Search for the η-mesic bound states with WASA-at-COSY facility

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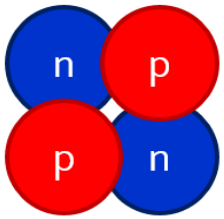
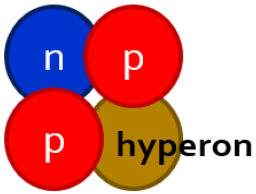
Outline

Introduction – exotic systems

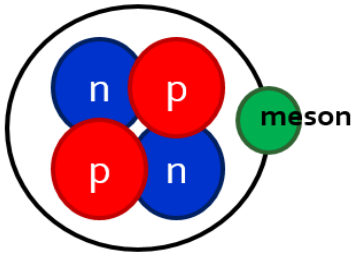


Classical nucleus
bound system of nucleons

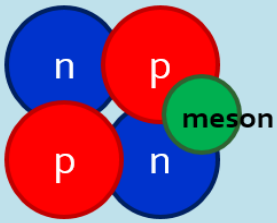
„Exotic" systems



Hypernucleus
bound system of nucleons
and hyperon (Λ,Σ)



Mesic atom
charged meson orbiting
around the nucleus (π)



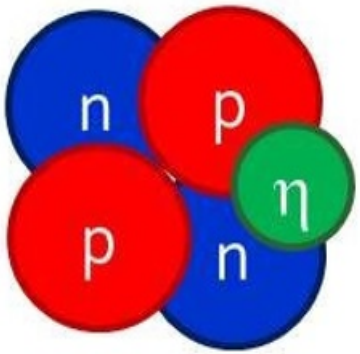
Mesic nucleus
bound system of nucleons
and meson (K,η,η',ω,...)

Introduction – η-mesic bound state

η-mesic nucleus

mezon η $u\bar{u}$, $d\bar{d}$, $s\bar{s}$

^4He-η



strong interaction

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

m_η=547.86 MeV
Γ=1.31 keV
$\tau=10^{-18}$ s

main decay channels:

$\eta\to 2\gamma$	~39%
$\eta\to 3\pi^0$	~33%
$\eta\to \pi^0\pi^+\pi^-$	~23%

(PDG 2015)

$$|Re(a_{\eta N})| > Im(a_{\eta N})$$

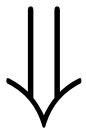
attraction>absorption

Introduction – η-mesic bound state

Attractive and strong interaction between η and nucleon

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

$(a_{\eta N}$=0.28+i0.19 fm)



Possible existence of η-mesic bound states postulated for atomic nuclei with A>12

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

Recent theoretical studies of hadronic- and photoproduction of η meson support the existence of light η-mesic nuclei like

$(^3\text{He}\text{-}\eta)_{bound}$ $(^4\text{He}\text{-}\eta)_{bound}$ 0.18 fm<Re($a_{\eta N}$)<1.03fm

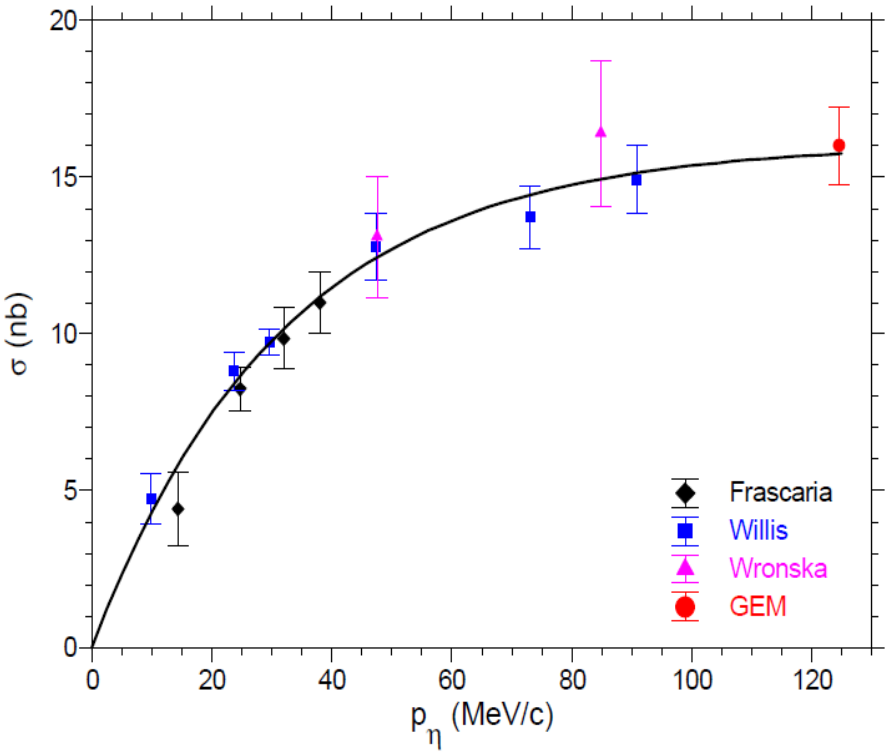
$B_s \in (2, 40)$ MeV, $\Gamma \in (7, 45)$ MeV 0.16 fm<Im($a_{\eta N}$)<0.49 fm

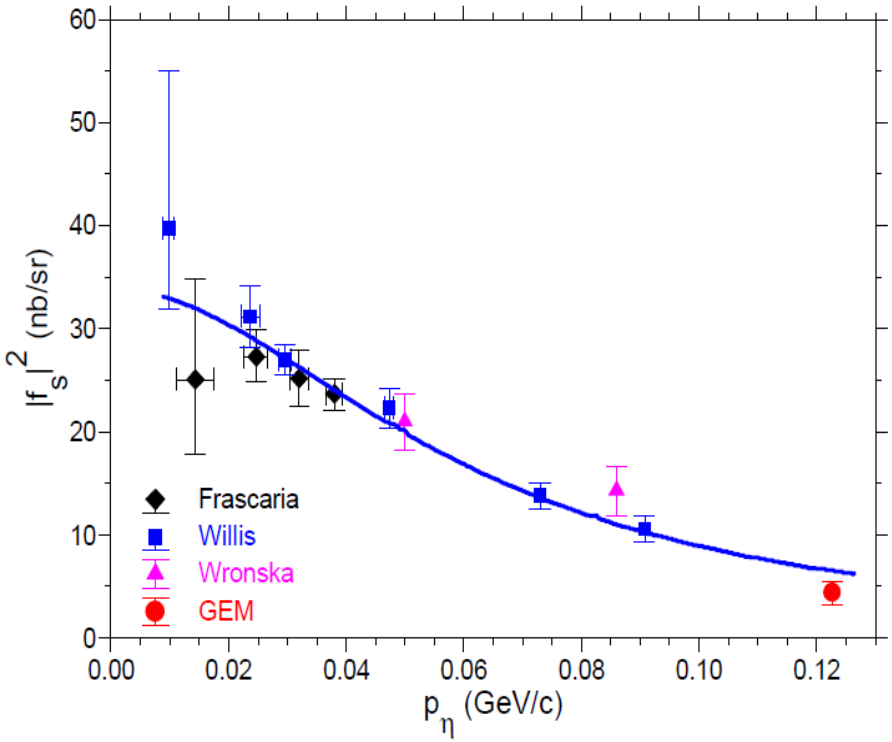
$dd \to (^4\text{He}\text{-}\eta)_{bound} \to {}^3\text{He}p\pi^-$: σ=**4.5 nb** | $pd \to (^3\text{He}\text{-}\eta)_{bound} \to Xp\pi^-$: σ=**80 nb**

N. G. Kelkar et al., Rept. Progr. Phys. 76, 066301 (2013)
S. Wycech, W. Krzemien, Acta. Phys. Polon B45, 745 (2014)
S. Wycech et al., Phys. Rev. C52, 544 (1995)
H. Machner, J. Phys. G42, 043001 (2015)
C. Wilkin, Acta. Phys. Pol. B45, 603 (2014)

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

total cross section $dd \rightarrow {}^4\text{He-}\eta$ $\quad |f_s|^2 = \frac{p_d}{p_\eta}\frac{\sigma}{4\pi}$

