International Symposium on Mesic Nuclei, Cracow, June 16th 2010

η production in nucleon-nucleon collisions

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Symposium: original definition

"A drinking party at which there was intellectual conversation" *

A game sometimes played at symposia was *kottabos*, in which players swirled the dregs of their wine in their *kylikes* (platter-like stemmed drinking vessels) and flung them at a target. **

(merely a suggestion for the barbecue in Czulowek !)

* www.yourdictionary.com

** en.wikipedia.org/wiki/Symposium

Menu

New or upcoming data

- The quasi-free $pn \to d\eta$ reaction (ANKE).
- Differential distributions for $pp \to pp\eta$ at excess energies of 40 and 72 MeV (CELSIUS).
- η and η' production in $pp \to \{pp\}_s \eta / \eta'$, where the final *pp* system is in a ${}^1S_0$ state (ANKE).

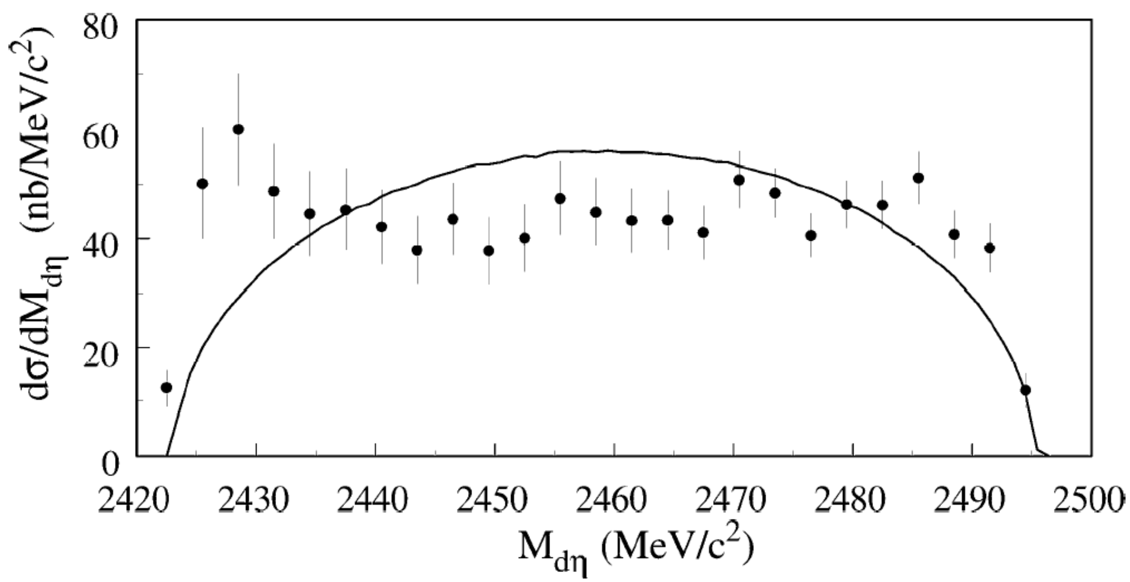
It is important to see how the low energy η-nucleus interaction varies as a function of *A*. We start the meeting with the *A*=2, *viz* $d\eta$ and $pp\eta$, systems.

The ηd interaction

The ηd interaction was studied long ago at CELSIUS in two different kinematical regimes, *viz* quasi-free $pd \to p_{sp} d \eta$* and the same reaction at much lower energies**. Consistent *FSI* description.

Typical (best?) case: cross section *versus* phase space at 1032 MeV, which is well below threshold.

Clear enhancement over about the first 10 MeV/c^2.



$pd \to pd\eta$ cross section at 1032 MeV found by measuring the deuteron and 2γ from the η decay**.

* H.Calén, PRL **79** (1997) 2642, **80** (1998) 2069
** R.Bilger, Phys. Rev. C **65** (2002) 044608

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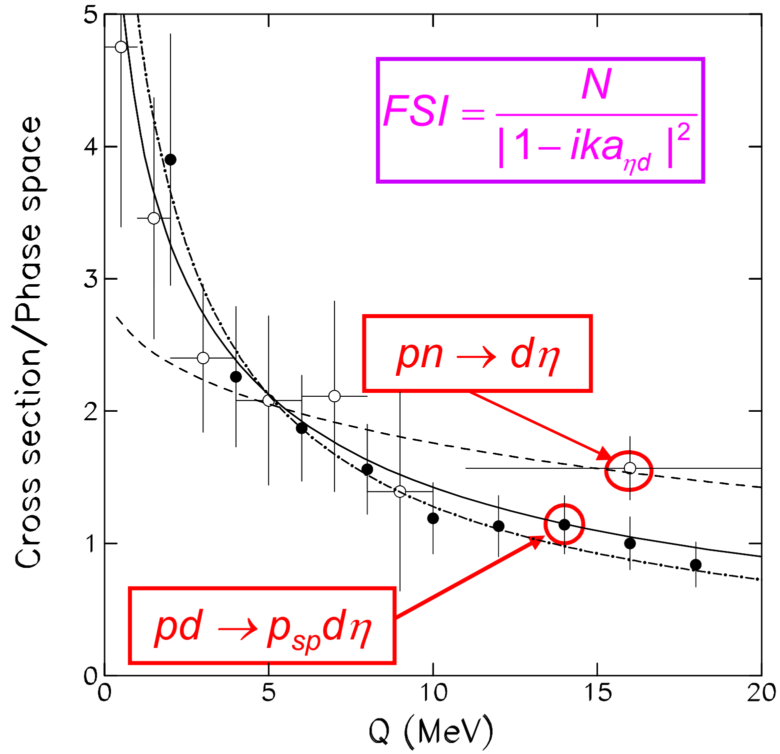
To show consistency of data, divide by the corresponding phase space, arbitrarily normalised. The ratio drops by about a factor of four over 10 MeV.



Three-body calculations* with different inputs (in fm):

$a_{\eta N}$	0.25+0.16i	0.55+0.30i	0.98+0.37i
curve	*dashed*	*solid*	*chain*
$a_{\eta d}$	0.73+0.56i	1.64+2.99i	-4.69+1.59i

Data need an ηd scattering length from strong or very strong input but cannot distinguish between cases where there is a quasi-bound state or not.

