

Search for the η -mesic ^4He with WASA-at-COSY

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Magdalena Skurzok
for the WASA-at-COSY collaboration



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Problems in Physics
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Exotic systems

„classical” nucleus:

bound state of protons and neutrons.

Hypernuclei:

bound state of protons and neutrons

+ hyperon Λ, Σ

Mesic atoms and nuclei:

bound state of protons and neutrons

+ meson $\pi, K, \eta, \eta', \omega, \dots$

strong interaction + e-m interaction



Exotic systems

„classical” nucleus:

bound state of protons and neutrons.

η -⁴He case

strong interaction + ~~e-m interaction~~

Hypernuclei:

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+ hyperon Λ, Σ

Mesic atoms and nuclei:

bound state of protons and neutrons

+ meson $\pi, K, \eta, \eta', \omega, \dots$



Why η -mesic nuclei

- **New bound state of hadrons**

- **Investigation η -N interactions**

- **Studies of η quark structure**

Binding energy and effective mass of η are sensitive to the gluon component of the flavour singlet function $|\eta_0\rangle$

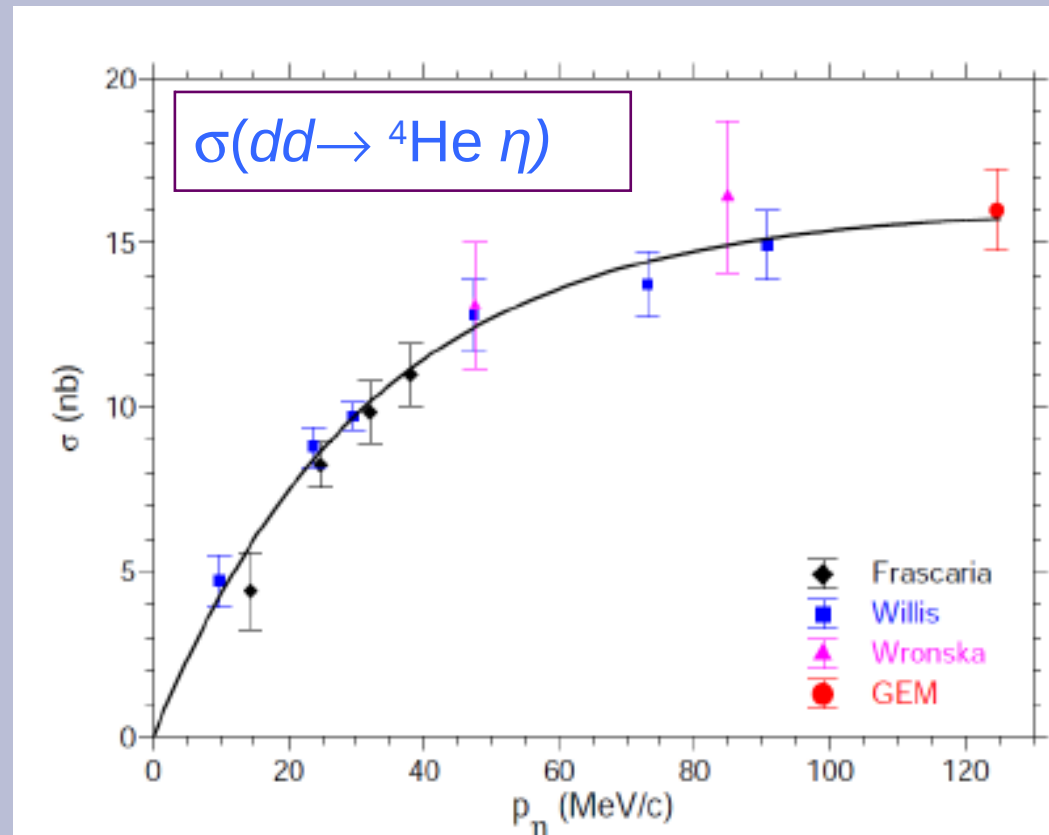
(more gluon content \rightarrow more attractive binding \rightarrow higher binding energy)

(*S.D. Bass, A.W. Thomas, Phys. Lett. B634 (2008)*)

- **Study of in-medium properties of $N^*(1535)$ resonance:**

N - η system is strongly coupled with $N^*(1535)$ resonances. Eta-mesic nucleus as a probe for testing different N^* models

Experimental indications of the existence of a bound state in the η - ^4He system



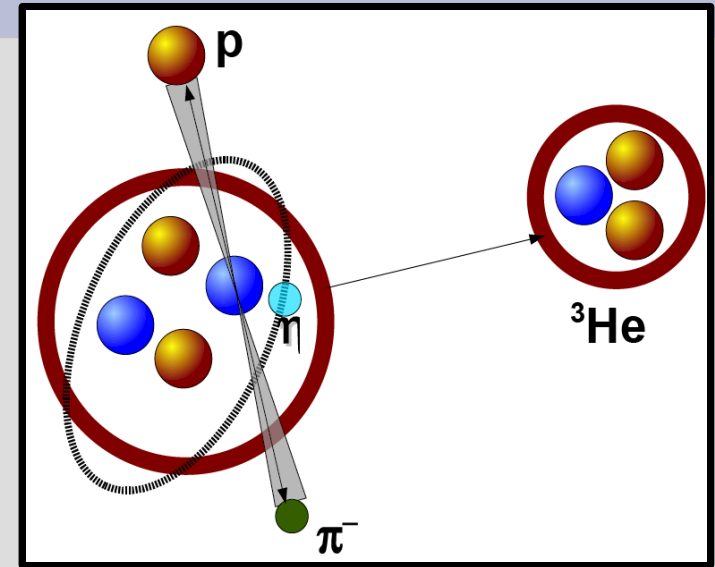
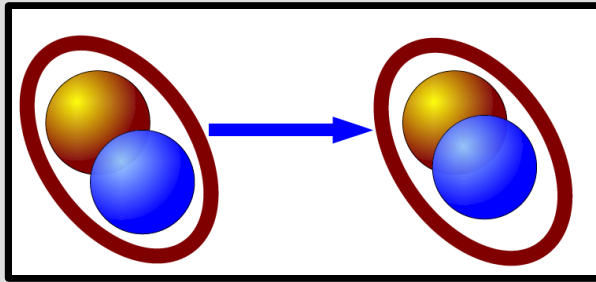
R. Frascaria et al., Phys. Rev. C 50 (1994) 573.

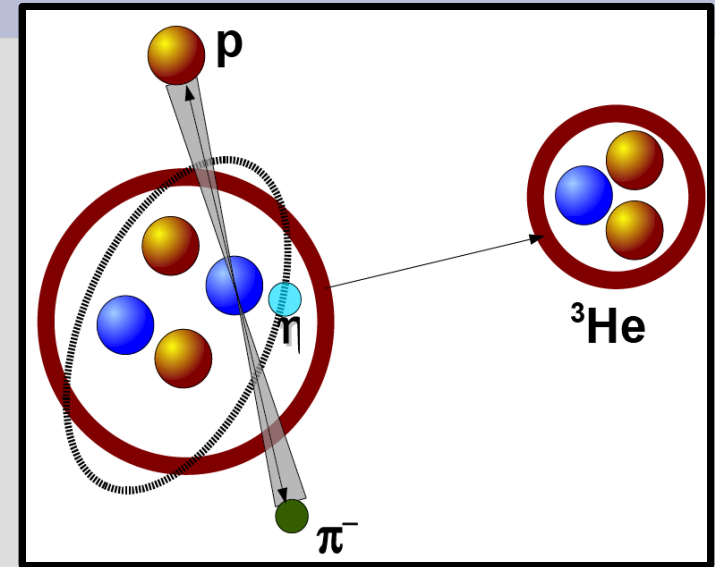
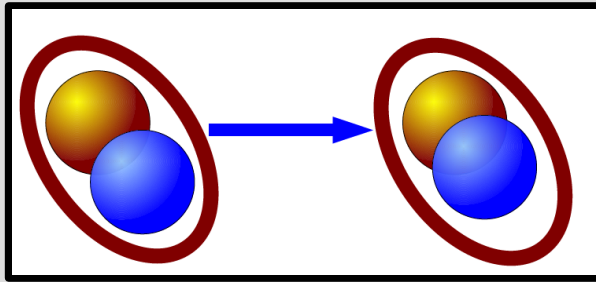
N. Willis et al., Phys. Lett. B 406 (1997) 14.

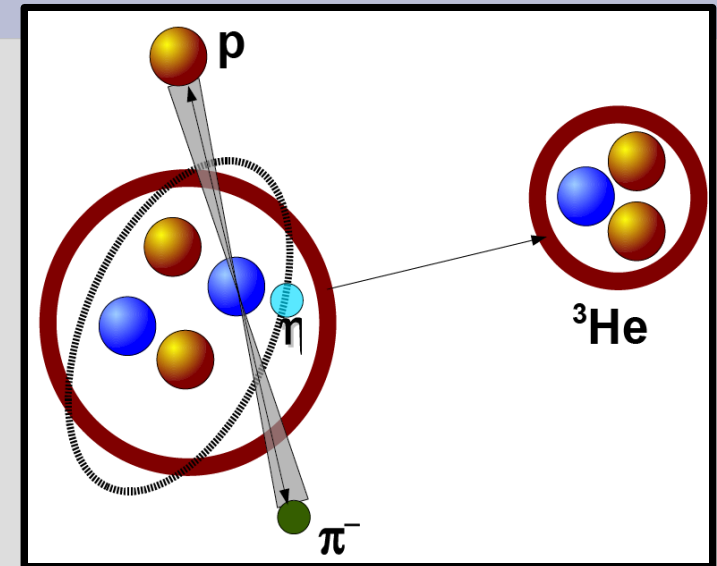
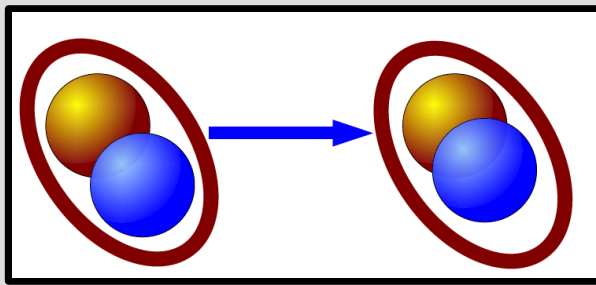
A. Wrońska et al., Eur.Phys.J. A26 (2005) 421-428.



Idea of measurement





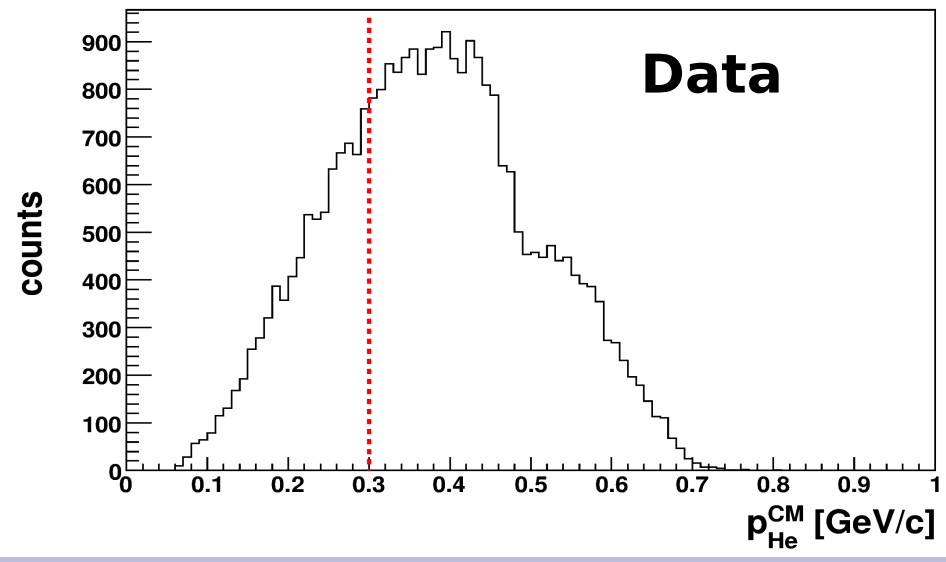
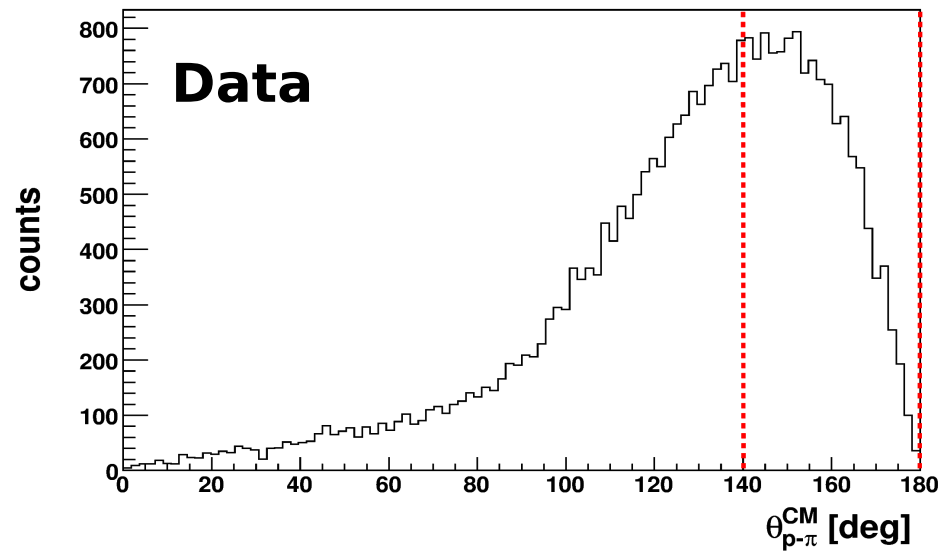
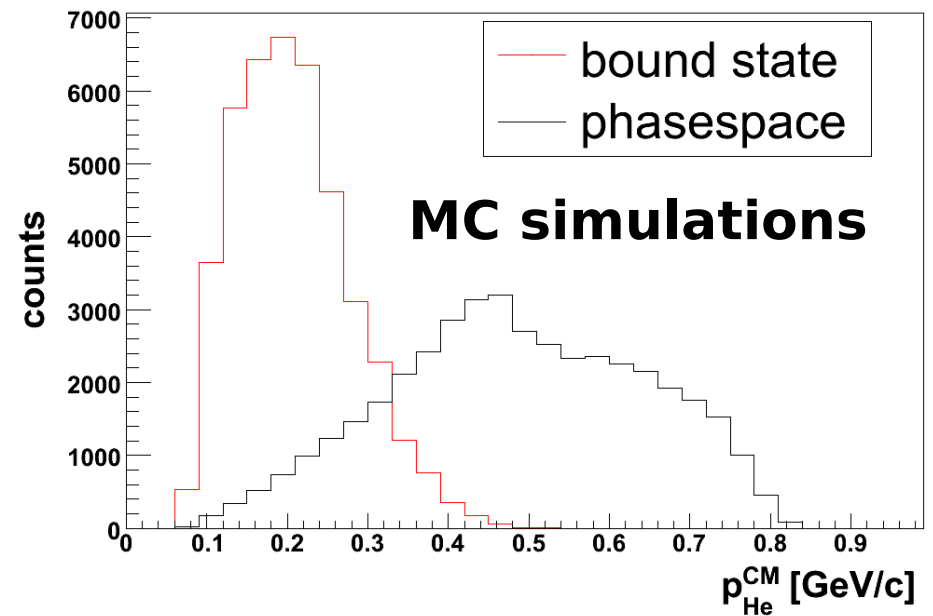
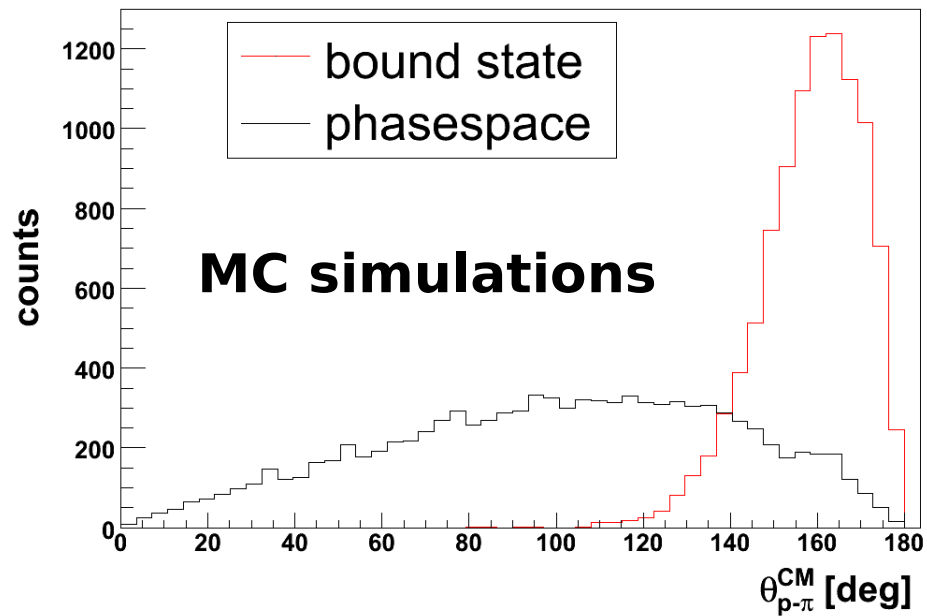


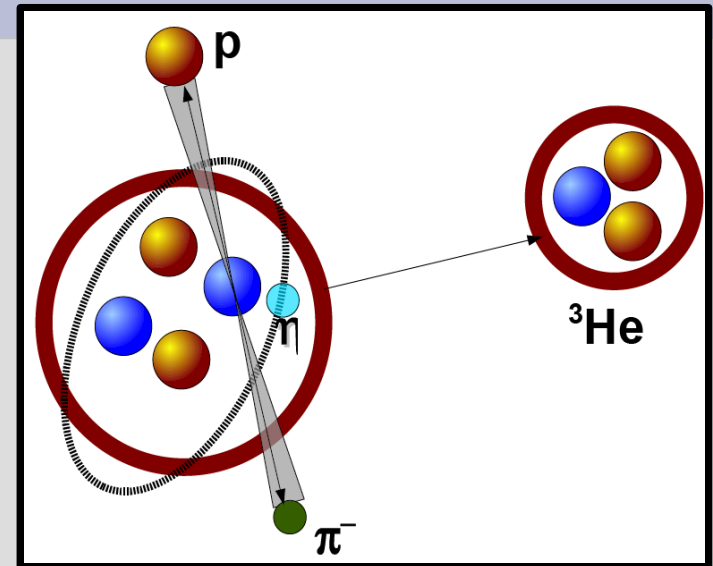
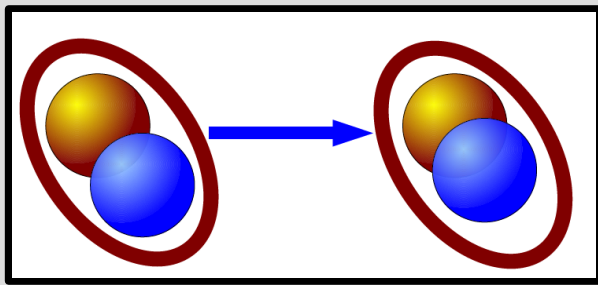
- relative $N\text{-}\pi$ angle in the CM : $\theta_{cm} \sim 180^\circ$
- low ${}^3\text{He}$ momentum in the CM

Signatures of the bound state

Opening angle $p-\pi^-$ in CM frame

^3He momentum in CM frame





$$m_{\text{BS}} = m_{\text{He}} + m_{\eta} - E_{\text{BE}}$$

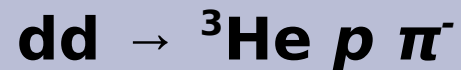
Search for a resonance-like structure
with maximum below the $\eta\text{-}^4\text{He}$ production threshold



Experiments

June 2008

Channels:



Normalization:

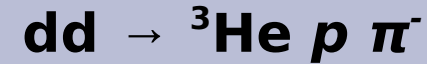


Q: -51 to 22 MeV

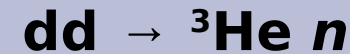
P: 2.185 to 2.4 GeV/c

November-December 2010

Channels:

