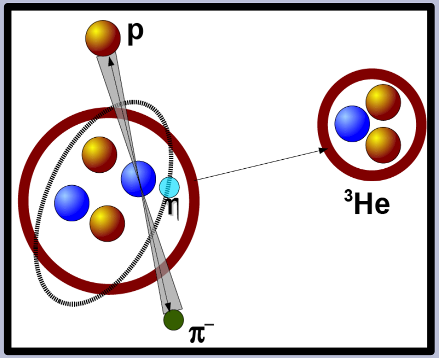
Overview of (η) meson nucleon interactions and mesic nuclei



Wojciech Krzemień

on behalf of the

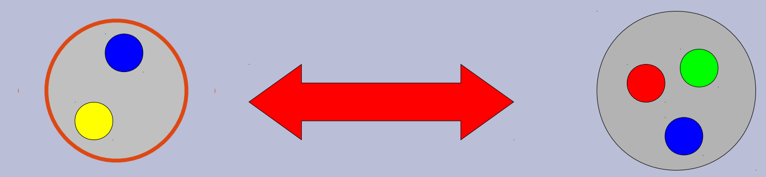
WASA-at-COSY collaboration

MesonNet Meeting 29th September 2014 – 1st October 2014

Outline

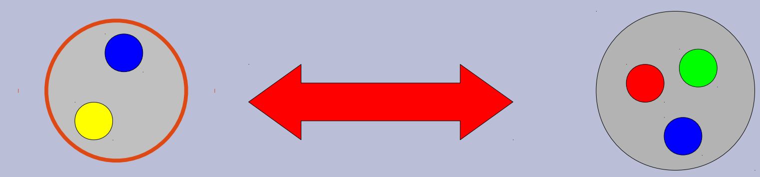
- General motivation,
- η-nucleon interaction and η-mesic nuclei,
- previous experiments,
- WASA-at-COSY measurements:
  - experimental method,
  - results (2008),
  - current status and future prospects (2010 & 2014 data),
- future activities

Meson-nucleon interaction



- Is interaction attractive or repulsive?
- How strong is the interaction?
- What type: strong + Coulomb

Meson-nucleon interaction



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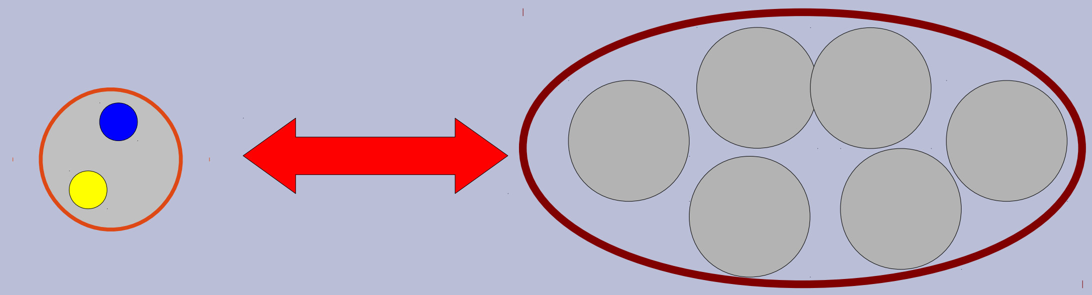
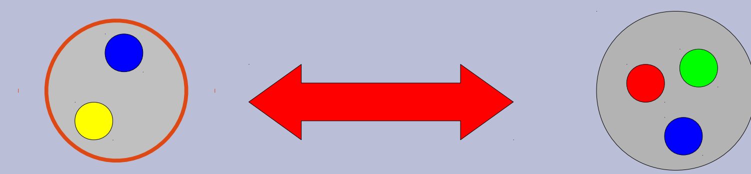


- **Can a bound system be formed ?**

Meson-nucleon interaction



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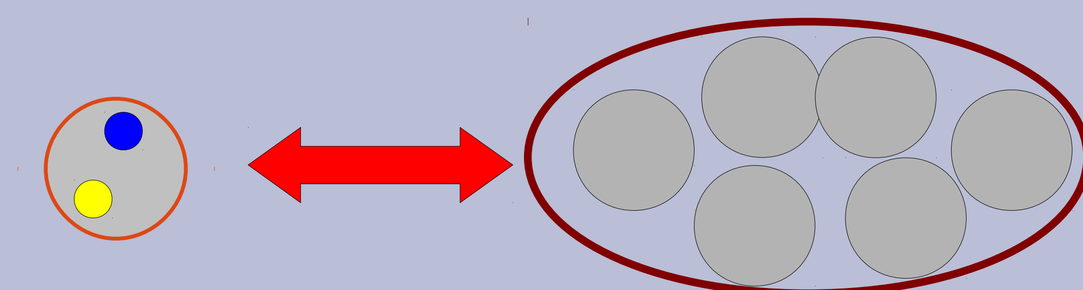


- **Can a bound system be formed ?**

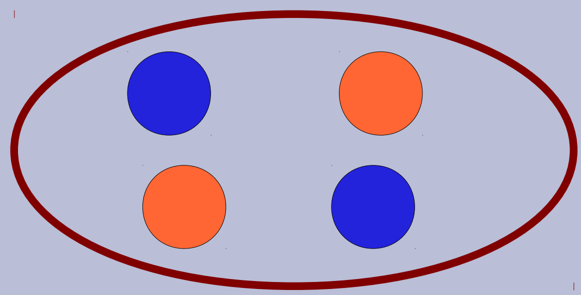
Experimental aspect: for short-lived mesons beams are unavailable

We can only study it in the final state (FSI)

„Exotic" systems

Classical nucleus:

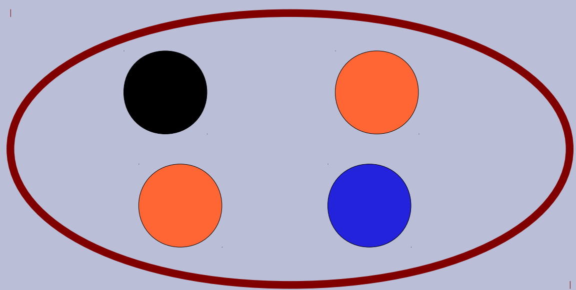
Bound state of nucleons



Hypernuclei:

Bound states of nucleons

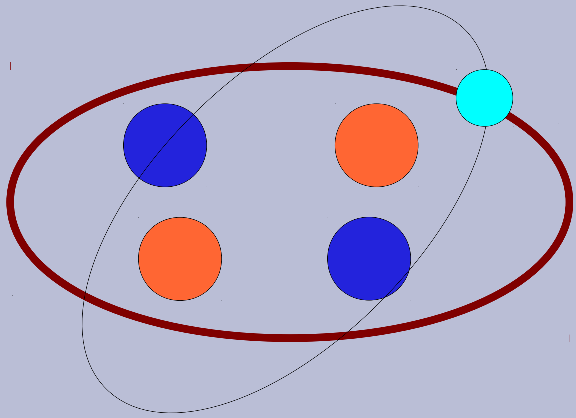
+ hyperion Λ, Σ



Mesic atoms and nuclei:

Bound state of nucleons

+ meson π, K, η, η', ω, ..



η-nucleon interaction

η interaction with nucleon

Still not well established !!

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

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

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

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

For low energies η-N interaction is dominated by **N*(1535)/S_{11}** resonance

η interaction with nucleon

$N^*(1535)/S_{11}$

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

$m = 1535$ MeV

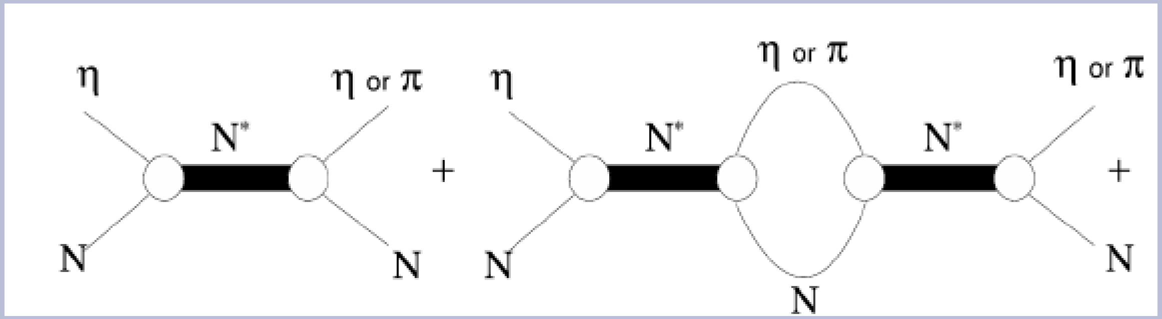
$\Gamma = 150$ MeV

Main decay channels:

$N^* \rightarrow \pi N \sim 35\text{-}55$ %

$N^* \rightarrow \eta N \sim 30\text{-}55$ %

$N^* \rightarrow \pi \pi N \sim 1\text{-}10$ %



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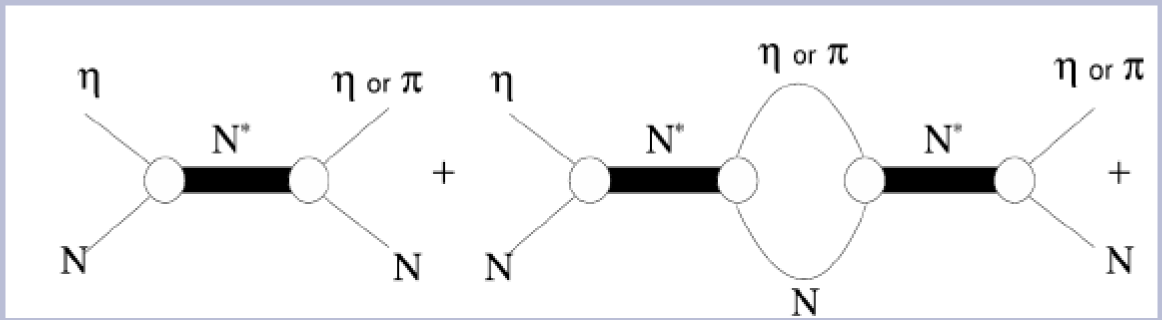


Attractive η-N interaction

R.S. Bhalerao and L.C. Liu, *Phys. Rev. Lett.* **54**, 865 (1985).

η bound states?

η interaction with nucleon

First η-mesic nuclei predictions (for A>12)

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

η-mesic nucleus = only strong interaction

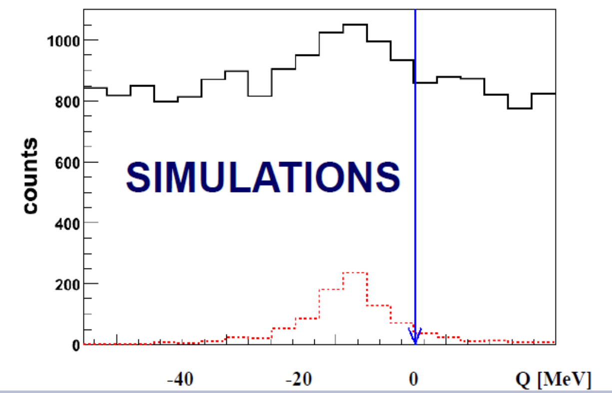
For recent calculations see:

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

How to look for bound states

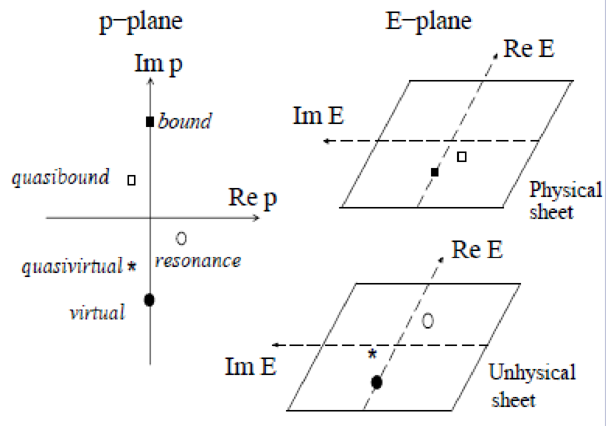
- **Direct method:**

  Search for some peak structure below the production threshold (e.g. in missing mass)



- **Indirect methods:**

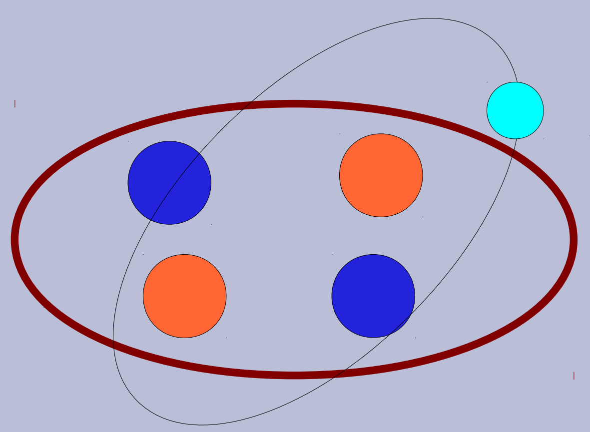
  Based on cross-section behaviour above the threshold (some theoretical model must be assumed)



Possible decay scenarios

- **Via N* resonance decay :**

$\eta + N \rightarrow N^* \rightarrow N + \pi$ (inside nucleus)



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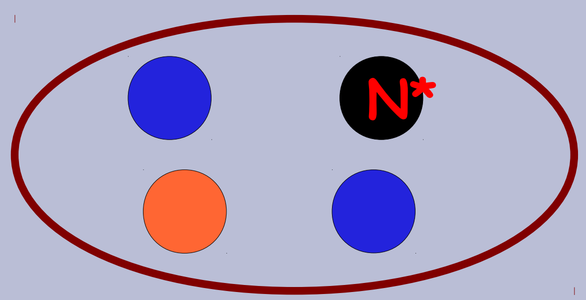

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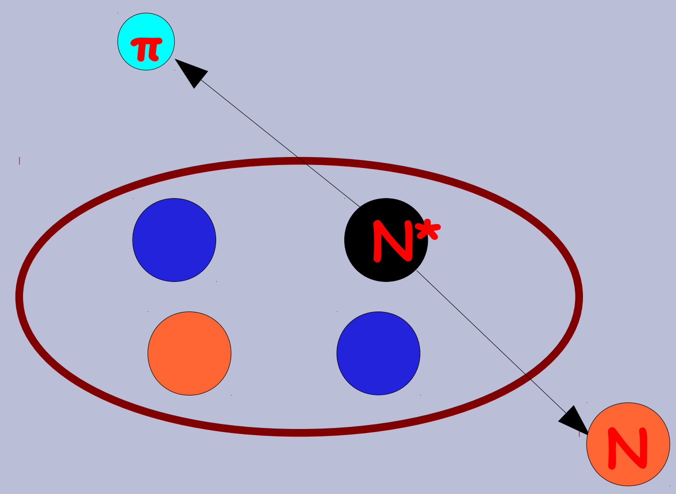
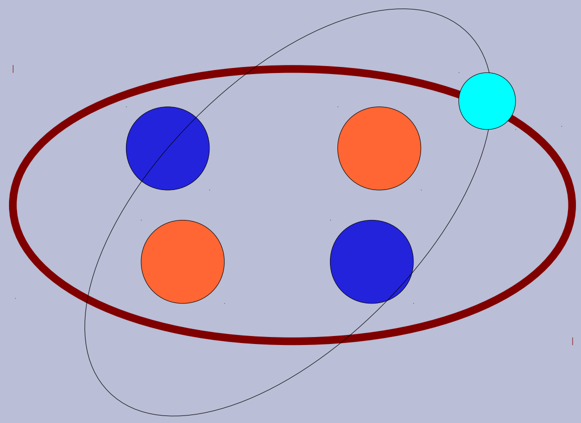


Possible decay scenarios

- **Absorption of orbiting *η*:**

$\eta \rightarrow 2\gamma$ (inside nucleus)



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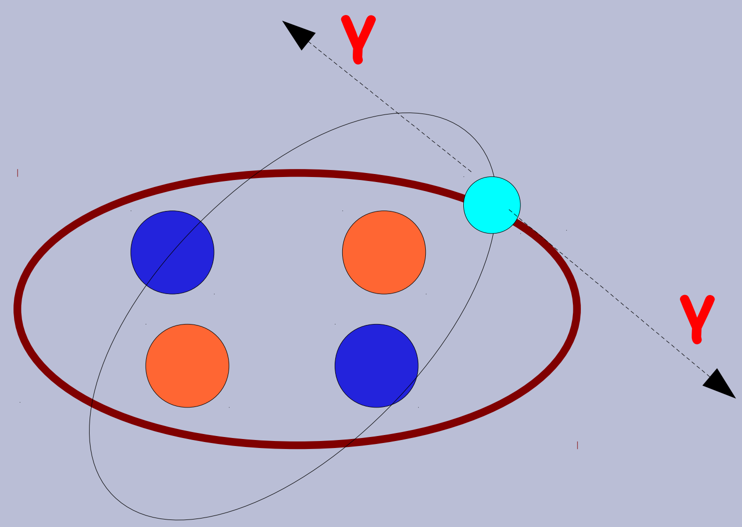
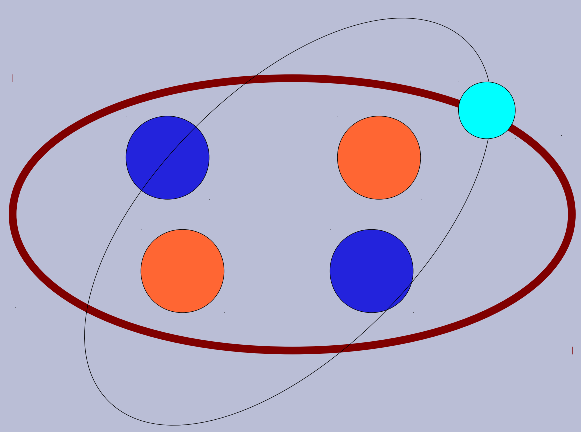