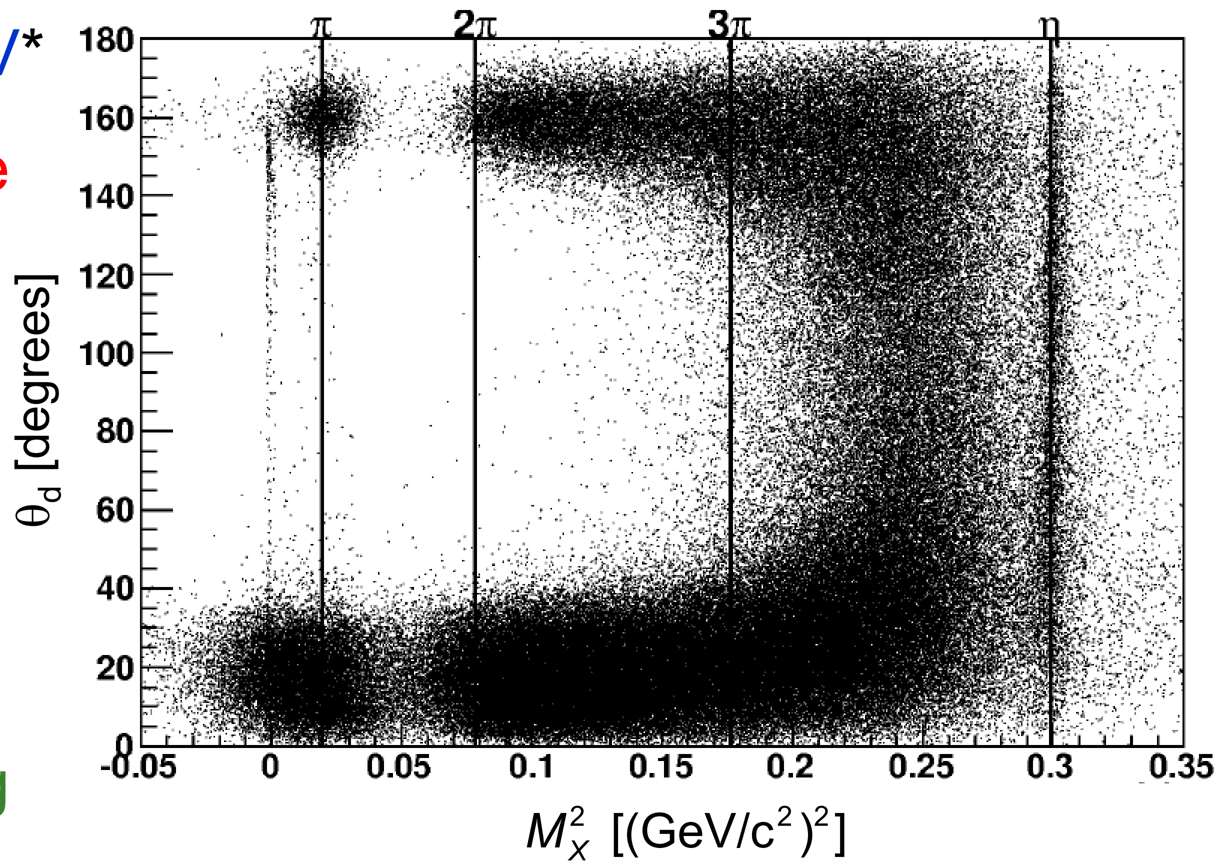
There are new preliminary data from ANKE ⇒ ⇒ ⇒

* N.Schevchenko, Phys. Rev. C **58** (1998) R3055

dp → *dpX* @ 2.27GeV*

Both the *d* and *p* were detected in the ANKE forward system under kinematic conditions where the final proton is a fast "spectator".

Only limited angular range is covered. For small M_X there are big holes in acceptance.



See strong quasi-free $np \to d\pi^0$ and much two-pion production (ABC?) near the forward/backward directions.

For η production, almost all $d\eta$ cm angles are sampled.

*S.Dymov, *analysis in progress*

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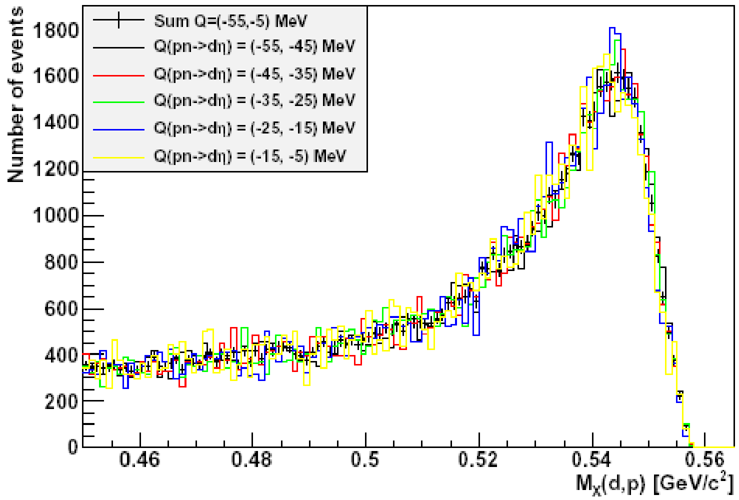
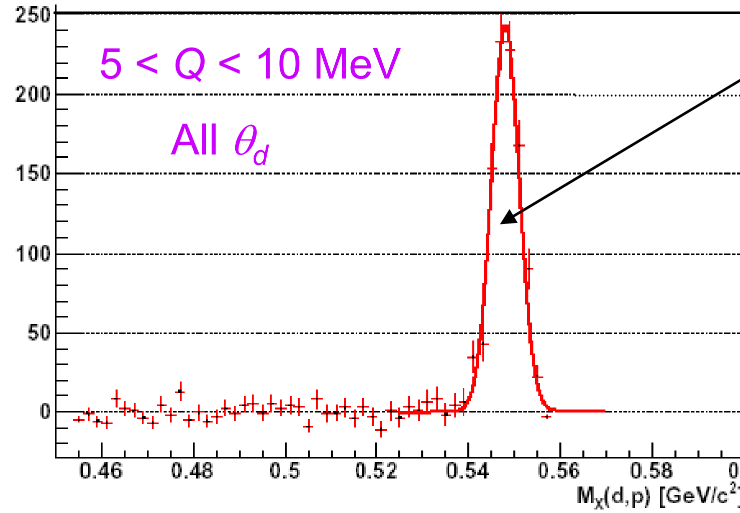