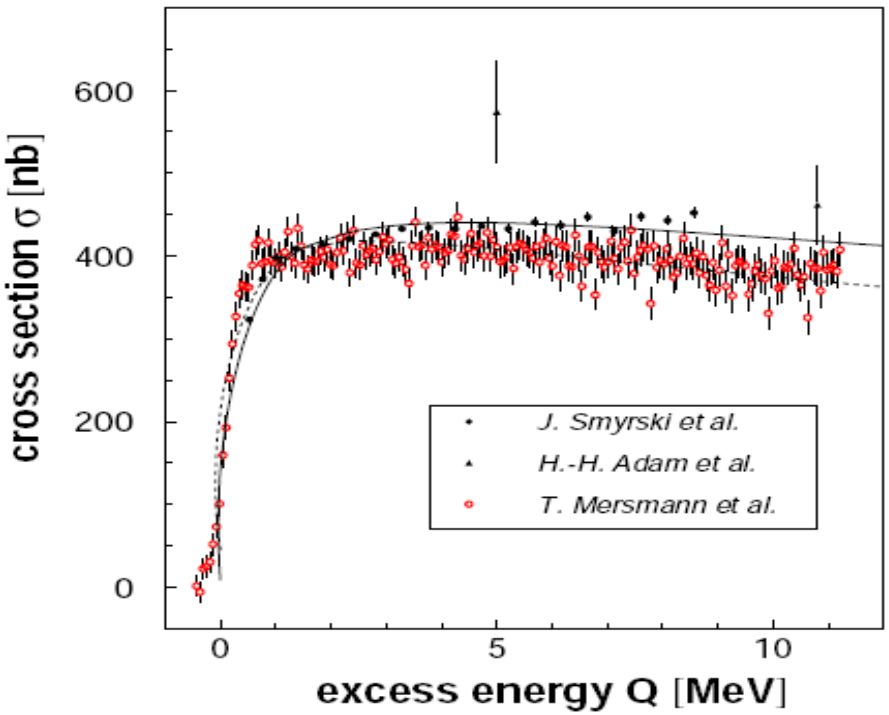


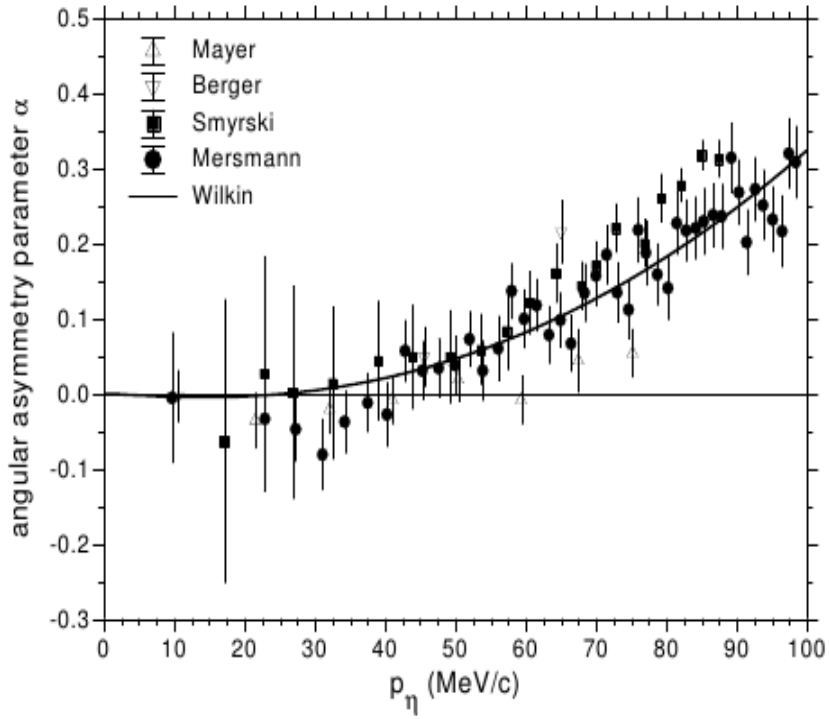


R. Frascaria et al., Phys. Rev. C50, 573 (1994)
N. Willis et al., Phys. Lett. B406, 14 (1997)
A. Wronska et al., Eur. Phys. J. A26, 421428 (2005)
A. Budzanowski et al., Nucl. Phys. A821, 193 (2009)

Exp. indications of the existence of the ^{3}He-η bound state

total cross section $pd \rightarrow {}^3\text{He}\text{-}\eta$ $\frac{d\sigma(\theta_\eta)}{d\Omega} = \frac{\sigma_{tot}}{4\pi}(1 - \alpha cos\theta_\eta)$





T. Mersmann et al., Phys. Rev. Lett. 98, 242301 (2007)
J. Smyrski et al., Phys. Lett. 649, 258 (2007)
H. H. Adam et al., Phys. Rev. C75, 014004 (2007)

Status of the search for η-mesic Helium at WASA

$(^4\text{He-}\eta)_{bound}$

- **2008**: $dd \rightarrow {}^3\text{He}p\pi^-$ reaction (W. Krzemień)
- **2010**: $dd \rightarrow {}^3\text{He}n\pi^0$ and $dd \rightarrow {}^3\text{He}p\pi^-$ reactions (M. Skurzok & W. Krzemień)

$(^3\text{He-}\eta)_{bound}$

- **2014**: search for bound state in pd reaction, analysis in progress (O. Rundel & O. Khreptak)