Possible decay scenarios

- **Non-resonant decay (absorption on two nucleons):**

$\eta + N\,N \rightarrow NN$ (inside nucleus)



Possible decay scenarios

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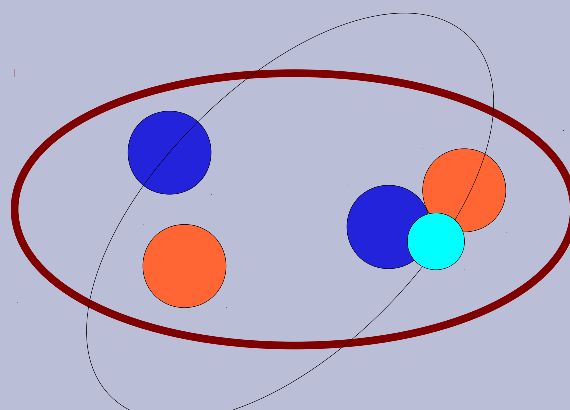

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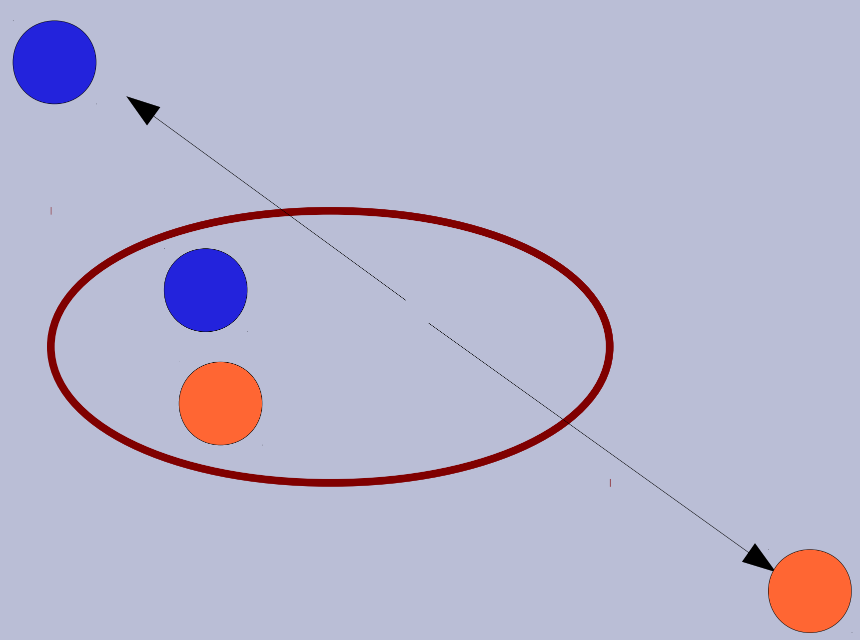
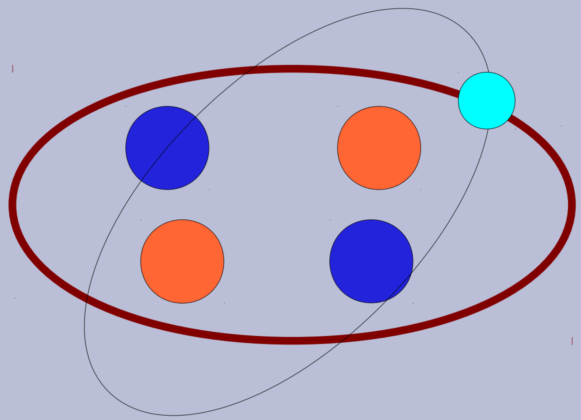


Possible decay scenarios



- Via N* resonance decay :

$\eta + N \rightarrow N^* \rightarrow N + \pi$ (inside nucleus)

- Absorption of an orbiting η:

$\eta \rightarrow 6\gamma$ (inside nucleus)

- Non-resonant decay (absorption on two nucleons):

$\eta + N\,N \rightarrow NN$ (inside nucleus)

Why η-mesic nuclei

- **New bound state of hadrons**

- **Investigation η-N interactions**

- **Studies of η quark structure**

  Binding energy and effective mass of η are sensitive to the gluon component of the flavour singlet function $|\eta_0\rangle$

  (more gluon content → more attractive binding → higher binding energy)

  (*S.D. Bass, A.W. Thomas, Phys. Lett. B634 (2008)*)

- **Study of in-medium properties of N*(1535) resonance:**

  N-η system is strongly coupled with N*(1535) resonances. η-mesic nucleus as a probe for testing different N* models

  Jido, Oka, Hosaka, Nemoto, PTP106(01)873
  Jido, Hatsuda, Kunirhiro, NPA671(00)471)
  Garcia-Recio, Nieves, Inoue, Oset, PLB550(02)47
  Jido, Nagahiro., Hirenzaki, PRC66(02)045202
  Inoue, Oset, NPA710(02) 354

Previous experiments
(direct method)

Heavy-nuclei

- BNL

R.E. Chrien *et al.*, *Phys. Rev. Lett.* **60**, 2595 (1988).

$\pi^+ + {}^{16}\mathrm{O} \rightarrow \mathrm{p} + \eta\text{-}{}^{15}\mathrm{O}$

- LAMPF:

J.D. Johnson *et al.*, *Phys. Rev.* **C47**, 2571 (1993).

$\pi^+ + {}^{18}\mathrm{O} \rightarrow \pi^- + \eta\text{-}{}^{18}\mathrm{O}$

- GSI:

A. Gillitzer, *Acta Phys. Slov.* **56**, 269 (2006).

$\mathrm{d} + {}^{7}\mathrm{Li} \rightarrow {}^{3}\mathrm{He} + \eta\text{-}{}^{6}\mathrm{He}$

$\mathrm{d} + {}^{12}\mathrm{C} \rightarrow {}^{3}\mathrm{He} + \eta\text{-}{}^{11}\mathrm{Be}$

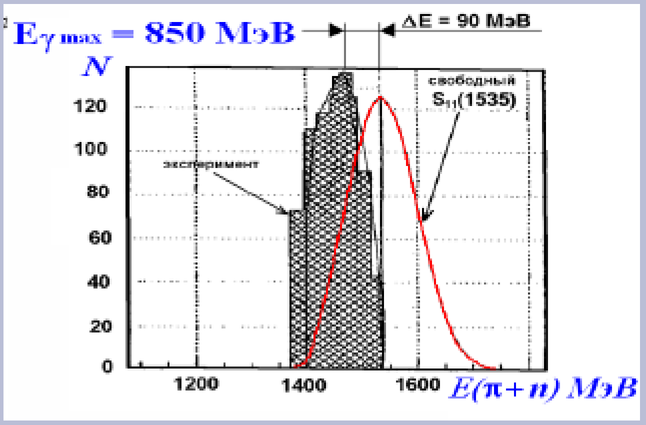
Heavy-nuclei

- LPI:

Sokol et al., LPI-HEPD-T-99-5 Journal-ref: Fizika B (Zagreb) 8 (1999) 85-90 .

$\gamma + {}^{12}C \rightarrow p(n) + \eta\text{-}{}^{11}Be\ (\eta\text{-}{}^{11}C) \rightarrow \pi^{+} + n + X$

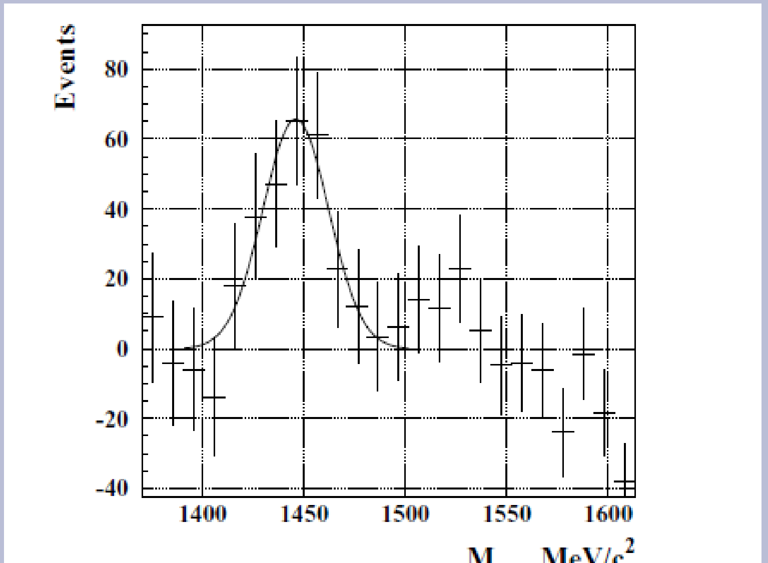
G. Sokol et al. Fizika B8, 85 (1999)
Part. Nucl. Lett. 5[102], 71 (2000)
Yad Fiz 71, 532 (2008)



- JINR, LHEP:

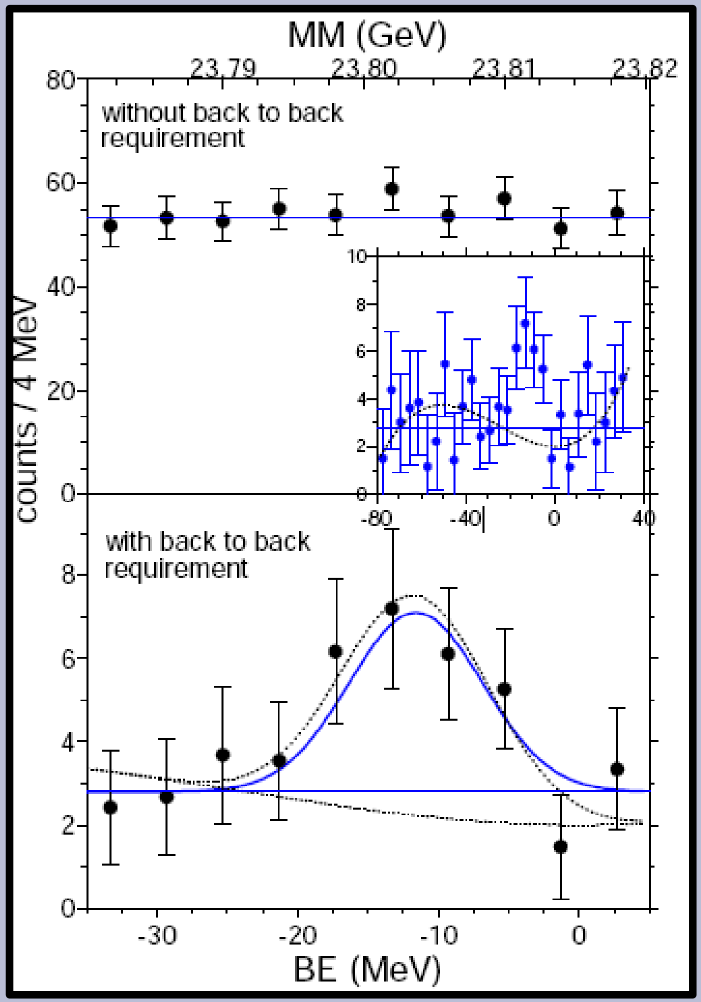
S.V. Afanasiev Nucl.Phys.Proc.Suppl. 245 (2013) 173-176.

$d + {}^{12}C \rightarrow X + \eta\text{-}A \rightarrow \pi + p + X$



COSY-GEM results

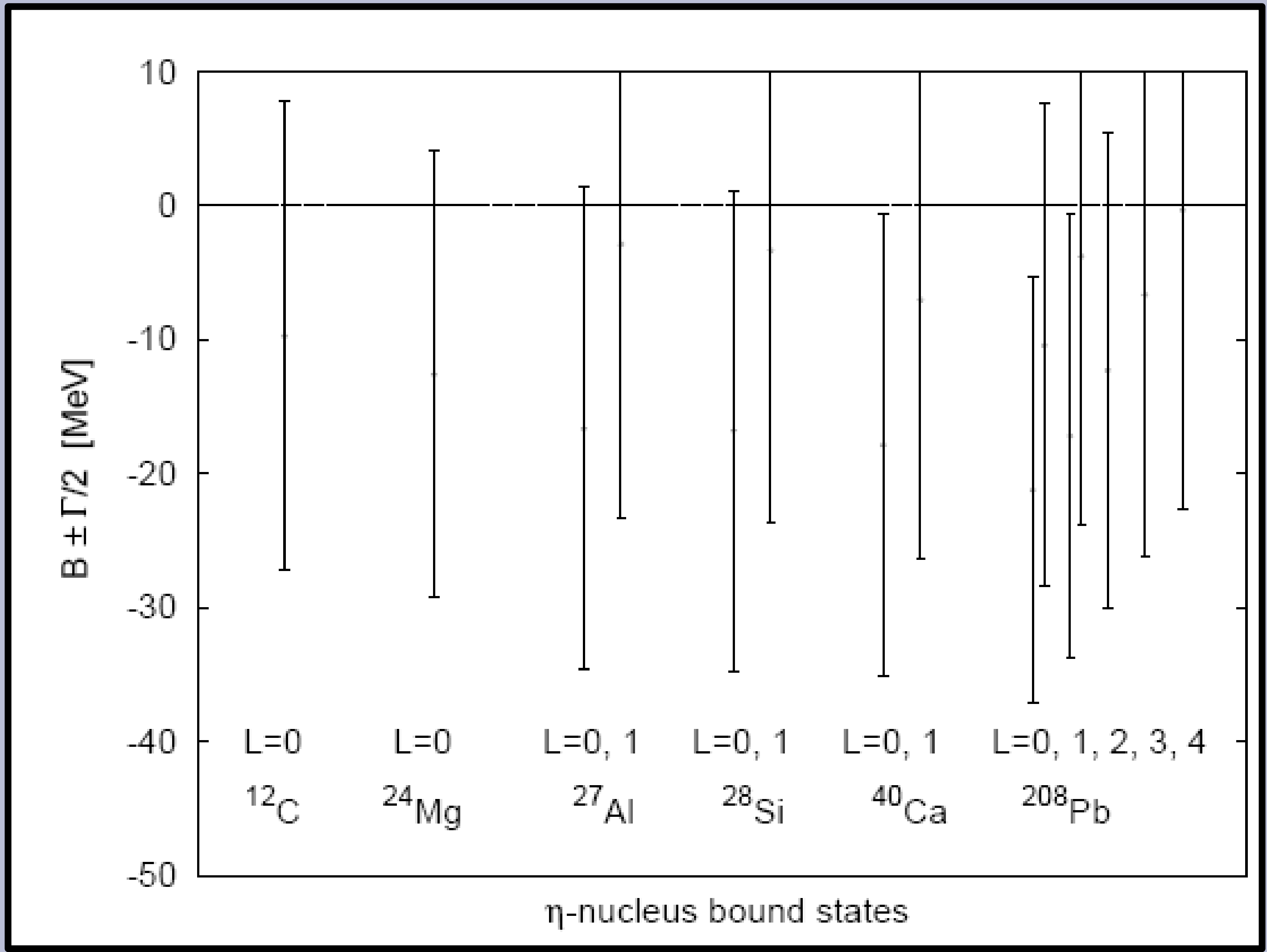
$p + {}^{27}Al \rightarrow {}^{3}He + (\eta - {}^{25}Mg) \rightarrow {}^{3}He + \pi^{-} + p + X$



MM(3HE)

