Status and perspectives of the search for the eta-mesic helium with WASA-at-COSY

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Hadrons in Nucleon Medium II

JPARC Tokai

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INTERNATIONAL PHD PROJECT IN APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES

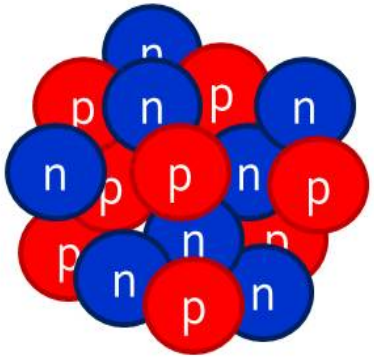
This project is supported by the Foundation for Polish Science-MPD program co-financed by the European Union within the European Regional Development Fund

Outline

- Introduction/Motivation
- 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: perspectives with 2014 data (^{3}He-η)
- Summary and Conclusions

η-mesic bound state

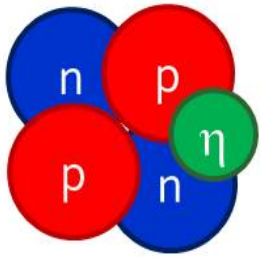
Atomic nucleus



STRONG INTERACTION

η-mesic nucleus

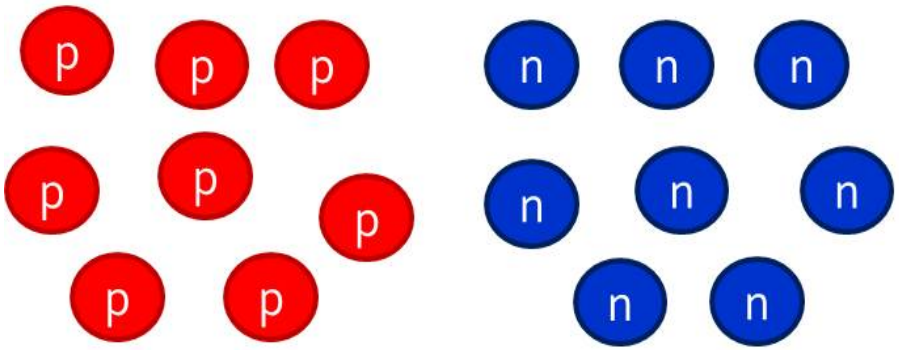
^4He-η

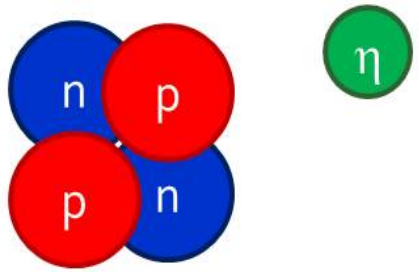


$$m = Z \cdot m_p + N \cdot m_n - B_s$$

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

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





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

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

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

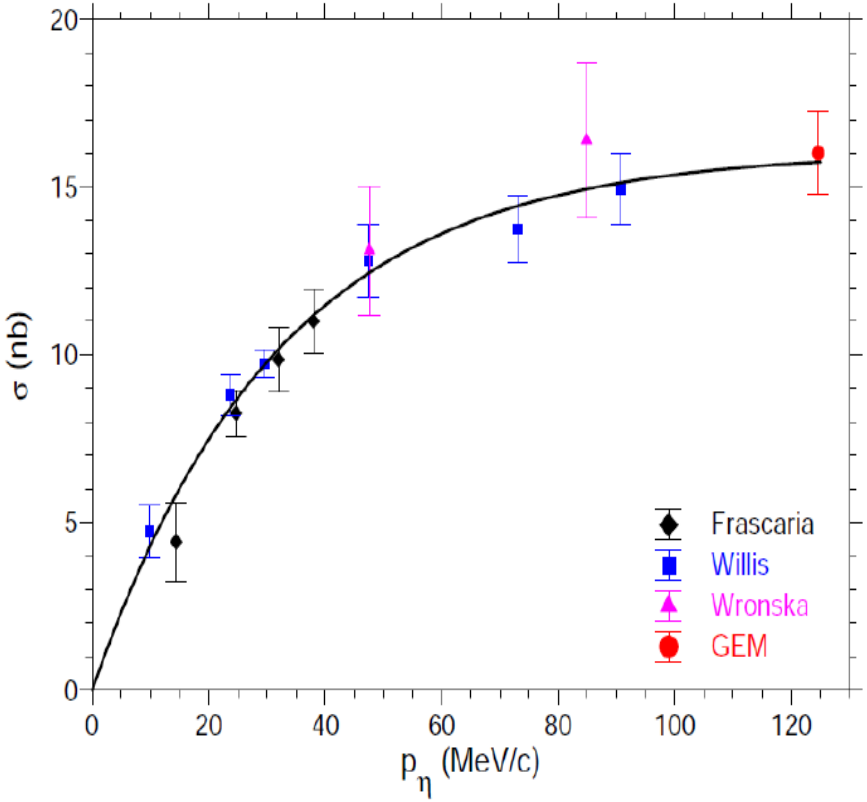
C. Wilkin, Acta. Phys. Pol. B 41, (2010), arXiv:1008.0482
S. Wycech, A. M. Green and J. A. Niskanen, Phys. Rev. C52, 544 (1995)

Motivation

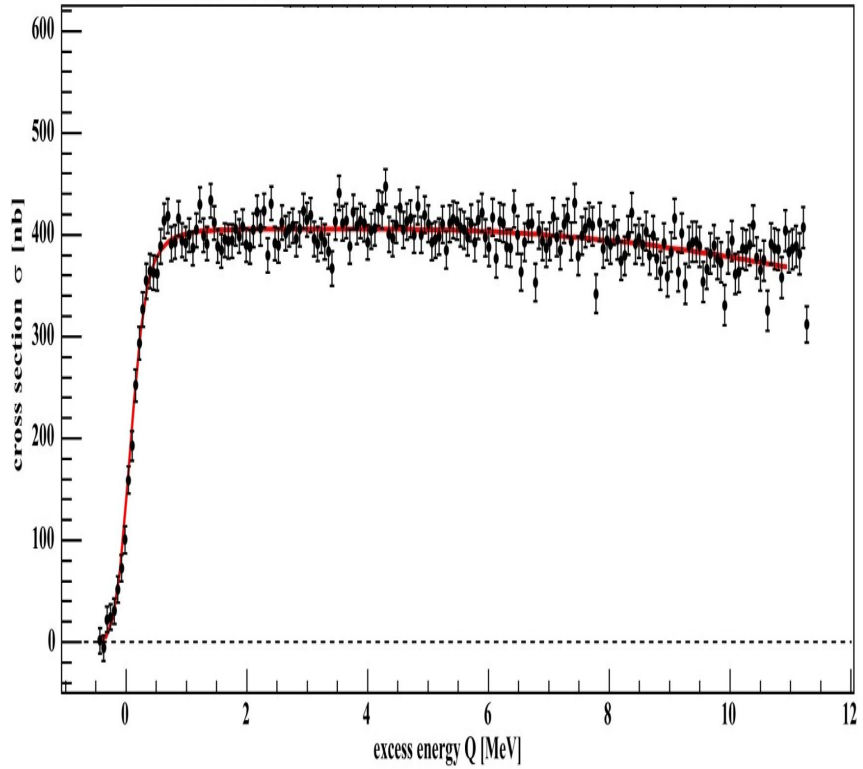
- Search for new kinds of nuclear matter
- Investigation of η and η' interaction with nucleons inside a nuclear matter
- Study of N*(1535) properties in nuclear matter
  D. Jido, H. Nagahiro, S. Hirenzaki, Phys. Rev. C66, 045202 (2002)
  S. Hirenzaki et al., Acta Phys. Polon. B41, 2211 (2010)
- Information about η, η' meson structure (contribution of the flavour singlet component of the quark-gluon wave function associated with axial U1 anomaly)
  S. Hirenzaki, H. Nagahiro, Acta Phys.Polon. B45, 619 (2014)
  H. Nagahiro, S. Hirenzaki, Phys. Rev. Lett. 94, 232503 (2005)
  S. D. Bass, A. W. Thomas, Phys. Lett. B634, 368 (2006)

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

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

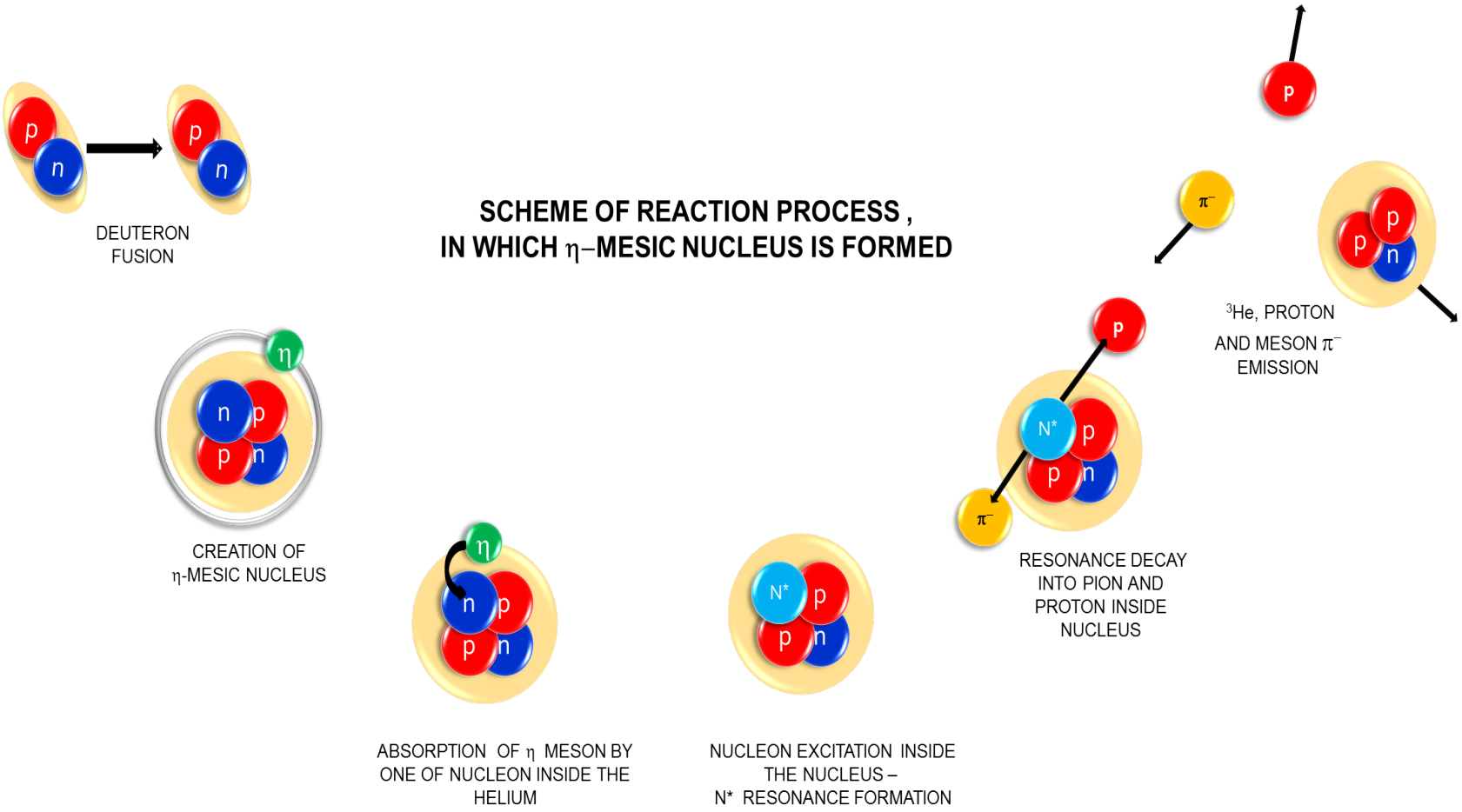
$$dd \rightarrow \left({}^4He - \eta\right)_{bs} \rightarrow {}^3He\ n\ \pi^0 \rightarrow {}^3He\ n\ \gamma\ \gamma$$

