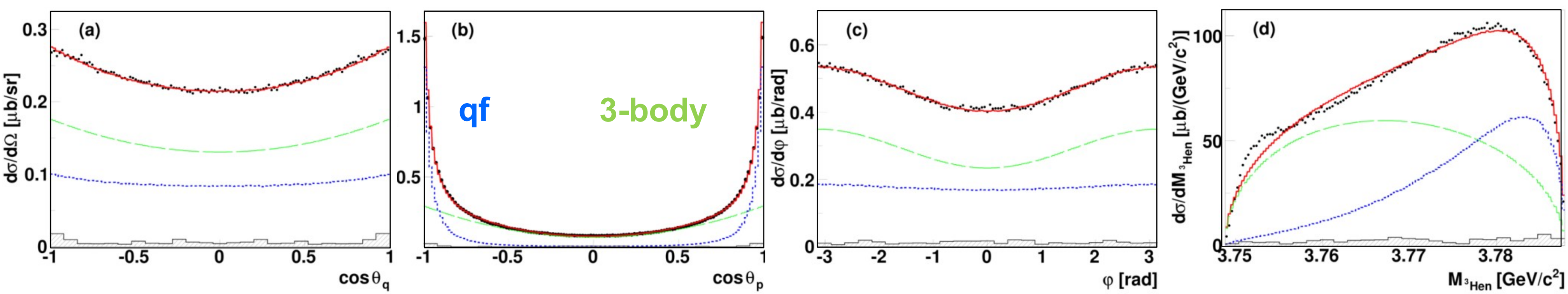
Luminosity determination:

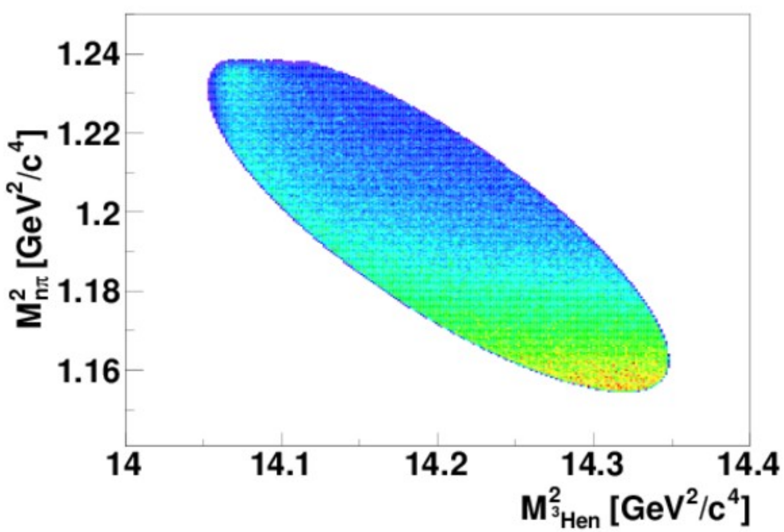
- two-body reaction $dd \to {}^3Hen$
  interpolated data from
  Bizard et al., PRC22 (1980) 1632:
  perfect match of expected angular distribution

Phys. Rev. C 88 (2013) 014004



Results





Phys. Rev. C 88 (2013) 014004

σ_{tot} = (2.89 ± 0.01_{stat} ± 0.06_{sys} ± 0.29_{norm}) μb

Model used for simulating
the dd → ^{3}He$n\pi^{0}$ background
in the dd → ^{4}Heπ^{0} measurement

