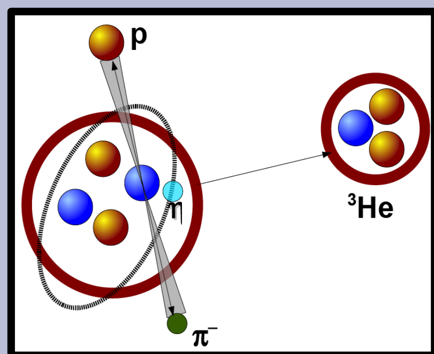
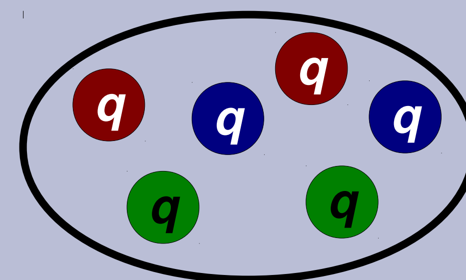
Search for the non-standard nuclear matter with WASA-at-COSY





Wojciech Krzemień

(National Centre for Nuclear Research)

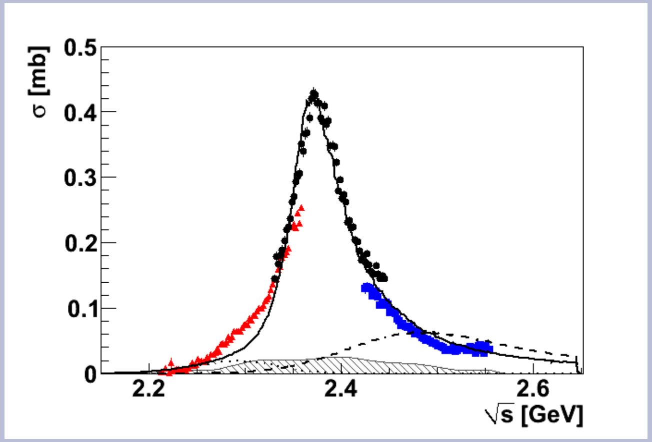
for WASA-at-COSY collaboration

08th of October 2016, Świerk

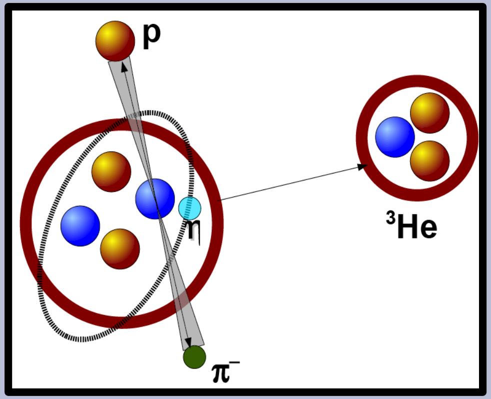
Various Faces of QCD 2

Outline

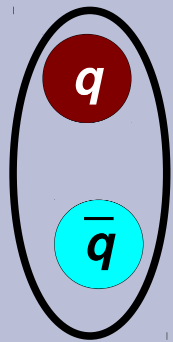
Discovery of the dibaryon state d*(2380)



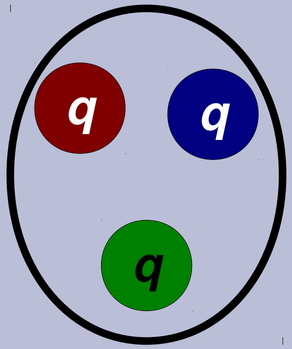
Can η form a bound state with a nucleus ?



Particle variety



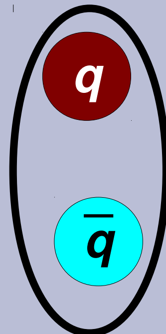
meson



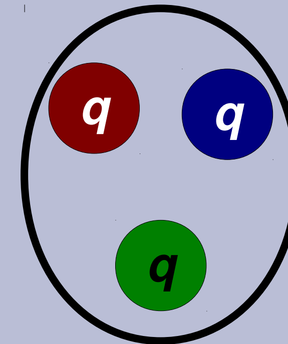
baryon

QCD does not forbid more complex combinations

Particle variety

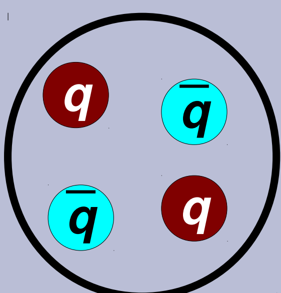


meson

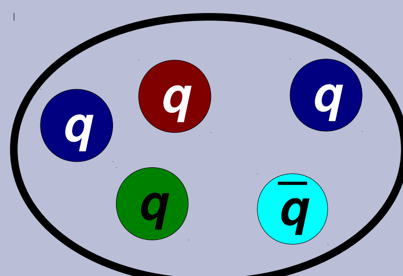


baryon

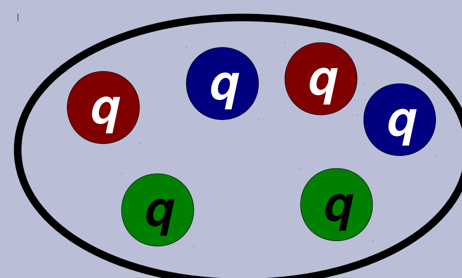
QCD does not forbid more complex combinations



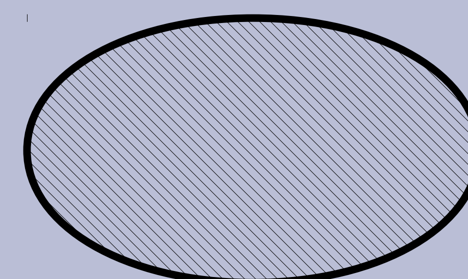
tetraquark



pentaquark



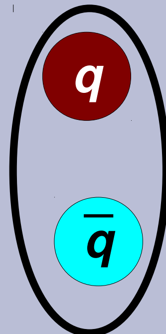
dibaryon



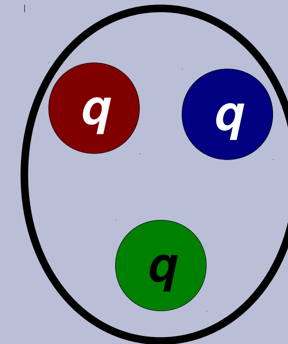
gluballs, hybrids,

...

Particle variety



meson



baryon

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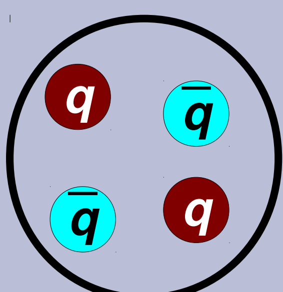
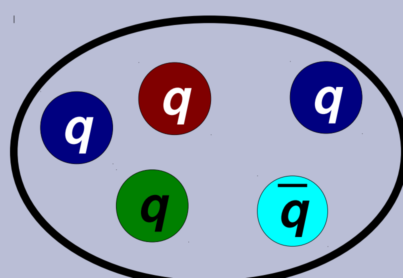
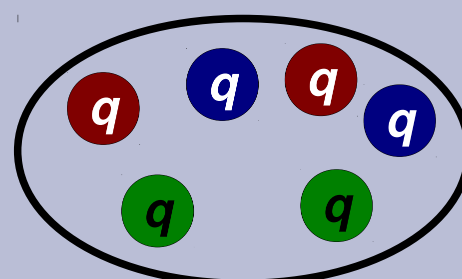
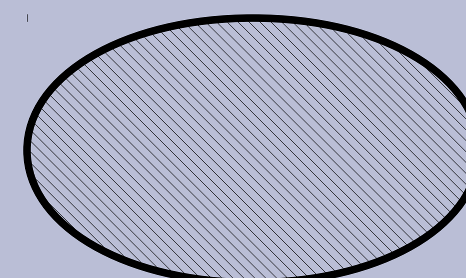




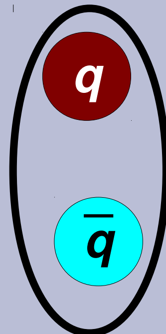




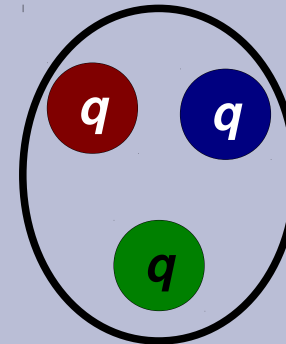
tetraquark **pentaquark** **dibaryon** **gluballs, hybrids, ...**

Multiquark exotics at LHCb
W. Wiślicki, tomorrow 12:00

Particle variety

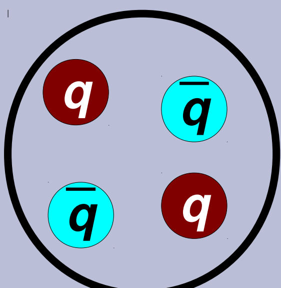


meson

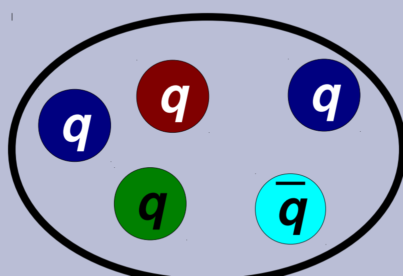


baryon

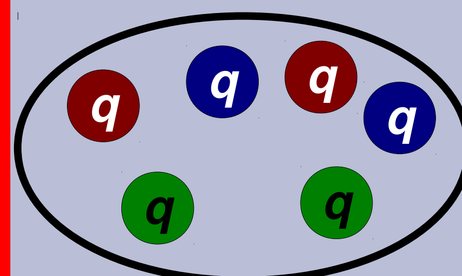
QCD does not forbid more complex combinations



tetraquark

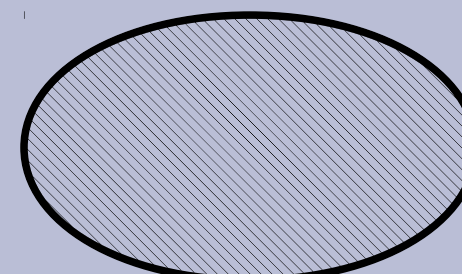


pentaquark



dibaryon

B = 2



gluballs, hybrids,

...

Multiquark exotics at LHCb
W. Wiślicki, tomorrow 12:00

hexaquark or molecule (deltaron) ?

Very short story of dibaryons

- Proposed by R. L. Jaffe in 1977: $\Lambda\Lambda$ bound state

  R. L. Jaffe Phys. Rev. Lett. 38 (5): 195 (1977)

- T. Goldmann et. al. in 1988 proposed „inevitable dibaryon"
  $\Delta\Delta$ bound state $I(J^P) = 0(3^+)$

  T. Goldmann et. al. Phys. Rev. C 39, 1889 (1989)

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  T. Goldmann et. al. Phys. Rev. C 39, 1889 (1989)

- Many experimental claims – **not confirmed**

- The word dibaryon "forbidden" for a long period

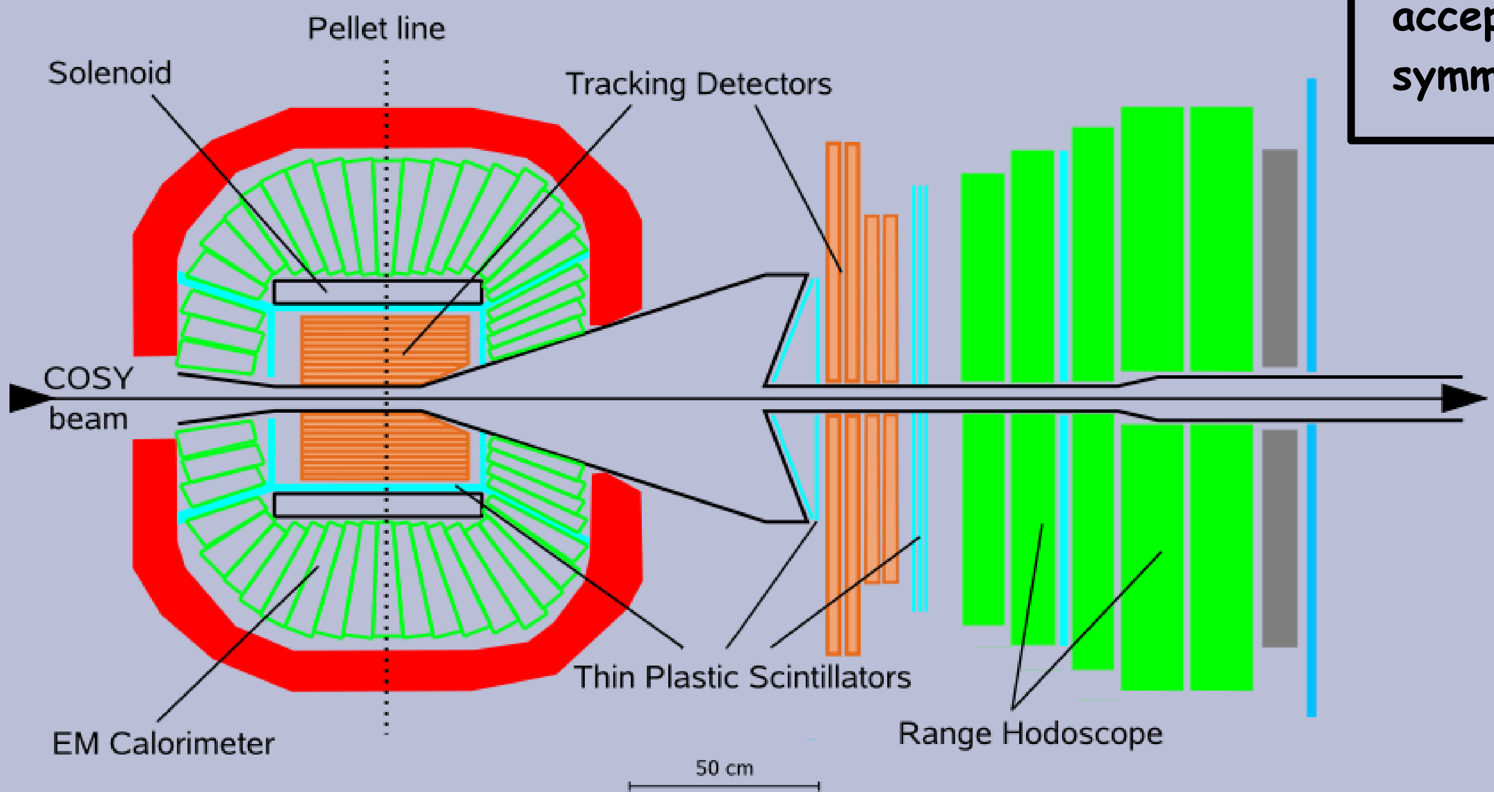
Freeman J. Dyson, Nguyen-Hue Xuong Phys. Rev. Lett. 13(1964) 815

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)
- $\Theta_{central}$ 20-169°

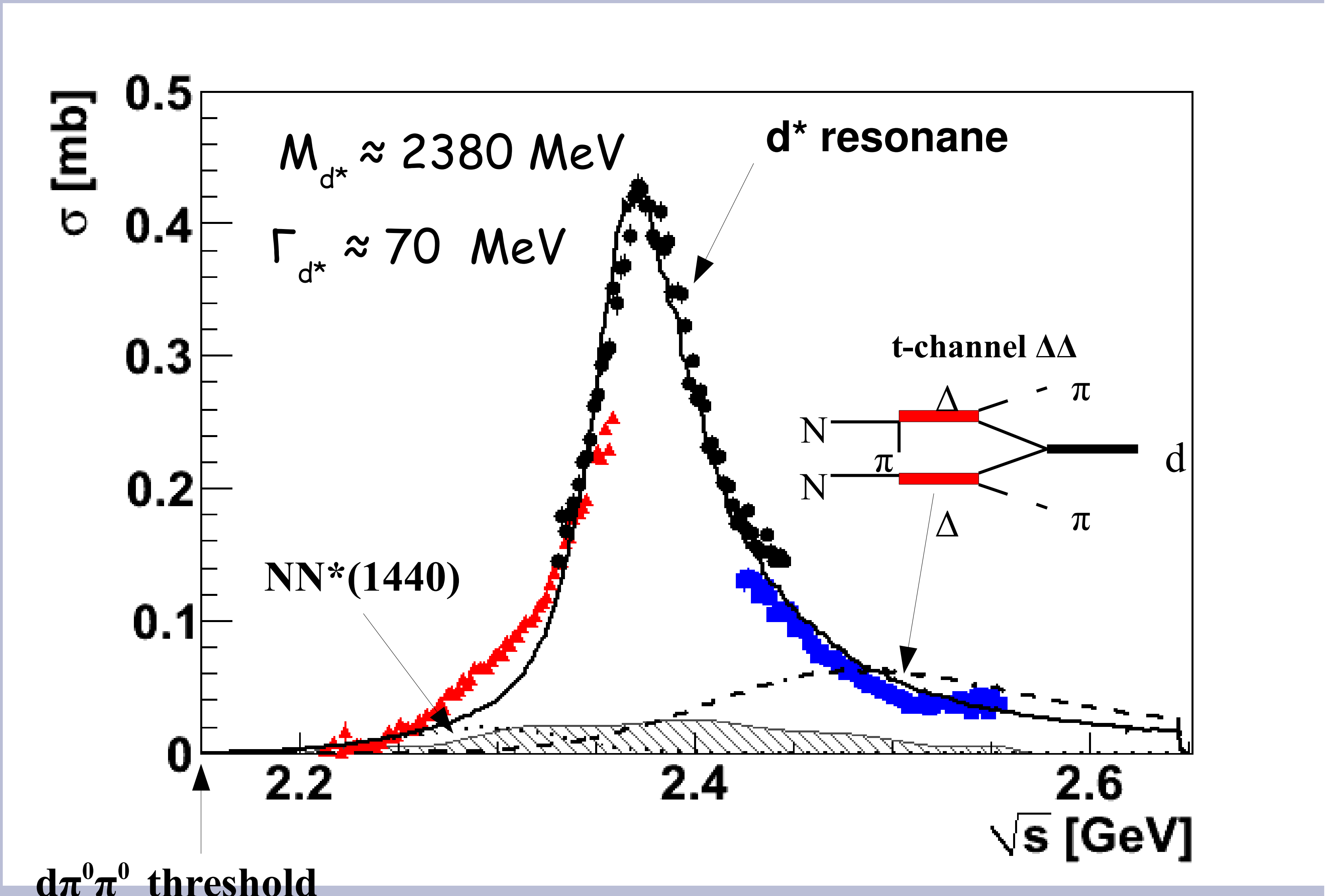
"Forward" Detector:

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

Total cross-section of $p+n \rightarrow d\pi^0\pi^0$

$p+d \rightarrow d\pi^0\pi^0 p_{spect}$

- $T_p = 1.0$ GeV
- $T_p = 1.2$ GeV
- $T_p = 1.4$ GeV



P. Adlarson et. al Phys. Rev. Lett. 106:242302, 2011

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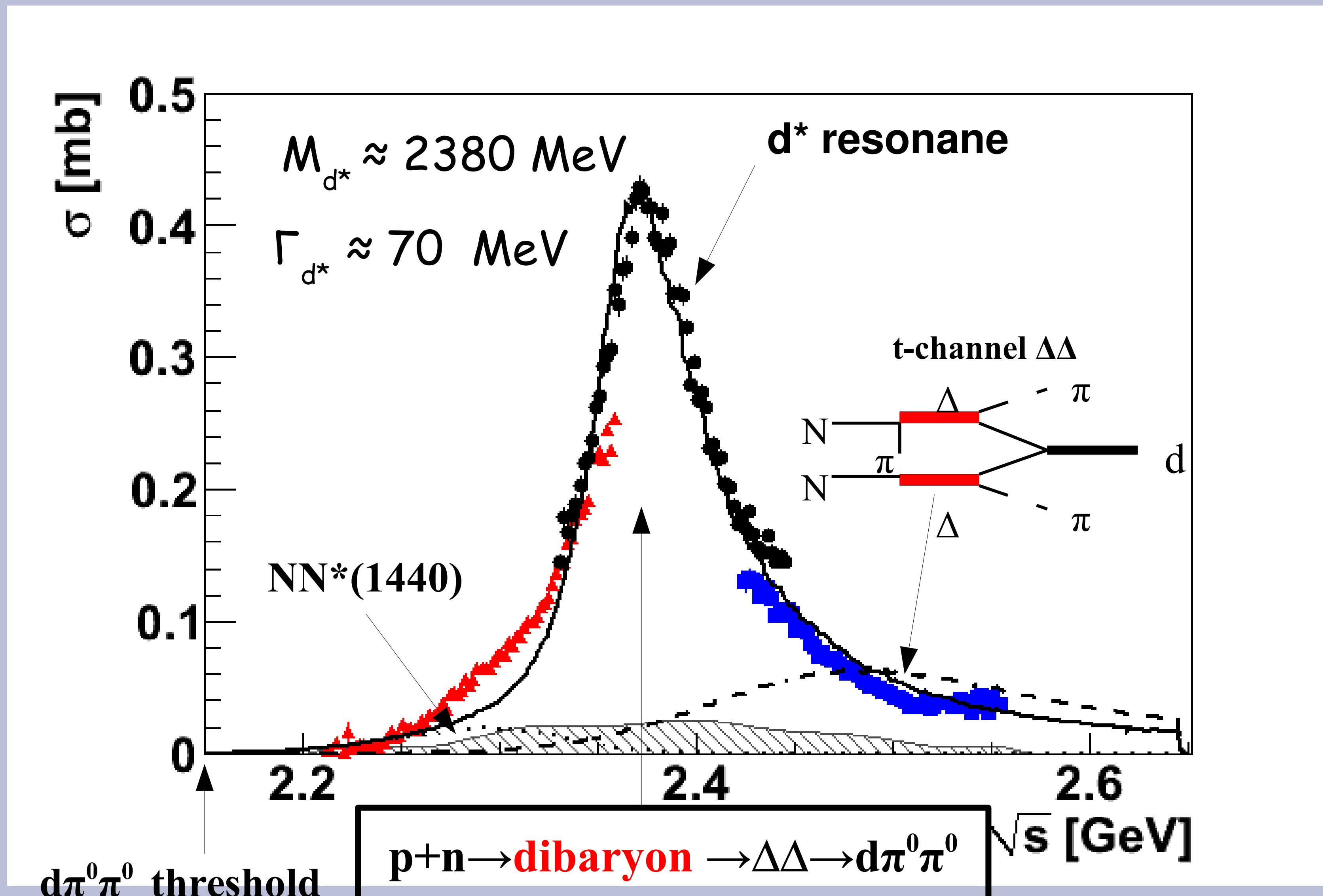
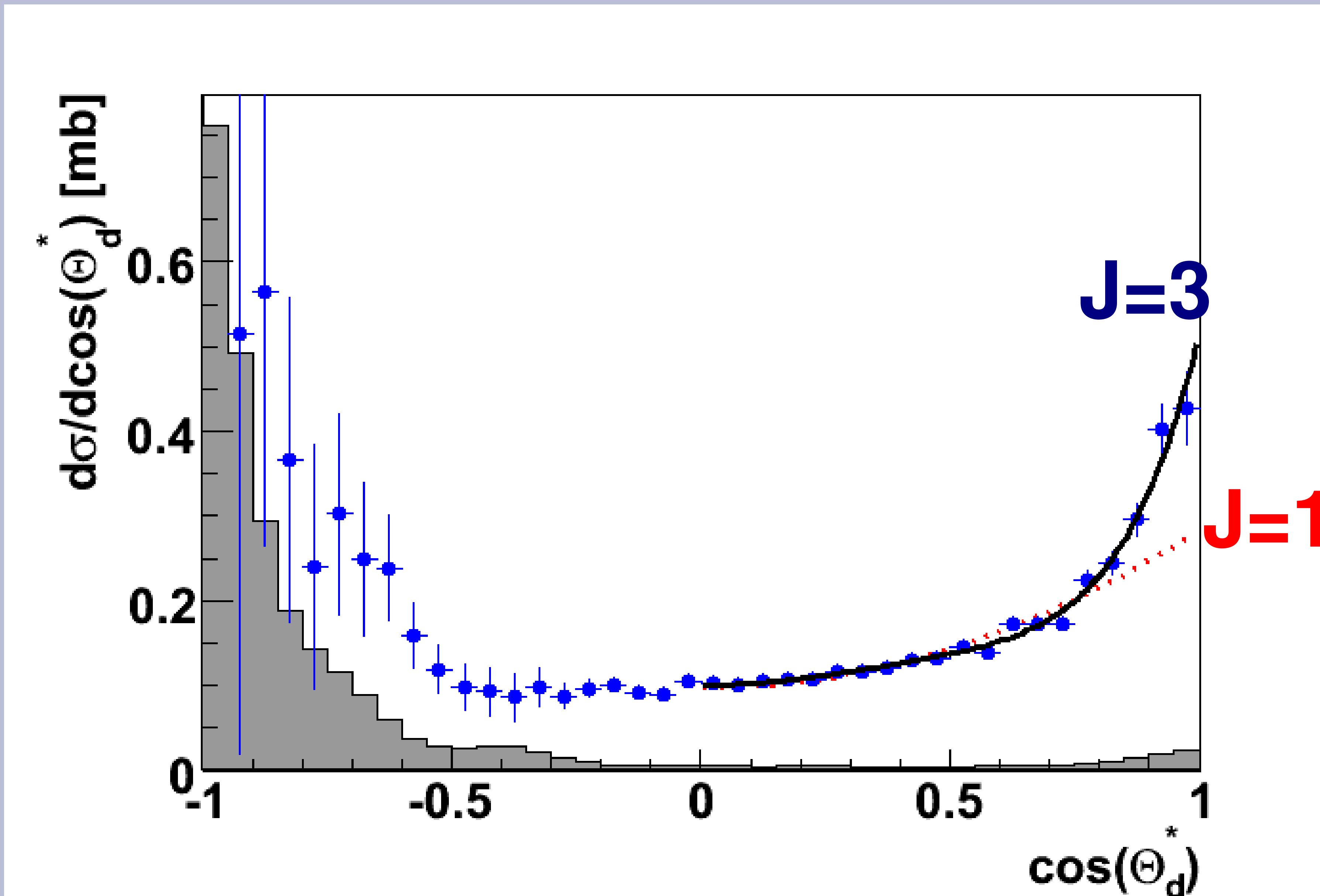


