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

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for WASA-at-COSY Collaboration

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Introduction – η-mesic bound state

η-mesic nucleus

^4He-η

strong interaction

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

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

$$\eta_1 = \frac{1}{\sqrt{3}}(d\bar{d} + u\bar{u} + s\bar{s}),$$
$$\eta_8 = \frac{1}{\sqrt{6}}(d\bar{d} + u\bar{u} - 2s\bar{s})$$
$$|\eta> = \eta_8 cos\theta - \eta_1 sin\theta,\ \theta = -15.5° \pm 1.3°$$

m_η=547.86 MeV
Γ=1.31 keV
τ=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 2020)

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

attraction > absorption

Attractive and strong interaction between η and nucleon

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

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

$\Downarrow$

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 $(^3\text{He}\text{-}\eta)_{bound}$ $(^4\text{He}\text{-}\eta)_{bound}$

$B_s \in (1, 40)$ MeV, $\Gamma \in (1, 45)$ MeV

$0.18\ \text{fm} < \text{Re}(a_{\eta N}) < 1.03\text{fm}$

$0.16\ \text{fm} < \text{Im}(a_{\eta N}) < 0.49\ \text{fm}$

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

J.-J. Xie et al., Eur. Phys. J. A 55 no.1, 6 (2019)
J.-J. Xie et al., Phys. Rev. C 95, 015202 (2017)
M. Skurzok et al., Nucl. Phys. A 993, 121647 (2020)
N. Ikeno et al., Eur. Phys. J A 53 no. 10, 194 (2017)
T. Ishikawa et al., Acta. Phys. Polon. B 51, 27 (2020)
T. Sekihara, H. Fujioka, T. Ishikawa, Phys. Rev. C 97, 045202 (2017)
A. Fix and O. Kolesnikov, Phys. Rev. C 97, 044001 (2018)
V. Metag, M. Nanova, E. Paryev, Prog. Part. Nucl. Phys. 97, 199 (2017)
J. Mares et al., Acta. Phys. Polon. B 51, 129 (2020)
N. G. Kelkar, H. Kamada, M. Skurzok, Int. J. Mod. Phys. E 28, 1950066 (2019)
N. G. Kelkar, D. Bedoya Fierro, H. Kamada, M. Skurzok, Nucl. Phys. A 996, 121698 (2020)
S. D. Bass and P. Moskal, Rev.Mod. Phys. 91, 015003 (2019)
S. Wycech, W. Krzemien, Acta. Phys. Polon B 45, 745 (2014)
C. Wilkin, Acta. Phys. Polon. B 45, 603 (2014)

Status of the search for η-mesic Helium at WASA

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

- **2008**: $dd \to {}^3\text{He}p\pi^-$ reaction

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

- **2010**: $dd \to {}^3\text{He}n\pi^0$ and $dd \to {}^3\text{He}p\pi^-$ reactions

  P. Adlarson et al., Nucl. Phys. A 959, 102-115 (2017)

  M. Skurzok, P. Moskal, et al., Phys. Lett. B782, 6-12 (2018)

$\Uparrow$

η meson absorption and excitation of one of the nucleons to an N^* resonance, which subsequently decays into an N - π pair

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

- **2014**:

  - $pd \to {}^3\text{He}2\gamma({}^3\text{He}6\gamma)$ reactions

  P. Adlarson et al., Phys. Lett. B 802, 135205 (2020)

  decay of the η - meson while it is still "orbiting" around a nucleus

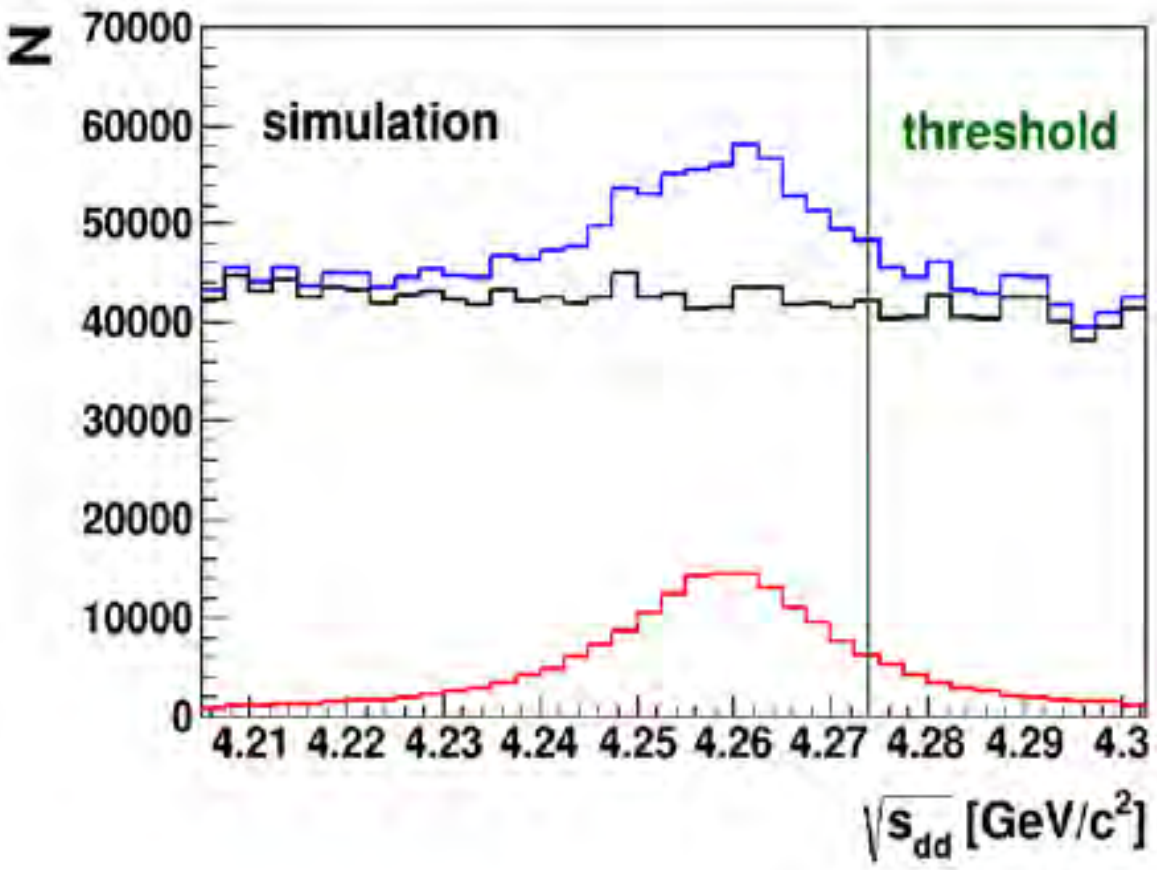
  - $pd \to ppp\pi^-(ppn\pi^0, dp\pi^0)$ reactions

  P. Adlarson et al., Phys. Rev. C 102, 044322 (2020)

η meson absorption and excitation of one of the nucleons to an N^* resonance, which subsequently decays into an N - π pair

Papers available at http://koza.if.uj.edu.pl/publications/wasa-at-cosy

Experimental method



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

and

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

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

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

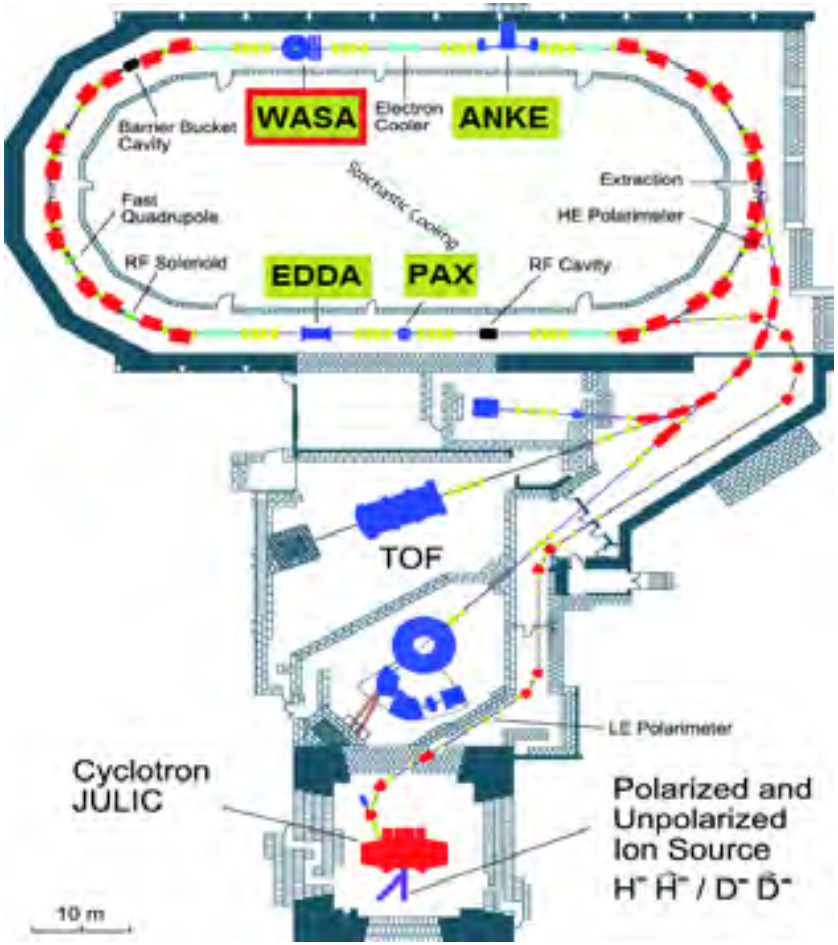
Excitation function

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

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

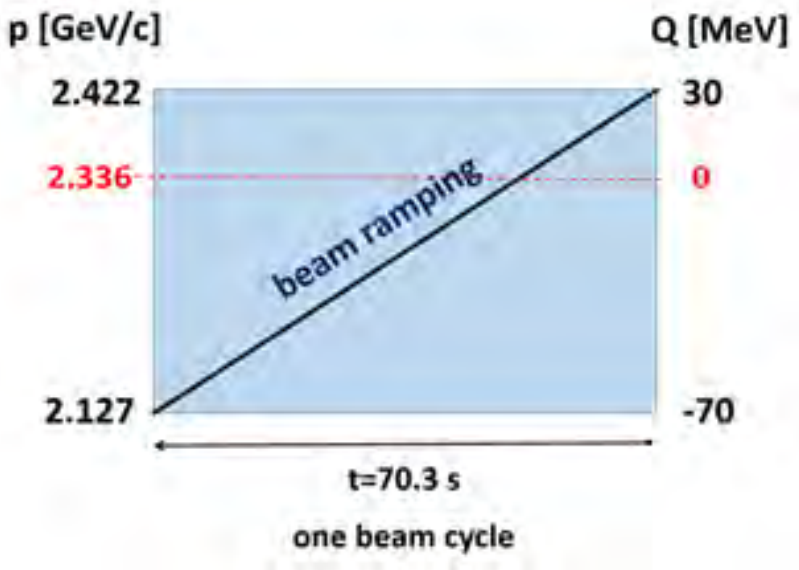
Exp. 186.1 & 186.2, FZ Jülich, Germany, 2008 and 2010

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



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

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

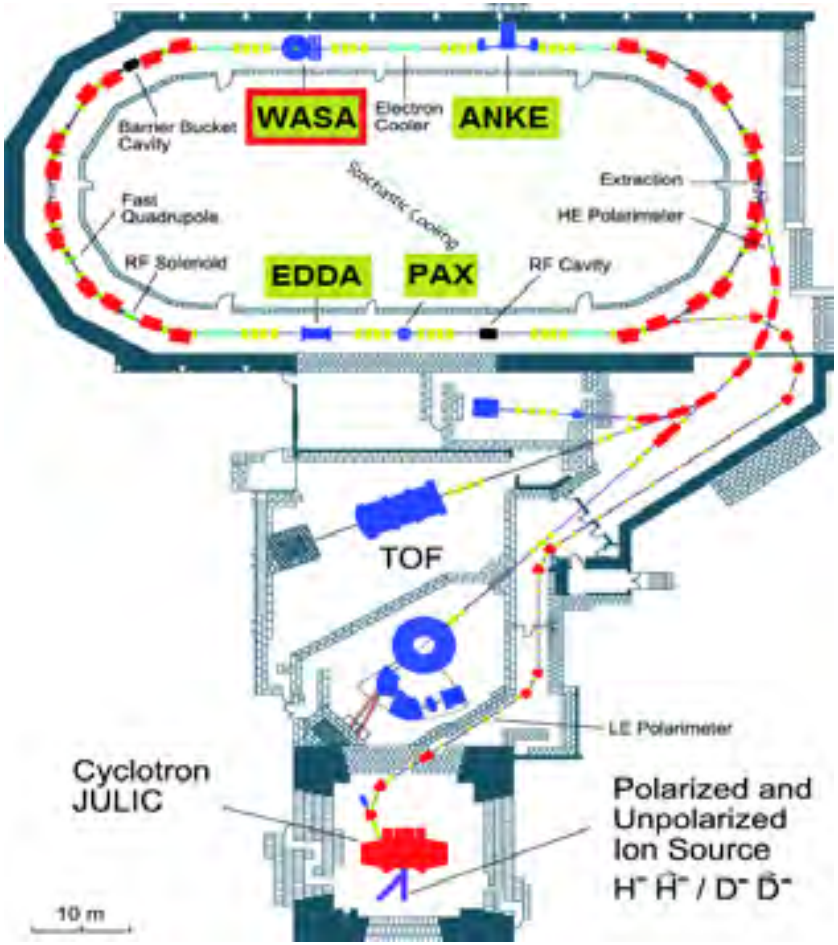


- **Data** were effectively taken with high acceptance (58%)

Search for $(^3\text{He-}\eta)_{bound}$ with WASA-at-COSY

Exp. 186.3, FZ Jülich, Germany 2014

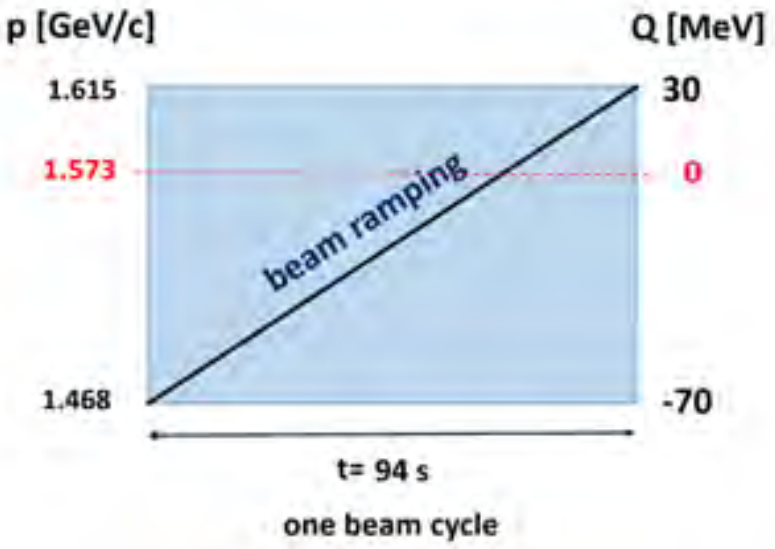
P. Moskal, W. Krzemien, M. Skurzok,
COSY proposal No. 186.3



$pd \to ppp\pi^-(ppn\pi^0, dp\pi^0)$

$pd \to {}^3\mathbf{He}2\gamma\ ({}^3\mathbf{He}6\gamma)$

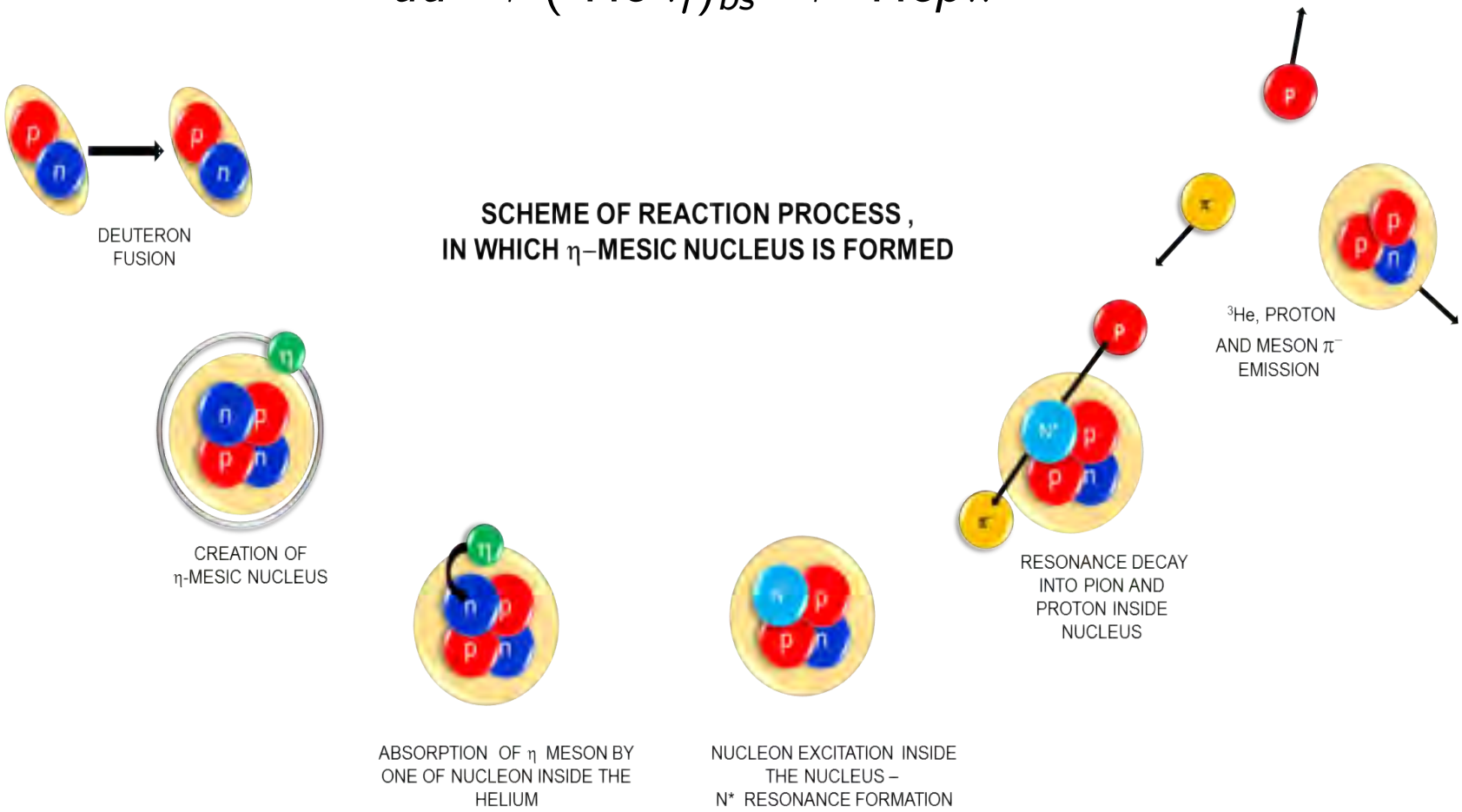
- **Measurement** with the **proton** beam momentum ramped and with the **deuteron** pellet target



- **Data** were effectively taken with high acceptance

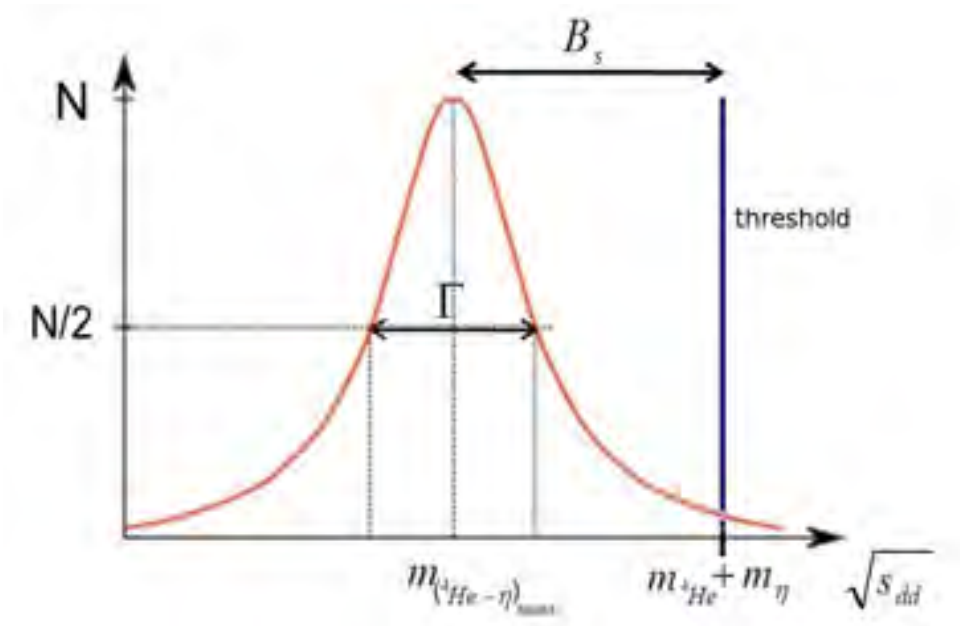
Kinematical mechanism of the reaction (via N^*)

