



Charge symmetry breaking in the $dd \rightarrow {}^4\text{He}\pi^0$ reaction with WASA-at-COSY

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Isospin Symmetry

Isospin symmetry - Two sources of violation:

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

Nucleon mass difference: $m_n > m_p$, static isospin symmetry breaking

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

-0.7 ± 0.3 MeV (from QED calculations)

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

Access to ΔM_{str}

Effective field theory: dynamic ISB

- 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 $\pi^\pm N$
- πNN production vertex

Lattice QCD

ΔM_{pn} [MeV]	ΔM_{str} [MeV]	ΔM_{em} [MeV]
1.51(16)(23)	2.52(17)(24)	-1.00(07)(14)

Sz. Borsanyi et al., Science 27 March 2015
Ab initio calculation of the neutron-proton mass difference

Charge Symmetry Breaking

Isospin Symmetry Breaking

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



Charge Symmetry Breaking

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

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

$$\Delta M_{str} = (1.5 \pm 0.8 \text{ (exp.)} \pm 0.5 \text{ (th.)}) \text{ MeV (LO)} [2]$$

- $dd \rightarrow {}^4\text{He } \pi^0$

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

σ_{total} measured at threshold [3]

Result consistent
with s-wave production

XPT

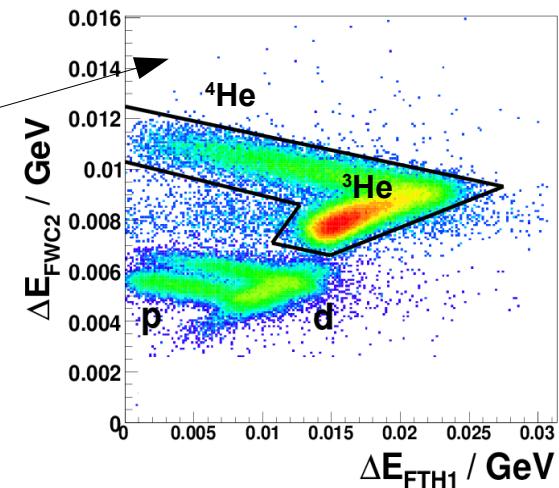
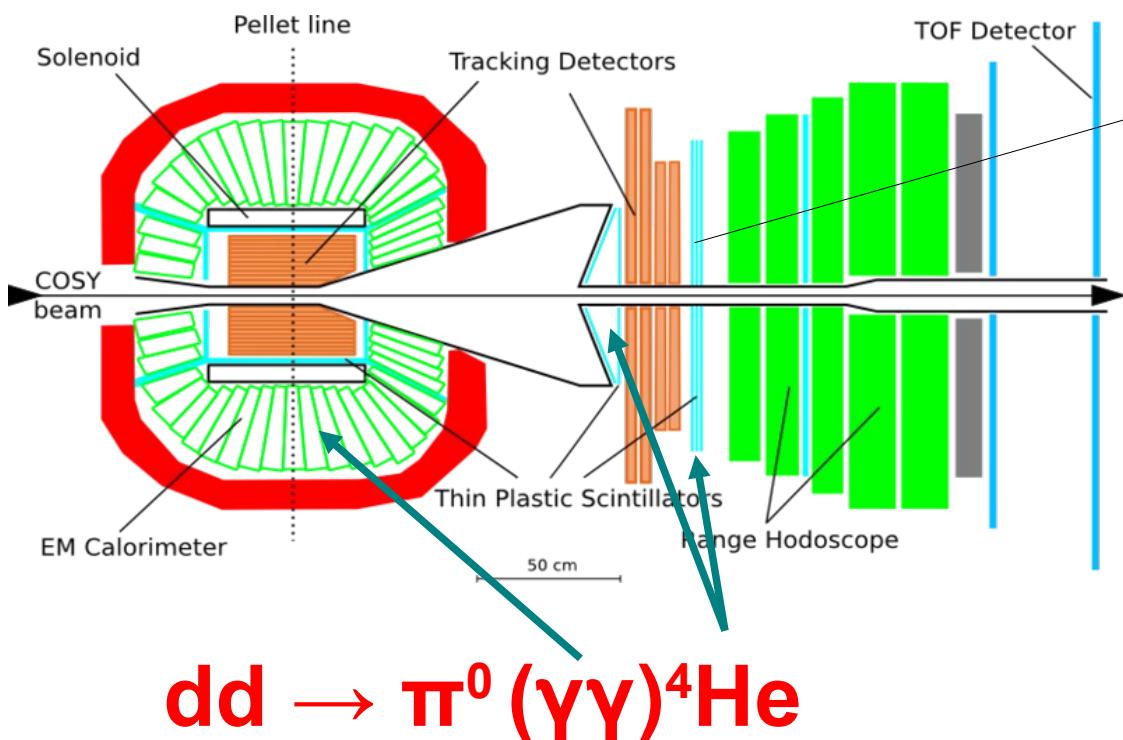
p -wave contribution in $dd \rightarrow {}^4\text{He}\pi^0$
at higher excess energies needed

[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

WASA-at-COSY experiment



Background:

- $dd \rightarrow (pnd, pn\bar{n}, tp) + \pi^0$
- $dd \rightarrow {}^3\text{He} n \pi^0$ (3·10⁵ higher)
- $dd \rightarrow {}^4\text{He} \gamma\gamma$ (physics background)

First beam time in 2008 (2 weeks) Goal: σ_{total} @ Q=60 MeV

Analysis

${}^4\text{He}$ - ${}^3\text{He}$ separation: overall **kinematic fit**

- 2 hypotheses fitted: $dd \rightarrow {}^4\text{He} \gamma\gamma$ and $dd \rightarrow {}^3\text{He} n \gamma\gamma$ (no constrain on π^0)
- Optimized cuts on cumulated probability distribution

dd \rightarrow ^3He n π^0 reaction measurement

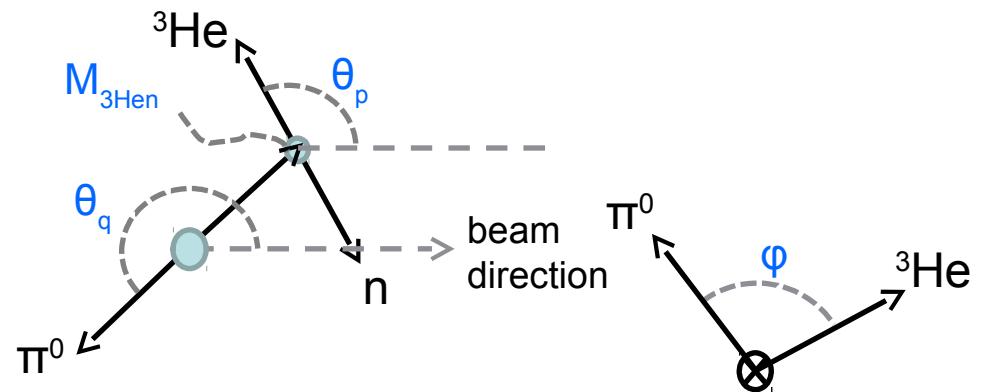
Two-fold model ansatz:

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

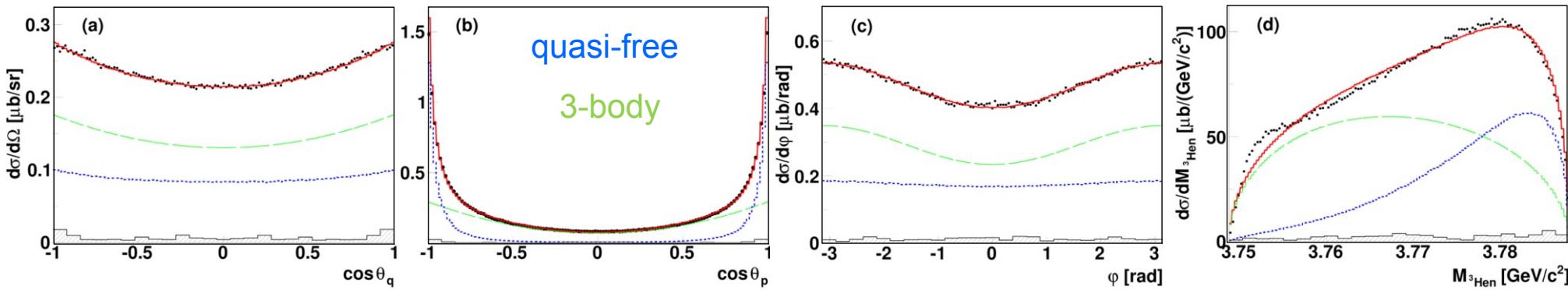
} full model
incoherent sum

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

Model used for **simulating**
the dd \rightarrow ^3He n π^0 background
and for **normalization**



4 independent variables $M_{^3\text{He}n}$, θ_p , θ_q , φ

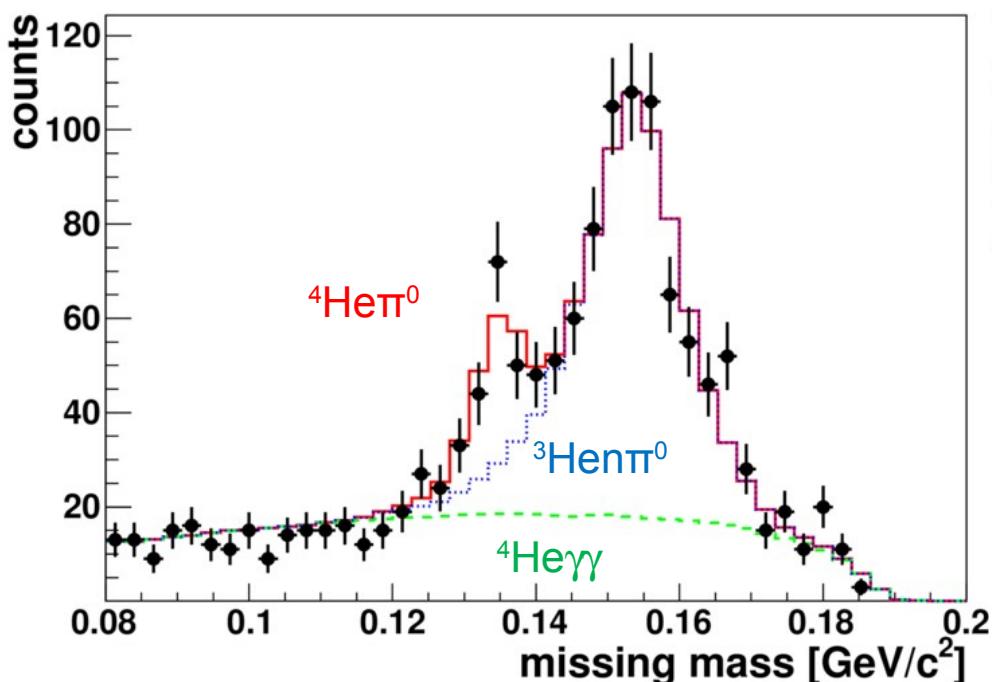


Phys. Rev. C 88 (2013) 014004

dd \rightarrow $^4\text{He}\pi^0$ reaction measurement

Results:

