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Charge Symmetry Breaking in $dd \rightarrow {}^4He\pi^0$ with WASA-at-COSY

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Probing quark mass effects

Hadron physics at COSY energies

- pertubative treatment (in α_s) of QCD not possible
- spontanously broken chiral symmetry $\Rightarrow$ effective field theory

Chiral Pertubation Theory

- shares all symmetries with QCD
- symmetry breaking: tests our understanding of QCD
- extraction of basic QCD parameters

Tool: Isospin Symmetry

- only approximate symmetry in QCD:
  - quark masses ←
  - electromagnetic interactions

isospin symmetry breaking: experimental handle on quark mass ratio

$$\frac{m_u - m_d}{m_u + m_d}$$

Isospin breaking

Static observables

- pion mass difference $m(\pi^{\pm}) > m(\pi^0)$ purely electro-magnetic
- nucleon mass difference $m_n > m_p$ strong + electro-magnetic
  - ΔM^{em} = (-0.7 ± 0.3) MeV
  - ΔM^{str} = (2.05 ± 0.3) MeV

Dynamic observables

- πN scattering length e.g. $a(\pi^0 p) - a(\pi^0 n) = f(\Delta M^{str})$
  - however: no direct measurement of π^0 N
    large e.m. corrections in $\pi^{\pm}$ N
- πNN vertex

Challenges:

- dominated by Δm_π
- small corrections on top of isospin conserving signals

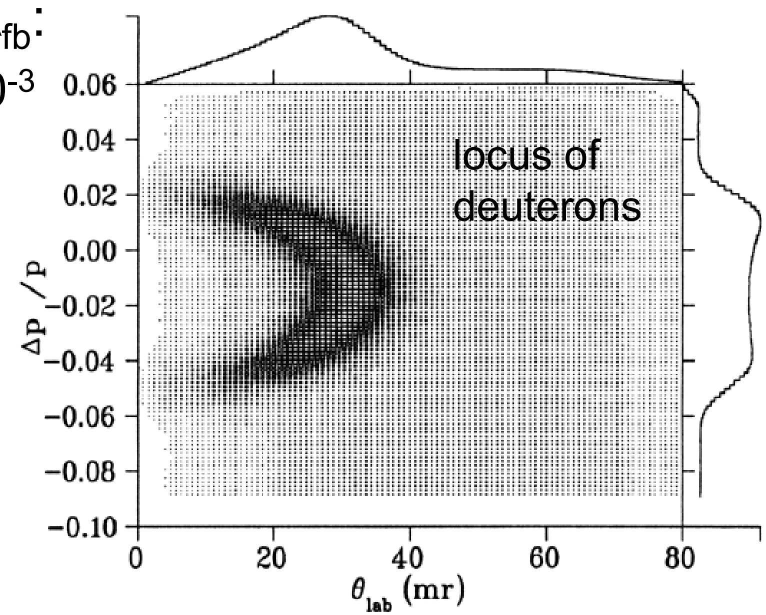
Charge Symmetry Breaking

Charge Symmetry

- subset of isospin symmetry:
  - rotation in isospin space, 180º around I_2-axis
  - “interchange” of u⇔d quarks: $|u\rangle \to |d\rangle$, $|d\rangle \to -|u\rangle$
- pion mass difference does not contribute to CS breaking

„Null experiments“: minimizing CS conserving contributions

- $np \to d\pi^0$ forward-backward assymmetry A_{fb}:
  - Opper et al., $A_{fb} = (17.2 \pm 8.0 \pm 5.5) \cdot 10^{-3}$ close to threshold ($Q \approx 2$ MeV)
    (PRL 91 (2003) 212302)
  - leading CSB term: πN rescattering
    Filin et al.: ChPT in LO
    $\Delta M^{str} = (1.5 \pm 0.8_{exp} \pm 0.5_{th})$ MeV
    (PLB 681 (2009) 423)
- $dd \to {}^4He\,\pi^0$



Charge Symmetry Breaking

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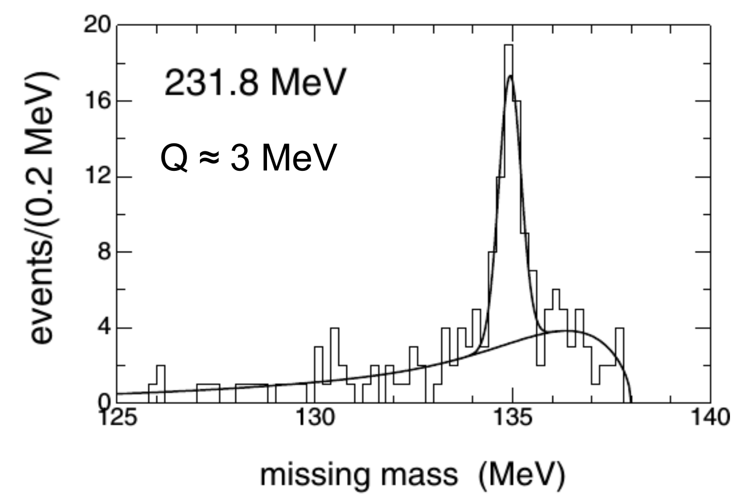
„Null experiments": minimizing CS conserving contributions

