Search for the ^{4}He-η bound state in $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$ and $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ reactions with the WASA-at-COSY facility

Magdalena Skurzok, Wojciech Krzemien, Pawel Moskal

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J-Symposium 2015, 10.06.2015

INNOWACYJNA GOSPODARKA NARODOWA STRATEGIA SPÓJNOŚCI

UNIWERSYTET JAGIELLOŃSKI W KRAKOWIE

FNP Fundacja na rzecz Nauki Polskiej

UNIA EUROPEJSKA EUROPEJSKI FUNDUSZ ROZWOJU REGIONALNEGO

INTERNATIONAL PHD PROJECT IN APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES

This project is supported by the Foundation for Polish Science-MPD program co-financed by the European Union within the European Regional Development Fund

Outline

Motivation

- Search for new kinds of nuclear matter
- Investigation of η and η' interaction with nucleons inside a nuclear matter
- Study of N*(1535) properties in nuclear matter
  D. Jido, H. Nagahiro, S. Hirenzaki, Phys. Rev. C66, 045202 (2002)
  S. Hirenzaki et al., Acta Phys. Polon. B41, 2211 (2010)
- Information about η, η' meson structure (contribution of the flavour singlet component of the quark-gluon wave function)
  S. D. Bass, A. W. Thomas, Phys. Lett. B634, 368 (2006)
  S. Hirenzaki, H. Nagahiro, Acta Phys.Polon. B45, 619 (2014)

η-mesic bound state

Conditions for the existence of eta-mesic nuclei ⇨

$$\mathrm{Re}\, a_{\eta-nucleus} < 0$$

$$|\mathrm{Re}\, a_{\eta-nucleus}| > |\mathrm{Im}\, a_{\eta-nucleus}|$$

Attractive interaction between η and N

R. Bhalerao, L. C. Liu, Phys. Lett. B54, 685 (1985)

$\Downarrow$

possible existence of η-mesic bound state for A>12

Q. Haider, L. C. Liu, Phys. Lett. B172, 257 (1986)

η-mesic bound state

Overview of η-nucleon interactions:

$0.18 \text{ fm} \leq \text{Re } a\eta N \leq 1.03 \text{ fm}$
$0.16 \text{ fm} \leq \text{Im } a\eta N \leq 0.49 \text{ fm}$

N. G. Kelkar et al., Rep. Prog. Phys. 76 (2013) 066301

B. Krusche, C. Wilkon
Progress in Particle and Nuclear Physics 80 (2015) 43

H. Machner
http://arxiv.org/abs/1410.6023

Some *η-mesic calculations*

S. Hirenzaki – todays talk

N. G. Kelkar – todays talk

N. Barnea, E. Friedman, A. Gal
http://arxiv.org/abs/1505.02588

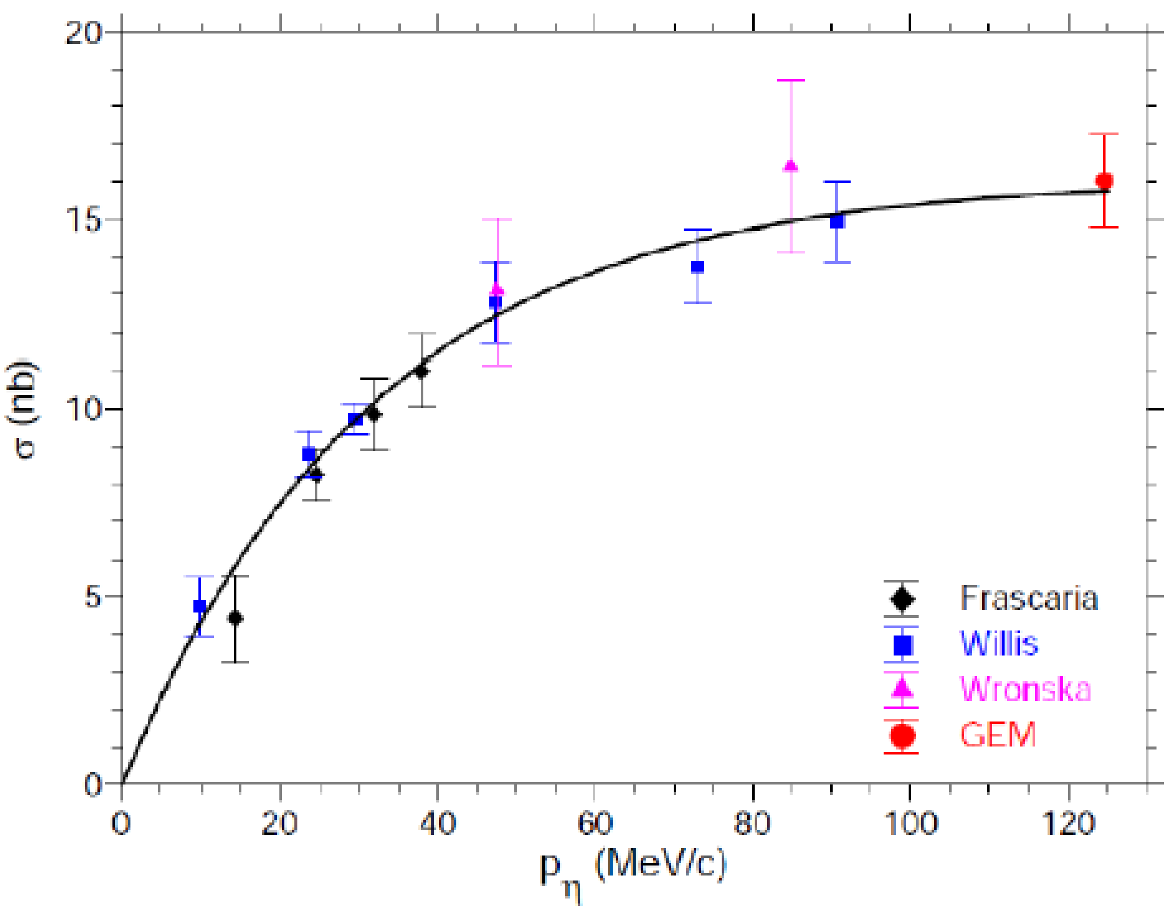
E. Friedman, A. Gal and J. Mares,
Phys. Lett. B725 (2013) 334.

S. Wycech, W. Krzemien.

Acta Phys. Polon. B 45 (2014) 745

Exp. indications of the ^{4}He-η bound state existence

$dd \to {}^4\text{He-}\eta$



R. Frascaria et al., Phys. Rev. C50, (1994) 573
N. Willis et al., Phys. Lett. B406, (1997) 14
A. Wronska et al., Eur. Phys. J. A26, (2005) 421428
A. Budzanowski et al., Nucl. Phys. A821, (2009) 193

Production of ^{4}He-η in dd collision

$$dd \rightarrow \left({}^4He - \eta\right)_{bs} \rightarrow {}^3He\ p\ \pi^-$$

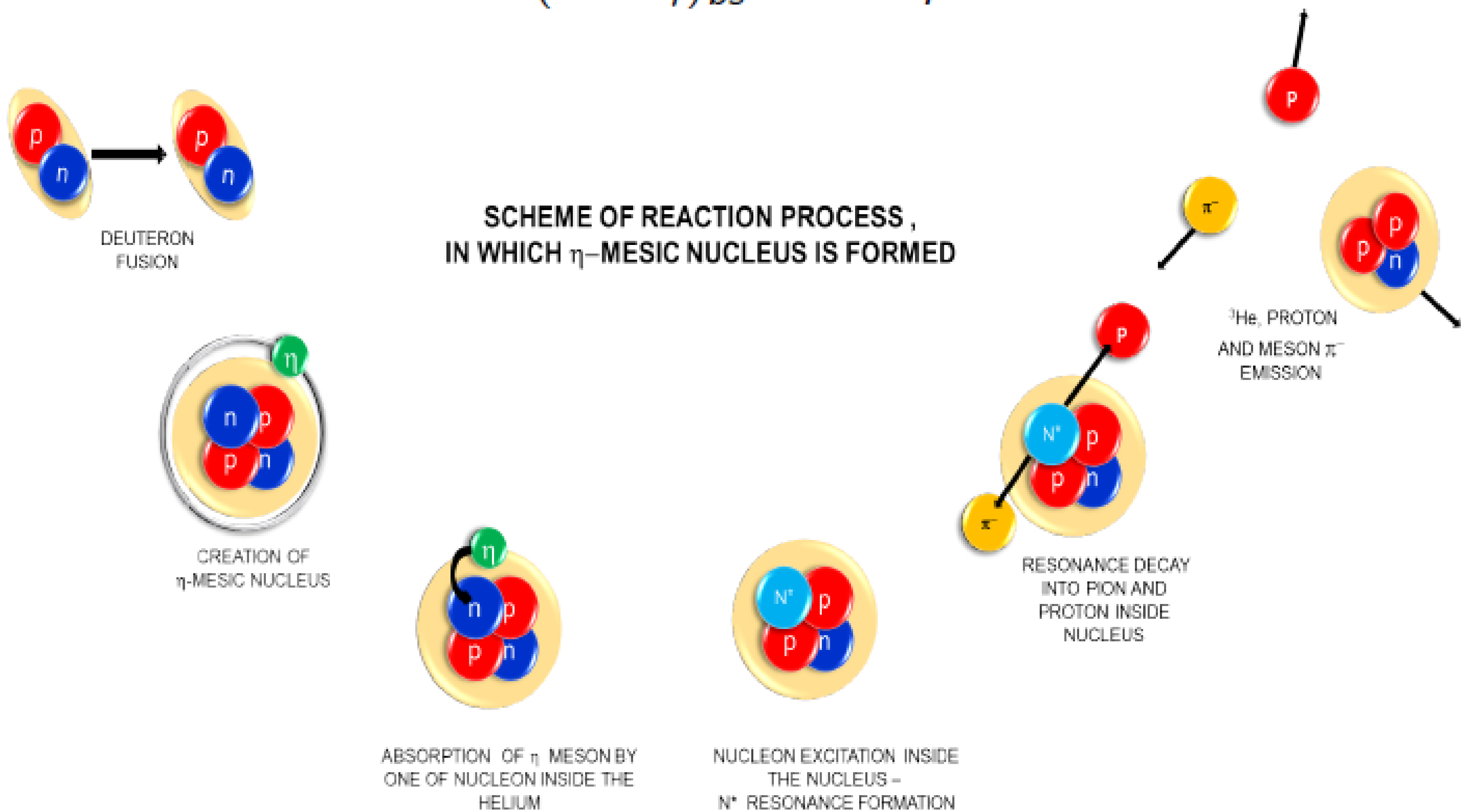
$$dd \rightarrow \left({}^4He - \eta\right)_{bs} \rightarrow {}^3He\ n\ \pi^0 \rightarrow {}^3He\ n\ \gamma\ \gamma$$

$$dd \rightarrow \left({}^4He - \eta\right)_{bs} \rightarrow d\ p\ p\ \pi^-$$

$$dd \rightarrow \left({}^4He - \eta\right)_{bs} \rightarrow T\ p\ \pi^0 \rightarrow T\ p\ \gamma\ \gamma$$