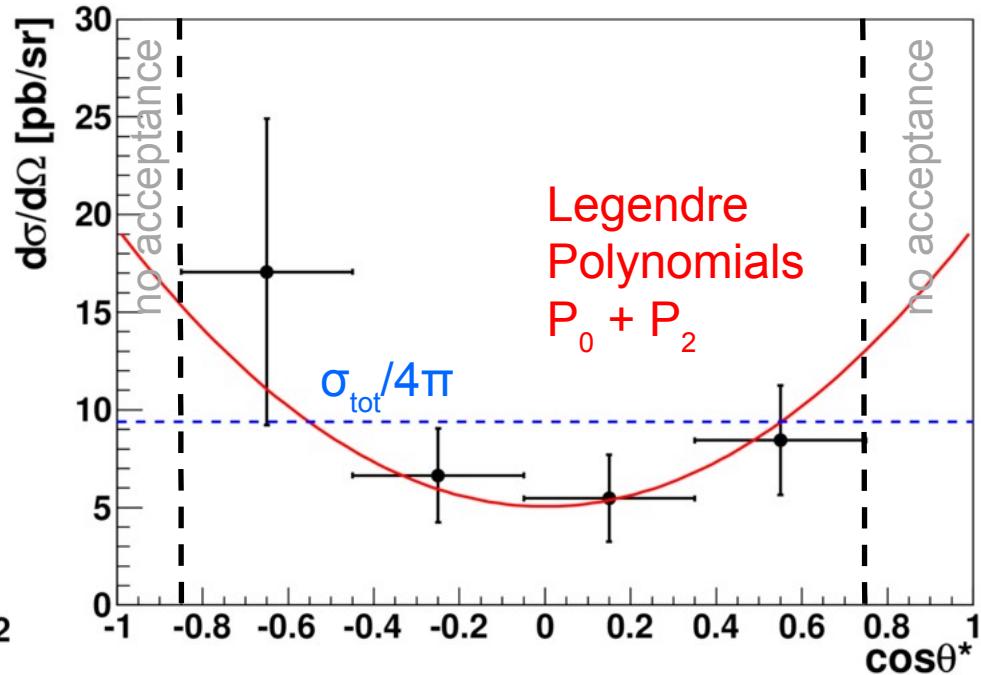
Phys. Lett. B 739 (2014) 44–49



Total cross section:

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

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



Fit including p -wave:

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

consistent with s-wave only

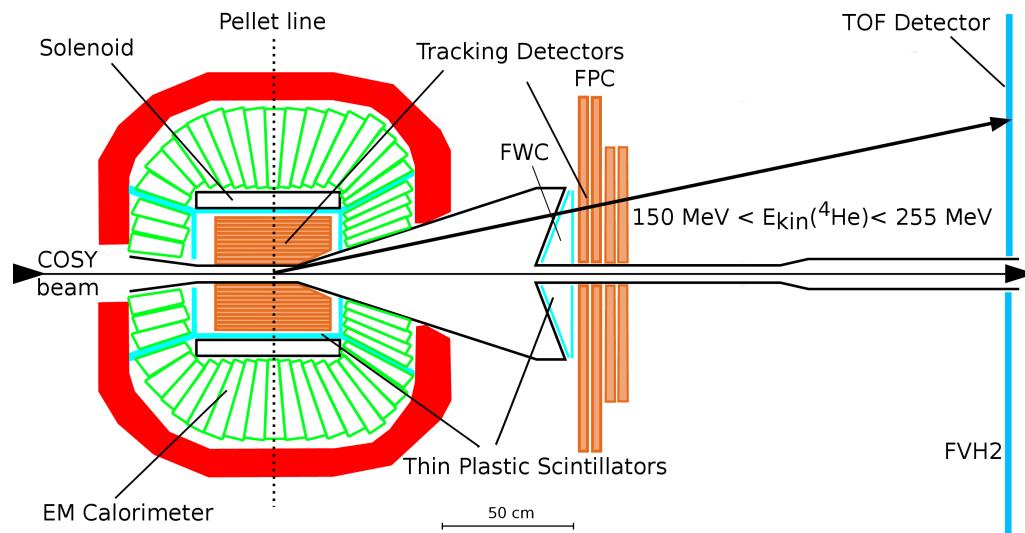
However: not decisive due to limited statistics

dd \rightarrow $^4\text{He}\pi^0$ reaction measurement

Challenges:

- Better ^4He - ^3He separation needed
- Better energy resolution

Solution:



Time-of-Flight (ToF)

Remove most of Forward Detector up to Forward Veto Hodoscope

- Particle identification method based on ToF- ΔE
- E_{kin} reconstruction using ToF

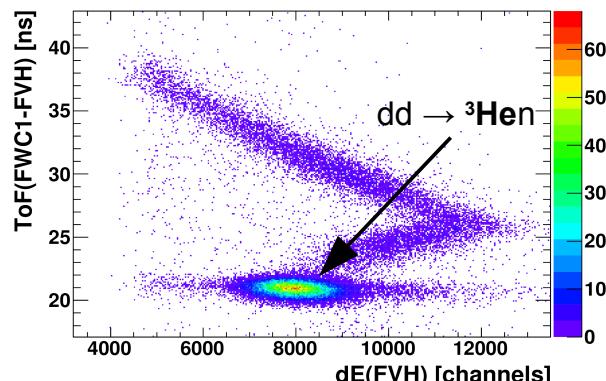
8 week long experimental run with an optimized detector setup

Goal: σ_{total} and angular distribution at Q=60 MeV

Detector Calibration

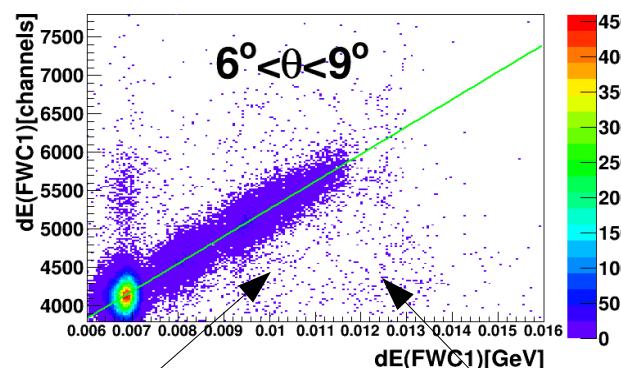
ToF Calibration

- $dd \rightarrow {}^3\text{He}n$ time peak position used
- Calibrate the data to the MC values for every detector element as a function of θ



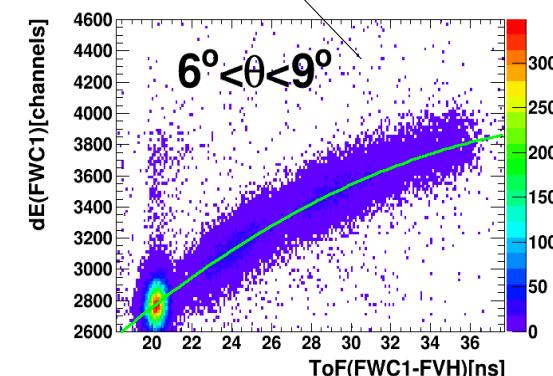
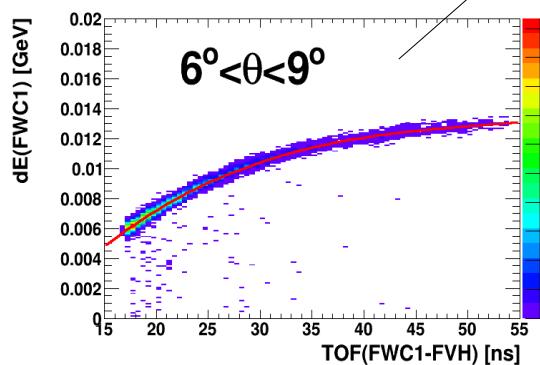
dE Calibration

- Based on ToF
 - **MC:** dE [GeV] vs ToF [ns] $\rightarrow dE_{\text{GeV}}(\text{ToF})$
 - **Data:** dE [channels] vs ToF [ns] $\rightarrow dE_{\text{ch}}(\text{ToF})$
- Run-wise correction, θ -dependency correction

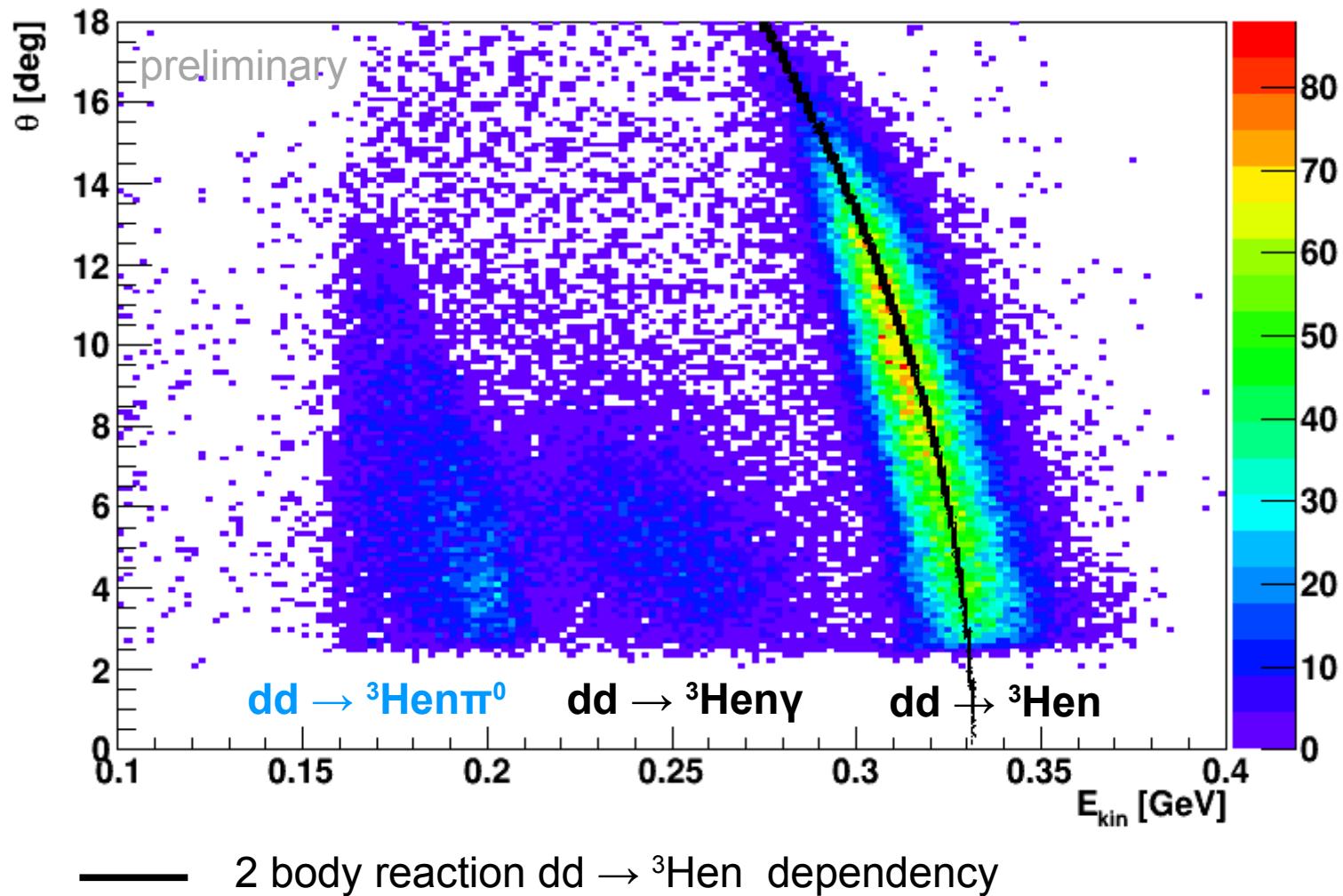


Kinetic Energy Reconstruction

- Based on $E_{\text{kin}}(\text{ToF}_1)$, $E_{\text{kin}}(\text{ToF}_2)$, $E_{\text{kin}}(dE_{\text{FWC1}})$, $E_{\text{kin}}(dE_{\text{FWC2}})$
- χ^2 fit used to obtain the best matching E_{kin}