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

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

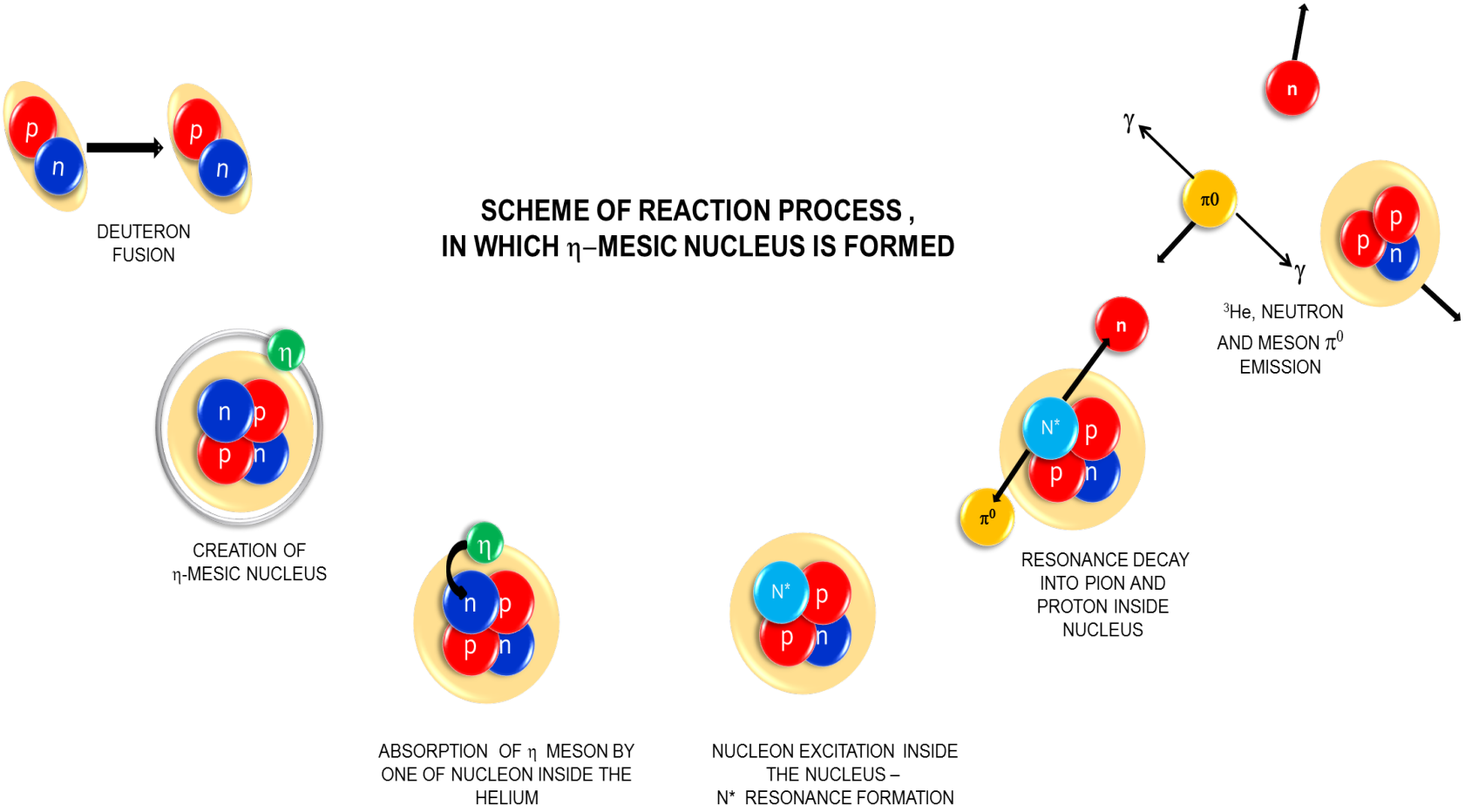
Kinematical mechanism of the reaction

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



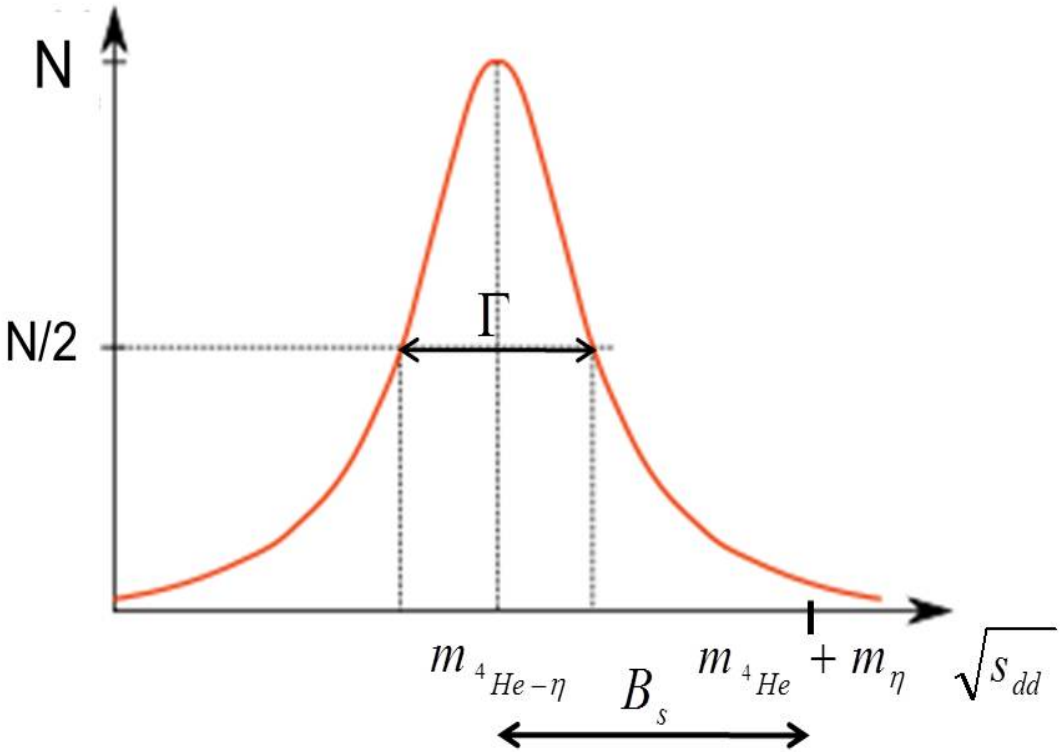
Kinematical mechanism of the reaction

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

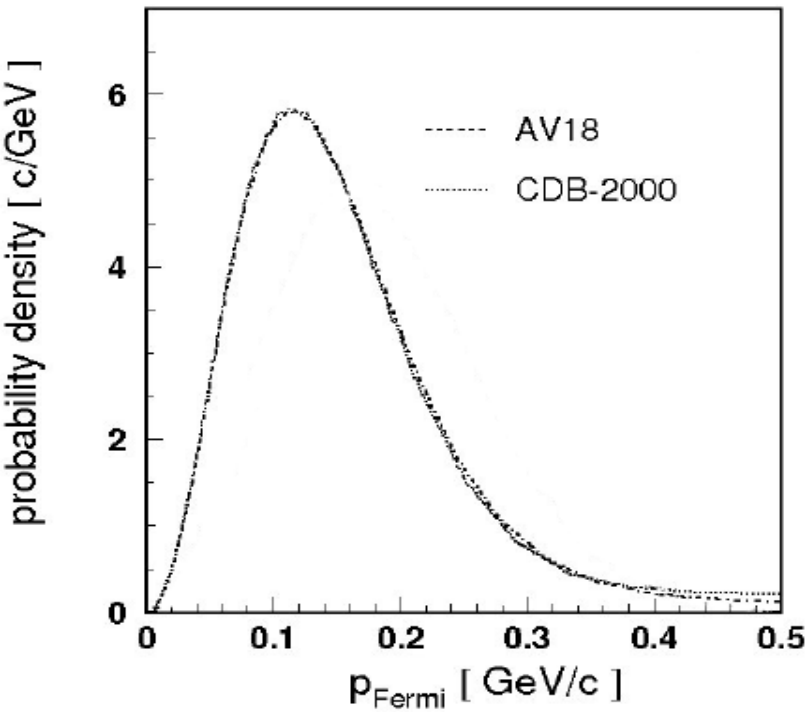


MC Simulations - assumptions

Breit-Wigner distribution



Spectator Model



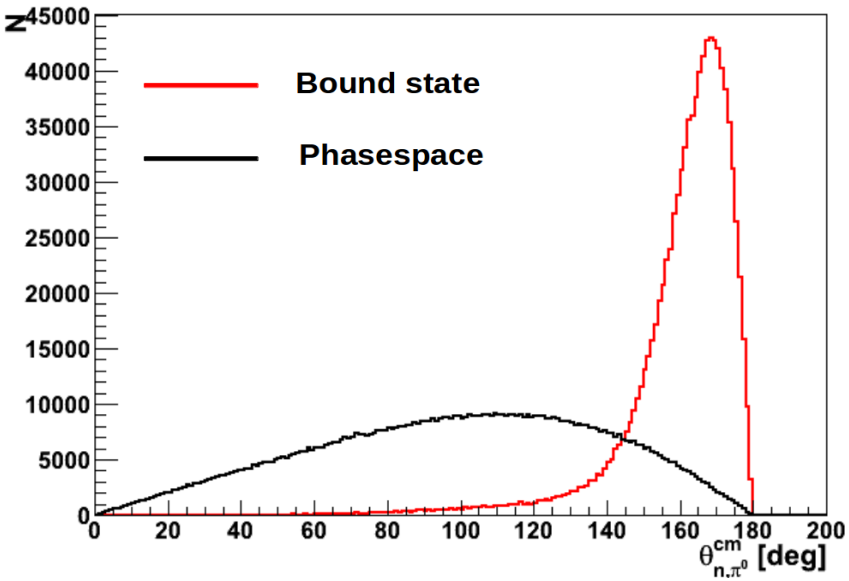
$$N\left(\sqrt{s_{dd}}\right) = \frac{1}{2\pi}\frac{\Gamma}{\left(\sqrt{s_{dd}}-m_{bs}\right)^2+\Gamma^2/4} \qquad \Gamma \in (5,40)\text{MeV}$$

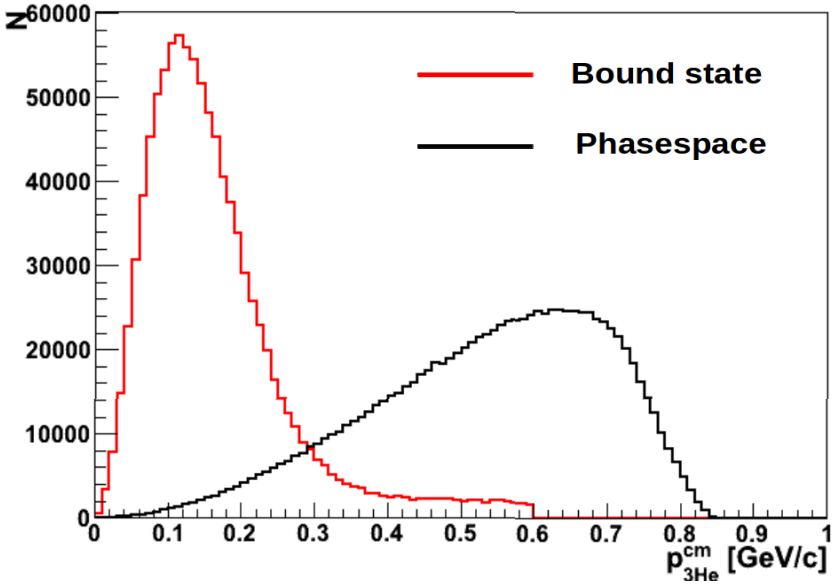
$$m_{^4He-\eta} = m_{^4He} + m_\eta - B_s \qquad B_s \in (5,20)\text{MeV}$$

