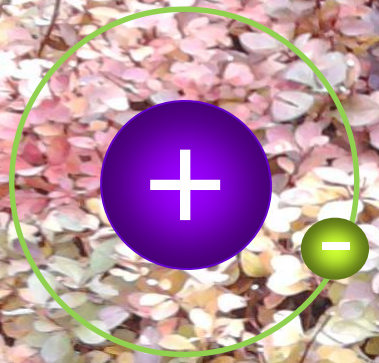
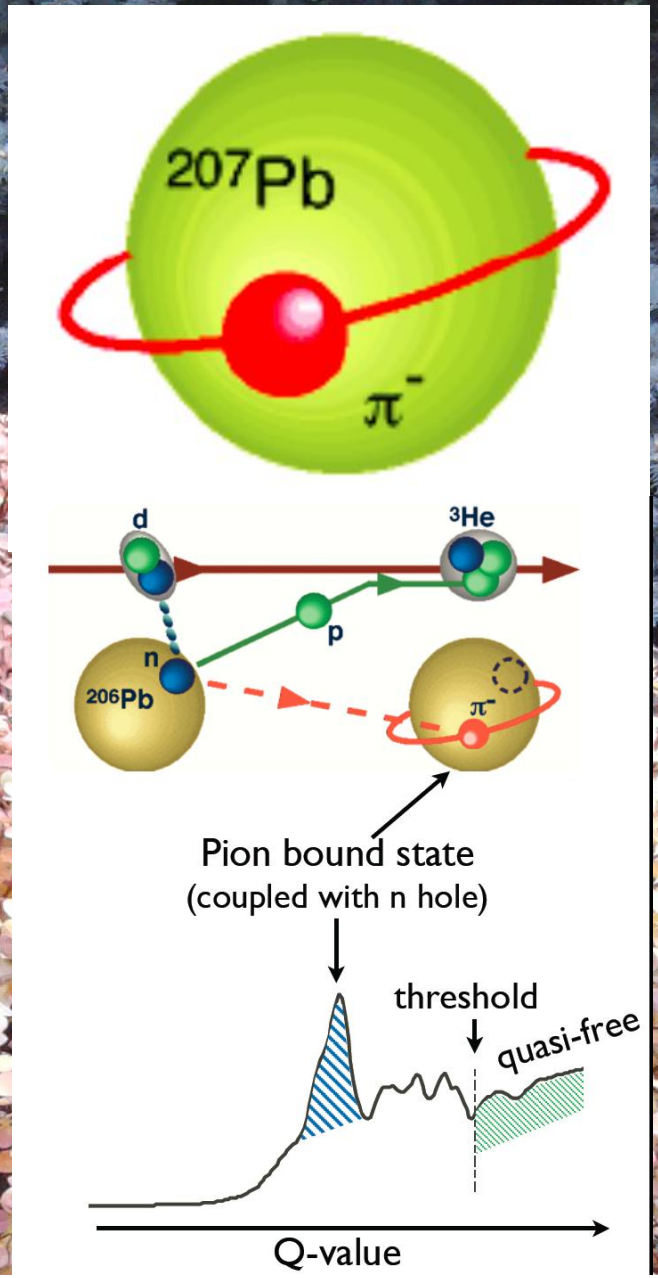
Search for eta-nucleus bound states

Abstract:
We report on the search for the new kind of nuclear matter in the form of eta-mesic helium

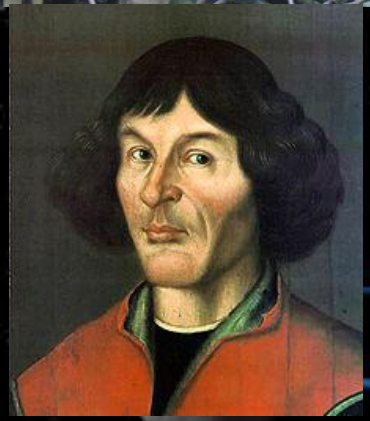
Paweł Moskal
Jagiellonian University, Cracow,Poland

WASA at GSI Workshop
GSI, 27 November 2017

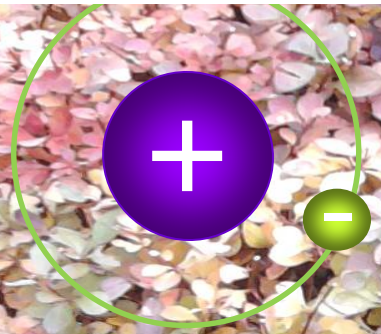


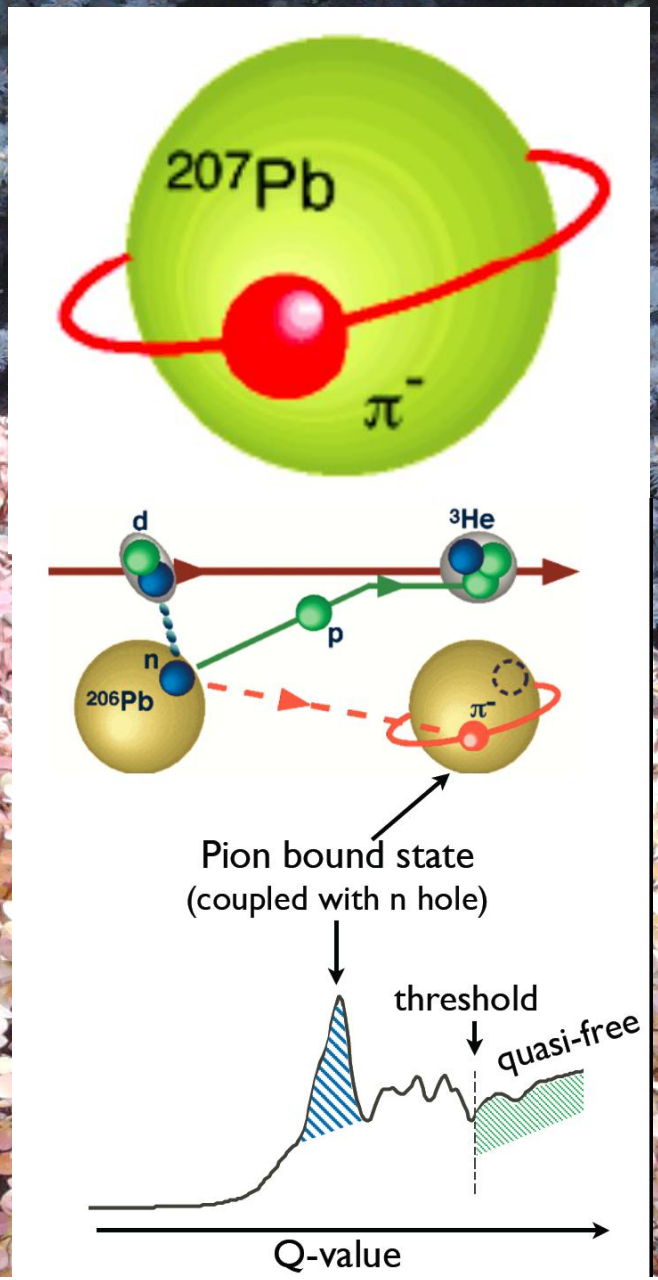


Kenta Itahashi, RIKEN
From talk at Symposium in Cracow 2013



Jagiellonian University
Student of astronomy in 1491-1495





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- **Recent experimental results**

  P. Adlarson et al., arXiv:1709.04547

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

  Y.K. Tanaka et al., Phys. Rev. Lett. 117 (2016) 202501

  ….

- **Recent theory results**

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

  N. Barnea et al., Phys. Lett. B 771 (2017) 297

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  A. Fix, O. Kolesnikov, Phys. Lett. B 772 (2017) 663

  N. Ikeno et al., Eur. Phys. J. A 53 (2017) 194

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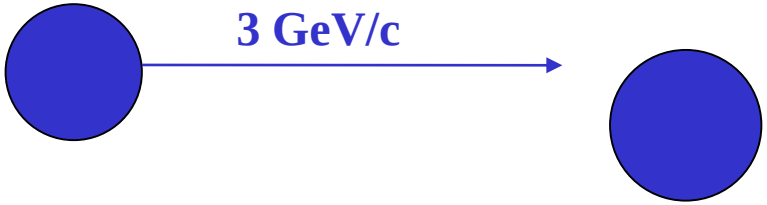
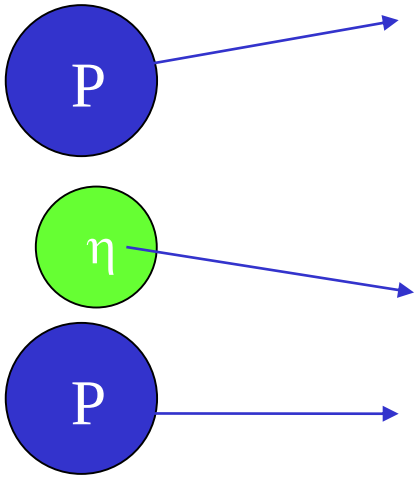
threshold as a spin filter

in the laboratory

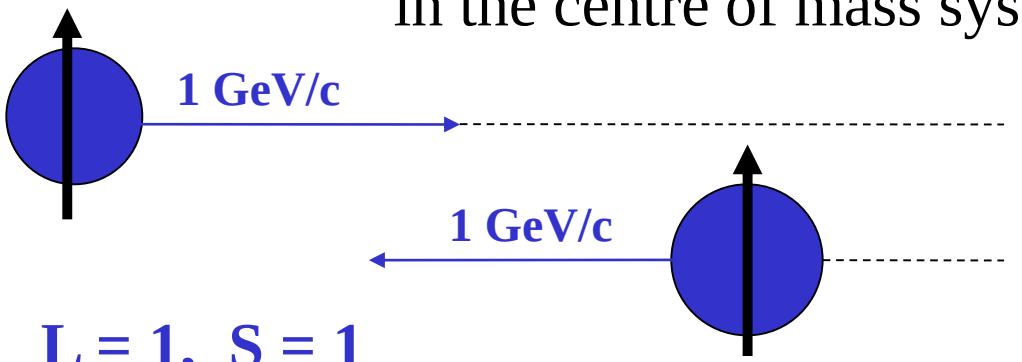


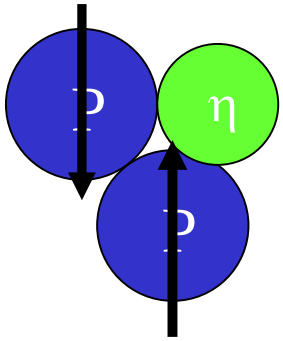


before reaction:

after reaction:

in the centre of mass system





L = 1, S = 1

L = 0, l=0

$$\boxed{{}^3P_0 \rightarrow {}^1S_0 s}$$

⇒ **Reaction parameter b ~ 0.2 fm**

TABLE I: List of allowed transitions ${}^{2s_i+1}L_J \to {}^{2s_f+1}\ell_J, \lambda$ for the lowest partial waves in the reaction $pp \to pp\eta$.

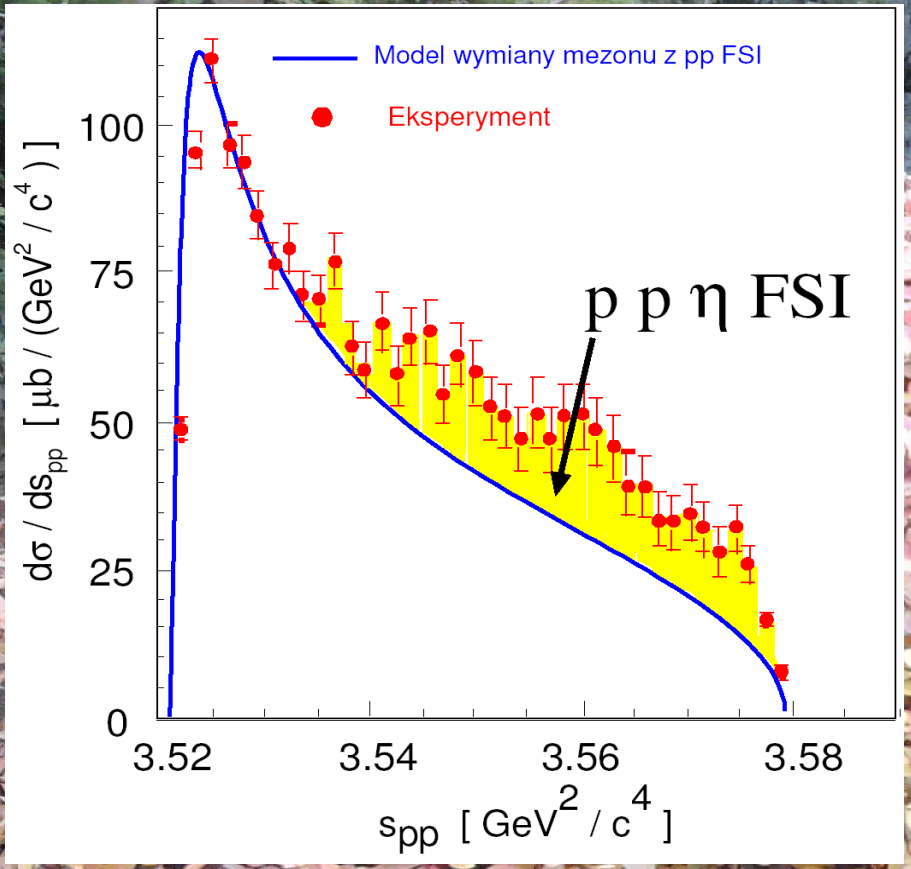
A. Deloff, nucl-th/0309059

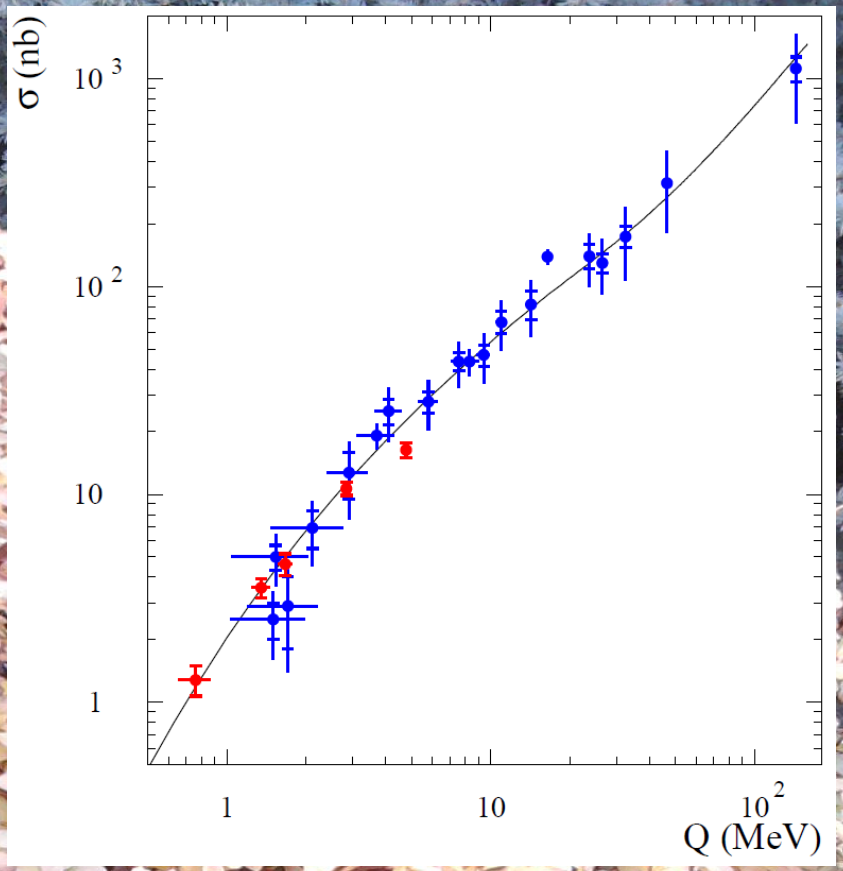
even ℓ	odd ℓ
${}^3P_0 \to {}^1S_0$,s	${}^1S_0 \to {}^3P_0$,s
${}^3P_2 \to {}^1S_0$,d	${}^1D_2 \to {}^3P_2$,s
${}^3F_2 \to {}^1S_0$,d	${}^3P_0 \to {}^3P_1$,p
${}^3P_2 \to {}^1D_2$,s	${}^3P_2 \to {}^3P_2$,p
${}^3F_2 \to {}^1D_2$,s	${}^3F_2 \to {}^3P_1$,p
	${}^3F_2 \to {}^3P_2$,p
	${}^3P_1 \to {}^3P_0$,p
	${}^3P_1 \to {}^3P_1$,p
	${}^3P_1 \to {}^3P_2$,p
	${}^3F_3 \to {}^3P_2$,p

Ss, ~~Sp~~, Sd, Ps, Pp

Ss, Sd, Ps, Pp

COSY-11



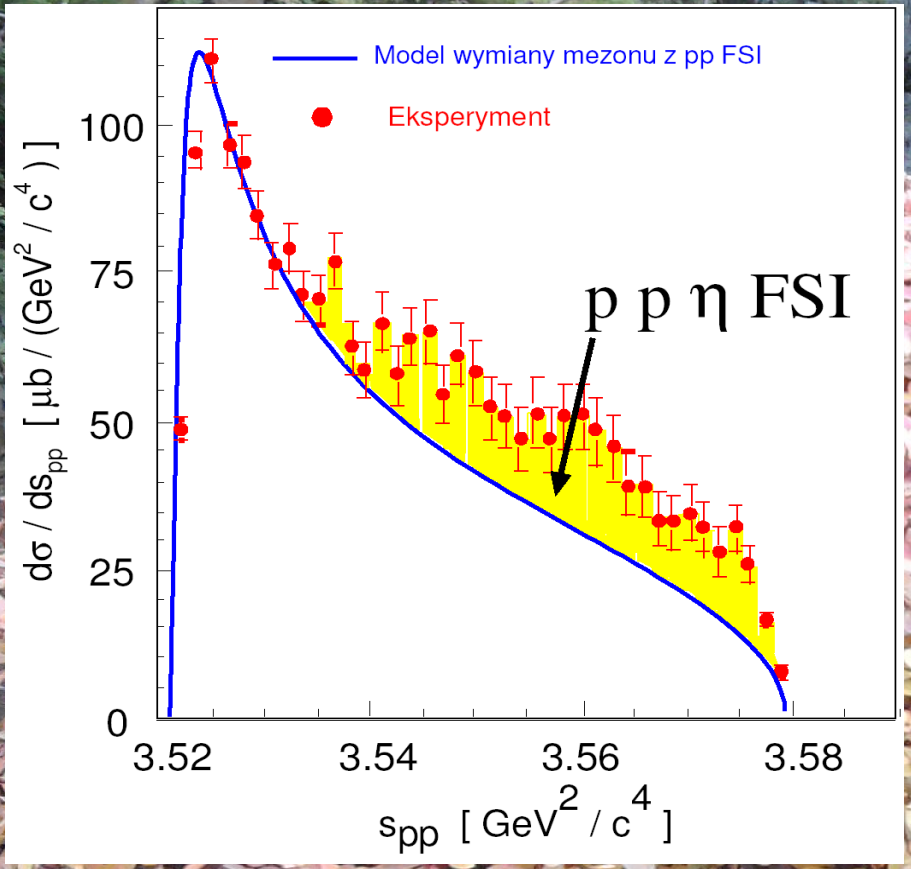


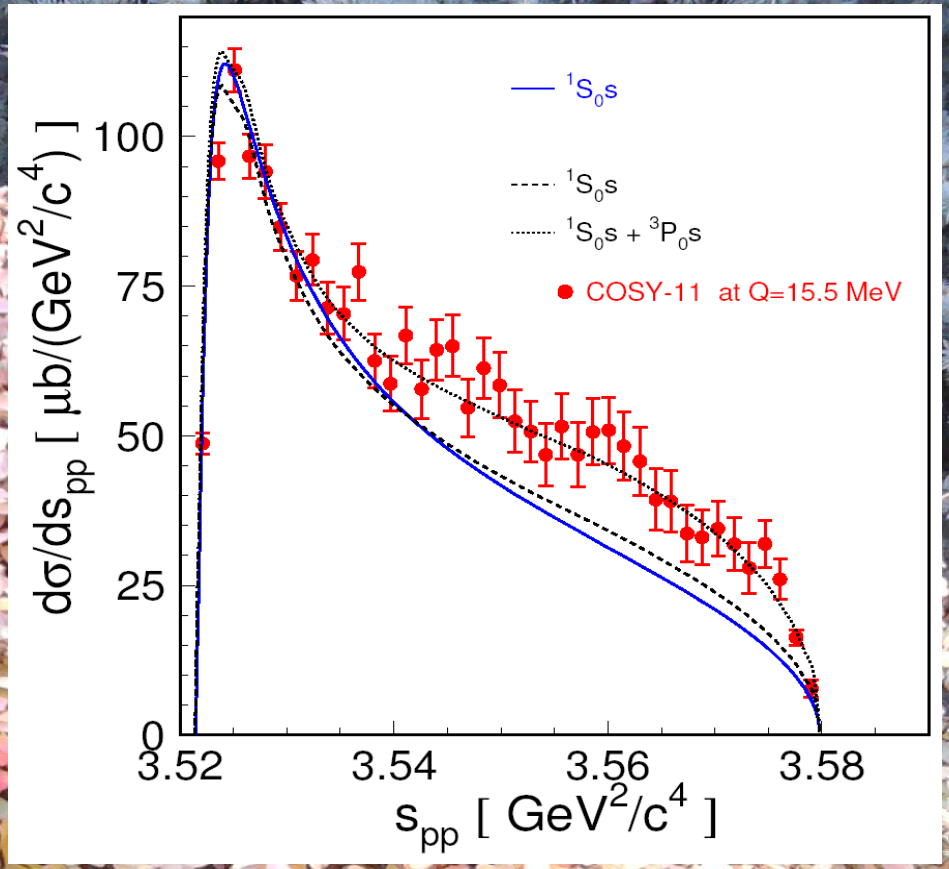
COSY-11: Phys. Rev. Lett. 113 (2014) 062004