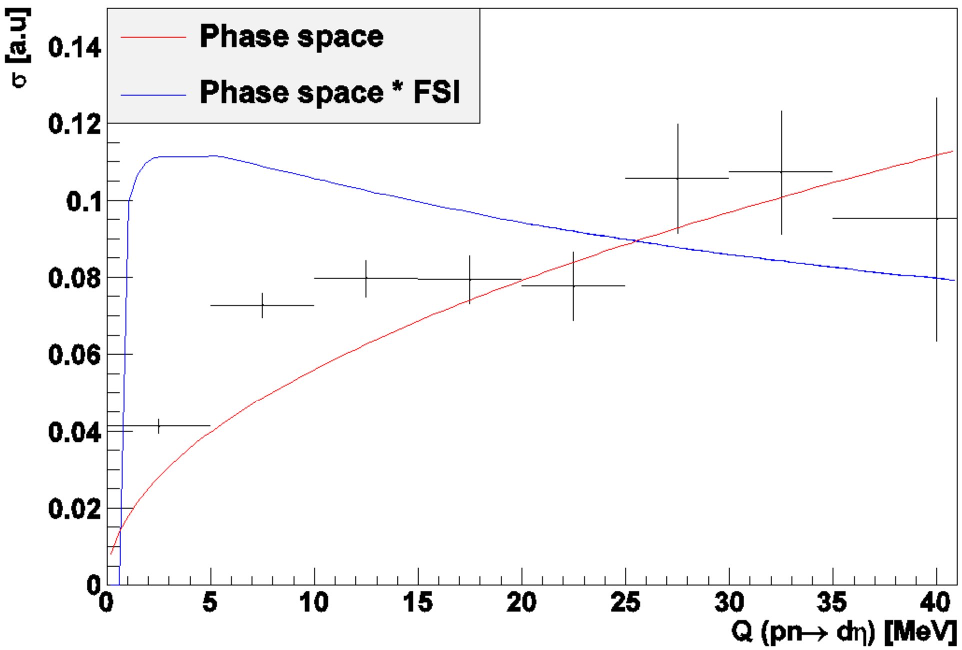
Background subtraction leaves η peak of width $\sigma \approx 3$ MeV/c^2

Background is very similar for all *Q*-bins below threshold if data are shifted to Q_{max}. Robust subtraction procedure.

η peak resolution varies with kinematics, being best close to threshold and backward-going (c.m.) deuterons.

Resolution in *Q* without any kinematic fit is about 3.5 MeV.
It is crucial to take this resolution into account.

Preliminary *pn* → *dη* results from ANKE



After unfolding the resolution, the cross section rises close to threshold faster than the phase-space √Q factor. Note that at CELSIUS the curves were normalised at about 15 MeV. Introducing the *FSI* factor with $a_{\eta d}$ = 1.64+2.99i fm seems to overdo things and a smaller scattering length would do better!

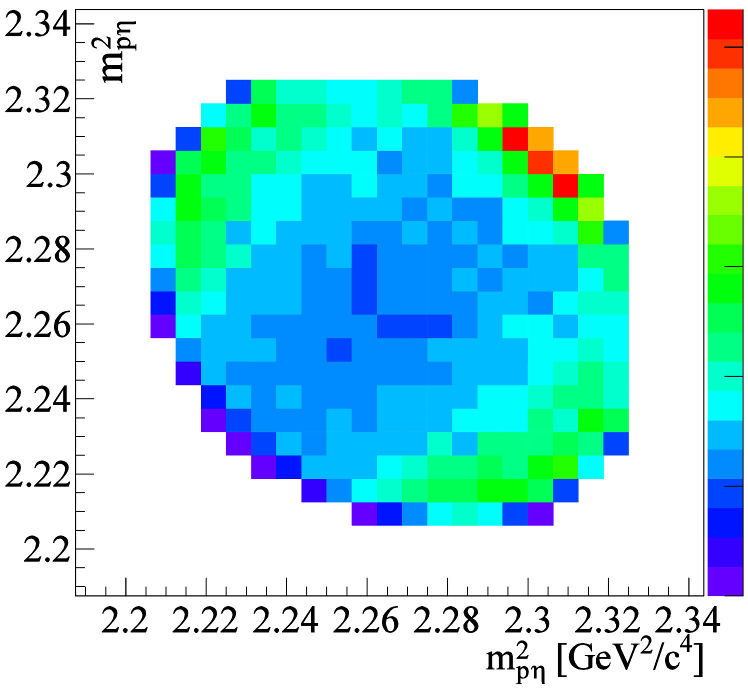
Although it is clear that there is a large *ηd* scattering length, limits on its value from the ANKE experiment will have to wait the final data analysis. Much better resolution could be achieved by using a deuterium target and detecting slow spectators in solid state telescopes.

The $pp \to pp\eta$ reaction away from threshold*

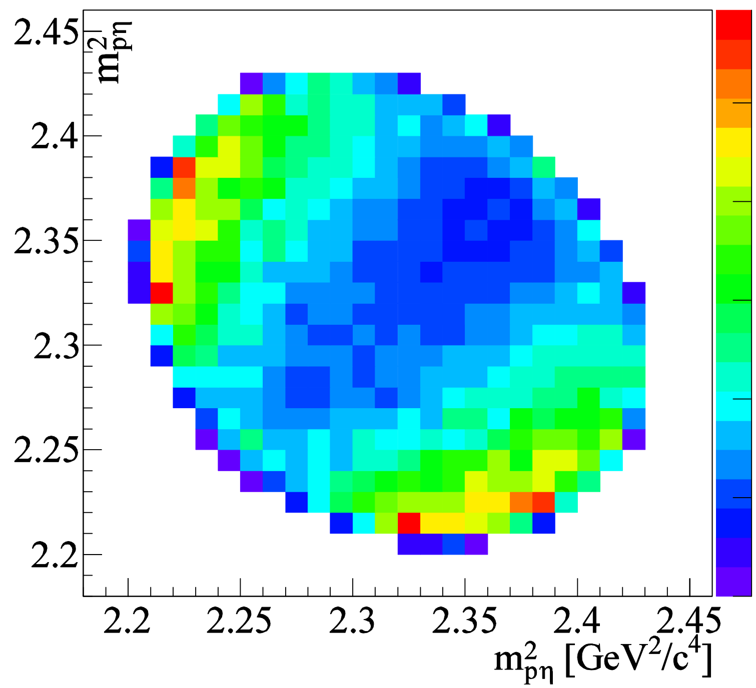
In order to study the effects of *S*-wave rescattering of the η meson from a proton pair, it is important to know at what point higher partial waves are needed for the description of the $pp \to pp\eta$ reaction. Thus one has to measure differential observables away from threshold.

η production in proton-proton scattering was investigated at CELSIUS-WASA at Q = 40 and 72 MeV. The meson was detected via its $3\pi^0$ decay [C.Pauly, Hamburg PhD thesis 2006] but data from the two-photon decay of the η have been subjected to a much more refined analysis, which is now reaching completion*.