The reaction $dd \rightarrow {}^4He\pi^0$ at p_d = 1.2 GeV/c

Experiment and data analysis

Beam time in summer 2008

- Dedicated two-weeks run on dd → $^4He\pi^0$

  Goal: σ_{total} @ Q=60 MeV

- Integrated luminosity **L = (4909 ± 348$_{sys}$) nb^{-1}**

  → Conditions tuned to maximum achievable luminosity

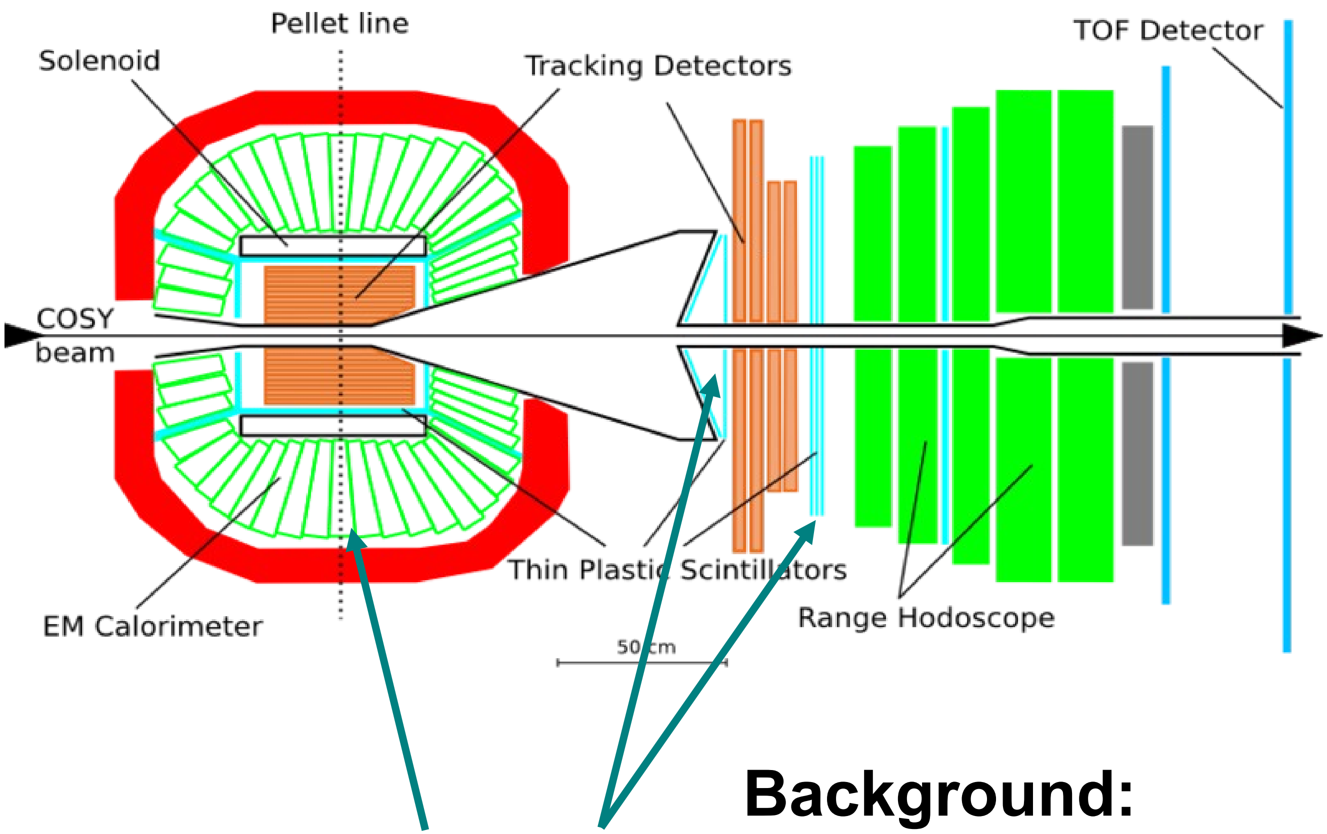
- Quite stable experimental conditions

  ↓

  $L_{avg} \approx 4*10^{30}$ cm^{-2}s^{-1} can serve as a realistic basis for future runs

- **Experimental setup:** standard WASA setup
- **Trigger:** high threshold in FD, ≥1 neutral in CD – threshold optimized to beam intensity of 2-3·10^{10} deuterons in flat top

Experiment and data analysis



$dd \rightarrow \pi^0 (\gamma\gamma)^4He$

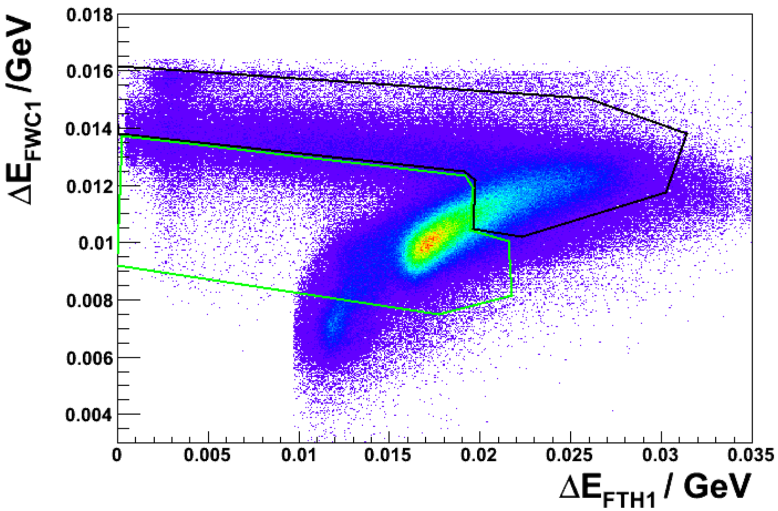
Background:

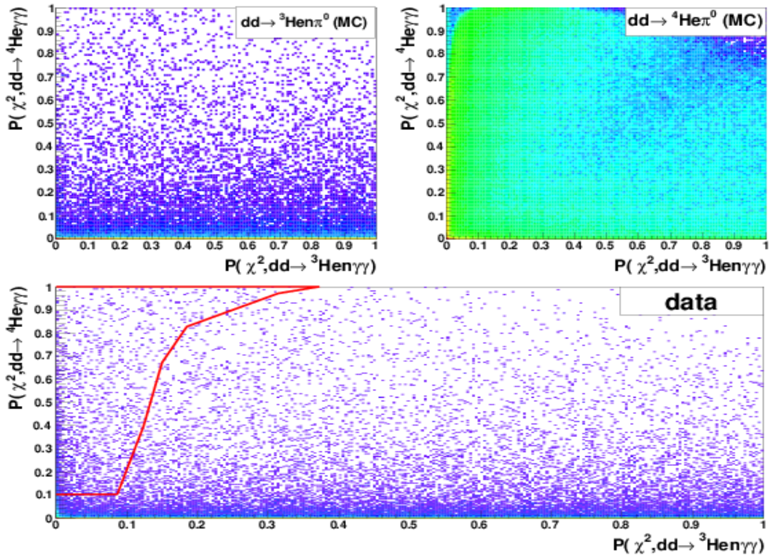
$dd \rightarrow (pnd, pnpn, tp) + \pi^0$

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

$dd \rightarrow {}^4He \gamma\gamma$ (physics background)

Experiment and data analysis

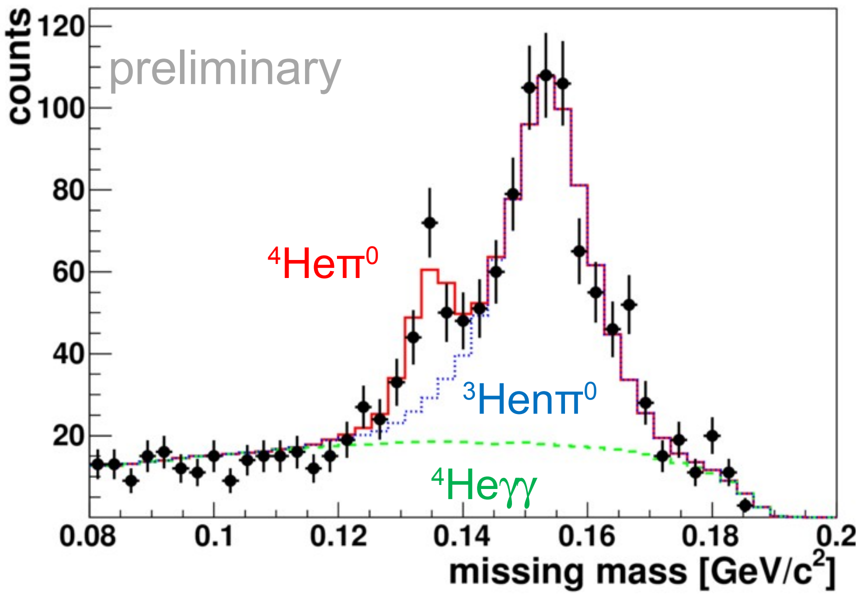




- Identification of ^{4}He: weak **cut on ΔE–ΔE** in FWC and FTH
- Overall **kinematic fit** used:
  - 2 hypotheses fitted:

    dd → ^{4}Heγγ and dd → ^{3}Henγγ (no constraint on 2γ invariant mass)
  - optimized cuts on cumulated probability distributions

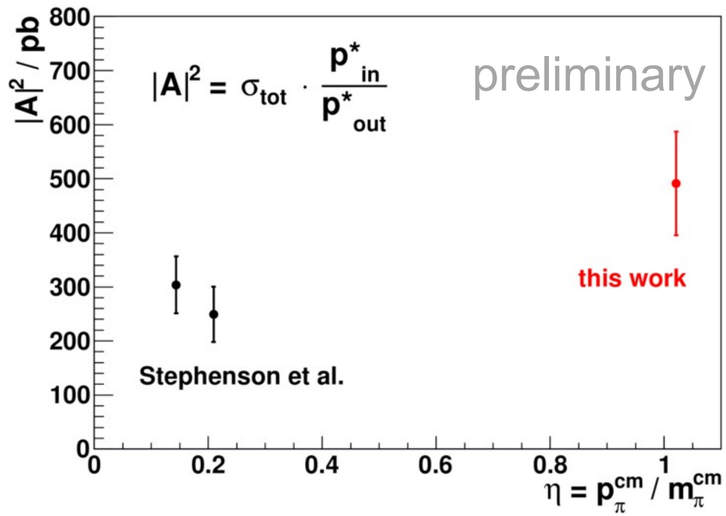
Results



Fitted with MC filtered distibution

- dd→^{4}Heγγ: homogeneous 3-body phase space distribution
- dd→^{3}Henπ^0: model from the previous analysis

Energy dependence:



Momentum dependence of the formation of the ^{4}He state – not included!