A. Budzanowski *et al.*, Phys Rev. C79 (2009).

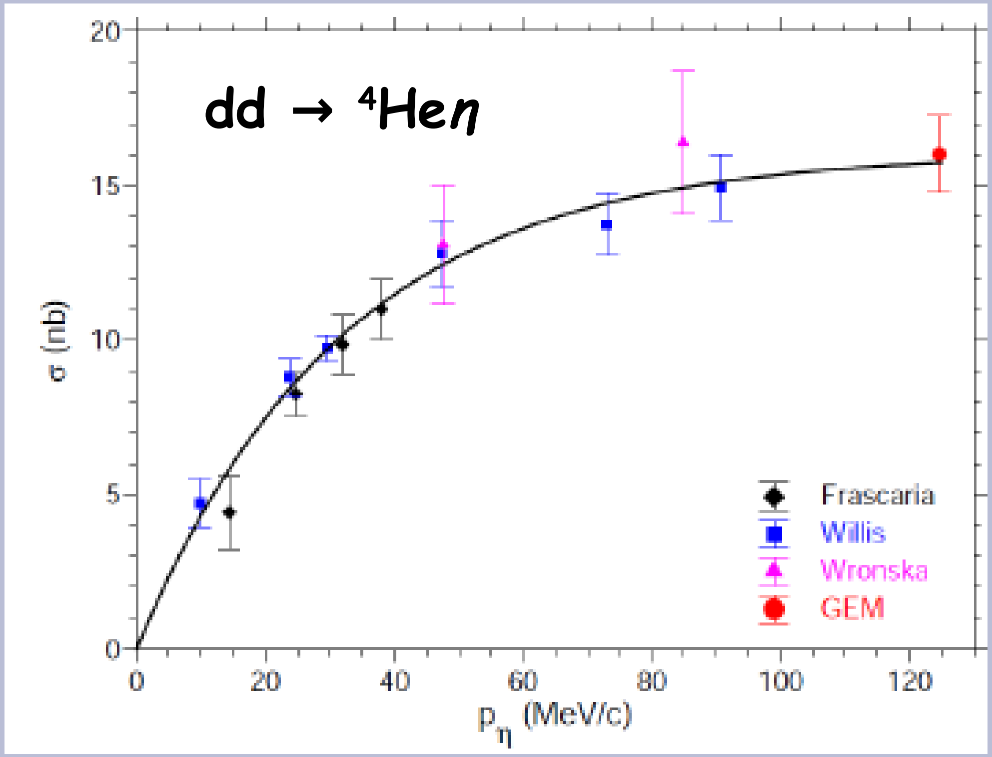
η-mesic nuclei in heavy systems



C. Garcia-Recio, T. Inoue, E. Oset Phys. Lett. B550 (2002) 47

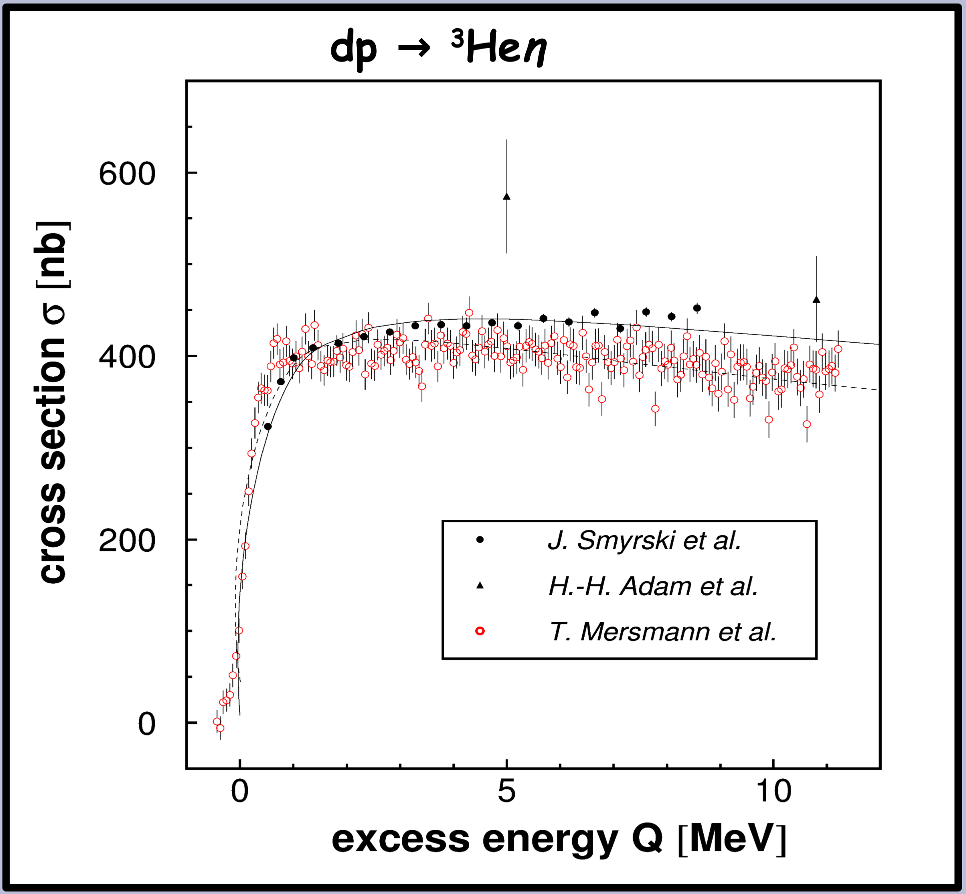
Experimental indications for light systems (^4He, ^3He)

Experimental indications of existence of a ^{4}He-η bound system

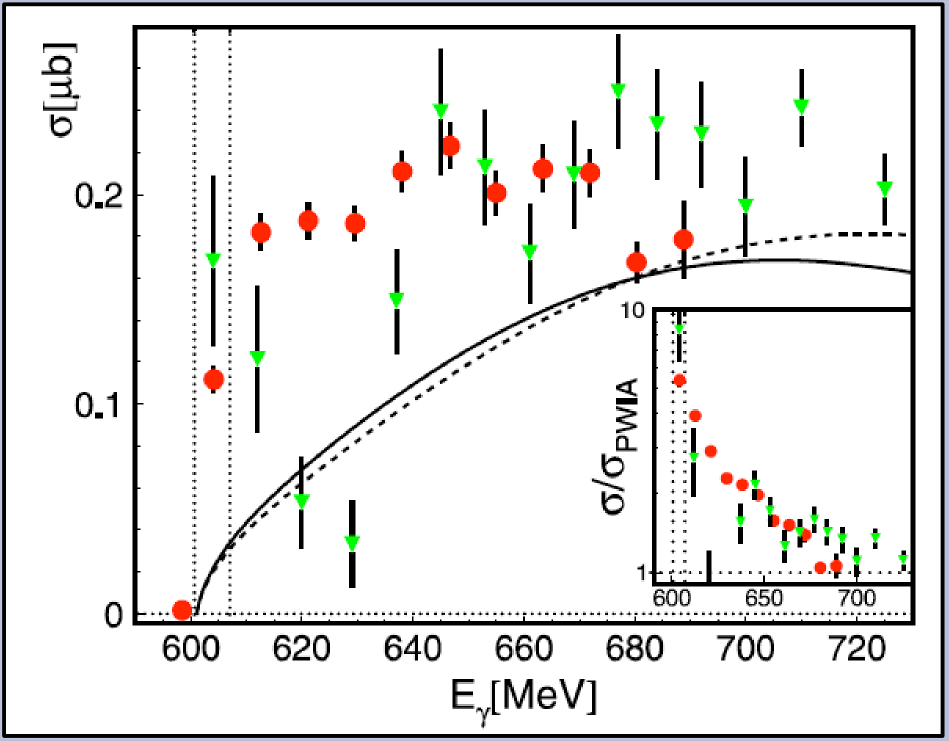


R. Frascaria et al., Phys. Rev. C 50 (1994) 573.
N. Willis et al., Phys. Lett. B 406 (1997) 14.
A. Wrońska et al., Eur.Phys.J. A26 (2005) 421-428.
A. Budzanowski et al., Nucl. Phys. A821, (2009) 193.

Experimental indications of existence of the ^{3}He-η bound system



γ^{3}He→ η^{3}He



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

COSY-11: J. Smyrski et al., Phys. Lett **B 649** 258-262 (2007)

MAMI:

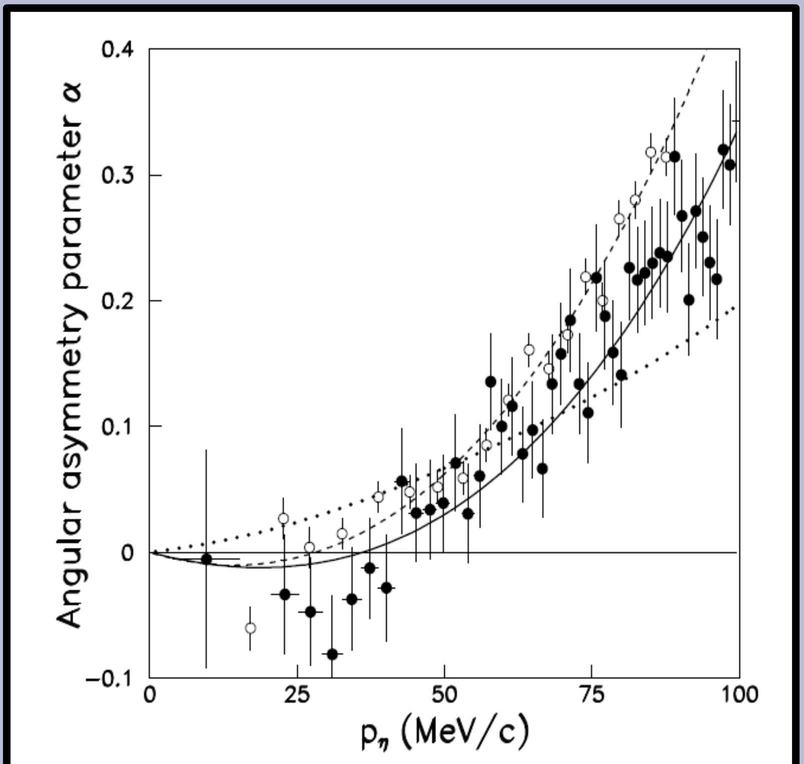
M. Pfeiffer et al., Phys. Rev. Lett. **92** 252001 (2004)

F. Pheron et al., Phys. Lett. **B709** 21 (2012)

Enhancement independent of input channel → Strong ^{3}He-η FSI

Experimental indications of existence of the ^{3}He-η bound system

C.Wilkin et al., Phys. Lett. B654 (2007) 92



$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{tot}}{4\pi}[1 + \alpha \cos\theta_\eta]$$

Full dots: *COSY-ANKE*

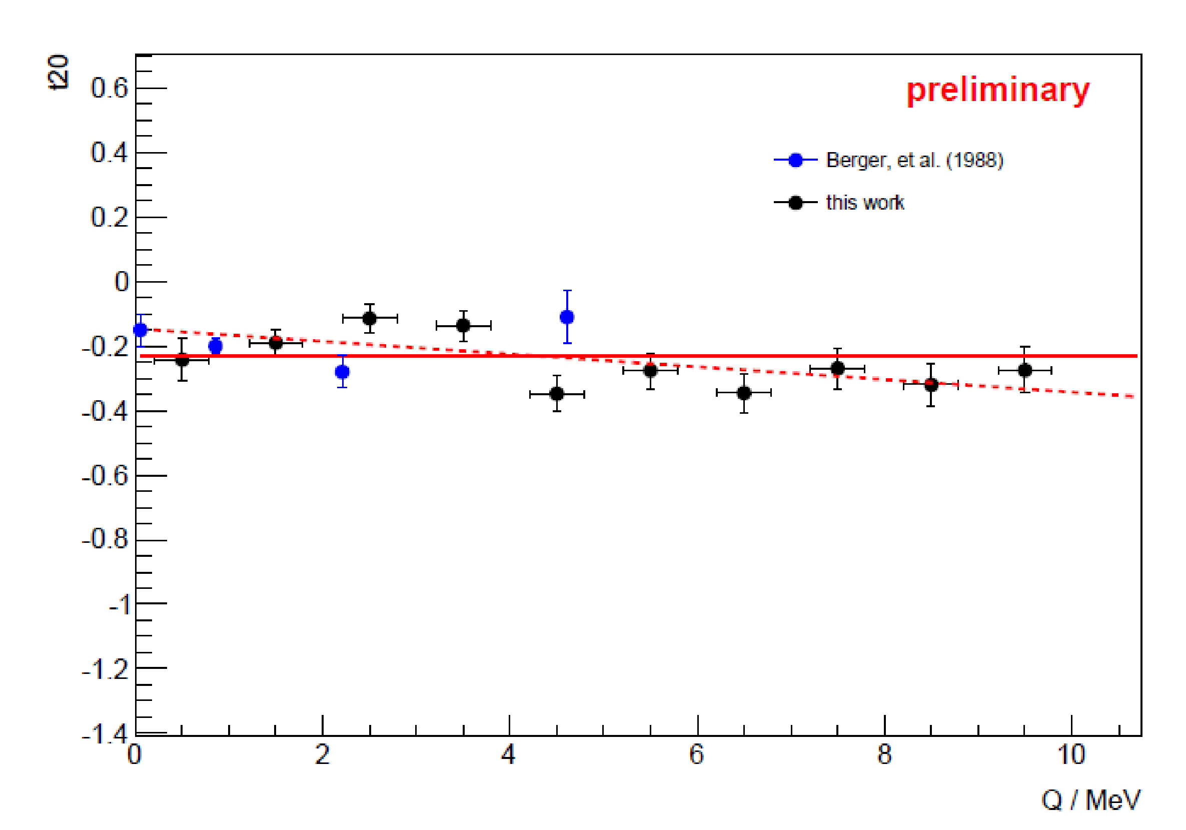
(T.Mersmann et al., Phys. Rev. Lett. 98 242301-1-4 (2007))

Empty circles: *COSY-11*

(J.Smyrski et al., Phys. Lett B 649 258-262 (2007))

Experimental indications of existence of the ^{3}He-η bound system

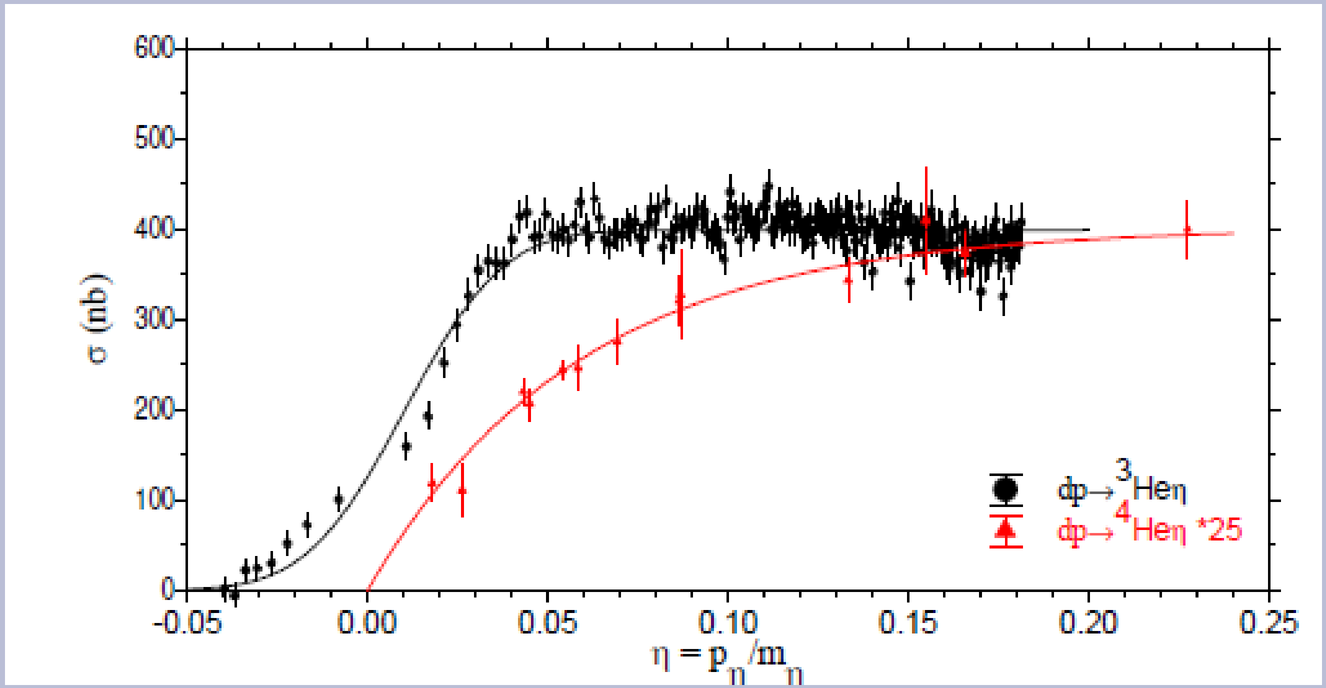
dp → ^{3}Heη



Tensor analysing power T_{20} almost flat → independent of the input channel state S = ½ I S = 3/2

Khoukaz et al. Acta Phys. Pol. B (2014)

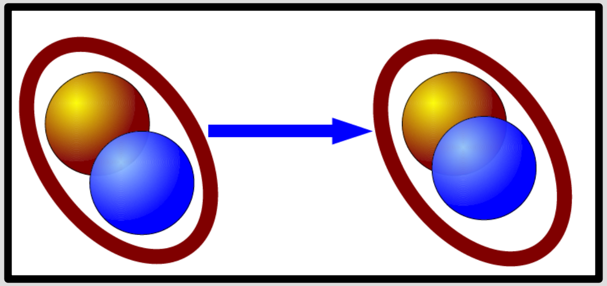
$^4He-\eta$ vs $^3He-\eta$ systems

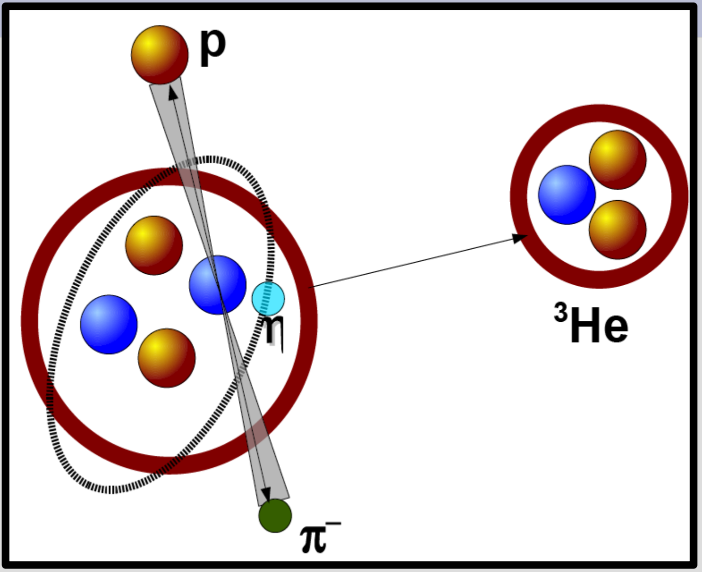


Machner et al. Acta Phys. Pol. B (2014).