* H.Petrén, PhD thesis + article in preparation



Q = 40 MeV



Q=72 MeV

Dalitz plots show deep valley for $m(\eta p_1) \approx m(\eta p_2)$. Probably due to the η being able to form the *N**(*1535*) with only one nucleon at a time. [The *pp FSI* is only seen at 40 MeV.] The valley requires higher partial waves in both the *pp* and η*{pp}* systems, at least *Pp*.

Since only the start of the *N**(1535) is sampled, try fitting the data with partial wave amplitudes with constant coefficients, *i.e.* No explicit *N**(*1535*).

Matrix-element-squared to second order in momentum and up to incident *D*-waves

$$\overline{|M|^2} = |A_{Ss}|^2 + \tfrac{1}{9}|A_{Sd}|^2 k^2\left[3(\hat{p}\cdot\vec{k})^2 + k^2\right]$$

$$+\tfrac{1}{9}|A_{Ds}|^2 q^2\left[3(\hat{p}\cdot\vec{q})^2 + q^2\right] + |A_{Ps}|^2 q^2 + 2|A_{Pp}|^2(\vec{k}\cdot\vec{q})^2$$

$$+\tfrac{2}{3}\mathrm{Re}\left\{A^*_{Ss}A_{Sd}\right\}\left[3(\hat{p}\cdot\vec{k})^2 - k^2\right] + \tfrac{2}{3}\mathrm{Re}\left\{A^*_{Ss}A_{Ds}\right\}\left[3(\hat{p}\cdot\vec{q})^2 - q^2\right]$$

$$+\tfrac{2}{9}\mathrm{Re}\left\{A^*_{Sd}A_{Ds}\right\}\left[9(\hat{p}\cdot\vec{k})(\hat{p}\cdot\vec{q})(\vec{k}\cdot\vec{q}) - 3\left(q^2(\hat{p}\cdot\vec{k})^2 + k^2(\hat{p}\cdot\vec{q})^2\right) + k^2q^2\right],$$

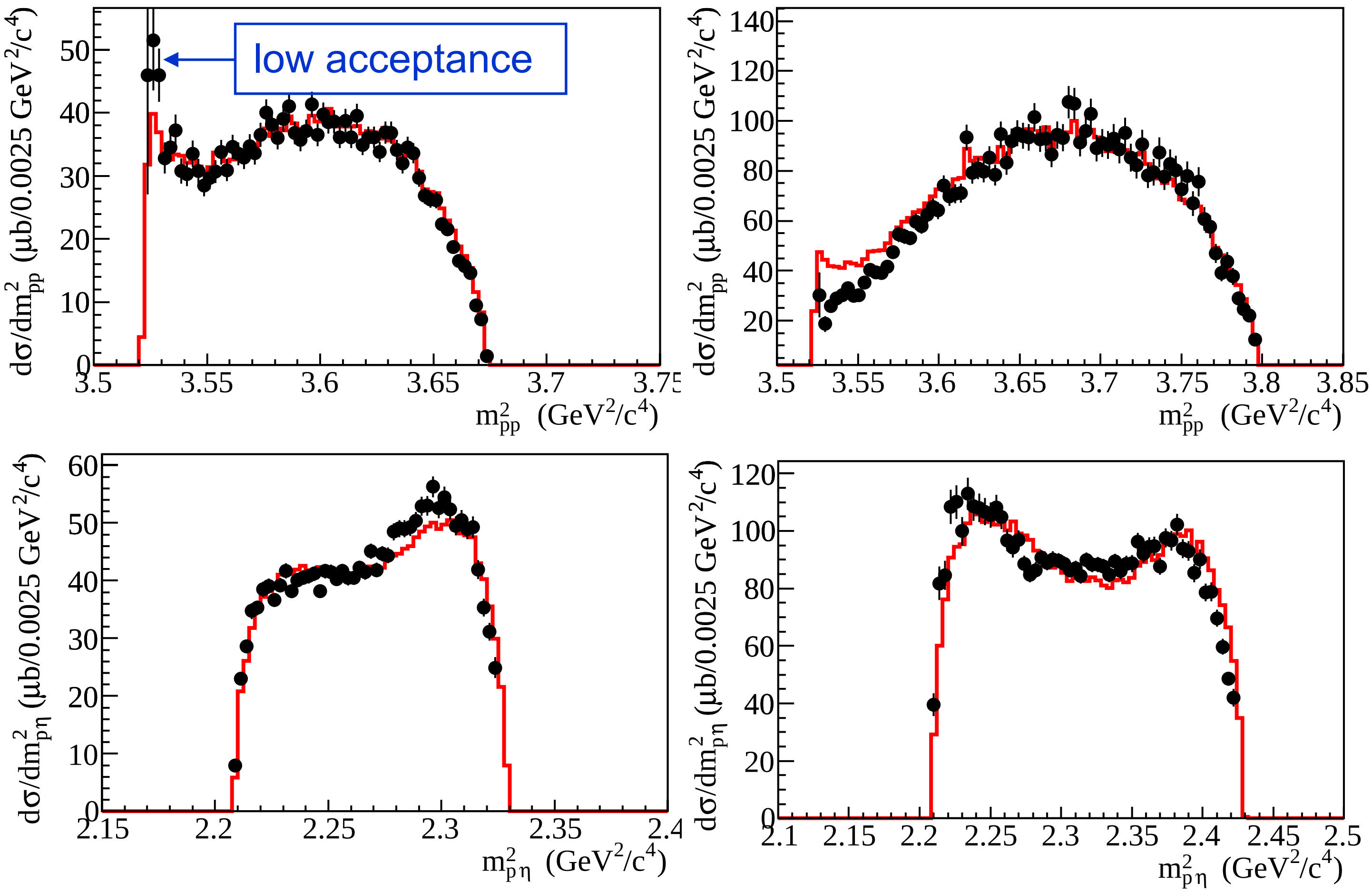
where $\vec{q}$ is the relative momentum in the pp rest frame and $\vec{k}$ the η momentum in the cm system, where $\hat{p}$ is a unit vector in the beam direction. The five partial wave amplitudes $A_{L\ell}$ are in standard notation, where *L* is the angular momentum in the *pp* system and ℓ that of the meson.

CRUCIAL ASSUMPTION: All amplitudes are constant except for the *FSI* that affects the *pp* *S*-wave. *FSI* included by multiplying by the *pp* wave function (including the phase) evaluated at 1 fm. Coulomb also included.