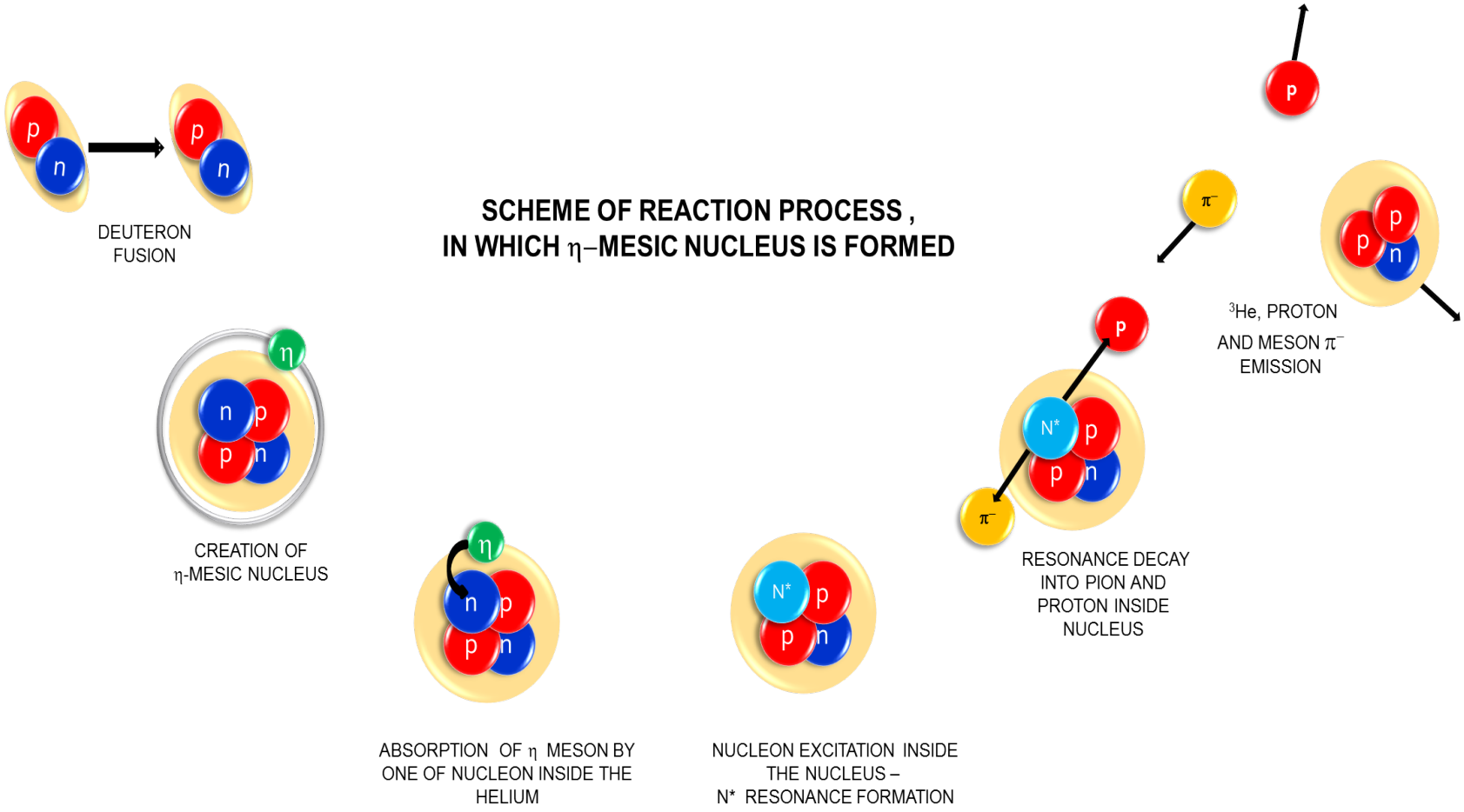
Production of ^{4}He-η in dd collision

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

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

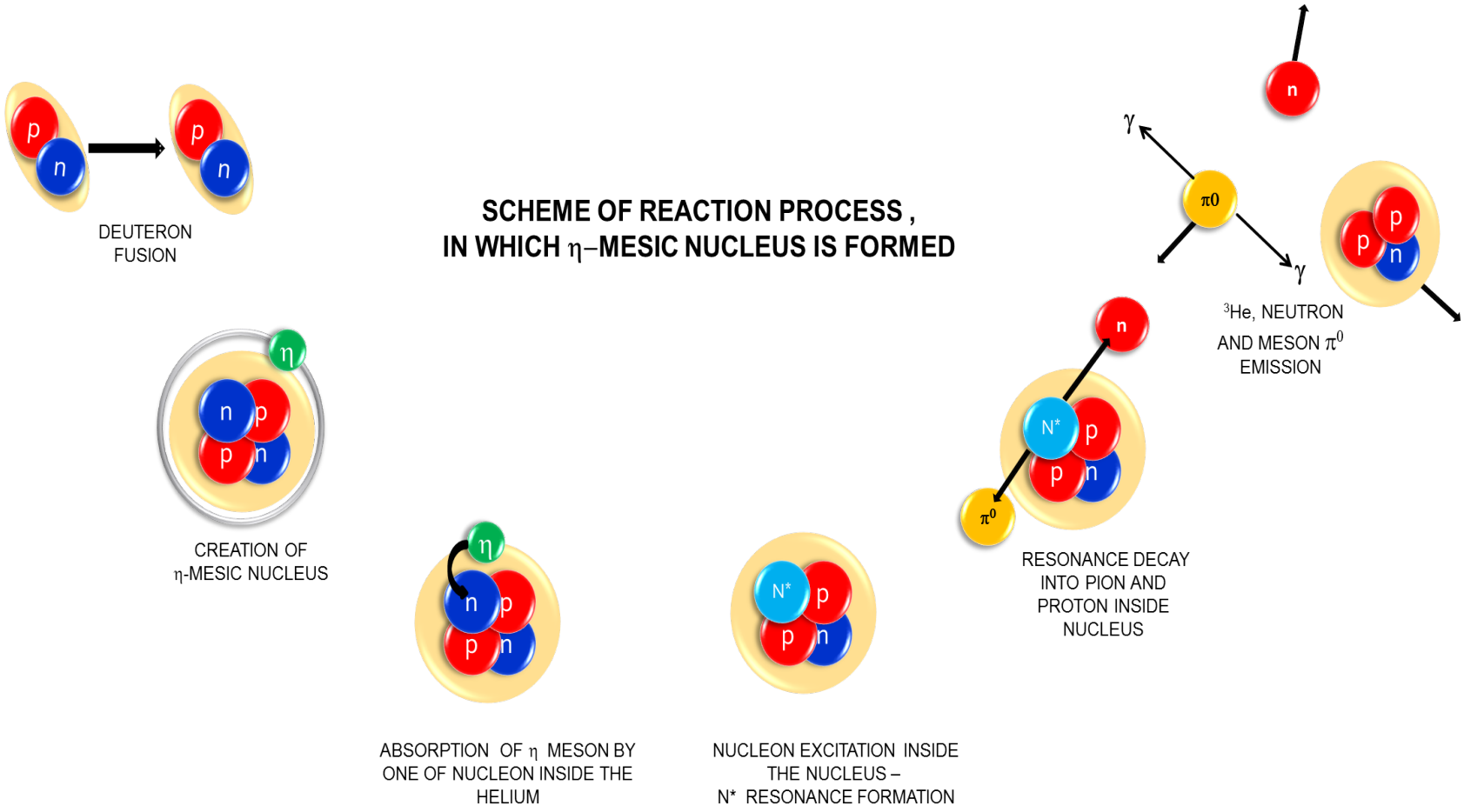
Kinematic mechanism of the reaction

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



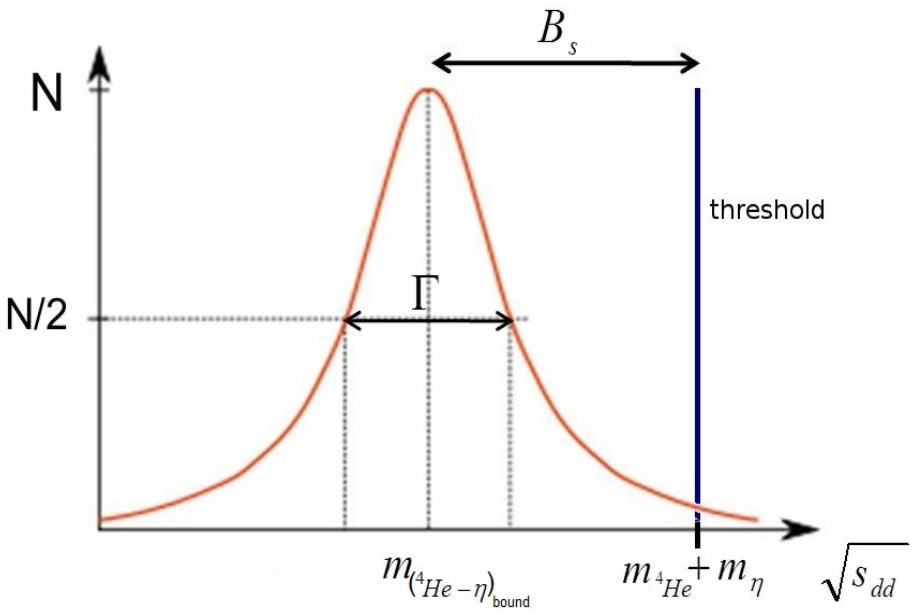
Kinematic mechanism of the reaction

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

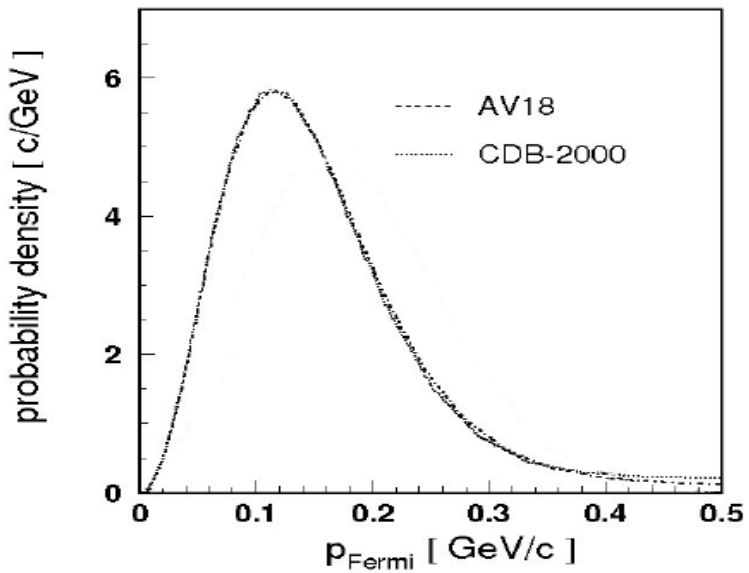


Simulation of $(^4\text{He-}\eta)_{bound}$ production and decay

Breit-Wigner distribution



Spectator Model



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

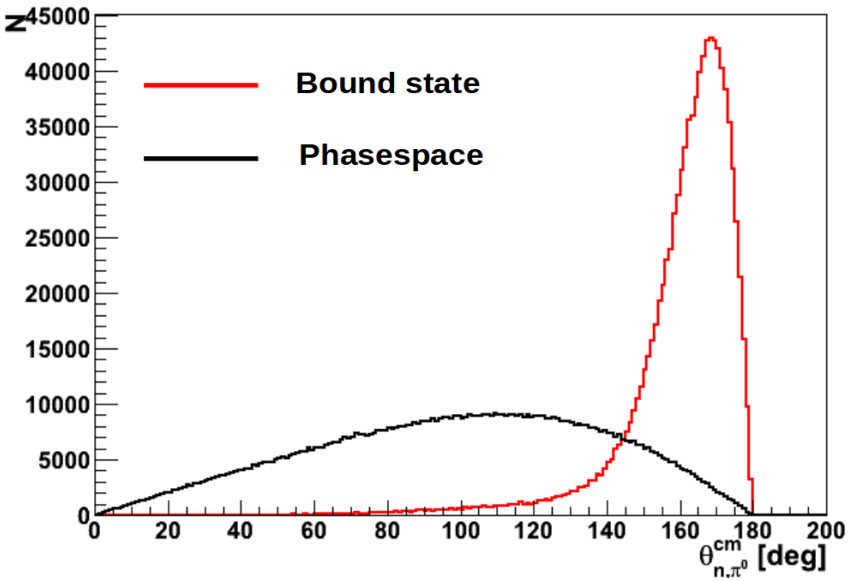
$$\left|\mathbb{P}_{^3He}\right|^2 = m^2_{^3He}$$

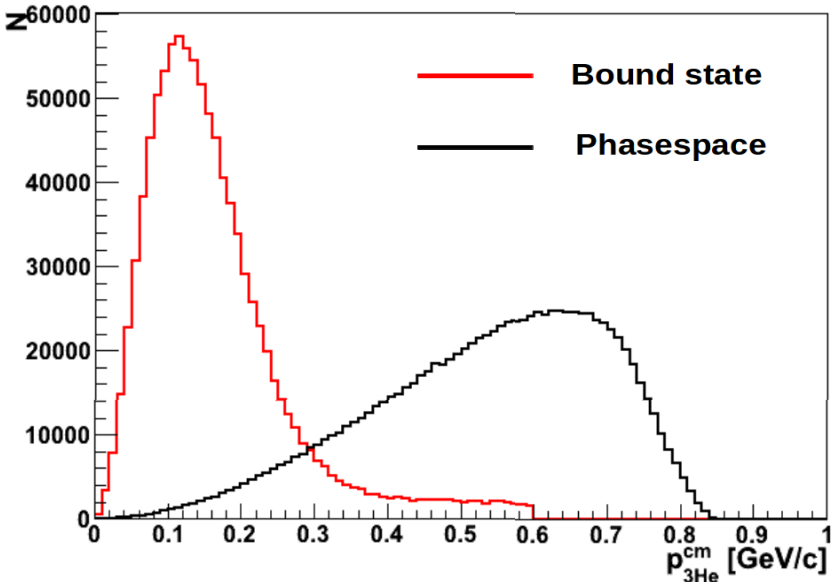
$$m_{(^4He-\eta)_{bound}} = m_{^4He} + m_\eta - B_s$$