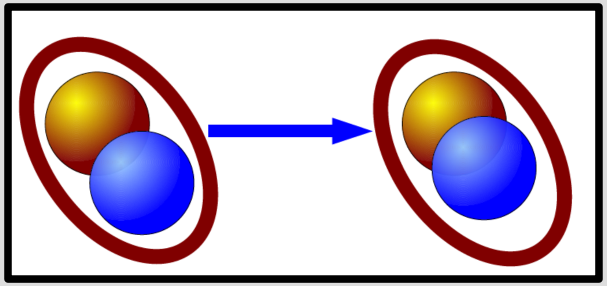
Experimental method

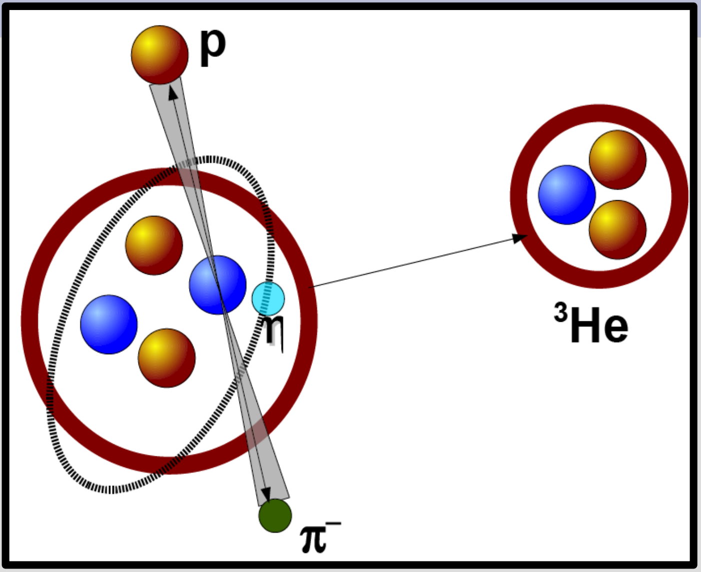
$$dd \rightarrow (\eta\text{-}{}^4He)_{bound} \rightarrow N + \pi + {}^3He$$





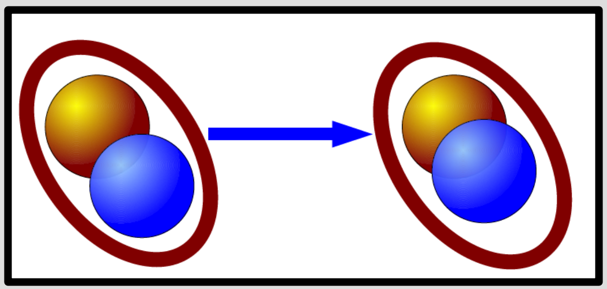
$dd \rightarrow (\eta\text{-}^4He)_{bound} \rightarrow N + \pi + {}^3He$

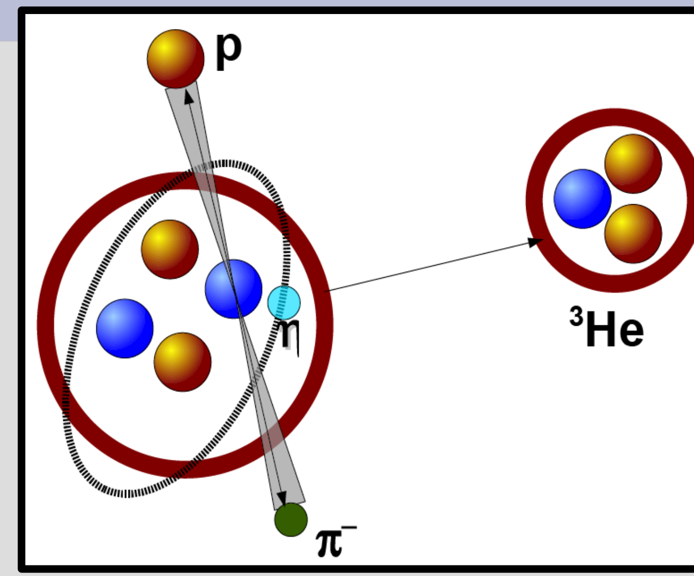




$\eta + N$ → $N^*(1535)$ → $N + \pi$

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

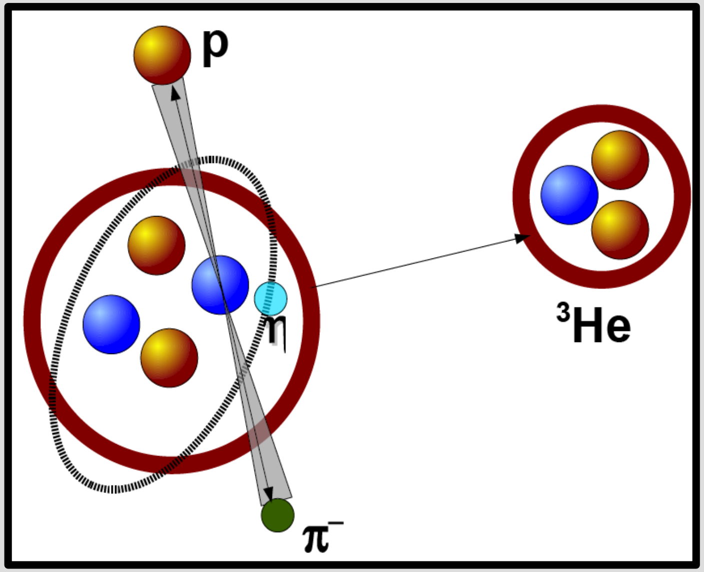




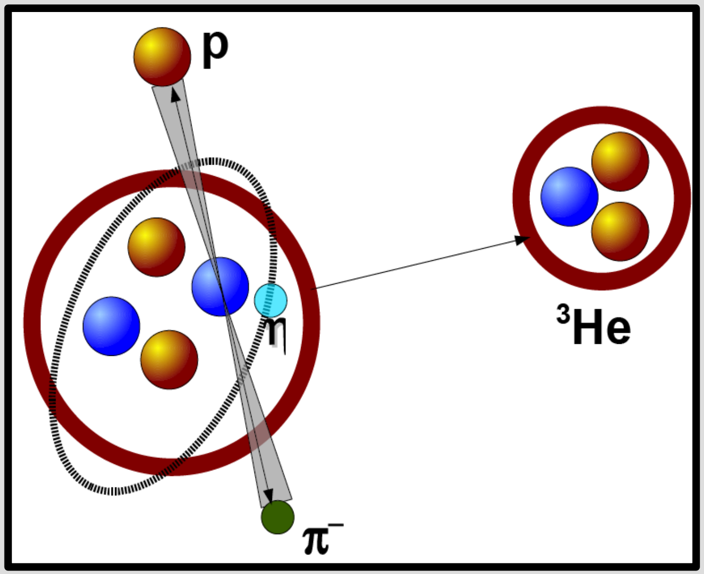
$\eta + N$ ➡ $N^*(1535)$ ➡ $N + \pi$

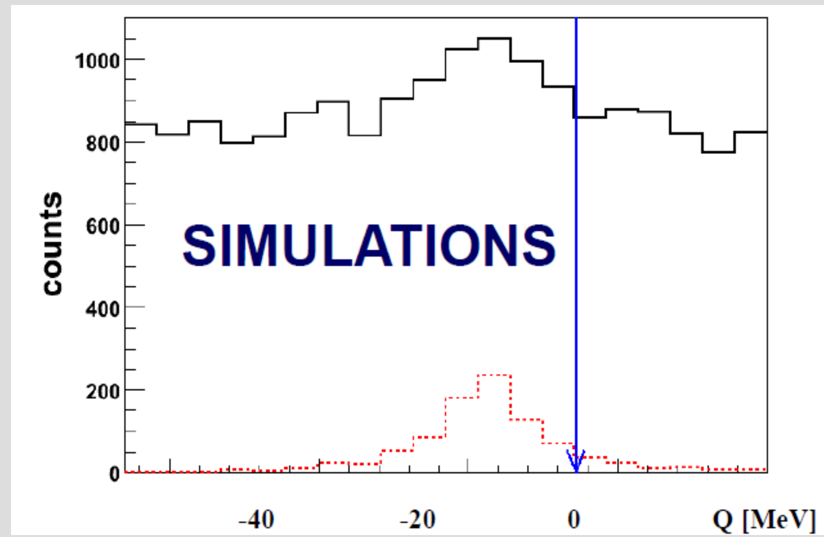
- relative N-π angle in the CM : $\theta_{cm} \sim 180^\circ$
- low ^3He momentum in the CM

dd → $(\eta\text{-}^{4}He)_{bound}$ → $N + \pi + {}^{3}He$



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





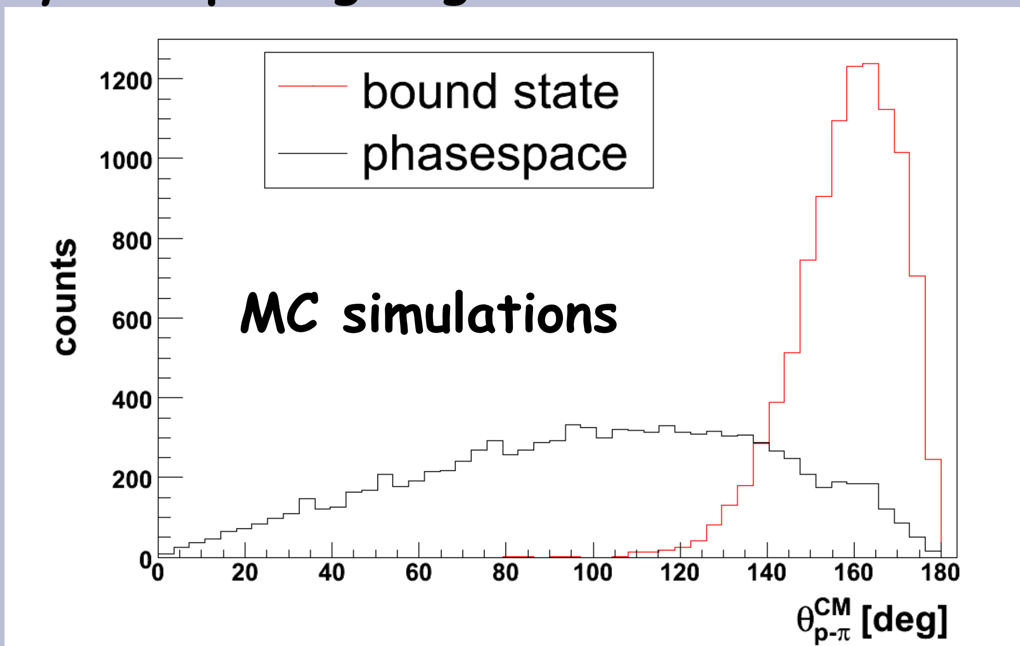
$$m_{BS} = m_A + m_\eta - E_{BE}$$

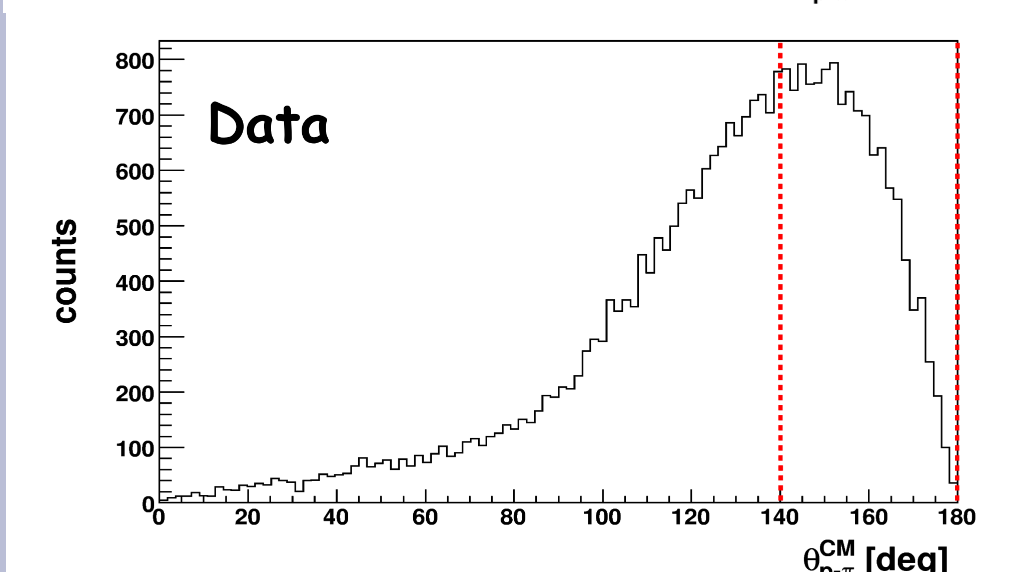
Search for a resonance-like structure

with maximum below the η-^{4}He production threshold

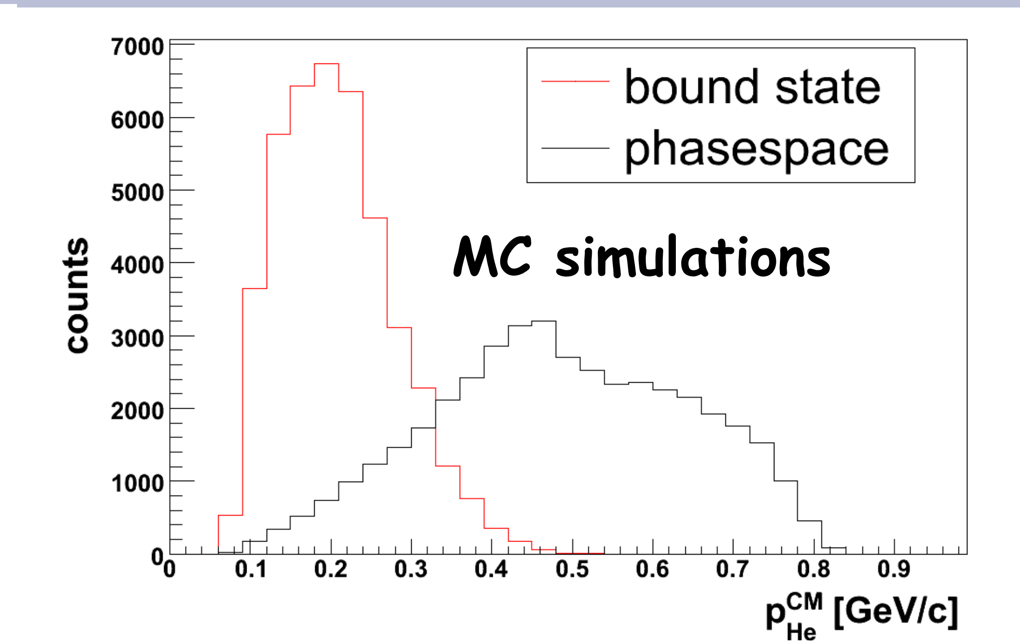
Signatures of the bound state

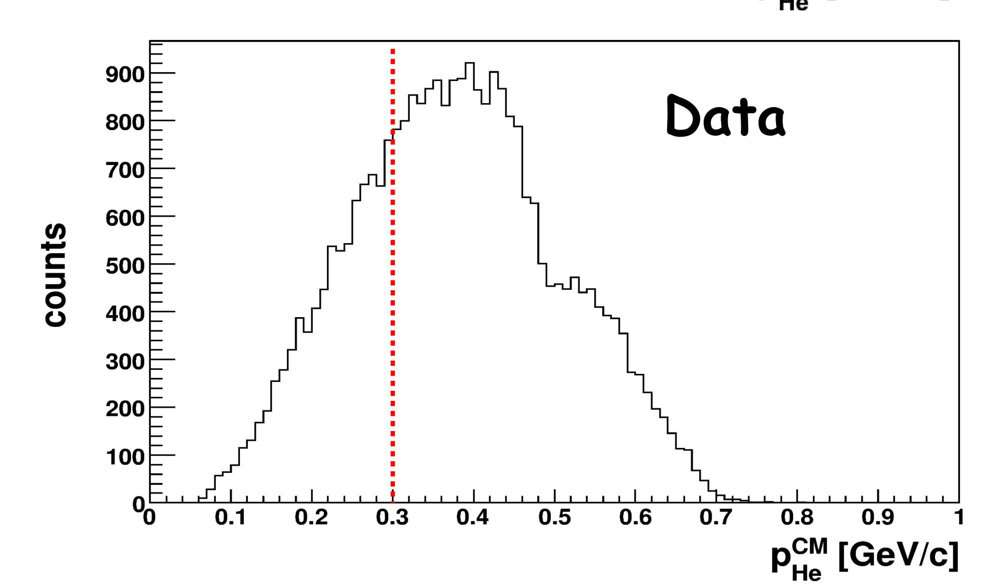
p-π^- opening angle in the CM frame





^{3}He momentum in the CM frame

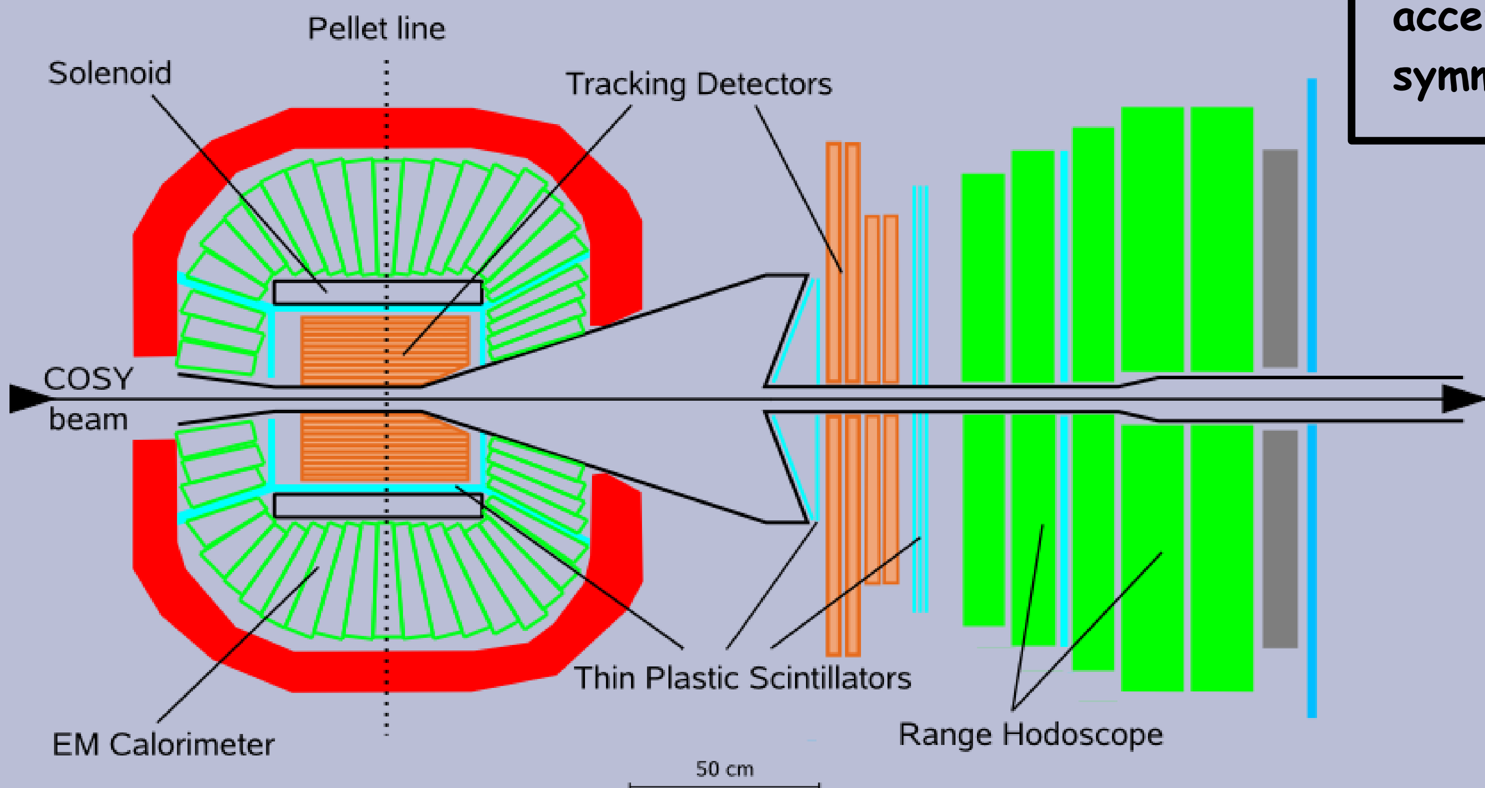




WASA detector

(Wide Angle Shower Apparatus)