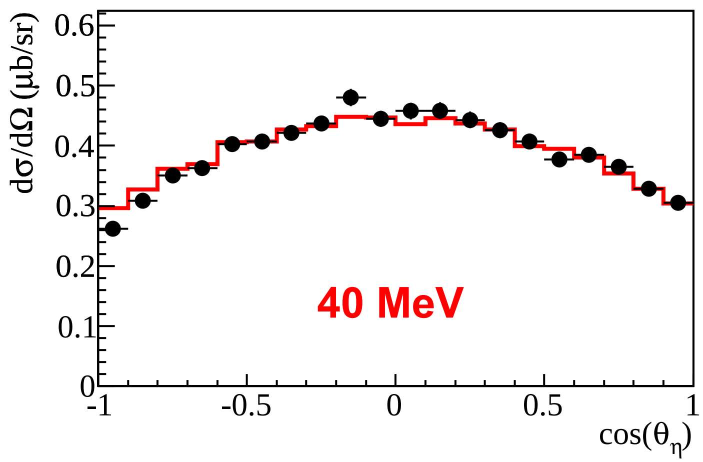
A large variety of one-dimensional data fitted simultaneously at 40 and 72 MeV in terms of SEVEN real parameters. [Phases of A_{Pp} and A_{Ps} are irrelevant at this level.] These include invariant mass distributions, η angular distributions as well as those in the Gottfried-Jackson angle. Fits were made to the raw spectra, after the model had been passed through the full simulation of the CELSIUS-WASA set-up.

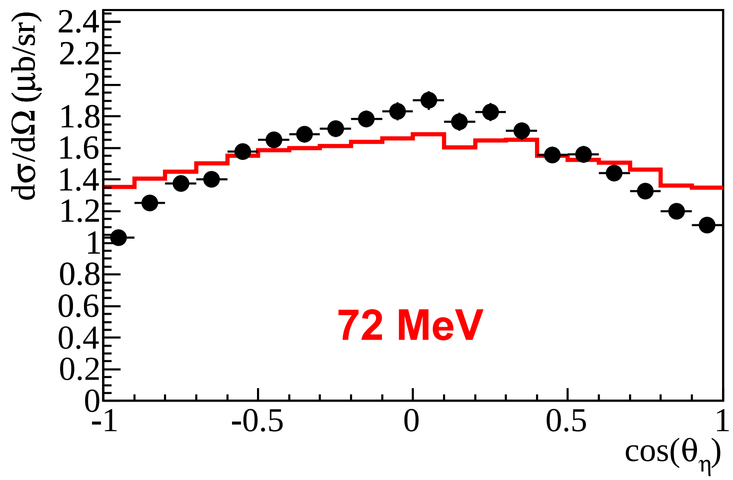
However, the results shown here are in terms of cross sections, after evaluating the acceptance with the model, using the best-fit parameters.

Invariant mass fits. Statistics at 72 MeV are higher, but fit is better at 40 MeV. *pp FSI* region poorly described at 72 MeV.



40 MeV **72 MeV**



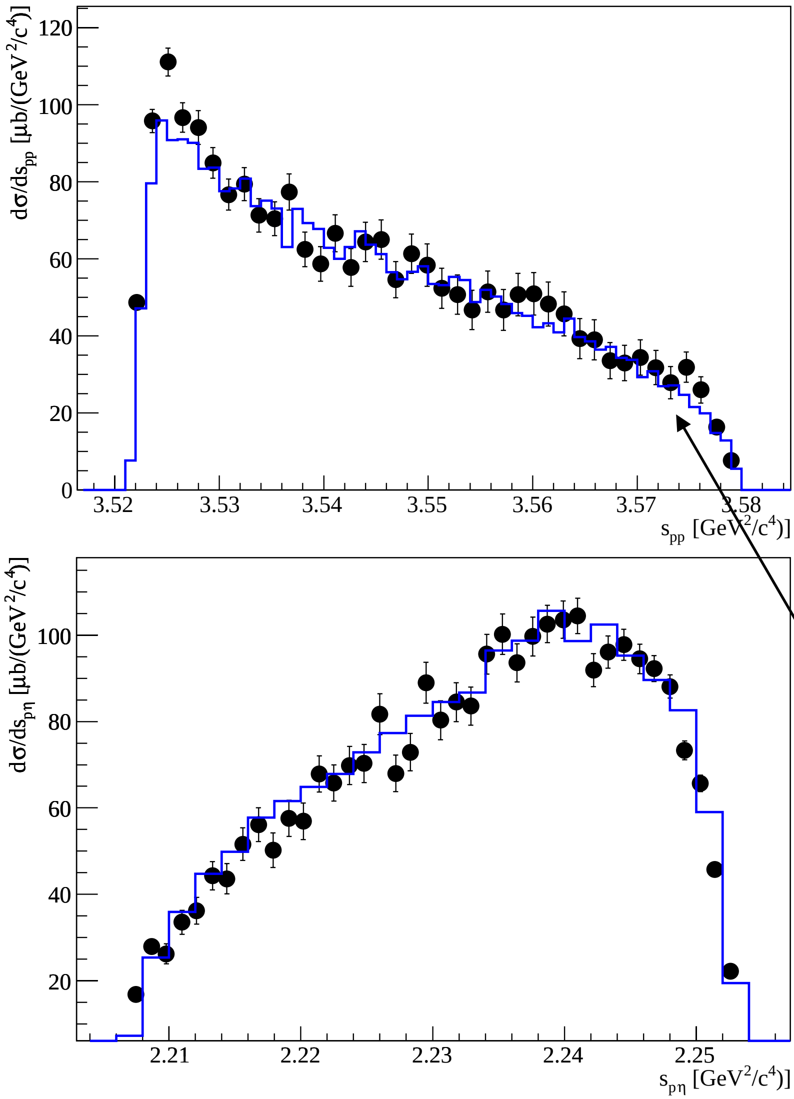


Deviations from forward/backward symmetry in the η c.m. angle are small and reflect minor defects in the understanding of the WASA detector.

More bowed than old COSY-TOF data at 41 MeV*. In the simple model, deviations from isotropy must come from *Ss-Sd* interference and these are clearly too small at 72 MeV. If higher partial waves cause problems at large *Q*, what happens at lower values of *Q*?

* M. Abdel-Bary, EPJA **16** (2003) 127.

Comparison with COSY-11 data at 15.5 MeV*



Parameters that fit the CELSIUS data also describe well the shapes of the COSY-11 results at much lower excess energy, Q = 15.5 MeV. [Overall normalisation discussed later.]

In this approach, higher partial waves in the *pp* system are vital for the description of the data at the largest s_{pp}.