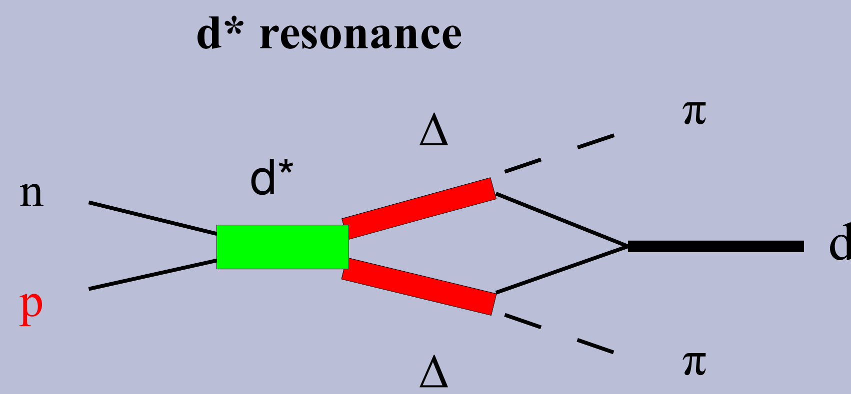
P. Adlarson et. al Phys. Rev. Lett. 106:242302, 2011

Angular distribution at the peak cross-setion (sqrt(s) = 2.38 GeV)



P. Adlarson et. al Phys. Rev. Lett. 106:242302, 2011

d*(2380) properties



$M_{d*} \approx 2380$ MeV $\approx M_{\Delta\Delta}$ - 80 MeV

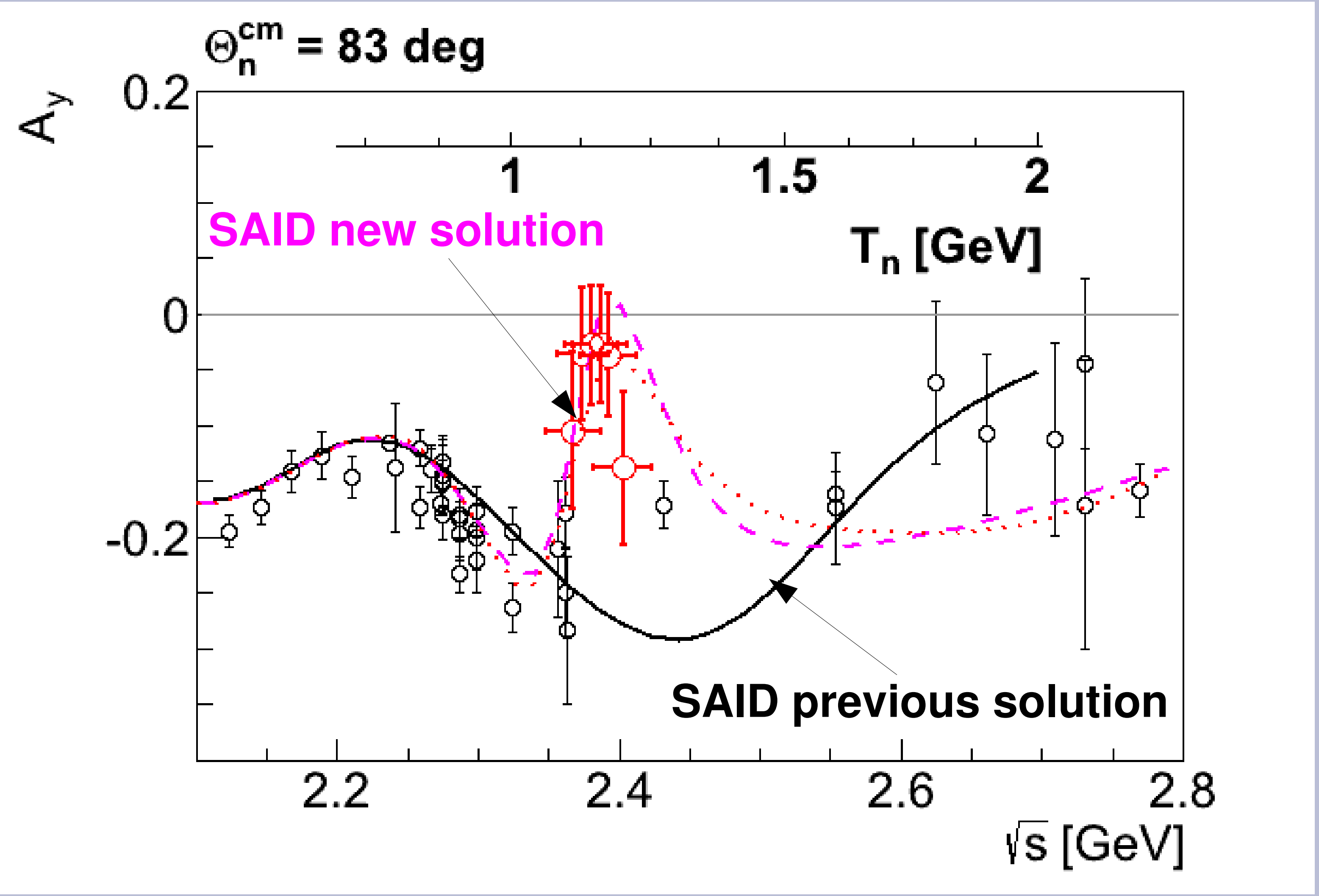
$\Gamma_{d*} \approx 70$ MeV $\ll \Gamma_{\Delta\Delta} = 240$ MeV

$I(J^P) = 0(3^+)$

Energy dependence of np analysing power

$\vec{n}p \longrightarrow d^* \longrightarrow pn$

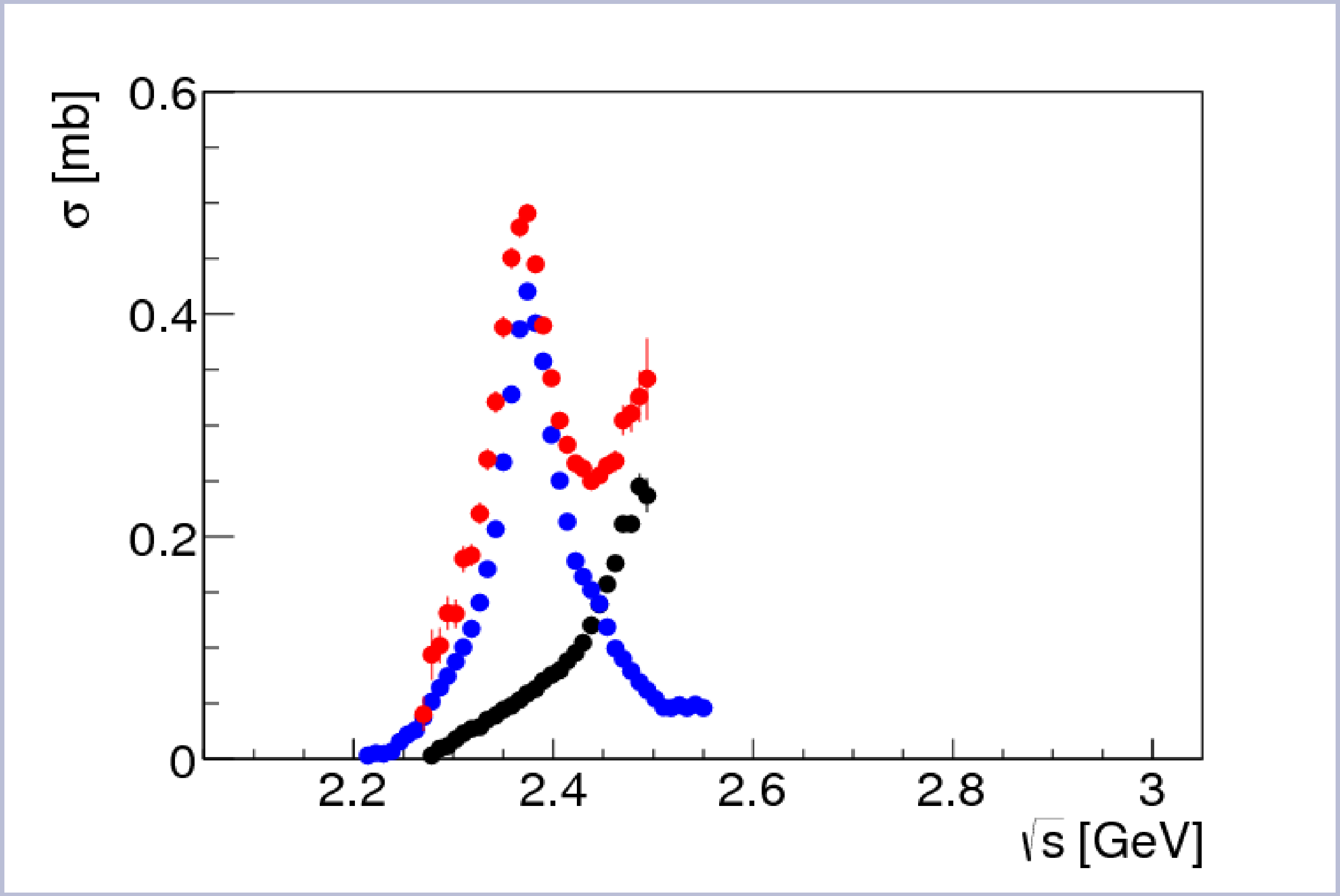
pole (2380±10 - i40±5) MeV



P. Adlarson et al. Phys. Rev. Lett. **112**, 202301, (2014)

$pn \rightarrow d\pi^+\pi^-$ (isospin I= 0 and 1)

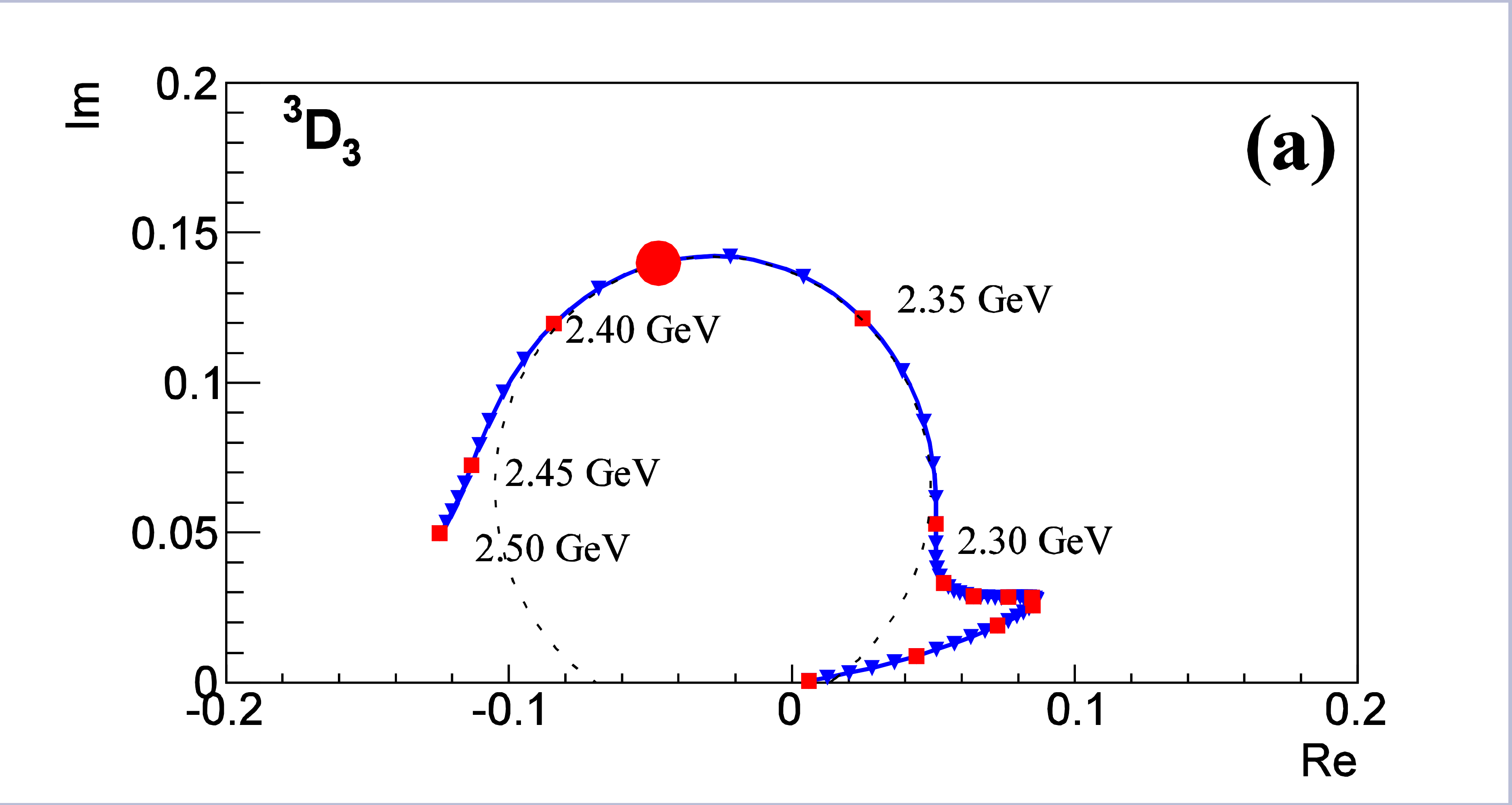
$$\sigma(pn \rightarrow d\pi^+\pi^-) = 2\,\overbrace{\sigma(pn \rightarrow d\pi^0\pi^0)}^{I=0} + \frac{1}{2}\,\overbrace{\sigma(pp \rightarrow d\pi^+\pi^0)}^{I=1}$$



- $pn \rightarrow d\pi^-\pi^+$
- $pn \rightarrow d\pi^0\pi^0$
- $pp \rightarrow d\pi^+\pi^0$

P. Adlarson et. al Phys. Lett. B721 (2013) 229

Argand plot

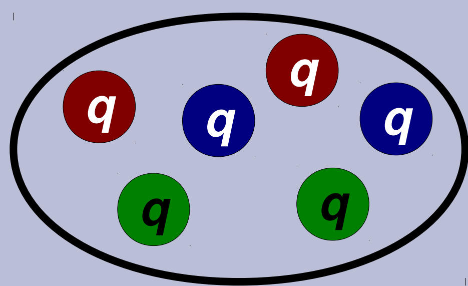


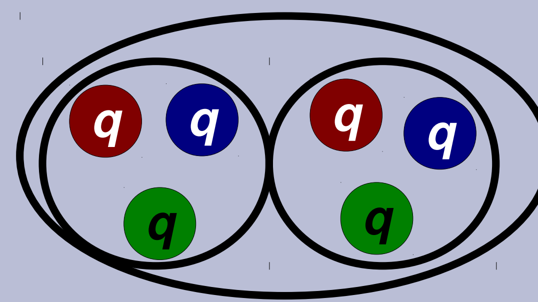
P. Adlarson et al. Phys. Rev. Lett. **112**, 202301, (2014)
P. Adlarson et al. Phys. Rev. C **90**, 035204 , (2014)

Dibaryon decay branches

Channel	Publications
d $\pi^0\pi^0$	**P. Adlarson et al., Phys. Rev. Lett. 106 (2011) 242302** P. Adlarson et al., Phys. Lett. B721 (2013) 229-236 P. Adlarson et al., Eur. Phys. J. A52 (2016) 147
d $\pi^+\pi^-$ **d $\pi^+\pi^0$**	P. Adlarson et al., Phys. Lett. B721 (2013) 229-236
pp$\pi^0\pi^-$	P. Adlarson et al., Phys. Rev. C 88 (2013) 055208
np$\pi^0\pi^0$	P. Adlarson et al., Phys. Lett. B743 (2015) 325-332
np	**P. Adlarson et al., Phys. Rev. Lett. 112 (2014) 202301** P. Adlarson et al., Phys. Rev. C**90** (2014) 035204
^{3}He $\pi\pi$	P. Adlarson et al., Phys. Rev. C91 (2015) 015201
^{4}He $\pi\pi$	P. Adlarson et al., Phys. Rev. C86 (2012) 032201

d*(2380) – hexaquark or molecule ?



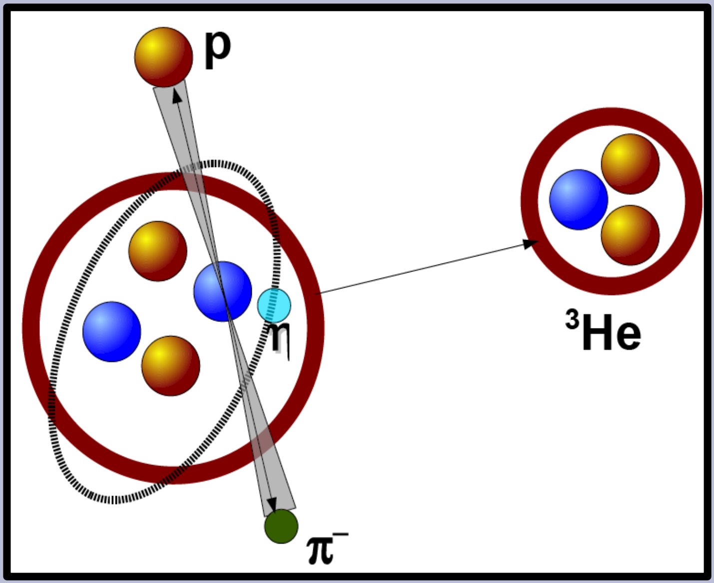


- d* → ΔΔ ~ 88 %
- d* → pn ~ 12 %

Many different theoretical models appeared:

- M. Bashkanov, Stanley J. Brodsky, H. Clement Phys.Lett. B727 (2013) 438-442
- F. Huang et al, Chin.Phys. C39 (2015) 7, 071001
- Avraham Gal, Humberto Garcilazo Nucl. Phys. A928, (2014), 73

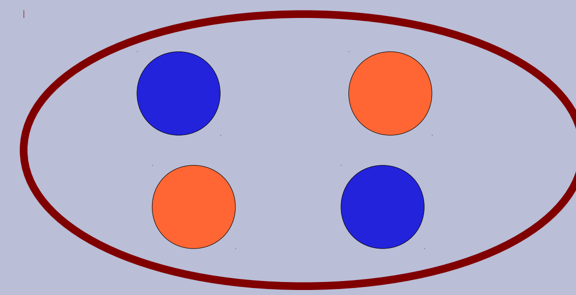
Search for eta-mesic nuclei



„Exotic" systems

Classical nucleus:

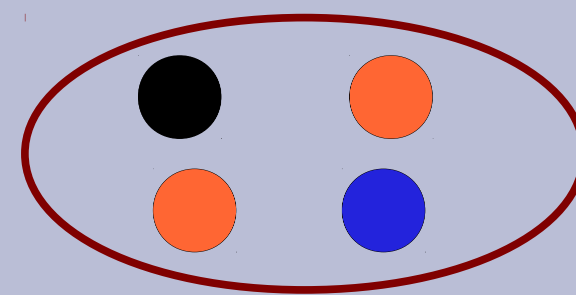
Bound state of nucleons



Hypernuclei:

Bound states of nucleons

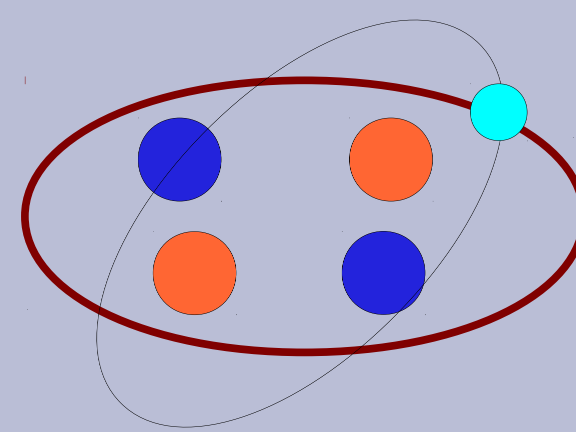
+ hyperion Λ, Σ



Mesic atoms and nuclei:

Bound state of nucleons

+ meson $\pi, K, \eta, \eta', \omega$, ..