COSY-11: Phys. Lett. B 684 (2010) 11

Rysunek 3. Widmo masy niezmienniczej podukładu proton-proton dla układu ppη (zielone punkty) oraz ppη′ (czerwone punkty)

COSY-11





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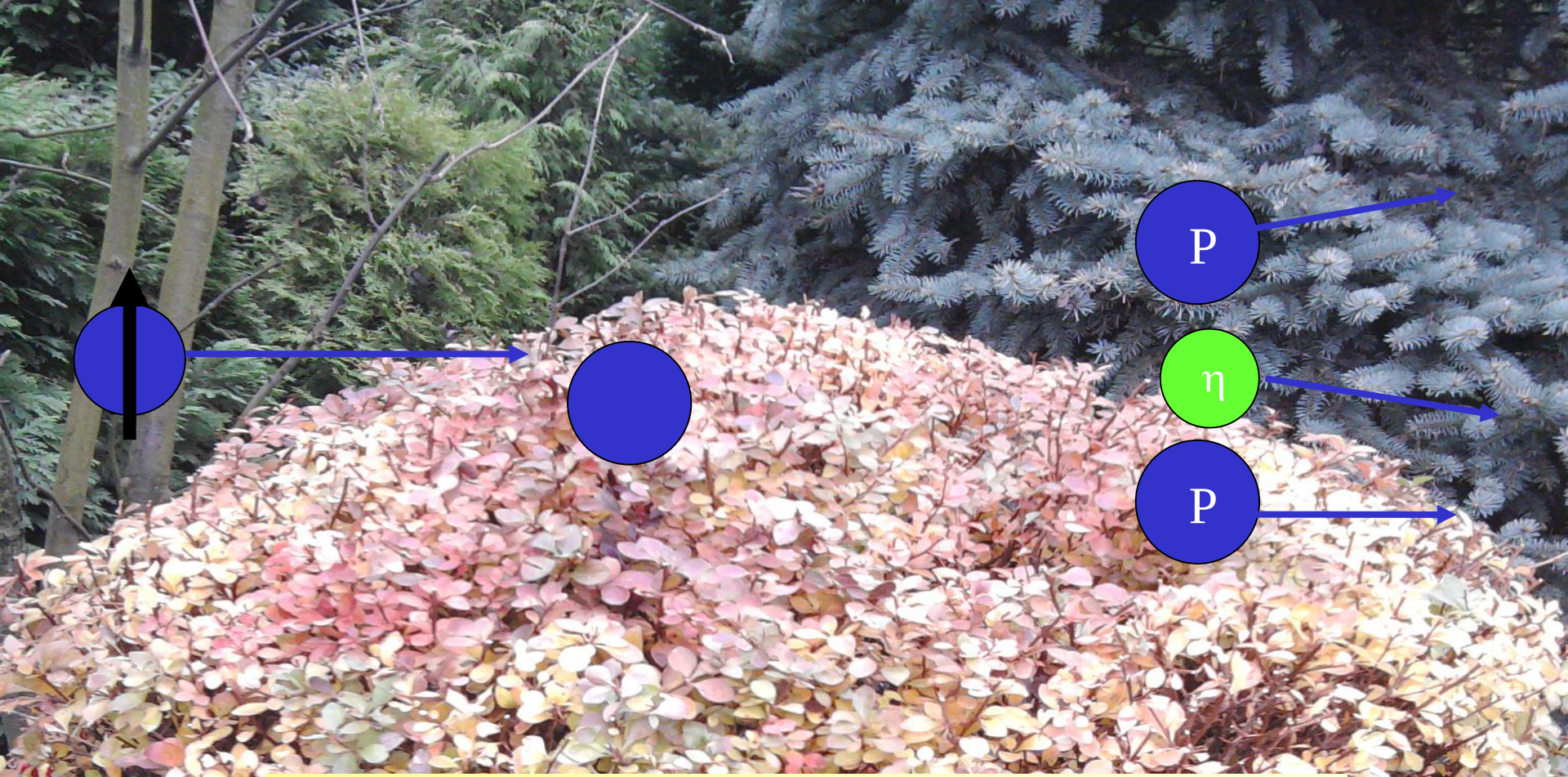


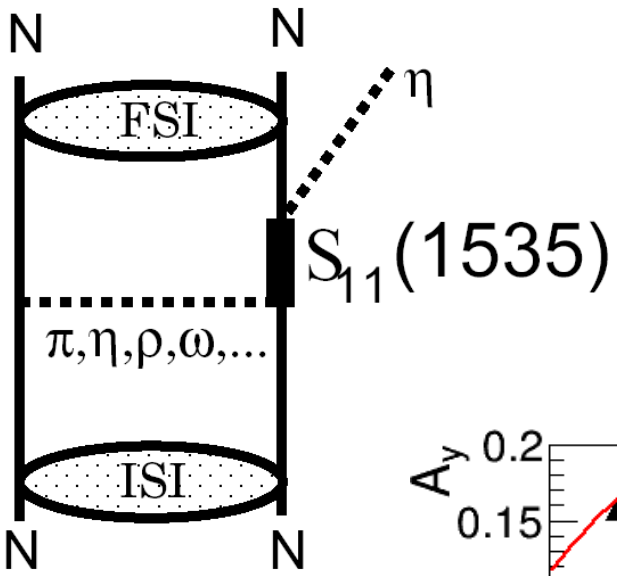
$$Ay \sim (Ps * Pp)\ \sin\theta_\eta$$

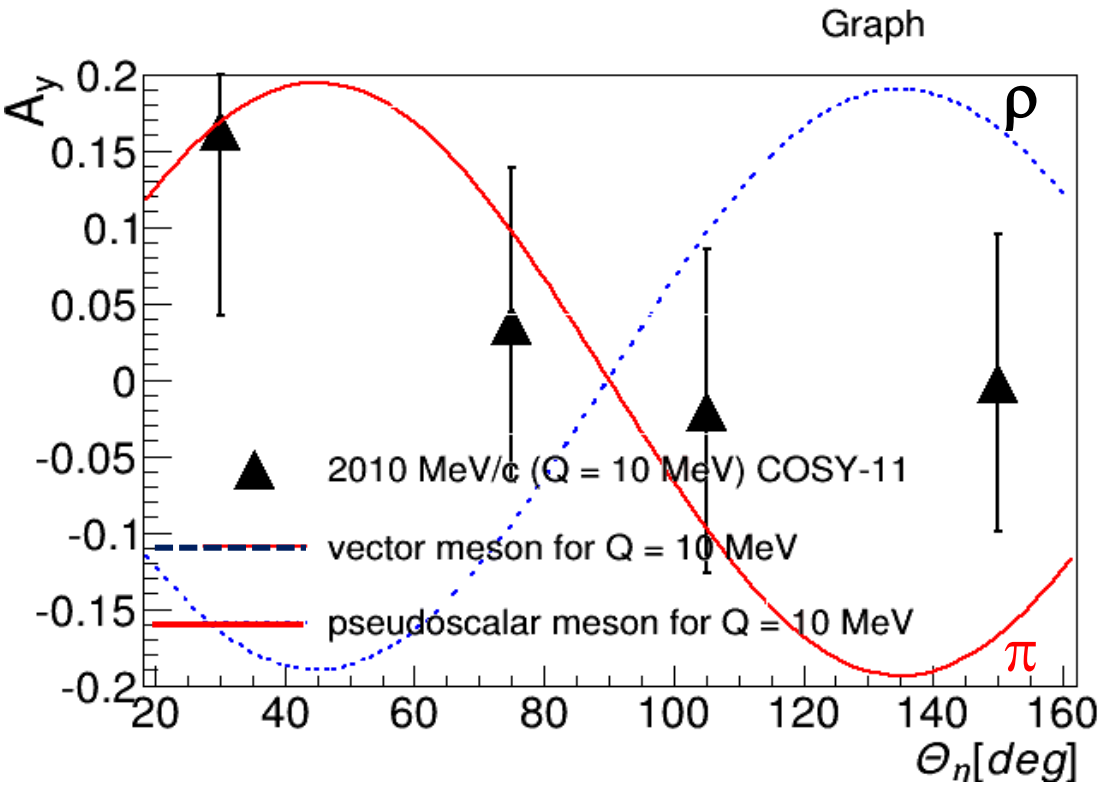
$$Ay \sim (Ss * Sd + Pp * Pp)\ \sin\theta_\eta\ \cos\theta_\eta$$

P. Winter et al., Phys. Lett. B544 (2002) 251

Ss, Sd, Ps, Pp

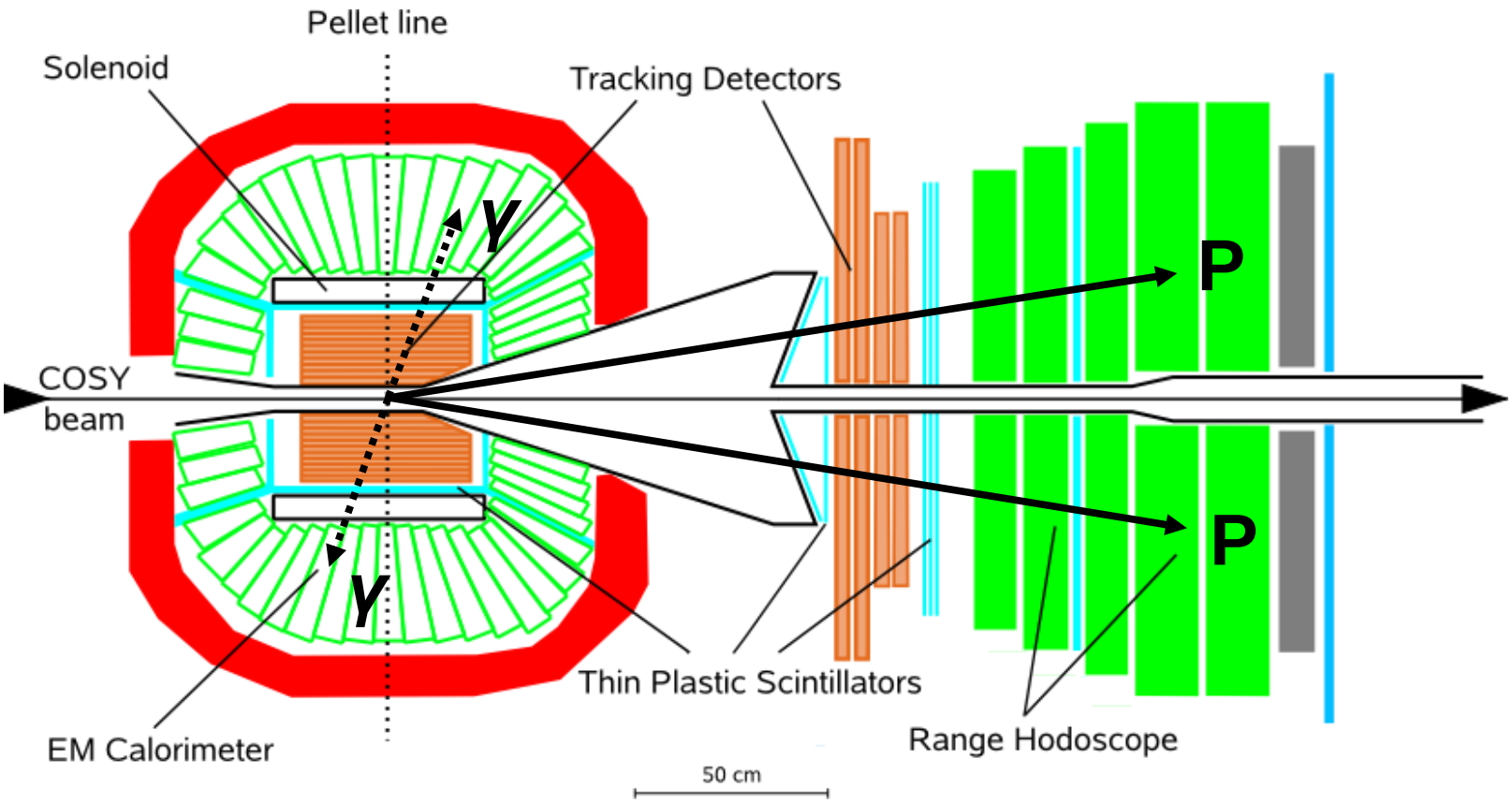
COSY-11: Phys. Rev. Lett. 98 (2007) 122003





K. Nakayama et al., Phys. Rev. C 65 (2002) 045210 pseudoscalar
G. F¨aldt and C. Wilkin, Phys. Scripta 64 (2001) 427 vector meson

WASA detector
H. H. Adam et al., nucl-ex/0411038



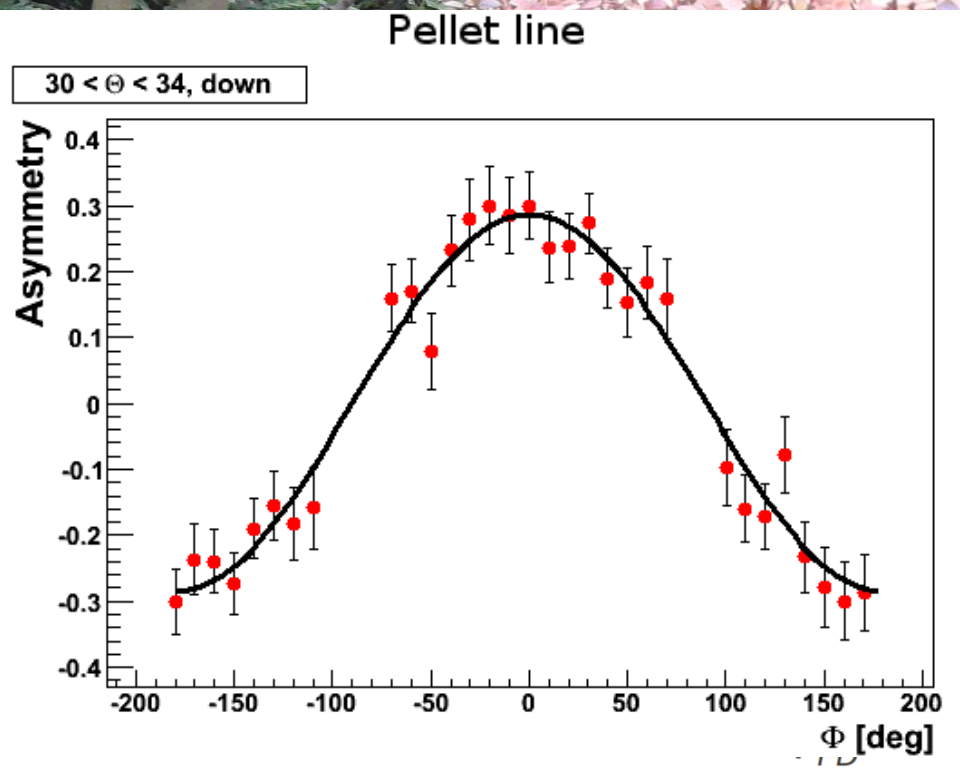
$$\vec{p}p \rightarrow pp\,\eta$$

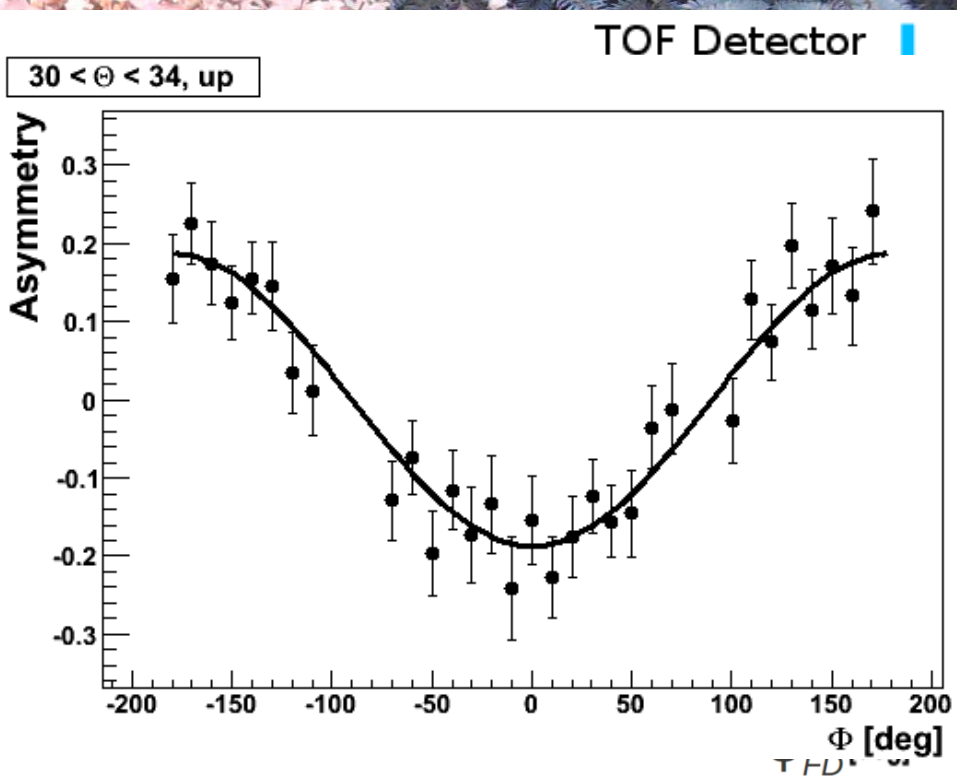
WASA-at-COSY

$\vec{p}p \rightarrow p\,p\,\eta$ 10^6 η mesons on discs ; Polarization of about 70%