* P. Moskal, Phys.Rev.C 69 (2004) 025203

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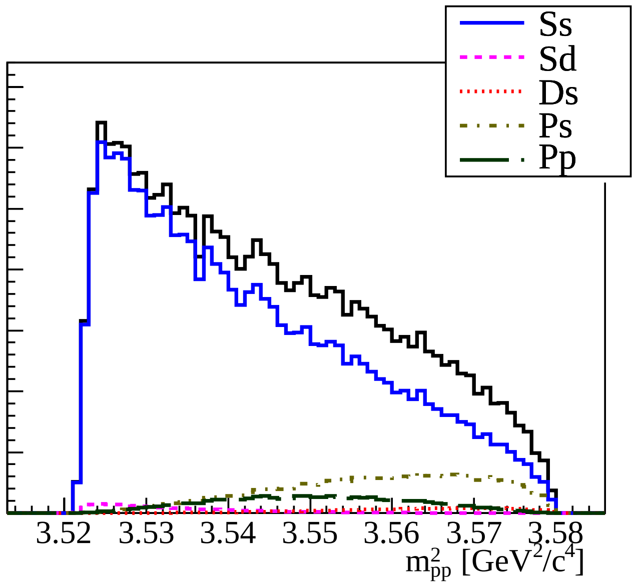
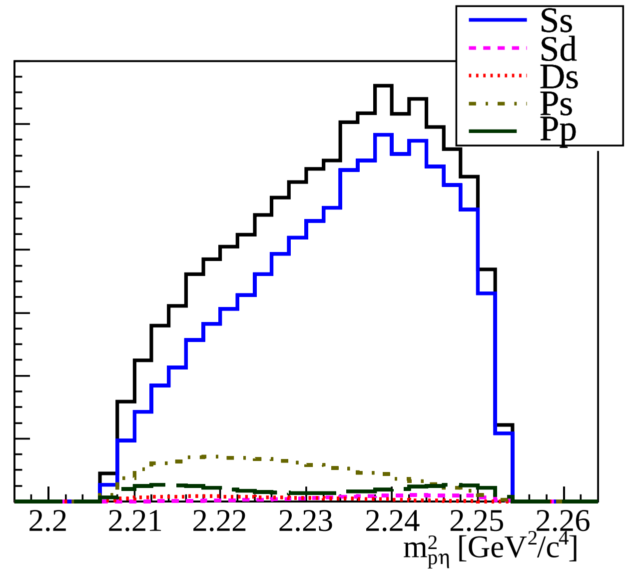
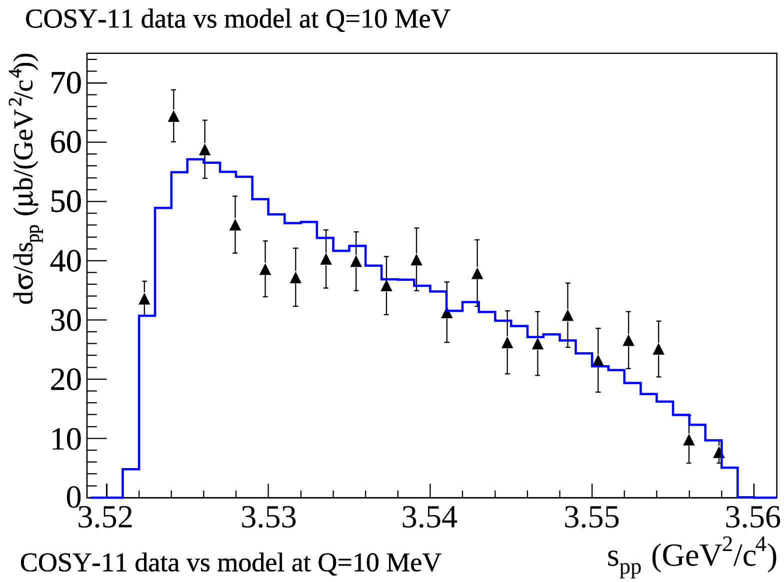
Partial wave contributions at 15.5 MeV

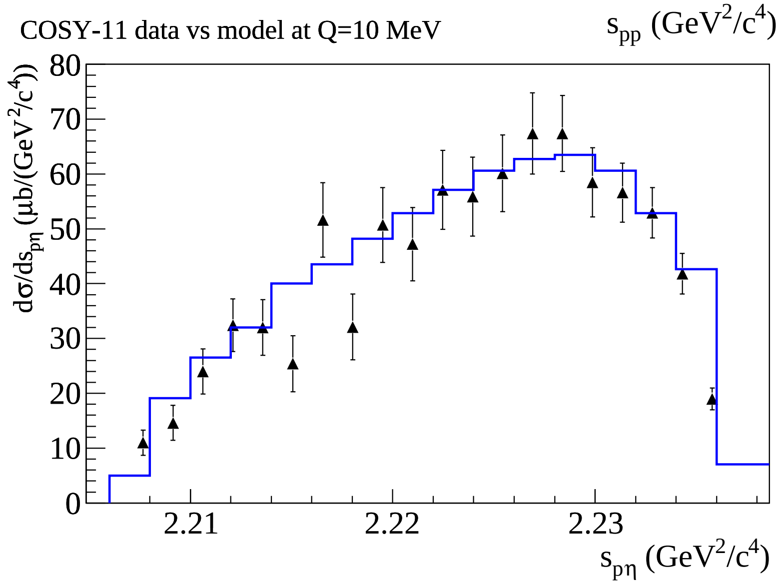




Within a model tuned to fit the 40 and 72 MeV data, there is a significant contribution from the *Ps* wave that gives events at high m_{pp} and hence low $m_{p\eta}$. Since there is no associated angular dependence, this is NOT a proof. To separate *P*s from *Ss* would require a measurement of the initial spin-spin correlation parameter.

Comparison with COSY-11 data at 10 MeV*





Conclusions at 10 MeV are rather similar to those at 15.5 MeV.

Although these COSY-11 data are not of the same quality as at the higher energy, the model does a very reasonable job in describing the invariant mass shapes.

