Search for the manifestation of η-mesic nuclei on the $dd \rightarrow {}^3He + N + \pi$ excitation function measured with WASA-at-COSY

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for the WASA-at-COSY collaboration

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Jagiellonian Univeristy, Kraków

Outline

- Short motivation of the research
- Idea of measurement
- Results from 2008 experiment
- Preliminary results from 2010 experiment
- Summary and outlook

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 $|\eta_0>$

  (more gluon content → more attractive binding → higher binding energy)

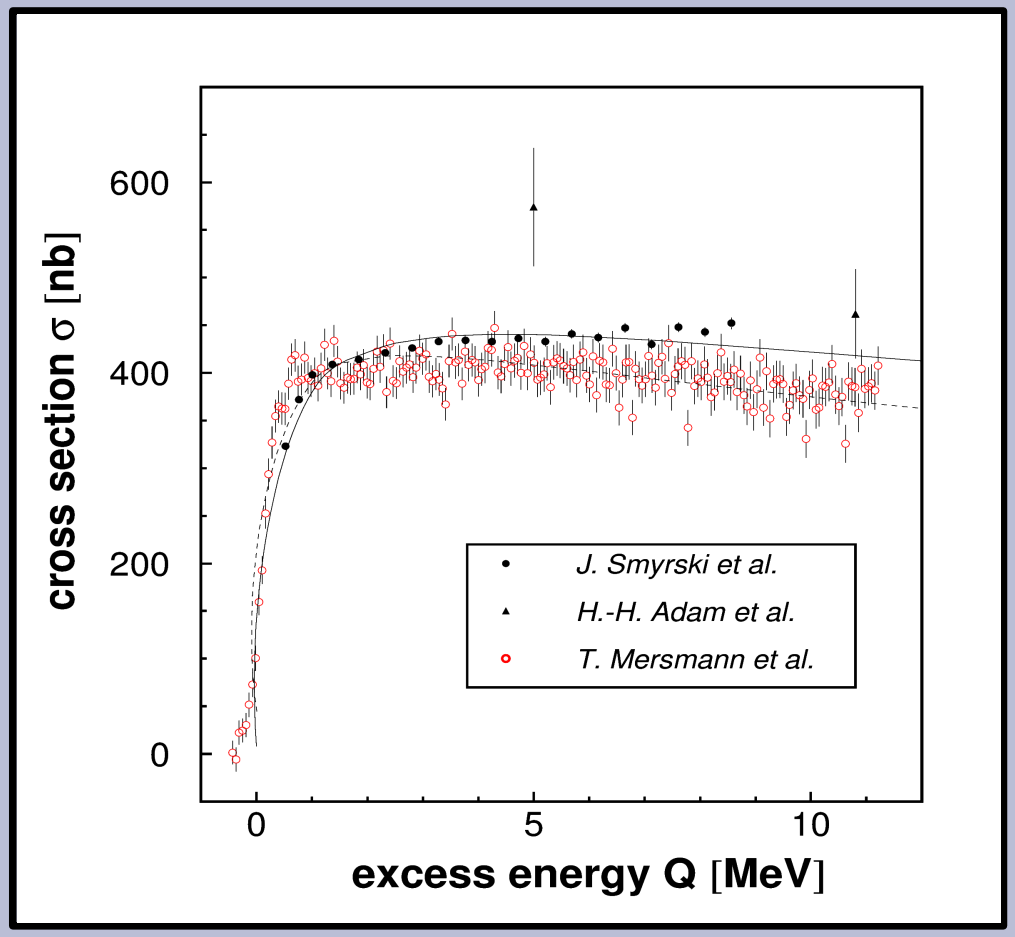
  (*S.D. Bass, A.W. Thomas, Phys. Lett. B634 (2008)*)

- **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

(Garcia-Recio, Nieves, Inoue, Oset, PLB550(02)47
Inoue, Oset, NPA710(02) 354
Jido, Oka, Hosaka, Nemoto, PTP106(01)873
Jido, Hatsuda, Kunirhiro, NPA671(00)471)

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



Full black squares: COSY-11

Empty red squares: COSY-ANKE

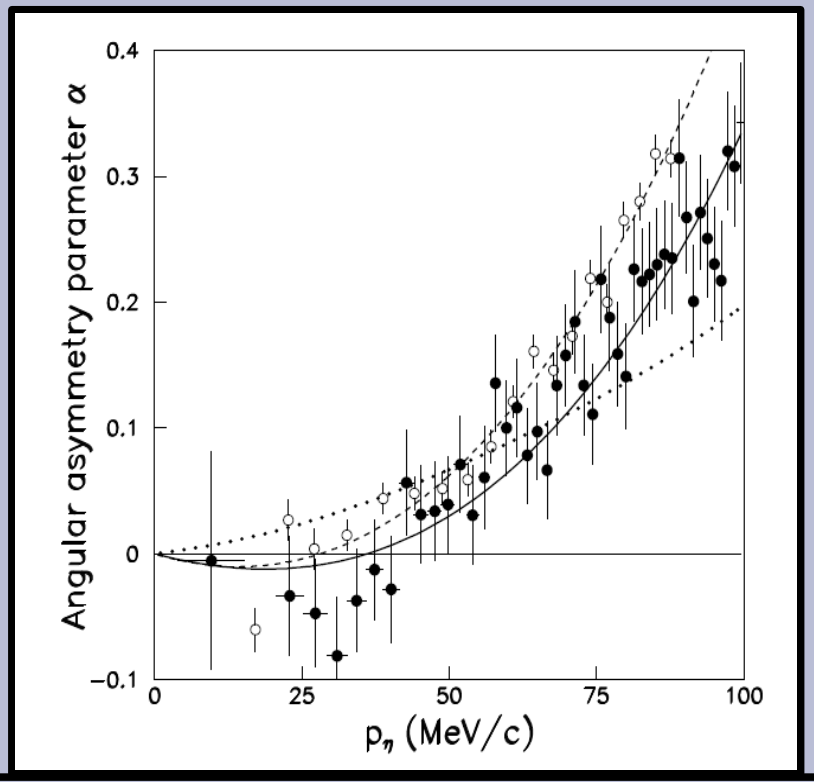
(*C.Wilkin et al. Phys.Lett. B654 (2007)*)

Also total x-section $pd \rightarrow {}^3He\eta$ and $dd \rightarrow {}^4He\eta$

SPES-3 and SPES-4 @SATURNE

N. Willis et al. Phys.Lett. B406(1997).

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



Full circles: COSY-ANKE

(T.Mersmann et al., Phys. Rev. Lett. 98 242301-1-4 (2007))

Empty circles: COSY-11

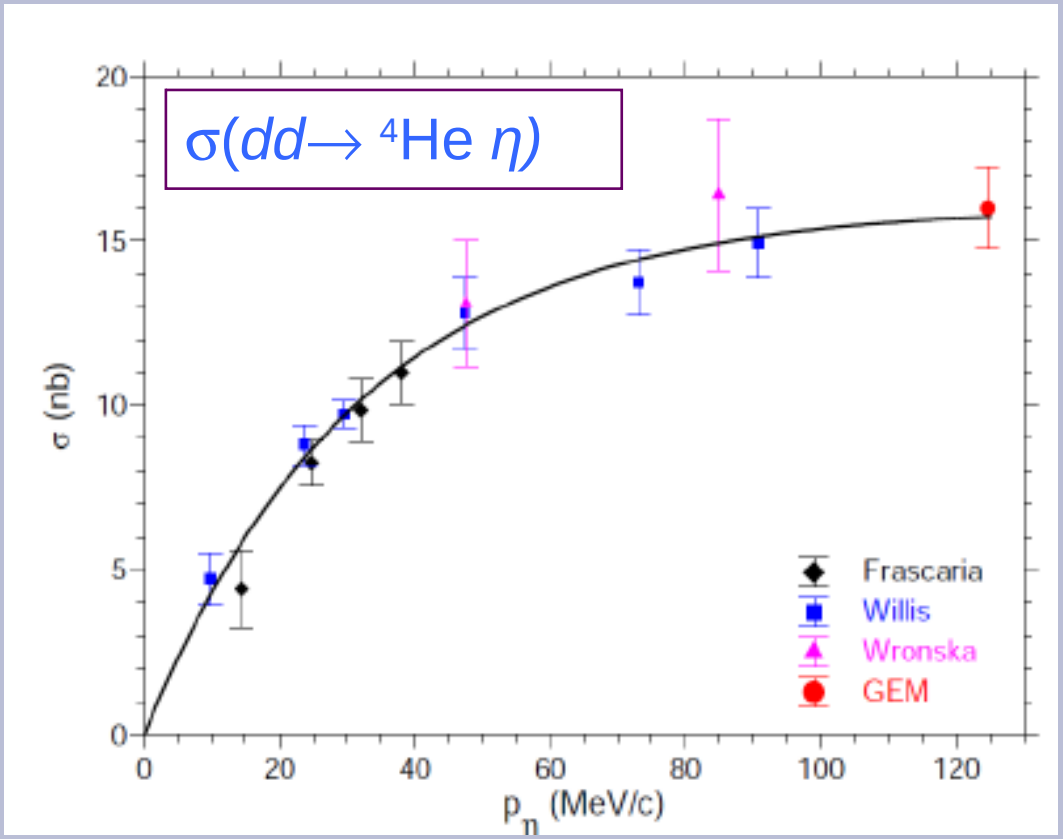
(J.Smyrski et al., Phys. Lett B 649 258-262 (2007))

Also total x-section $\gamma {}^3He \rightarrow \eta {}^3He$

Crystal Ball-TAPS@MAMI

F. Pheron et al. Phys.Lett. B709 (2012).

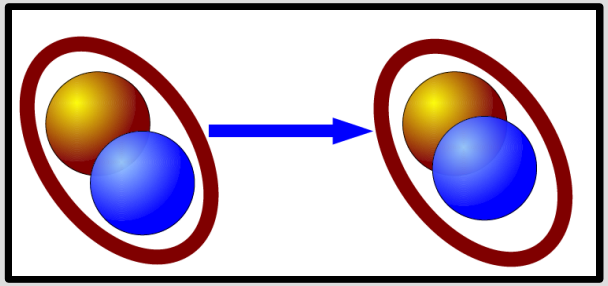
Experimental indications of the existence of a bound state in the η-^{4}He system

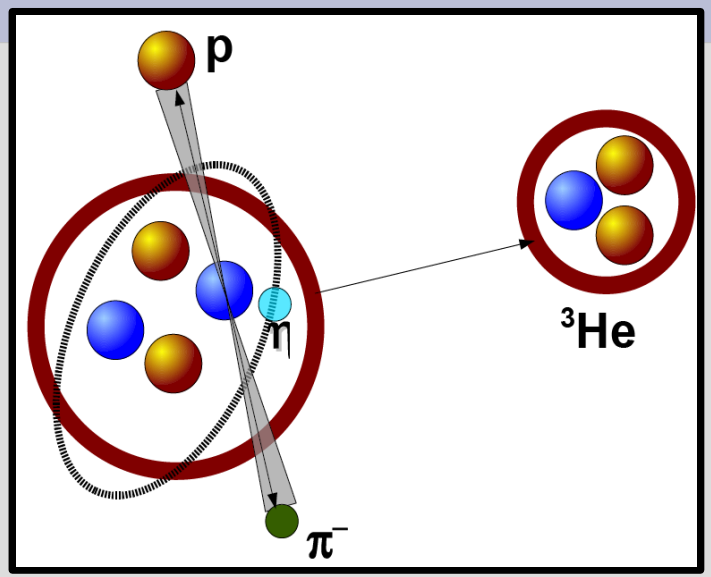


R. Frascaria et al., Phys. Rev. C 50 (1994) 573.
N. Willis et al., Phys. Lett. B 406 (1997) 14.
A. Wrońska et al., Eur.Phys.J. A26 (2005) 421-428.

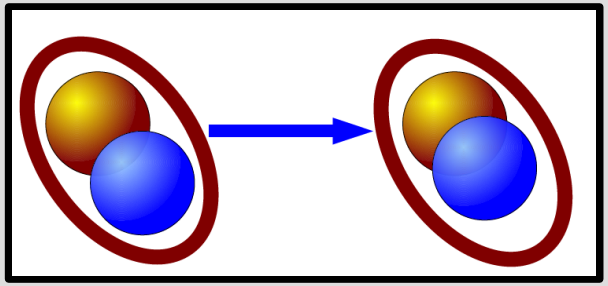
Idea of measurement

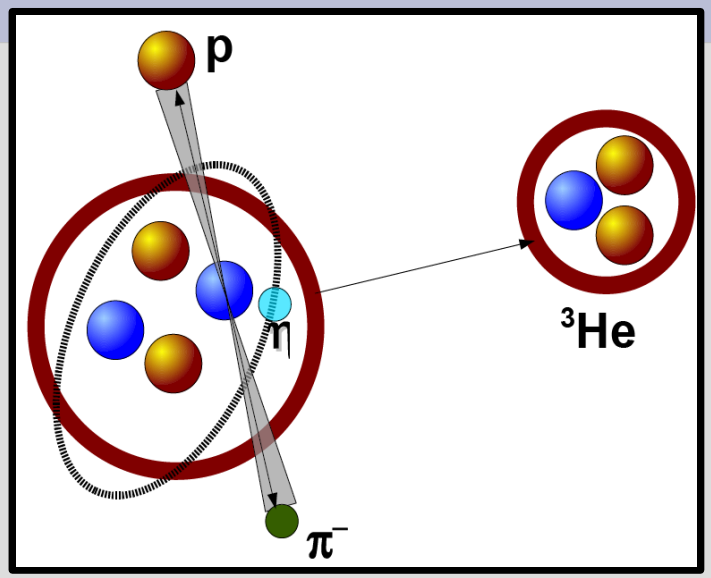
$dd \rightarrow (\eta\text{-}^4He)_{bound} \rightarrow N + \pi + {}^3He$





$dd \rightarrow (\eta\text{-}^4He)_{bound} \rightarrow N + \pi + {}^3He$





$\eta + N$ → N*(1535) → $N + \pi$

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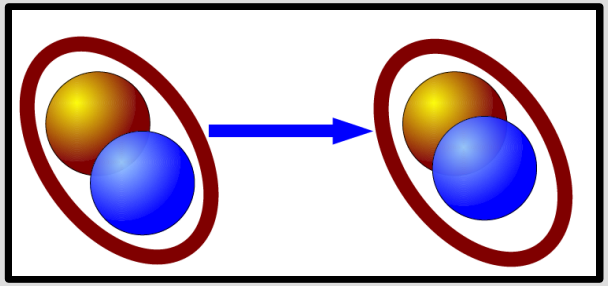
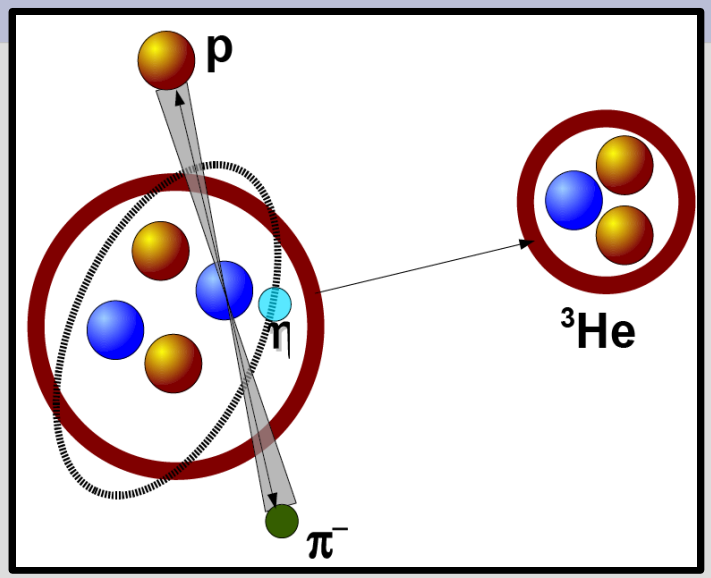


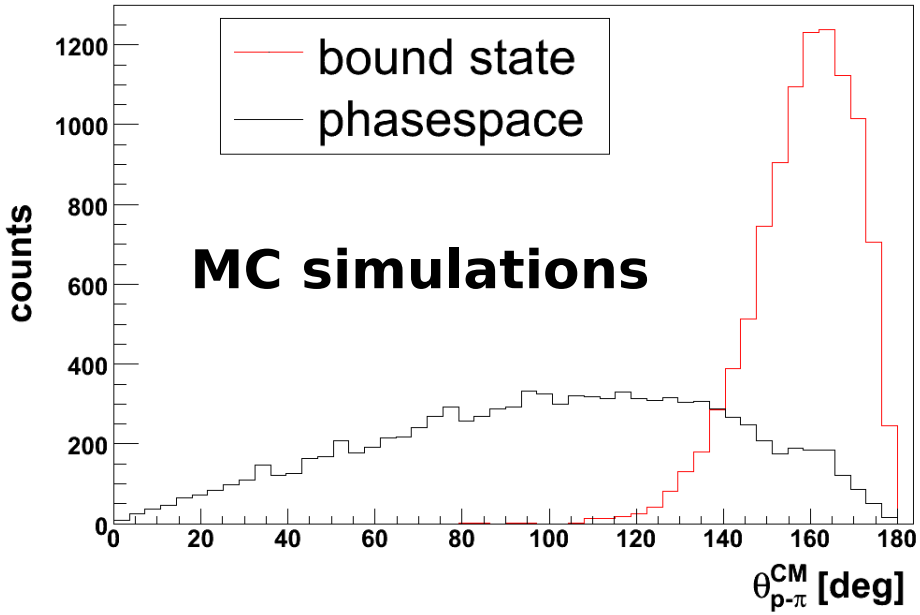


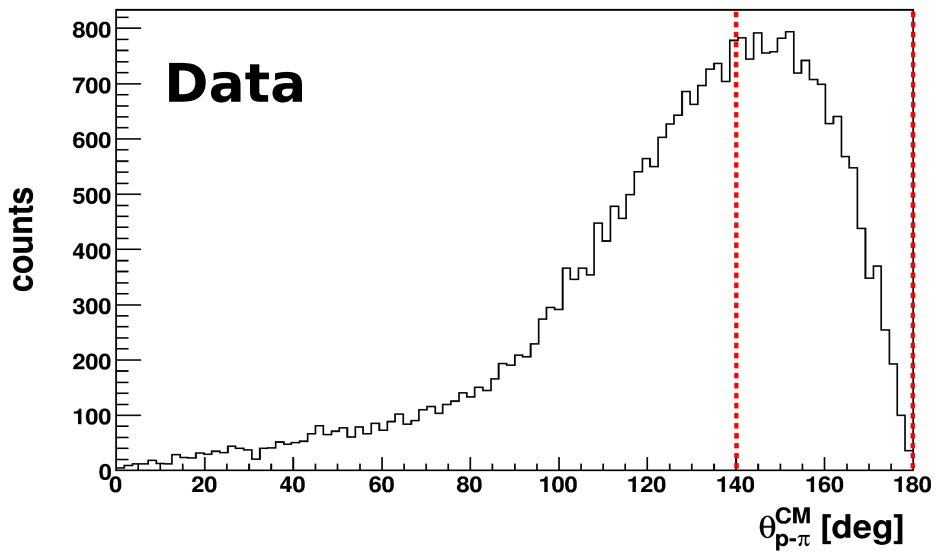
$\eta + N$ → N*(1535) → $N + \pi$

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

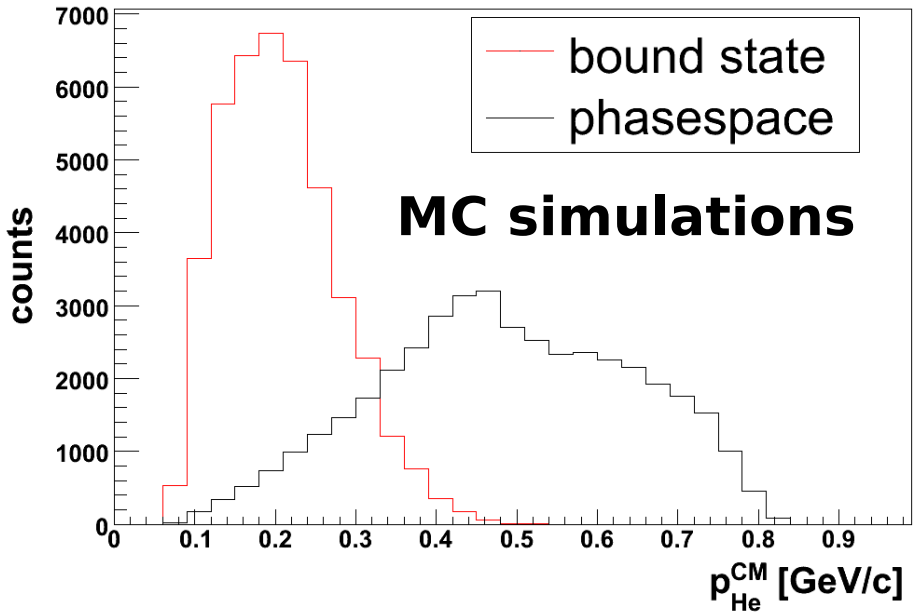
Signatures of the bound state

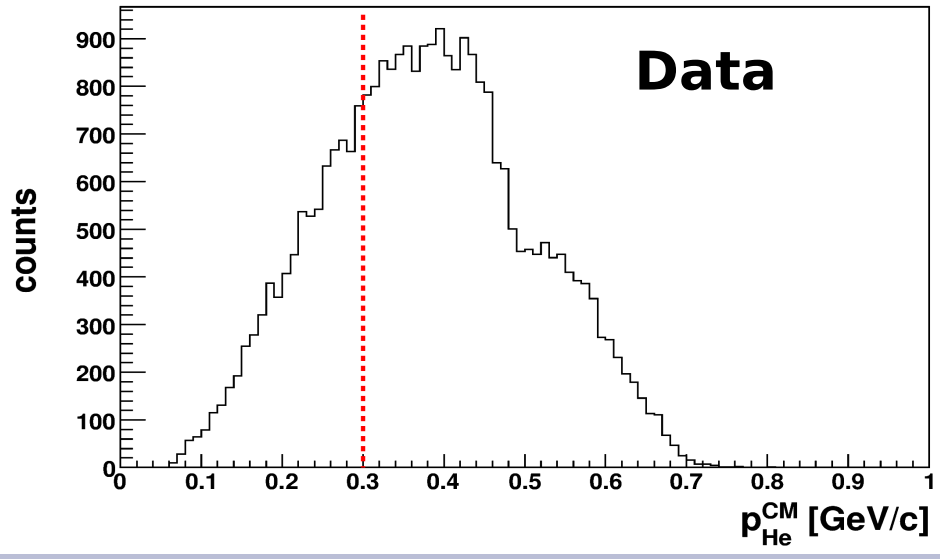
Opening angle p-π^- in CM frame



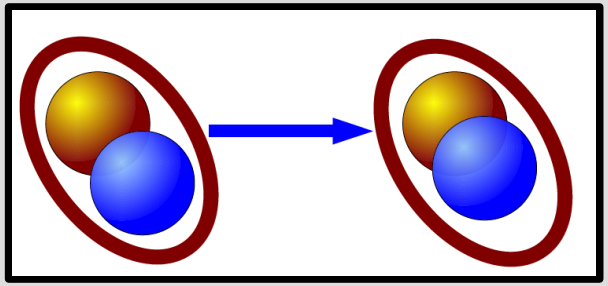


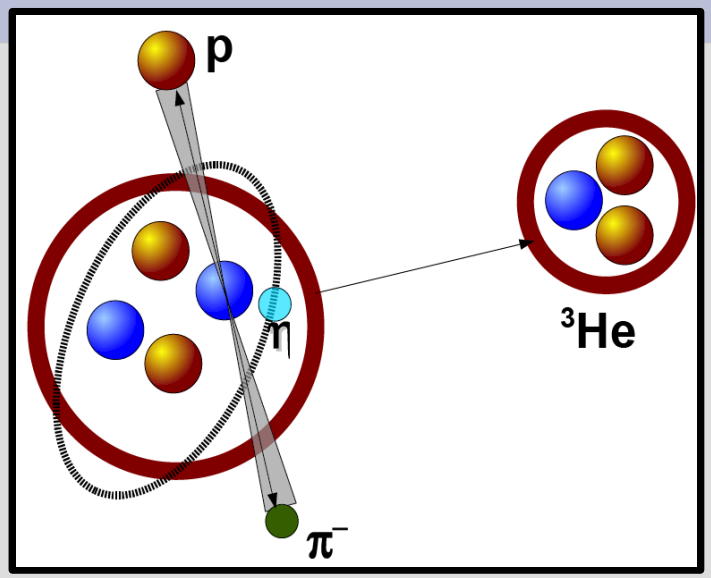
^{3}He momentum in CM frame





$dd \rightarrow (\eta\text{-}^4He)_{bound} \rightarrow N + \pi + {}^3He$





$\eta + N$ → N*(1535) → $N + \pi$

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

Search for a resonance-like structure

with maximum below the η-^{4}He production threshold

Experiments

June 2008

Channels:

dd → ^{3}He p π^-

Normalization:

dd → ^{3}He n

Q: -51 to 22 MeV

P: 2.185 to 2.4 GeV/c

November-December 2010

Channels:

dd → ^{3}He p π^-

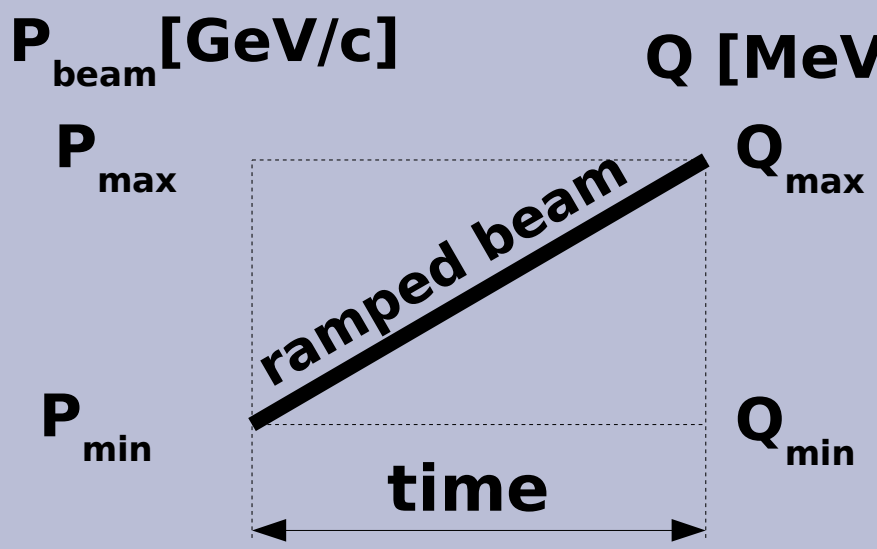
dd → ^{3}He n π^0 → ^{3}He n $\gamma\gamma$