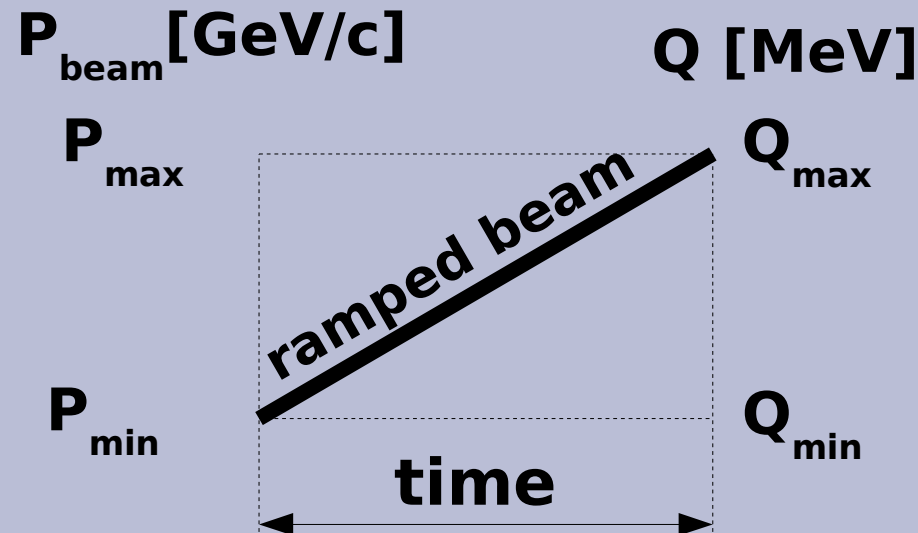


Normalization:



Q: -70 to 30 MeV

P: 2.127 to 2.422 GeV/c

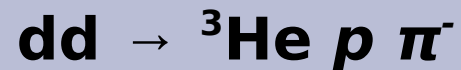




Experiments

June 2008

Channels:



Normalization:

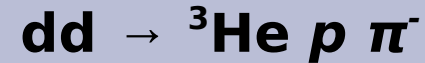


Q: -51 to 22 MeV

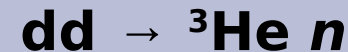
P: 2.185 to 2.4 GeV/c

November-December 2010

Channels:



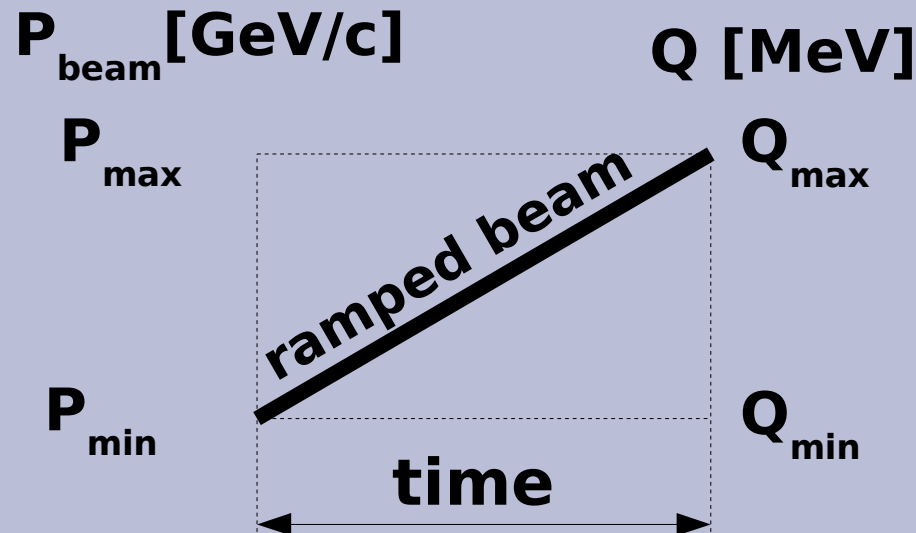
Normalization:



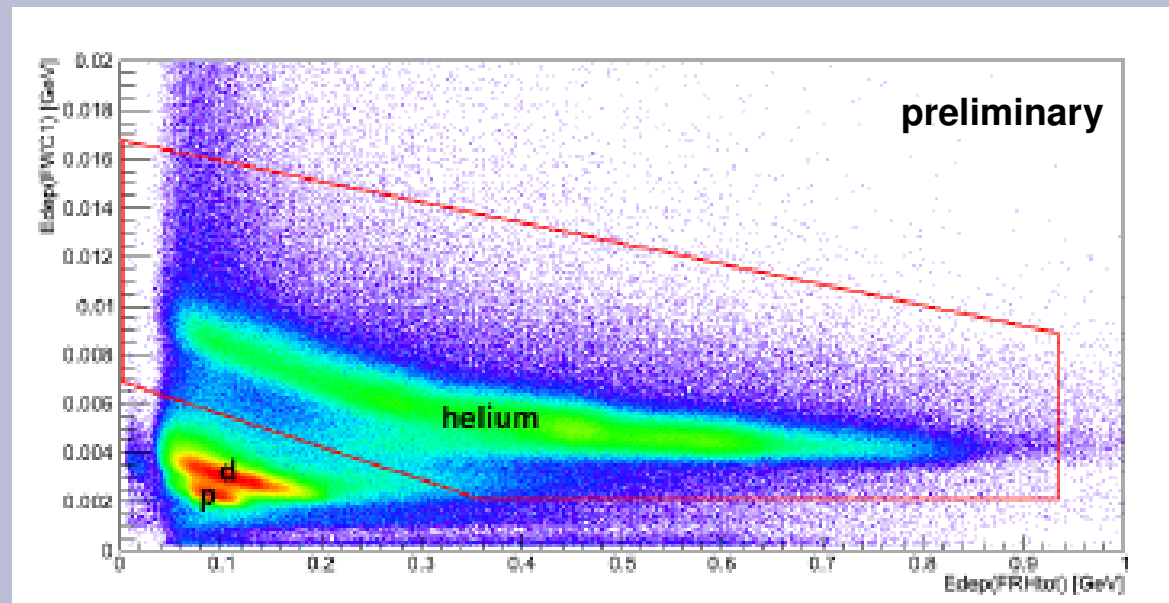
Q: -70 to 30 MeV

P: 2.127 to 2.422 GeV/c

~40 x more statistics

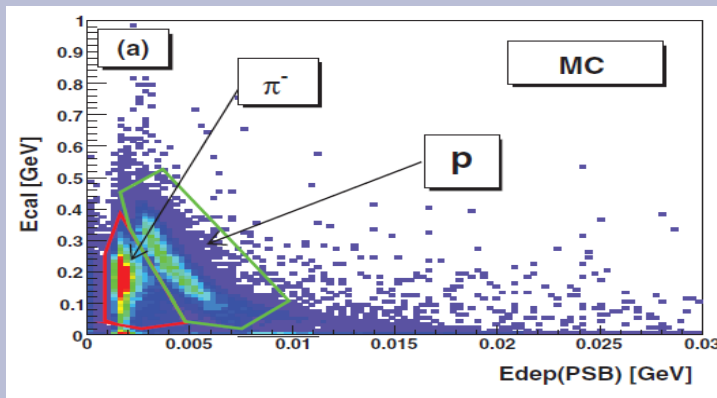
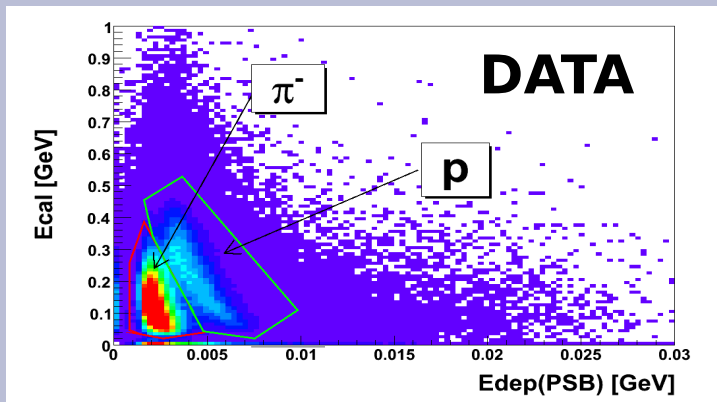
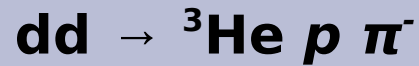


^3He ions identification in Forward Detector

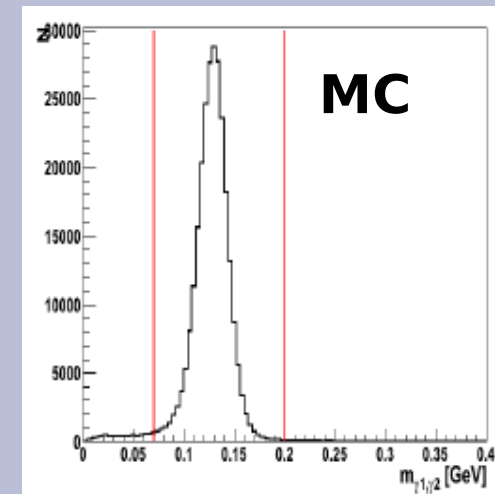
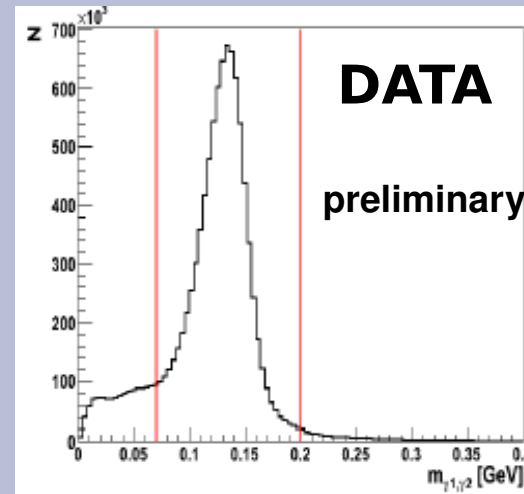




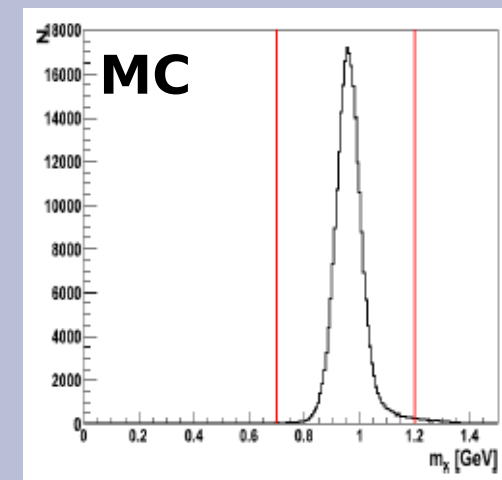
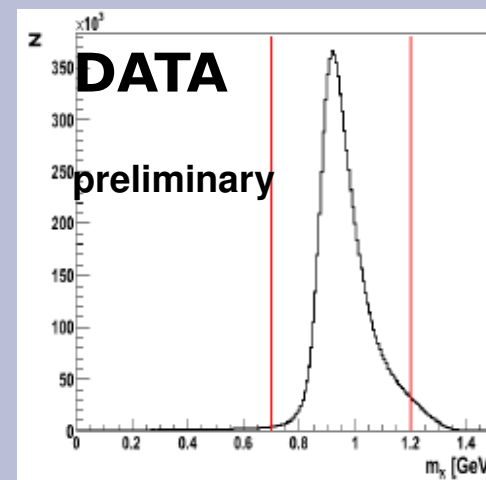
N- π identification



**p- π^- identification
in Central Detector**

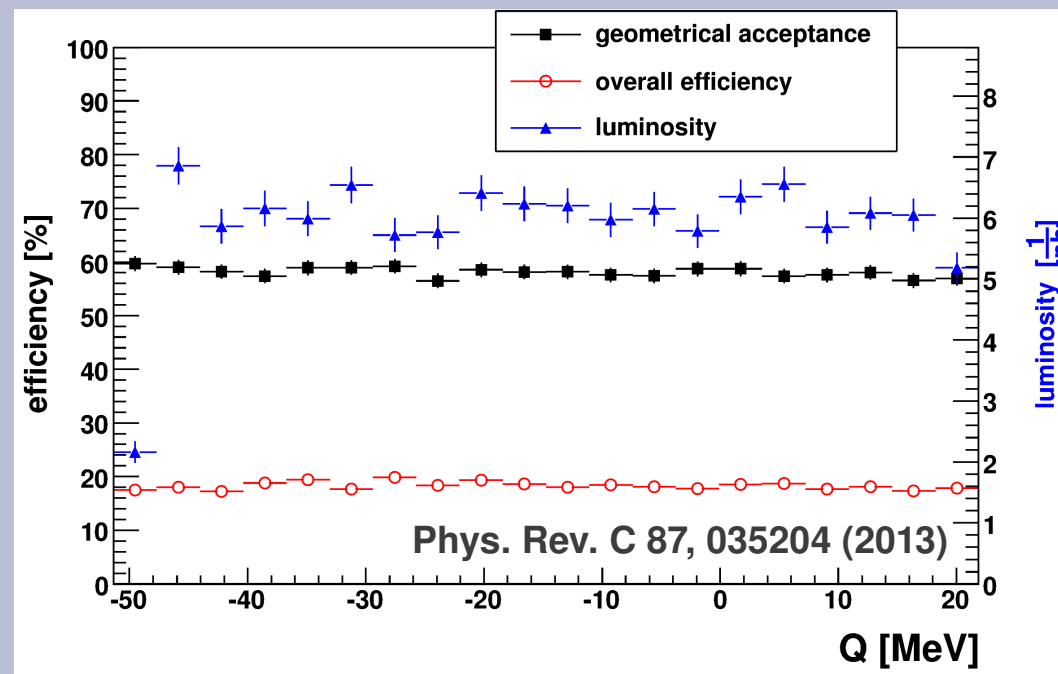
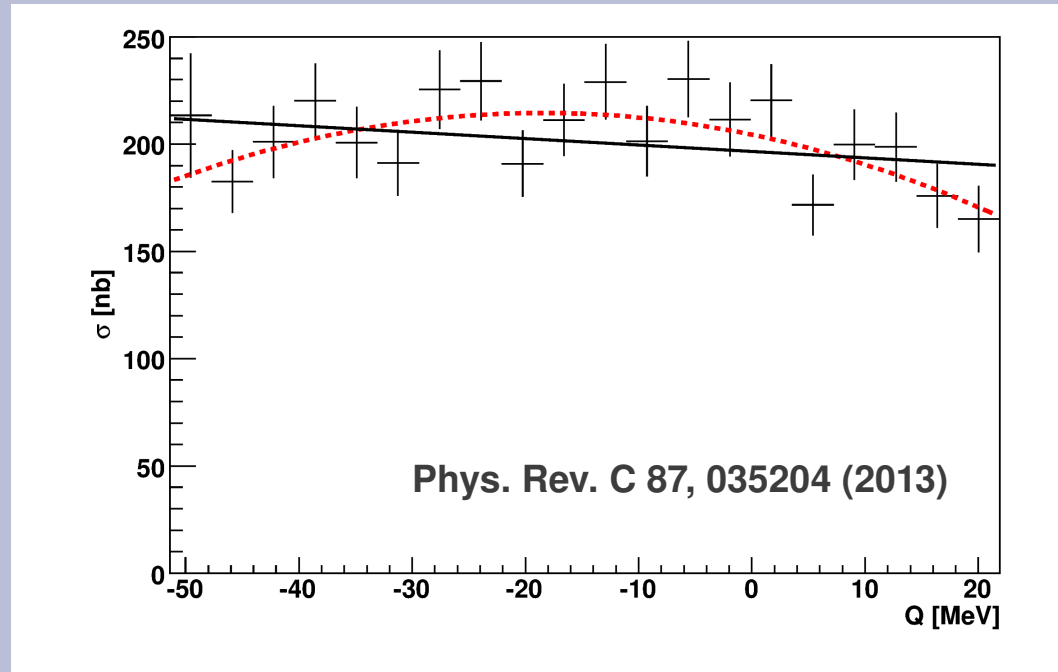


π^0 identification in Central Detector



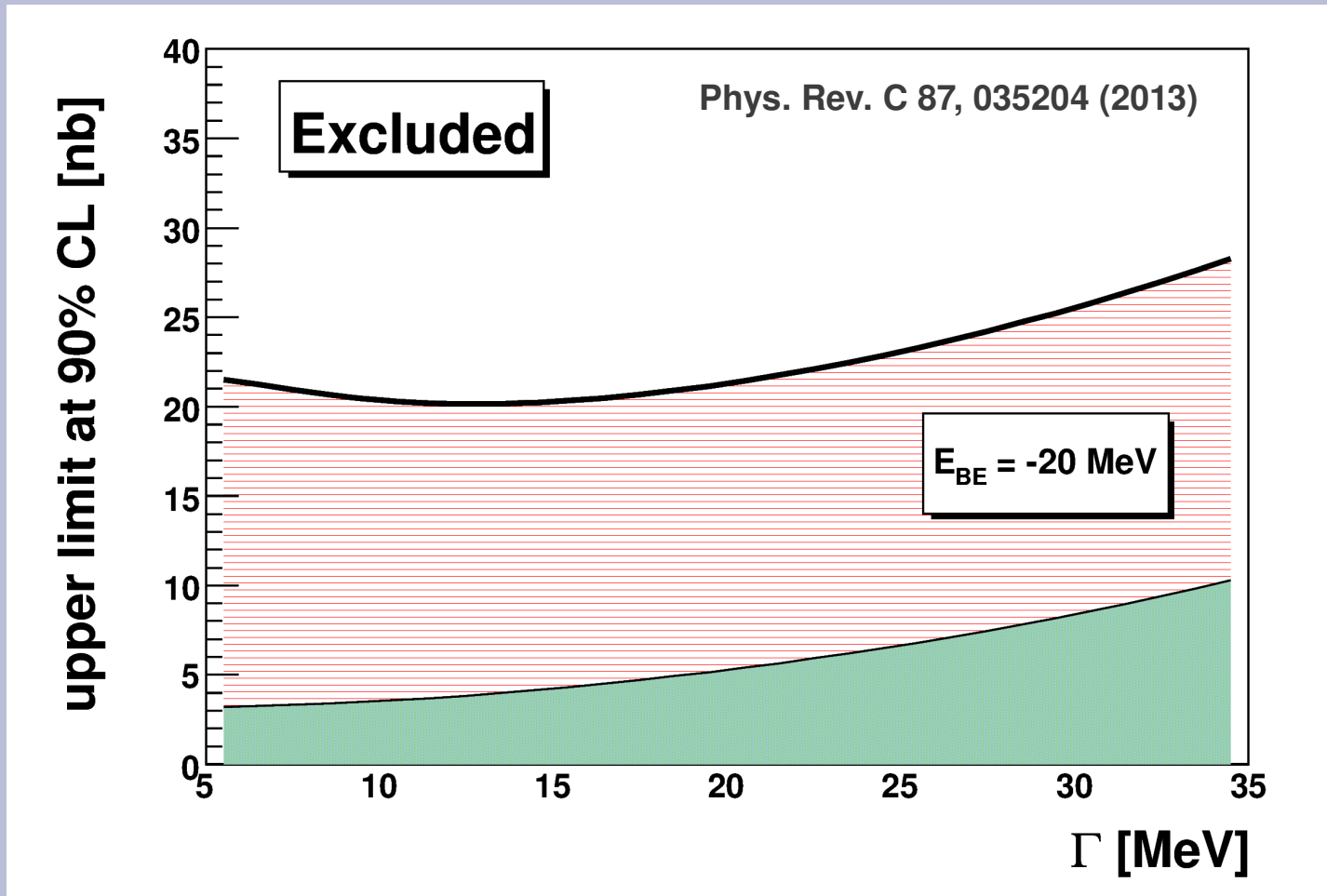
n identification via missing mass technique

Excitation function (normalized and corrected for efficiency)





Upper limit of the maximum cross-section for the reaction $dd \rightarrow ({}^4\text{He} - \eta)_{\text{bound}} \rightarrow {}^3\text{He} p \pi^-$