η meson

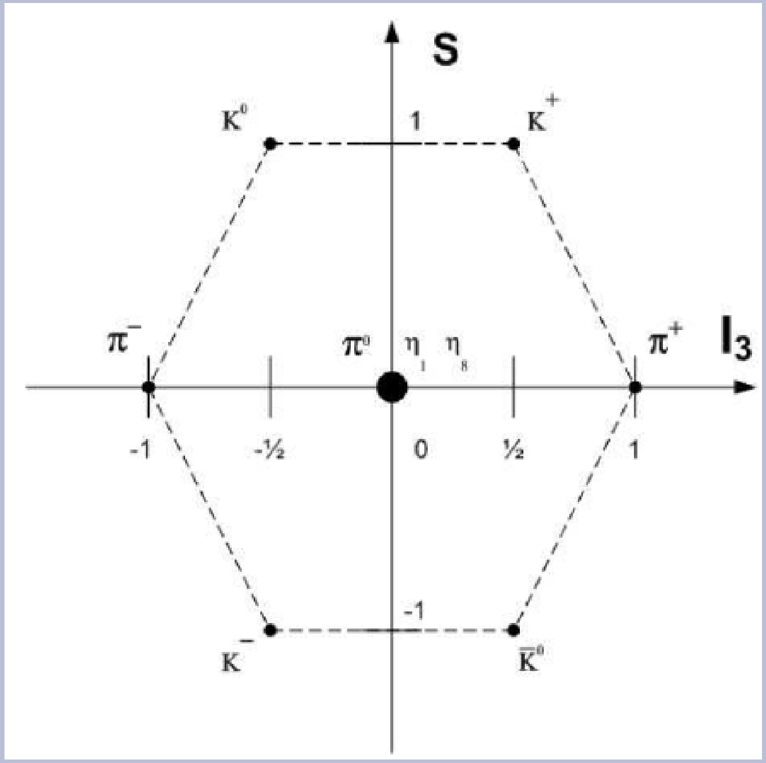
m_η = 547.3 MeV

Γ = 1.18 keV

C |η > = +1 |η >

P |η > = - 1 |η >

t= 10^{-19} s



$$|\eta> = \cos\theta|\eta_8> - \sin\theta|\eta_1>$$

$$|\eta_8> = (d\bar{d} + u\bar{u} - 2s\bar{s})/\sqrt{6},$$

$$|\eta_1> = (d\bar{d} + u\bar{u} + s\bar{s})/\sqrt{3}$$

Mixing angle θ ~ -15 degree

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

(2 and 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 interaction with nucleon

$$0.18\,fm \le \mathrm{Re}\, a_{\eta N} \le 1.03\,fm$$
$$0.16\,fm \le \mathrm{Im}\, a_{\eta N} \le 0.49\,fm$$

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

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

Recent review:

B. Krusche, C. Wilkin Progress in Particle and Nuclear Physics 80 (2015) 43

η interaction with nucleon

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

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

m = 1535 MeV

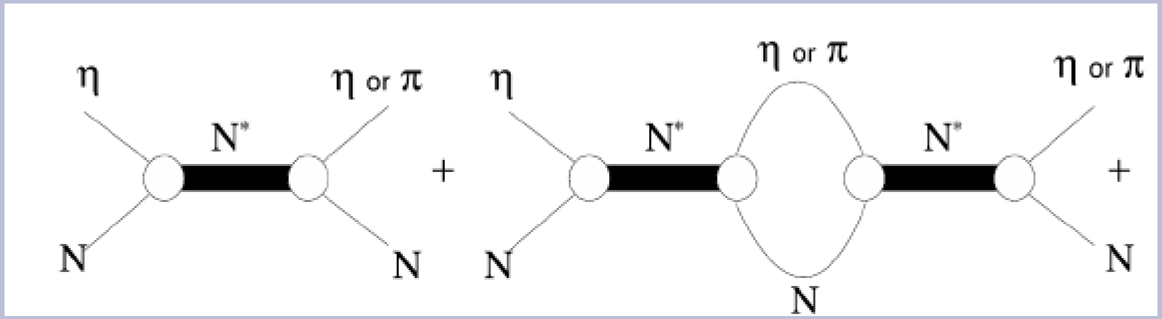
Γ = 150 MeV

Main decay channels:

$N^* \rightarrow \pi N$ ~ 35-55 %

$N^* \rightarrow \eta N$ ~ 30-55 %

$N^* \rightarrow \pi \pi N$ ~ 1-10 %

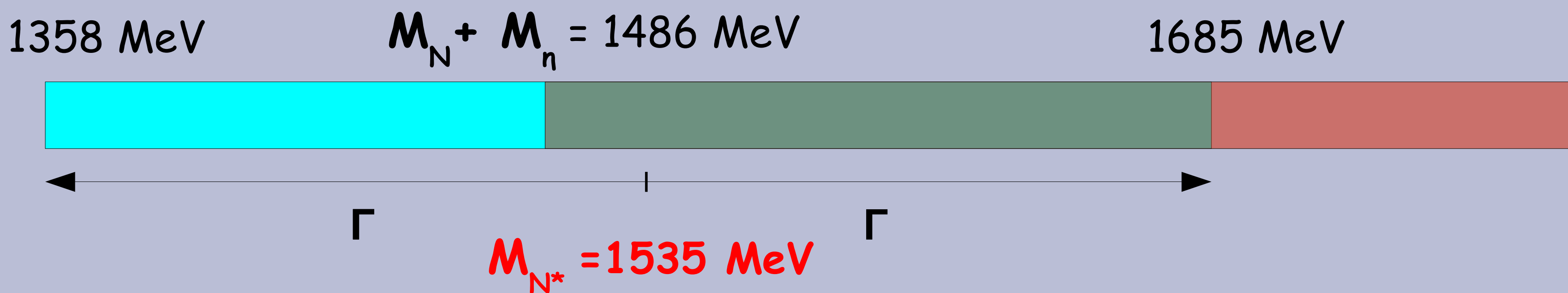


Attractive η-N interaction

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

η interaction with nucleon

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



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

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

η-mesic nucleus = only strong interaction

For recent calculations see:

E. Friedman, A. Gal and J. Mares, Phys. Lett. B725 (2013) 334.
Q. Haider, L. C. Liu, Int. J. Mod. Phys. E24 (2015) 1530009

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)*)

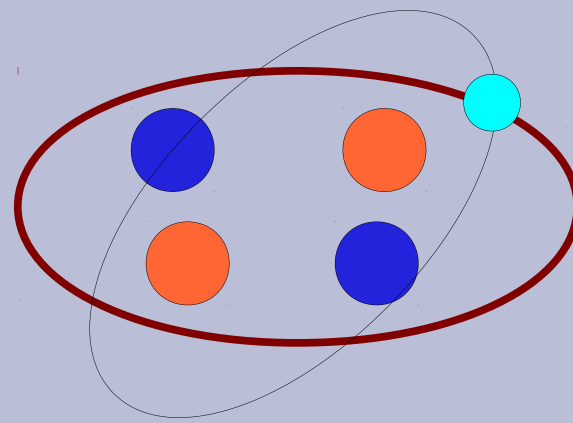
- **Study of in-medium properties of N*(1535) resonance:**

  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

η bound states with light nuclei

C. Wilkin, Phys. Rev. C47 (1993) 938



Supported by model calculations of:

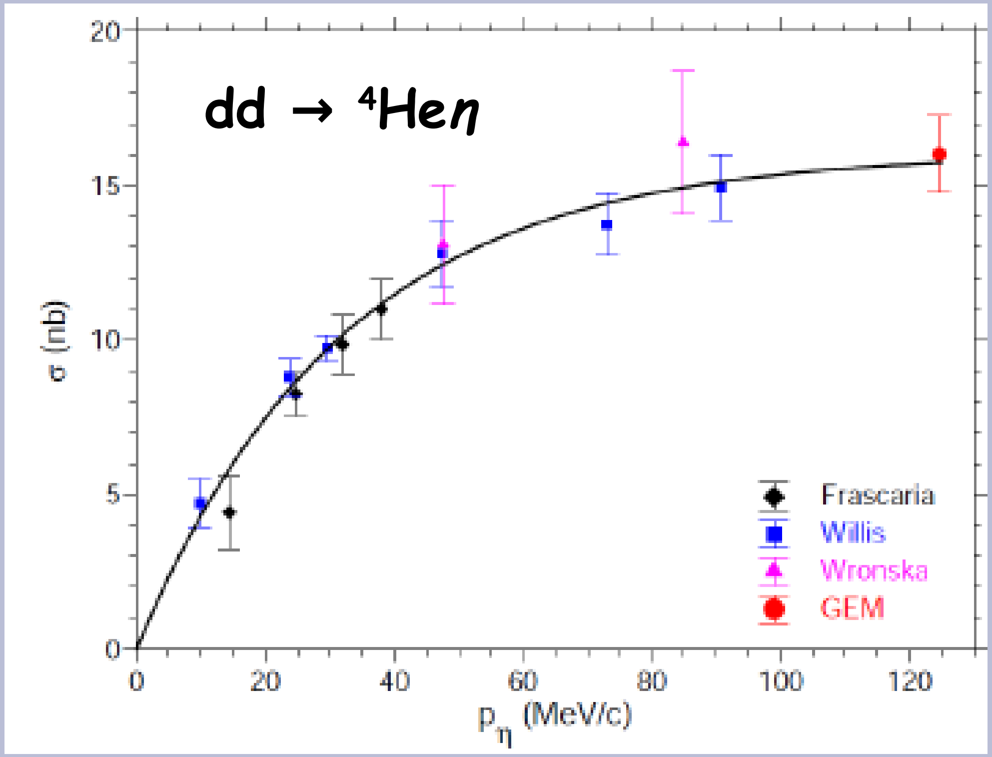
- S. Wycech et al., Phys. Rev. C52(1995)544

(multiple scattering theory)

η-nuclear bound states revisited:

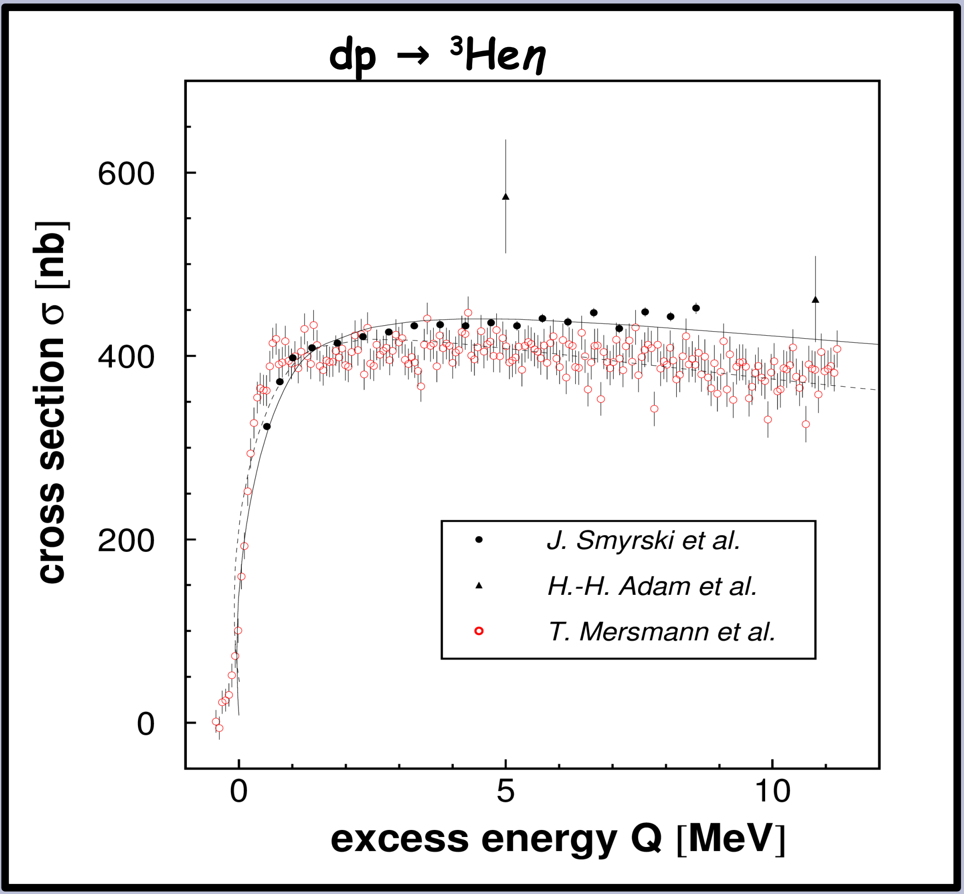
- E. Friedman, A. Gal, J. Mares Physics Letters B 725 (2013) 334-338
- Q. Haider, L. C. Liu, Int. J. Mod. Phys. E24 (2015) 1530009
- H. Machner, J. Phys. G42 (2015) 043001
- N. Barnea, E. Friedman, A. Gal Phys. Lett. B 747 (2015) 345-350

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

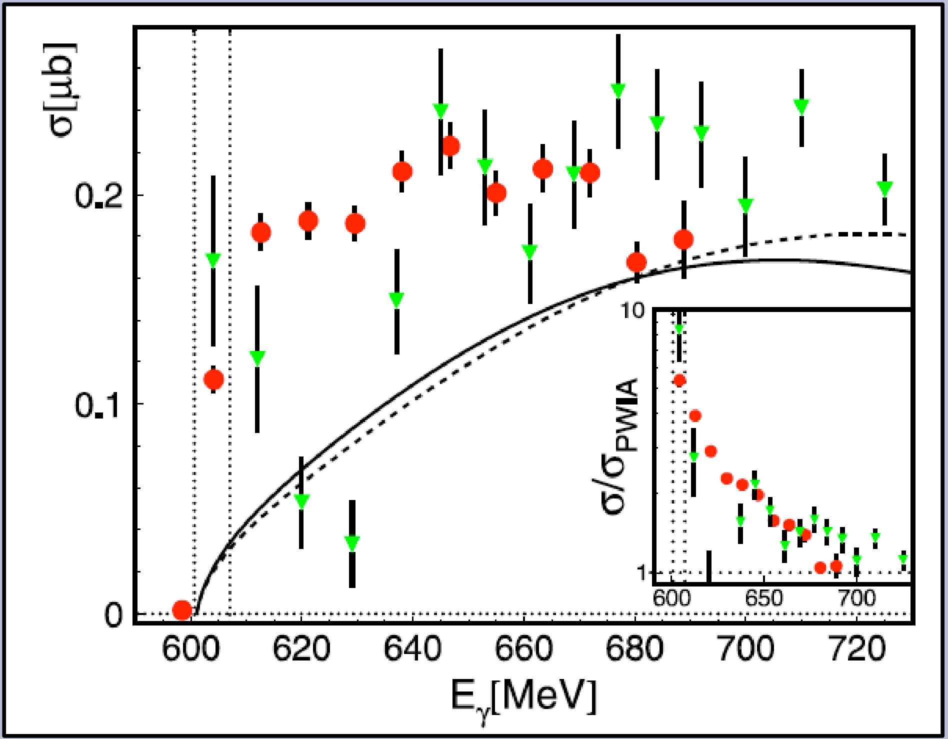


R. Frascaria et al., Phys. Rev. C 50 (1994) 573.
N. Willis et al., Phys. Lett. B 406 (1997) 14.
A. Wrońska et al., Eur.Phys.J. A26 (2005) 421-428.
A. Budzanowski et al., Nucl. Phys. A821, (2009) 193.

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



γ^3He→ η^3He



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)

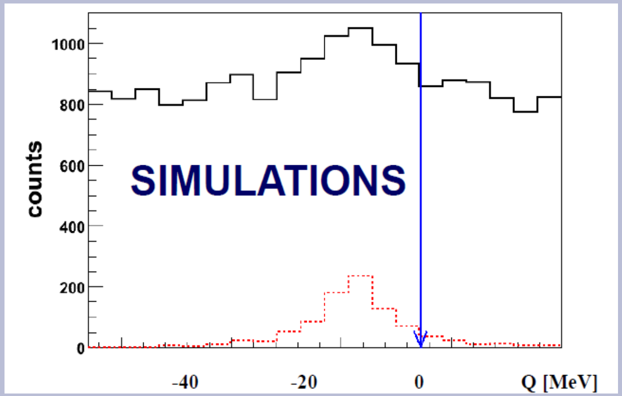
F. Pheron et al., Phys. Lett. **B709** 21 (2012)

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

How to look for bound states

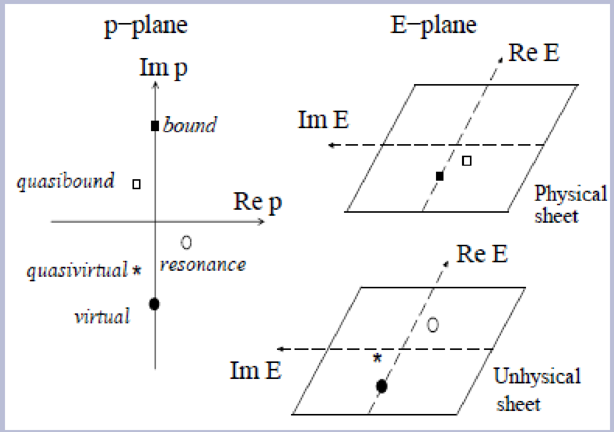
- **Direct method:**

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

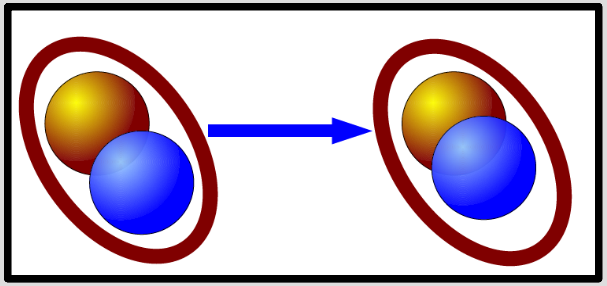


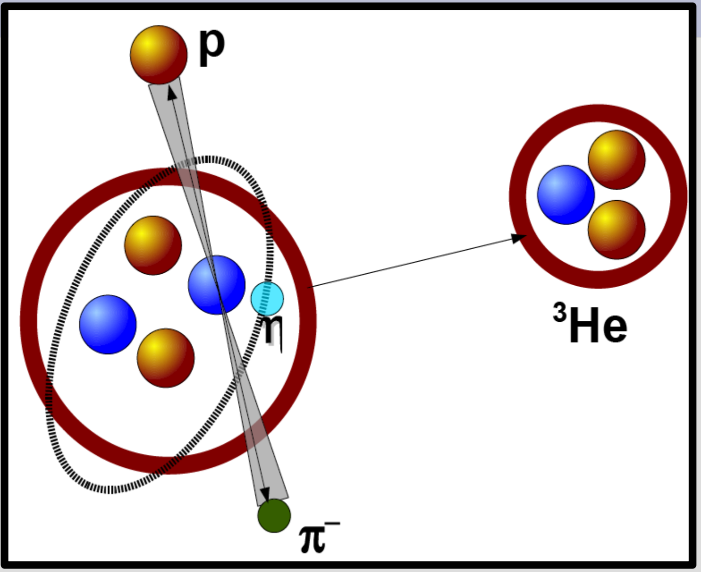
- **Indirect methods:**

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

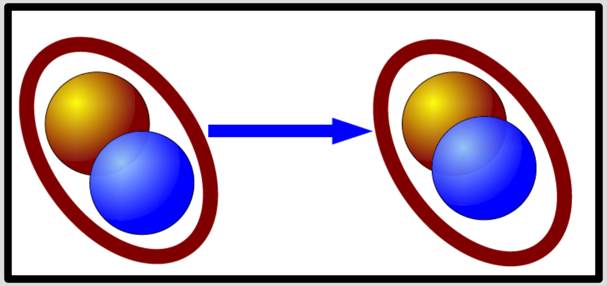


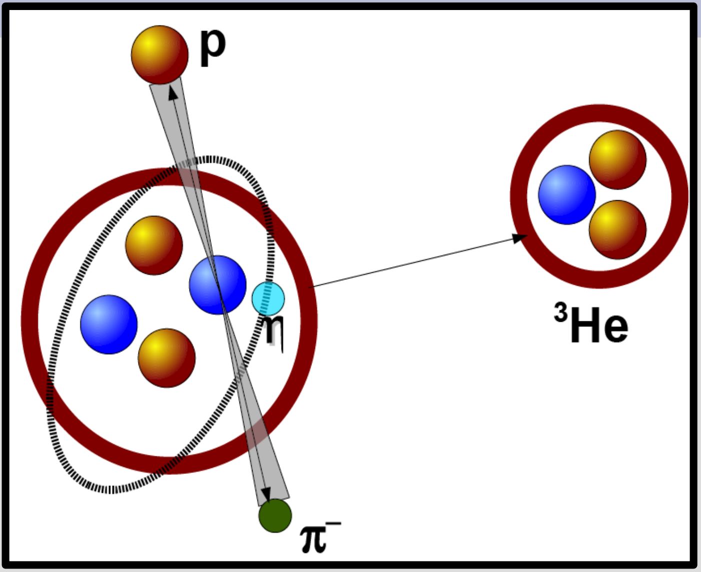
$dd \rightarrow (\eta\text{-}^4He)_{bound} \rightarrow N + \pi + {}^3He$





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

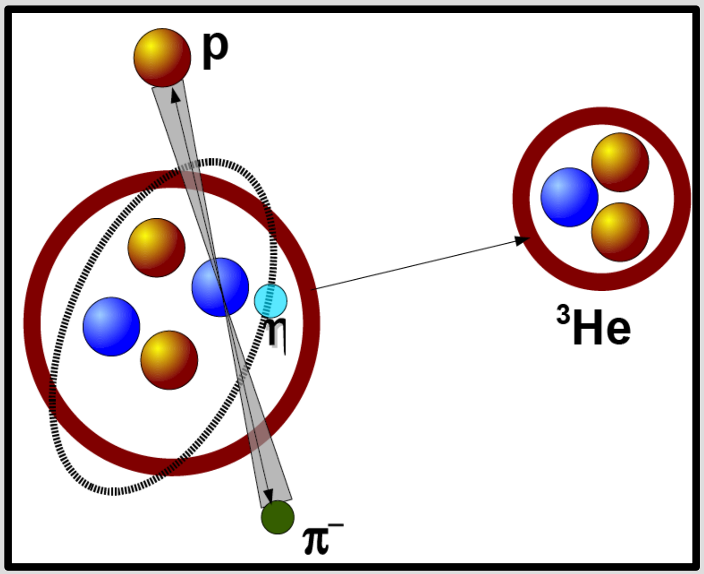


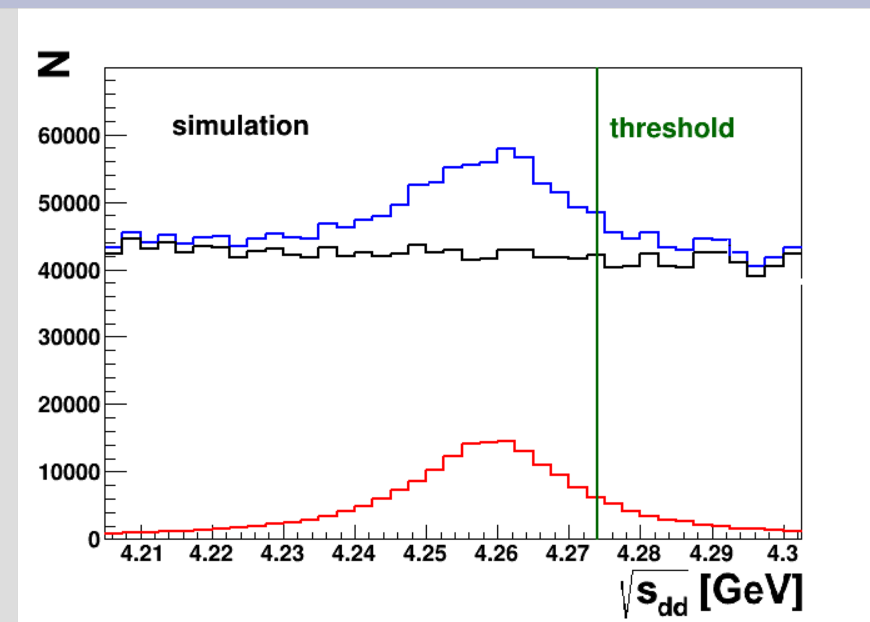


η + N → N*(1535) → N + π

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

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





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

Search for a resonance-like structure with maximum below the η-^{4}He production threshold

^{4}He η experiments

June 2008

Channels: ^{3}He n

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

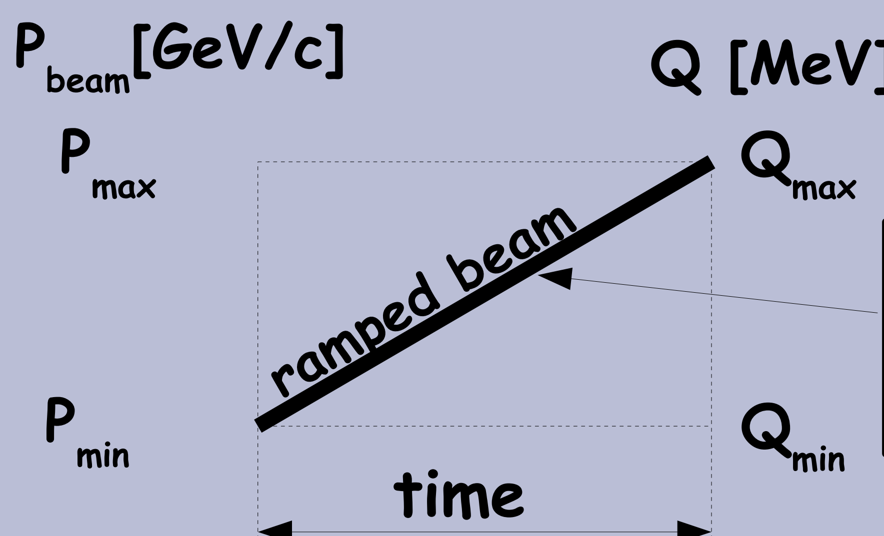
Normalization:

$dd \rightarrow {}^3$He n

Q: -70 to 30 MeV

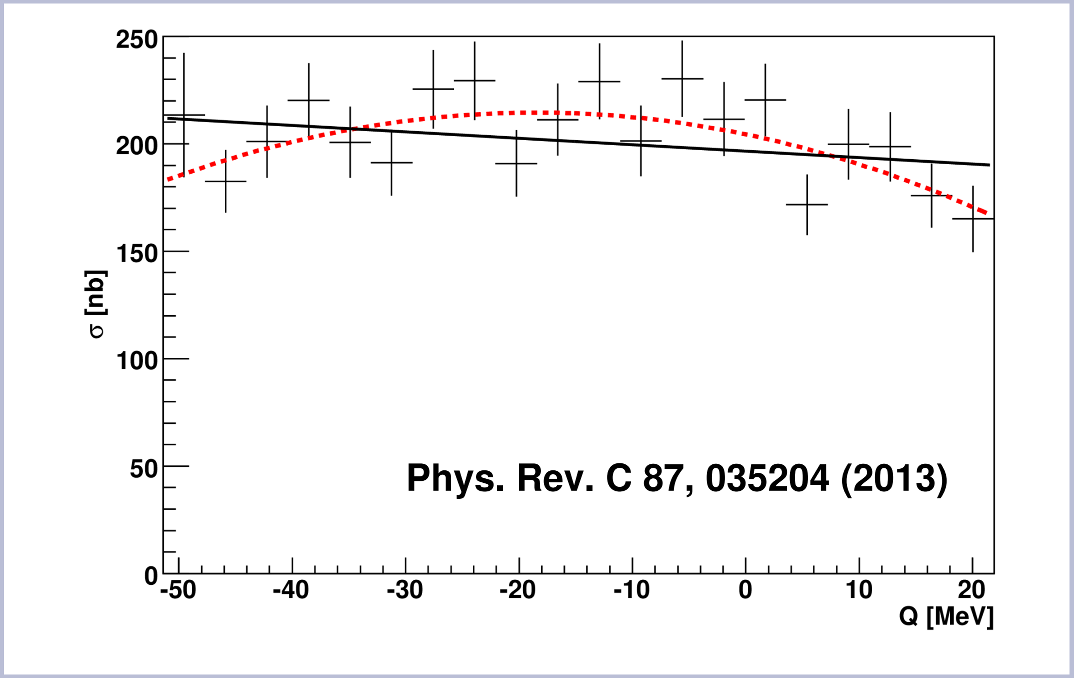
P: 2.127 to 2.422 GeV/c

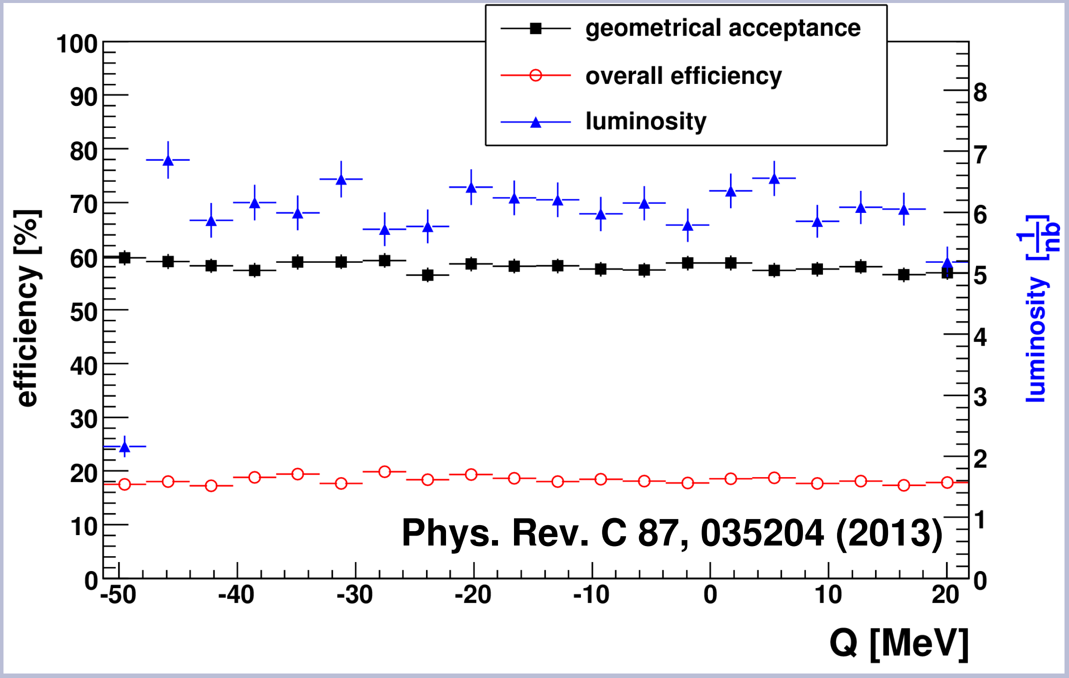
~20 x more statistics



Unique COSY accelerator feature

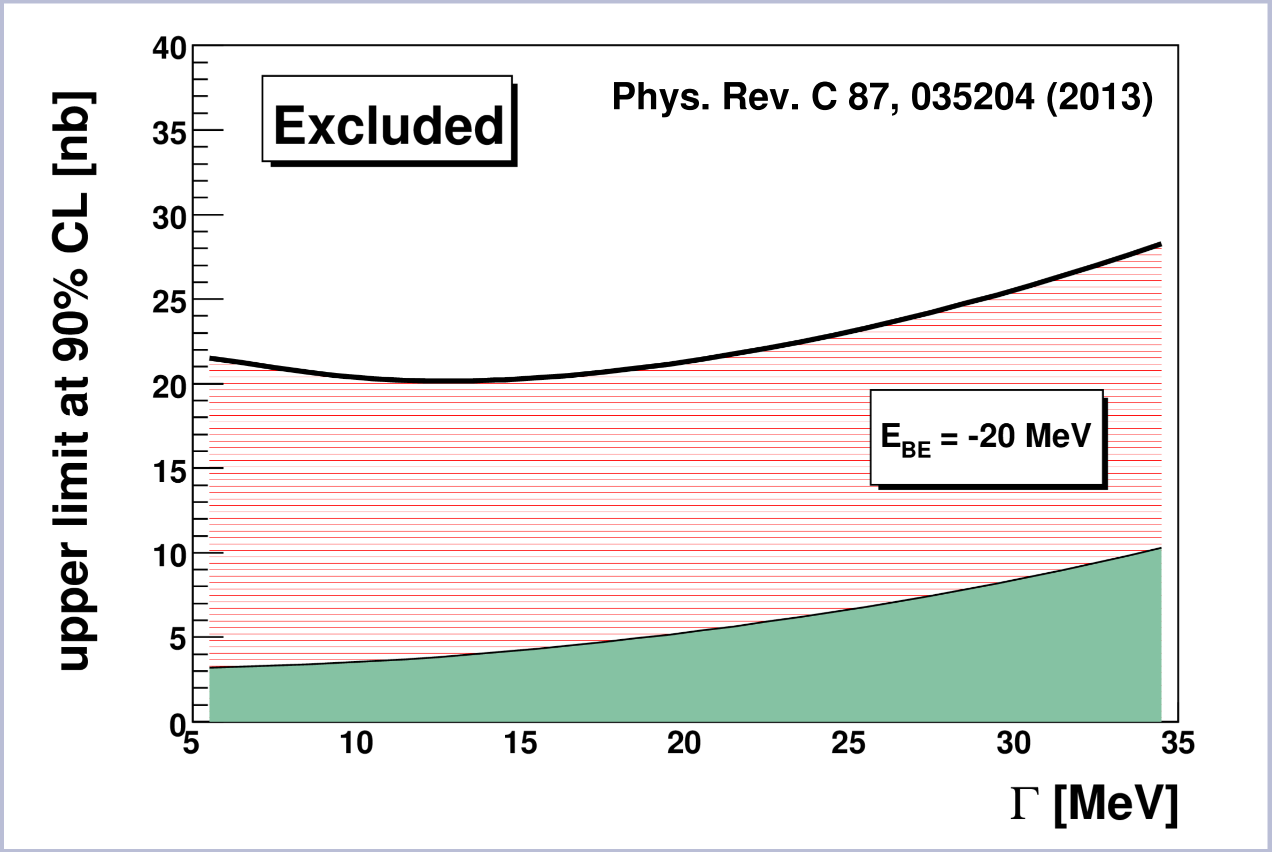
Excitation function
(normalized and corrected for efficiency)





Upper limit of the maximum cross-section

for the reaction $dd \rightarrow (^4He - \eta)_{bound} \rightarrow {}^3He\, p\, \pi^-$



Signal:

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

Background:

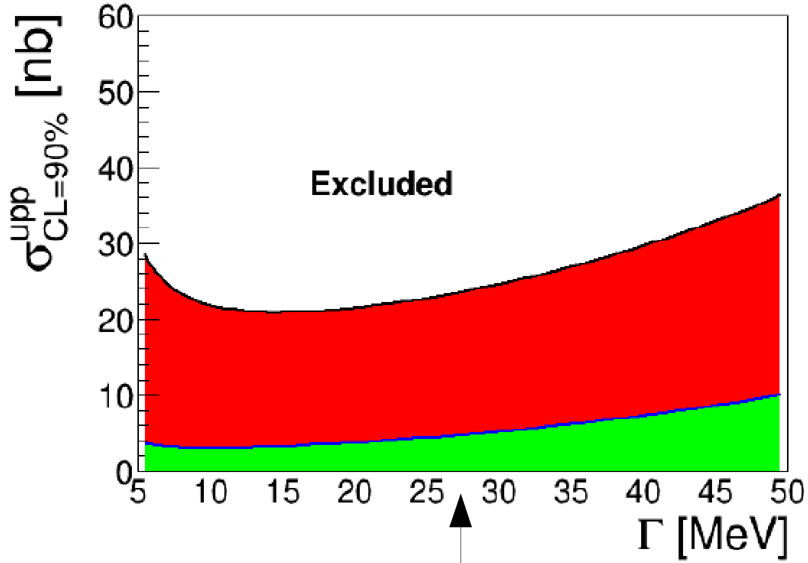
$$BG = a_0 + a_1 Q + a_2 Q^2 \quad \textbf{or} \quad BG = a_0 + a_1 Q$$

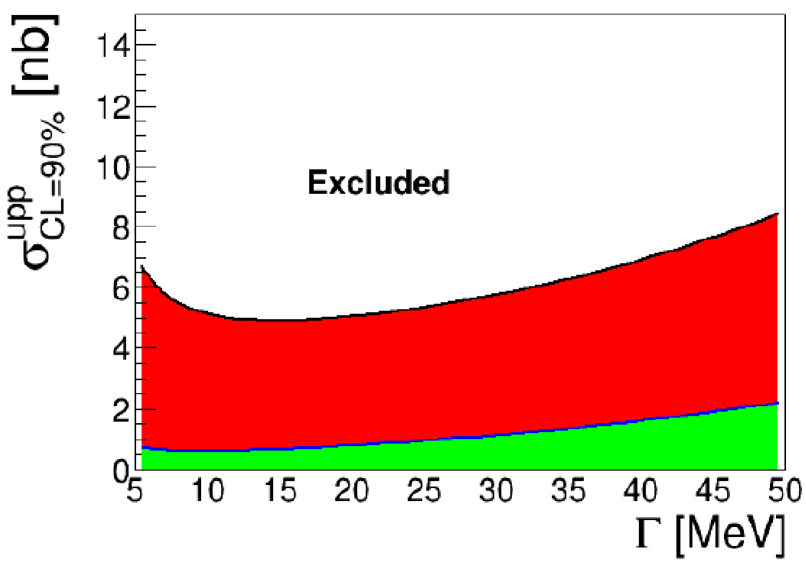
Upper limit of the maximum cross-section for the reaction dd → $(^{4}He - \eta)_{bound}$ → $^{3}He\ N\ \pi$

Upper limit of the total cross section at CL=90%, B_s =30 MeV

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

PRELIMINARY





PhD thesis of Magdalena Skurzok

few nb!

Acta Phys. Polonica B vol.47 (2016)

New experiment in May-June 2014

May-June 2014

Channels:

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

p+d → $(^3He-\eta)_{bound}$ → d + p + π^0

p+d → $(^3He-\eta)_{bound}$ → p + p + n + π^0

Non-resonant decays (on 2 N):

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

p+d → $(^3He-\eta)_{bound}$ → p + dw

Orbiting eta:

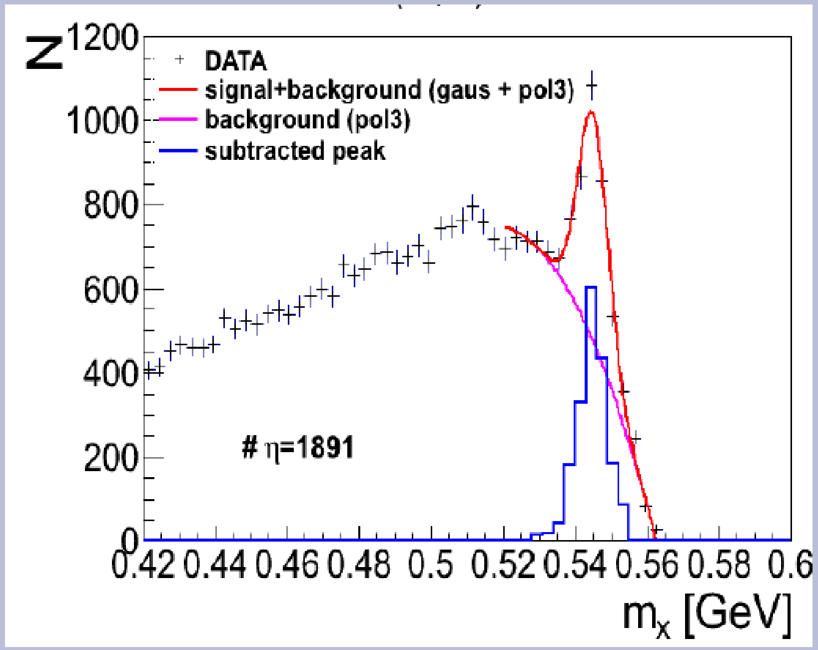
p+d → $(^3He-\eta)_{bound}$ → ^3He 6γ

Normalization:

pd → ^3He η

pd → ^3He π^{0w}

Test plot from experiment



Q: -50 to 20 MeV

P: 1468 to 1615 MeV/c

PhD theses of Oleksandr Khreptak & Oleksandr Rundel (work ongoing)

Predictions for He system

η - ^{4}He

~ 6 nb -- Present preliminary experimental upper limit

~ 4 nb -- Theoretical estimation

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

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) 60

~ 10nb -- expected from New WASA-at-COSY data collected in May 2014

Conclusions

Dibaryon discovery

- A resonance structure at **2380 MeV** in the total cross-section of $p+n \rightarrow d\pi^0\pi^0$ reaction
- Confirmed by the SAID partial wave analysis of np elastic scattering: **2380 ± 10-i40±5 MeV**
- WASA has intensively studied the d* in many different processes,
- Upper limits for the the mirror partner of d*: $3(0^+)$ - $p+p \rightarrow pp\ \pi^+\pi^-\pi^+\pi^-$ **(*accepted in PLB*),**
- Further measurements to determine the d*(2380) internal structure planned at MAMI and JLAB,

Conclusions

Dibaryon discovery

- A resonance structure at **2380 MeV** in the total cross-section of **$p+n \rightarrow d\pi^0\pi^0$** reaction
- Confirmed by the SAID partial wave analysis of np elastic scattering: **2380 ± 10-i40±5 MeV**
- WASA has intensively studied the d* in many different processes,
- Upper limits for the the mirror partner of d*: $3(0^+)$ - **$p+p \rightarrow pp\ \pi^+\pi^-\pi^+\pi^-$** **(*accepted in PLB*)**,
- Further measurements to determine the d*(2380) internal structure planned at MAMI and JLAB,

---

Can eta form a bound state with a nucleus ?

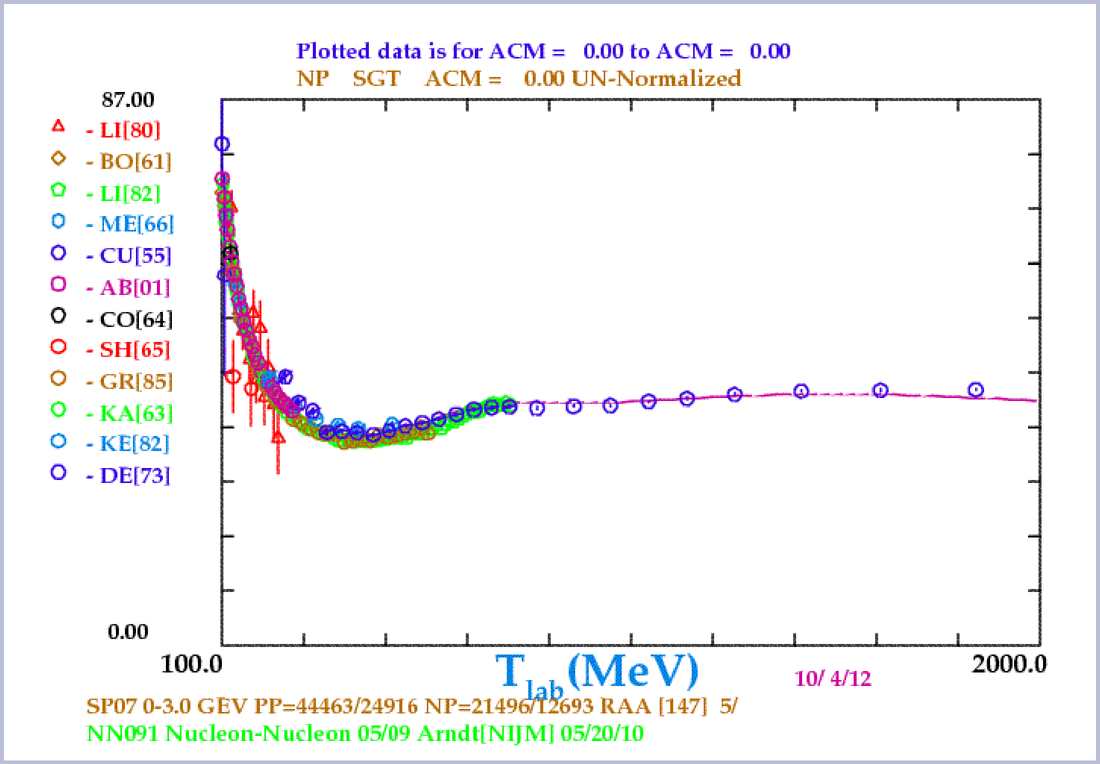
- η-mesic nuclei not unequivocally confirmed experimentally so far,
- Search for a light mesic nuclei in **η-^{3}He** and **η-^{4}He** systems with WASA-at-COSY:

Exclusive, high-acceptance measurement with **ramped beam**,

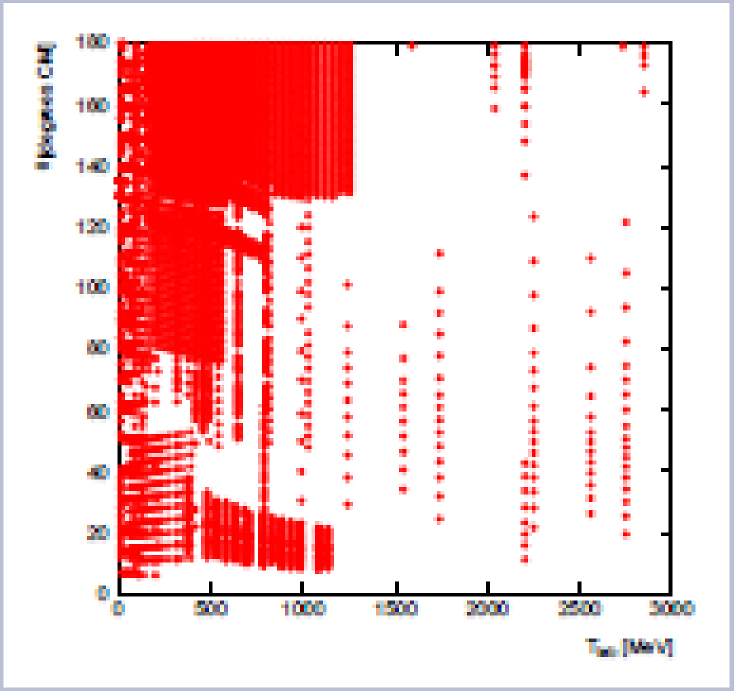
- New data set (η-^{3}He) with perspectives to lower the current upper limit **~ 30 times**, Thank you for your attention

Backup slides

pn data



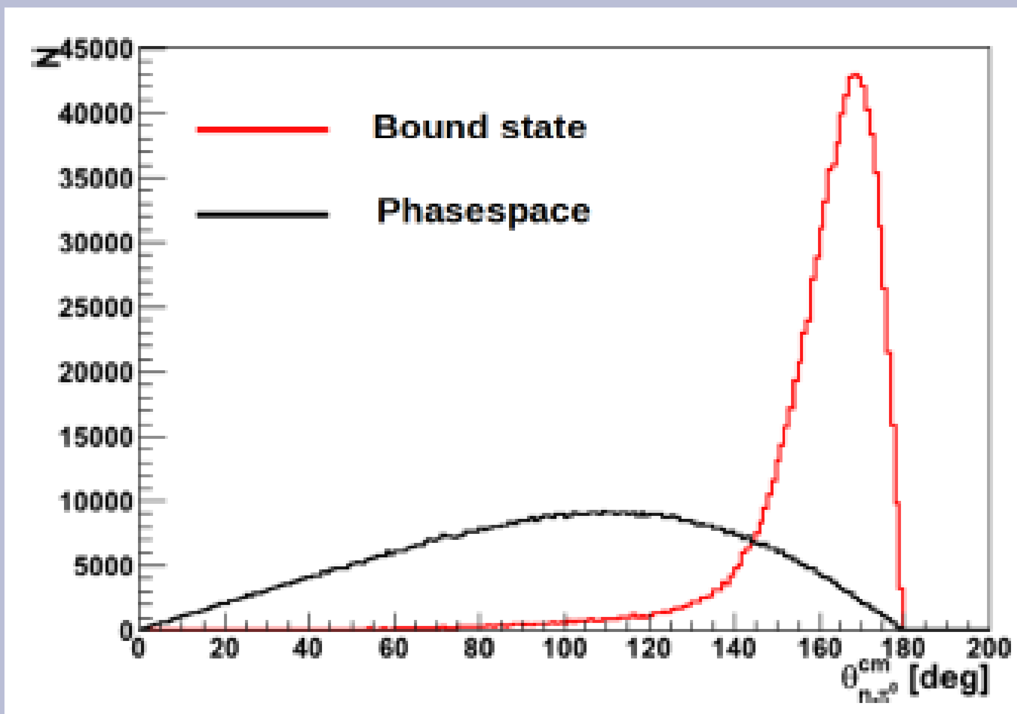
Plotted data is for ACM =   0.00 to ACM =   0.00
NP   SGT   ACM =   0.00 UN-Normalized
87.00
- LI[80]
- BO[61]
- LI[82]
- ME[66]
- CU[55]
- AB[01]
- CO[64]
- SH[65]
- GR[85]
- KA[63]
- KE[82]
- DE[73]
0.00
100.0
T_{lab} (MeV)
10/ 4/12
2000.0
SP07 0-3.0 GEV PP=44463/24916 NP=21496/12693 RAA [147] 5/
NN091 Nucleon-Nucleon 05/09 Arndt[NIJM] 05/20/10



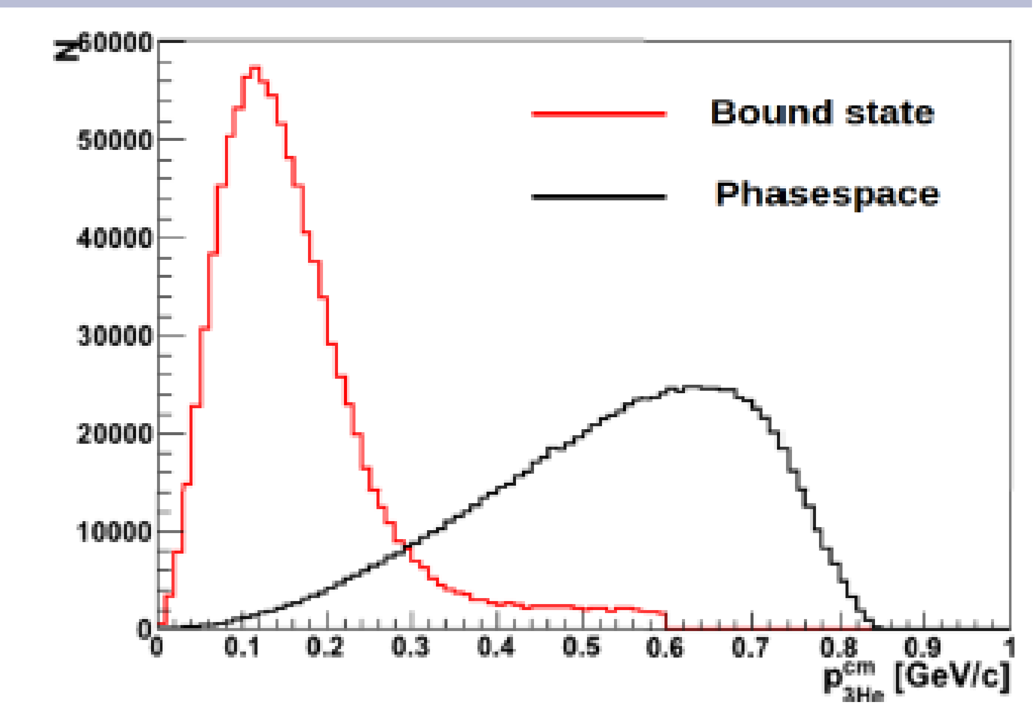
0
20
40
60
80
100
120
140
160
180
0
500
1000
1500
2000
2500
3000