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

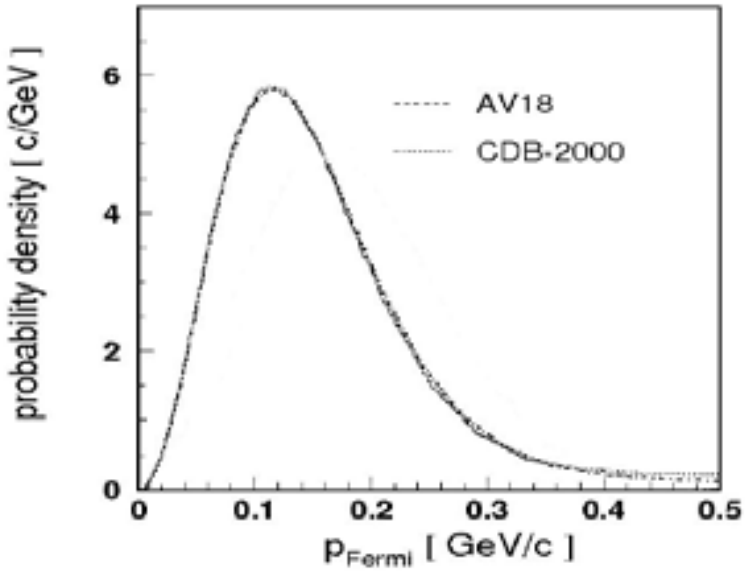


Simulation of $(^4\text{He-}\eta)_{bound}$ production and decay

Breit-Wigner distribution



Spectator Model



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

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

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

Experiment-Nov/Dec 2010

- **Channels:** $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$
  $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$
  (norm: $dd \to {}^3\text{He}n$ and $dd \to ppn_{sp}n_{sp}$)
- **Measurement:** beam momentum ramped from **2.127GeV/c to 2.422GeV/c** $\Rightarrow$ the range of excess energy **Q$\in$(-70,30)MeV**
- **Luminosity:** L=1200$\frac{1}{nb}$
- **Acceptance:** A=53%

$\Downarrow$

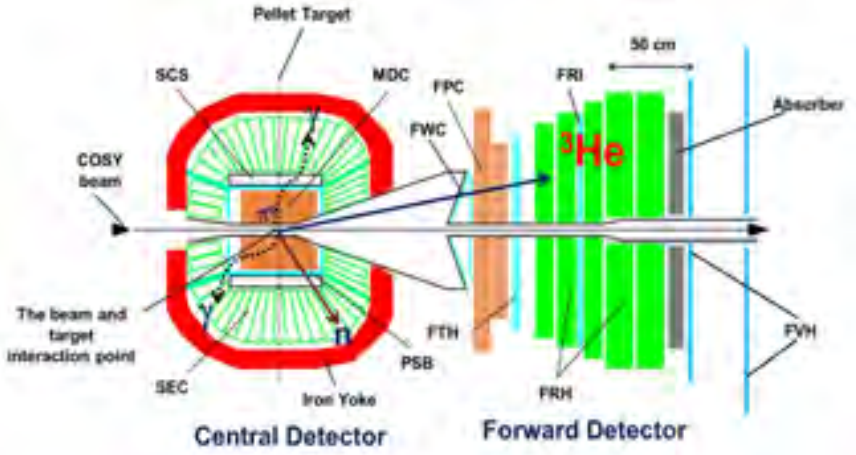
about 10 times higher statistics than in 2008

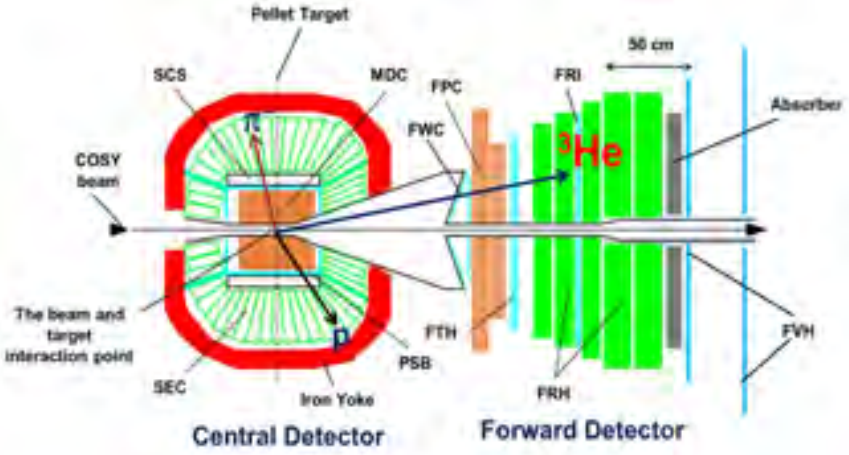
P. Adlarson et al., Phys. Rev. C87 (2013), 035204

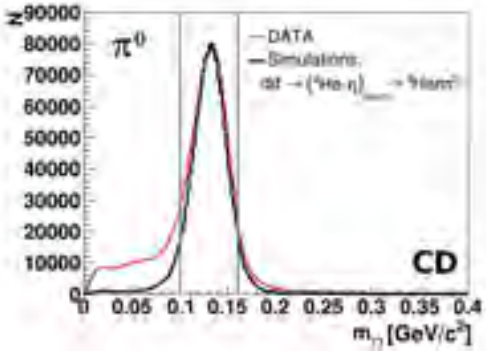
ANALYSIS:

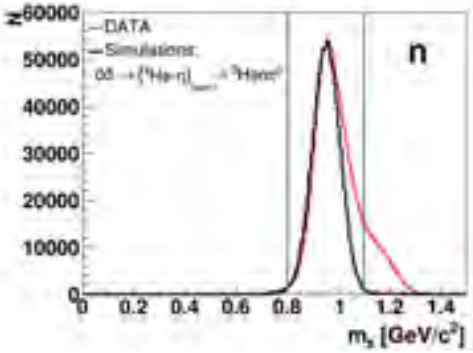
- Particles identification
- Selection bound state region
- Determination of excitation functions
- Determination the upper limit of the total cross section

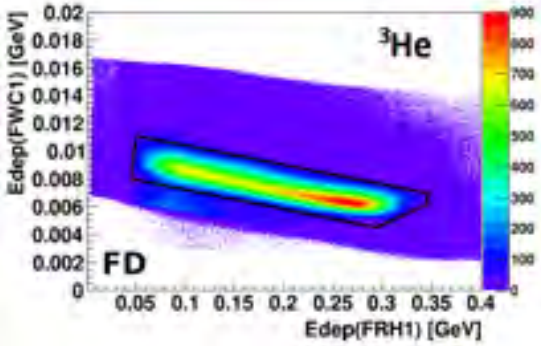
Search for $(^4\text{He-}\eta)_{bound}$ in $dd \to {}^3\text{He}N\pi$ reaction | PID

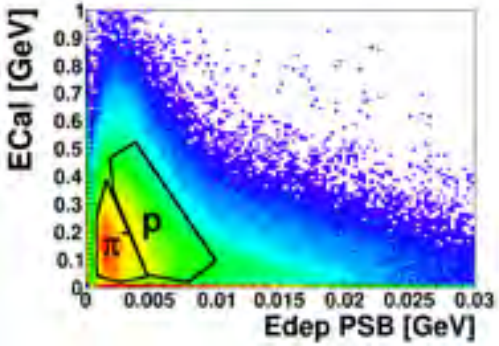


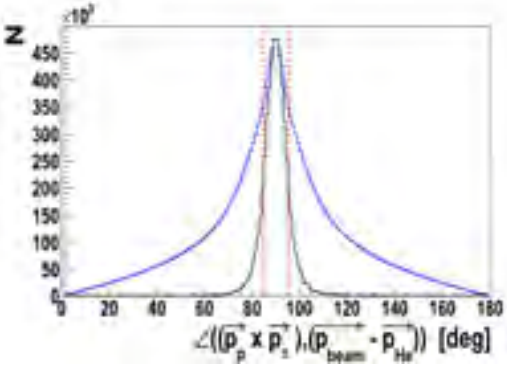




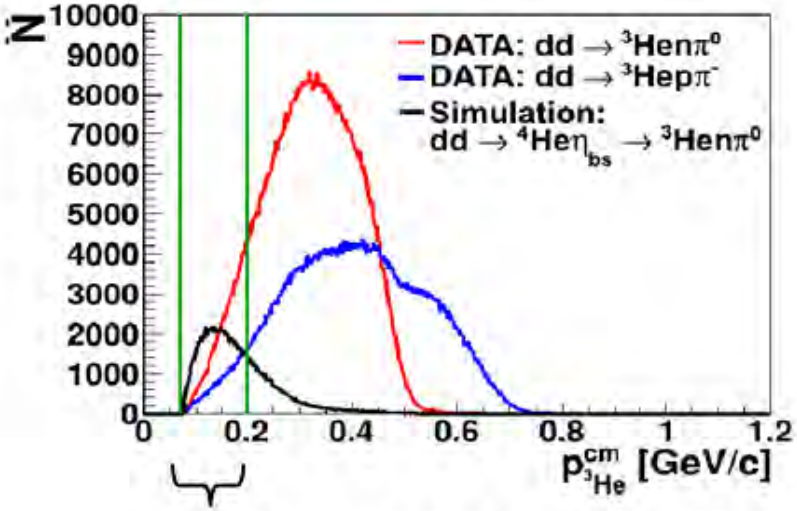




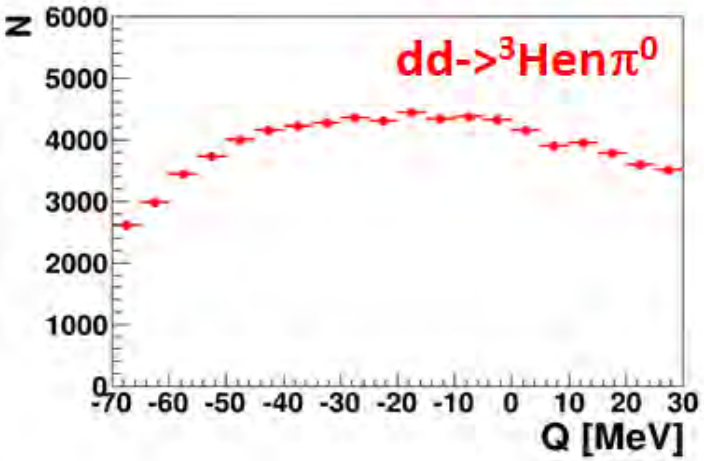


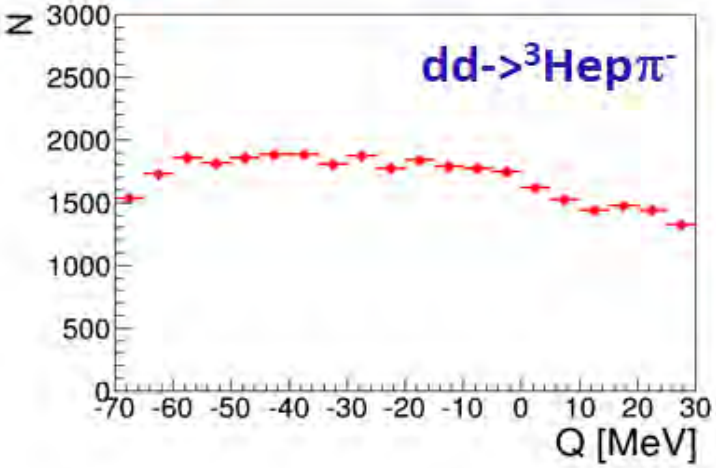


Determination of the excitation function



region rich in signal

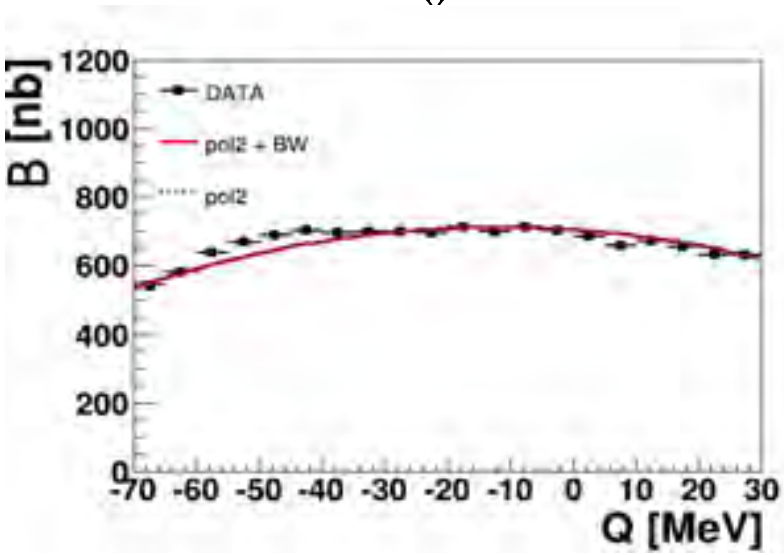




Determination of the upper limit of the total cross section for $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}N\pi$ processes at CL=90%

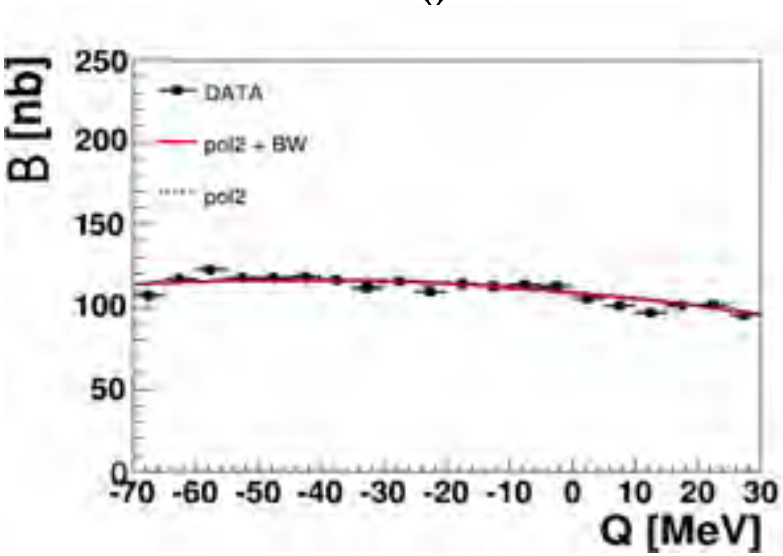
$dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$

$\Downarrow$



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

$\Downarrow$



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

Breit-Wigner (signal) + pol2 (background)

taking into account the **isospin relation** between the both of the considered channels:

$$P(N^* \to p\pi^-) = 2P(N^* \to n\pi^0)$$

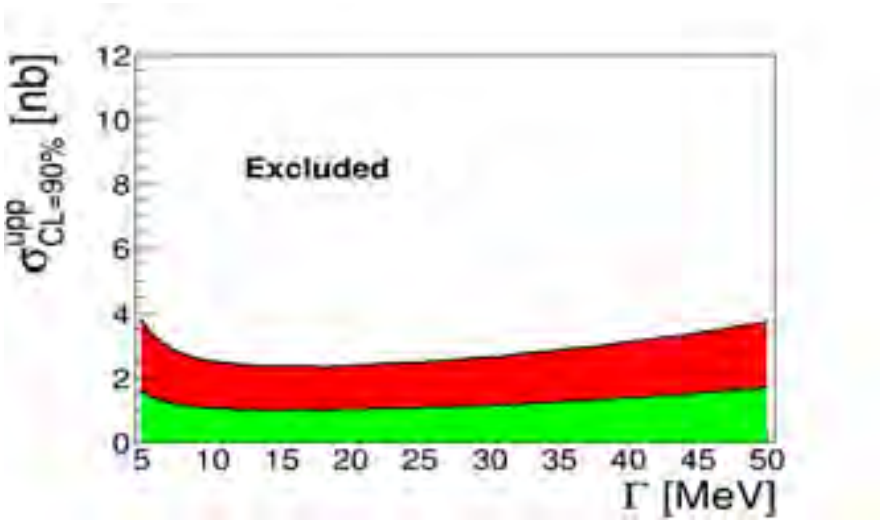
B_s,Γ - fixed parameters | A, B, C, D - free parameters || $\sigma^{upp}_{CL=90\%} = k \cdot \sigma_A$, k=1.64 (for CL=90%)

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

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

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

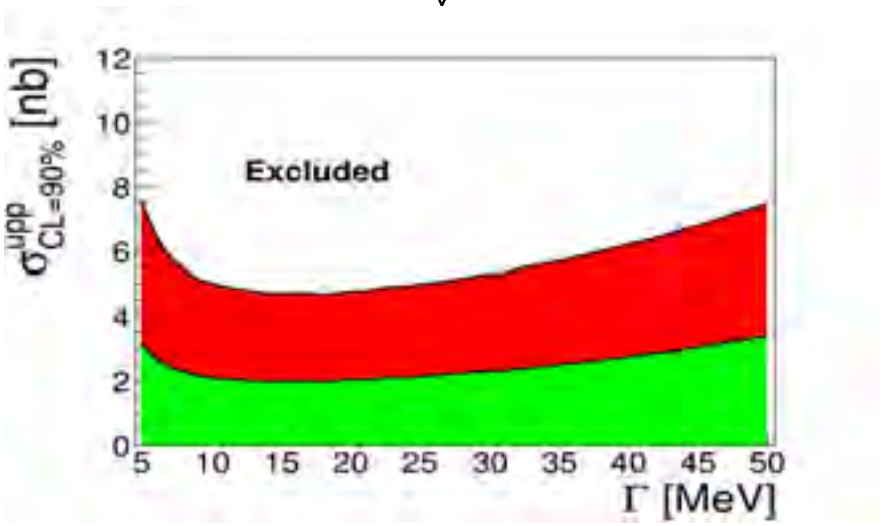
$\Downarrow$



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

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

$\Downarrow$



RESULT:

$\sigma_{dd \to ({}^4He-\eta)_{bound} \to {}^3He n\pi^0} < 3.5\ nb$

RESULT:

$\sigma_{dd \to ({}^4He-\eta)_{bound} \to {}^3He p\pi^-} < 7\ nb$

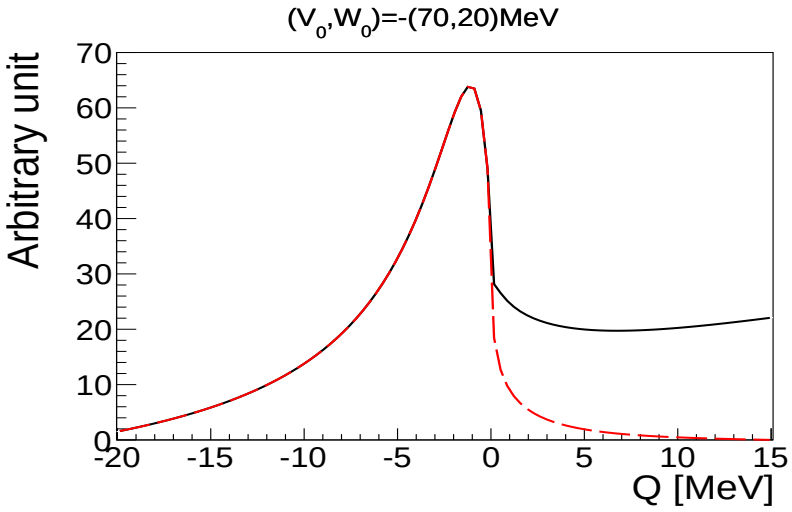
2008: $\sigma < 27\ nb$

P. Adlarson et al., Nucl. Phys. A 959, 102-115 (2017)

Comparison with N. Ikeno et al. model prediction

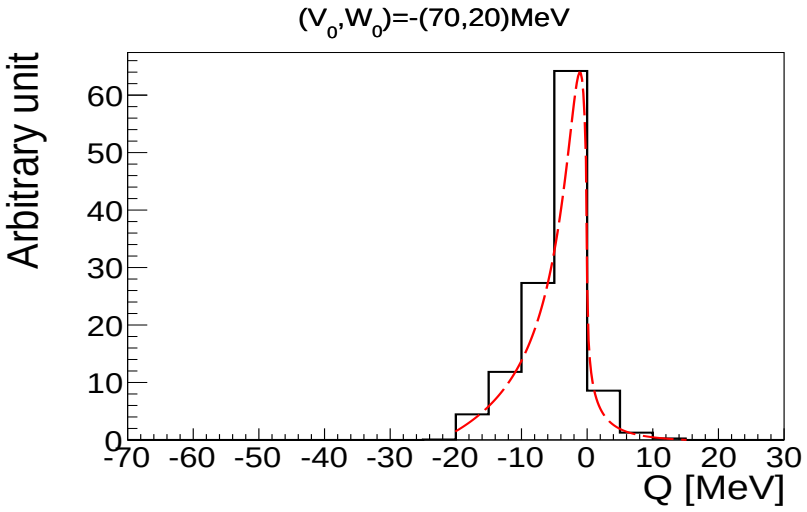
N. Ikeno, H. Nagahiro, D. Jido, S. Hirenzaki, Eur. Phys. J. A 53, 194 (2017)

- total cross sections for the $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}N\pi$ reaction determined based on phenomenological calculations
- the model reproduced the data on the $dd \rightarrow {}^4\text{He}\ \eta$ reaction quite well
- $\sigma = \sigma_{conv} + \sigma_{esc}$
- σ_{conv} - determined for different parameters V_0 and W_0 of a spherical η-^{4}He optical potential $V(r) = (V_0 + iW_0)\frac{\rho_\alpha(r)}{\rho_\alpha(0)}$ (the total cross section in the subthreshold excess energy region where the η meson is absorbed by the nucleus)
- normalization in the sense that the escape part reproduces the measured cross sections for the $dd \rightarrow {}^4\text{He}\eta$ process



