Search for the eta-mesic helium with WASA-at-COSY

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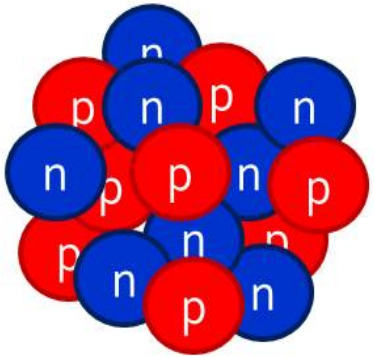
INTERNATIONAL PHD PROJECT IN APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES
This project is supported by the Foundation for Polish Science-MPD program co-financed by the European Union within the European Regional Development Fund

Outline

- Introduction
- Search for η-mesic nuclei with WASA-at-COSY (idea of the measurement)
- Experimental status
  - Past: results from 2008 experiment (^{4}He-η)
  - Present: analysis in progress, 2010 experiment (^{4}He-η)
  - Future: prospects with 2014 data (^{3}He-η)
- Summary and Conclusions

η-mesic bound state

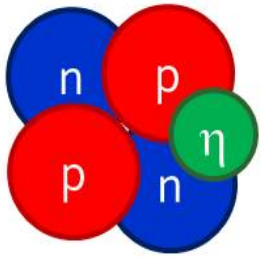
Atomic nucleus



STRONG INTERACTION

η-mesic nucleus

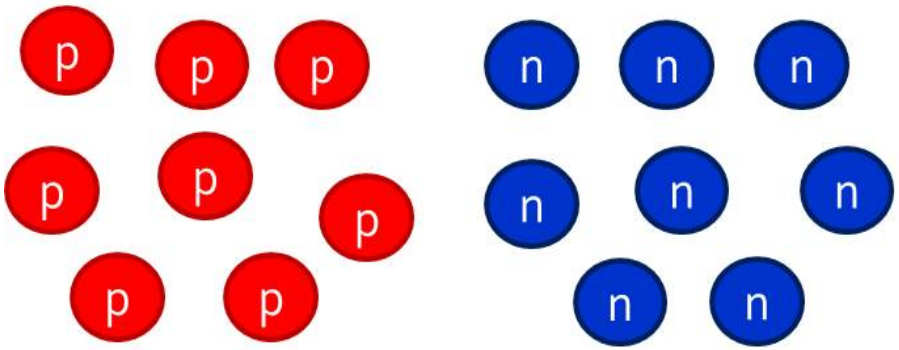
^4He-η

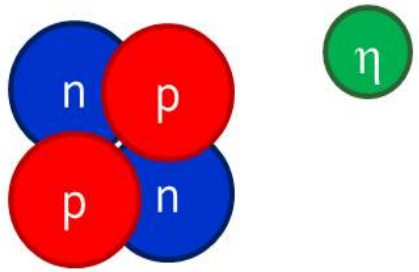


$$m = Z \cdot m_p + N \cdot m_n - B_s$$

$$B_s = \Delta m c^2$$

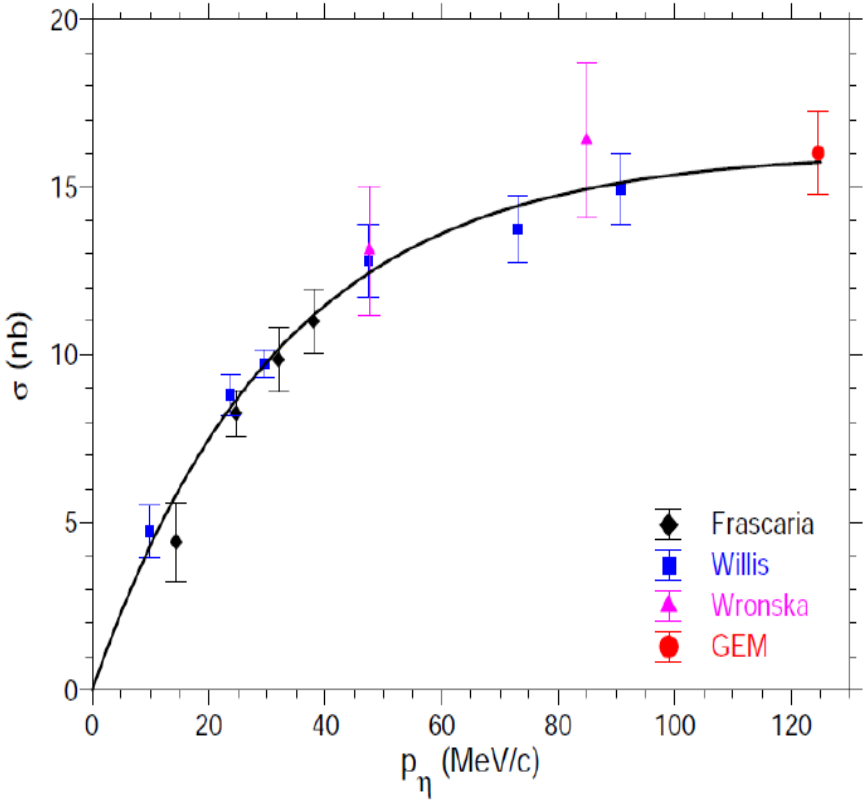
$$m_{bs} = m_{^4He} + m_\eta - B_s$$



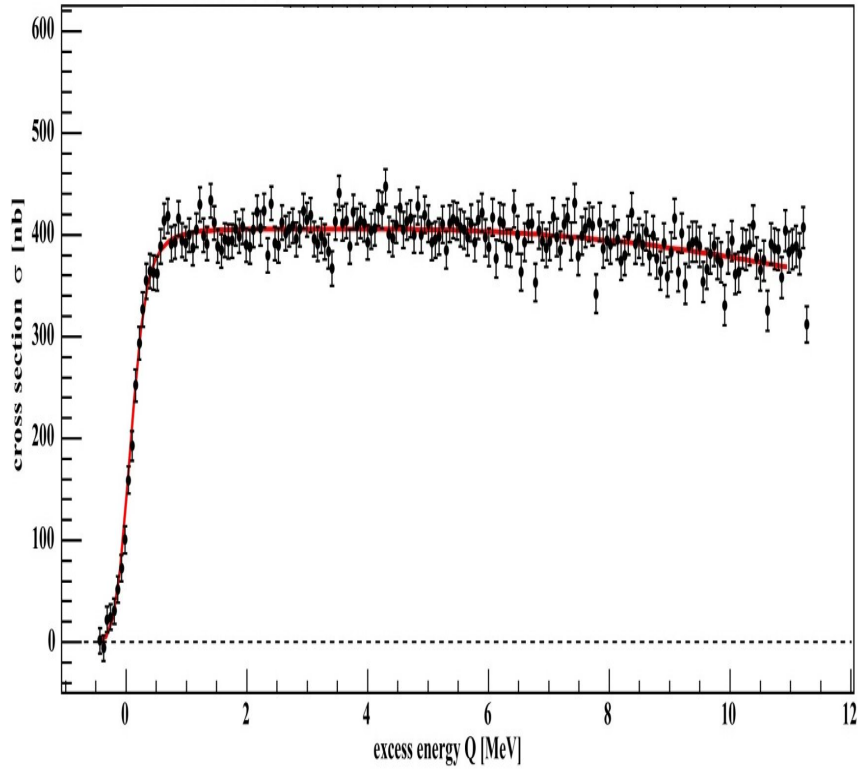


Exp. indications of the He-η bound state existence

$dd \rightarrow {}^4$He-η



$dp \rightarrow {}^3$He-η



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

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

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

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

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

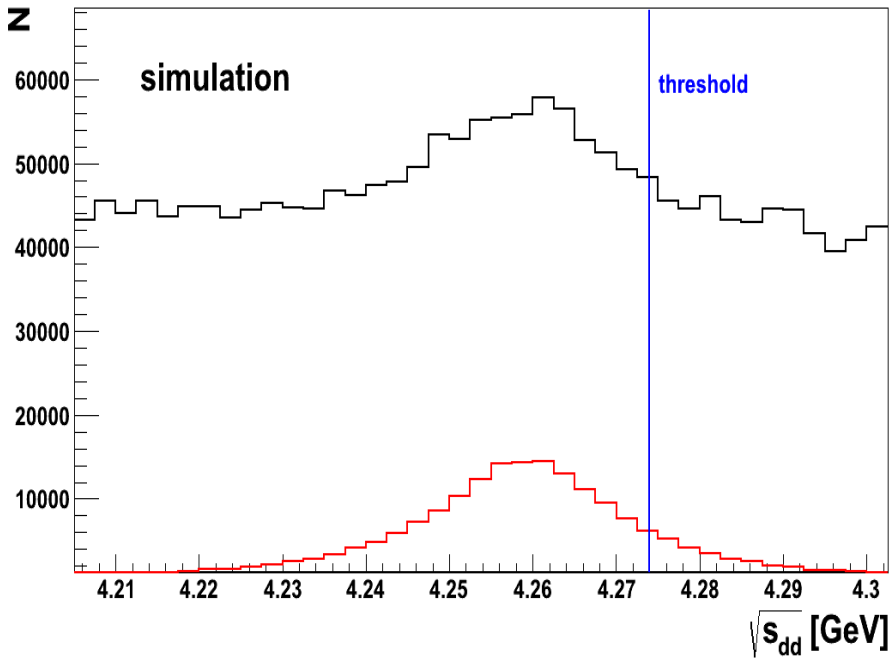
$$dd \rightarrow \left({}^4He - \eta\right)_{bs} \rightarrow d\ p\ p\ \pi^-$$