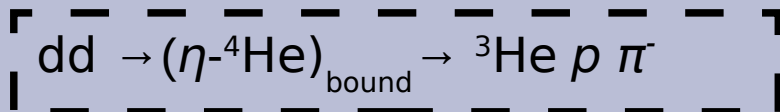
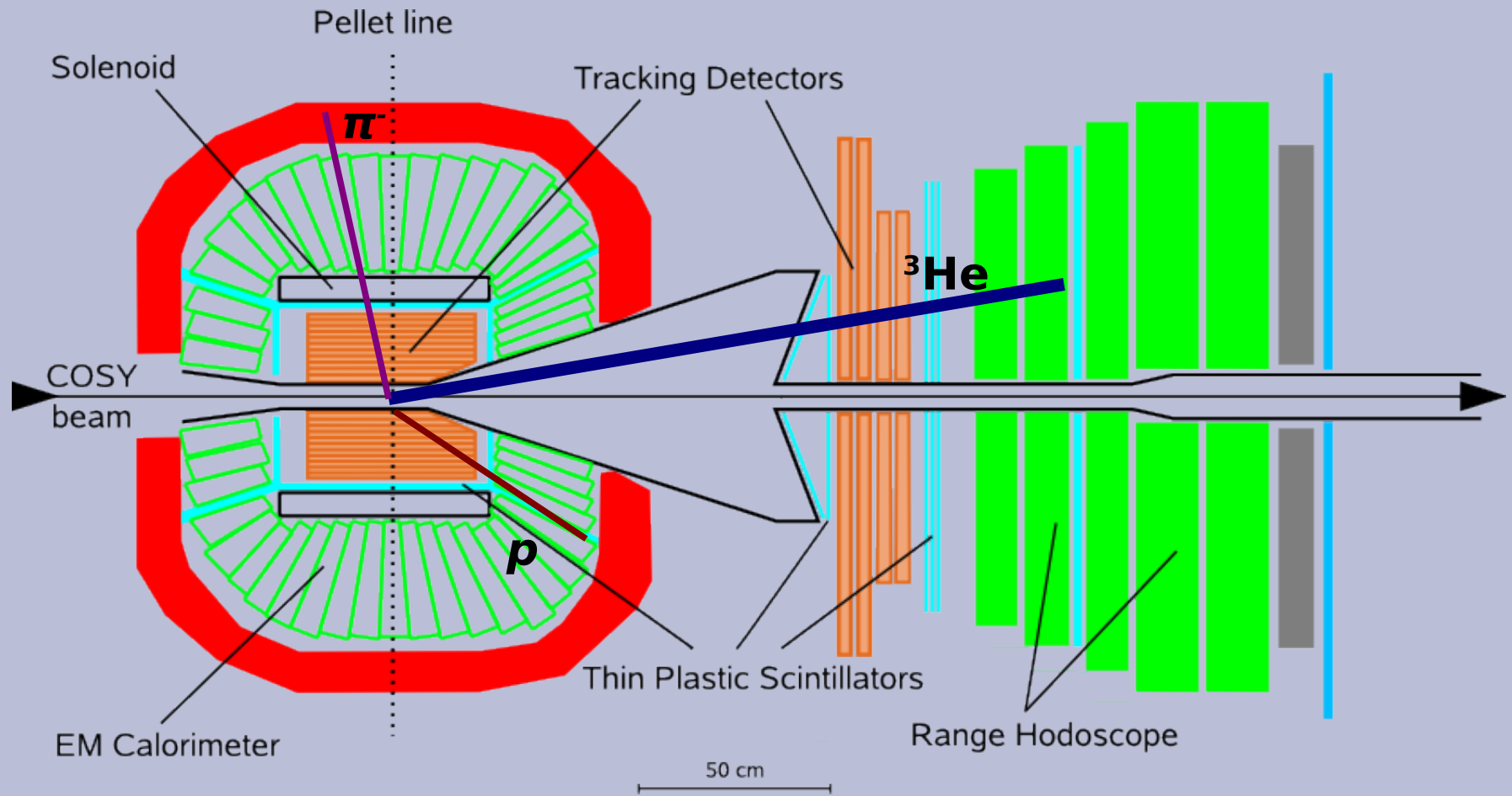
Summary

- Exclusive measurement with ramped beam
- two reaction channels:
 - $dd \rightarrow {}^3\text{He } p \pi^-$
 - $dd \rightarrow {}^3\text{He } n \pi^0 \rightarrow {}^3\text{He } n \gamma\gamma$
- no η - ${}^4\text{He}$ bound state observed in (2008 data).
- upper limit estimated: from 20 to 27 nb (on 90 % C.L.) (2008 data)
- analysis of the new data set is ongoing.

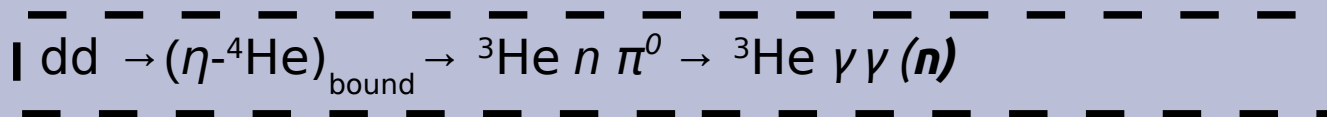
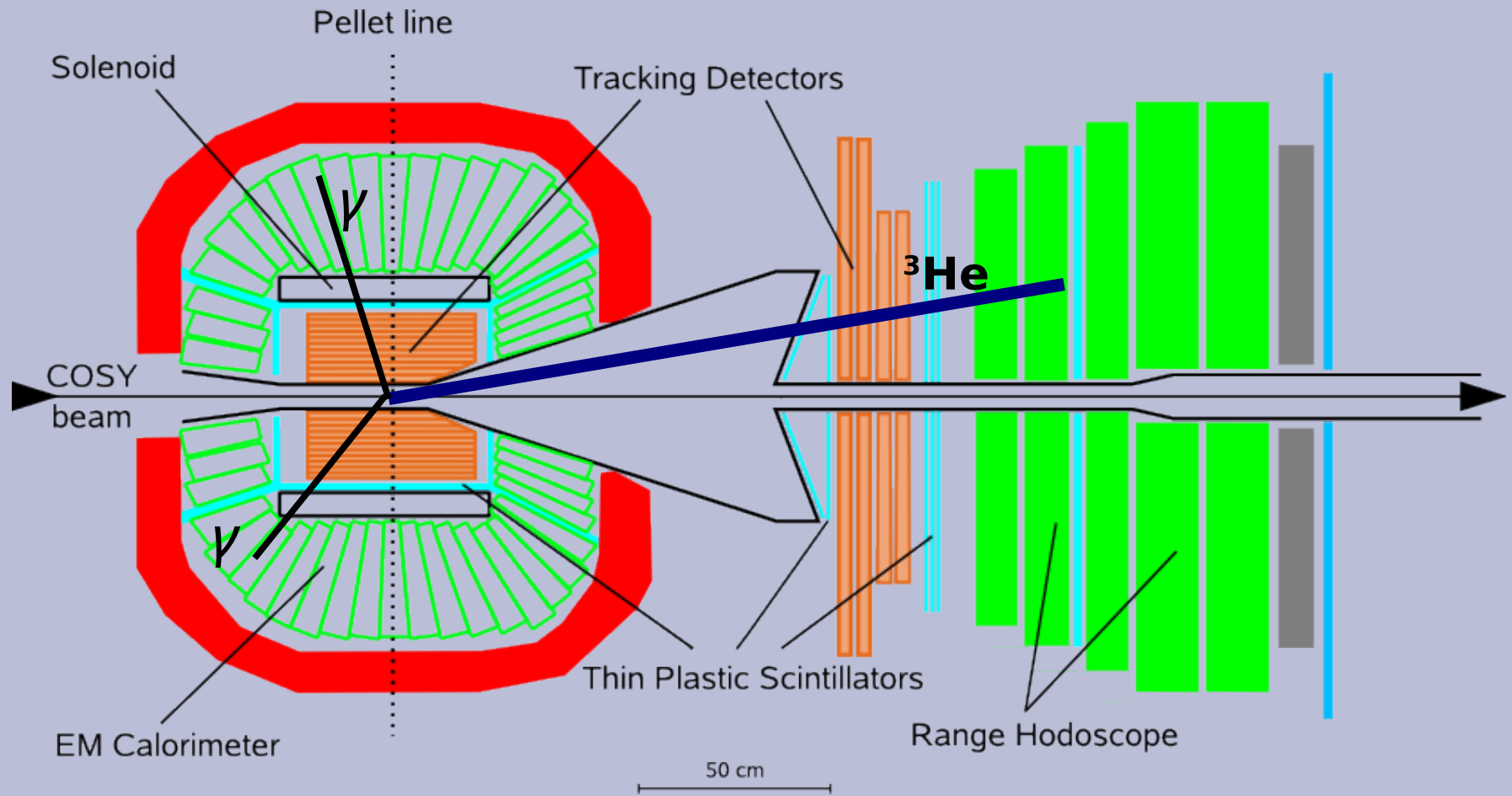


Thank you

WASA-at-COSY

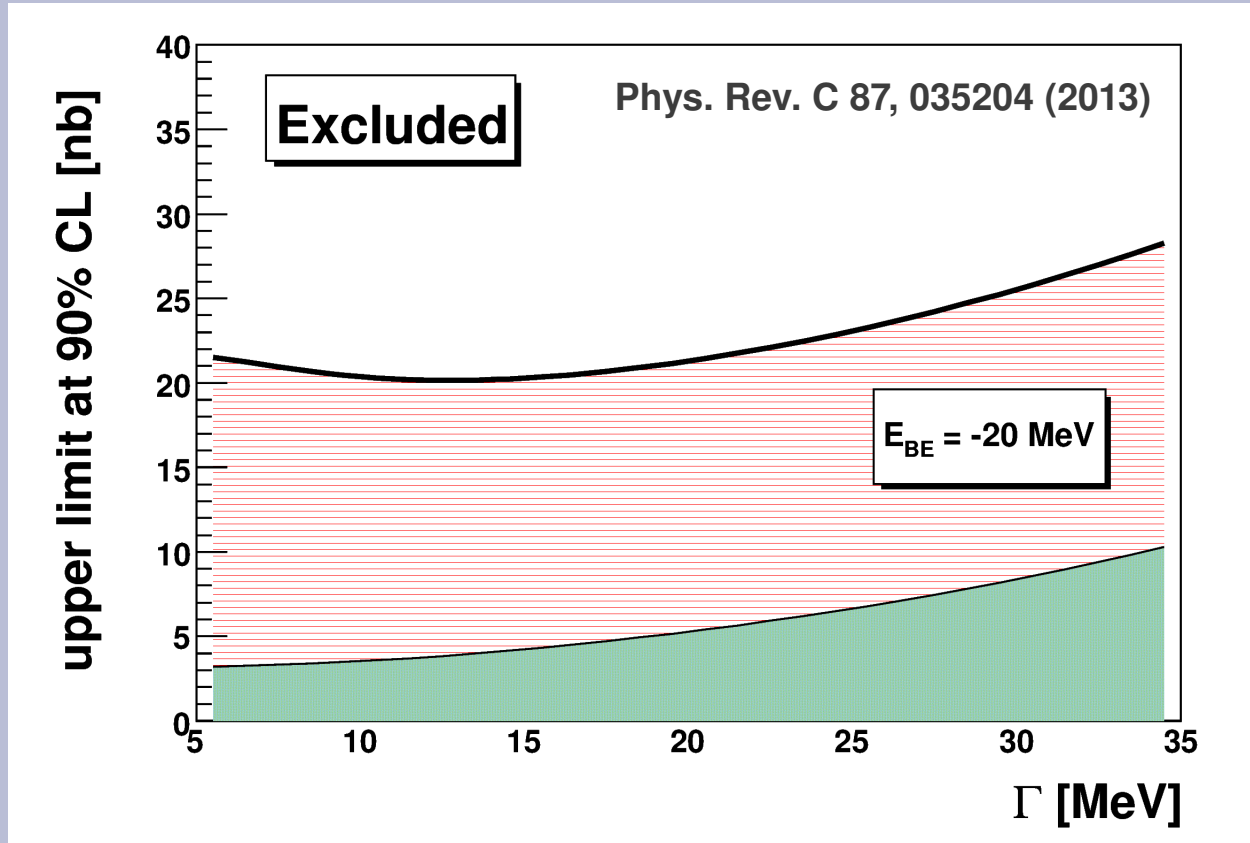


WASA-at-COSY





Upper limit of the maximum cross-section for the reaction $dd \rightarrow ({}^4\text{He} - \eta)_{\text{bound}} \rightarrow {}^3\text{He} p \pi^-$



Signal:

$$\sigma(Q, E_{BE}, \Gamma, A) = \frac{A \left(\frac{\Gamma}{2}\right)^2}{(Q - E_{BE})^2 + \left(\frac{\Gamma}{2}\right)^2}$$

Background: $BG = a_0 + a_1 Q + a_2 Q^2$ **or** $BG = a_0 + a_1 Q$

History of a search for η -mesic nuclei



- **1985: Bhalerao & Liu:**

attractive interaction η -N

- **1986: Haider & Liu:**

first predictions for η -mesic nuclei (for $A > 10$)

- **Series of experiments (no conclusive results):**

Chrien et al. (1998) $\pi^+ + {}^{16}\text{O} \rightarrow p + \eta\text{-}^{15}\text{O}$

Johnson et al. (1993) $\pi^+ + {}^{18}\text{O} \rightarrow \pi^- + \eta\text{-}^{18}\text{O}$

- **1993-2002 new data:**

η -N scattering length much bigger than expected.

- **1991-2002 T. Ueda, C. Wilkin, S.A. Rakityansky and others:**

new calculations and theoretical models which predict the existence of the η -mesic nuclei with light nuclei e.g. $d\text{-}\eta$, ${}^3\text{He}\text{-}\eta$, ${}^4\text{He}\text{-}\eta$, $\text{T}\text{-}\eta$



COSY accelerator in Juelich (Germany)



Beam:

- Unpolarized and polarized protons or deuterons.

Energy range:

- T_p to 2.8 GeV
- T_d to 2.3 GeV

(maximum momentum: 3.7 GeV/c)

Cooling:

- stochastic
- Electron beam

Nb of particles: 10^{11}

Ramped beam

Experiments, detectors:

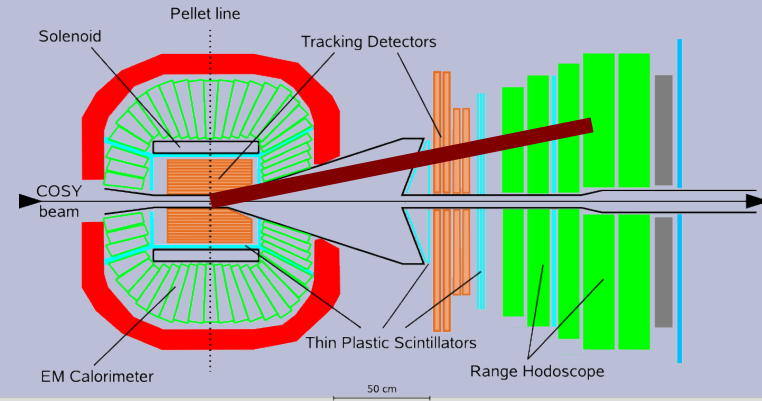
ANKE, EDDA, WASA, TOF

(COoler SYnchrotron)



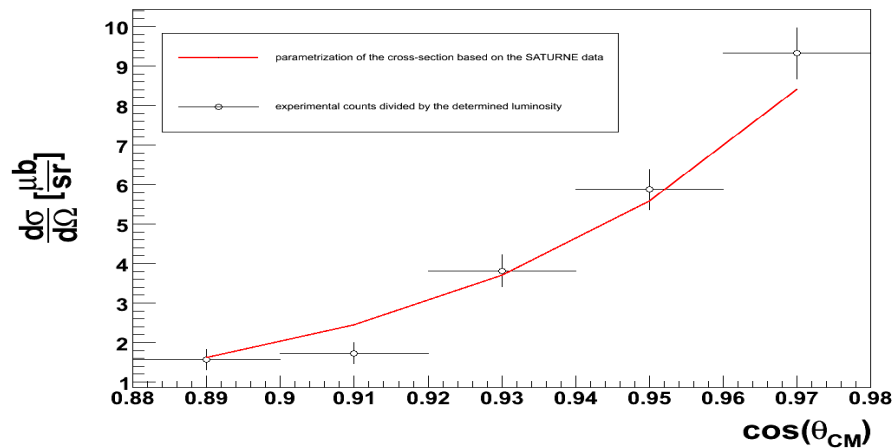
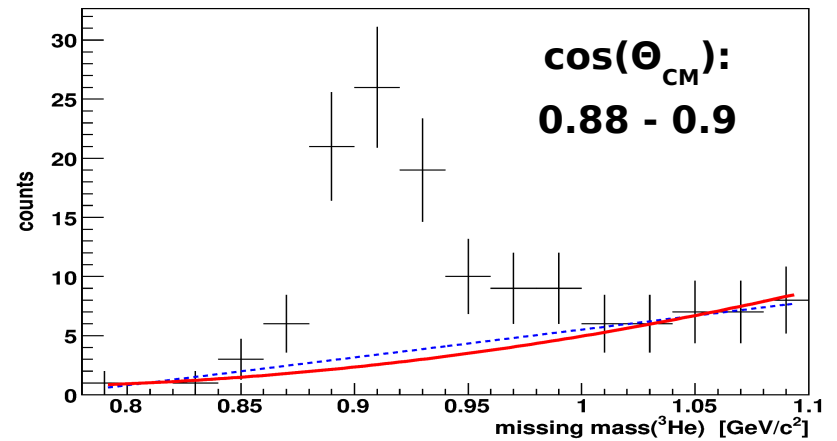
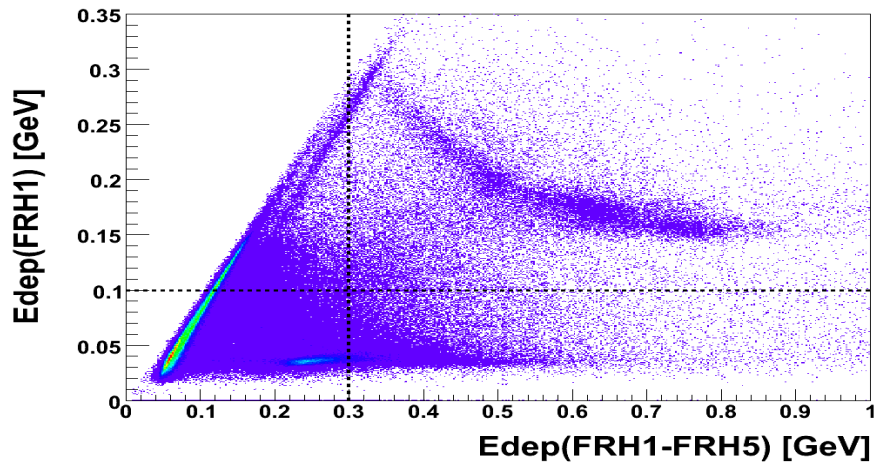
Luminosity I

Absolute normalization
 $dd \rightarrow {}^3\text{He} n$



${}^3\text{He}$ selection

MM(${}^3\text{He}$) -neutron



$$L = 117.9 \pm 13.6 \text{ nb}^{-1}$$

stat: $\pm 4.5\%$
syst(background subtract): $\pm 8\%$
param. from SATURNE: $\pm 7\%$

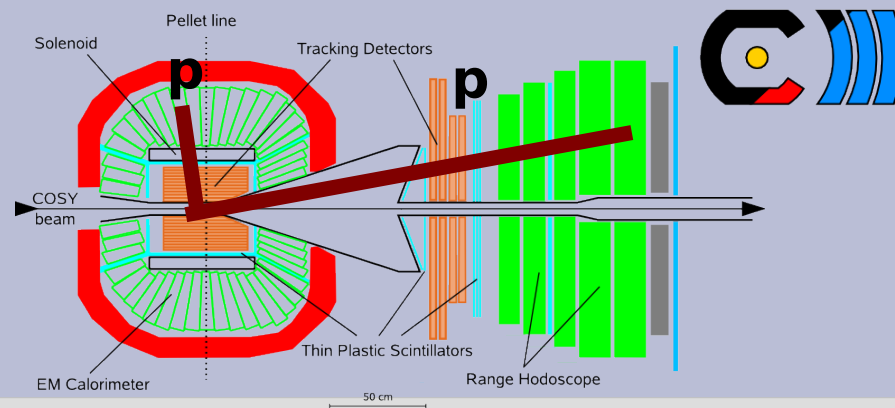
Parametrization from: Annette Pricking PhD
Universität Tübingen, Germany (2011)

Reference to SATURNE data: G.~Bizard et al., Phys. Rev. C 22 (1980) 1632.