more than factor of 100 larger statistics

I. Ozerianska, P.M., M. Zieliński, Acta Phys. Pol. B 46 (2015) 153

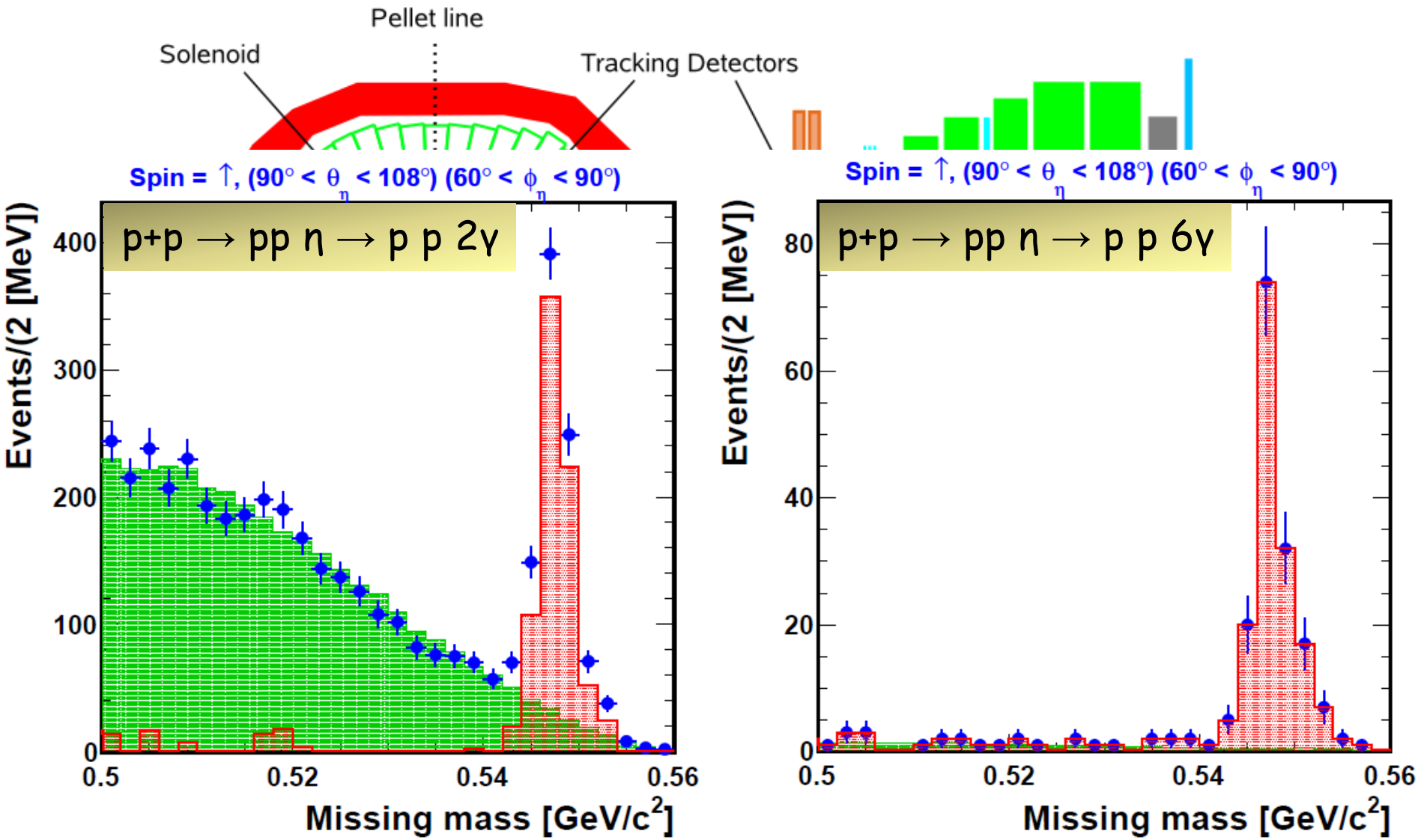




SPIN DOWN

SPIN UP

WASA-at-COSY: P. Adlarson et al., arXiv:1709.04547



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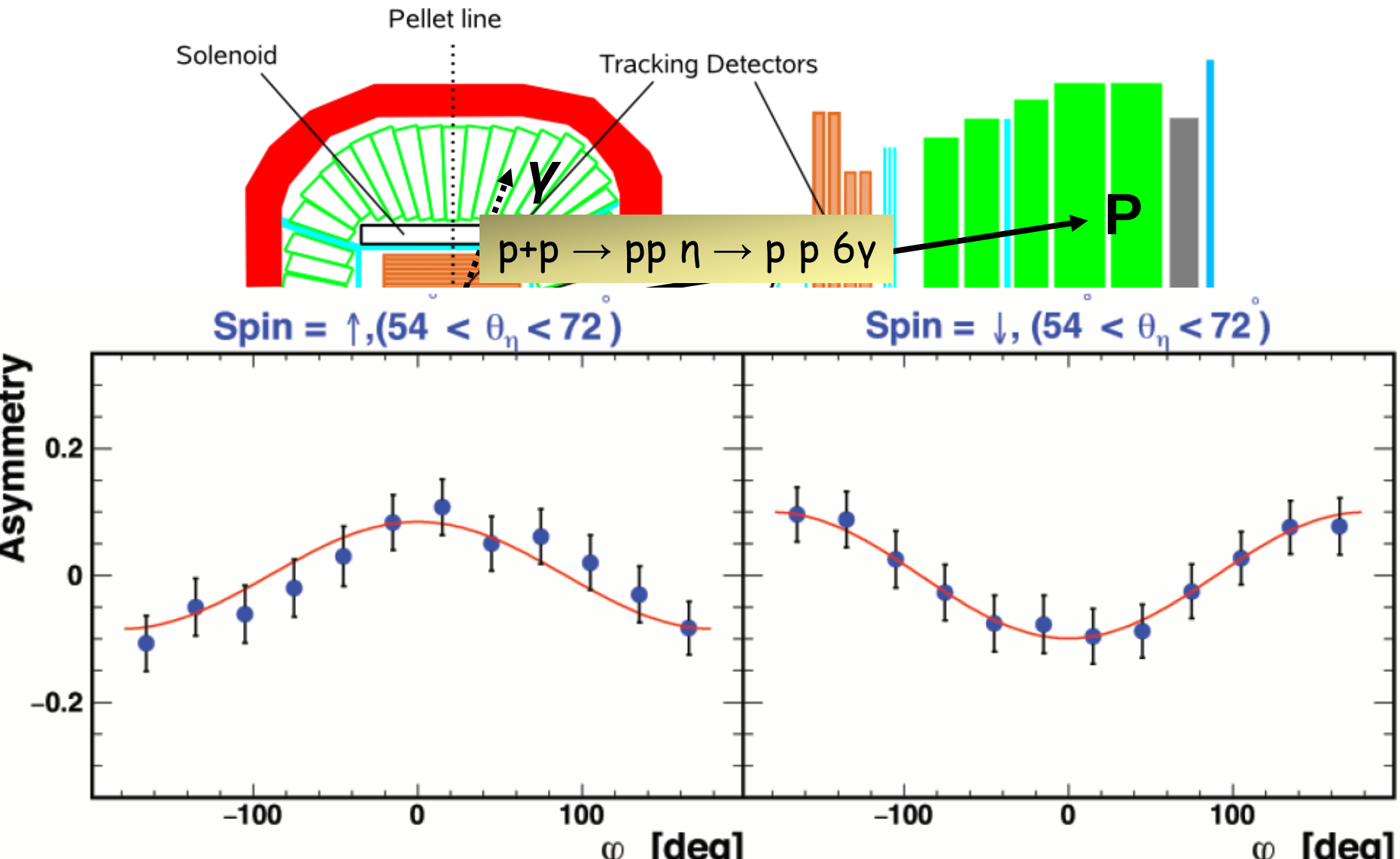

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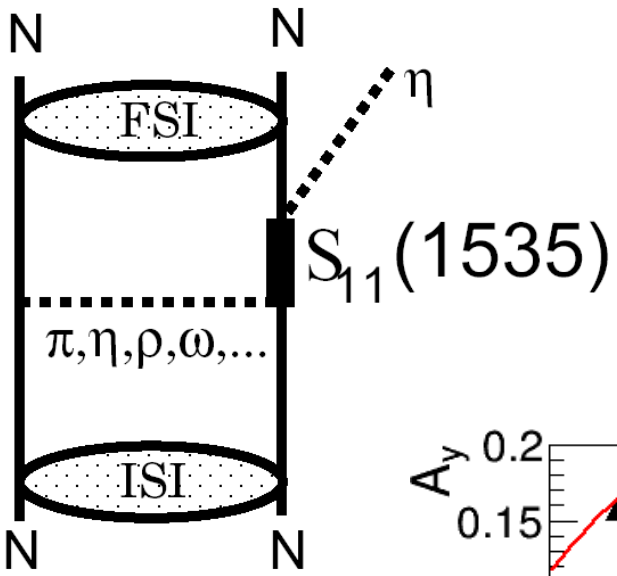
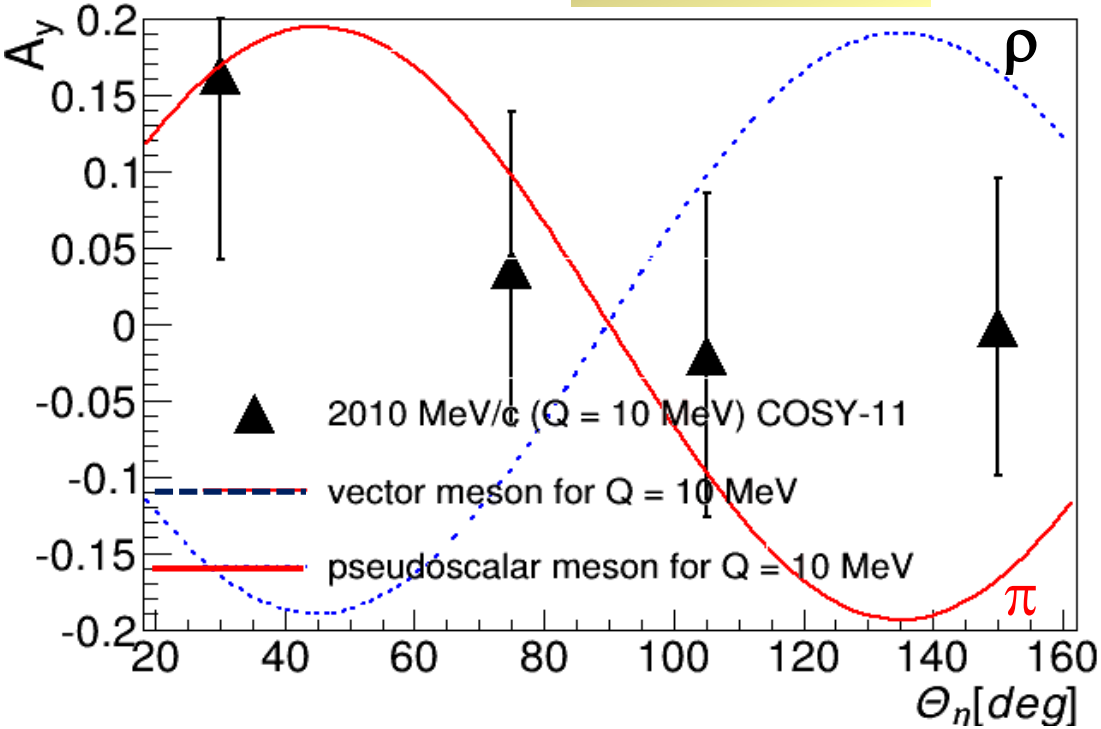


pp->ppη



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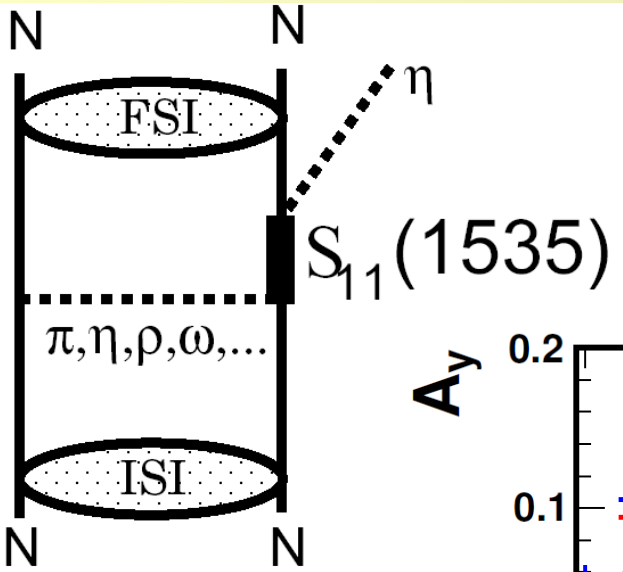

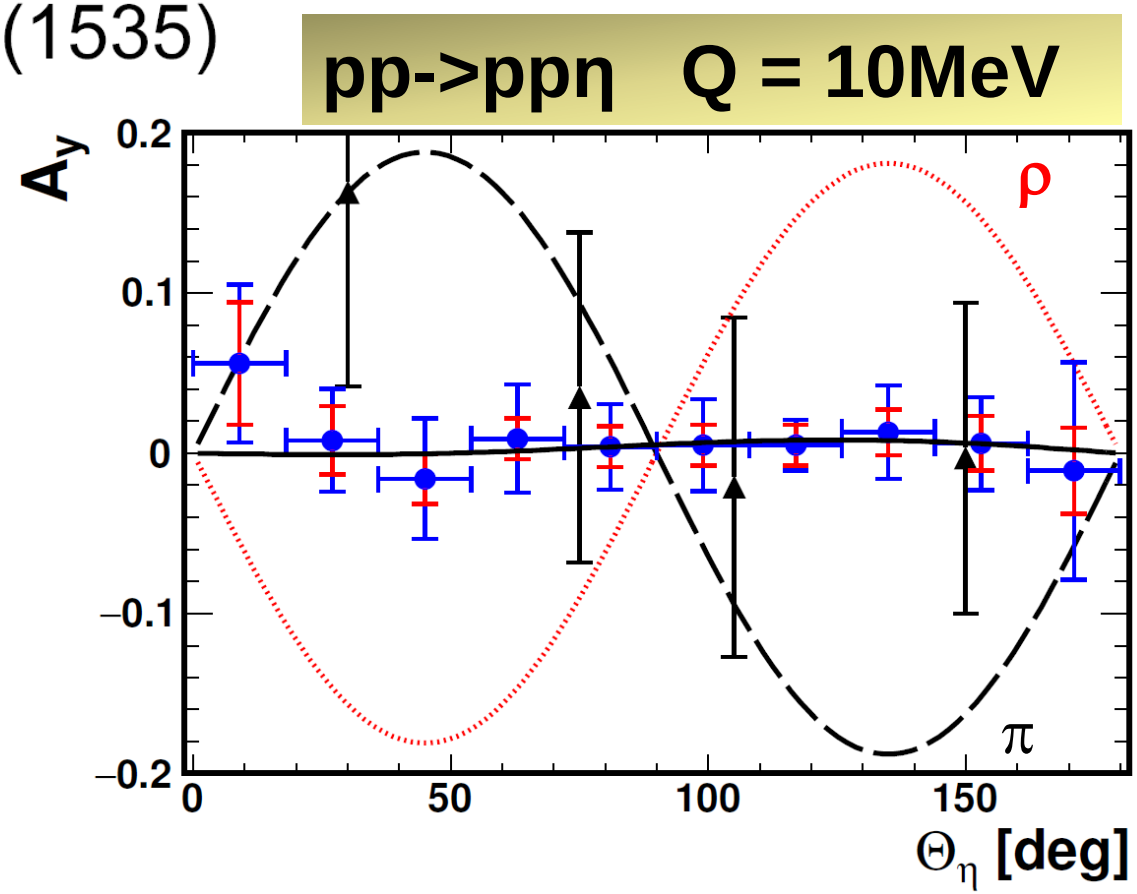

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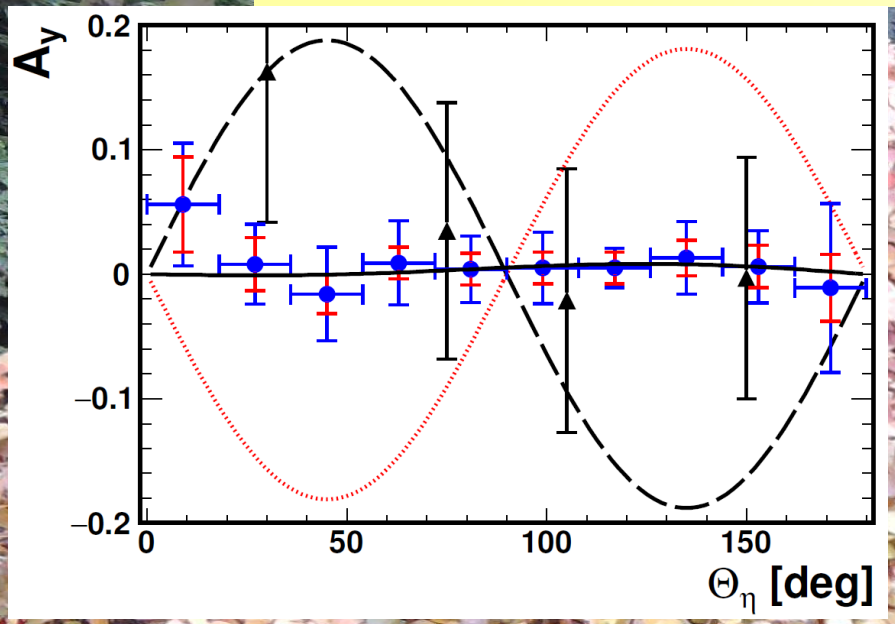
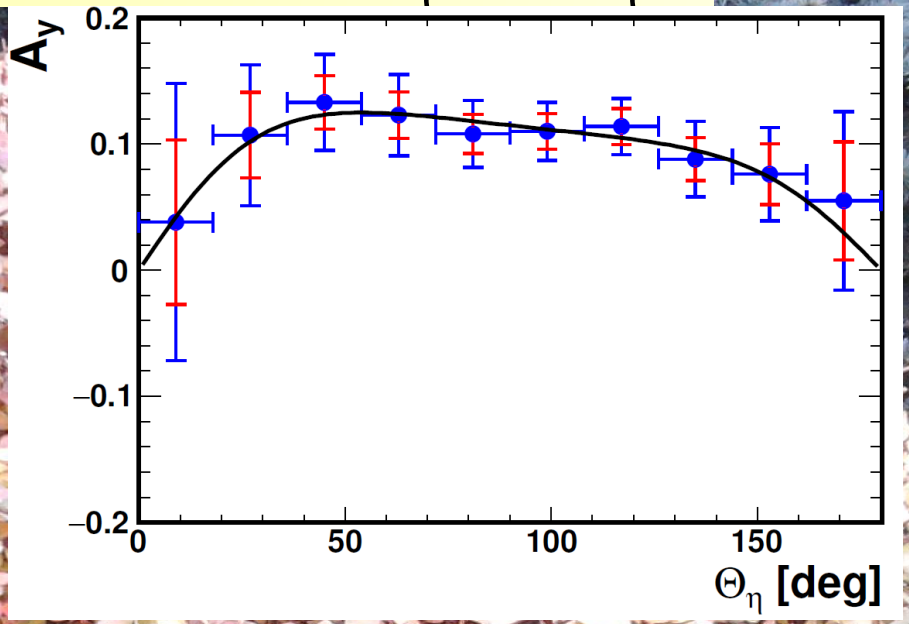
WASA-at-COSY: P. Adlarson et al., arXiv:1709.04547