Normalization:

dd → ^{3}He n

Q: -70 to 30 MeV

P: 2.127 to 2.422 GeV/c



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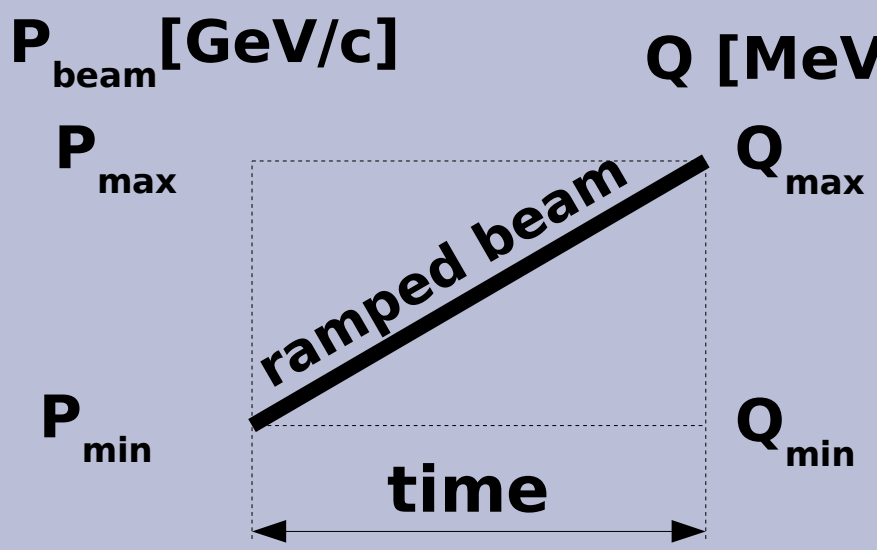
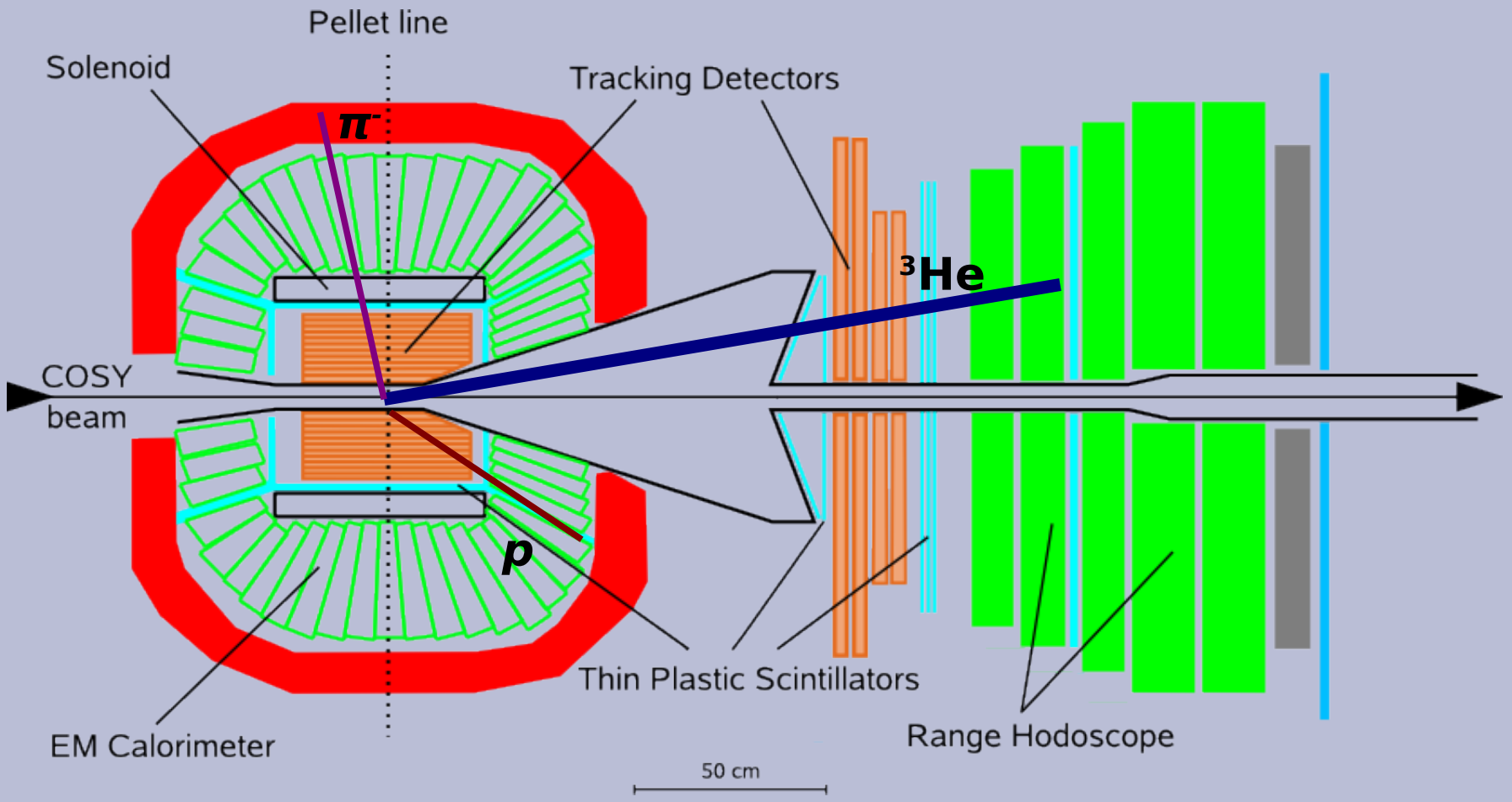
~20 x more statistics

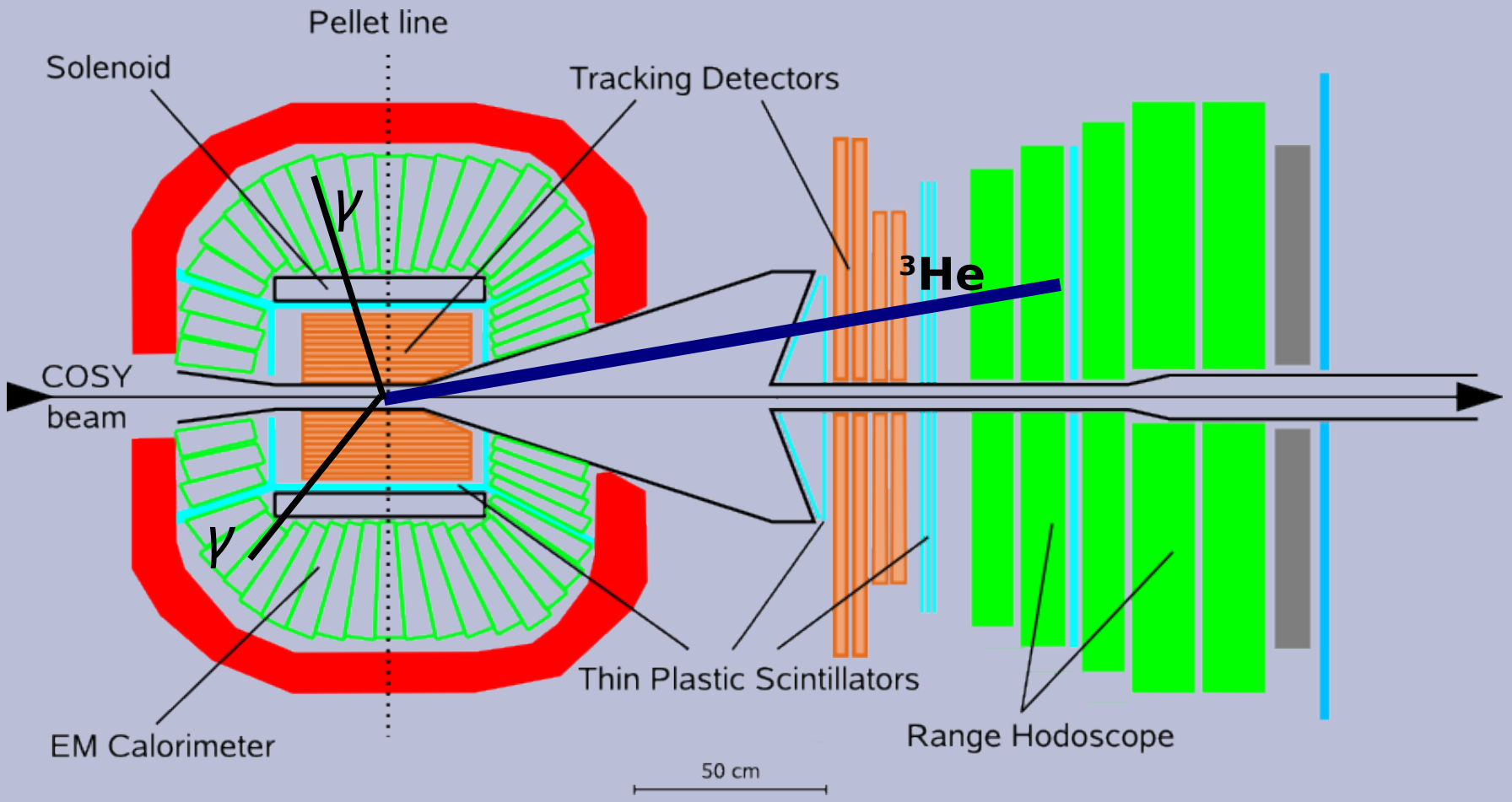


WASA-at-COSY



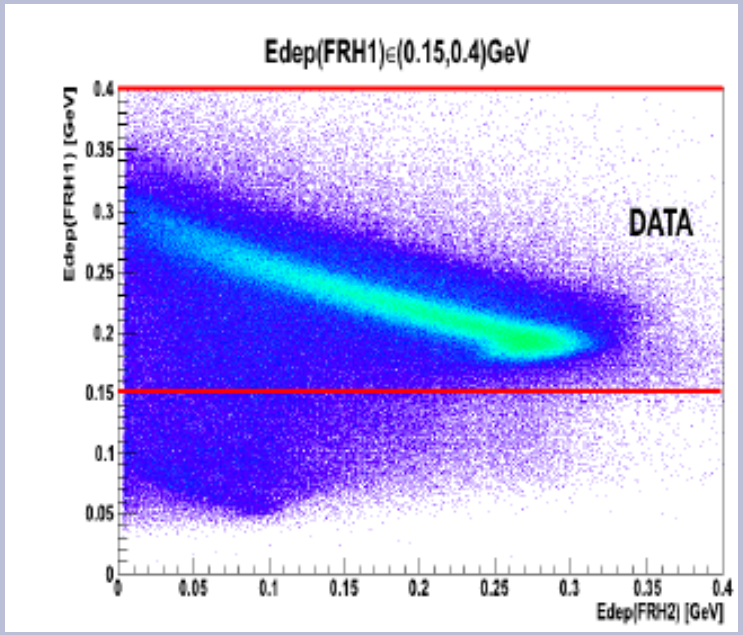
$dd \rightarrow (\eta\text{-}{}^4\mathrm{He})_{\mathrm{bound}} \rightarrow {}^3\mathrm{He}\, p\, \pi^-$

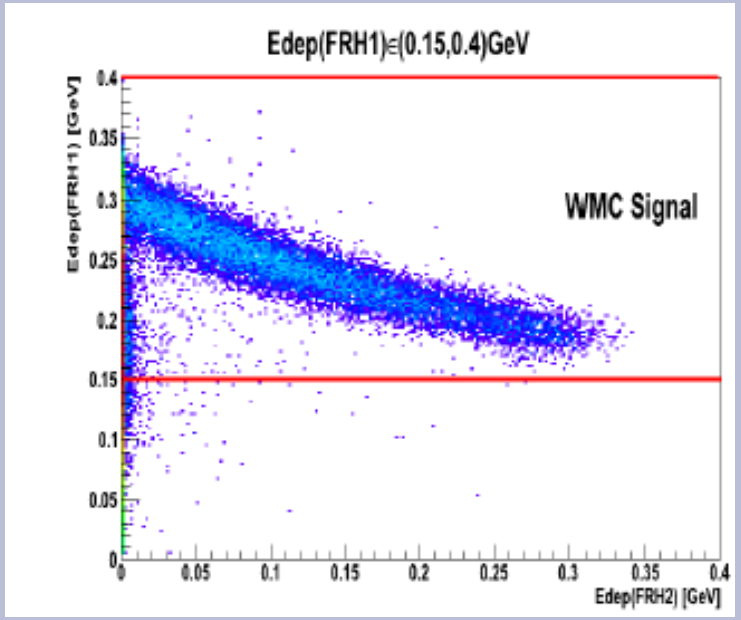
WASA-at-COSY



$$dd \rightarrow (\eta\text{-}{}^4\mathrm{He})_{\mathrm{bound}} \rightarrow {}^3\mathrm{He}\, n\, \pi^0 \rightarrow {}^3\mathrm{He}\, \gamma\gamma\ (\boldsymbol{n})$$

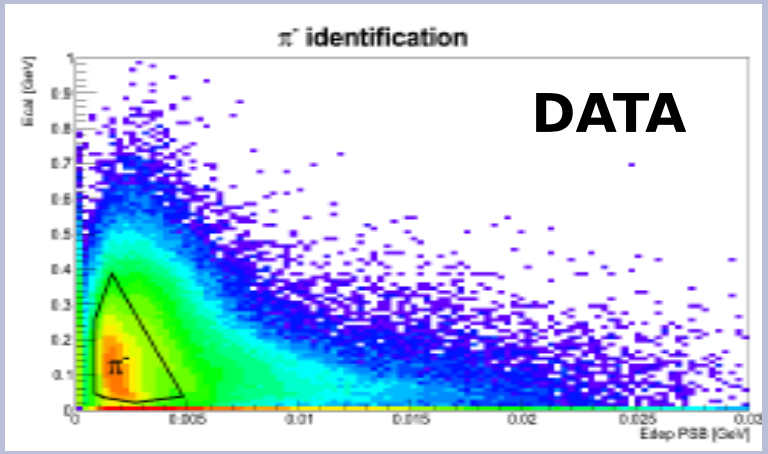
^{3}He ions identification in Forward Detector

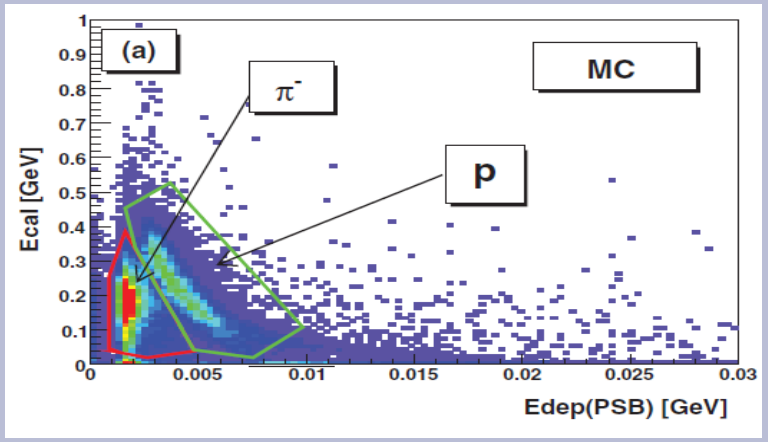




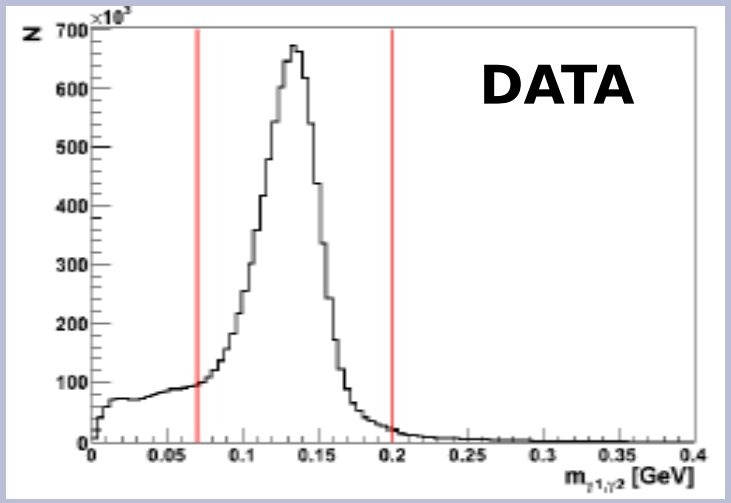
Pion identification in the Central Detector

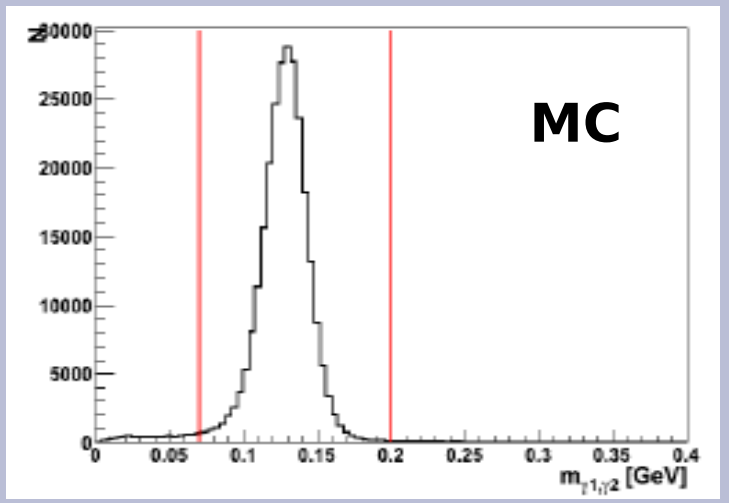
dd → ^{3}He p π^-





dd → ^{3}He n π^0 → ^{3}He n $\gamma\gamma$



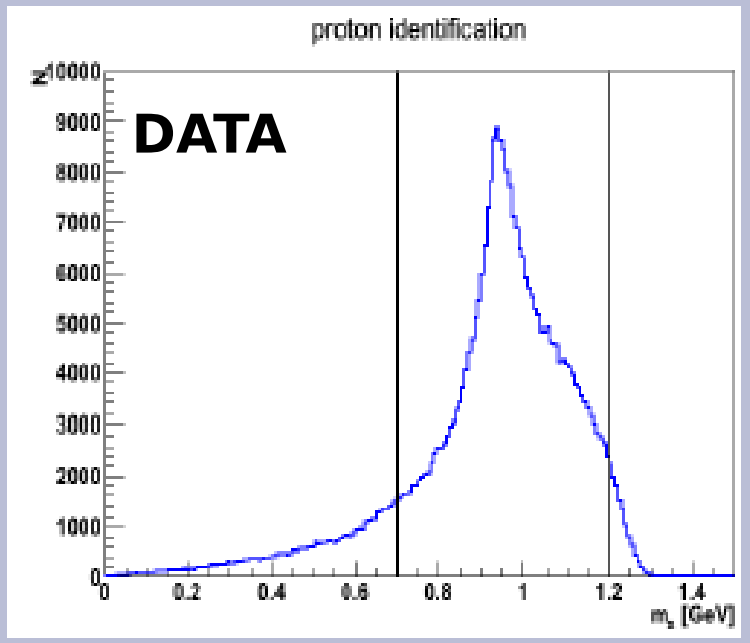


π^- identification

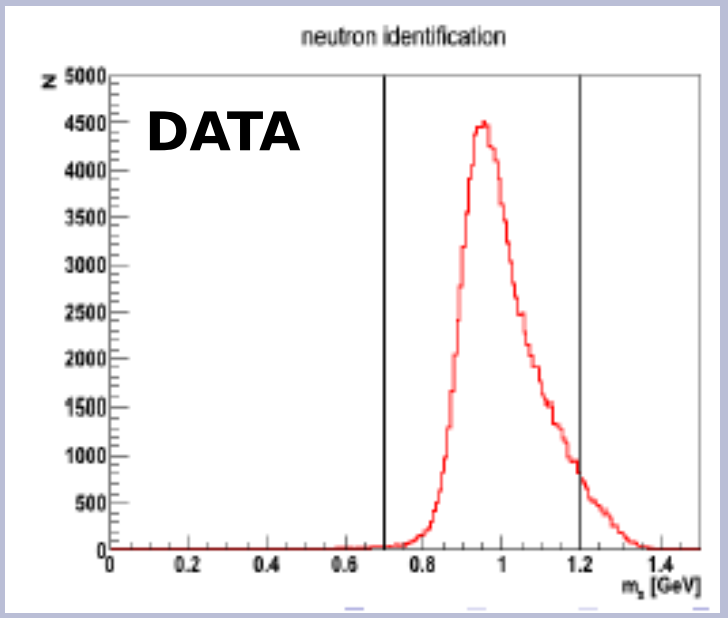
π^0 identification

Nucleon identification (missing mass method)