σ —

σ_{conv} - -

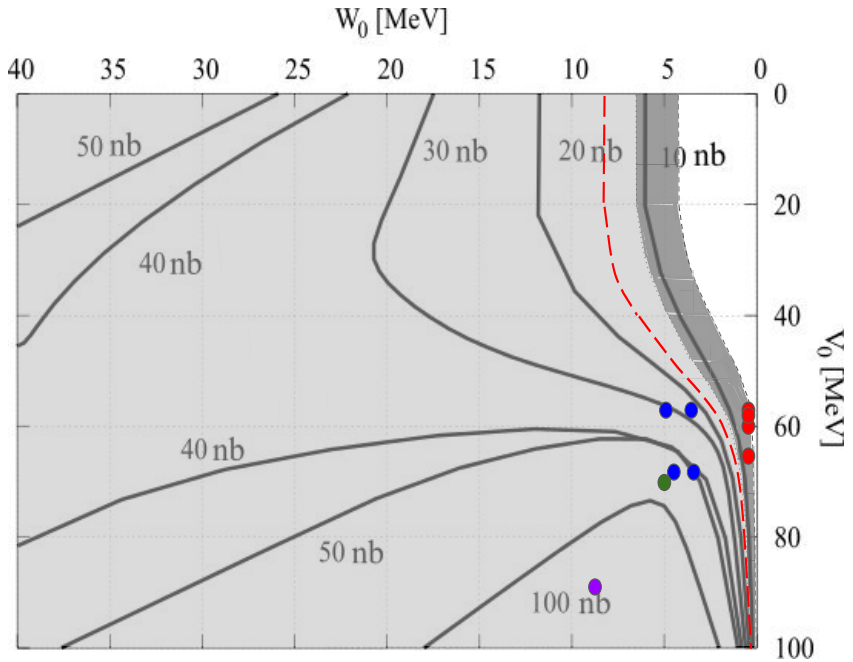


σ_{conv} spectrum convoluted with the experimental resolution functions

Comparison with N. Ikeno et al. model prediction

results obtained for different optical potential parameters (V_0, W_0)

V_0	W_0	A (fit) [nb]	$\sigma_{upp}^{CL=90\%}$ [nb]
-30	-5	-5.0±3.9	6.5
-30	-20	-2.2±3.5	5.8
-30	-40	0.2±3.8	6.3
-50	-5	0.1±3.8	6.3
-50	-20	3.3±4.1	6.8
-50	-40	6.0±4.2	6.9
-70	-5	6.4±4.5	7.4
-70	-20	7.9±4.5	7.4
-70	-40	7.5±3.7	6.1
-100	-5	6.3±4.5	7.4
-100	-20	6.9±3.9	6.4
-100	-40	5.3±3.1	5.2

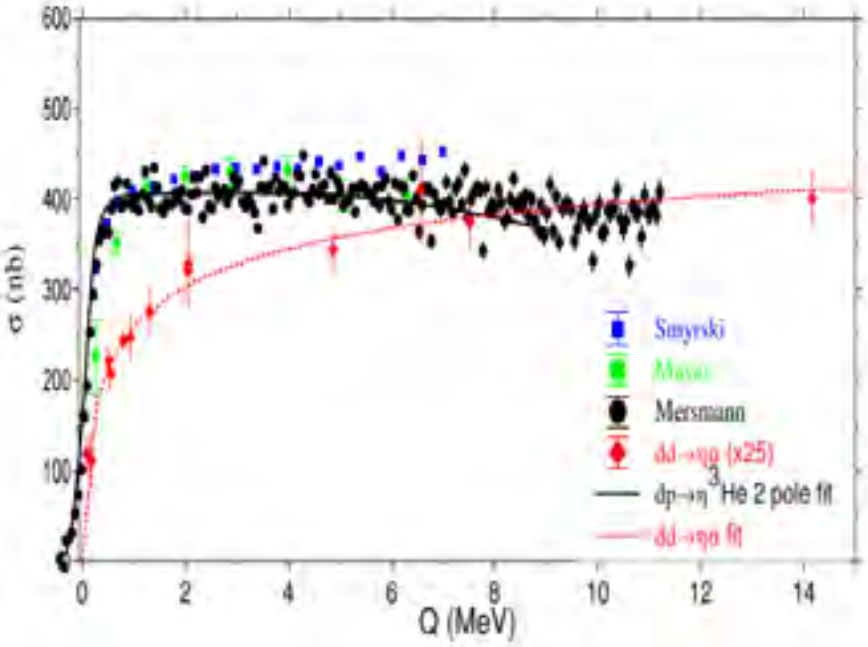


Contour plot of the theoretically determined conversion cross section in $V_0 - W_0$ plane.

The allowed parameter space ($|V_0| <\sim 60$ MeV and $|W_0| <\sim 7$ MeV) excludes most optical model predictions of $\eta-^4$He nuclei except for some loosely bound narrow states.

M. Skurzok, P. Moskal, et al., Phys. Lett. B 708, 6 (2018)

Search for $(^3\text{He-}\eta)_{bound}$ with WASA-at-COSY



$$\sigma_{pd\to^3He-\eta} \approx 25\sigma_{dd\to^4He-\eta}$$

About 2 weeks of measurement allowed us to reach sensitivity of **few nb** ($L \approx 4500\frac{1}{nb}$)

Measurement: p_{beam} : 1.468-1.615GeV/c, **Q∈(-70,30)MeV**

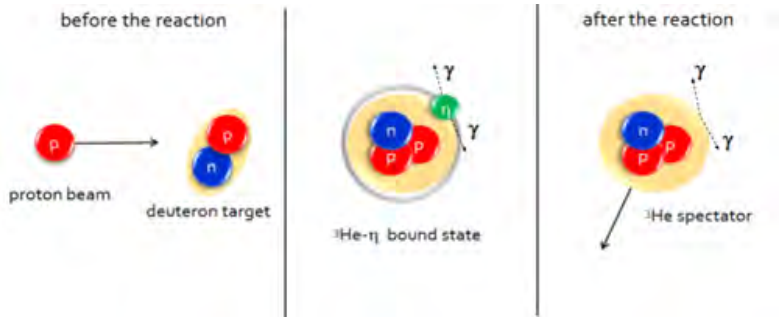
Channels:

- **Via the resonance decay N^*:**
  1) $pd \to (^3\text{He-}\eta)_{bound} \to pp\pi^-$
  2) $pd \to (^3\text{He-}\eta)_{bound} \to pn\pi^0$
  3) $pd \to (^3\text{He-}\eta)_{bound} \to dp\pi^0$

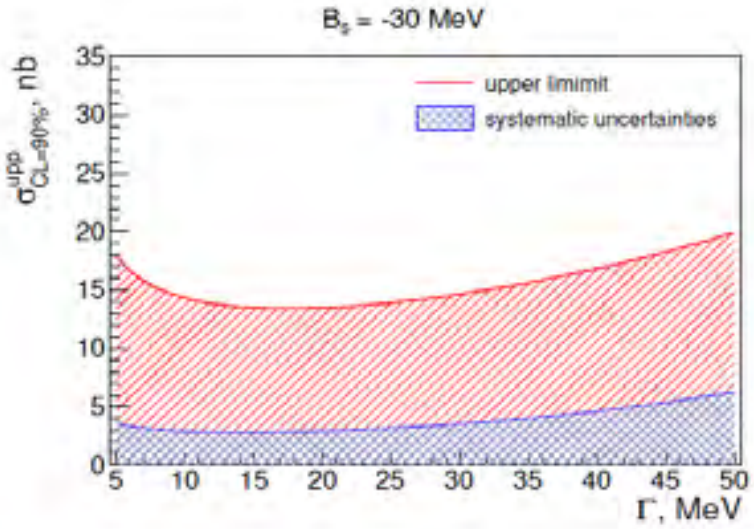
  Aleksander Khreptak PhD

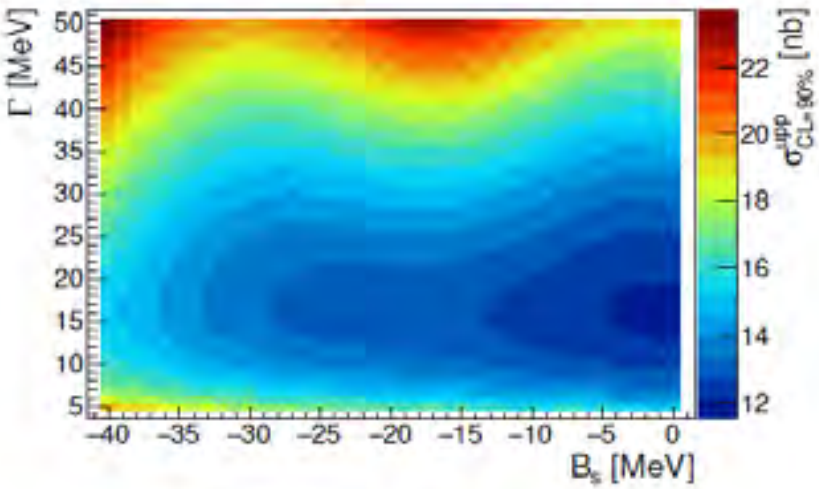
- **Absorption of orbiting η**
  4) $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 2\gamma$
  5) $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 6\gamma$

  Oleksandr Rundel PhD



Upper limit of the total cross section





Result

$$13\ nb \leq \sigma^{upp}_{pd\to(^3\text{He-}\eta)_{bound}\to dp\pi^0} \leq 24\ nb$$

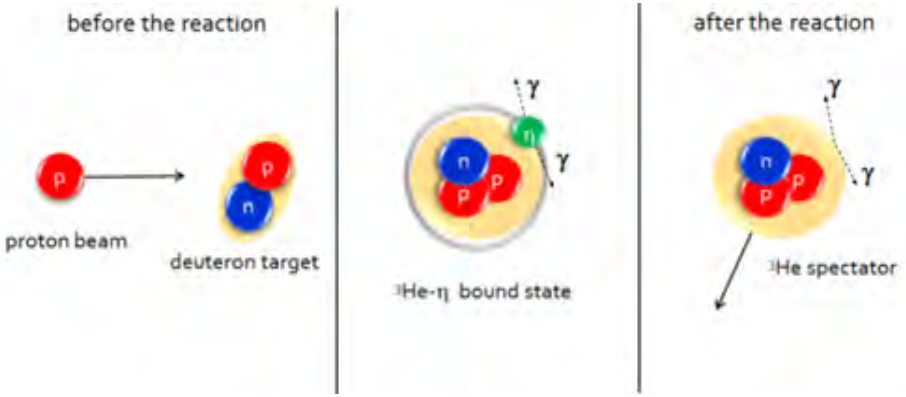
P. Adlarson et al., Phys. Rev. C 102, 044322 (2020)

Previous result:

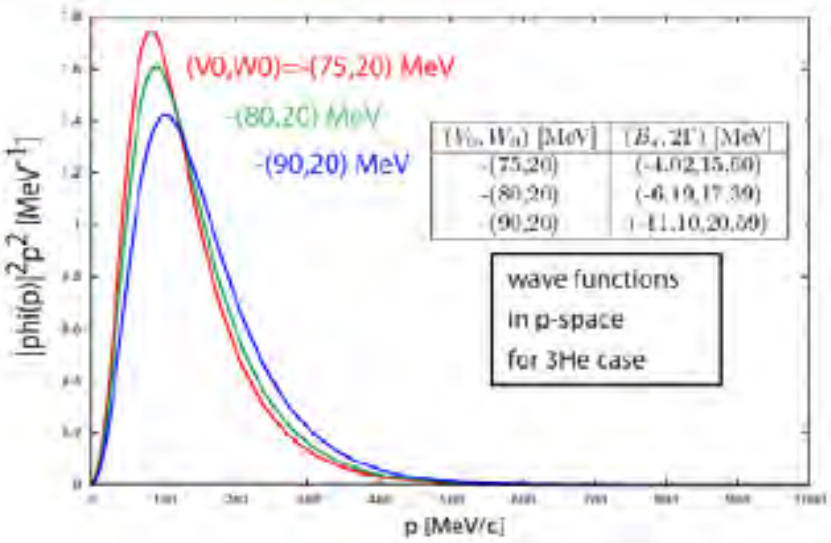
COSY-11 $\sigma_{pd\to(^3He-\eta)_{bound}\to^3He\pi^0} < 70\ nb$

J. Smyrski et al., Nucl. Phys. A 790 (2007) 438

Simulation of $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 2\gamma(6\gamma)$



- **^{3}He is spectator** $|\mathbb{P}_{^3He}|^2 = m^2_{^3He}$
- **Fermi momentum distribution of the η meson in ^{3}He-η bound system**



- **bound η decays to 2γ or $3\pi^0$**

M. Skurzok et al., Nucl. Phys. A 993, 121647 (2020)

Structure of hypothetical ^{3}He-η bound state can be described as a solution of Klein-Gordon equation:

$$\left[-\vec{\nabla}^2 + \mu^2 + 2\mu U_{opt}(r)\right]\psi(\vec{r}) = E^2_{KG}\psi(\vec{r})$$

where: E_{KG} - Klein -Gordon energy, μ - ^{3}He-η reduced mass

optical potential:

$$U_{opt}(r) = (V_0 + iW0)\frac{\rho(r)}{\rho_0}$$

where: $\rho(r)$ - density distr. for ^{3}He, ρ_0 - normal nuclear density

KG equation solved for several sets of (V_0, W_0)

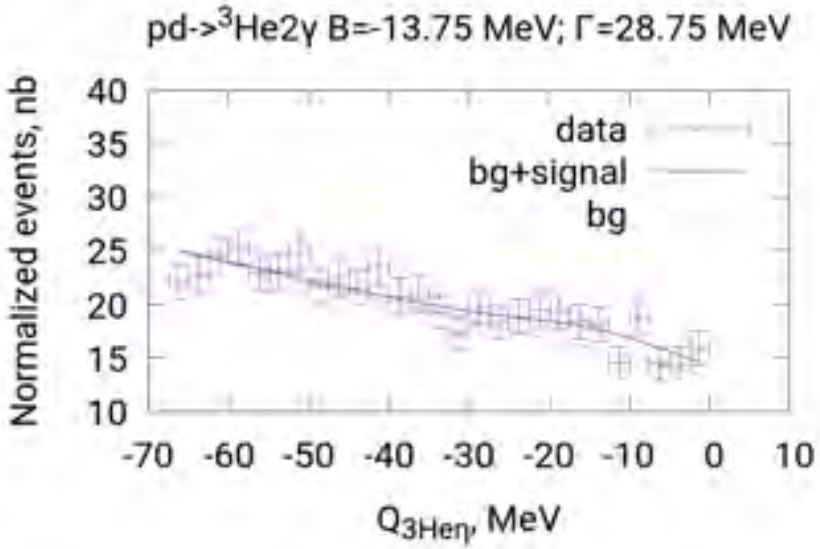
$$\Downarrow$$

$$E_{KG},\ \psi(\vec{r})$$

Determination of the upper limit of the total cross section for $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma(6\gamma)$ processes at CL=90%

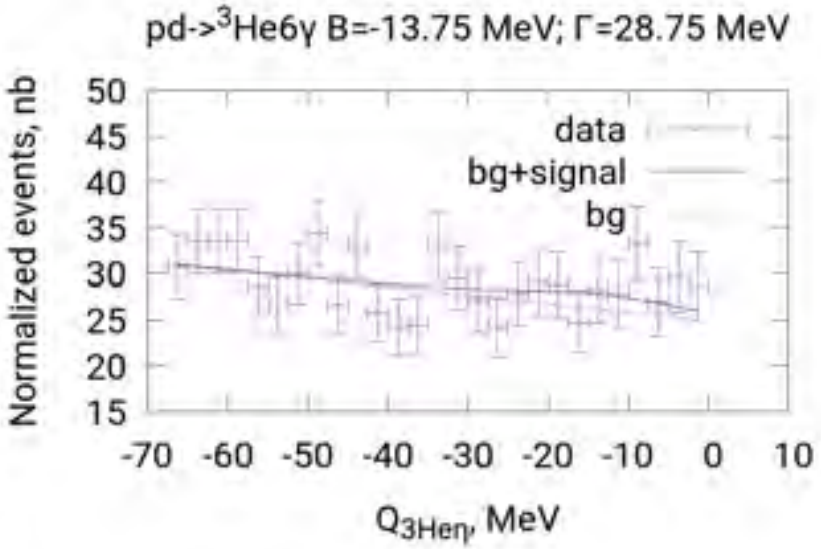
$pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma$

$\Downarrow$



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

$\Downarrow$



simultaneous fit with $P_{\eta decay} \frac{A \cdot \Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4} + BQ + C$

Breit-Wigner (signal) + pol2 (background)

where $P_{\eta decay}$ are branching ratios for η decays:
$P_{\eta \to 2\gamma}$=0.3941, $P_{\eta \to 3\pi^0}$=0.3268

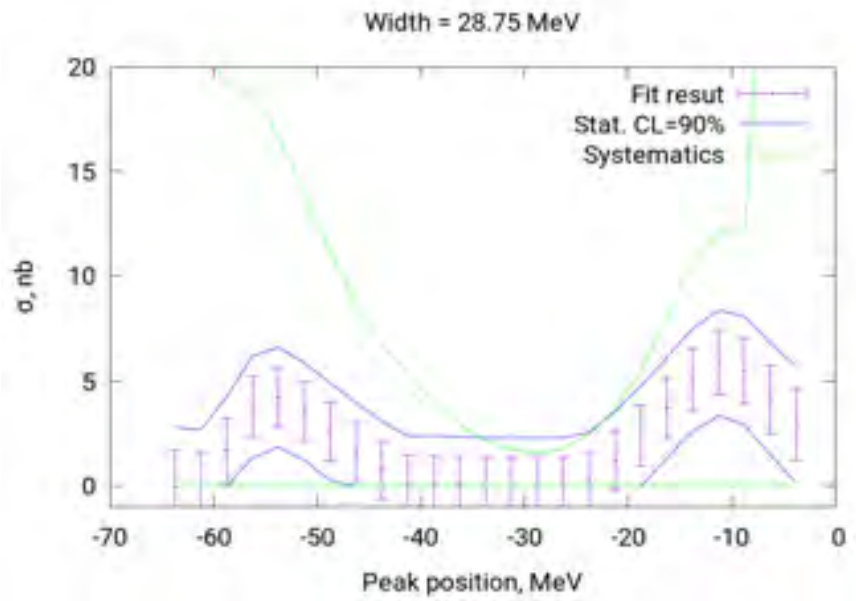
B_s,Γ - fixed parameters | A, B, C - free parameters || $\sigma^{upp}_{CL=90\%} = A + k \cdot \sigma_A$, k=1.64(for CL=90%)

Determination of the upper limit of the total cross section for $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma(6\gamma)$ process at CL=90%

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

$pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma(6\gamma)$

$\Downarrow$



RESULT:

$\sigma_{pd \to (^3He-\eta)_{bound} \to {}^3He2\gamma(6\gamma)} < 15\ nb$

INDICATION:-)

slight indication of the signal from the bound state for $\Gamma > 20$ MeV and $B_s \in (0, 15)$ MeV

$\Downarrow$

However, the observed indication is within the range of the systematic error

$\Downarrow$

we cannot make a definite conclusion here on possible bound state formation

Previous result:

COSY-11

$\sigma_{pd \to (^3He-\eta)_{bound} \to {}^3He\pi^0} < 70\ nb$

J. Smyrski et al., Nucl. Phys. A 790 (2007) 438

P. Adlarson et al., Phys. Lett. B 802, 135205 (2020)

Summary of the search for η-mesic Helium at WASA

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

- **2008**: $dd \to {}^3\text{He}p\pi^-$ reaction

$\sigma_{dd\to(^4He-\eta)_{bound}\to^3Hep\pi^-} < 27\ nb$

- **2010**: $dd \to {}^3\text{He}n\pi^0$ and $dd \to {}^3\text{He}p\pi^-$ reactions

$\sigma_{dd\to(^4He-\eta)_{bound}\to^3Hep\pi^-} < 7\ nb$

$\sigma_{dd\to(^4He-\eta)_{bound}\to^3Hen\pi^0} < 3.5\ nb$

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

- **2014**: $pd \to {}^3\text{He}2\gamma$ and $pd \to {}^3\text{He}6\gamma$ reactions

$\sigma_{pd\to(^3He-\eta)_{bound}\to^3He2\gamma(6\gamma)} < 15\ nb$

- **2014**: $pd \to dp\pi^0$ reaction

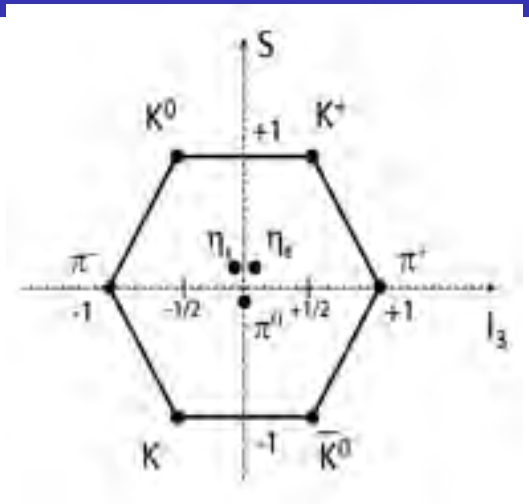
$\sigma_{pd\to(^3He-\eta)_{bound}\to dp\pi^0} < 24\ nb$

Thank you for attention

Properties of η meson

mass	547.862 ± 0.017 MeV
width	1.31 ± 0.05 keV
$I^G(J^{PC})$	$0^+(0^{-+})$
η is an eigenstate to	P, C, G and CP
C $\|\eta>$=+1 $\|\eta>$	P $\|\eta>$=-1 $\|\eta>$
Decay modes	**Branching ratio**
Charged modes	28.10±0.34 %
$\eta \to \pi^+\pi^-\pi^0$	22.92±0.28 %
$\eta \to \pi^+\pi^-\gamma$	4.22±0.16 %
other modes	0.76 %
Neutral modes	72.912±0.34 %
$\eta \to 2\gamma$	39.41±0.20 %
$\eta \to 3\pi^0$	32.68±0.23 %
other modes	0.03 %

P. A. Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).



$\eta_1 = \frac{1}{\sqrt{3}}(d\bar{d} + u\bar{u} + s\bar{s})$,
$\eta_8 = \frac{1}{\sqrt{6}}(d\bar{d} + u\bar{u} - 2s\bar{s})$.

