Search for the η-mesic Helium with the WASA-at-COSY detector

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for the WASA-at-COSY collaboration

Meson 2012

Outline

- Motivation
- Idea of the measurement
- WASA detector at the COSY accelerator
- Data analysis
- Summary

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 π, K, η, η' ω, ...

strong interaction + e-m interaction

Exotic systems

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***η*-^{4}He case**

strong interaction + ~~e-m interaction~~

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

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:**

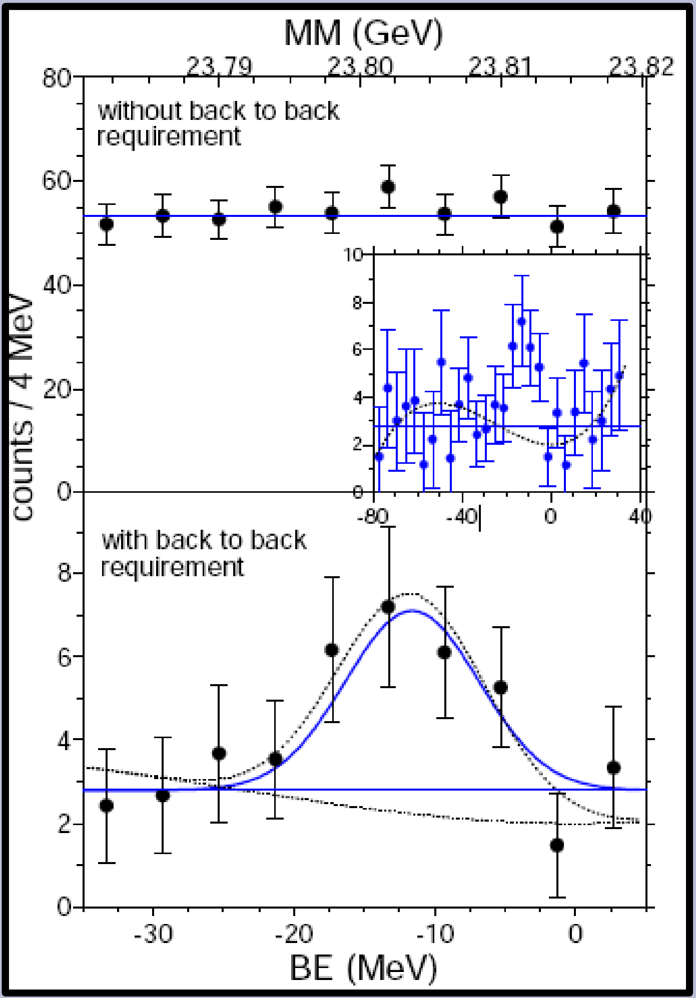
  η-N scattering length much bigger than expected.

- **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-GEM results

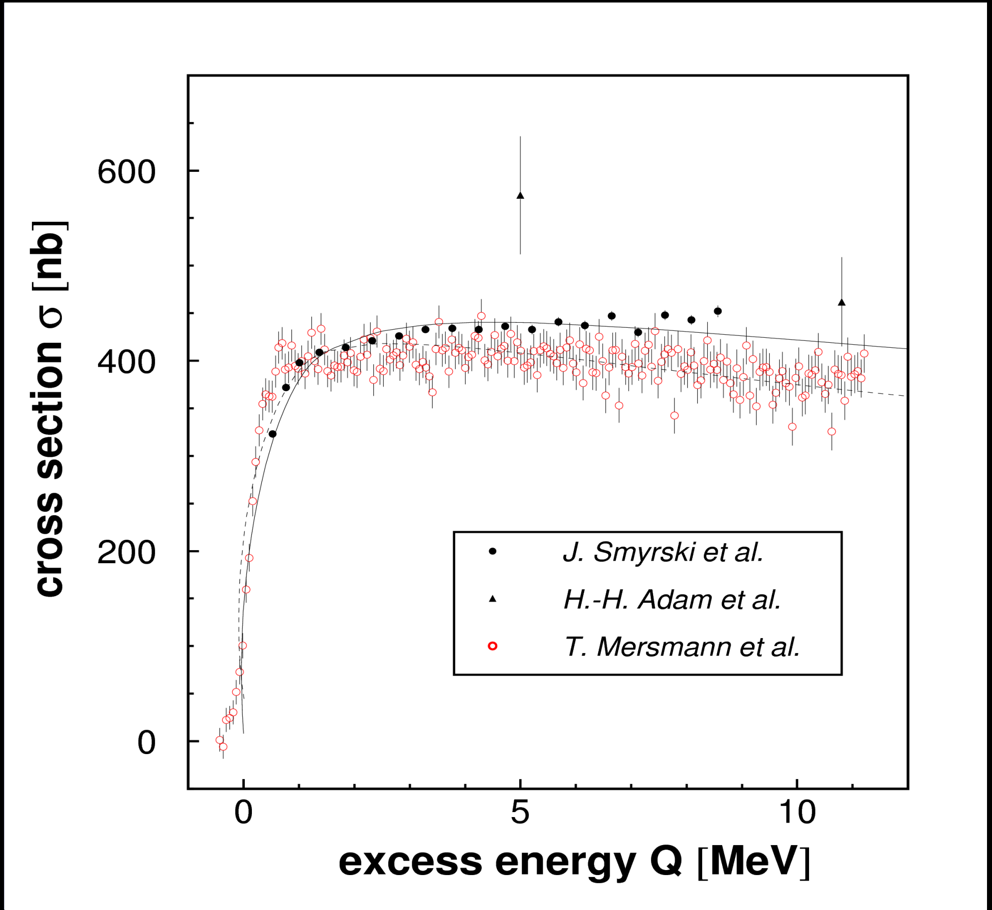
$p+{}^{27}Al \rightarrow {}^{3}He+(\eta\text{-}{}^{25}Mg) \rightarrow {}^{3}He+\pi^{-}+p+X$



MM(3HE)

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

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

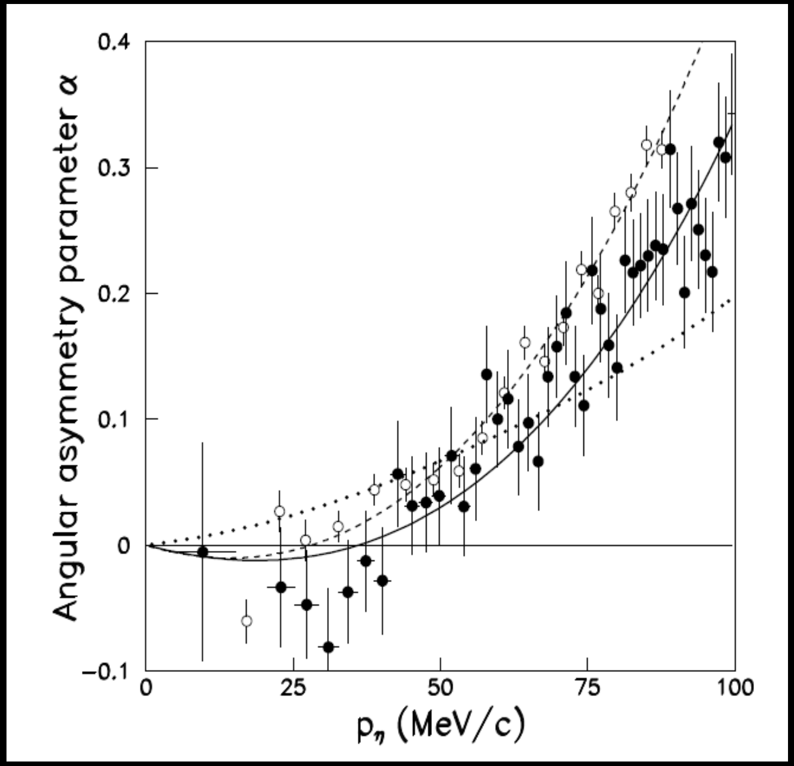


Full black squares: COSY-11

Empty red squares: COSY-ANKE

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

d*p* → ^{3}He*η*



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* → ^{3}He*η* and dd → ^{4}He*η*

SPES-3 and SPES-4 @SATURNE

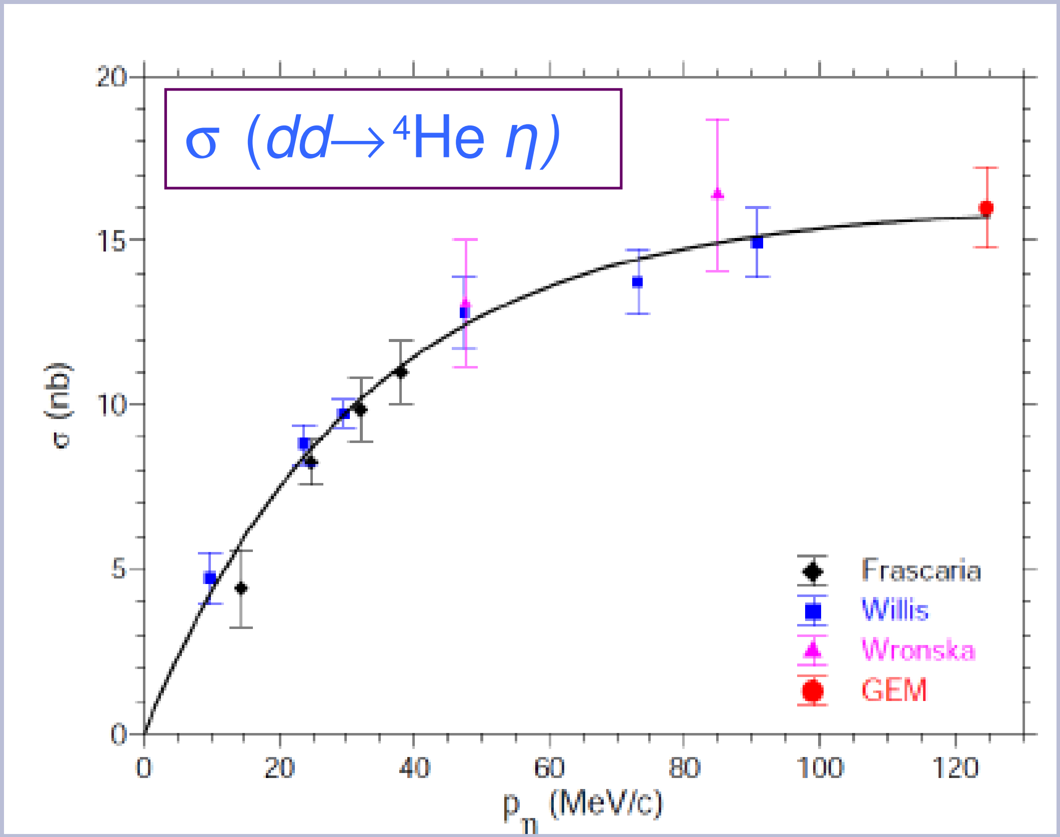
N. Willis et al. Phys.Lett. B406(1997).

Also total x-section *γ*^{3}He→ *η*^{3}He

Crystal Ball-TAPS@MAMI

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

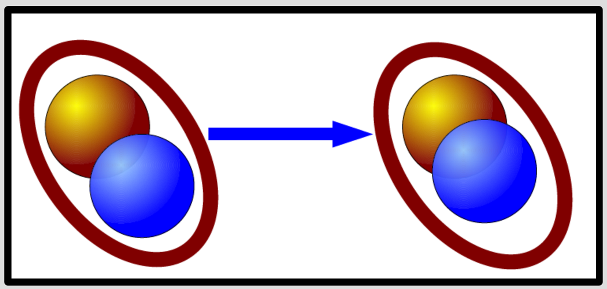
Experimental indications of the existence of a bound state in the η-^{4}He system

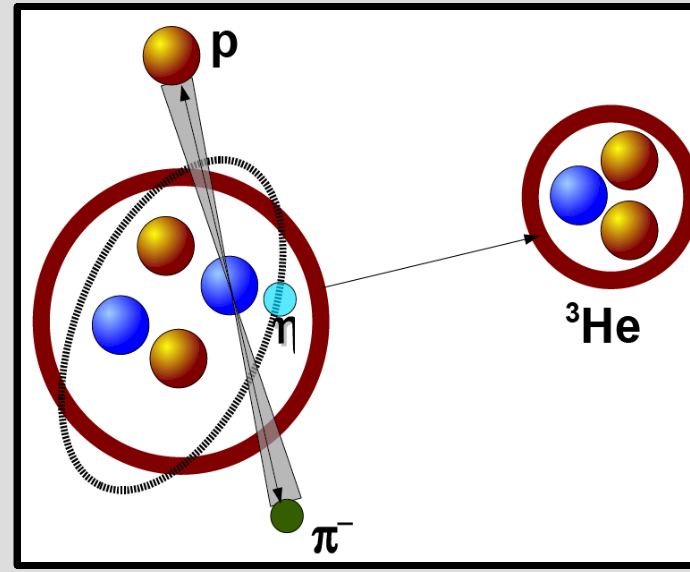


R. Frascaria et al., Phys. Rev. C 50 (1994) 573.
N. Willis et al., Phys. Lett. B 406 (1997) 14.
A. Wrońska et al., Eur.Phys.J. A26 (2005) 421-428.

Idea of the measurement

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





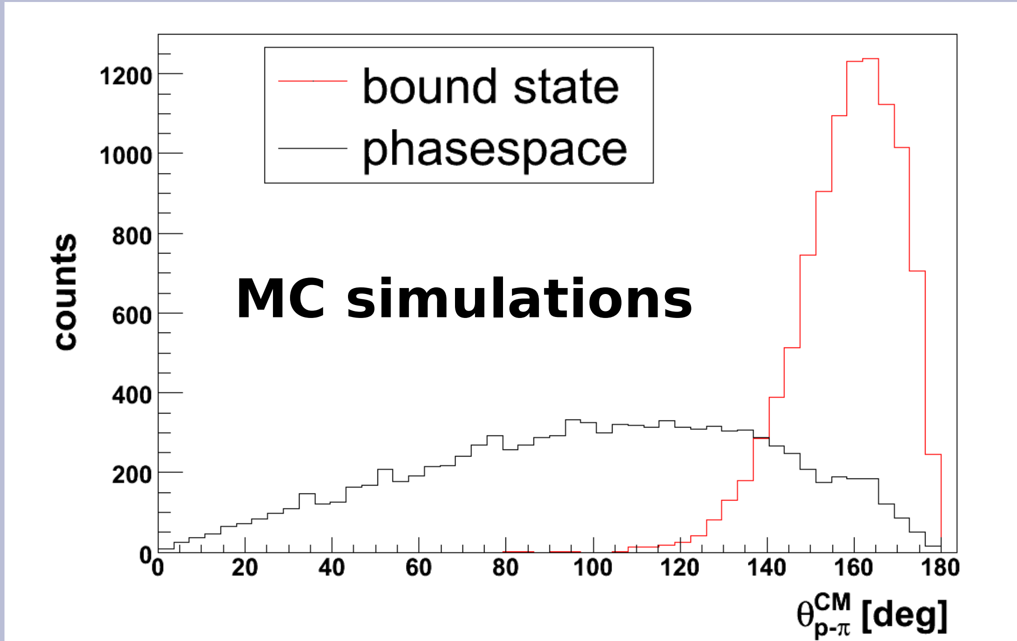
$\eta + p$ → $N^*(1535)$ → $p + \pi^-$

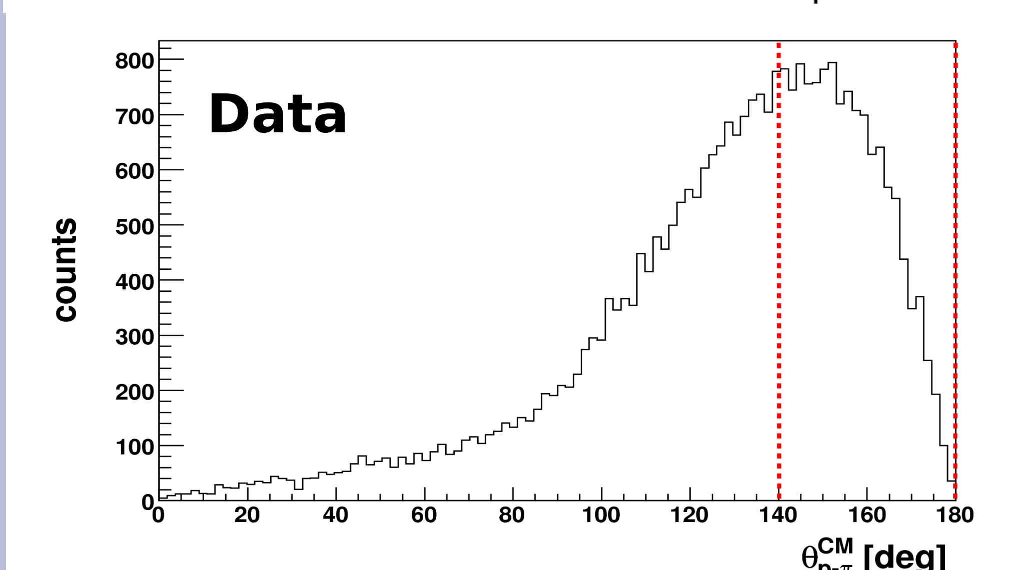
Relative *p-π* angle in the CM : $\theta_{cm} \sim 180^\circ$

Search for a resonance-like structure with maximum below the η-^{4}He production threshold