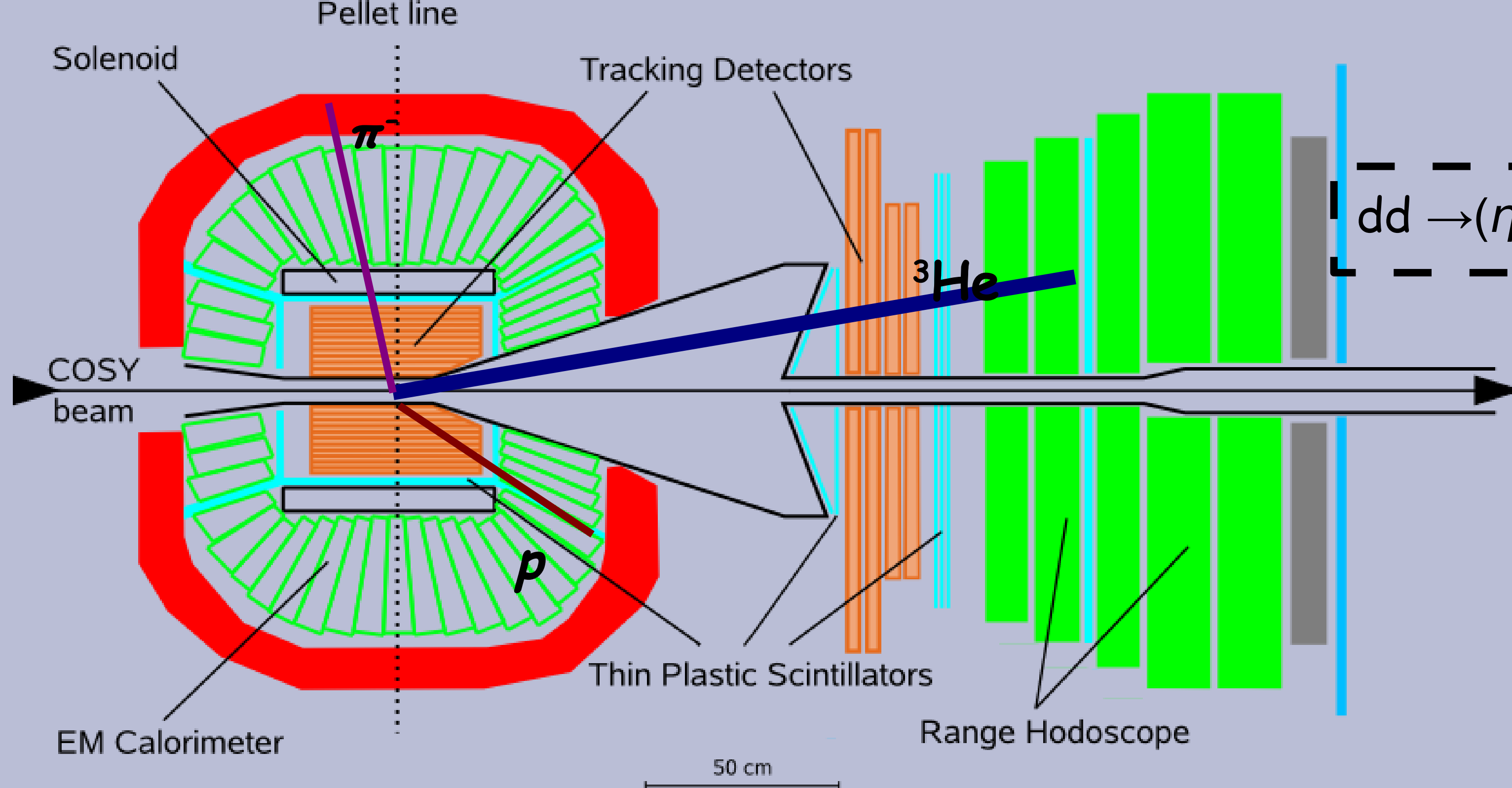
Signatures of the bound state

p-π^- opening angle in the CM frame



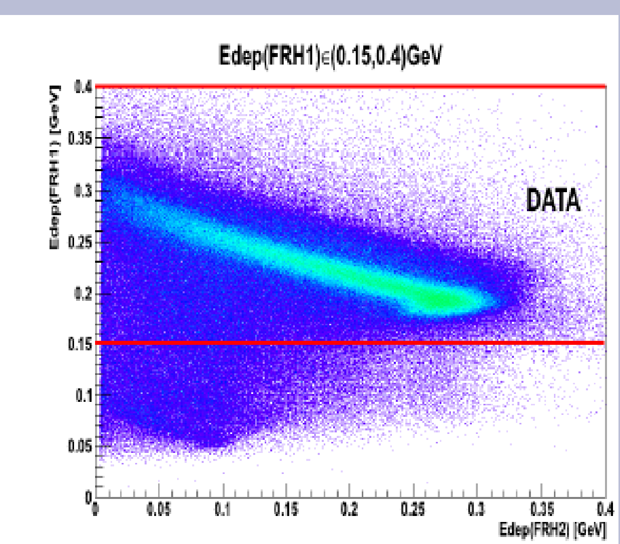
^{3}He momentum in the CM frame

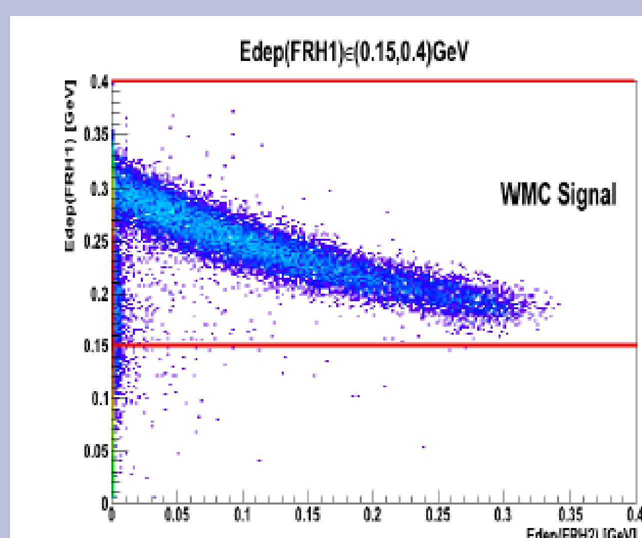


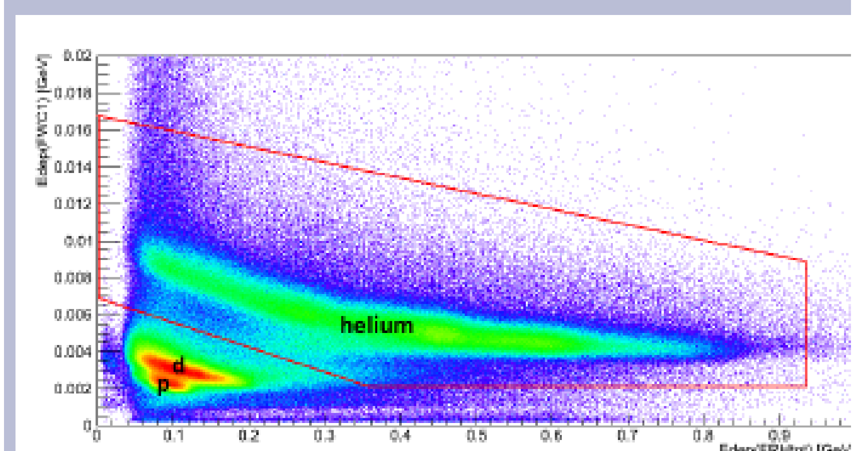


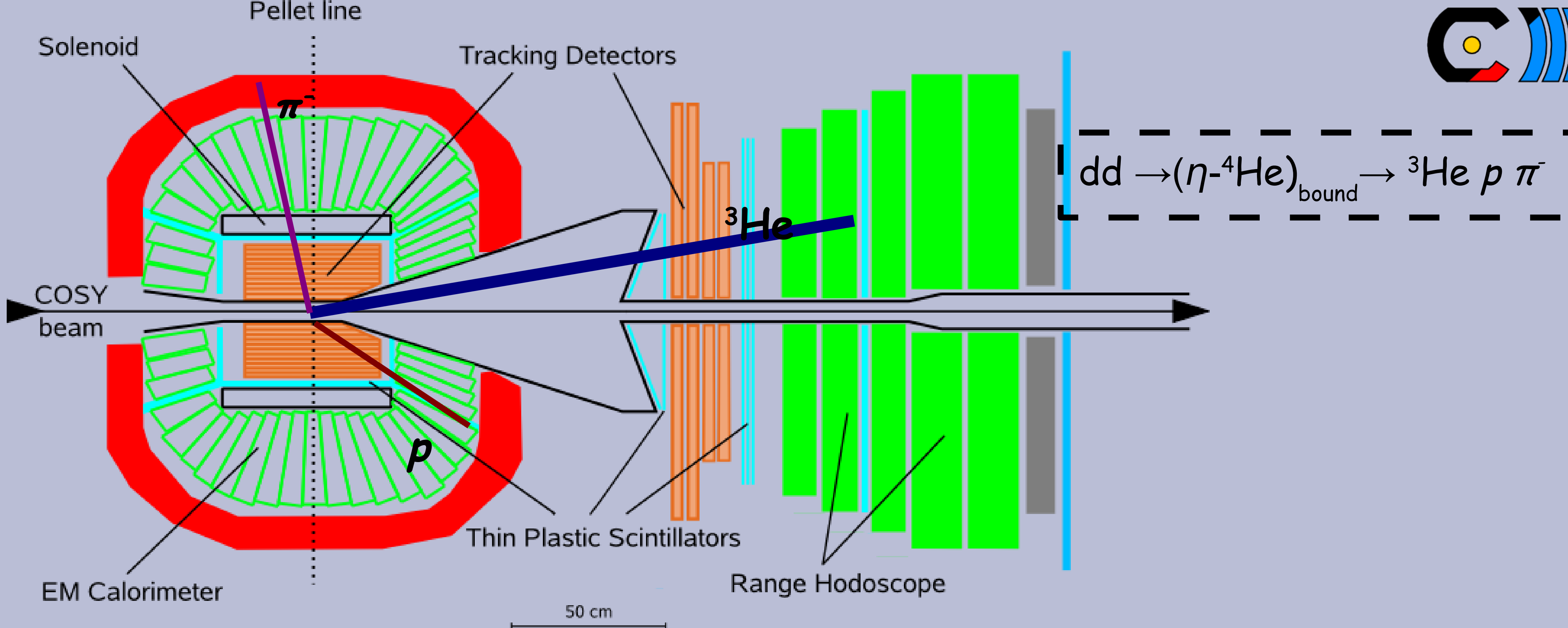
$dd \rightarrow (\eta\text{-}^4He)_{bound} \rightarrow {}^3He\ p\ \pi^-$

^{3}He ions identification in Forward Detector (ΔE -ΔE and ΔE -E methods)

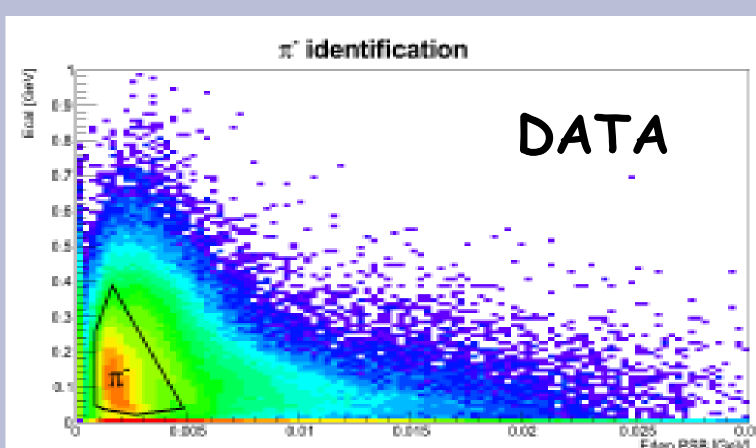


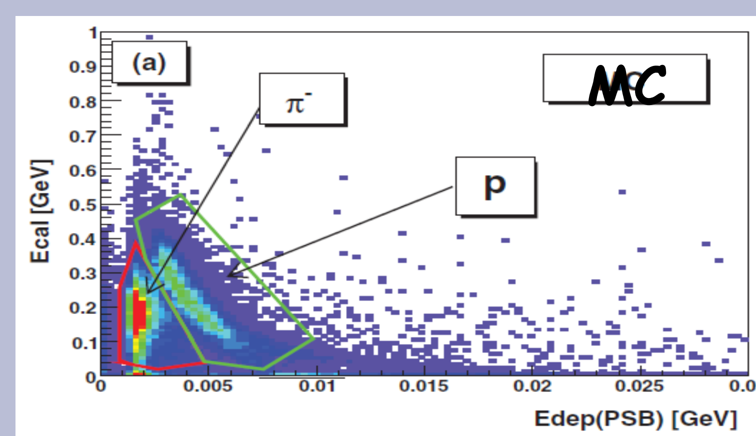


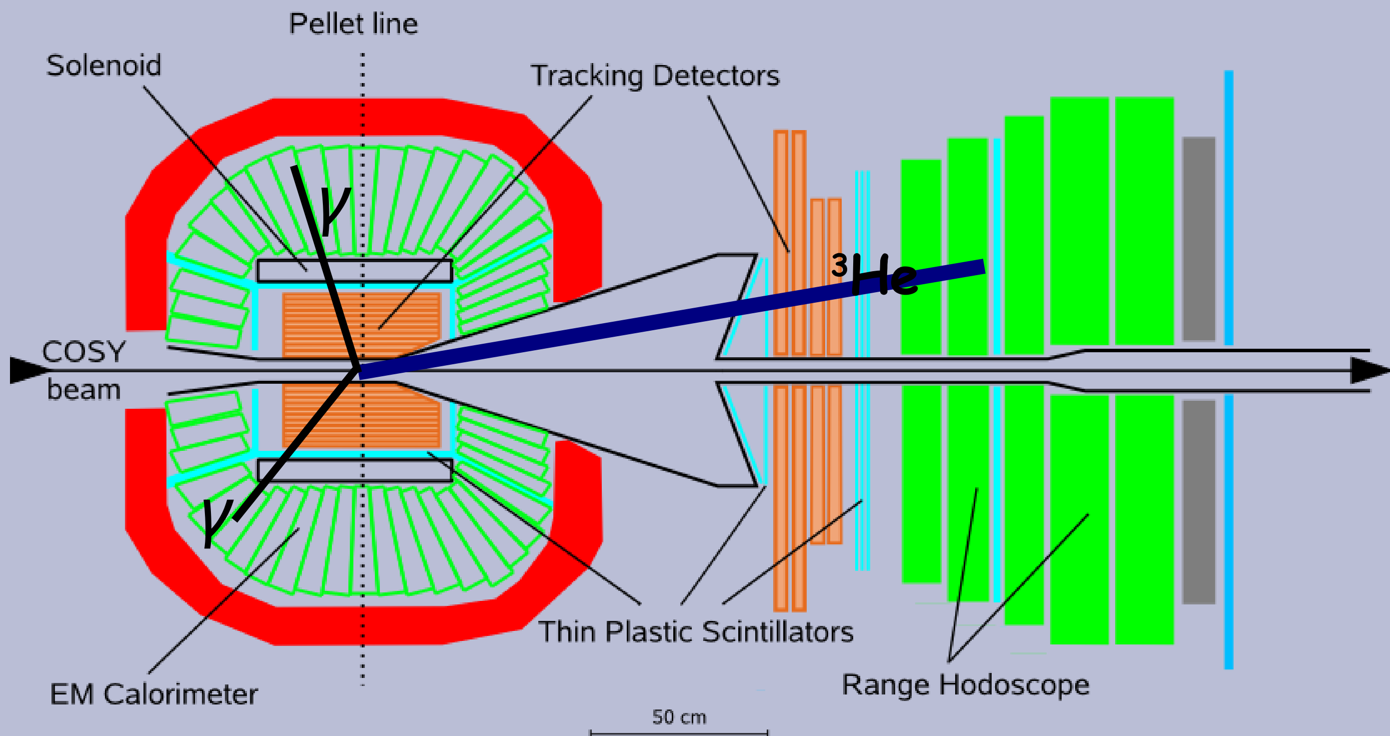




Pion identification in the Central Detector

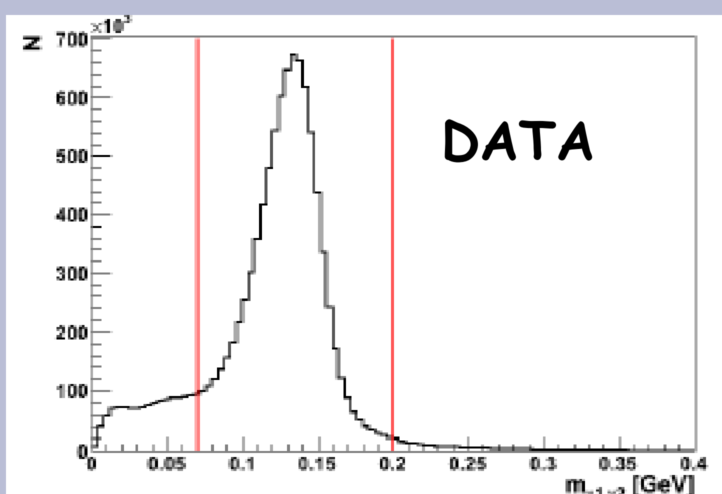


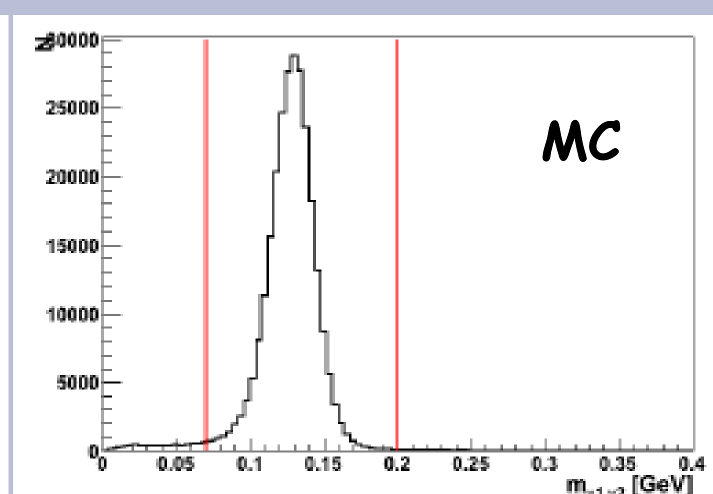


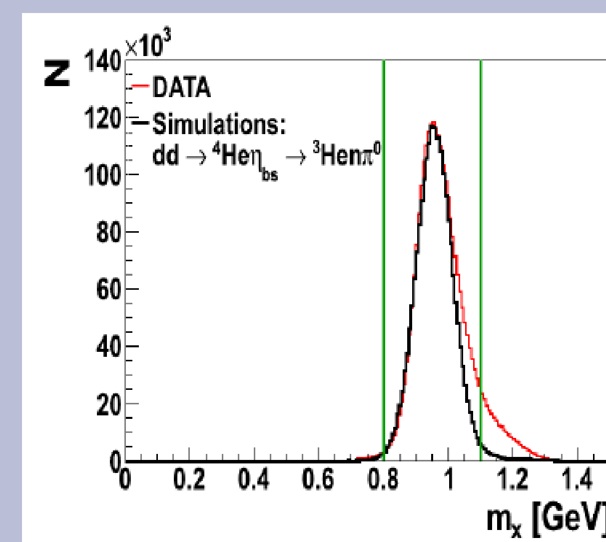


$dd \rightarrow (\eta\text{-}^{4}He)_{bound} \rightarrow {}^{3}He\ n\ \pi^{0}$
$\rightarrow {}^{3}He\ \gamma\gamma\ (n)$

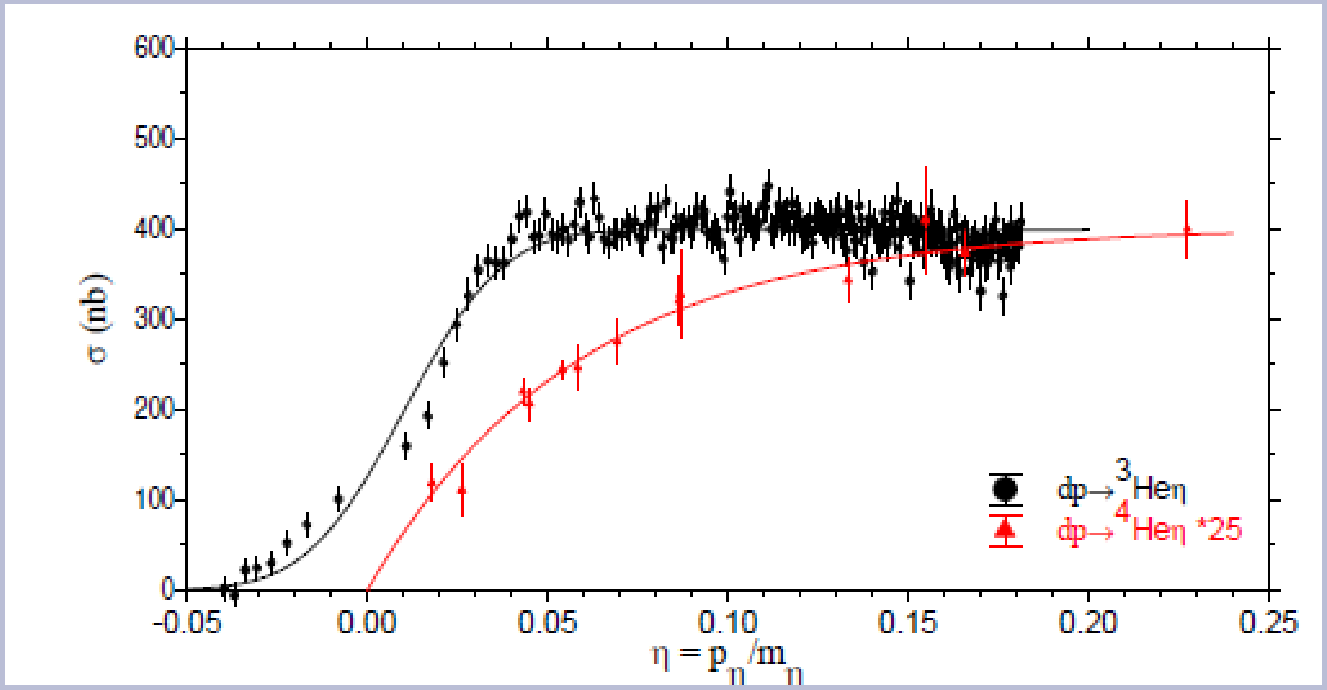
Pion and neutron in the Central Detector