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

Experimental method

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

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

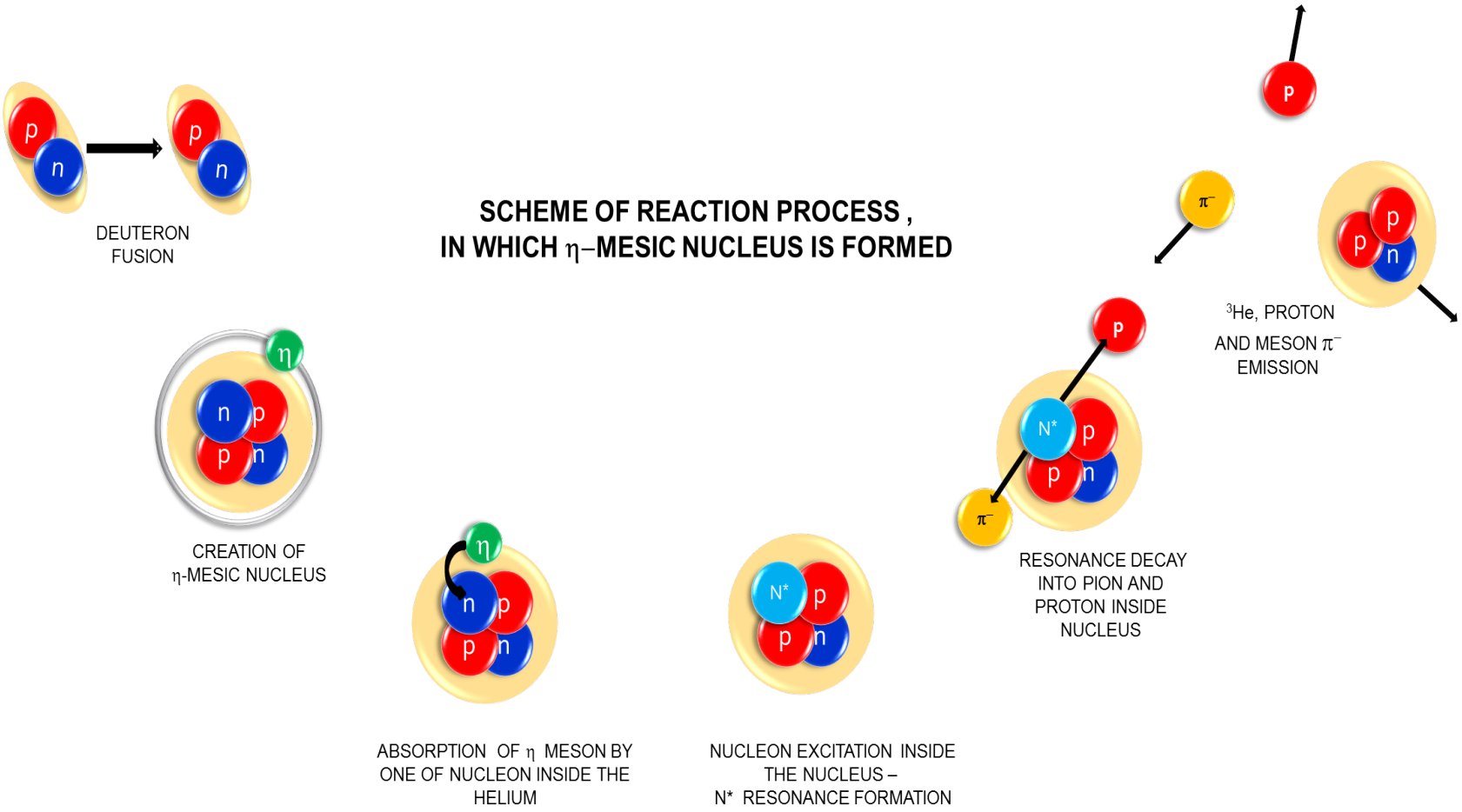


Excitation function

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

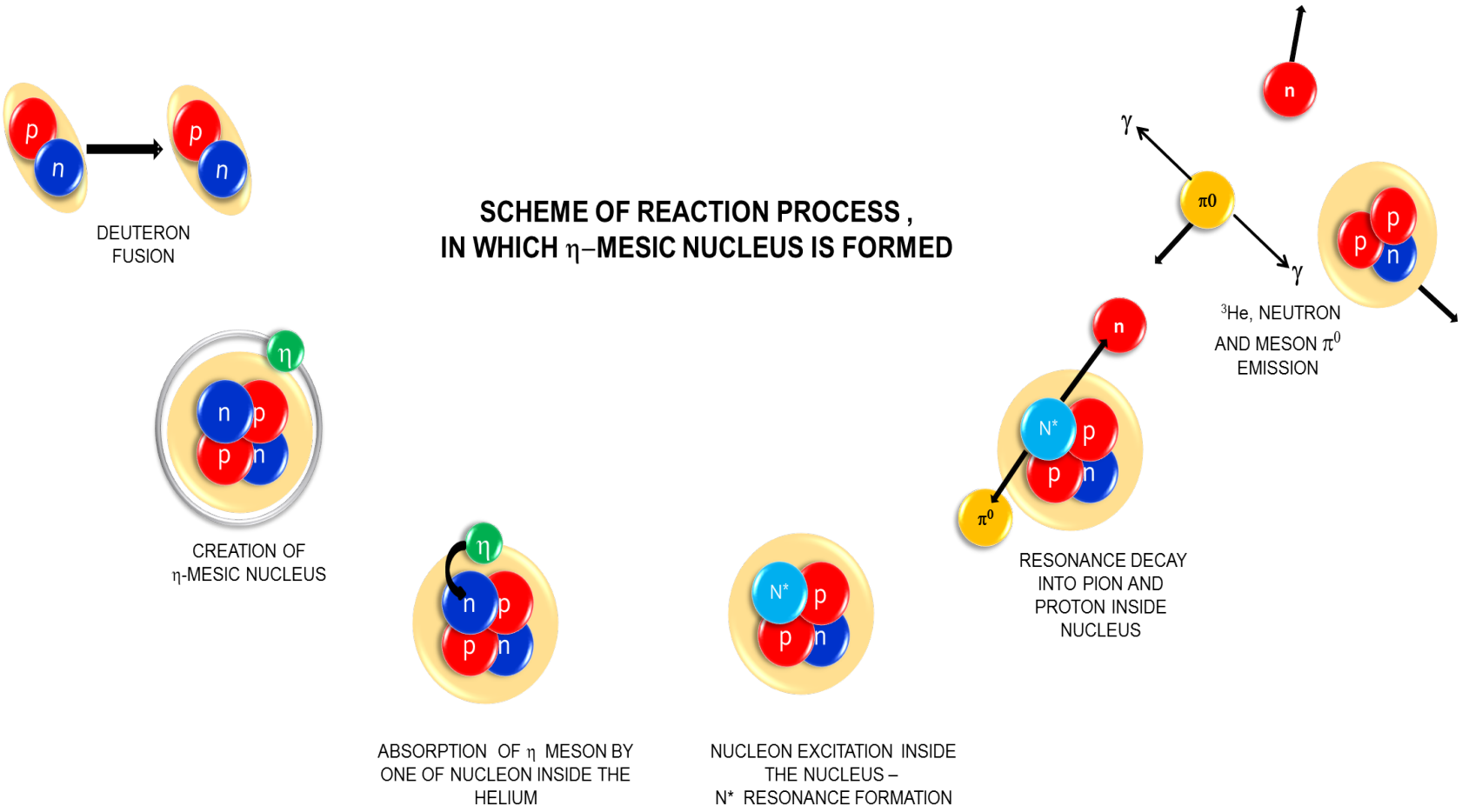
Kinematical mechanism of the reaction

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



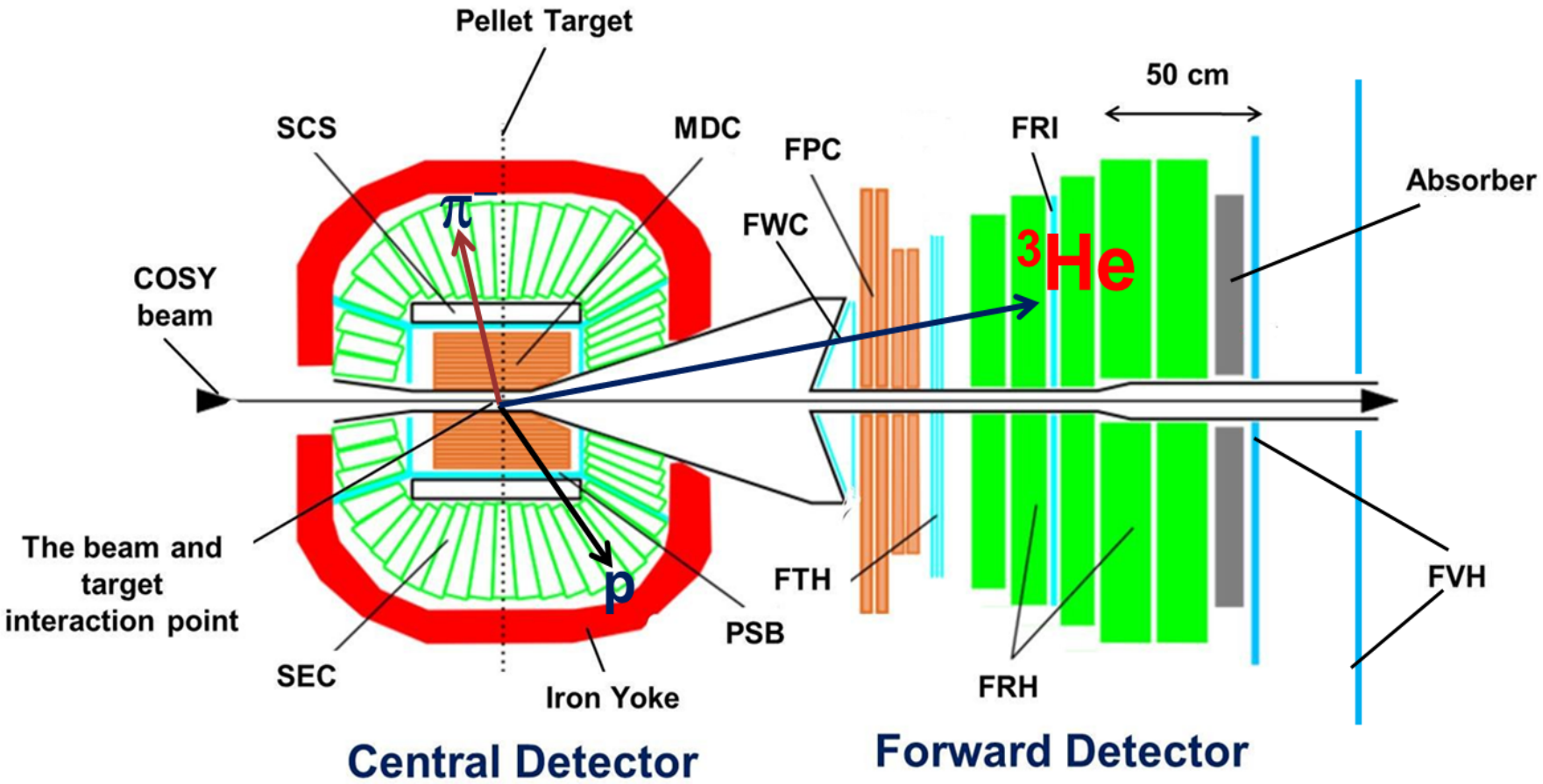
Kinematical mechanism of the reaction