* P.Moskal, Eur.Phys.J. A **43** (2010) 131

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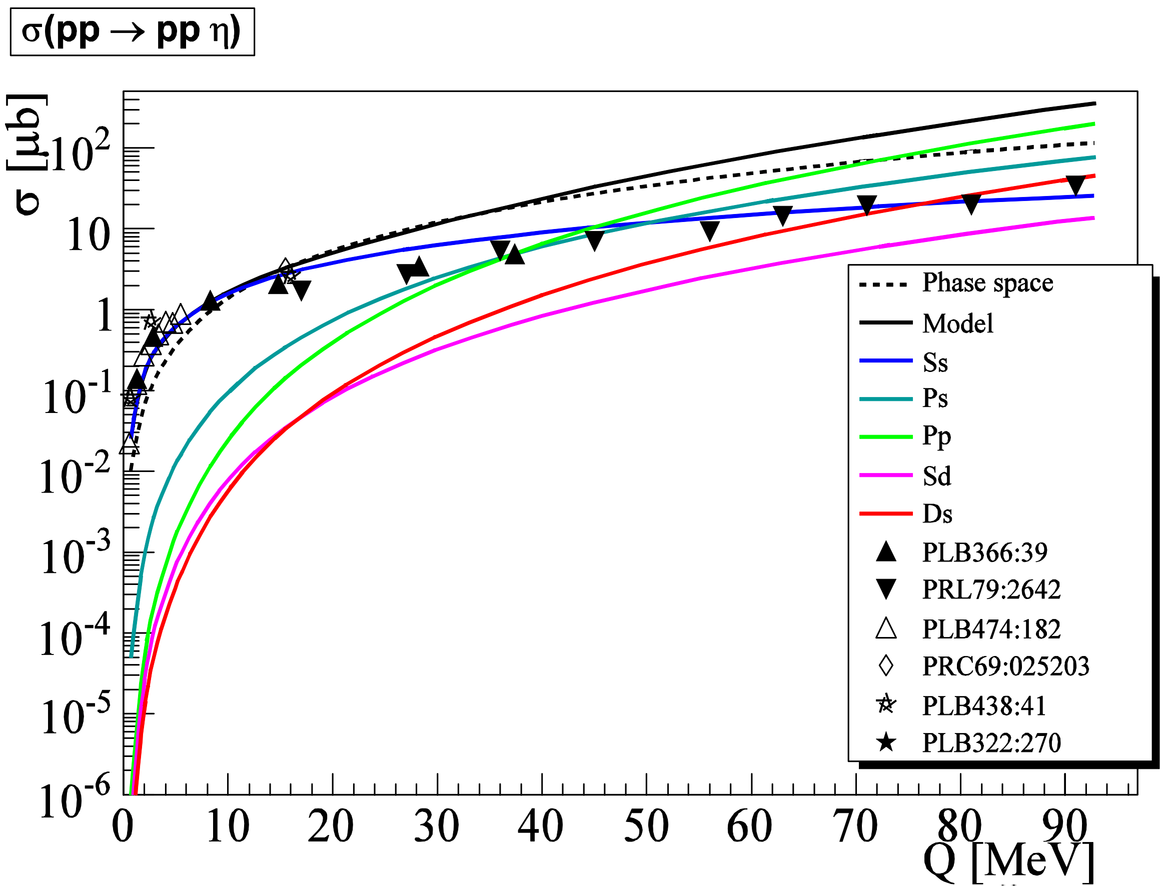
Energy dependence of the total $pp \to pp\eta$ cross section

If the only energy dependence of the partial wave amplitudes were through the kinematic factors, one could predict σ_{tot}.

Since model can be scaled, we don't know if disagreement is due to a *FSI* effect at small excess energy or the constancy *ansatz* at large *Q*.

The *FSI* for $pn \to d\eta$ extends up to 10 MeV and this could go even further up for $pp \to pp\eta$ because the *pp* can take some of the energy.



Conclusions on CELSIUS-WASA $pp \to pp\eta$

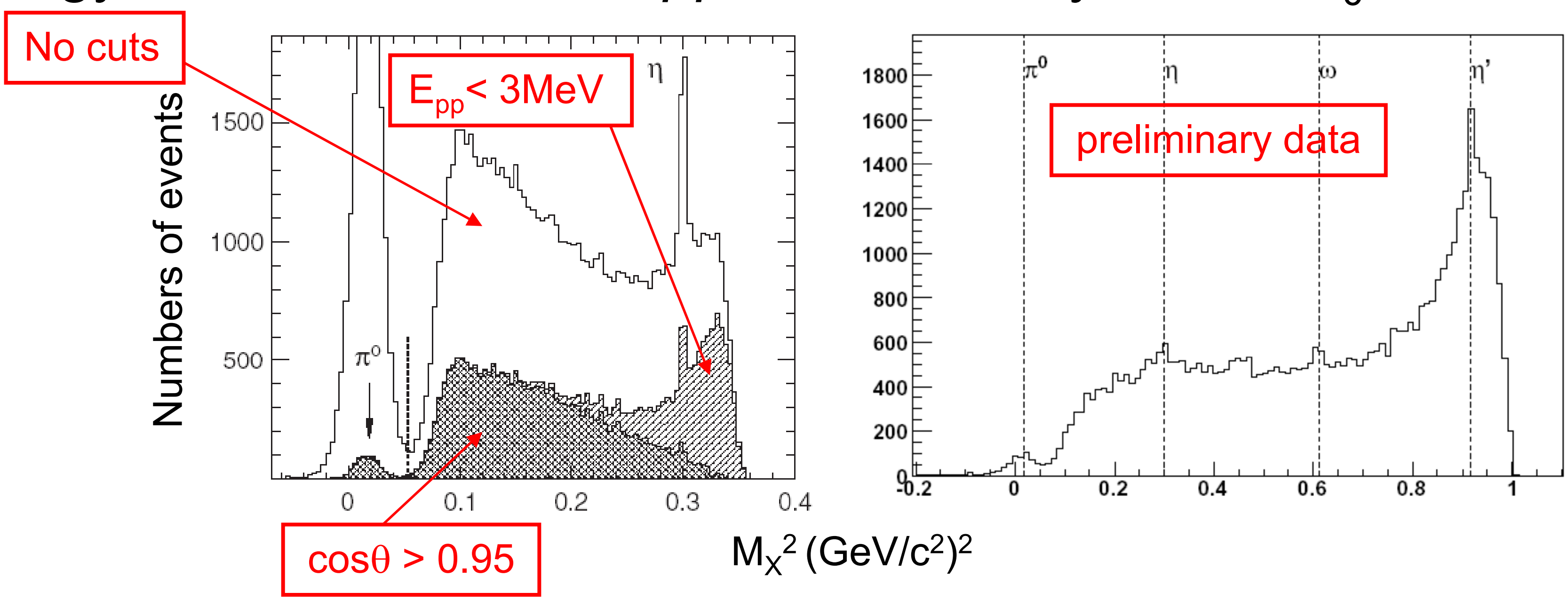
- Dalitz plots at 40 & 72 MeV show higher partial waves.
- The η wants to form an *N** with both protons.
- Need at least *Pp* waves.
- Model with constant amplitudes (apart from kinematic factors) fitted to the 40 MeV data describes very well the 10 and 15.5 MeV results. At 72 MeV even higher partial waves may be needed.
- *S*-waves only dominate up to 15-20 MeV.
- However, the parameterisation is <u>far</u> from unique. For example, we have neglected the *Sd* amplitude for an incident *pp F*-wave.
- Constant amplitudes (apart from the *FSI* and kinematic factors) must overpredict the cross section at large *Q*.