C1 -> (Ps *Pp) $\sin\theta_\eta$

C2 -> (Ss *Sd + Pp *Pp) $\sin\theta_\eta \cos\theta_\eta$





Q = 10 MeV

C1 = 0 .001 ± 0.001

C2 = -0.002 ±0.003

Ss, ~~Sd, Ps, Pp~~

Q = 72 MeV

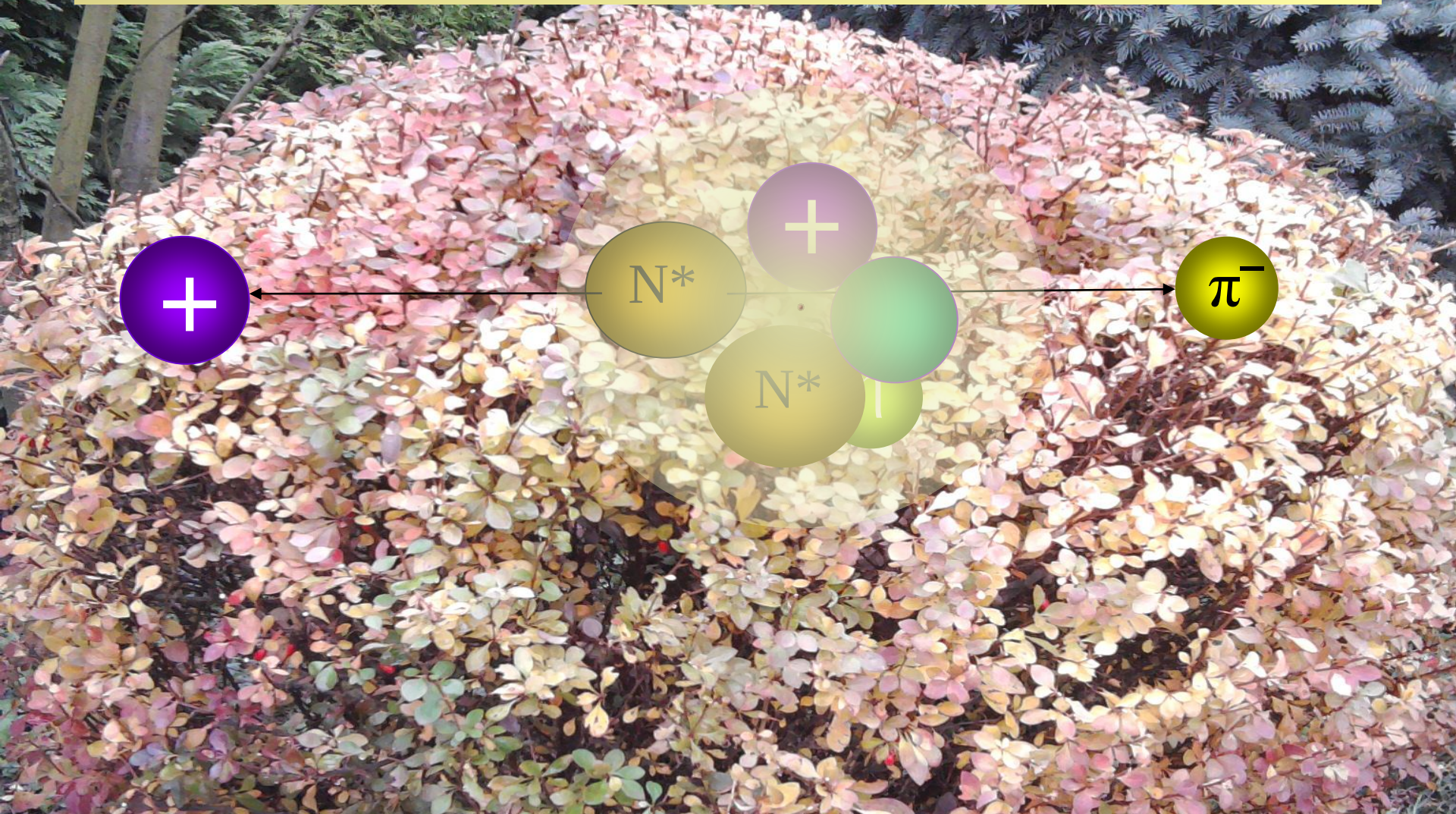
C1 = 0.104 ± 0.006

C2 = 0.020 ± 0.012

Ss*Sd and Pp*Pp cancel out

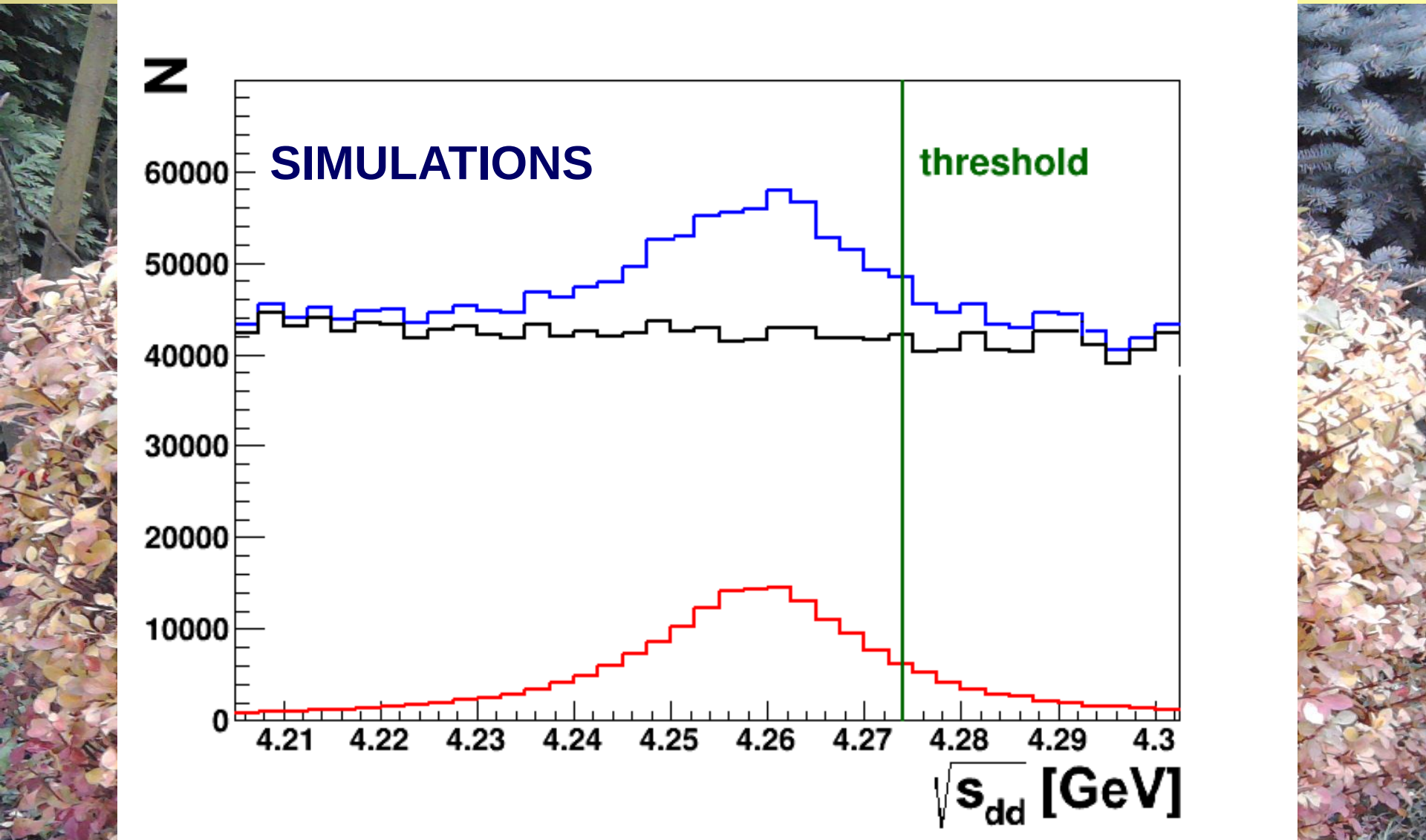
THE ETA-MESIC NUCLEUS

η meson bound with nucleus via STRONG INTERACTION



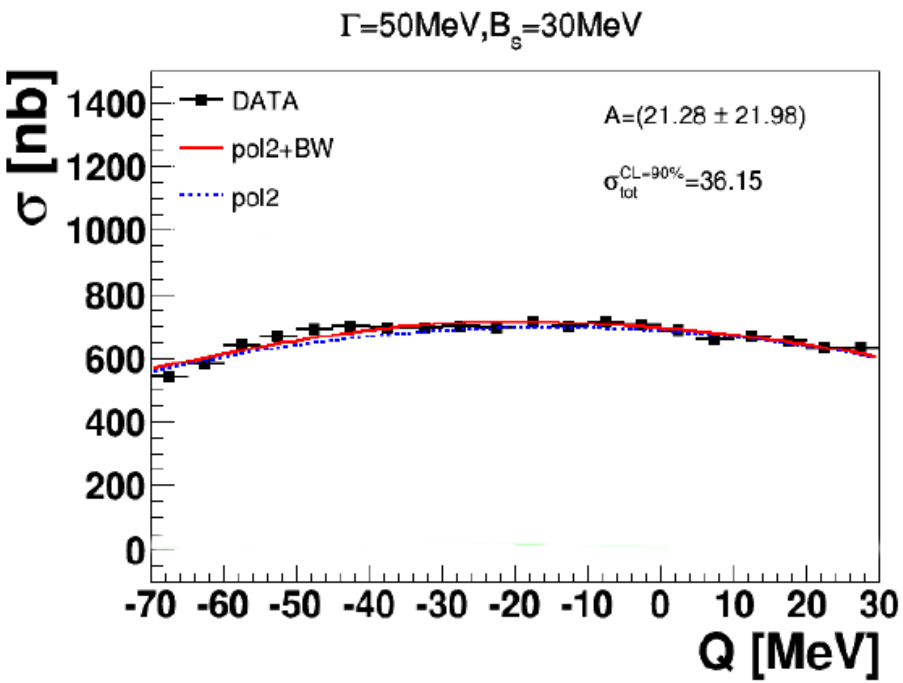
$$d+d \rightarrow (^4He\text{-}n)_{bound} \rightarrow {}^3He + p + \pi^-$$

$$d+d \rightarrow {}^3He + p + \pi^-$$

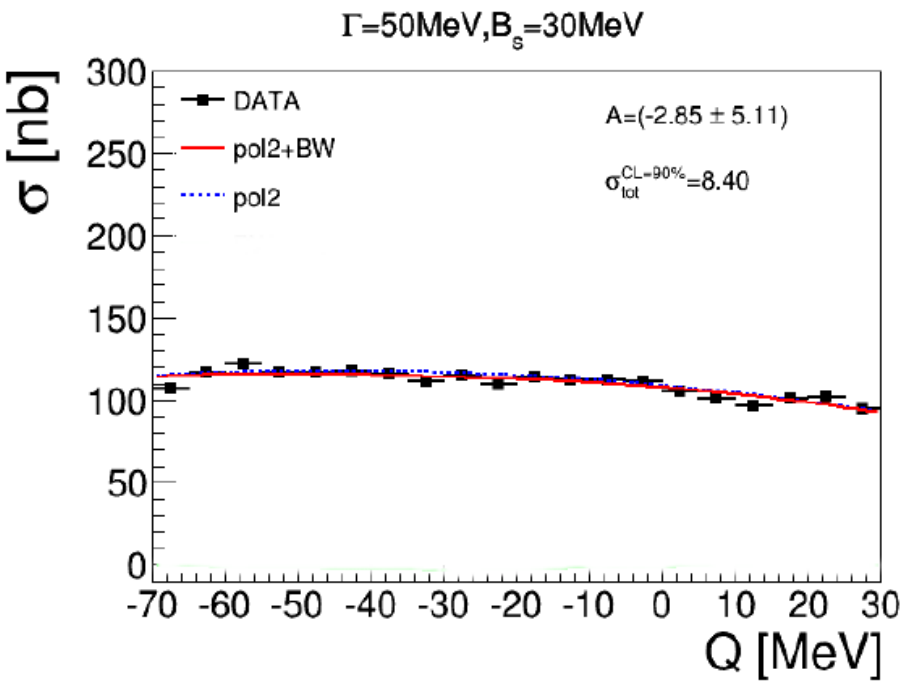


WASA-at-COSY:
P. Adlarson et al., Nucl. Phys. A 959 (2017) 102

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



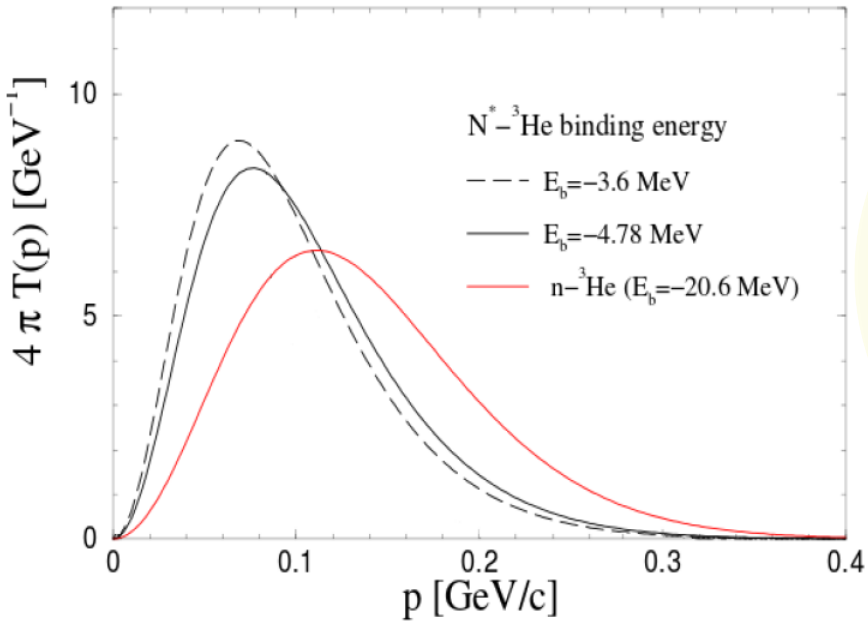
$dd \to {}^3\mathrm{He}p\pi^-$

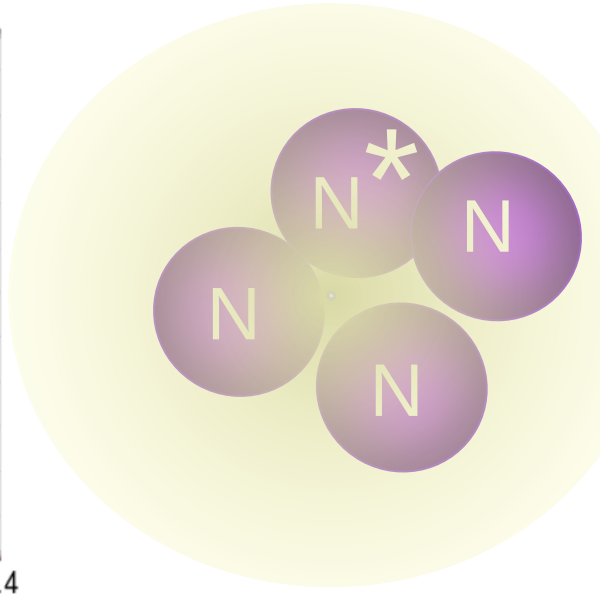


$$\sigma(Q,\Gamma,B_s,A) = \frac{A\cdot\Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4}$$

Systematics

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





N^*-^3He **momentum distribution - model proposed by prof. Neelima G. Kelkar**
(evaluation of N^*-nucleus potential by folding N^*N elementary interaction (constructed within $\pi + \eta$ exchange model) with nuclear density)

$$\Downarrow$$

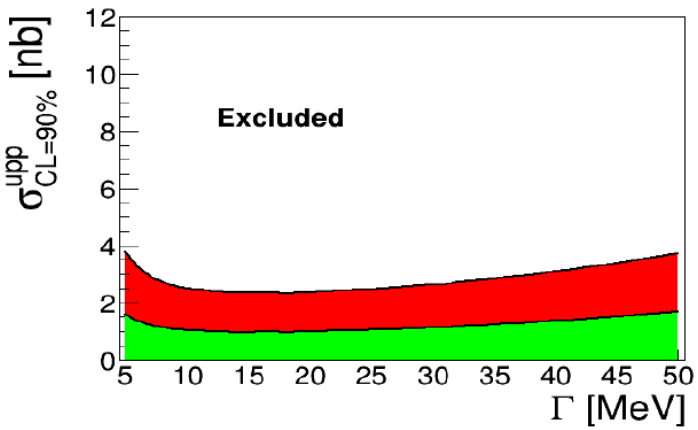
N. G. Kelkar, Eur. Phys. J. A 52 (2016) 309.

WASA-at-COSY:
P. Adlarson et al., Nucl. Phys. A 959 (2017) 102

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

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

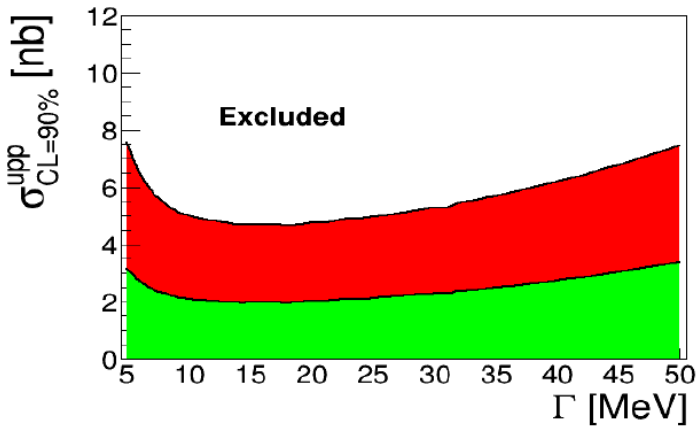
$\Downarrow$



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

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

$\Downarrow$



RESULT:

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

RESULT:

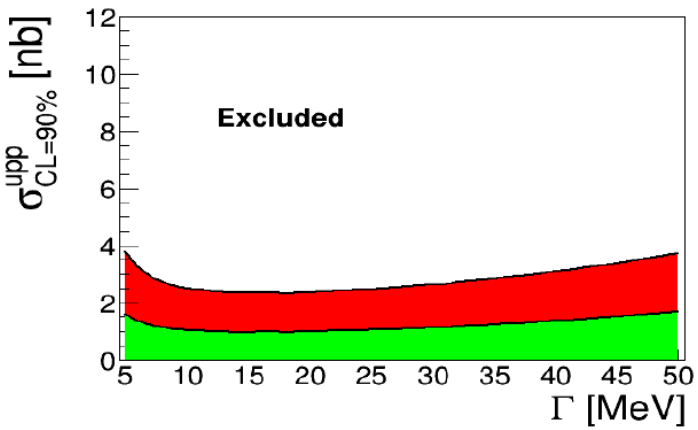
$\sigma_{dd\rightarrow({}^4He-\eta)_{bound}\rightarrow{}^3Hep\pi^-} < 7\ nb$

WASA-at-COSY:
P. Adlarson et al., Nucl. Phys. A 959 (2017) 102

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

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

$\Downarrow$



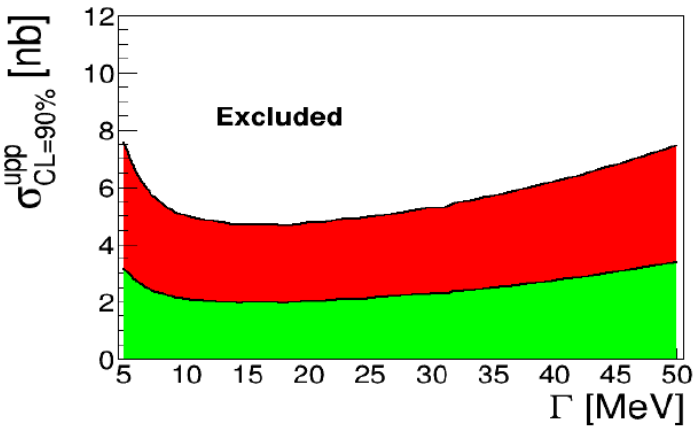
RESULT:

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

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

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

$\Downarrow$



RESULT:

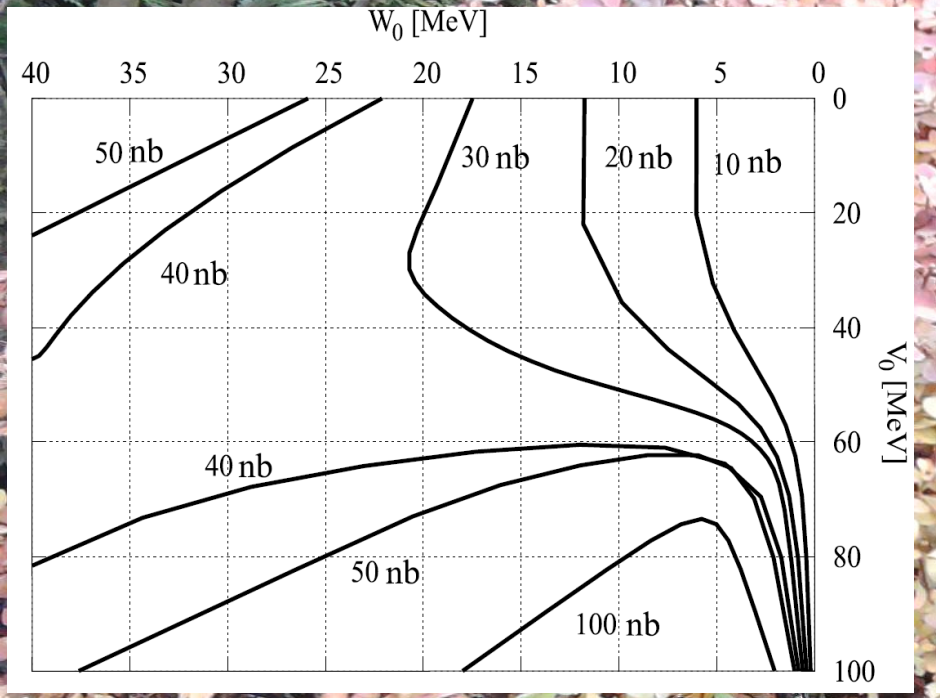
$\sigma_{dd\to({}^4He-\eta)_{bound}\to{}^3Hep\pi^-} < 7\ nb$

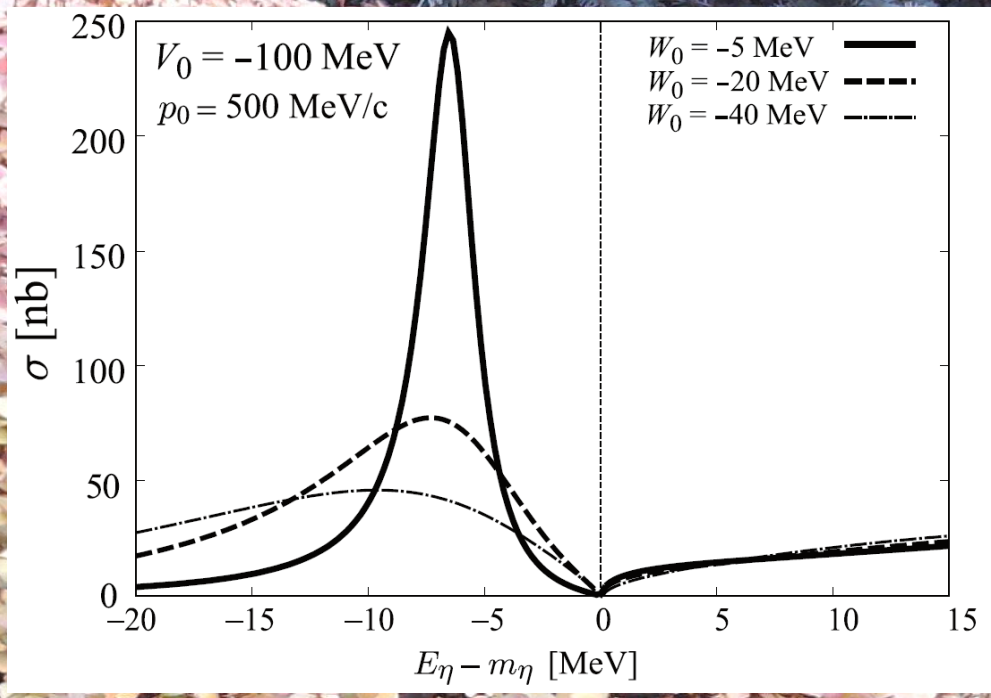
N. Barnea, B. Bazak, E. Friedman, A. Gal, Phys. Lett. B 771 (2017) 297
N. Barnea, Friedman, A. Gal, Nucl. Phys. A 968 (2017) 35
A. Fix, O. Kolesnikov, Phys. Lett. B 772 (2017) 663

...