- $np \rightarrow d\pi^0$ forward-backward assymmetry A_{fb}
- $dd \rightarrow {}^4He\ \pi^0$:
  - $\sigma \propto |M_{CSB}|^2$, complementary to $np \rightarrow d\pi^0$
  - Stephenson et al., σ_{tot} close to threshold
    σ_{tot} (Q ≈ 1.4 MeV) = 12.7 ± 2.2 pb
    σ_{tot} (Q ≈ 3.0 MeV) = 15.1 ± 3.1 pb
    (PRL 91 (2003) 142302)
  - energy dependence consistent with *s*-wave pion production



Further investigations on dd → ^{4}He π^0

Current status

theory collaboration working on consistent analysis in terms of ChPT of

- forward-backward asymmetry in np → dπ^0 Opper et al., ., PRL 91 (2003) 212302
- cross section at threshold of dd → ^{4}He π^0 Stephenson et al., PRL 91 (2003) 142302

Further input from WASA-at-COSY

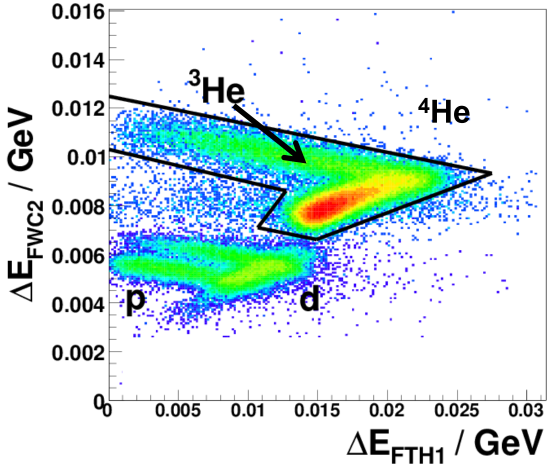
- reaction dynamics of dd → ^{3}He N π (CSC)
  → differential cross sections: input to fix dd initial state, 4N final state
  → Phys. Rev. C 88 (2013) 014004
- dd → ^{4}He π^0 at higher excess energies (p = 1.2 GeV/c, Q = 60 MeV)
  → preliminary results on total cross section and diff. distributions
  → publication in preparation

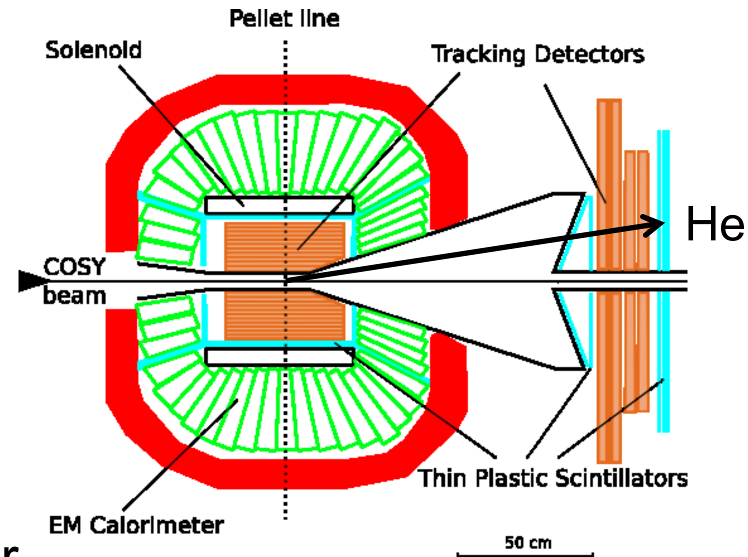
⇕

theoretical analysis of np → dπ^0 and dd → ^{4}He π^0 (*s*-wave)
once finished: non-trivial ChPT prediction on p-wave contribution
NLO calculation → expected uncertainty 20% - 30%

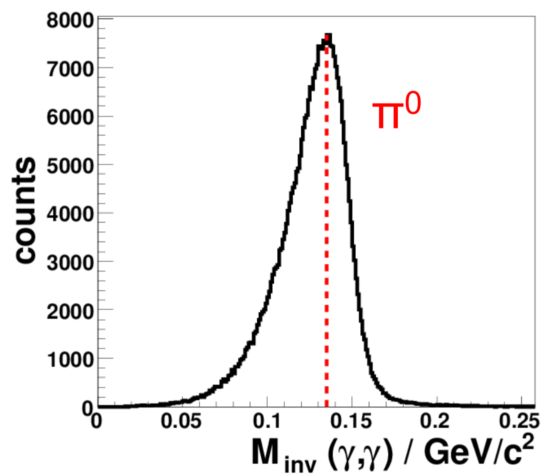
Basic analysis: dd → $^3He\ n\ \pi^0$ / $^4He\ \pi^0$

- Helium identification





- 2 coincident photons in calorimeter



$^3He n\pi^0$ as benchmark for $^4He\pi^0$:

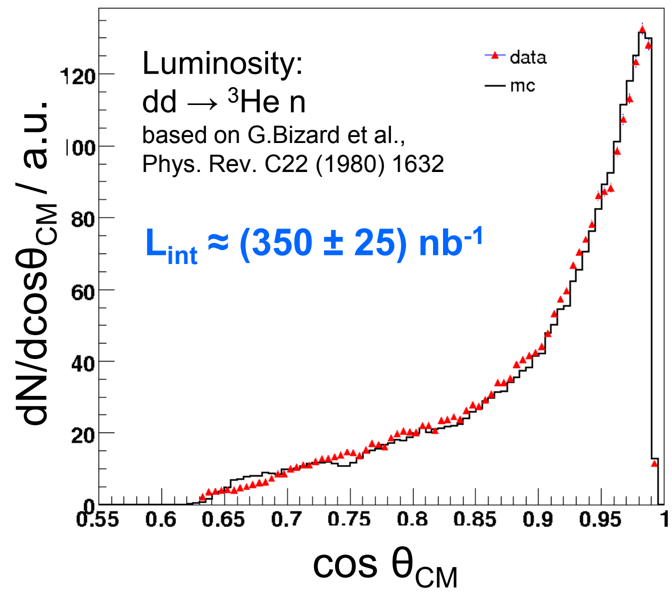
- clean selection of ^3He - π^0 coincidences
- final step:
  kinematic fit to ensure overall energy and momentum conservation
- 3.4×10^6 fully reconstructed events
- nearly full coverage of Dalitz plots

dd → ^{3}He n π^0

Phys. Rev. C 88 (2013) 014004

Luminosity determination:

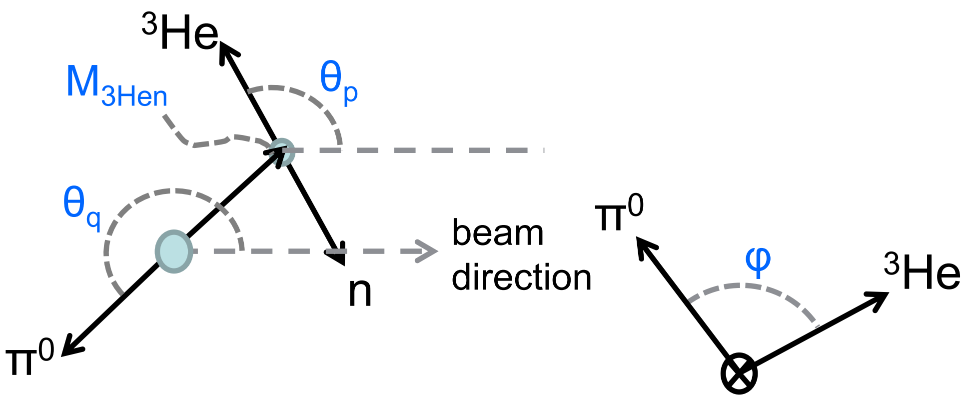
- two-body reaction dd → ^{3}He n
  interpolated data from
  Bizard et al., PRC22 (1980) 1632:
  perfect match of expected angular distribution



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 → 3Heπ^0 + n_{spec}
  - partial decomposition of the
    3-body final state (limited to L≤1)

  full model = incoherent sum

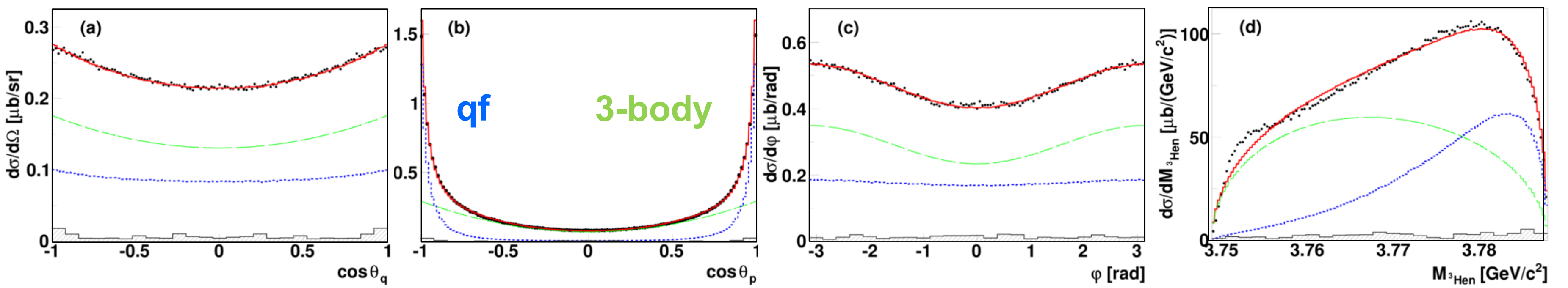


dd → ^{3}He n π^0

Phys. Rev. C 88 (2013) 014004

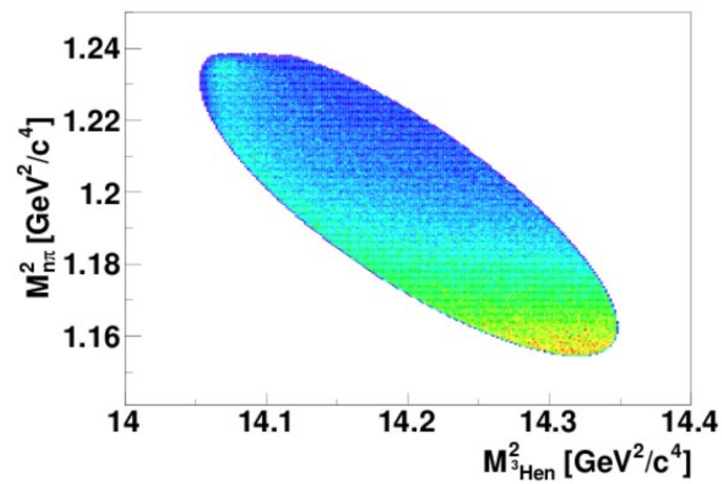
Global fit to data:

$$\frac{d^4\sigma}{2\pi\, dM_{^3\mathrm{He}n}\, d\cos\theta_p\, d\cos\theta_q\, d\varphi} = C \cdot pq \left[A_0 + A_1 q^2 + A_3 p^2 + \frac{1}{4}A_2 q^2(1+3\cos 2\theta_q) + \frac{1}{4}A_4 p^2(1+3\cos 2\theta_p) + A_5 pq\cos\theta_p\cos\theta_q + A_6 pq \sin\theta_p \sin\theta_q \cos\varphi\right]$$
$$+ A_7 \cdot f_{\mathrm{quasi-free}}(M_{^3\mathrm{He}n}, \cos\theta_p, \cos\theta_q, \varphi)$$



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

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



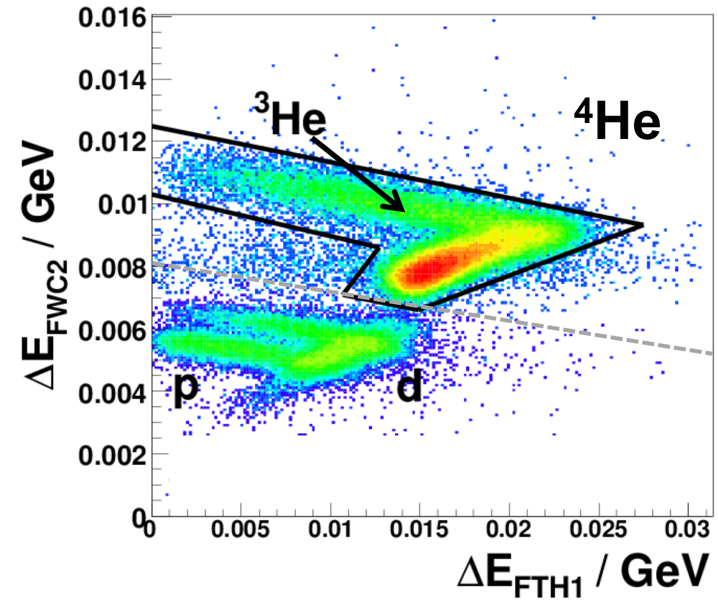
dd → ^{4}Heπ^0: analysis

- data taken at maximum luminosity:

  → L_{int} = (4909 ± 348_{sys}) nb^{-1} in 2 weeks
- initial Helium and photon detection as for dd → ^{3}He n π^0
- event selection:

  1) weak condition on ΔE- ΔE

     and γγ in calorimeter



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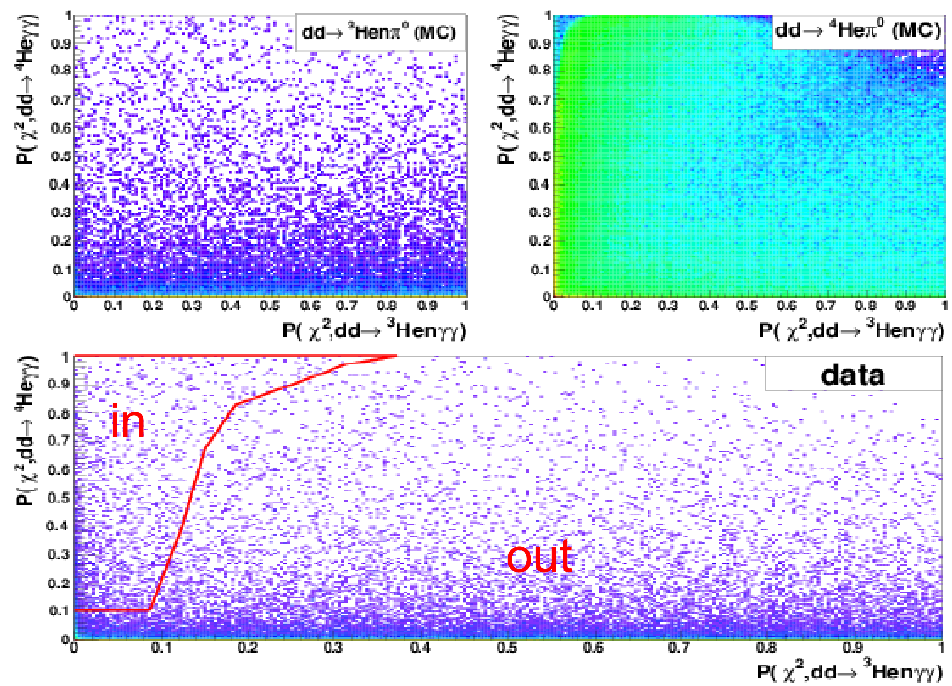
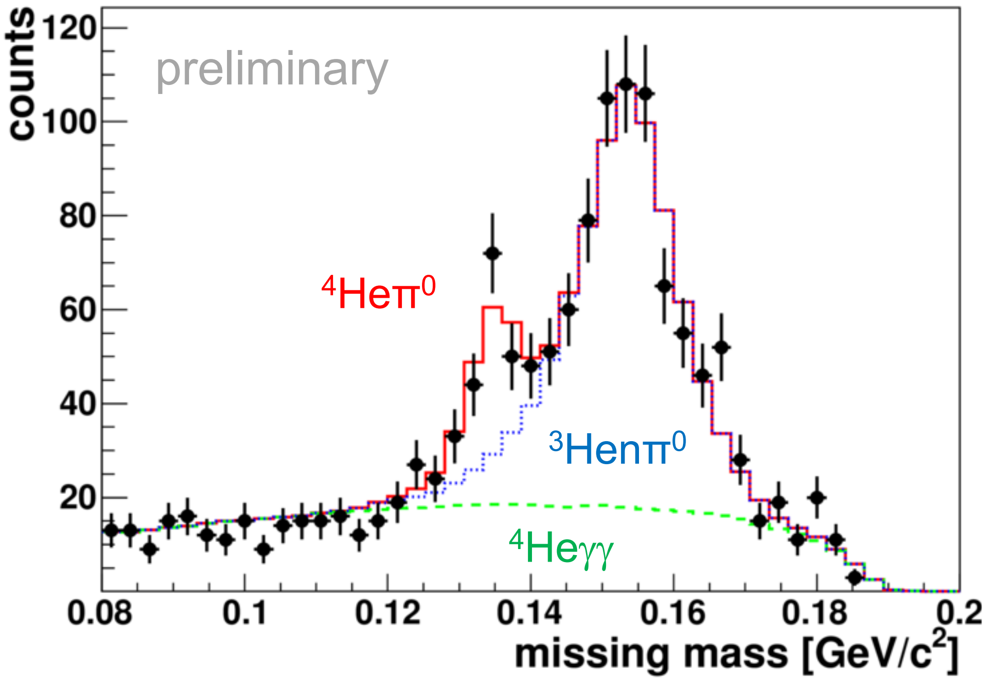
- event selection:
  1) weak condition on ΔE- ΔE
     and γγ in calorimeter
  2) 2-body vs 3-body kinematics:
     kinematic fit
     a) dd → ^{3}He n γγ
     b) dd → ^{4}He γγ

     Note: only E-p conservation
     no π^0 constraint
     included!



→ ^{3}Henπ^0 suppression > 10^4

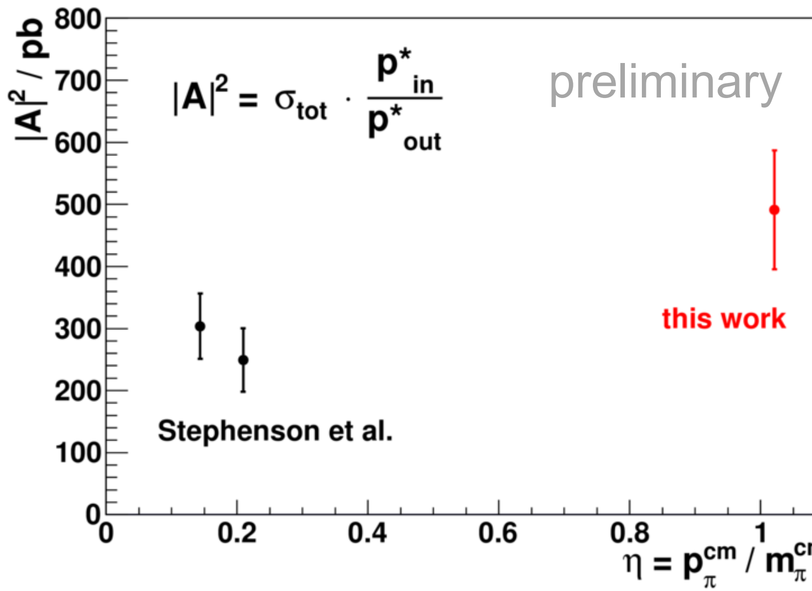
dd → ^{4}Heπ^0: total cross section



Sum of Monte-Carlo generated template functions matches data (individual height fitted):

- ^{4}He$\gamma\gamma$ (3-body phase space)
- ^{3}Henπ^0 (derived model)
- ^{4}Heπ^0 (2-body phase space)

Energy dependence:

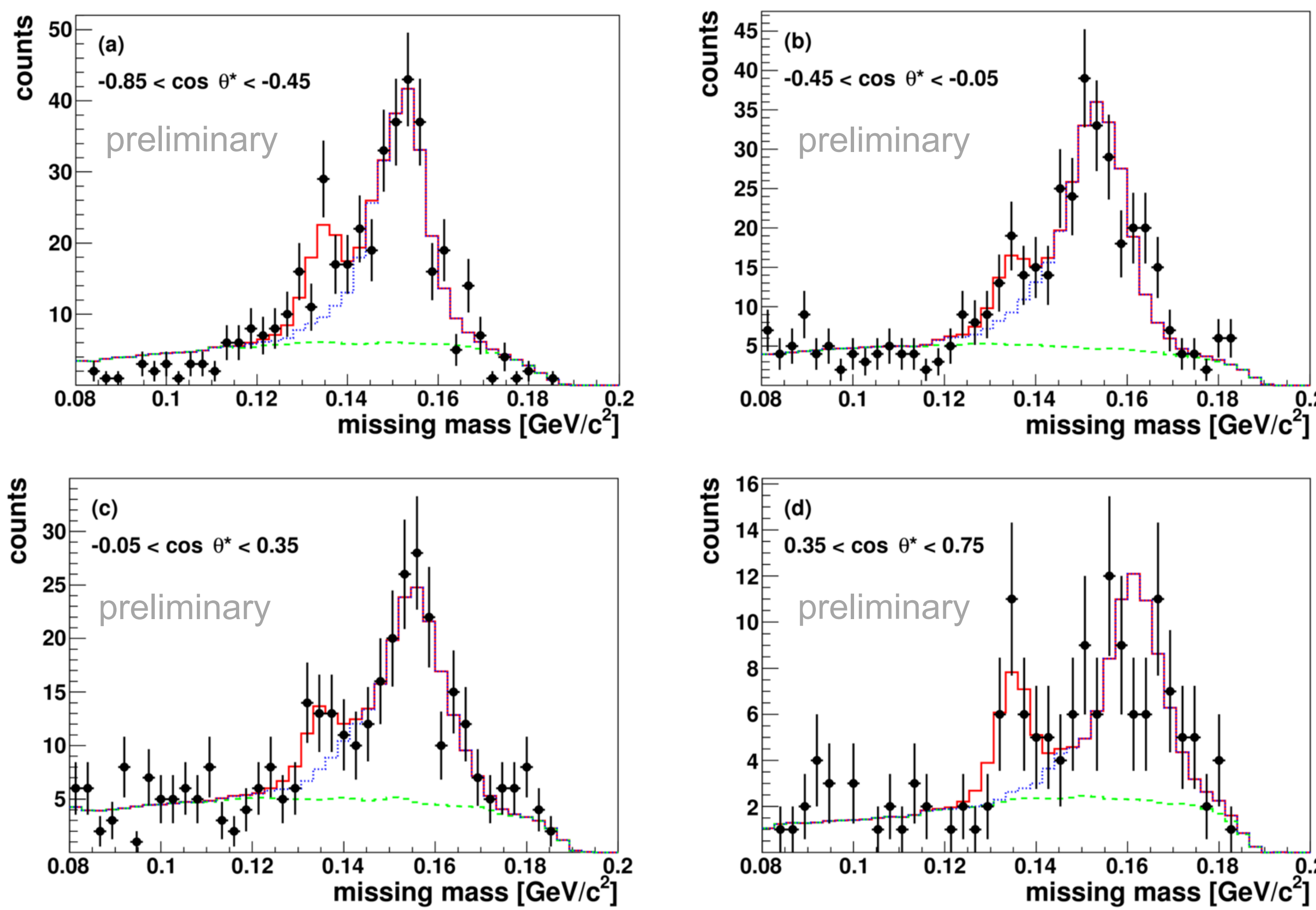


Preliminary total cross sections:

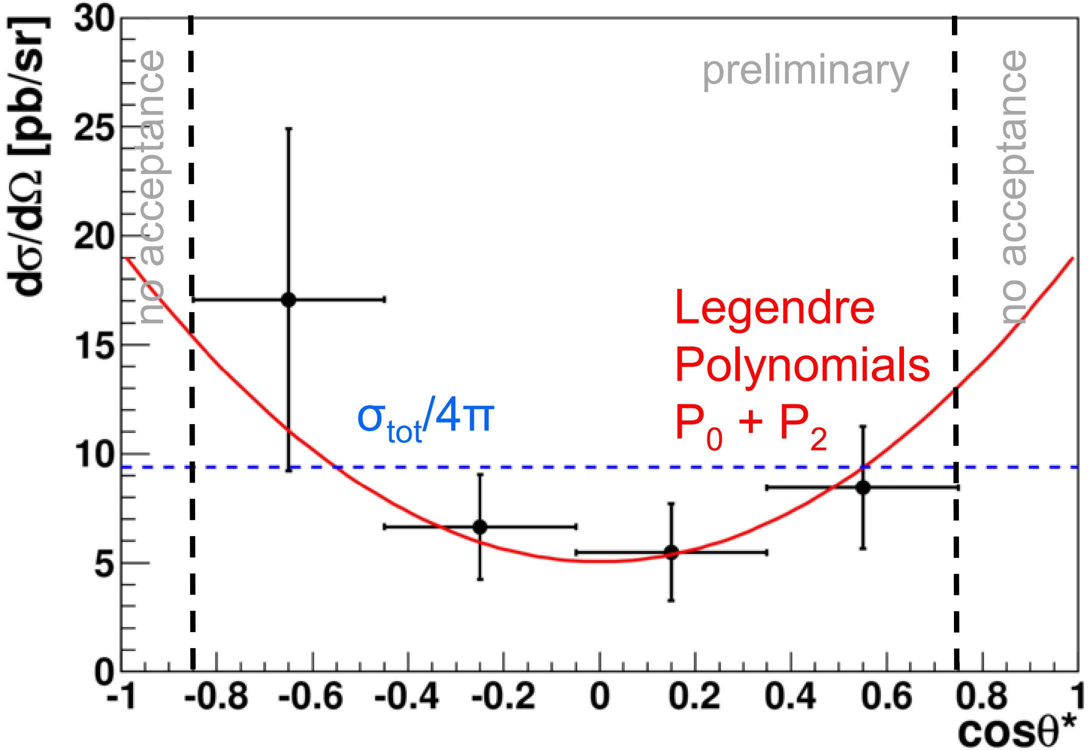
$\sigma_{4He\pi0} = (118 \pm 18_{stat} \pm 13_{sys} \pm 8_{ext})$ pb