Luminosity II

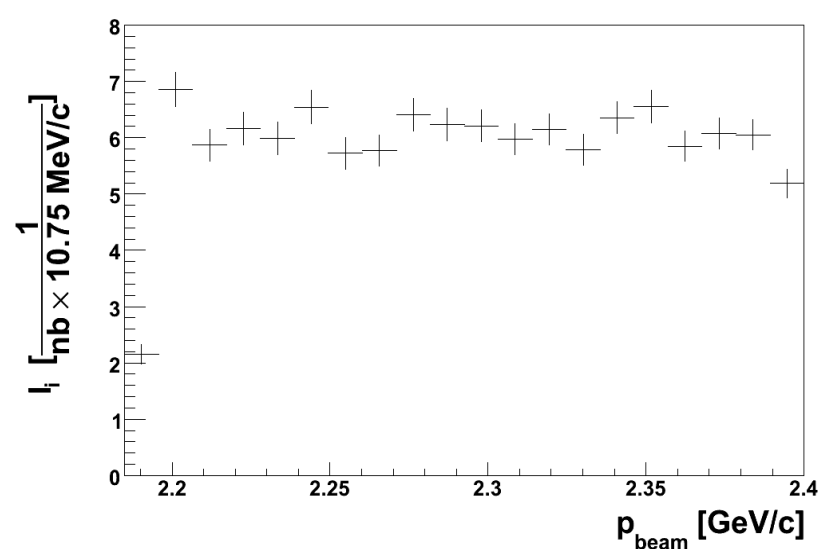
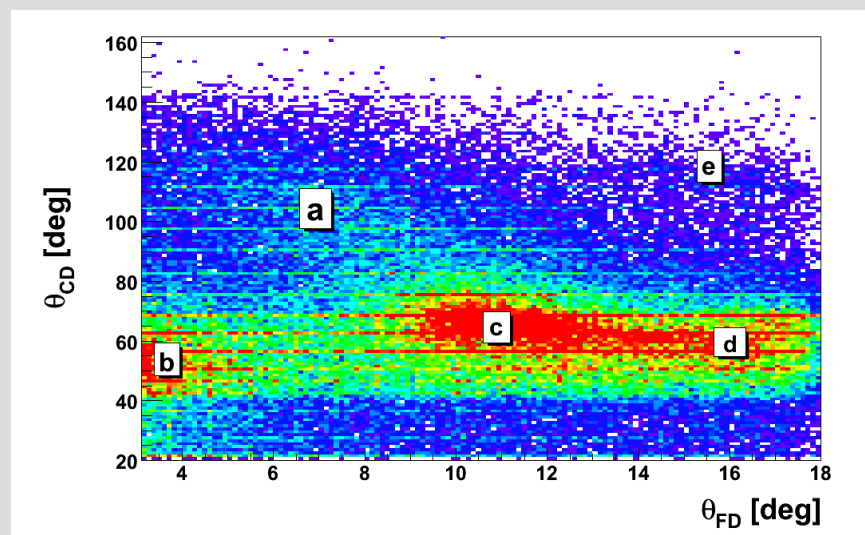
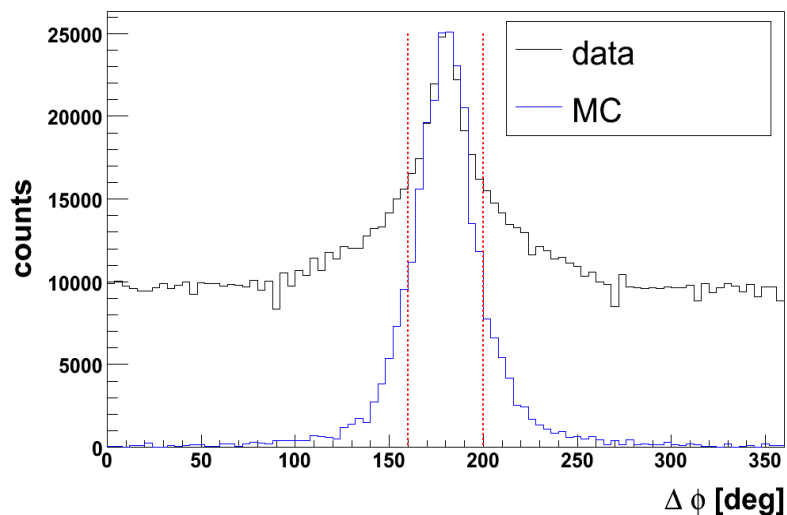
(beam momentum dependence)

Quasi-elastic scattering:
 $dd \rightarrow pp (nn)_{\text{spec}}$



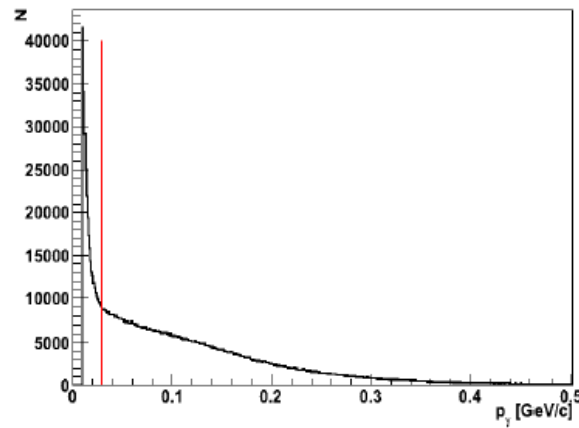
- One charged in FD & one charged track in CD.
- Coplanarity condition $\Delta\phi < 20 \text{ deg.}$
- Cut on E in scintillator barrel (π background reduction).

Coplanarity

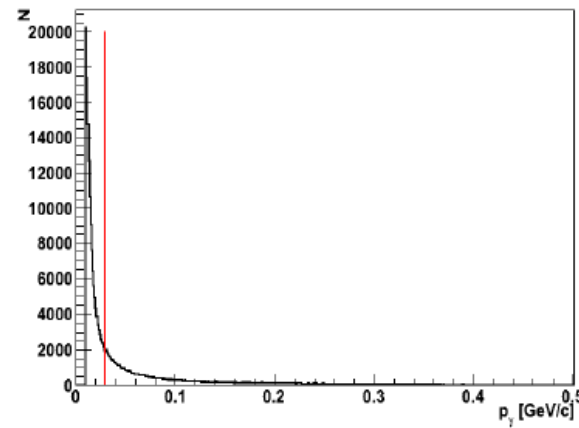




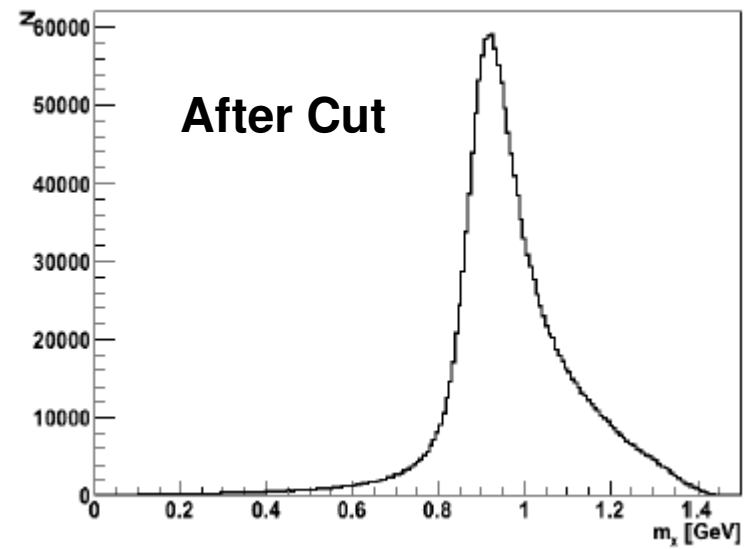
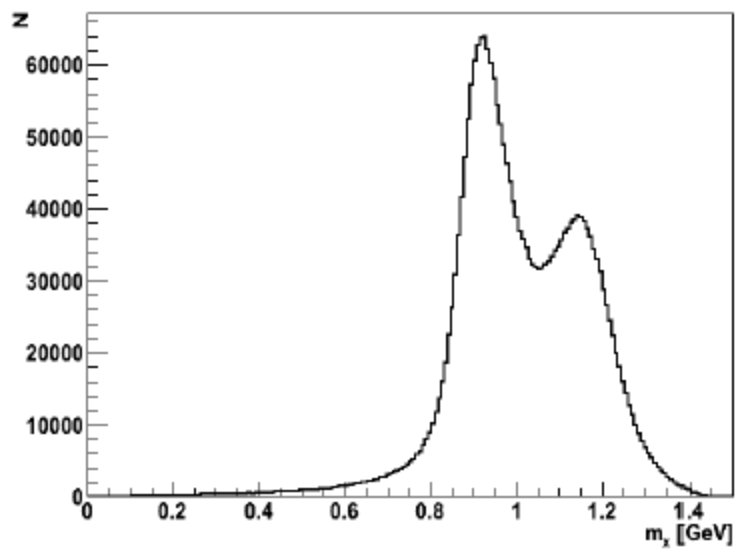
combination of 2γ



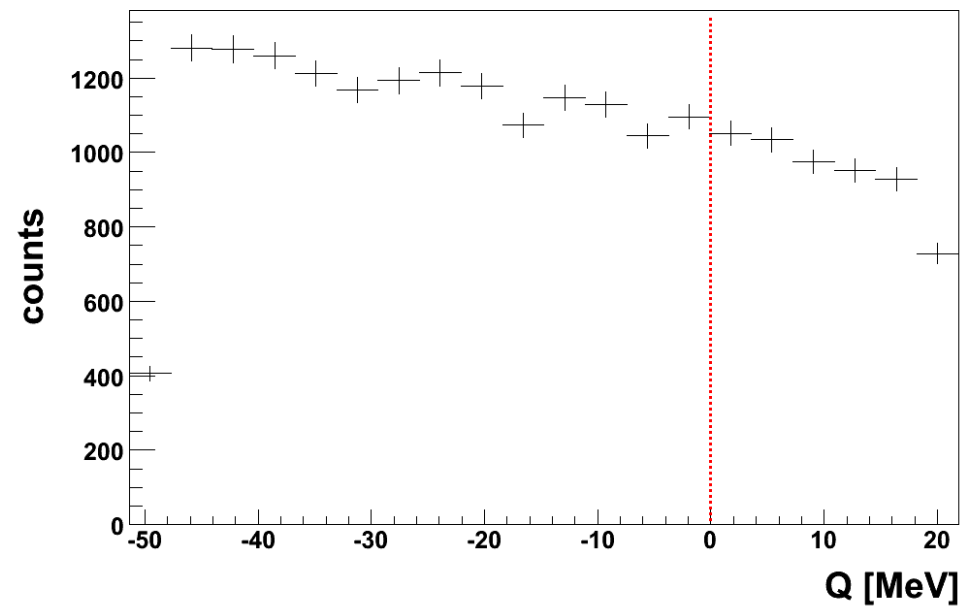
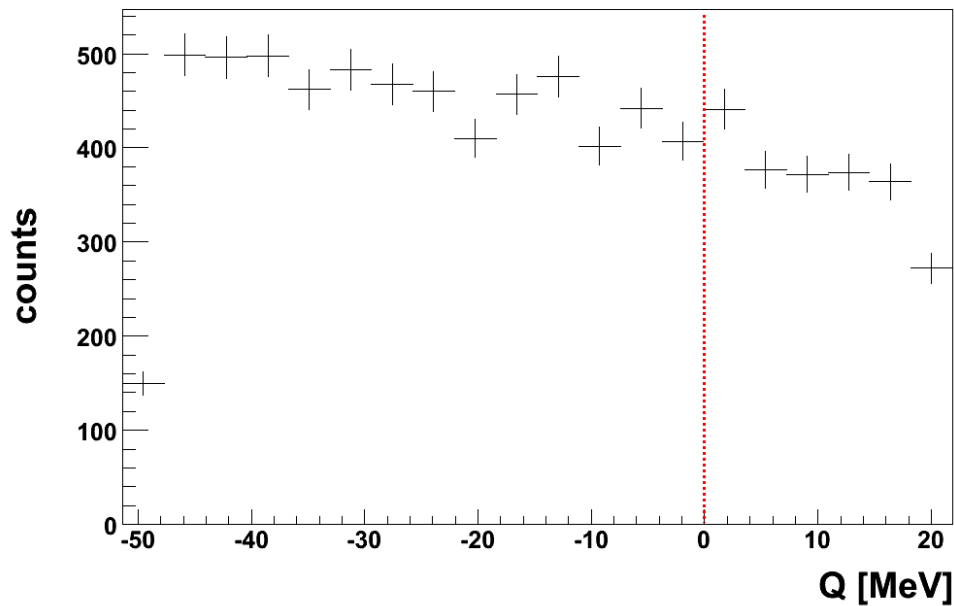
DATA



WMC

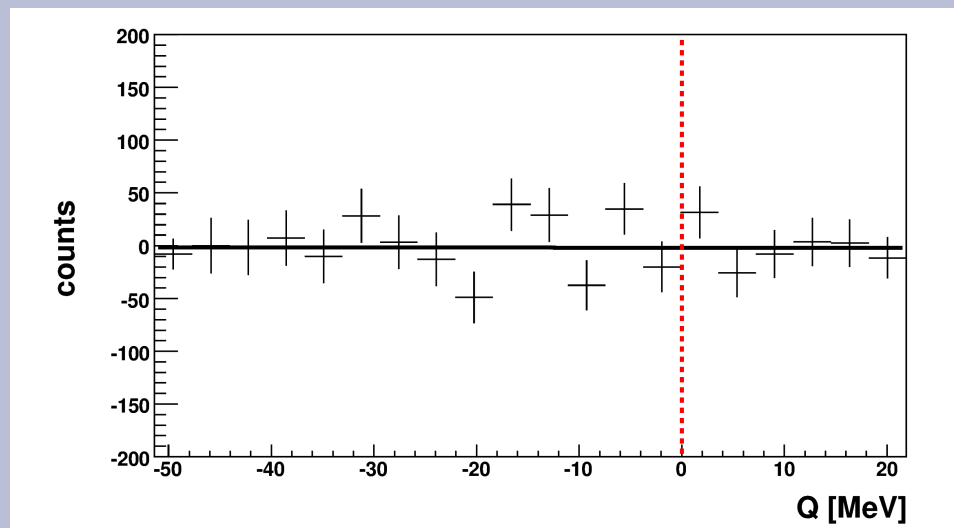


Excitation functions (not normalized)



“Signal-rich” region
($P_{HE}^{CM} < 0.3 \text{ GeV}/c$)

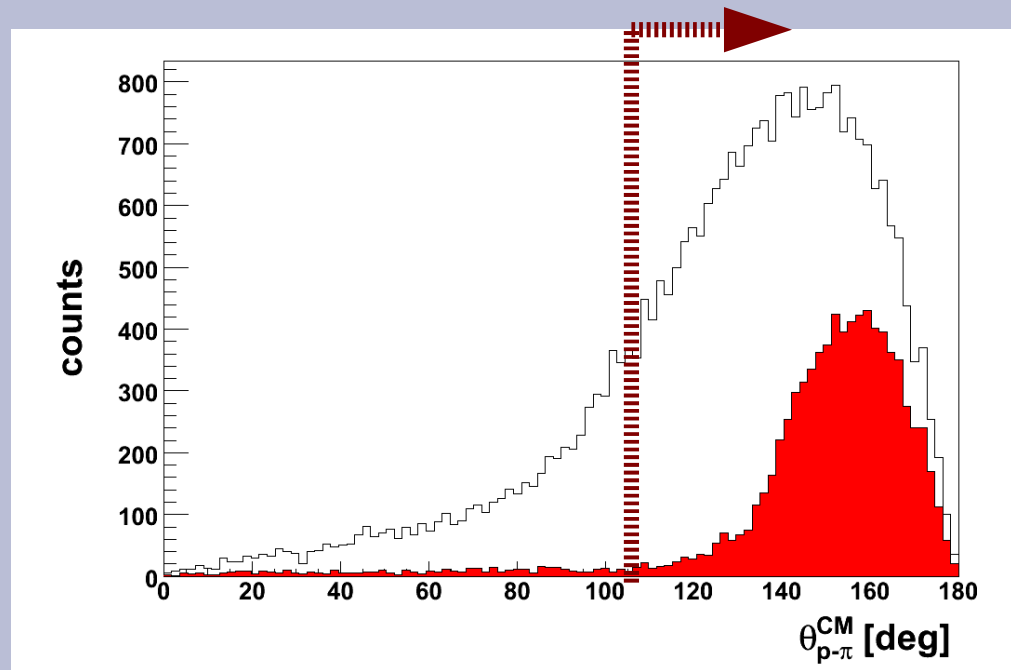
“Signal-poor” region
($P_{HE}^{CM} \geq 0.3 \text{ GeV}/c$)