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



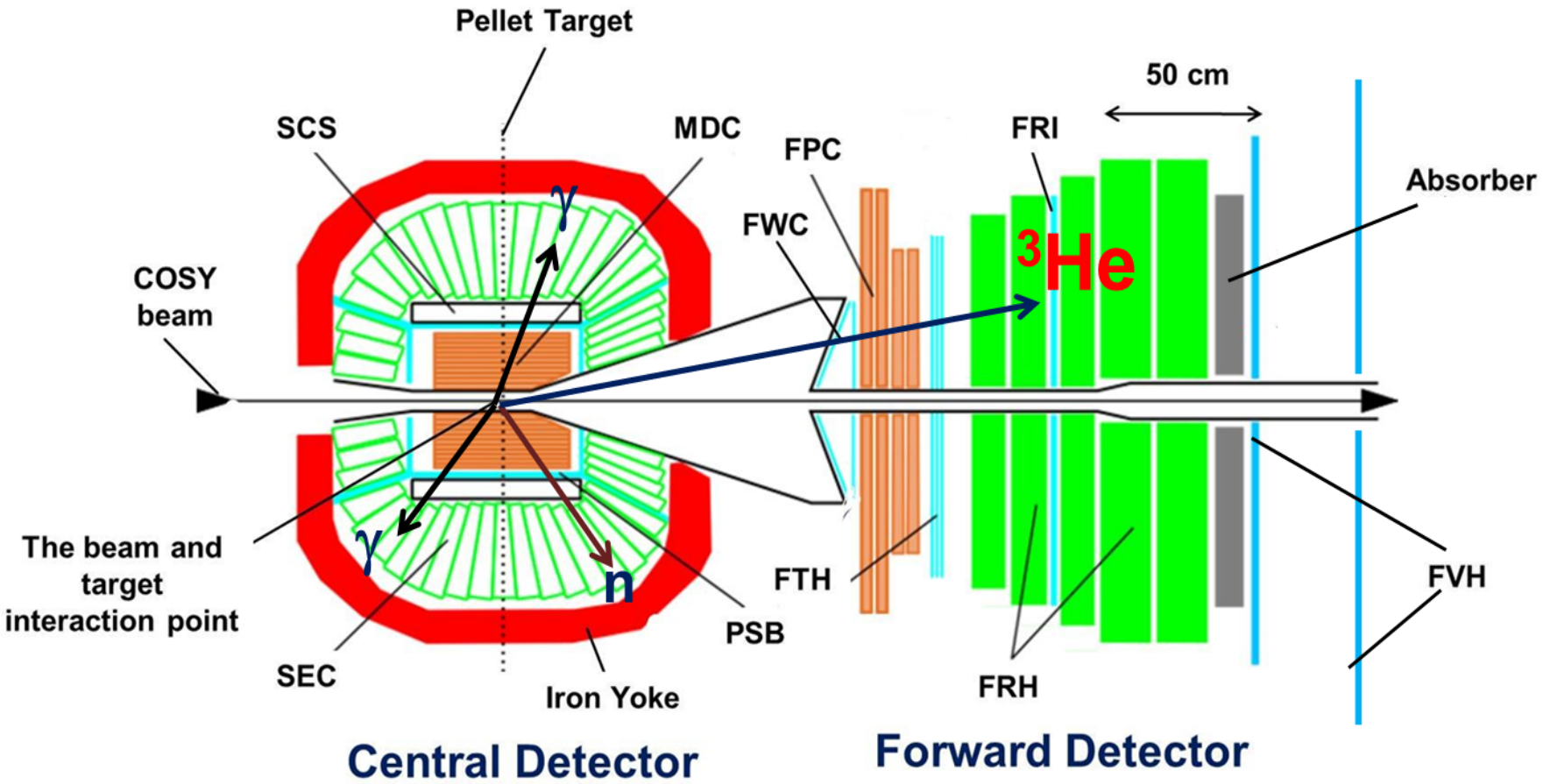
Search for η-mesic nuclei with WASA-at-COSY

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



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

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



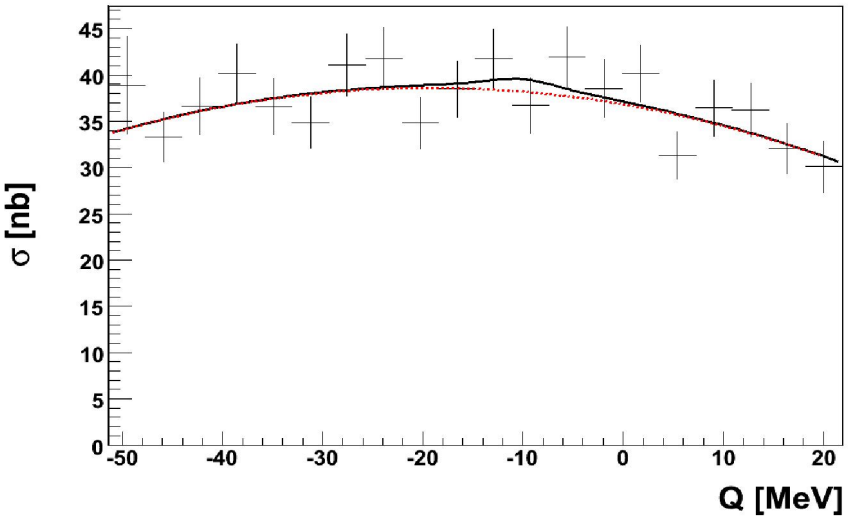
Experiment-May 2008

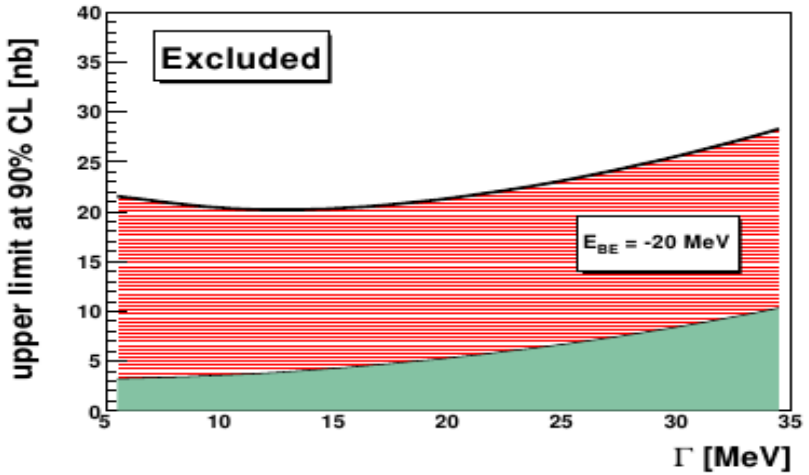
Channel: $dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^-$