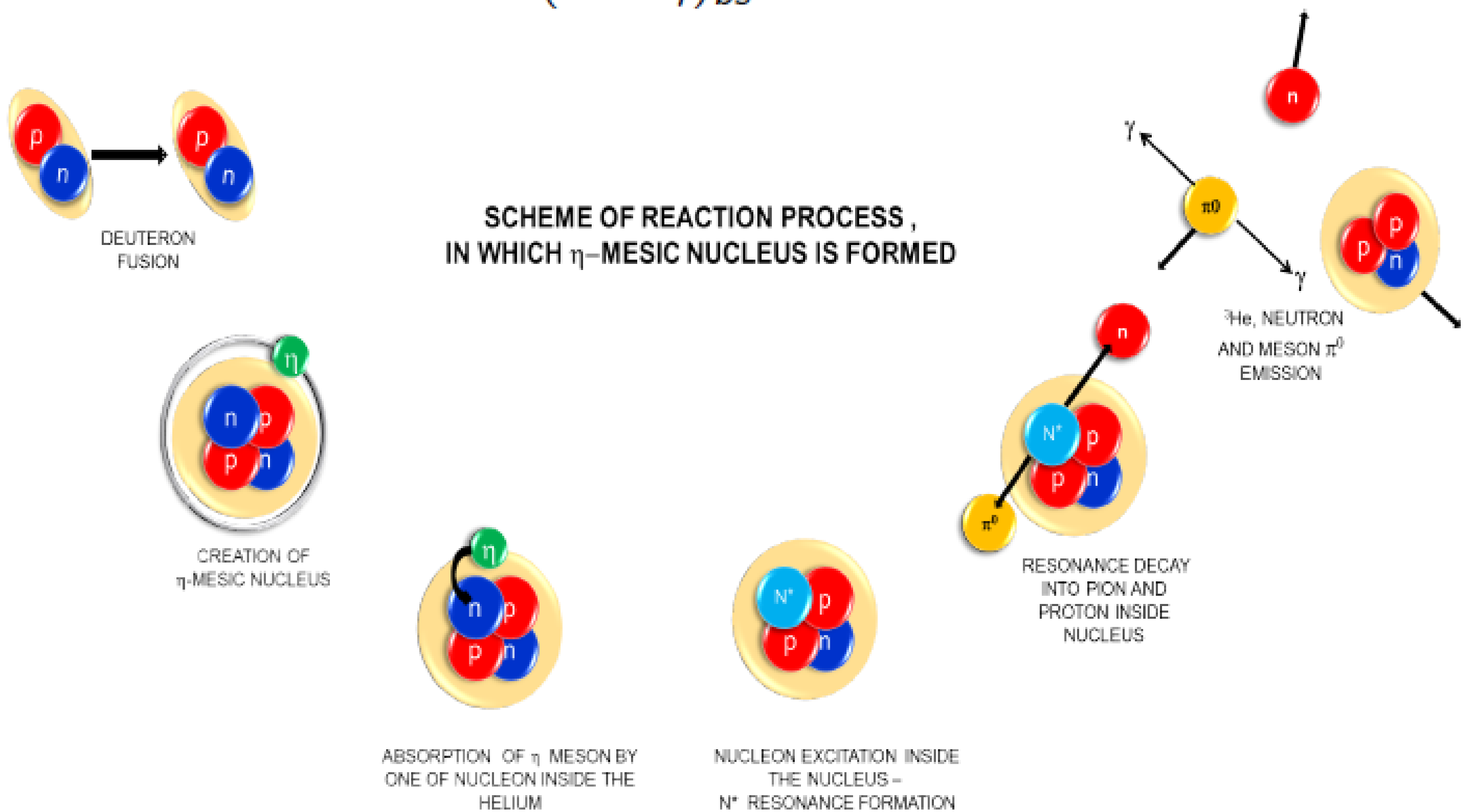
Kinematical mechanism of the reaction

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



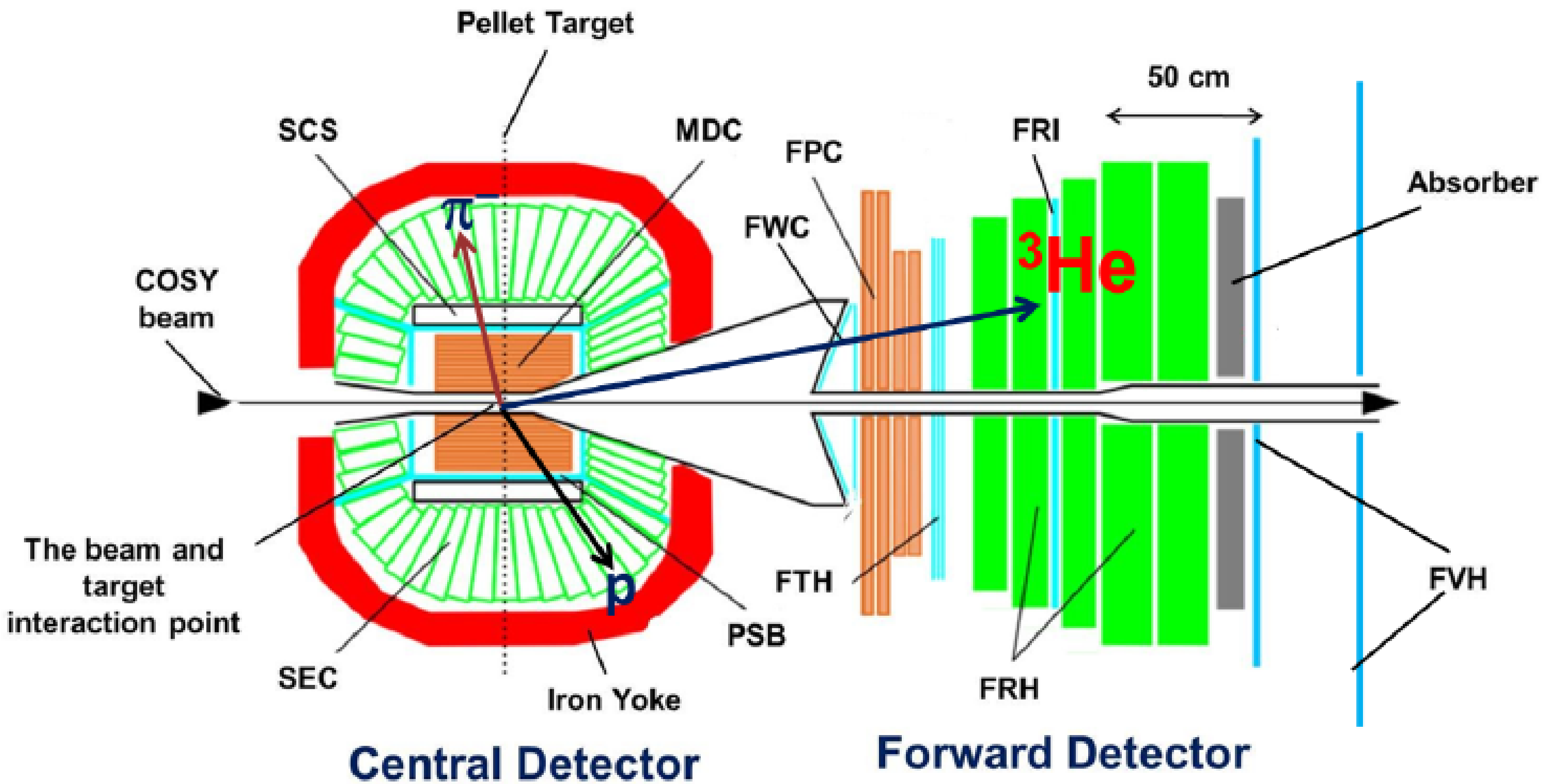
Kinematical mechanism of the reaction

$$dd \to (^4\text{He-}\eta)_{bs} \to {}^3\text{He} n \pi^0$$



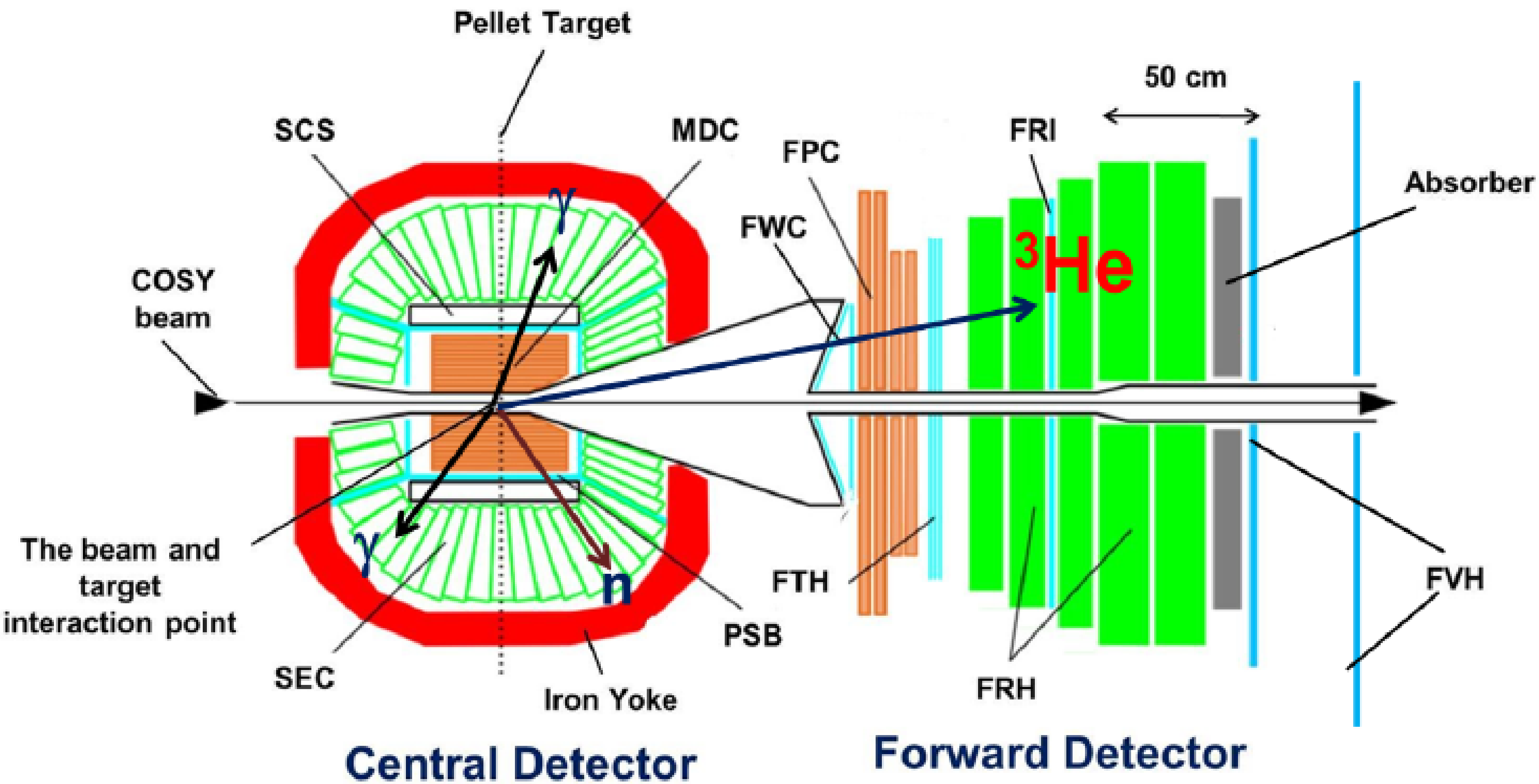
Search for η-mesic nuclei with WASA-at-COSY

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



Search for η-mesic nuclei with WASA-at-COSY

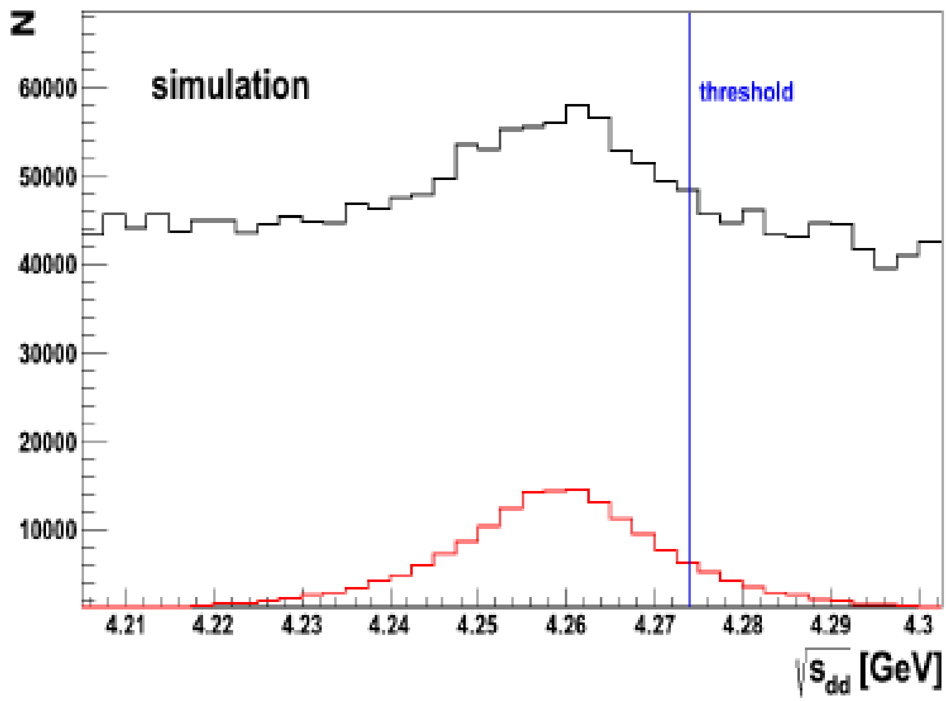
$$dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}n\pi^0$$



Experimental method

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

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



Excitation function

$({}^4\mathrm{He}\text{-}\eta)_{bs}$ **existence manifested by resonant-like structure below η production threshold**