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



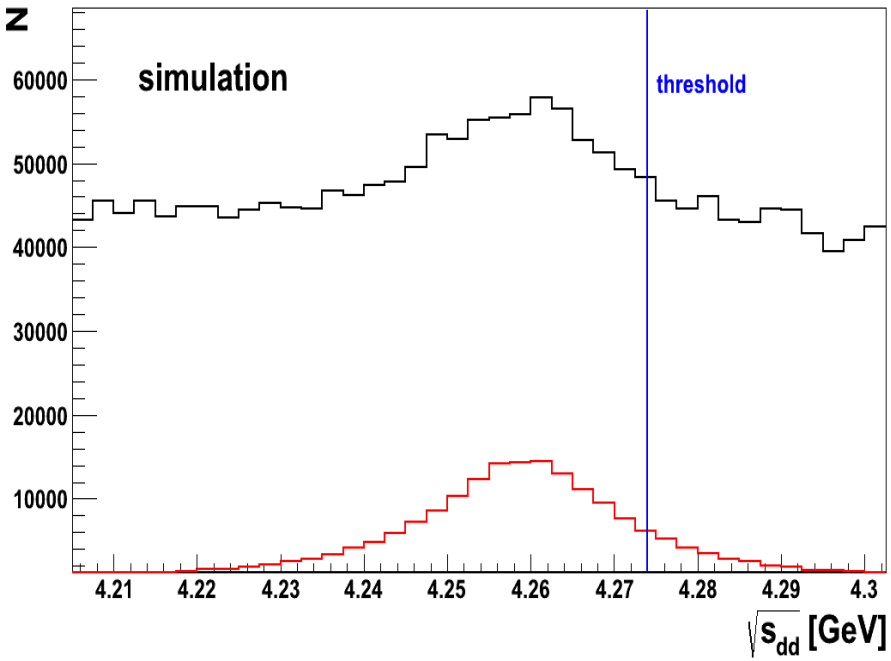


Discussion - 26.11, 14:00

Experimental method

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

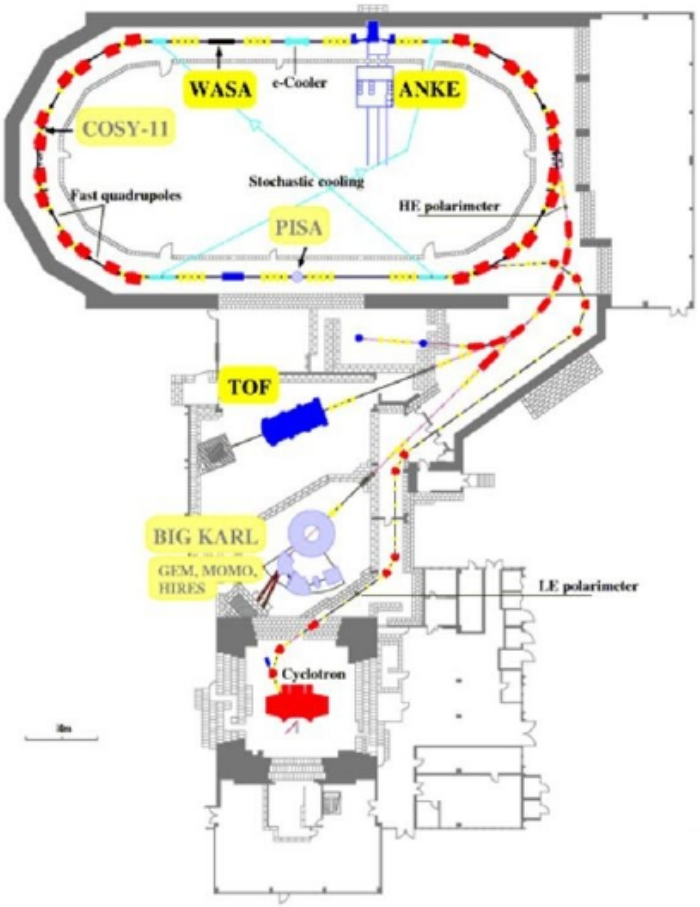
$$dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bs} \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$$

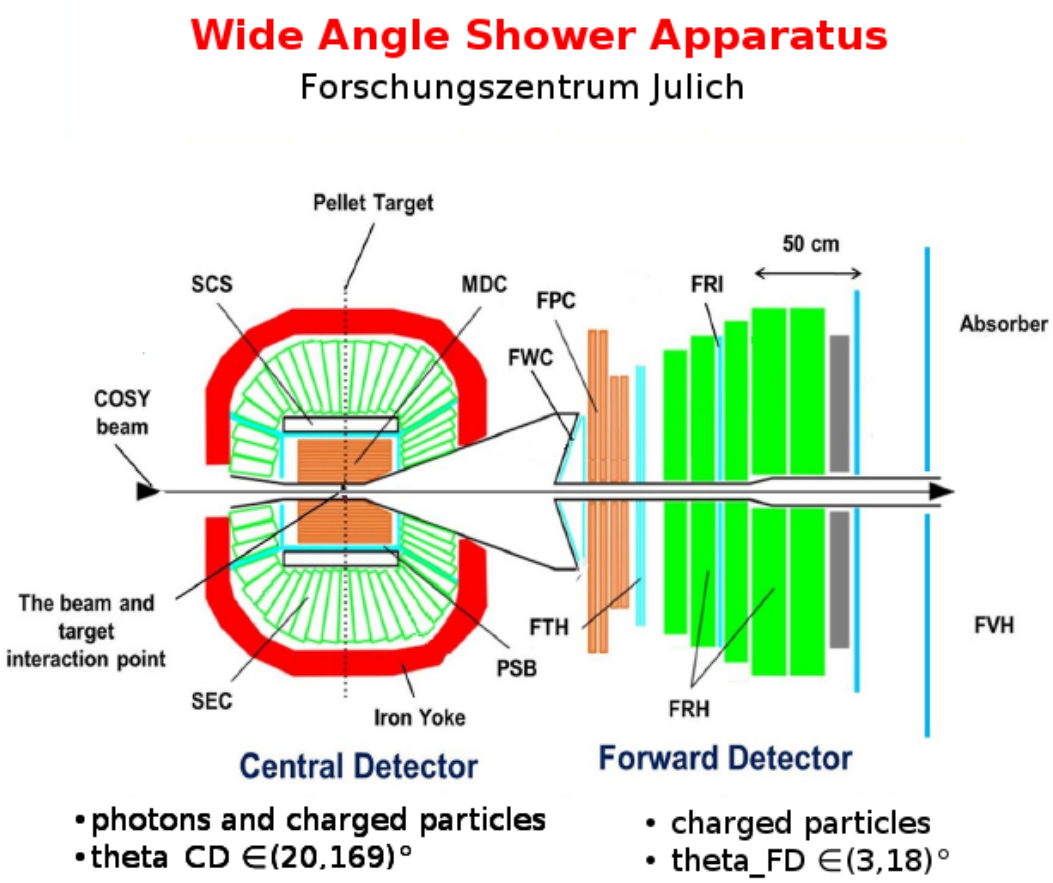


Excitation function

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

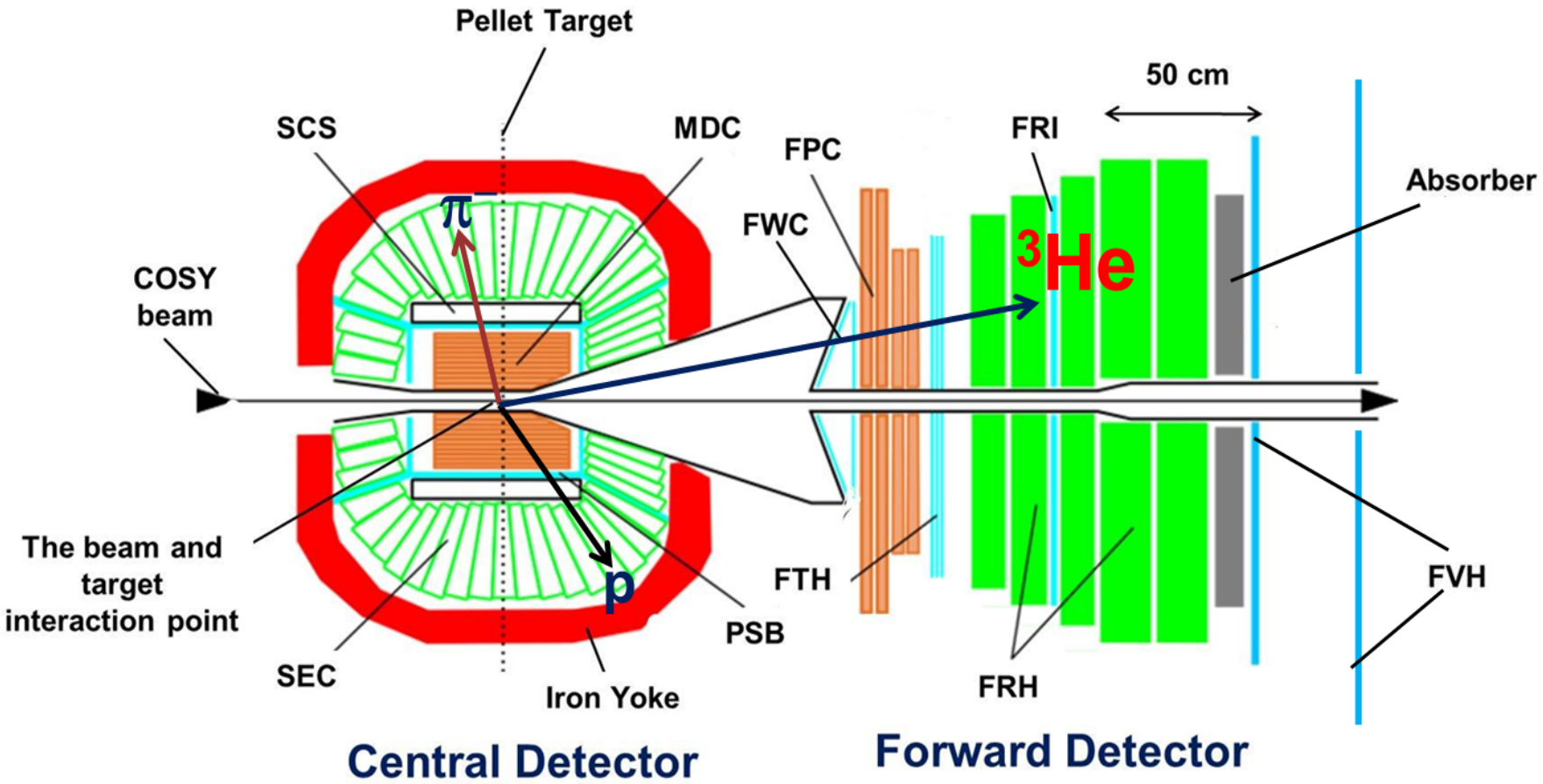
Search for η-mesic nuclei with WASA-at-COSY