dd → ^{3}He p π^-

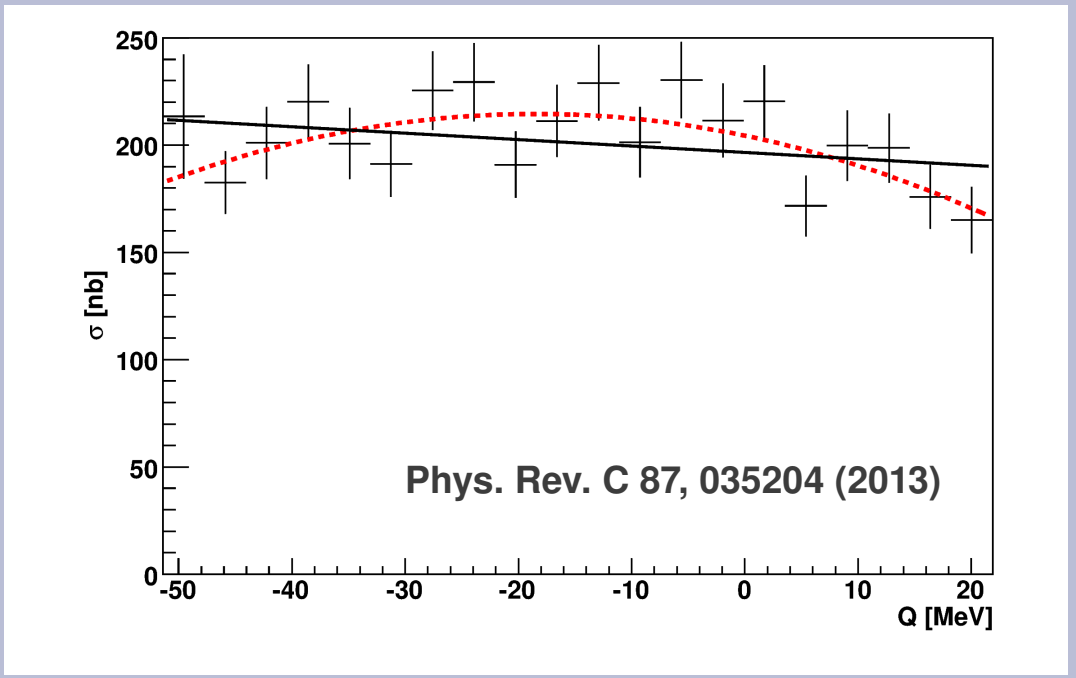


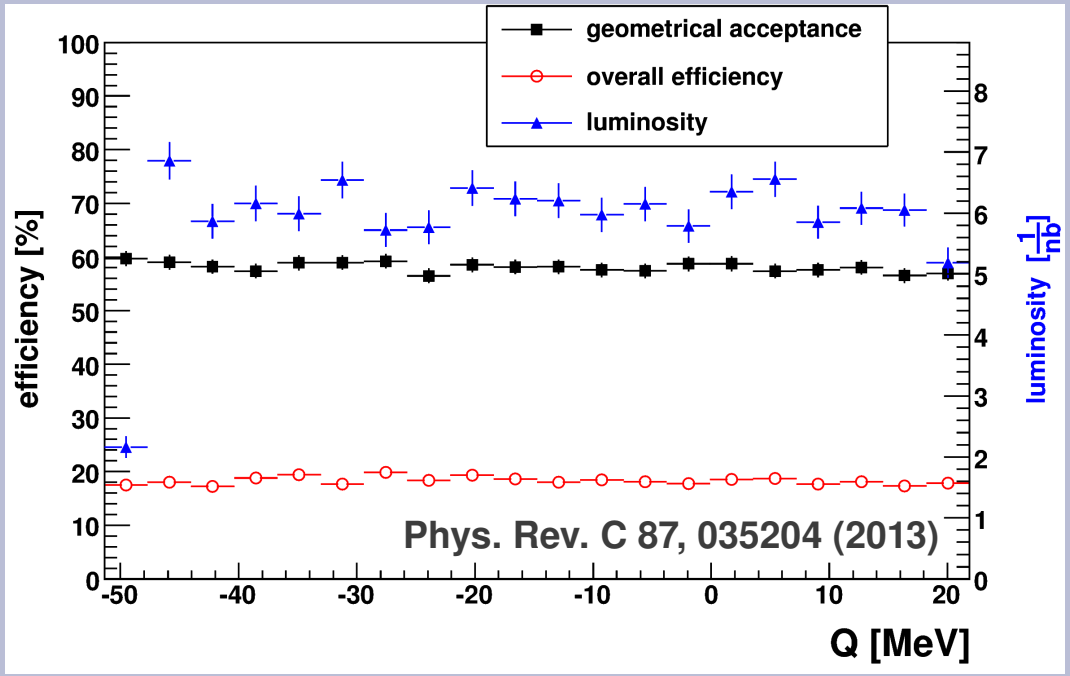
dd → ^{3}He n π^0 → ^{3}He n $\gamma\gamma$



Results from 2008 data

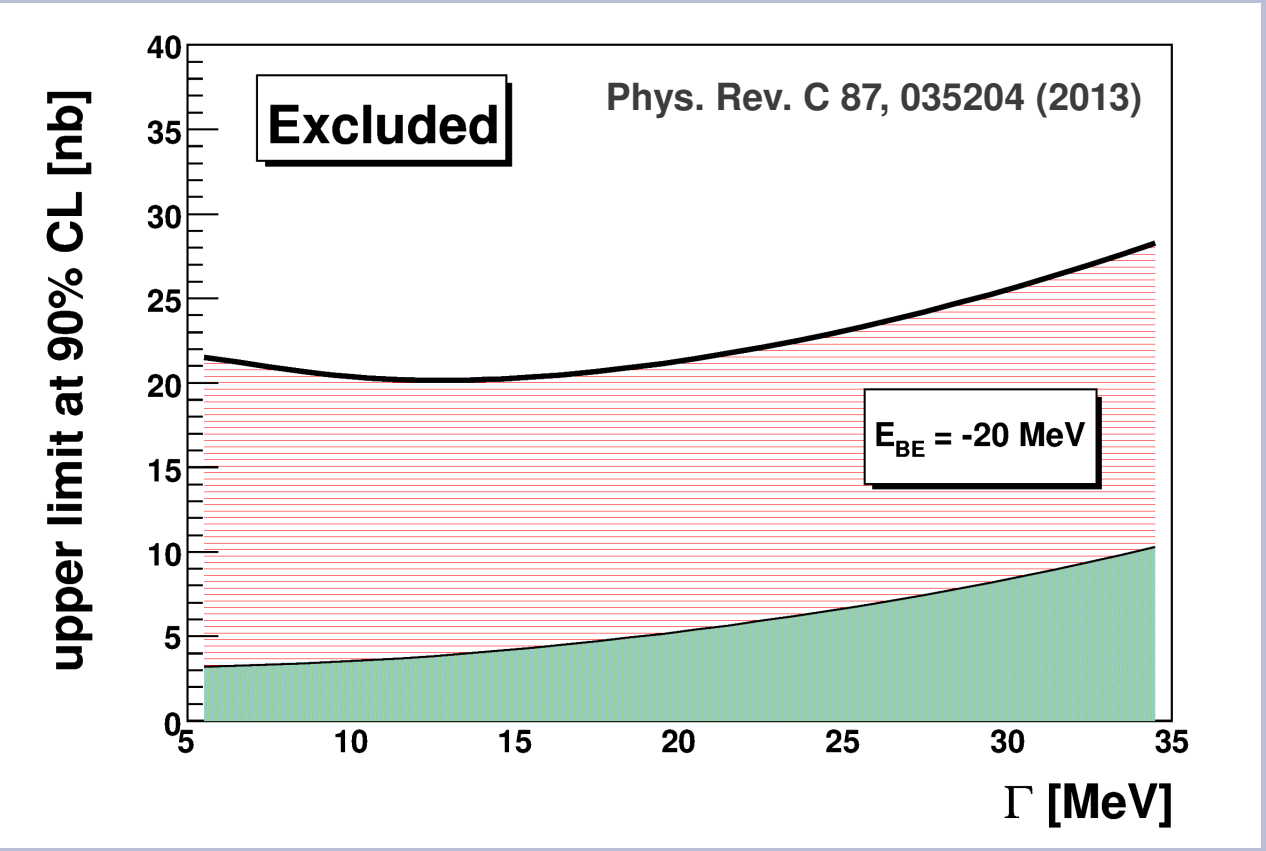
Excitation function (normalized and corrected for efficiency)





Upper limit of the maximum cross-section

for the reaction dd → (^{4}He -η)$_{bound}$ → ^{3}He p π$^-$



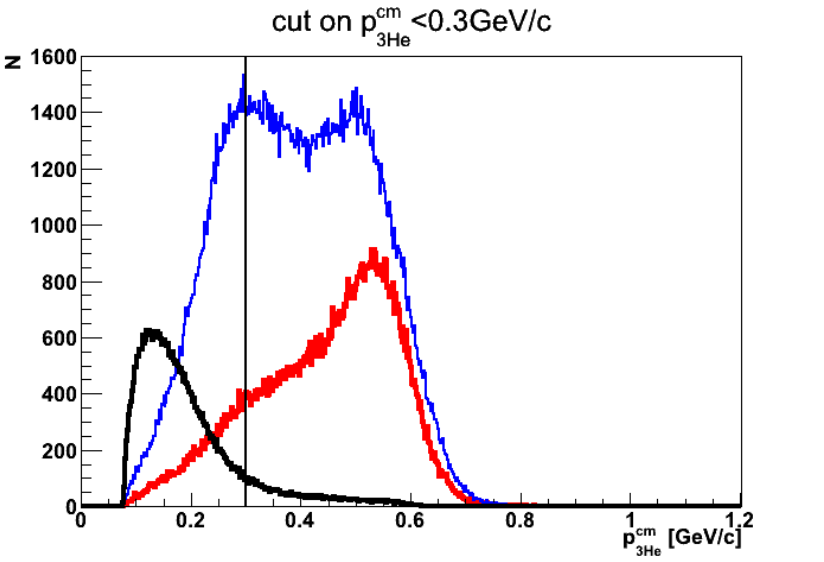
Signal:

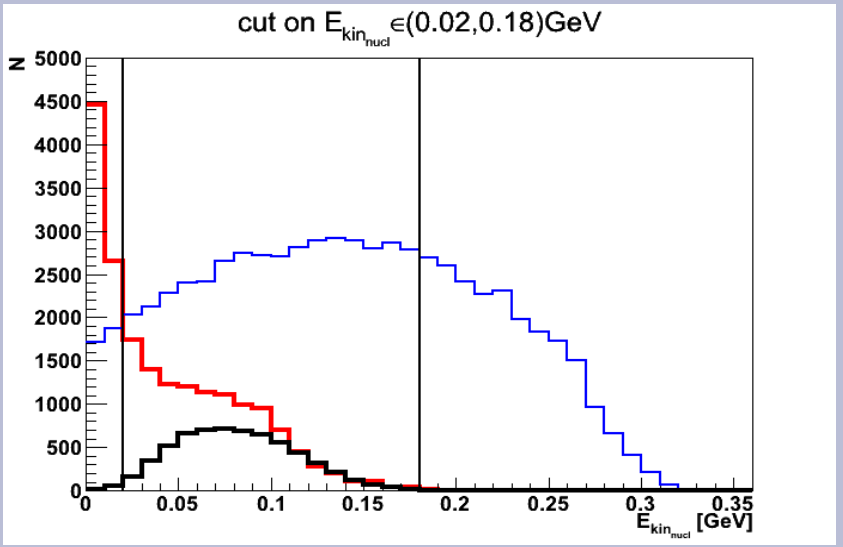
$$\sigma(Q, E_{BE}, \Gamma, A) = \frac{A\left(\frac{\Gamma}{2}\right)^2}{(Q - E_{BE})^2 + \left(\frac{\Gamma}{2}\right)^2}$$

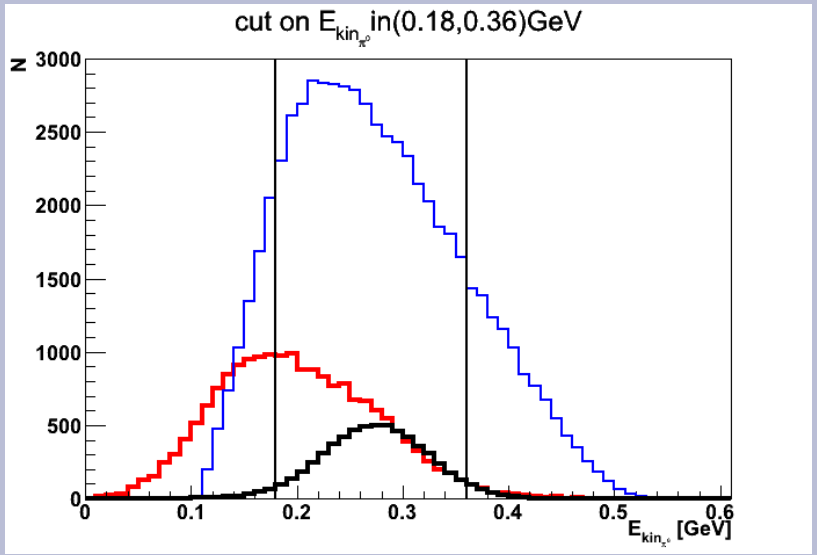
Background: $BG = a_0 + a_1 Q + a_2 Q^2$ **or** $BG = a_0 + a_1 Q$

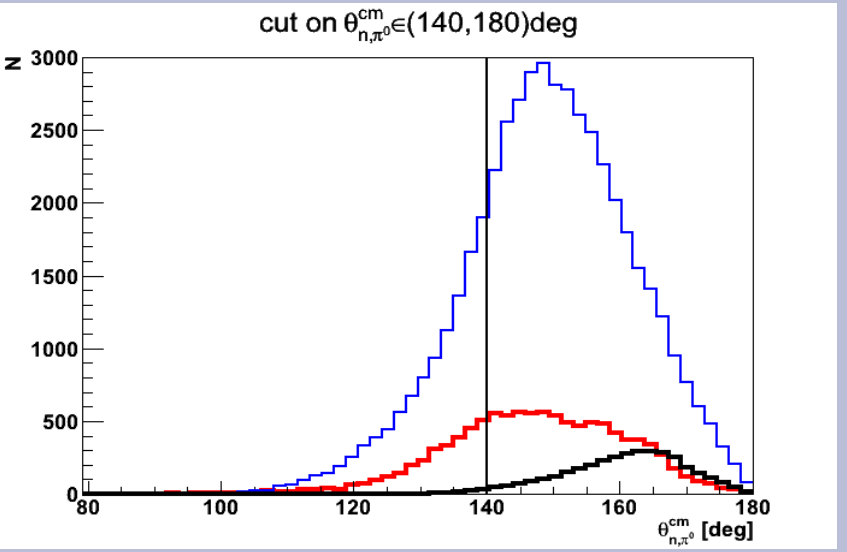
Preliminary results from 2010 data

Kinematical conditions
(3% of the full data sample)







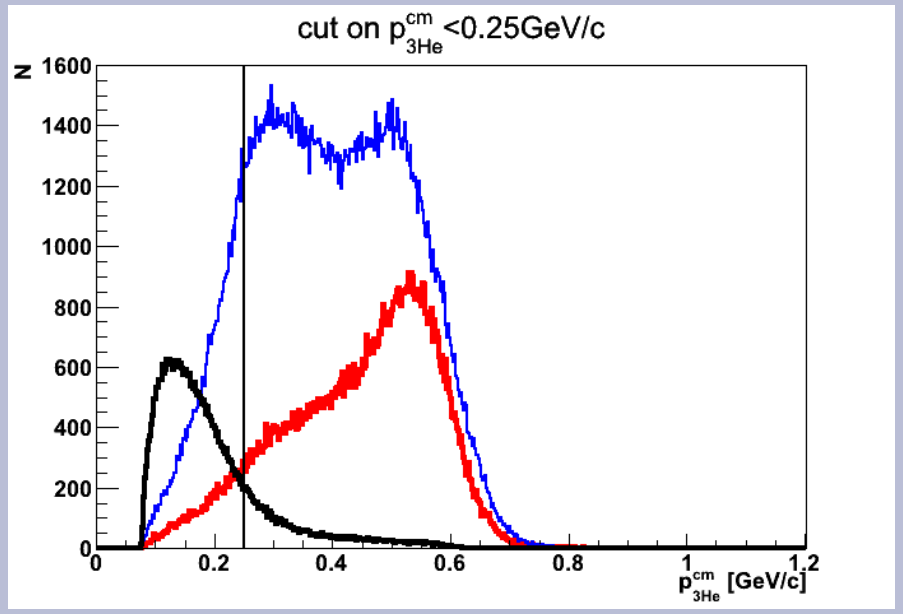


red line: dd → ^{3}He *n* π^0

blue line: dd → ^{3}He *p* π^-

black line (MC): dd → (^{4}He -η)$_{bound}$ → ^{3}He n π^0

Excitation functions for the „signal-rich” region



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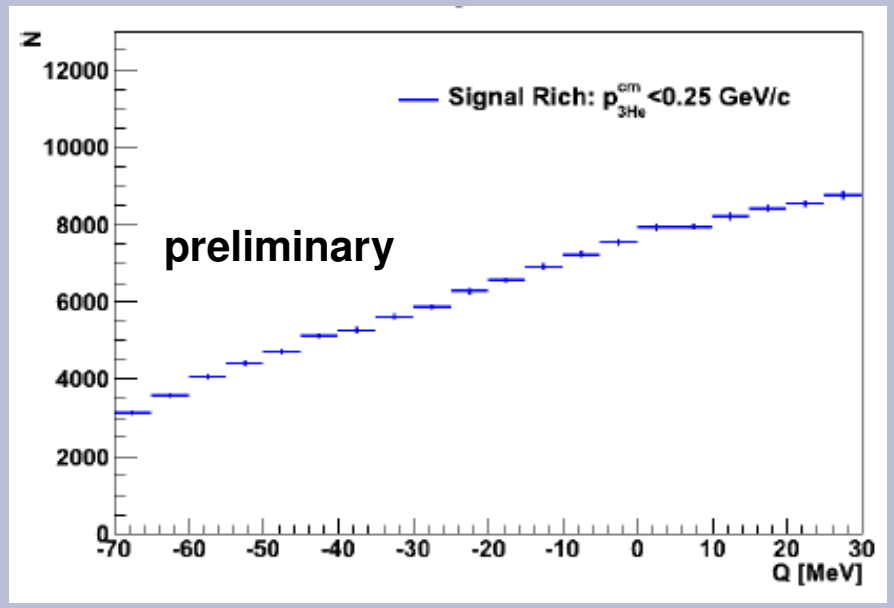
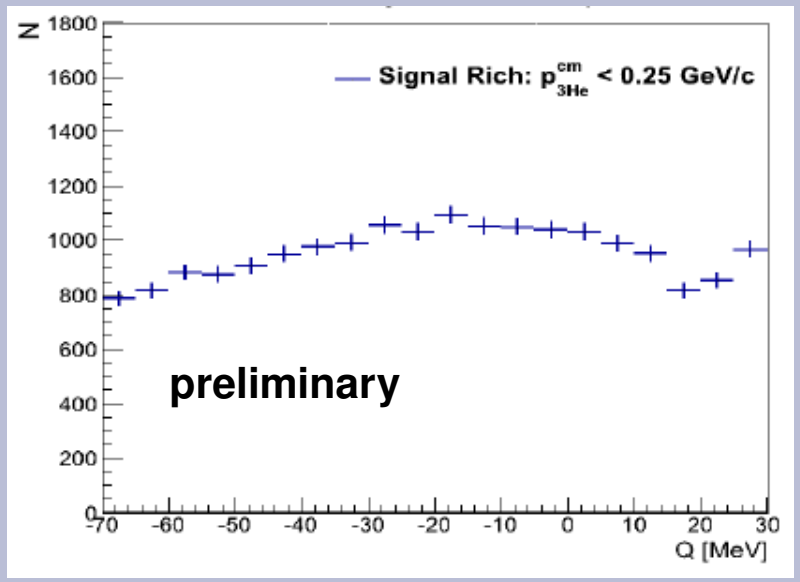
black line(MC): dd → (^{4}He -η)$_{bound}$ → ^{3}He n π^0

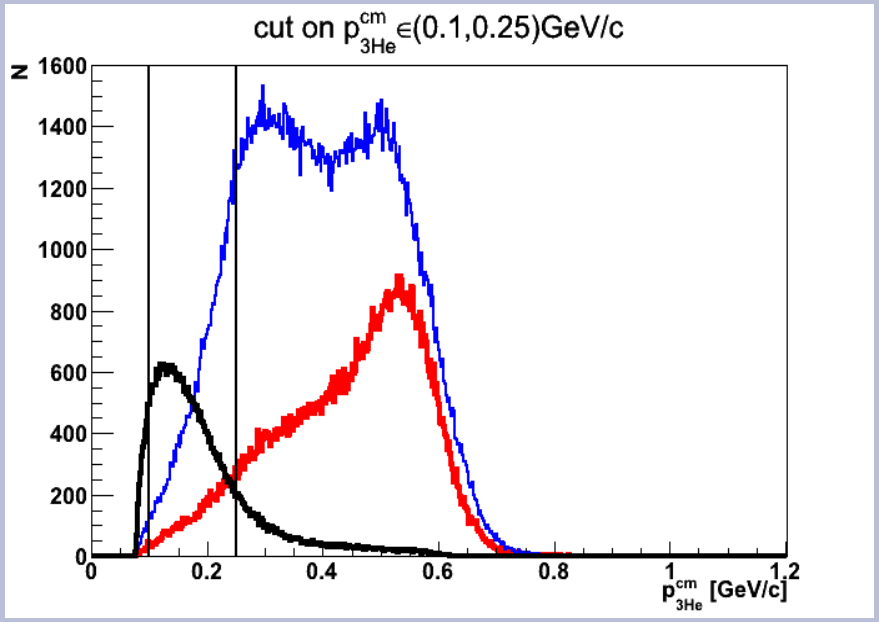




dd → ^{3}He *n* π^0 (full data sample)

dd → ^{3}He *p* π^- (3% of data)

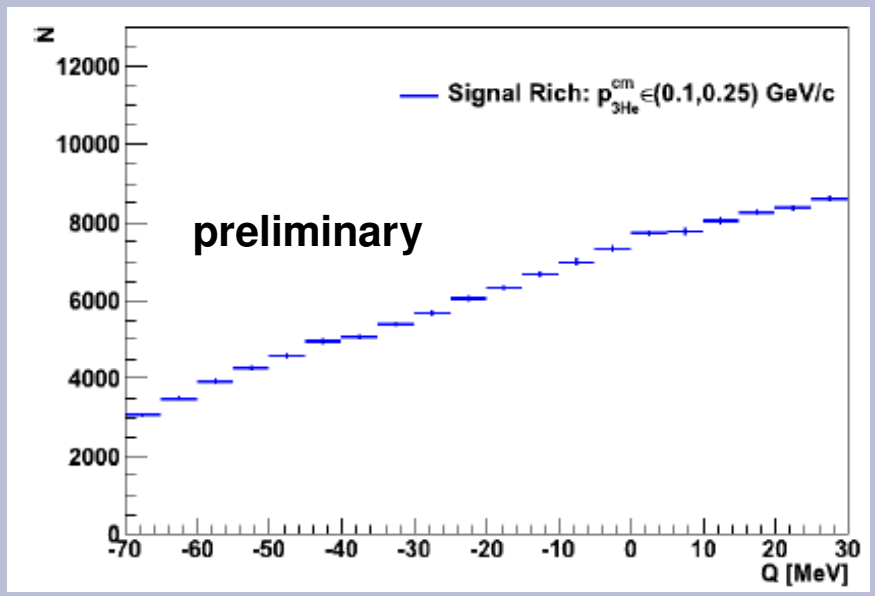
Excitation functions for the „signal-rich” region