Pellet target



acceptance ~4 π
symmetric with respect to φ

Central Detector:

- photons and charged particles (ΔE-p, ΔE-E)
- $\Theta_{central}$ 20-170 °

"Forward" Detector:

- charged particles (ΔE-ΔE, ΔE-E)
- $\Theta_{forward}$ 3-18 °

Experiments

June 2008

Channels:

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

Normalization:

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

Q: -51 to 22 MeV

P: 2.185 to 2.4 GeV/c

November-December 2010

Channels:

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

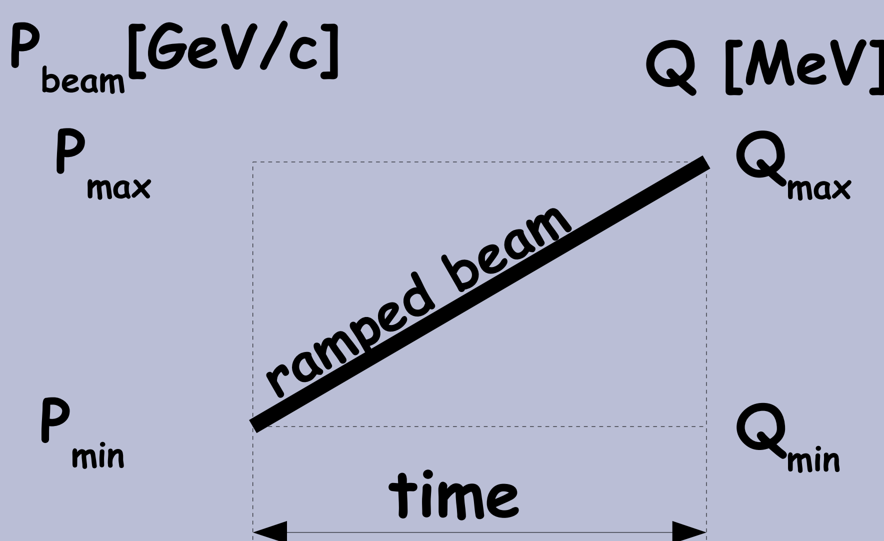
$dd \rightarrow {}^3He\ n\ \pi^0 \rightarrow {}^3He\ n\ \gamma\gamma$

Normalization:

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

Q: -70 to 30 MeV

P: 2.127 to 2.422 GeV/c



Experiments

June 2008

Channels:

dd $\rightarrow$ ^{3}He p π^-

Normalization:

dd $\rightarrow$ ^{3}He n

Q: -51 to 22 MeV

P: 2.185 to 2.4 GeV/c

November-December 2010

Channels:

dd $\rightarrow$ ^{3}He p π^-

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

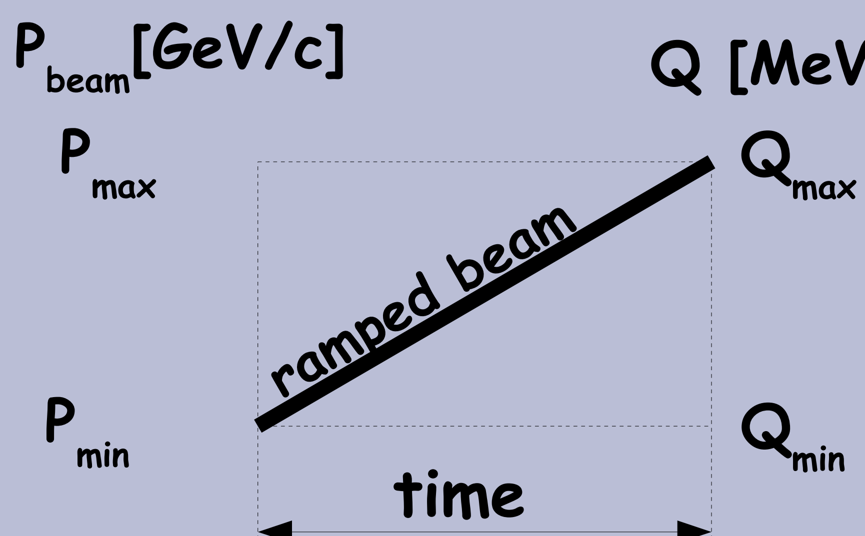
Normalization:

dd $\rightarrow$ ^{3}He n

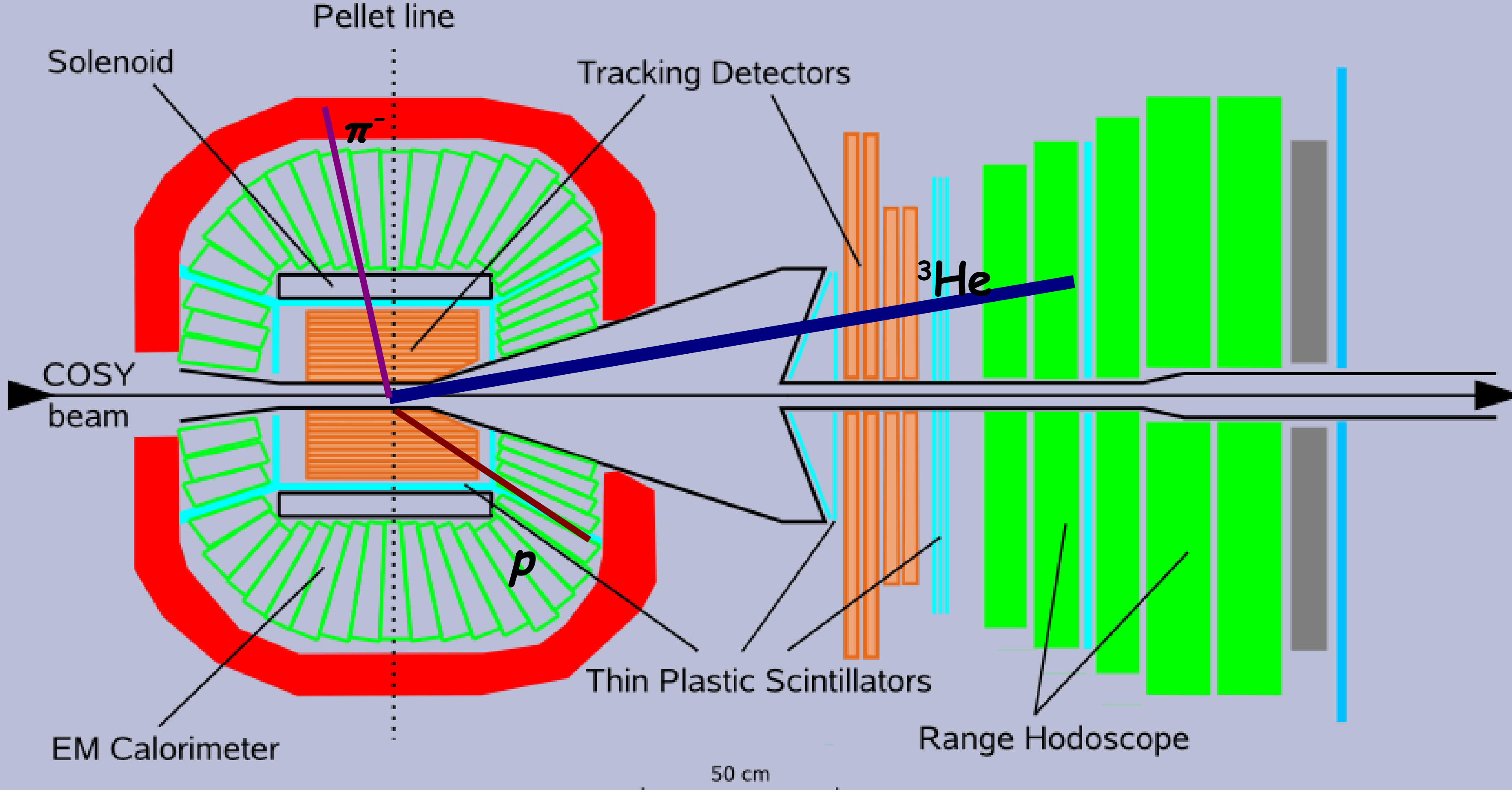
Q: -70 to 30 MeV

P: 2.127 to 2.422 GeV/c

~20 x more statistics

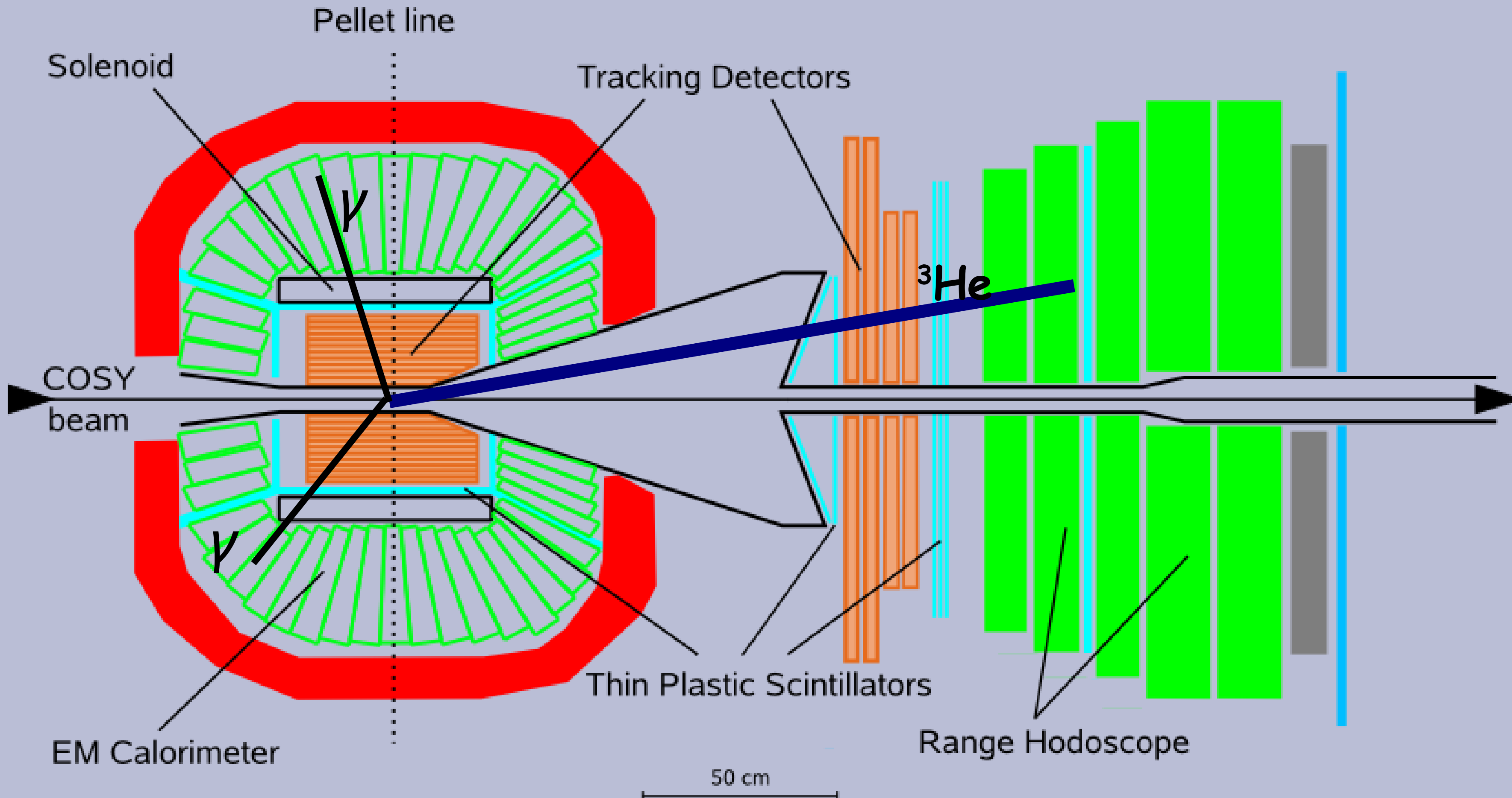


WASA-at-COSY



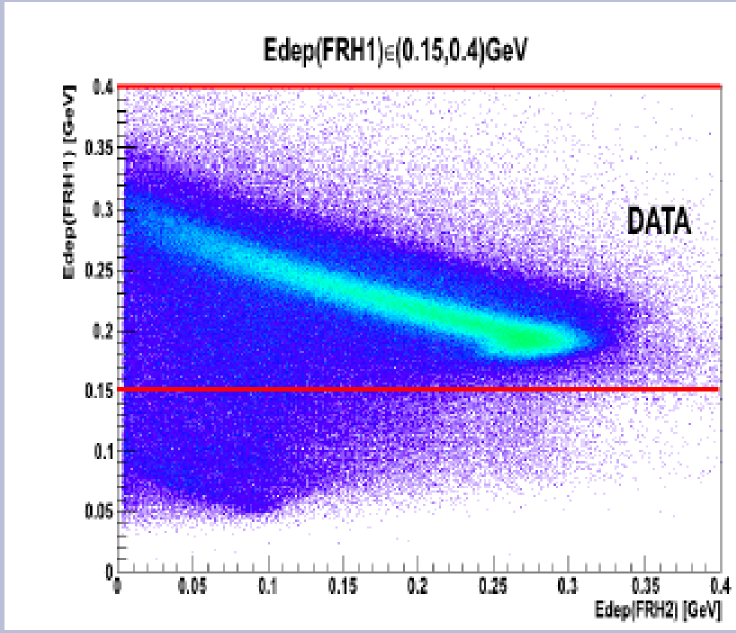
$dd \rightarrow (\eta\text{-}^4He)_{bound} \rightarrow {}^3He\ p\ \pi^-$

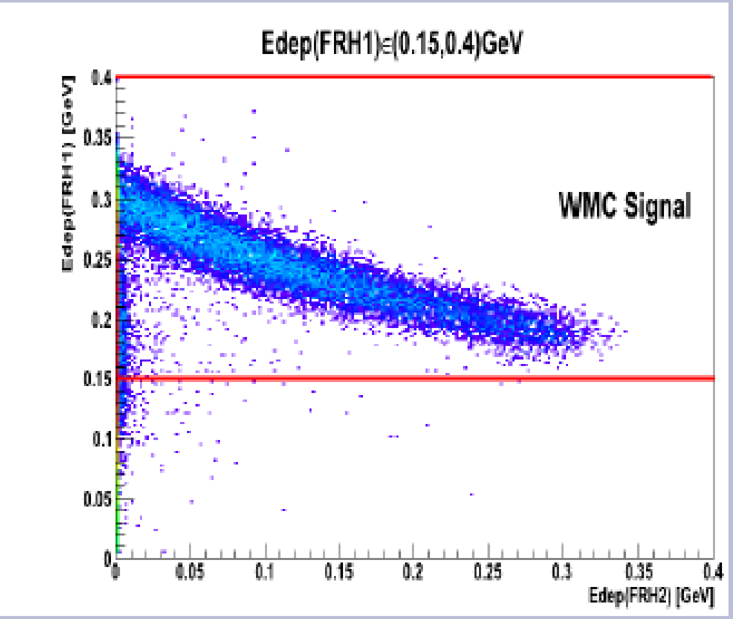
WASA-at-COSY



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

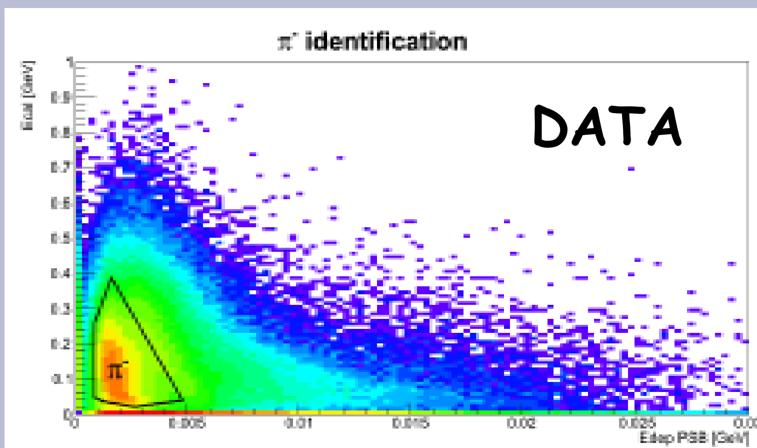
^{3}He ions identification in Forward Detector