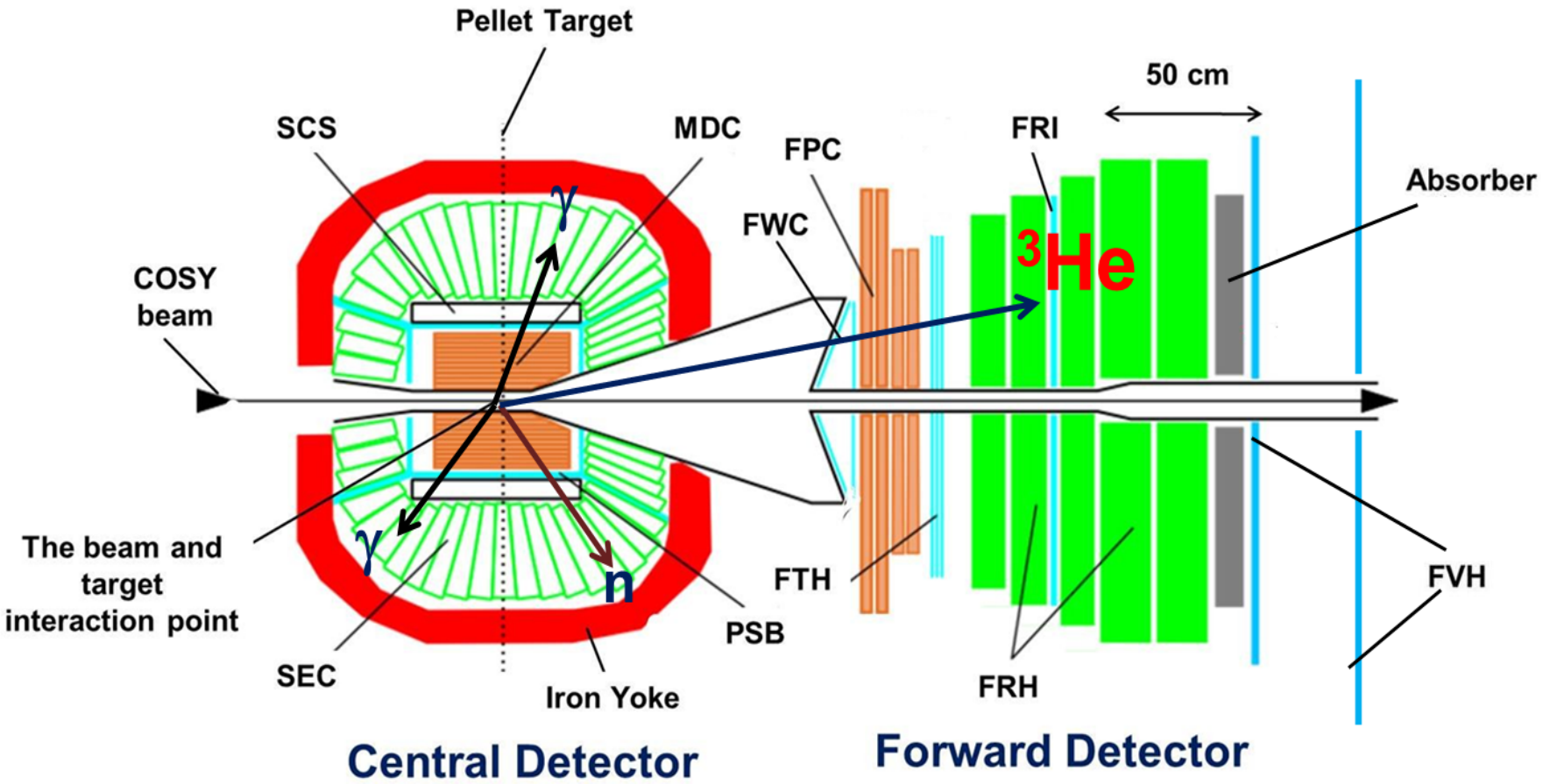
Search for η-mesic nuclei with WASA-at-COSY

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



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

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



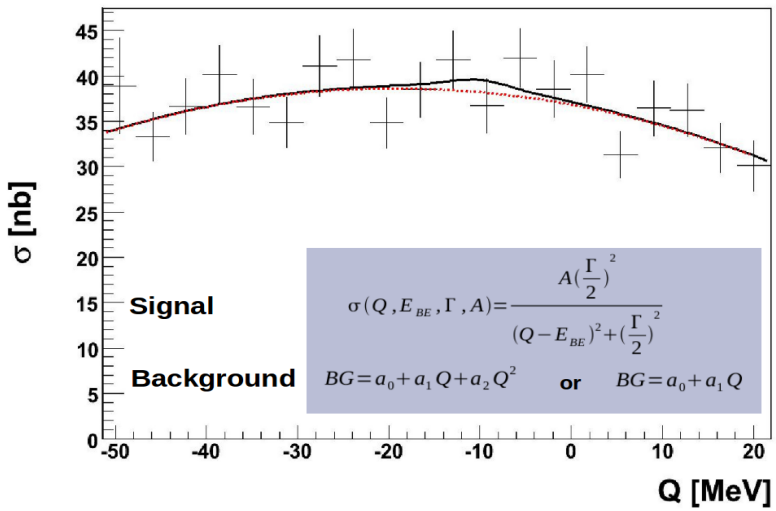
Experiment-May 2008

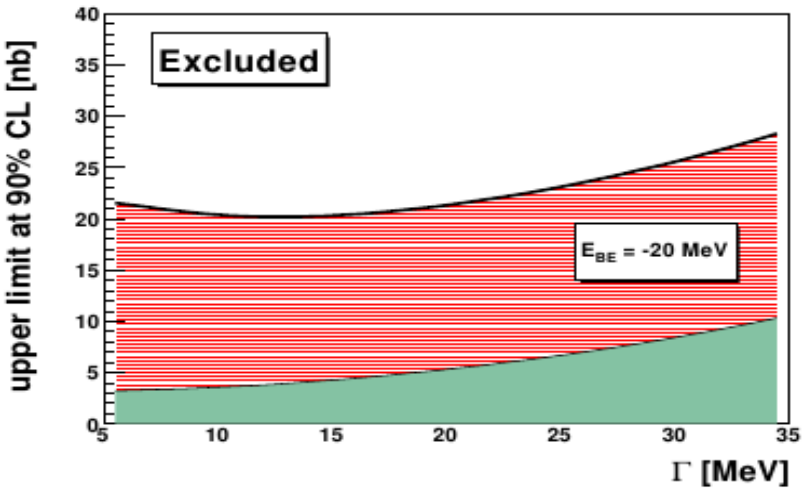
Channel: $dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^- $ (norm: $dd \rightarrow {}^3\text{He}n$)

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%





W. Krzemien et al., Phys. Rev. C87 (2013), 035204

Experiment-Nov/Dec 2010

Beamtime: Nov 26 - Dec 13, 2010

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

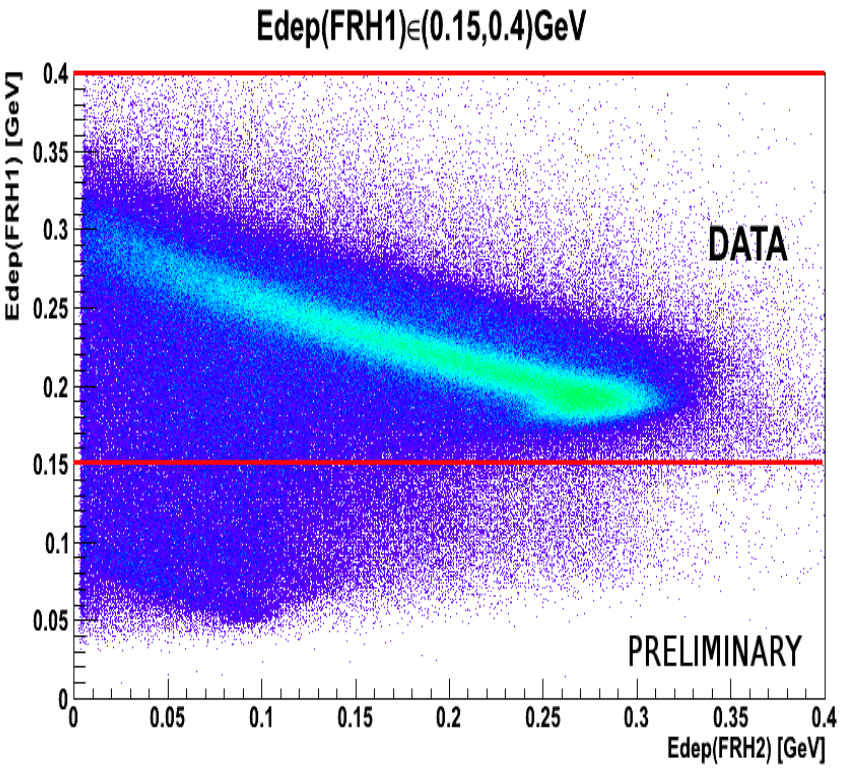
Measurement: performed with the beam momentum ramped from **2.127GeV/c to 2.422GeV/c**, corresponding to the range of excess energy **Q∈(-70,30)MeV**
Acceptance: A=53%
Luminosity: L≈1100$\frac{1}{nb}$ ($dd \rightarrow {}^3\text{He}n$ and $dd \rightarrow ppn_{sp}n_{sp}$)