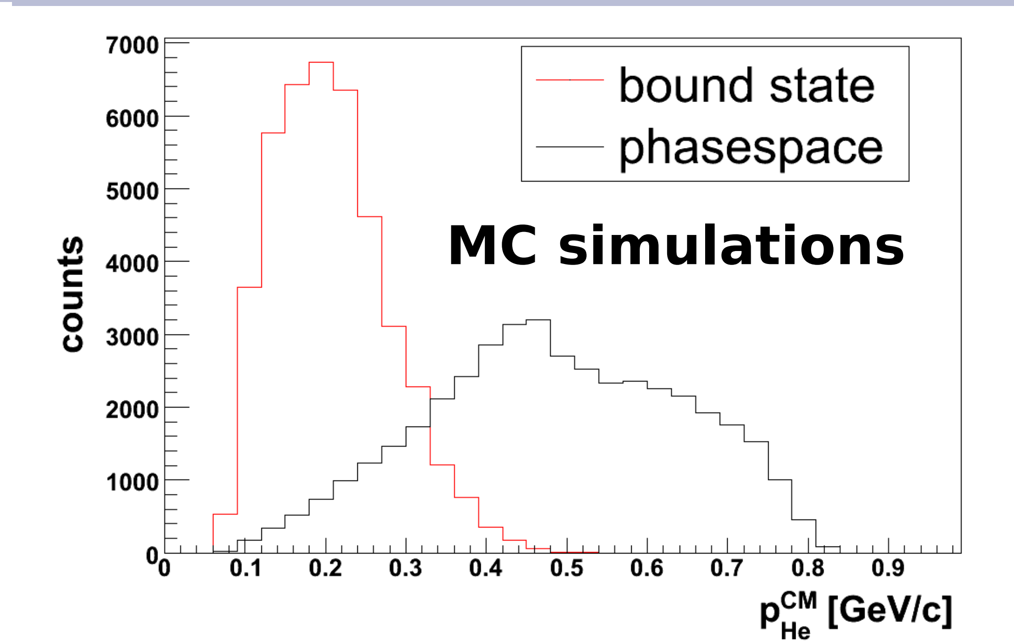
Signatures of the bound state

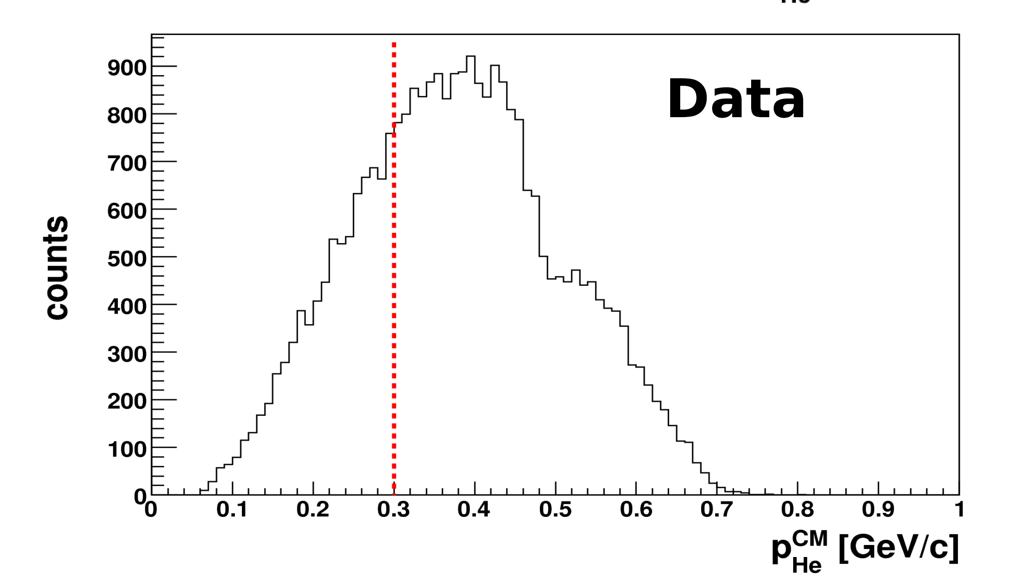
Opening angle p-π^- in CM frame





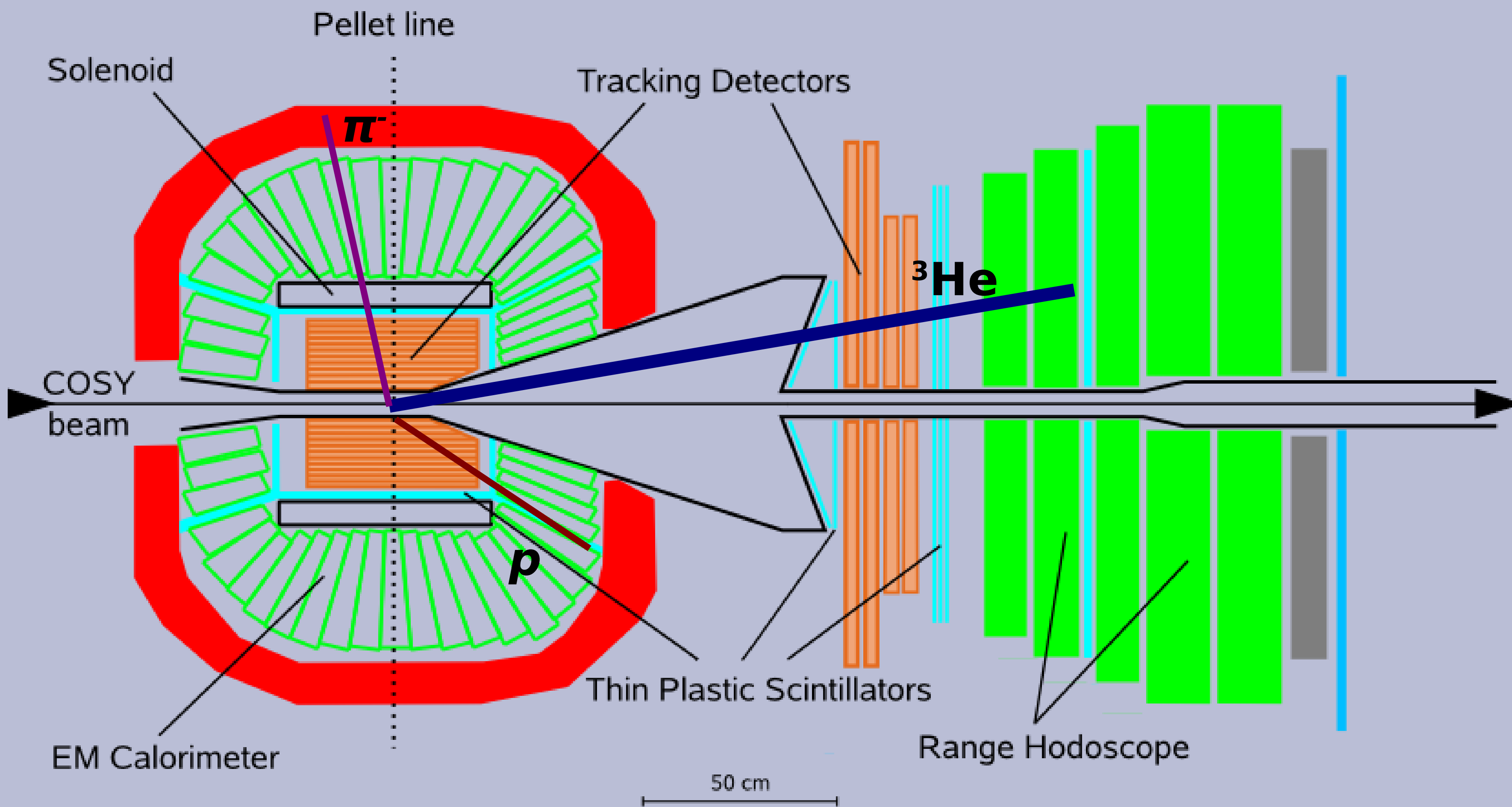
^{3}He momentum in CM frame





WASA detector at the COSY accelerator

WASA-at-COSY



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

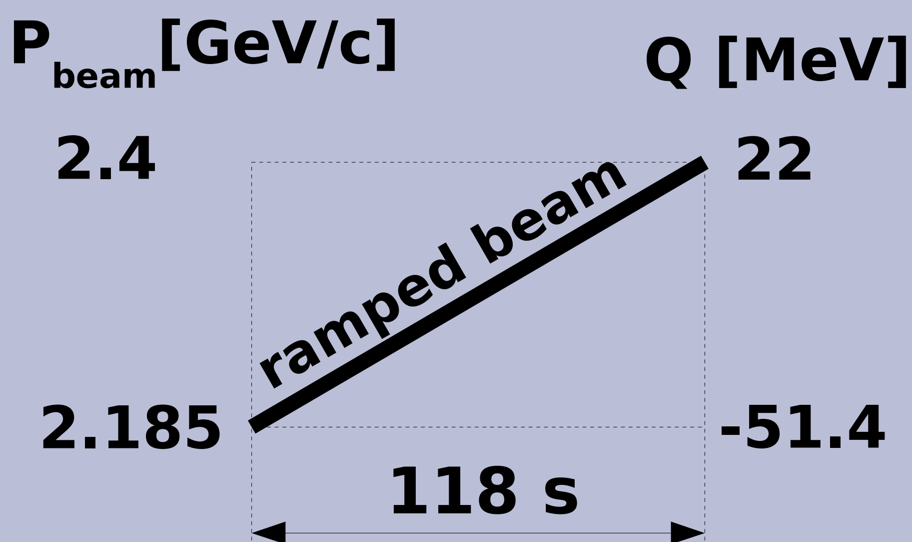
Measurement in June 2008

Channels:

dd → ^{3}He$p\pi^{-}$

dd → ^{3}He n

- **Time: ~16 hours**



Q: -51 to 22 MeV

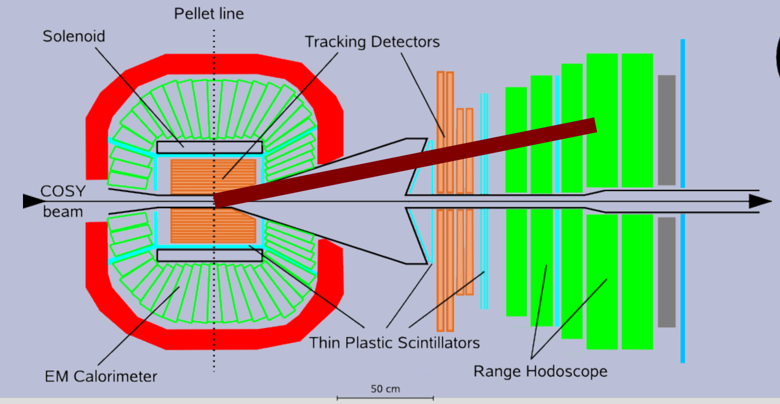
P: 2.185 to 2.4 GeV/c

T: 1.005 to 1.171 GeV

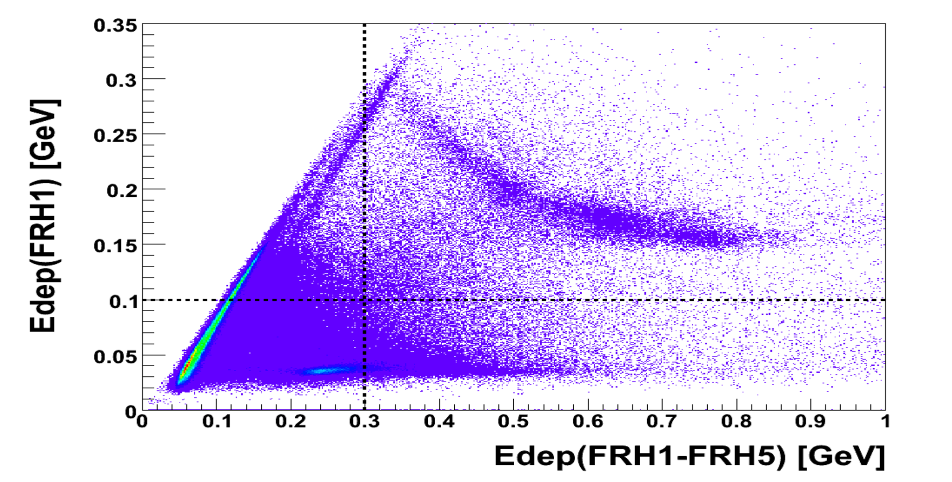
Luminosity I

Absolute normalization

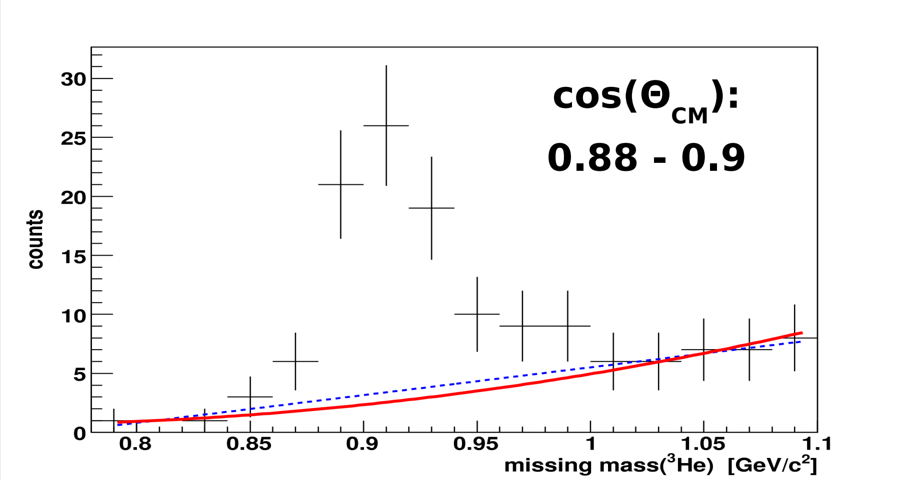
dd → ³He *n*

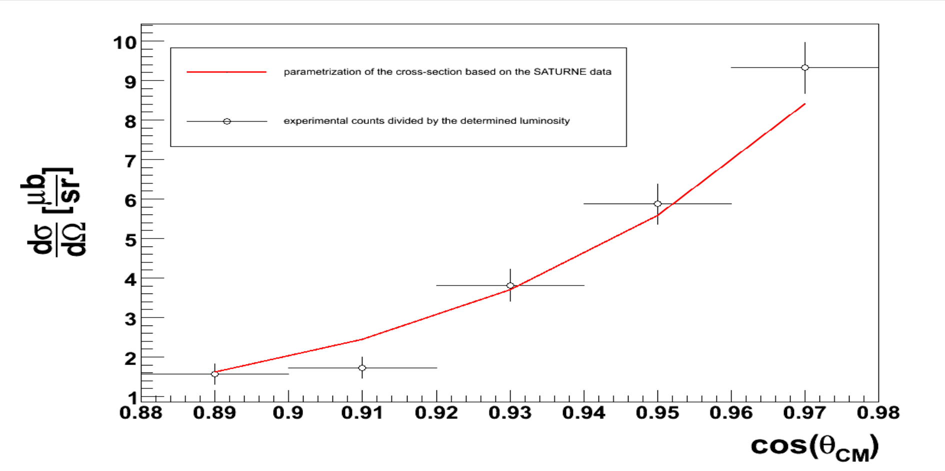


³He selection



MM(³He) -neutron





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

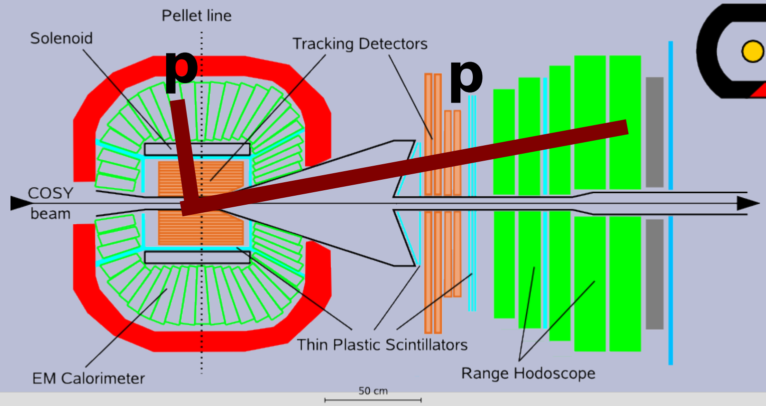
stat: ±4.5 %
syst(background subtract):±8%
param. from SATURNE: ±7%

Parametrization done by Annette Pricking

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

Luminosity II
(beam momentum dependence)

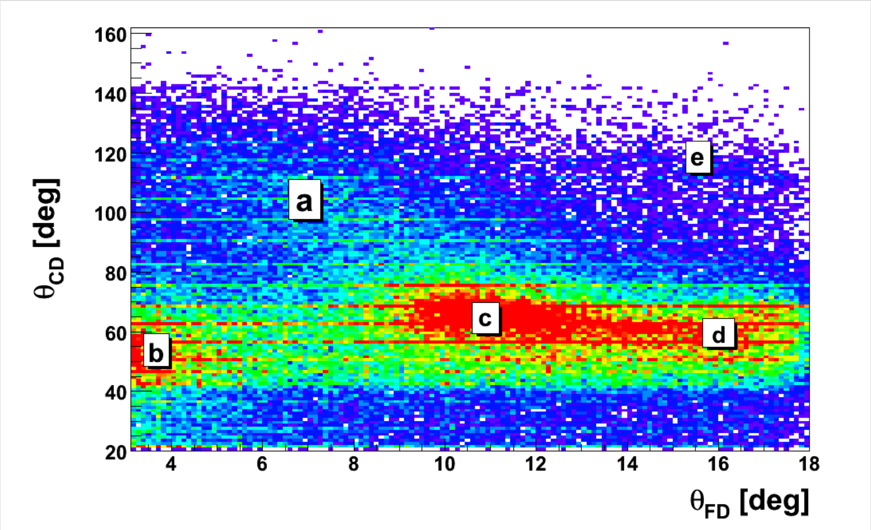
Quasi-elastic scattering:
$dd \rightarrow pp\,(nn)_{spec}$



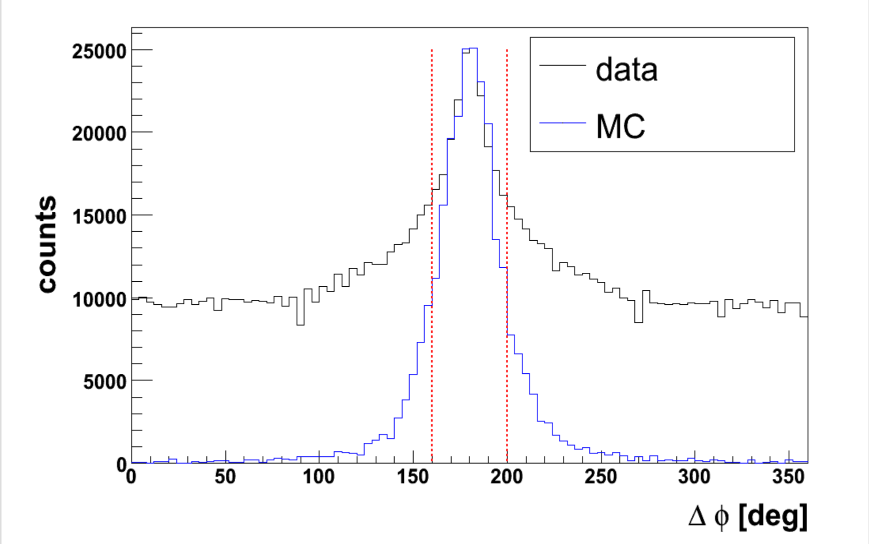
• One charged in FD && one charged track in CD.

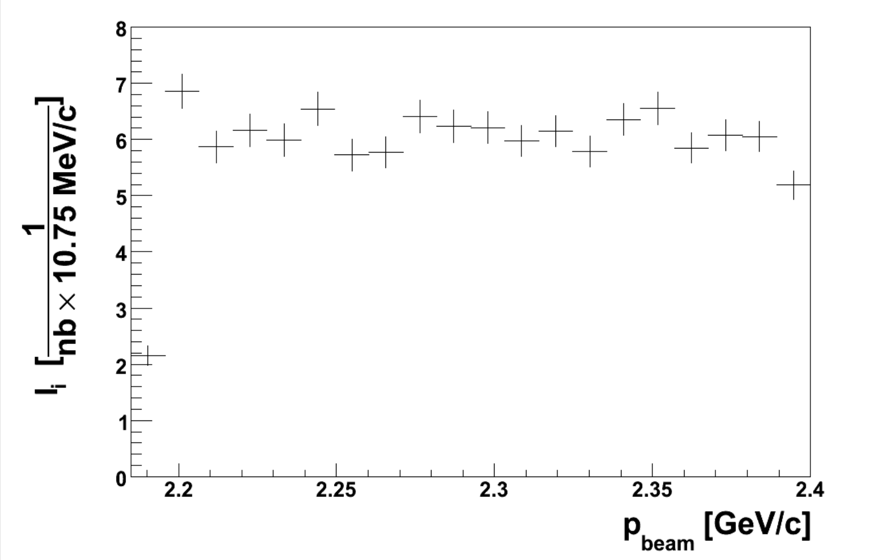
• Coplanarity condition **Δφ<20 deg.**

• Cut on E in scintillator barrell (π background reduction).