Preliminary total cross sections:

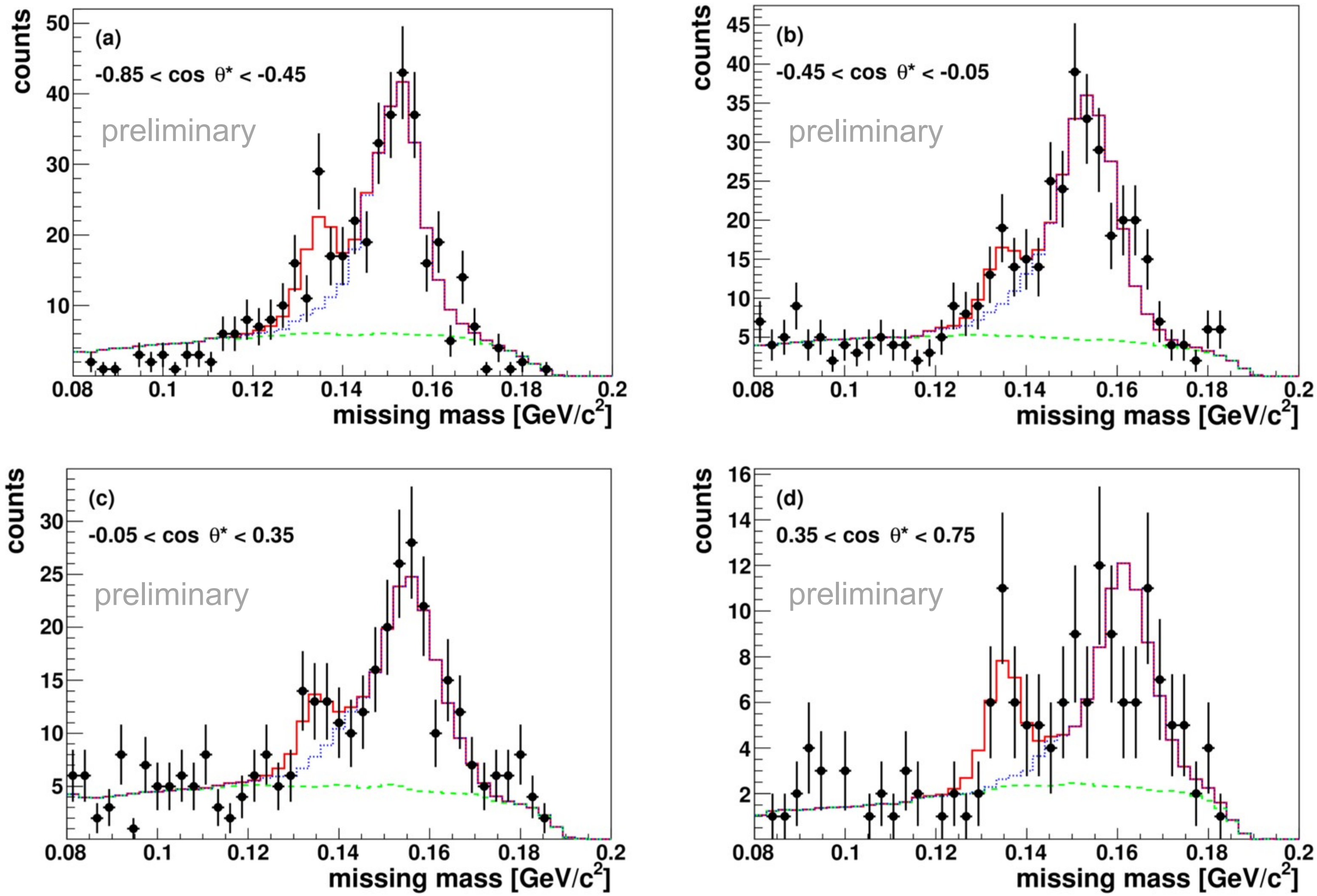
^{4}Heπ^0:

$\sigma = (118 \pm 18_{stat} \pm 13_{sys} \pm 8_{ext})$ pb

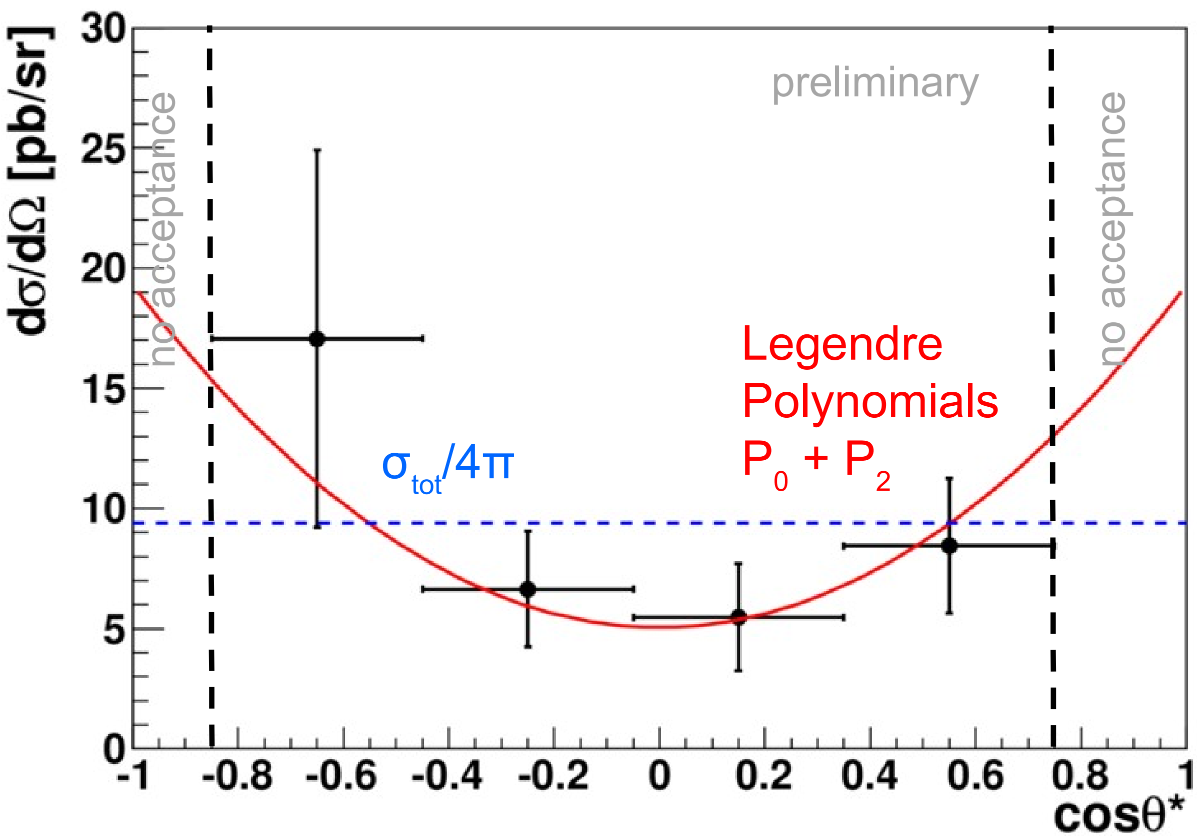
^{4}Heγγ:

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

Results – angular distribution



Results



Fit including *p*-wave:

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

→ consistent with *s*-wave only

However:
not decisive due to limited statistics

Measurement with modified detector setup

Challenges

- better ^{3}He - ^{4}He separation needed
- independent energy reconstruction

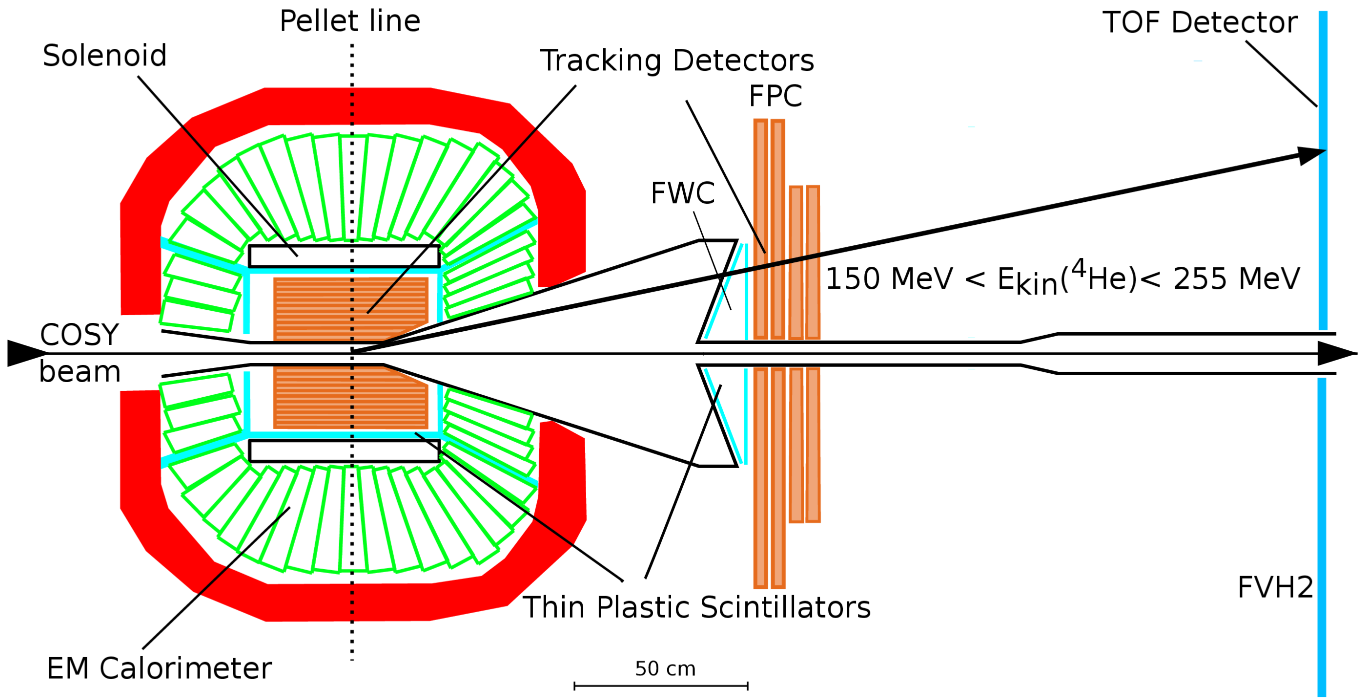
  (not influenced by quenching)