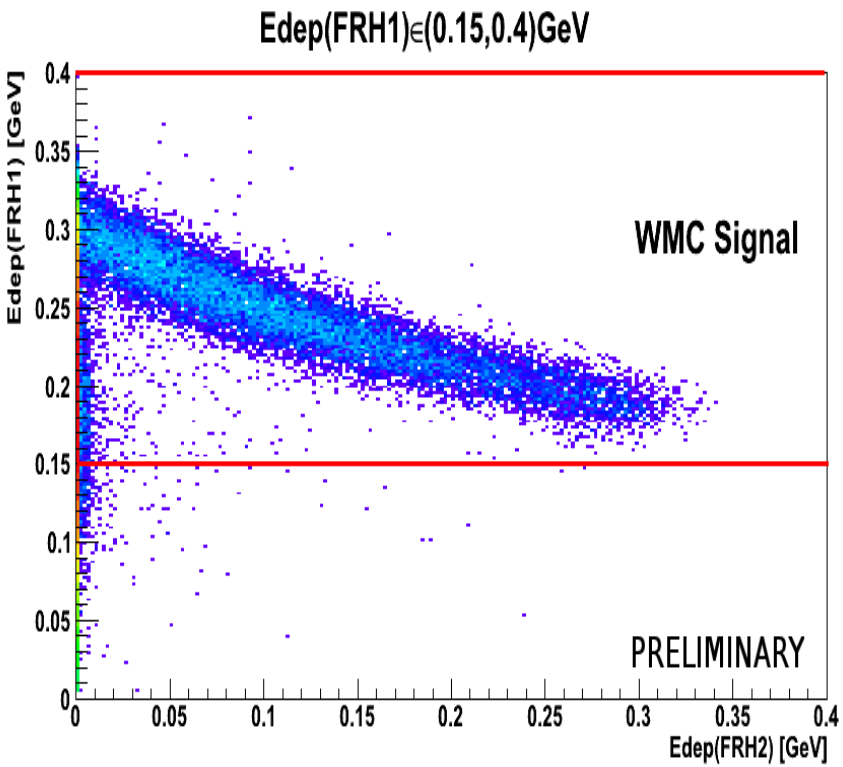
$\Downarrow$

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

^{3}He identification in Forward Detector

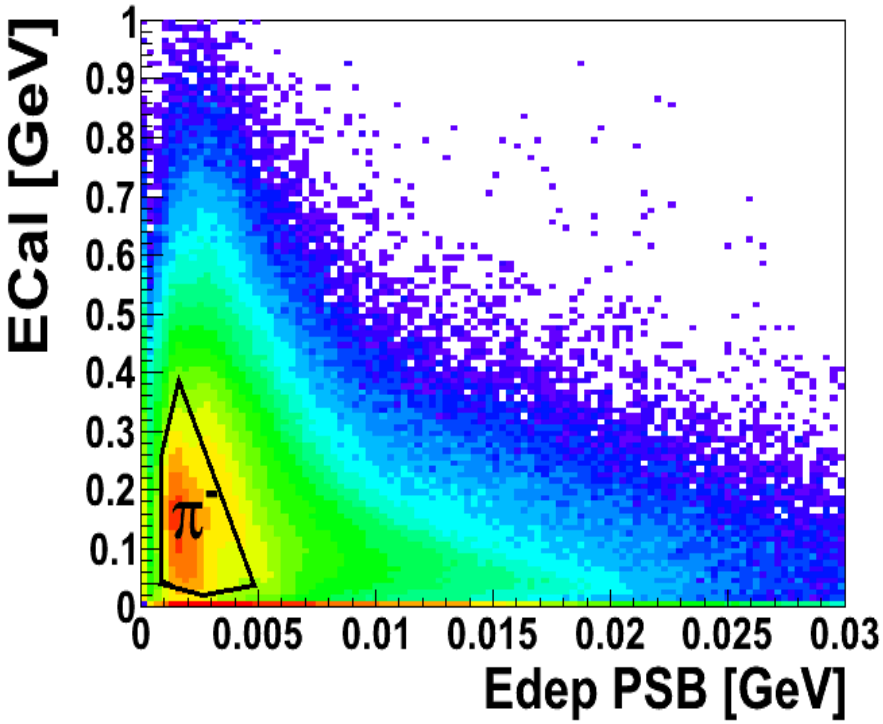
$dd \rightarrow {}^3\mathrm{He}p\pi^-$ $dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$