$\sigma_{4He\gamma\gamma} = (920 \pm 70_{stat} \pm 100_{sys} \pm 70_{ext})$ pb

dd → ^{4}Heπ^0: angular distributions (1)



dd → $^4He\pi^0$: angular distributions (2)



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

Outlook:

Possible improvements:

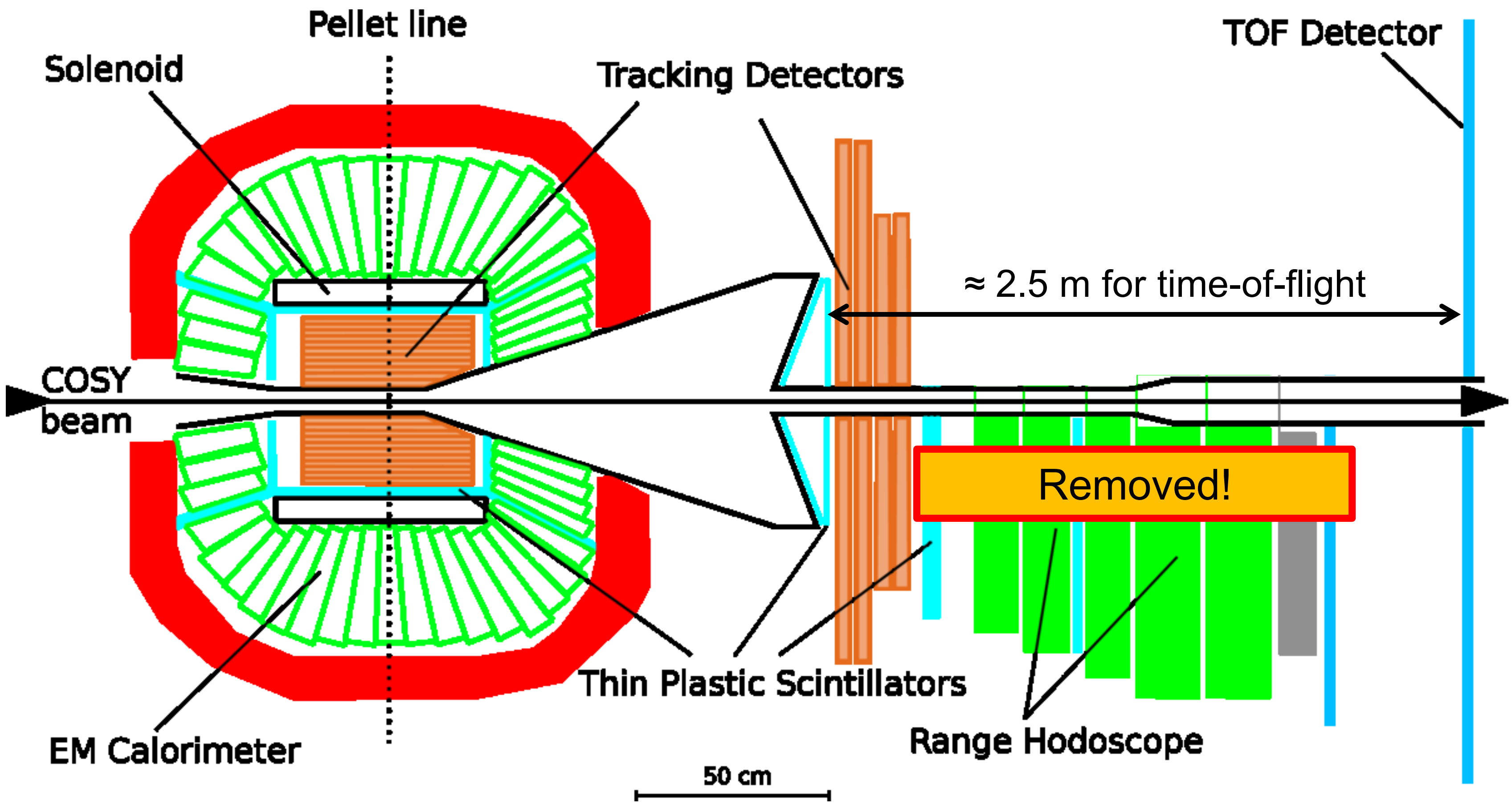
- better ^{3}He/^{4}He discrimination: $\sigma(^3\mathrm{He}n\pi^0) \approx 3\cdot10^4\ \sigma(^4\mathrm{He}\pi^0)$
- more precise energy reconstruction:
  currently solely based on ΔE
- benchmark for ^{4}He energy reconstruction:
  relies now on ΔE from MC simulations
  (quenching? insensitive material?)