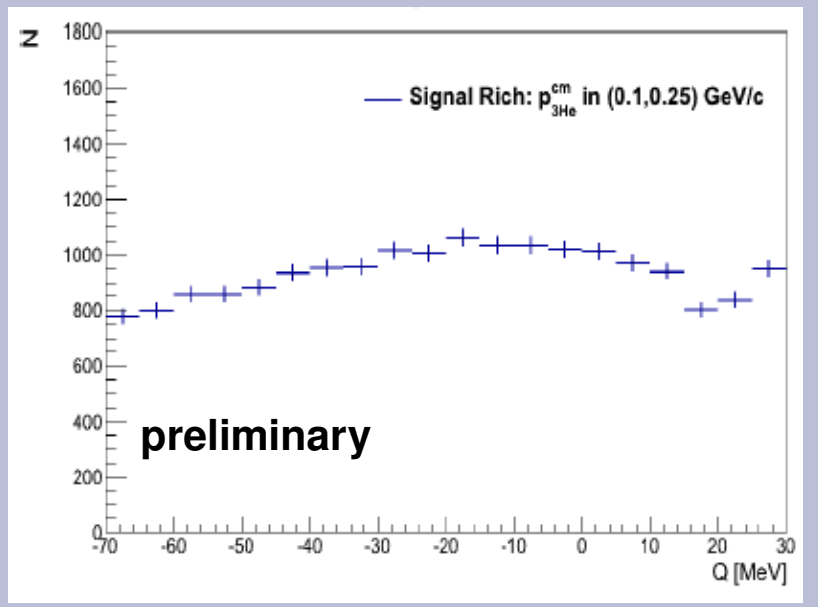
red line: dd → ^{3}He *n* π^0

blue line: dd → ^{3}He *p* π^-

black line MC dd → (^{4}He -η)$_{bound}$ → ^{3}He n π^0



dd → ^{3}He *n* π^0
(full data sample)



dd → ^{3}He *p* π^-
(3% of data)

Summary

- Exclusive measurement with the ramped beam
- two reaction channels:
  - dd → ^{3}He p π^-
  - dd → ^3He n π^0 → ^3He n $\gamma\gamma$
- no η-^{4}He bound state observed in 2008 data.
- upper limit estimated: from 20 to 27 nb (on 90 % C.L.) (2008 data)
- preliminary excitation functions of the 2010 data does not reveal signal of the mesic nucleus (3% data sample for ^{3}He p π^- and full data sample for ^3He n π^0)
- ongoing analysis

Thank you

dd → ^{3}He p π^- vs dd → ^{3}He n π^0

$$|I I_3 > d : |00 > dd : |00 > {}^3\mathrm{He} : |\frac{1}{2}\frac{1}{2}>$$

$$I_3(dd) = I_3({}^3\mathrm{He}) + I_3(\mathrm{N}^*)$$

$$N* : |\frac{1}{2} - \frac{1}{2}>$$

$$p : |\frac{1}{2}\frac{1}{2}> \pi^- : |1 - 1> n : |\frac{1}{2} - \frac{1}{2}> \pi^0 : |10>$$

$$\frac{\sigma(\mathrm{N}^* \to p\pi^-)}{\sigma(\mathrm{N}^* \to p\pi^0)} = \frac{|<\frac{1}{2}\frac{1}{2} \quad 1 - 1|\frac{1}{2} - \frac{1}{2}>|^2}{|<\frac{1}{2} - \frac{1}{2} \quad 1 \quad 0|\frac{1}{2} - \frac{1}{2}>|^2} = \frac{|-\sqrt{\frac{2}{3}}|^2}{|\sqrt{\frac{1}{3}}|^2} = 2$$

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) $\pi^+ + {}^{16}O \rightarrow p + \eta\text{-}{}^{15}O$

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

- **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-η, ^{3}He-η, ^{4}He-η, T-η

COSY accelerator in Juelich (Germany)

(COoler SYnchrotron)

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

All cuts

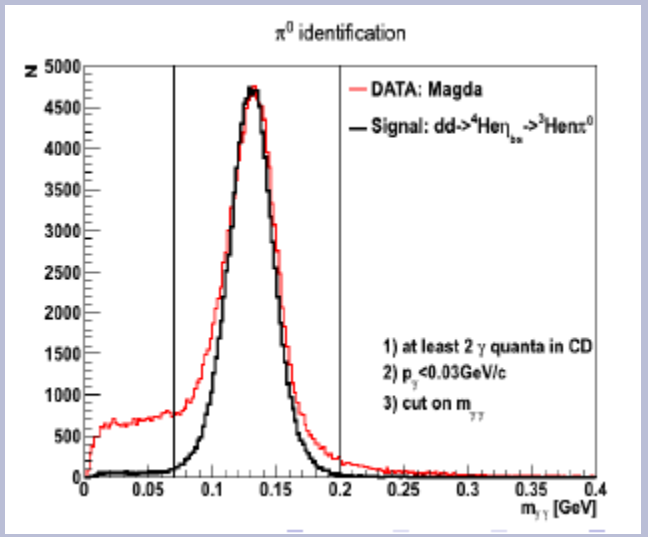
- Level_0 -general cuts (data preselection)
- Level_1 -^{3}He identification
- Level_2 -nucleon-pion identification
- Level_3 -search for the $(^4\text{He}\text{-}\eta)_{bound}$ - Signal Rich Region

1) before cuts (preselection)
2) Trigger7
3) no El22_FRH2

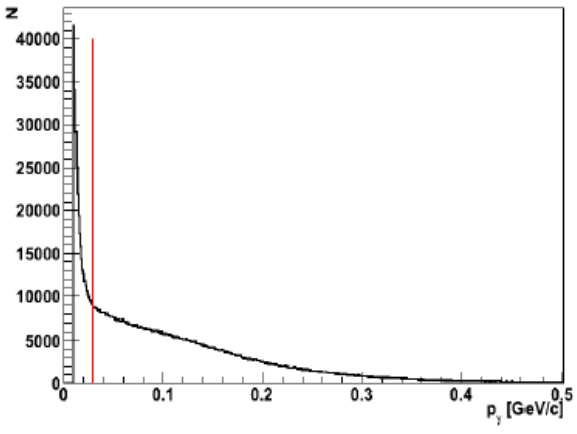
1) 1 charged in FD
2) Veto FRH3,FRH4,FRH5
3) Edep(FRH1)∈(0.15,0.4)GeV

Wojtek:
1) 2 charged in CD
2) π^- identification
3) proton identification via m_x

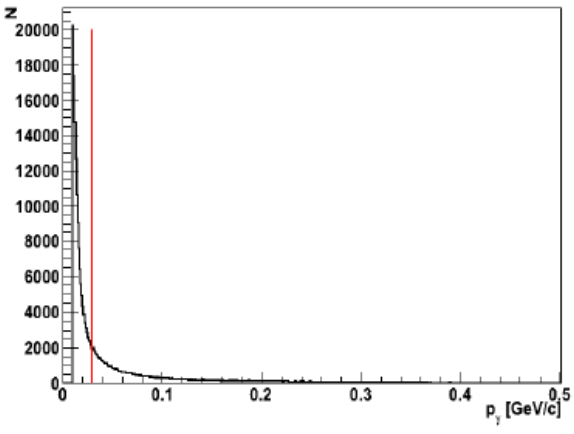
Magda:
1) no charged in CD
2) π^0 identification
3) neutron identification via m_x



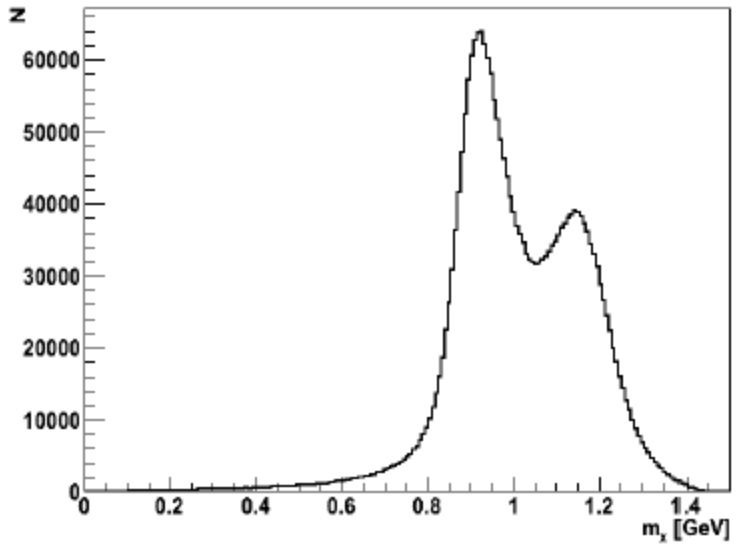
combination of 2γ

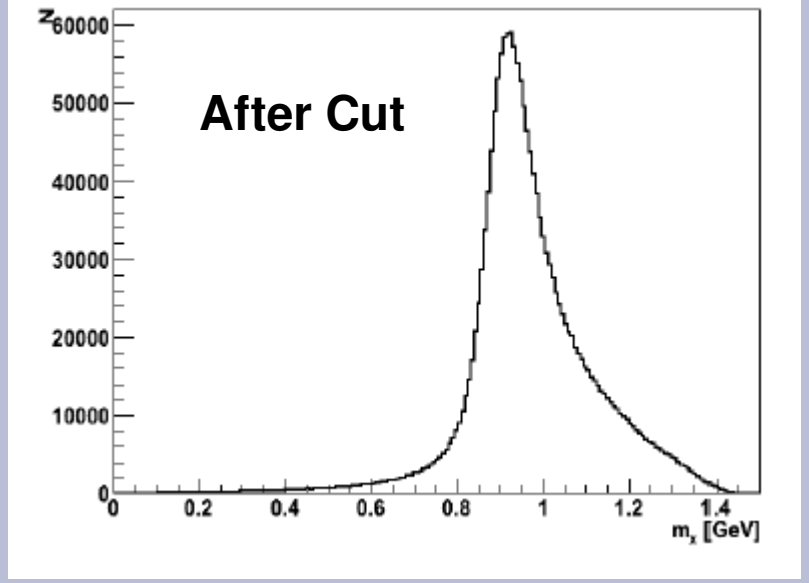


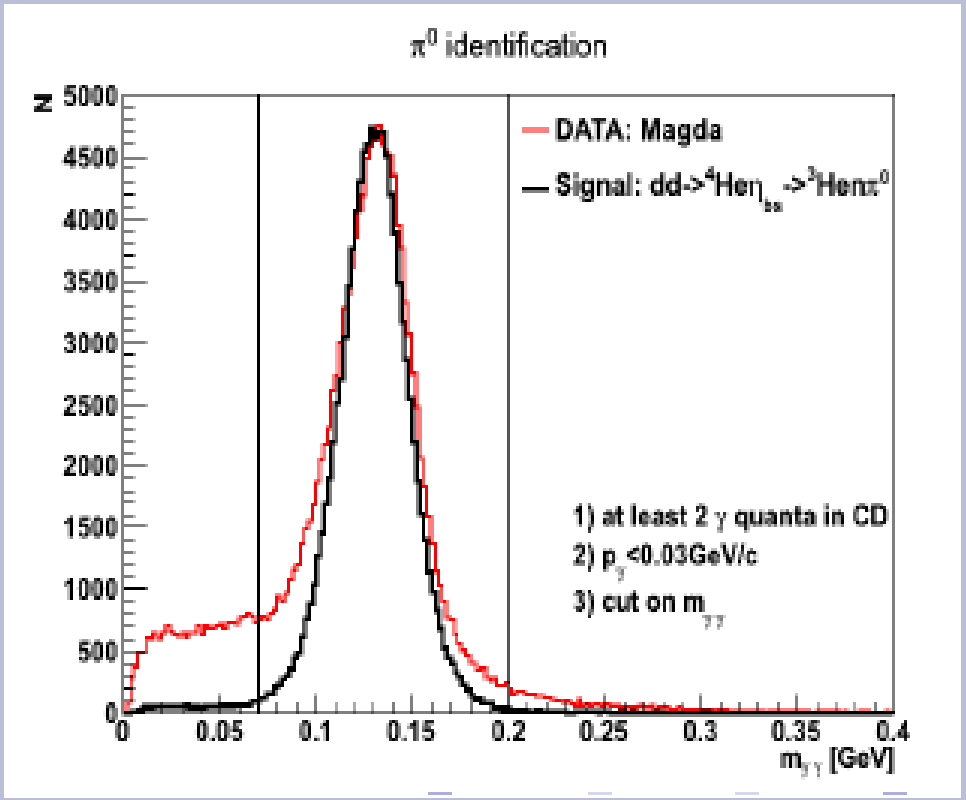
DATA



WMC



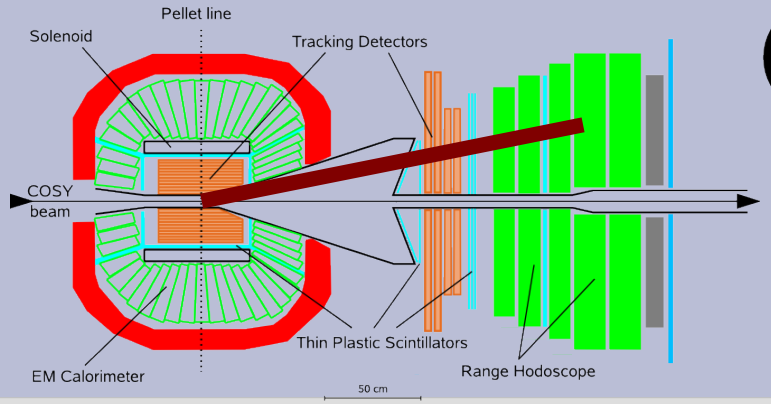



π^0 identification
N
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
$m_{\gamma\gamma}$ [GeV]
DATA: Magda
Signal: dd->^{4}Heη_{bs}->^{3}Heπ^0
1) at least 2 γ quanta in CD
2) p_γ<0.03GeV/c
3) cut on $m_{\gamma\gamma}$

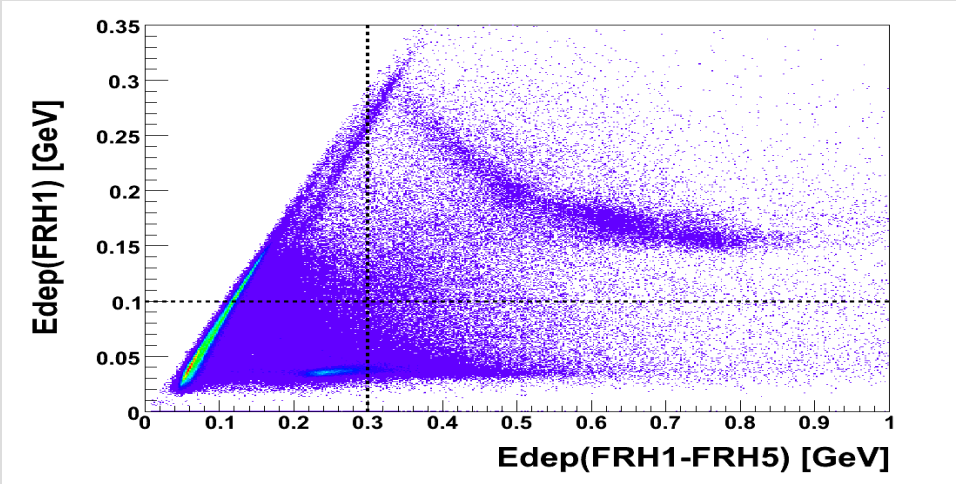
Luminosity I

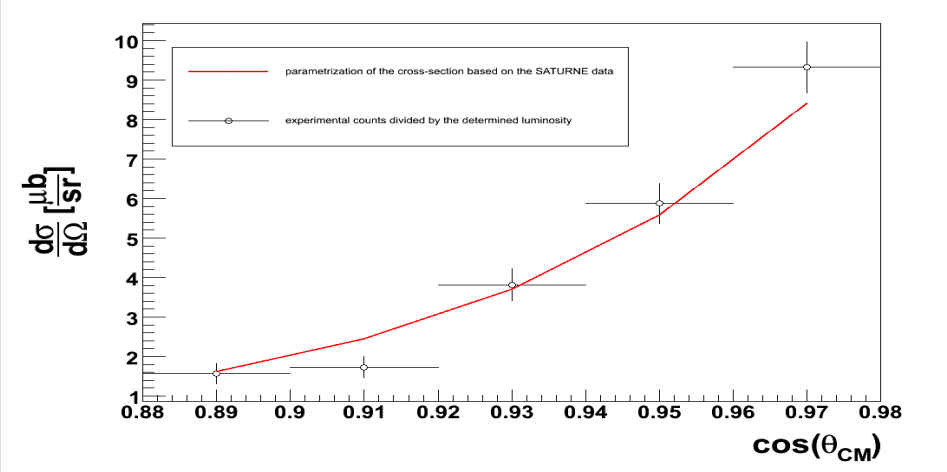
Absolute normalization

dd → ^{3}He *n*

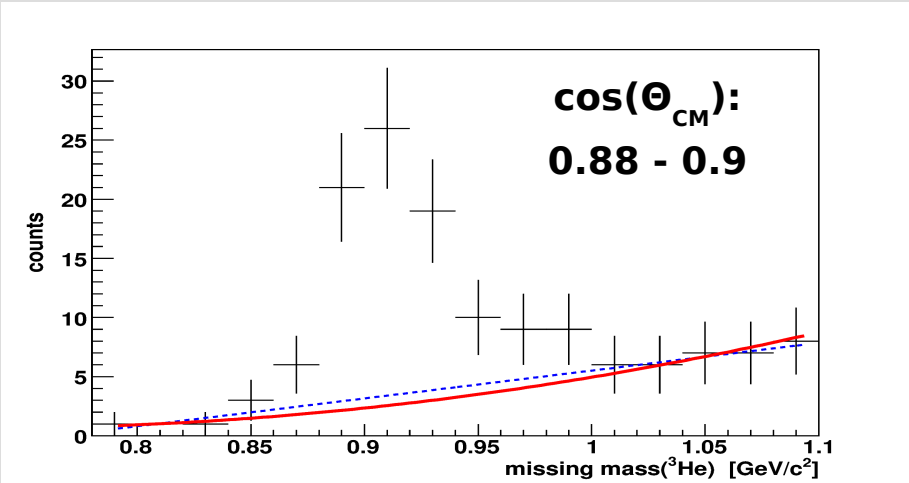


^{3}He selection





MM(^{3}He) -neutron



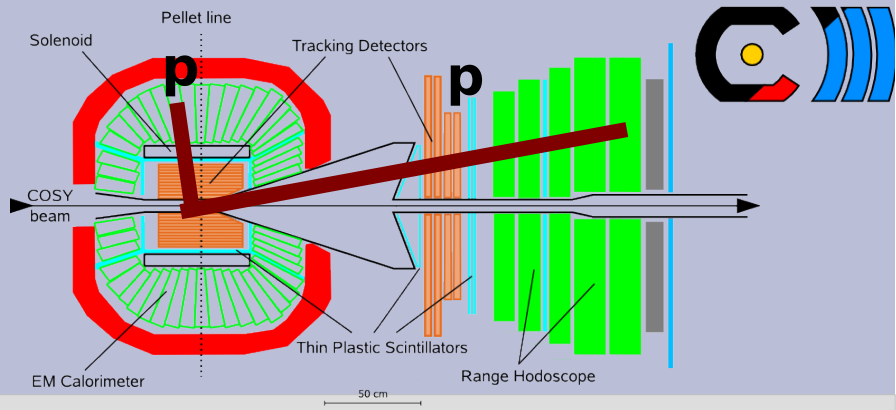
L=117.9 ±13.6 nb^{-1}

stat: ±4.5 %
syst(background subtract):±8%
param. from SATURNE: ±7%

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

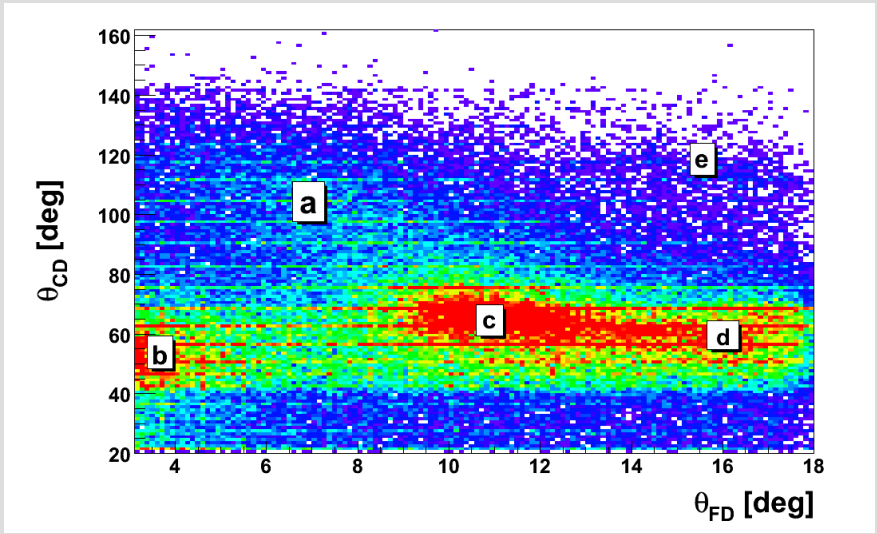
Reference to SATURNE data: G.~Bizard et al., Phys. Rev. C 22 (1980) 1632.

Luminosity II
(beam momentum dependence)

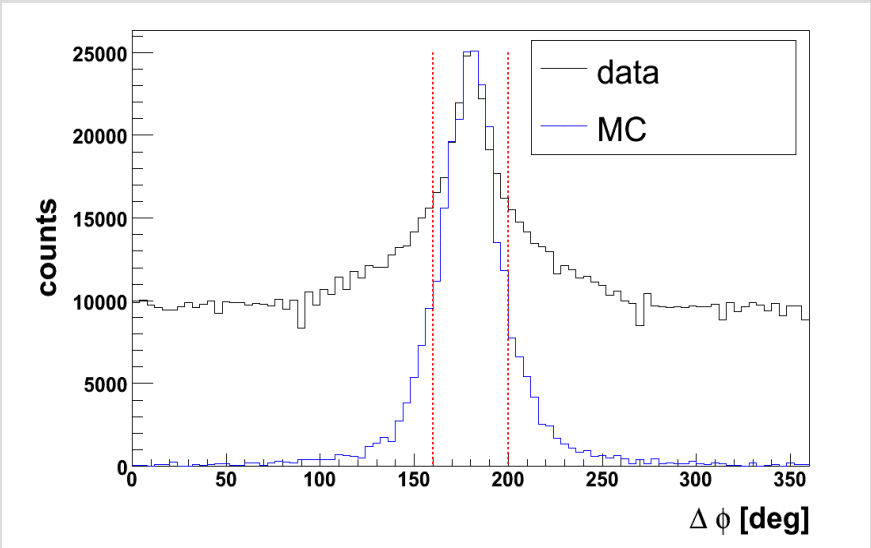


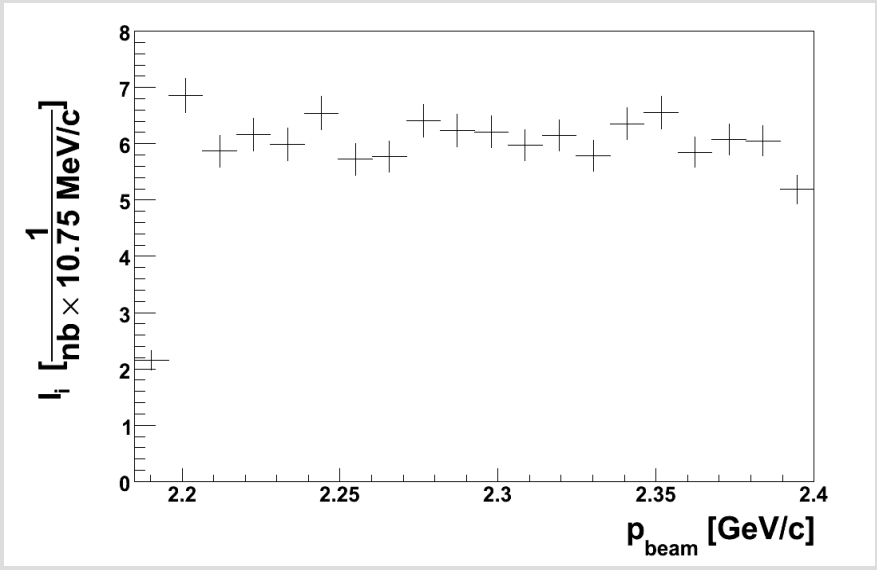
Quasi-elastic scattering:
dd → pp (nn)$_{spec}$

- One charged in FD && one charged track in CD.
- Coplanarity condition **Δφ<20 deg.**
- Cut on E in scintillator barrell (π background reduction).