Simulation of $(^4\text{He}\text{-}\eta)_{bound}$ production and decay

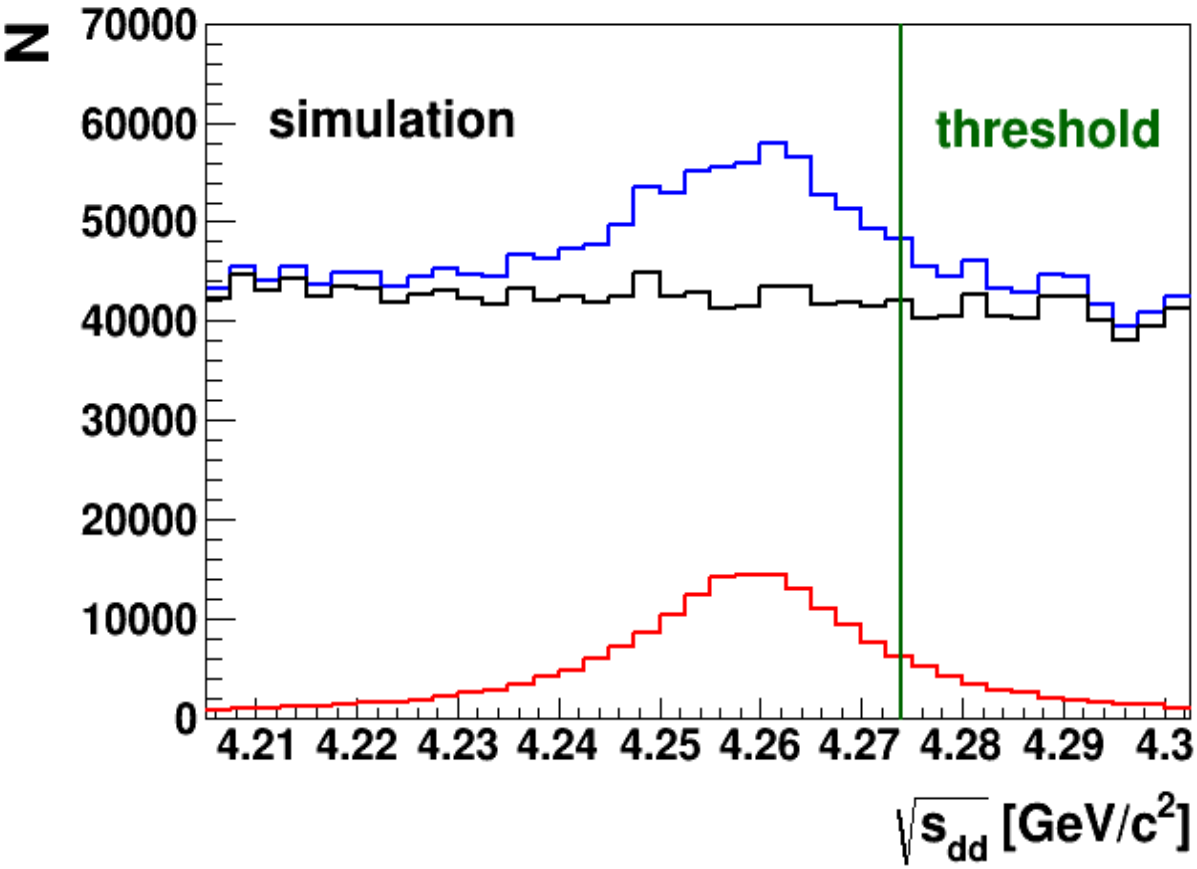
$$\eta + N \Rightarrow N^*(1535) \Rightarrow N + \pi = \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$$

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





Experimental method



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

and

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

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

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

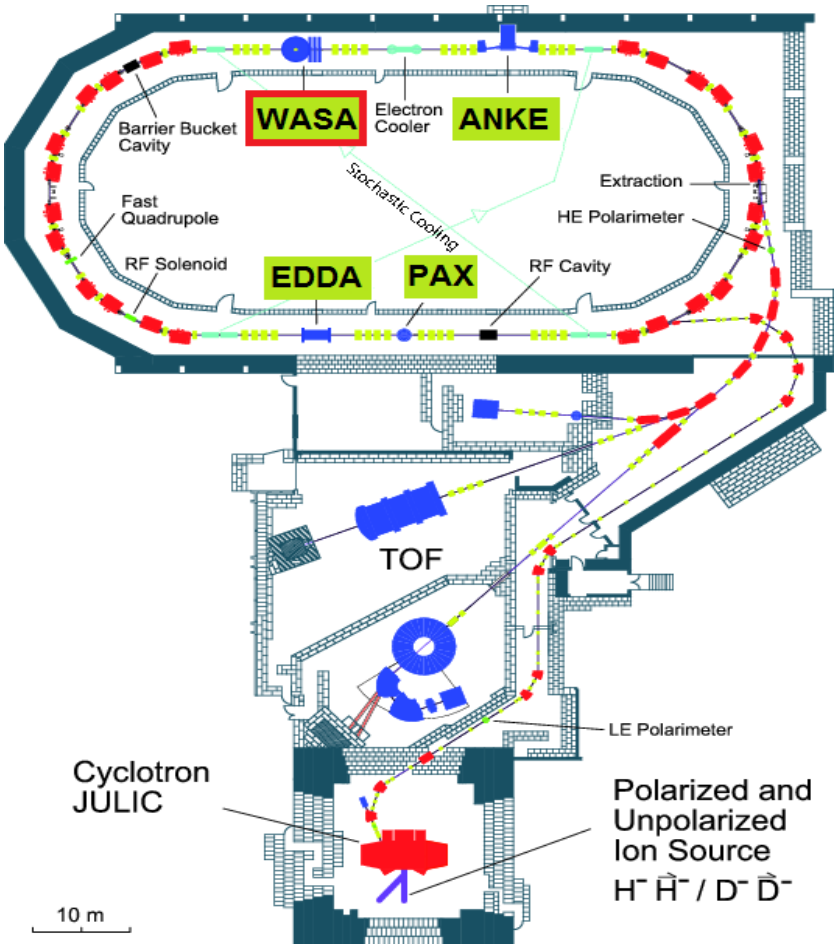
Excitation function

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

Search for $(^4\text{He-}\eta)_{bound}$ with WASA-at-COSY

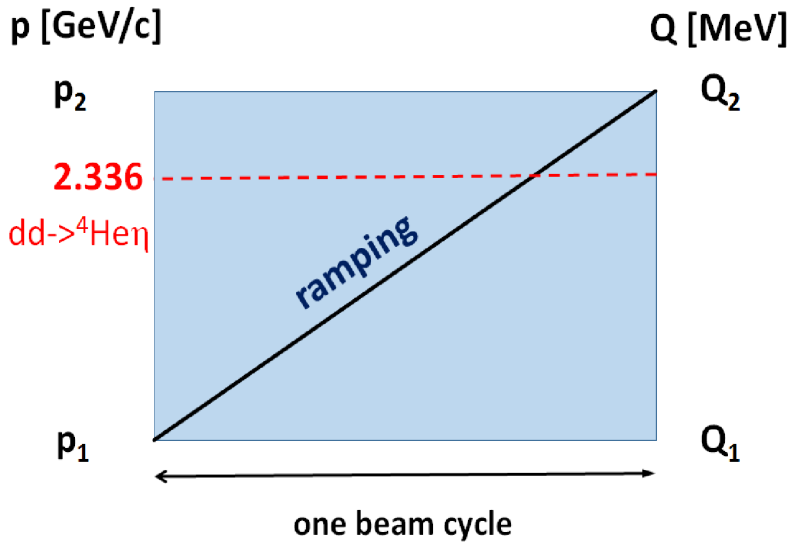
Exp. 186.1 & 186.2, FZ Jülich, Germany, 2008 and 2010

P. Moskal, W. Krzemien, J. Smyrski,
COSY proposal No. 186.1 & 186.2



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

- **Measurement** with the deuteron beam momentum ramped and with the deuteron pellet target



- **Data** were effectively taken about 160h with high acceptance (58%) and luminosity $(2.4{\cdot}10^{30}\frac{1}{cm^2 s})$

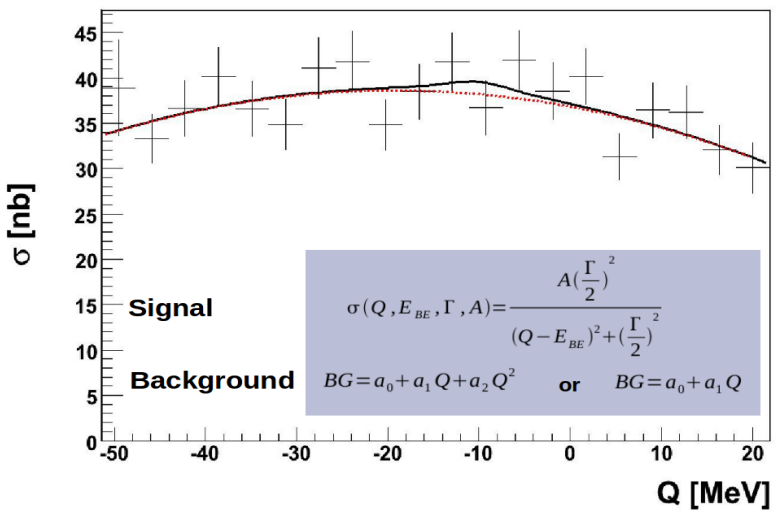
Experiment-May 2008

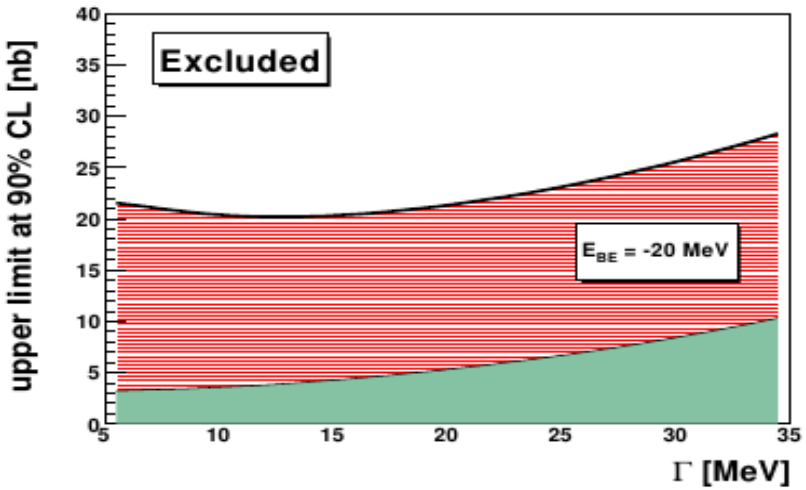
Channel: $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ (norm: $dd \rightarrow {}^3\text{He}n$)