→ optimized detector setup

- improved statistics mandatory for a decisive angular distribution

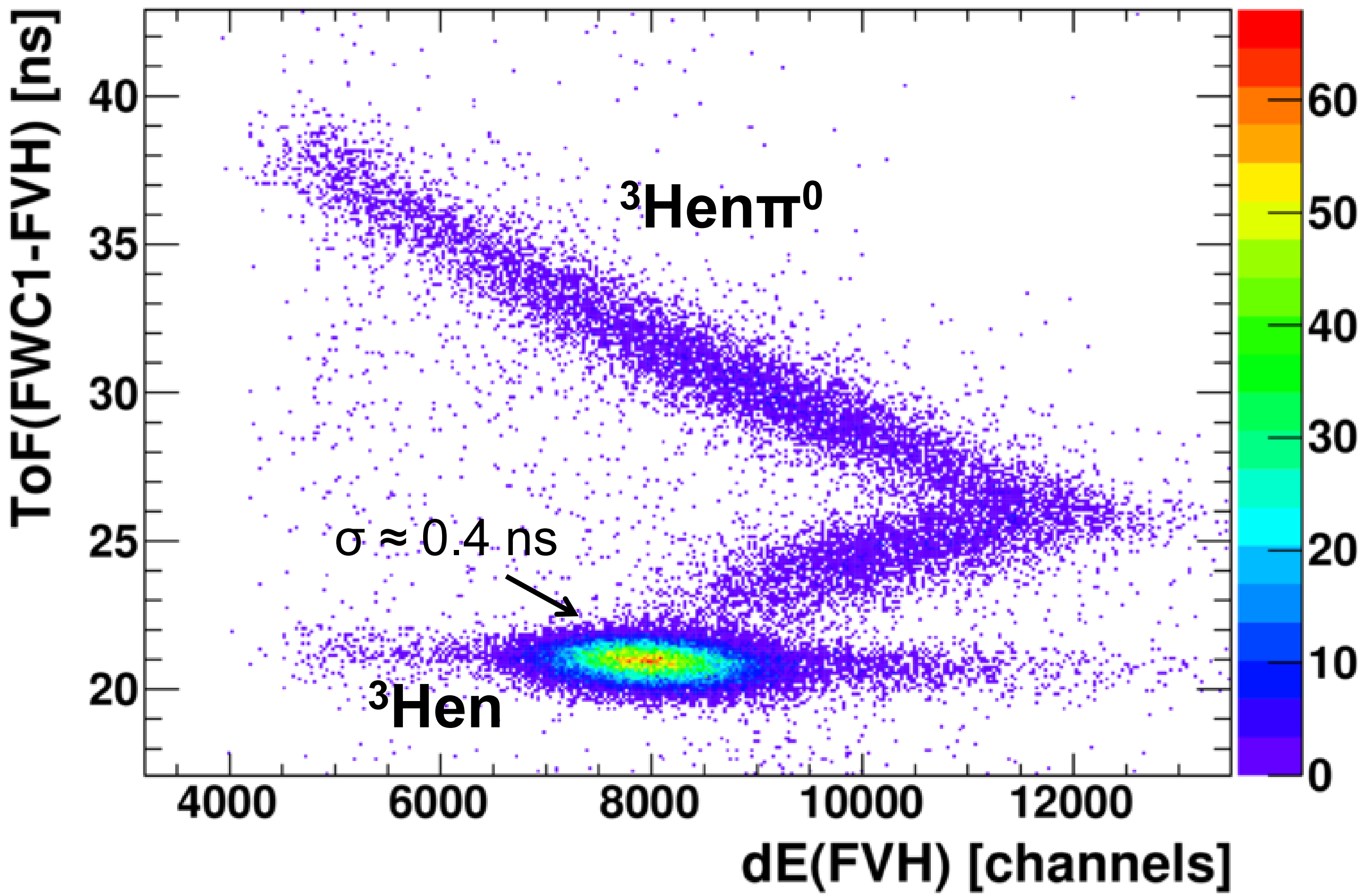
→ recent 8 weeks run in February – April 2014

Detector modification



old:	3 x ΔE
new:	3 x ΔE + 2 x Δt

Example: time-of-flight vs energy deposit



Summary & Outlook

- Charge Symmetry Breaking used to access quark mass effects
- Theoretical tool: Chiral Pertubation Theory
- Status
  - high statistics data on $dd \rightarrow {}^3He\, n\, \pi^0$:
    - *results on total and differential cross sections*
    - *data modeled with quasi-free mechanism + partial wave decomposition*
  - preliminary results on $dd \rightarrow {}^4He\, \pi^0$ (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