The observed η particle is the combination of the η_1 and η_8 states:

$|\eta>= \eta_8 cos\theta - \eta_1 sin\theta$, θ = -15.5°±1.3°

Hadronic decays (3π) (isospin breaking: $m_u - m_d$)

Radiative decays ($\gamma\gamma$ ($\pi\pi$))

(Semi-) leptonic decays (l l (γ))

$\eta \to e^+e^-\gamma$

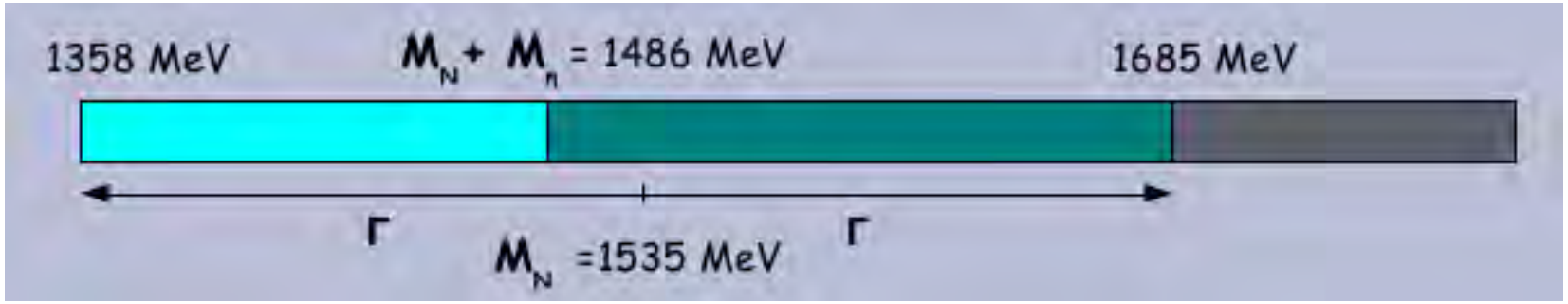
$\eta \to e^+e^-e^+e^-$

η interaction with nucleon

For low energies η-N interaction dominated by N^*

N^* resonance: $m_N^* \approx$1535MeV $\Gamma \approx$150MeV $J^P = \frac{1}{2}^-$

Main decay channels:
$N^* \to \pi N$ (35-55 %)
$N^* \to \eta N$ (30-55 %)
$N^* \to \pi\pi N$ (1-10 %)



impossible to create the η beams $\Rightarrow$ η-N studies based on the investigation of ηN scattering amplitude for the processes like πN $\to$ ηN, γN $\to$ ηN $\Rightarrow$ N^* domination (coupled mainly to ηN and πN)

Coupled channel calculations $\Rightarrow$ fit to available experimental data

Motivation

- Search for new kind of nuclear matter
- Investigation of η interaction with nucleons inside a nuclear matter
- Information about η meson structure:
  the η meson binding inside nuclear matter is very sensitive to the singlet component (η-η' mixing) in the wave function of the η meson
  η-η' mixing $\Rightarrow$ binding increase

  S. D. Bass and P. Moskal, Rev. Mod. Phys. 91, 015003 (2019)
  S. D. Bass, A. W. Thomas, Phys. Lett. B634, 368 (2006)

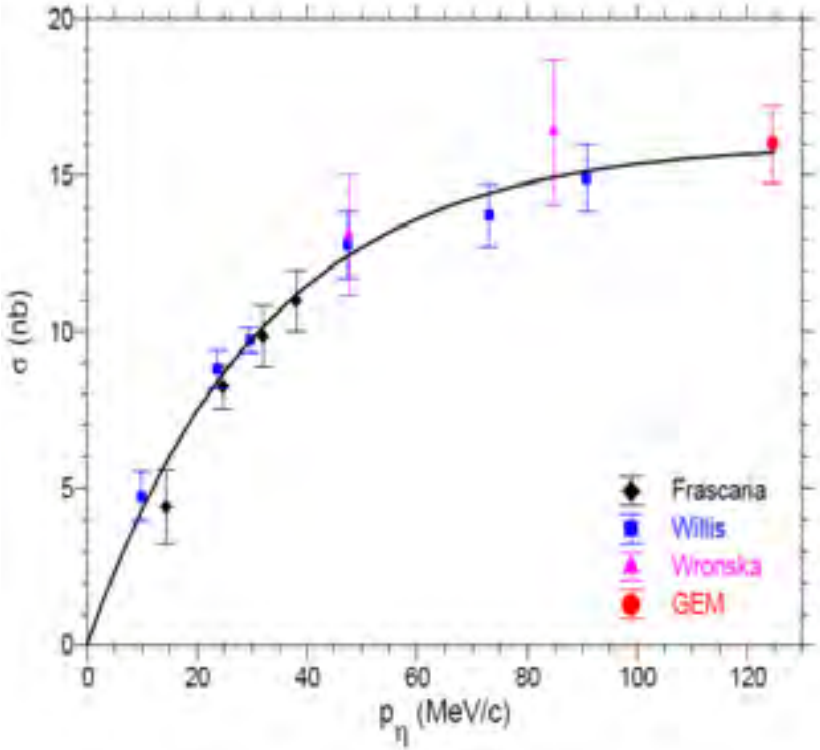
  S. Hirenzaki, H. Nagahiro, Acta Phys. Polon. B45, 619 (2014)
- Study of N*(1535) properties in medium (probe of testing different N*(1535) models)

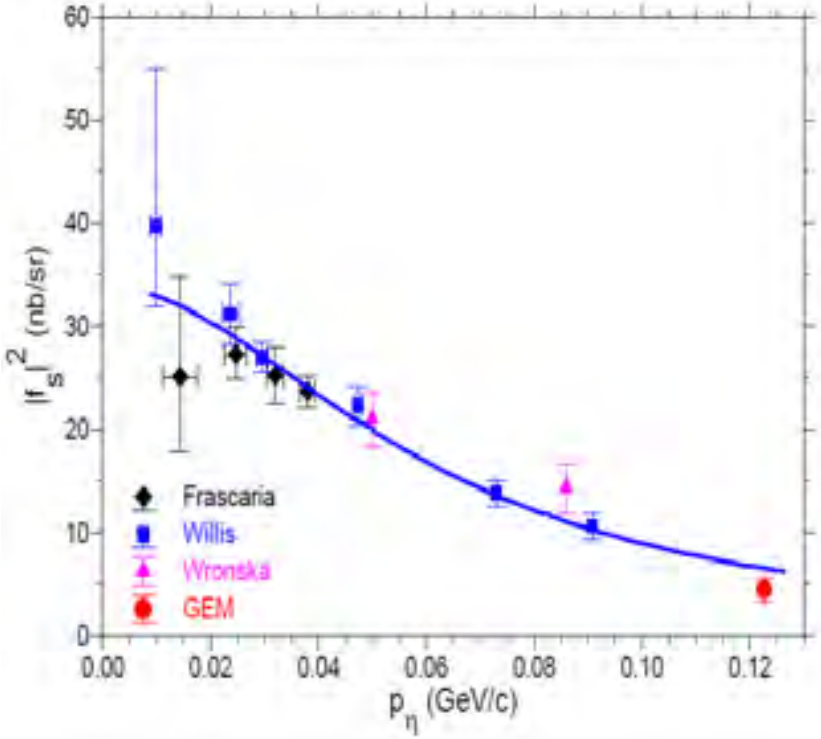
  S. Hirenzaki et al., Acta Phys. Polon. B41, 2211 (2010)
  D. Jido, H. Nagahiro, S. Hirenzaki, Phys. Rev. C66, 045202 (2002)

  Z.-W. Liu et al., Phys. Rev. Lett. 116, 082004 (2016)

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

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

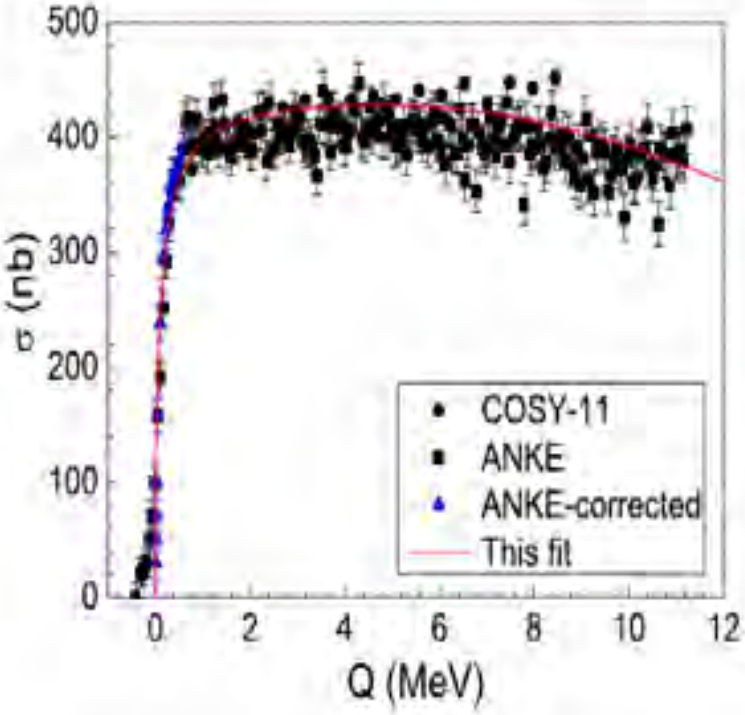


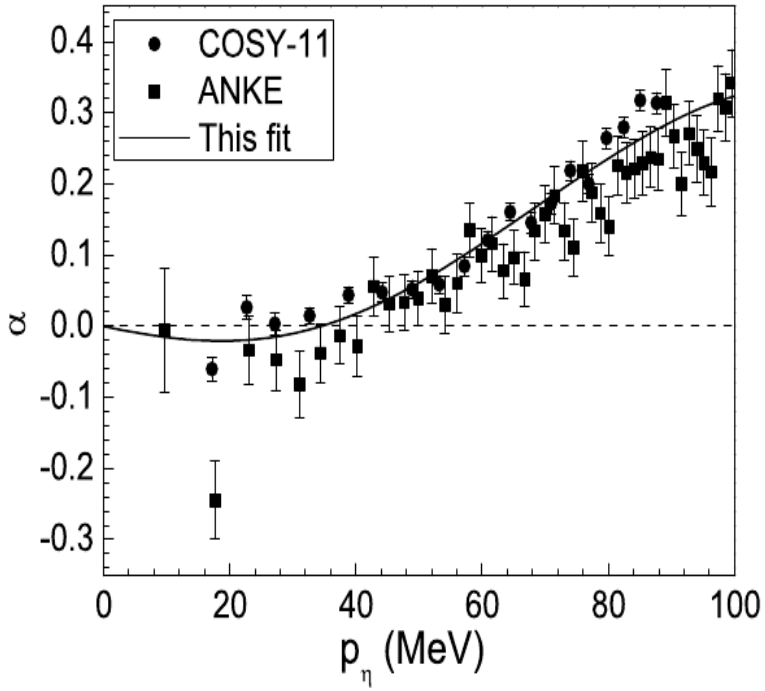


R. Frascaria et al., Phys. Rev. C50, 573 (1994)
N. Willis et al., Phys. Lett. B406, 14 (1997)
A. Wronska et al., Eur. Phys. J. A26, 421428 (2005)
A. Budzanowski et al., Nucl. Phys. A821, 193 (2009)

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

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





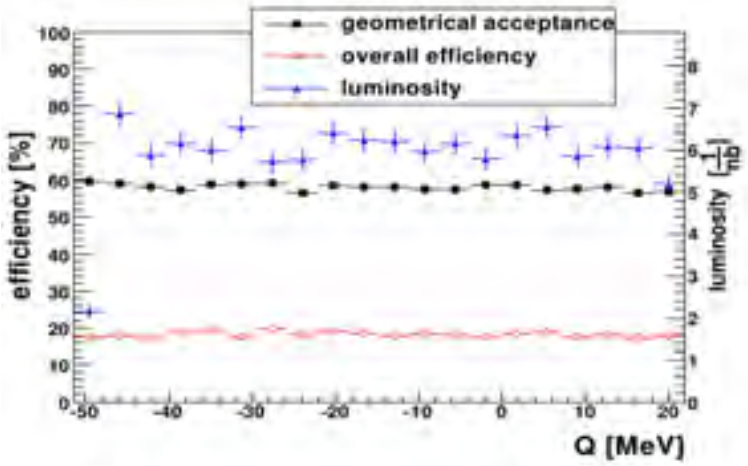
$\Downarrow$

J.-J. Xie, et al., Phys. Rev. C 95, 015202 (2017)

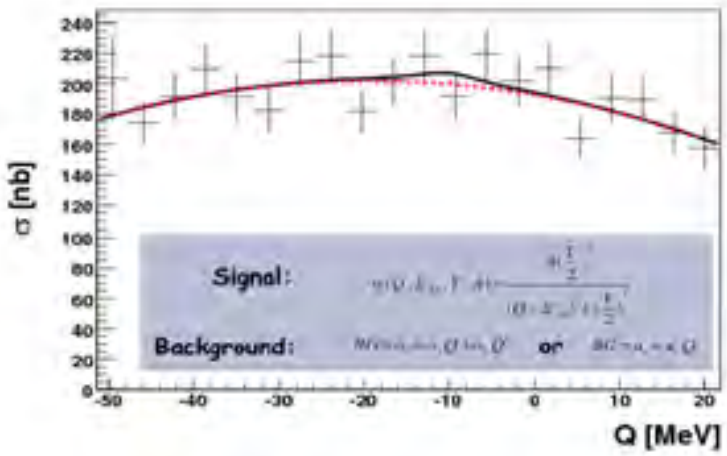
"weakly bound ^{3}He-η state with binding energy *of the order of* 0.3 MeV *and a* width *of the order of* 3 MeV*", $a_{\eta 3He} = [-(2.23 \pm 1.29) - i(4.89 \pm 0.57)]$ fm*

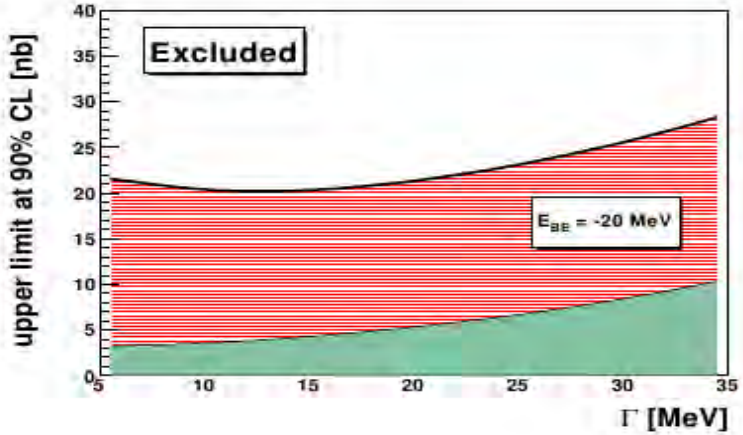
Experiment-May 2008

- **Channel:** $dd \to ({}^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$ (norm: $dd \to {}^3\text{He}n$)
- **Measurement:** beam momentum ramped from **2.185GeV/c to 2.400GeV/c** $\Rightarrow$ the range of excess energy **Q∈(-51,22)MeV**
- **Luminosity:** L=118$\frac{1}{nb}$
- **Acceptance:** A=53%



Excitation function



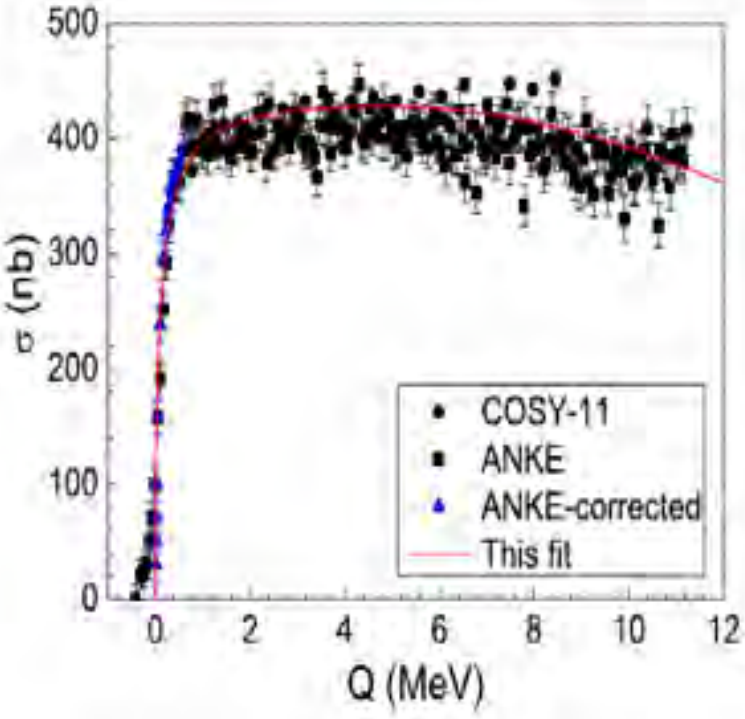


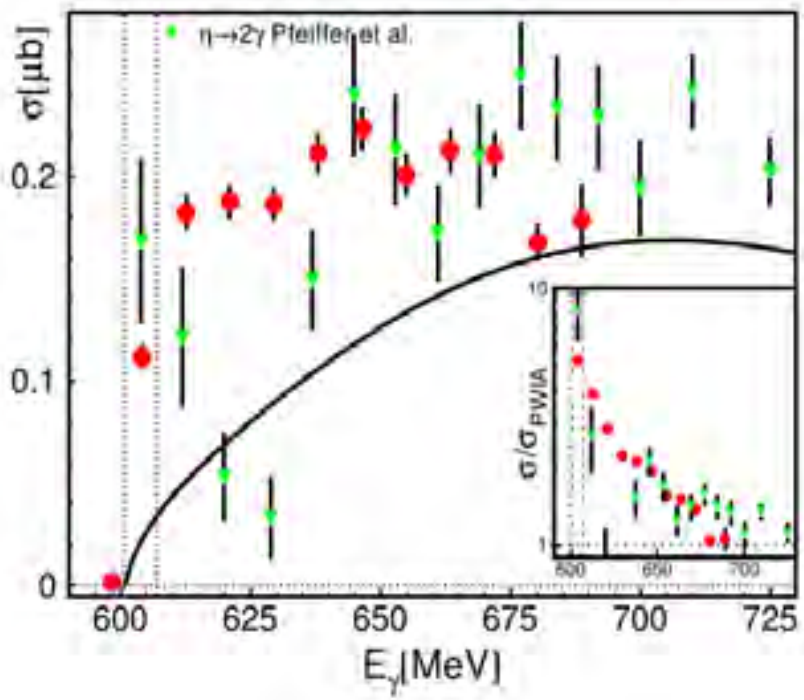
P. Adlarson et al., Phys. Rev. C87 (2013), 035204
W. Krzemien, Ph. D Thesis, Jagiellonian University (2012)

RESULT: $\sigma_{dd\to({}^4He-\eta)_{bound}\to{}^3Hep\pi^-} < 27\ nb$

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

total cross section $pd \to {}^3\text{He}\text{-}\eta$ $\gamma^3\text{He} \to {}^3\text{He}\text{-}\eta$