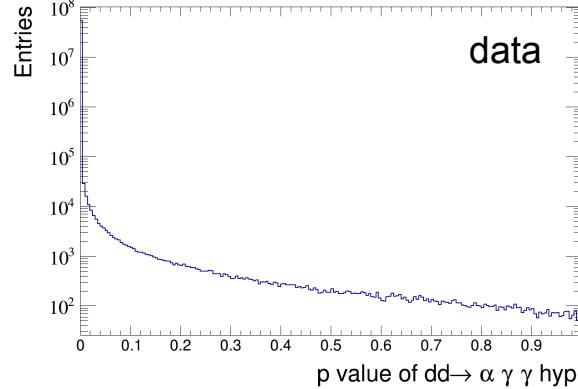
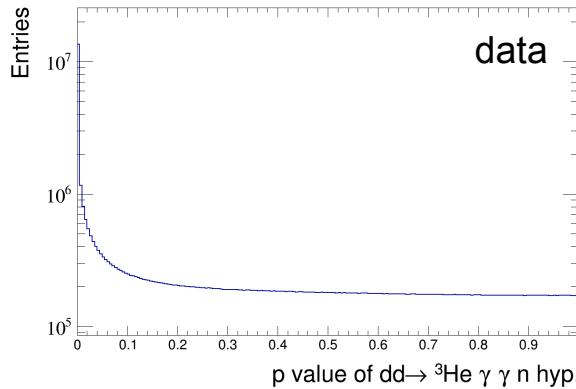


Kinematic distribution



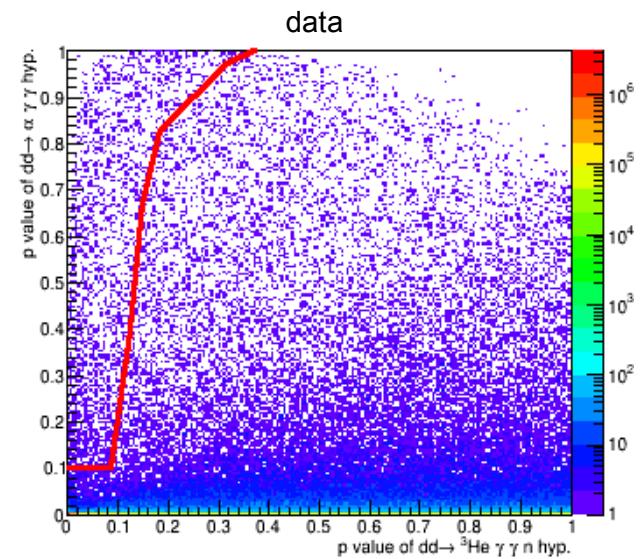
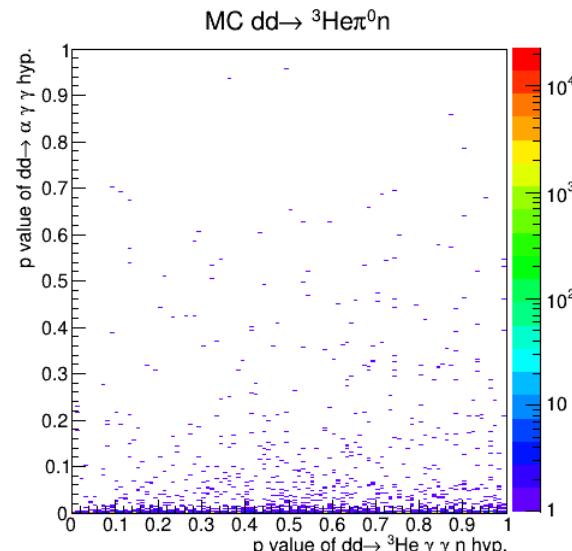
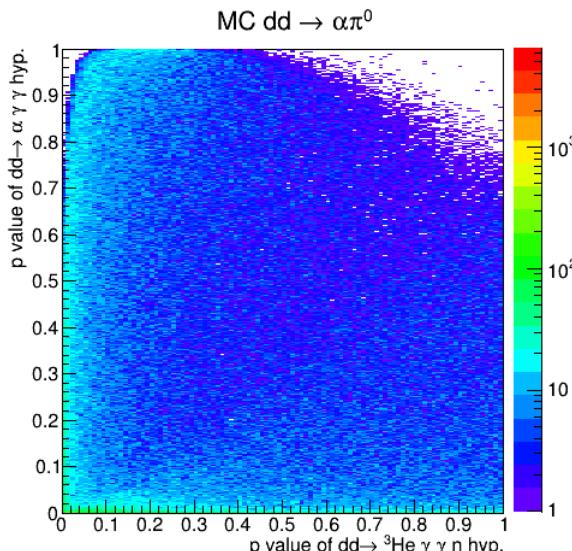
Kinematic fit

- 2 hypotheses fitted: $\text{dd} \rightarrow {}^4\text{He}\gamma\gamma$ and $\text{dd} \rightarrow {}^3\text{He}\gamma\gamma$ (no constrain on π^0)

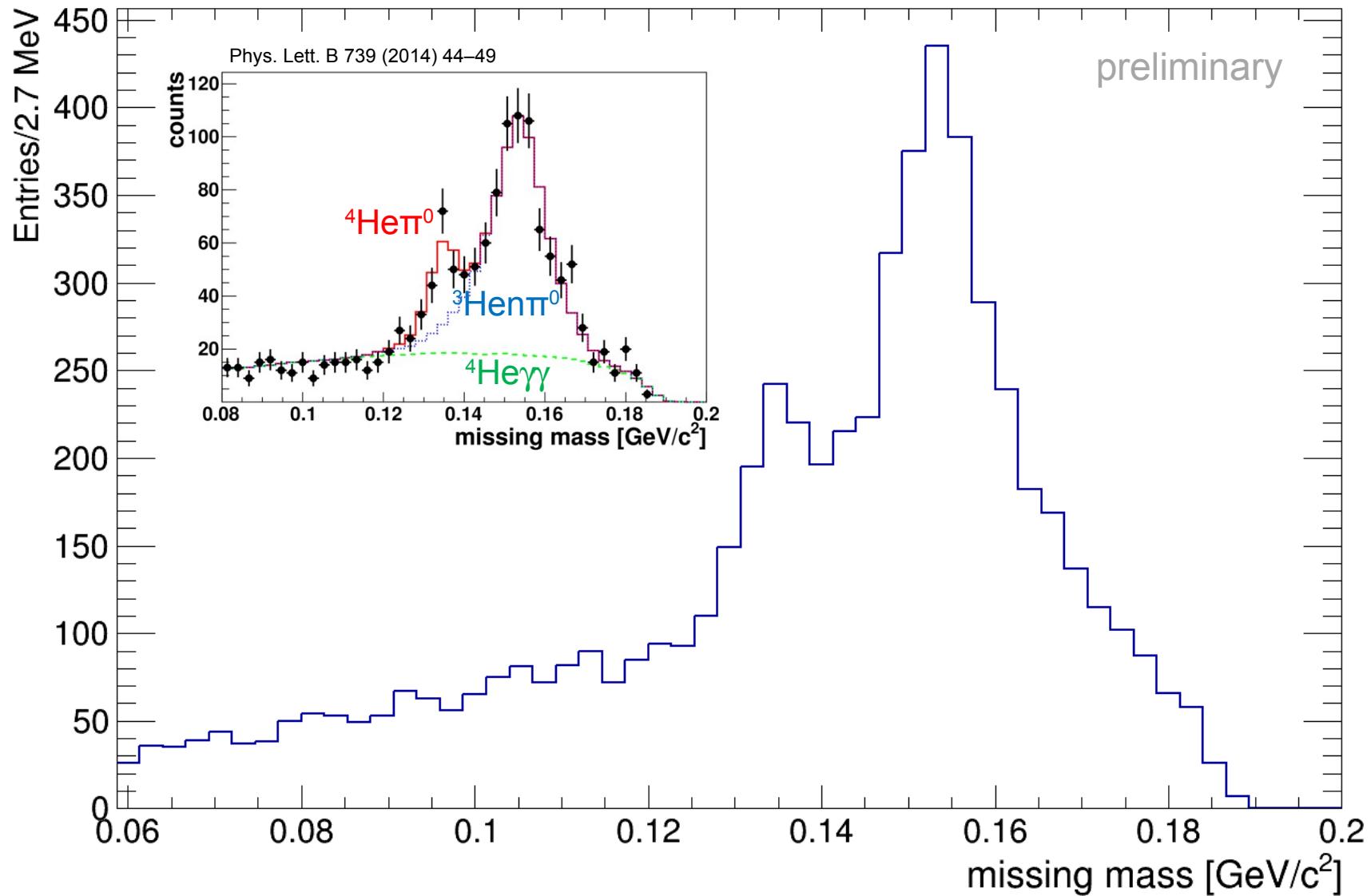


→ χ^2 fit with energy-momentum conservation constrain
→ on the plots: cumulated probability distribution for 2 fitted hypotheses