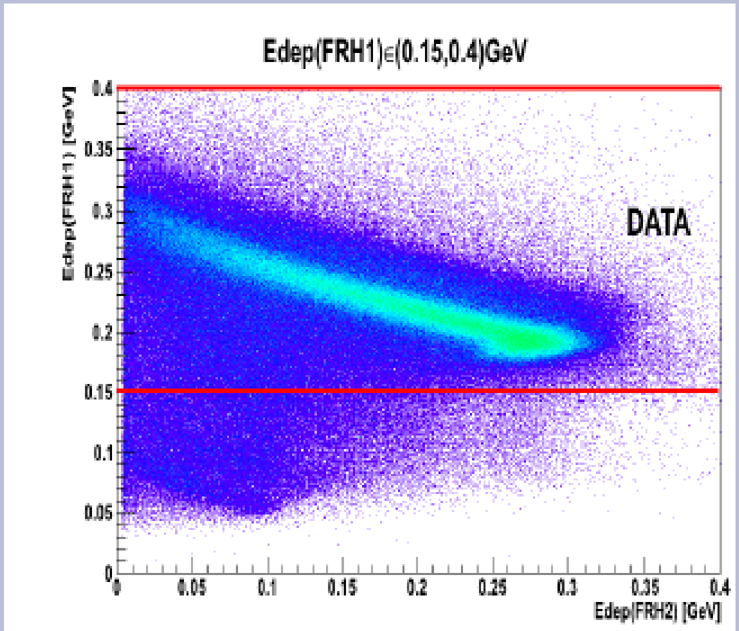


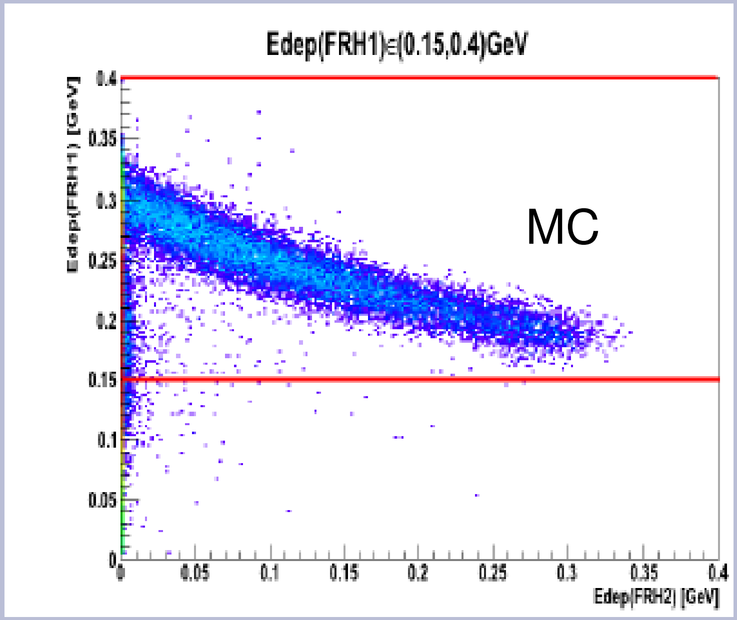
^{4}He-η vs ^{3}He-η systems

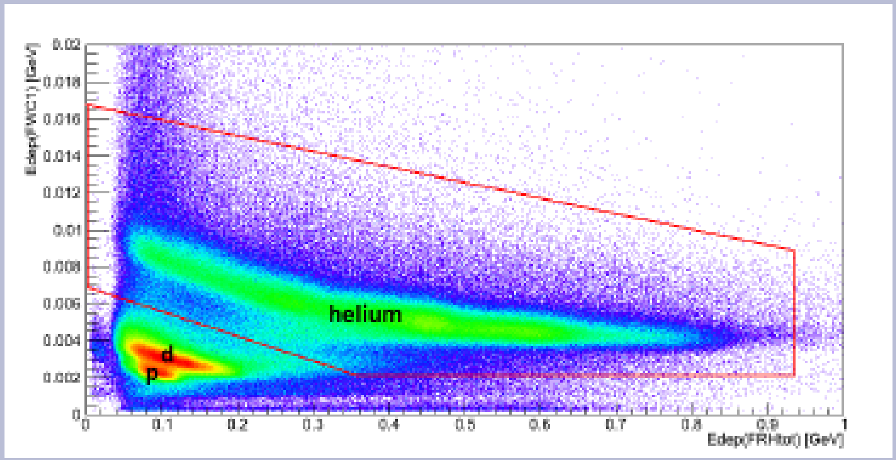


Machner et al. Acta Phys. Pol. B (2014)

^{3}He ions identification in Forward Detector (ΔE -ΔE and ΔE -E methods)

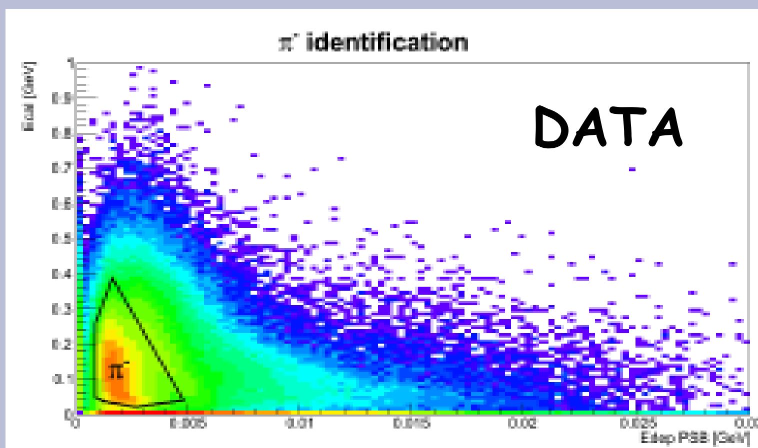


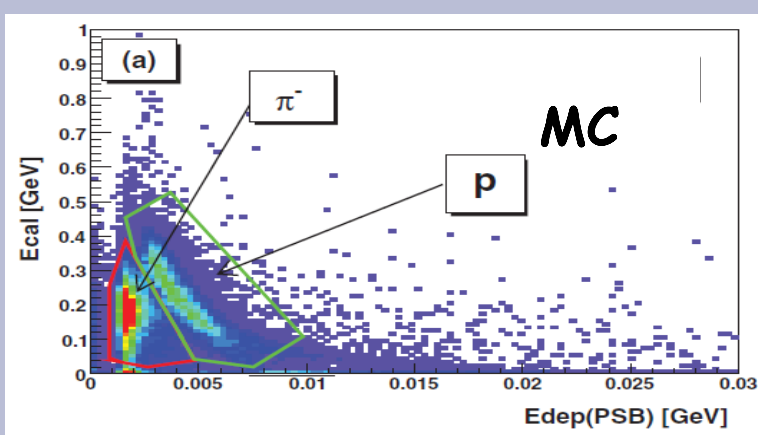




Pion identification in the Central Detector

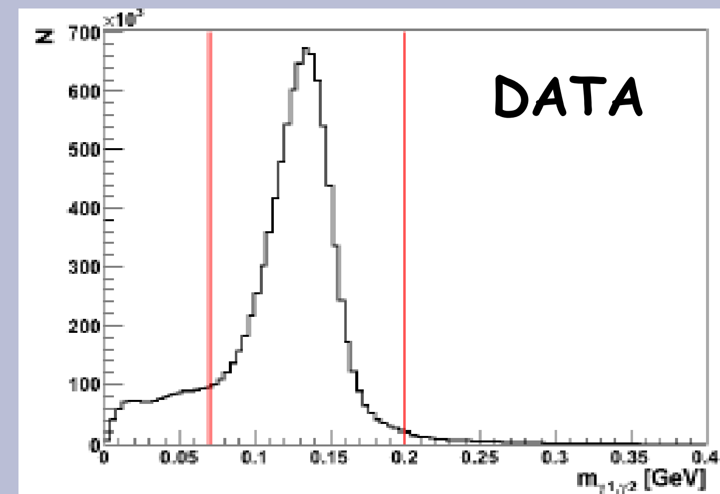
dd → ^{3}He p π^-

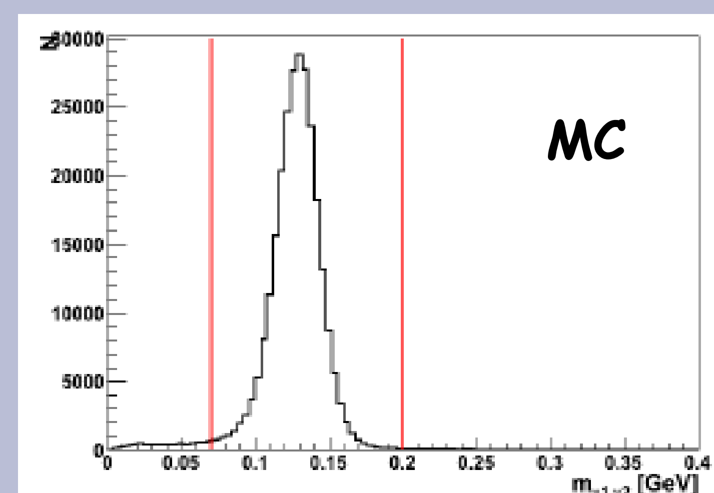




p π^- identification

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

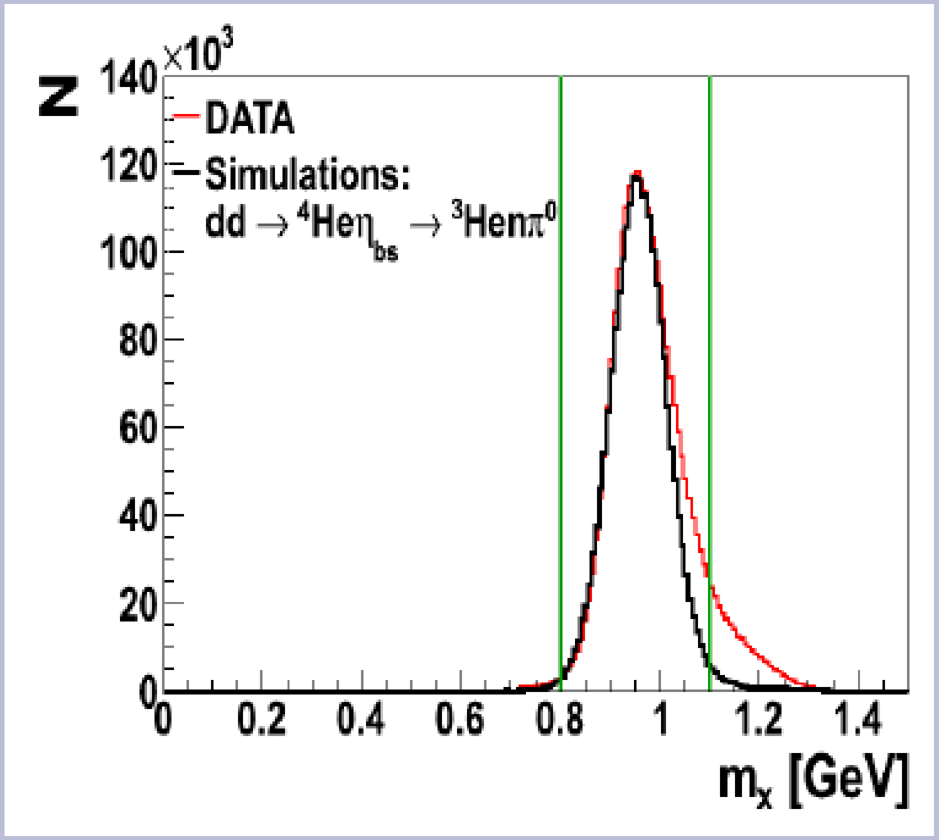




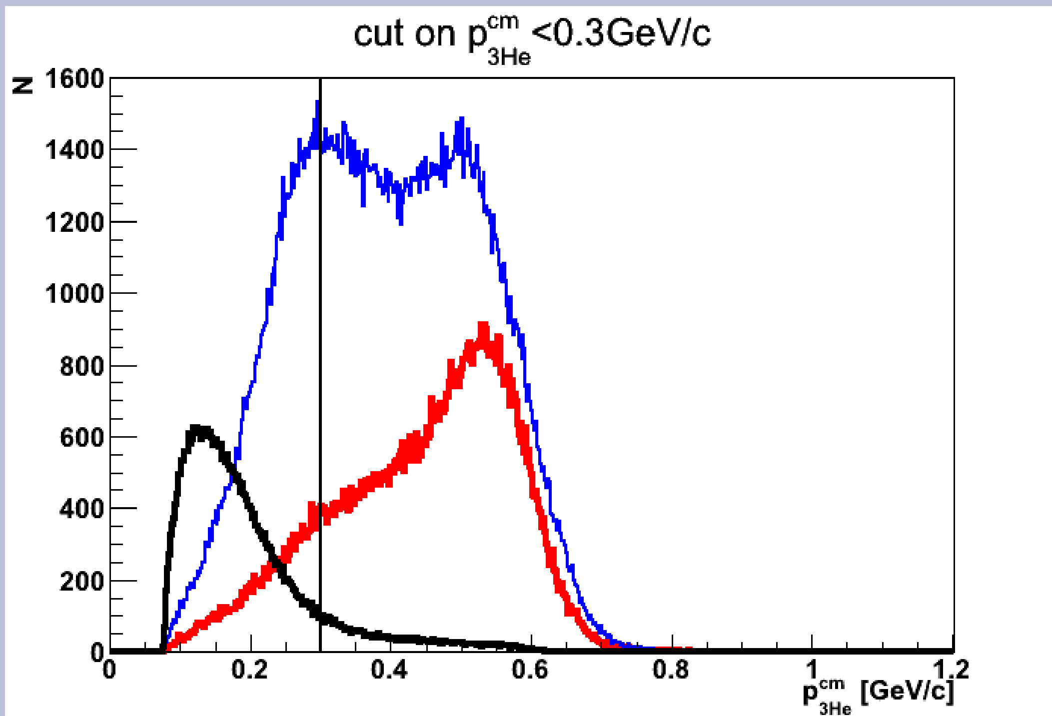
π^0 identification

Neutron identification (missing mass method)

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



„Signal-rich" vs „Signal-poor" area



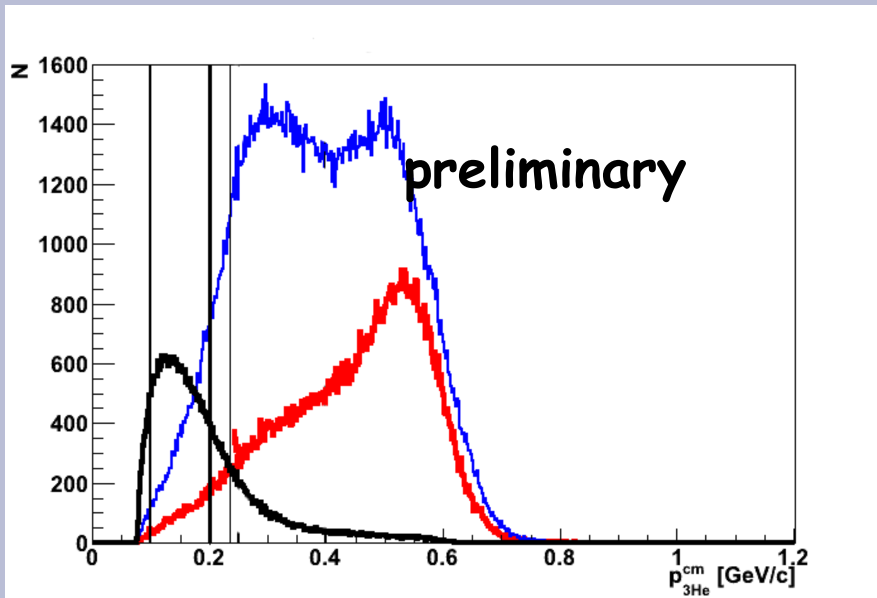
red line (data): dd $\rightarrow$ ^{3}He n π^{0}

blue line (data): dd $\rightarrow$ ^{3}He p π^{-}

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

Low ^{3}He momentum in the CM expected from the bound state decay.

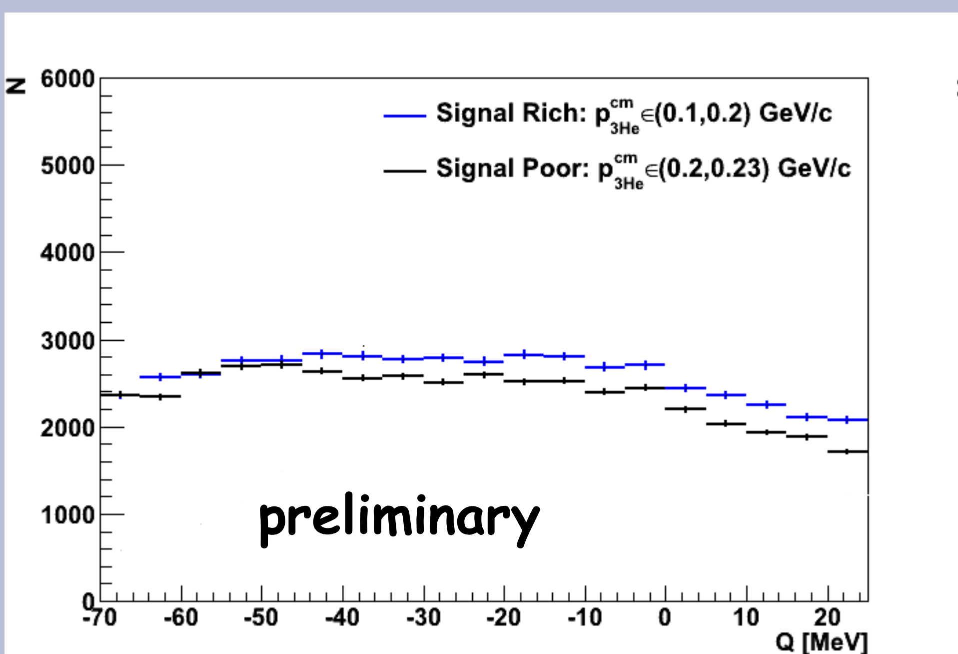
Excitation function examples



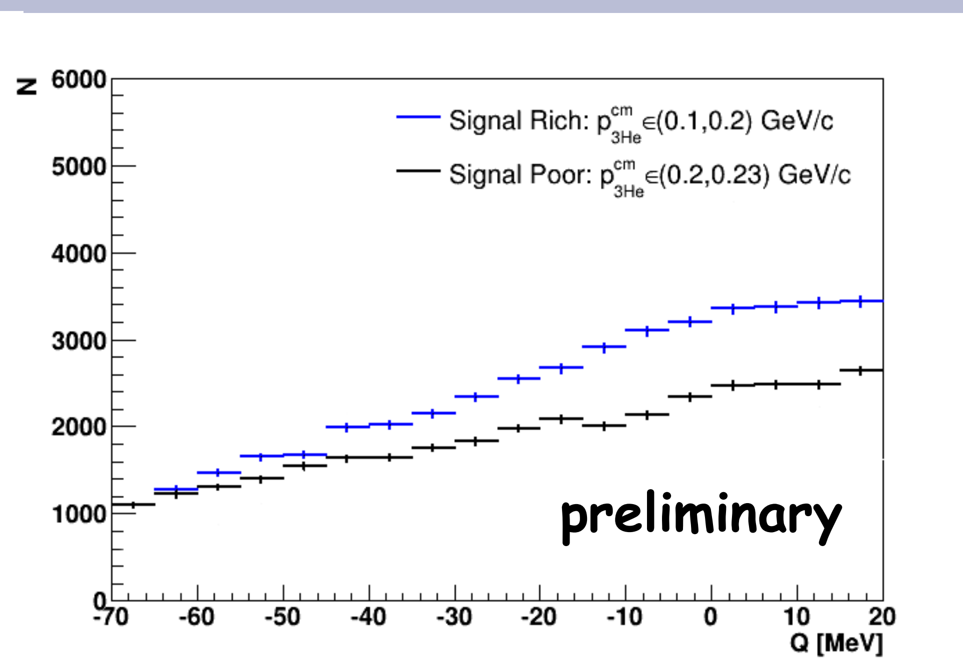
red line: dd → ^{3}He n π^0

blue line: dd → ^{3}He p π^-

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



dd → ^{3}He p π^-



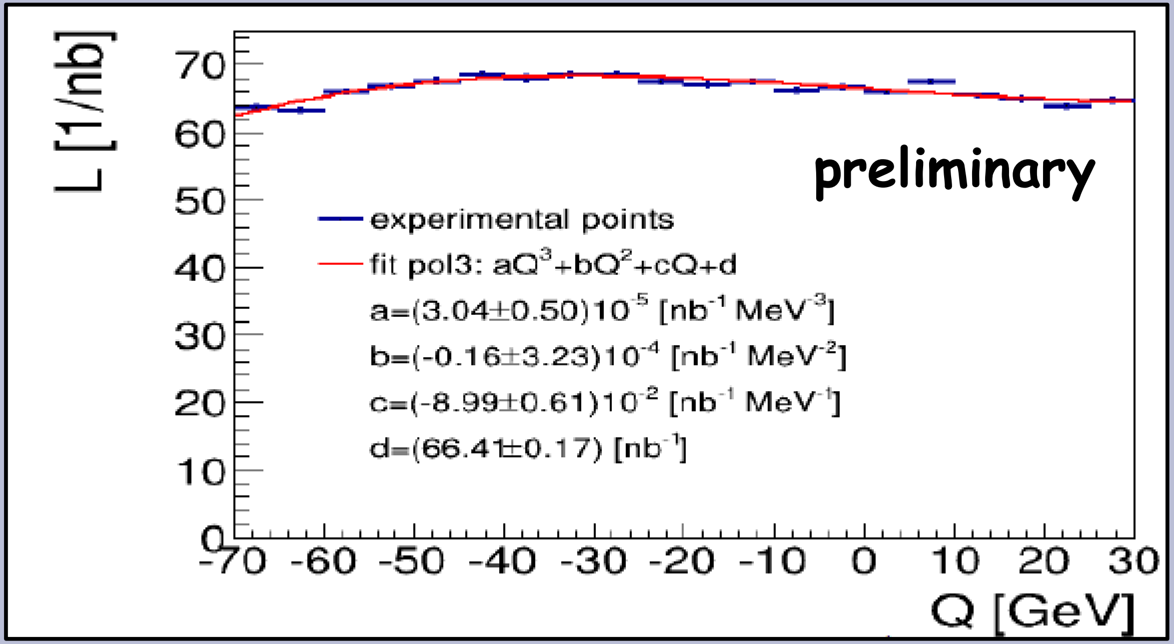
dd → ^{3}He n π^0

Normalization

Total integrated luminosity determined in two independent processes:

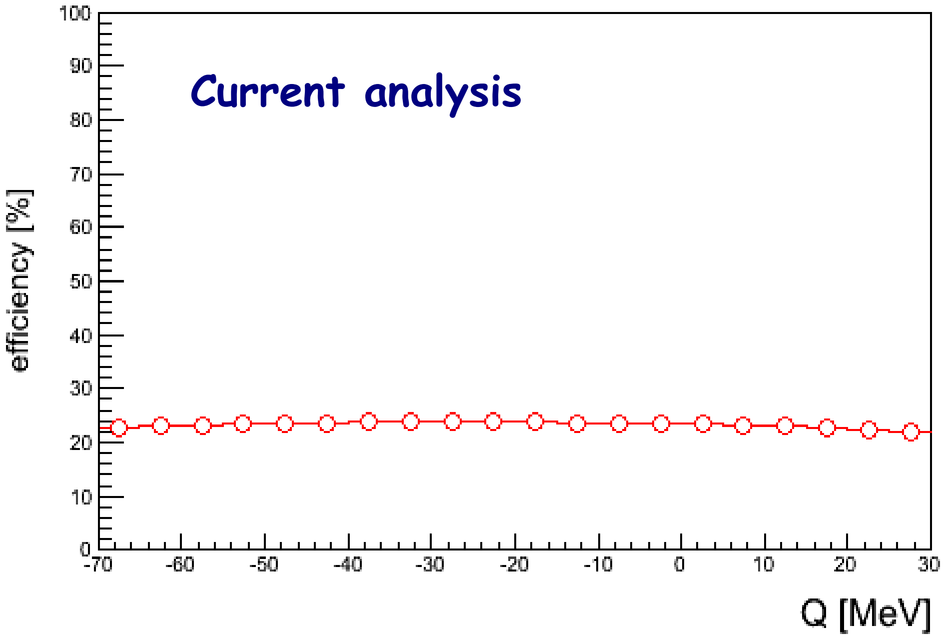
- **$dd \rightarrow {}^3He + n$**
- **$dd \rightarrow p + p\ (n\ n)$** quasi-free p + p collisions

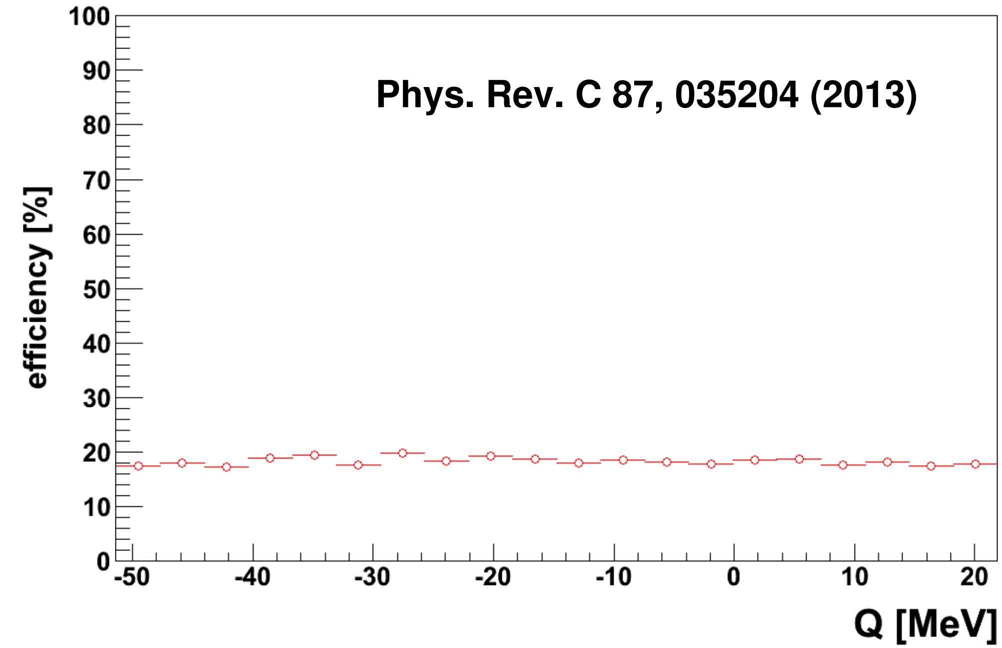
Luminosity variation as function of beam energy based on quasi free **$dd \rightarrow p + p\ (n\ n)$**.



$$L_{tot} = (1329 \pm 2)\,nb^{-1}$$

Overall reconstruction efficiency



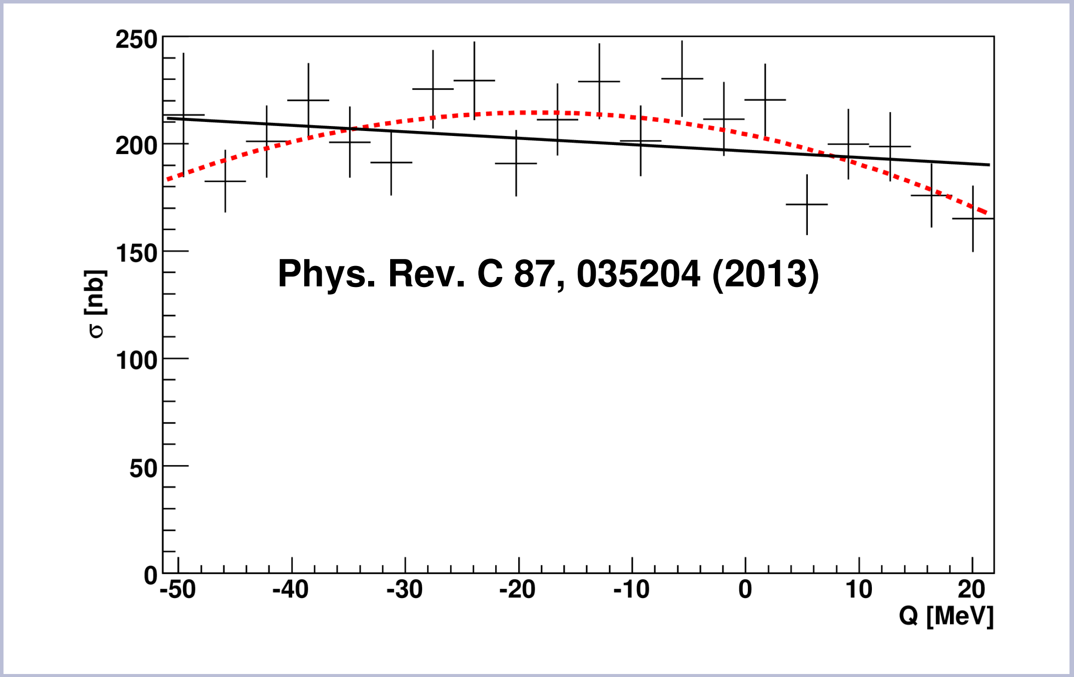


Current analysis Q range: from -70 to 30 MeV

Phys. Rev. C 87, 035204 (2013): **from -50 to 20 MeV**

Efficiency flat as a function of excess energy !!!