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, Ph. D Thesis, Jagiellonian University (2012)

Experiment-Nov/Dec 2010

Beamtime: 26.11 - 13.12.2010

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

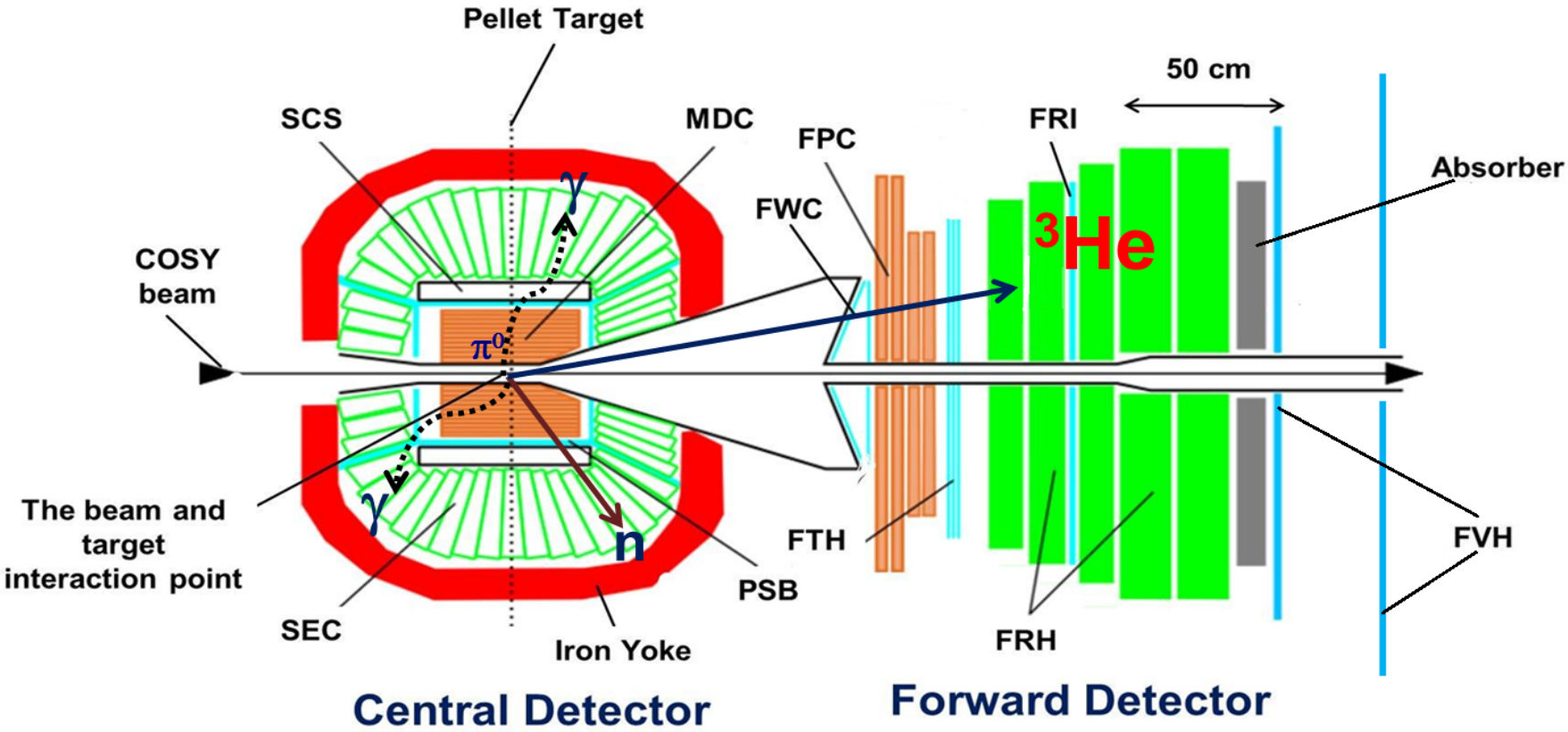
Measurement: performed with the beam momentum ramped from **2.127GeV/c to 2.422GeV/c**, corresponding to the range of excess energy **Q∈(-70,30)MeV**

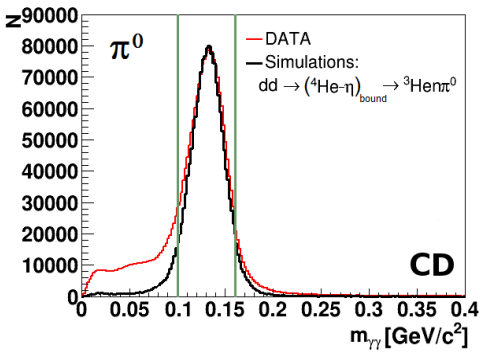
Acceptance: A=53%
Luminosity: L≈1200$\frac{1}{nb}$ ($dd \rightarrow {}^3\text{He}n$ and $dd \rightarrow ppn_{sp}n_{sp}$)

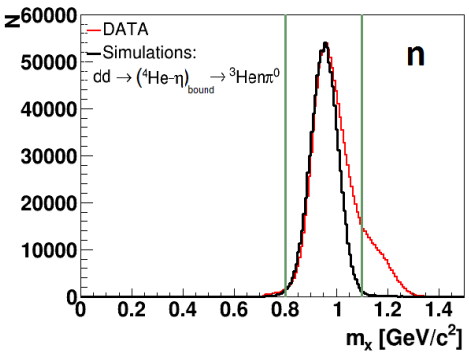
$\Downarrow$

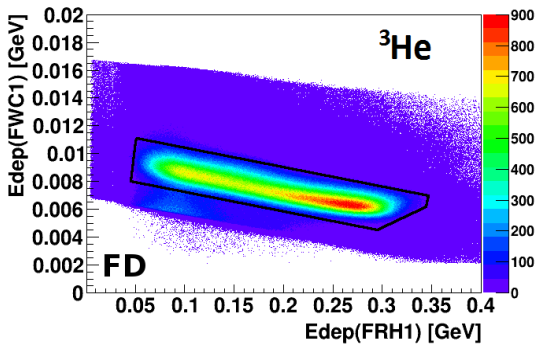
More than **10 times higher** statistics and two reactions were collected than in 2008 experiment.

Search for $(^4\text{He-}\eta)_{bound}$ in $dd \rightarrow {}^3\text{He}n\pi^0$ reaction | PID