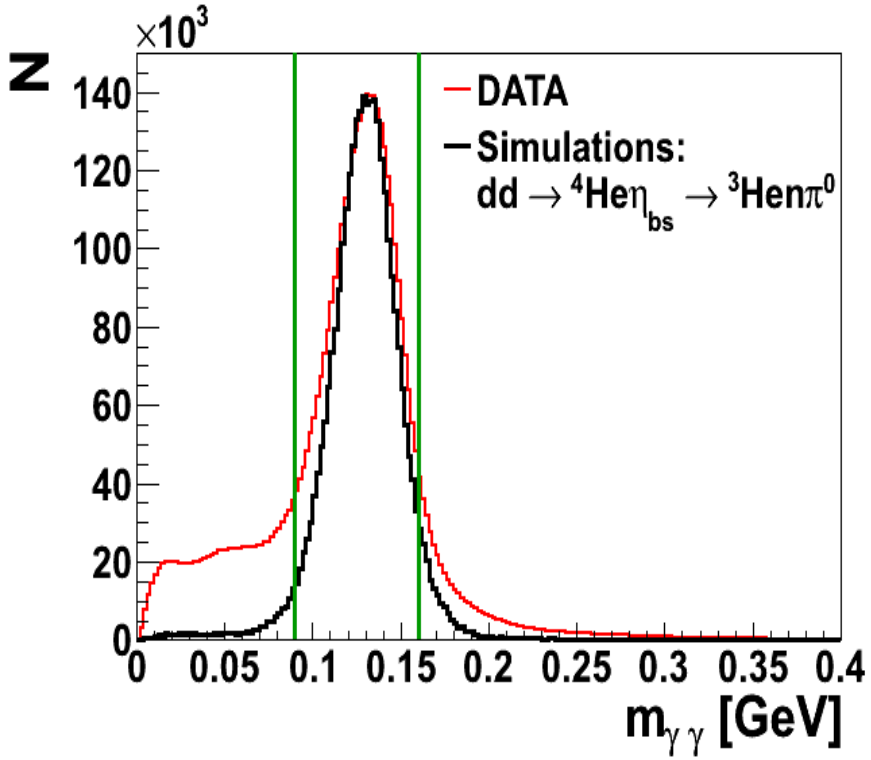


Pion identification in Central Detector

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

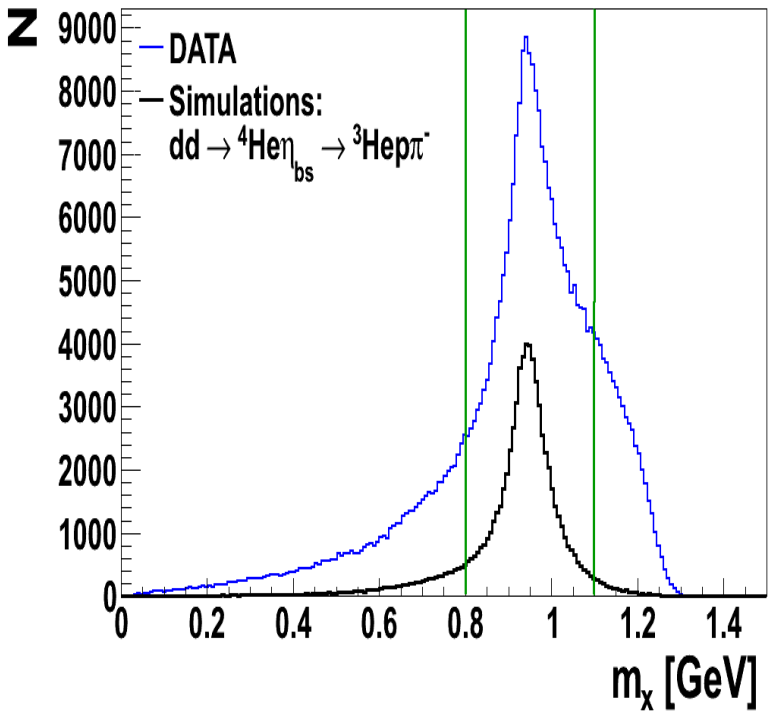


$dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$

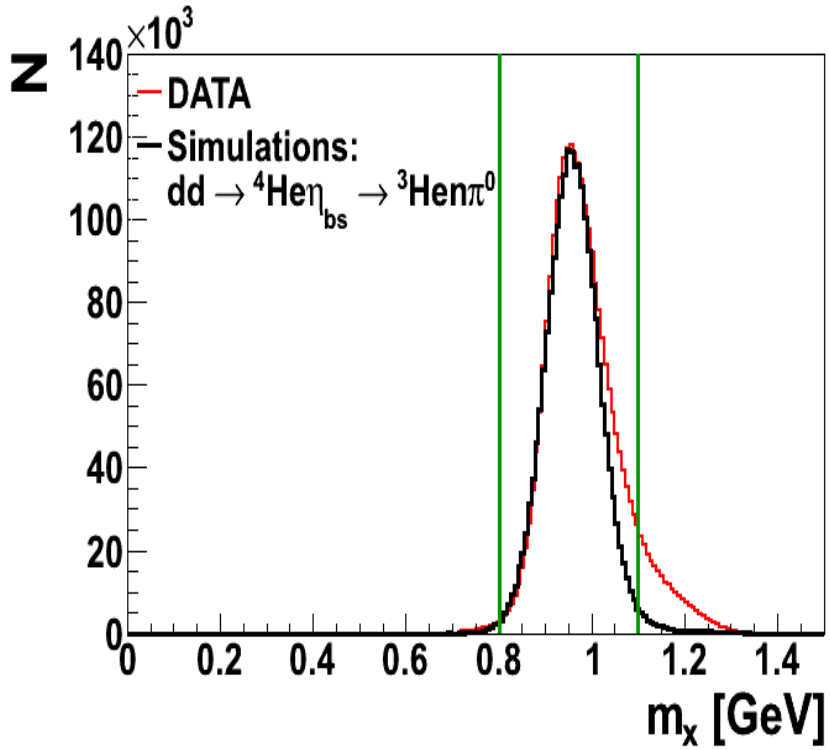


Nucleon identification in Central Detector via missing mass

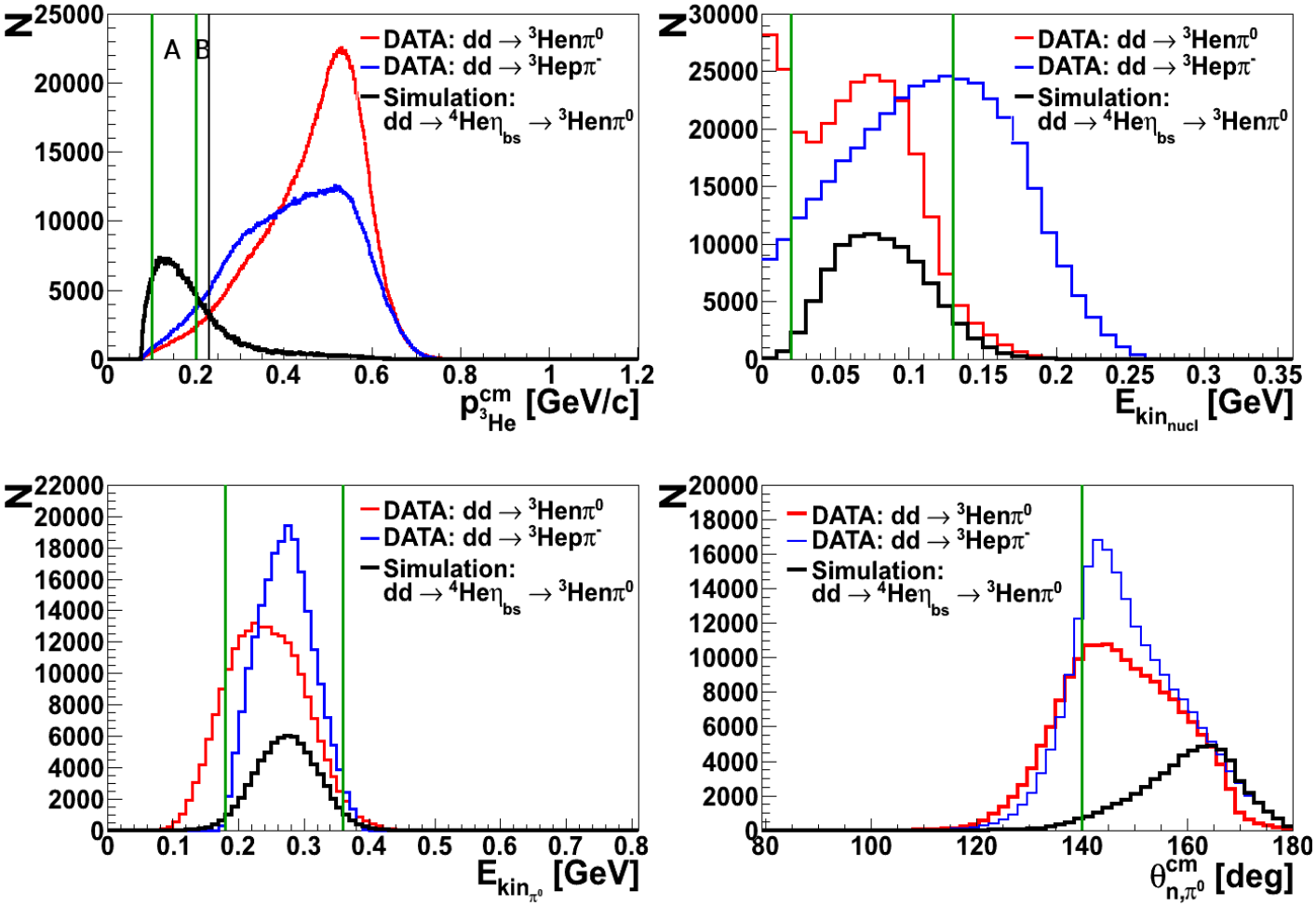
$dd \rightarrow {}^3\mathrm{He}p\pi^-$



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



Kinematical conditions

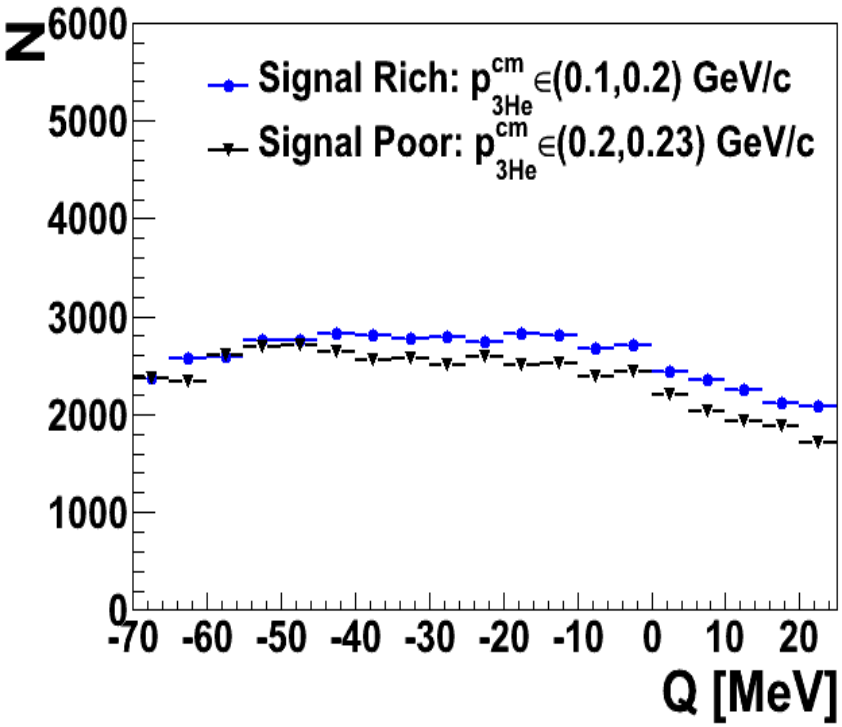


DATA: $dd \rightarrow {}^3\mathrm{He}p\pi^-$
DATA: $dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$

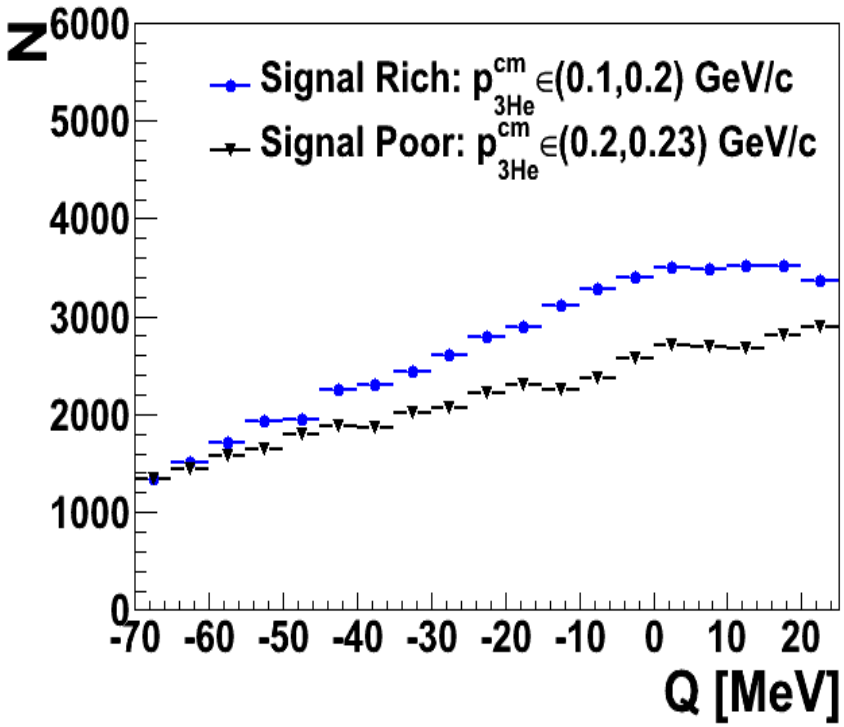
Signal: $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bs} \rightarrow {}^3\mathrm{He}n\pi^0$

Excitation functions

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



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



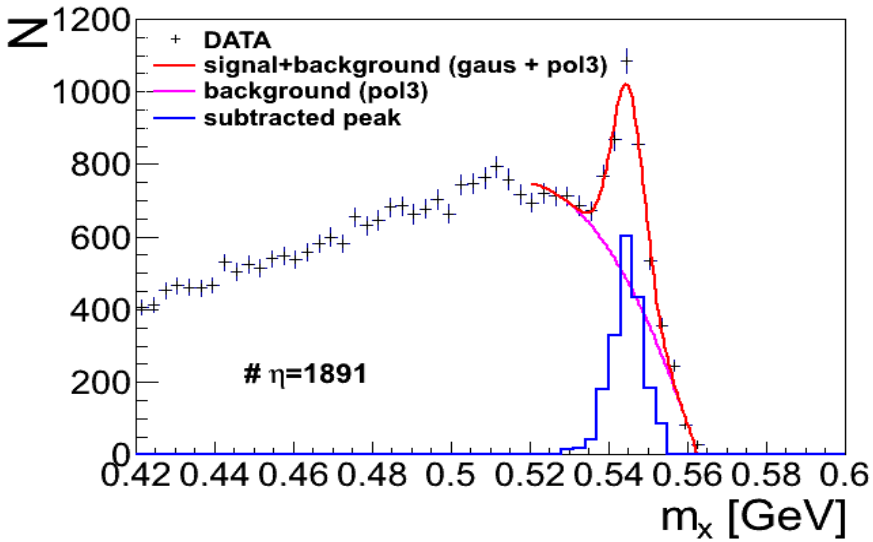
New experiment-May/June 2014

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 **Discussion - 26.11, 14:00**
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} : 1.468-1.615GeV/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

INTERNATIONAL PHD PROJECT IN APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES

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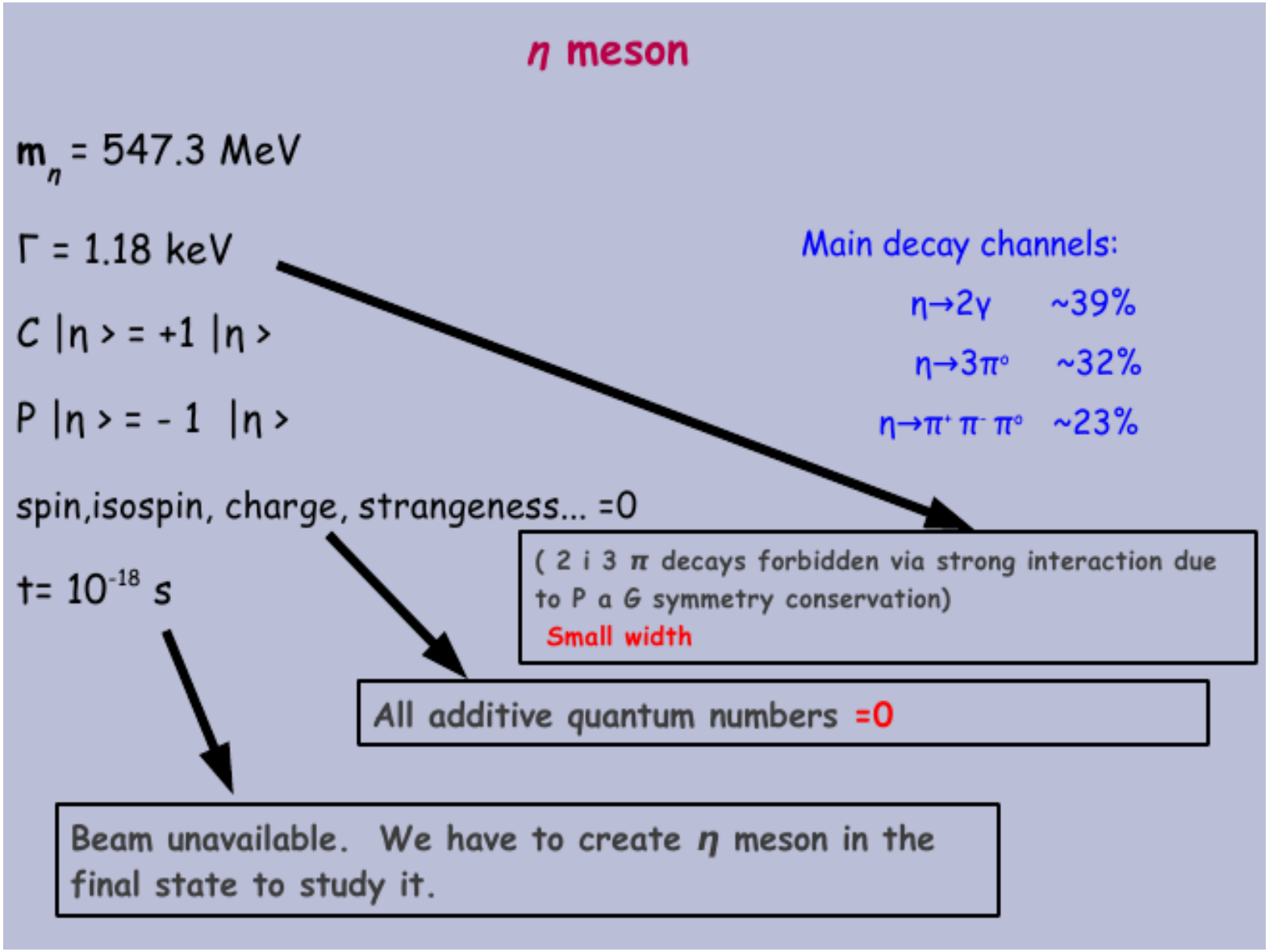

η meson
m_η = 547.3 MeV
Γ = 1.18 keV
C |η > = +1 |η >
P |η > = - 1 |η >
spin,isospin, charge, strangeness... =0
t= 10^-18 s
Main decay channels:
η→2γ ~39%
η→3π° ~32%
η→π⁺ π⁻ π° ~23%
(2 i 3 π decays forbidden via strong interaction due to P a G symmetry conservation)
Small width
All additive quantum numbers =0
Beam unavailable. We have to create η meson in the final state to study it.

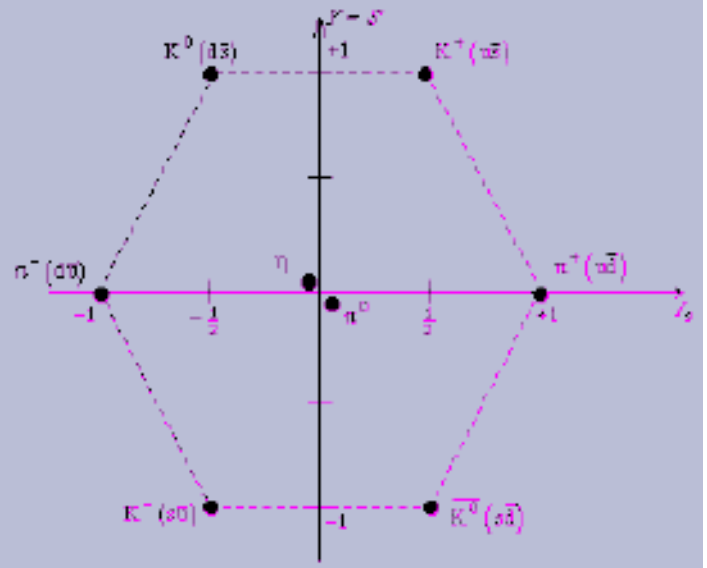
η meson

$$|\eta> = \cos\theta\,|\eta_8> - \sin\theta\,|\eta_0>$$
$$|\eta'> = \sin\theta\,|\eta_8> + \cos\theta\,|\eta_0>$$

$$\eta_0 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

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

Mixing angle θ ~ -15 degree



Bramon et al. Eur.Phys.J. C7 (1999) 271-27

η interaction with nucleon

- For low energies η-N interaction is dominated by N*(1535).