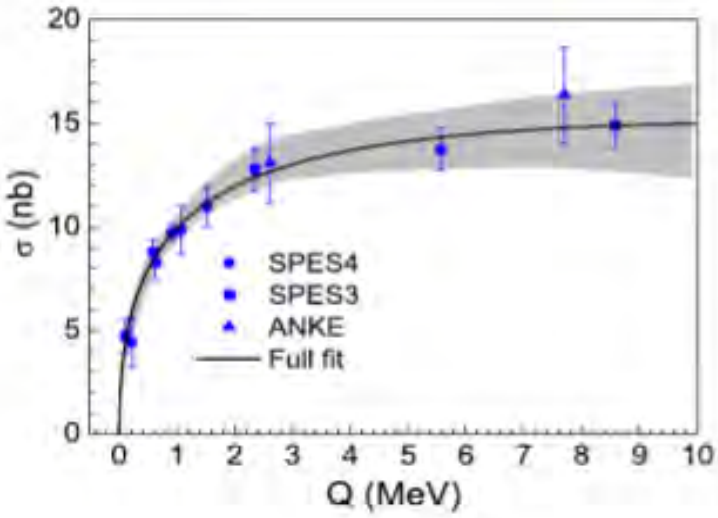


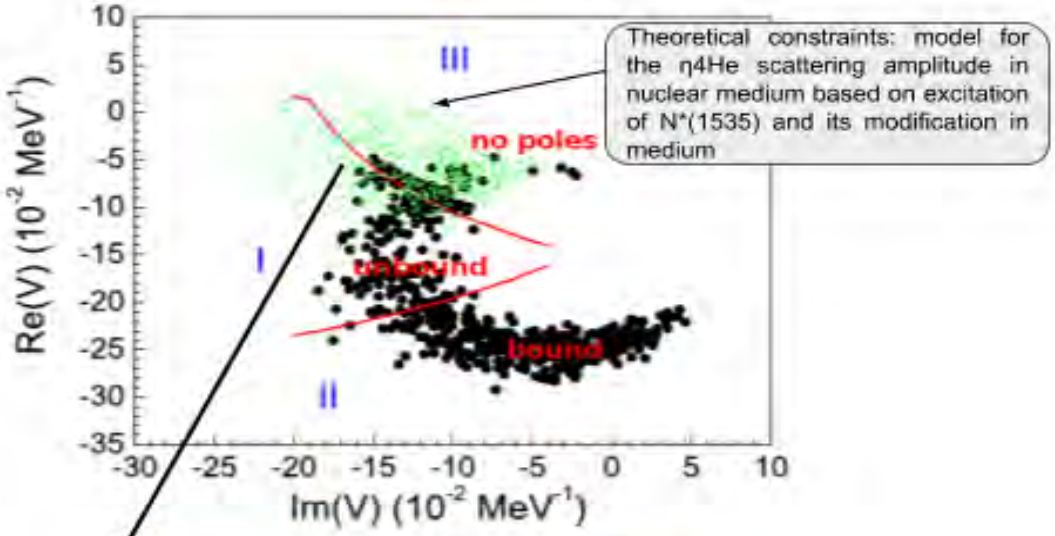


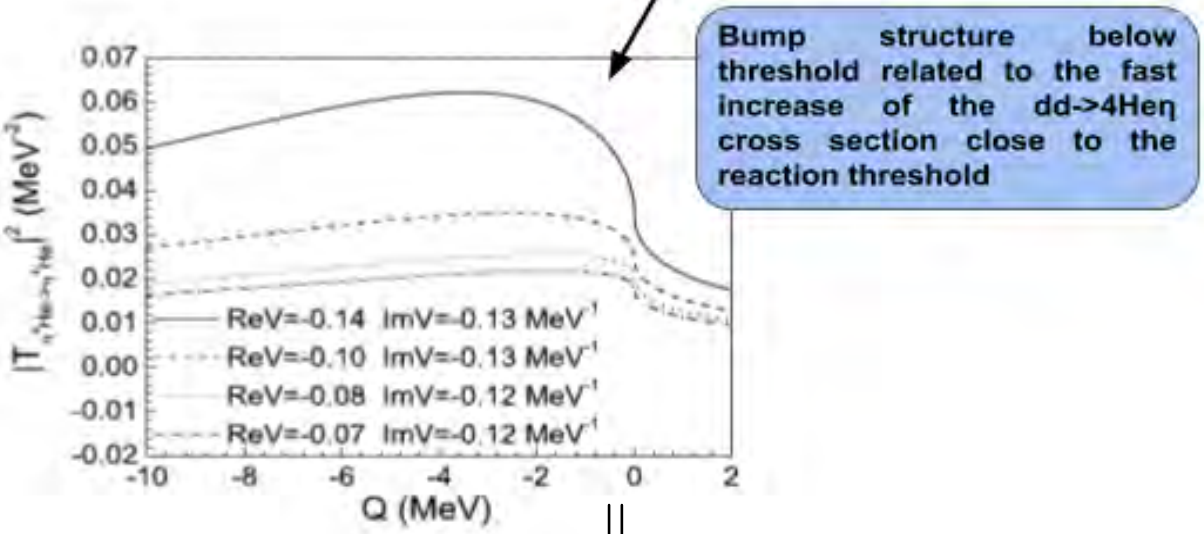
$\Downarrow$

J. Smyrski, et al., Phys. Lett. 649, 258 (2007)
T. Mersmann, et al., Phys. Rev. Lett. 98, 242301 (2007)
J.-J. Xie, et al., Phys. Rev. C 95, 015202 (2017)
B. Krusche, C. Wilkin, Prog. Part. Nucl. Phys. 80, 43 (2014)

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



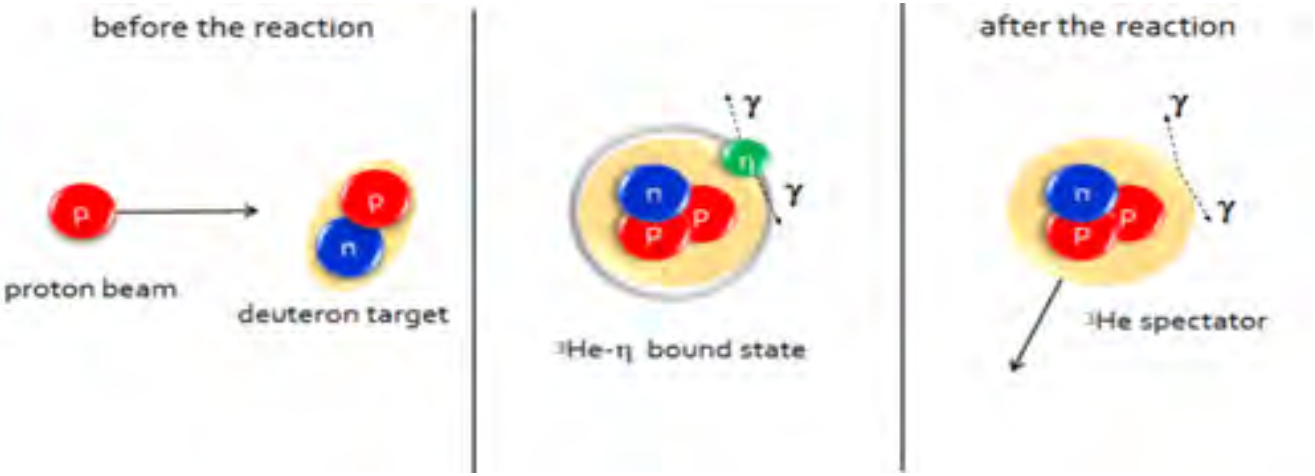


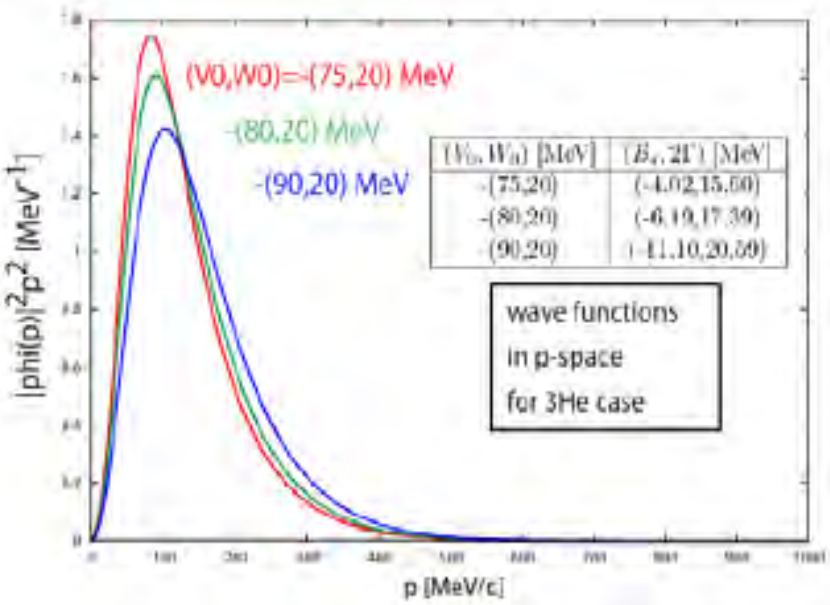


⇓

J.-J. Xie et al., Eur. Phys. J. A55 no.1, 6 (2019)

Analysis of $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 2\gamma$ process





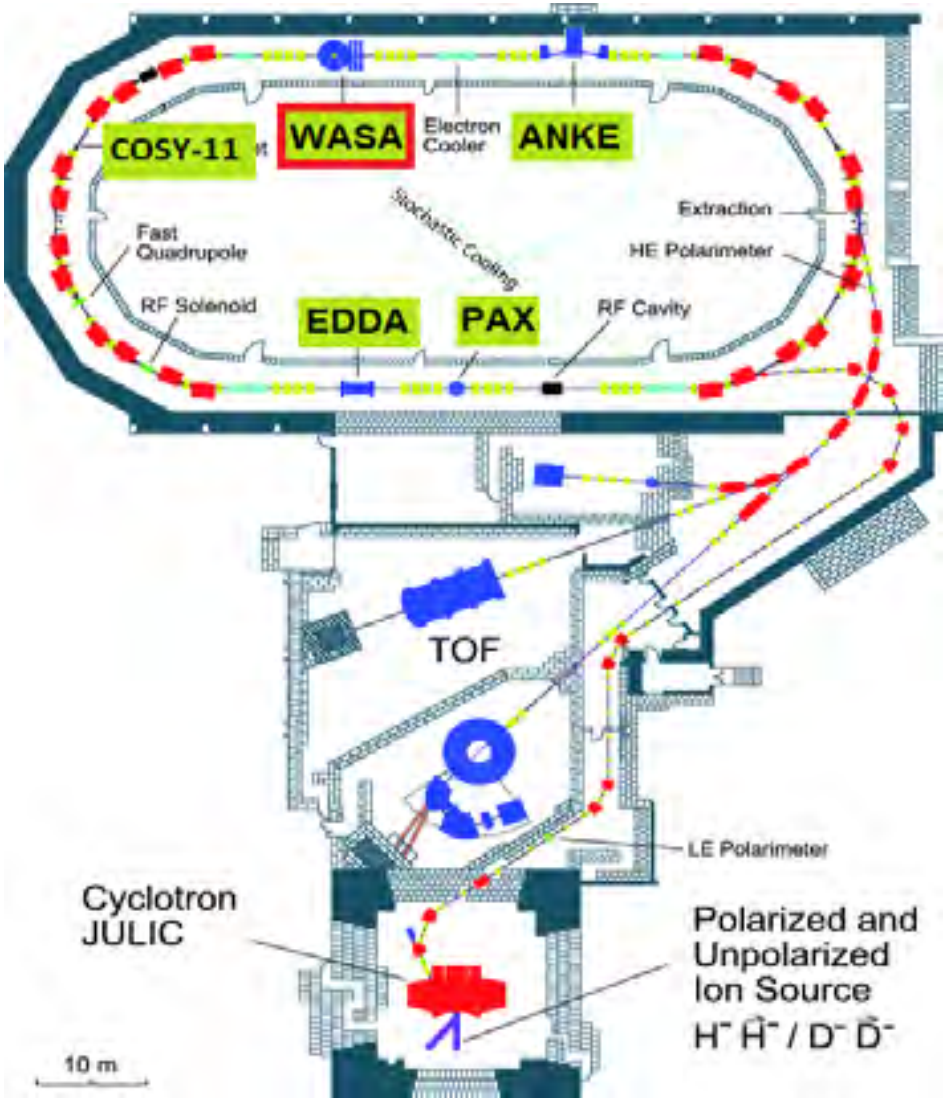
S. Hirenzaki, H. Nagahiro, Private communication (2016)

- ^{3}He spectator
- $P_{^3He}$: $p_{^3He} = \sqrt{m^2_{^3He} + p^2_{fermi}}$, distributed isotropically
- $P_{\eta_{bound}} = P_p + P_d - P_{^3He} \Rightarrow m_{\eta_{bound}} = |P_{\eta_{bound}}|$

Forschungszentrum Jülich, Germany

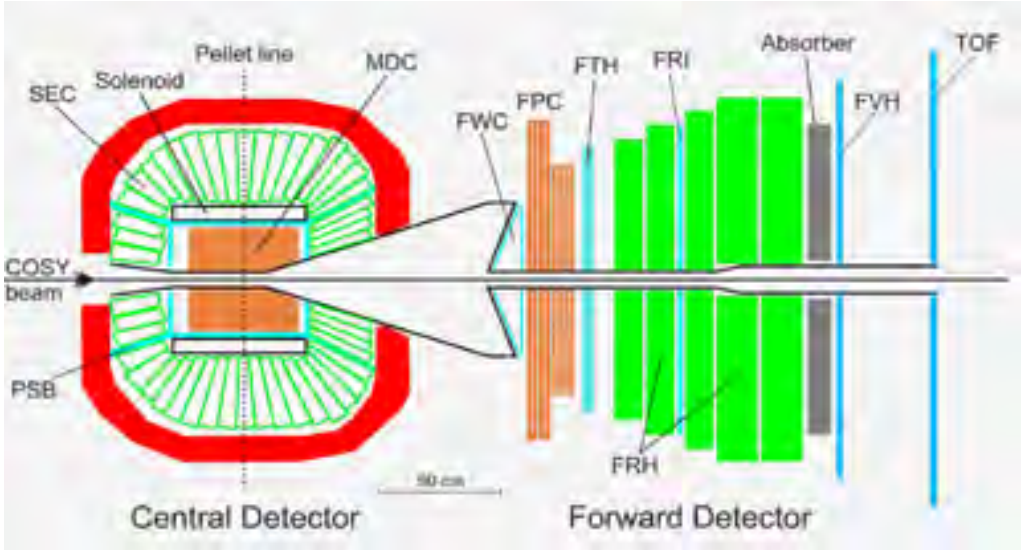
COoler SYnchrotron COSY

COoler SYnchrotron COSY



- 184 m circumference cooler synchrotron
- Polarized and unpolarized proton and deuteron beam
- Momentum range 0.3 - 3.7 GeV/c
- Stochastic and electron cooling
- 10^{11} particles in ring - luminosities 10^{31} - 10^{32} $cm^{-2}s^{-1}$
- Ramped beam (search for η-mesic nuclei)

WASA-at-COSY experiment



- **Pellet Target**
  ▶ frozen pellets of hydrogen or deuterium

- **Forward Detector**
  ▶ identification of heavier projectiles and target-recoil particles such as p, d and He in forward direction

  ▶ angular information about the particles provided by FPC

  ▶ PID based on measurement of energy loss in scintillators

- **Central Detector**
  ▶ charged particles momenta reconstructed in magnetic field (MDC)

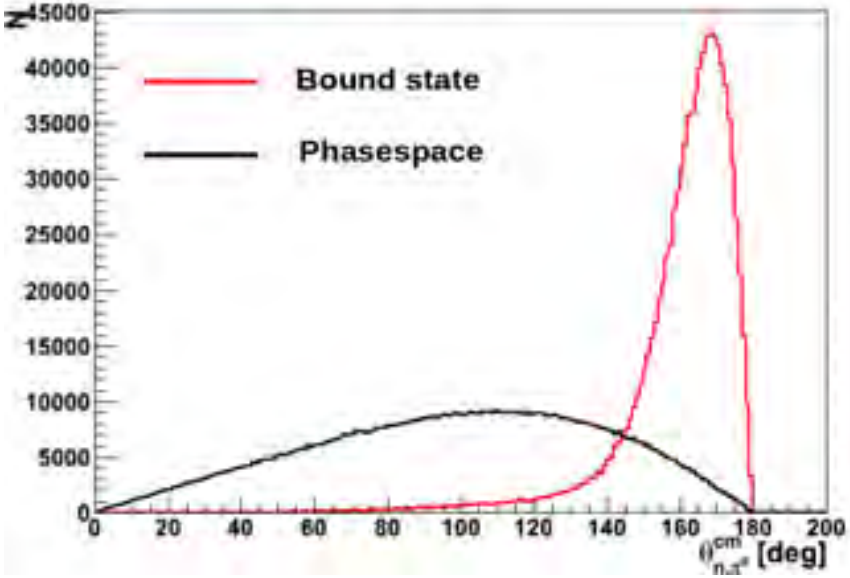
  ▶ PID based on measurement of energy loss in scintillators

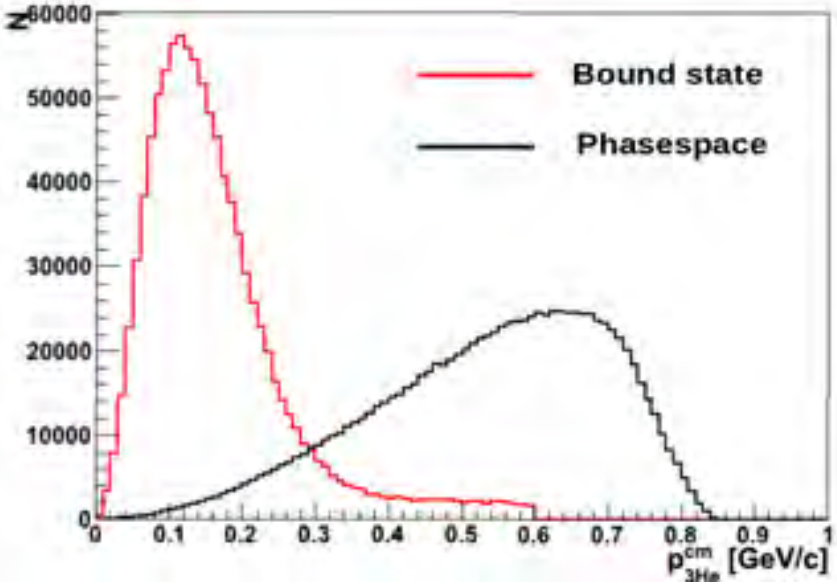
  ▶ photons identified in calorimeter

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

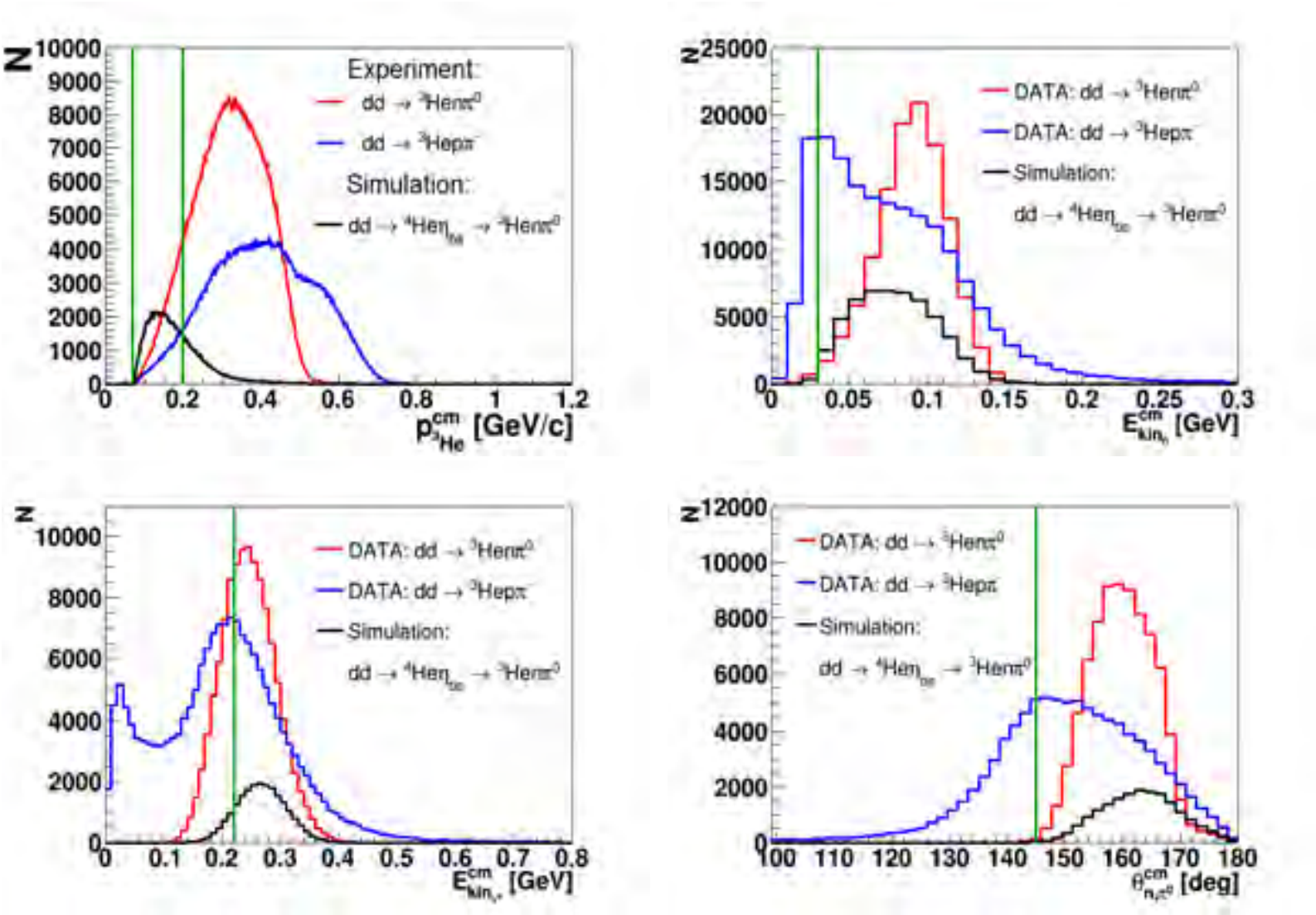
$$\eta + N \Rightarrow N^*(1535) \Rightarrow N + \pi = \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$$