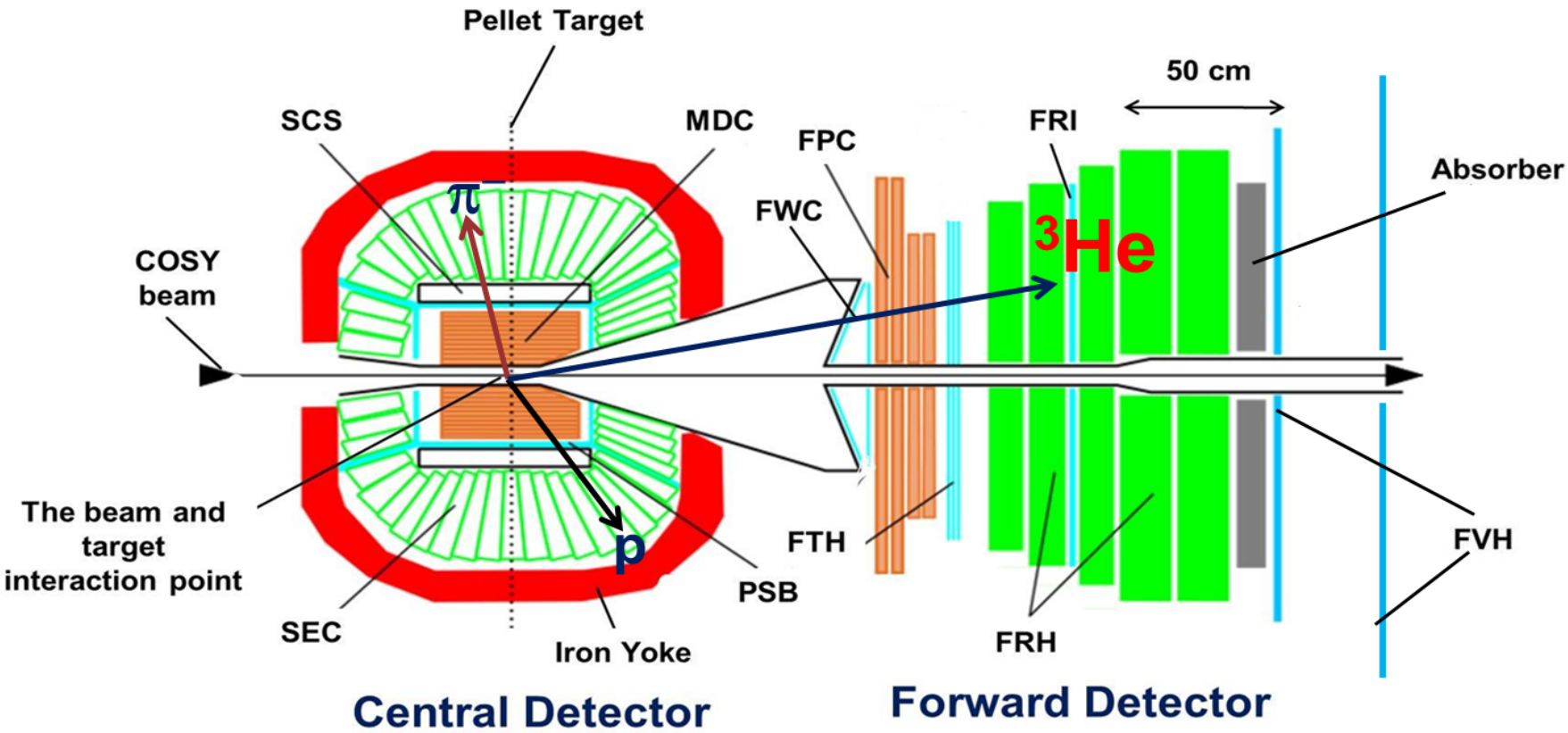


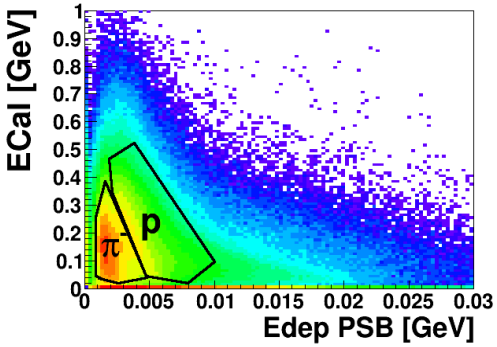


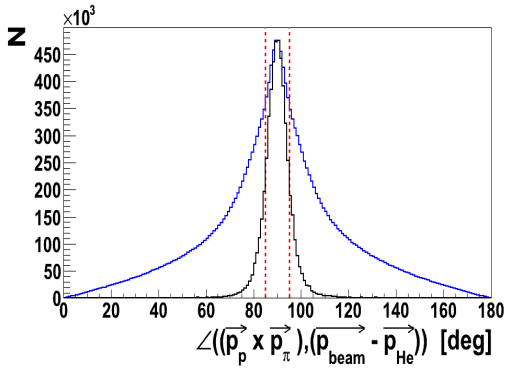


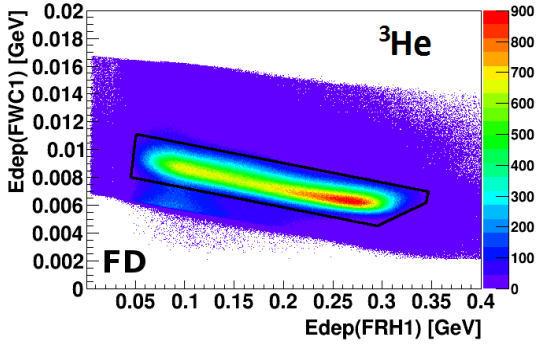


Search for $(^4\text{He-}\eta)_{bound}$ in $dd \rightarrow {}^3\text{He}p\pi^-$ reaction | PID

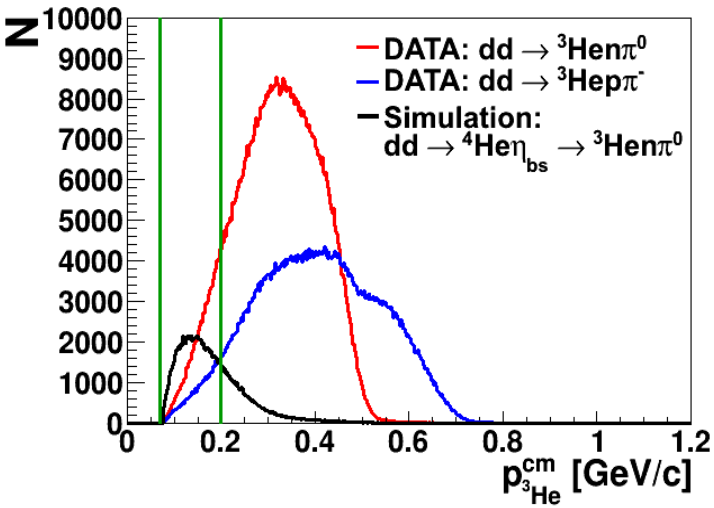


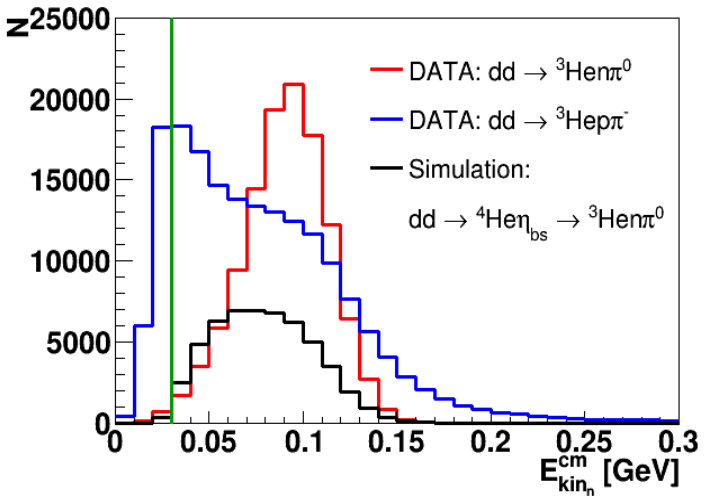


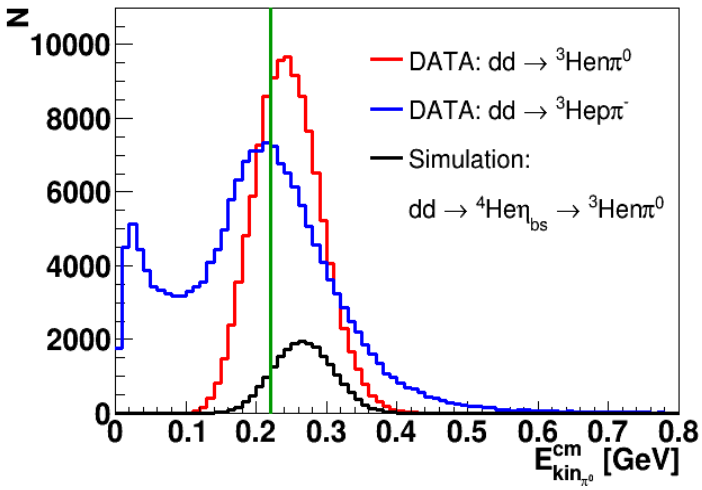


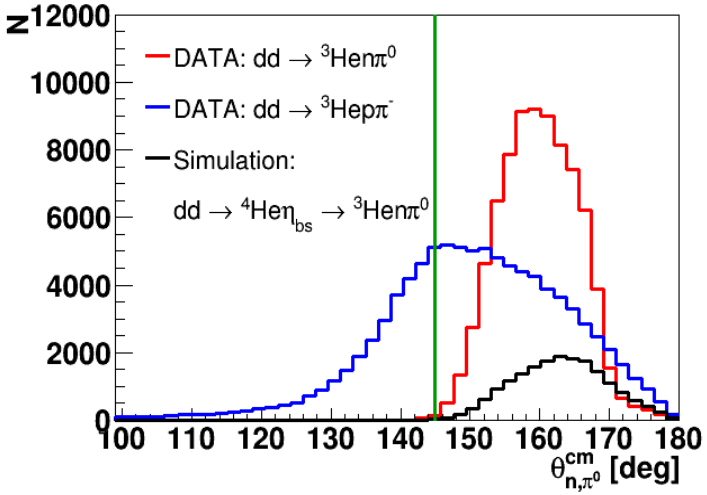


Search for $(^4\text{He-}\eta)_{bound}$ | Selection criteria





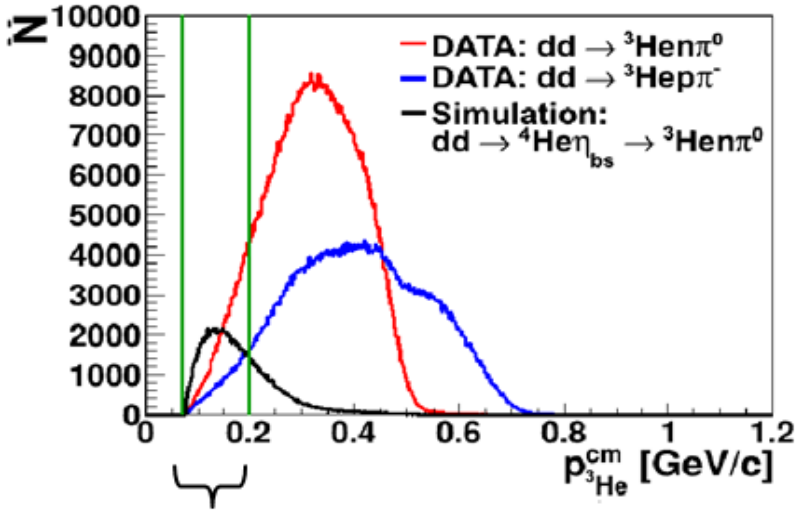




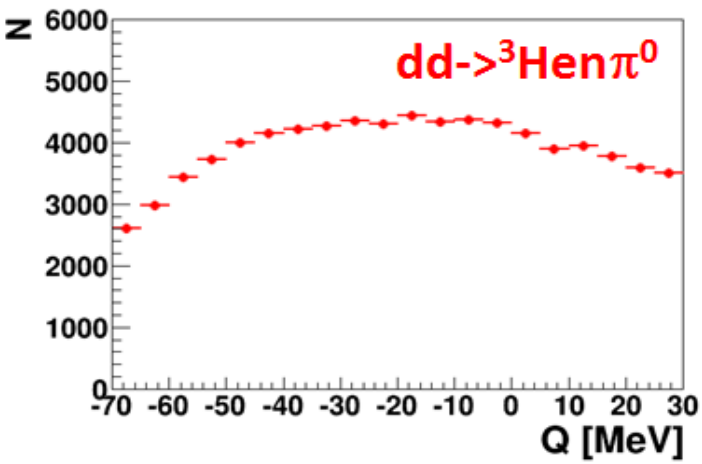
DATA: $dd \rightarrow {}^3\text{He}p\pi^-$
DATA: $dd \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$