Coplanarity

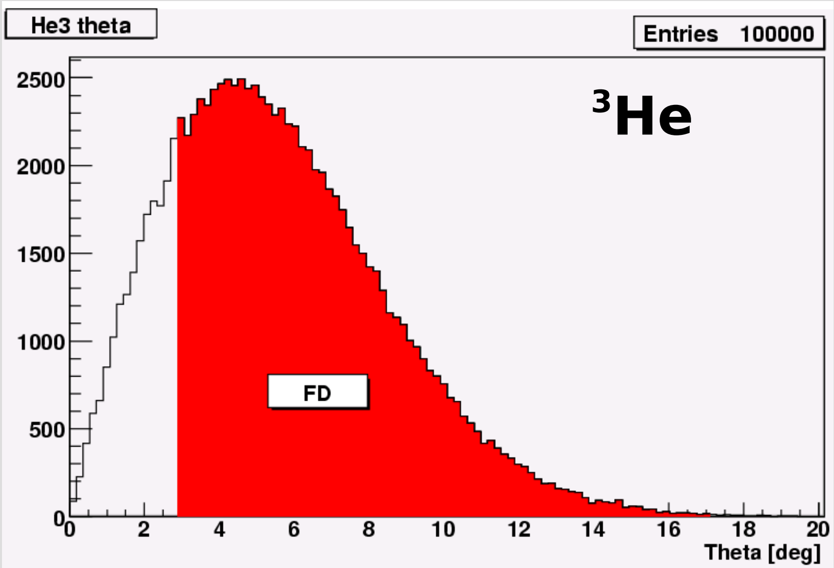


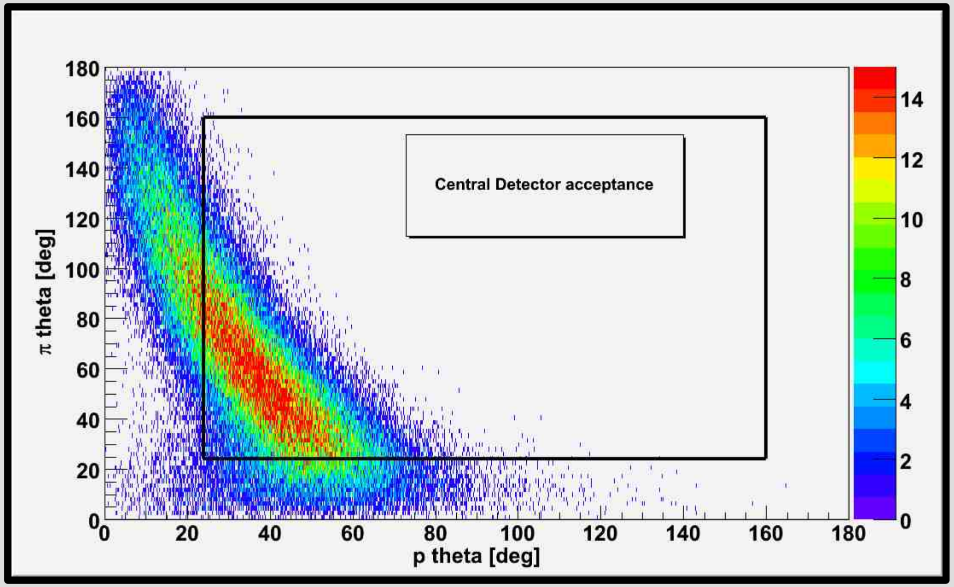


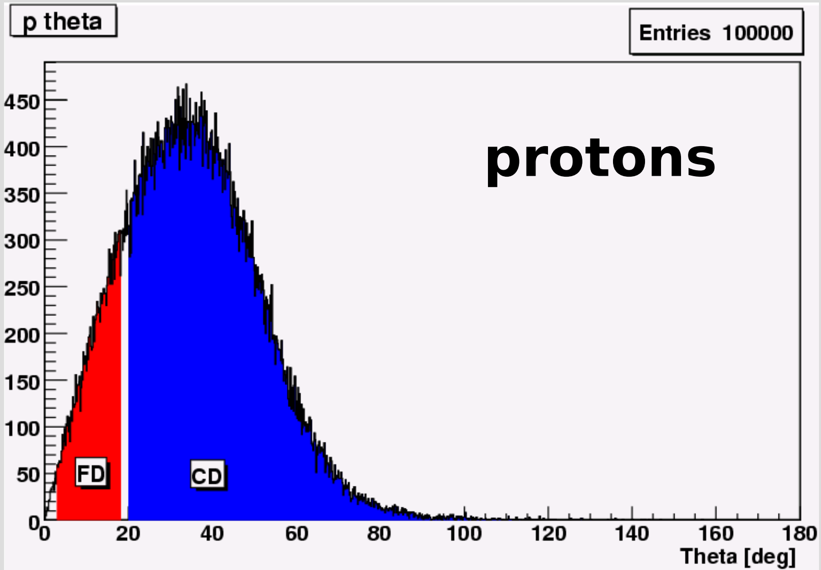
Analysis of

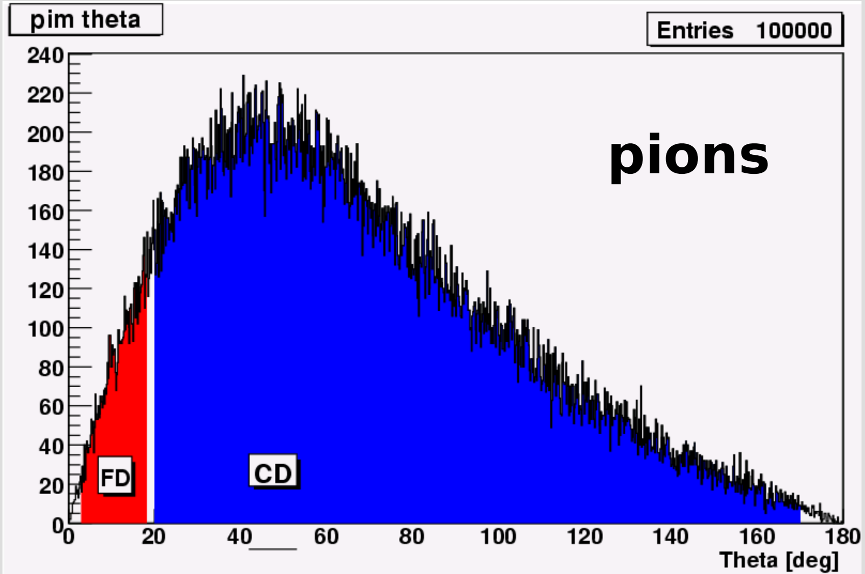
$dd \rightarrow (\eta\text{-}^4He)_{bound} \rightarrow {}^3He\ p\ \pi^-$

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

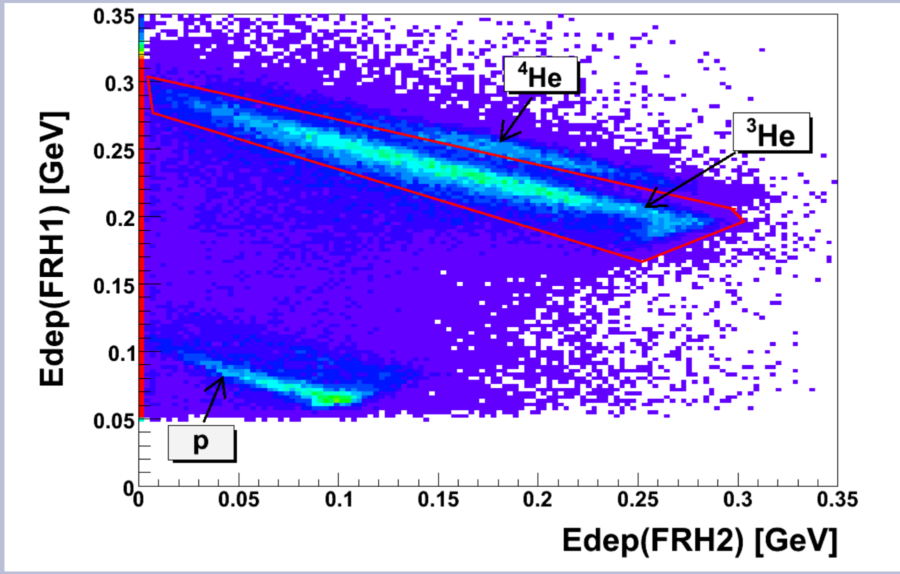




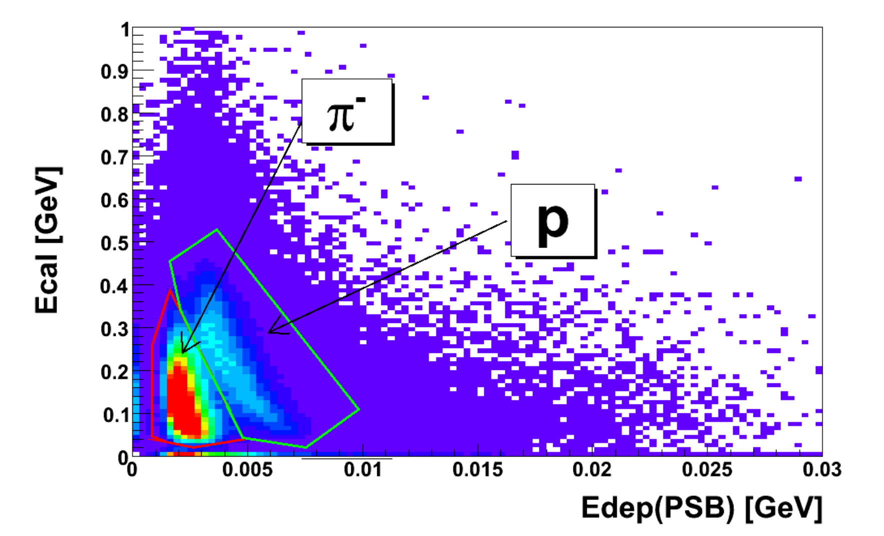




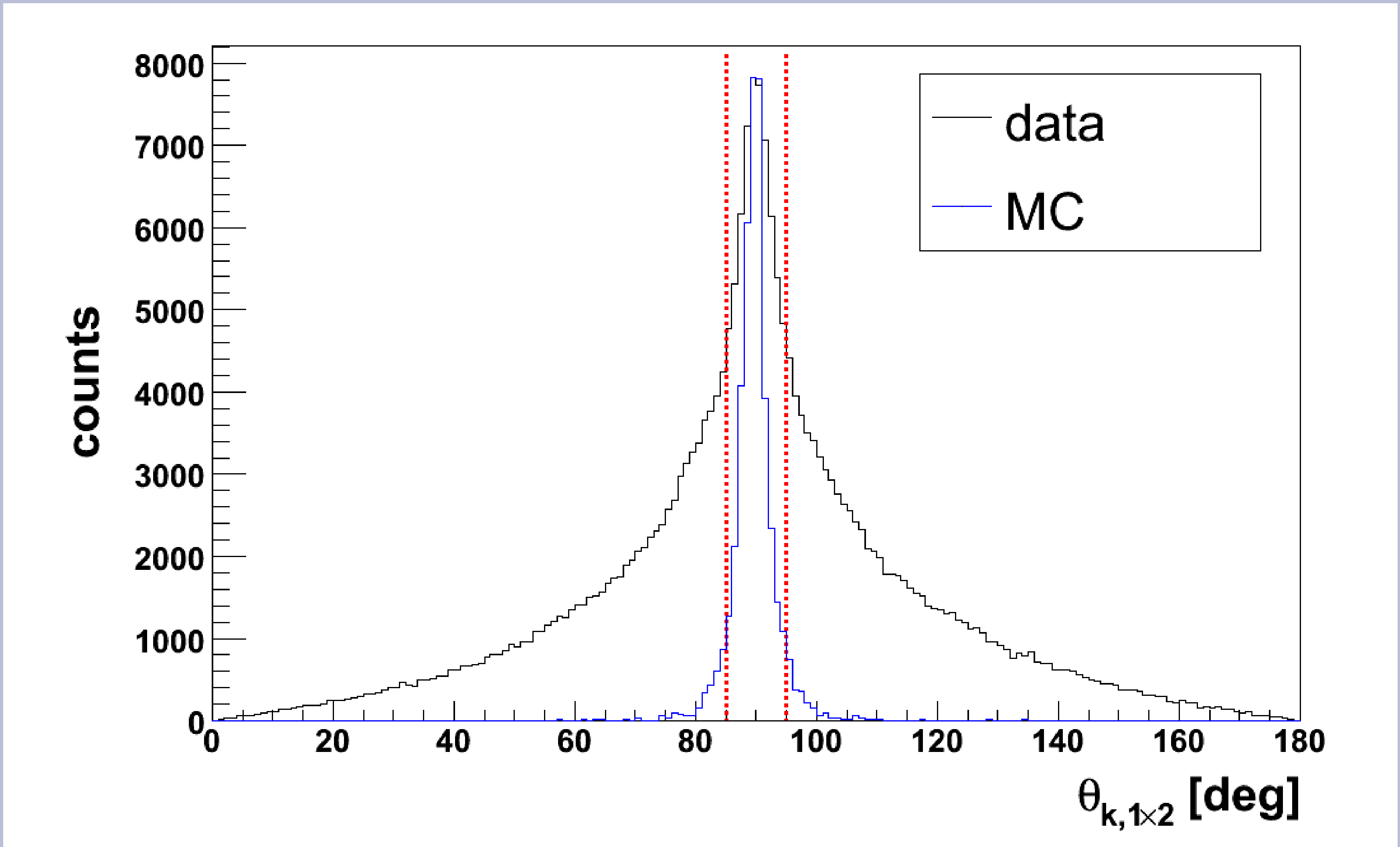
^{3}He ions identification in Forward Detector



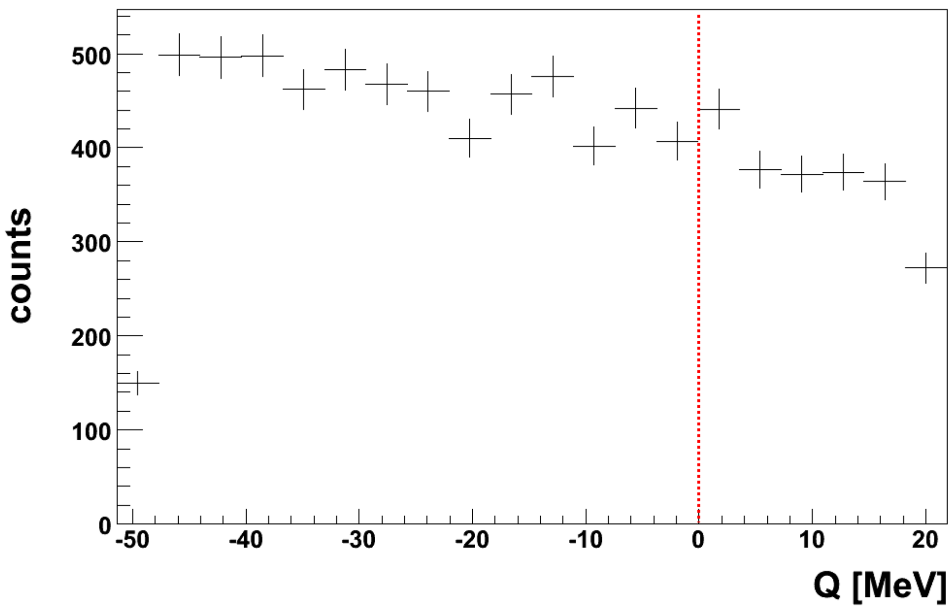
p-π^- identification in Central Detector

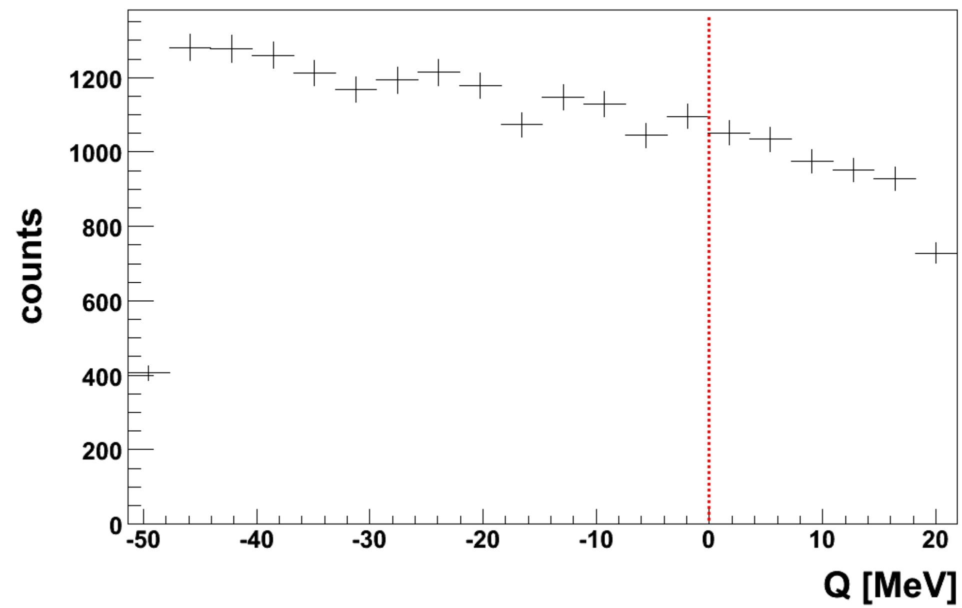


Three-particle cut



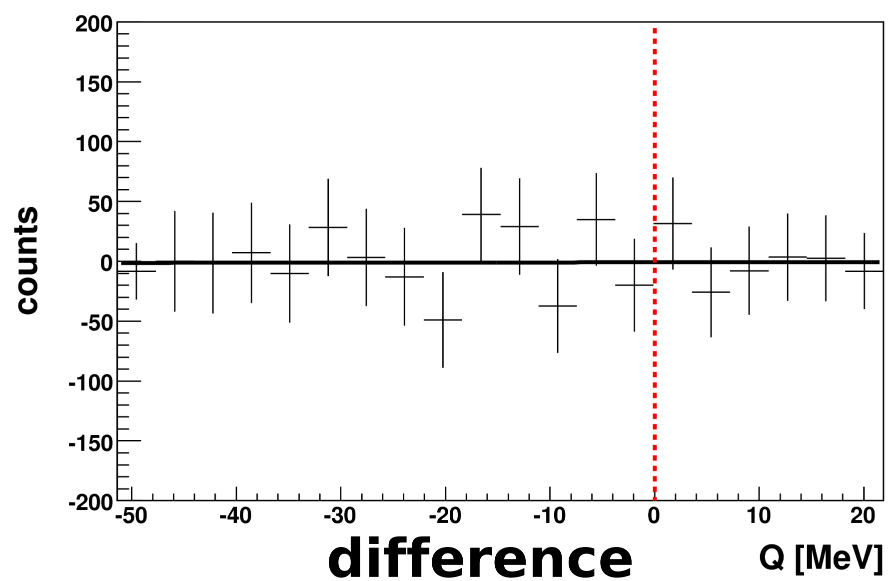
Excitation functions (not normalized)





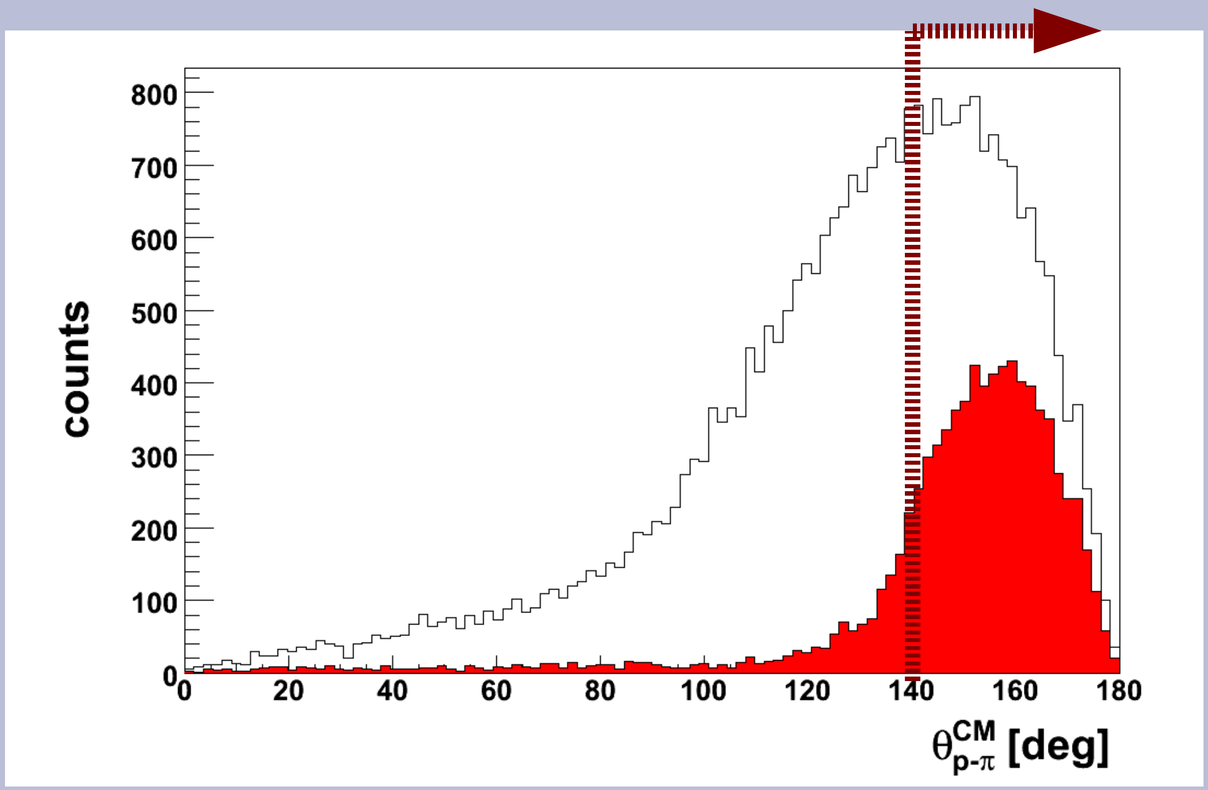
“Signal-rich” region
(P_{HE}^{CM} <0.3 GeV/c)