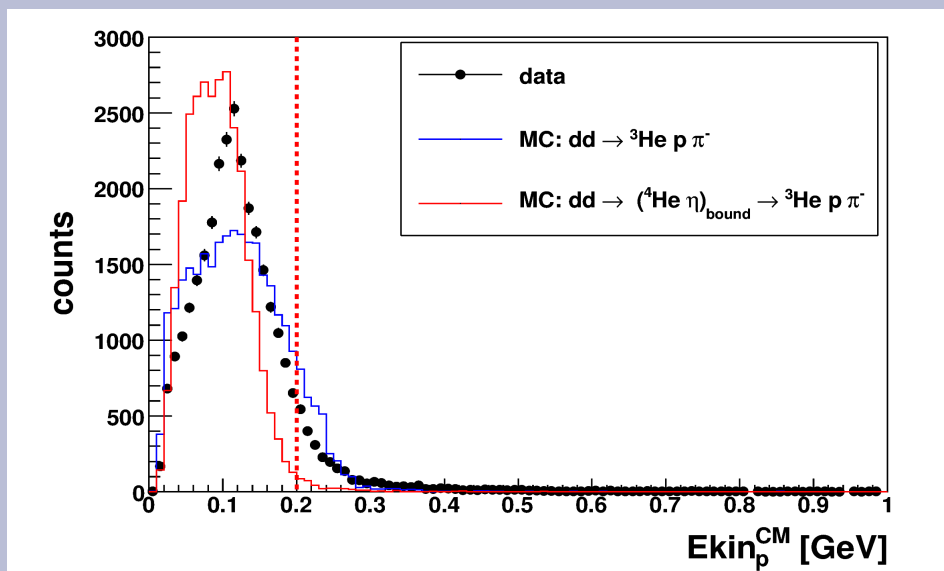
difference



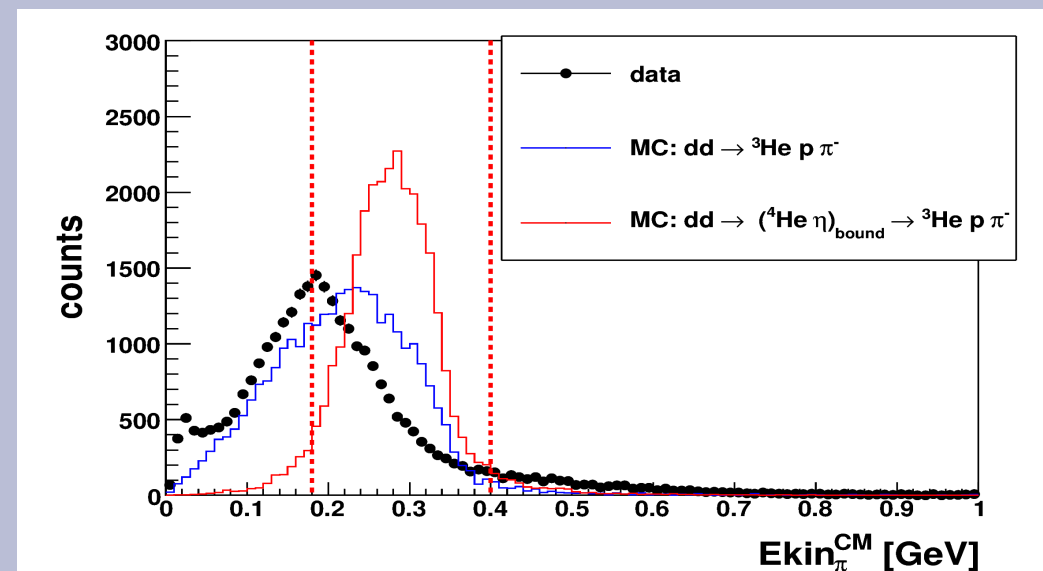
Additional cuts



$$\Theta_{p-\pi}^{\text{CM}} > 140$$

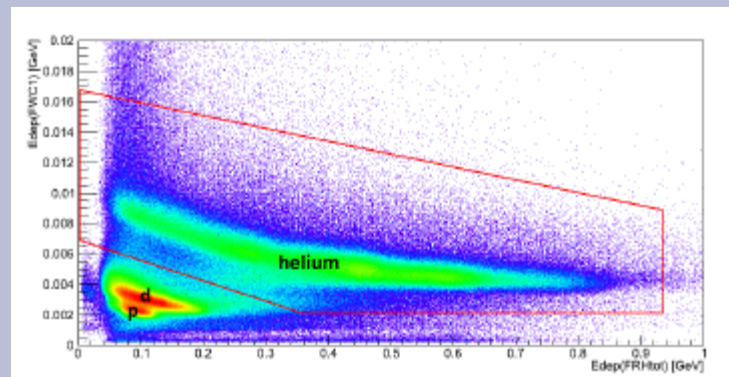
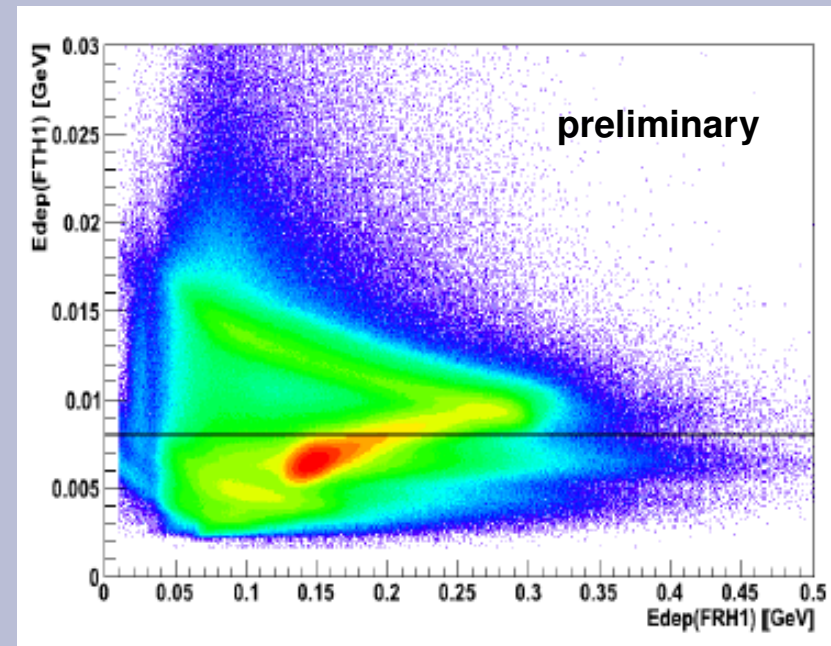
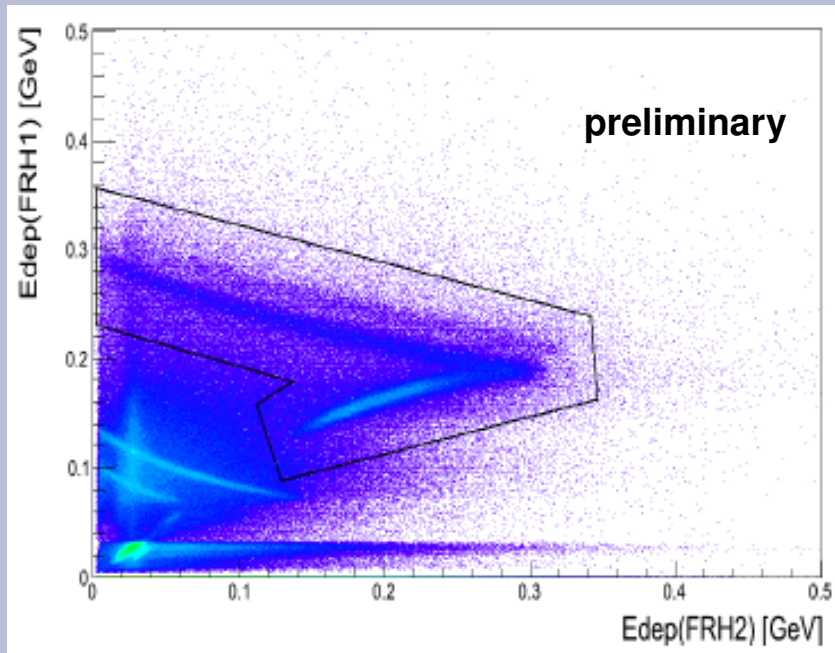


$$E_{\text{kin}_p}^{\text{CM}} < 200 \text{ MeV}$$



$$E_{\text{kin}_\pi}^{\text{CM}} > 180 \text{ MeV} \ \&\& \ E_{\text{kin}_\pi}^{\text{CM}} < 400 \text{ MeV}$$

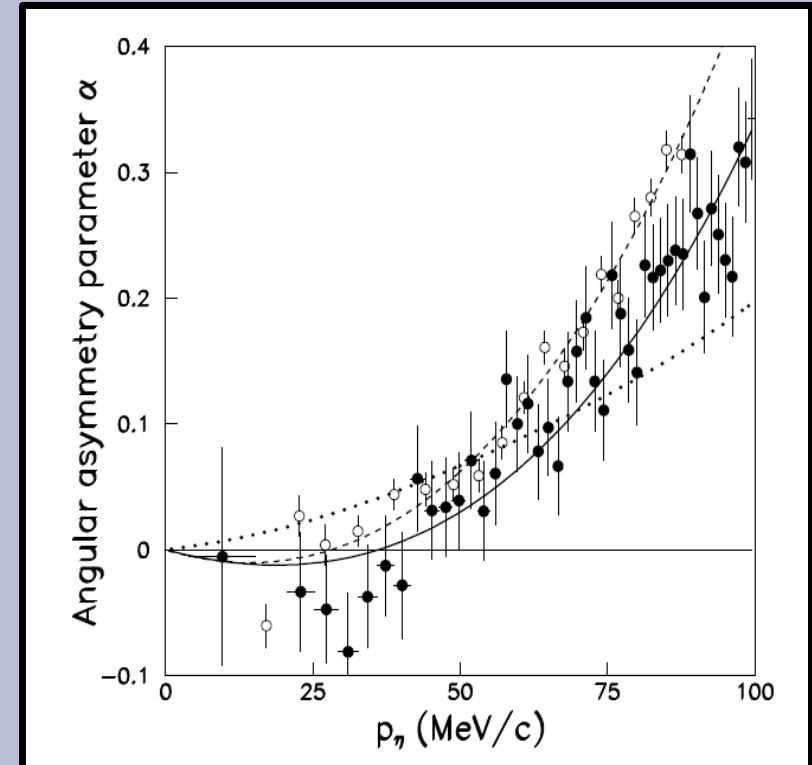
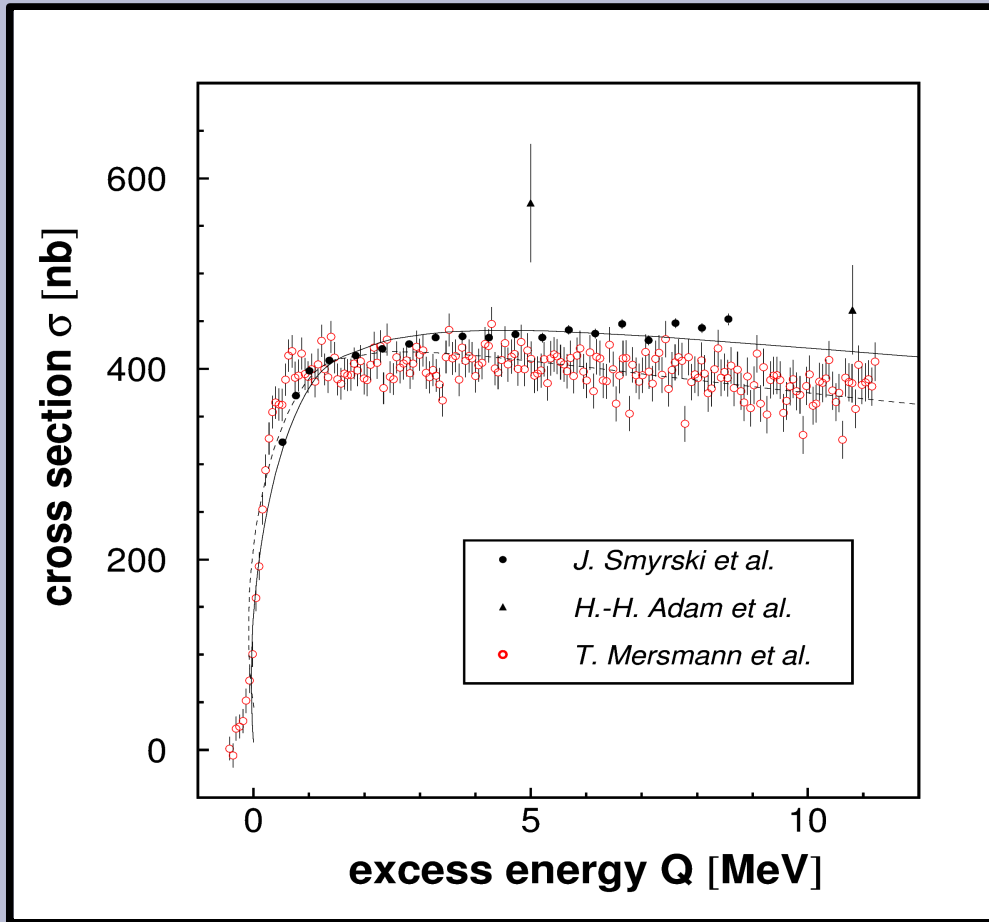
^3He ions identification in Forward Detector



Experimental indications of the existence of a bound state in the η -He system



$dp \rightarrow {}^3\text{He}\eta$



Full black squares: COSY-11
Empty red squares: COSY-ANKE
 (C.Wilkin et al. Phys.Lett. B654 (2007))

Full circles: COSY-ANKE
 (T.Mersmann et al., Phys. Rev. Lett. 98 242301-1-4 (2007))
Empty circles: COSY-11
 (J.Smyrski et al., Phys. Lett B 649 258-262 (2007))

Also total x-section $pd \rightarrow {}^3\text{He}\eta$ and $dd \rightarrow {}^4\text{He}\eta$
 SPES-3 and SPES-4 @SATURNE
 N. Willis et al. Phys.Lett. B406(1997).

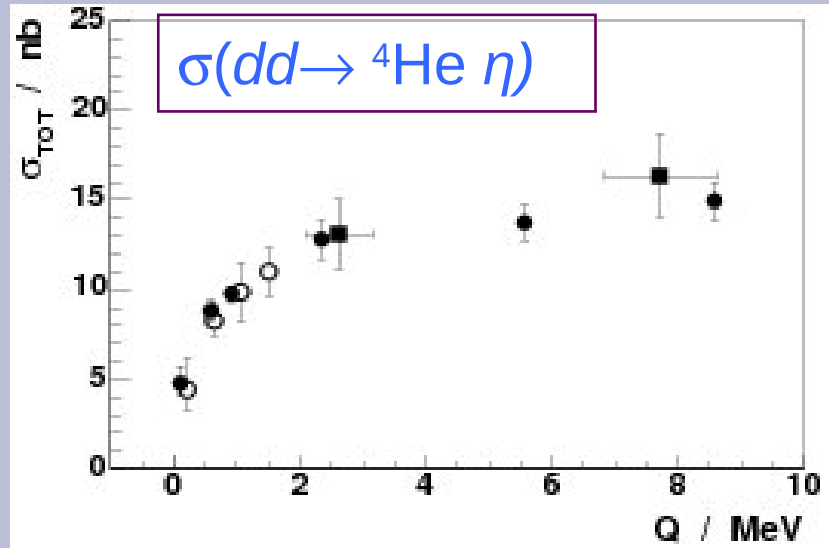
Also total x-section $\gamma{}^3\text{He} \rightarrow \eta{}^3\text{He}$
 Crystal Ball-TAPS@MAMI
 F. Pheron et al. Phys.Lett. B709 (2012).



Cross-section estimate

$dd \rightarrow {}^4\text{He} \eta \rightarrow {}^3\text{He} p \pi^-$

$\sigma \sim 15 \text{ nb}$



R. Frascaria et al., Phys. Rev. C 50 (1994) 573.
 N. Willis et al., Phys. Lett. B 406 (1997) 14.
 A. Wrońska et al., Eur.Phys.J. A26 (2005) 421-428.

Probability of the decay $({}^4\text{He} \eta)_{\text{bound}} \rightarrow {}^3\text{He} p \pi^-$
 $\sim 1/4 \times 1/2 = 1/8$

$dd \rightarrow {}^3\text{He} p \pi^-$

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

$dd \rightarrow T n \pi^+$

$dd \rightarrow T p \pi^0$

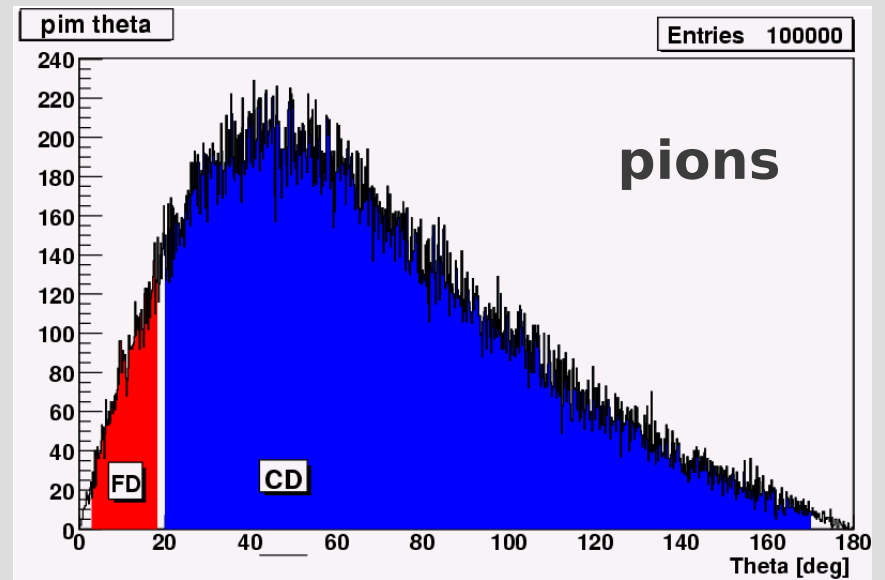
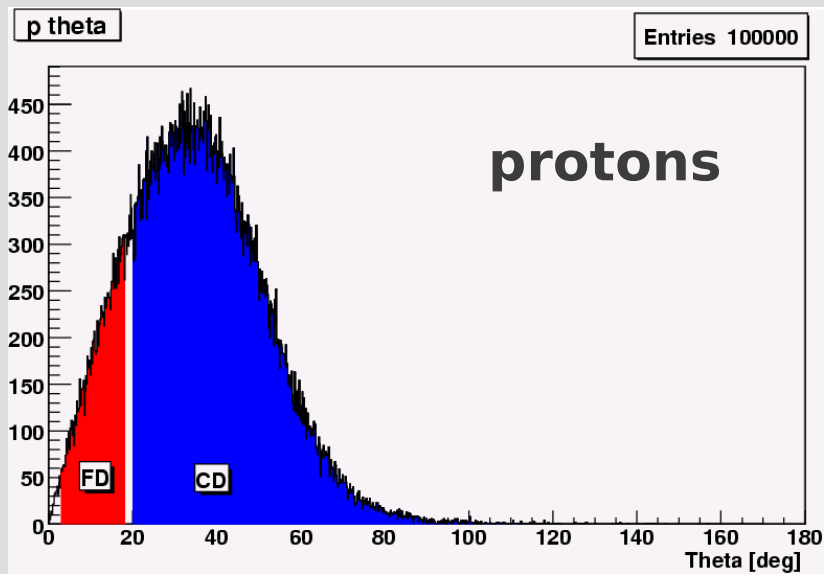
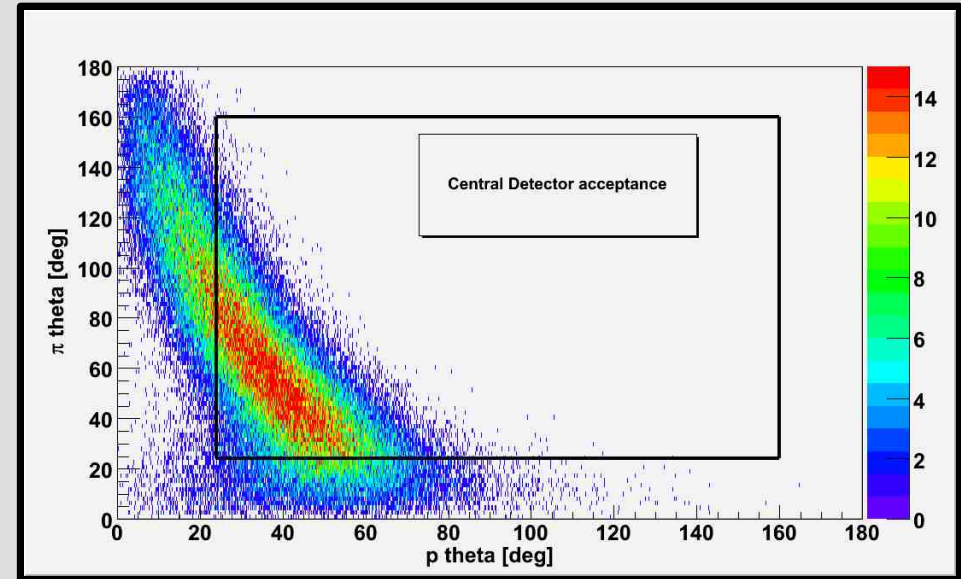
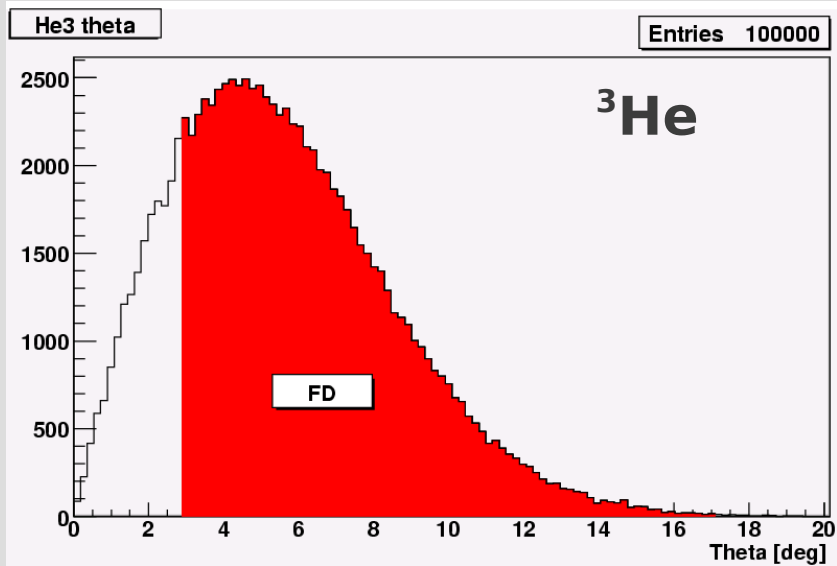
$\eta n \rightarrow p \pi^-$
one of the possible four channels

*Probability that the spectator nucleons (ppn) will form ${}^3\text{He}$
 Per analogy to ${}^4\text{He} \Lambda \rightarrow {}^3\text{He} p \pi^-$*

$\sigma(dd \rightarrow ({}^4\text{He} \eta)_{\text{bound}} \rightarrow {}^3\text{He} p \pi^-) = 2 \text{ nb}$

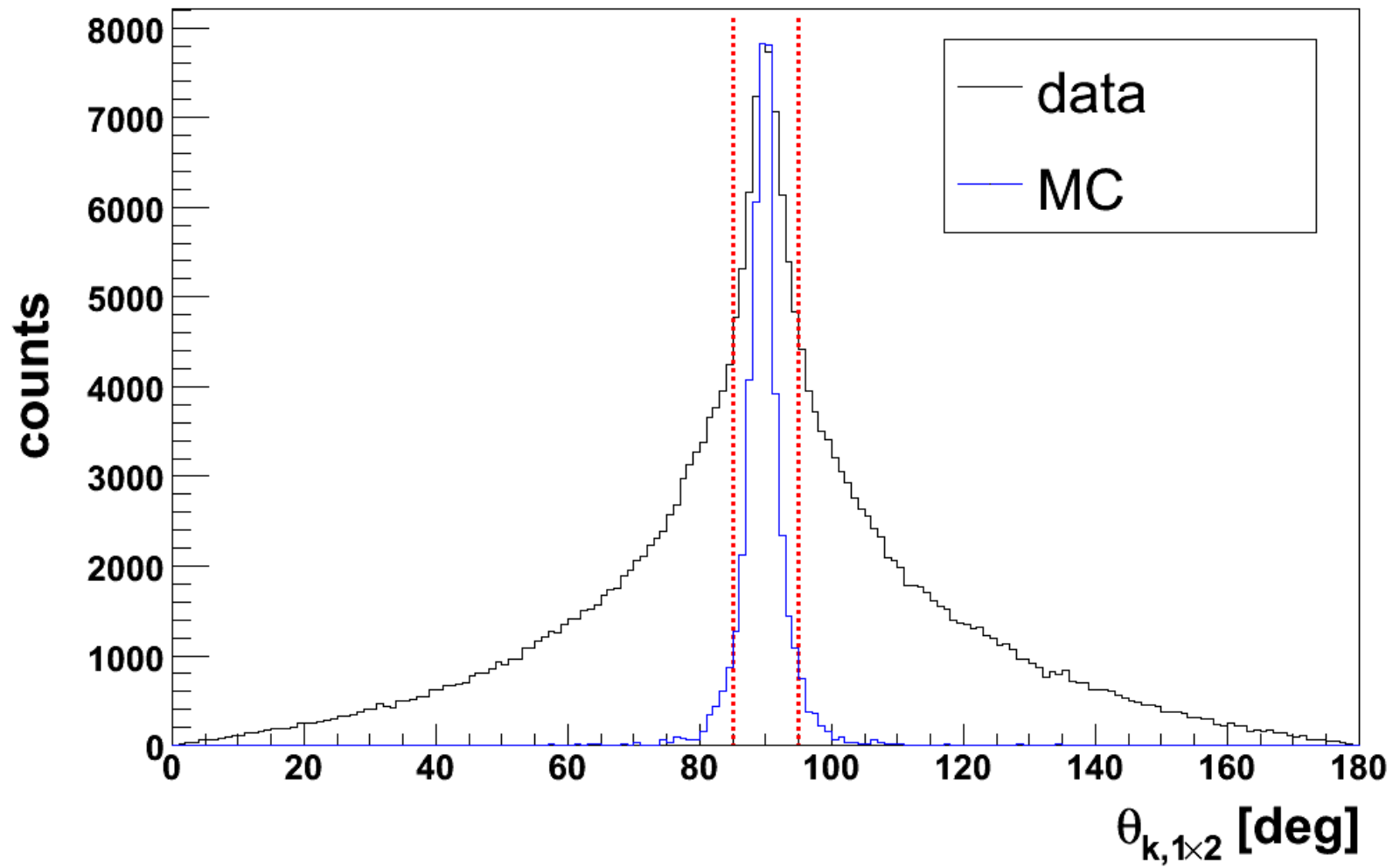


Acceptance for $dd \rightarrow (\eta\text{-}^4\text{He})_{\text{bound}} \rightarrow {}^3\text{He} p \pi^-$