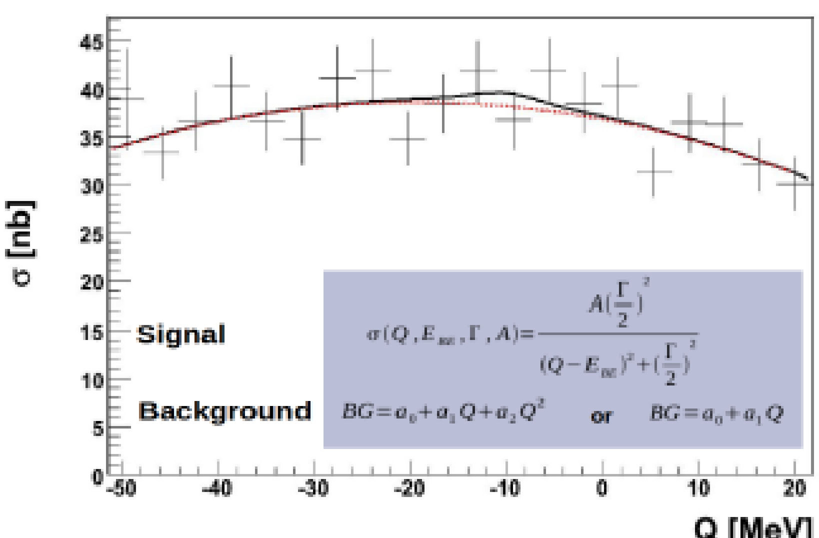
Experiment-May 2008

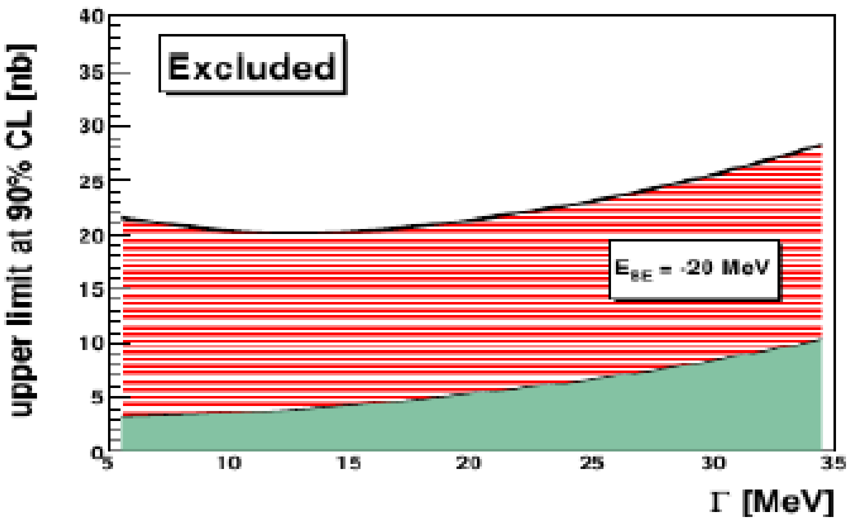
Channel: $dd \to (^4\text{He-}\eta)_{bs} \to {}^3\text{He}p\pi^-$ (norm: $dd \to {}^3\text{He}n$)

Measurement: performed with the beam momentum ramped from **2.185GeV/c to 2.400GeV/c**, corresponding to the range of excess energy **Q∈(-51,22)MeV**

Luminosity: L=118 $\frac{1}{nb}$

Acceptance: A=53%





P. Adlarson et al., Phys. Rev. C87 (2013), 035204; W. Krzemien, PhD

Experiment-Nov/Dec 2010

Beamtime: Nov 26 - Dec 13, 2010

Channels: $dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^-$
$dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$

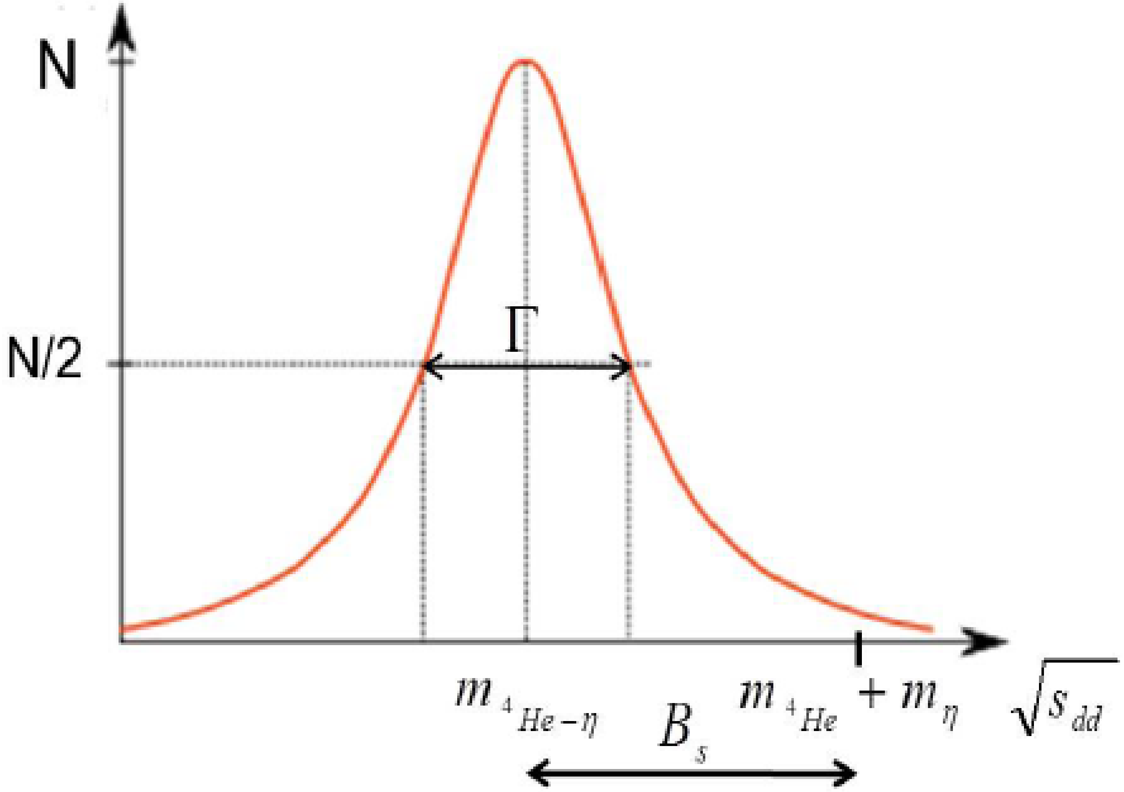
Measurement: performed with the beam momentum ramped from **2.127GeV/c to 2.422GeV/c**, corresponding to the range of excess energy **Q∈(-70,30)MeV**
Acceptance: A=53%
Luminosity: $L \approx 1100 \frac{1}{nb}$ ($dd \rightarrow {}^3\text{He}n$ and $dd \rightarrow ppn_{sp}n_{sp}$)

$\Downarrow$

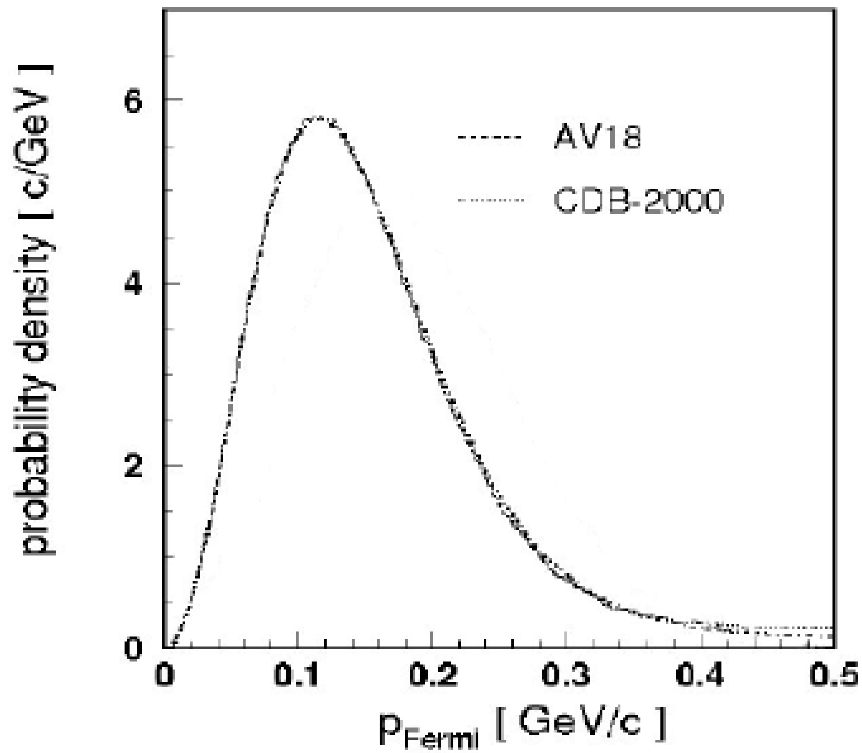
More than **10 times higher** statistics and two reactions were collected than in 2008 experiment.

MC Simulations - assumptions

Breit-Wigner distribution



Spectator Model



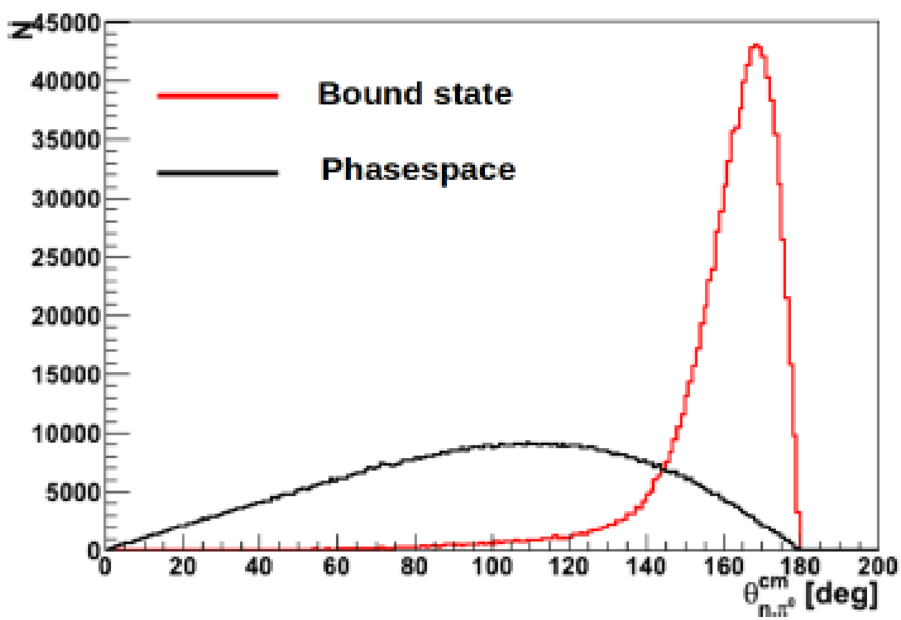
$$N\left(\sqrt{s_{dd}}\right) = \frac{1}{2\pi}\frac{\Gamma}{\left(\sqrt{s_{dd}} - m_{bs}\right)^2 + \Gamma^2/4}$$

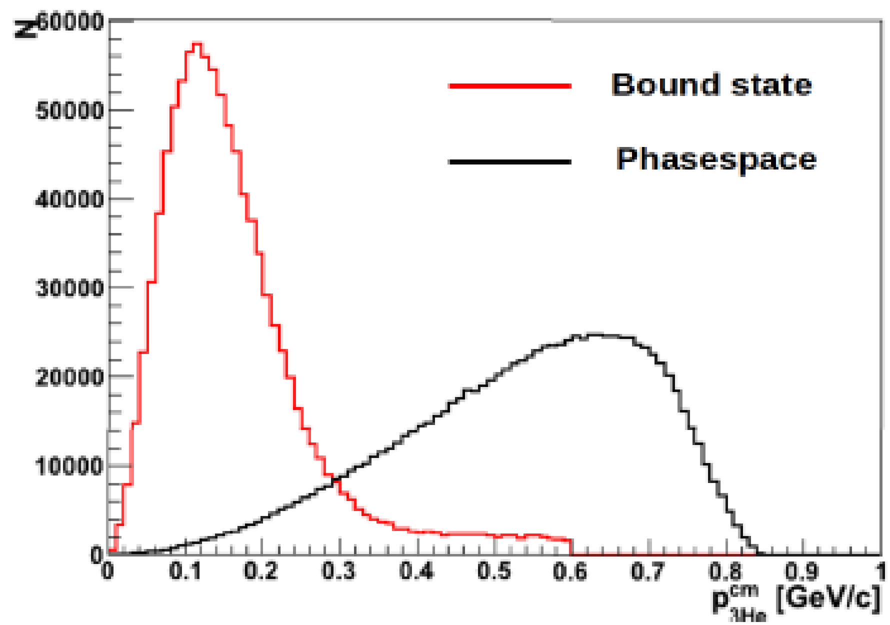
$$m_{^4He-\eta} = m_{^4He} + m_\eta - B_s$$