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



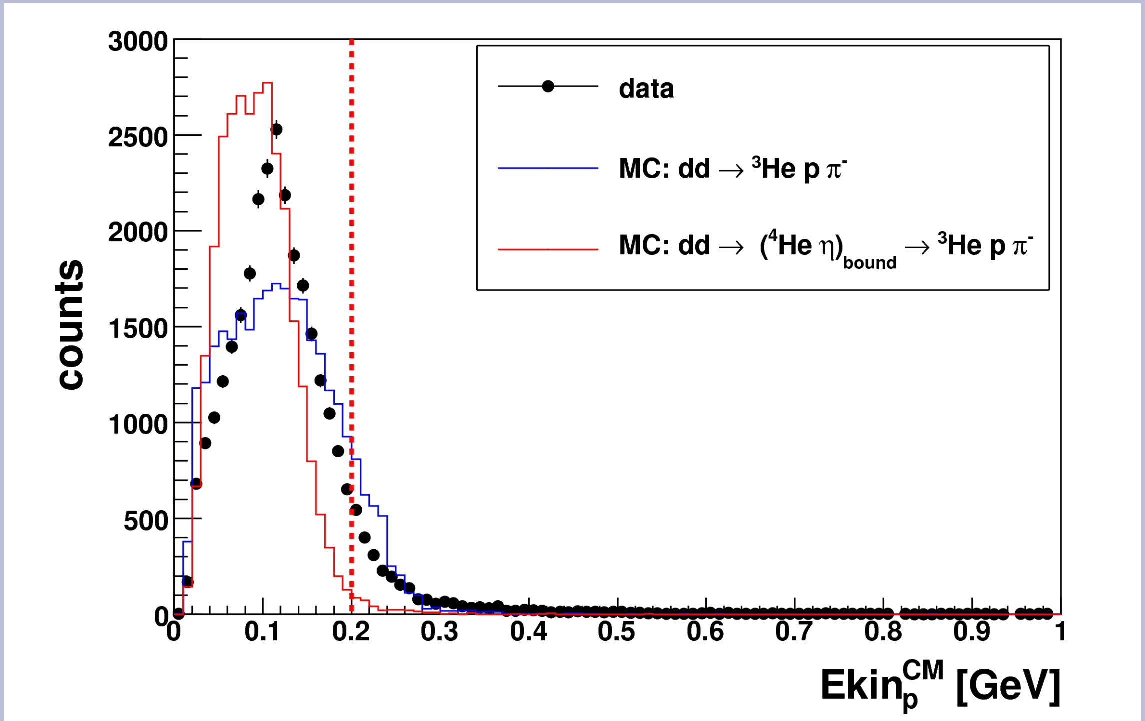
difference

Additional cuts – Opening angle

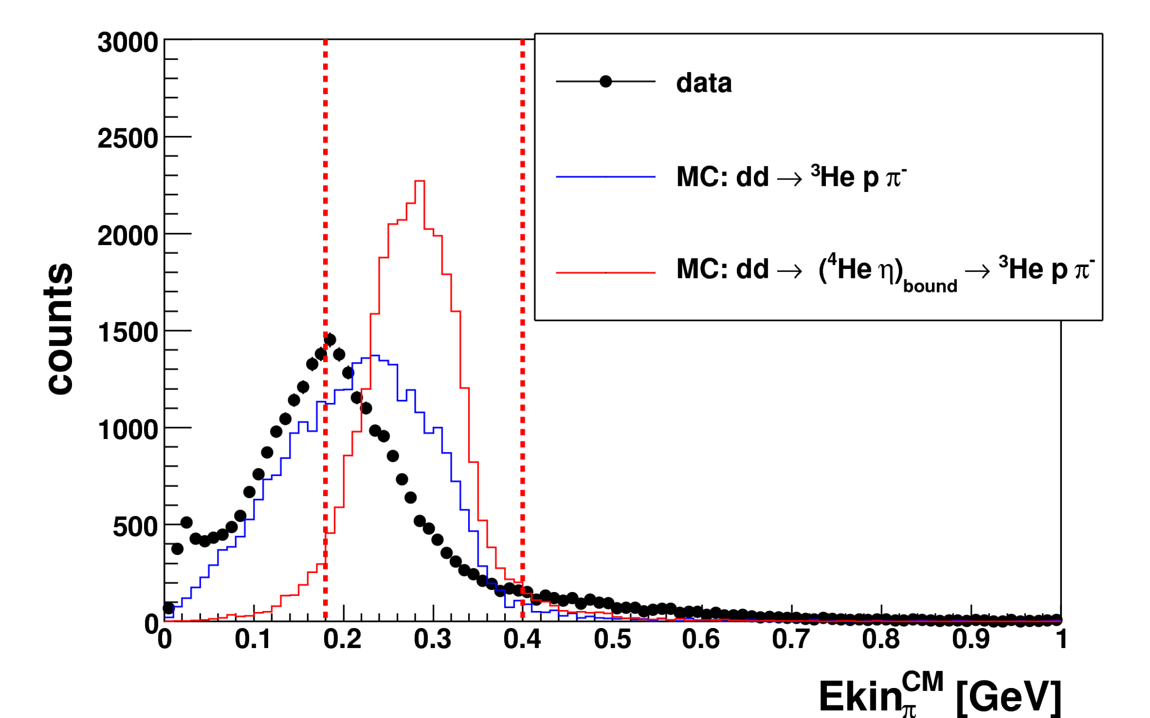


$\Theta^{CM}_{p-\pi} > 140$

Additional cuts – Ekin of p/π^- in CM



$\mathrm{Ekin}^{CM}_{p} < 200$ MeV

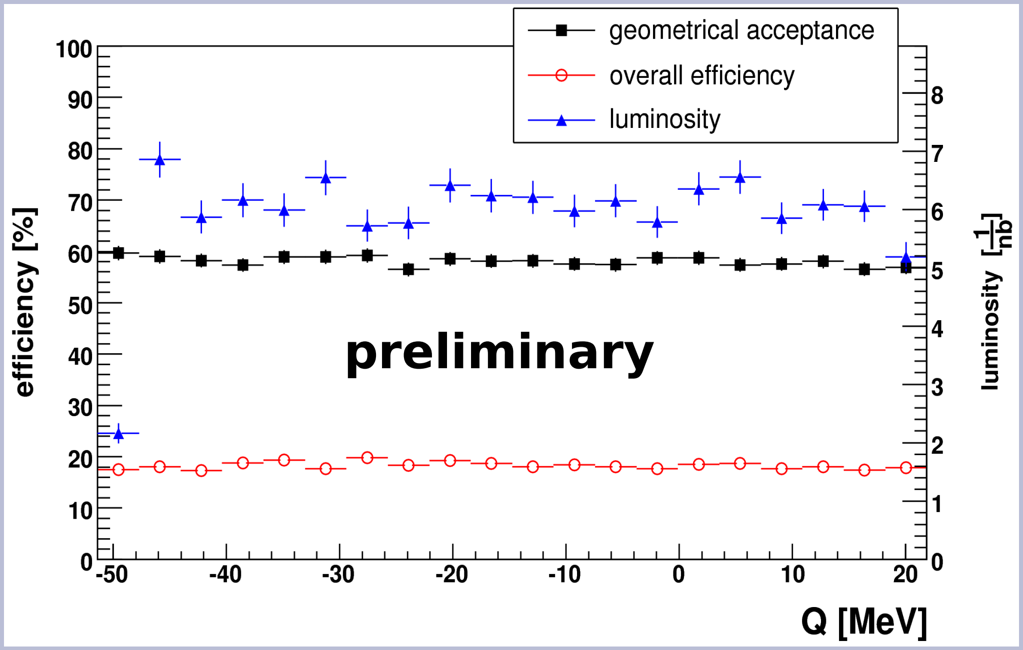


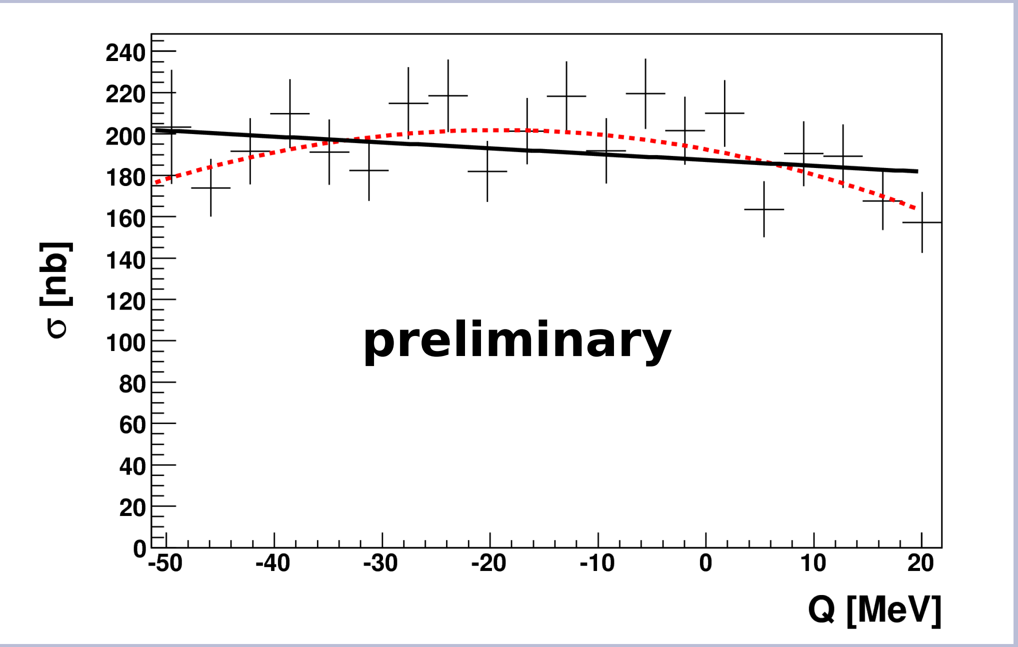
$\mathrm{Ekin}^{CM}_{\pi} > 150$ MeV

&&

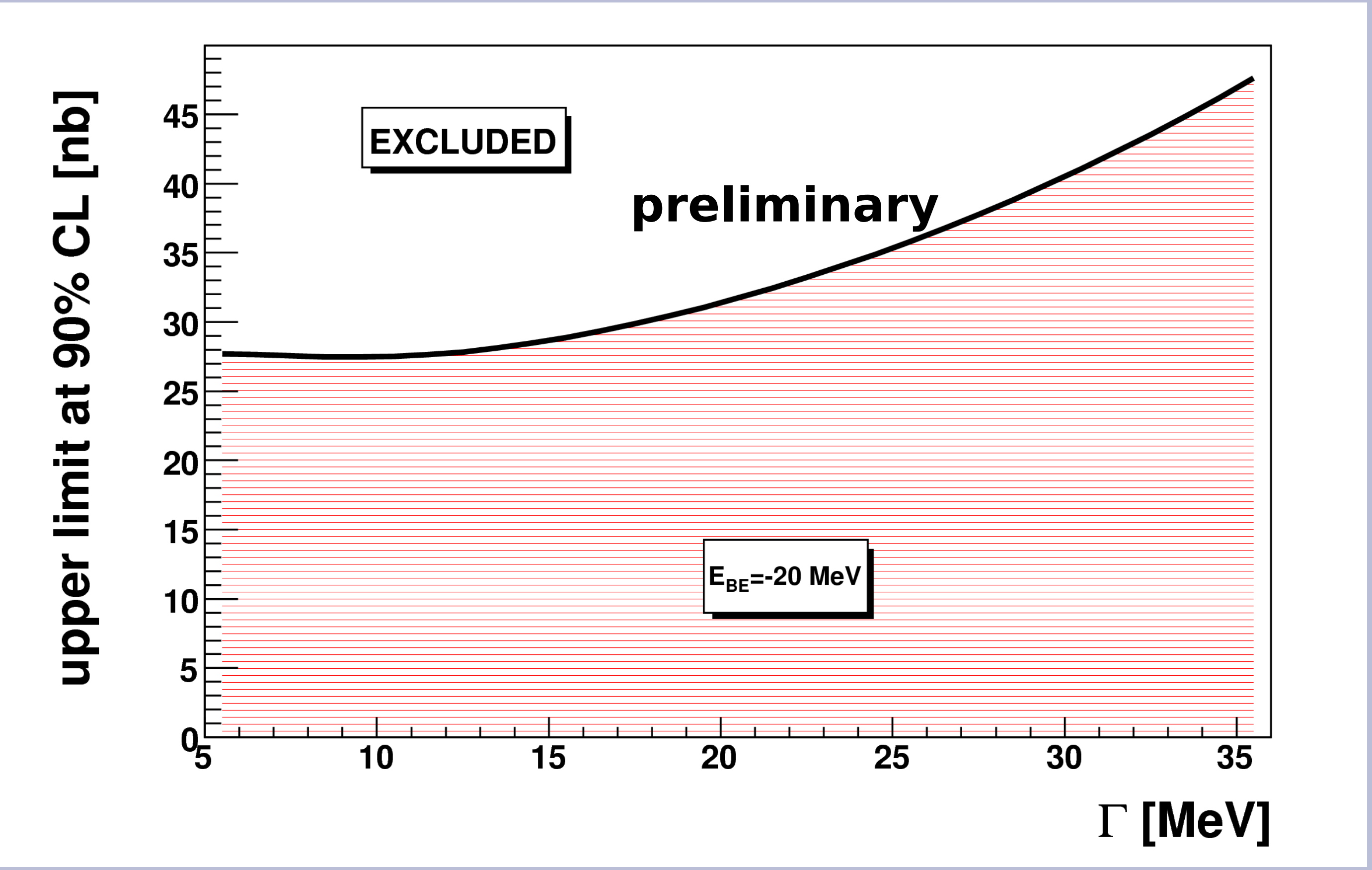
$\mathrm{Ekin}^{CM}_{\pi} < 400$ MeV

Excitation function
(normalized and corrected for efficiency)





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



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:

$$BG = a_0 + a_1 Q + a_2 Q^2$$

Summary

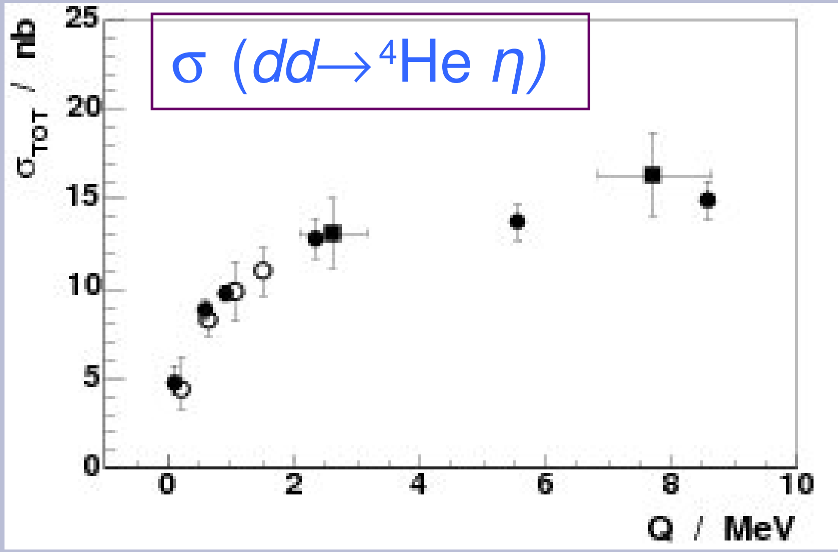
- Exclusive measurement with ramped beam of the reaction

  dd → ^{3}He p π^-
- No η-^{4}He bound state observed in current analysis
- Upper limit estimated
- New data: December 2010

  (~20 x statistics, magnetic field, additional channel ^{3}He n π^0)

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

$\sim 1/4\ \mathrm{x}\ \ 1/2 = 1/8$

$dd \rightarrow {}^3\mathrm{He}\ p\pi^-$
$dd \rightarrow {}^3\mathrm{He}\ n\pi^0$
$dd \rightarrow \mathrm{T}\ n\pi^+$
$dd \rightarrow \mathrm{T}\ p\pi^0$

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

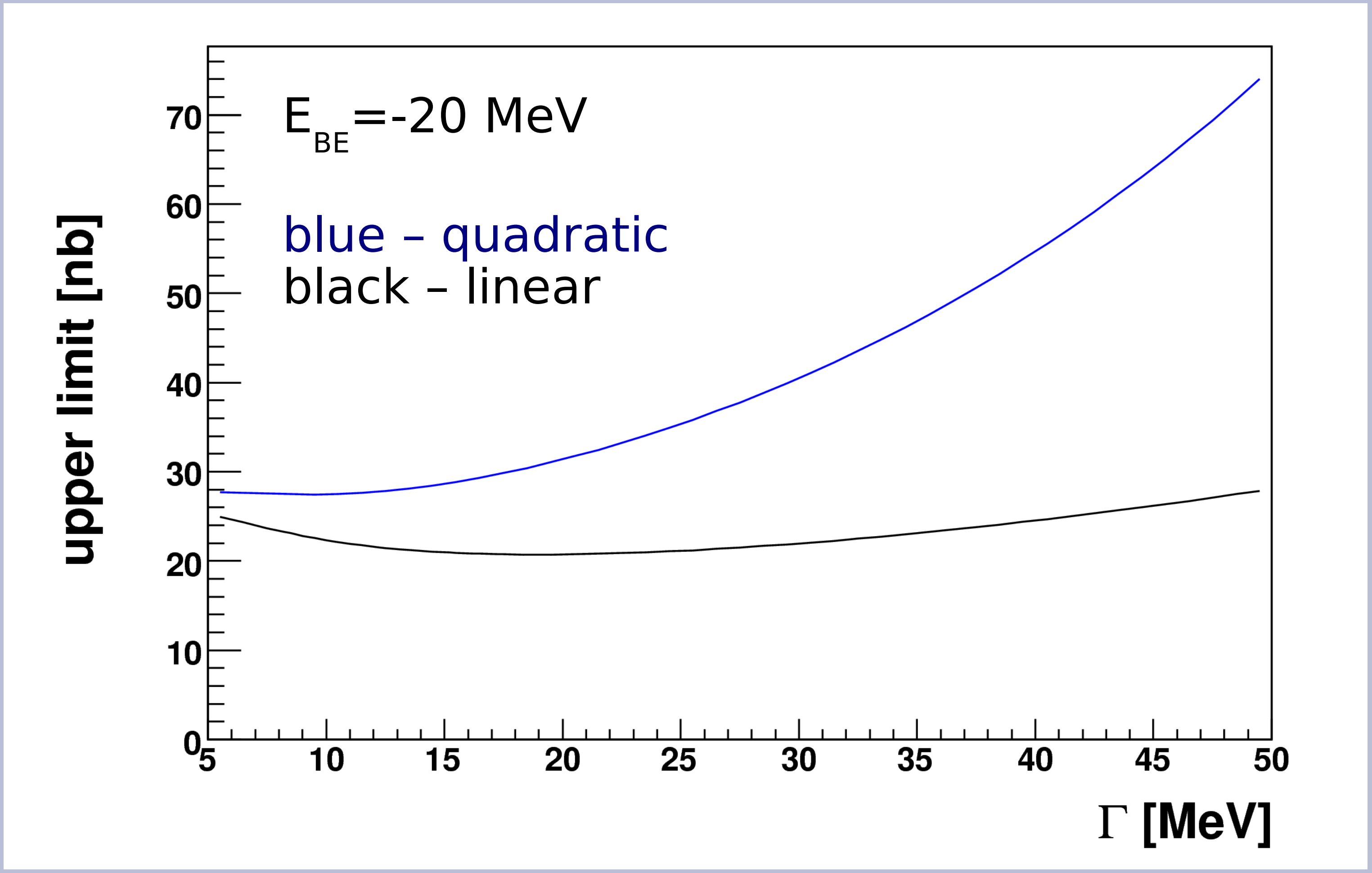
Probability that the spectator
nucleons (ppn) will form ^{3}He
Per analogy to ^{4}He Λ → ^{3}He $p\pi^-$