- 2D cut on cumulated probability distribution

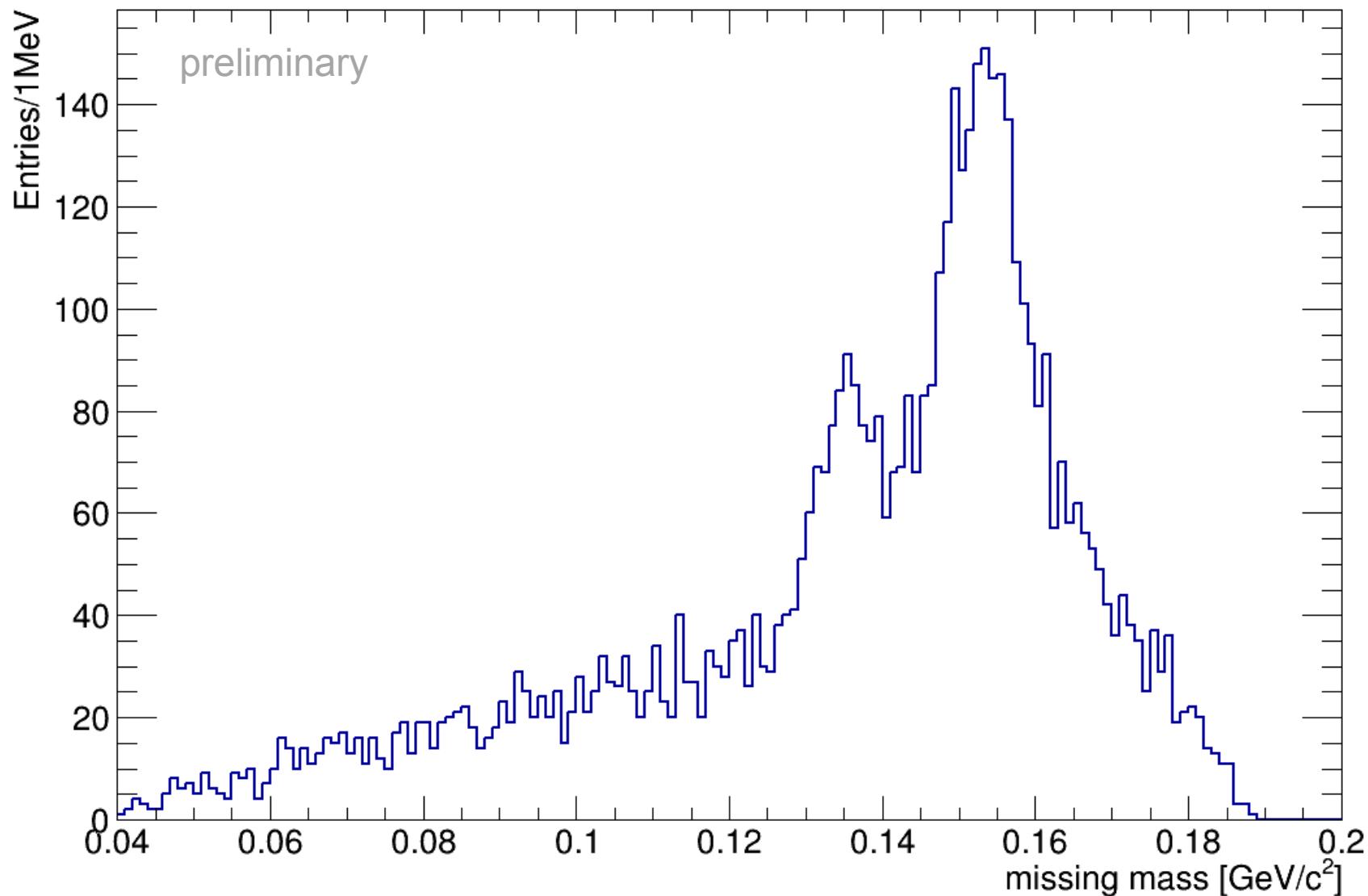


Invariant mass distribution



- Further optimization of 2D cut on cumulated probability distribution needed
- Introduction of ToF based particle identification method planned

Invariant mass distribution



Summary

- Charge Symmetry Breaking used to access quark mass effects
Theoretical tool: Chiral Perturbation Theory
- Results of the $dd \rightarrow {}^3He\pi^0$ reaction measurement published
- First results of the $dd \rightarrow {}^4He\pi^0$ reaction measurement published
 - Total cross section obtained
 - Angular distribution not decisive to identify *p*-wave contribution
- 8 weeks production run with an optimized detector setup performed.
Data analysis in progress

Backup

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
 - $\Delta M_{\text{em}} = (-0.7 \pm 0.3) \text{ MeV}$
 - $\Delta M_{\text{str}} = (2.05 \pm 0.3) \text{ MeV}$

Dynamic ISB

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

However:

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

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)

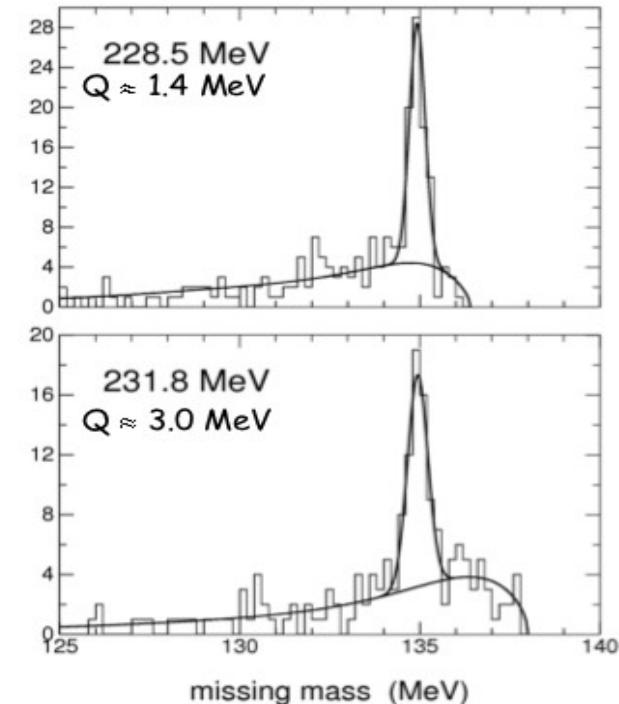
- Pion production in $dd \rightarrow {}^4\text{He} \pi^0$

CSC $\Rightarrow \sigma = 0$

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

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)

$$\sigma_{\text{tot}} (Q=1.4 \text{ MeV}) = 12.7 \pm 2.2 \text{ pb}$$

$$\sigma_{\text{tot}} (Q=3.0 \text{ MeV}) = 15.1 \pm 3.1 \text{ pb}$$

Result consistent with s-wave production

Next Steps

Theory effort

Theory collaboration working on a consistent analysis of

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

Experimental input

- reaction dynamics of $dd \rightarrow {}^3\text{He}\pi^0$ (CSC)

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



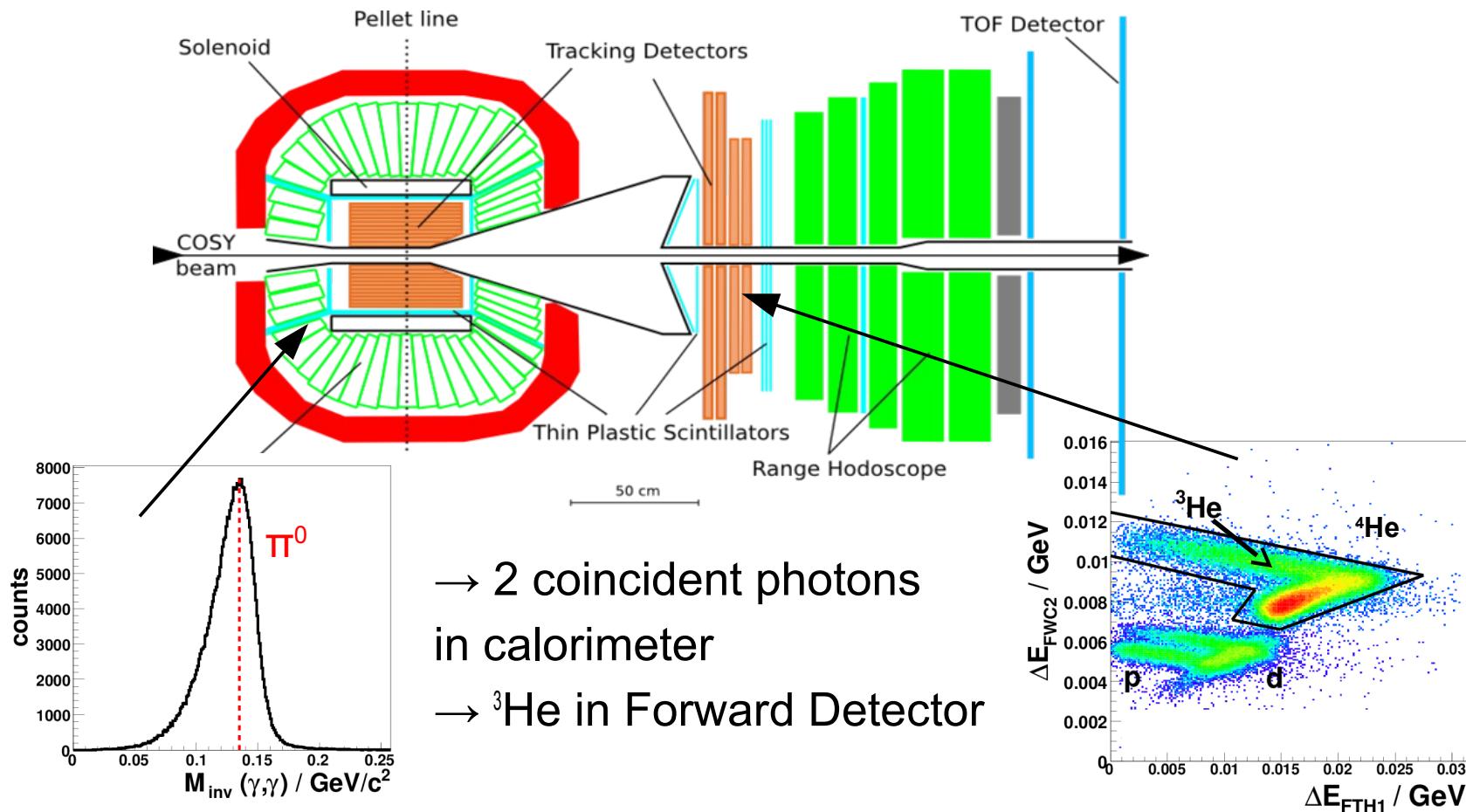
- p -wave contribution in $dd \rightarrow {}^4\text{He}\pi^0$ at higher excess energies
 \rightarrow NLO calculation \rightarrow expected uncertainty 20% - 30%

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

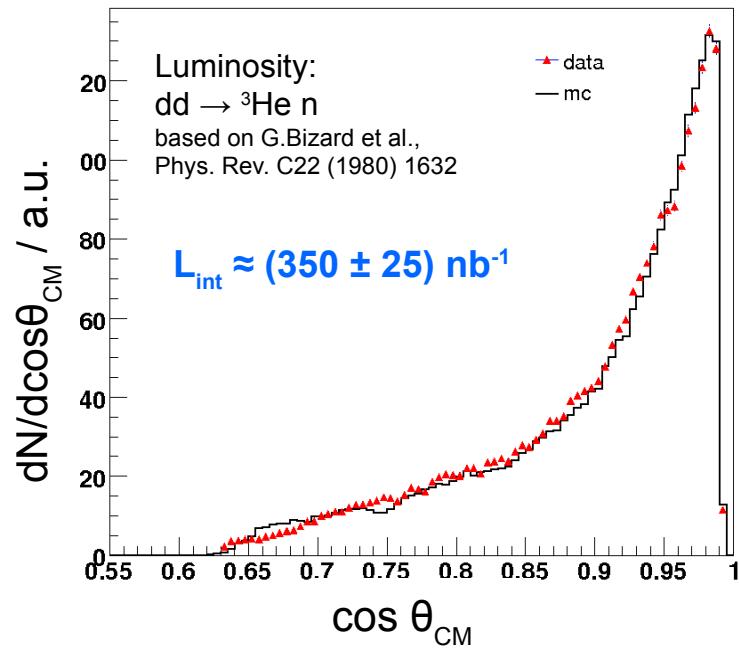
Data Analysis

Benchmark for ${}^4\text{He}\pi^0$:

- clean selection of ${}^3\text{He} - \pi^0$ 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



Data Analysis



Luminosity determination:

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

Phys. Rev. C 88 (2013) 014004

Further analysis

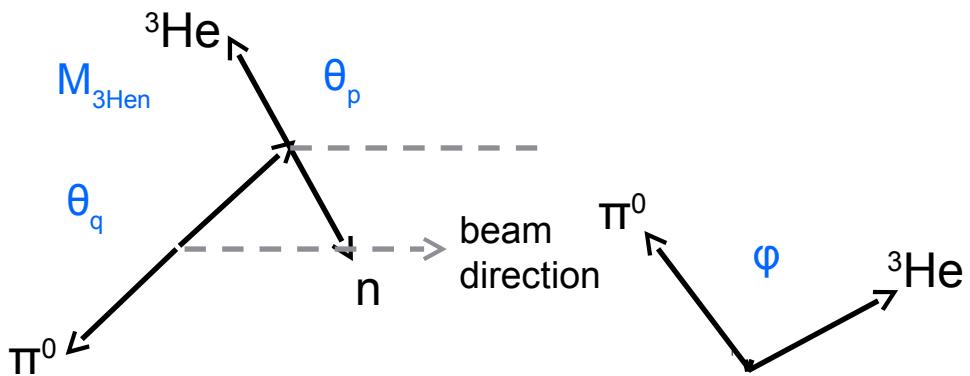
→ **3-body final state, unpolarized:**

$9 - 4 - 1 = 4$ independent variables

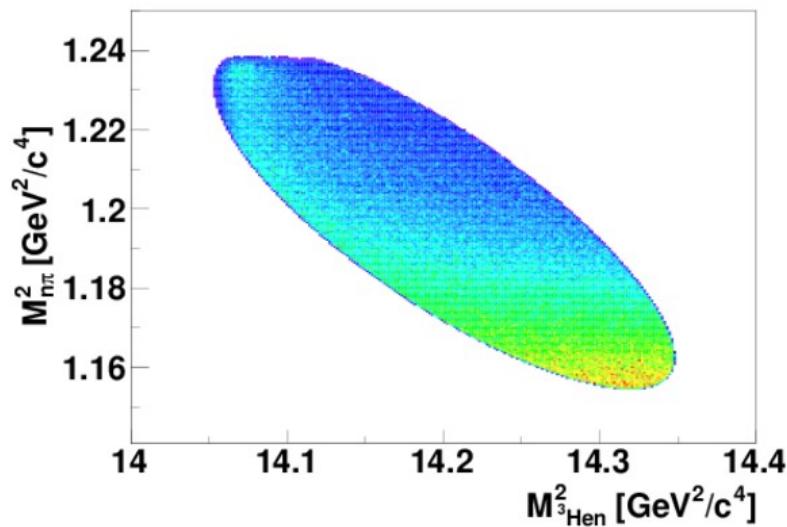
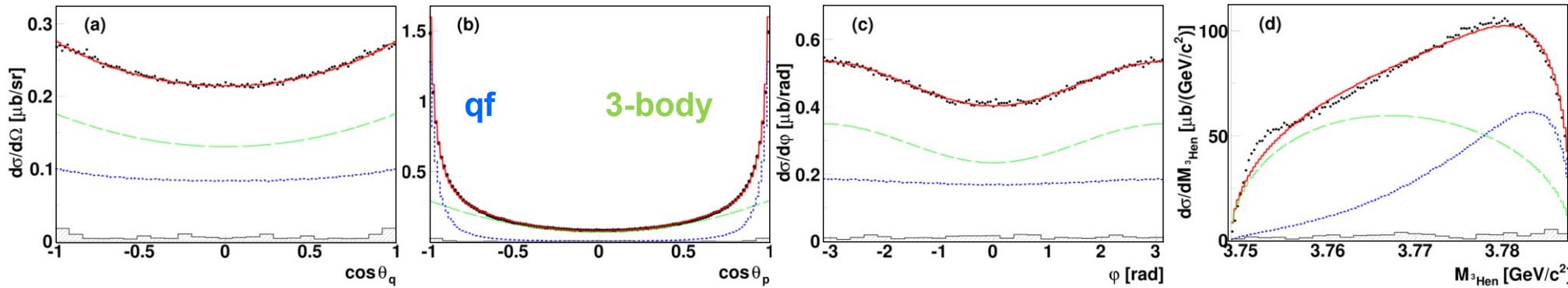
$M_{{}^3\text{He}n}$, θ_p , θ_q , φ

→ **two-fold model ansatz:**

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



Results



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

Model used for simulating
the $\text{dd} \rightarrow {}^3\text{He}\pi^0$ background
in the $\text{dd} \rightarrow {}^4\text{He}\pi^0$ measurement

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The reaction $dd \rightarrow {}^4\text{He}\pi^0$

at $p_d = 1.2 \text{ GeV}/c$

Experiment and data analysis

Beam time in summer 2008

- Dedicated two-weeks run on dd → ${}^4\text{He}\pi^0$
Goal: σ_{total} @ Q=60 MeV

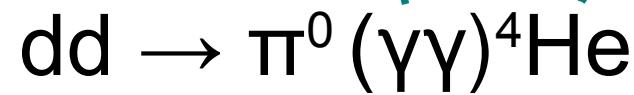
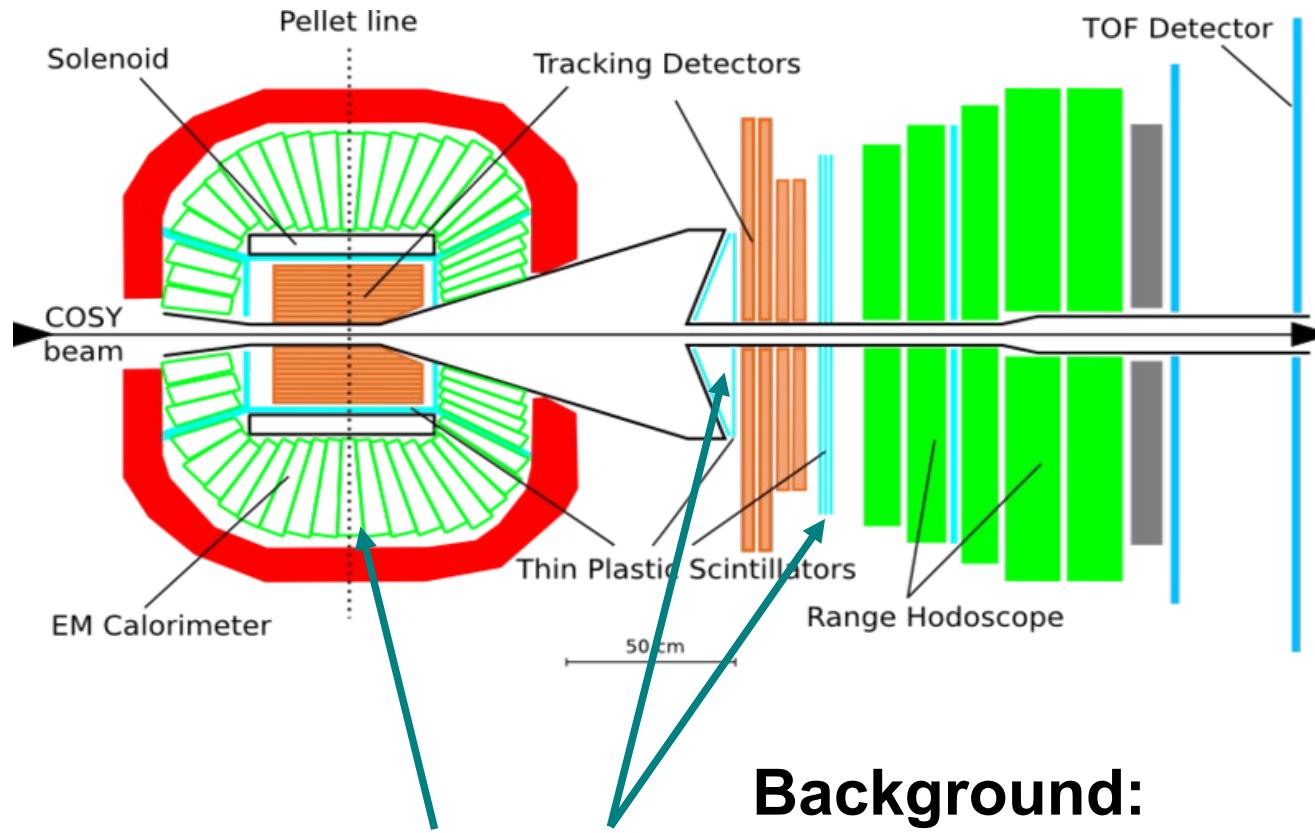
- Integrated luminosity $L = (4909 \pm 348_{\text{sys}}) \text{ nb}^{-1}$
→ Conditions tuned to maximum achievable luminosity
- Quite stable experimental conditions



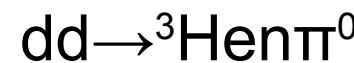
$L_{\text{avg}} \approx 4 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ can serve as a realistic basis for future runs

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

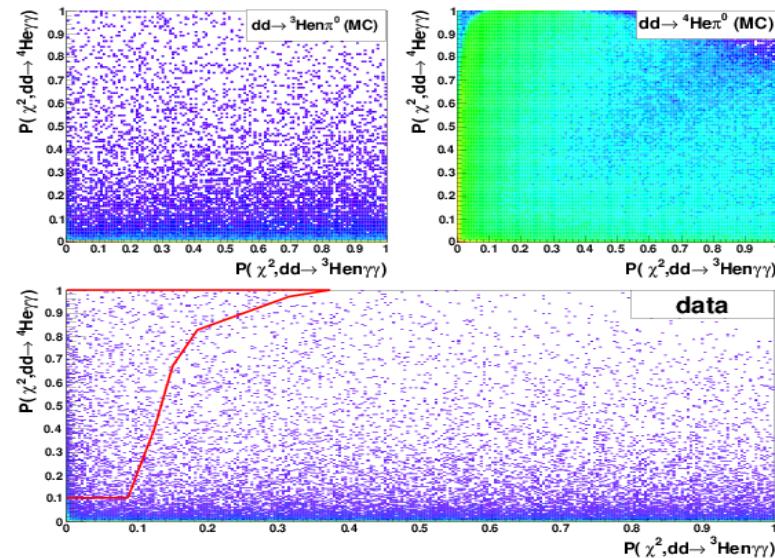
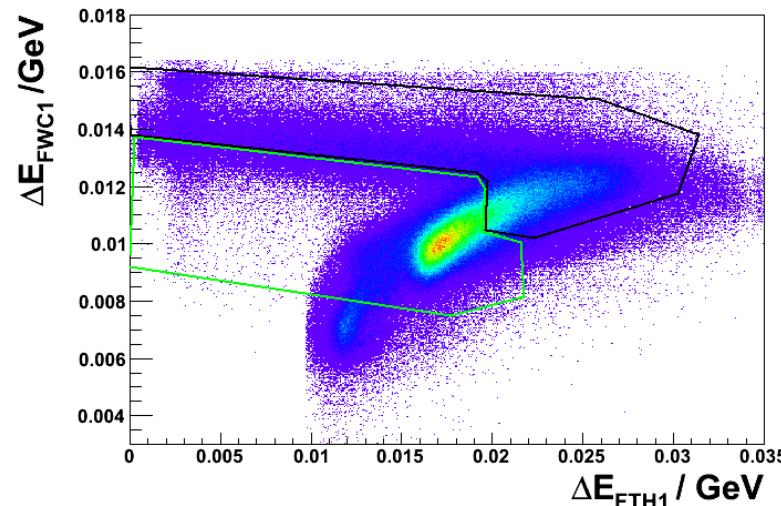
Experiment and data analysis



Background:

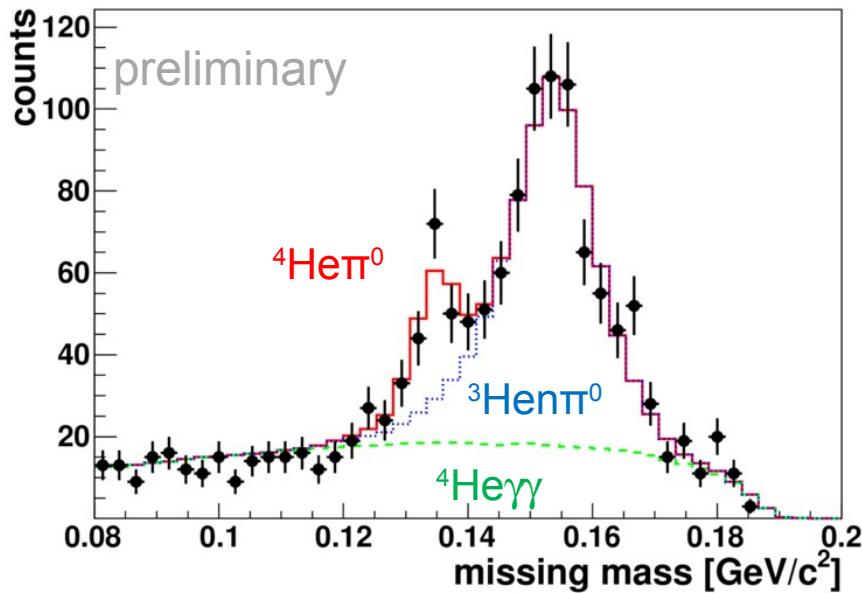


Experiment and data analysis



- Identification of ${}^4\text{He}$: weak **cut on $\Delta E - \Delta E$** in FWC and FTH
- Overall **kinematic fit** used:
 - 2 hypotheses fitted:
 $\text{dd} \rightarrow {}^4\text{He}\gamma\gamma$ and $\text{dd} \rightarrow {}^3\text{He}\gamma\gamma$ (no constraint on 2γ invariant mass)
 - optimized cuts on cumulated probability distributions

Results



Preliminary total cross sections:

${}^4\text{He}\pi^0$:

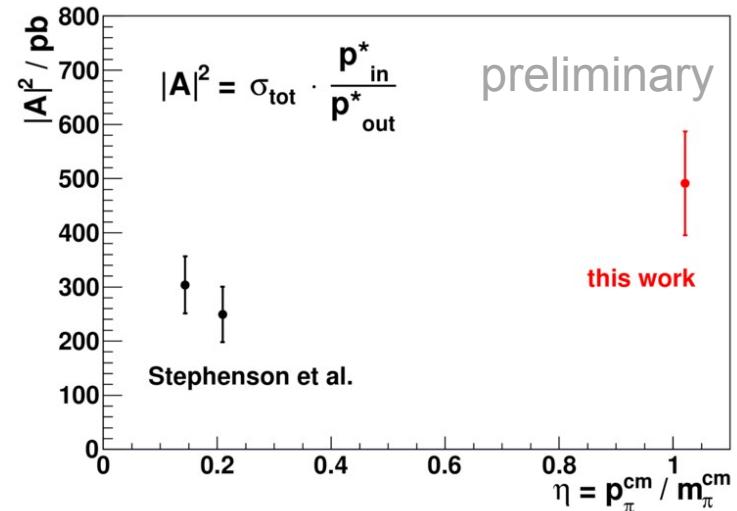
$$\sigma = (118 \pm 18_{\text{stat}} \pm 13_{\text{sys}} \pm 8_{\text{ext}}) \text{ pb}$$

${}^4\text{He}\gamma\gamma$:

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

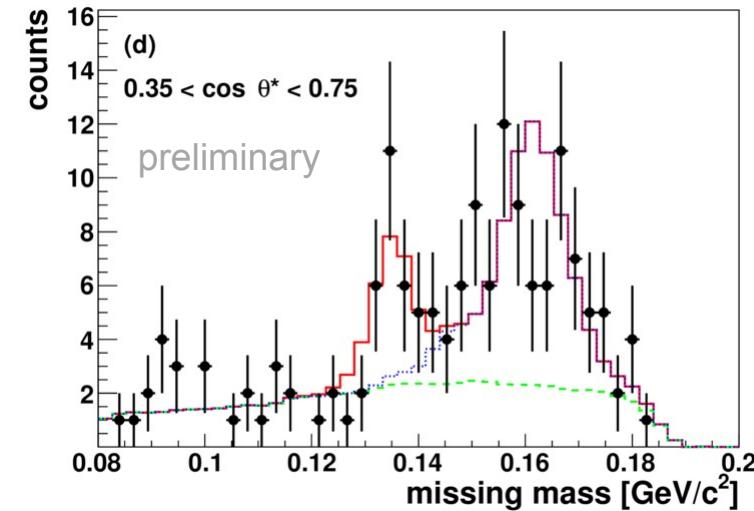
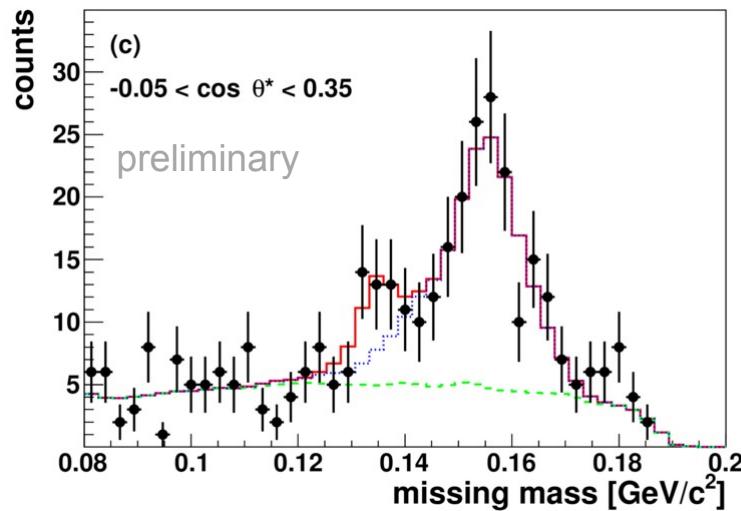
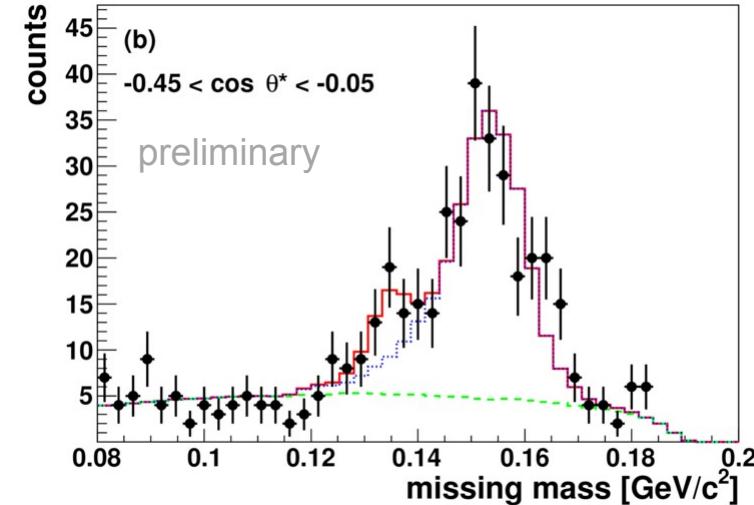
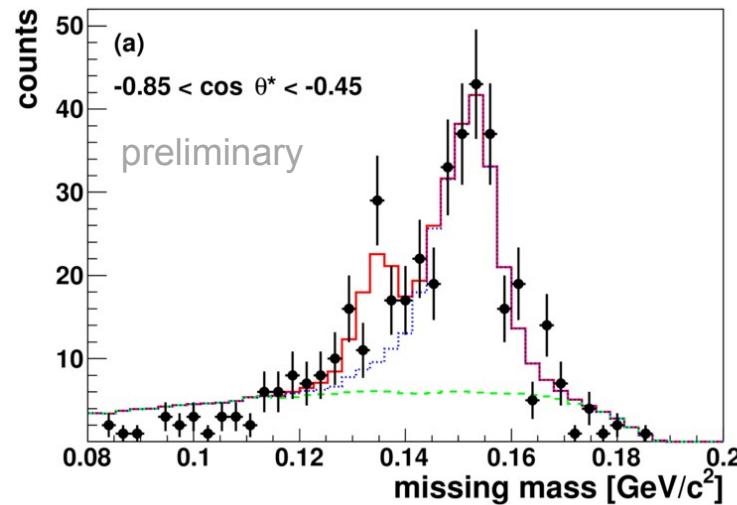
- Fitted with MC filtered distribution
- $\text{dd} \rightarrow {}^4\text{He}\pi^0$: homogeneous 3-body phase space distribution
 - $\text{dd} \rightarrow {}^3\text{He}\pi^0$: model from the previous analysis

Energy dependence:

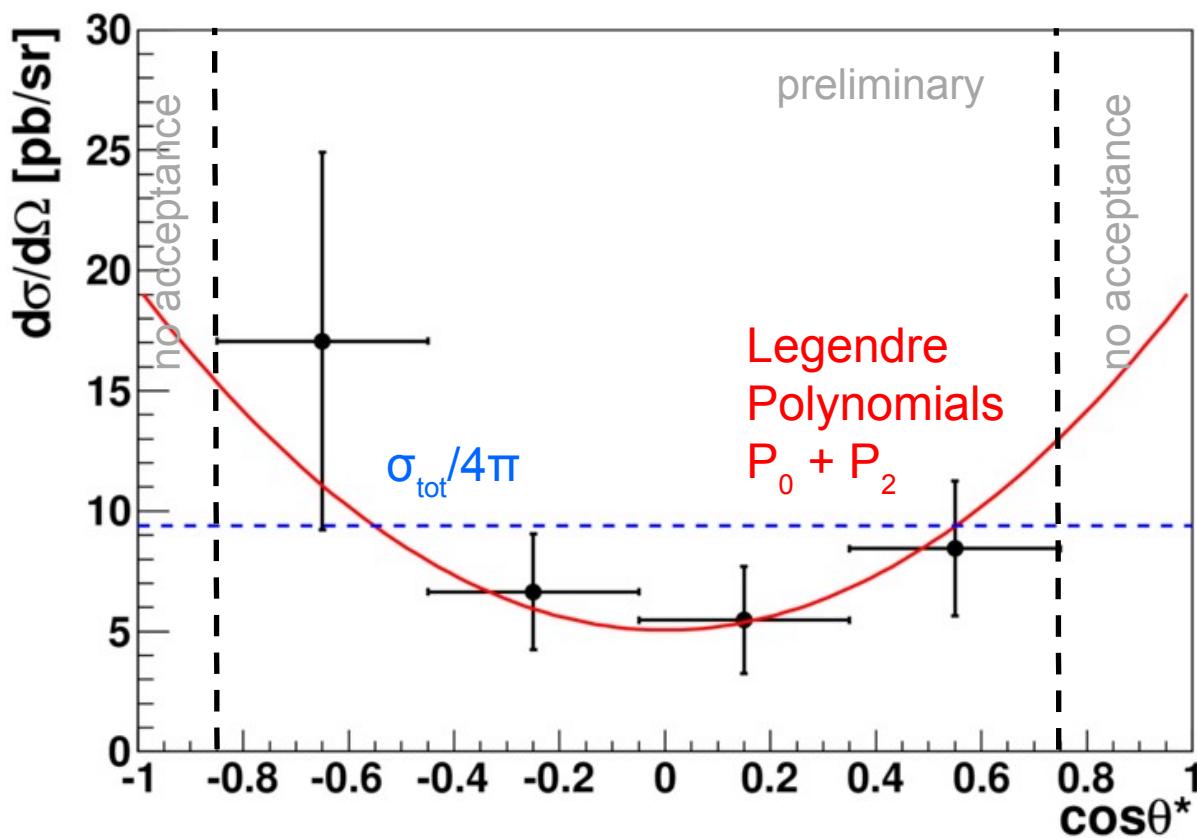


Momentum dependence of the formation of the ${}^4\text{He}$ state – not included!