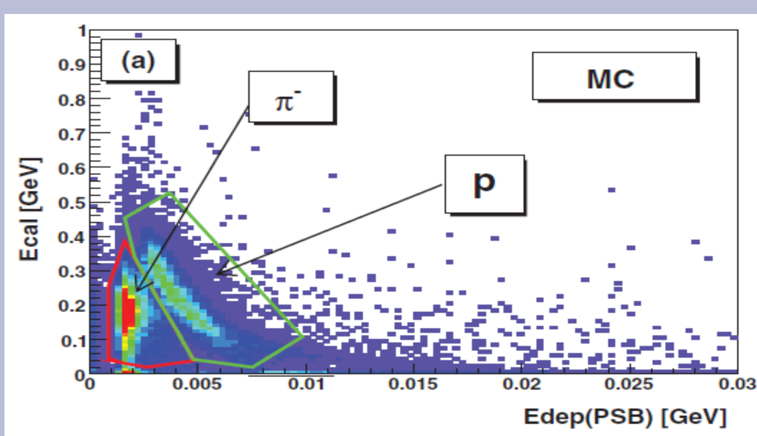




Pion identification in the Central Detector

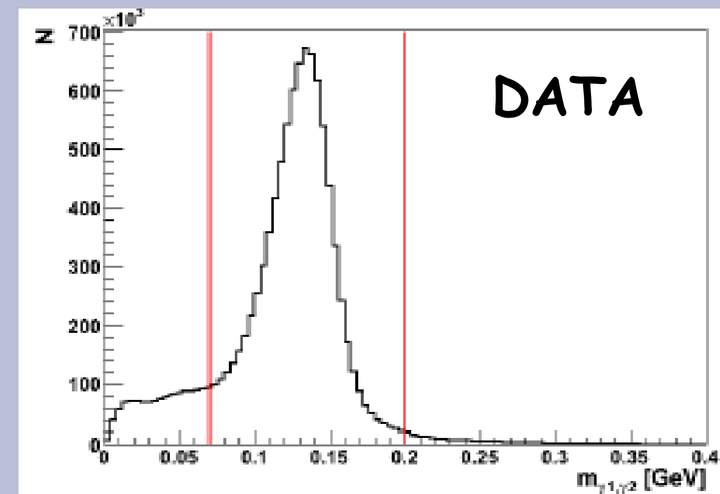
dd → ^{3}He p π^-

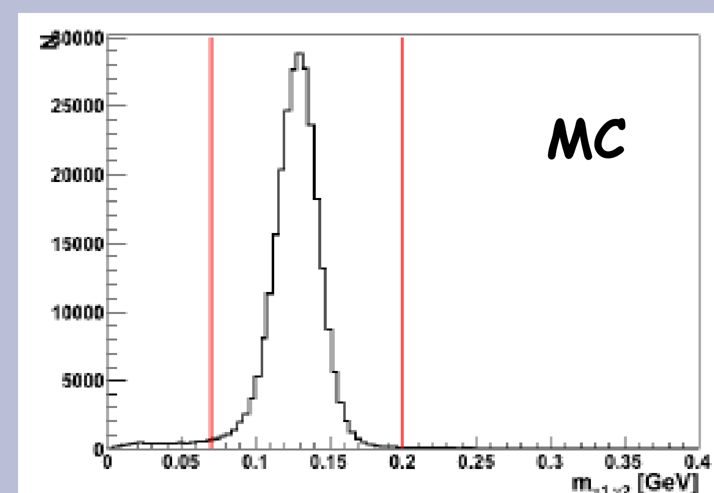




π^- identification

dd → ^{3}He n π^0 → ^{3}He n $\gamma\gamma$

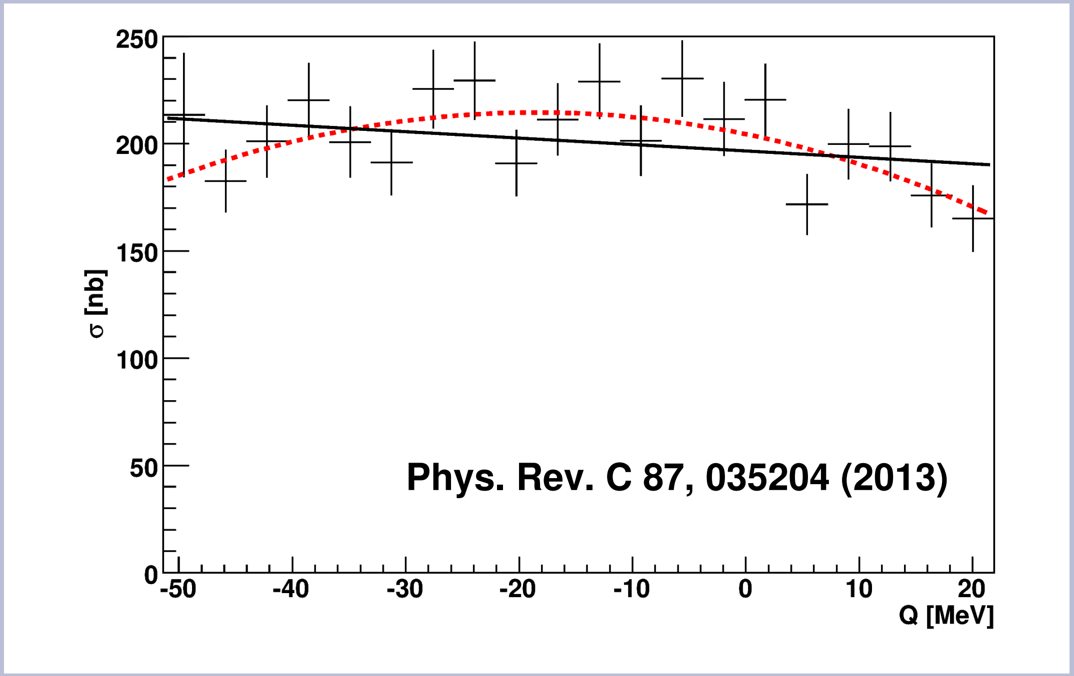


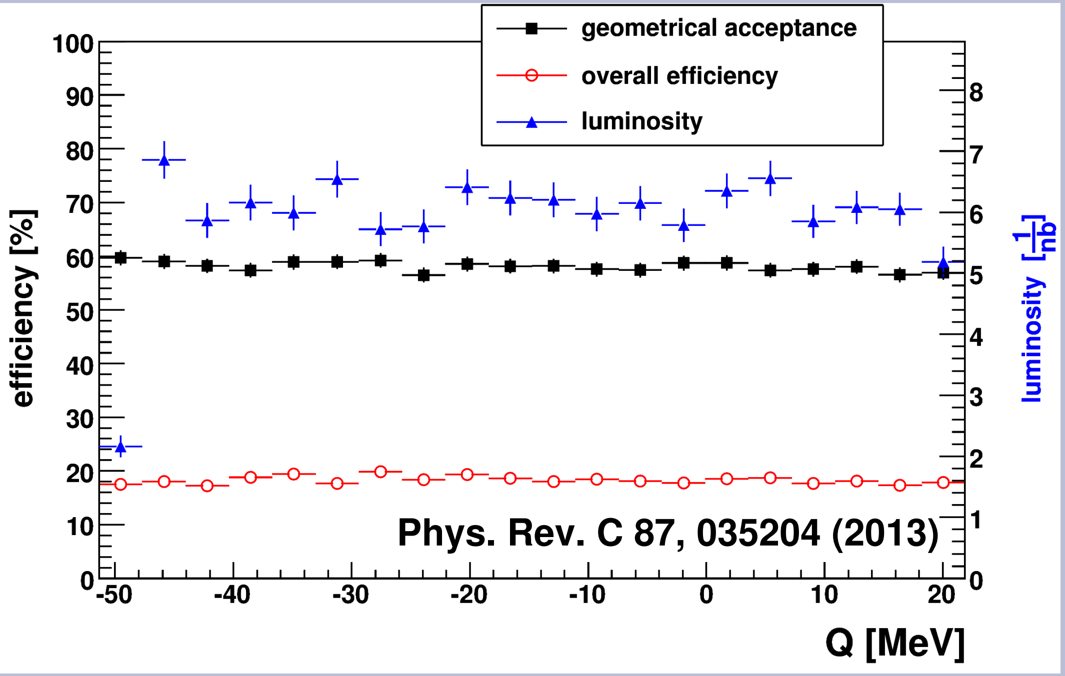


π^0 identification

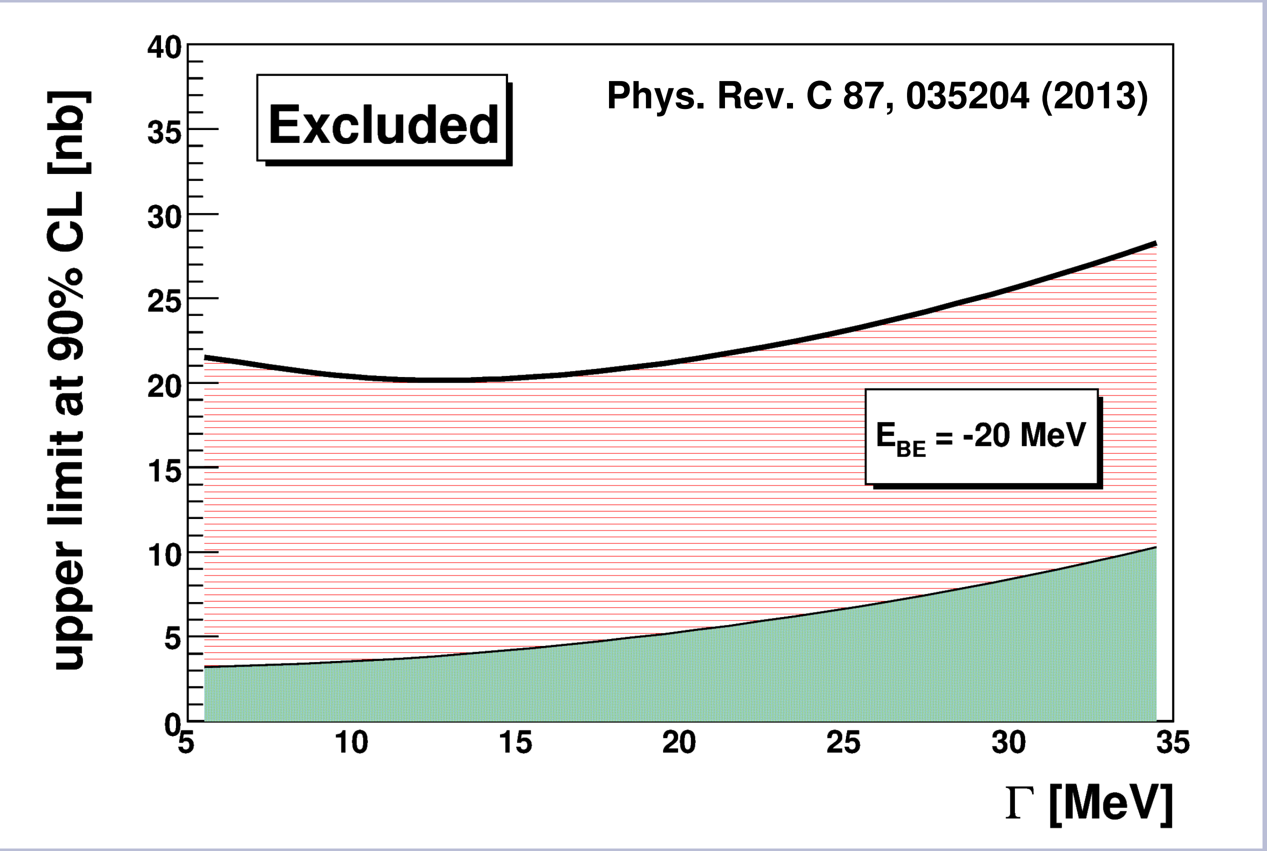
Results from 2008 data

Excitation function
(normalized and corrected for efficiency)





Upper limit of the maximum cross-section for the reaction $dd \rightarrow (^4He-\eta)_{bound} \rightarrow {}^3He\, p\, \pi^-$



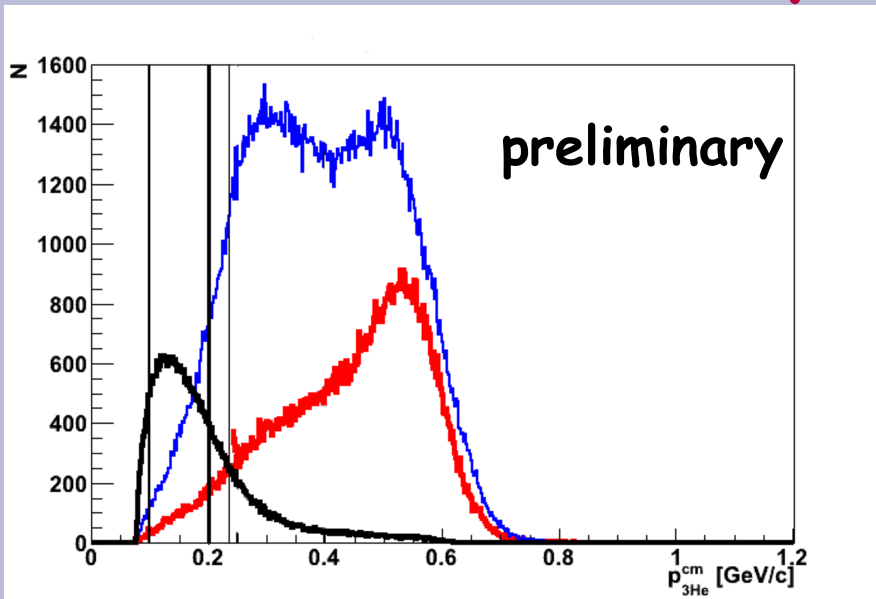
Signal:

$$\sigma(Q, E_{BE}, \Gamma, A) = \frac{A\left(\frac{\Gamma}{2}\right)^2}{(Q - E_{BE})^2 + \left(\frac{\Gamma}{2}\right)^2}$$

Background: $BG = a_0 + a_1 Q + a_2 Q^2$ **or** $BG = a_0 + a_1 Q$

Preliminary results from 2010 data

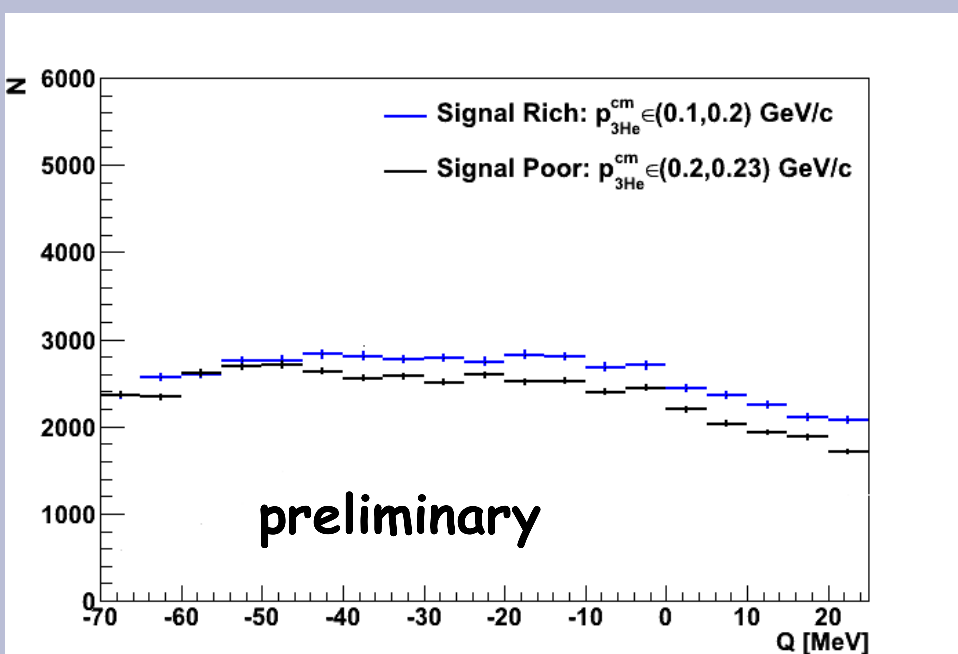
Preliminary results from 2010



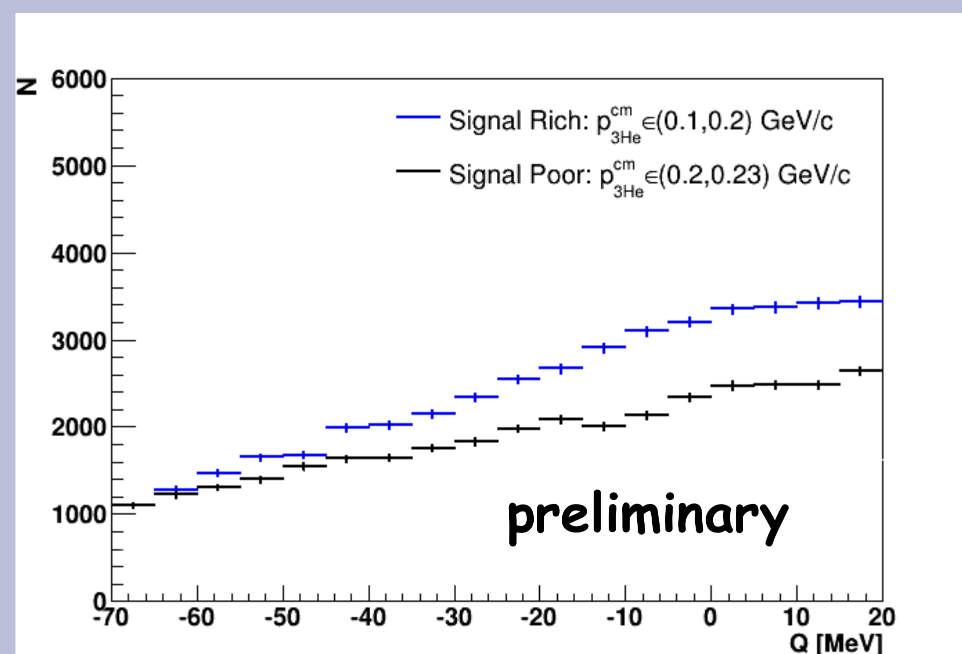
red line: dd → ^{3}He n π^0

blue line: dd → ^{3}He p π^-

black line(MC): dd → $(^4\text{He} - \eta)_{bound}$ → ^{3}He n π^0



dd → ^{3}He p π^-



dd → ^{3}He n π^0

New experiment (May-June 2014)