→ time-of-flight → remove most of FD up to FVH1

↓

8 week long experimental run with an optimized detector setup finished recently

Status



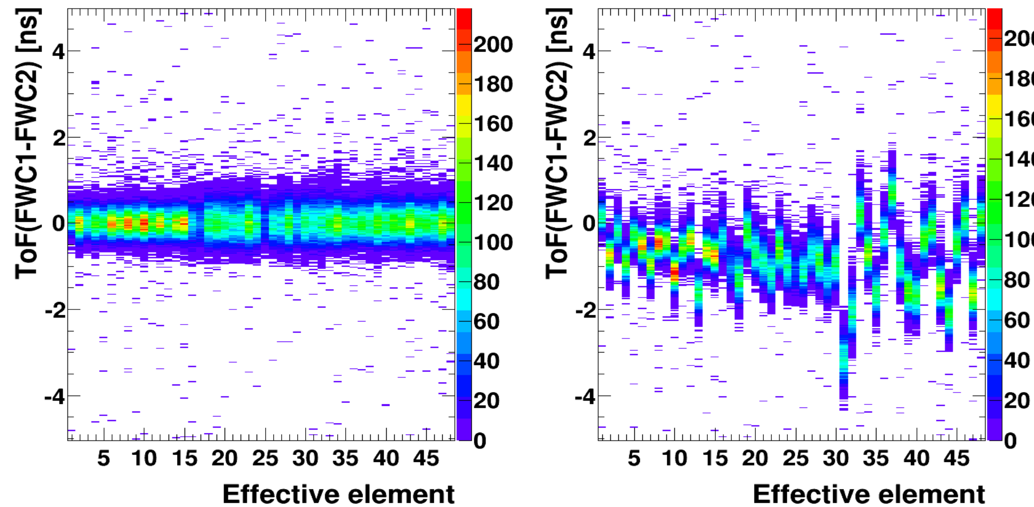
- FVH will take over the role of FTH
- For p_{beam}=1.2 GeV/c all ^{4}He which reach FVH2, stopped in this layer

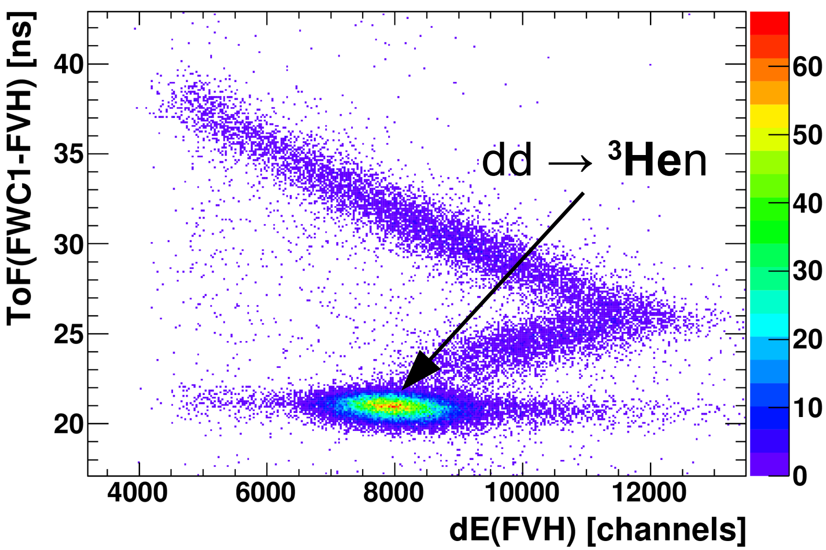
Time of Flight Calibration

FWC time readout alignment

→ ToF(FWC1-FWC2) for ^{3}He with θ = 5°-6° for every FWC1 and FWC2 element

→ Alignament corrections obtained from a set of equations for ToF(FWC1-FWC2) for every FWC element