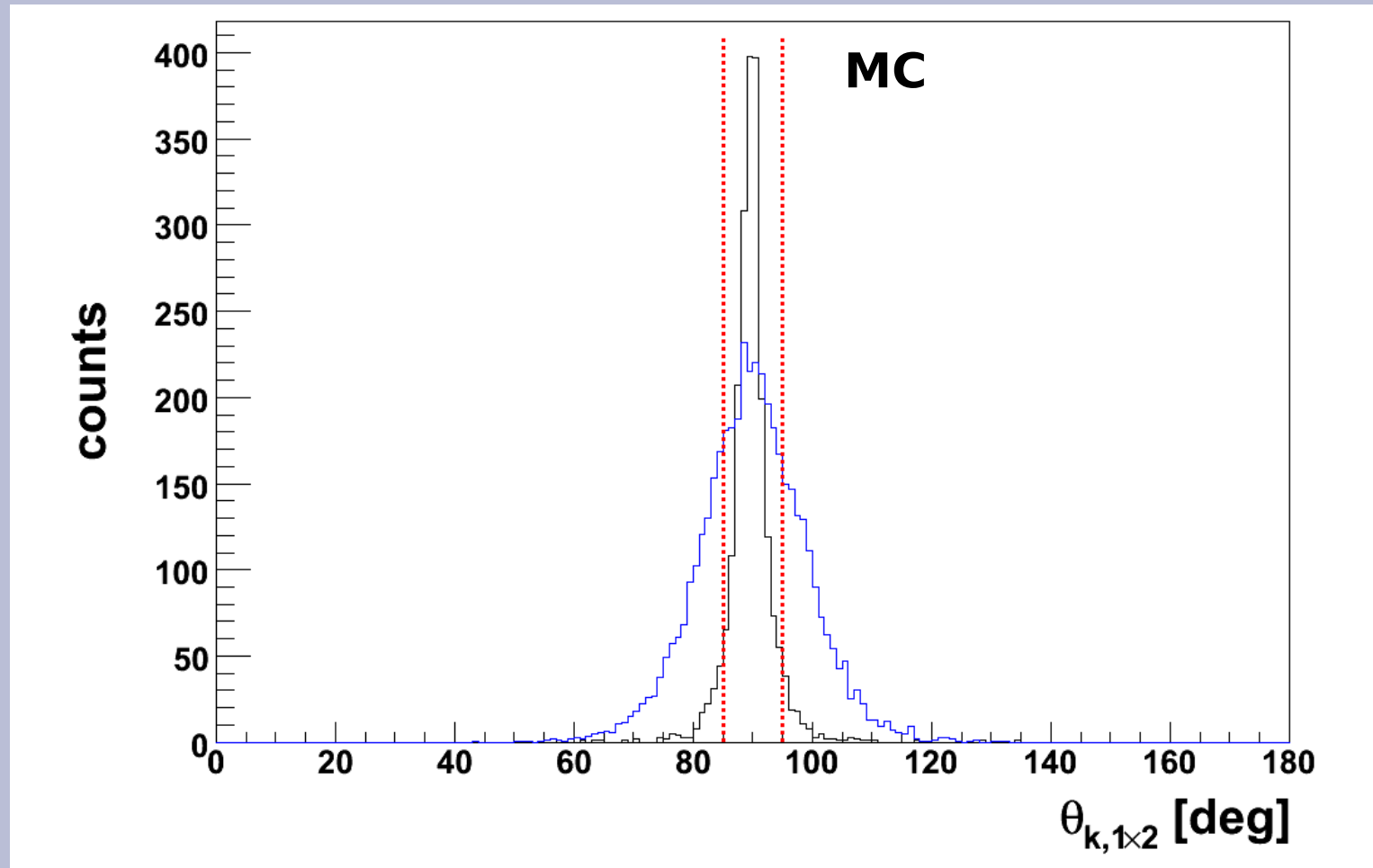




Three-particle cut



Four-particle reactions



- black : $dd \rightarrow {}^3\text{He } p \pi^-$
- blue : $dd \rightarrow {}^3\text{He } p \pi^- \pi^0$



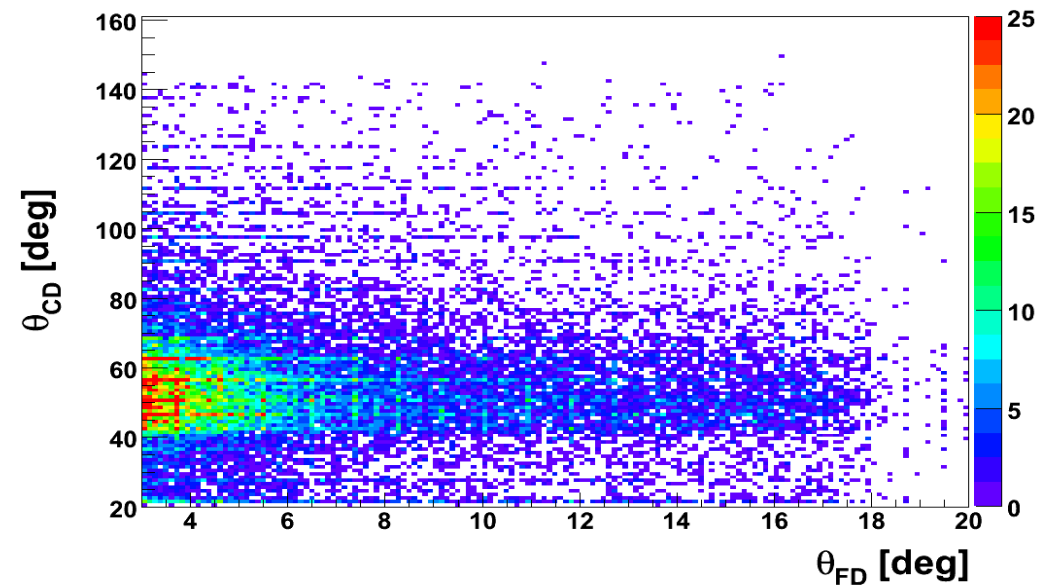
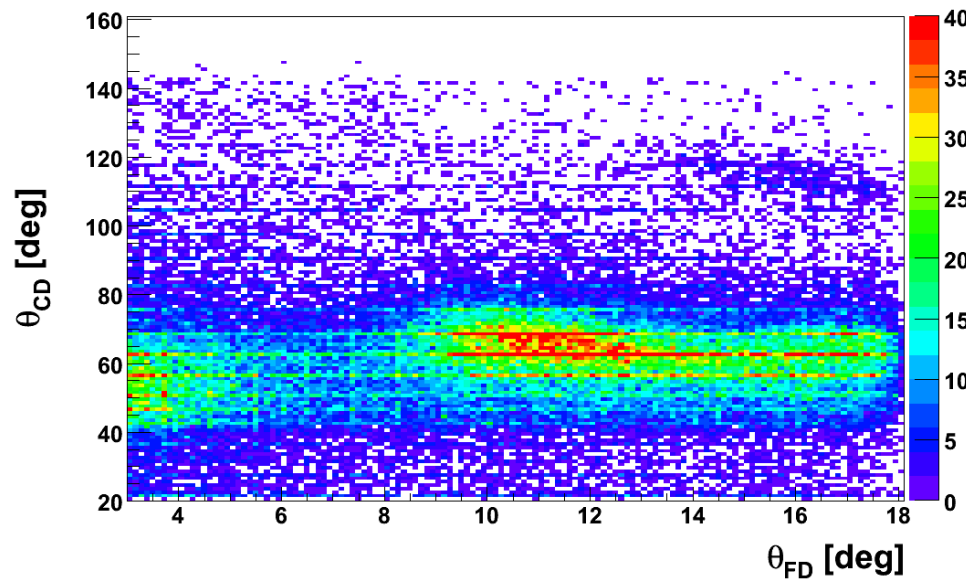
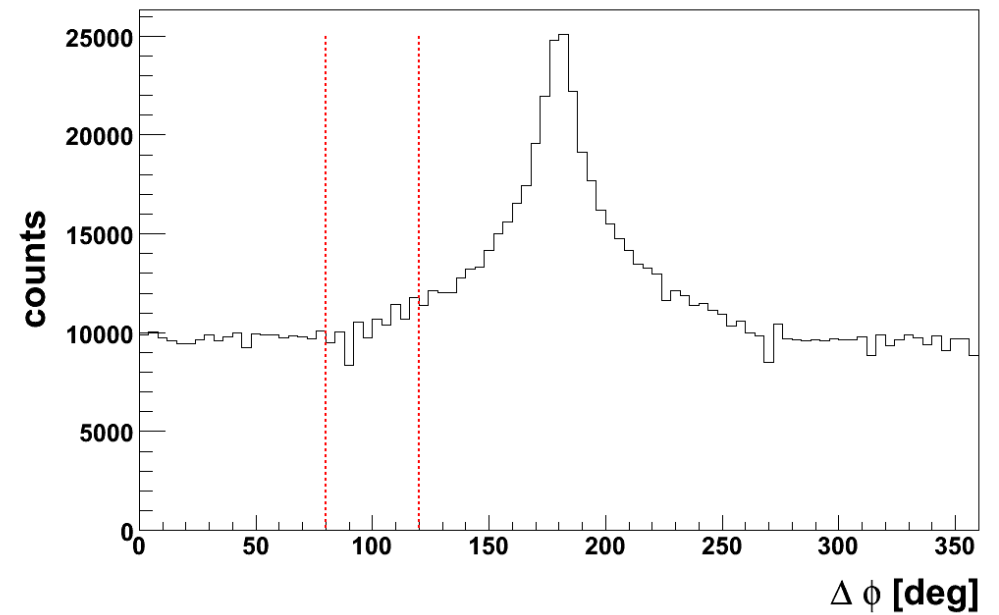
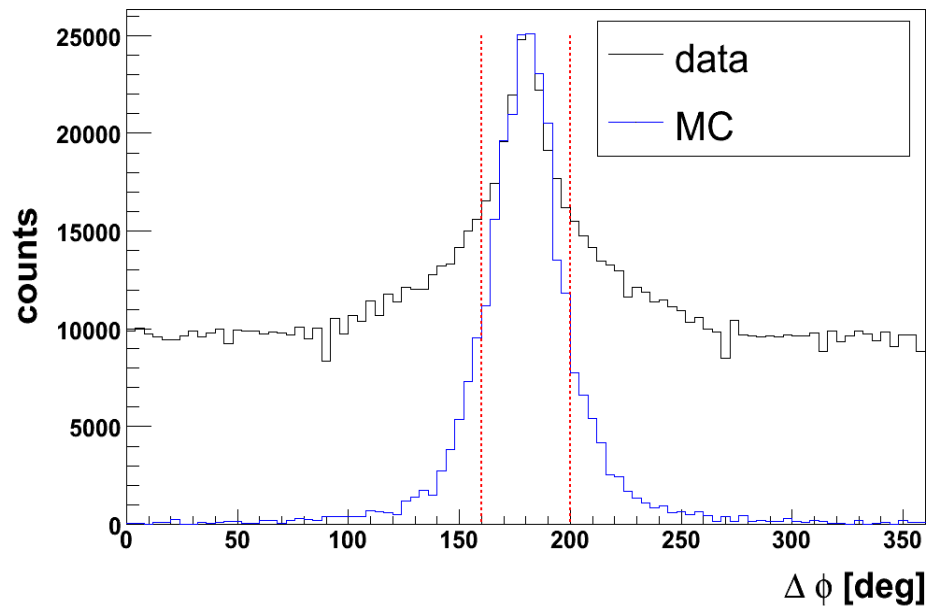
Quasi-elastic reactions



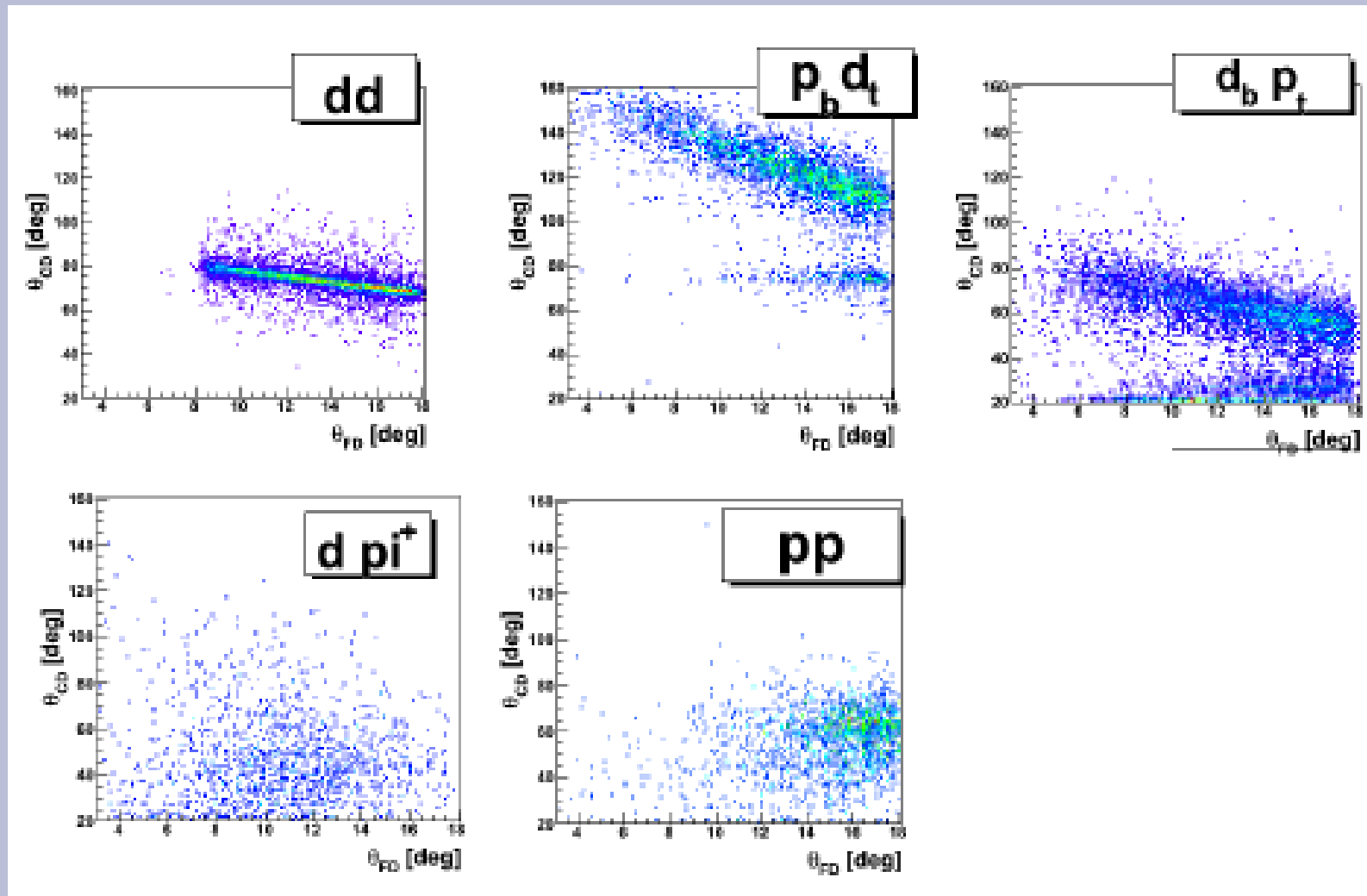
other reactions (non-coplanar)



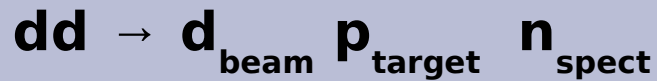
Quasi-elastic reactions background



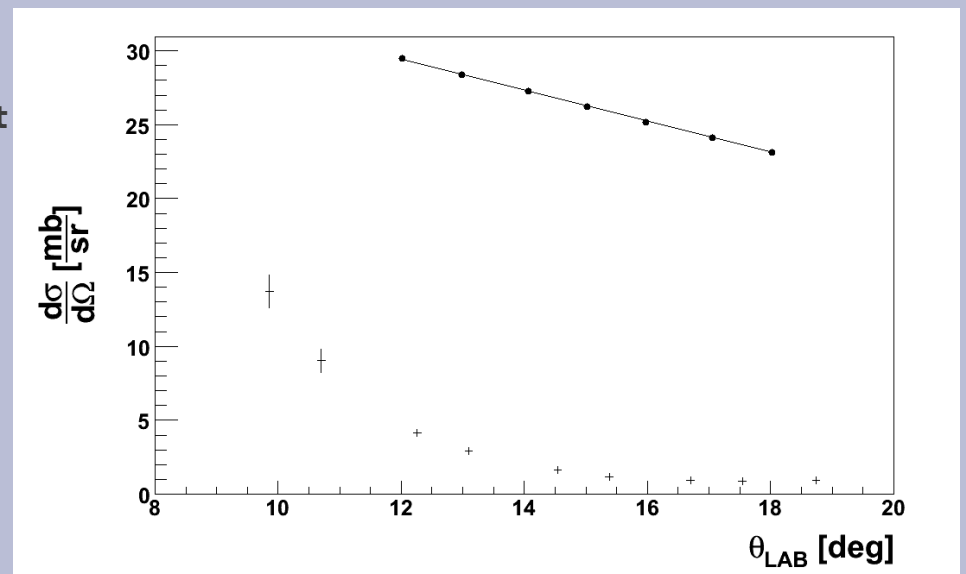
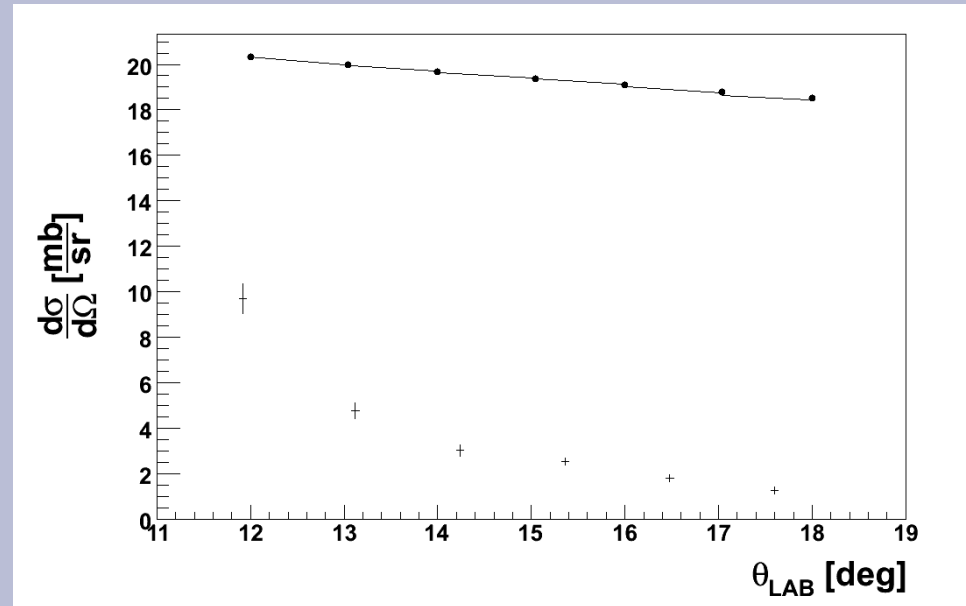
Quasi-elastic reactions MC simulations