Excitation functions



Current analysis Q range: from -70 to 30 MeV

Phys. Rev. C 87, 035204 (2013)): **from -50 to 20 MeV**

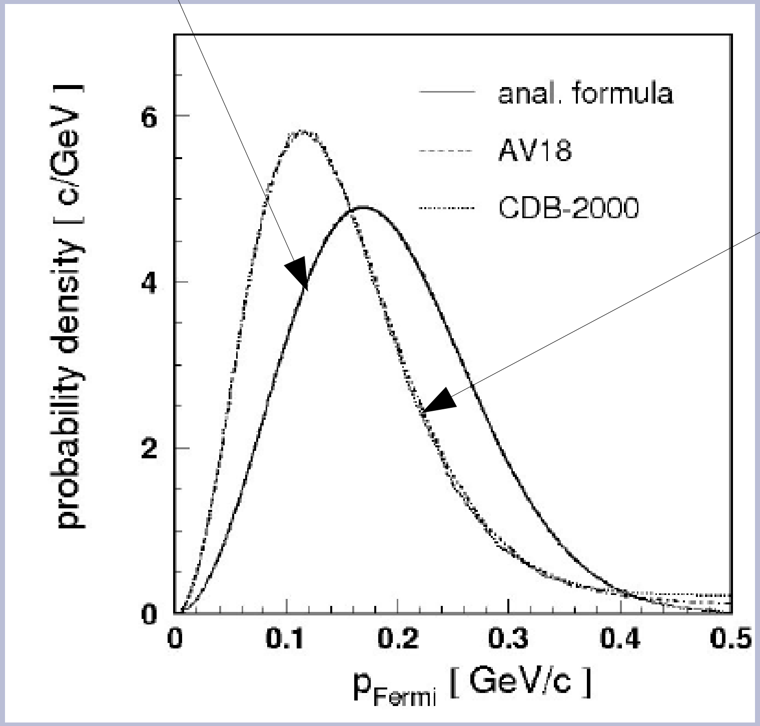
2014 -background

No.	Reaction	$\epsilon_{(0,3)}[\%]$	$\epsilon_{(3,18)}[\%]$	$\sigma[\mu b]$	$\epsilon_{(0,3)}\cdot\sigma[\mu b]$	$\epsilon_{(3,18)}\cdot\sigma[\mu b]$
1	$pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}3\pi^0$	5.3	16	0.13	0.007	0.021
2	$pd \to pd\eta \to pd3\pi^0$	0.9	13	0.05	0.0004	0.006
3	$pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}2\gamma$	1.8	5.4	0.157	0.003	0.008
4	$pd \to pd\eta \to pd2\gamma$	0.9	13	0.05	0.0004	0.006
5	$pd \to {}^3\mathrm{He}3\pi^0$	3	18	0.027	0.0008	0.005
6	$pd \to {}^3\mathrm{He}2\pi^0$	0.0007	0.08	2.8	$2\cdot10^{-5}$	0.002
7	$pd \to pd3\pi^0$	0.02	7.2	0.068	$1.4\cdot10^{-5}$	0.005
8	$pd \to pd2\pi^0$	0.0001	0.003	1.26	$1.3\cdot10^{-6}$	$4\cdot10^{-5}$
9	$pp \to pp3\pi^0$	4.3	8.4	$2.8\cdot10^{-8}$	$1.2\cdot10^{-9}$	$2.4\cdot10^{-9}$
10	$pp \to pp2\pi^0$	0.0001	0.021	0.849	$8.5\cdot10^{-7}$	$1.8\cdot10^{-4}$
11	$pn \to pn3\pi^0$	5.4	9	$8.4\cdot10^{-8}$	$4.5\cdot10^{-9}$	$7.5\cdot10^{-9}$
12	$pn \to pn2\pi^0$	2.5	21.8	2.55	0.064	0.56

No.	Reaction	$p_{beam}^{thr}[GeV/c]$	$E_{beam}^{thr}[GeV]$	$A_{(0,3)}^{thr}[\%]$	$A_{(3,18)}^{thr}[\%]$
1	$pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}3\pi^0$	1.573	0.893	60	0
2	$pd \to pd\eta \to pd3\pi^0$	1.583	0.902	0 (5)	0 (30)
3	$pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}2\gamma$	1.573	0.893	85	0
4	$pd \to pd\eta \to pd2\gamma$	1.583	0.902	0 (12)	0 (42)
5	$pd \to {}^3\mathrm{He}3\pi^0$	1.273	0.643	8	53
6	$pd \to {}^3\mathrm{He}2\pi^0$	0.977	0.416	3	68
7	$pd \to pd3\pi^0$	1.283	0.651	0.07	23
8	$pd \to pd2\pi^0$	0.988	0.424	0.01	9
9	$pp \to pp3\pi^0$	1.578	0.898	0 (25)	0 (9)
10	$pp \to pp2\pi^0$	1.192	0.579	0.08	30
11	$pn \to pn3\pi^0$	1.577	0.897	0 (28)	0 (15)
12	$pn \to pn2\pi^0$	1.1915	0.578	2	42

Nucleon momentum distribution in ^{4}He

Used in old analysis



Used in new analysis

Analytical formula derived based on:

J. S. McCarthy et al., Phys. Rev. C 15, 1396 (1977).

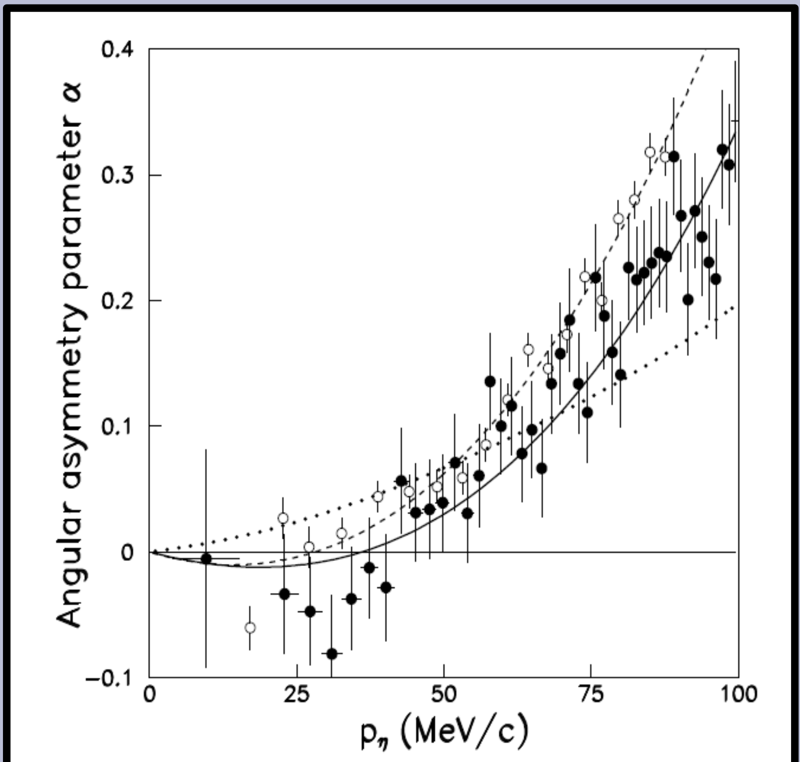
More details in Magdalena Skurzok's Master thesis: arXiv:1009.5503v2

- the difference was included as systematic uncertainty in previous results.
- After discussions with theoreticians (S. Wycech, S. Hirenzaki, A. Nogga) we decided for AV18 version:

H. Kamada et al., Phys. Rev. C64 044001 ("Benchmark test calculation of a four-nucleon bound state")

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

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



Full dots: COSY-ANKE

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

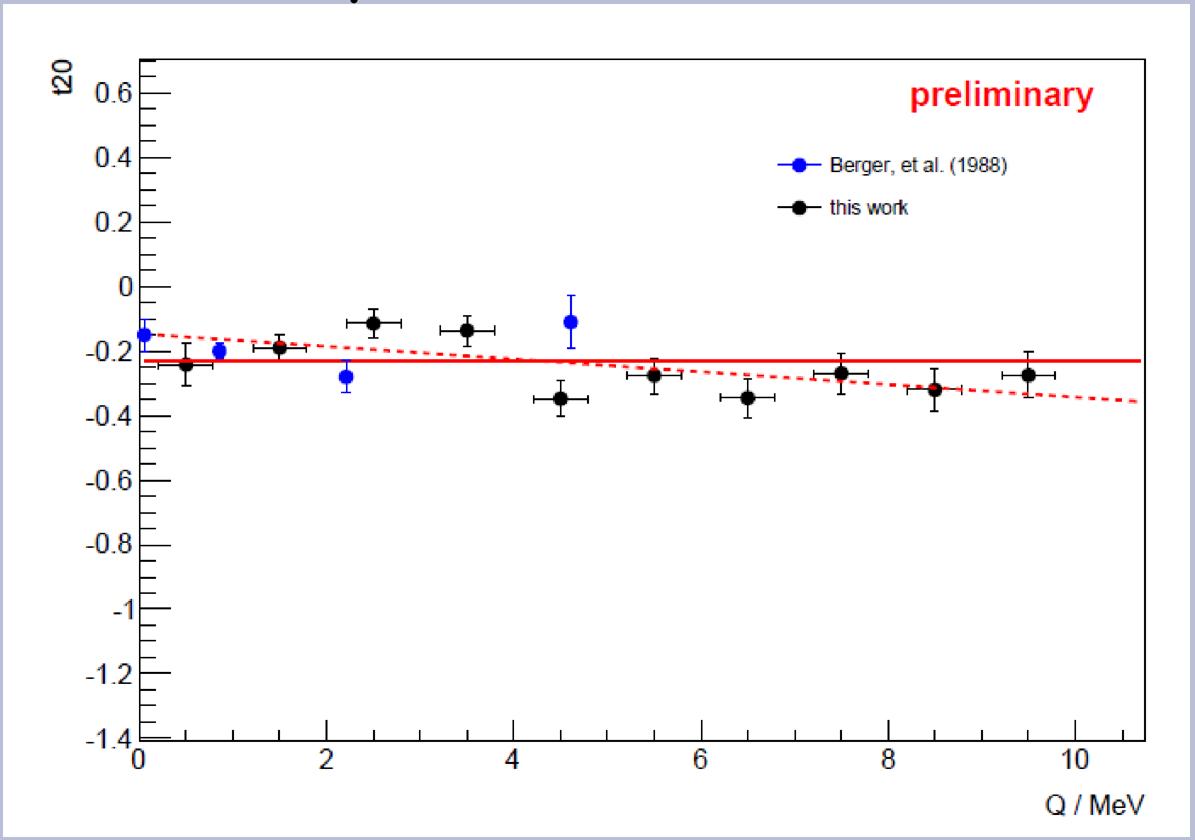
Empty circles: COSY-11

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

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

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

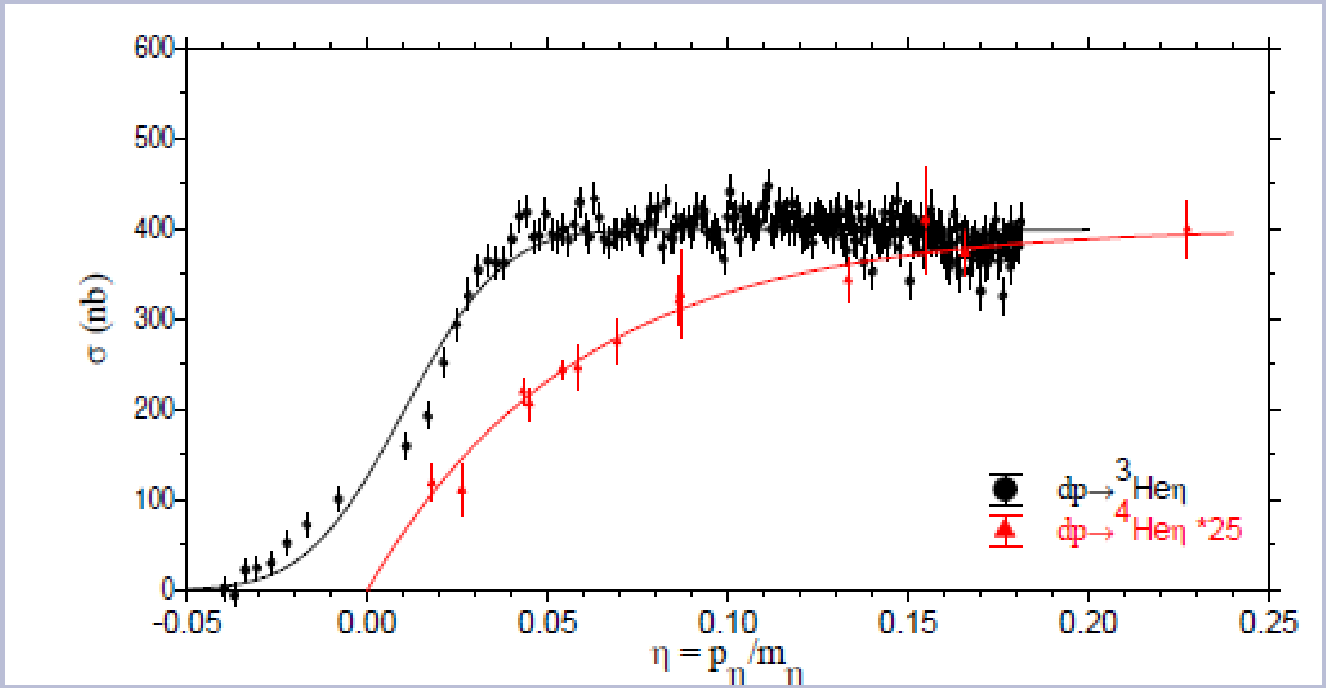
dp → ^{3}Heη



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).

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)

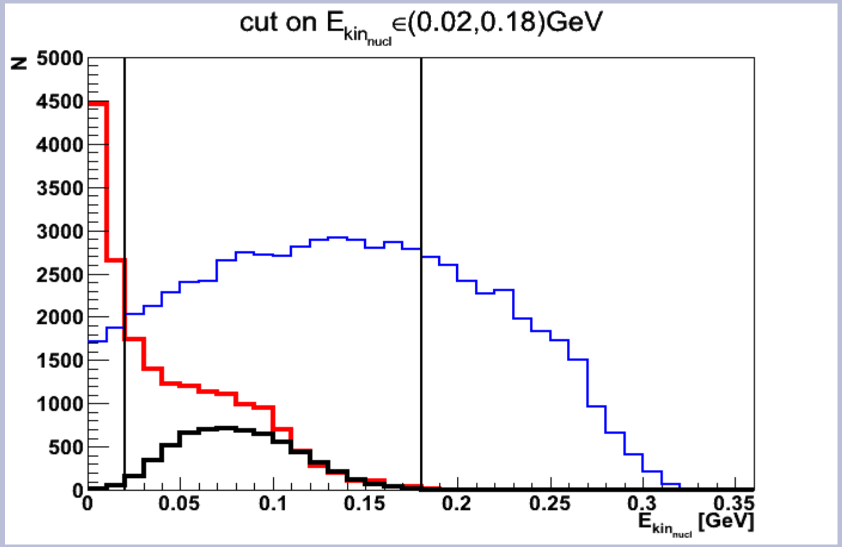
Cooling:

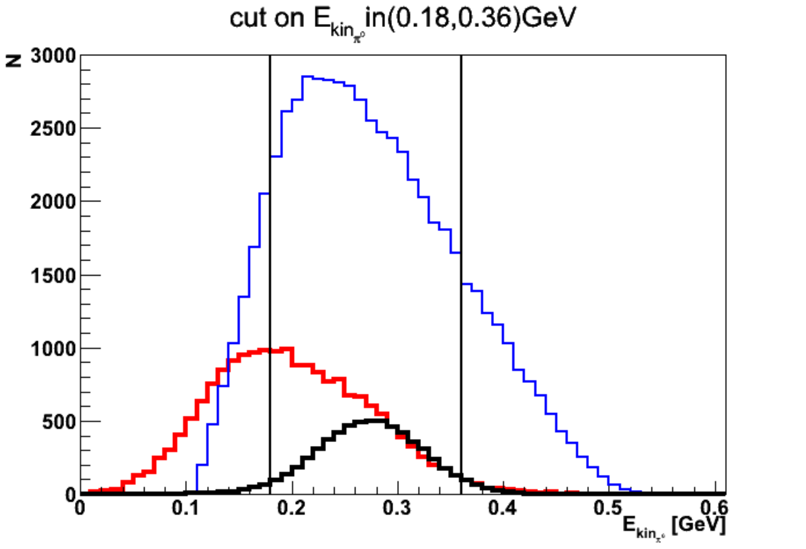
- stochastic
- electron beam

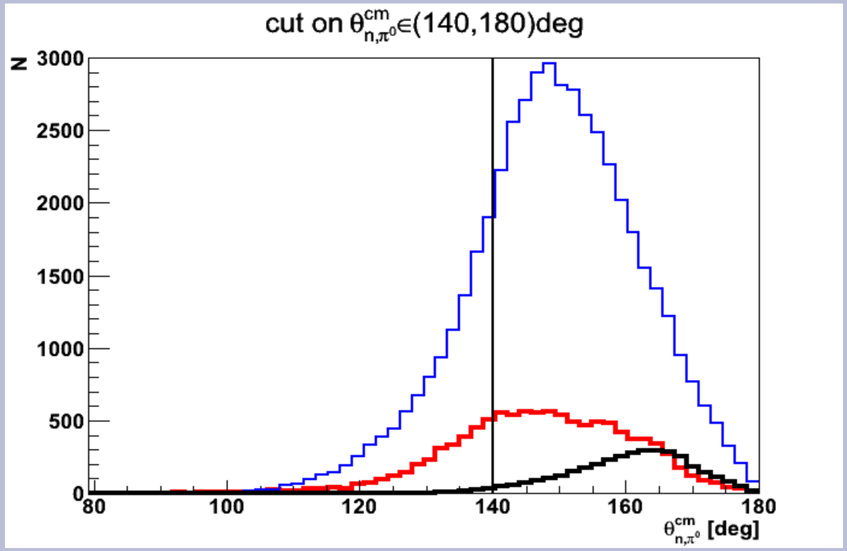
Nb of particles: 10^{11}

Ramped beam

Kinematical conditions







red line: dd → $^3He\ n\ \pi^0$

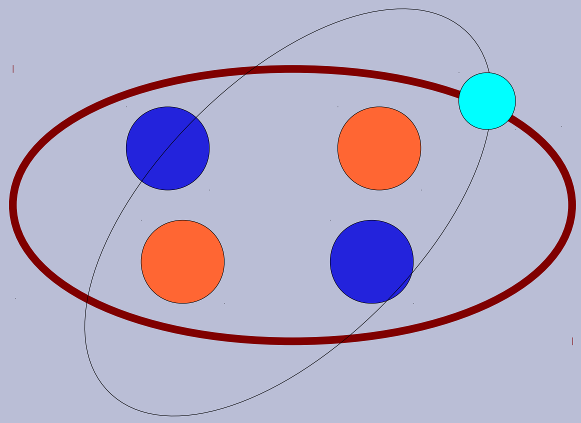
blue line: dd → $^3He\ p\ \pi^-$

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

Possible decay scenarios

- **Absorption of orbiting *η*:**

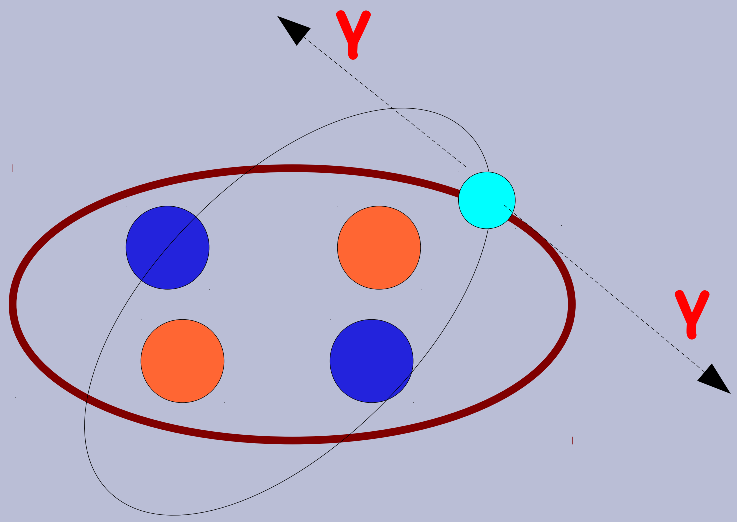
η → 2γ   (inside nucleus)



Possible decay scenarios

- **Absorption of orbiting *η*:**

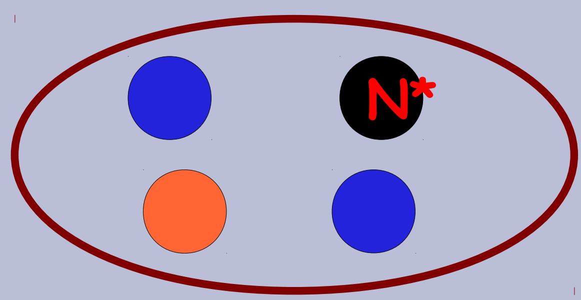
$\eta \rightarrow 2\gamma$ (inside nucleus)