MC: dd → ^{3}Hen time peak position for 6 θ-bins

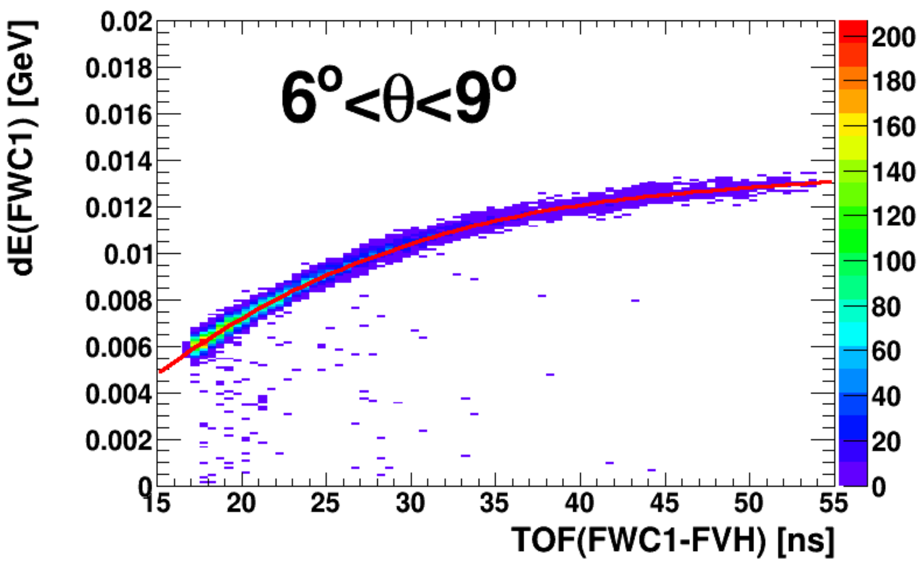
Data: shitf to value from MC simulation

1: calibration FVH element wise for 6 θ-bins
→ FVH time readout alignment

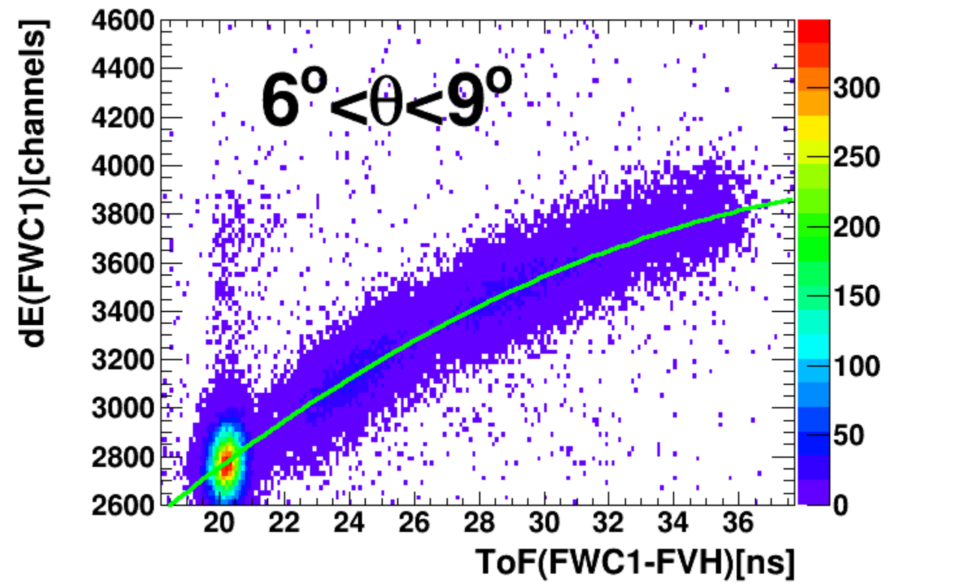
2: calibration FWC element wise for 18 θ-bins
→ θ-dependency correction

Energy losses calibration in FWC

MC simulation: dE [GeV] vs ToF [ns] for ^{3}He in Forward Detector → $dE_{GeV}(ToF)$