N*(1535)

$J^P = \frac{1}{2}^-$

M = 1535 MeV

Γ =150 MeV

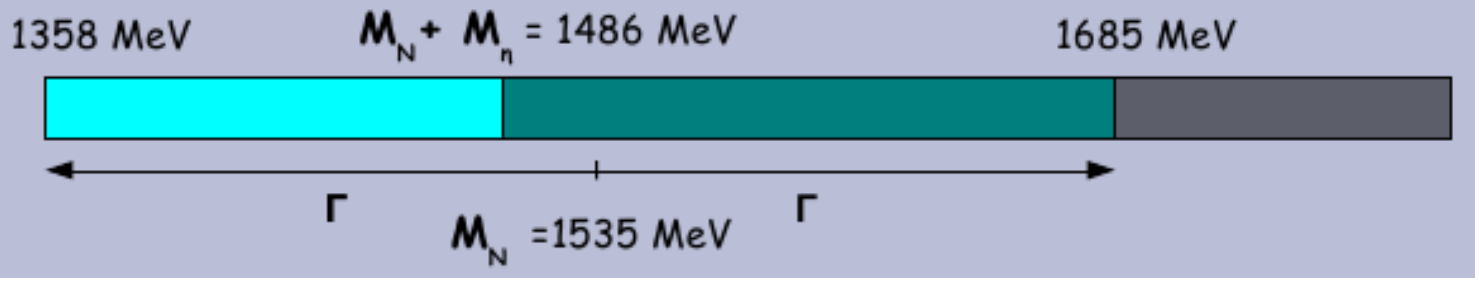
Main decay channels:

N* → π N ~ 35-55 %

N* → η N ~ 30-55 %

N* → π π N ~ 1-10 %

Coupled-channel analysis



History of a search for η-mesic nuclei

- **1985: Bhalerao & Liu:**

  attractive interaction η-N

- **1986: Haider & Liu:**

  first predictions for η-mesic nuclei (for A>10)

- **Series of experiments (no conclusive results):**

  Chrien et al. (1998) $\pi^+ + {}^{16}O \rightarrow p + \eta + {}^{15}O$

  Johnson et al. (1993) $\pi^+ + {}^{18}O \rightarrow \pi^- + \eta + {}^{18}O$

- **1993-2002 new data:**

  η-N scattering length much bigger than expected.

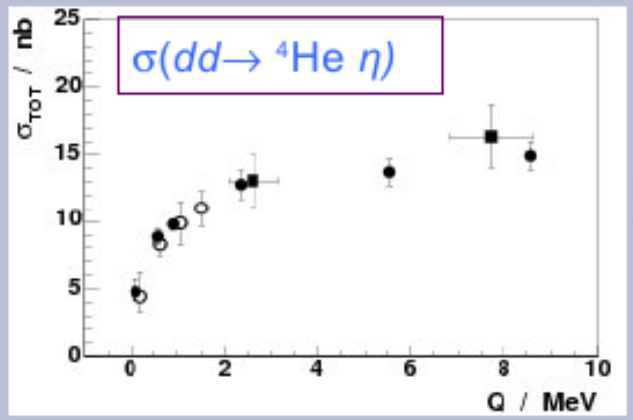
- **1991-2002 T. Ueda, C. Wilkin, S.A. Rakityansky and others:**

  new calculations and theoretical models which predict the existence of the η-mesic nuclei with light nuclei e.g. d-η, ^{3}He-η, ^{4}He-η, T-η

Cross-section estimate

dd → ^{4}He η → ^{3}He p π^-

$\sigma \sim$ 15 nb



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

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

$\sim 1/4 \times 1/2 = 1/8$

dd → ^{3}He $p\pi^-$
dd → ^{3}He nπ^0
dd → T nπ^+
dd → T $p\pi^0$

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

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

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

Theoretical predictions

$d + d \rightarrow {}^4He\ \eta \rightarrow {}^3He\ N\ \pi$

- Binding energies close to threshold, ~MeV
- Half width : 1 - 20 MeV
- Cross-section :4.5 nb (Wycech et Krzemień. Acta Phys. Polon. B 45 (2014) 745)

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)

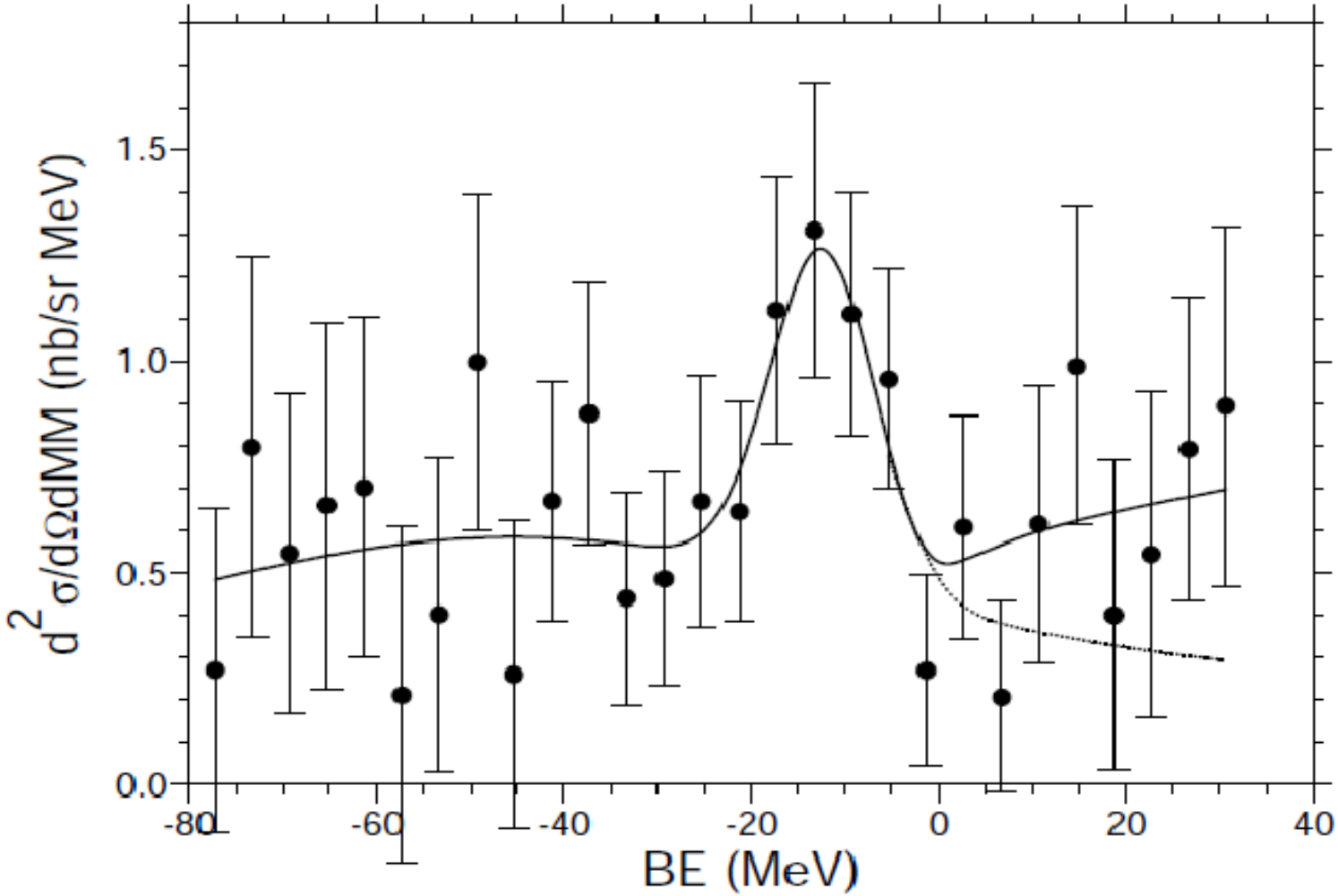
JINR/LHE Dubna/Russia: $d + {}^{13}\mathrm{C} \rightarrow ({}^{12}\mathrm{C})_{\eta} + \ldots \rightarrow p + \pi + \ldots$
S. V. Afanasiev, Phys. Part. Nucl. Lett. 8, 1073 (2011)

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)