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





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



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

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

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

Cross section

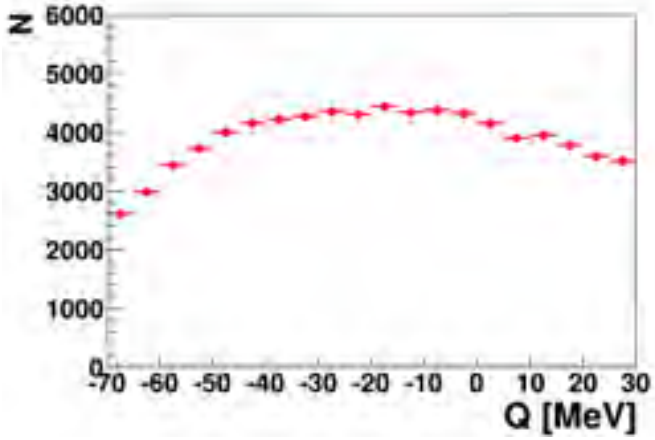
$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

N - number of experimental events

L - integrated luminosity

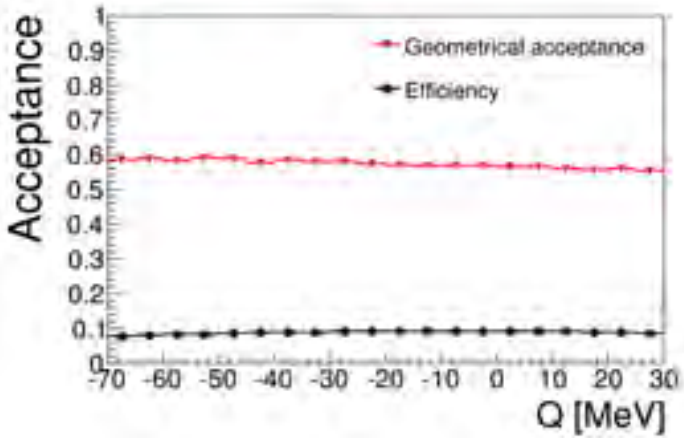
ϵ - full detection efficiency

Excitation function



Efficiency

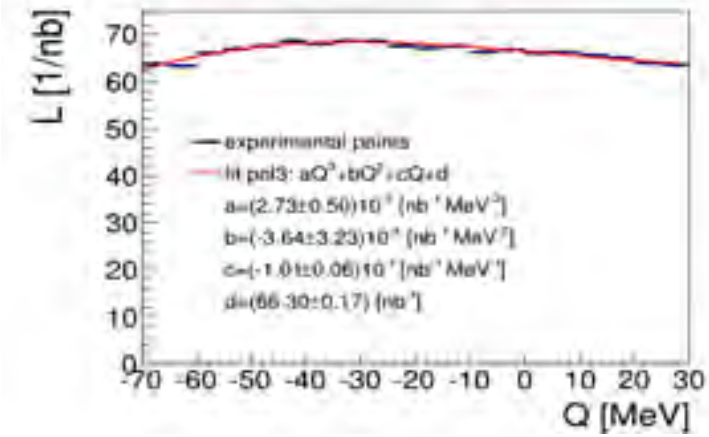
$dd \to ({}^4\mathrm{He}\text{-}\eta)_{bound} \to {}^3\mathrm{He}n\pi^0$



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

Integrated luminosity

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



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

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

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

Cross section

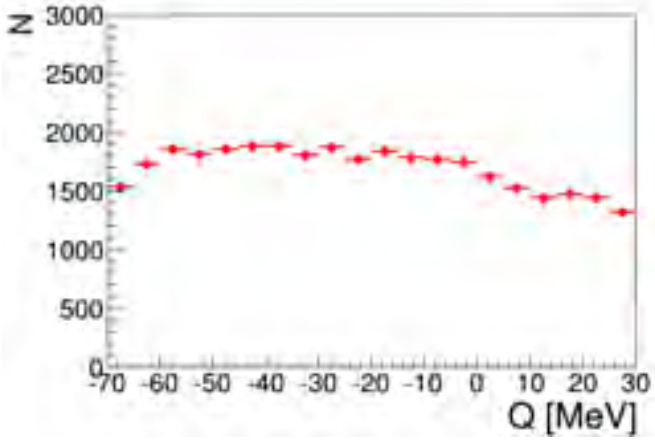
$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

N - number of experimental events

L - integrated luminosity

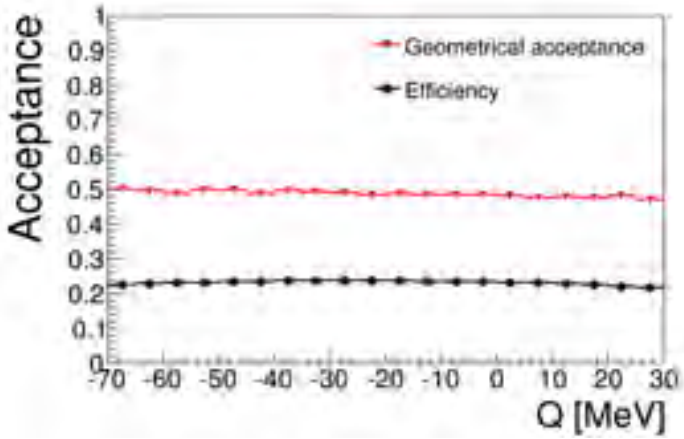
ϵ - full detection efficiency

Excitation function



Efficiency

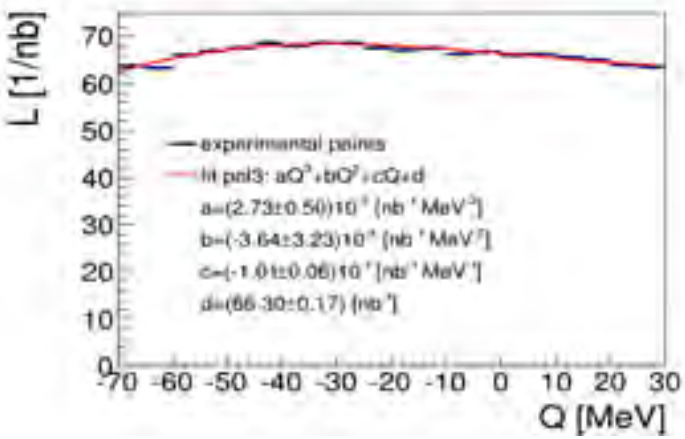
$dd \to ({}^4\mathrm{He}\text{-}\eta)_{bound} \to {}^3\mathrm{He}n\pi^0$



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

Integrated luminosity

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

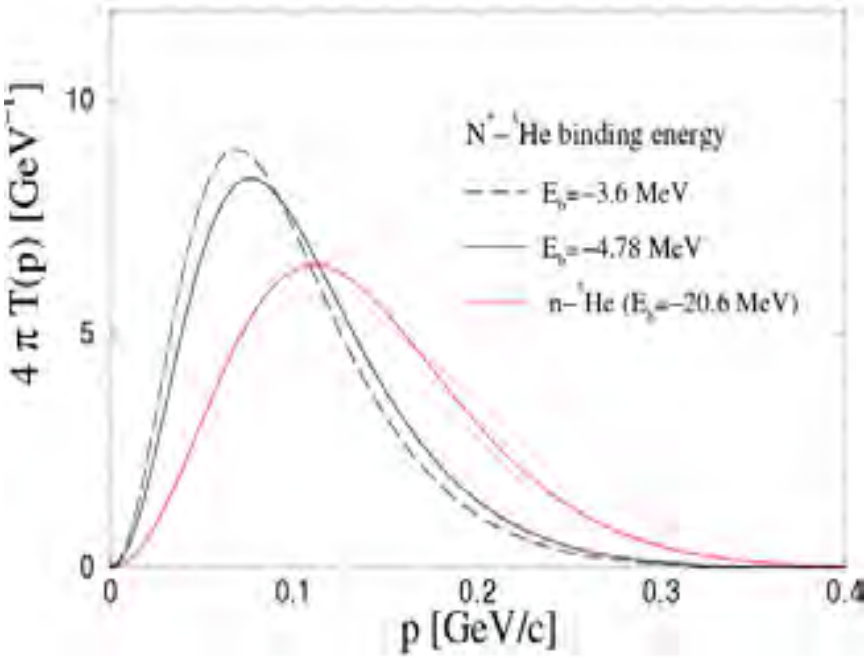


$dd \to ppn_{sp}n_{sp}$: L=$(1329 \pm 2_{stat} \pm 108_{syst} \pm 64_{norm})nb^{-1}$

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

Systematics

Main contribution: momentum distribution for N^* inside He



assumption that N^* resonance has a momentum distribution identical to the distribution of nucleons inside He

N^*-^3He momentum distribution determined: the elementary $NN^* \to NN^*$ interaction constructed within π and η meson exchange model $\Rightarrow$ N^*-He potential evaluated by folding NN^* interaction with a nuclear density

$$\Downarrow$$

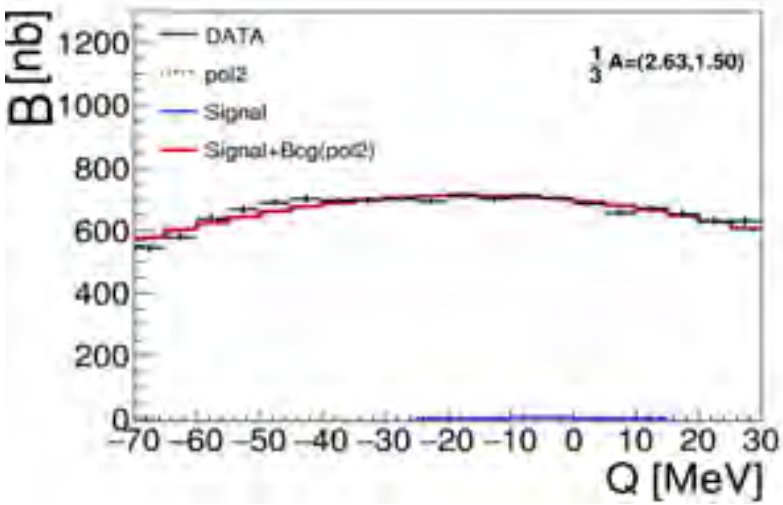
Details:

N. G. Kelkar, Eur. Phys. J. A 52, 309 (2016)
N. G. Kelkar, D. Bedoya Ferro, P. Moskal, Acta Phys. Pol. B 47, 299 (2016)

Comparison with N. Ikeno et al. model prediction

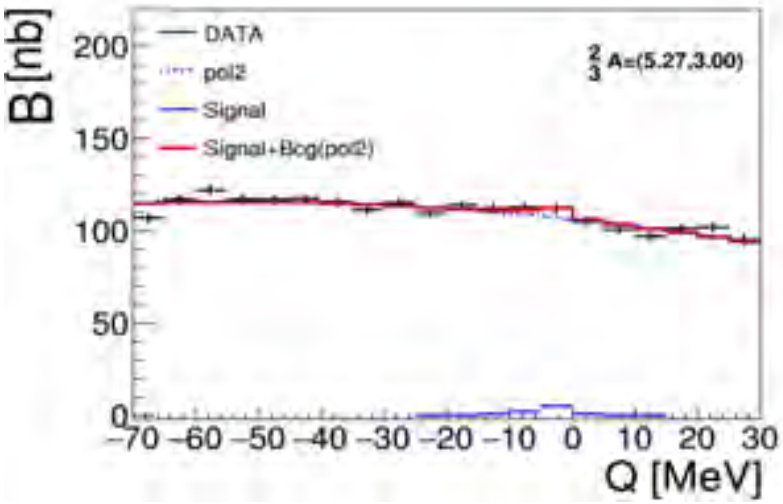
$dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$

$\Downarrow$



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

$\Downarrow$



$$\sigma_{n\pi^0}(Q) = \frac{1}{3}A \cdot Theory(Q) + B_1 Q^2 + C_1 Q + D_1$$

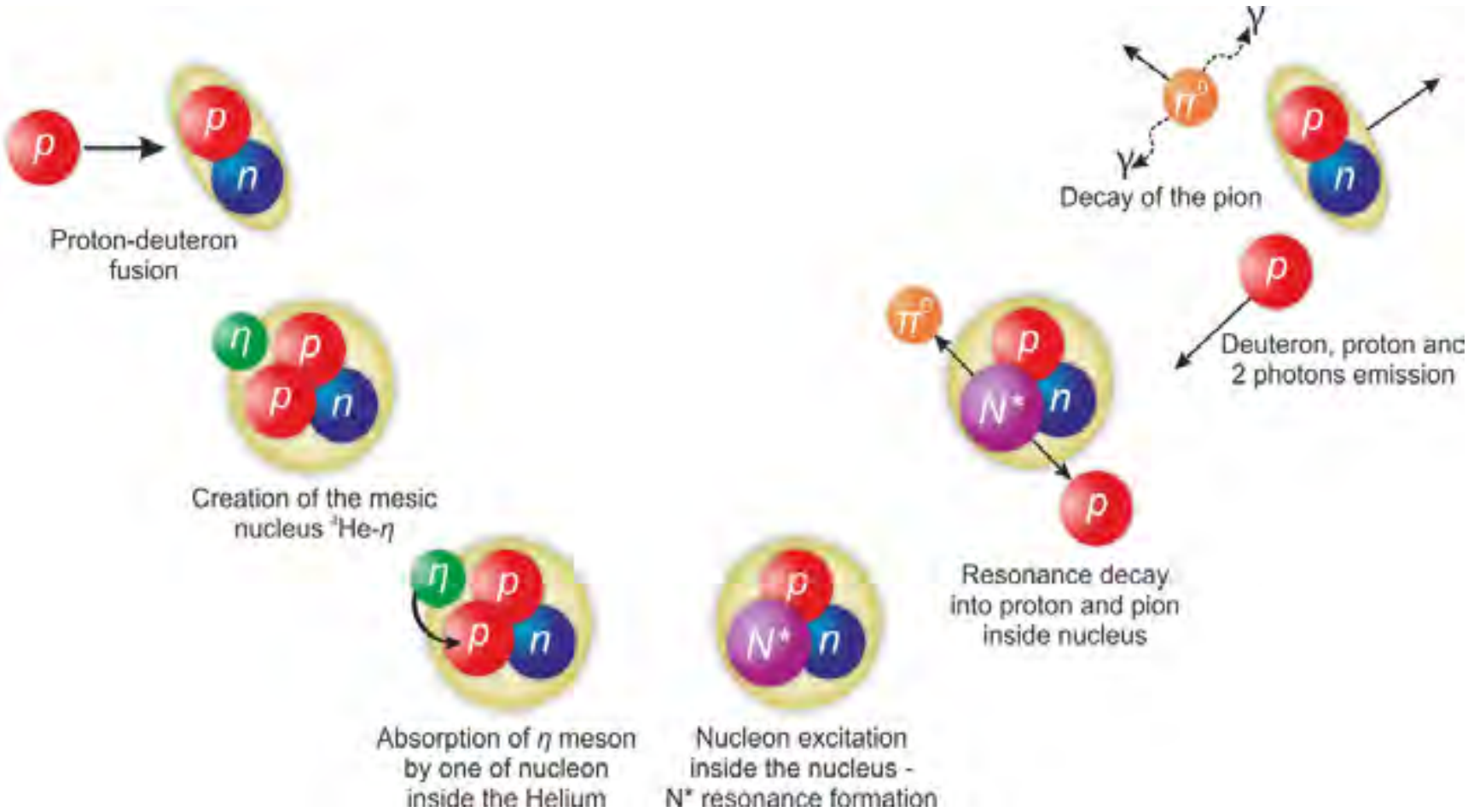
$$\sigma_{p\pi^-}(Q) = \frac{2}{3}A \cdot Theory(Q) + B_2 Q^2 + C_2 Q + D_2$$

isospin relation between the both of the considered channels

$Theory(Q)$ - theoretical function after binning with the amplitude normalized to unity
$B_{1,2}Q^2 + C_{1,2}Q + D_{1,2}$ - polynomial of the second order

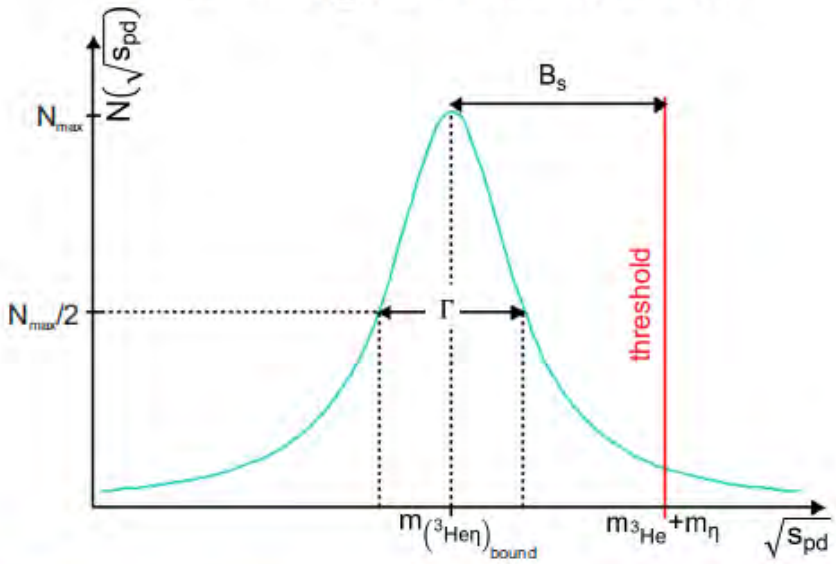
Fit performed for theoretical spectra obtained for different optical potential parameters (V_0, W_0)

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

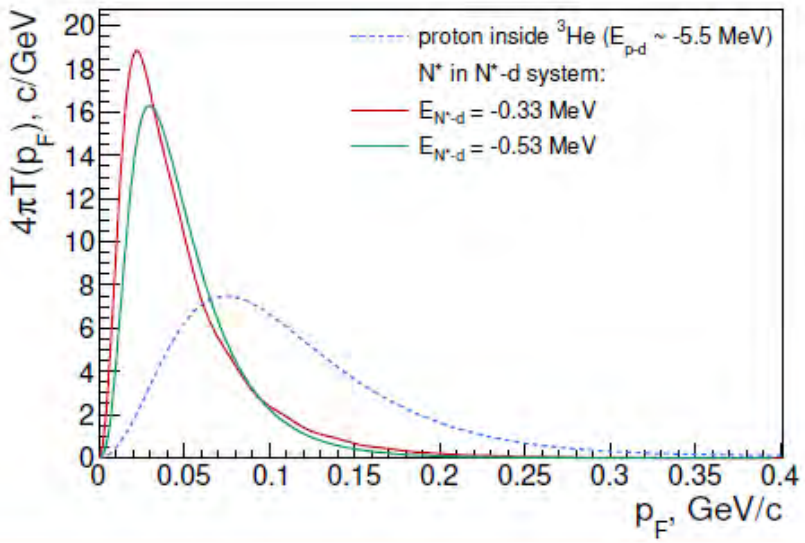


Simulation of $pd \to (^3\text{He-}\eta)_{bound} \to dp\pi^0$

Breit-Wigner distribution



N* momentum distribution



Breit-Wigner formula

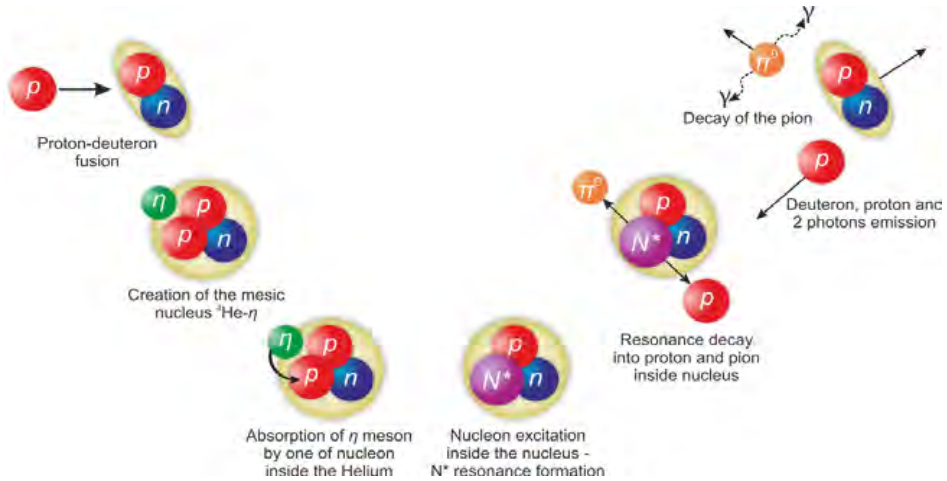
$$N(\sqrt{s_{pd}}) = \frac{\Gamma^2/4}{\left(\sqrt{s_{pd}} - (m_\eta + m_{^3He} - B_s)\right)^2 + \Gamma^2/4}$$

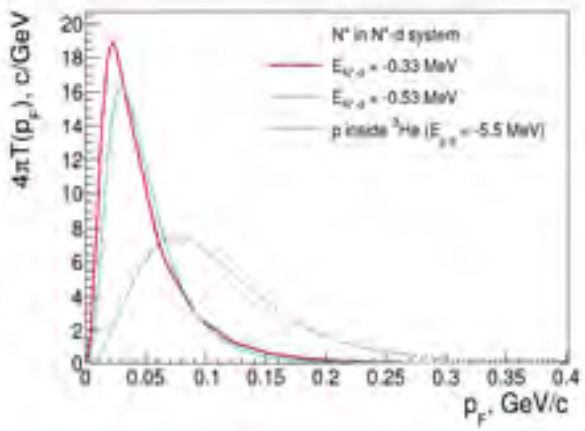
$$B_s \in (0, 40)\ MeV; \Gamma \in (5, 50)\ MeV$$