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%





WASA-at-COSY: Phys. Rev. C87 (2013) 035204

Experiment-Nov/Dec 2010

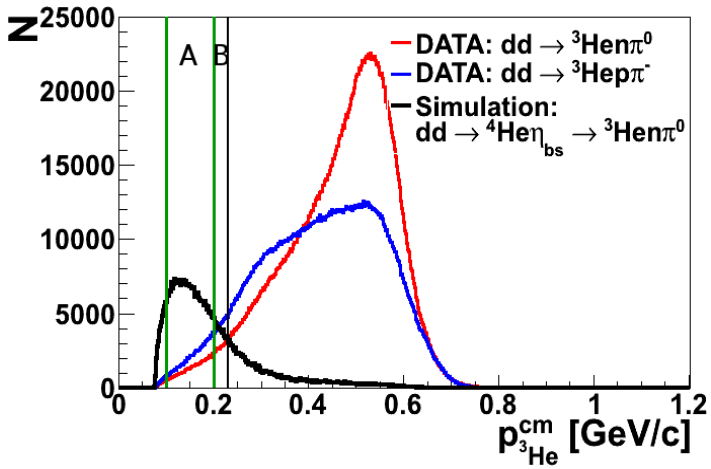
Beamtime: Nov 26 - Dec 13, 2010

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≈1100$\frac{1}{nb}$ ($dd \rightarrow {}^3\text{He}n$ and $dd \rightarrow ppn_{sp}n_{sp}$)

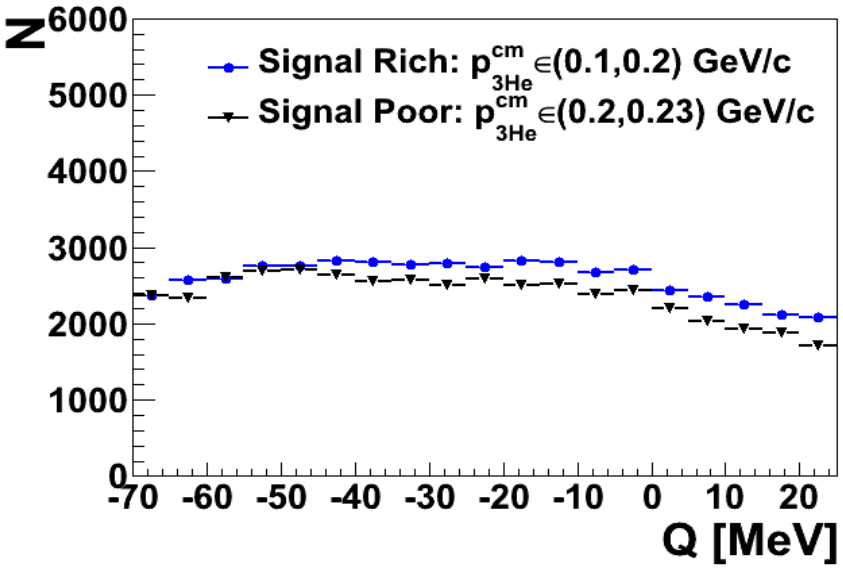
$\Downarrow$

More than **20 times higher** statistics were collected than in experiment carried out in 2008.

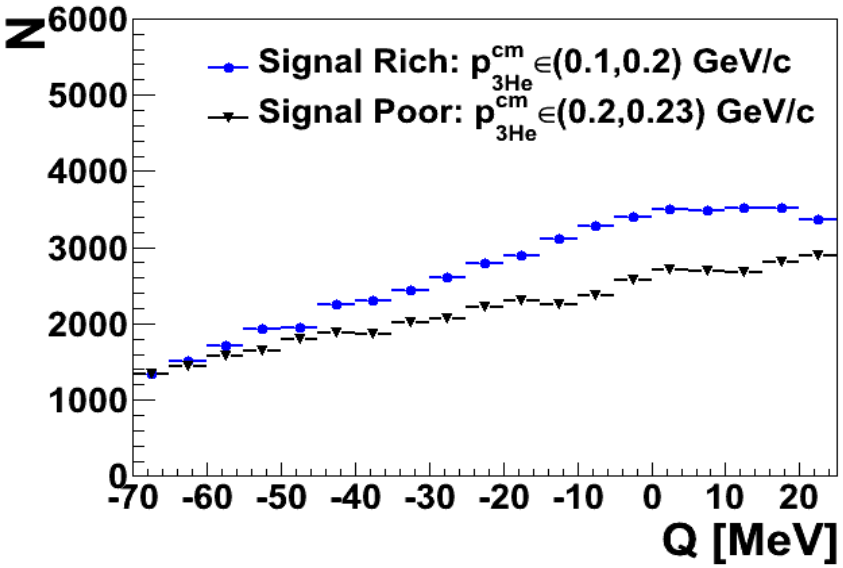


Excitation functions

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



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



New experiment-May/June 2014

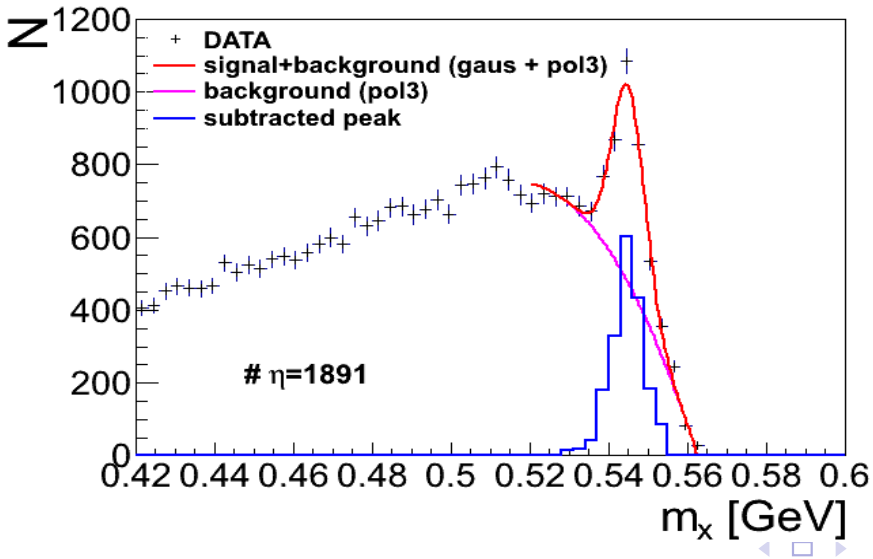
Channels: 1) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow ppp\pi^-$
2) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow ppn\pi^0$ 3) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow dp\pi^0$

Orbiting η
4) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}\ 2\gamma$ 5) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}\ 6\gamma$

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

Luminosity: L$\approx$5000$\frac{1}{nb}$ $(pd \rightarrow {}^3\text{He-}\eta)$

test plot



η - ^{4}He

~25nb -- Present experimental upper limit

WASA-at-COSY: Phys. Rev. C87(2013) 035204

~ 4 nb -- Theoretical estimation

S. Wycech, W. Krzemien , Acta. Phys. Pol. B45 (2014) 745

~ few nb -- WASA-at-COSY data collected in 2010

η - ^{3}He

~270 nb -- Present experimental upper limit pppπ$^-$

COSY-11: Acta Phys. Pol B41 (2010) 21

~80 nb -- Theoretical estimation

C. Wilkin, Acta. Phys. Pol. B45 (2014) 603

~ 10nb -- expected from New WASA-at-COSY data collected in May 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, we can reach sensitivity in order of few nanobarns in MeV Q bins
- 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 signal of η-mesic nuclei
- Analysis is in progress
- New data set in ^{3}He-η system - Experiment in May 2014

Thank you for attention

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η-mesic bound state

Conditions for the existence of eta-mesic nuclei

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

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

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)

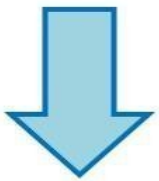
η-mesic bound state

Recent theoretical investigations of hadronic- and photoproduction of η meson

$$0.18\,fm \leq \mathrm{Re}\,a_{\eta N} \leq 1.03\,fm$$

$$0.16\,fm \leq \mathrm{Im}\,a_{\eta N} \leq 0.49\,fm$$

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



$(^4\mathrm{He}\text{-}\eta)_{bs}$ $(\mathrm{T}\text{-}\eta)_{bs}$

$(^3\mathrm{He}\text{-}\eta)_{bs}$ $(\mathrm{d}\text{-}\eta)_{bs}$

Motivation

- Search for new kinds of nuclear matter
- Investigation of η and 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 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)

Search for η, η' -mesic bound states

COSY-11 and ANKE Jülich/Germany: $dp \rightarrow {}^{3}\mathrm{He}\eta$
T. Mersmann et al., Phys. Rev. Lett. 98, 242301 (2007)
J. Smyrski et al., Phys. Lett. B649, 258 (2007)