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

Systematics

- **Efficency:** flat as a function of p_{beam} : ± 1%
- **Normalization (from quasi-elastic pp):** flat as a function of p_{beam} : ± 1 nb^{-1}
- **Additional checks of the background in pp case.**
- **Shape of the excitation function**
- **Fits of the final excitation function**:
  - Linear vs quadratic background
  - $\mathbf{E_{BE}}$, Γ dependency
  - Binning dependency

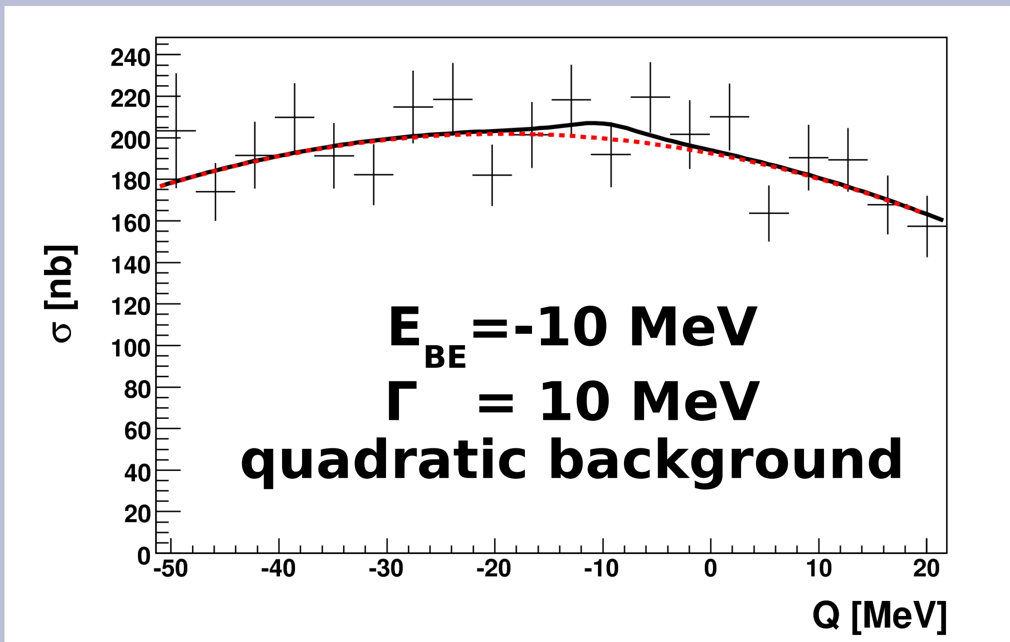
Upper limit linear vs quadratic background

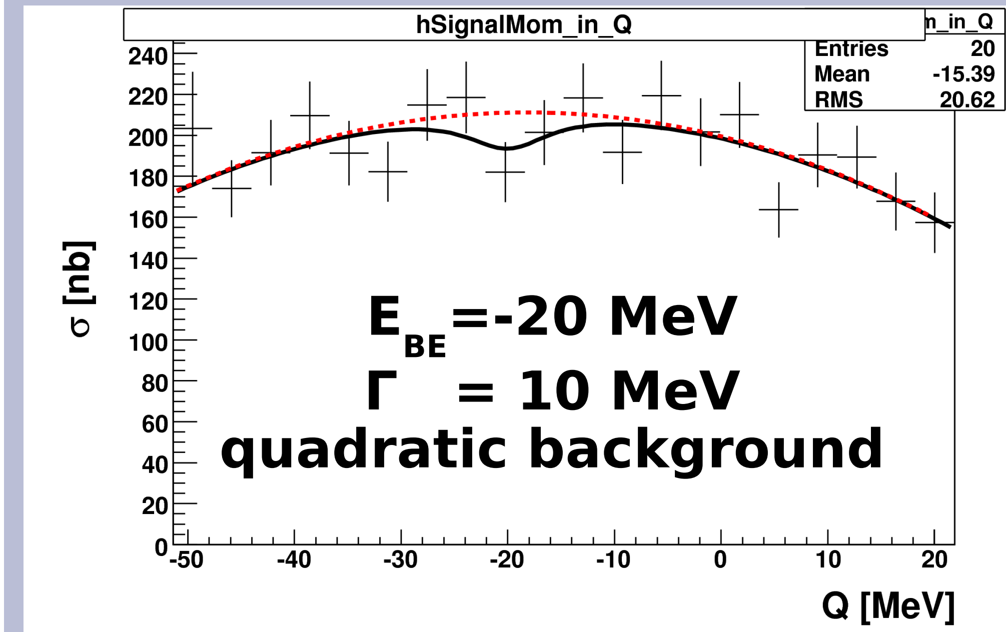


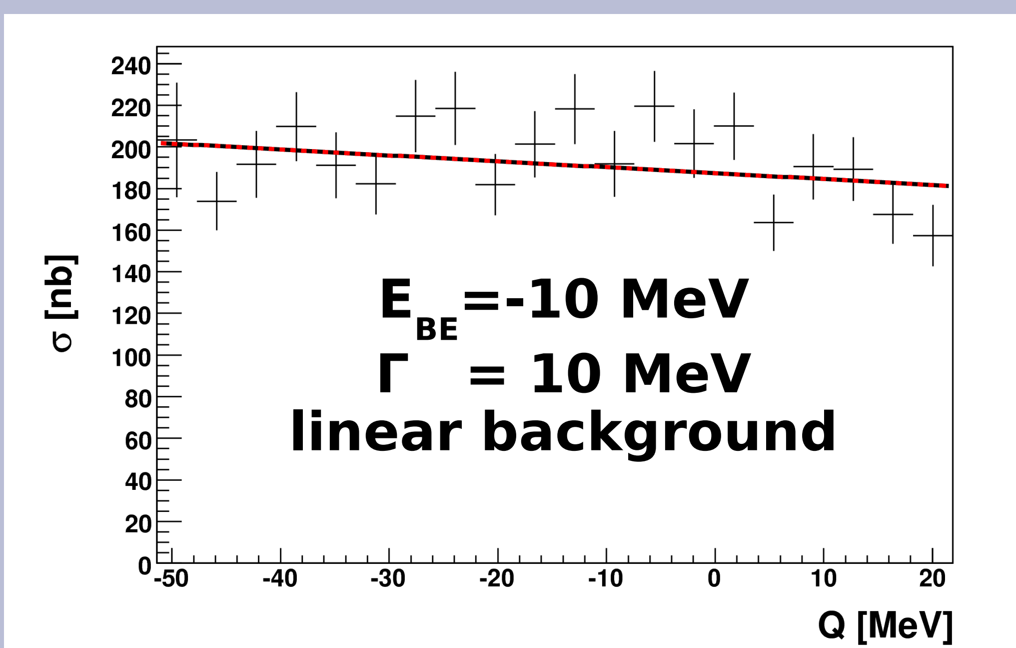
linear background: Chi-2 =21,3 Chi-2_{red}= 1.25,

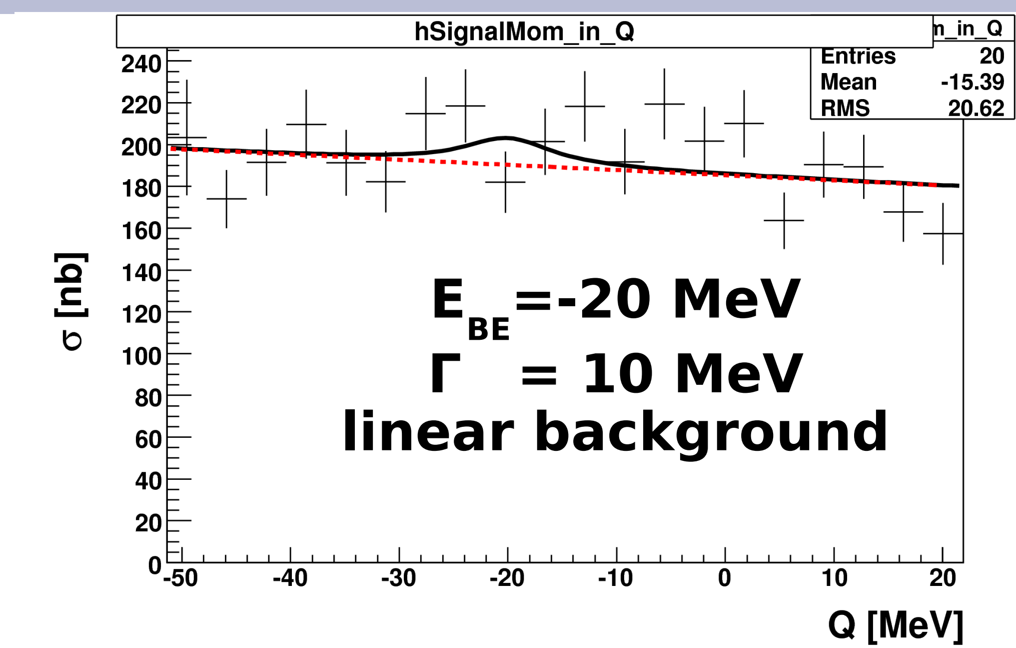
quadratic background: Chi-2=17,7, Chi-2_{red}= 1.1