Data: dE [channels] vs ToF [ns] → $dE_{ch}(ToF)$

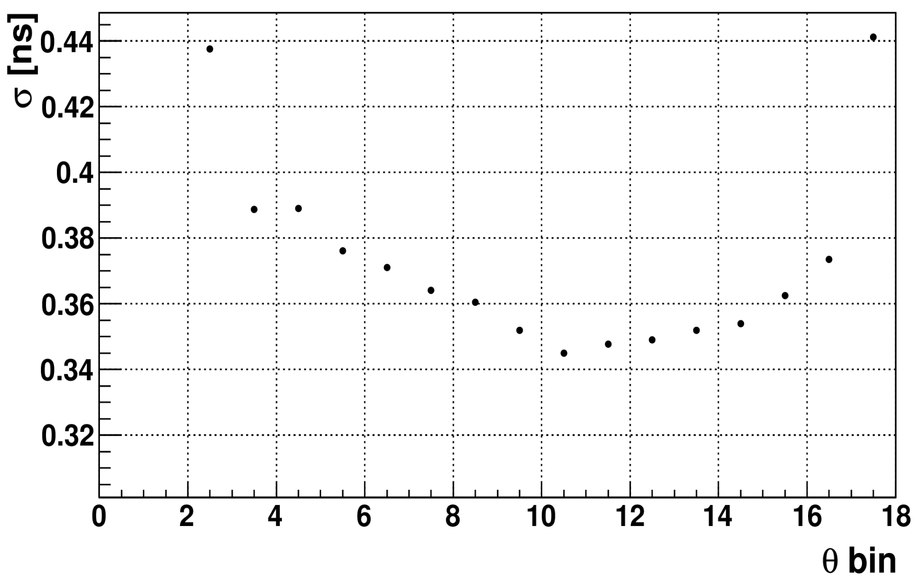


↓

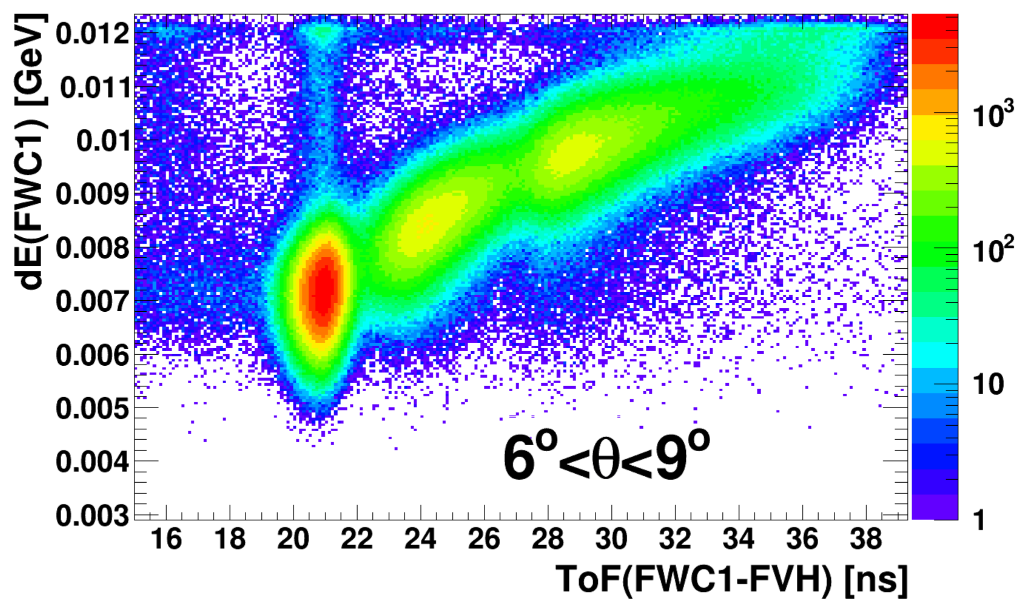
$$dE_{GeV}(ToF(dE_{ch})) \rightarrow dE_{GeV}(dE_{ch})$$

Status of Calibration

ToF calibration



Energy losses calibration



Summary

Charge Symmetry Breaking used to access quark mass effects

Theoretical tool: Chiral Perturbation Theory

Status

high statistics data on $dd \rightarrow {}^3\mathrm{He}n\pi^0$:

results on total and differential cross sections

data modeled with quasi-free mechanism + partial wave decomposition

preliminary results on $dd \rightarrow {}^4\mathrm{He}\pi^0$ (2 weeks run):

$\sigma_{tot} = (118 \pm 18_{stat} \pm 10_{sys} \pm 8_{ext})$ pb at p = 1.2 GeV/c (Q = 60 MeV)

data consistent with s-wave pion production

background well reproduced by simulations

Outlook

8 weeks production run with an optimized detector setup finished recently