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

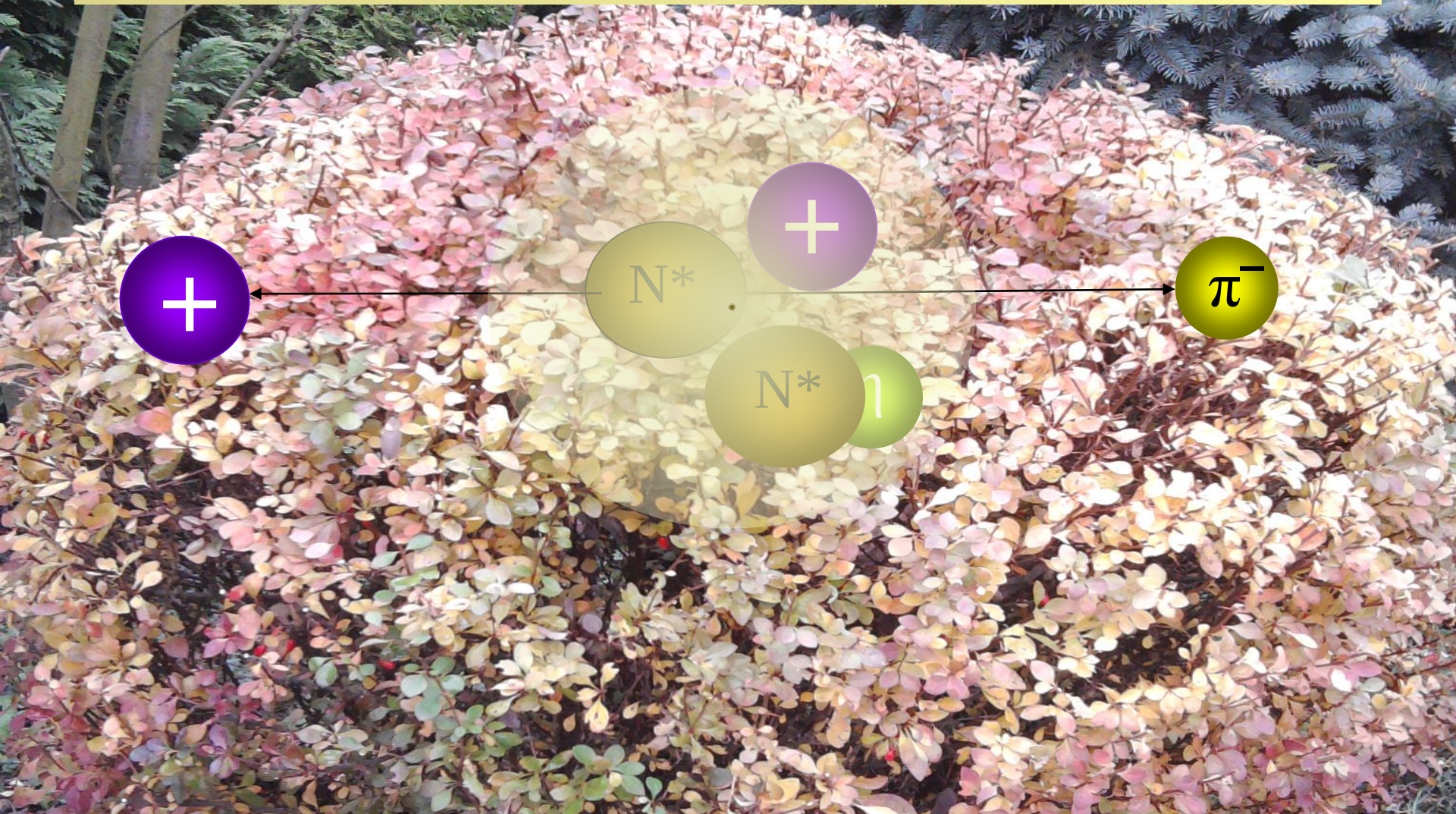
d+d → $(^4He\text{-}\eta)_{bound}$ → X





THE ETA-MESIC NUCLEUS

η meson bound with nucleus via STRONG INTERACTION



THE ETA-MESIC NUCLEUS

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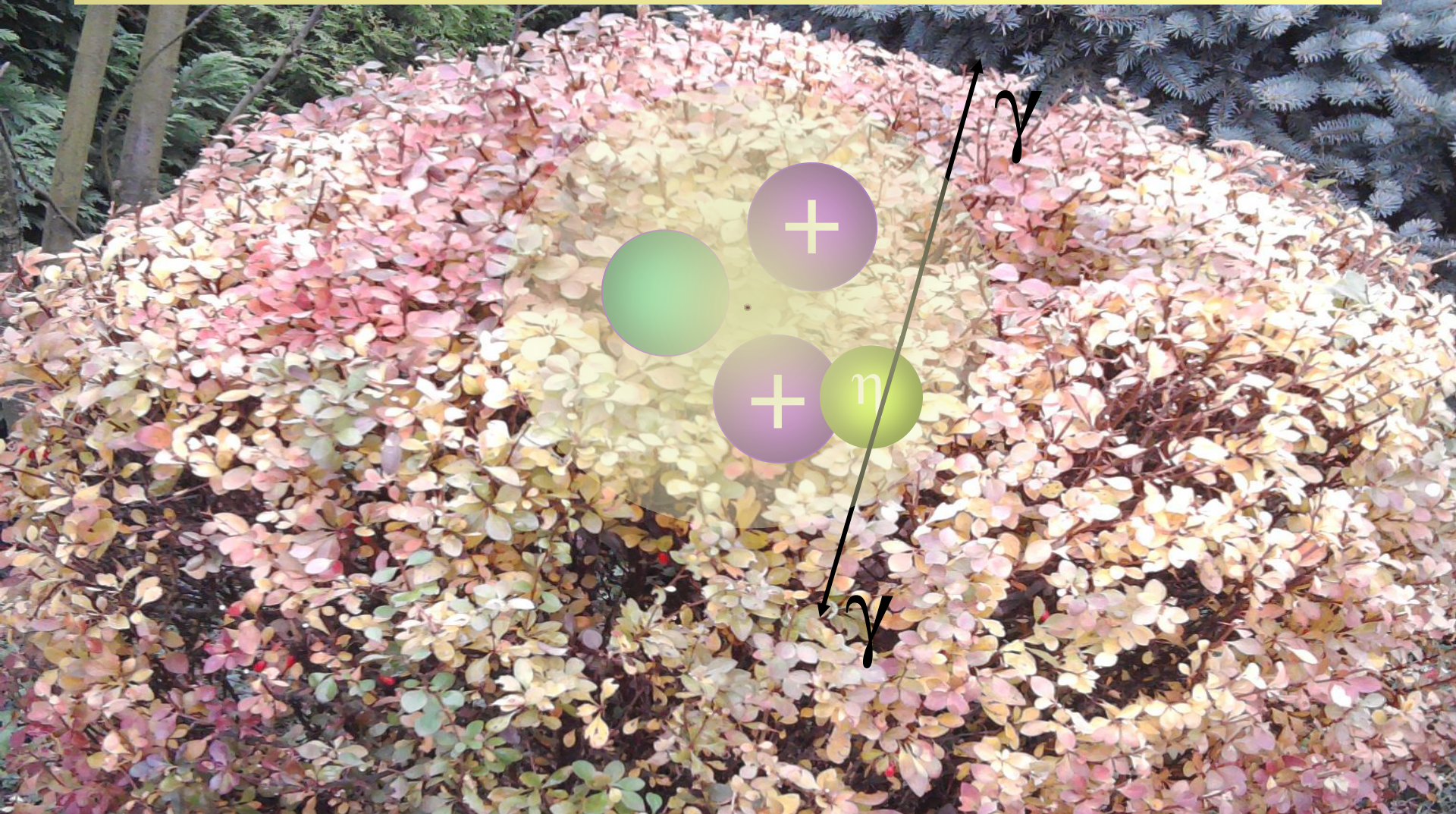
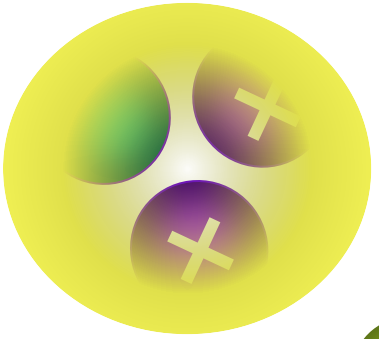
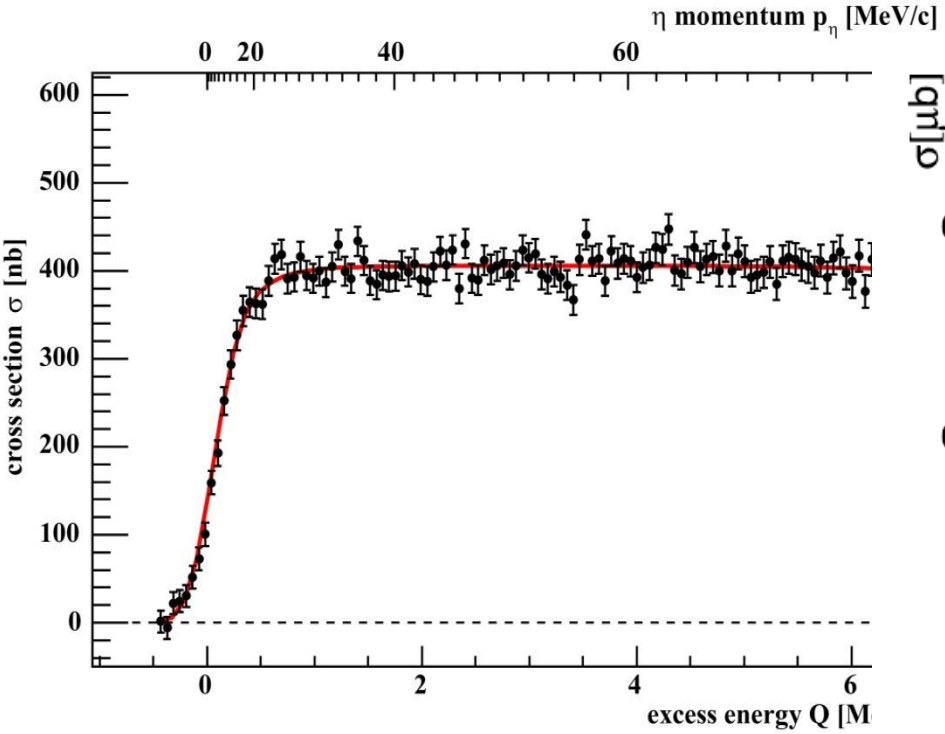


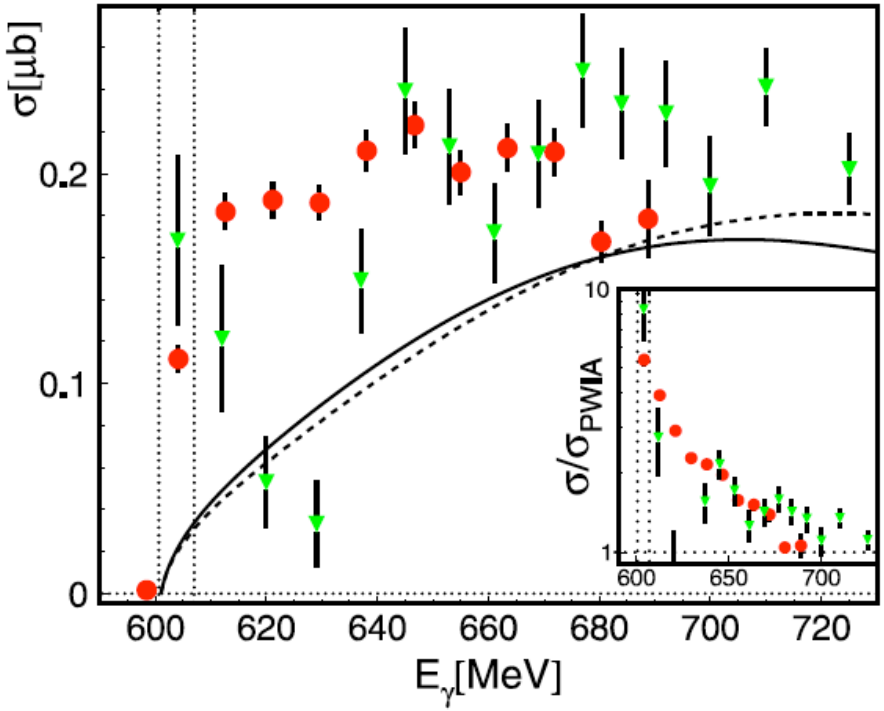
η - ^{3}He



- $dp \rightarrow {}^3\mathrm{He}\eta$

COSY





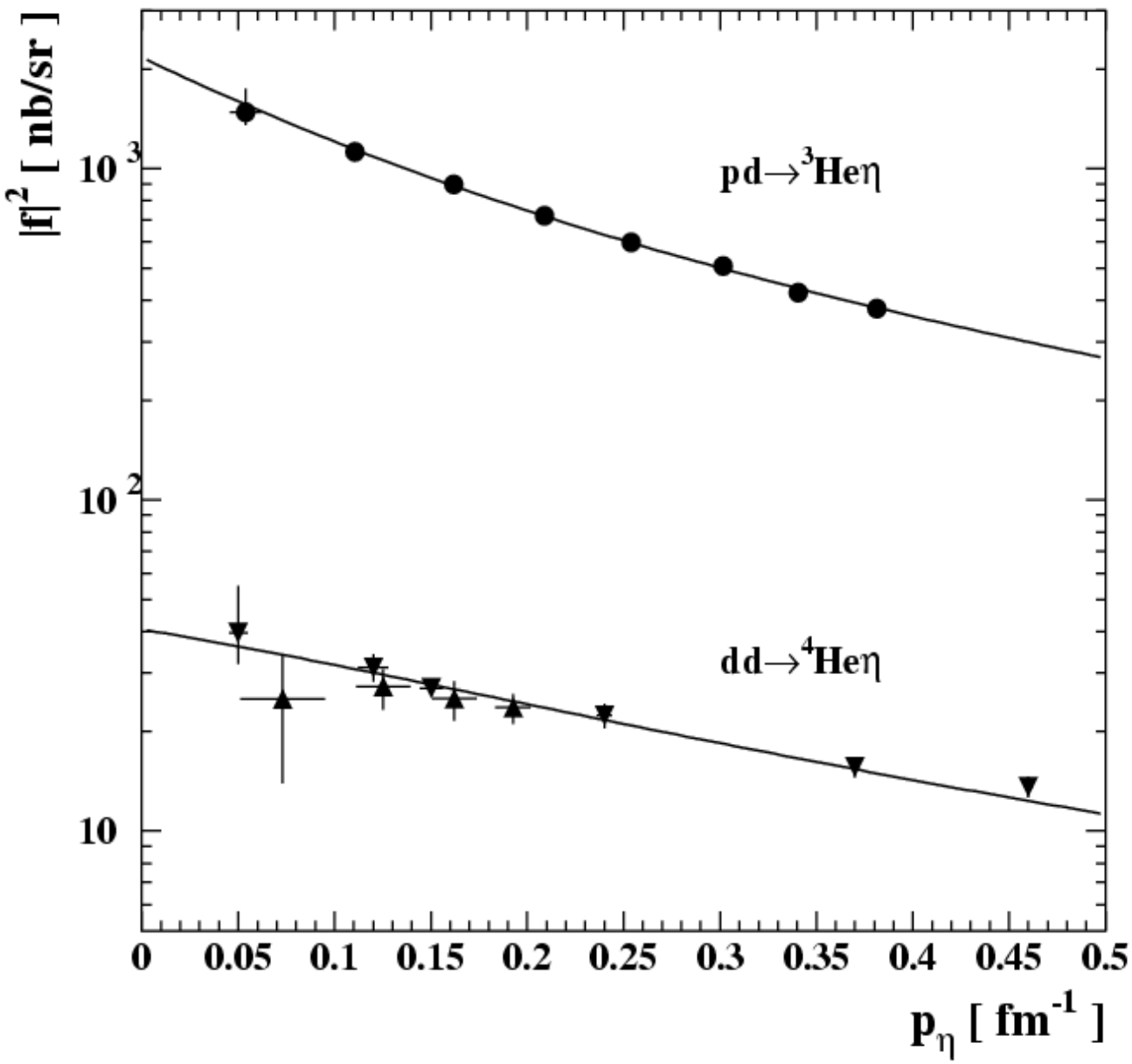
ANKE: T. Mersmann et al., Phys. Rev. Lett. **98** 242301 (2007)

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)