N. Kelkar et al., Int. J. Mod. Phys. E 28, 1950066 (2019);
N. Kelkar et al., Nucl. Phys. A 996, 121698 (2020)

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

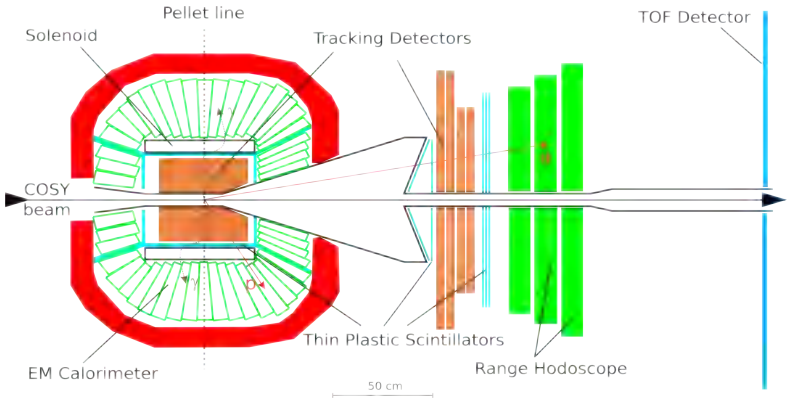
Simulations

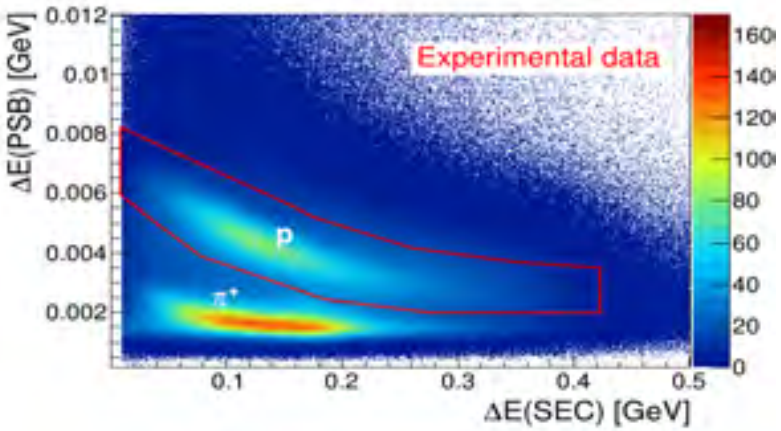




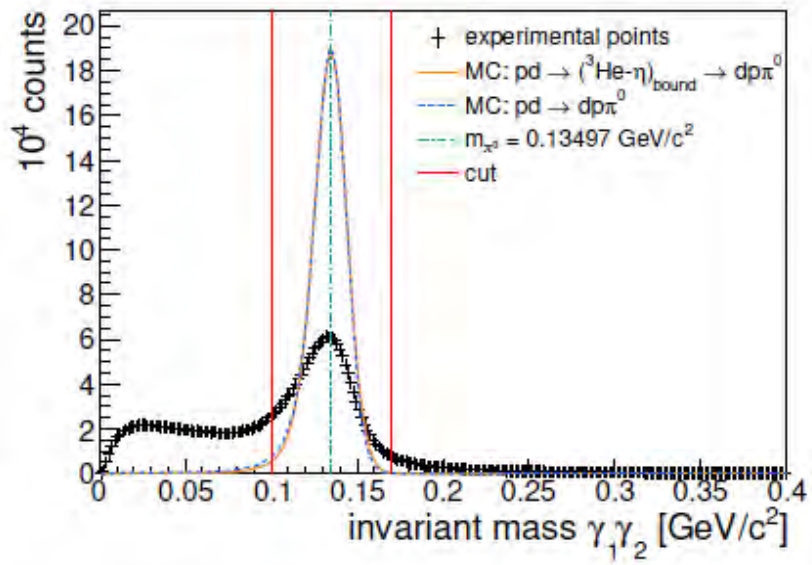
N. Kelkar et al., Int. J. Mod. Phys. E 28, 1950066 (2019);
N. Kelkar et al., Nucl. Phys. A 996, 121698 (2020)

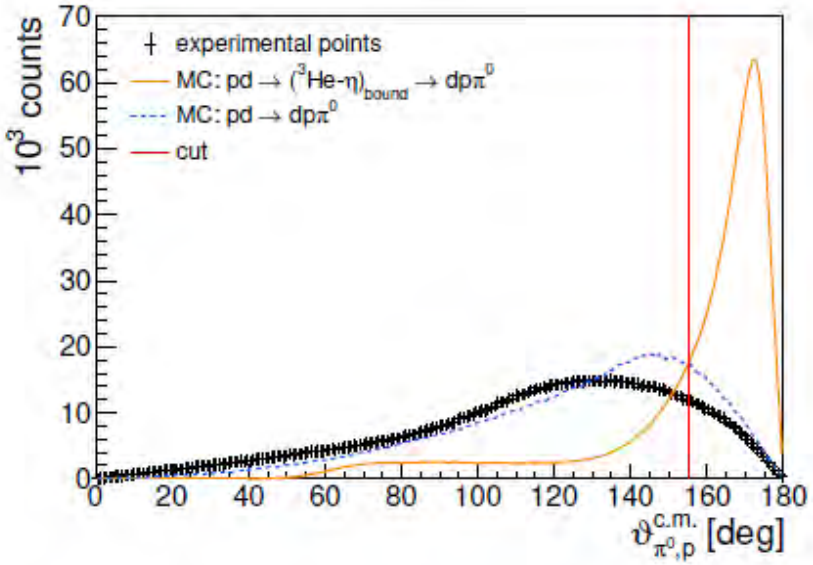
Events selection

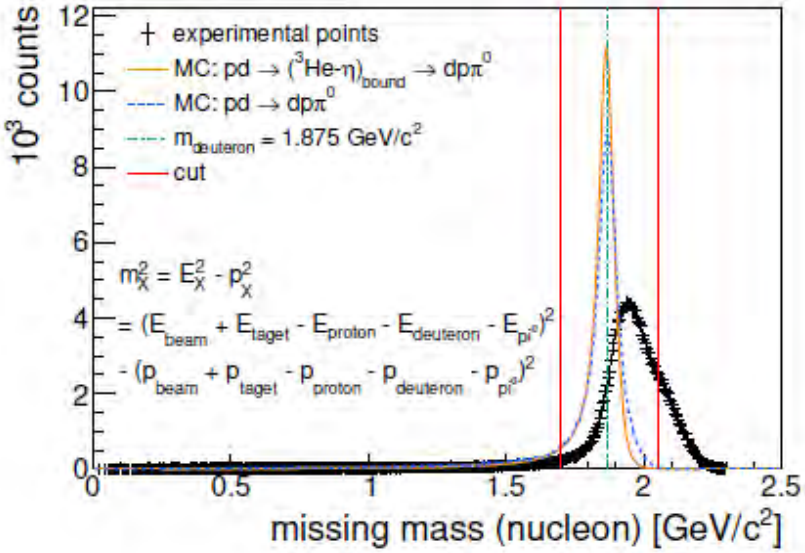


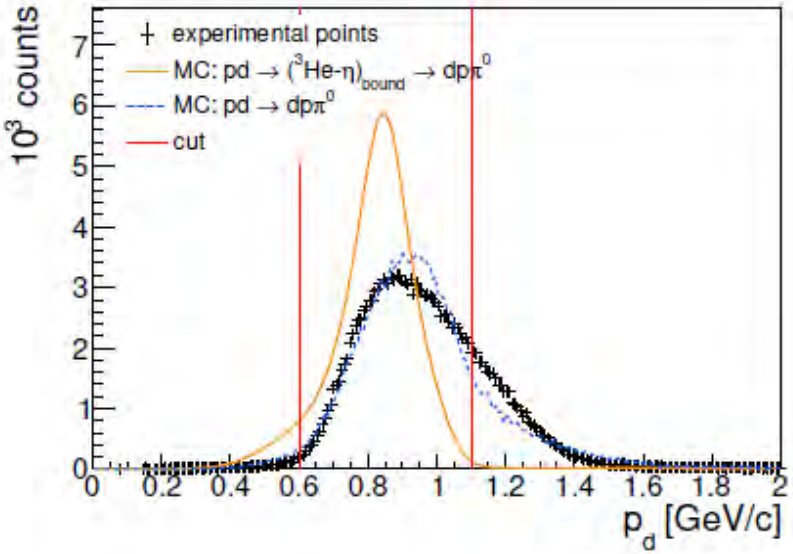


Selection criteria









Determination of the excitation function

Excitation function

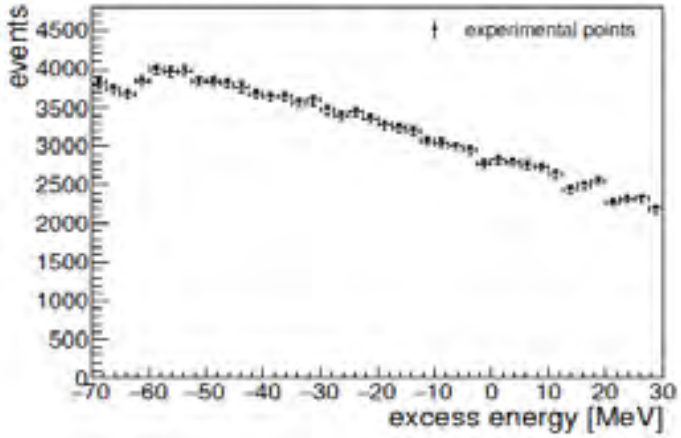
$$\sigma(Q) = \frac{N(Q)}{\varepsilon(Q) \cdot L(Q)}$$

N – number of experimental events

ε – reconstruction efficiency

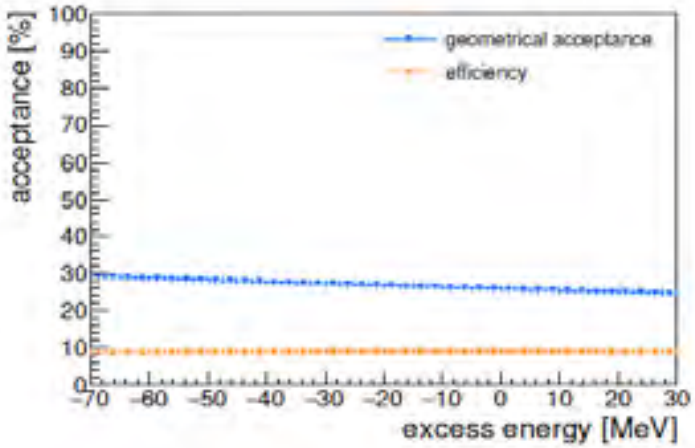
L – integrated luminosity

Number of events



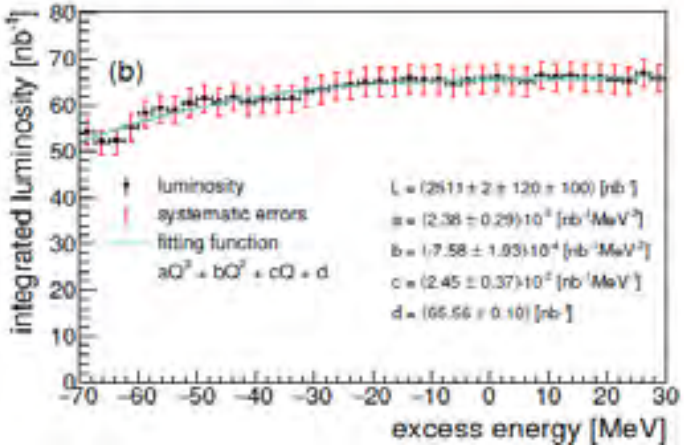
Efficiency

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

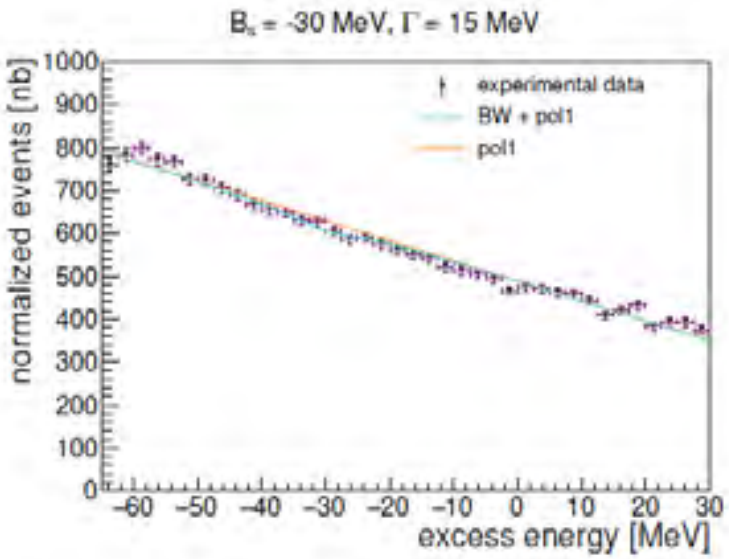


Integrated luminosity

$pd \to ppn_{spectator}$



Upper limit of the total cross section



Fit with a Breit–Wigner function combined with a first order polynomial:

$$\frac{A \cdot \frac{\Gamma^2}{4}}{(Q - B_s)^2 + \frac{\Gamma^2}{4}} + BQ + C$$

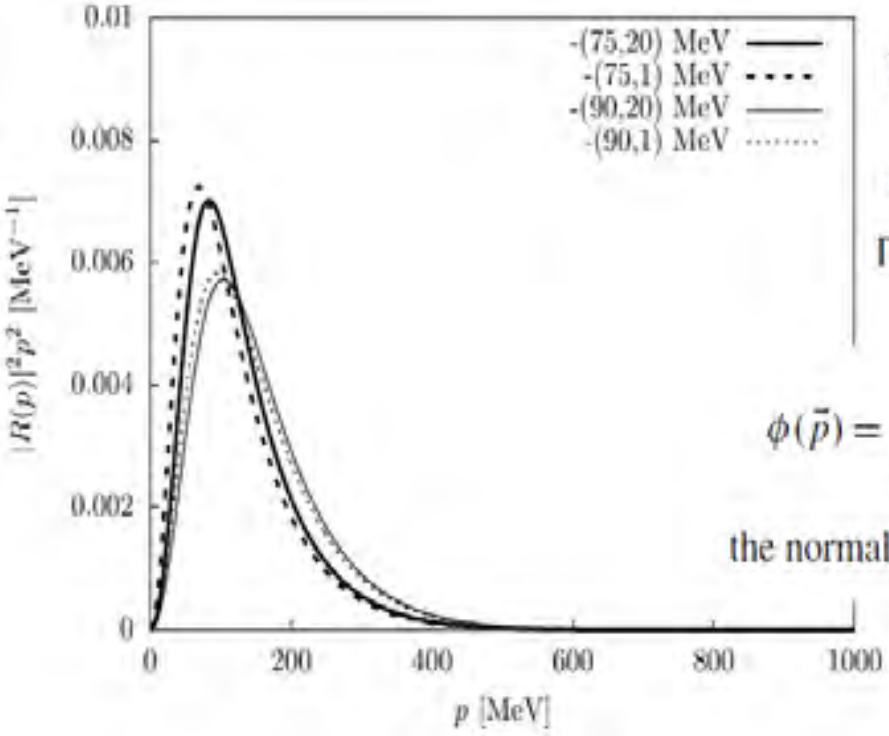
Breit-Wigner (signal) + pol1 (background)

B_s and Γ are fixed parameters; A, B, C are free parameters.

$$\sigma^{upp}_{CL=90\%} = k \cdot \sigma_A, \; k = 1.64 \; (CL = 90\%)$$

Ikeno et al.

(V_0, W_0) [MeV]	(B_s, Γ_{abs}) [MeV]	$BR^*_{\eta\to 2\gamma}$	$BR^*_{\eta\to 3\pi^0}$
−(75,20)	(4.06, 15.66)	3.30×10^{-5}	2.73×10^{-5}
−(90,20)	(11.16, 20.65)	2.50×10^{-5}	2.07×10^{-5}
−(75,1)	(5.96, 0.76)	6.78×10^{-4}	5.62×10^{-4}
−(90,1)	(12.67, 1.02)	5.06×10^{-4}	4.20×10^{-4}



$$BR^*_{\eta\to 2\gamma/\eta\to 3\pi^0} = \frac{\Gamma_{\eta\to 2\gamma/\eta\to 3\pi^0}}{(\Gamma^{tot}_\eta + \Gamma_{abs})}.$$

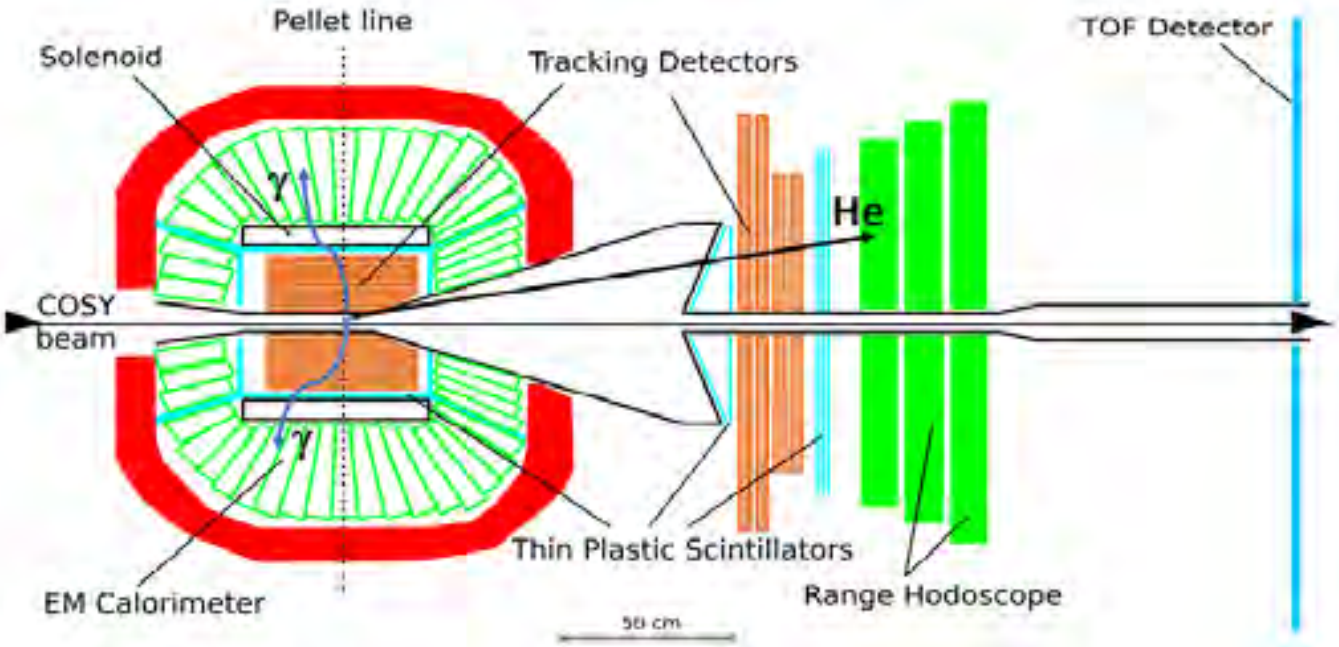
$$\Gamma_{\eta\to 2\gamma} = 0.3941 \times 1.31\ \text{keV} = 0.516\ \text{keV}$$

$$\Gamma_{\eta\to 3\pi^0} = 0.3268 \times 1.31\ \text{keV} = 0.428\ \text{keV}$$

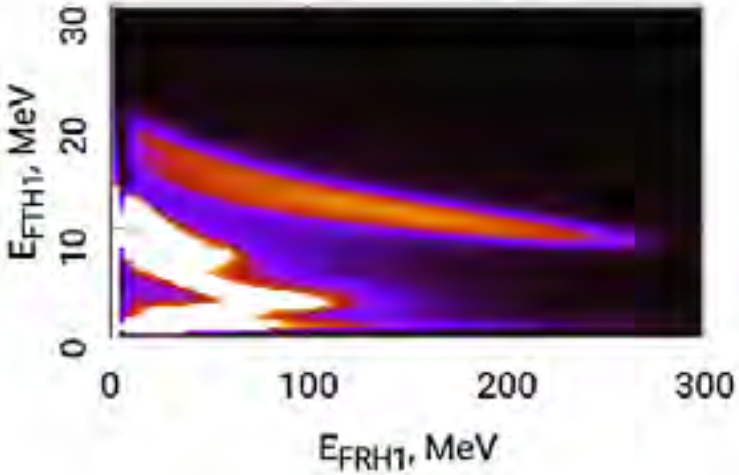
$$\phi(\vec{p}) = \frac{1}{(2\pi)^{3/2}} \int e^{i\vec{p}\cdot\vec{r}} \psi(\vec{r}) d\vec{r},$$

the normalization condition $\int |R(p)|^2 p^2 dp = 1$

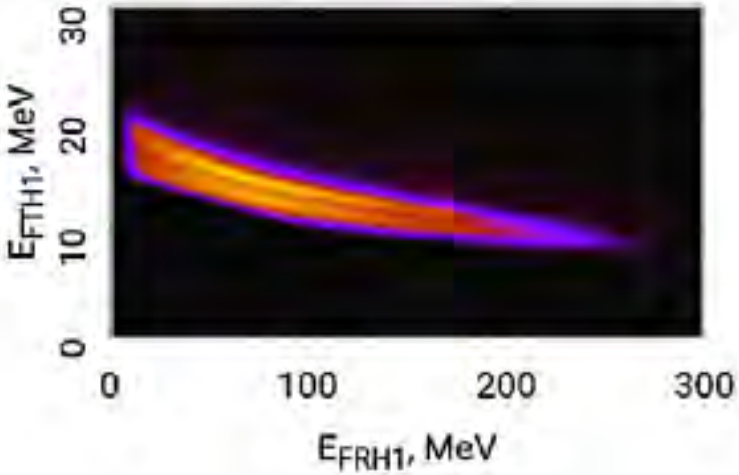
Search for $(^3\text{He-}\eta)_{bound}$ | Selection criteria