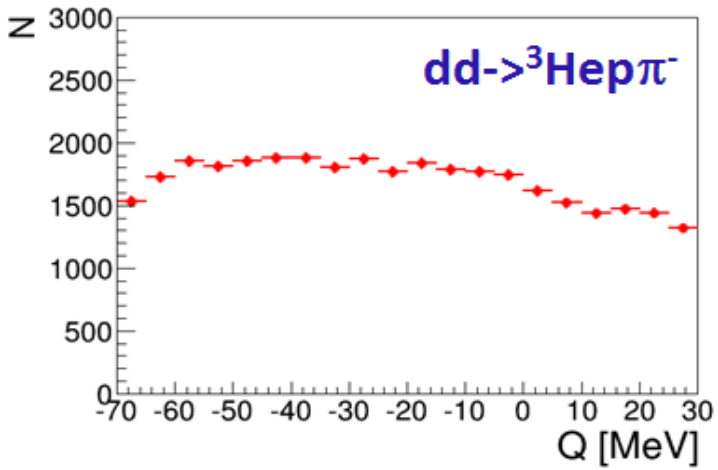
Signal: $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$

Determination of the excitation function



region rich in signal





Determination of the total cross section for $dd \rightarrow {}^3\mathrm{He}n\pi^0$ reaction

Cross section

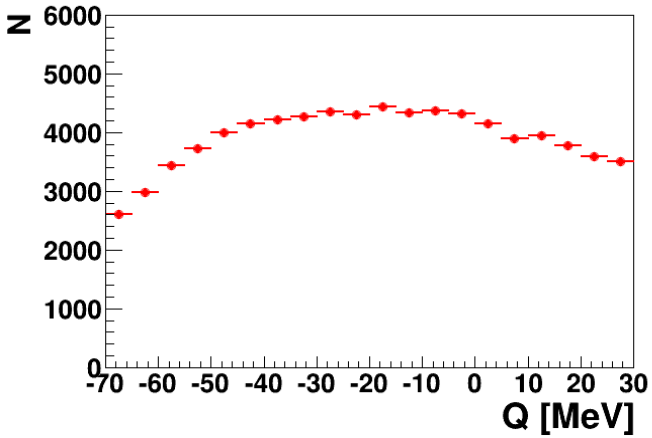
$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

N - number of experimental events

L - integrated luminosity

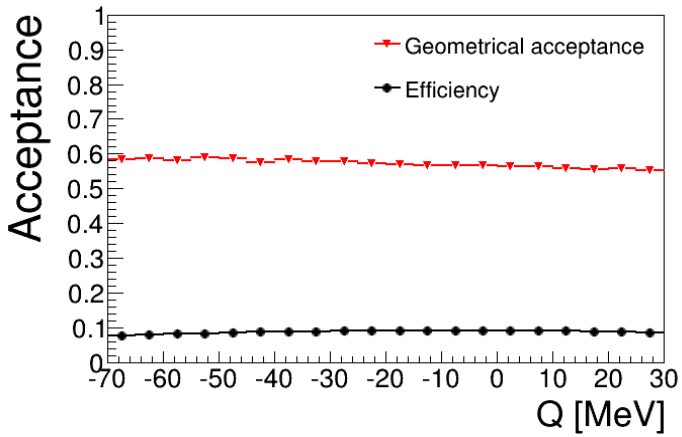
ϵ - full detection efficiency

Excitation function



Efficiency

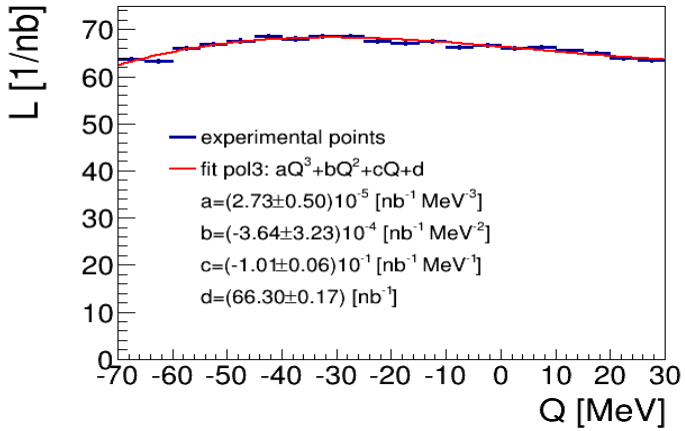
$dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$



from simulations: $\epsilon = \frac{N_{acc}}{N_{gen}}$

Integrated luminosity

$dd \rightarrow ppn_{sp}n_{sp}$



$dd \rightarrow ppn_{sp}n_{sp}$: $\mathrm{L}=(1329 \pm 2_{stat} \pm 108_{syst} \pm 64_{norm})nb^{-1}$

$dd \rightarrow {}^3\mathrm{He}n$: $\mathrm{L}=(1102 \pm 2_{stat} \pm 28_{syst} \pm 107_{norm})nb^{-1}$

Determination of the total cross section for $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction

Cross section

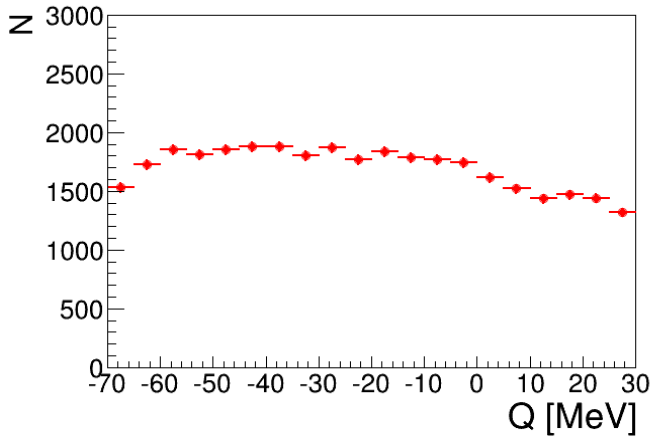
$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

N - number of experimental events

L - integrated luminosity

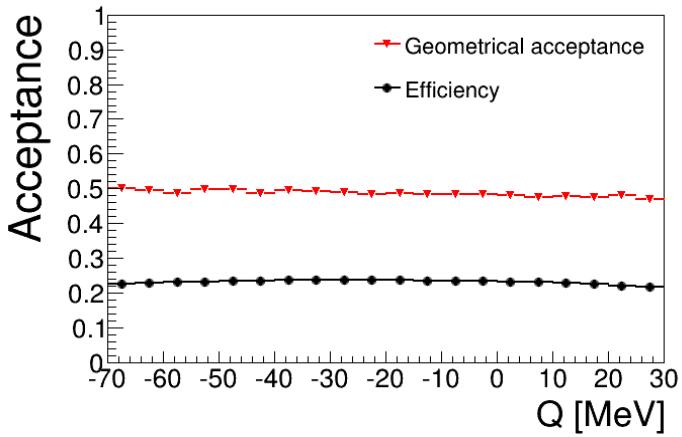
ϵ - full detection efficiency

Excitation function



Efficiency

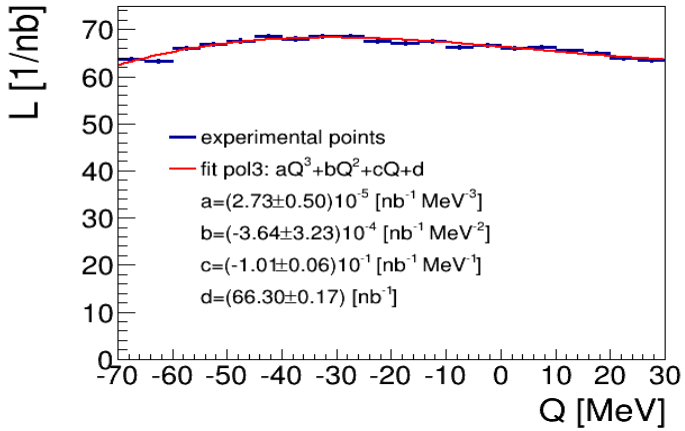
$dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$



from simulations: $\epsilon = \frac{N_{acc}}{N_{gen}}$

Integrated luminosity

$dd \rightarrow ppn_{sp}n_{sp}$



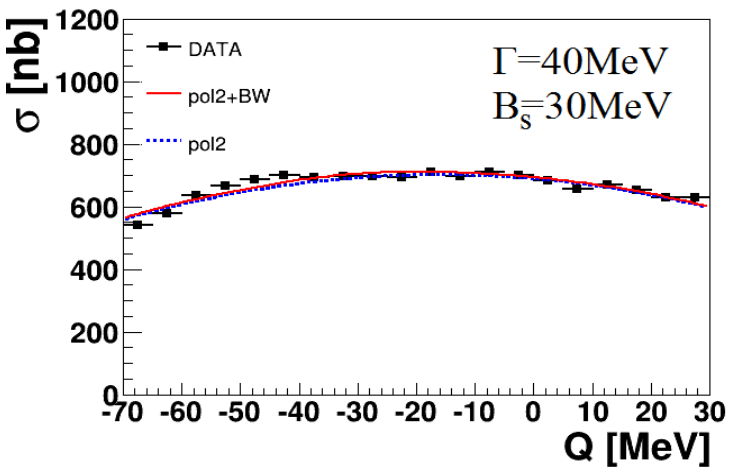
$dd \rightarrow ppn_{sp}n_{sp}$: $\mathrm{L}=(1329 \pm 2_{stat} \pm 108_{syst} \pm 64_{norm})nb^{-1}$