Kinematical mechanism of the reaction

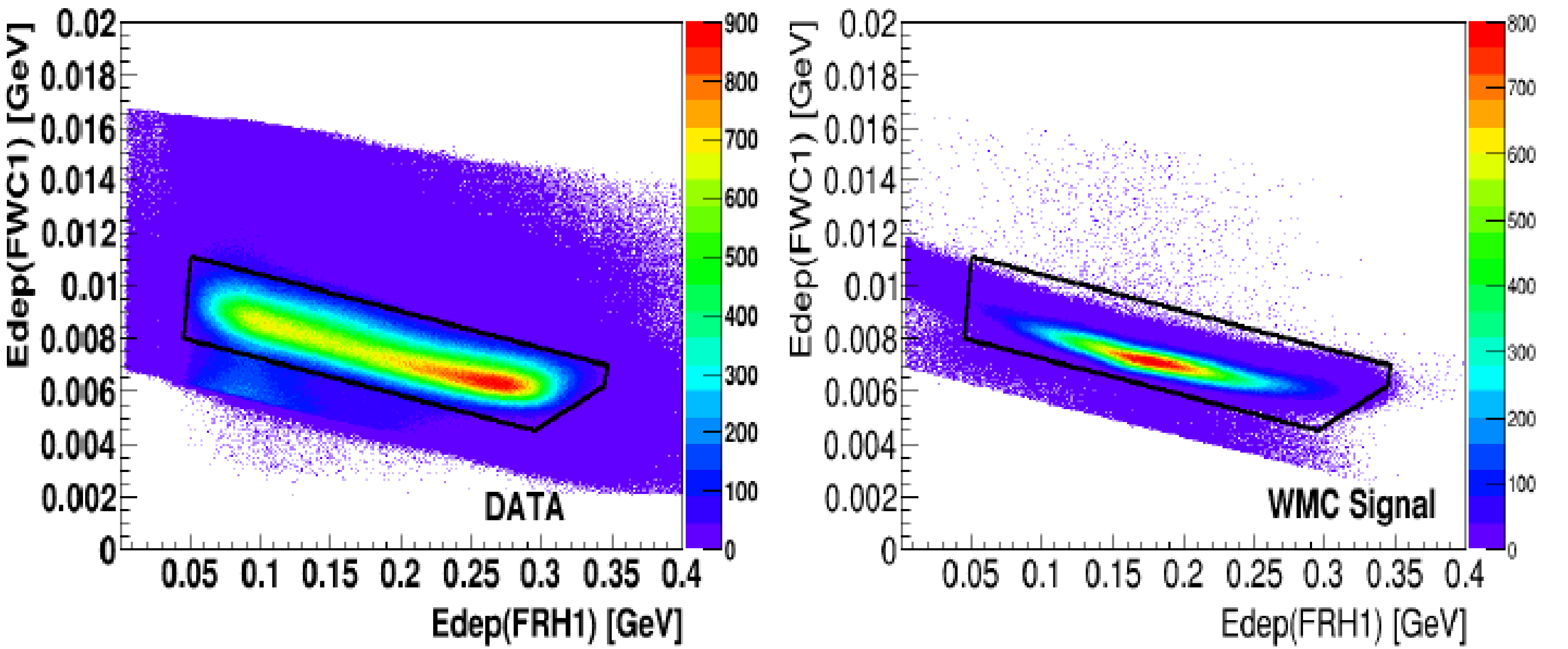
$$\eta + N \Rightarrow N^*(1535) \Rightarrow N + \pi = \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$$

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

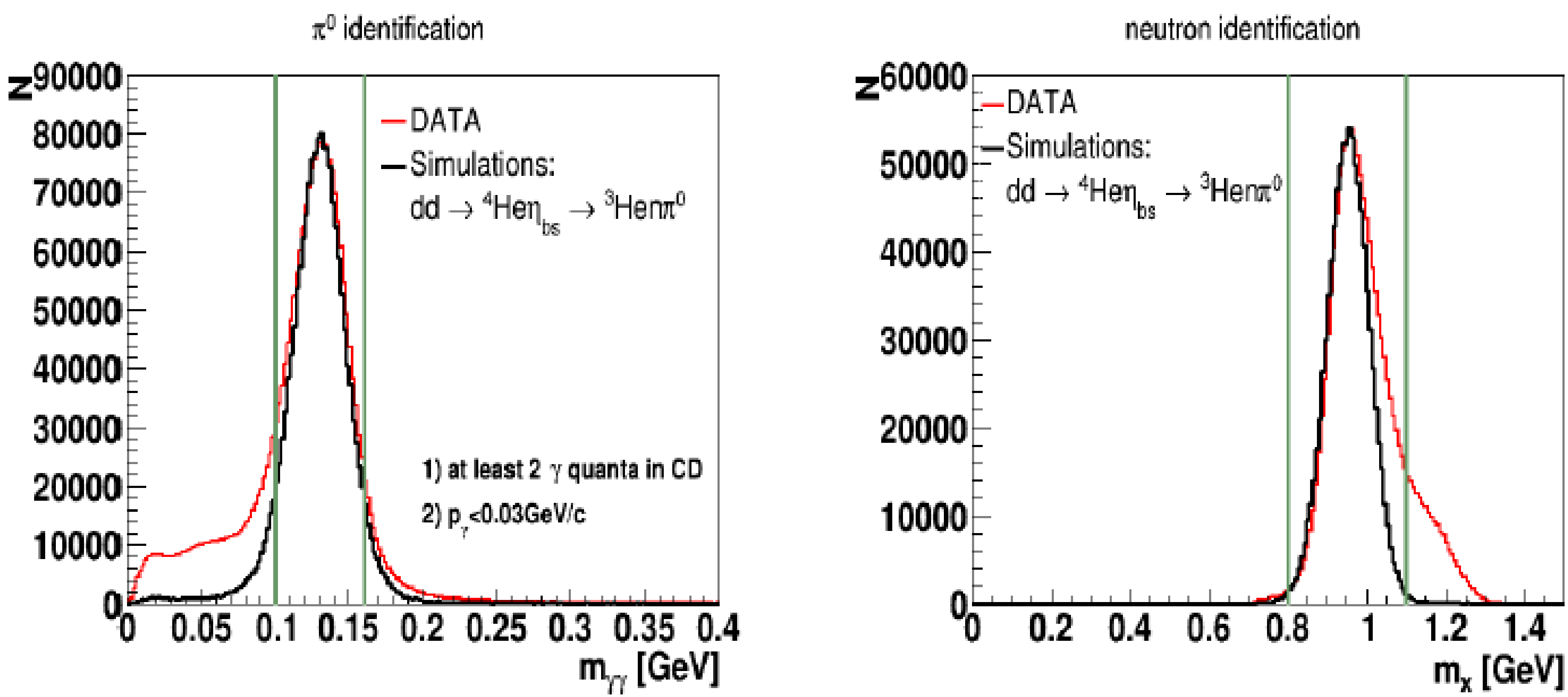




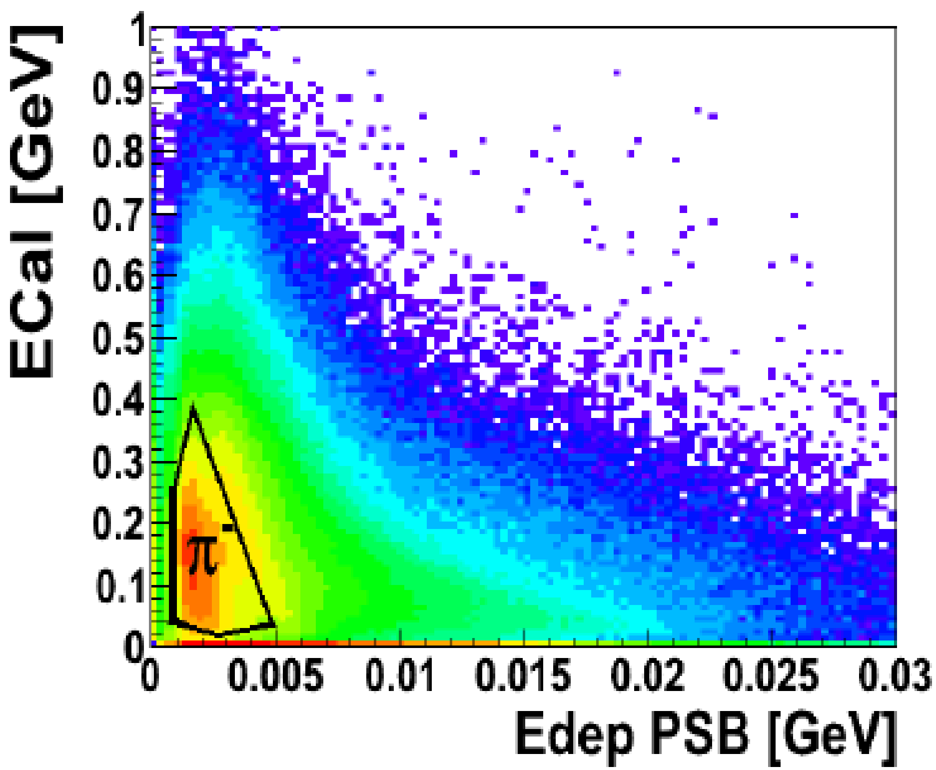
^{3}He identification in Forward Detector