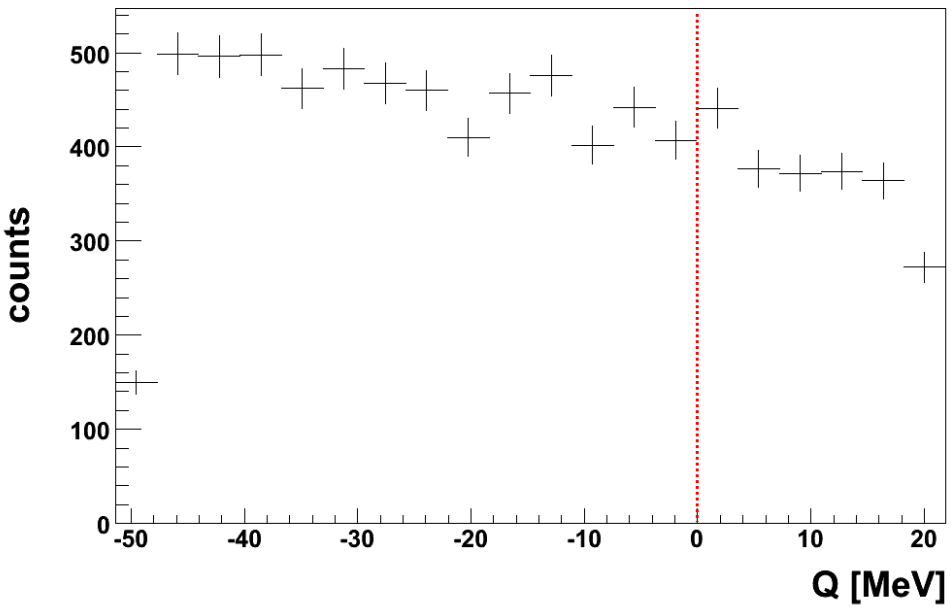


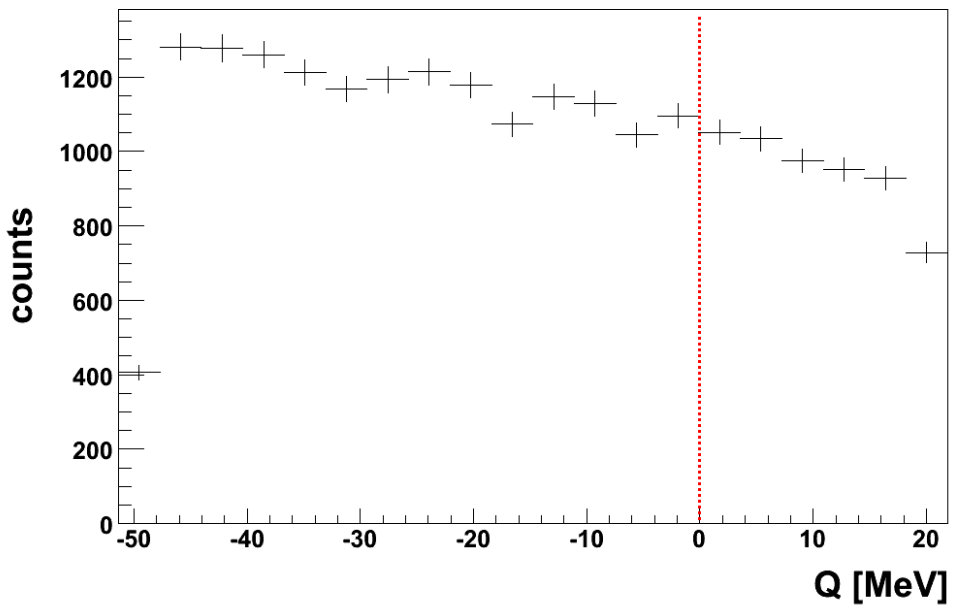
Coplanarity





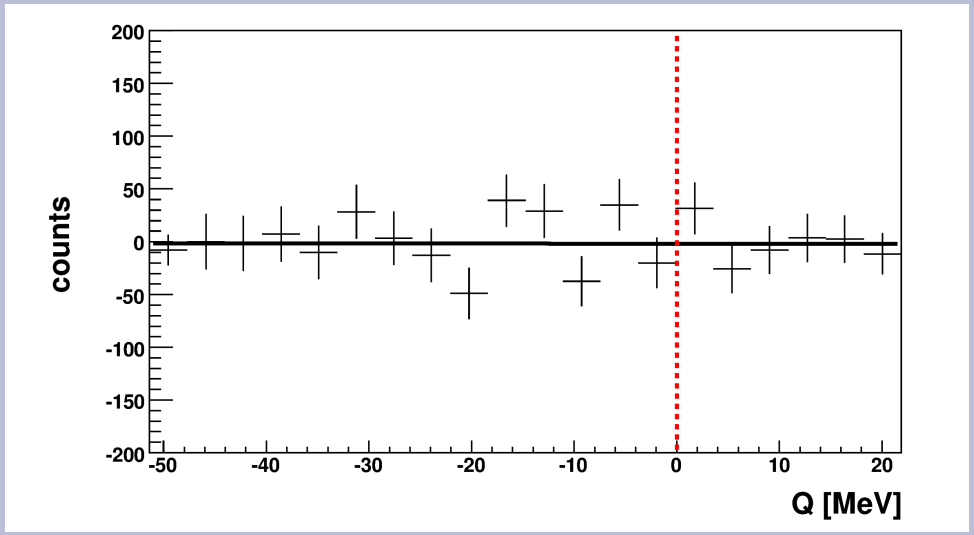
Excitation functions (not normalized)





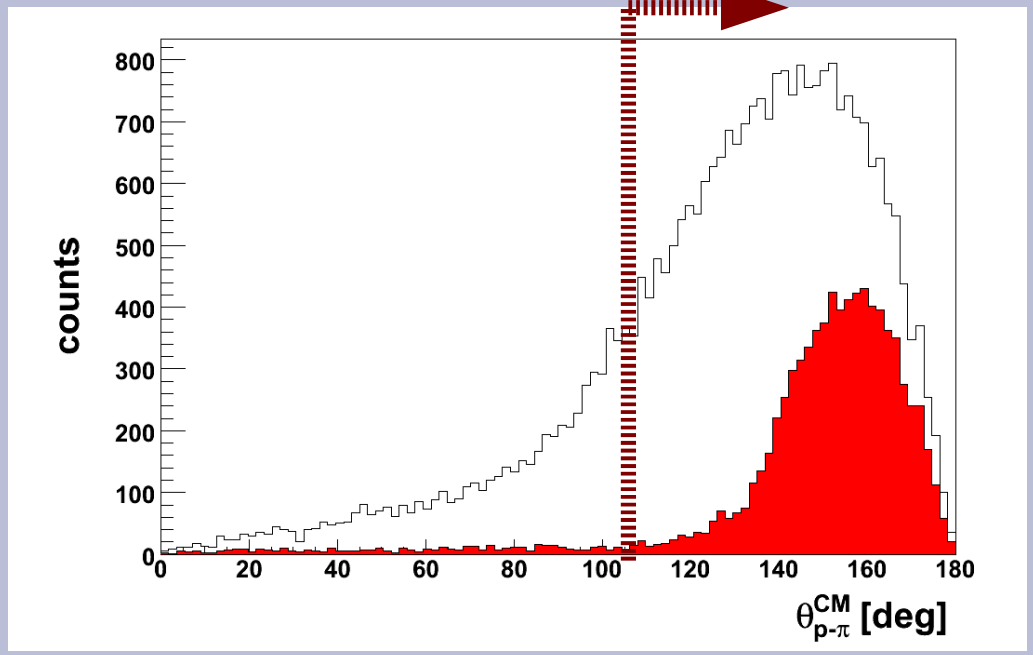
“Signal-rich” region (P_{HE}^{CM} <0.3 GeV/c)

“Signal-poor” region (P_{HE}^{CM} >=0.3 GeV/c)

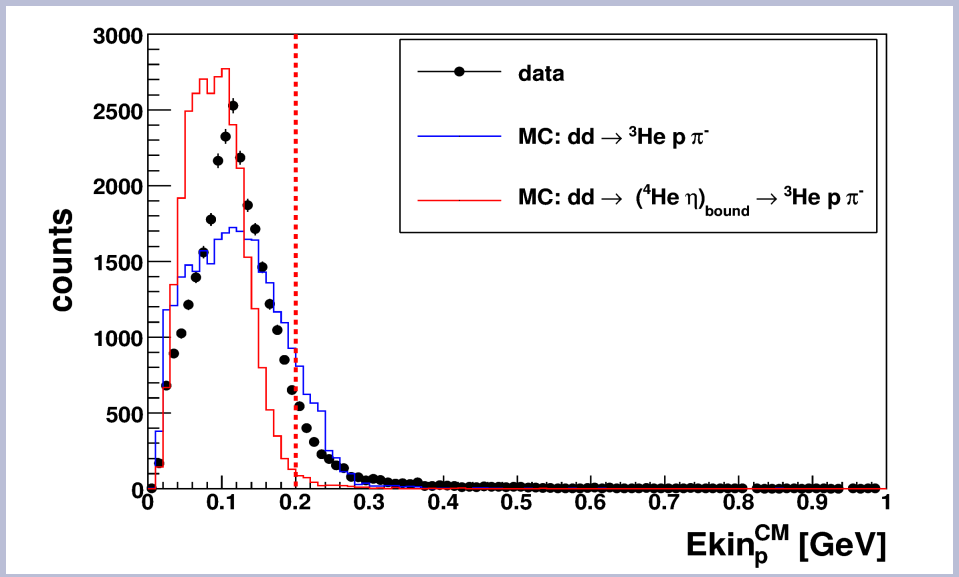


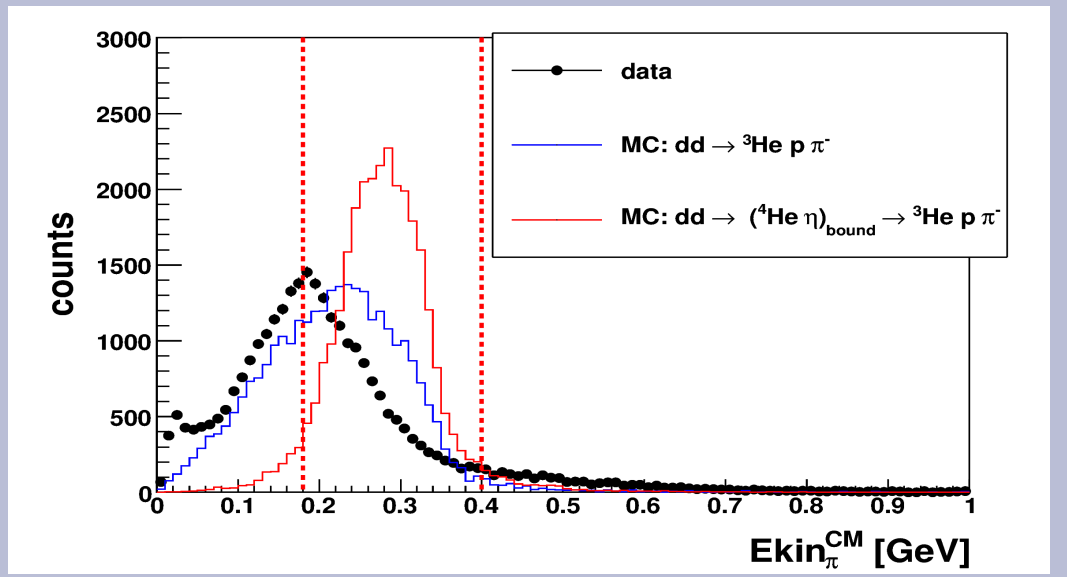
difference

Additional cuts



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

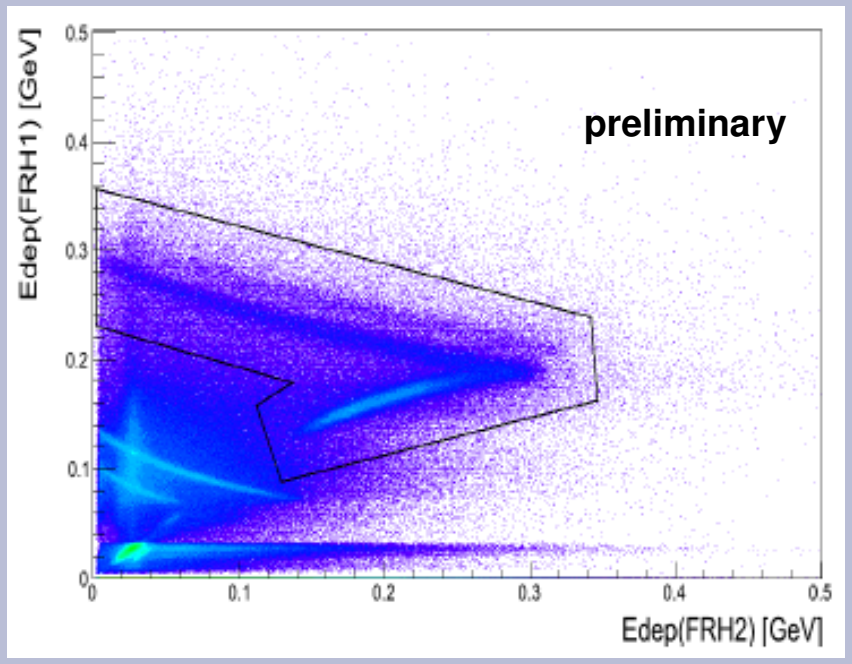


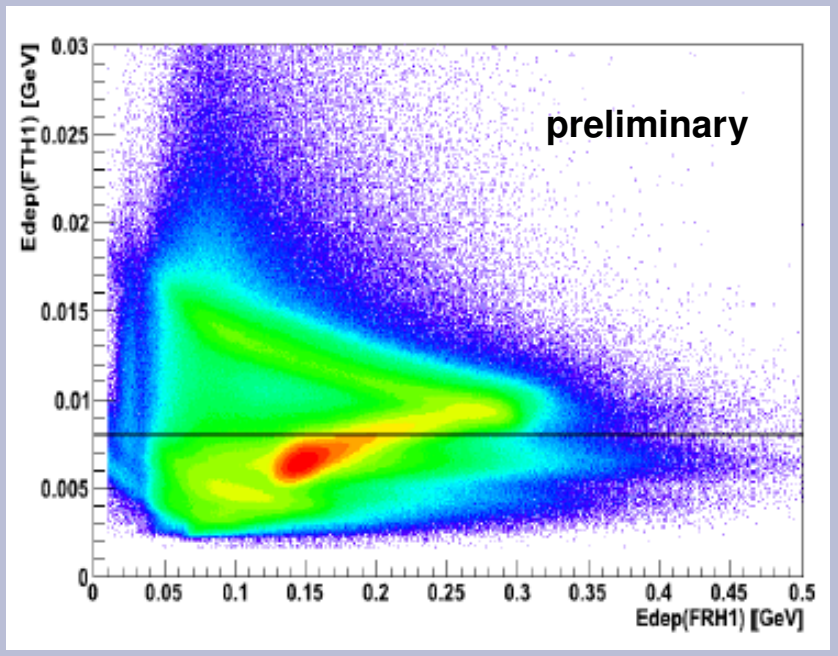


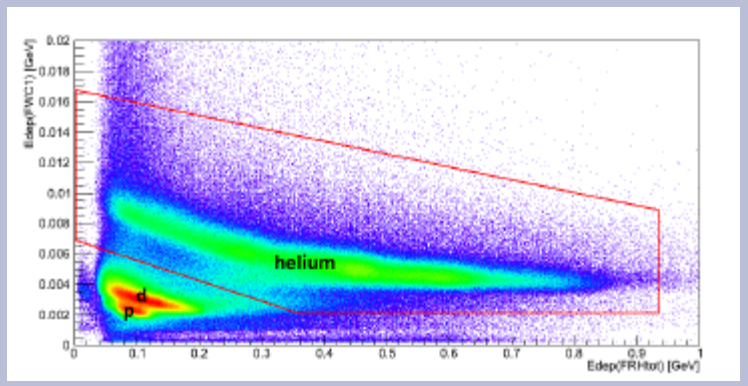
$Ekin^{CM}_p < 200$ MeV

$Ekin^{CM}_\pi > 180$ MeV && $Ekin^{CM}_\pi < 400$ MeV

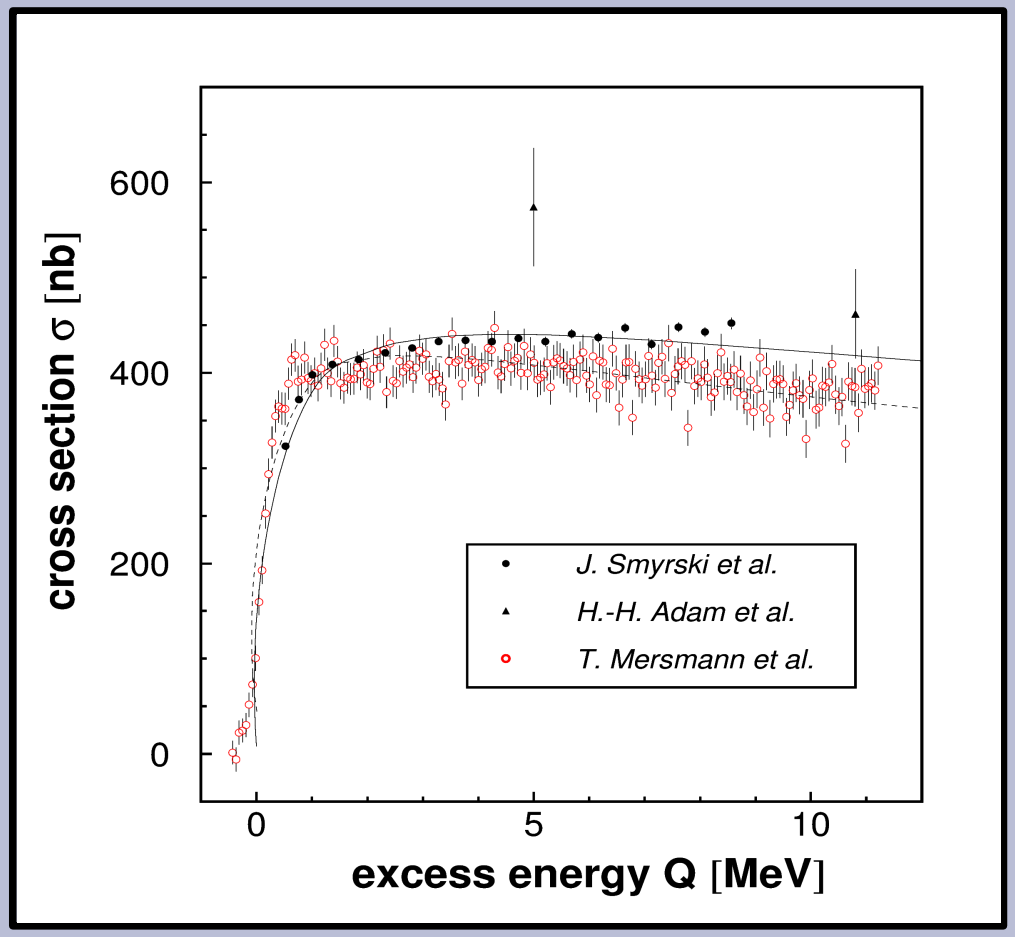
^{3}He ions identification in Forward Detector







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



Full black squares: COSY-11

Empty red squares: COSY-ANKE

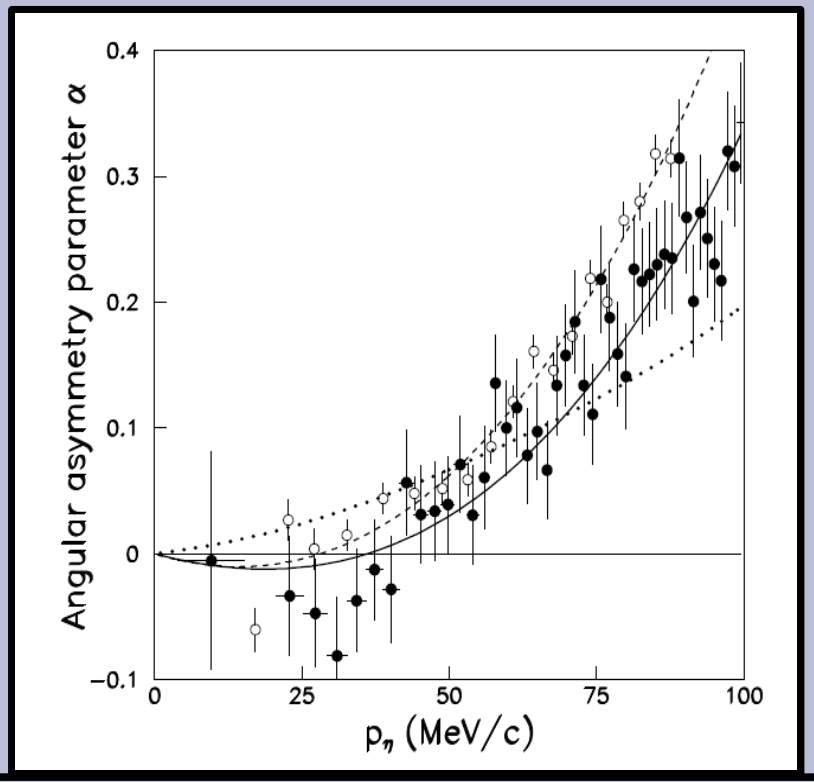
(*C.Wilkin et al. Phys.Lett. B654 (2007)*)

Also total x-section $pd \rightarrow {}^3He\eta$ and $dd \rightarrow {}^4He\eta$

SPES-3 and SPES-4 @SATURNE

N. Willis et al. Phys.Lett. B406(1997).

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



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))

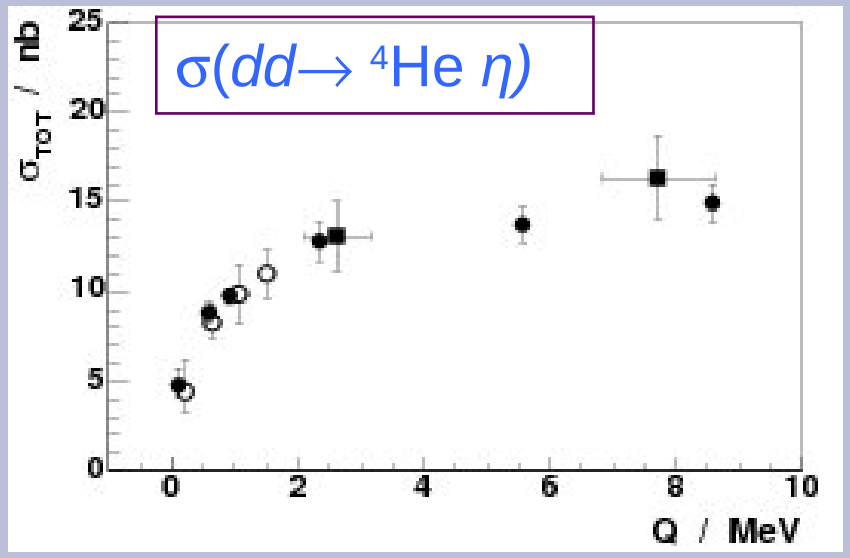
Also total x-section $\gamma {}^3He \rightarrow \eta {}^3He$

Crystal Ball-TAPS@MAMI

F. Pheron et al. Phys.Lett. B709 (2012).

Cross-section estimate
dd → ^{4}He η →^{3}He p π^-

$\sigma \sim$ 15 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.