Fit examples

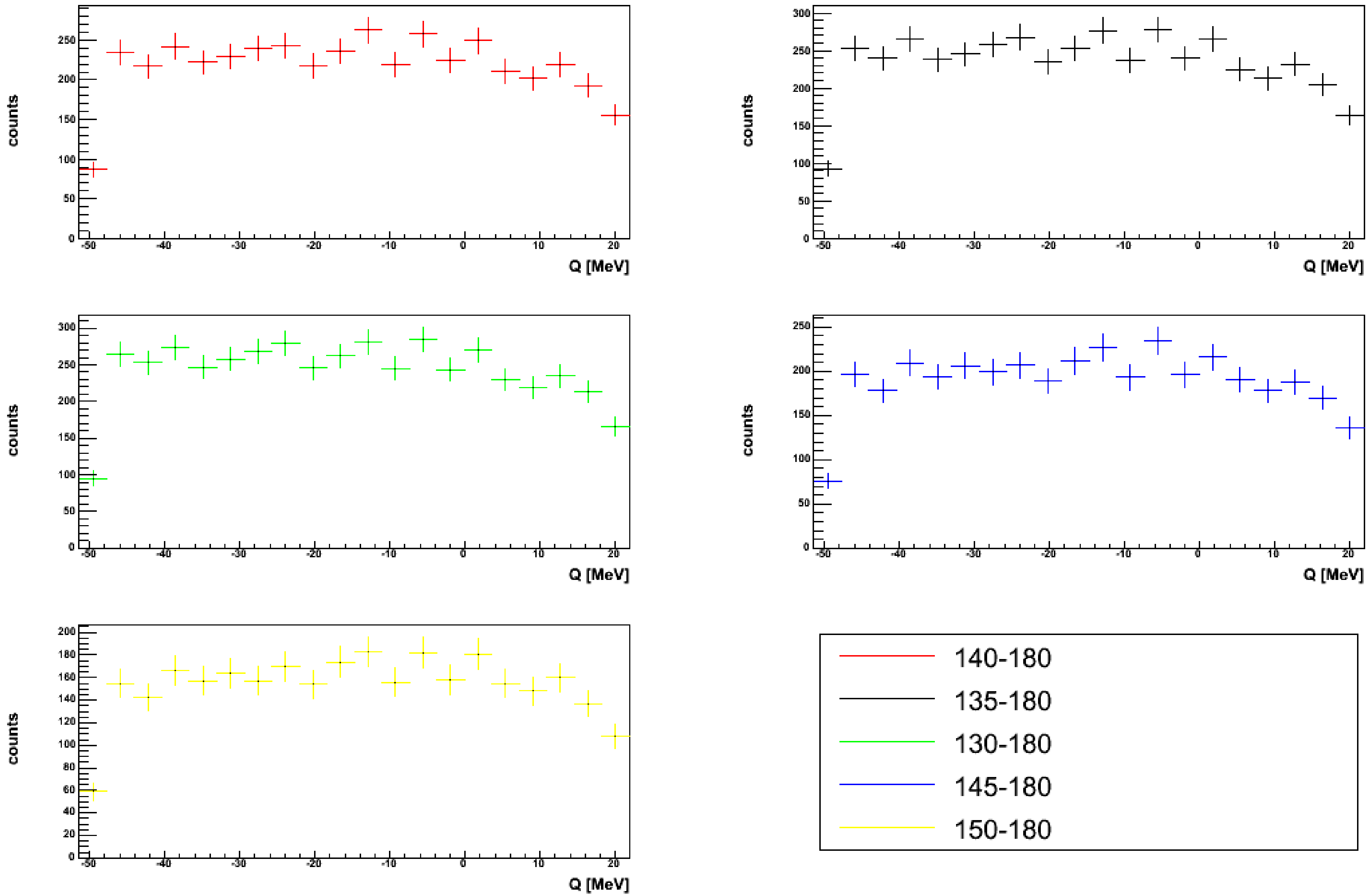




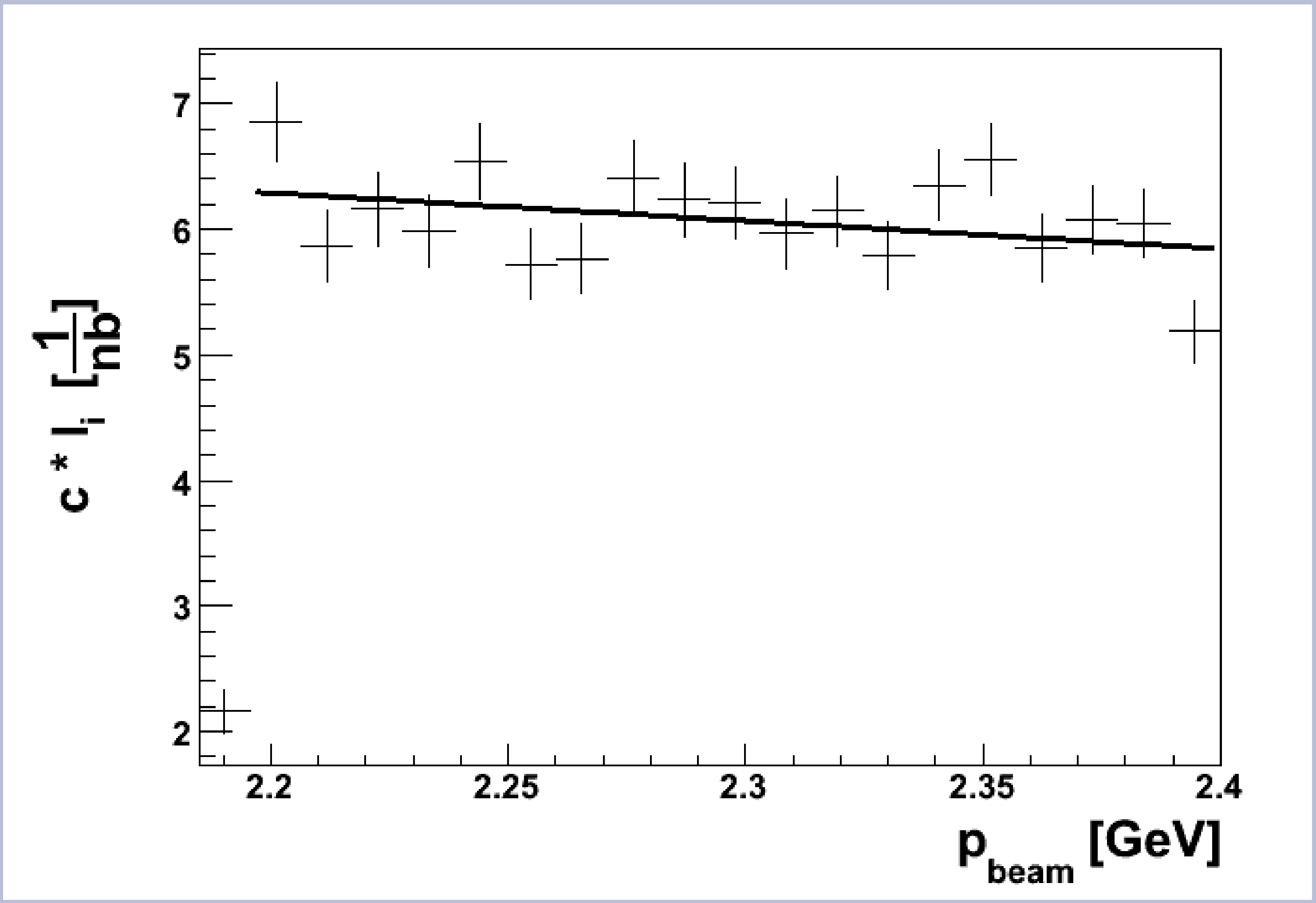




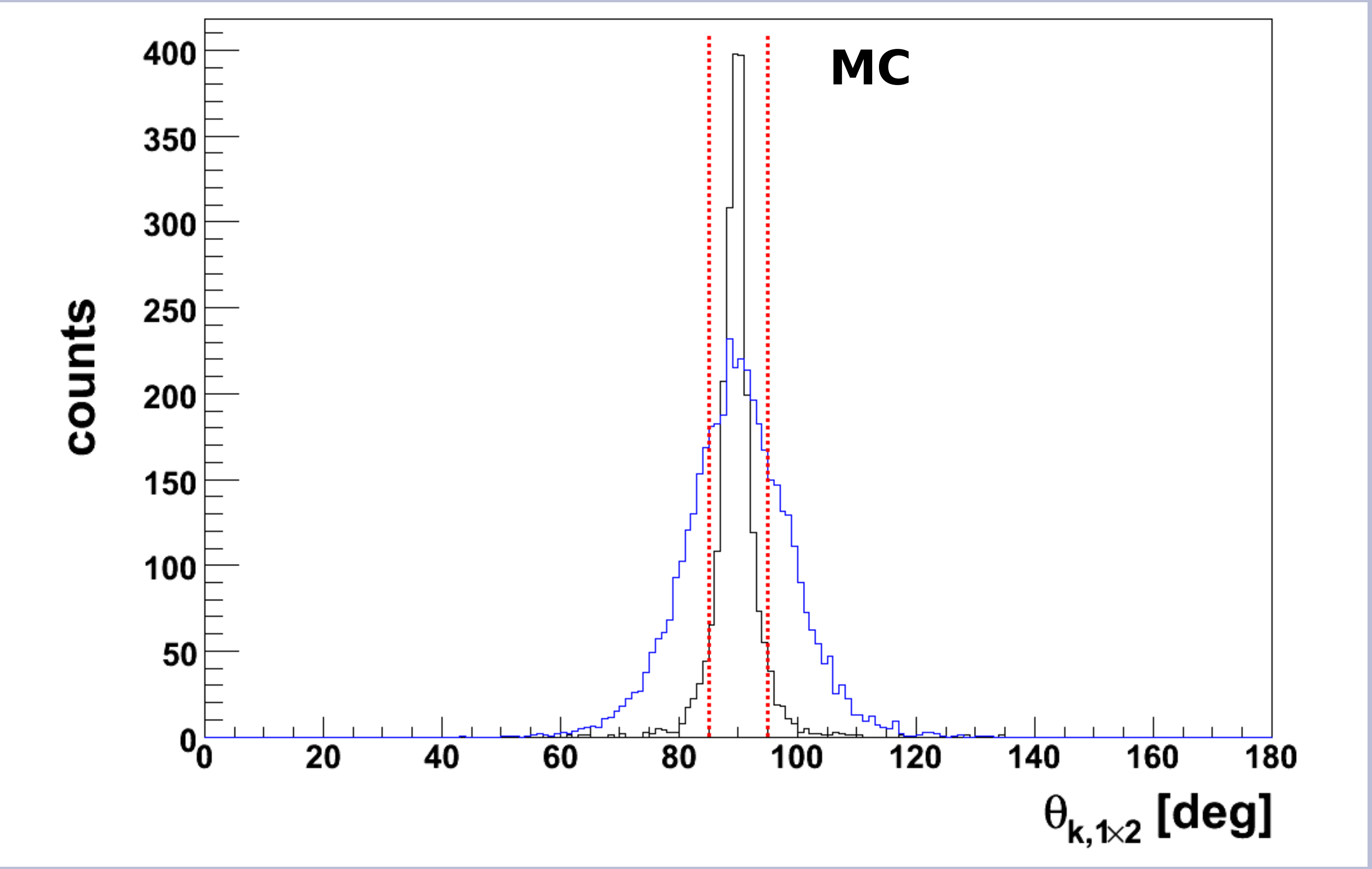
Cross-check opening angle-cuts



Luminosity variation

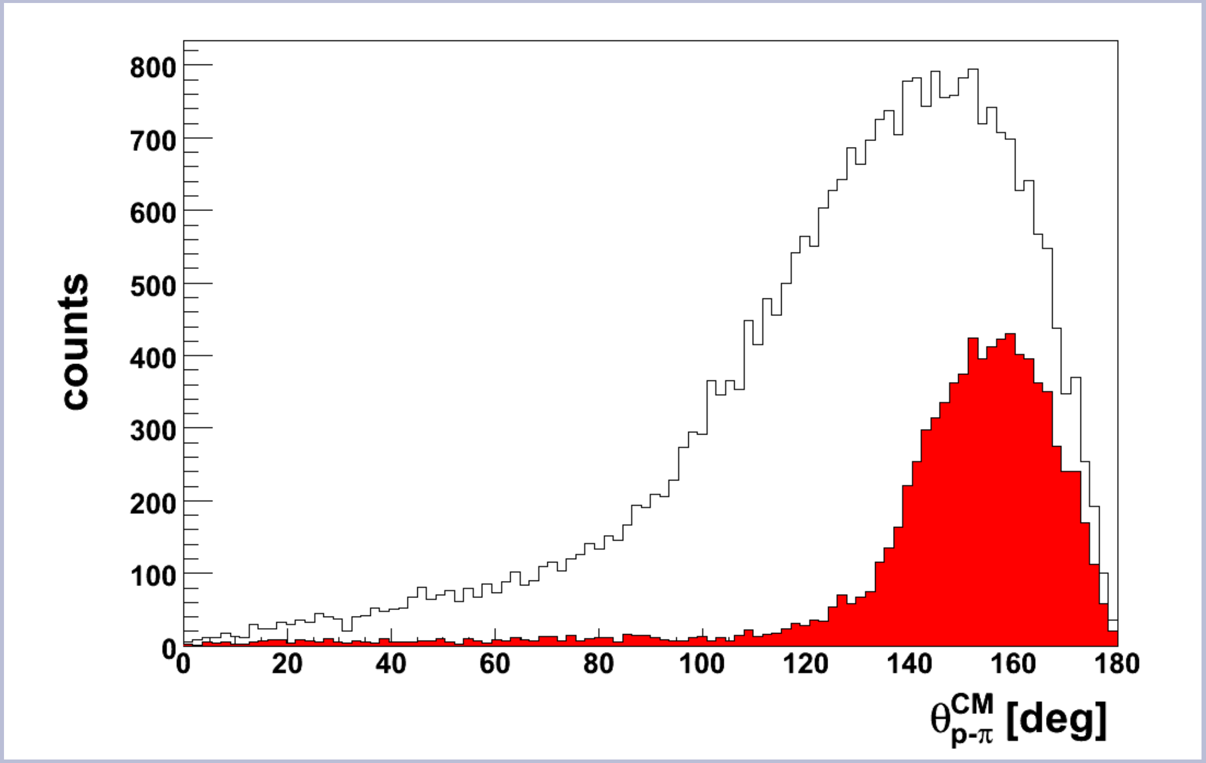


Four-particle reactions



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

Back-to-back after He3 momentum cut in CM



Quasi-elastic reactions

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

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

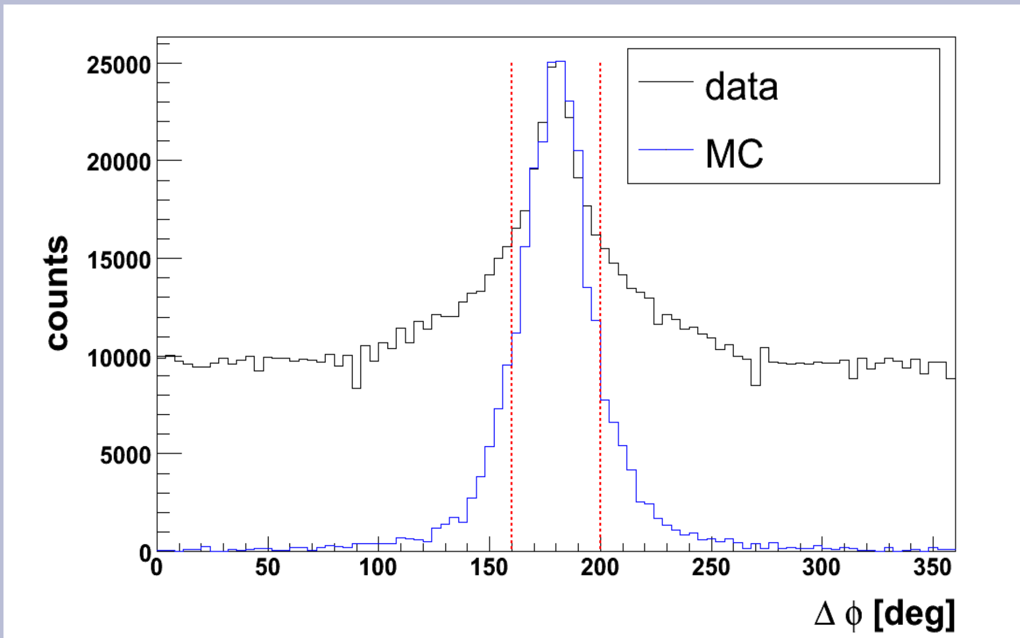
$dd \rightarrow p_{beam}\ d_{targed}\ \ n_{spect}$

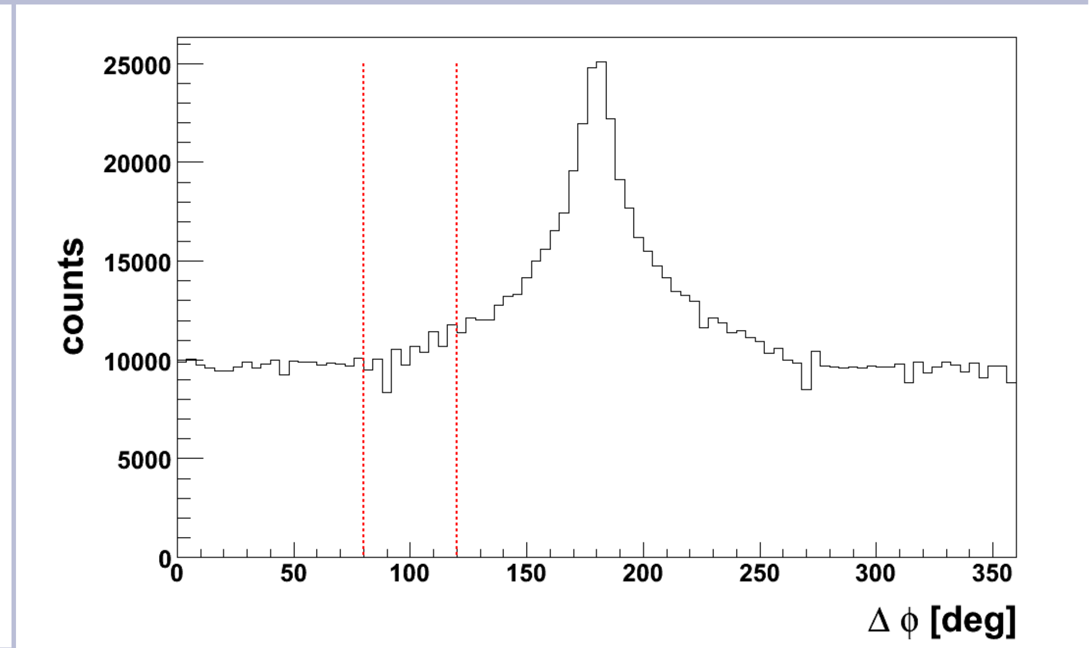
$dd \rightarrow pp\ (nn)_{spect} \rightarrow d\ \pi^{+}\ (nn)_{spect}$

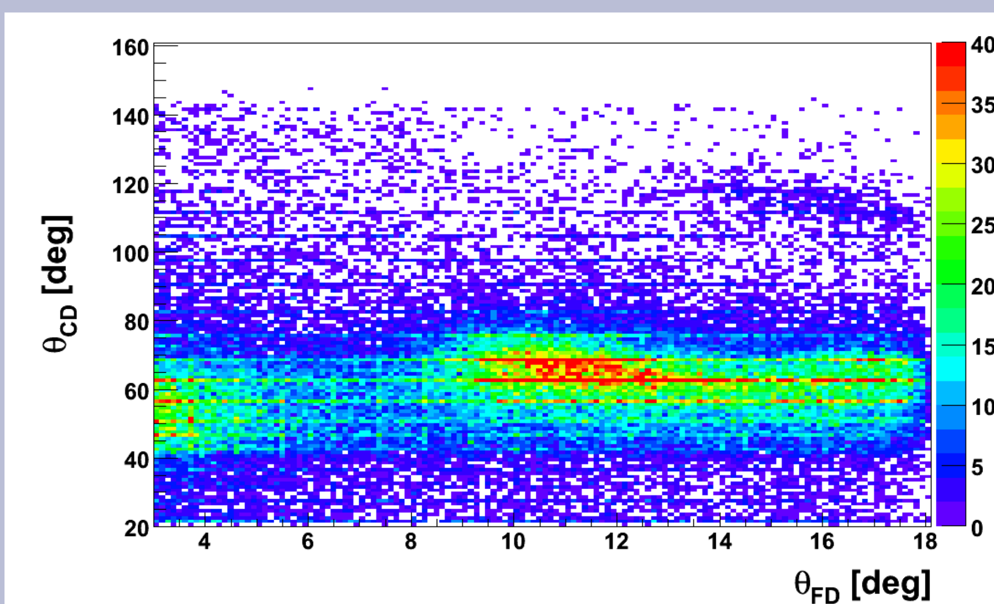
$dd \rightarrow dd$

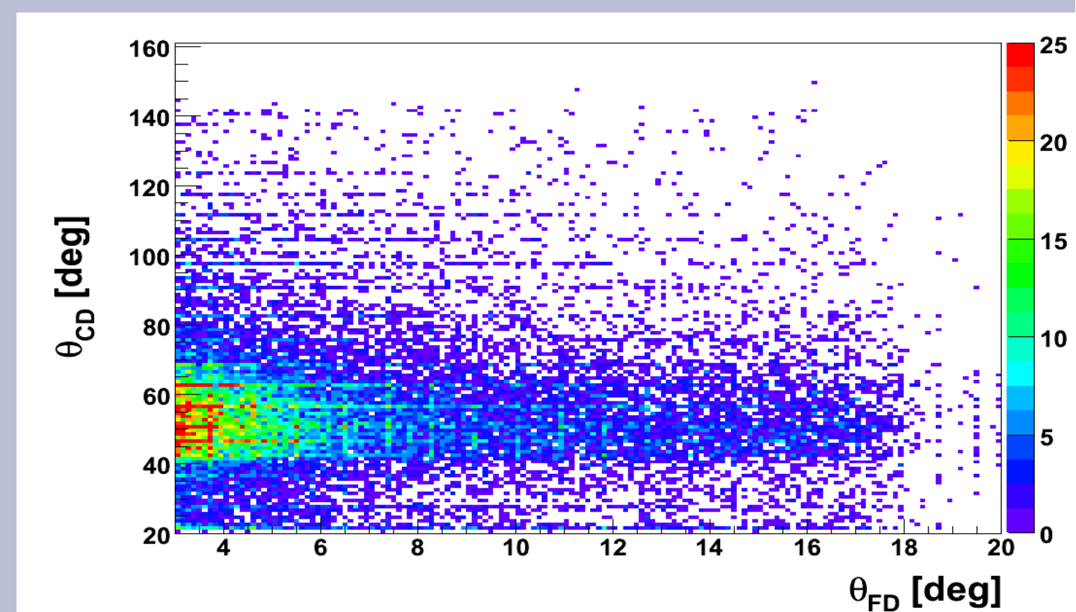
other reactions (non-coplanar)

Quasi-elastic reactions background

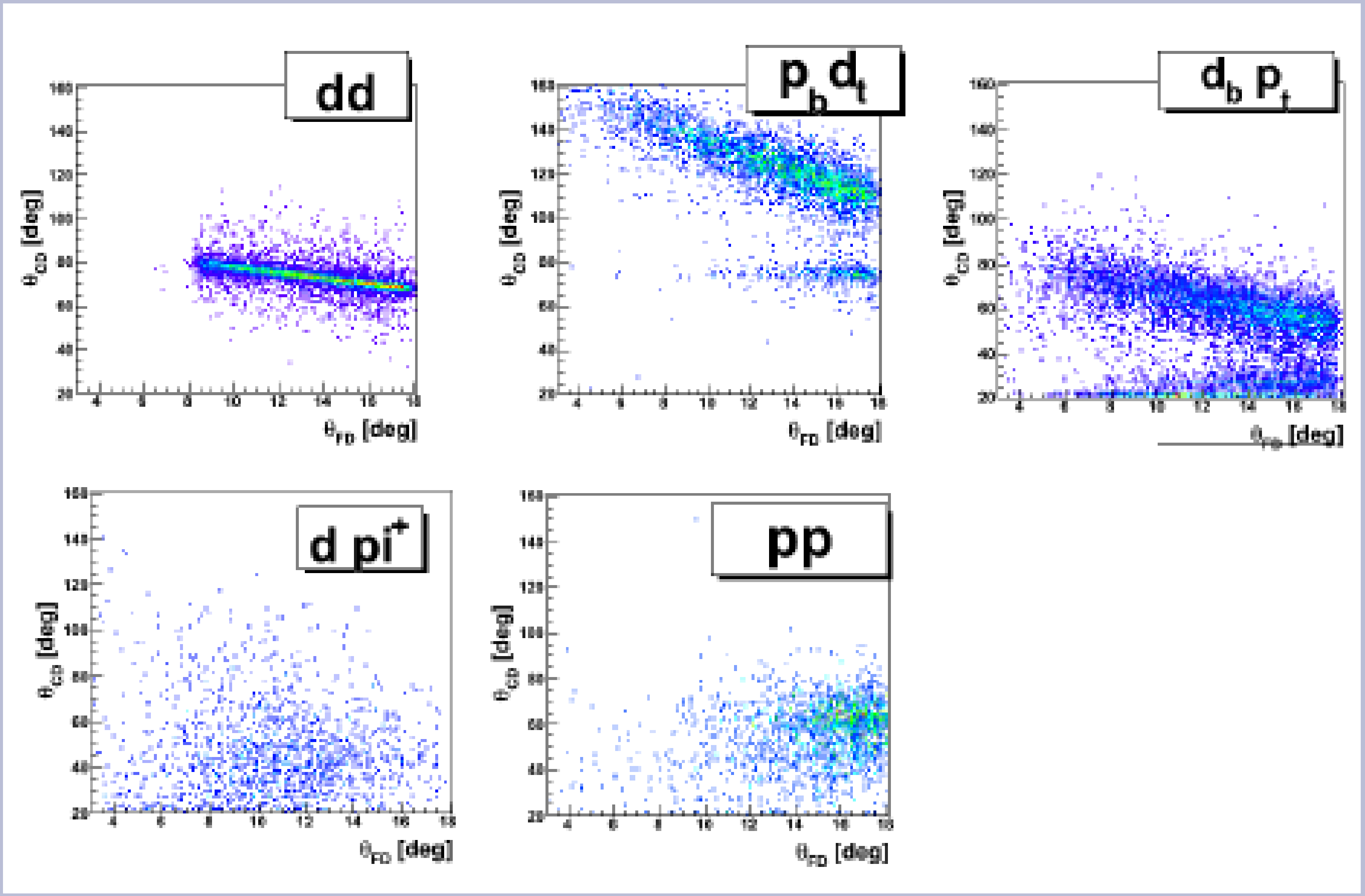




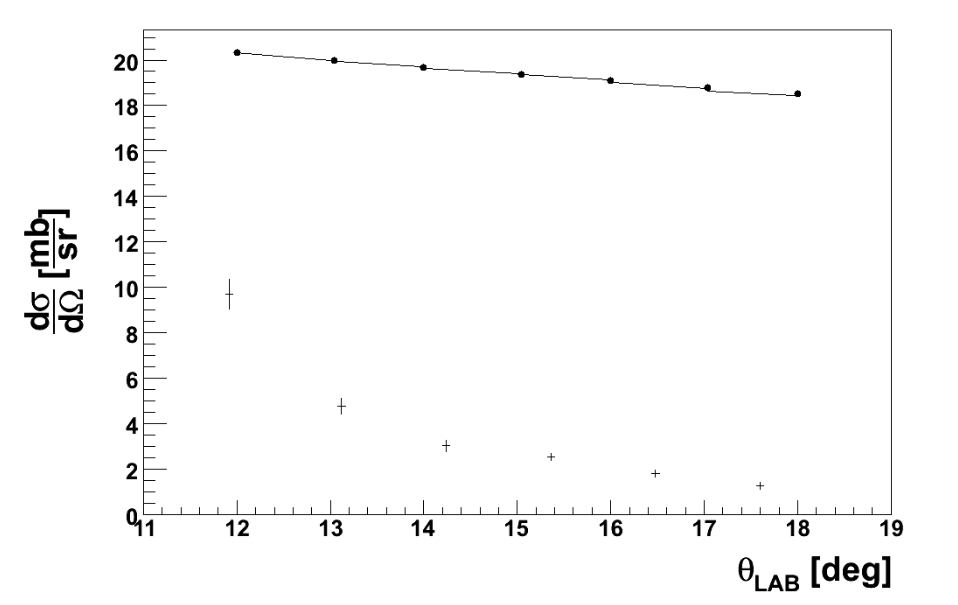




Quasi-elastic reactions
MC simulations



Quasi-elastic reaction
(dp)