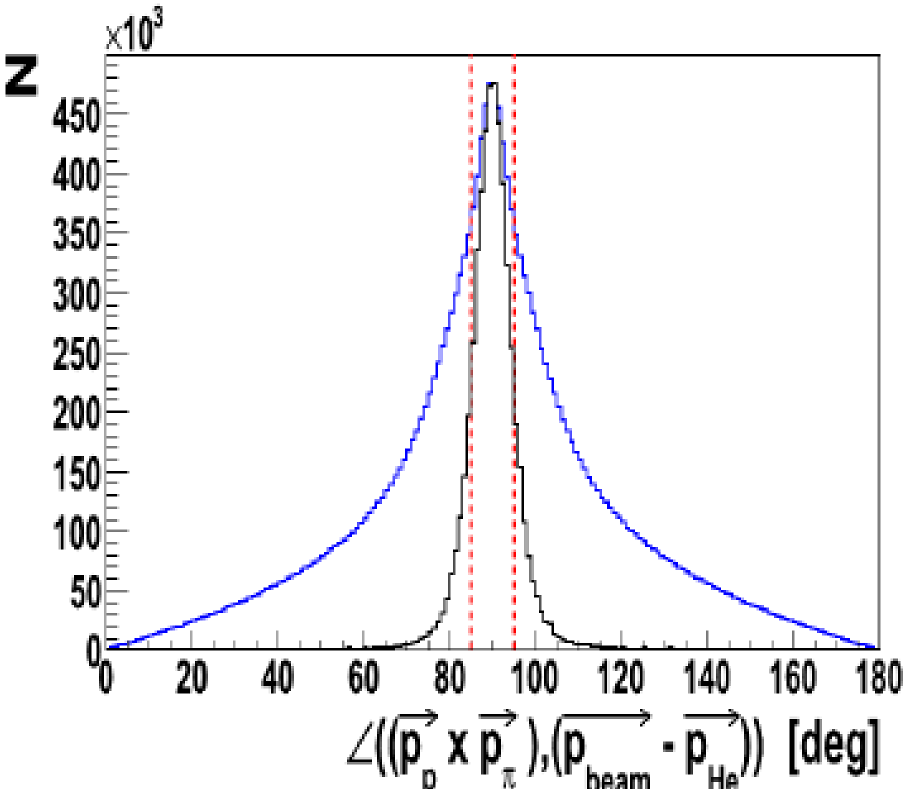


π^0 and neutron identification in Central Detector

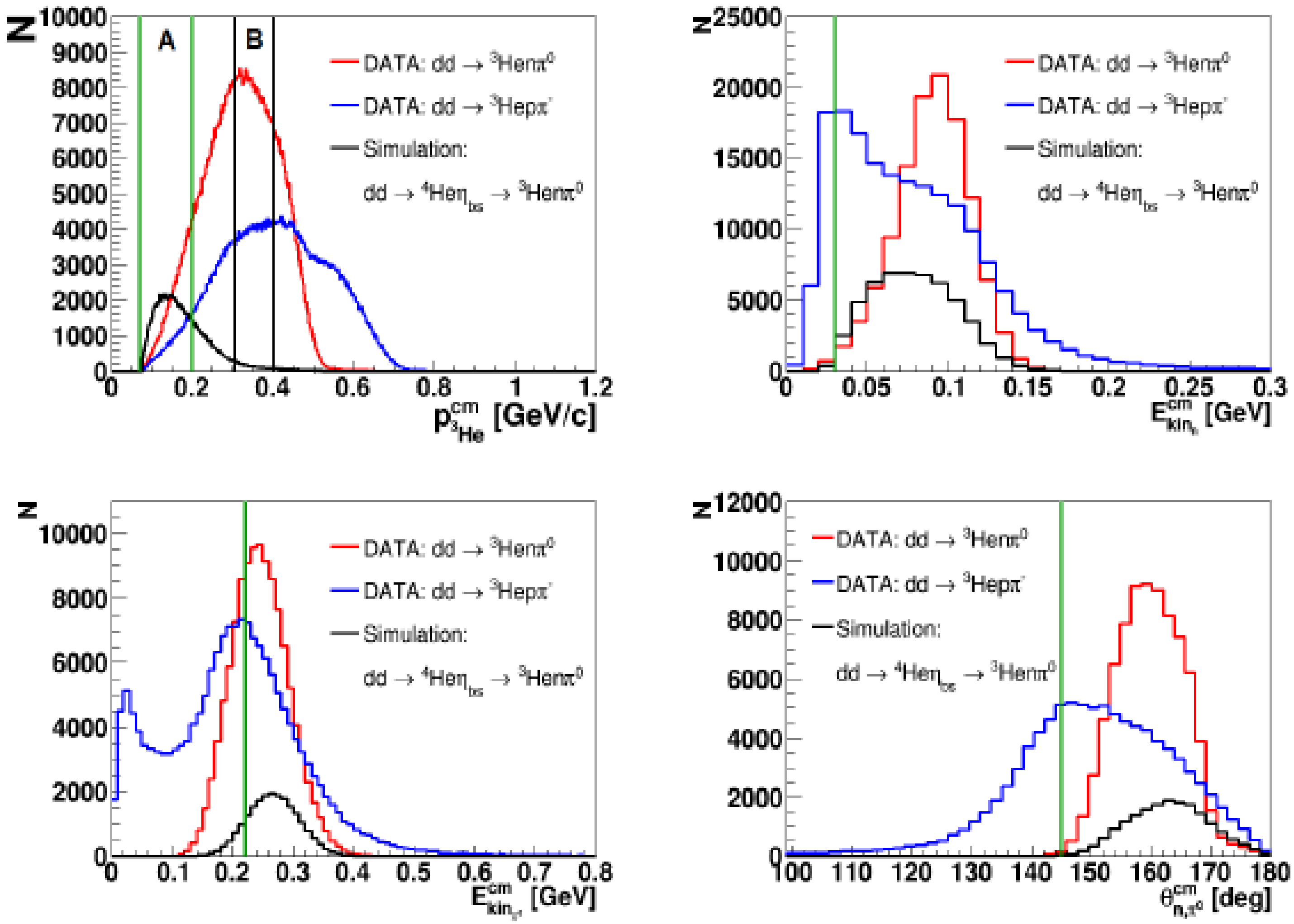


π^- and proton identification in Central Detector





Kinematical conditions
PRELIMINARY

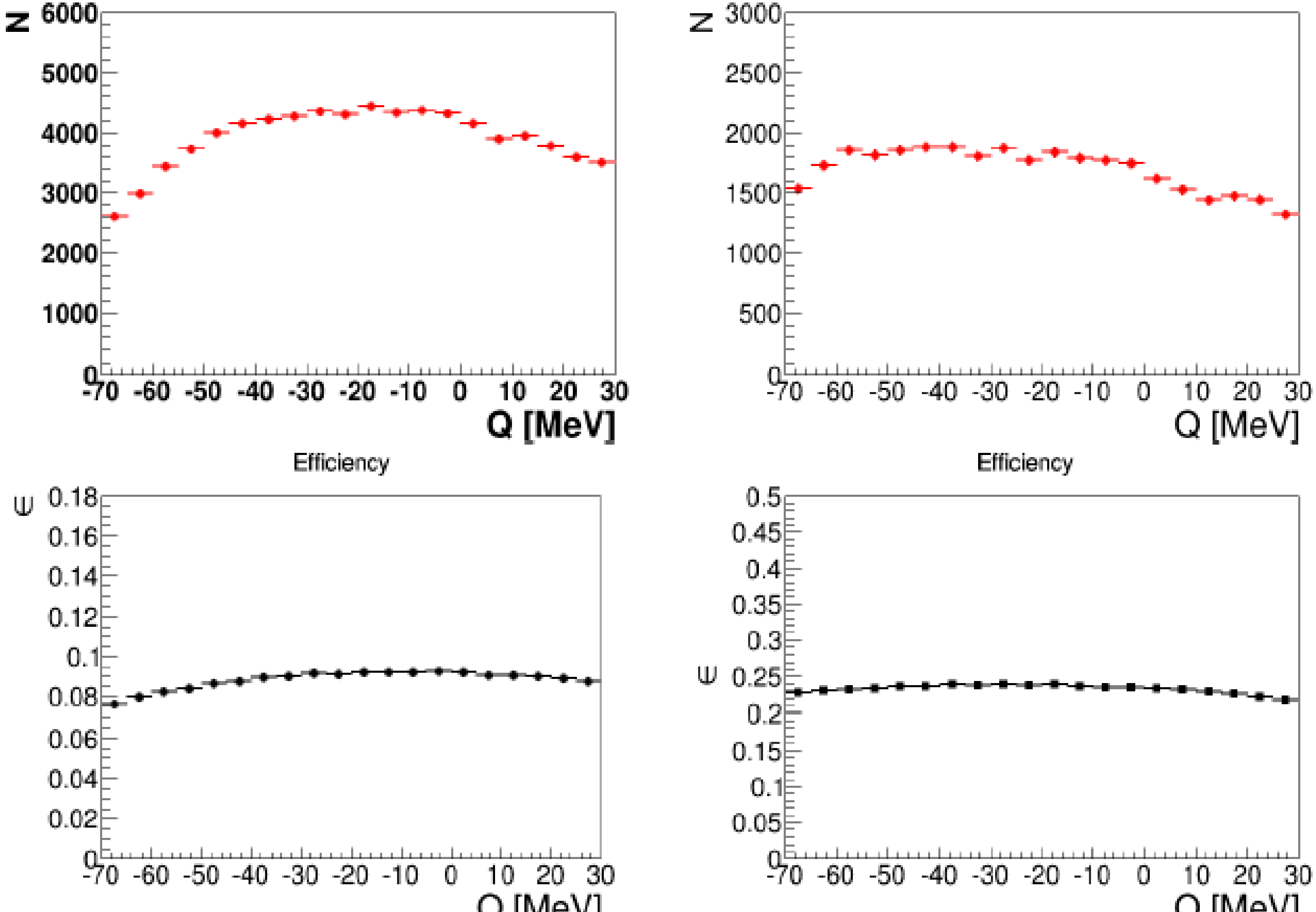


DATA: $dd \to {}^3\text{He}p\pi^-$ Signal: $dd \to ({}^4\text{He-}\eta)_{bs} \to {}^3\text{He}n\pi^0$

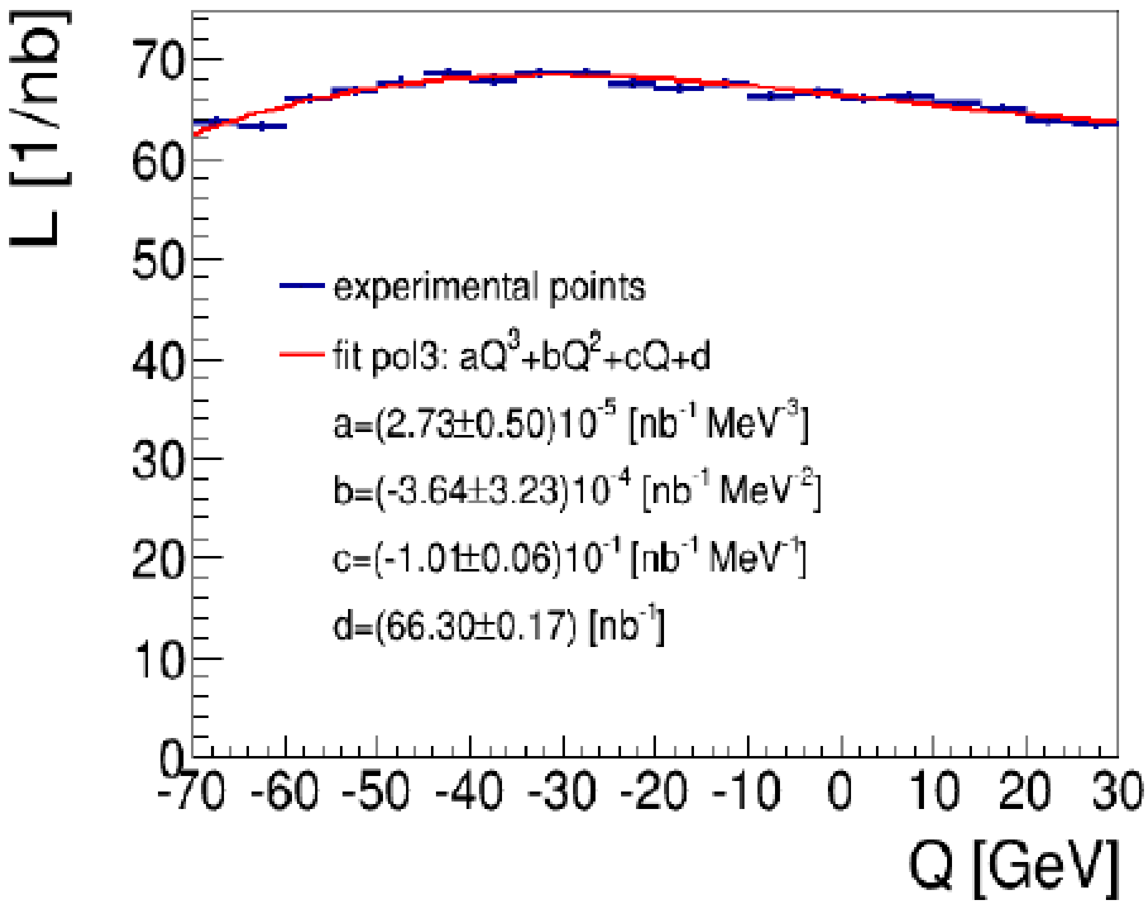
DATA: $dd \to {}^3\text{He}n\pi^0 \to {}^3\text{He}n\gamma\gamma$

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

PRELIMINARY

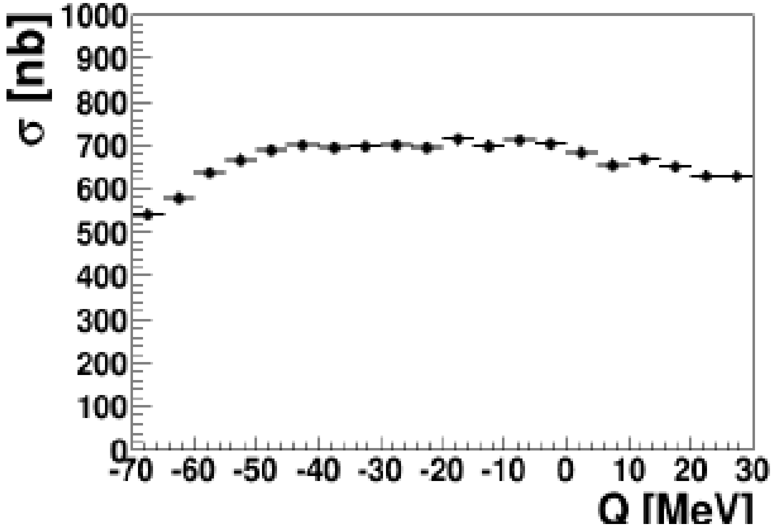


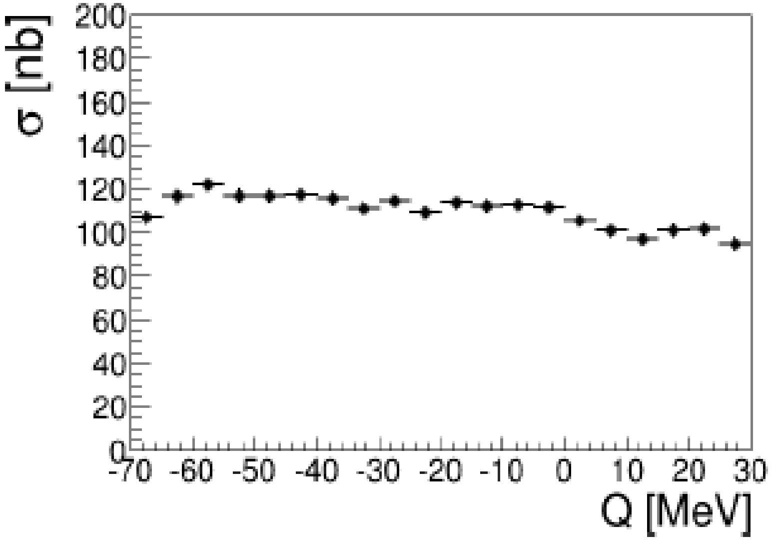
Luminosity as a function of excess energy Q