Probablity of the decay (^{4}He η)$_{bound}$ → ^{3}He $p\pi^-$

~ 1/4 x 1/2 = 1/8

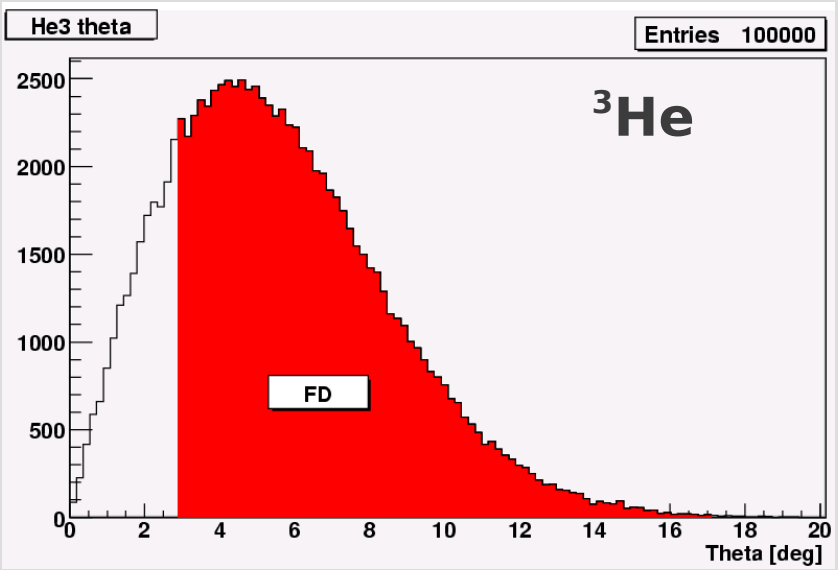
dd → ^{3}He $p\pi^-$
dd → ^{3}He nπ^0
dd → T nπ^+
dd → T $p\pi^0$

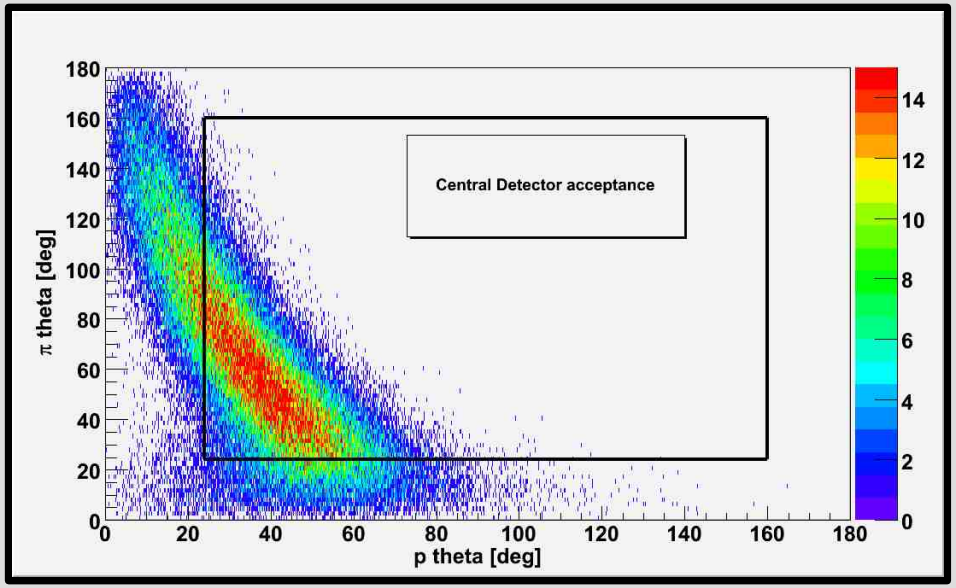
η n → pπ-
one of the possible four channels

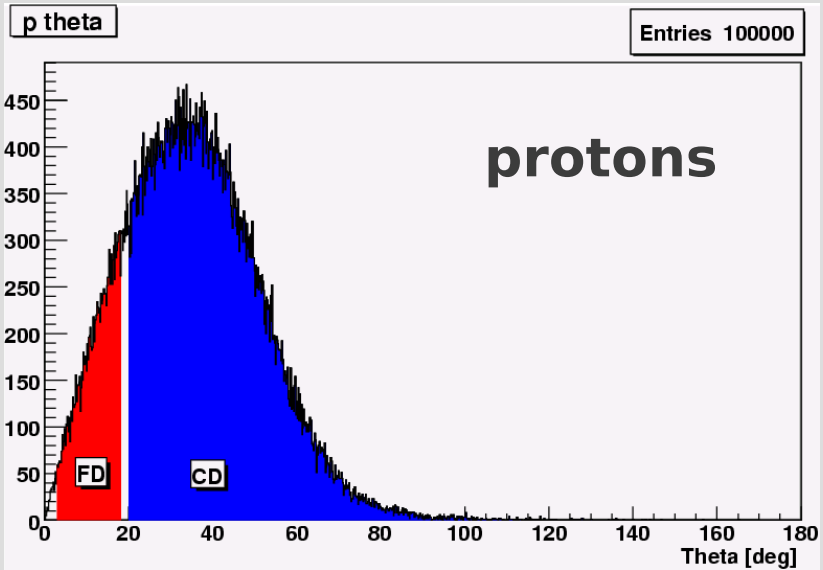
Probability that the spectator nucleons (ppn) will form ^{3}He
Per analogy to ^{4}He Λ → ^{3}He $p\pi^-$

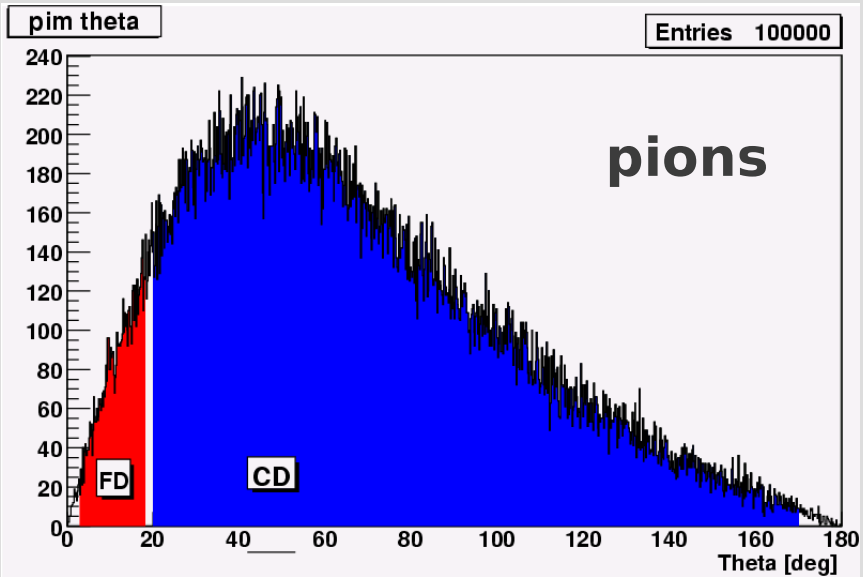
σ(dd →(^{4}He η)$_{bound}$ → ^{3}He $p\pi^-$) = 2 nb

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

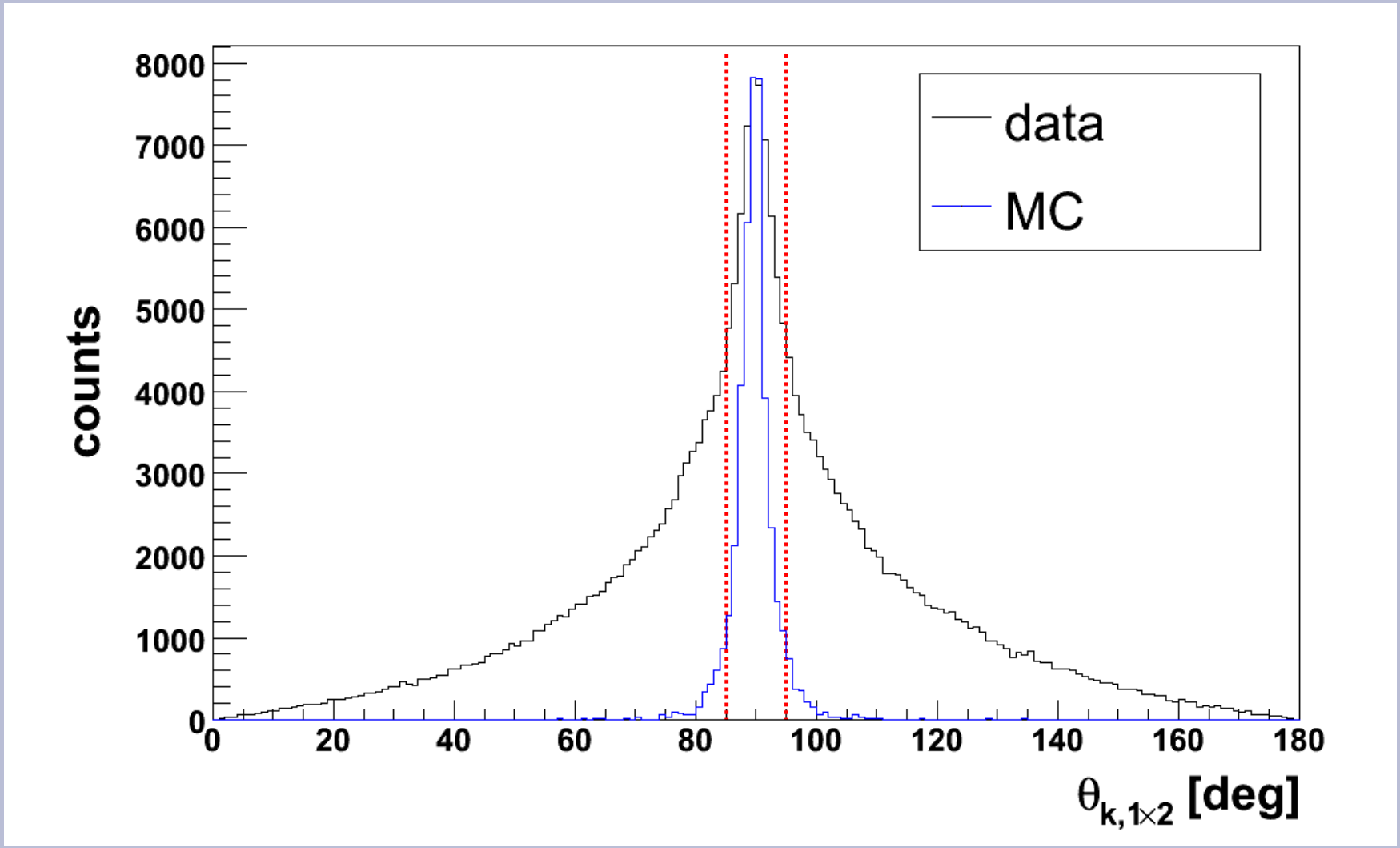




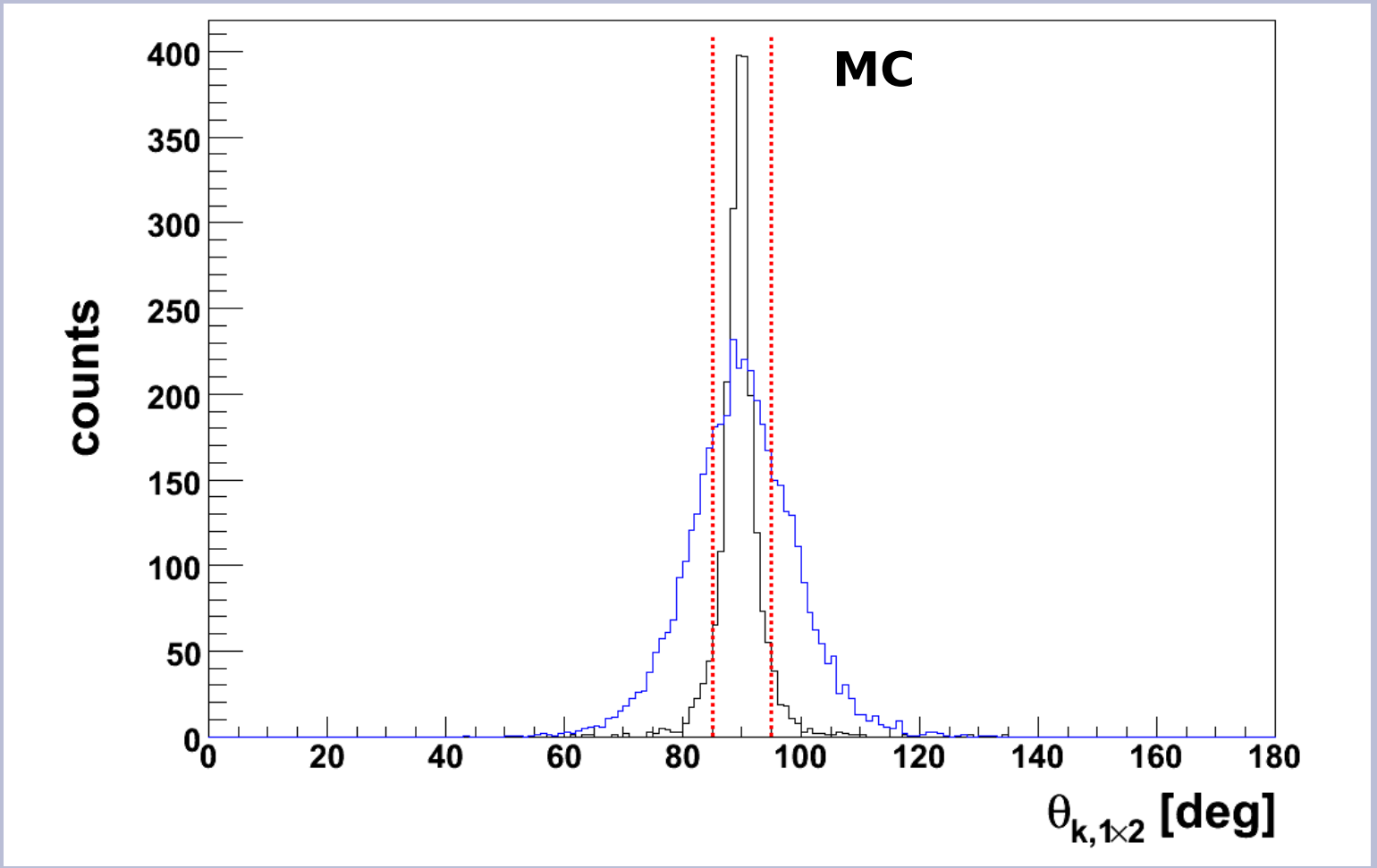




Three-particle cut



Four-particle reactions



- black :dd → ^{3}He p π^-
- blue :dd → ^{3}He p π^- π^0

Quasi-elastic reactions

$dd \rightarrow pp\,(nn)_{spect}$

$dd \rightarrow d_{beam}\ p_{target}\ n_{spect}$

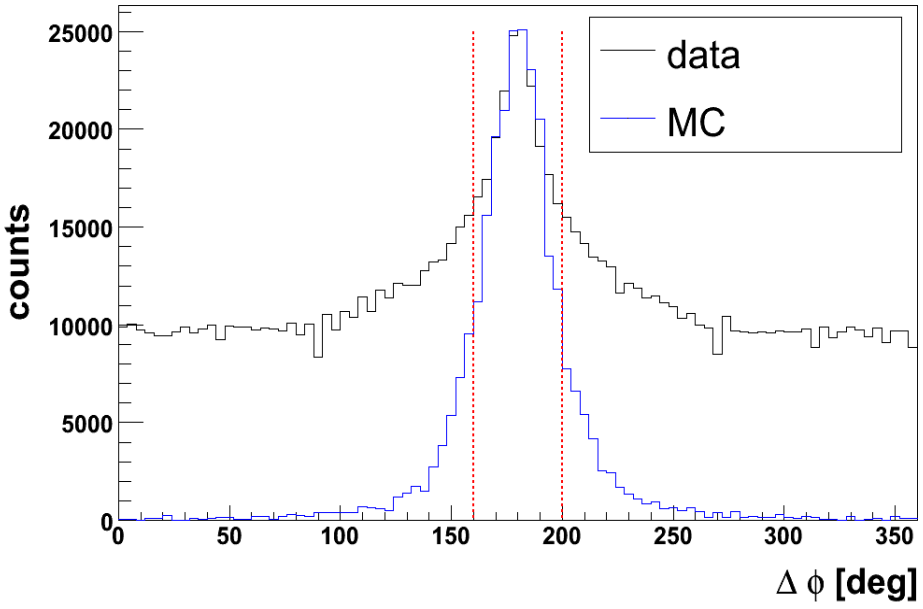
$dd \rightarrow p_{beam}\ d_{targed}\ n_{spect}$

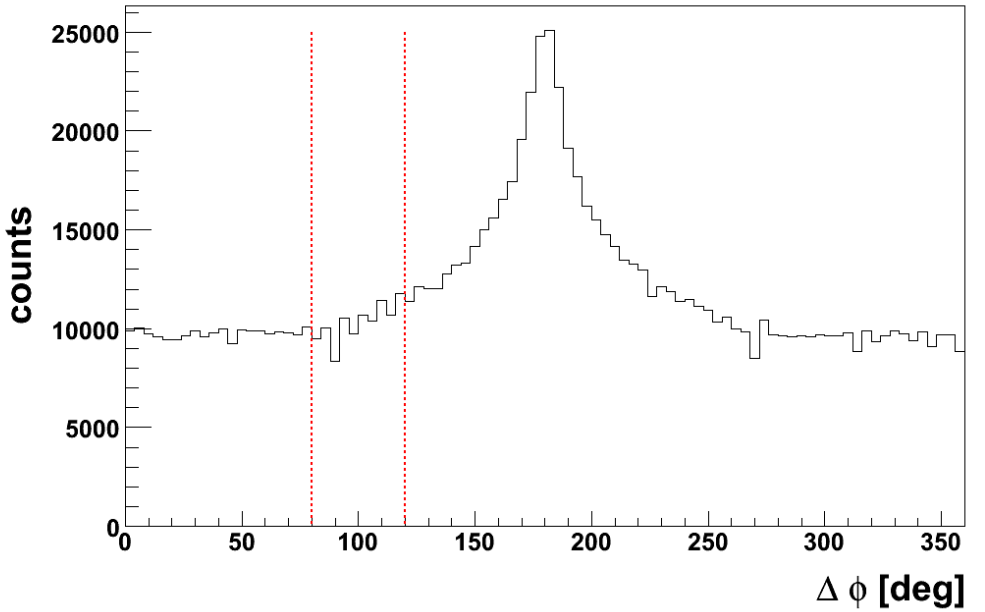
$dd \rightarrow pp\,(nn)_{spect} \rightarrow d\,\pi^{+}\,(nn)_{spect}$

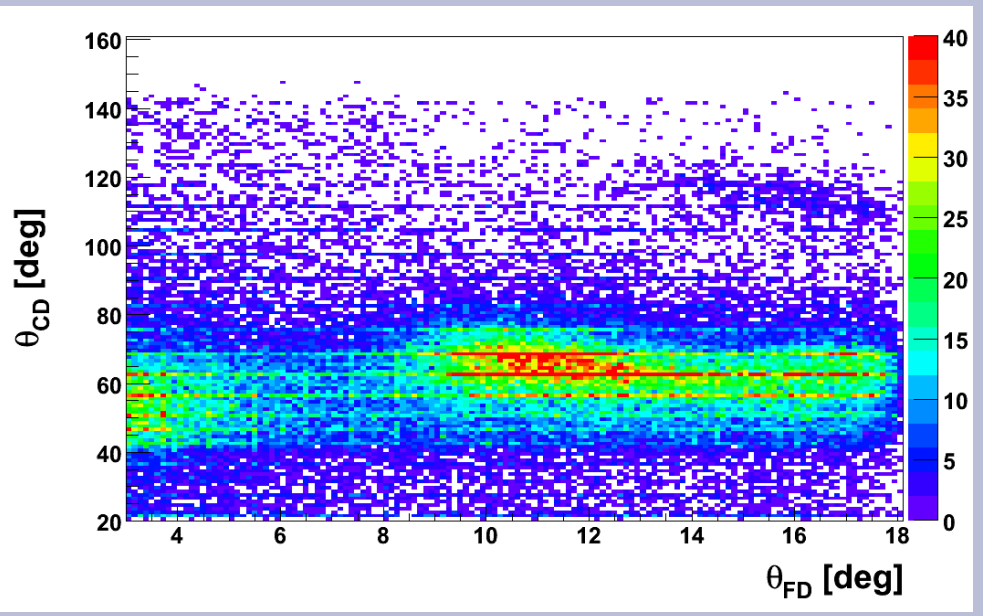
$dd \rightarrow dd$

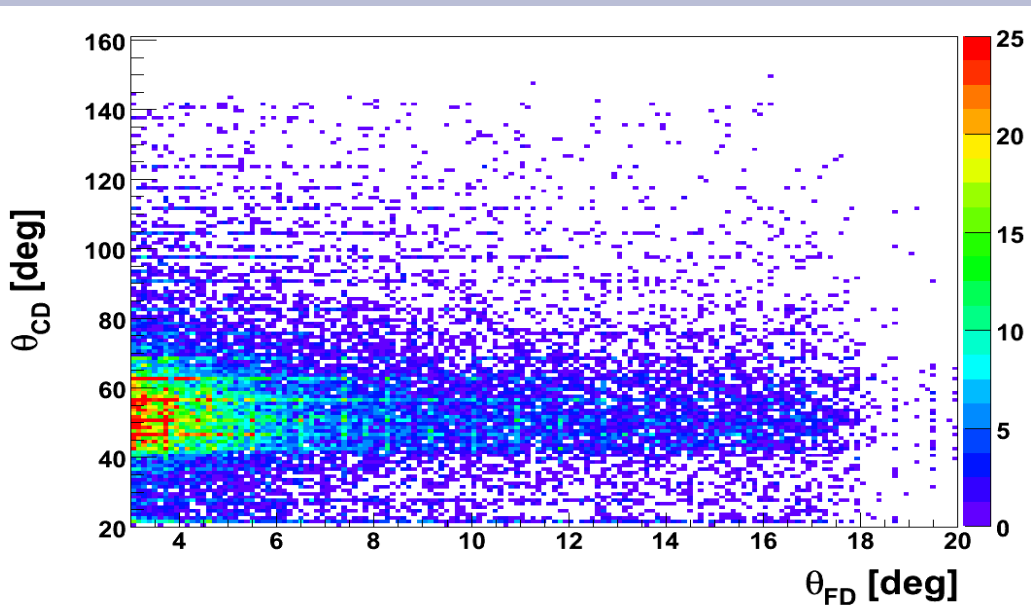
other reactions (non-coplanar)