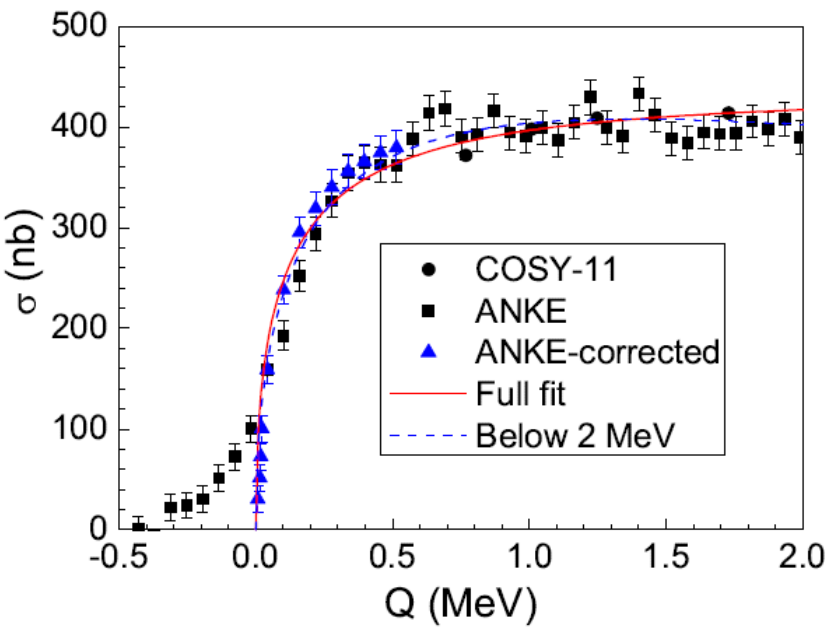


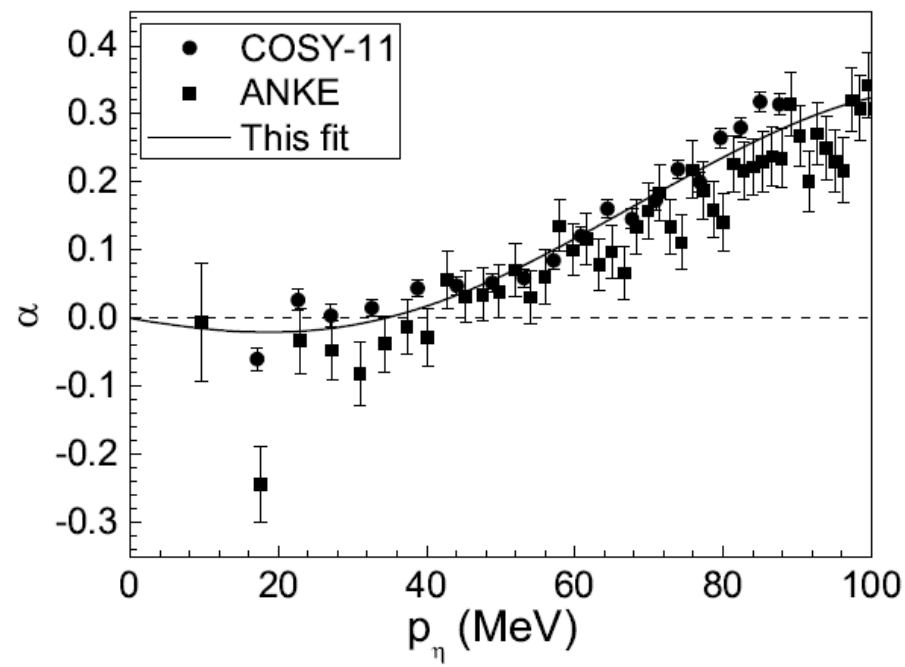
Prog. Part. Nucl. Phys. 49 (2002) 1

J.-J. Xie, W.-H. Liang, E.Oset et al.,
Phys. Rev. C 95 (2017) 015202

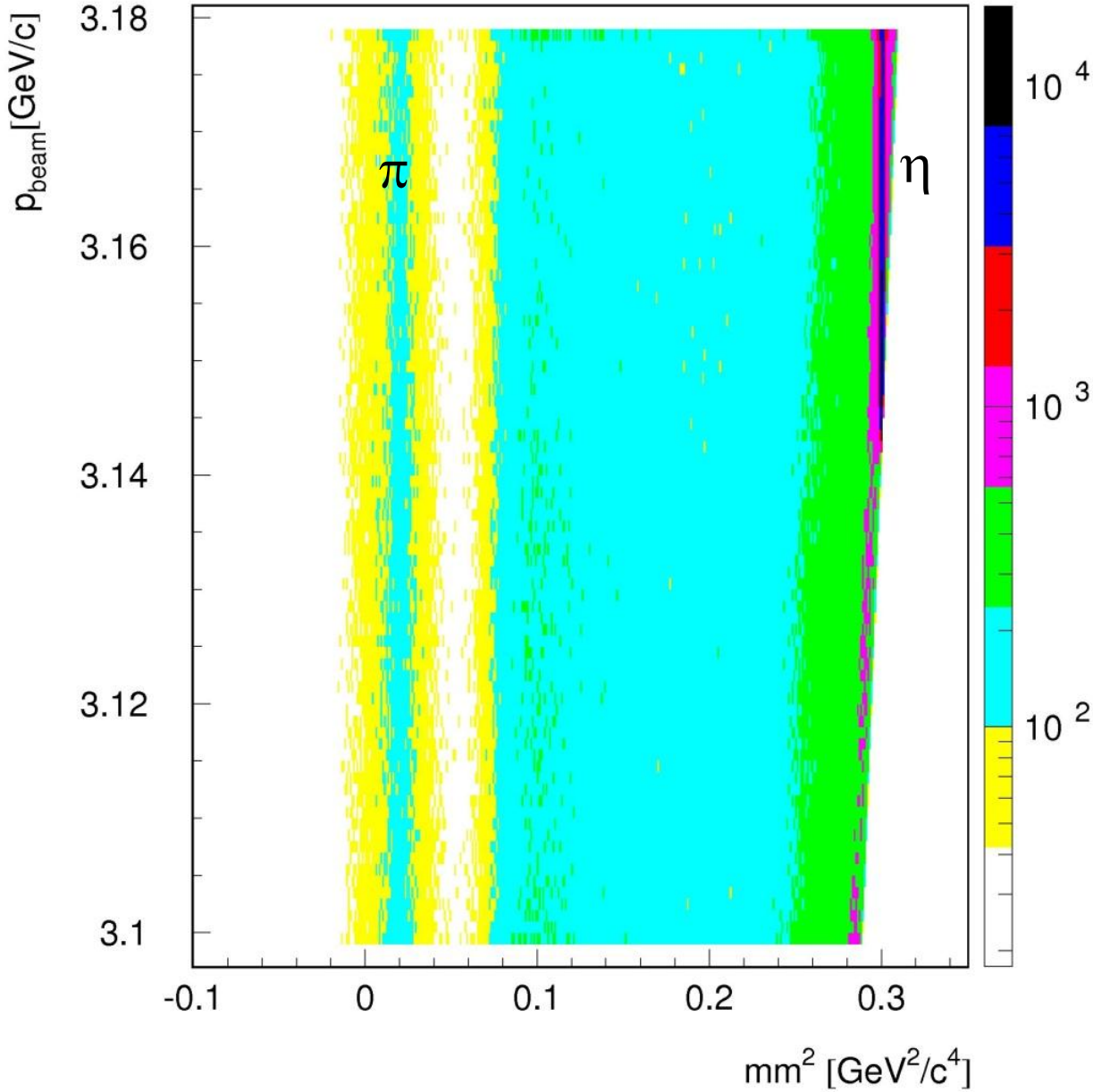
Chiral unitary approach

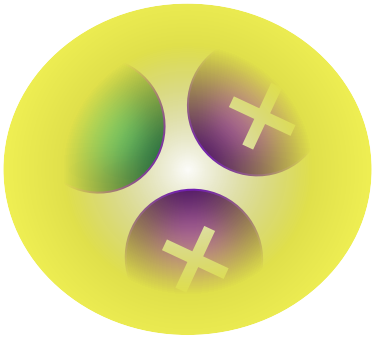
Generates the 3He-eta amplitude from the eta-3He potential fitted to the data. With this optical potential solve the BSE for the η 3He system and find an η bound state around 0.3 MeV and a width around 3 MeV,

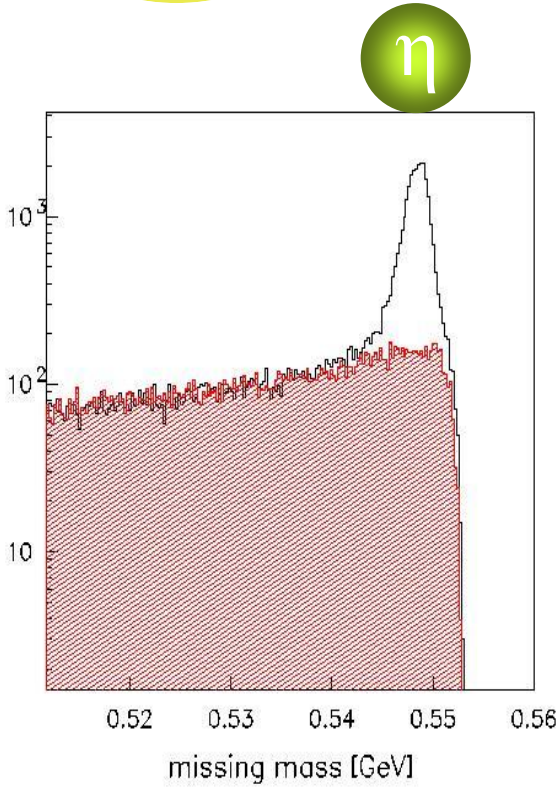




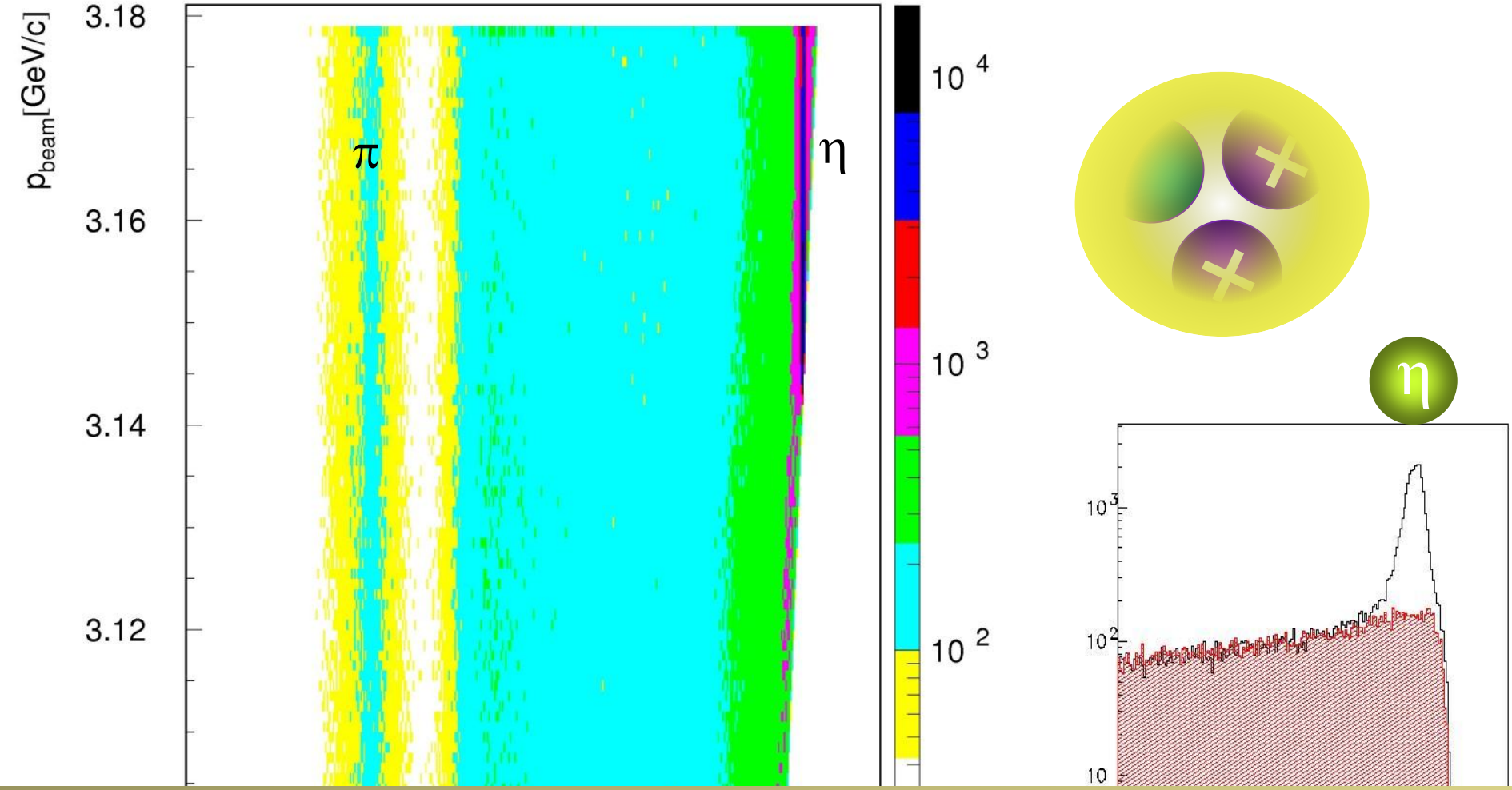
COSY-11 dp → ^{3}He X







COSY-11 dp → ^{3}He X



P.M., J. Smyrski, Acta Phys. Pol. B41 (2010) 2281

$\sigma(d+p \rightarrow (^3He\text{-}\eta)_{bound} \rightarrow {}^3He\ \pi^0) < 70$ nb

$\sigma(d+p \rightarrow (^3He\text{-}\eta)_{bound} \rightarrow p\ p\ p\ \pi^-) < 270$ nb

via N*

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

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

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

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

decay while orbiting

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

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

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 $pp p\pi^-$

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

~80 nb -- Theoretical estimation

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

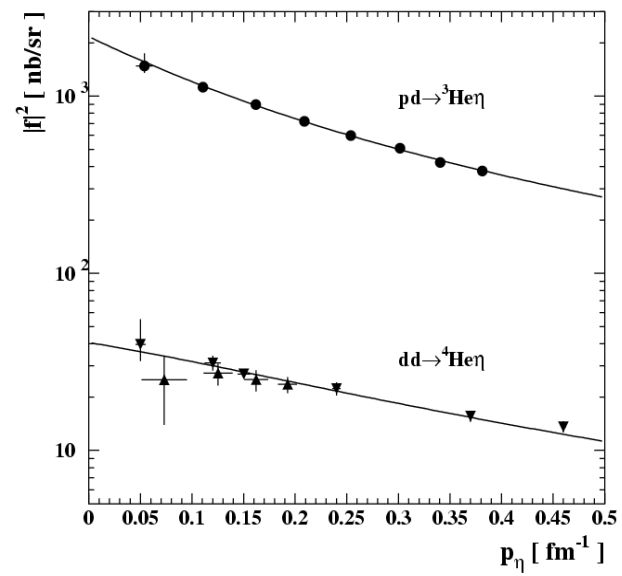
~ 10nb -- expected from New WASA-at-COSY data collected in May 2014

η - ^{4}He

~ 6 nb -- Present preliminary experimental upper limit

~ 4 nb -- Theoretical estimation

S. Wycech, W. Krzemien , Acta. Phy



Prog. Part. Nucl. Phys. 49 (2002) 1

η - ^{3}He

~270 nb -- Present experimental u

COSY-11: Acta Phys. Pol B41 (2

~80 nb -- Theoretical estimation

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

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


THANK YOU
FOR YOUR ATTENTION

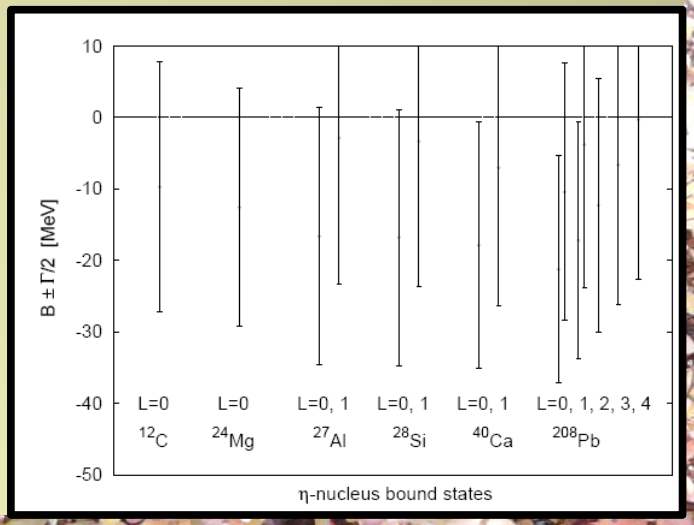
Attractive interaction between η and N

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

possible existence of bound states of the η meson with nuclei for A>10

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

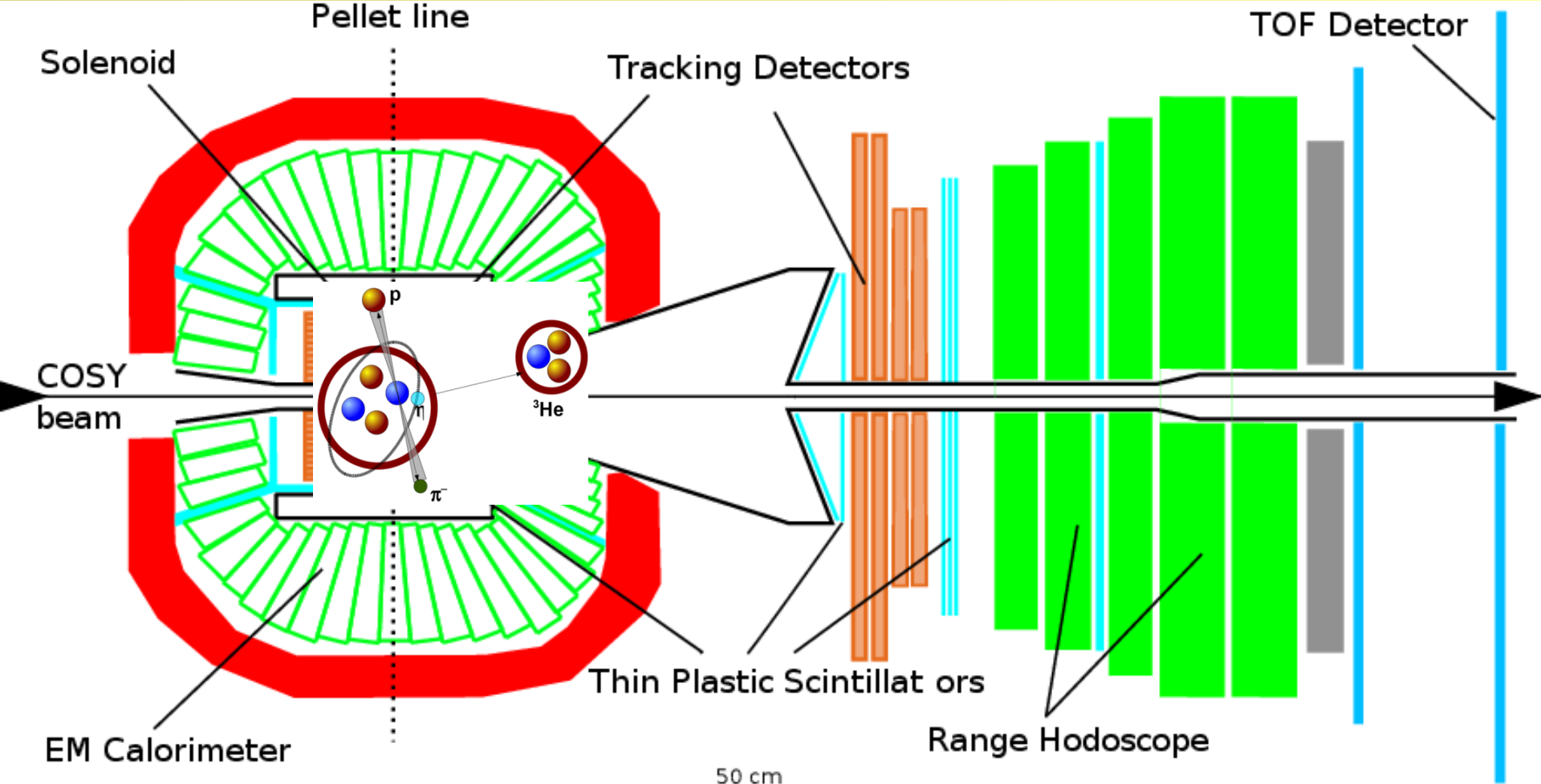
(C.Garcia-Recio, T. Inoue, J.Nieves, E. Oset, Phys. Lett. B550 (2002) 47).

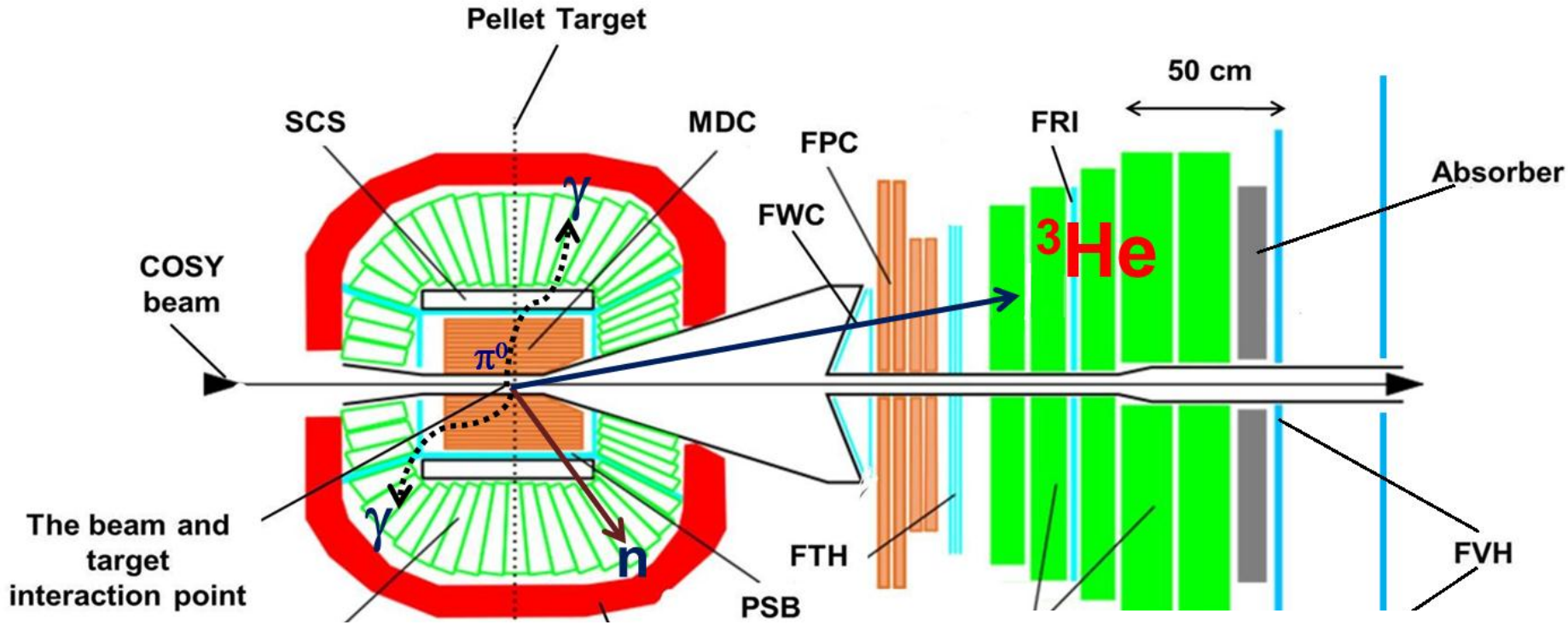


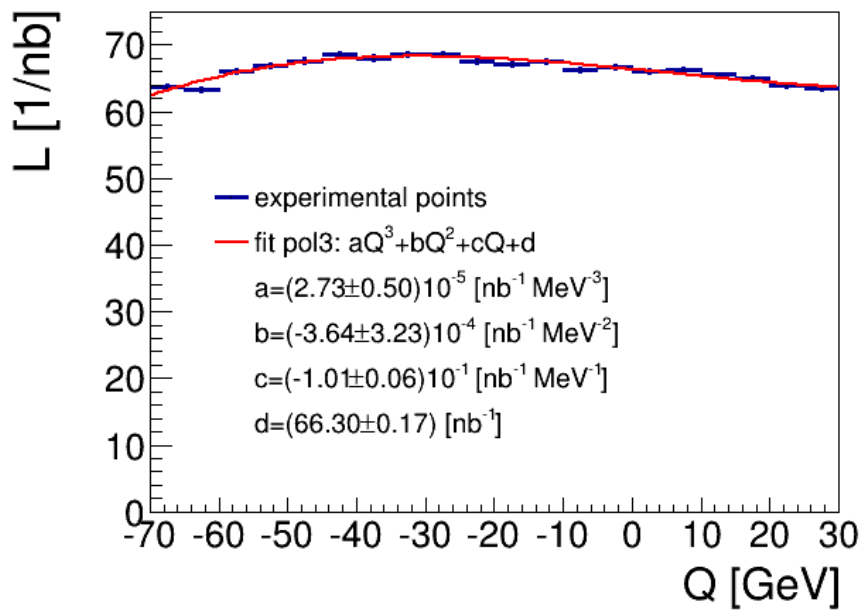
WASA-at-COSY

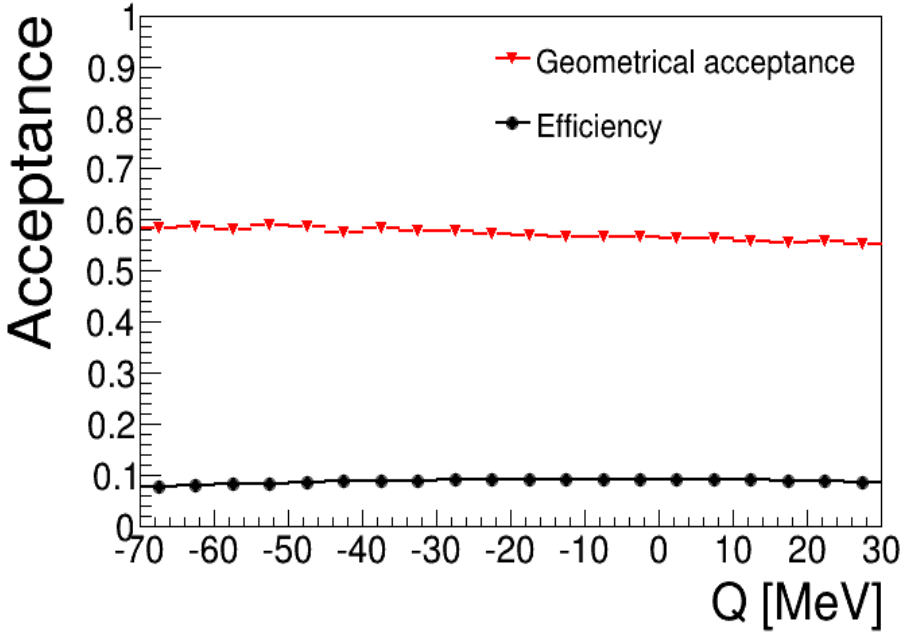
$$d+d \rightarrow (^4He\text{-}n)_{bound} \rightarrow {}^3He + p + \pi^-$$