COSY-GEM Jülich/Germany: $p + {}^{27}\mathrm{Al} \rightarrow$
$(\eta + {}^{25}\mathrm{Mg}) + {}^{3}\mathrm{He} \rightarrow ({}^{25}\mathrm{Mg}\text{-}\eta)_{bs} + {}^{3}\mathrm{He}$
A. Budzanowski et al., Phys. Rev. C79, 012201 (2009)

JINR/LHE Dubna/Russia: $d + {}^{13}\mathrm{C} \rightarrow ({}^{12}\mathrm{C})_{\eta} + \ldots \rightarrow p + \pi + \ldots$
S. V. Afanasiev, Phys. Part. Nucl. Lett. 8, 1073 (2011)

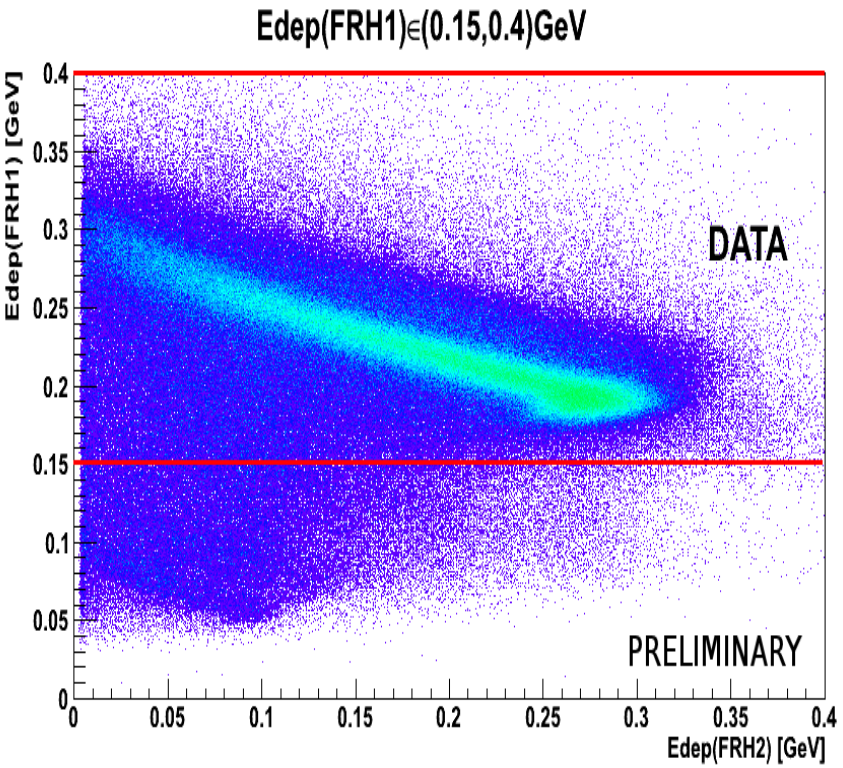
ELSA Mainz/Germany: $\gamma + {}^{12}\mathrm{C} \rightarrow \eta' + X$
M. Nanova et al., Phys. Lett. B727, 417 (2013)

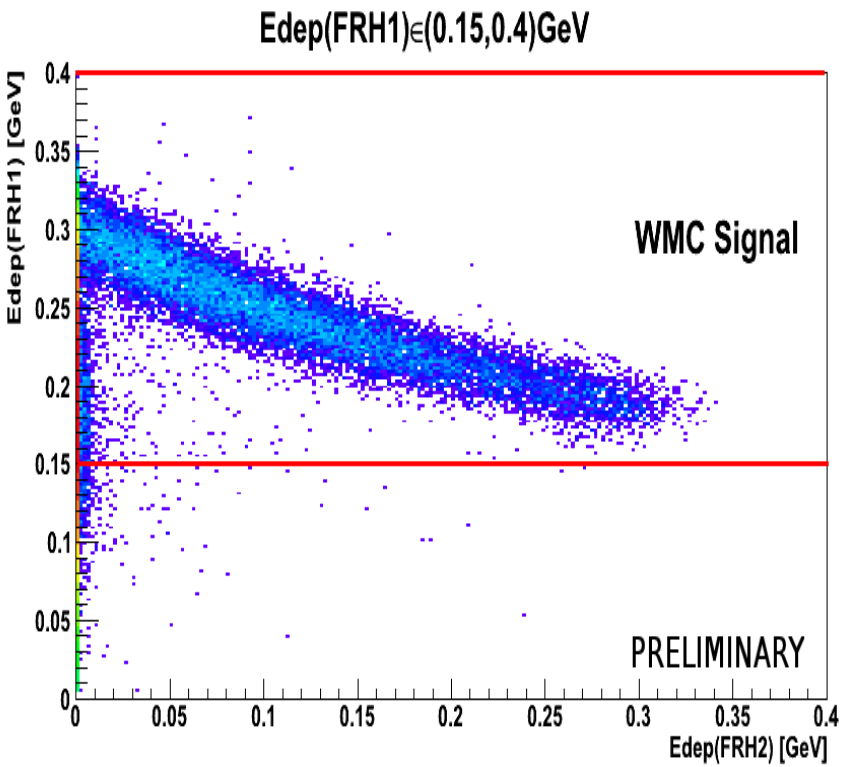
FRS-GSI Darmstadt/Germany: ${}^{11}\mathrm{C}\text{-}\eta'$ in ${}^{12}\mathrm{C}(p, d)$
Y. K. Tanaka et al., Few Body Syst. 54, 1263 (2013)

J-PARC Tokai/Japan: ${}^{11}\mathrm{C}\text{-}\eta'$ in ${}^{12}\mathrm{C}(\pi^{+}, p)$
H. Nagahiro, Prog. Theor. Phys. Suppl. 186, 316 (2010)

^{3}He identification in Forward Detector

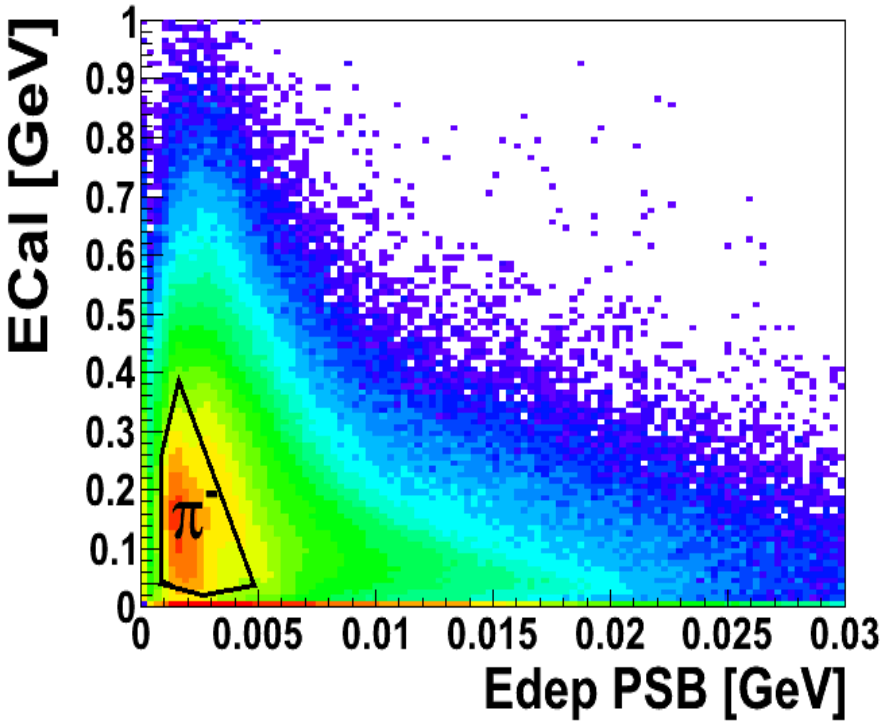
$dd \rightarrow {}^3\mathrm{He}p\pi^-$ $dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$