Quasi-elastic reactions background

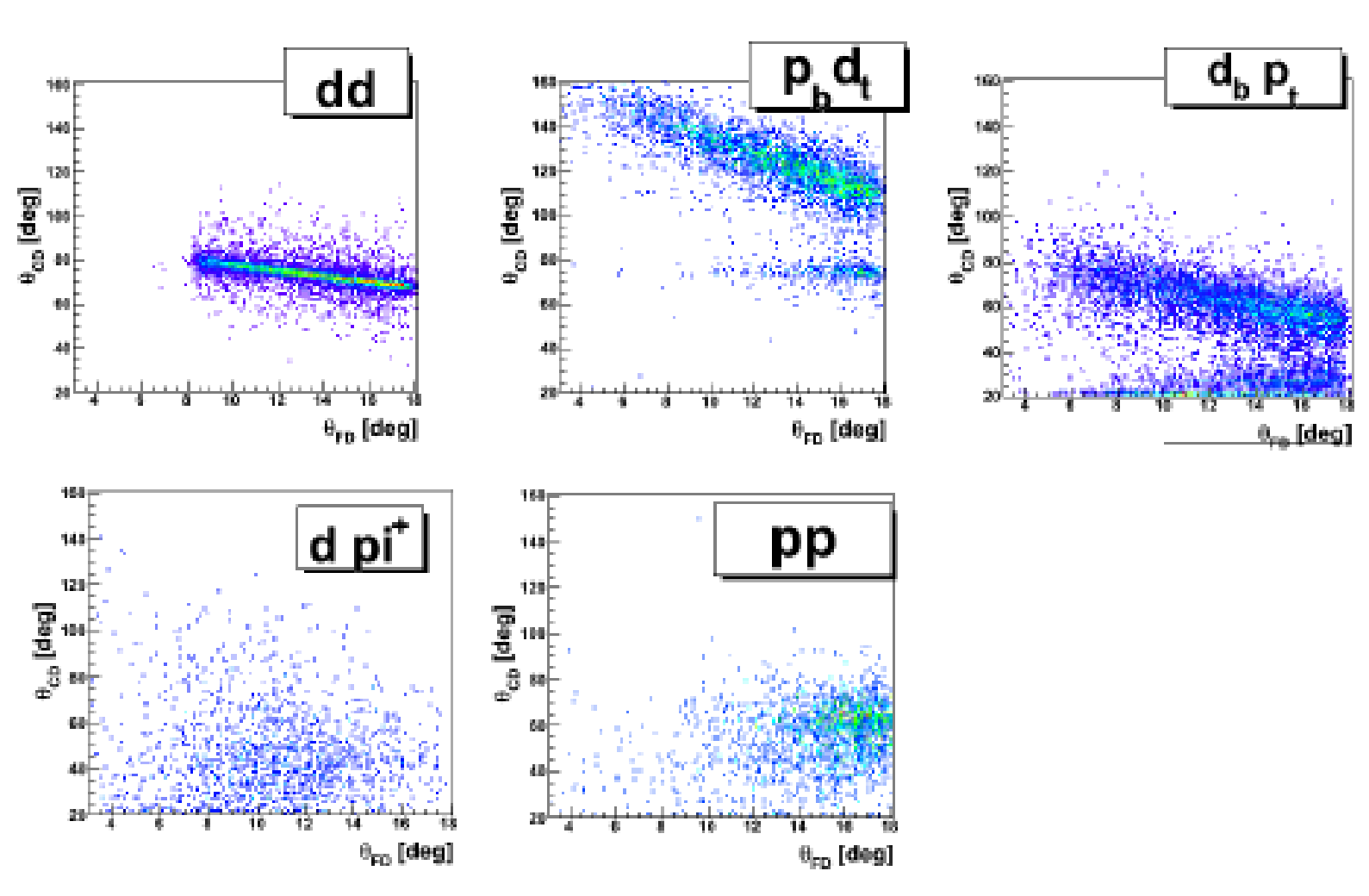








Quasi-elastic reactions
MC simulations



Quasi-elastic reaction (dp)

dd → pp (nn)$_{spect}$

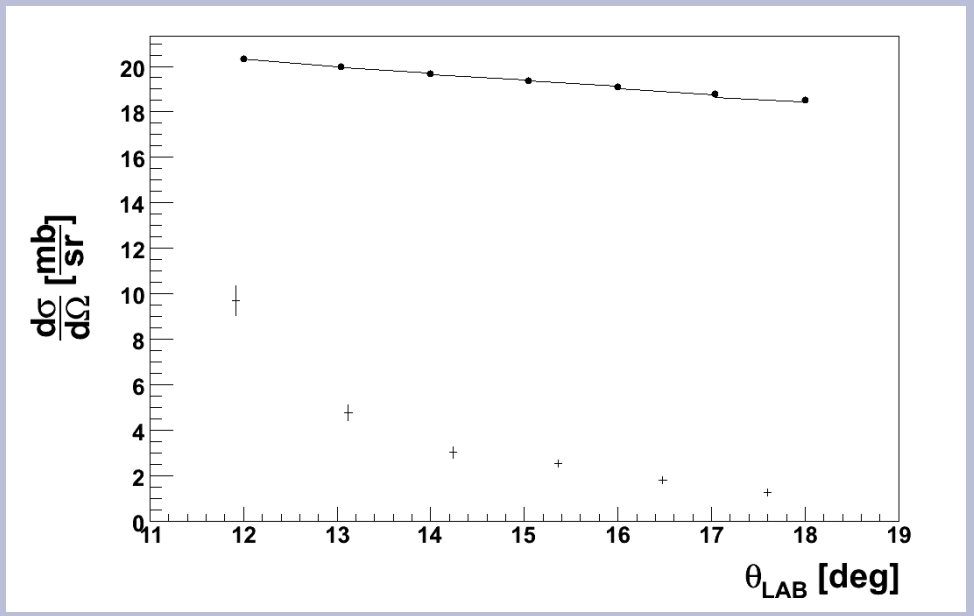
dd → d$_{beam}$ p$_{target}$ n$_{spect}$

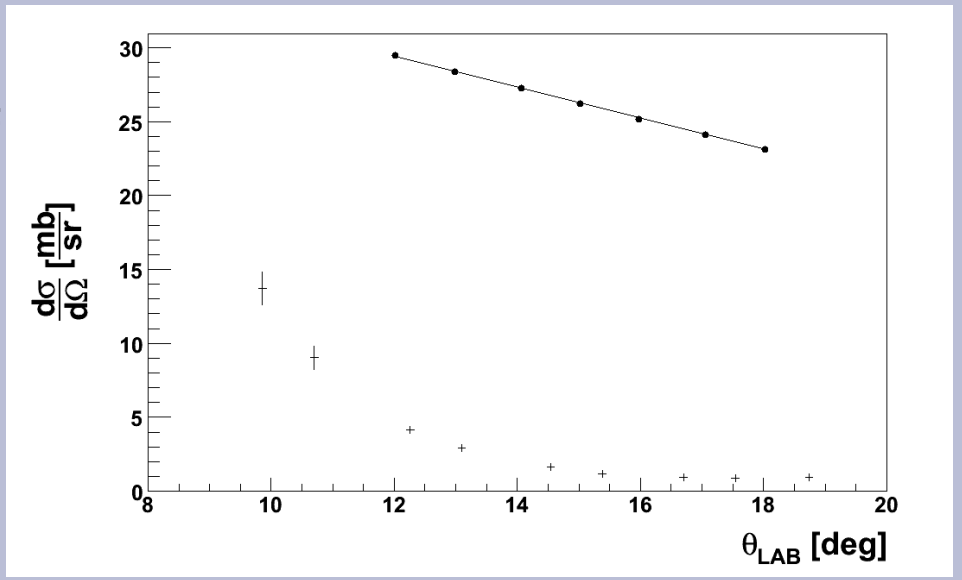
dd → p$_{beam}$ d$_{targed}$ n$_{spect}$

dd → pp (nn)$_{spect}$ → d π^+ (nn)$_{spect}$

dd → dd

other reactions





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

$dd \rightarrow pp\,(nn)_{spect}$

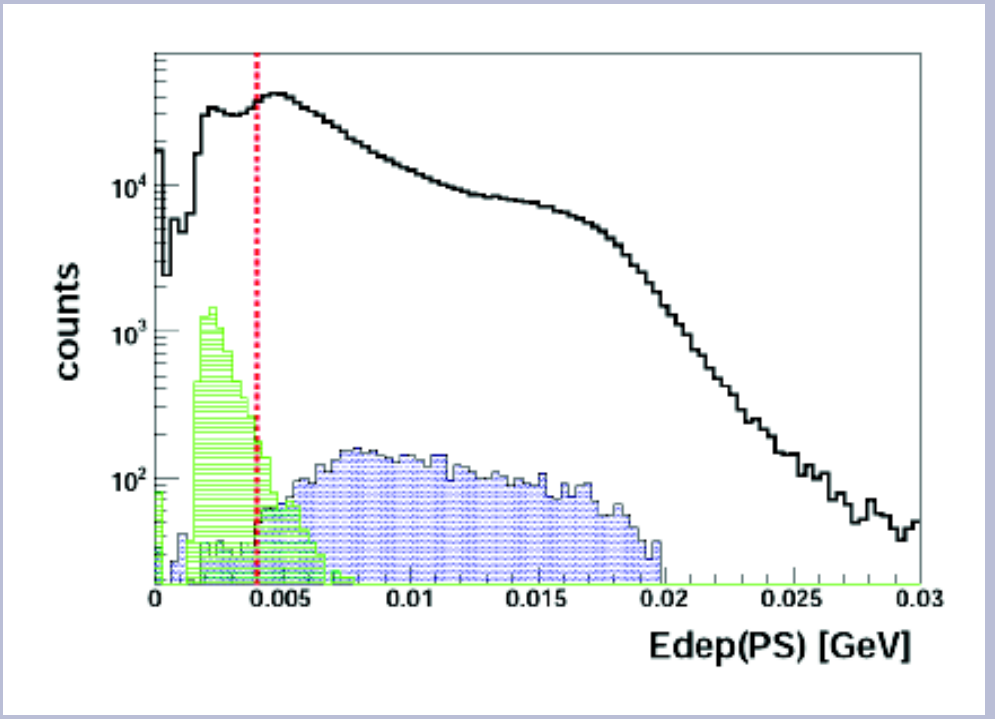
$dd \rightarrow d_{beam}\ p_{target}\ n_{spect}$

$dd \rightarrow p_{beam}\ d_{targed}\ n_{spect}$

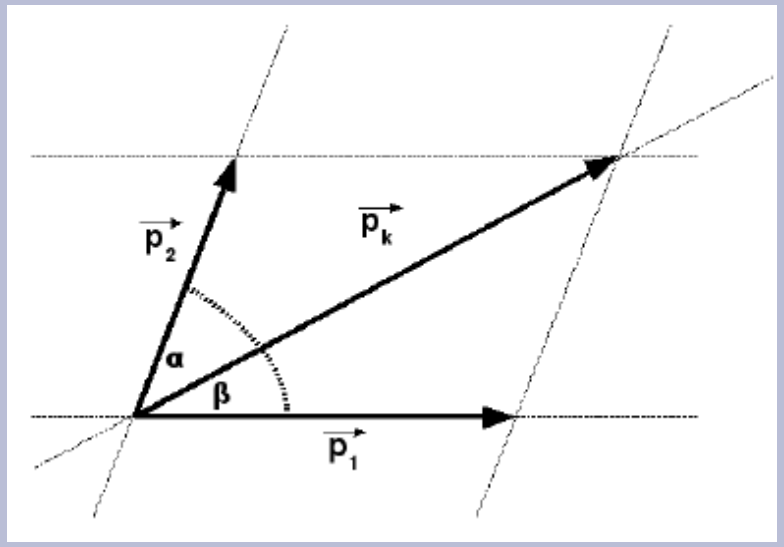
$dd \rightarrow pp\,(nn)_{spect} \rightarrow d\,\pi^+\,(nn)_{spect}$

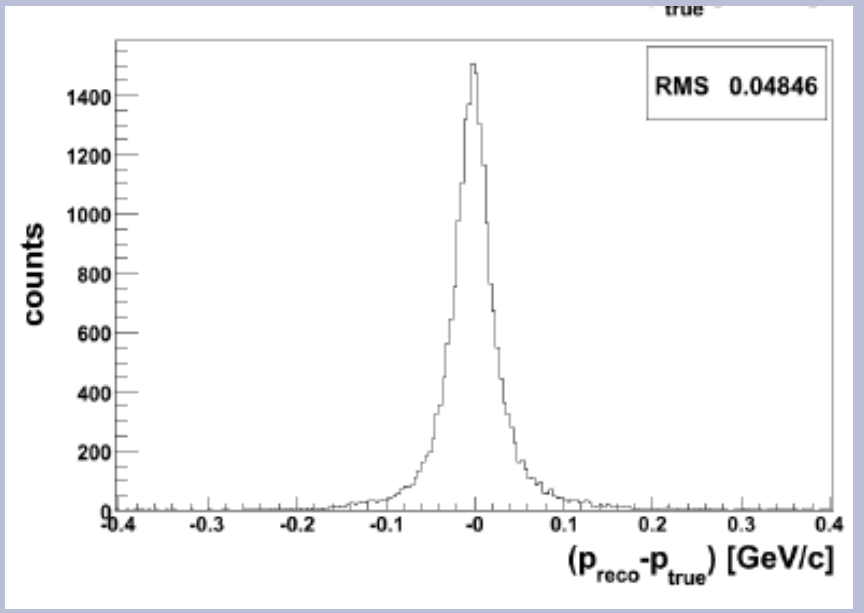
$dd \rightarrow dd$

other reactions



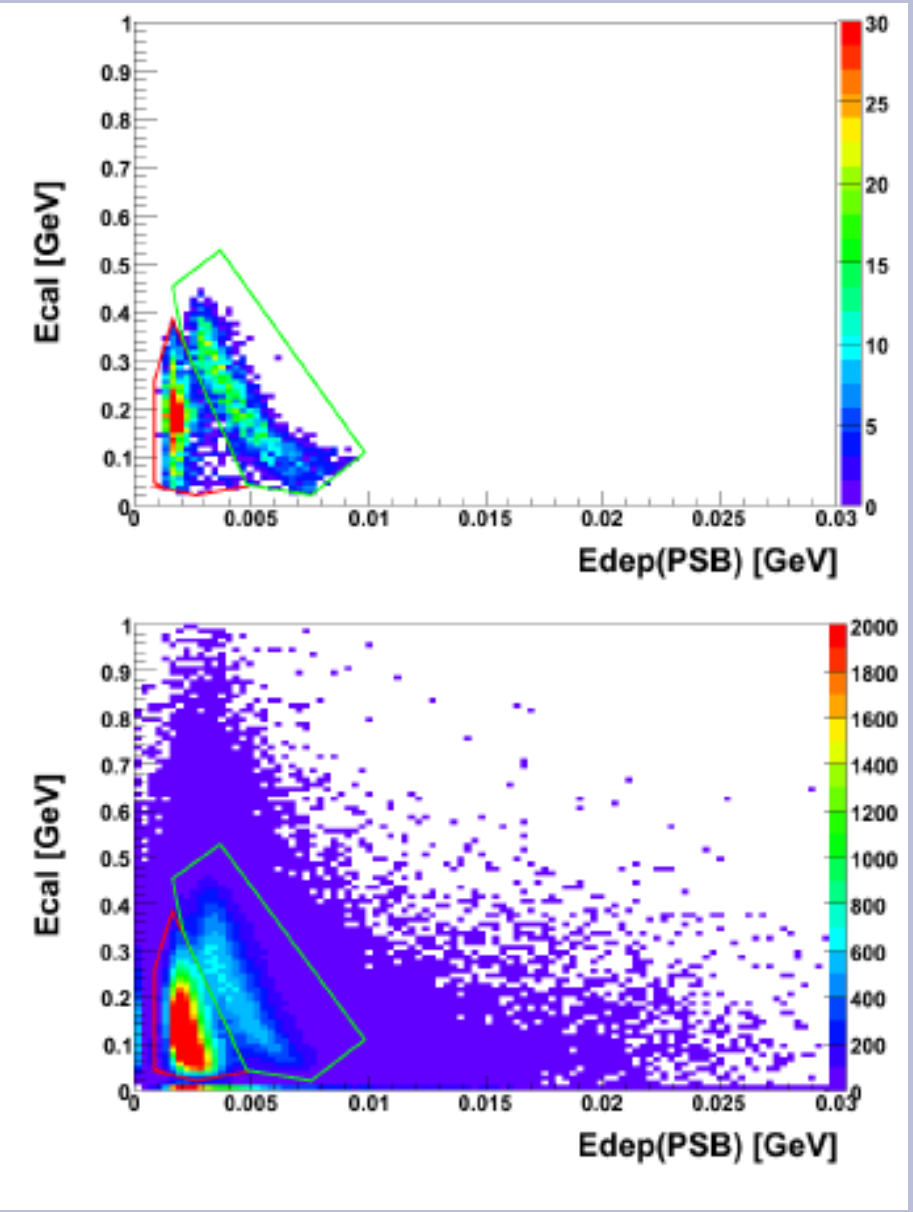
Momentum reconstruction for p and π^-



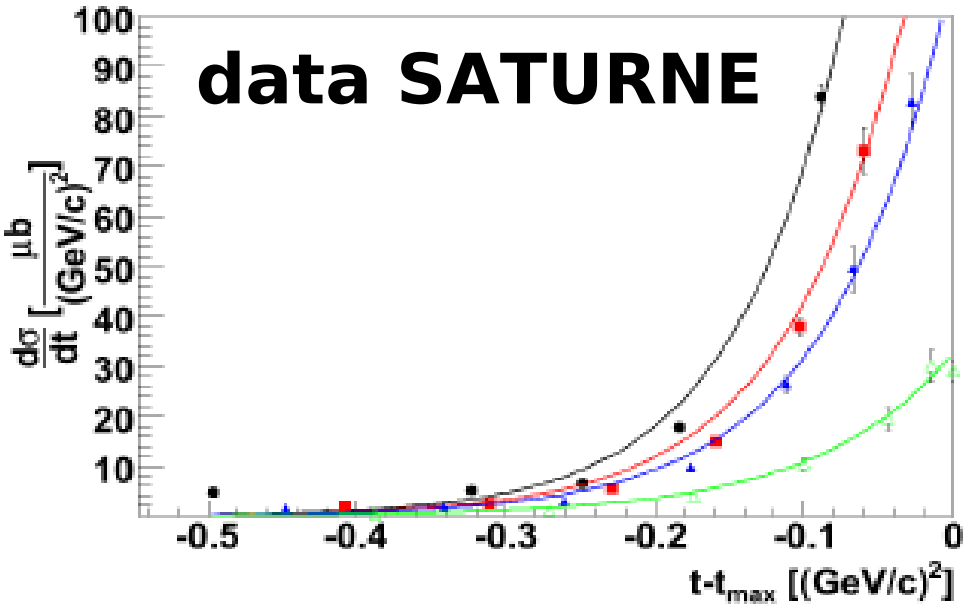


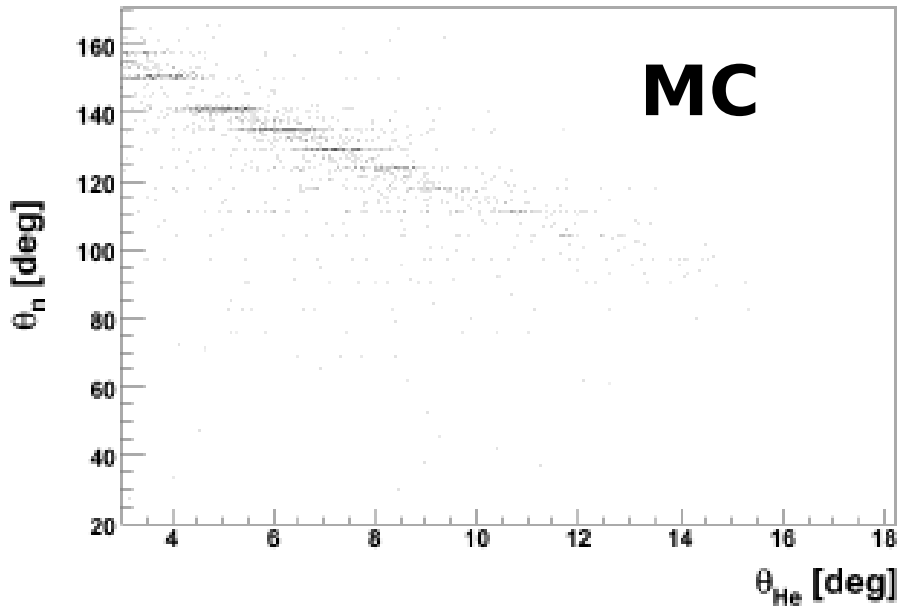
$$|\vec{p}_1| = |\vec{p}_k| \times \frac{\sin\beta}{\sin(\alpha+\beta)}, |\vec{p}_2| = |\vec{p}_k| \times \frac{\sin\alpha}{\sin(\alpha+\beta)}$$

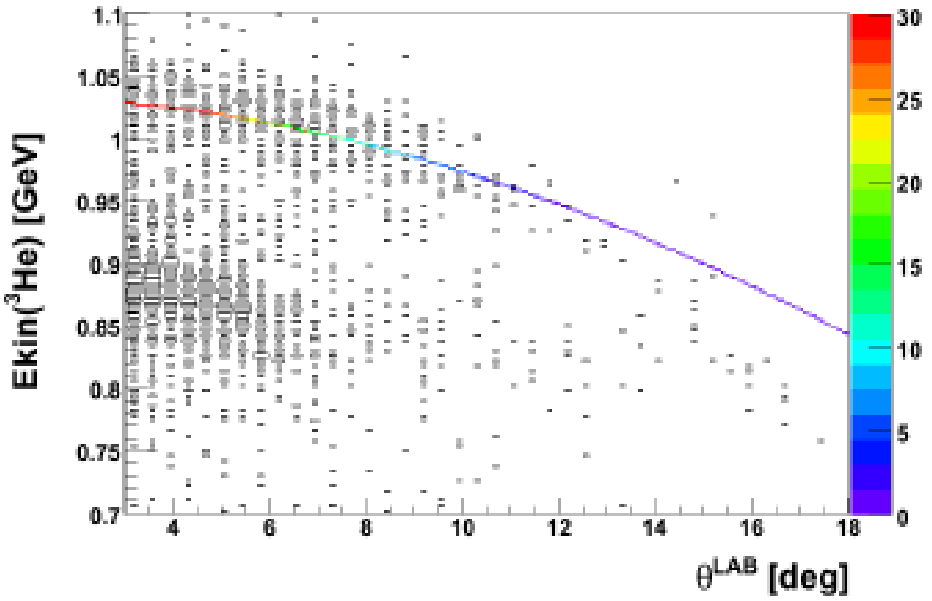
Proton / pion identification

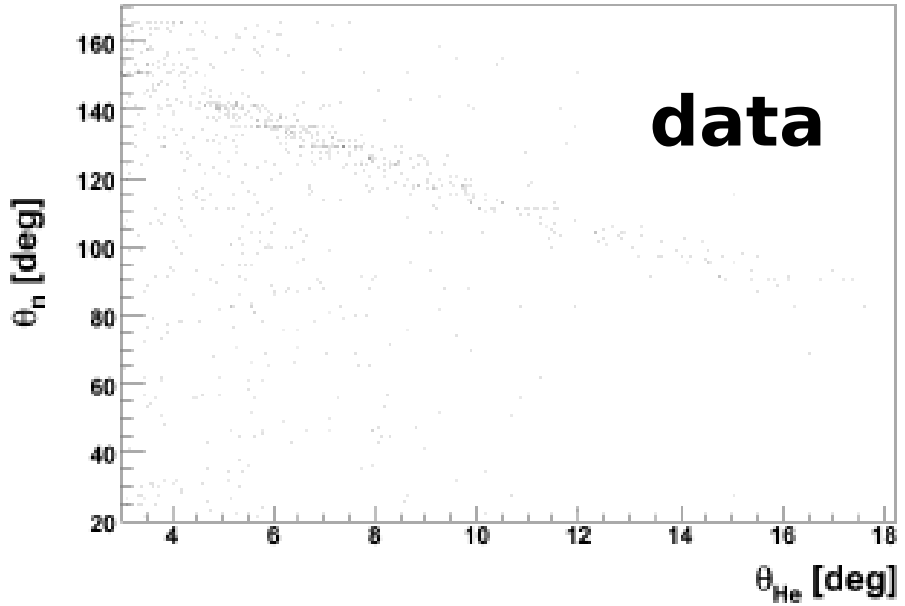


dd → ^{3}He *n*

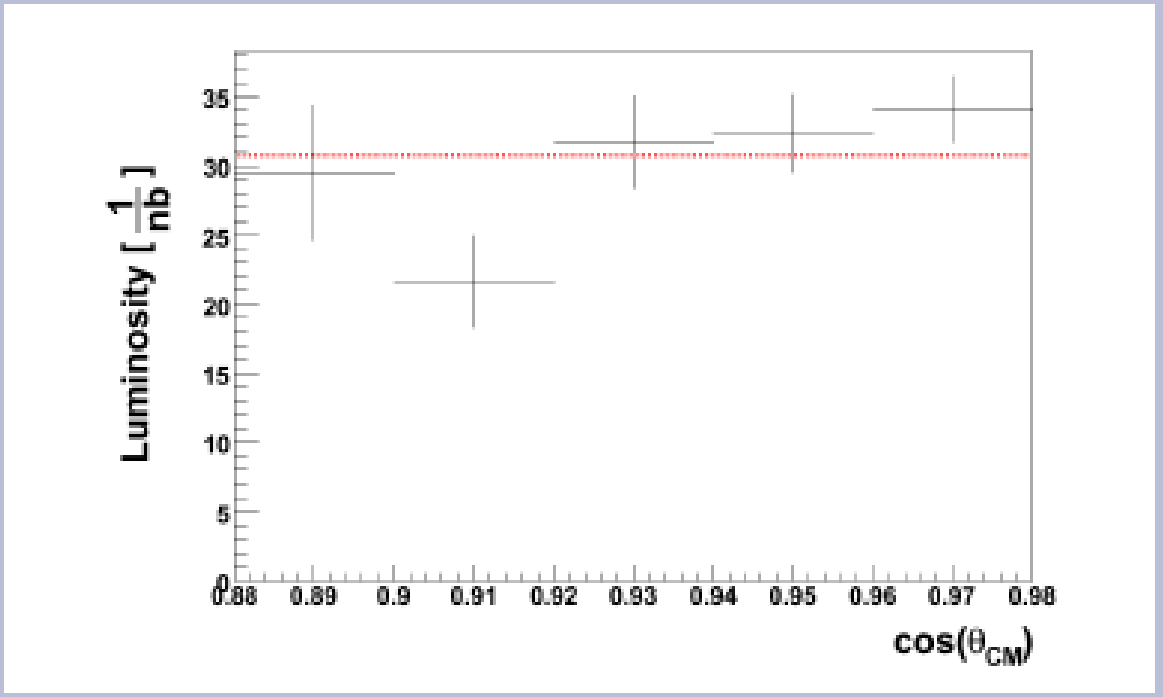

data SATURNE
dσ/dt [μb/(GeV/c)²]
t-t_max [(GeV/c)²]