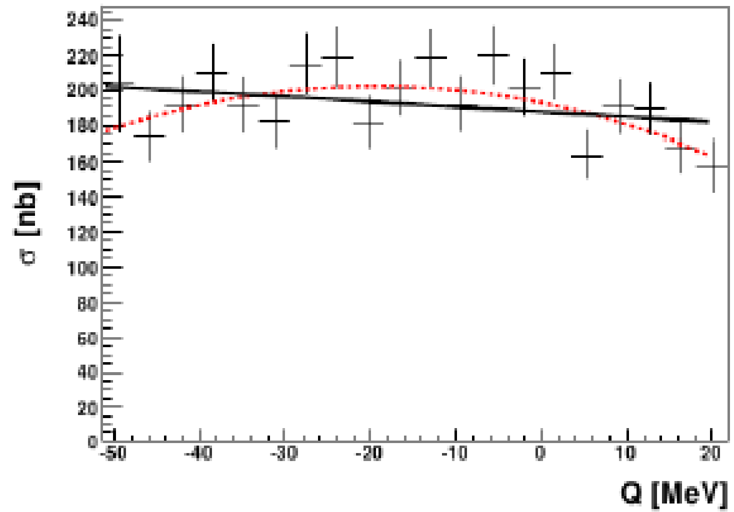


$dd \to {}^3\mathrm{He}n\pi^0$ $dd \to {}^3\mathrm{He}p\pi^-$

PRELIMINARY





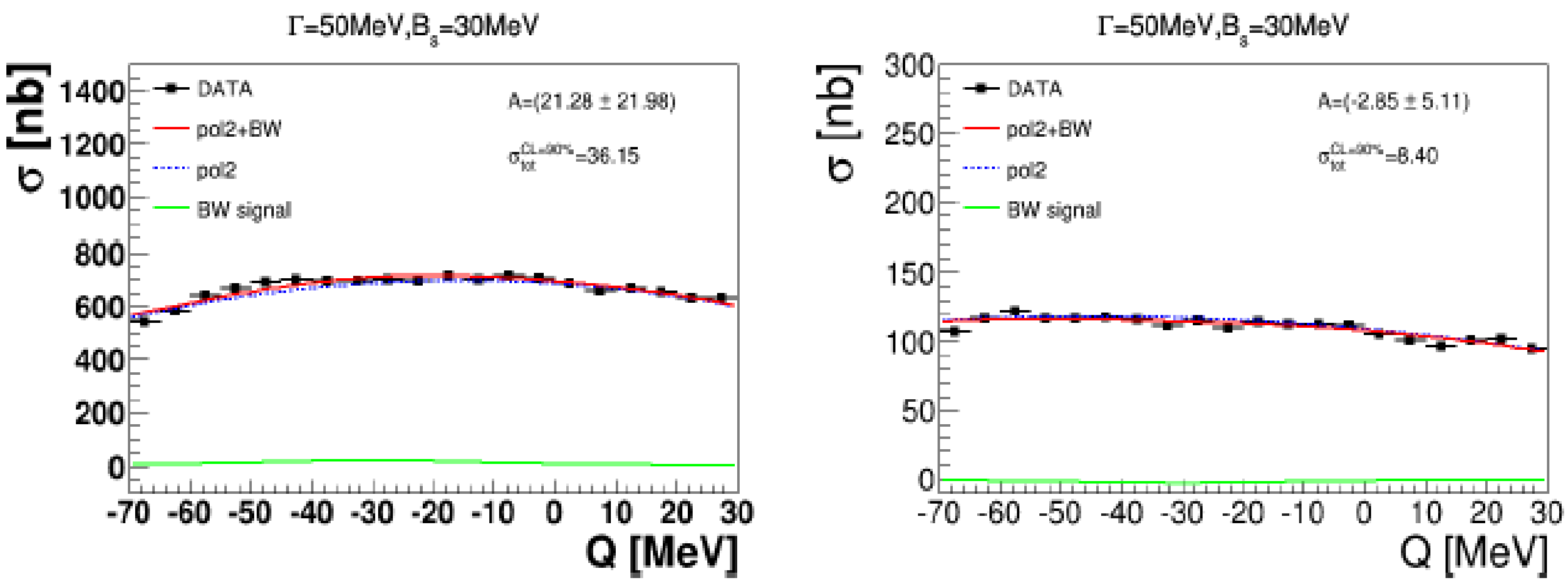


P. Adlarson et al., Phys. Rev. C87 (2013) 035204

Upper limit of the total cross section at CL=90%

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

PRELIMINARY

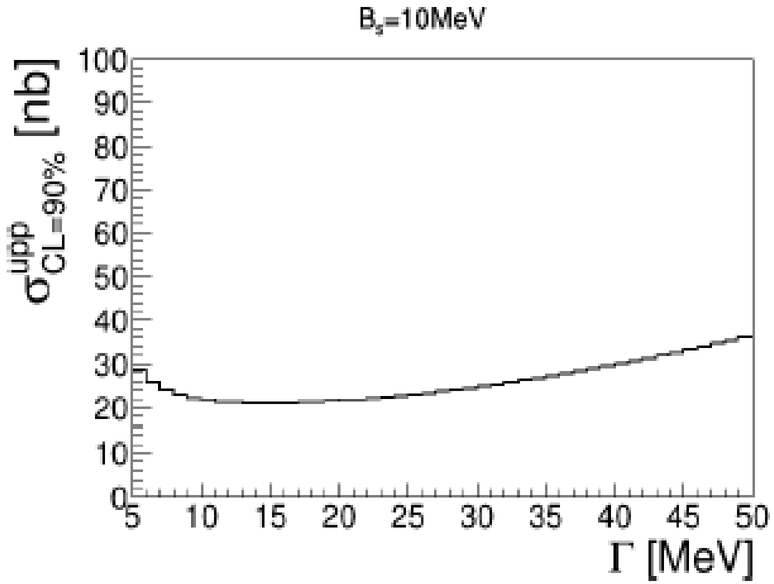


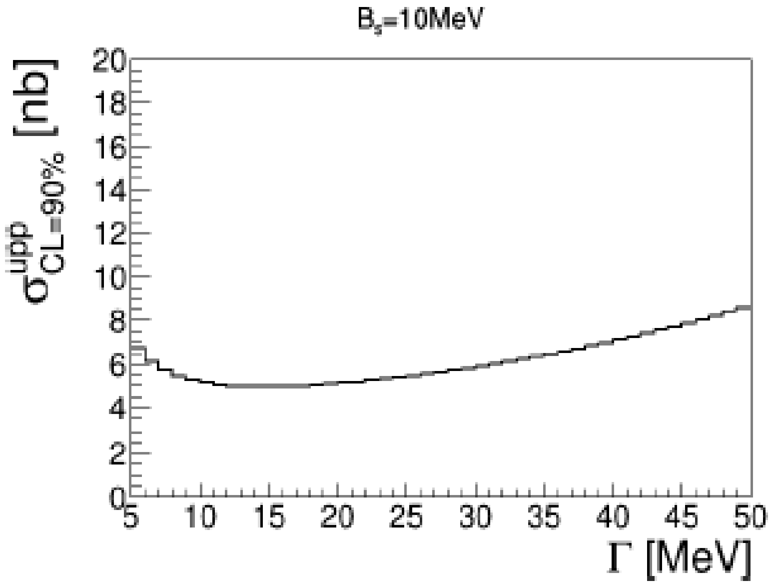
$$\sigma(Q,\Gamma,B_s,A) = \frac{A\cdot\Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4}$$

Upper limit of the total cross section at CL=90%

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

PRELIMINARY



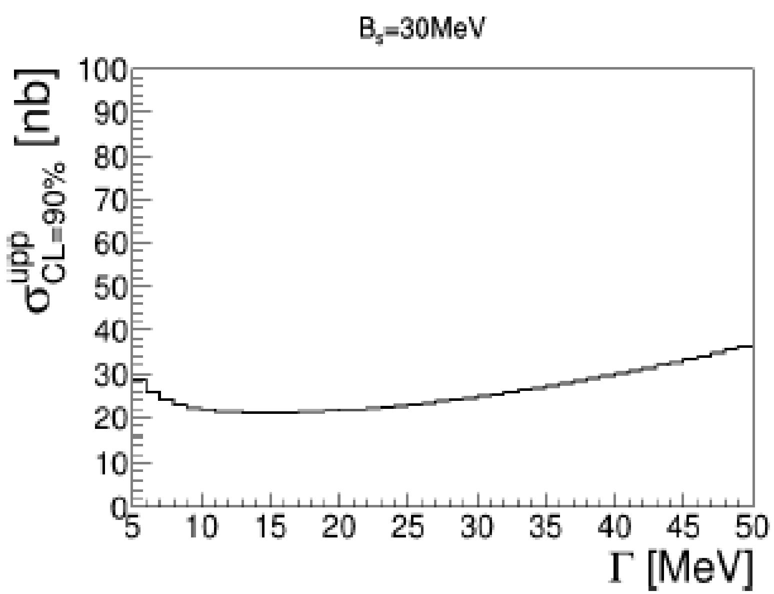


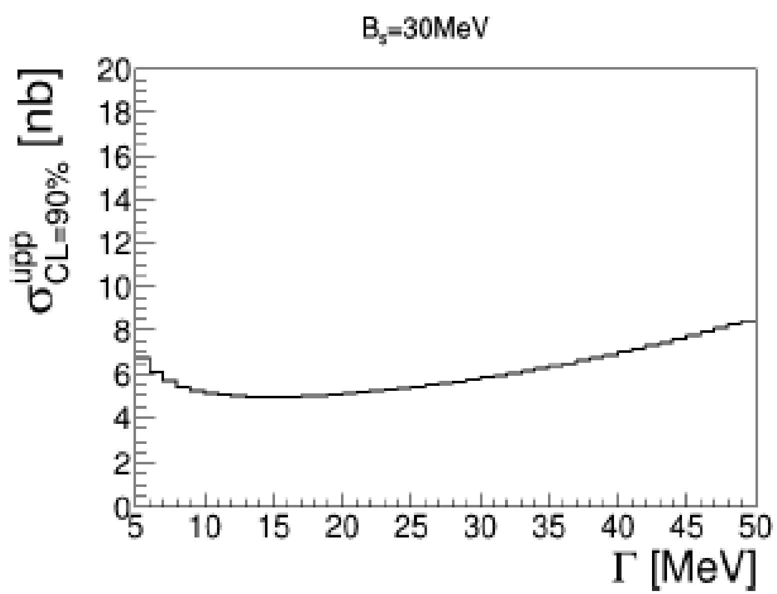
few nb!