$dd \rightarrow {}^3\mathrm{He}n$: $\mathrm{L}=(1102 \pm 2_{stat} \pm 28_{syst} \pm 107_{norm})nb^{-1}$

Determination of the upper limit of the total cross section for $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$ process at CL=90%

Excitation function does not reveal narrow structure $\Rightarrow$

$\Uparrow$



fit $\frac{A\cdot\Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4} + BQ^2 + CQ + D$

Breit-Wigner (signal) + pol2 (background)

B_s,Γ - fixed parameters
A, B, C, D - free parameters

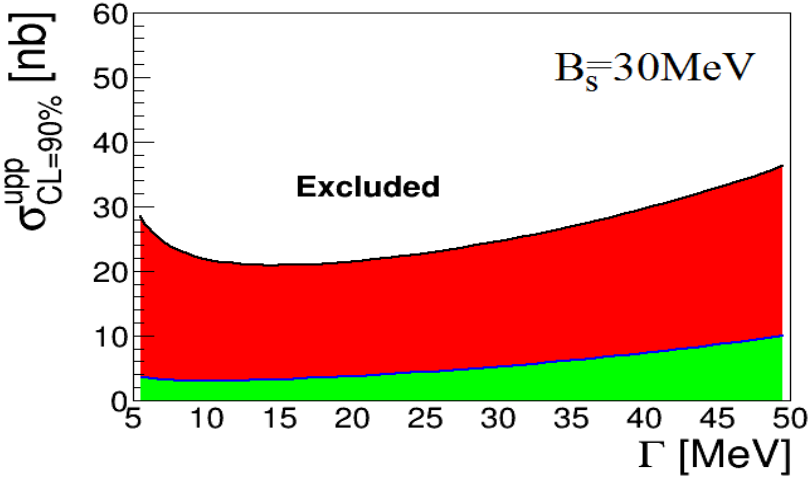
$$\sigma^{upp}_{CL=90\%} = k \cdot \sigma_A$$

k=1.64485 (for CL=90%)

$\sigma^{upp}_{CL=90\%}$ for

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

$\Downarrow$



PRELIMINARY

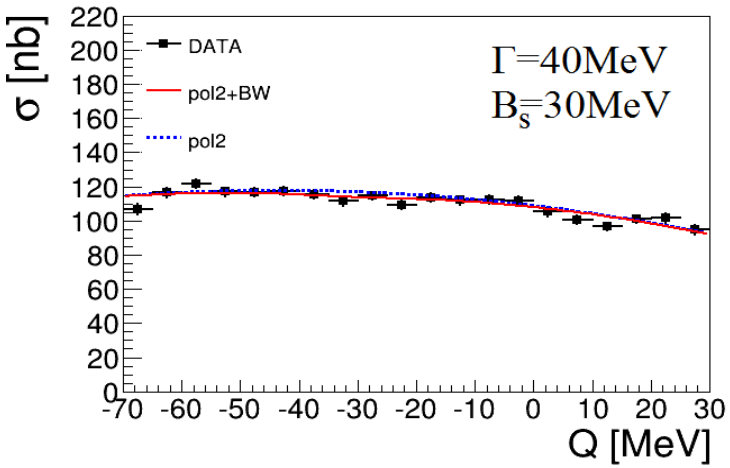
Result: $\sigma_{dd\rightarrow(^4He-\eta)_{bound}\rightarrow{}^3Hen\pi^0} < 36\ nb$

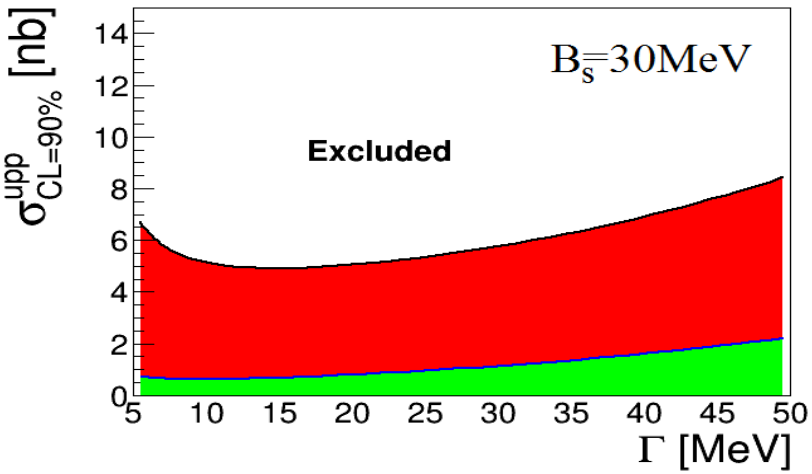
the first result obtained for $dd \rightarrow {}^3\text{He}n\pi^0$

Determination of the upper limit of the total cross section for $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ process at CL=90%

Excitation function does not reveal narrow structure $\Rightarrow$ $\sigma^{upp}_{CL=90\%}$ for $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$

$\Uparrow$ $\Downarrow$





fit $\frac{A\cdot\Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4} + BQ^2 + CQ + D$

Breit-Wigner (signal) + pol2 (background)

B_s,Γ - fixed parameters
A, B, C, D - free parameters

$$\sigma^{upp}_{CL=90\%} = k \cdot \sigma_A$$

k=1.64485 (for CL=90%)

PRELIMINARY Result:

$\sigma_{dd\rightarrow(^4He-\eta)_{bound}\rightarrow{}^3Hep\pi^-} < 9\ nb$

2008: $\sigma < 27\ nb$

New experiment - May/Jun 2014 - $(^3\text{He-}\eta)_{bound}$

Beamtime: p_{beam} : 1.468-1.615GeV/c, **Q$\in$(-50,20)MeV**

Via the resonance decay N^*:

1) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppp\pi^-$

2) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppn\pi^0$

3) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow dp\pi^0$

Absorption of orbiting η

4) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\ 2\gamma$

5) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\ 6\gamma$

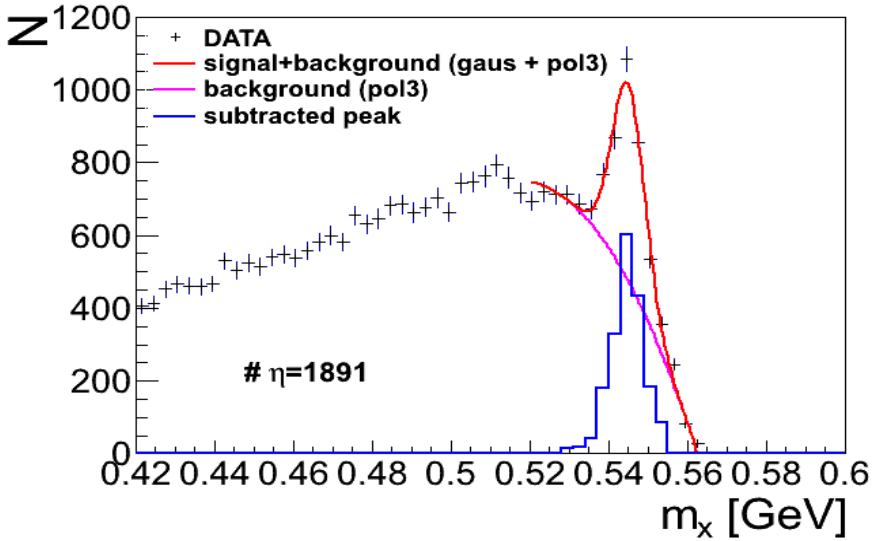
Nonresonant decay (absorption on two nucleons) as proposed by prof. Wycech

6) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppn$

7) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow pd$

Luminosity: L$\sim$1000$\frac{1}{nb}$ $(pd \rightarrow {}^3\text{He-}\eta)$

test plot



More: P. Moskal, W. Krzemień, M. Skurzok, COSY proposal No. 186.3 (2014).

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 was for the first time determined for $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$ reaction
- The upper limit for $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ reaction in order of **few nb**!
- New data set in ${}^3\mathrm{He}\text{-}\eta$ system (Experiment in May 2014) - **the best statistics in the world!**

Thank you for attention

INTERNATIONAL PHD PROJECT IN APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES

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