Results – angular distribution



Results



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

Experiment and data analysis

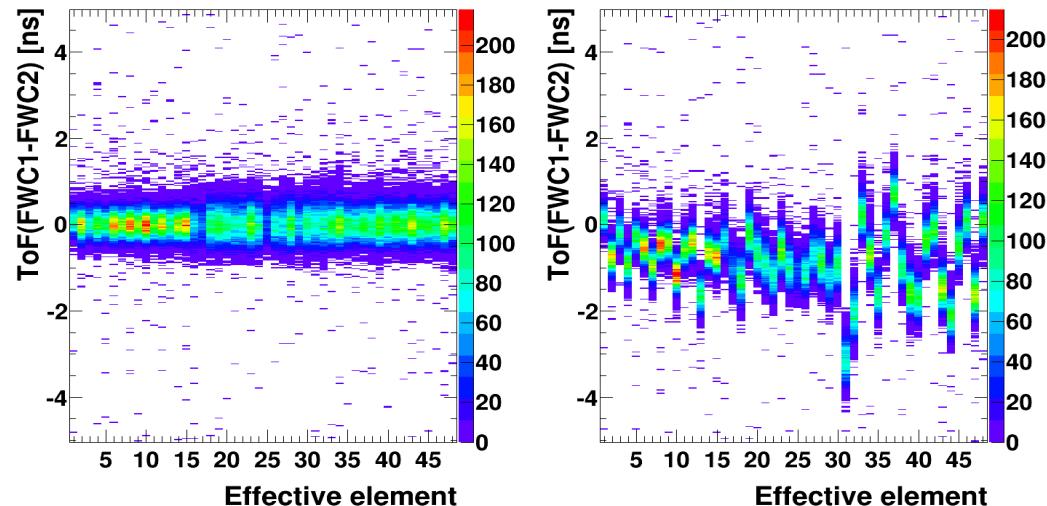
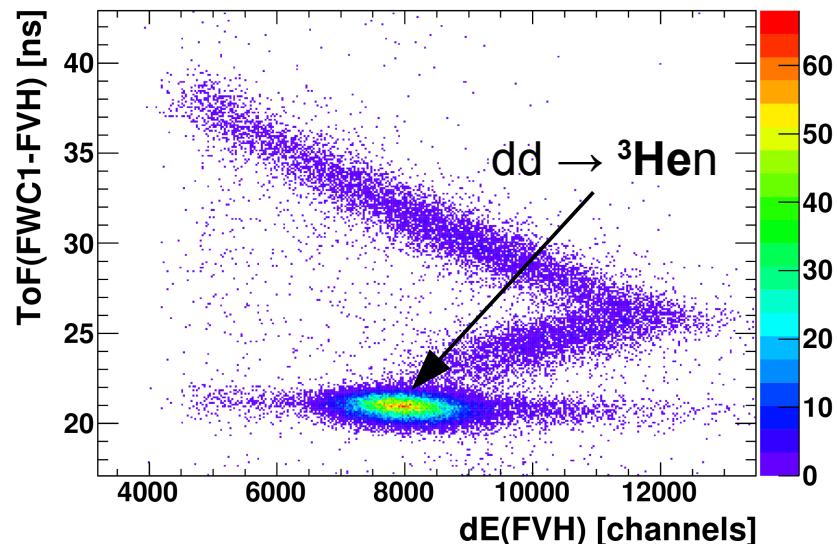
Beam time in spring 2014

- Dedicated eight week run on dd → ${}^4\text{He}\pi^0$
 - Goal: σ_{total} and angular distribution @ Q=60 MeV
 - Conditions tuned to maximum achievable luminosity
- Quite stable experimental conditions
 - ↓
- **Experimental setup:** modified WASA setup
- **Trigger:** high threshold in FD, ≥ 1 neutral in CD – threshold optimized to beam intensity of $2\text{-}3\cdot 10^{10}$ deuterons in flat top

Time of Flight Calibration

FWC time readout alignment

- ToF(FWC1-FWC2) for ${}^3\text{He}$ with $\theta = 5^\circ\text{-}6^\circ$ for every FWC1 and FWC2 element
- Alignment corrections obtained from a set of equations for ToF(FWC1-FWC2) for every FWC element

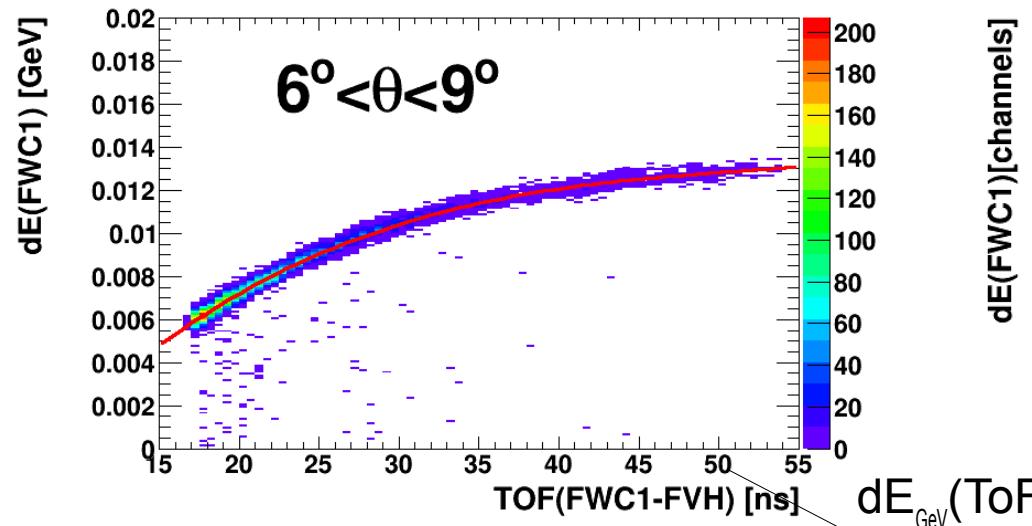


- MC: dd → ${}^3\text{He}$ time peak position for 6 θ -bins
- Data: shift to value from MC simulation
- 1: calibration FVH element wise for 6 θ -bins
→ FVH time readout alignment
- 2: calibration FWC element wise for 18 θ -bins
→ θ -dependency correction

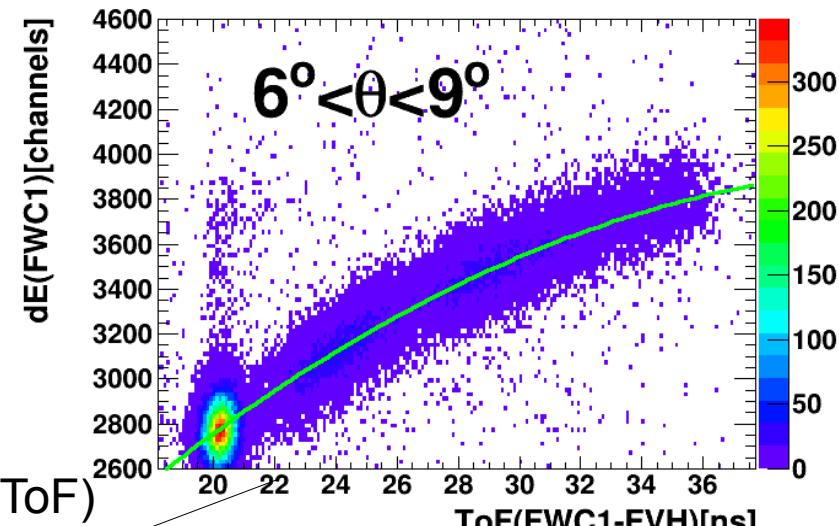
Energy losses calibration in FWC

Based on the ToF

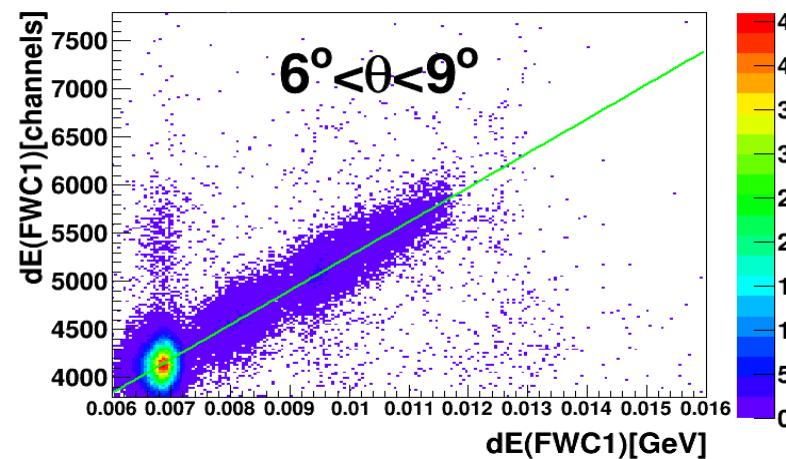
MC simulation: dE [GeV] vs ToF [ns] for ${}^3\text{He}$ in Forward Detector $\rightarrow dE_{\text{GeV}}(\text{ToF})$



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

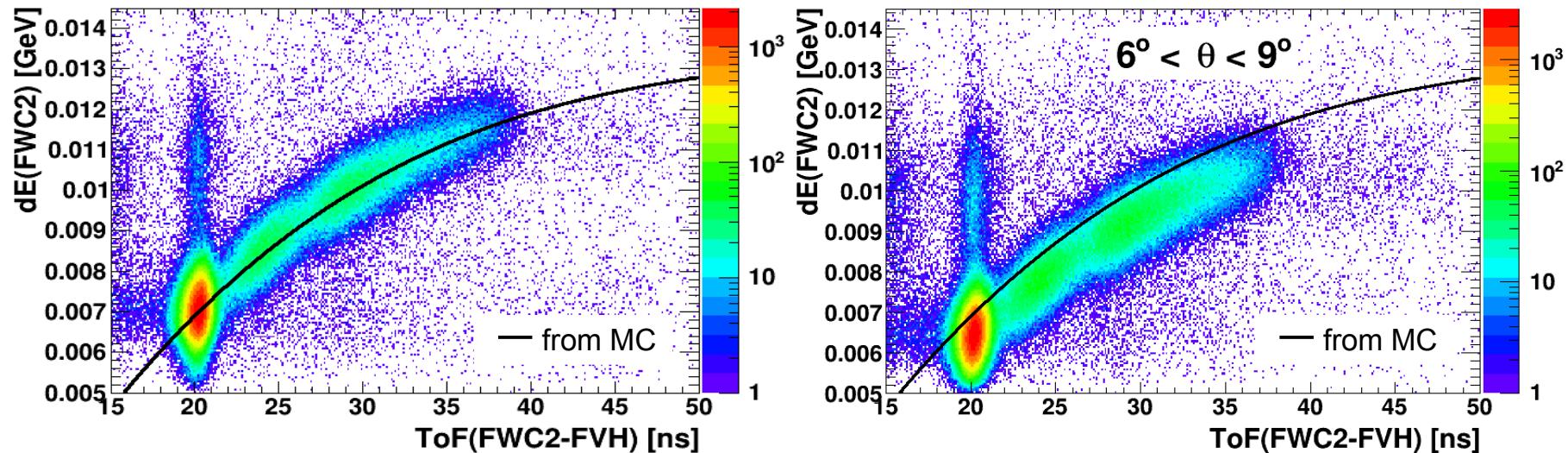


Linear dependency
 \rightarrow good quenching simulation in MC
 \rightarrow nonlinear response of PM not visible