Upper limit of the total cross section at CL=90%

$dd \to {}^3\mathrm{He} n \pi^0$ $dd \to {}^3\mathrm{He} p \pi^-$

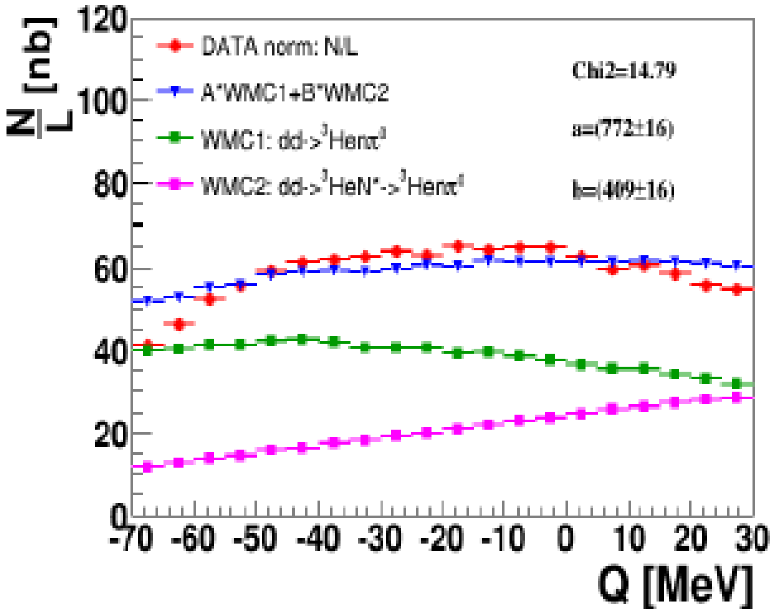
PRELIMINARY

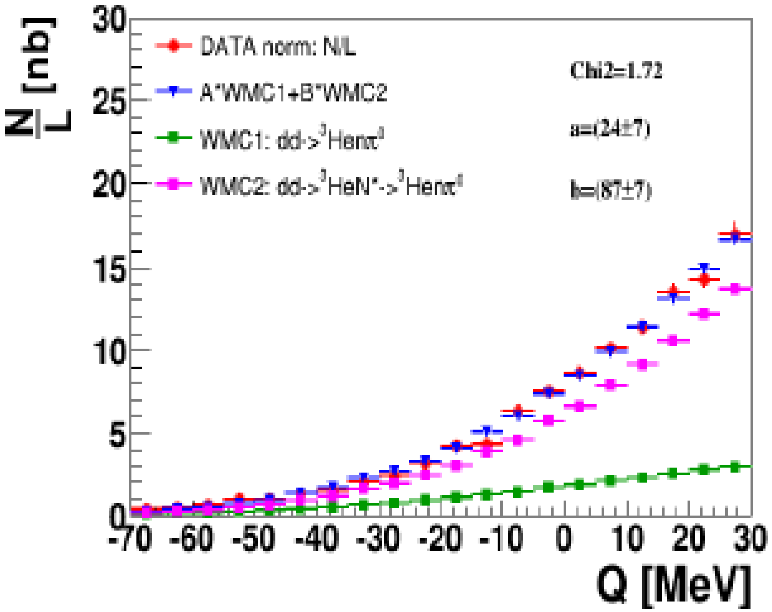




few nb!

Background studies $dd \to {}^3\mathrm{He}n\pi^0$





Summary and Conclusions

- Exclusive measurement of the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ and $dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$ reactions was carried out using the ramped beam technique.
- No bound state signal visible in 2008 data (upper limit of the total cross section for the bound state production determined)
- Preliminary result from 2010 measurement doesn't show a narrow signal of η-mesic nuclei
- The upper limit of the total cross section in order of **few nb**!

New experiment in May-June 2014

May-June 2014

Channels:

$p+d \rightarrow ({}^3He-n)_{bound} \rightarrow p + p + p + \pi^-$

$p+d \rightarrow ({}^3He-n)_{bound} \rightarrow d + p + \pi^0$

$p+d \rightarrow ({}^3He-n)_{bound} \rightarrow p + p + n + \pi^0$

Orbiting eta:

$p+d \rightarrow ({}^3He-n)_{bound} \rightarrow {}^3He\ 6\gamma$

Normalization:

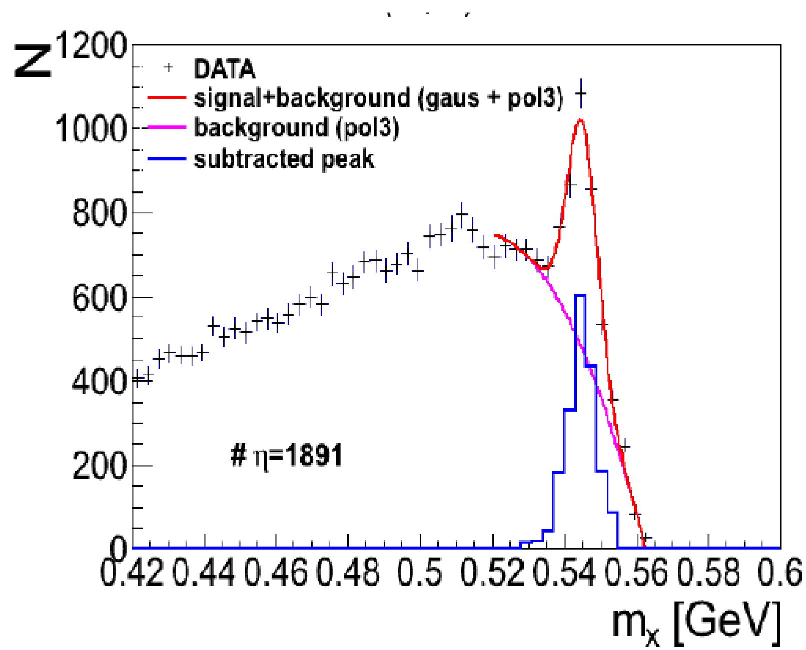
$pd \rightarrow {}^3He\ \eta$

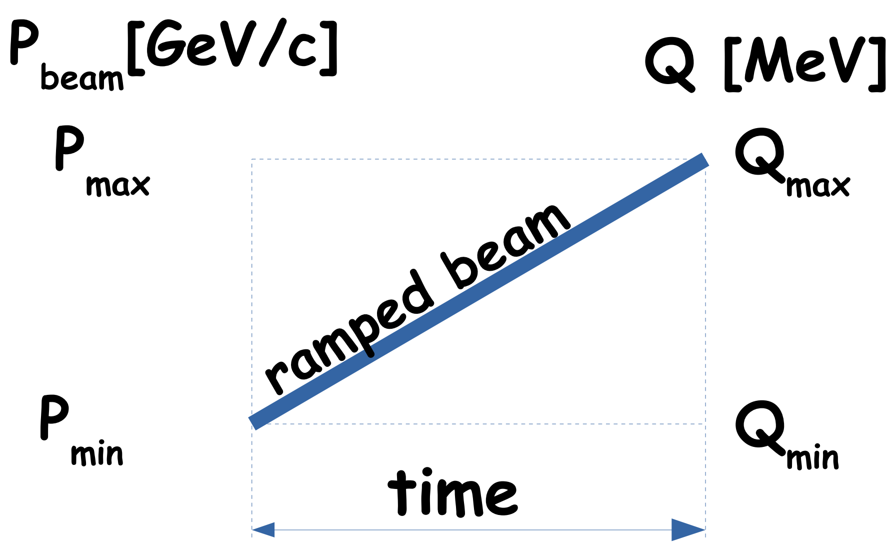
$pd \rightarrow {}^3He\ \pi^0$

Q: -50 to 20 MeV

P: 1.468 to 1.615 GeV/c

Test plot from experiment





Thank you for attention

INNOWACYJNA GOSPODARKA
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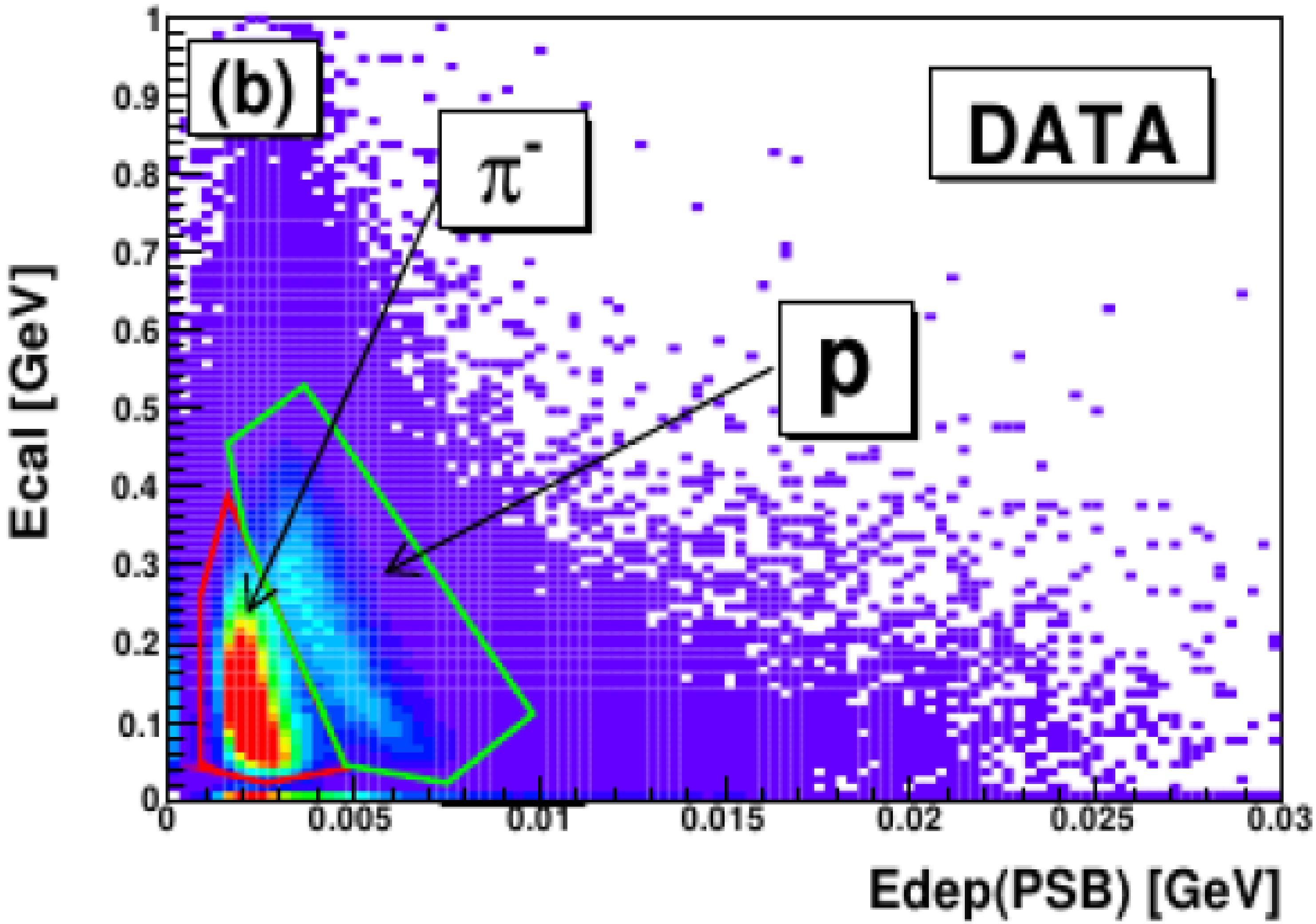

(b)
DATA
π^-
p
Ecal [GeV]
Edep(PSB) [GeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.005
0.01
0.015
0.02
0.025
0.03

1. The deuteron beam momentum value p_{beam} is generated with uniform probability density distribution in range of $p_{beam} \in(2.127,2.422)$ GeV/c and then the square of invariant mass of the whole system s_{dd} is calculated using Eq. (5.2) presented in Sec. 5.2 while describing the simulation of main reaction considered in this thesis.

2. The square root $\sigma(\sqrt{s_{dd}})$ is distributed randomly according to the distribution presented as follows:

$$\sigma(\sqrt{s_{dd}}) = \int_{W_{min}}^{W_{max}} PS(W) \cdot BW\left(\sqrt{s_{dd}} - W - m_{^3He}, \Gamma_{N^*}, E_{N^*}\right) \cdot dW, \tag{D.1}$$

where:

- $W = \sqrt{s_{dd}} - m_{N^*} - m_{^3He}$

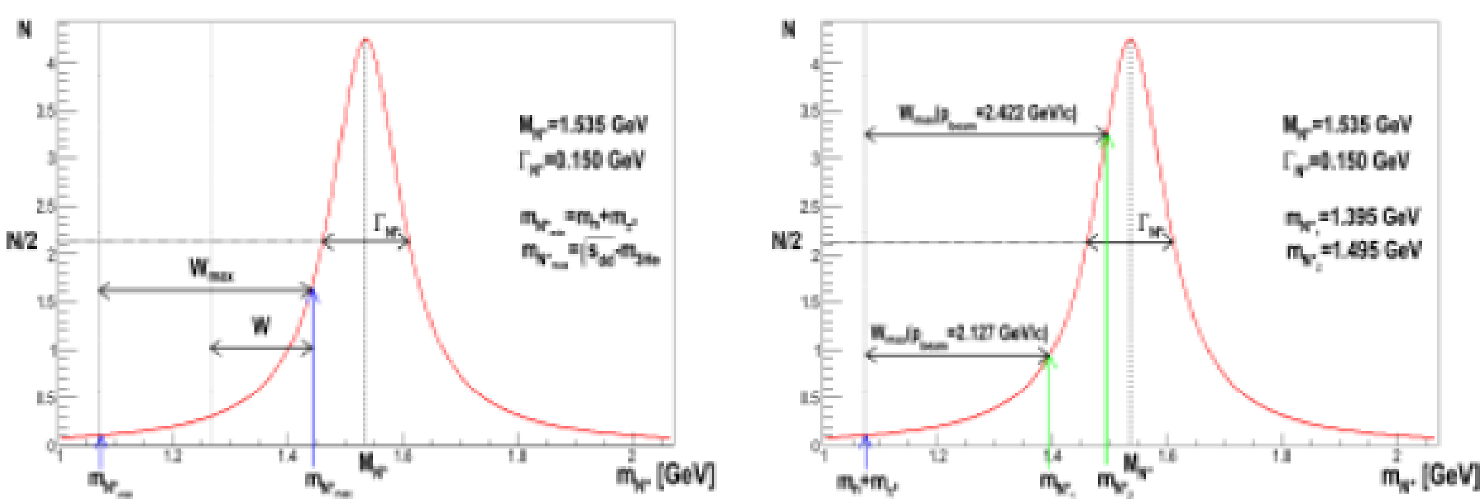
is the excess energy avaliable in the CM frame with minimum and maximum values equal to $W_{min} = 0$ and $W_{max} = \sqrt{s_{dd}} - m_{\pi^0} - m_n - m_{^3He}$,