May-June 2014

Channels:

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

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

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

Orbiting eta:

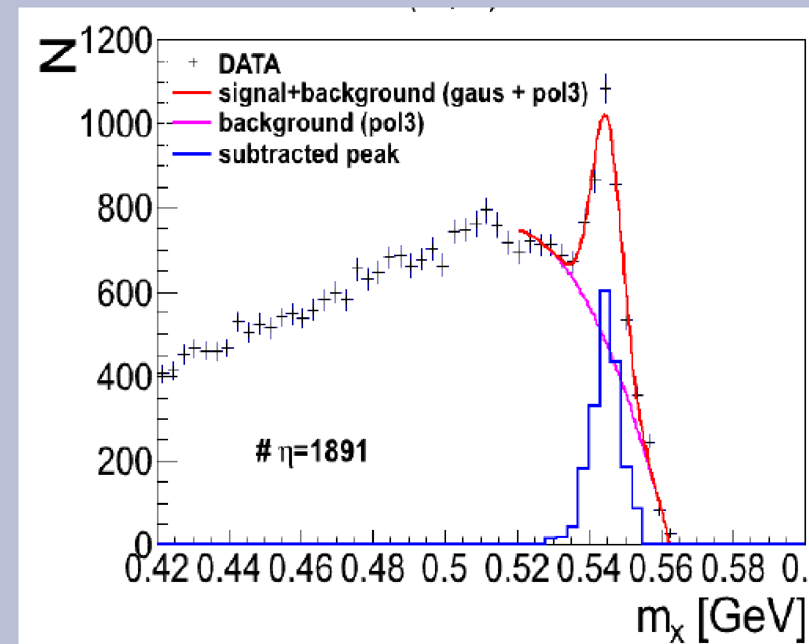
$p+d \rightarrow (^3He\text{-}\eta)_{bound} \rightarrow {}^3He\ 6\gamma$

Normalization:

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

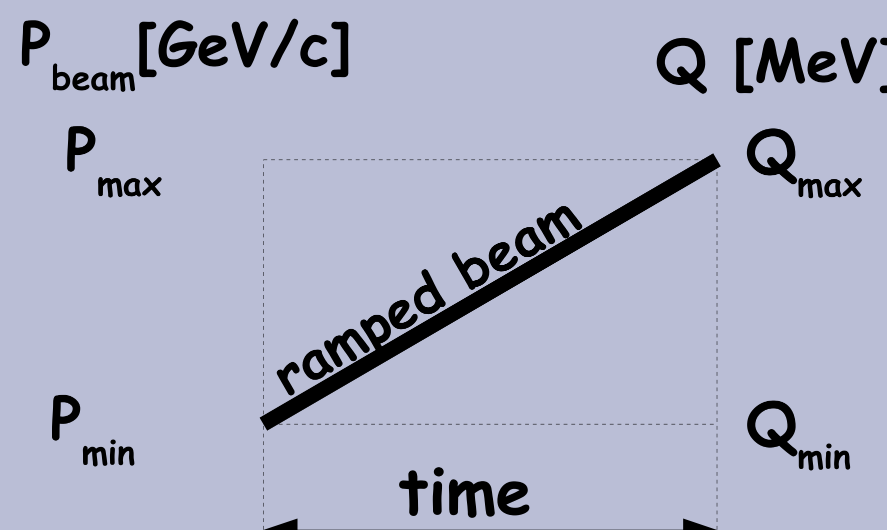
$pd \rightarrow {}^3He\ \pi^0$

Test plot from experiment



Q: -50 to 20 MeV

P: 1.468 to 1.615 GeV/c



Predictions for He system

η - ^4He

~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 - ^3He

~270 nb -- Present experimental upper limit $ppp\pi^-$

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

Conclusions

• Exotic atoms and nuclei as systems to study meson-nucleon interaction and partial restoration of the chiral symmetry,

• η-nucleon interaction still not well described, despite many years of studies,

• η-mesic nuclei not unequivocally confirmed so far,

• Search for a light mesic nuclei in ***η-^{3}He*** and ***η-^{4}He*** systems with WASA-at-COSY:
Exclusive, high-acceptance measurement with **ramped beam.**
New data set (η-^{3}He) with perspectives to lower the current upper limit **~ 30 times,**

• New experiments planned (**η'-mesic nuclei**): J-PARC, GSI, ELSA

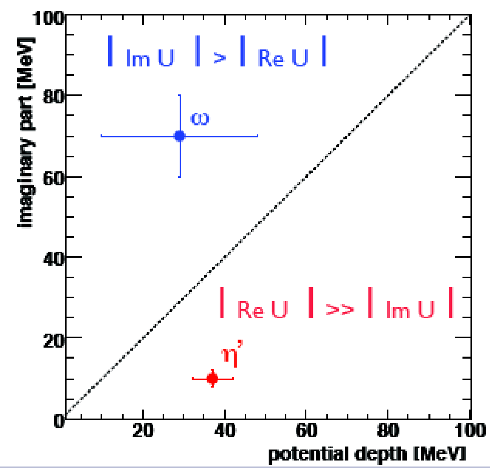
ω and η' mesic nuclei

Many results from CBELSA/TAPS, CB/TAPS:

- Transparency ratios
- Excitation functions
- Momentum distributions

$U_{\omega A}(\rho=\rho_0)=$ $-(29\pm19(stat)\pm20(syst) + i(70\pm10)$ MeV

$U_{\eta' A}(\rho=\rho_0)=$ $-(37\pm5(stat)\pm10(syst) + i(10\pm3)$ MeV



| Im U | > | Re U | ; ⇨ ω not a good candidate to search for meson-nucleus bound states!

| Re U | >> | Im U | ; ⇨ η' promising candidate to search for mesic states

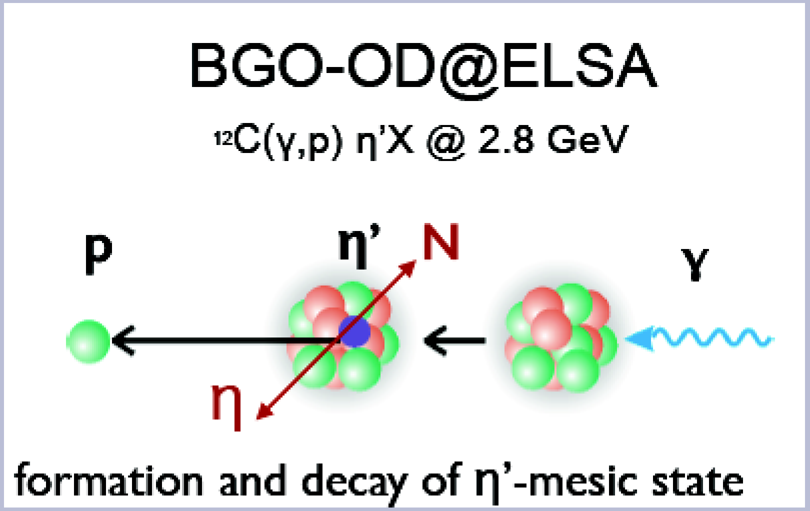
V. Metag's talk at EXA 2014, Vienna, Austria

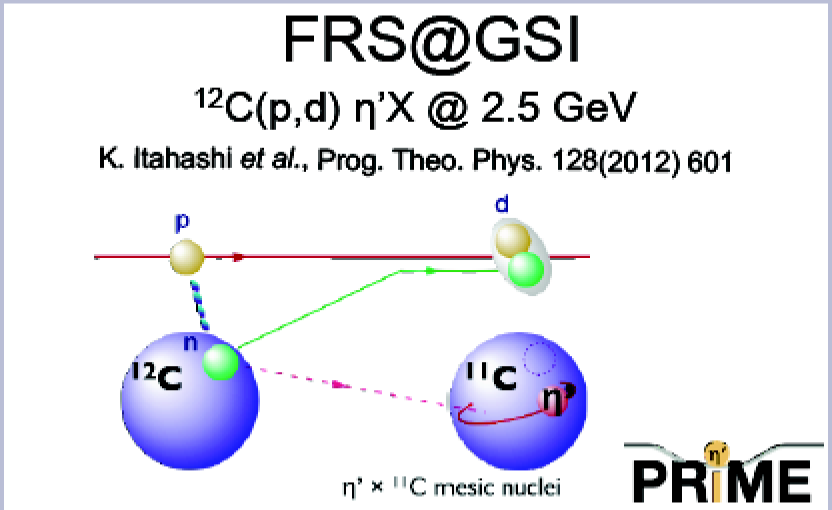
https://indico.gsi.de/conferenceTimeTable.py?confId=2604#20140915

η' mesic nuclei

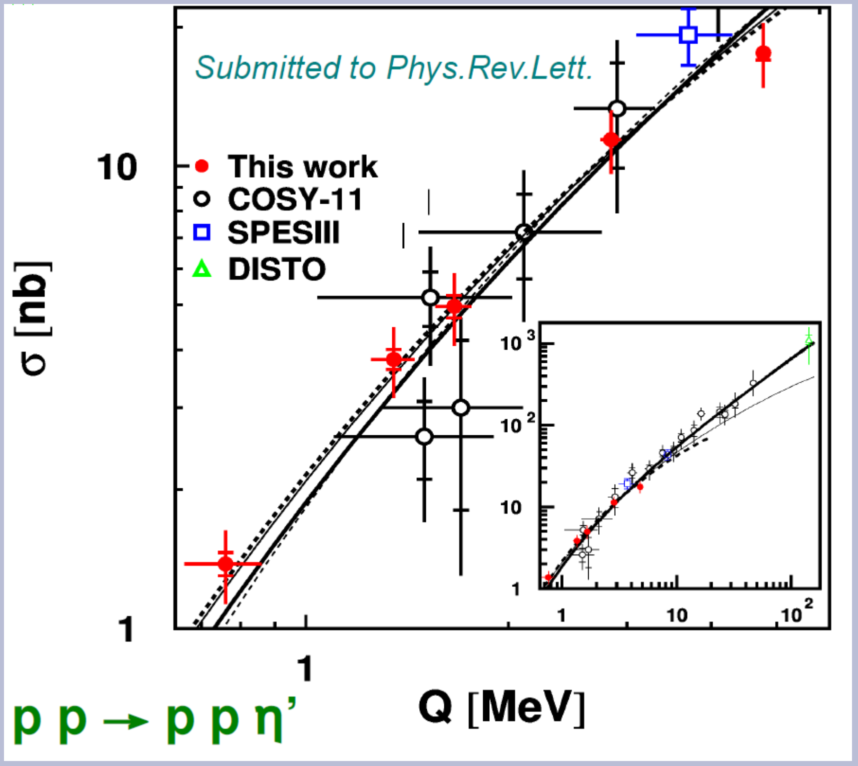
Experiments planned:

- GSI
- ELSA
- J-PARC





η' mesic nuclei ?



$$\mathrm{Re}(a_{p\eta'}) = 0 \pm 0.43 \text{ fm and } \mathrm{Im}(a_{p\eta'}) = 0.37\ ^{+0.40}_{-0.16} \text{ fm.}$$

COSY-11: Phys. Rev. Lett. 113 (2014) 062004

Thank you

Backup slides

Other decay channels

- Via N* resonance decay:

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

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

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

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

- Absorption of an orbiting η:

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

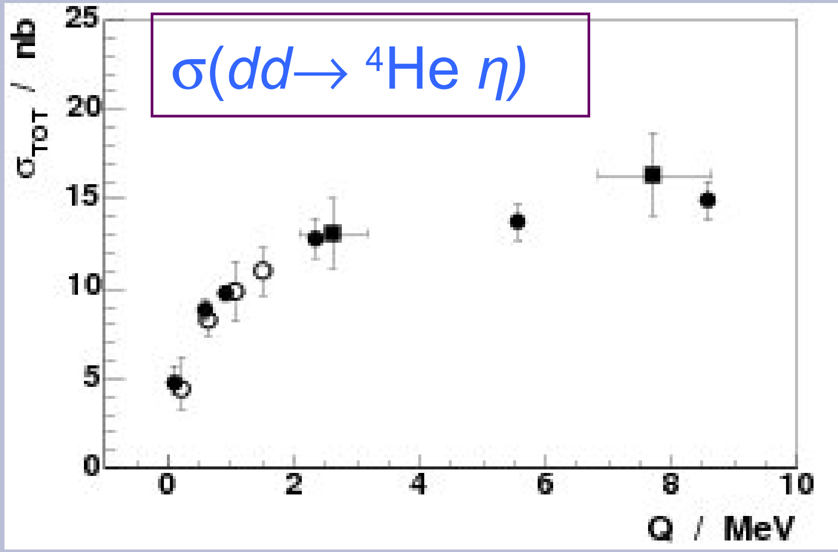
- Non-resonant decay (absorption on two nucleons):

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

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

Cross-section estimate
dd → ^{4}He η → ^{3}He p π^-

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

~ 1/4 x 1/2 = 1/8

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

η n → pπ-
one of the possible four channels

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

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

New experiment predictions

Via N* decay:

- x-section(η-^{3}He) ~ 80 nb , x-section(background) ~ 2500 nb, sensitivity ~ 10 nb

Orbiting *η*:

- x-section(η-^{3}He) ~ 0.4 nb, x-section(background) ~ 16 nb, sensitivity~ 0.4 nb

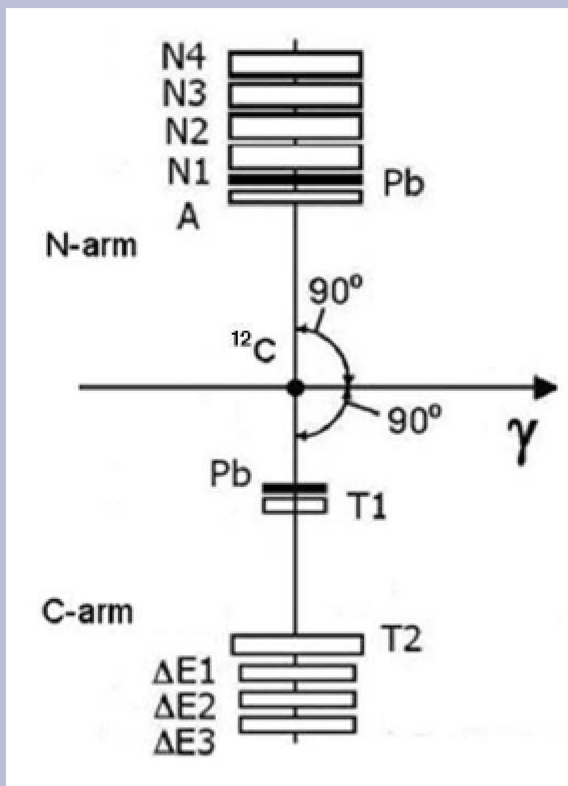
Colin Wilkin

Is it possible to detect the decay of an η-meson while it is orbiting a nucleus?

Total η width is about 1.3 keV, of which 39% corresponds to 2γ decay. The $^3_\eta$He width is less than 500 keV. Hence, if this is a quasi-bound system, about one in a thousand should decay through 2γ emission. The 6γ branch will be slightly less.
Small but clean!