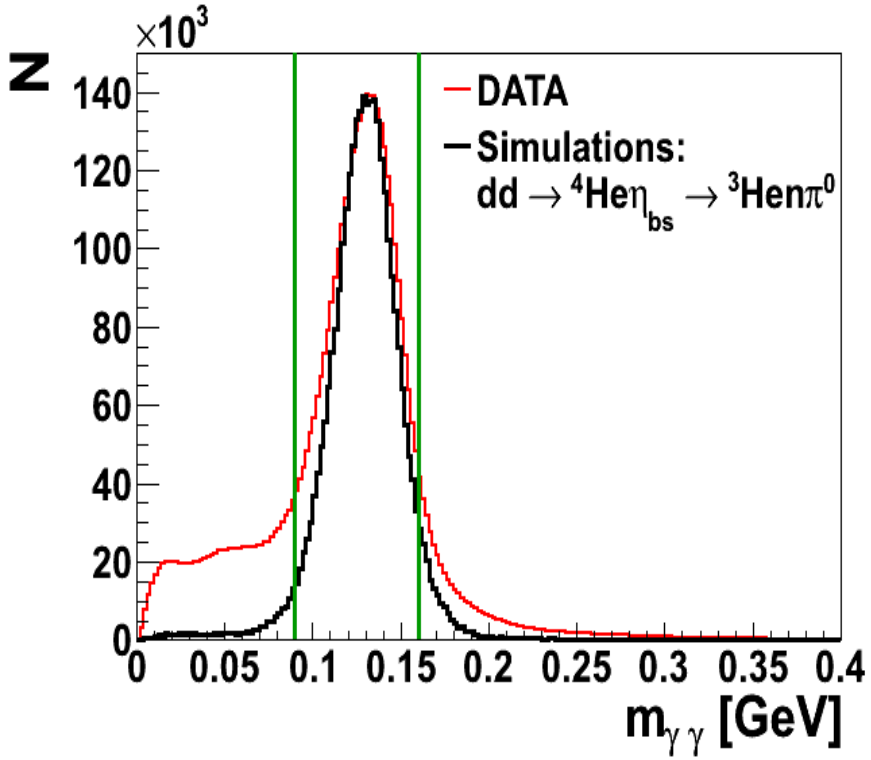


Pion identification in Central Detector

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

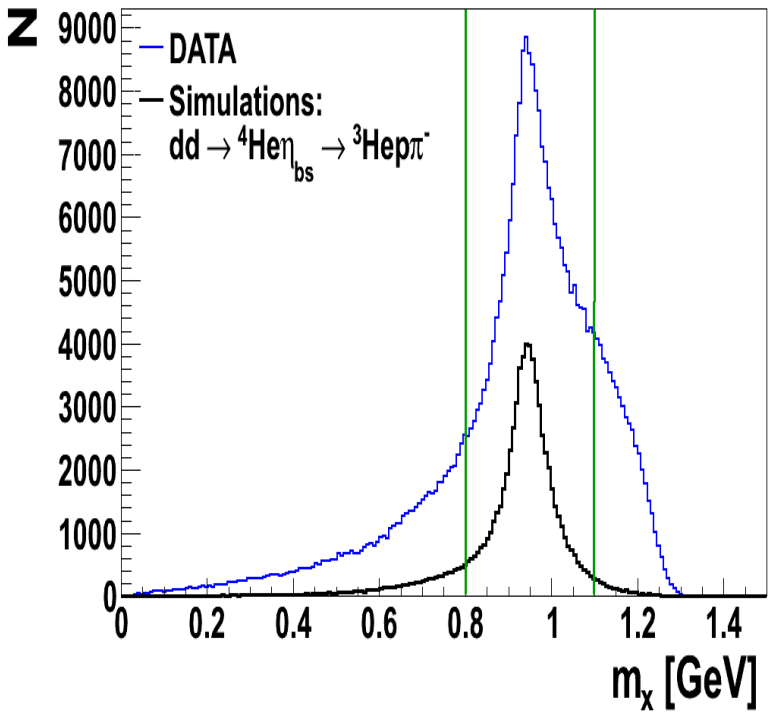


$dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$

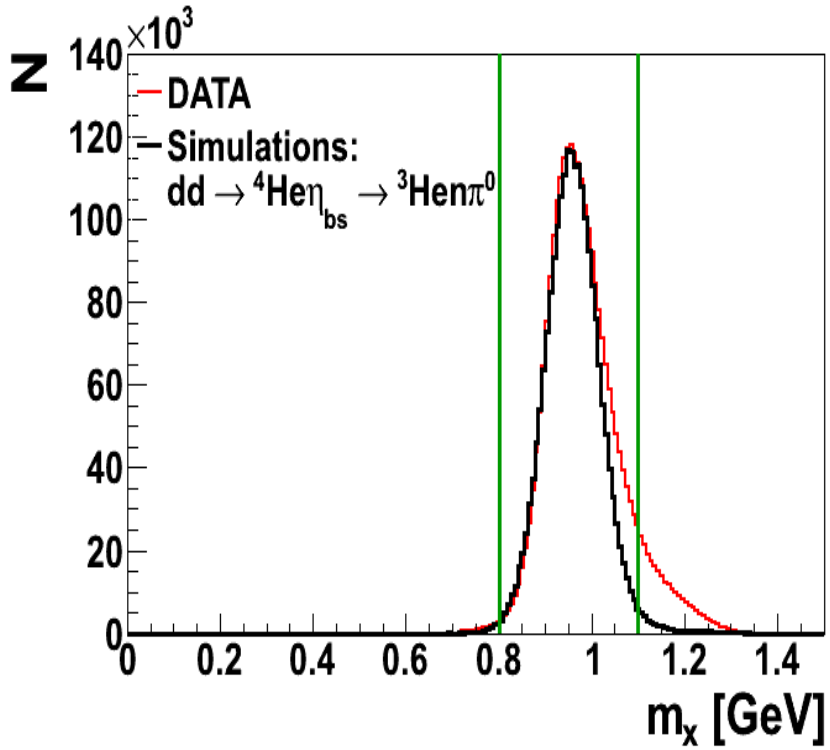


Nucleon identification in Central Detector via missing mass

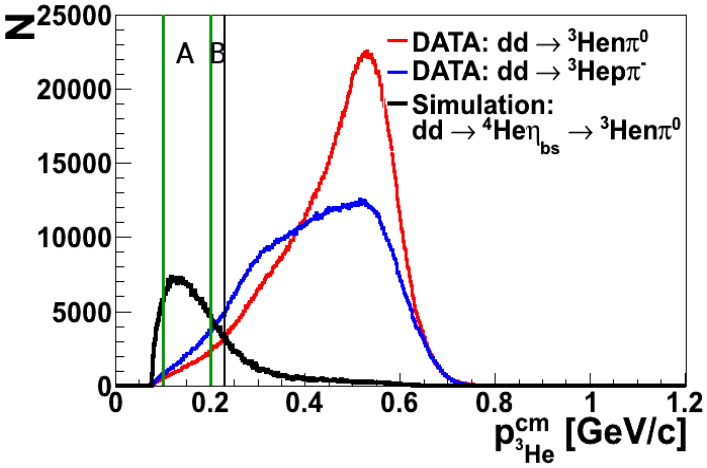
$dd \rightarrow {}^3\mathrm{He}p\pi^-$

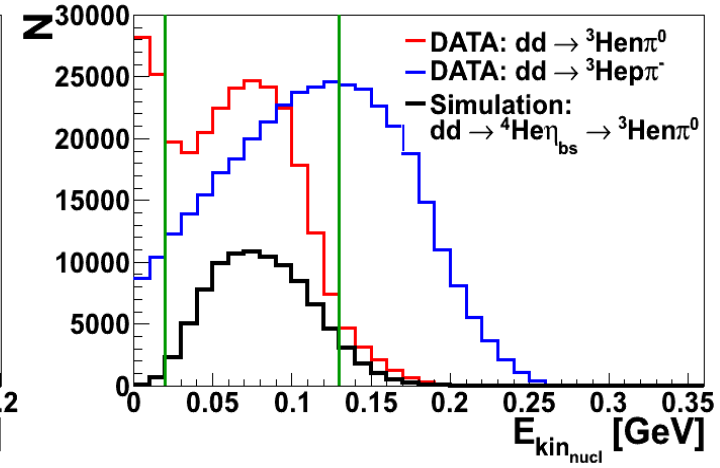


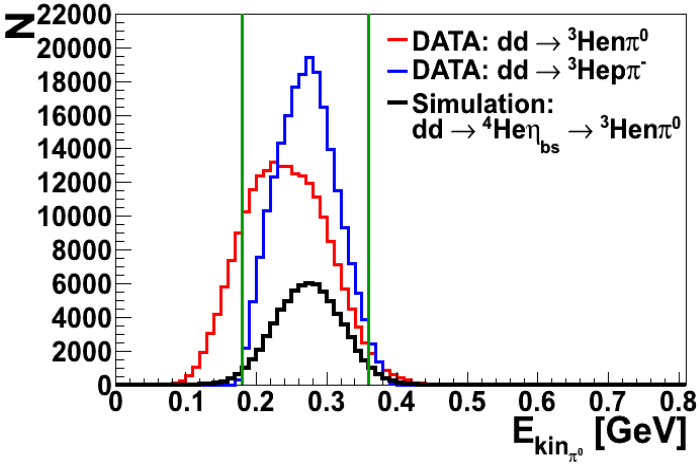
$dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$