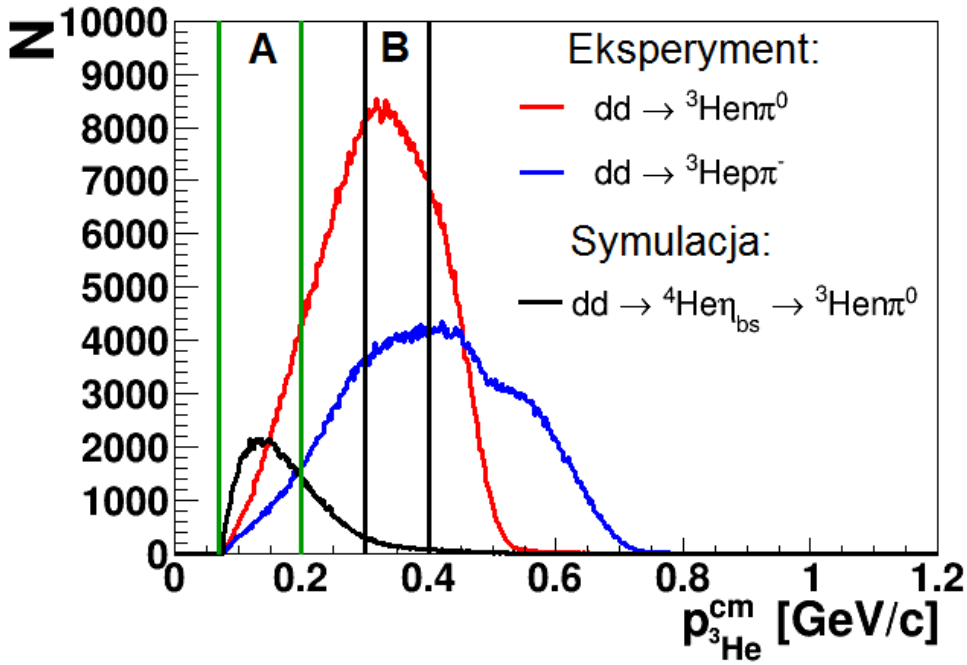
$$d+d \rightarrow {}^3He + p + \pi^-$$

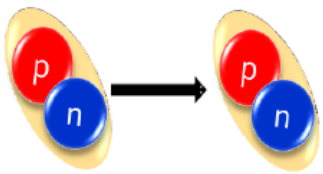



Pellet Target
SCS
MDC
FPC
FRI
50 cm
Absorber
FWC
COSY beam
^{3}He
γ
π^0
γ
n
The beam and target interaction point
FTH
PSB
FVH

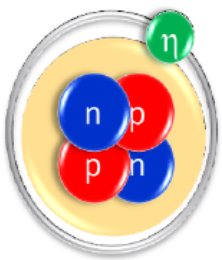

L [1/nb]
experimental points
fit pol3: aQ^3+bQ^2+cQ+d
$a=(2.73\pm0.50)10^{-5}$ [nb^{-1} MeV^{-3}]
$b=(-3.64\pm3.23)10^{-4}$ [nb^{-1} MeV^{-2}]
$c=(-1.01\pm0.06)10^{-1}$ [nb^{-1} MeV^{-1}]
$d=(66.30\pm0.17)$ [nb^{-1}]
Q [GeV]


Acceptance
Geometrical acceptance
Efficiency
Q [MeV]

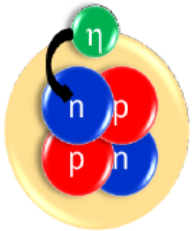




DEUTERON FUSION

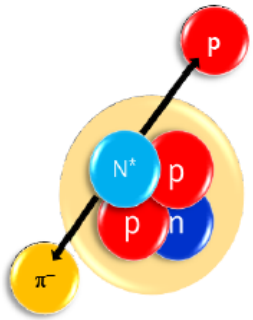


CREATION OF η-MESIC NUCLEUS

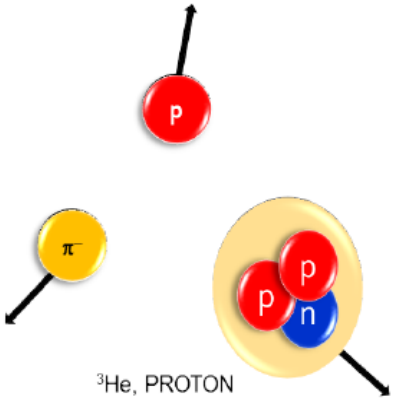


ABSORPTION OF η MESON BY ONE OF NUCLEON INSIDE THE HELIUM

NUCLEON EXCITATION INSIDE THE NUCLEUS – N* RESONANCE FORMATION



RESONANCE DECAY INTO PION AND PROTON INSIDE NUCLEUS

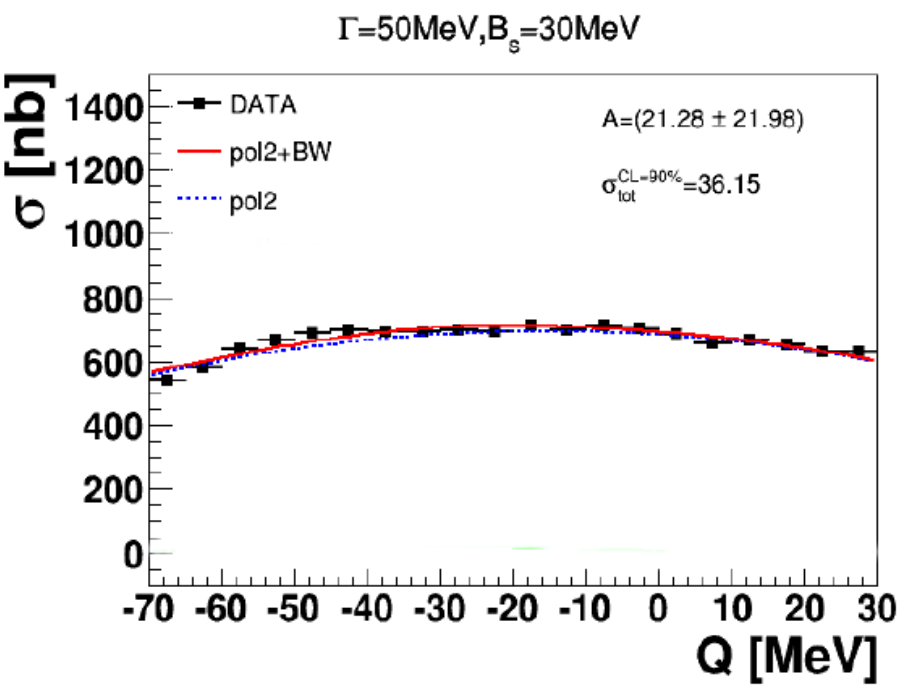


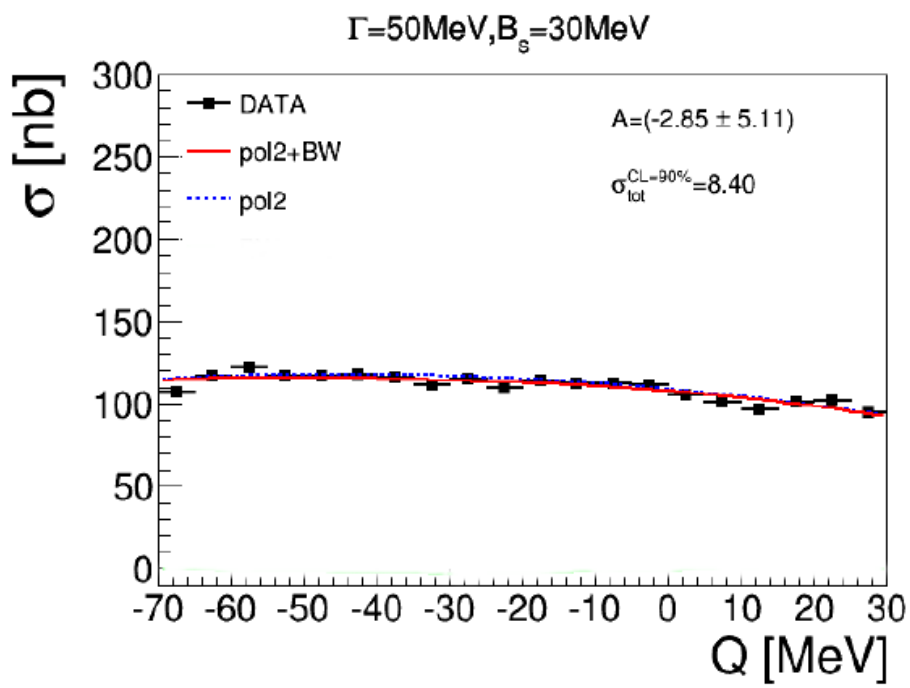
³He, PROTON AND MESON π⁻ EMISSION

Upper limit of the total cross section at CL=90%

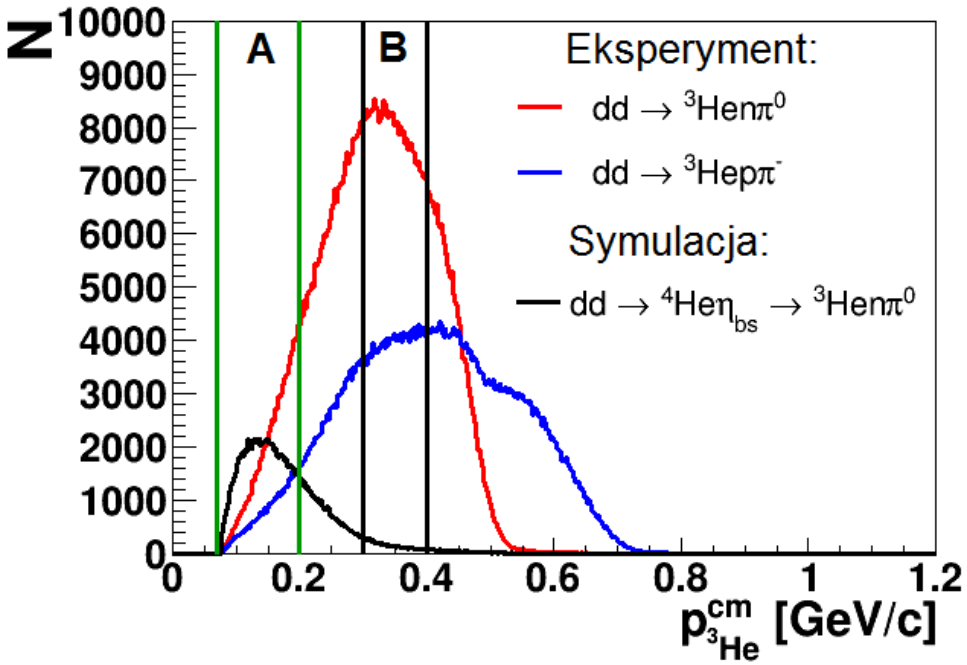
$dd \to {}^3\mathrm{He}n\pi^0$ $\qquad$ $dd \to {}^3\mathrm{He}p\pi^-$

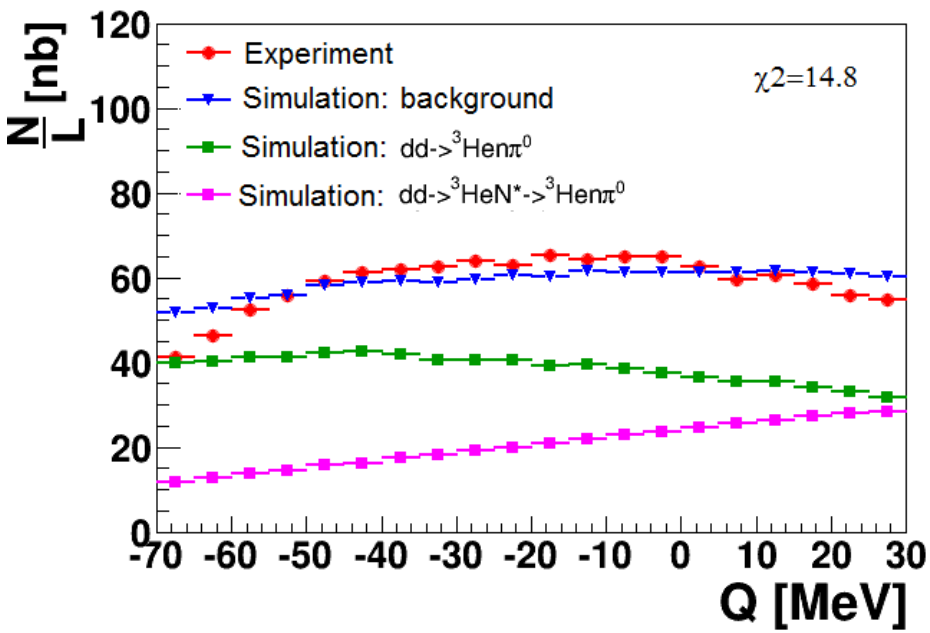
PRELIMINARY

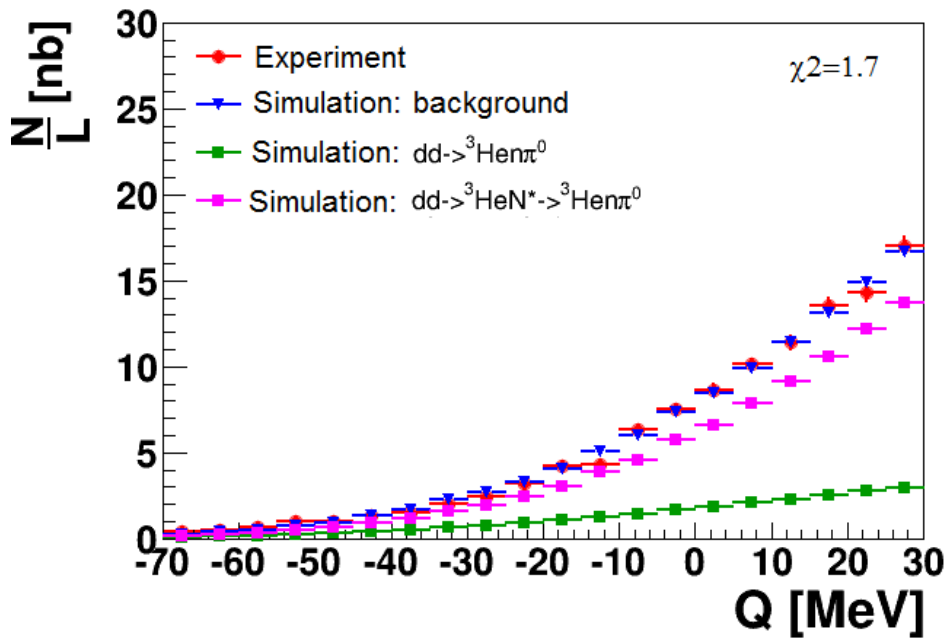


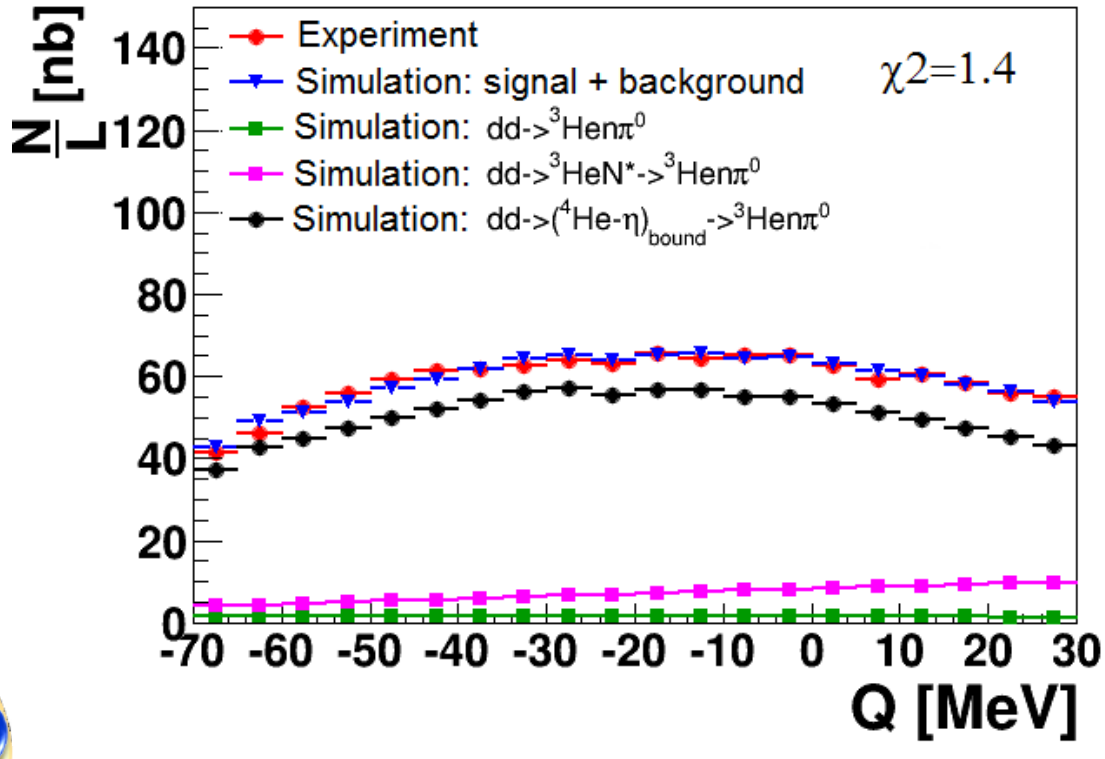


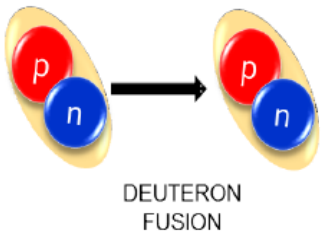
$$\sigma(Q,\Gamma,B_s,A) = \frac{A\cdot\Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4}$$


N
A
B
Eksperyment:
dd → ³Henπ⁰
dd → ³Hepπ⁻
Symulacja:
dd → ⁴Heη_bs → ³Henπ⁰
p^cm_³He [GeV/c]

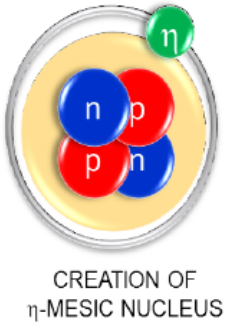

N/L [nb]
Experiment
Simulation: background
Simulation: dd->³Henπ⁰
Simulation: dd->³HeN*->³Henπ⁰
χ2=14.8
Q [MeV]

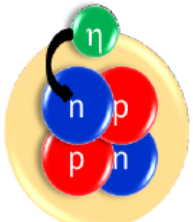

N/L [nb]
Experiment
Simulation: background
Simulation: dd->³Henπ⁰
Simulation: dd->³HeN*->³Henπ⁰
χ2=1.7
Q [MeV]