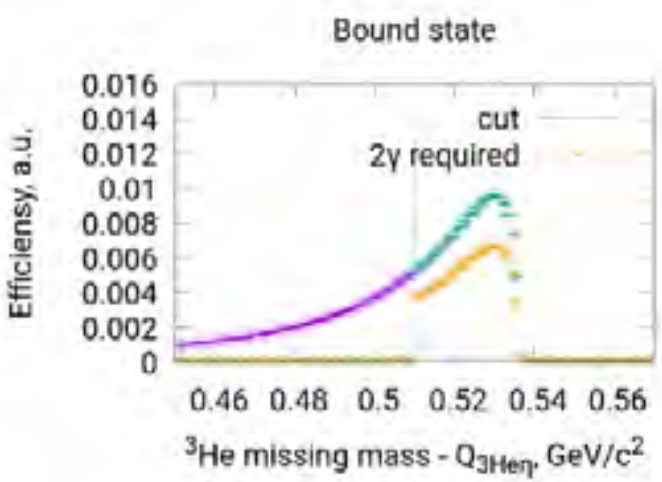
Reconstructable tracks

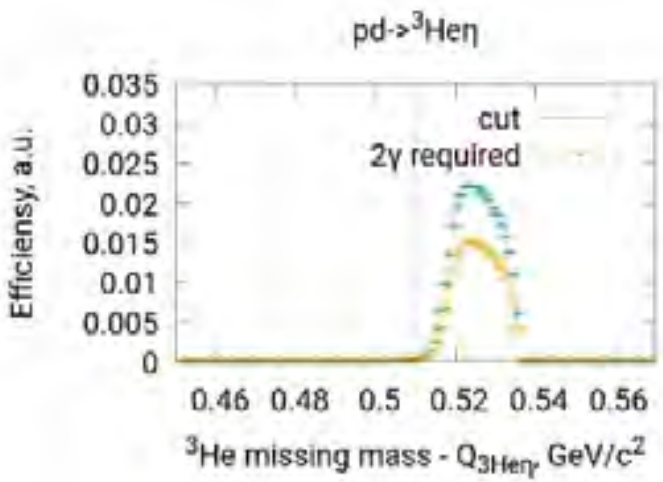


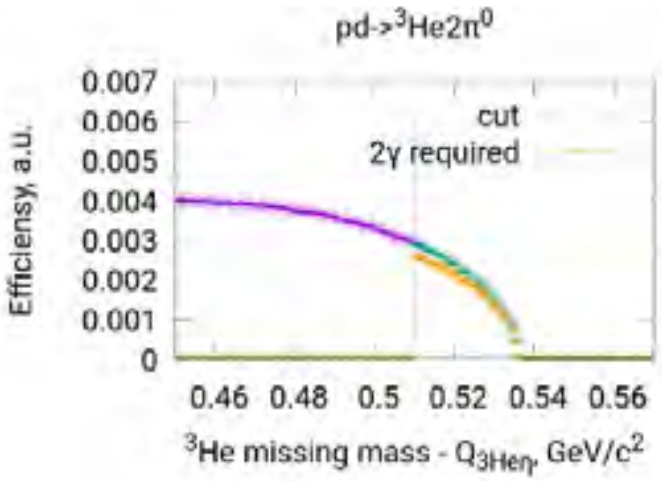
Identified as 3He

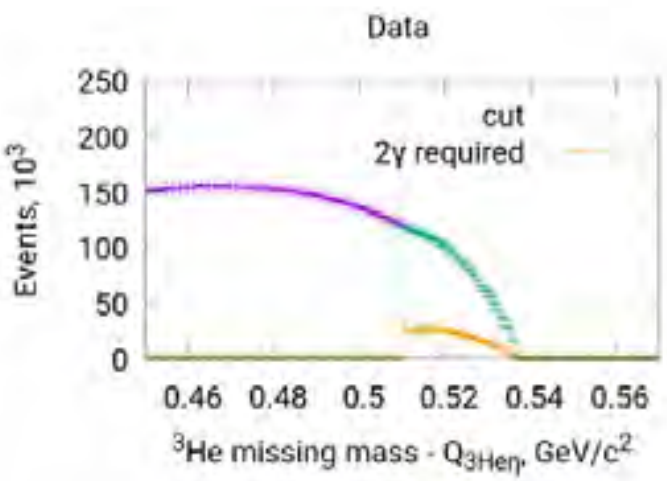


Events selection - $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He } 2\gamma$

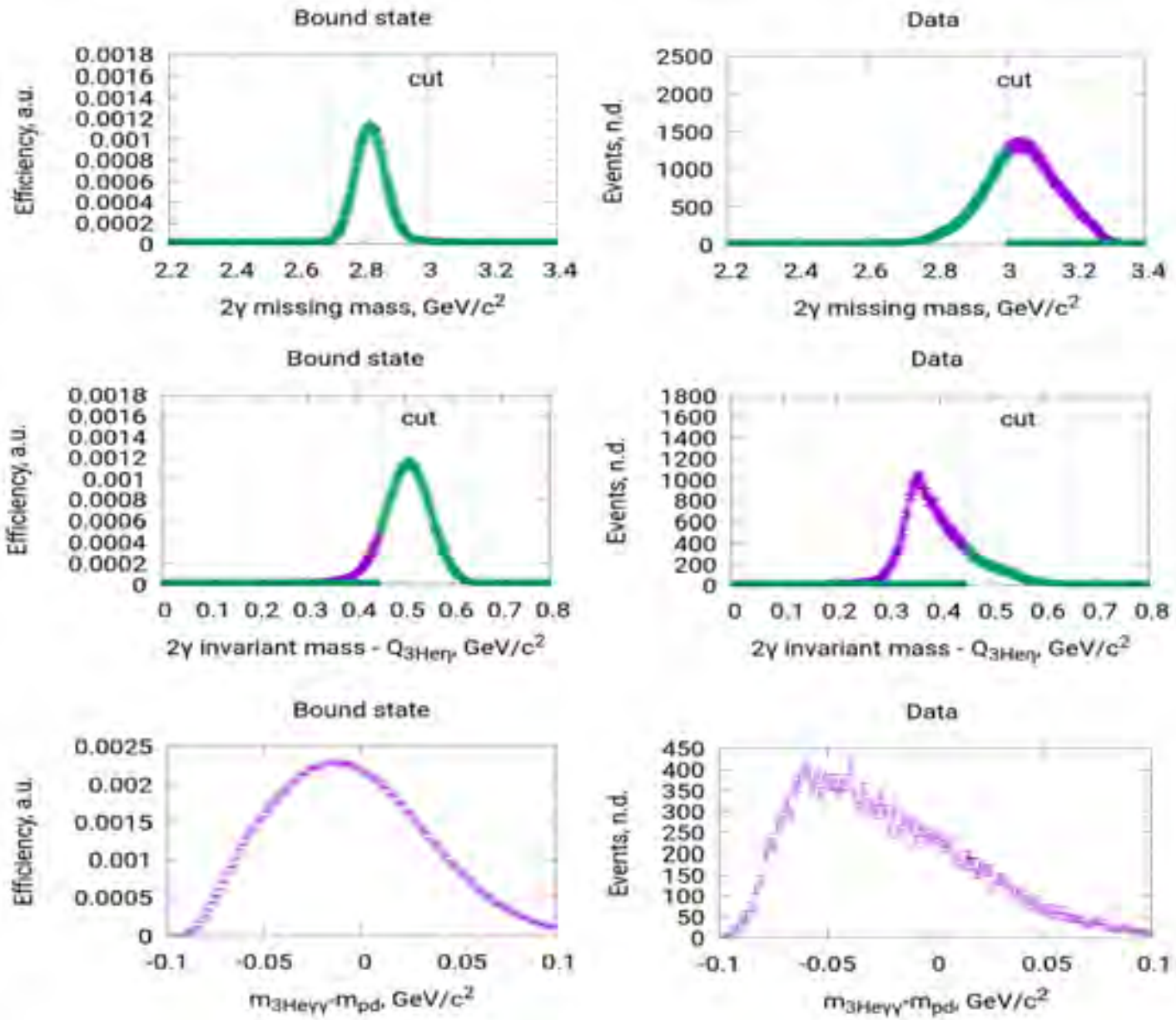




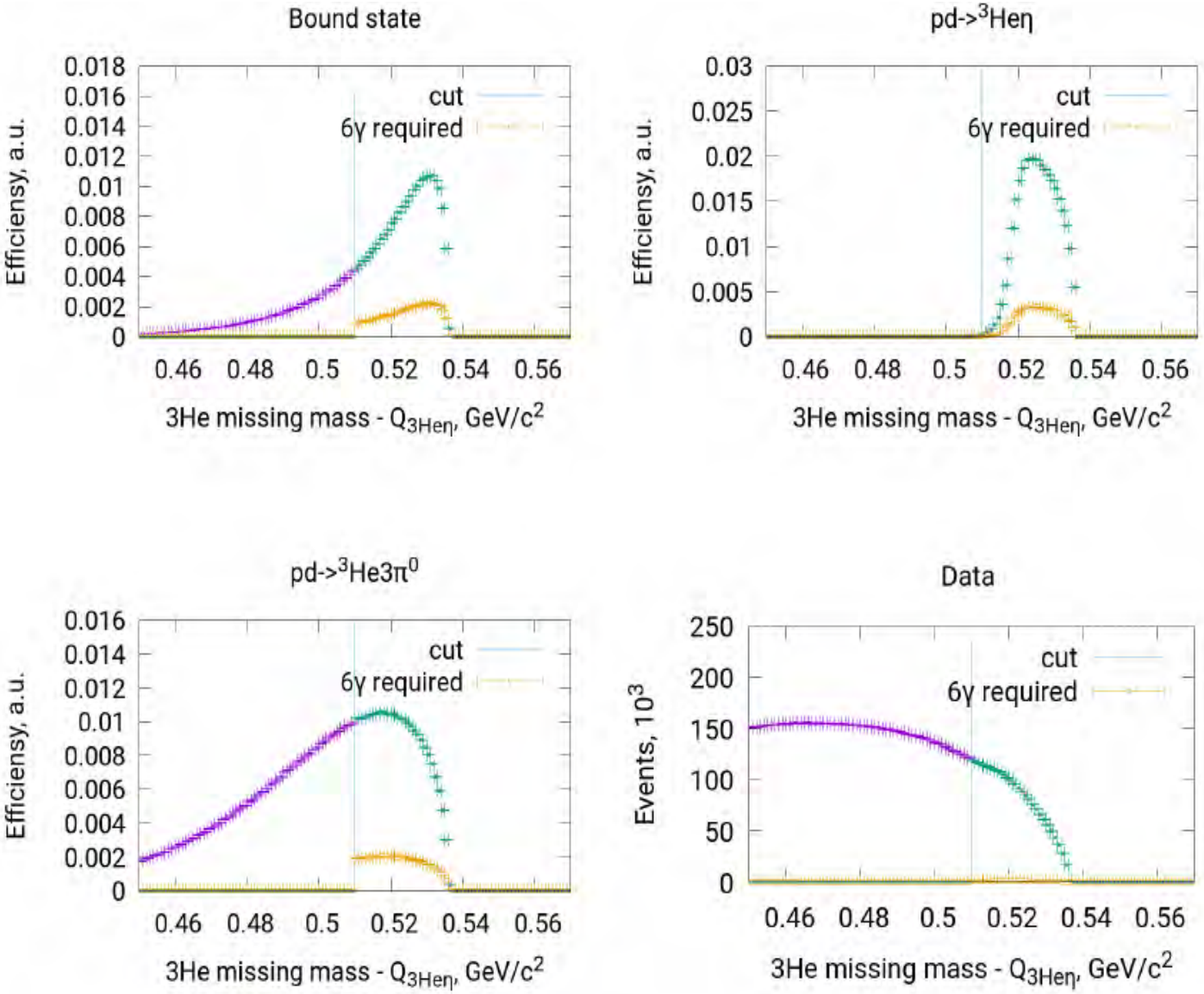




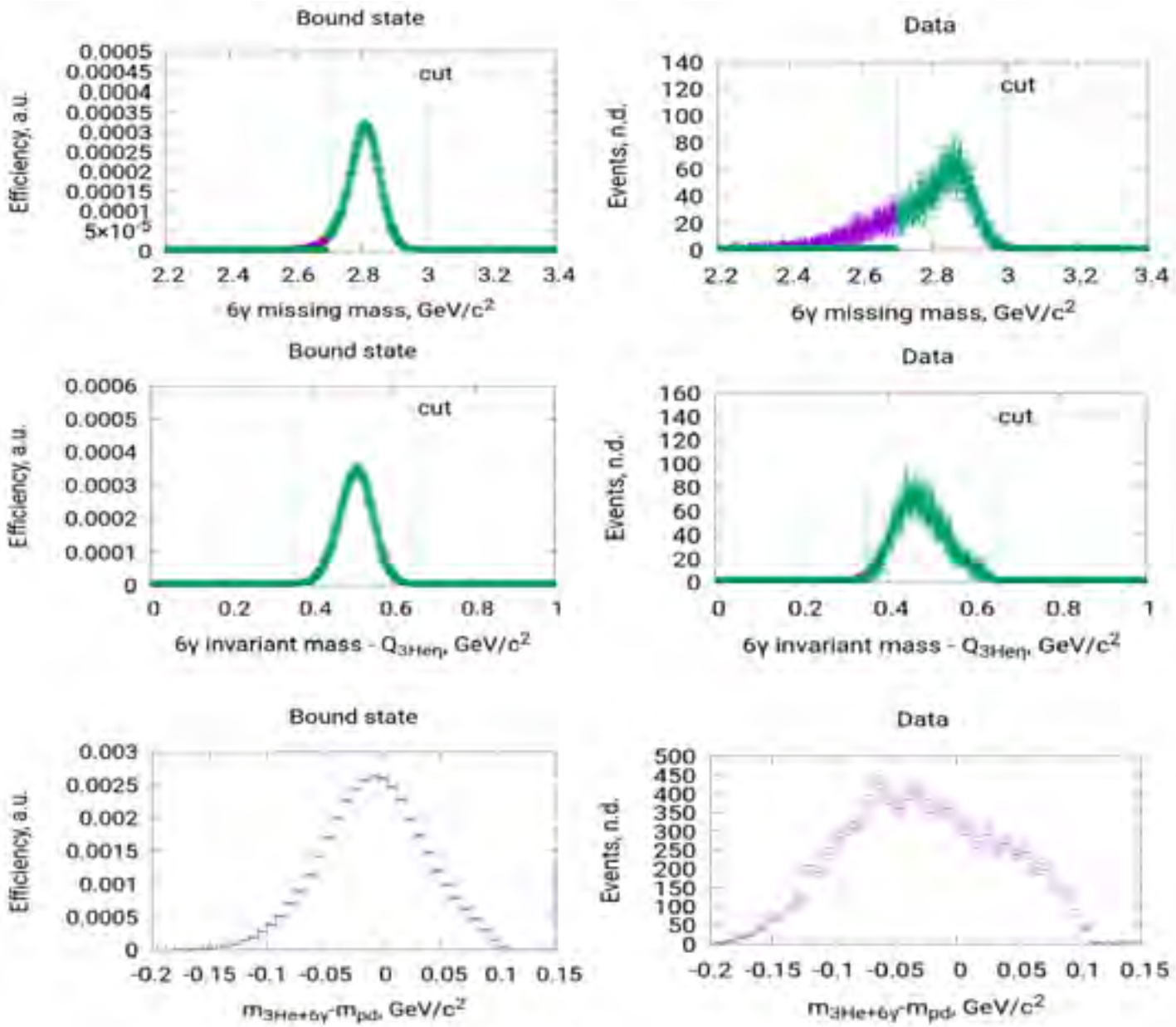
Events selection - $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\ 2\gamma$



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



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



Excitation function $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 2\gamma$

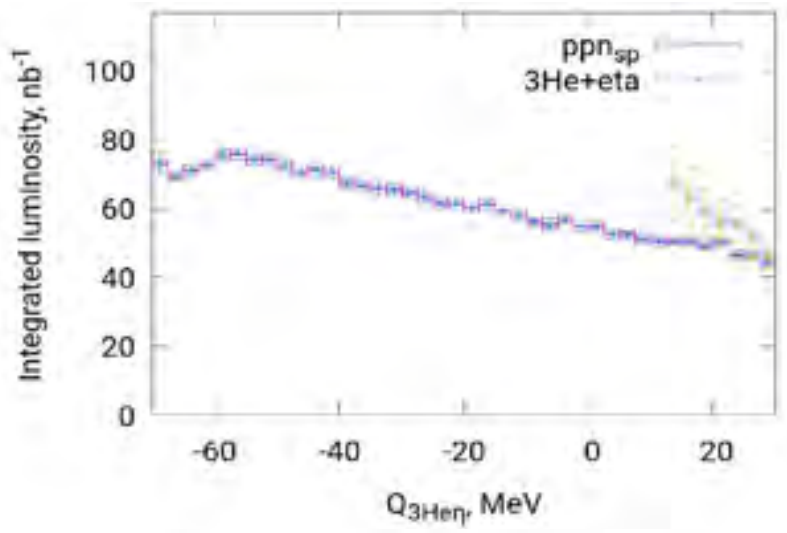
Cross section

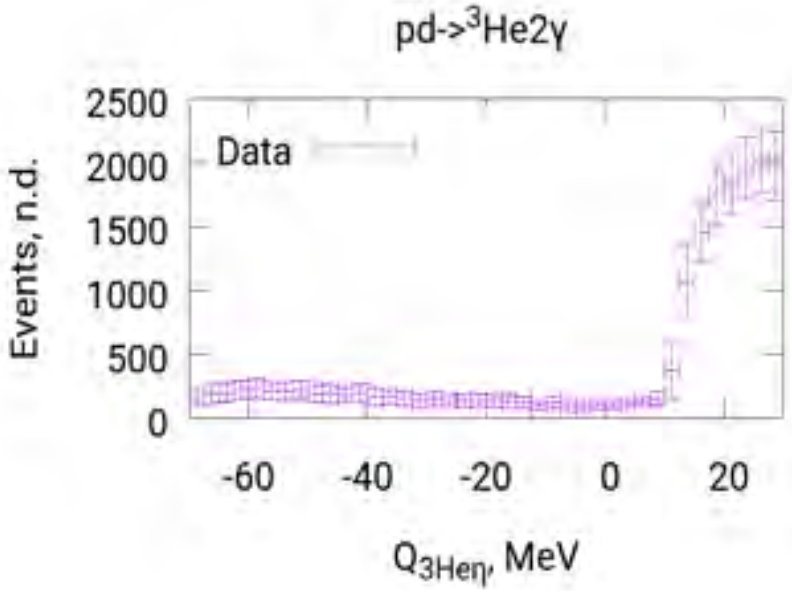
$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

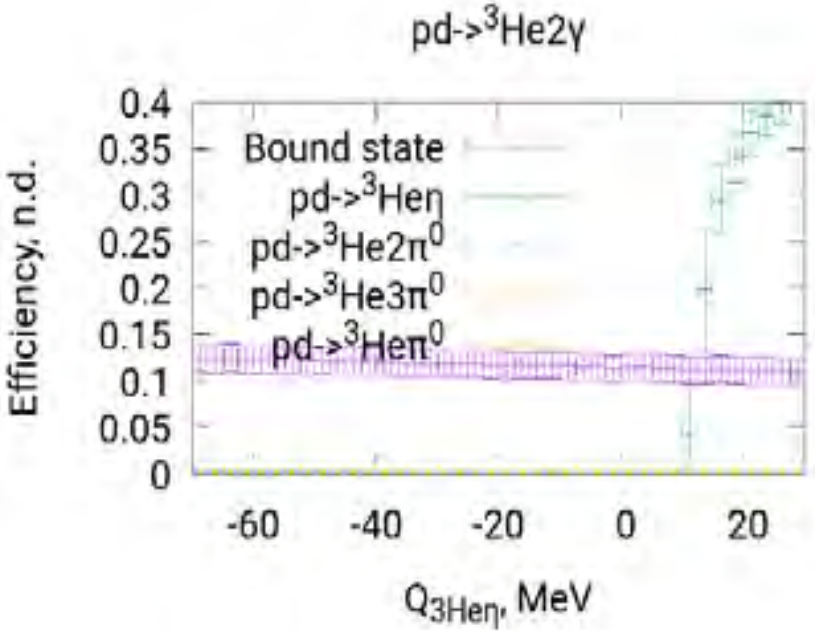
N - number of experimental events

L - integrated luminosity

ϵ - full detection efficiency







Excitation function $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 6\gamma$

Cross section

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

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