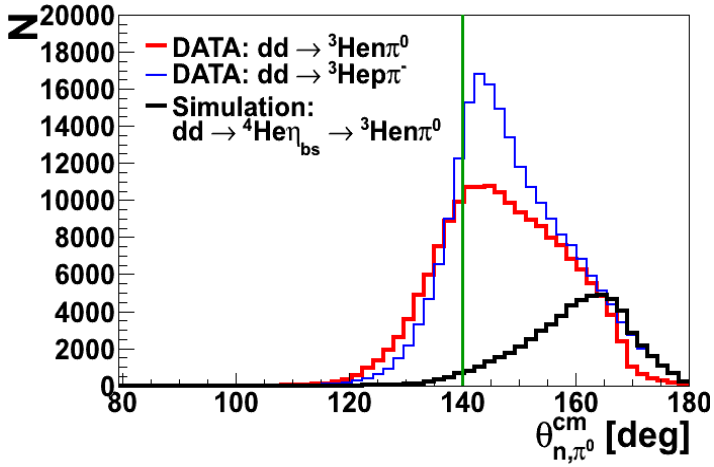


Kinematical conditions





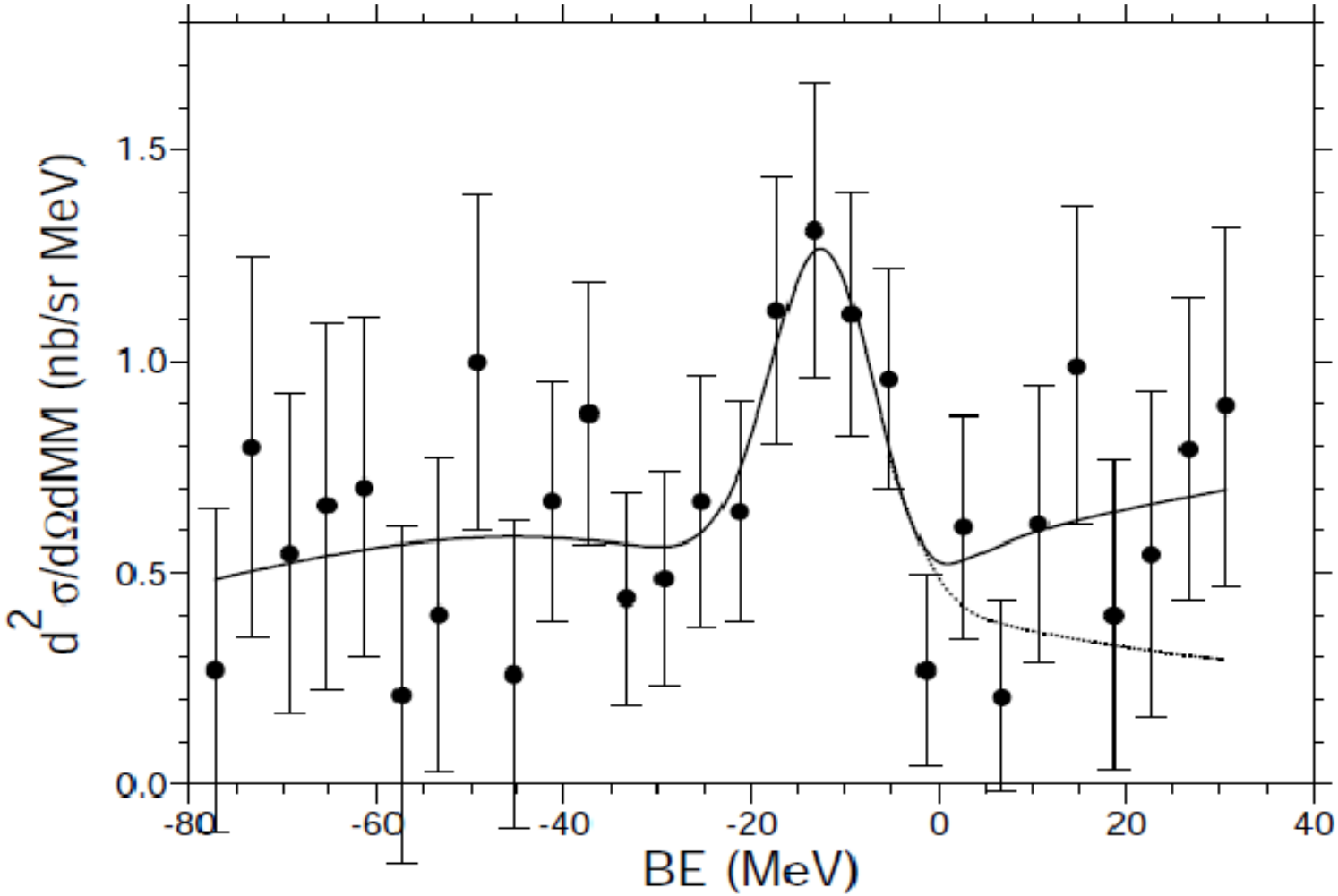




DATA: $dd \rightarrow {}^3\mathrm{He}p\pi^-$
DATA: $dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$

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

COSY-GEM



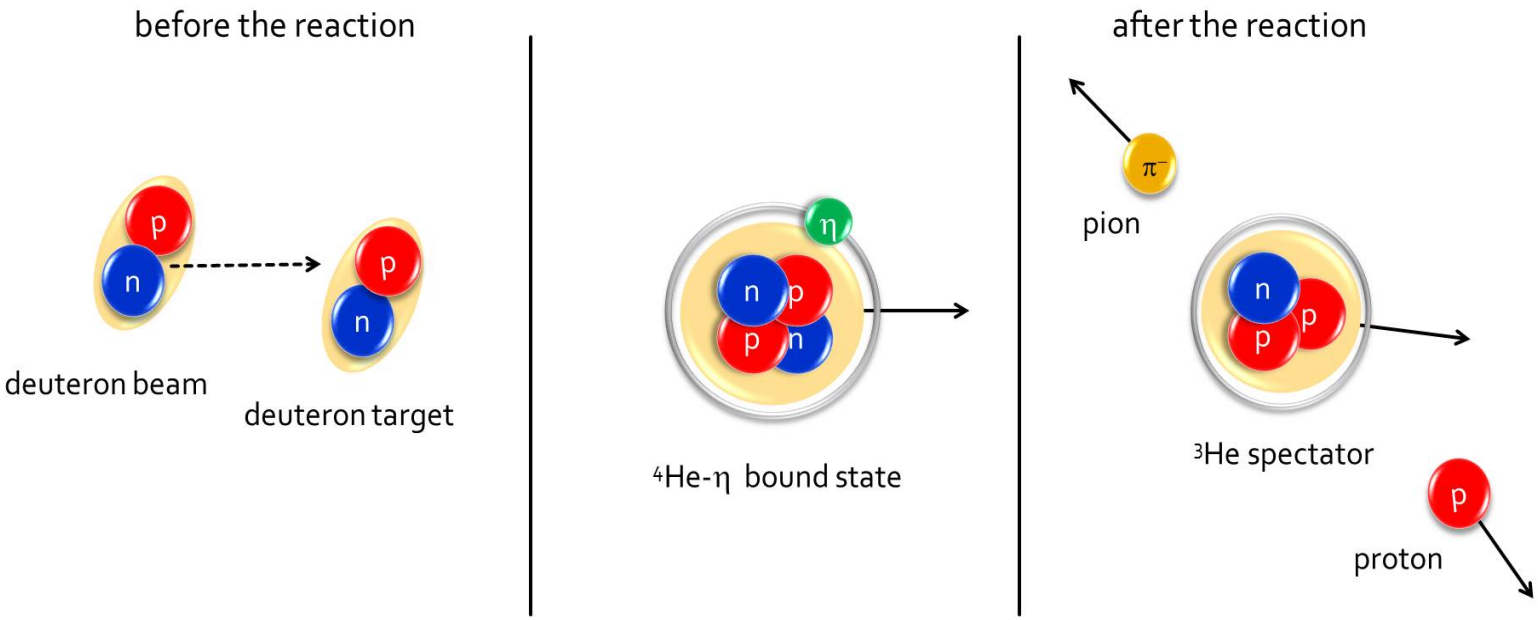
Search for η'-mesic bound states

FRS-GSI Darmstadt/Germany: η' meson bound states in ^{11}C nuclei via inclusive missing mass spectroscopy of $^{12}C(p,d)$ reaction near the η' production threshold

Search for K-mesic bound states

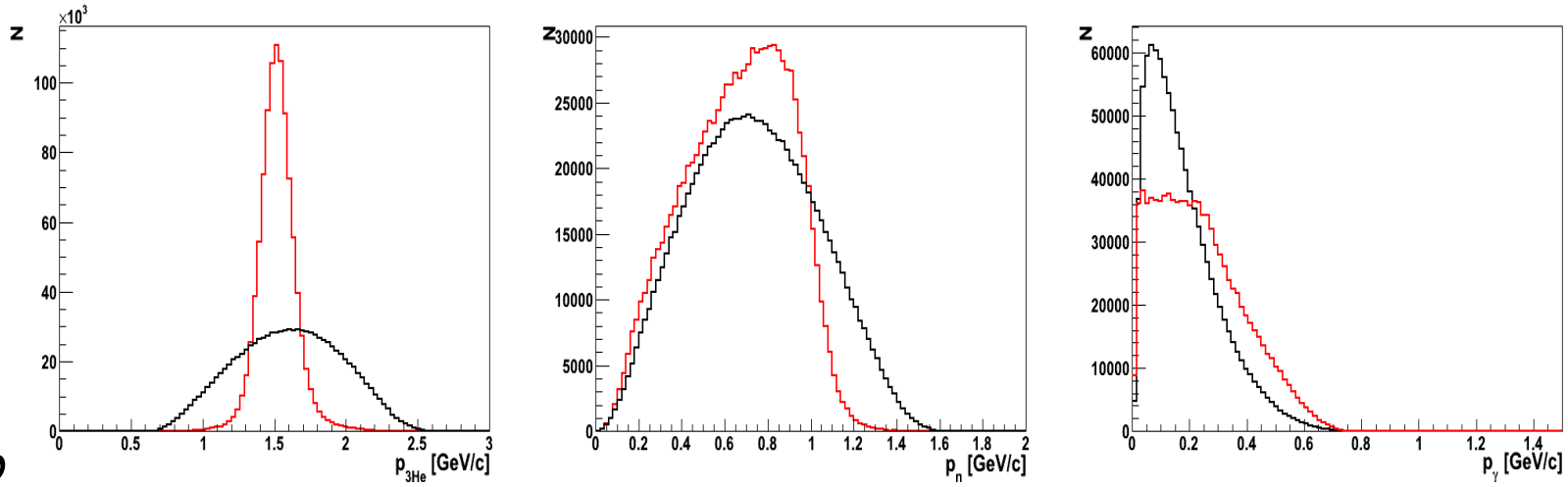
AMADEUS/DAFNE Frascati/Italy:
$K^- + {}^3\mathrm{He} \rightarrow ppK^- + n$
$K^- + {}^4\mathrm{He} \rightarrow ppnK^- + n$
$K^- + {}^4\mathrm{He} \rightarrow pnnK^- + p$
J-PARC Tokai/Japan: $K^-\ {}^3\mathrm{He} \rightarrow (K^- pp)_{bs} + n$