Quasi-elastic reaction (dp)



other reactions



Quasi-elastic reaction ($d\pi^+$)

dd \rightarrow **pp (nn)**_{spect}

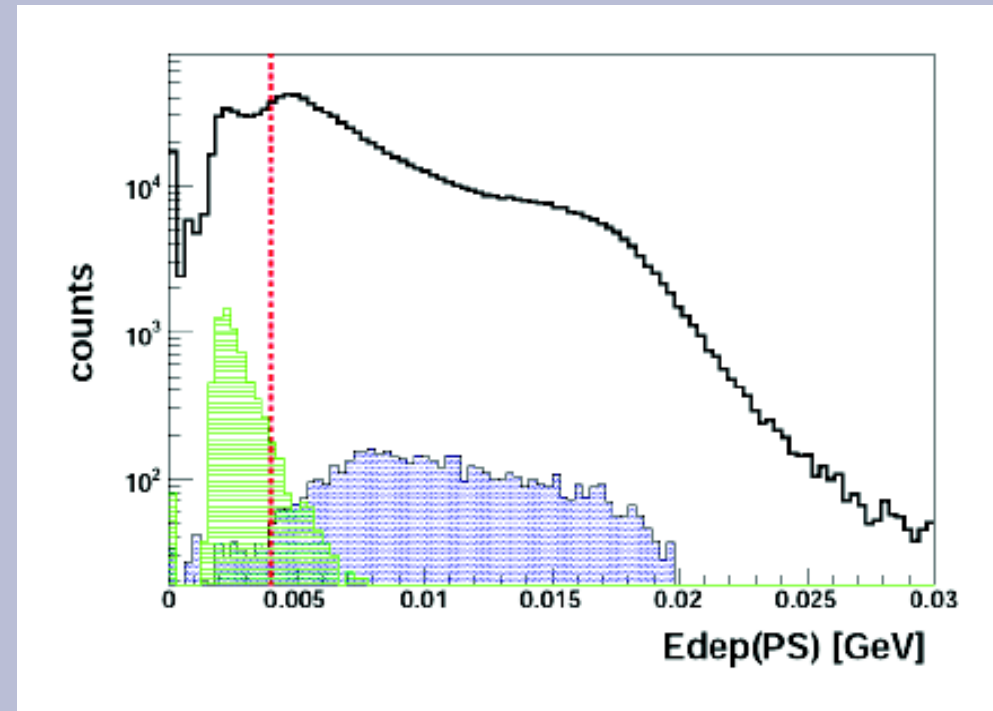
dd \rightarrow **d**_{beam} **p**_{target} **n**_{spect}

dd \rightarrow **p**_{beam} **d**_{targed} **n**_{spect}

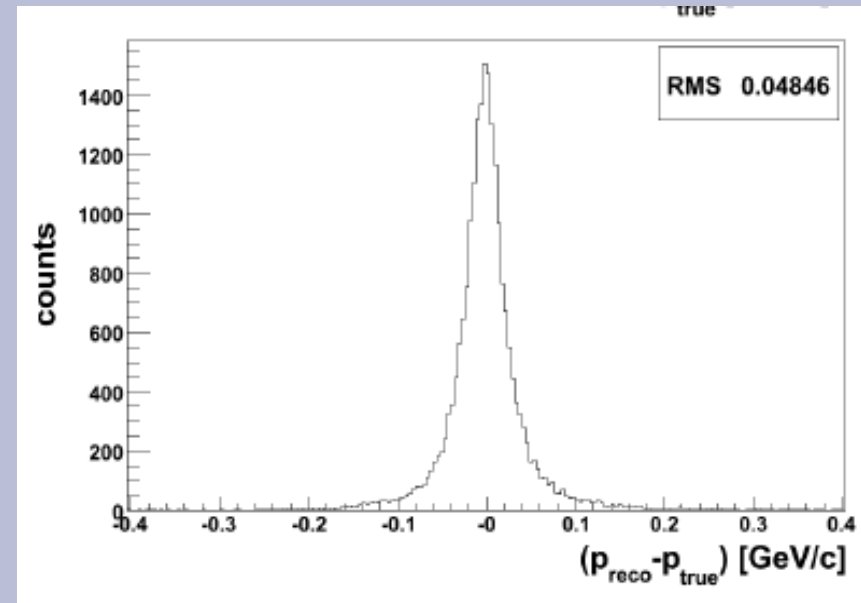
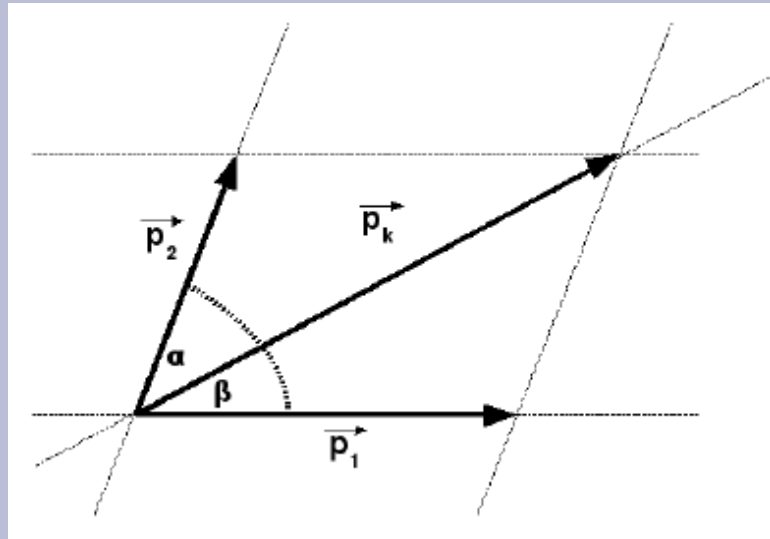
dd \rightarrow **pp (nn)**_{spect} \rightarrow **d π^+ (nn)**_{spect}

dd \rightarrow **dd**

other reactions

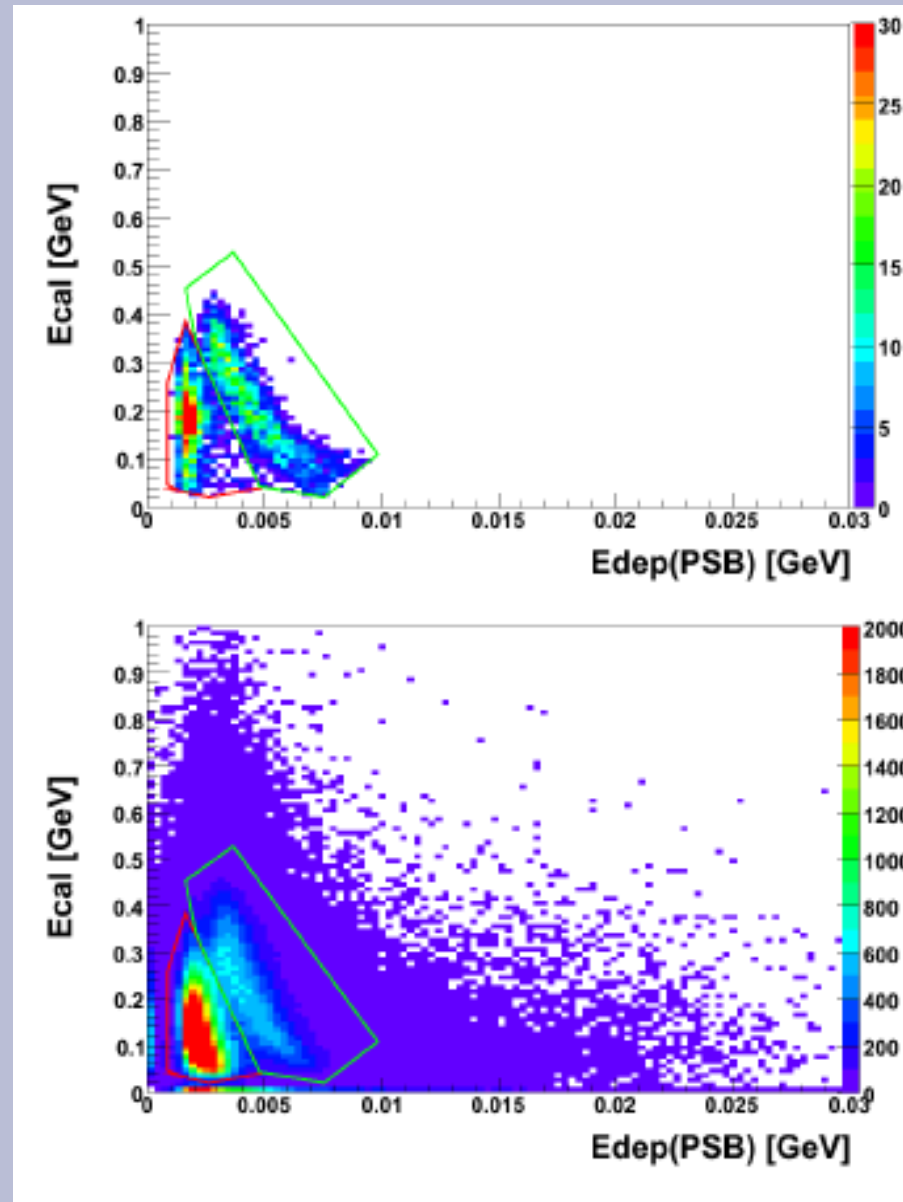


Momentum reconstruction for p and π^-



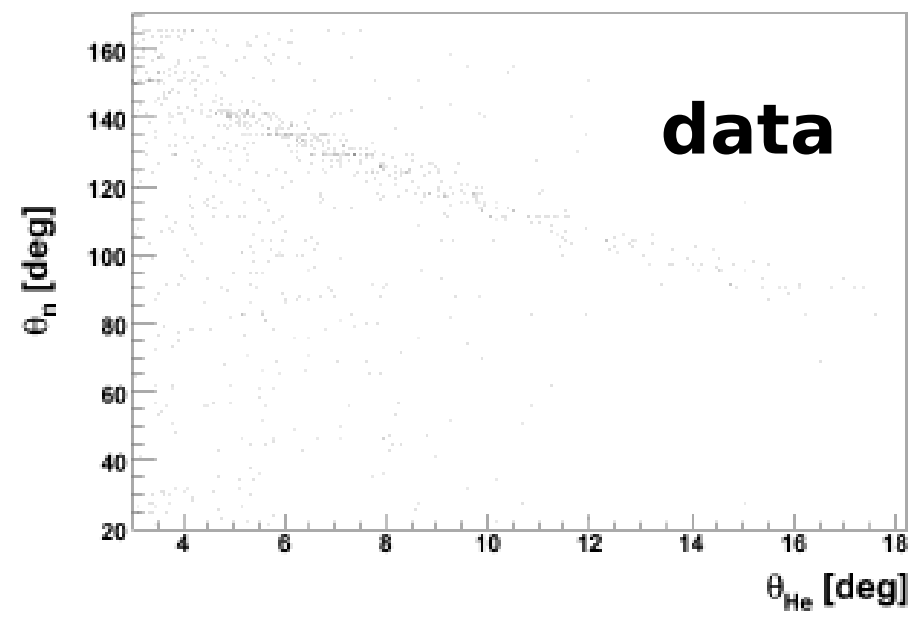
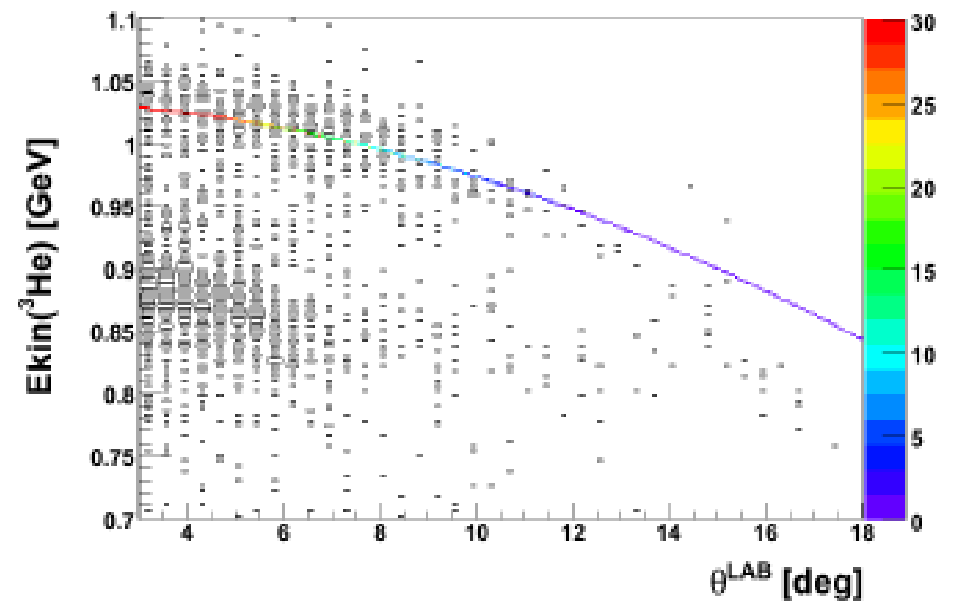
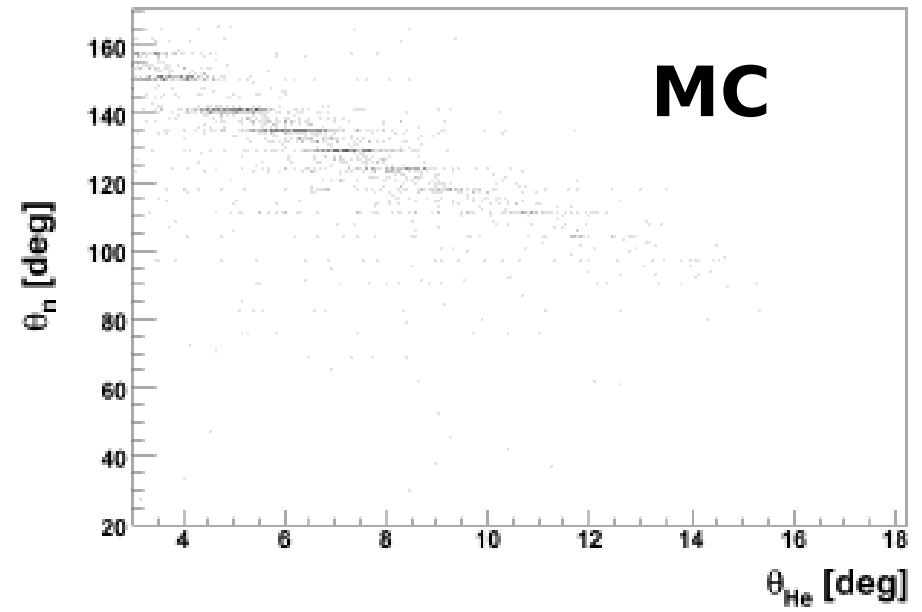
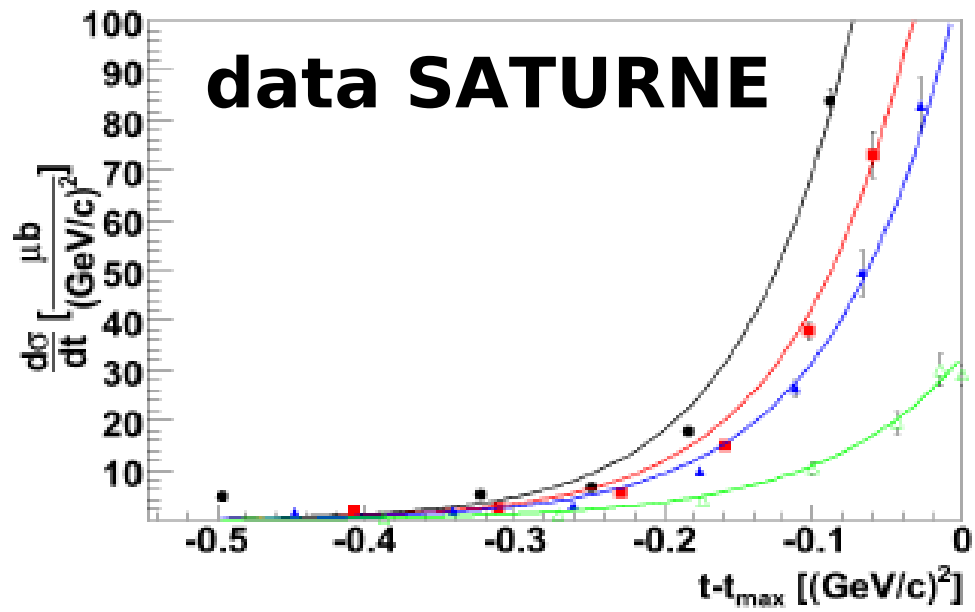
$$|\vec{p}_1| = |\vec{p}_k| \times \frac{\sin \beta}{\sin(\alpha + \beta)}, \quad |\vec{p}_2| = |\vec{p}_k| \times \frac{\sin \alpha}{\sin(\alpha + \beta)}$$

Proton / pion identification



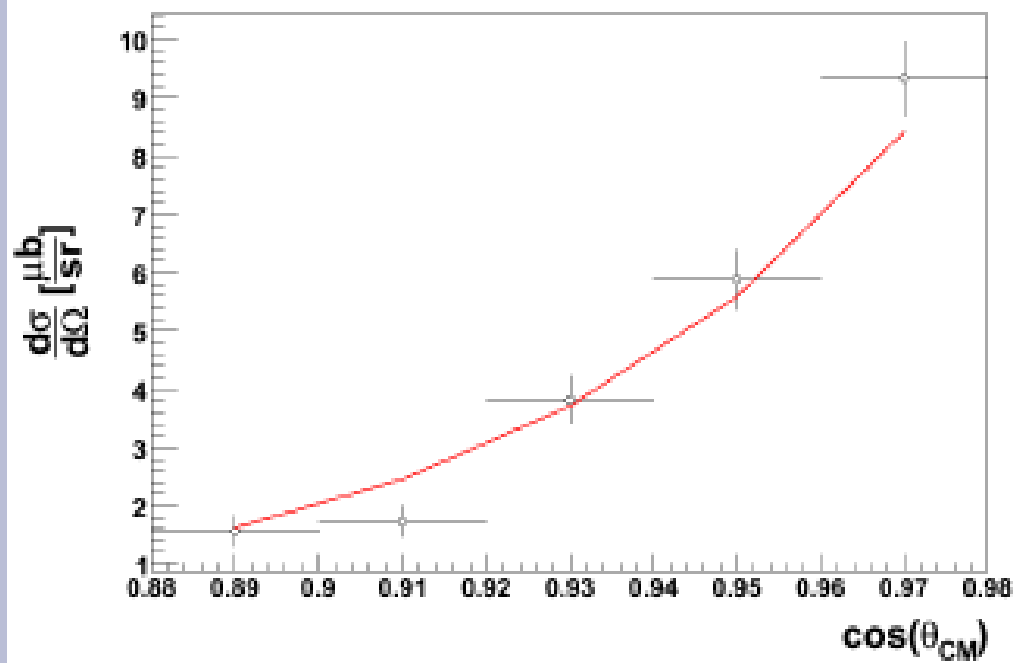
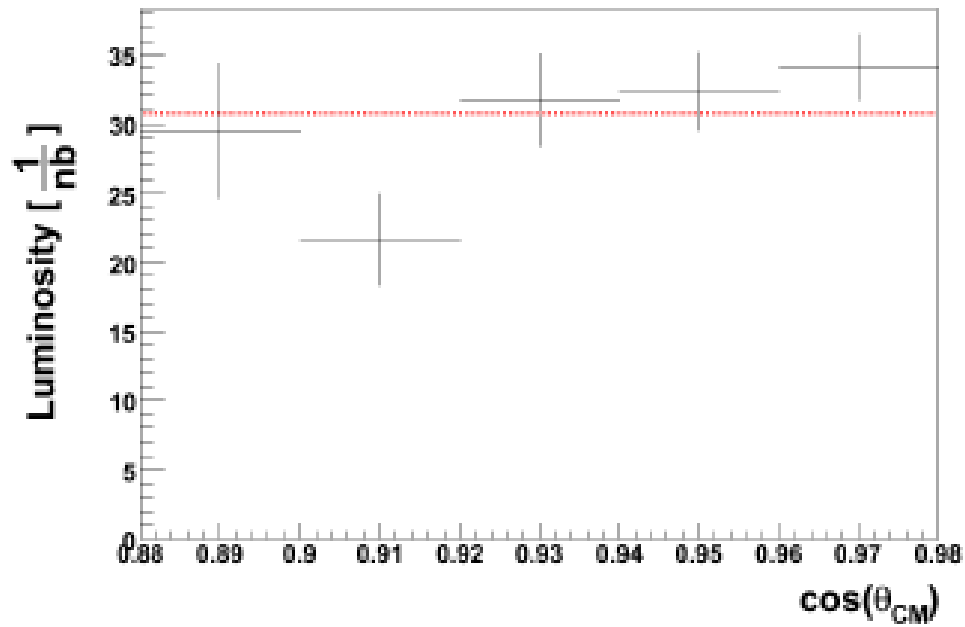