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

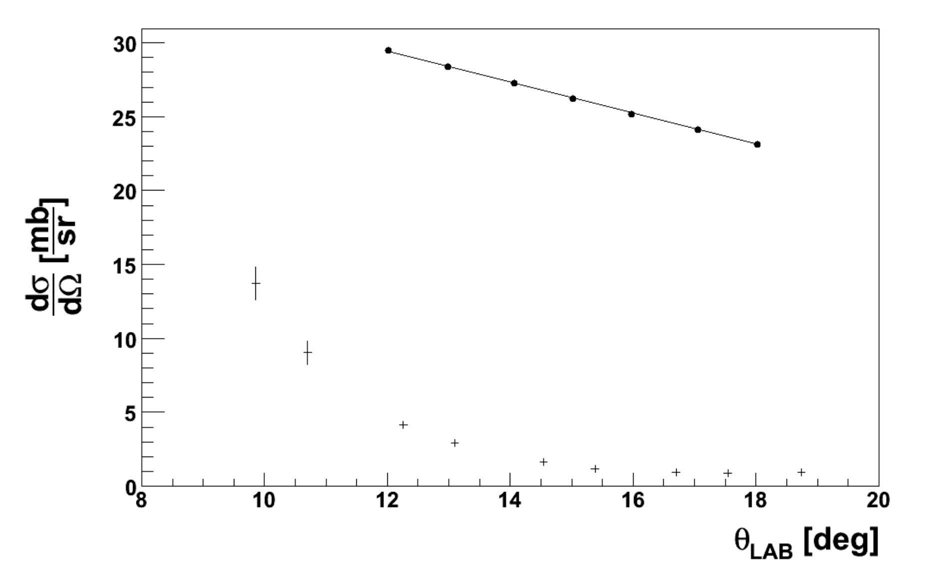
$dd \rightarrow d_{beam}\ p_{target}\ n_{spect}$

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

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

$dd \rightarrow dd$

other reactions



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

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

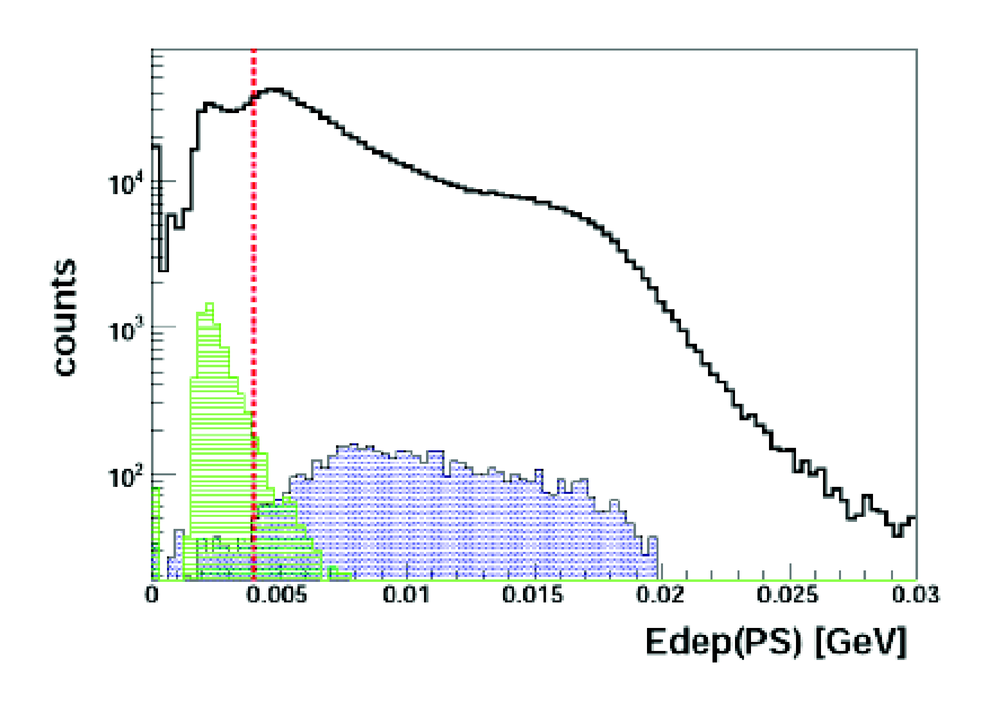
$dd \rightarrow d_{beam}\ p_{target}\ \ n_{spect}$

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

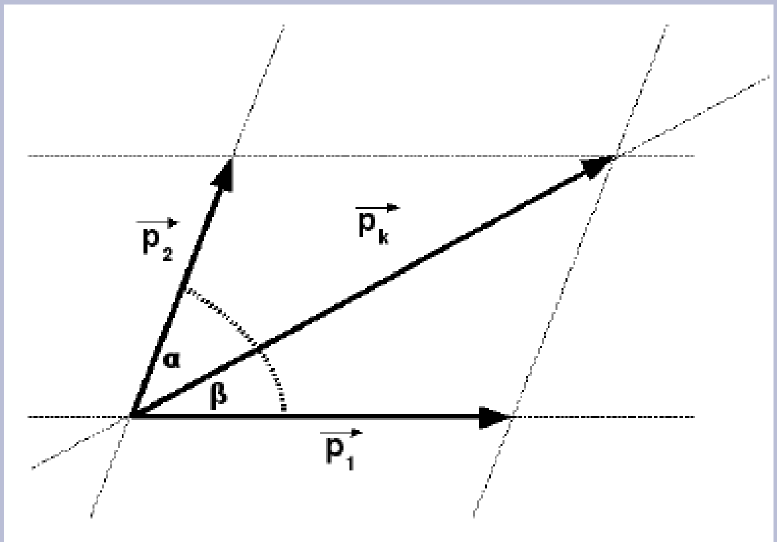
$dd \rightarrow pp\ (nn)_{spect} \rightarrow d\ \pi^+\ (nn)_{spect}$

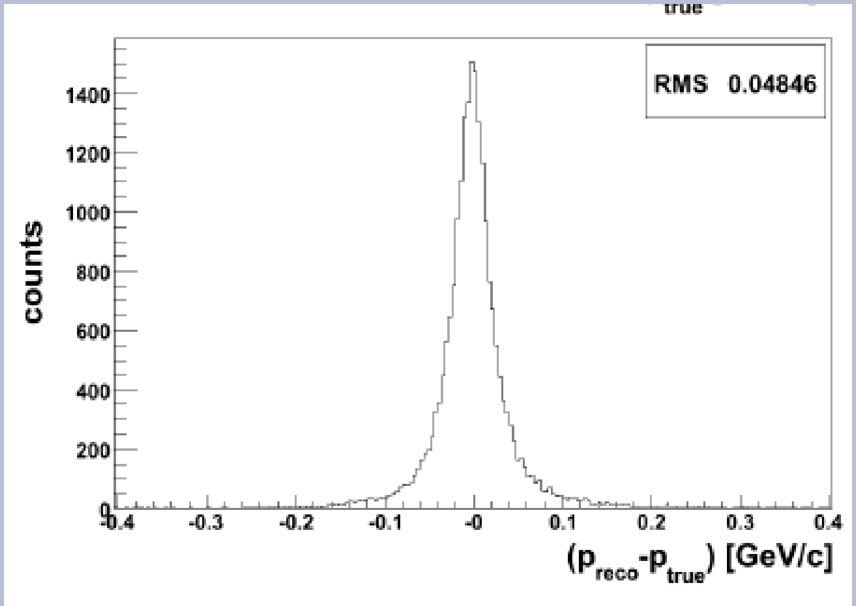
$dd \rightarrow dd$

other reactions



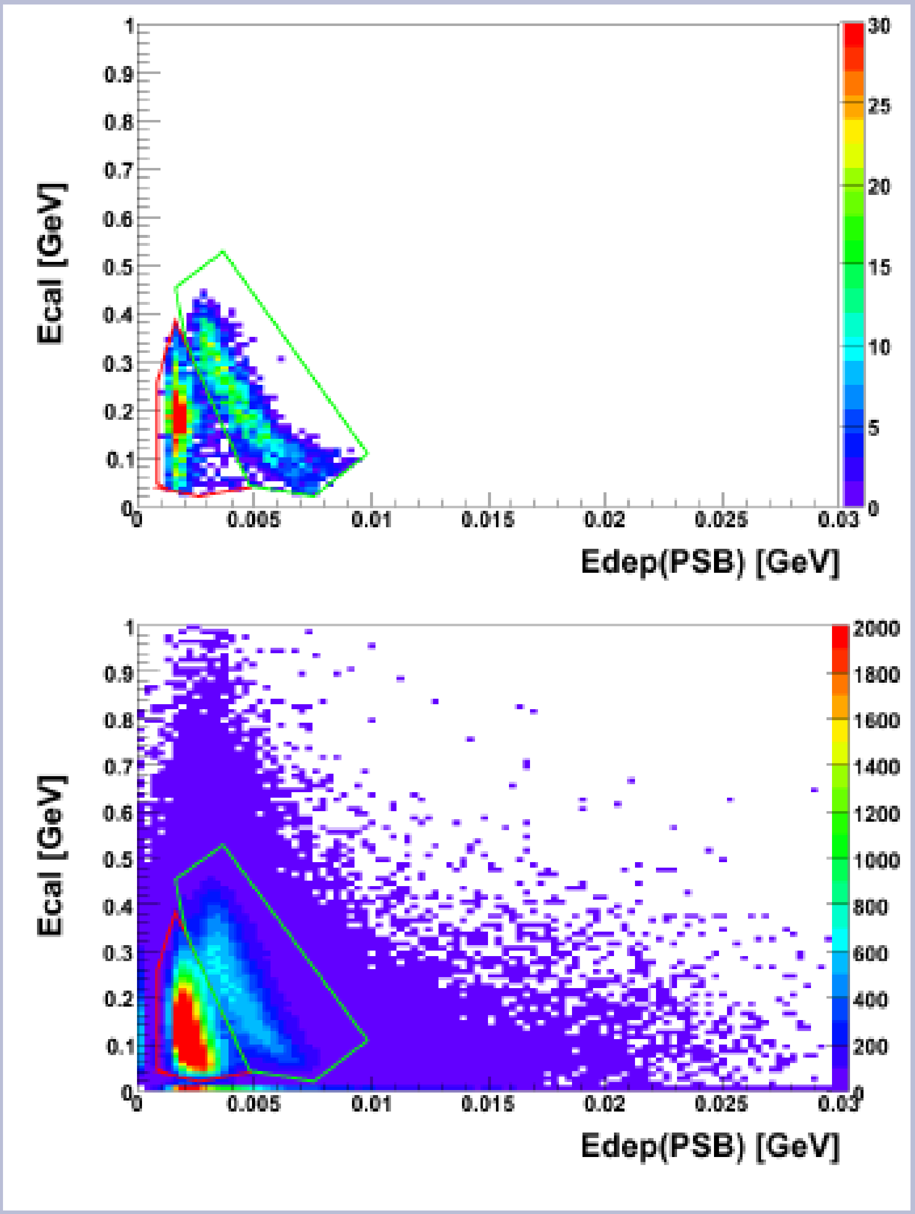
Momentum reconstruction for p and π^-



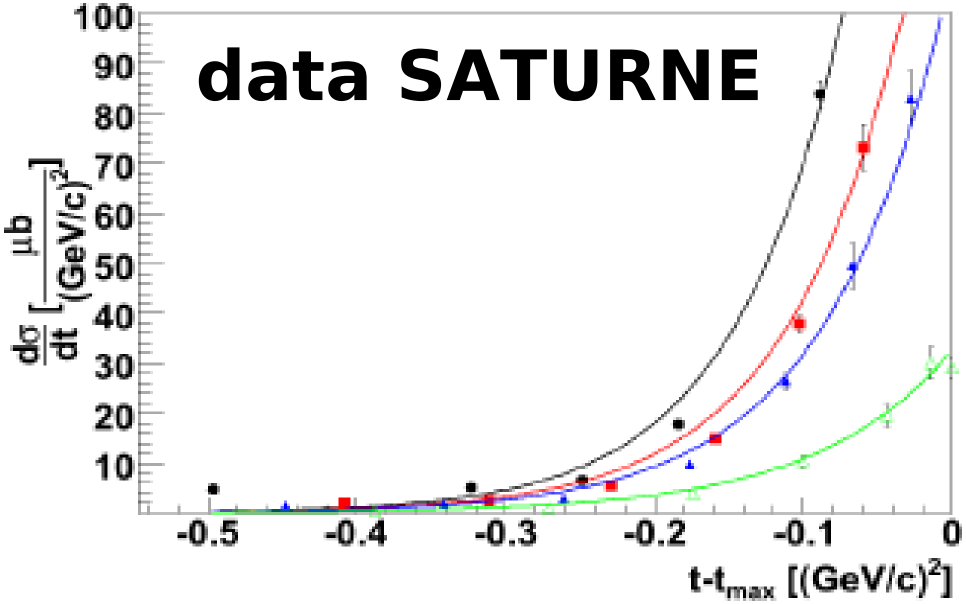


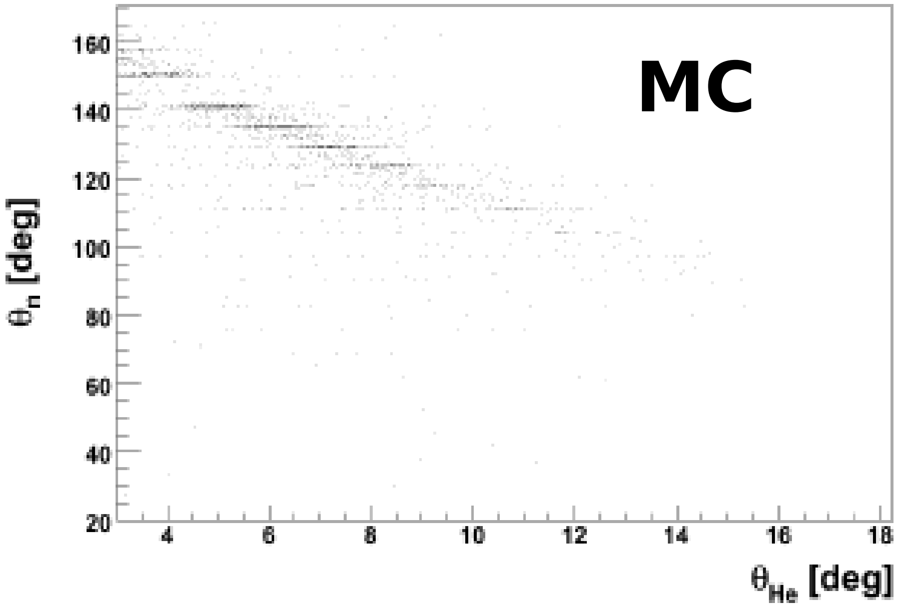
$$|\vec{p}1| = |\vec{p}_k| \times \frac{\sin\beta}{\sin(\alpha+\beta)}, |\vec{p}2| = |\vec{p}_k| \times \frac{\sin\alpha}{\sin(\alpha+\beta)}$$

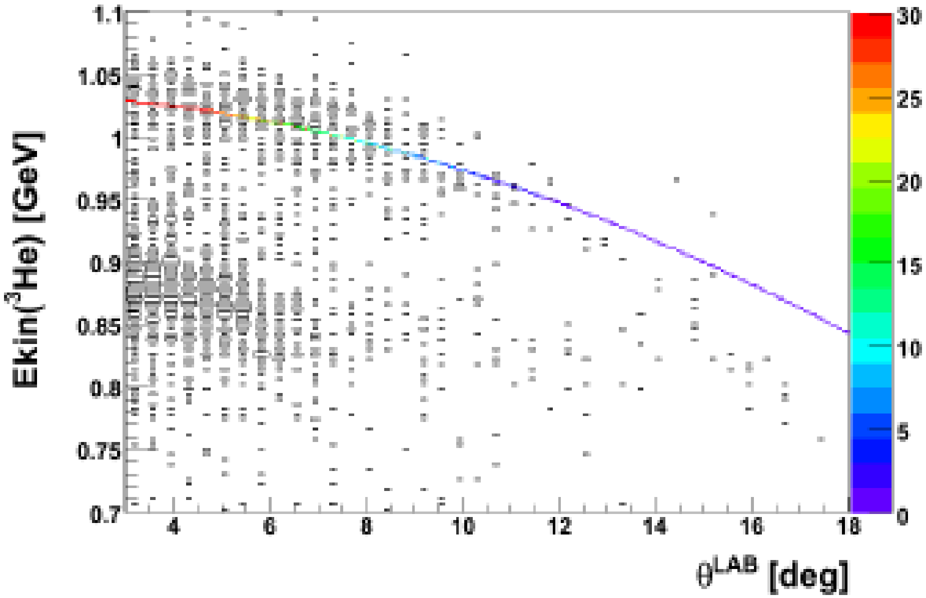
Proton / pion identification

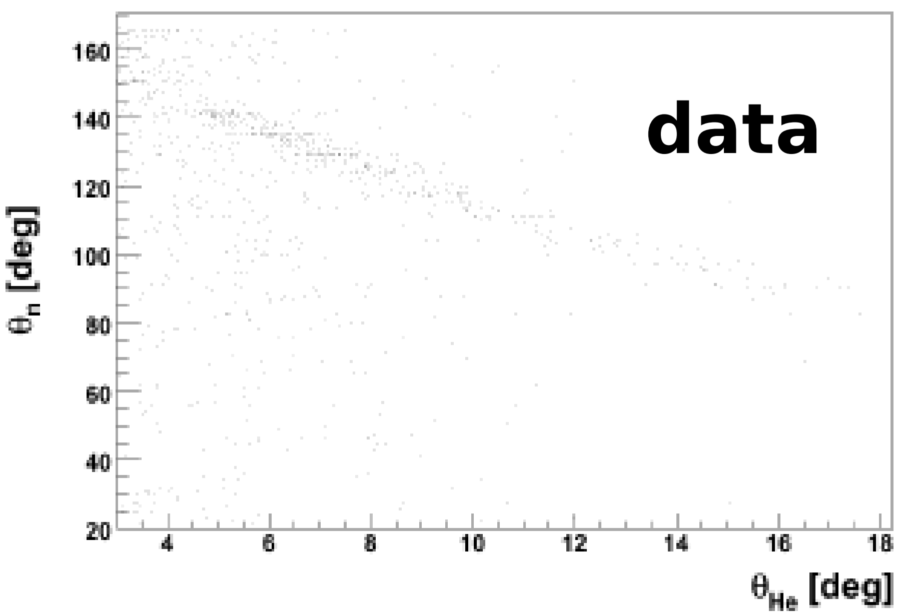


dd → ^{3}He *n*

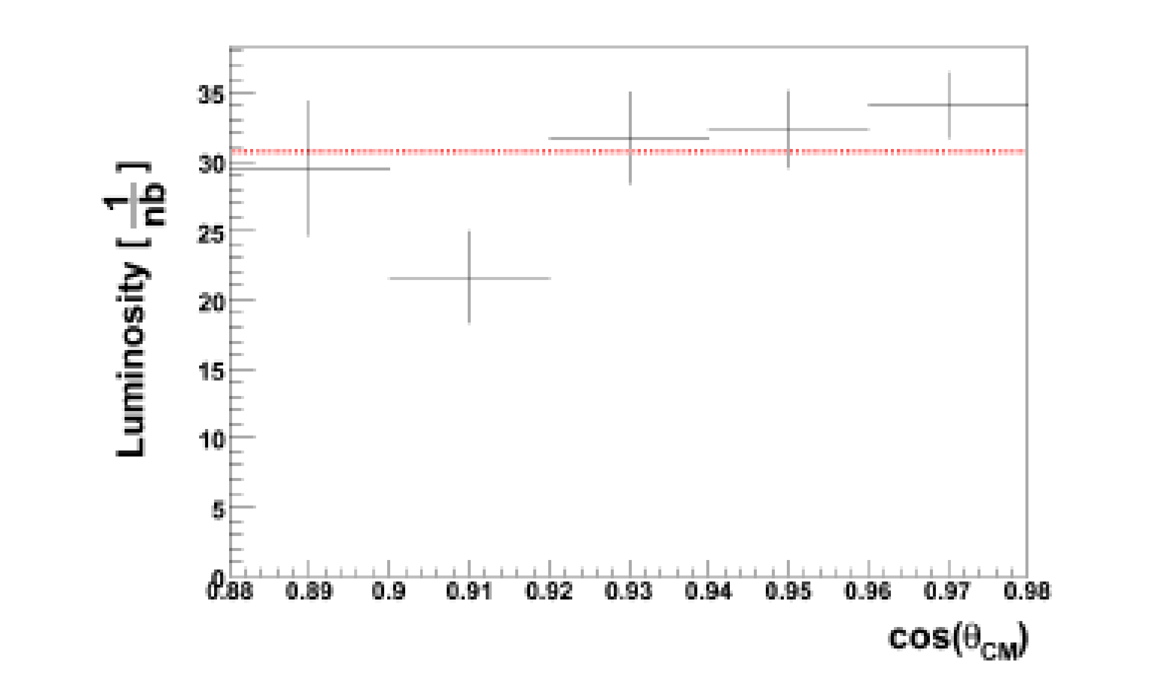

data SATURNE
$\frac{d\sigma}{dt}$ [$\frac{\mu b}{(GeV/c)^2}$]
t-t_{max} [(GeV/c)^2]