COSY-GEM



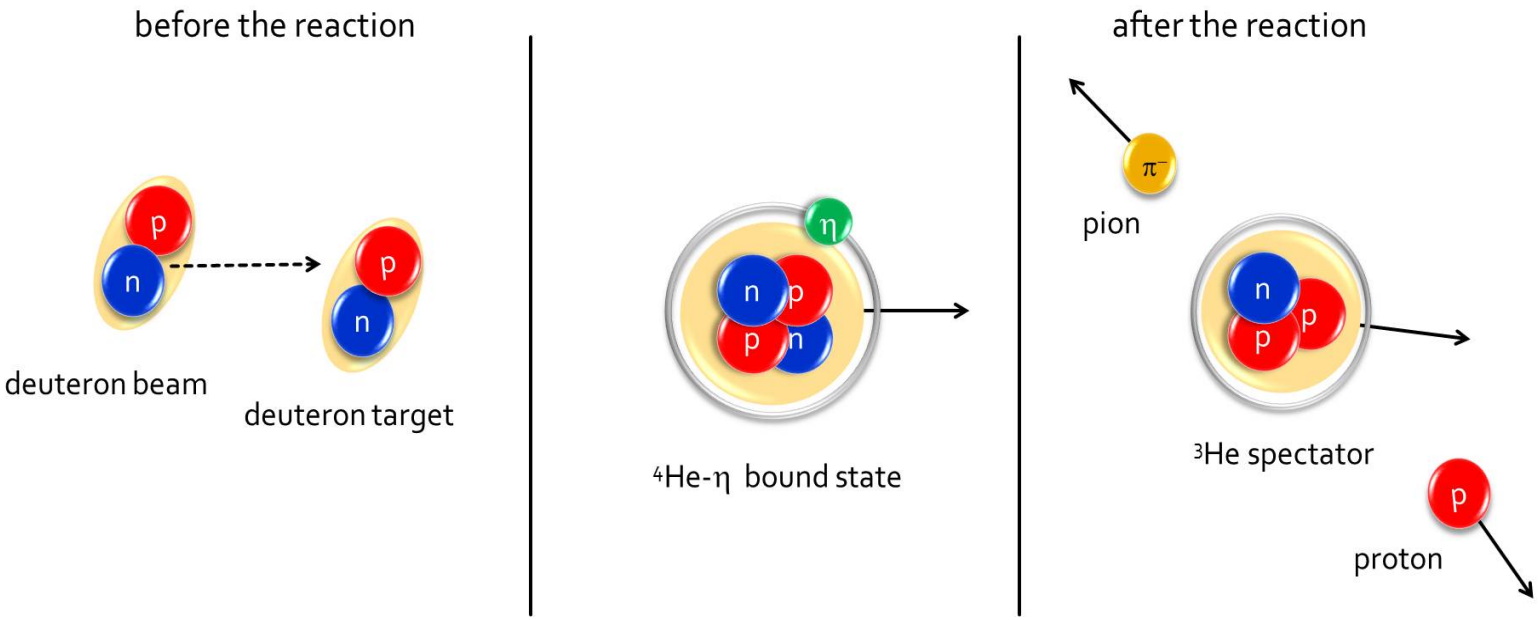
Search for η'-mesic bound states

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

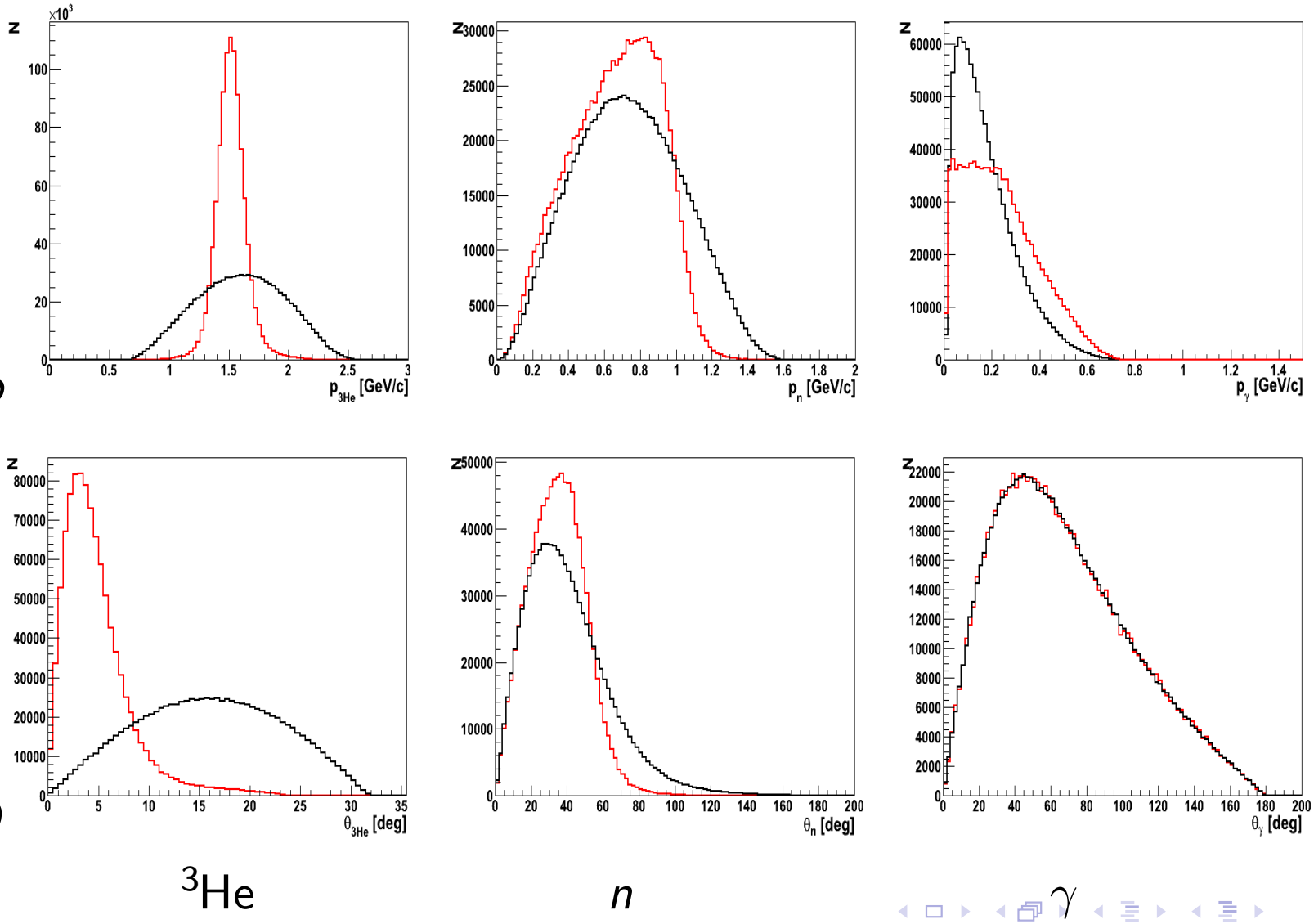
AMADEUS/DAFNE Frascati/Italy:
$K^- + {}^3\mathrm{He} \rightarrow ppK^- + n$
$K^- + {}^4\mathrm{He} \rightarrow ppnK^- + n$
$K^- + {}^4\mathrm{He} \rightarrow pnnK^- + p$
J-PARC Tokai/Japan: $K^-\ {}^3\mathrm{He} \rightarrow (K^- pp)_{bs} + n$

Spectator model

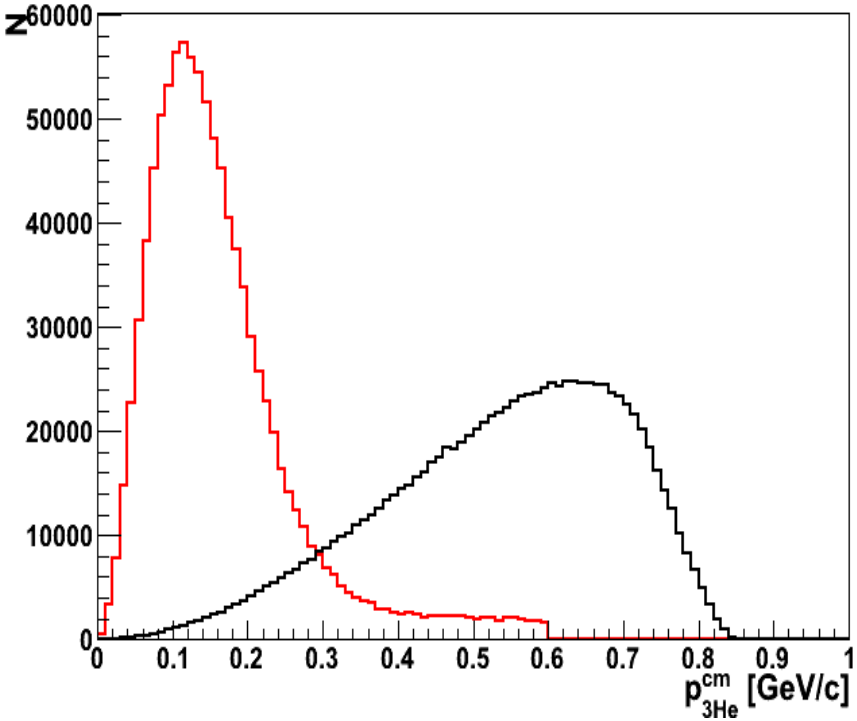


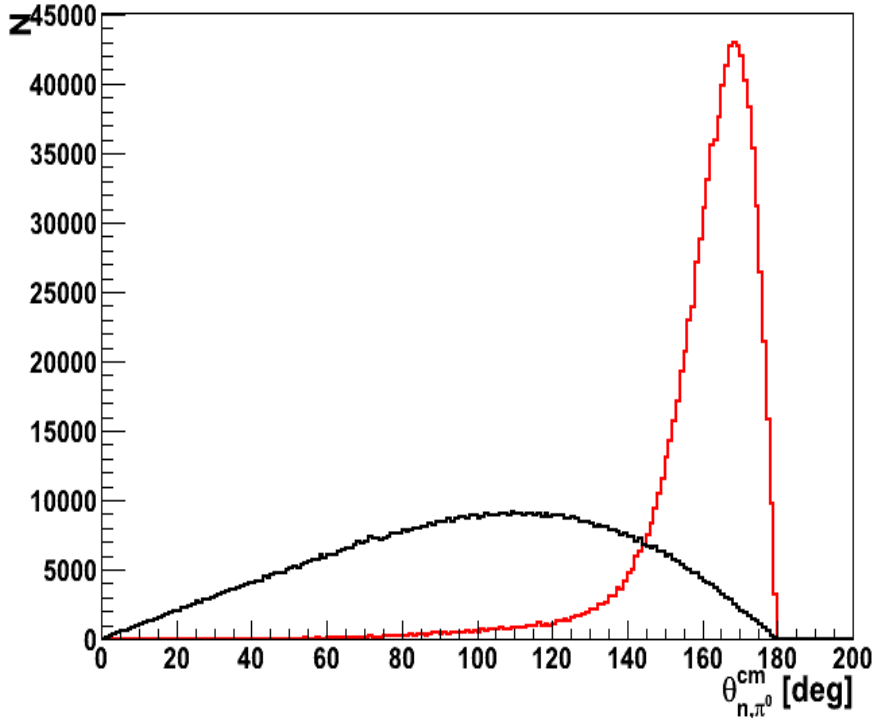
$$dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^- \qquad |\mathbb{P}_{sp}|^2 = m_{sp}^2$$

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



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





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:
$n\pi^0$: $|\frac{1}{2}\ -\frac{1}{2}\rangle\ |10\rangle$
$p\pi^-$: $|\frac{1}{2}\frac{1}{2}\rangle\ |1\ -1\rangle$

$$|JM\rangle = \langle\ -\tfrac{1}{2}-1|\ \tfrac{3}{2}\ -\tfrac{3}{2}\rangle\ |-\tfrac{1}{2}\ -1\rangle + \langle\ -\tfrac{1}{2}0|\ \tfrac{3}{2}\ -\tfrac{1}{2}\rangle\ |-\tfrac{1}{2}\ 0\rangle + \underline{\langle\ -\tfrac{1}{2}0|\ \tfrac{1}{2}\ -\tfrac{1}{2}\rangle\ |-\tfrac{1}{2}\ 0\rangle} + \langle\ -\tfrac{1}{2}1|\ \tfrac{3}{2}\ \tfrac{1}{2}\rangle\ |-\tfrac{1}{2}\ 1\rangle + \langle\ -\tfrac{1}{2}1|\ \tfrac{1}{2}\ \tfrac{1}{2}\rangle\ |-\tfrac{1}{2}\ 1\rangle + \langle\ \tfrac{1}{2}\ -1|\ \tfrac{3}{2}\ -\tfrac{1}{2}\rangle\ |\tfrac{1}{2}\ -1\rangle + \underline{\langle\ \tfrac{1}{2}\ -1|\ \tfrac{1}{2}\ -\tfrac{1}{2}\rangle\ |\tfrac{1}{2}\ -1\rangle} + \langle\ \tfrac{1}{2}\ 0|\ \tfrac{3}{2}\ \tfrac{1}{2}\rangle\ |\tfrac{1}{2}\ 0\rangle + \langle\ \tfrac{1}{2}\ 0|\ \tfrac{1}{2}\ \tfrac{1}{2}\rangle\ |\tfrac{1}{2}\ 0\rangle + \langle\ \tfrac{1}{2}\ 1|\ \tfrac{3}{2}\ \tfrac{3}{2}\rangle\ |\tfrac{1}{2}\ 1\rangle.$$

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

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

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

$$|JM\rangle = \langle\ -\tfrac{1}{2}\ -\tfrac{1}{2}|\ 1\ -1\rangle\ |-\tfrac{1}{2}\ -\tfrac{1}{2}\rangle + \underline{\langle\ -\tfrac{1}{2}\ \tfrac{1}{2}|\ 0\ 0\rangle\ |-\tfrac{1}{2}\ \tfrac{1}{2}\rangle} + \langle\ -\tfrac{1}{2}\ \tfrac{1}{2}|\ 1\ 0\rangle\ |-\tfrac{1}{2}\ \tfrac{1}{2}\rangle +$$
$$\underline{\langle\ \tfrac{1}{2}\ -\tfrac{1}{2}|\ 0\ 0\rangle\ |\ \tfrac{1}{2}\ -\tfrac{1}{2}\rangle} + \langle\ \tfrac{1}{2}\ -\tfrac{1}{2}|\ 1\ 0\rangle\ |\ \tfrac{1}{2}\ -\tfrac{1}{2}\rangle + \langle\ \tfrac{1}{2}\ \tfrac{1}{2}|\ 1\ 1\rangle\ |\tfrac{1}{2}\ \tfrac{1}{2}\rangle$$

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

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