$dd \rightarrow {}^3\text{He} n$





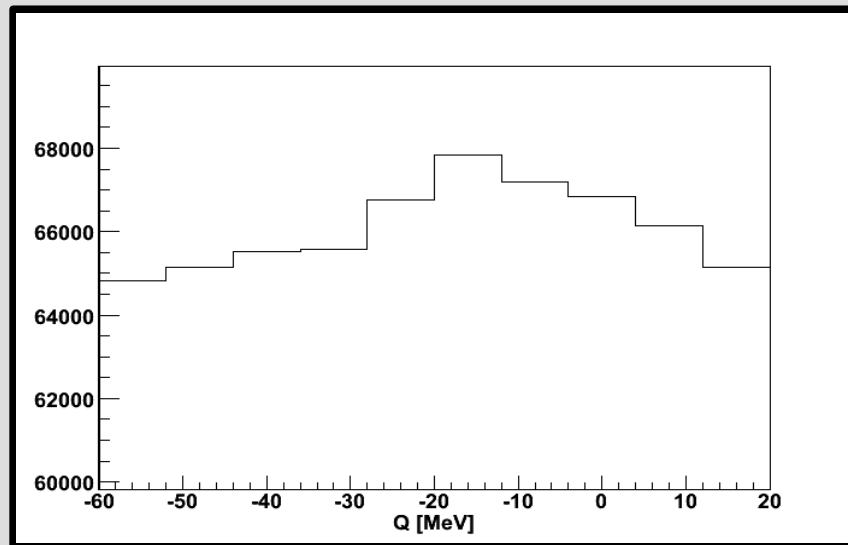
$dd \rightarrow {}^3\text{He} n$



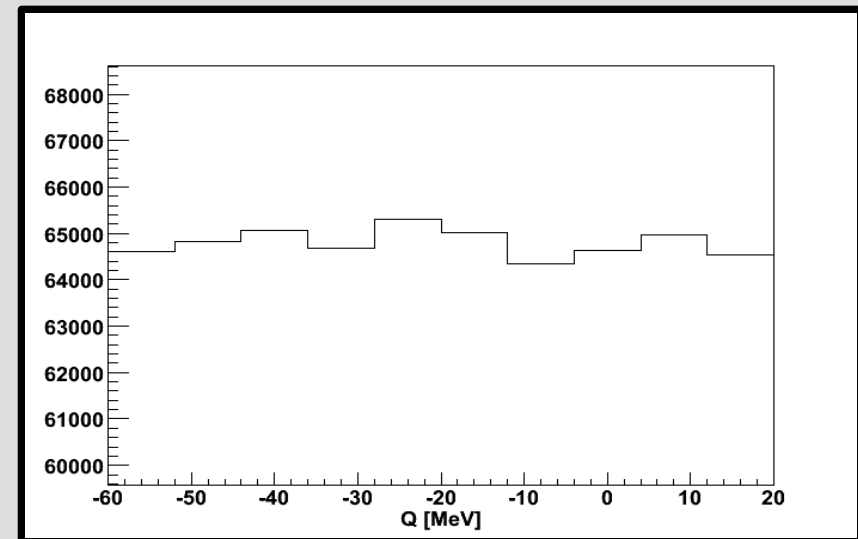


Example of the excitation function (simple simulation)

n.p. $\theta_{cm} = 150-170$



n.p. $\theta_{cm} = 130-150$



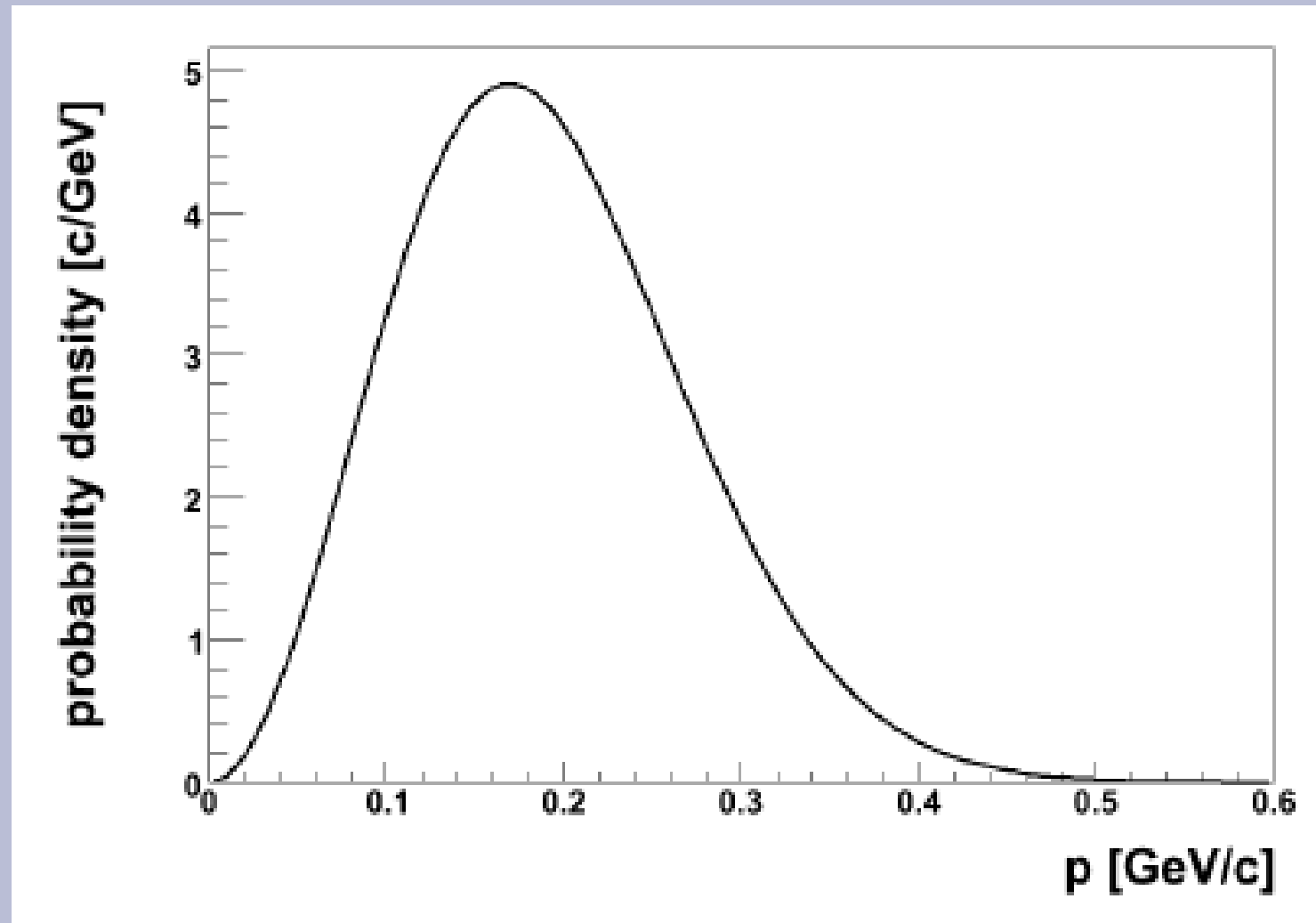
x-section=10 nb, $L=10^{31} \text{ cm}^{-2}\text{s}^{-1}$
T=10 dni
Breit-Wigner: $E_0=-20 \text{ MeV}$, $\Gamma=25 \text{ MeV}$

Search for the resonance-like structure

with the maximum below the $dd \rightarrow {}^4\text{He } \eta$ threshold



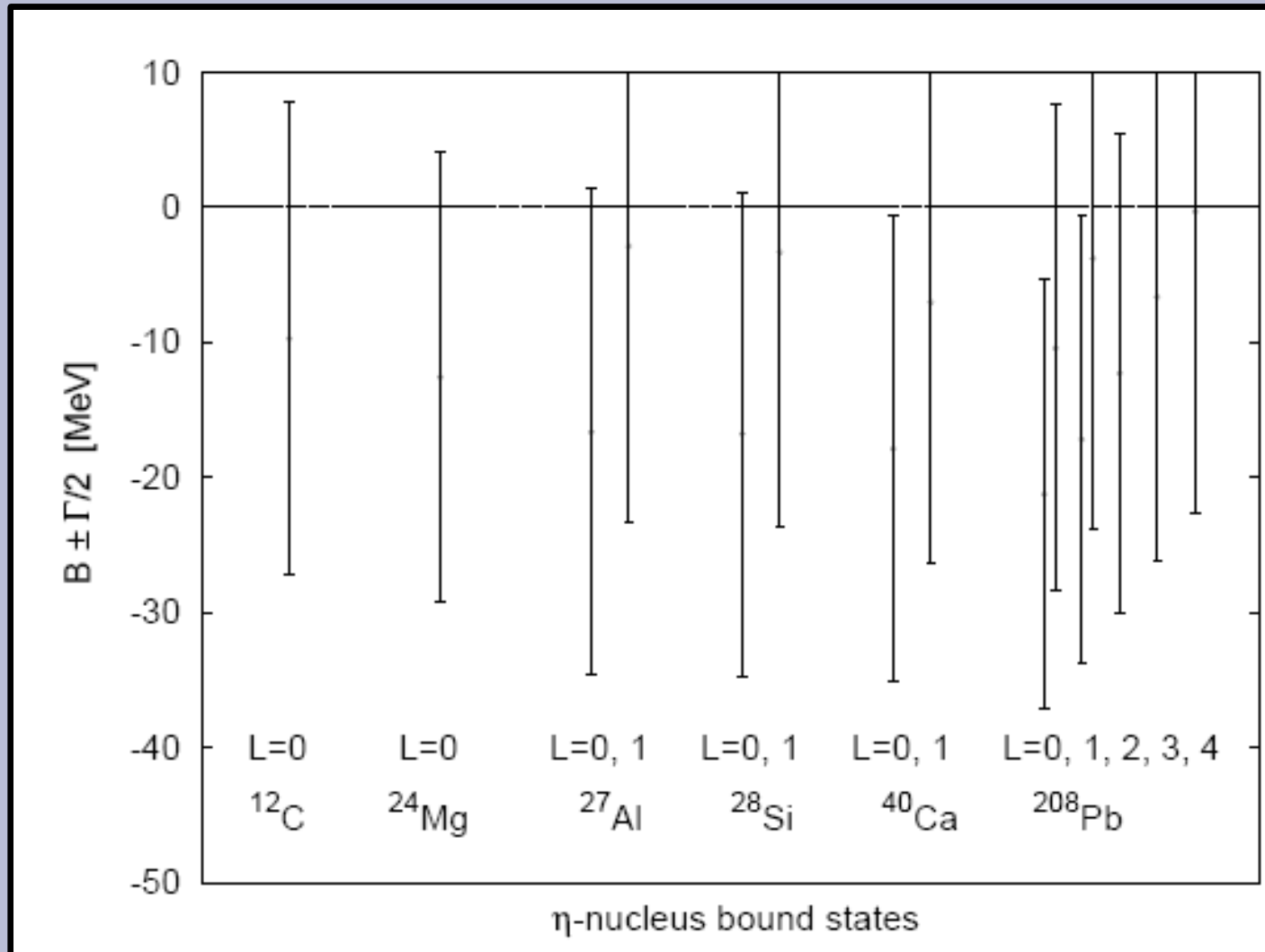
Nucleon momentum distribution in ^4He



V. Hejny, PhD Thesis, Justus-Liebig University Gissen (1998).

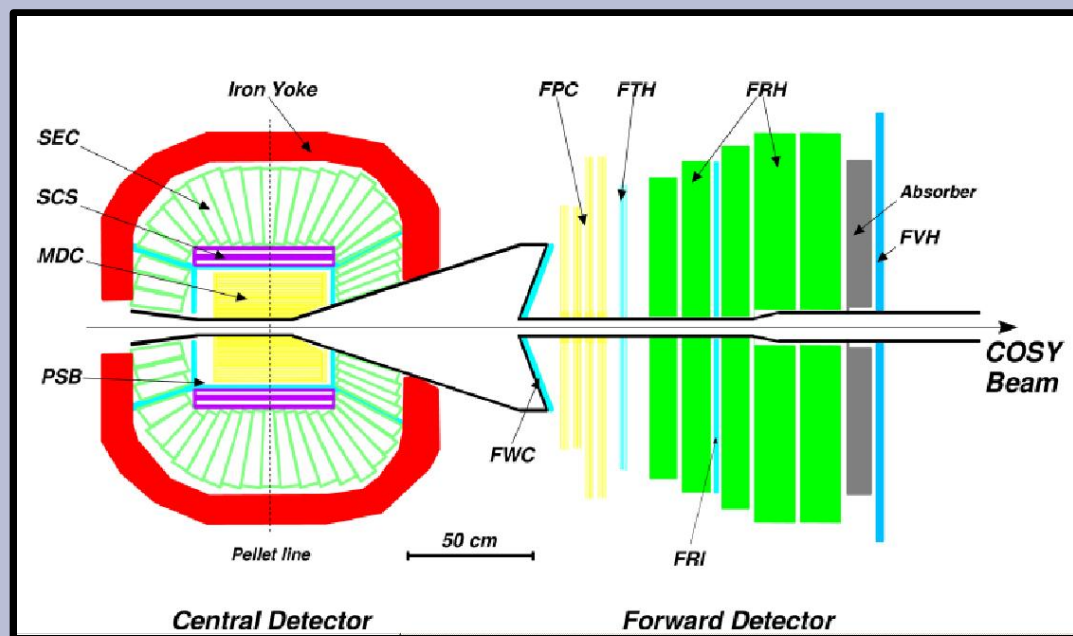
J. S. McCarthy *et al.*, *Phys. Rev.* **C15**, 13961414 (1977).

η -mesic nuclei in heavy systems



WASA-at-COSY

4 π detector for charged and neutral particles



Central detector:

Max. stopping energy

$\pi^\pm/p/d$ 190/400/450 MeV

Angular resolution

charged $\sim 1.2^\circ$

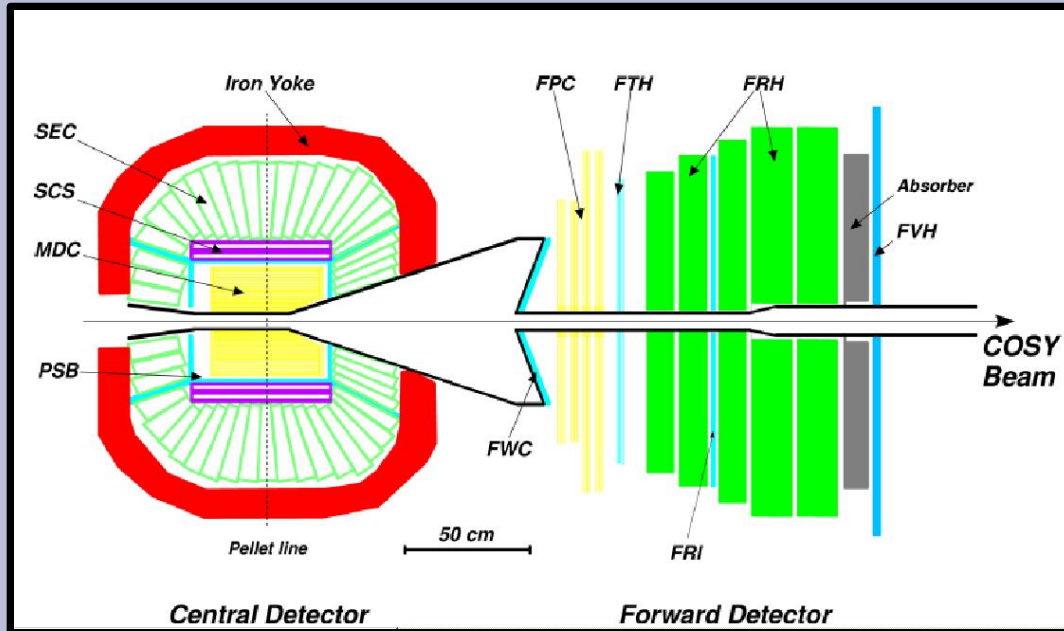
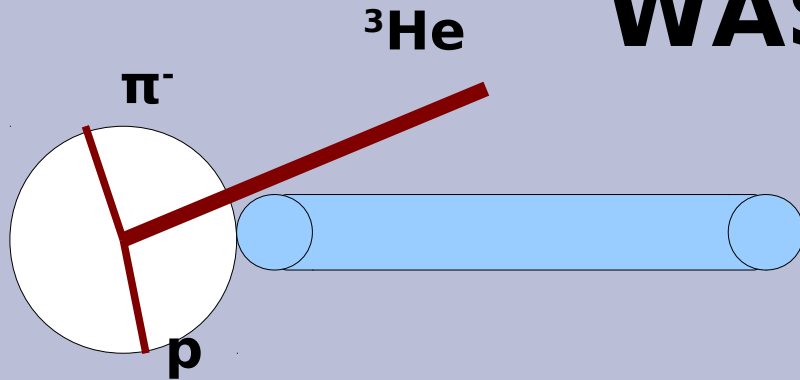
neutral $\sim 5^\circ$

Relative energy resolution by SE

photons $\sim 8\%$

stopped charged particles $\sim 3\%$

WASA-at-COSY



Forward detector:

Scattering angle coverage 3° - 18°

Scattering angle resolution 0.2°

Maximum energies for stopping

$\pi^\pm/p/d/\alpha$ 170/300/400/900 MeV

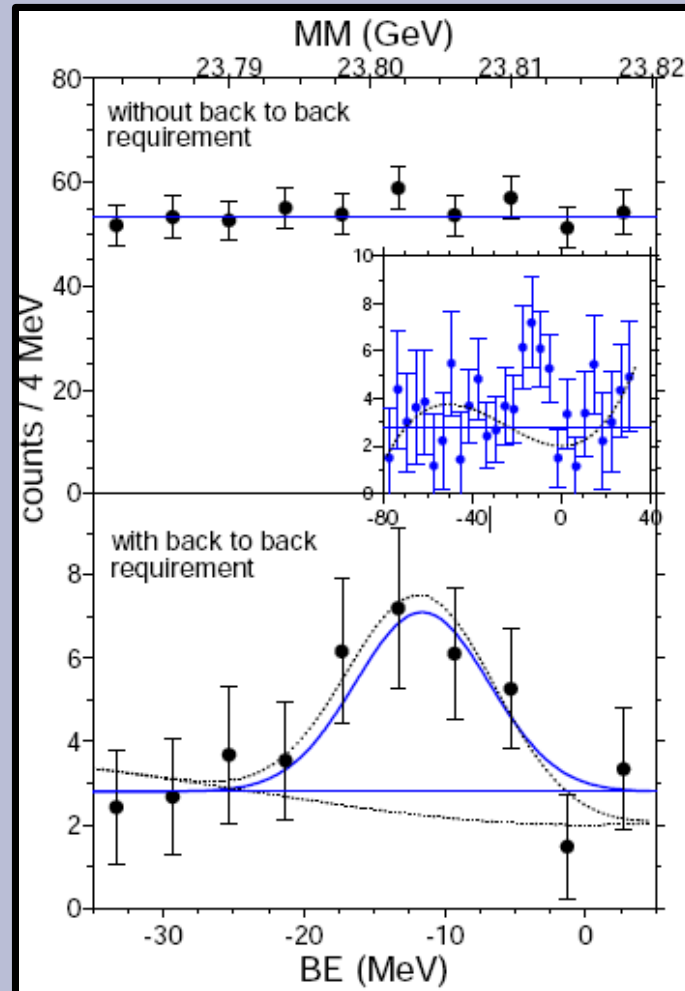
Time resolution $<3\text{ns}$

Relative energy resolution

particles $T_{\text{stop}} < T < 2T_{\text{stop}}$ 3-8%

stopped particles $T < T_{\text{stop}}$ 1.5-3%

COSY-GEM results



MM(3HE)

A. Budzanowski *et al.*, Phys Rev. C79 (2009).