Possible decay scenarios

- **Via N* resonance decay :**

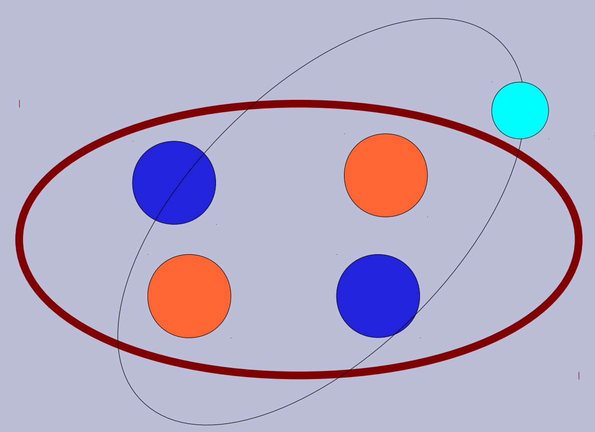
$\eta + N \rightarrow N^* \rightarrow N + \pi$ (inside nucleus)



Possible decay scenarios

- **Via N* resonance decay :**

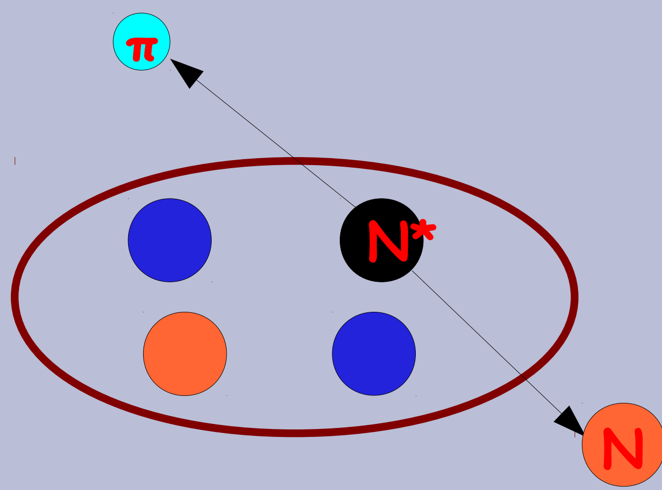
$\eta + N \rightarrow N^* \rightarrow N + \pi$ (inside nucleus)



Possible decay scenarios

- **Via N* resonance decay :**

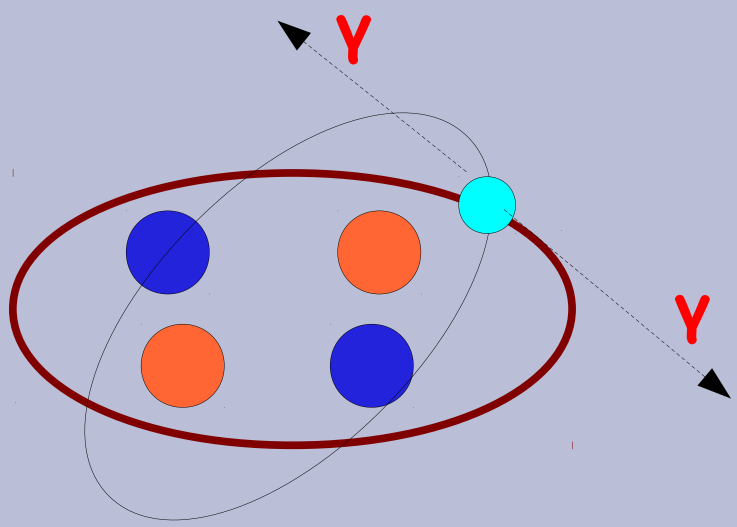
$\eta + N \rightarrow N^* \rightarrow N + \pi$ (inside nucleus)



Possible decay scenarios

- **Absorption of orbiting η:**

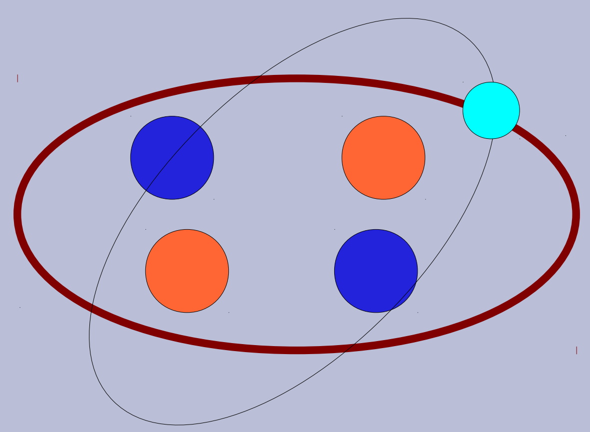
$\eta \rightarrow 2\gamma$ (inside nucleus)



Possible decay scenarios

- **Absorption of orbiting η:**

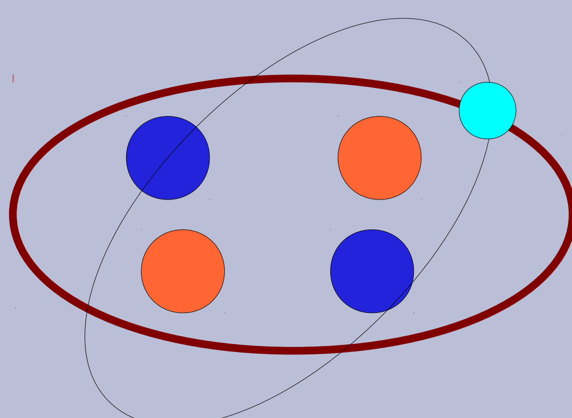
$\eta \rightarrow 2\gamma$ (inside nucleus)



Possible decay scenarios

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

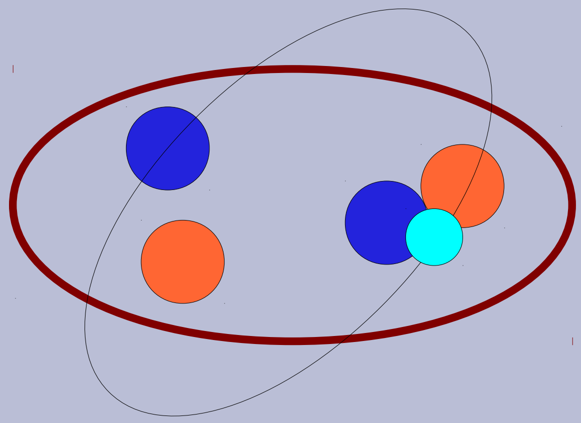
η + N N → NN (inside nucleus)



Possible decay scenarios

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

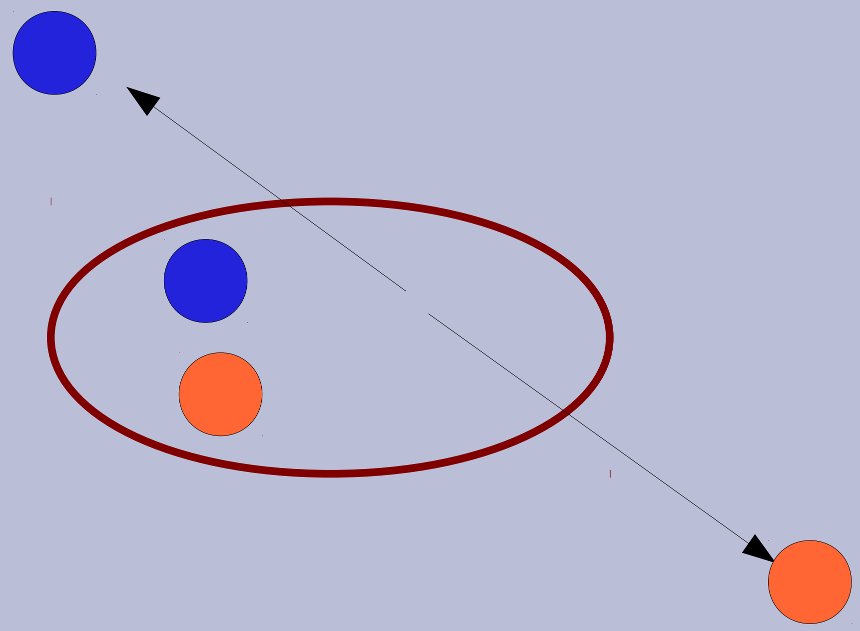
η + N N → NN (inside nucleus)



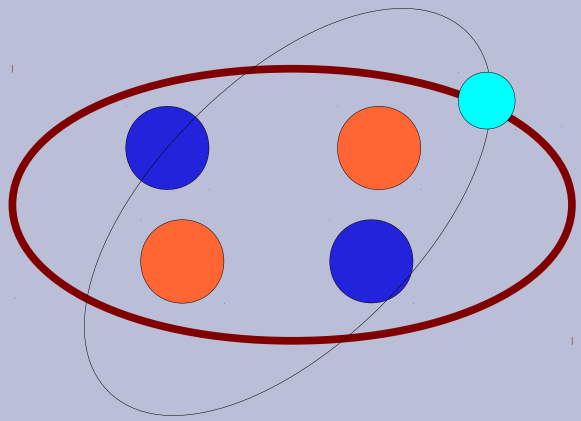
Possible decay scenarios

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

η + N N → NN (inside nucleus)



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)

Dominant 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*:

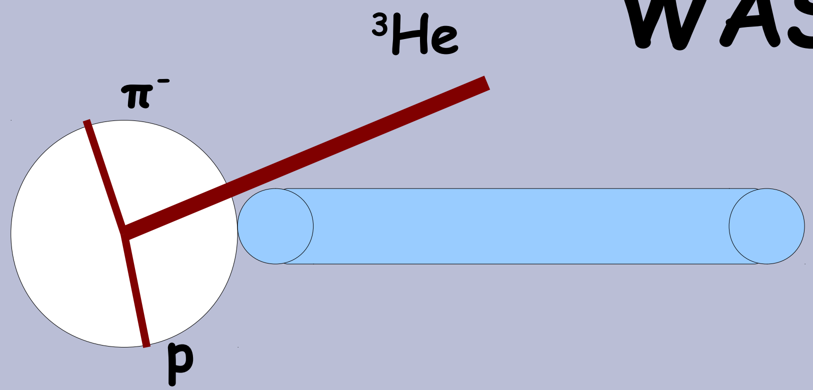
$p+d \rightarrow (^3He\text{-}\eta)_{bound} \rightarrow {}^3He + 6\gamma$

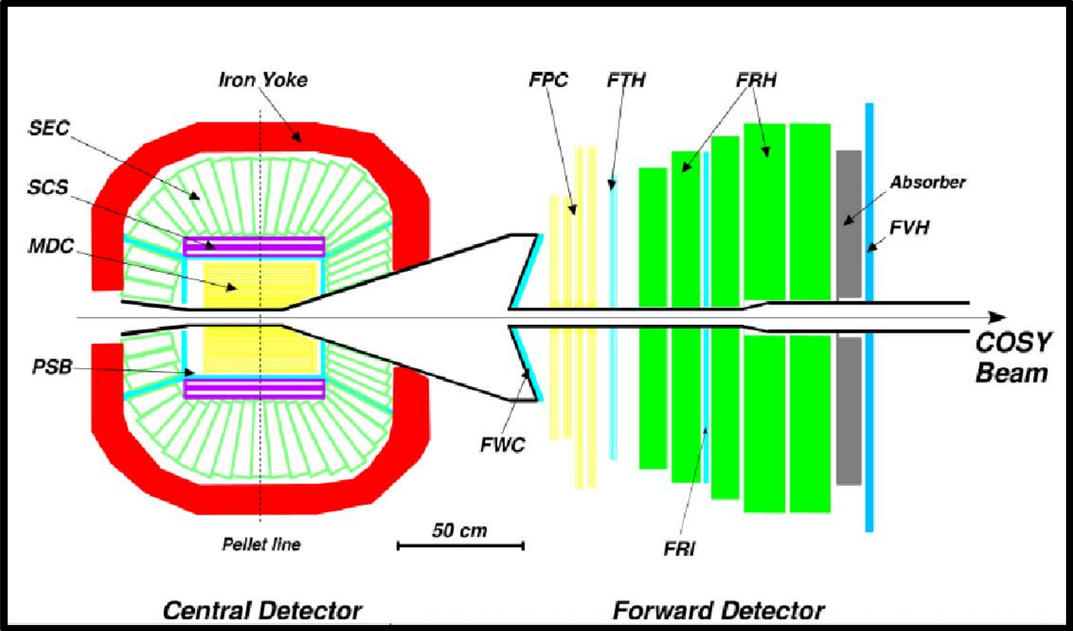
- Non-resonant decay (absorption on two nucleons):

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

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

WASA-at-COSY





Forward detector:

Scattering angle coverage 3°-18°

Scattering angle resolution 0.2°

Maximum energies for stopping

π ±/p/d/α 170/300/400/900 MeV

Time resolution <3ns

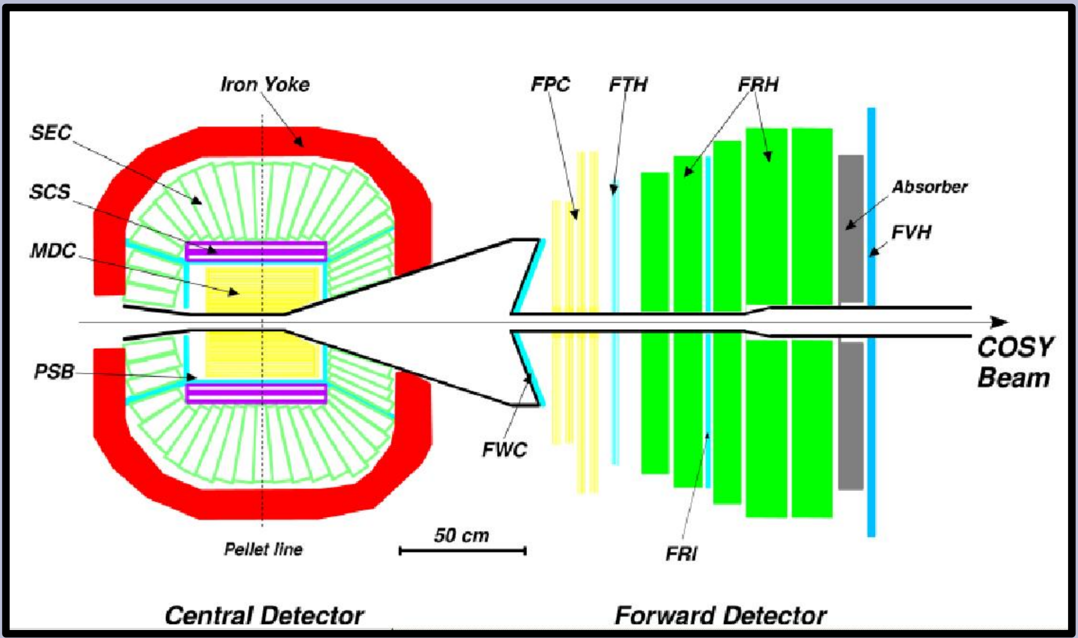
Relative energy resolution

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

π ±/p/d 190/400/450 MeV

Angular resolution

charged ~1.2°

neutral ~5°

Relative energy resolution by SE

photons ~8%

stopped charged particles ~3%

Heavy-nuclei

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

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

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

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

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

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

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

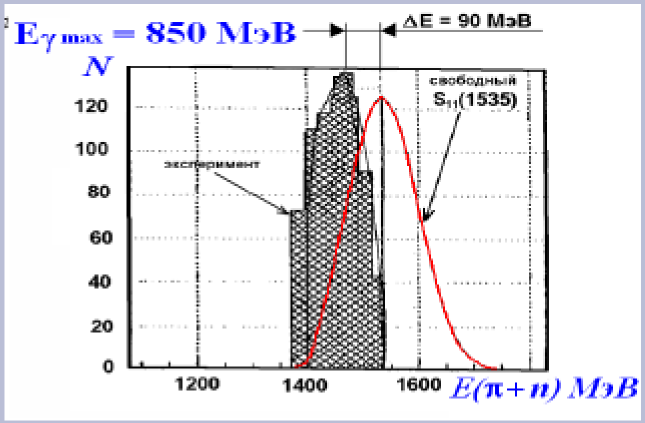
Heavy-nuclei

- LPI:

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

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

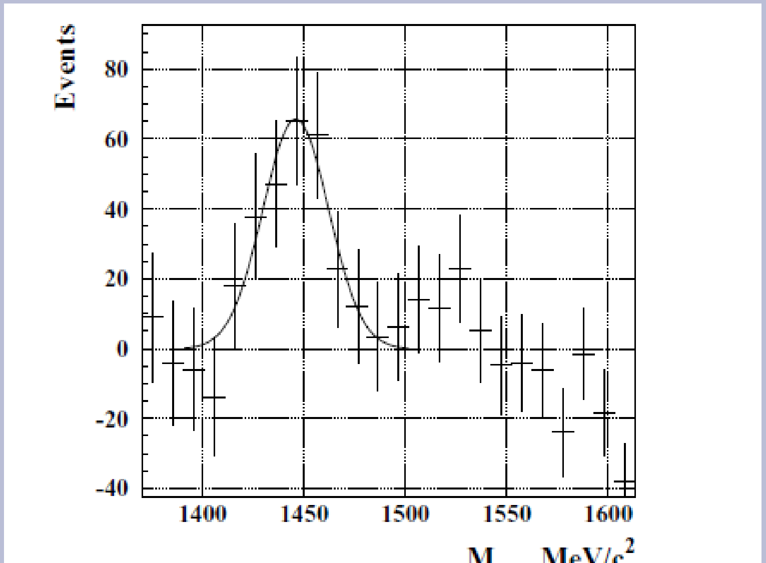
G. Sokol et al. Fizika B8, 85 (1999)
Part. Nucl. Lett. 5[102], 71 (2000)
Yad Fiz 71, 532 (2008)



- JINR, LHEP:

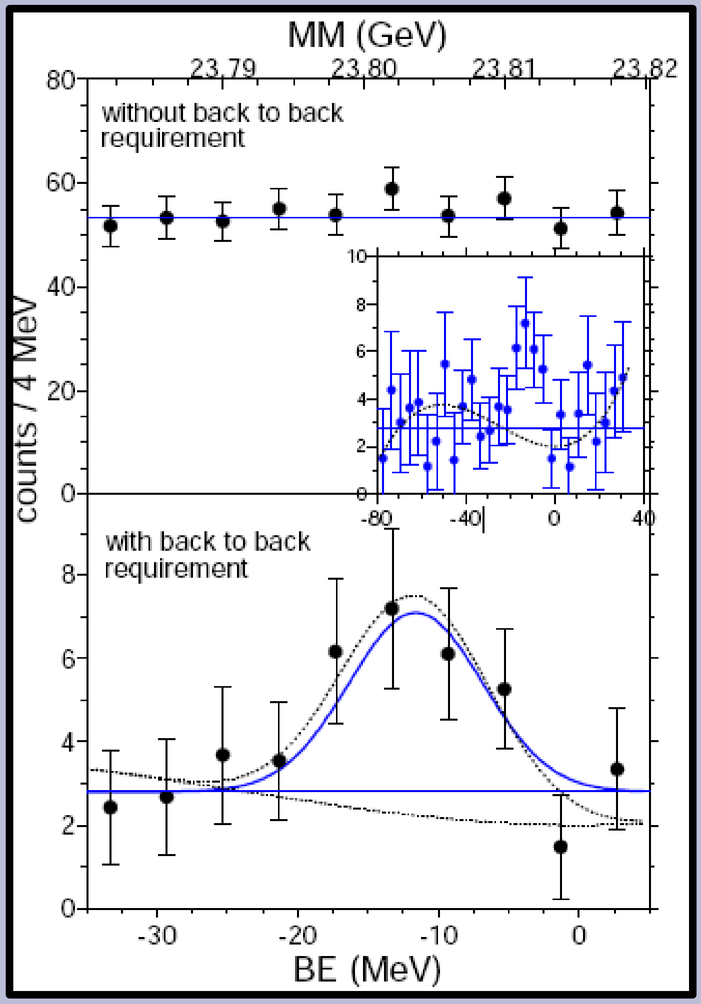
S.V. Afanasiev Nucl.Phys.Proc.Suppl. 245 (2013) 173-176.

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



COSY-GEM results

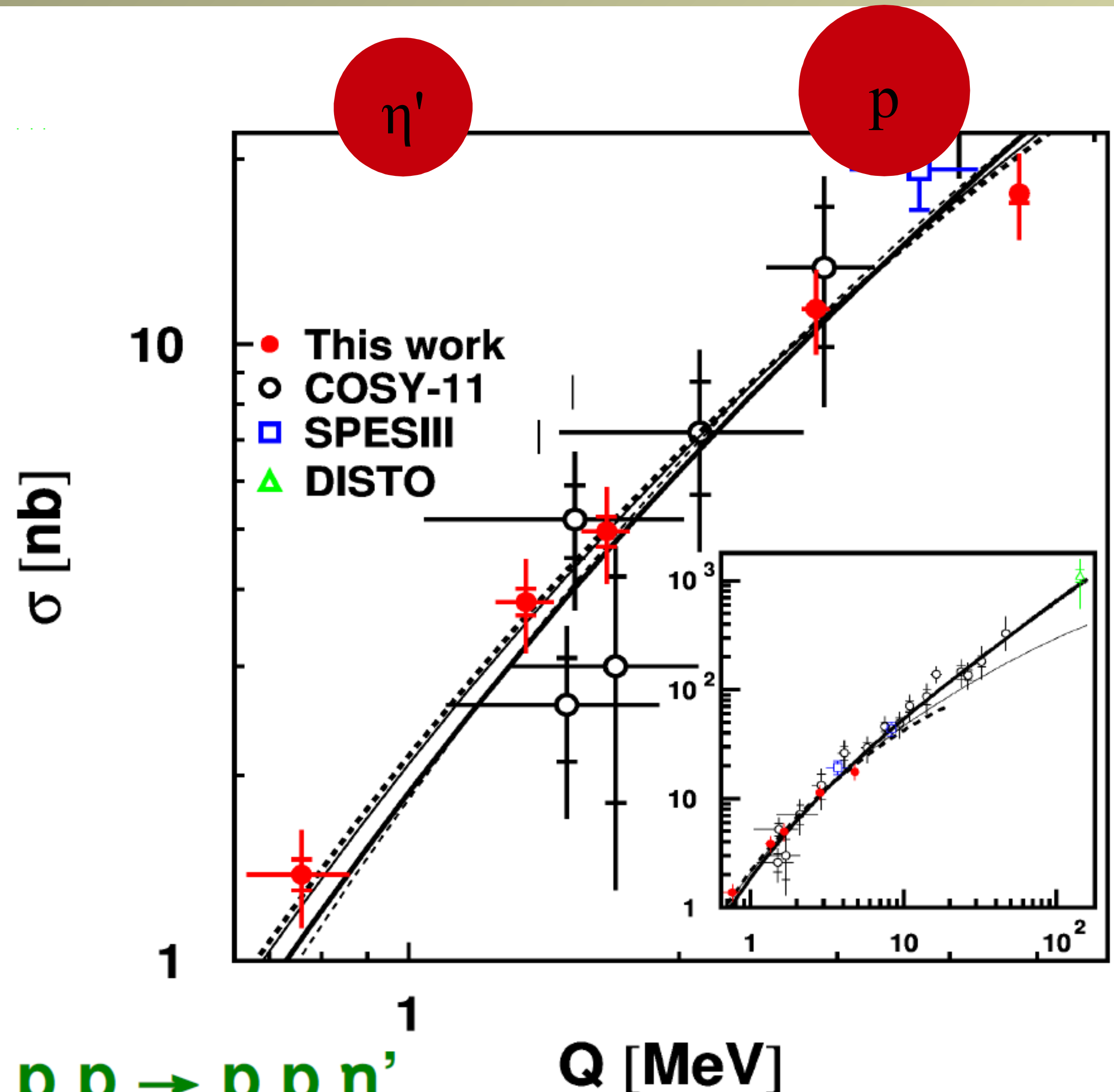
$p + {}^{27}Al \rightarrow {}^{3}He + (\eta - {}^{25}Mg) \rightarrow {}^{3}He + \pi^{-} + p + X$



MM(3HE)

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

The η′ - proton hadronic interaction



p p → p p η’

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

E. Czerwiński, P.M. et al., Phys. Rev. Lett. 113 (2014) 062004