Spectator model

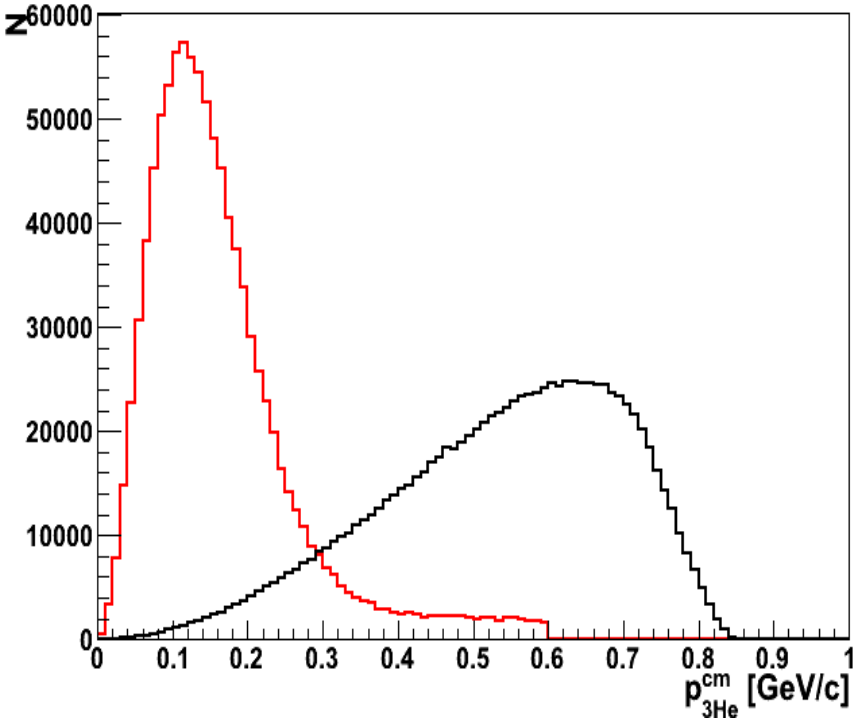


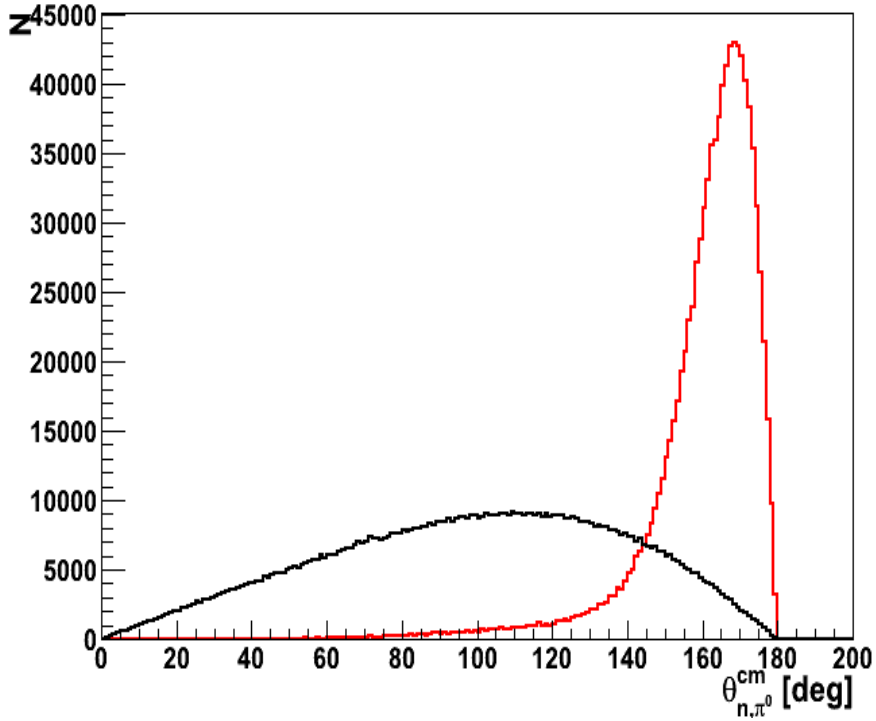
$$dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^- \qquad |\mathbb{P}_{sp}|^2 = m_{sp}^2$$

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



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





Probability of the $dd \to ({}^4\text{He-}\eta)_{bs} \to {}^3\text{He}N^* \to {}^3\text{He}n\pi^0$ and $dd \to ({}^4\text{He-}\eta)_{bs} \to {}^3\text{He}N^* \to {}^3\text{He}p\pi^-$ reactions

	d	^{4}He	η	^{3}He	N^*	n	p	π^-	π^0
I	0	0	0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1
I_z	0	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	-1	0

$dd \to ({}^4\text{He-}\eta)_{bs} \to {}^3\text{He}N^* \to {}^3\text{He}n\pi^0$ $(N^* \to n\pi^0)$
$dd \to ({}^4\text{He-}\eta)_{bs} \to {}^3\text{He}N^* \to {}^3\text{He}p\pi^-$ $(N^* \to p\pi^-)$
Eigenstates:
$n\pi^0$: $|\frac{1}{2}\ -\frac{1}{2}\rangle\ |10\rangle$
$p\pi^-$: $|\frac{1}{2}\frac{1}{2}\rangle\ |1\ -1\rangle$

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$n\pi^0$: $\langle\ -\frac{1}{2}0|\ \frac{1}{2}\ -\frac{1}{2}\rangle = \sqrt{\frac{1}{3}} \Rightarrow \mathrm{P}(N^* \to n\pi^0) = \frac{1}{3}$

$p\pi^-$: $\langle\ \frac{1}{2}\ -1|\ \frac{1}{2}\ -\frac{1}{2}\rangle = -\sqrt{\frac{2}{3}} \Rightarrow \mathrm{P}(N^* \to p\pi^-) = \frac{2}{3}$.

Probability of the $dd \to {}^3\mathrm{He}n\pi^0$ and $dd \to {}^3\mathrm{He}p\pi^-$ reactions

	d	^{4}He	η	^{3}He	N^*	n	p	π^-	π^0
I	0	0	0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1
I_z	0	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	-1	0

$n\pi^0$:$\langle\ -\frac{1}{2}0|\ \frac{1}{2}\ -\frac{1}{2}\rangle\ |-\frac{1}{2}\ 0\rangle \Rightarrow j_1' = \frac{1}{2}$ or $\langle\ -\frac{1}{2}0|\ \frac{3}{2}\ -\frac{1}{2}\rangle\ |-\frac{1}{2}\ 0\rangle \Rightarrow j_1' = \frac{3}{2}$

$p\pi^-$:$\langle\ \frac{1}{2}\ -1|\ \frac{1}{2}\ -\frac{1}{2}\rangle\ |\frac{1}{2}\ -1\rangle \Rightarrow j_1' = \frac{1}{2}$ or $\langle\ \frac{1}{2}\ -1|\ \frac{3}{2}\ -\frac{1}{2}\rangle\ |\frac{1}{2}\ -1\rangle \Rightarrow j_1' = \frac{3}{2}$

$n\pi^0$: $\langle\ -\frac{1}{2}0|\ \frac{1}{2}\ -\frac{1}{2}\rangle = \sqrt{\frac{1}{3}}$ $\quad$ $p\pi^-$: $\langle\ \frac{1}{2}\ -1|\ \frac{1}{2}\ -\frac{1}{2}\rangle = -\sqrt{\frac{2}{3}}$

^{3}He: $|\frac{1}{2}\ \frac{1}{2}\rangle \Rightarrow j_2' = \frac{1}{2}$ $\quad$ dd: $|0\ 0\rangle$

$j_1' = \frac{1}{2}$ and $j_2' = \frac{1}{2}$:

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$\langle\ -\frac{1}{2}\frac{1}{2}|\ 0\ 0\rangle = \langle\ \frac{1}{2}\ -\frac{1}{2}|\ 0\ 0\rangle = \sqrt{\frac{1}{2}}$

$\mathrm{P}(dd \to {}^3\mathrm{He}p\pi^-) > \mathrm{P}(dd \to {}^3\mathrm{He}n\pi^0)$