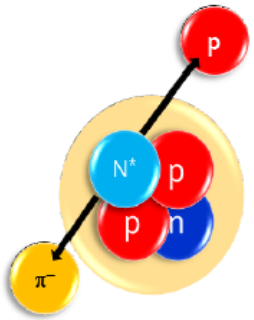


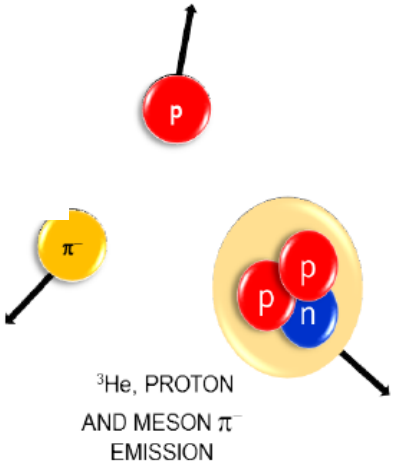


SCHEME OF REACTION PROCESS ,
IN WHICH η–MESIC NUCLEUS IS FORMED

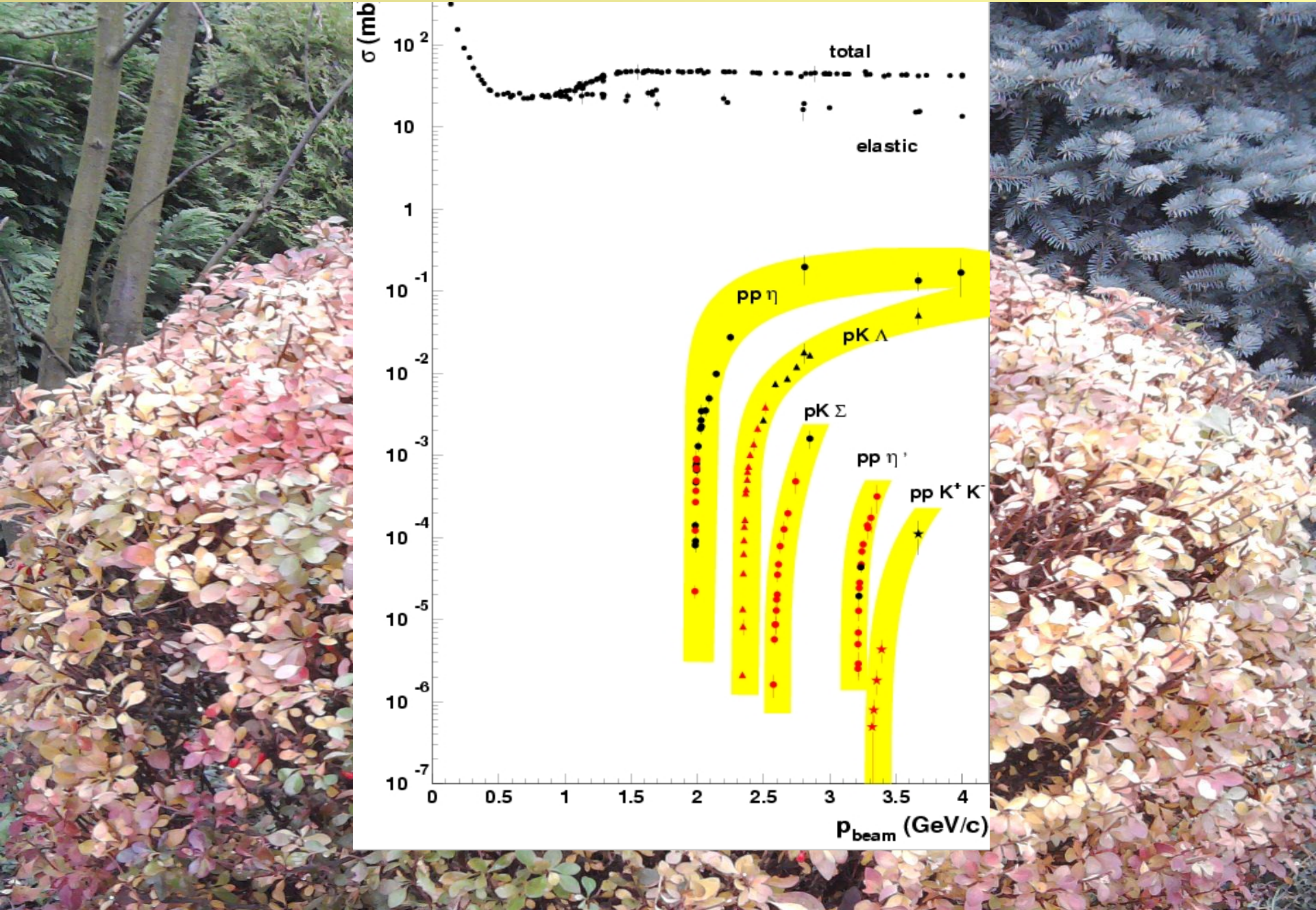








experimental challenge !

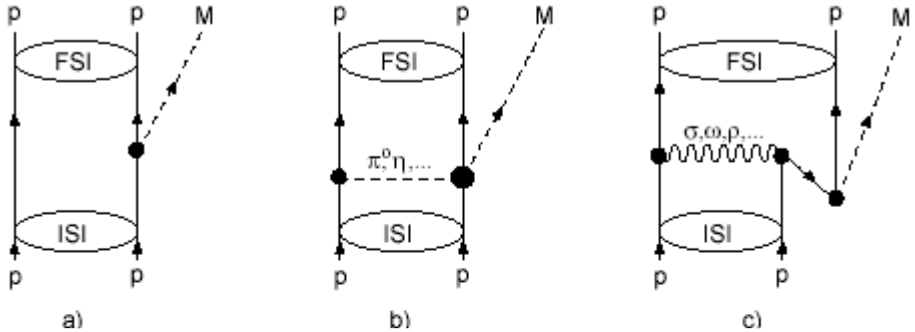


production dynamics e.g. meson η

$$\sigma = \frac{1}{F}\int dV_{ps}\,|M|^2$$

$$|M|^2 \sim |M_0|^2\,|M_{FSI}|^2$$

dynamics $\rightarrow$ $|M_0|^2$

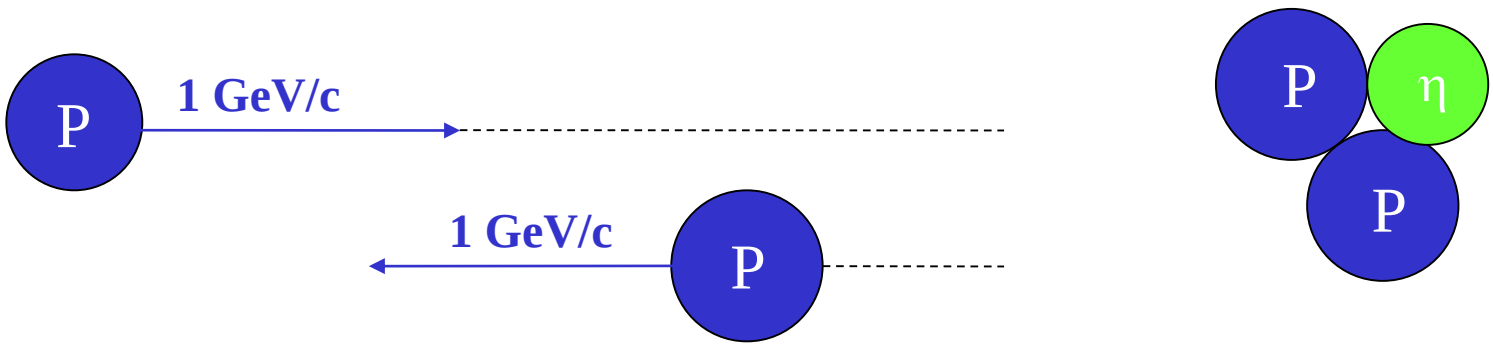


What would the first experimental physicists tell us?

Salviati. *But if, of many computations,*
not even two came out in agreement,
what would you think of that?

Simplicio. *If that is how the matters stand,*
it is truly a serious defect

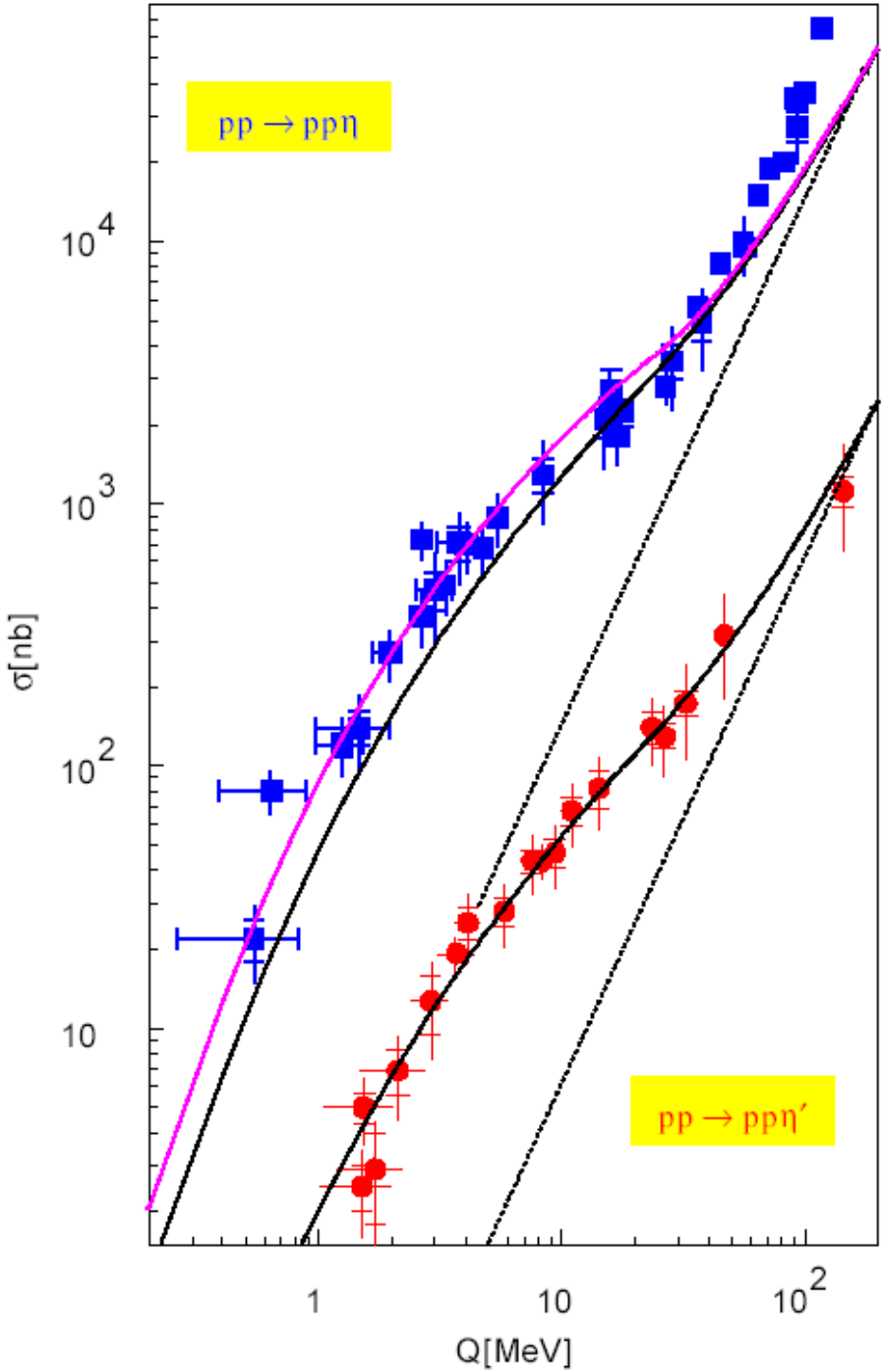
GALILEO GALILEI
"Dialogue concerning the two chief world systems"



cannot have innumerable explanations

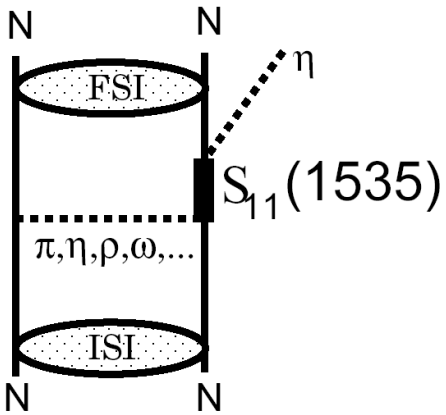
ONE NUMBER and MANY GRAPHS

NICOLAUS COPERNICUS
"Minor Works III, Letter against Wagner"



dynamics → $|M_0|^2$

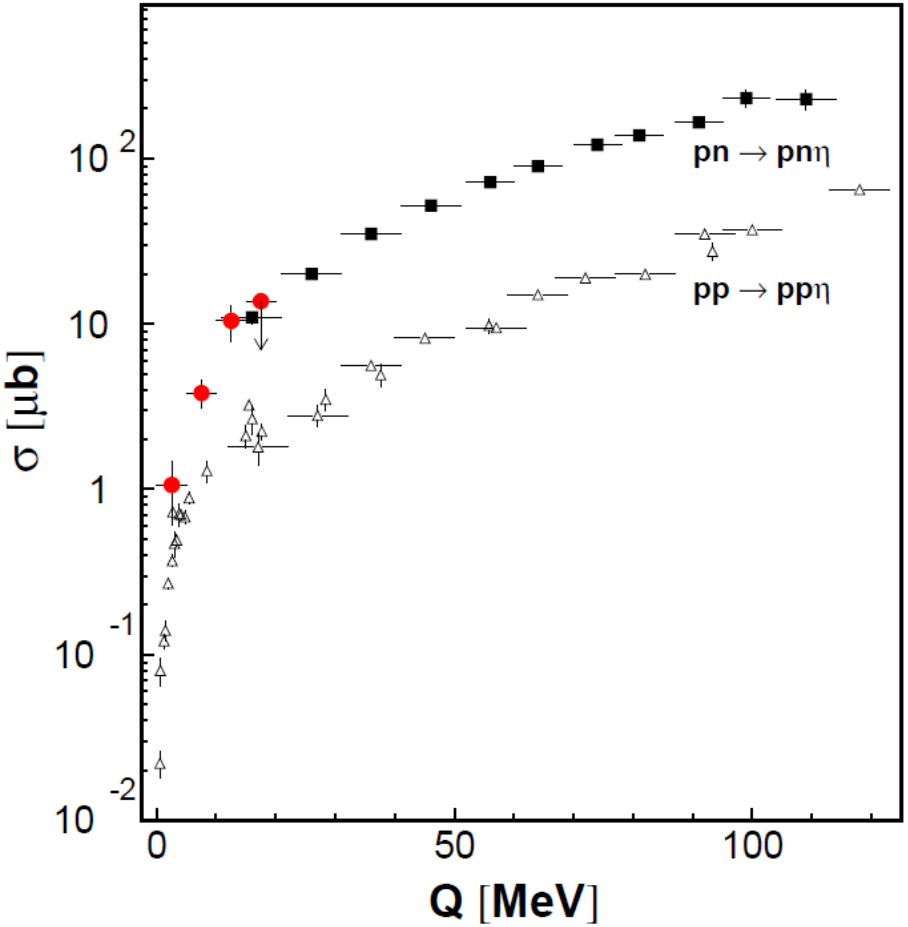
LARGE → RESONANSE

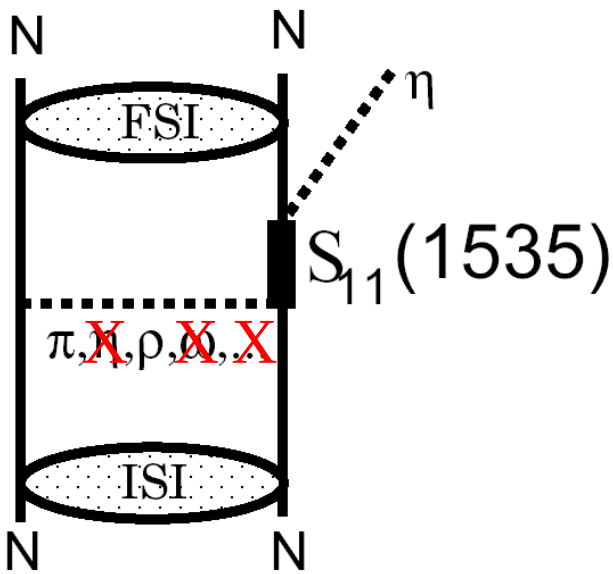


CELSIUS

COSY

SATURNE





STRONG ISOSPIN DEPENDENCE

Eta meson is by factor of 12

more coupiously produced

when the total isospin of nucleons

is equal to 0

than when it is equal to 1

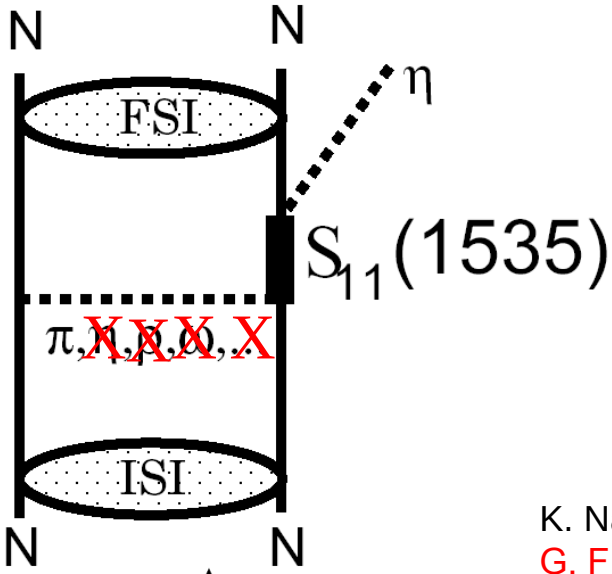
Strong evidence of isovector meson

exchange in production mechanism

CELSIUS

COSY

SATURNE

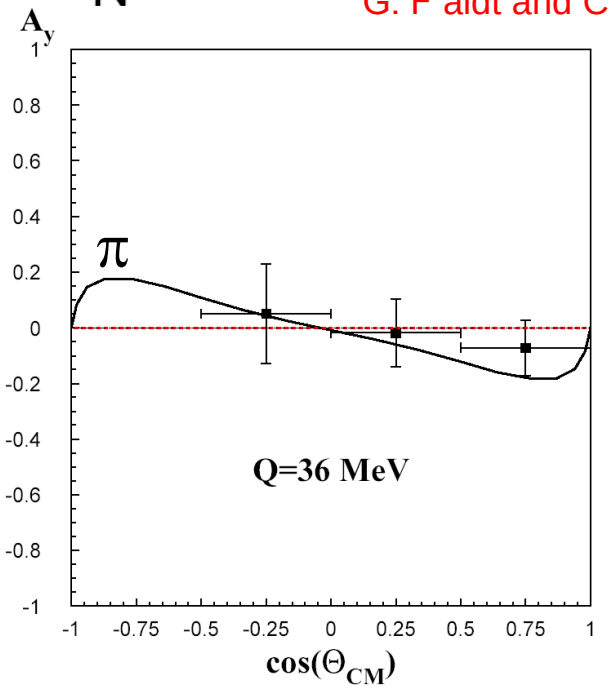


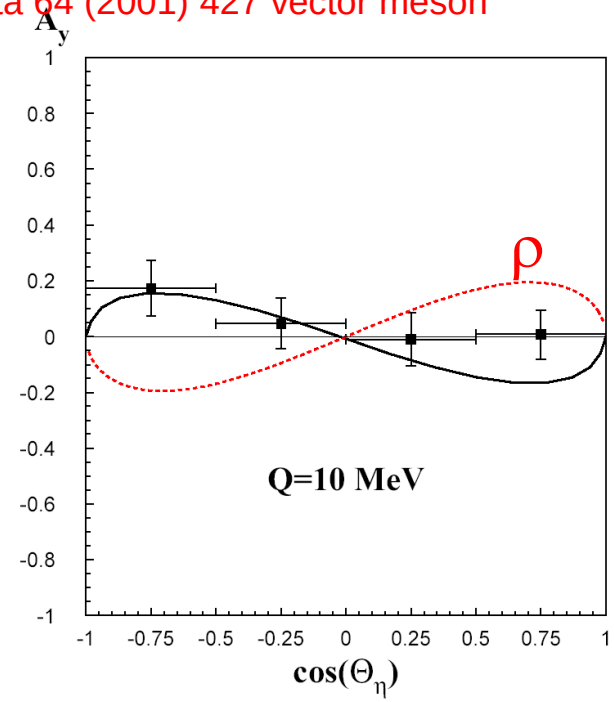
This was PREDICTED already about 2500 years ago by the very first physicists

Thus, it is suggested that among created beings there must be some basic agent which will move things and bring them together

ARISTOTLE
"Metaphysics"

K. Nakayama et al., Phys. Rev. C 65 (2002) 045210 pseudoscalar
G. F¨aldt and C. Wilkin, Phys. Scripta 64 (2001) 427 vector meson





COSY-11: Phys. Rev. Lett. 98 (2007) 122003