Experiment at LPI

- $\gamma + {}^{12}C \rightarrow p(n) + \eta\ \text{-}{}^{11}Be\ (\eta\ \text{-}{}^{11}C) \rightarrow \pi^{+} + n + X$

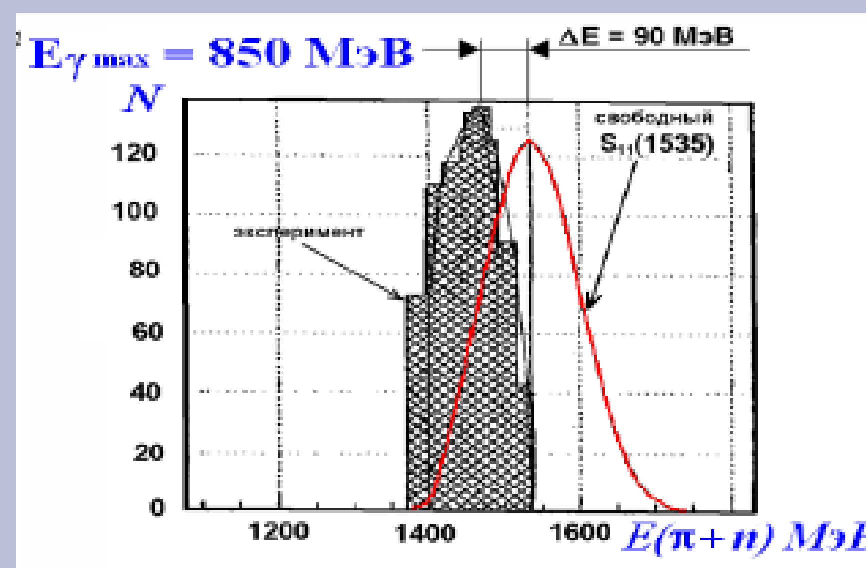


E= 850 MeV

E =650 MeV (for background measurement)

TOF resolution ~ 200 ps (1sigma)

TOF base: 1.3 m



G. Sokol et al. Fizika B8, 85 (1999)
Part. Nucl. Lett. 5[102], 71 (2000)
Yad Fiz 71, 532 (2008)

Experiment at JINR (NUCLOTRON)

$d + {}^{12}C \rightarrow X + \eta\text{-}A \rightarrow \pi + p + X$

T_d = 1,1 -2.2 GeV/nucl

Resolution ~ 10 MeV

$$\sigma(A_\eta) \approx \frac{4\pi}{\Omega} \frac{N_{\text{effect}} - N_{\text{backgr}}}{N_{\text{in}}} \sigma_{\text{in}} \approx 11 \pm 8\ \mu\text{b}.$$

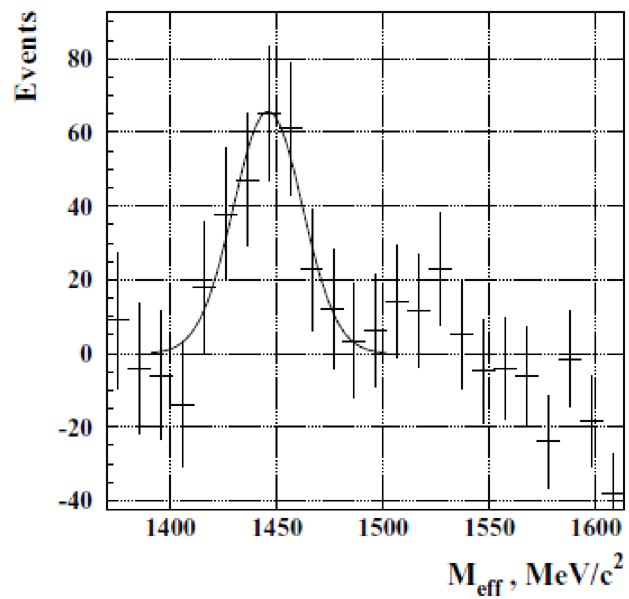
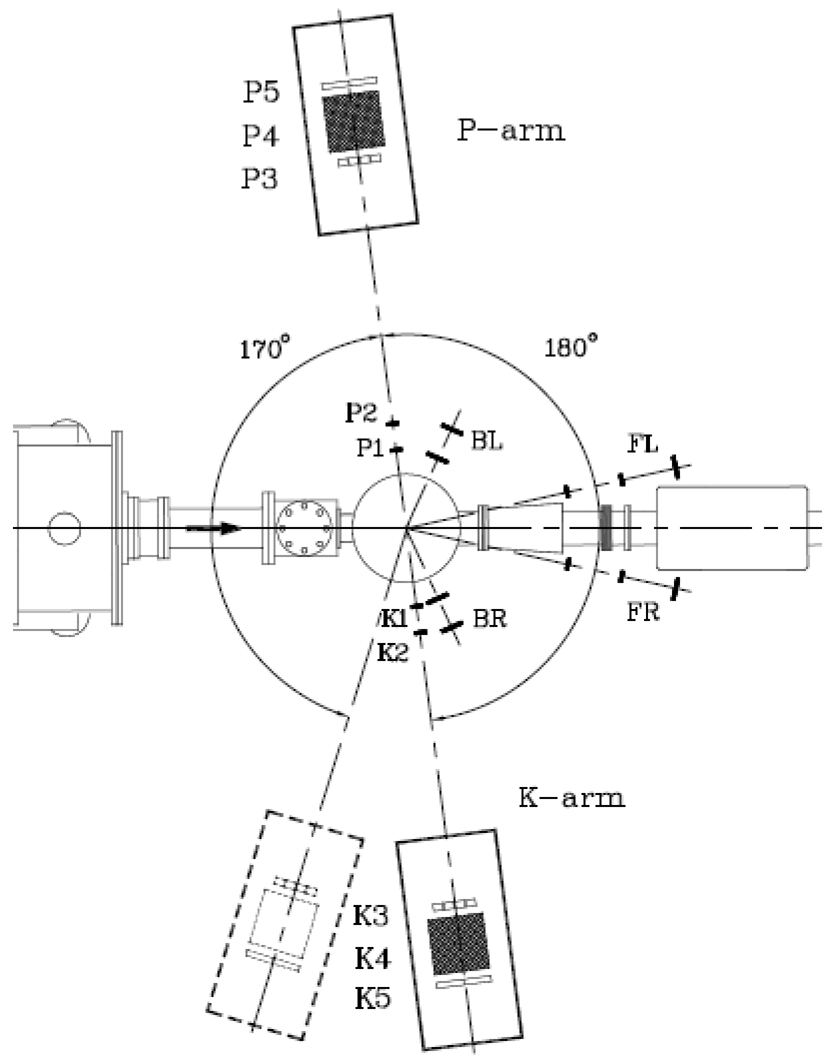


Figure 2: The effective mass of correlated πp pairs after background subtraction for T_d = 2.1 GeV/nucl.

1447.8 ± 3.6 MeV/c^2 with the width 38.8 ± 10.4

$$M_{\text{eff}} = \frac{m_1}{\sqrt{1-\beta_1^2}} + \frac{m_2}{\sqrt{1-\beta_2^2}}.$$



Theoretical predictions

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

- 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)

COSY accelerator in Juelich (Germany)

(COoler SYnchrotron)

Beam:

- Unpolarized and polarized protons or deuterons.

Energy range:

- T_p to 2.8 GeV
- T_d to 2.3 GeV

(maximum momentum: 3.7 GeV/c)

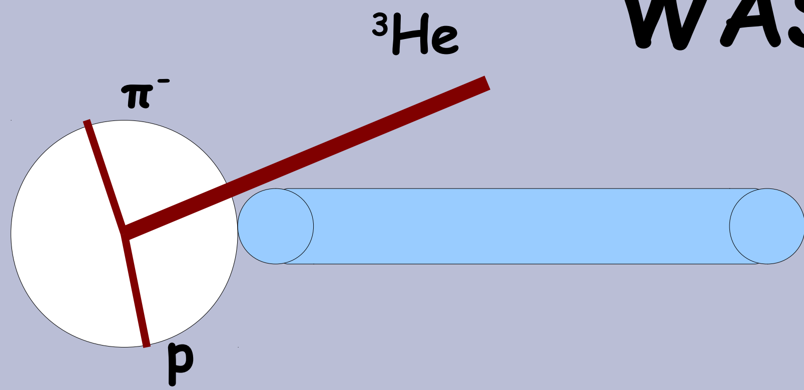
Cooling:

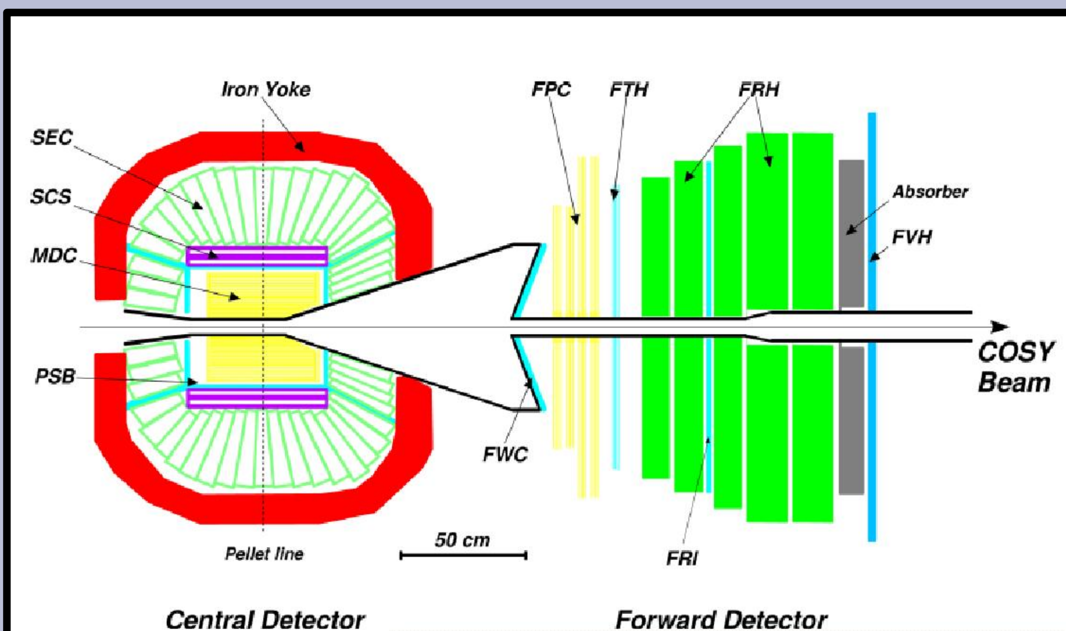
- stochastic
- electron beam

Nb of particles: 10^{11}

Ramped beam

WASA-at-COSY





Forward detector:

Scattering angle coverage 3°-18°

Scattering angle resolution 0.2°

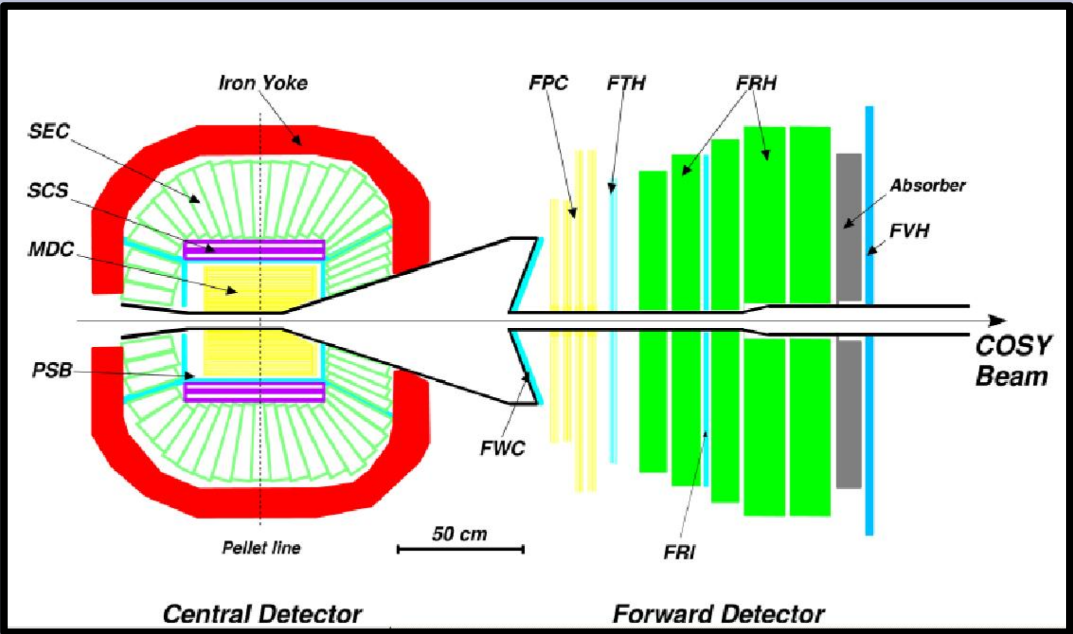
Maximum energies for stopping
$\pi^{\pm}$/p/d/α 170/300/400/900 MeV

Time resolution <3ns

Relative energy resolution
particles $T_{stop} < T < 2T_{stop}$ 3-8%
stopped particles $T < T_{stop}$ 1.5-3%

WASA-at-COSY

4 π **detector for charged and neutral particles**



Central detector:

Max. stopping energy

$\pi^{\pm}$/p/d 190/400/450 MeV

Angular resolution

charged ~1.2°

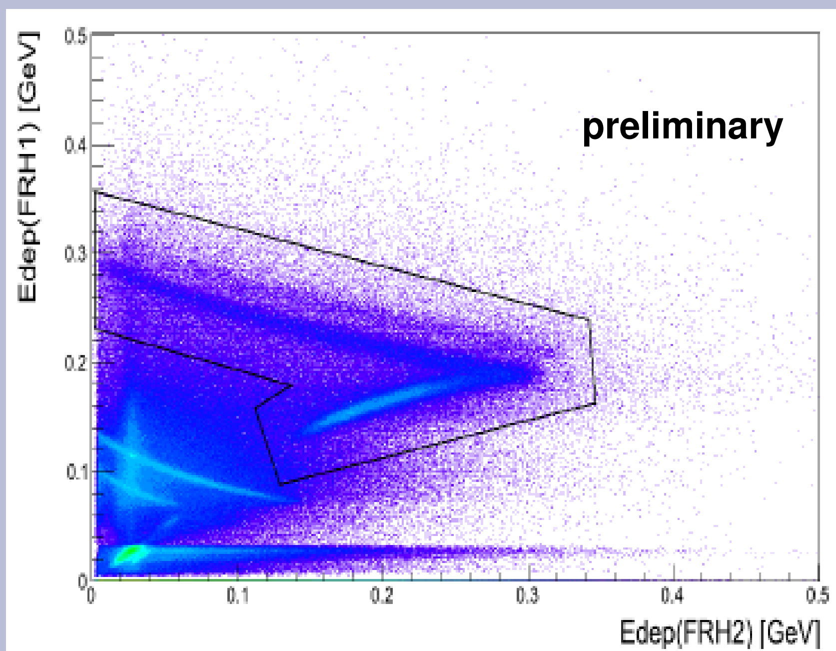
neutral ~5°

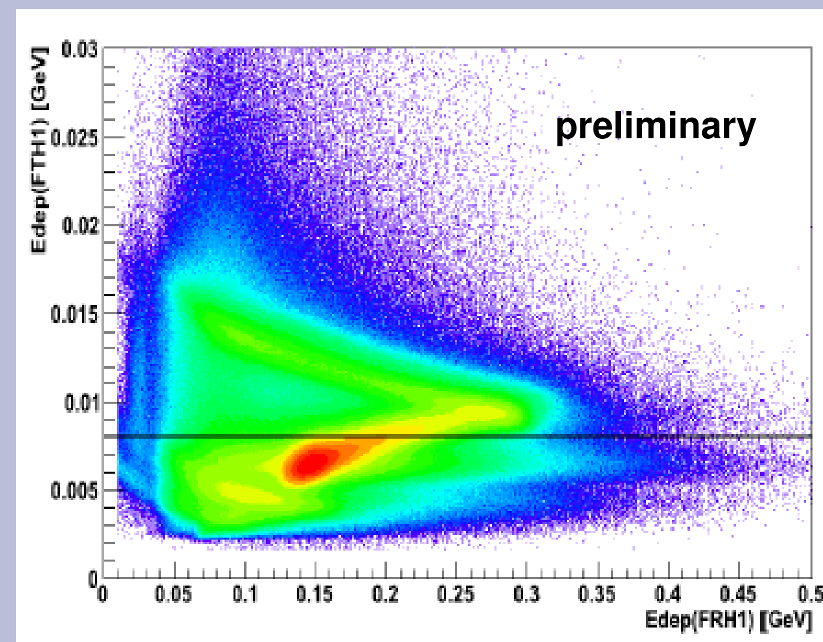
Relative energy resolution by SE

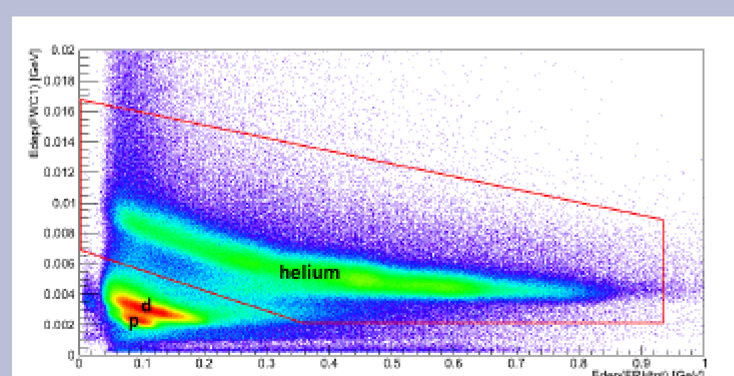
photons ~8%

stopped charged particles ~3%

^{3}He ions identification in Forward Detector

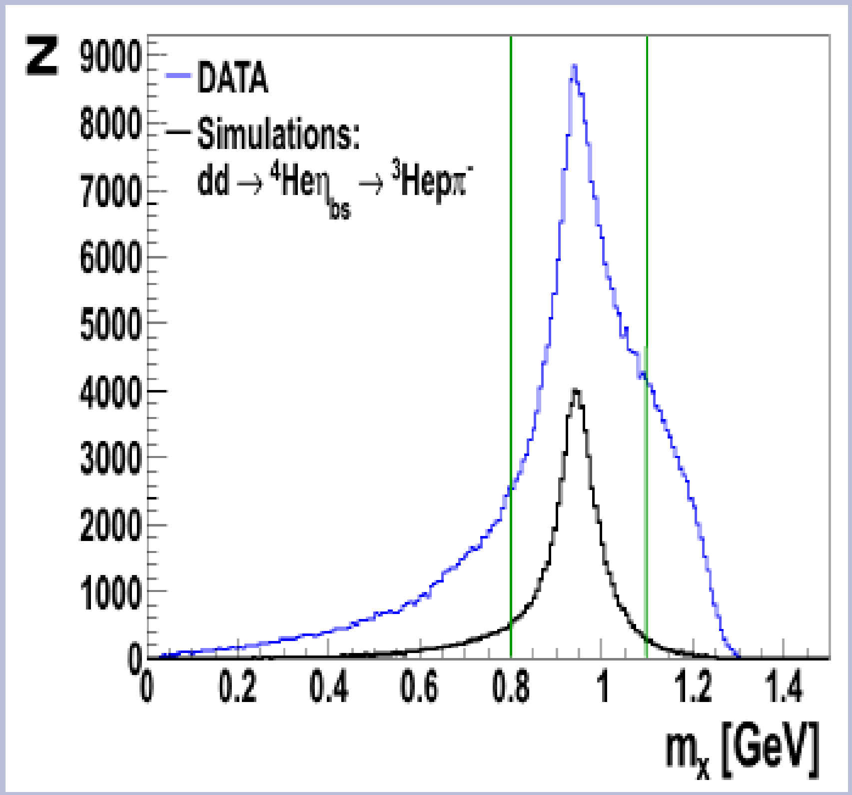






Nucleon identification (missing mass method)

dd $\rightarrow$ ^{3}He p π^{-}



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