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

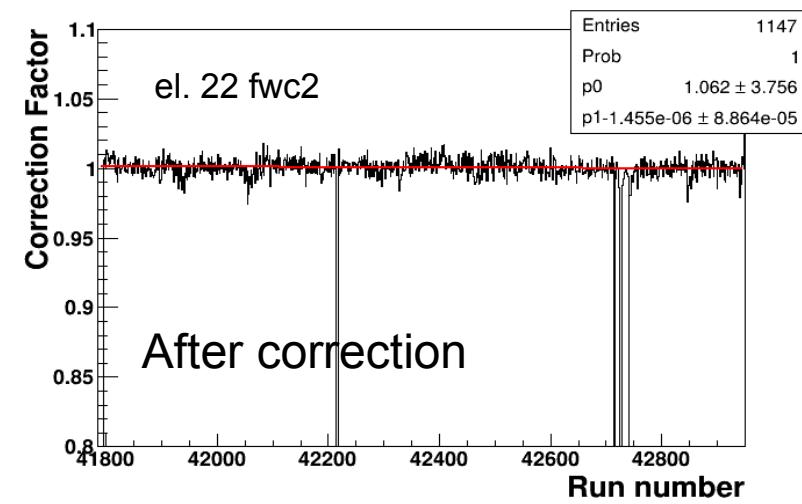
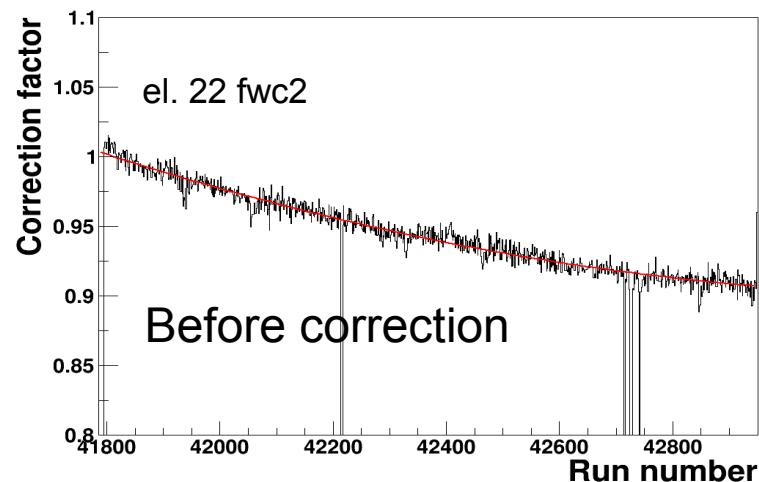
Energy losses calibration in FWC



beginning of the beamtime

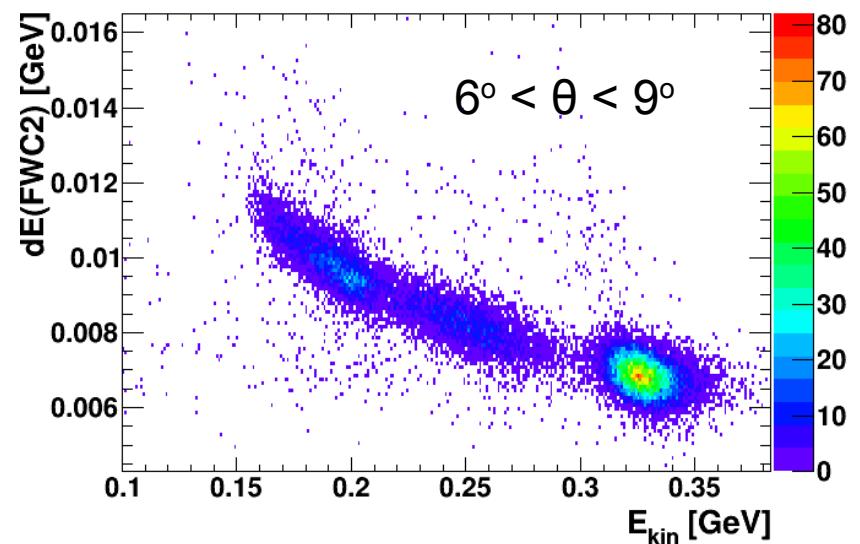
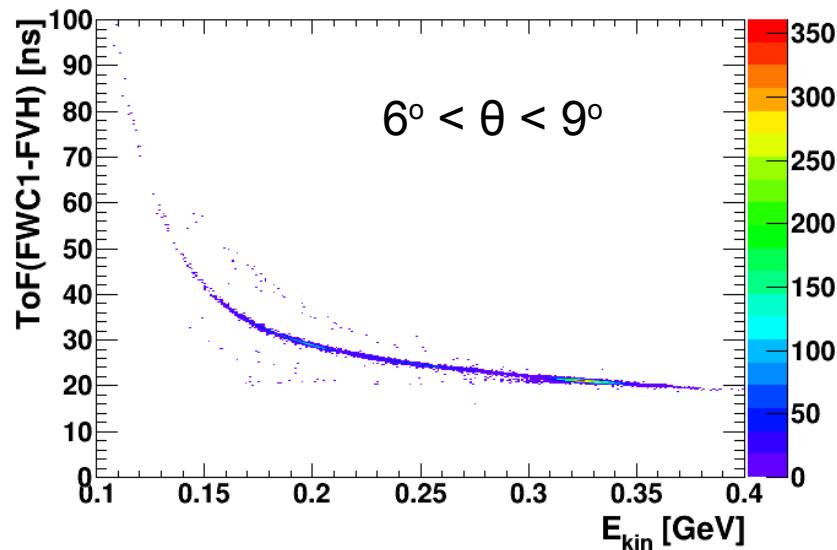
830 runs after beginning of the beamtime
(about $\frac{1}{4}$ of all runs)

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

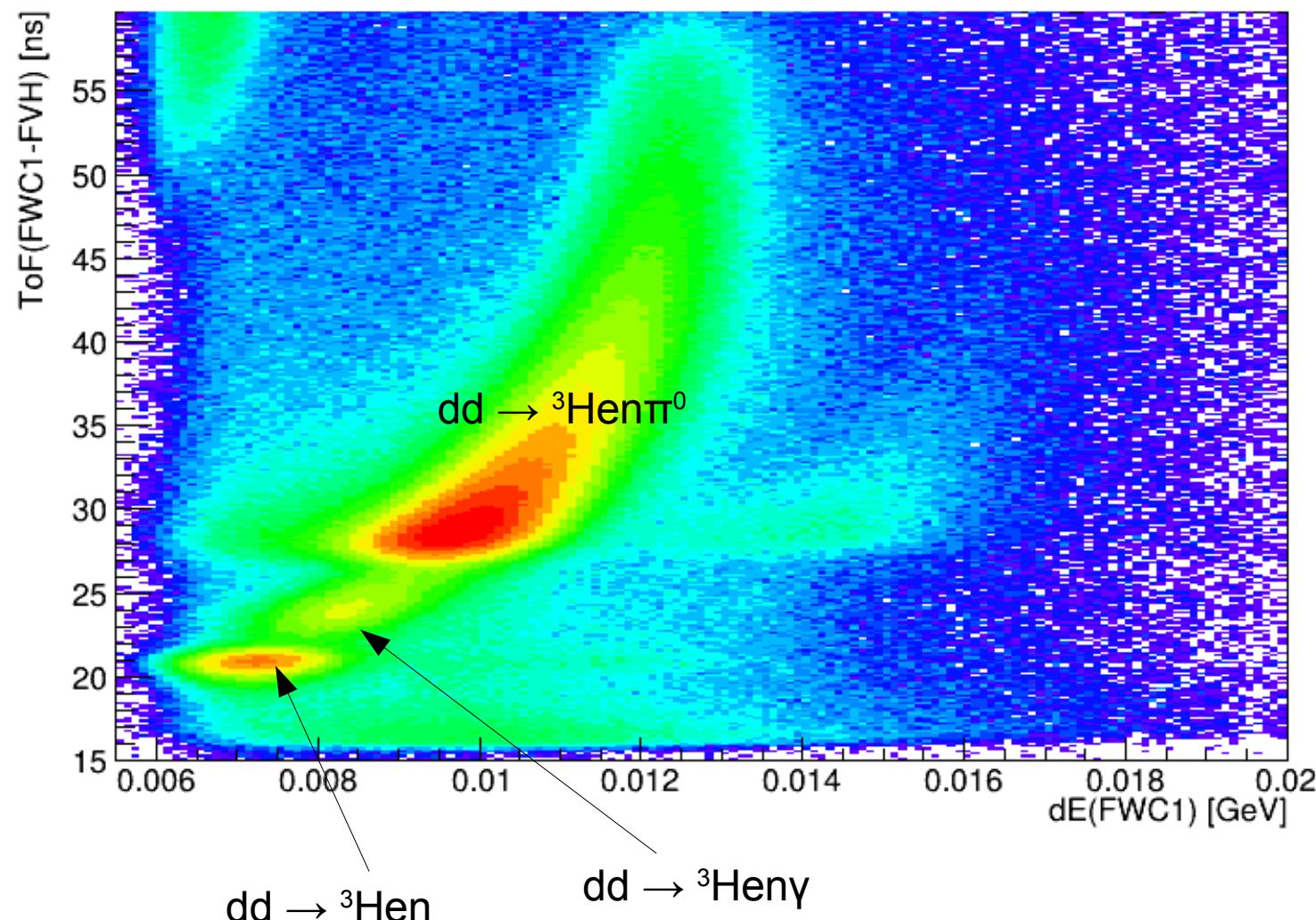


Kinetic energy calibration

- Minimization of χ^2 :
$$\chi^2 = \sum_{i=1}^n \frac{(dE_i^{meas} - dE(E_{kin})_i)^2}{\sigma_i^2} + \sum_{j=1}^m \frac{(\text{TOF}_j^{meas} - \text{TOF}(E_{kin})_j)^2}{\sigma_j^2}$$
- $E_{kin}(\text{ToF}_1)$, $E_{kin}(\text{ToF}_2)$, $E_{kin}(dE_{FWC1})$, $E_{kin}(dE_{FWC2})$ dependency from MC
- Data based uncertainties of ToF(dE) as a function of ToF(dE) (first iteration)



ToF vs Energy Losses



Further data analysis

- Central Detector Calibration – run dependent (Michaela Schever)
- Kinematic Fit performed for 2 hypothesis:

$$\text{dd} \rightarrow {}^3\text{He}\gamma\gamma \text{ and } \text{dd} \rightarrow {}^4\text{He}\gamma\gamma$$

- Error parametrization (MC smearing to match data uncertainties in ToF and dE)
- Cut on 2 dim spectra of p-value from fit