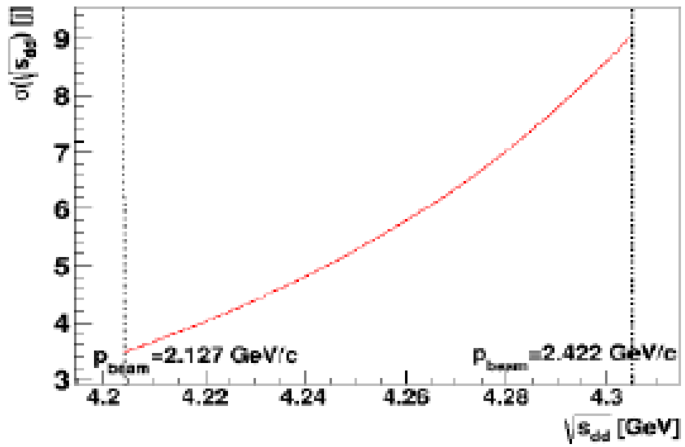
- $PS(W) = \sqrt{W}\left[\sqrt{s_{dd}} + m_{N^*} + m_{^3He}\right]^{1/2}\left[s_{dd} - (m_{N^*} - m_{^3He})^2\right]^{1/2} / \left(2\sqrt{s_{dd}}^3\right)$
$= \sqrt{W}\left[2\sqrt{s_{dd}} - W\right]^{1/2}\left[s_{dd} - (\sqrt{s_{dd}} - W - 2m_{^3He})^2\right]^{1/2} / \left(2\sqrt{s_{dd}}^3\right)$

is a Phase Space factor for 2-body reactions which is proportional to $\sqrt{W}$ near the η production threshold and to 1/W above the threshold [58],

- $BW\left(\sqrt{s_{dd}} - W - m_{^3He}, \Gamma_{N^*}, E_{N^*}\right) = \frac{\Gamma^2_{N^*}/4}{(m_{N^*} - E_{N^*})^2 + \Gamma^2_{N^*}/4} = \frac{\Gamma^2_{N^*}/4}{(\sqrt{s_{dd}} - W - m_{^3He} - E_{N^*})^2 + \Gamma^2_{N^*}/4}$

is a Breit Wigner distribution of N^* resonance with energy E_{N^*}=1535 MeV and width Γ_{N^*}=150 MeV. The BW distribution is presented schematically in Fig. D.1 while $\sigma(\sqrt{s_{dd}})$ distribution in Fig. D.2.





3. Excess energy available in the CM frame W is distributed according to the $PS(W) \cdot BW\,(\sqrt{s_{dd}} - W - m_{^3He}, \Gamma_{N^*}, E_{N^*})$ distribution.

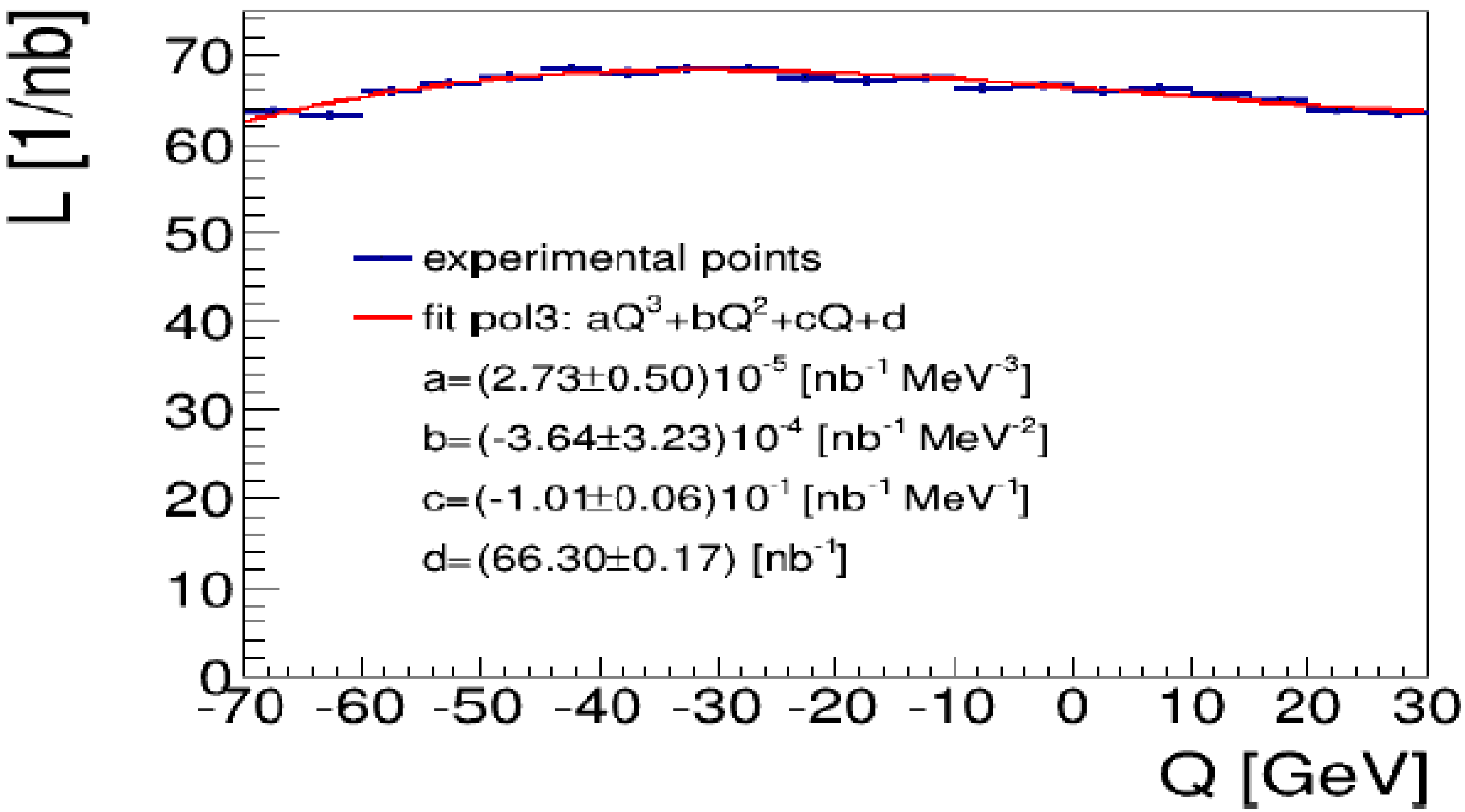
4. The resonance mass m_{N^*} is calculated as $m_{N^*} = \sqrt{s_{dd}} - W - m_{^3He}$ and is limited, because of two conditions:
   - $m_{N^*} + m_{^3He} \leq \sqrt{s_{dd}}$ (the whole avaliable energy is used to produce N^* and ^3He),
   - $m_{N^*} \geq m_{\pi^0} + m_n$ (resonance mass should be enough to decay into neutron and π^0).

5. The neutron and pion momentum vectors are simulated isotropically in the N^* frame in spherical coordinates and transformed into Cartesian coordinates. The absolute value of neutron and pion momenta $\vec{p}^{\,**}_{n,\pi^0}$ is fixed by equation (5.5) described in Sec. 5.2.

6. The gamma quanta are simulated isotropically in the π^0 frame in spherical coordinates with momenta $\vec{p}^{\,***}_{\gamma} = m_{\pi^0}/2$.

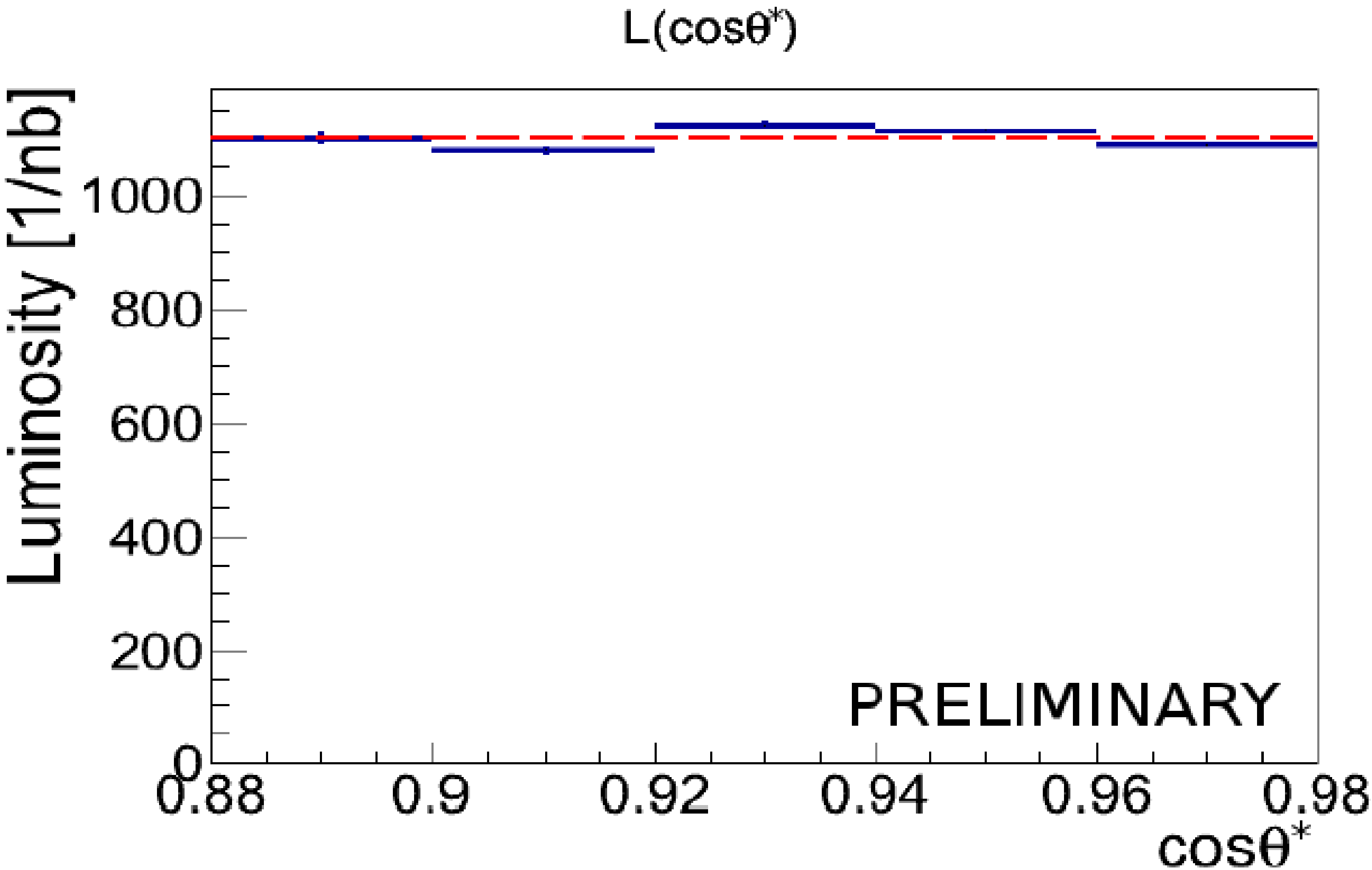
7. The four momentum vectors of ^{3}He, neutron and gamma quanta are transformed into the center of mass frame and next into laboratory frame

total luminosity



$$L_{tot} = (1329 \pm 2) nb^{-1}$$

$$\mathrm{L} = (1329 \pm 2_{stat} \pm 108_{syst} \pm 64_{norm}) nb^{-1}$$



$$L_{av} = (1102 \pm 2)\,nb^{-1}$$

$$L = (1102 \pm 2_{stat} \pm 28_{syst} \pm 107_{norm})\,nb^{-1}$$