MC
θ_n [deg]
θ_{He} [deg]

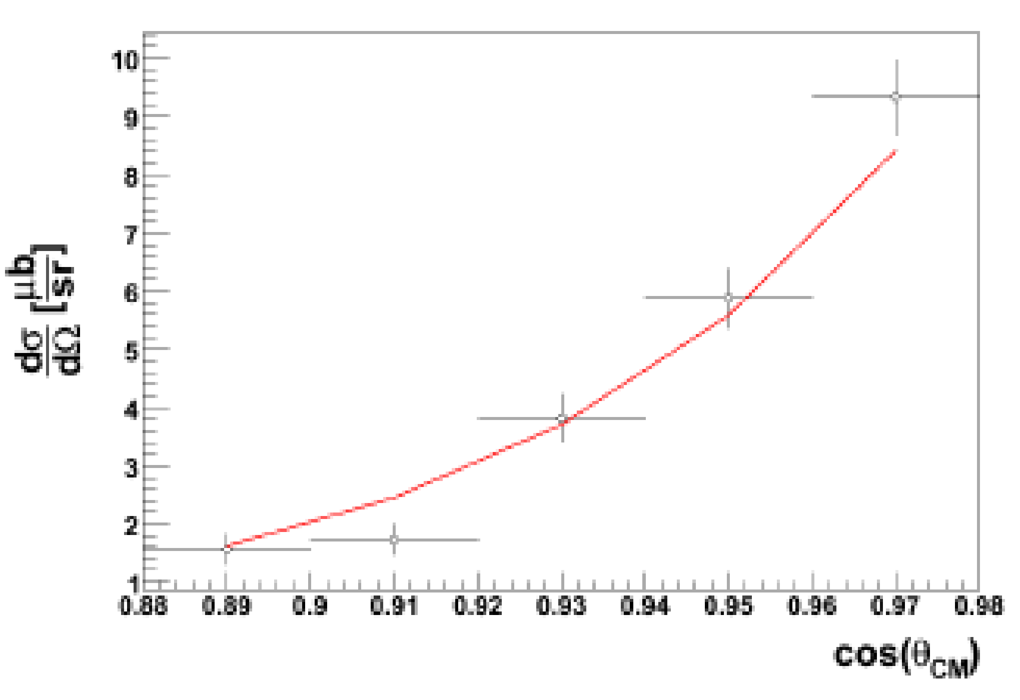

Ekin(^{3}He) [GeV]
θ^{LAB} [deg]


data
θ_n [deg]
θ_{He} [deg]

dd → ^{3}He n



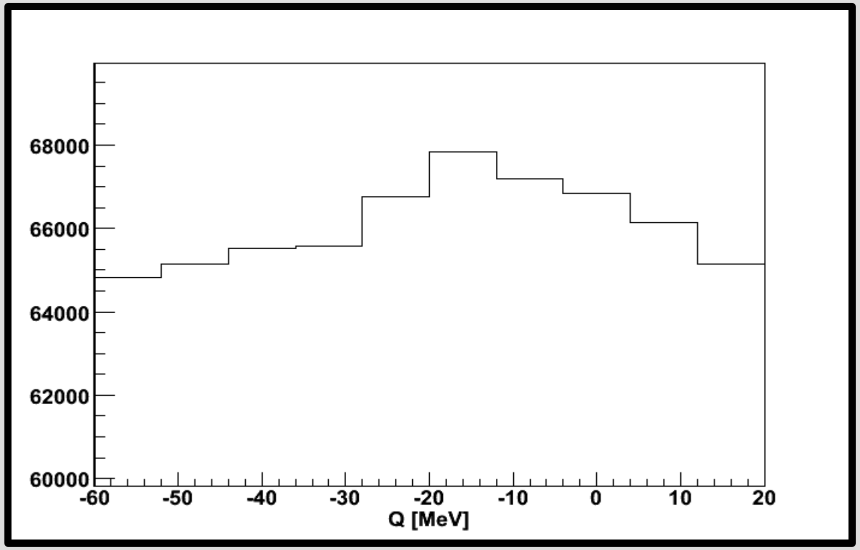
Luminosity [1/nb]
35
30
25
20
15
10
5
0
0.88
0.89
0.9
0.91
0.92
0.93
0.94
0.95
0.96
0.97
0.98
cos(θCM)



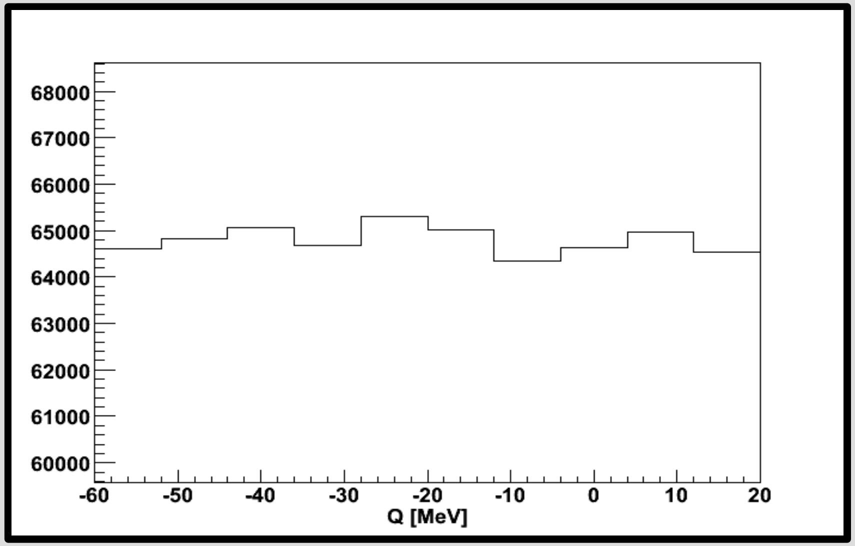
dσ/dΩ [μb/sr]
10
9
8
7
6
5
4
3
2
1
0.88
0.89
0.9
0.91
0.92
0.93
0.94
0.95
0.96
0.97
0.98
cos(θCM)

Example of the excitation function (simple simulation)

n.p. θ_{cm} =150-170



n.p. θ_{cm} =130-150

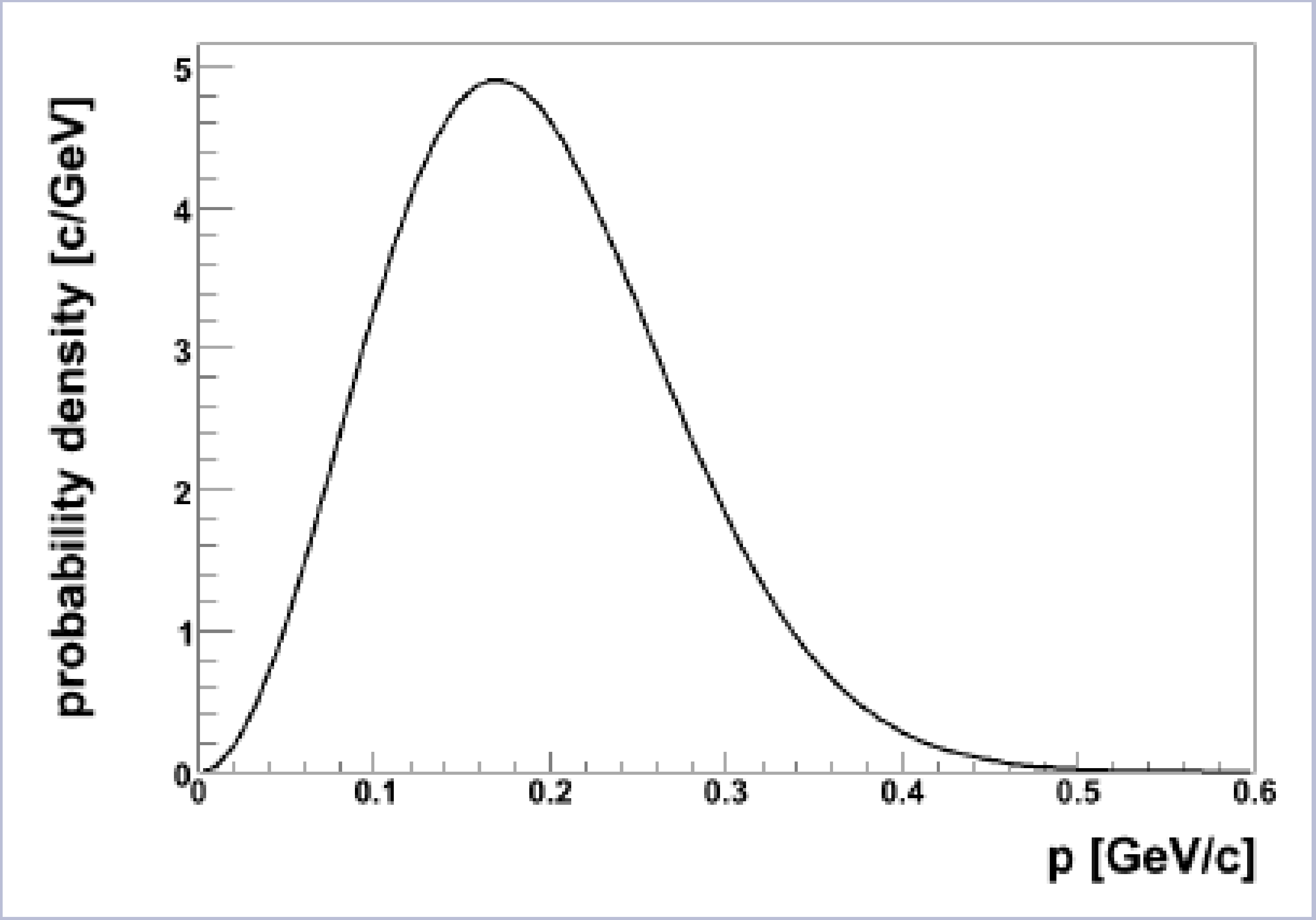


x-section=10 nb, L=10^{31} $cm^{-2}s^{-1}$
T=10 dni
Breit-Wigner: E0=-20 MeV, Γ=25 MeV

Search for the resonance-like structure

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

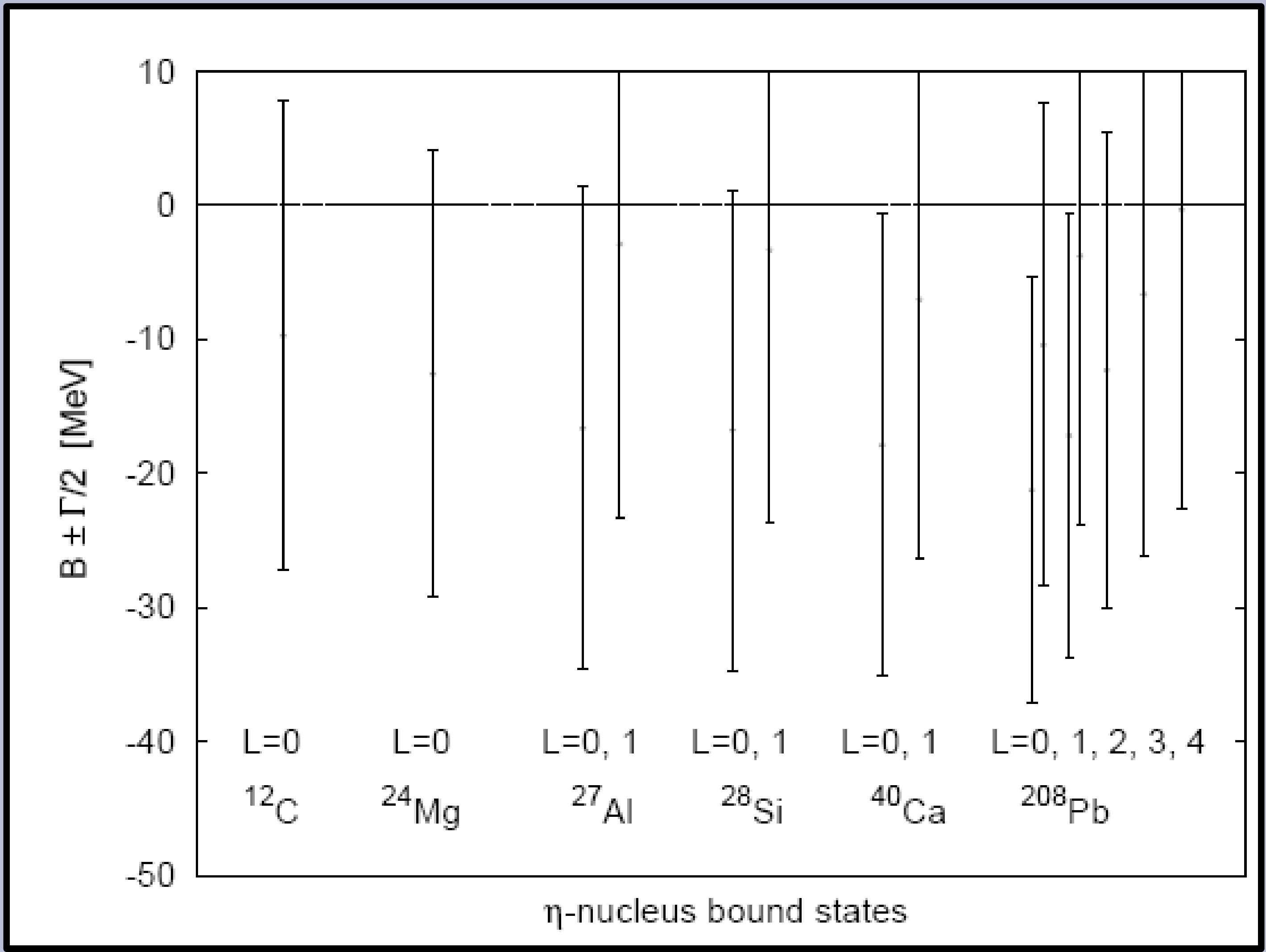
Nucleon momentum distribution in ^4He



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

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

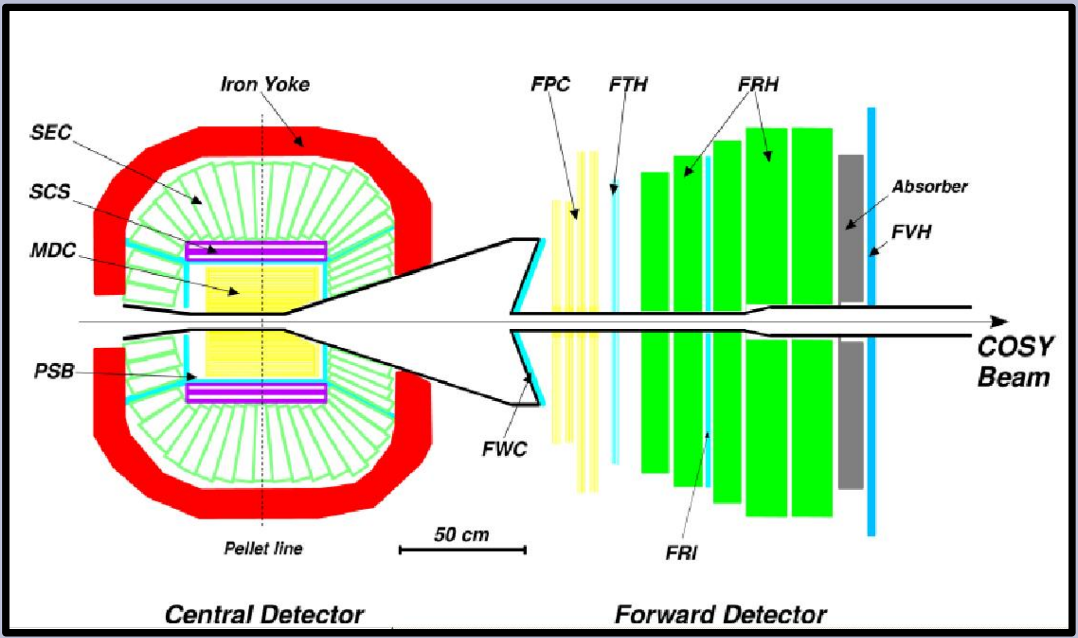
*η-m*esic nuclei in heavy systems



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°

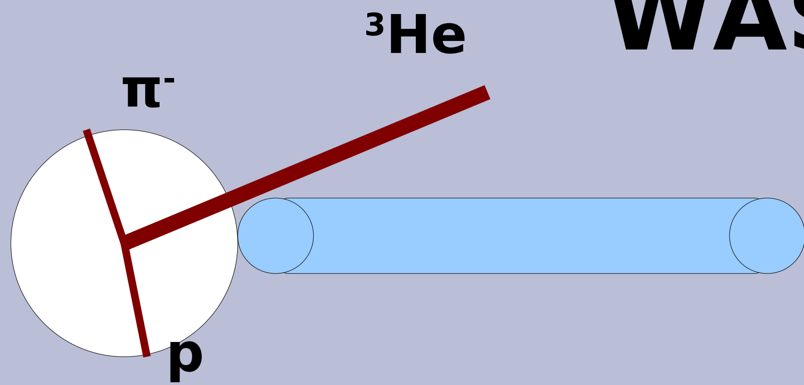
neutral ~5°

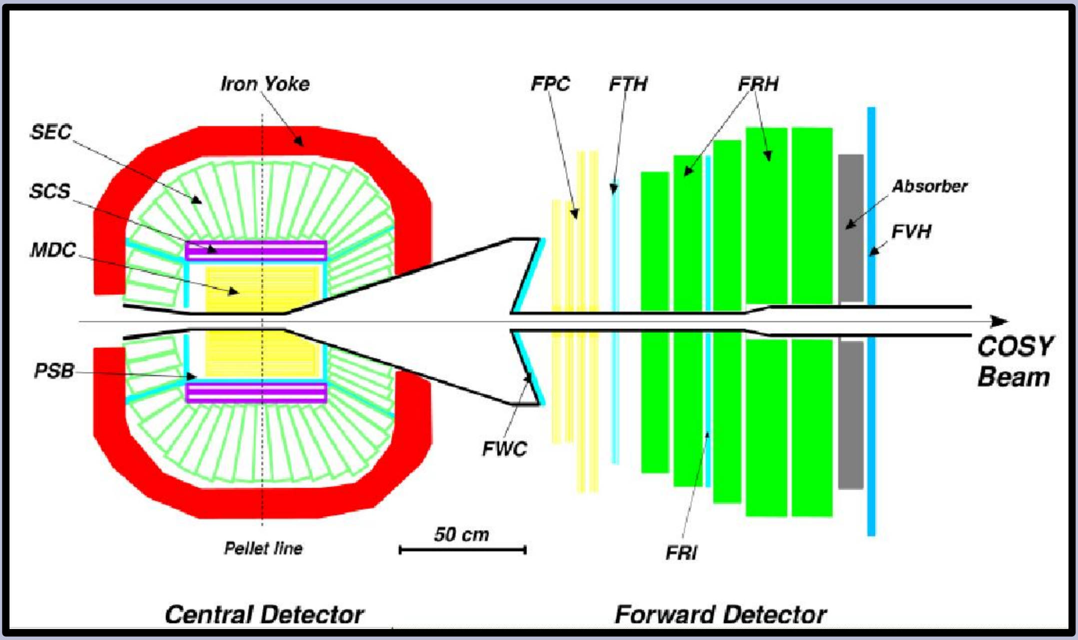
Relative energy resolution by SE

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%