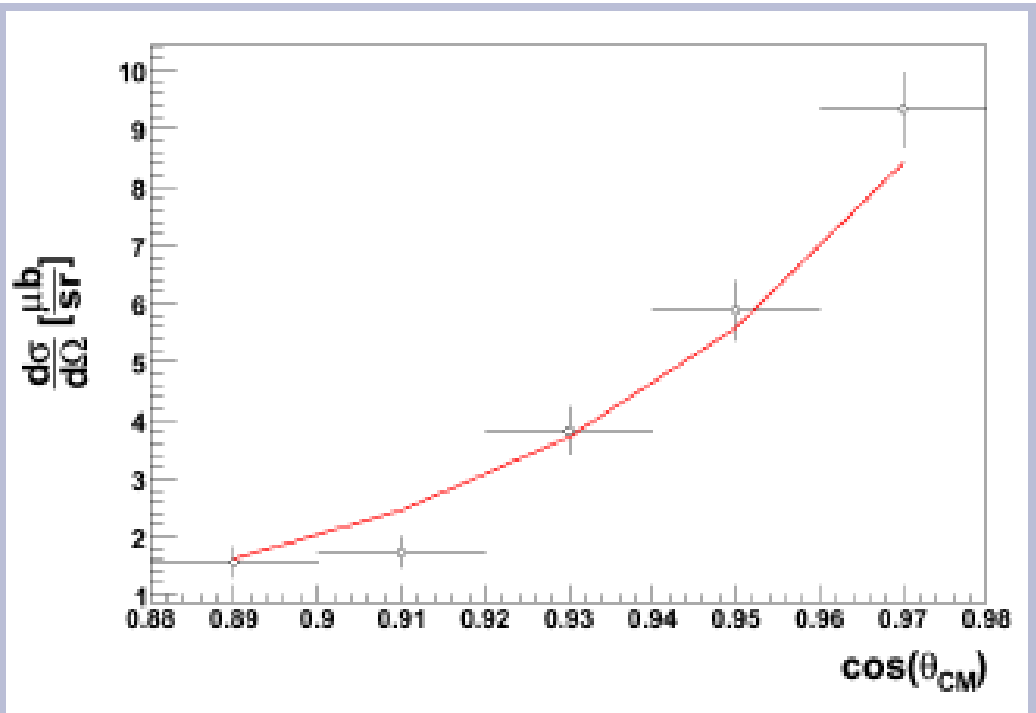

MC
θ_n [deg]
θ_He [deg]


Ekin(³He) [GeV]
θ^LAB [deg]


data
θ_n [deg]
θ_He [deg]

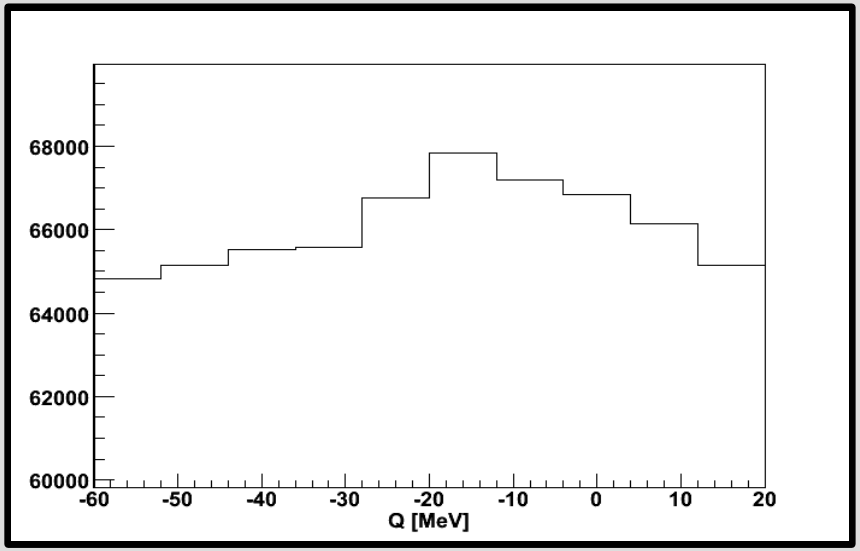
dd → ^{3}He *n*


Luminosity [1/nb]
35
30
25
20
15
10
5
0
0.88
0.89
0.9
0.91
0.92
0.93
0.94
0.95
0.96
0.97
0.98
cos(θCM)

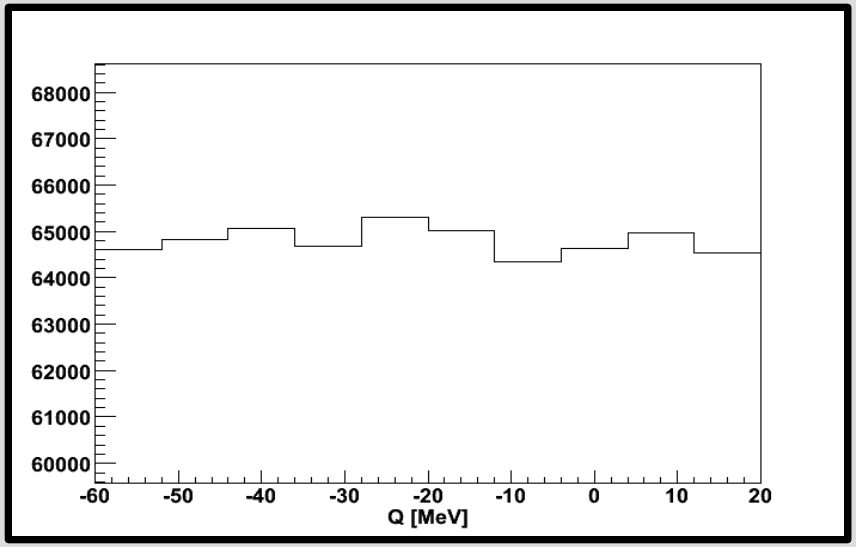

dσ/dΩ [μb/sr]
10
9
8
7
6
5
4
3
2
1
0.88
0.89
0.9
0.91
0.92
0.93
0.94
0.95
0.96
0.97
0.98
cos(θCM)

Example of the excitation function (simple simulation)

n.p. θ_{cm} =150-170



n.p. θ_{cm} =130-150

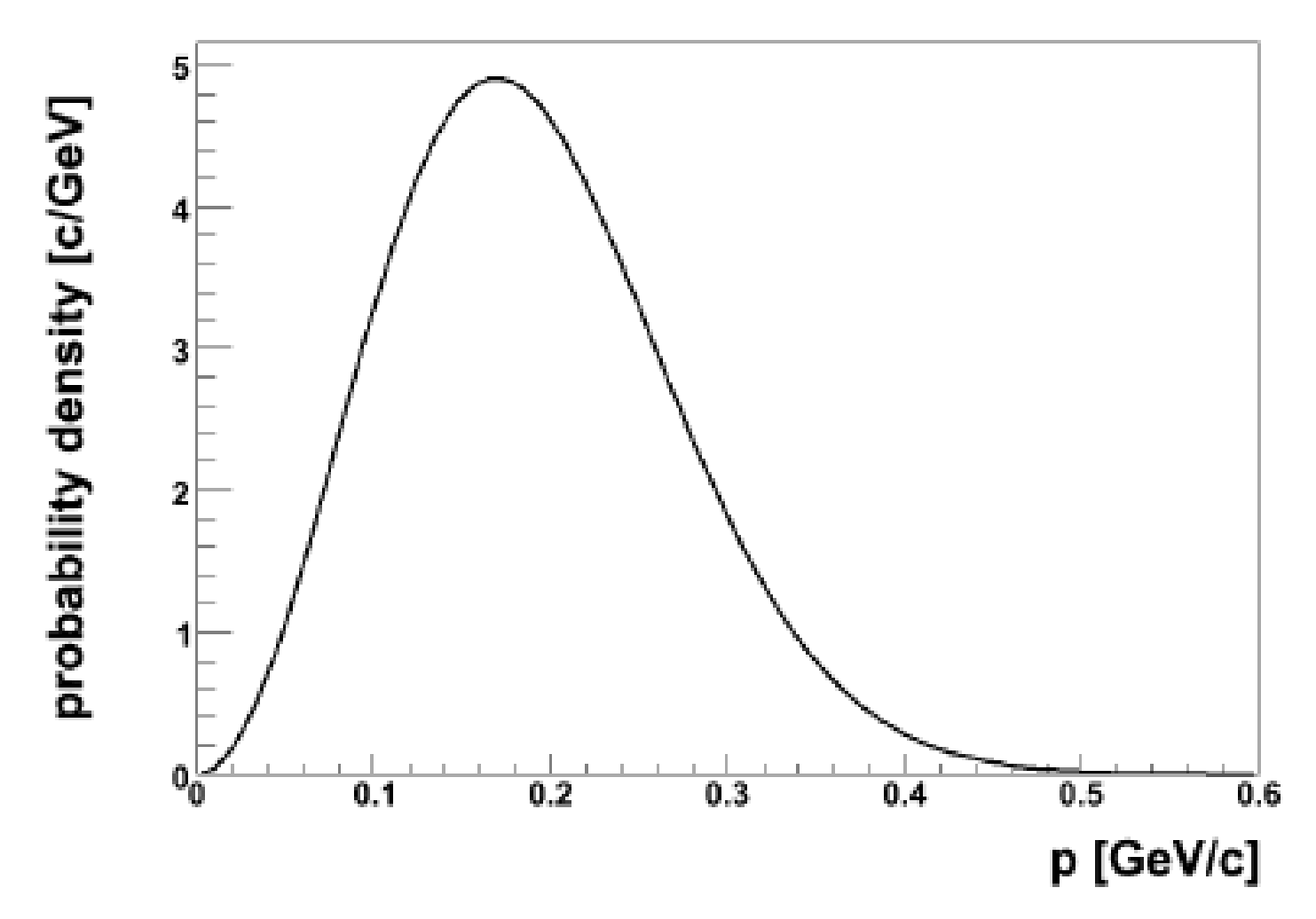


x-section=10 nb, $L=10^{31}$ $cm^{-2}s^{-1}$
T=10 dni
Breit-Wigner: E0=-20 MeV, Γ=25 MeV

Search for the resonance-like structure

with the maximum below the dd → ^{4}He η threshold

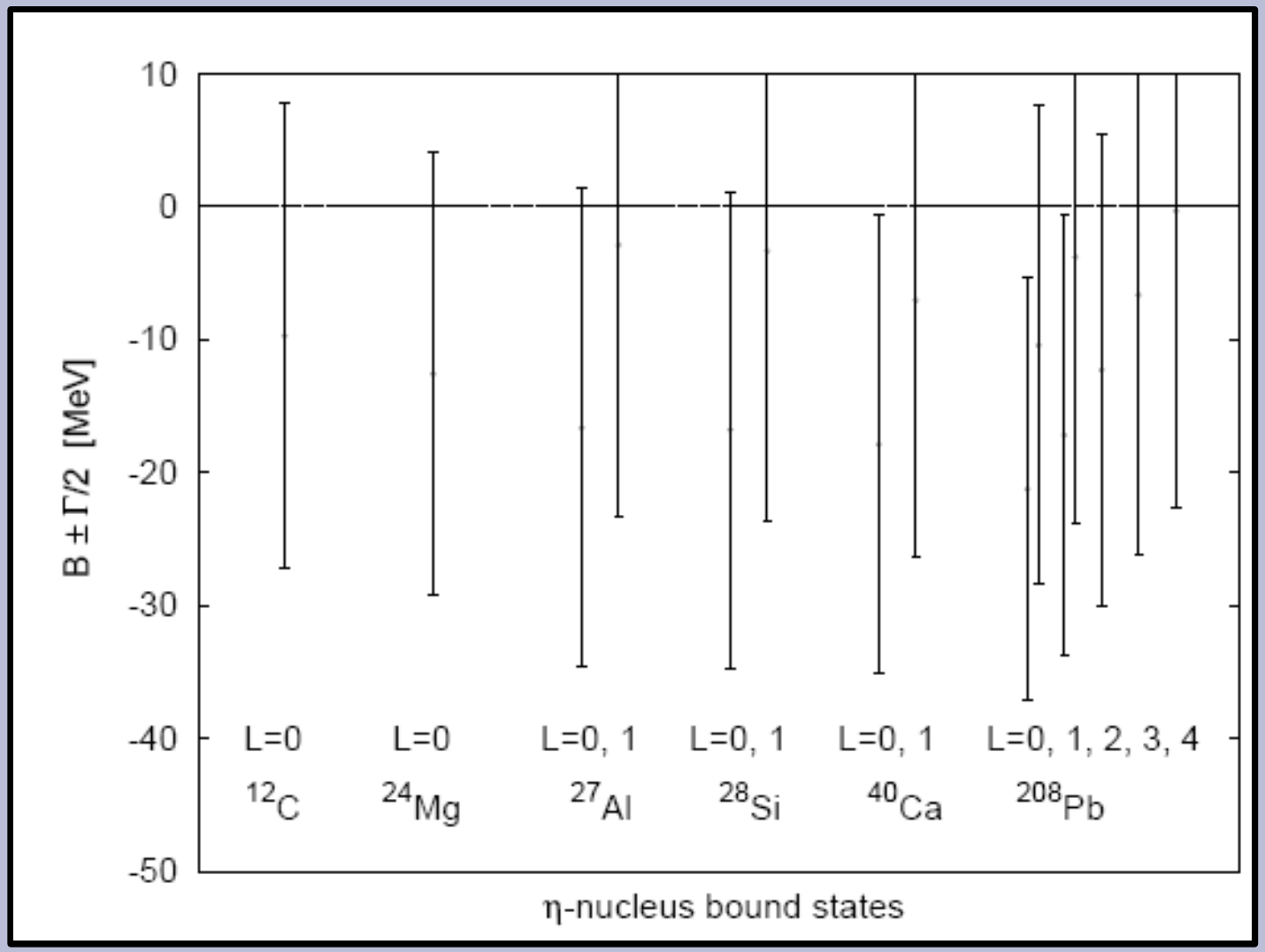
Nucleon momentum distribution in ^{4}He



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

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

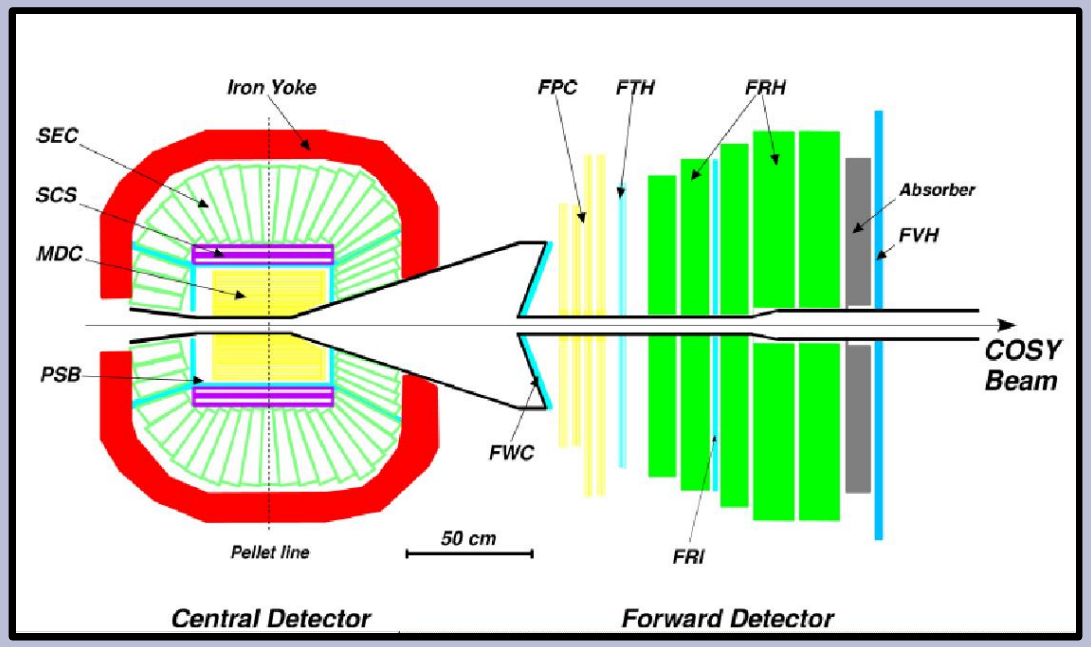
*η-m*esic nuclei in heavy systems



C. Garcia-Recio, T. Inoue, E. Oset Phys. Lett. B550 (2002) 47

WASA-at-COSY

4 π detector for charged and neutral particles



Central detector:

Max. stopping energy

π ±/p/d 190/400/450 MeV

Angular resolution

charged ~1.2°

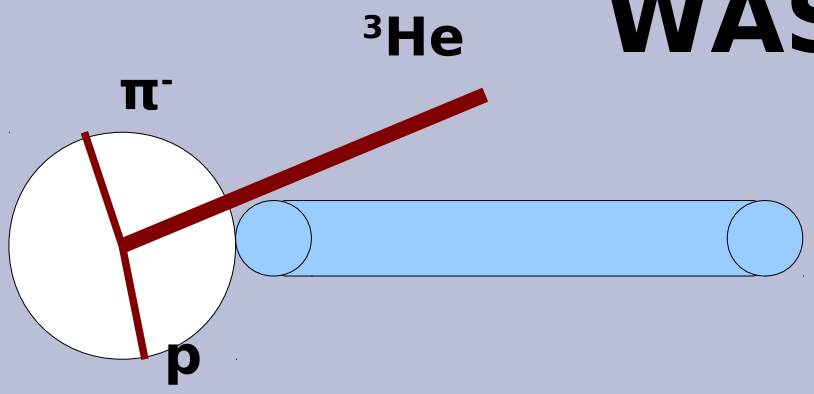
neutral ~5°

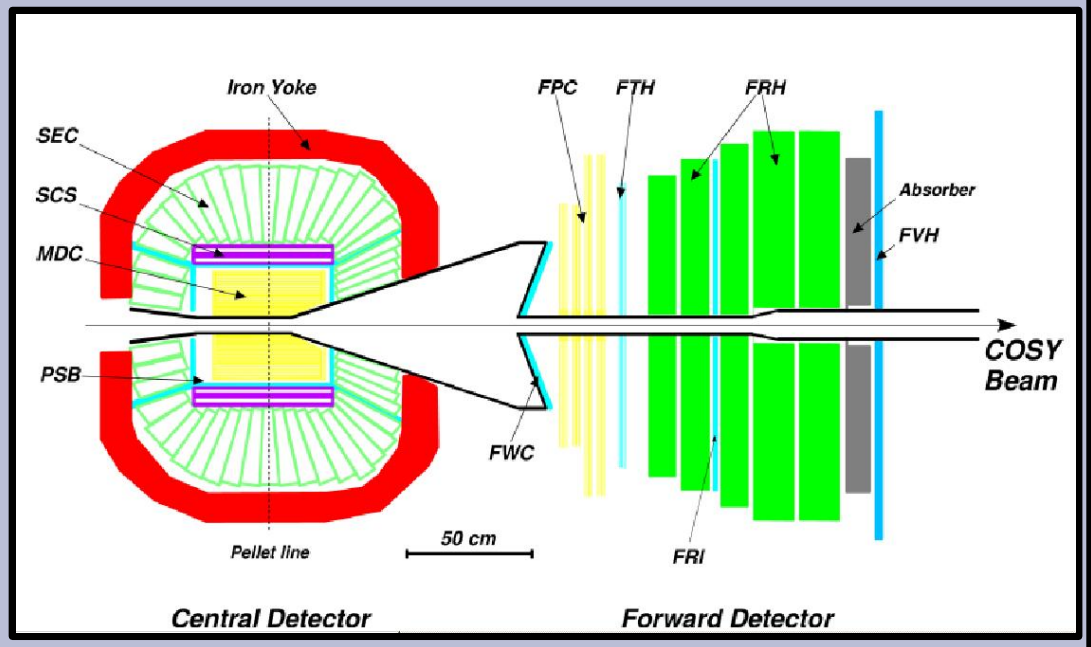
Relative energy resolution by SE

photons ~8%

stopped charged particles ~3%

WASA-at-COSY





Forward detector:

Scattering angle coverage 3°-18°

Scattering angle resolution 0.2°

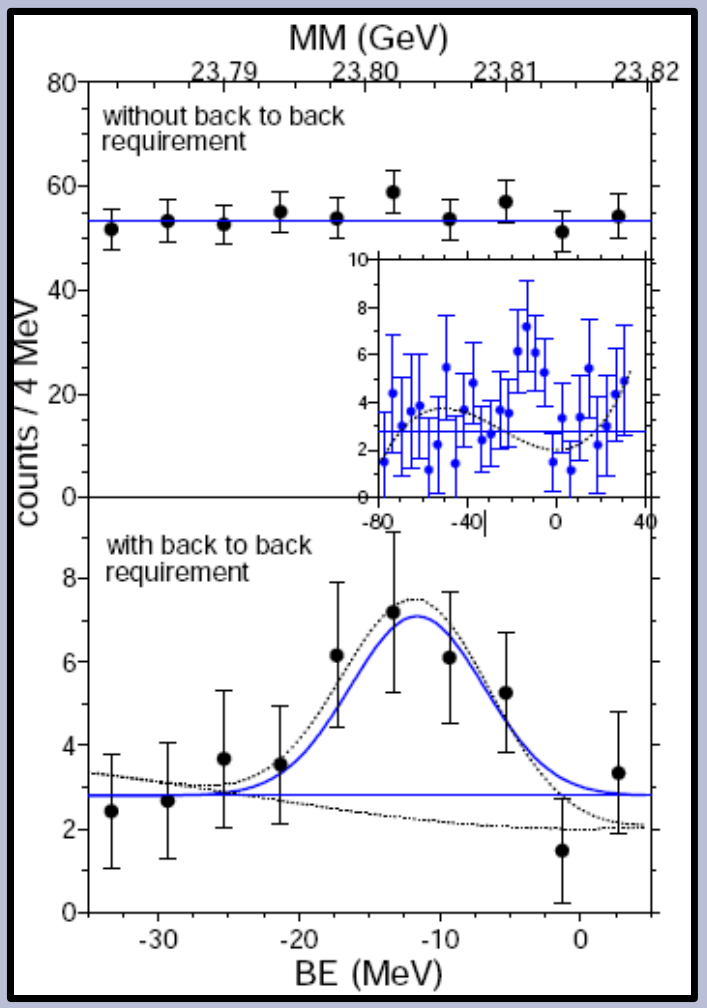
Maximum energies for stopping
π ±/p/d/α 170/300/400/900 MeV

Time resolution <3ns

Relative energy resolution
particles $T_{stop}<T<2T_{stop}$ 3-8%
stopped particles $T<T_{stop}$ 1.5-3%

COSY-GEM results

$p + {}^{27}Al \rightarrow {}^{3}He + (\eta - {}^{25}Mg) \rightarrow {}^{3}He + \pi^{-} + p + X$



MM(3HE)

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