- The "Dalitz valley" is likely to be a consequence of the two *N** possibilities. Leads to the *Pp* wave that seems to dominate at 72 MeV. Better introduce the *N** explicitly.
- The high mass part of the s_{pp} spectrum is "explained" here as due to higher partial waves in the *pp* system.
- However, similar spectrum is seen in COSY-11 $pp \to pp\eta'$ data*. Does this mean that *Ps* waves enter at the same relative rate in the two reactions?
- To study the ηpp *FSI* experimentally, we need to control to some extent the higher partial waves or have excellent data in the near-threshold region.
- ηd is simpler because it is a two-body system, which leads me to my final few points.

* P.Klaja, Phys.Lett.B **684** (2010) 11

Quasi-two-body $pp \to pp\eta(\eta')$*

The ANKE spectrometer has only limited acceptance, but it can measure well $pp \to \{pp\}_S X$, where $\{pp\}_S$ has an excitation energy below 3 MeV. Final pp is dominantly in the $^1S_0$ state.



Both the $pp \to \{pp\}_S\eta$ and $pp \to \{pp\}_S\eta'$ are seen in quasi-two-body conditions at $Q \approx 55$ MeV . Expect ≈ 500 η' events.

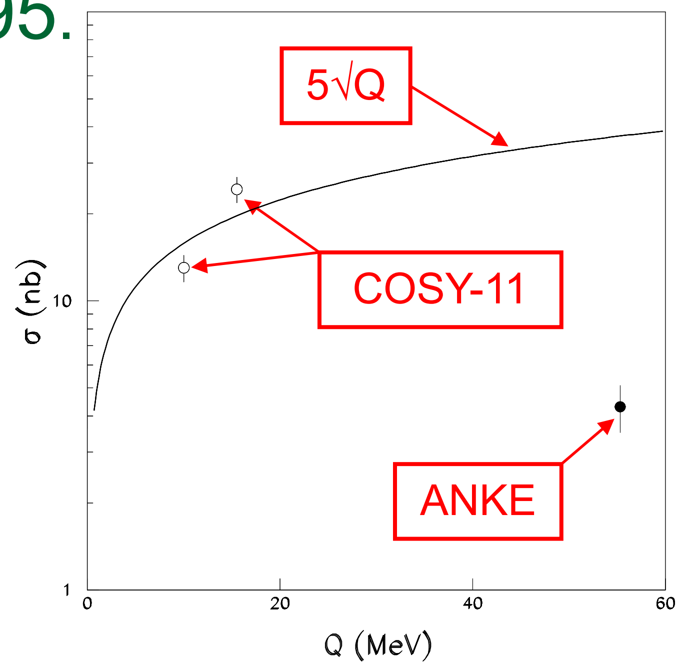
* S.Dymov, PRL **102** (2009) 192301

$pp \to \{pp\}_s\eta$ cross section; $E_{pp} < 3$ MeV and $\cos\theta_{pp} > 0.95$.

Very few data points yet. COSY-11 at 10 and 15.5 MeV [Pawel K+M, private communications] and ANKE at 55 MeV.

Deviations from $\sqrt{Q}$ at small Q due in part to $\{pp\}_S$ not being bound.

There must be Physics in the behaviour between 15 and 55 MeV.



The fall-off could be influenced by the $\eta\{pp\}_s$ *FSI*. Need more data with the small E_{pp} kinematics.

SUMMARY

- New ANKE data show some ηd interaction, but perhaps not as strong as CELSIUS and much weaker than η^3He.

- CELSIUS $pp \rightarrow pp\eta$ differential distributions show large effects from higher partial waves at Q = 40 and 72 MeV. *Ss* only dominates below 10-15 MeV; At 72 MeV, *Pp* is the largest. Detecting ηpp *FSI* complicated by higher waves.

- The introduction of the *pp FSI* is model-dependent but the s_{pp} distribution can be explained in terms of partial waves.

- Description with "constant" amplitudes needs modification at high Q. Should introduce an explicit $N^*(1535)$.

- Quasi-two-body kinematics perhaps better to study *pp FSI*.

Thanks and Goodbye!

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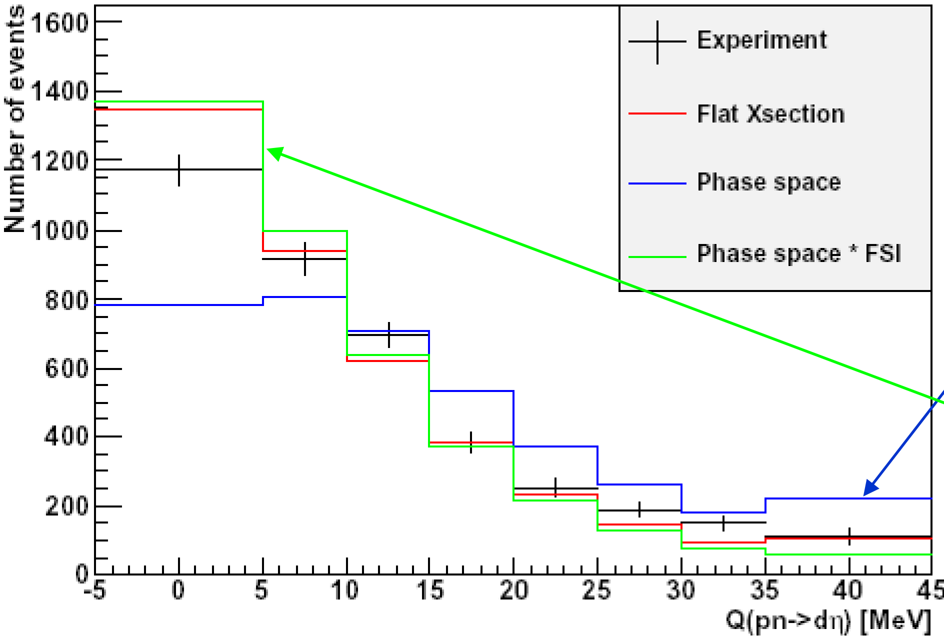
Perhaps we can get back soon to the Greek definition of symposium!

Preliminary $pn \to d\eta$ results from ANKE



Numbers of experimental events fall monotonically with *Q*. Due to the resolution, there is no sign of the $\sqrt{Q}$ factor. Smeared phase space does not fall off fast enough. When the *FSI* factor is introduced with $a_{\eta d}$ = 1.64+2.99i fm, the description is improved but a smaller scattering length would do even better!

Although it is clear that there is a large ηd scattering length, limits on its value from the ANKE experiment will have to wait the final data analysis. Much better resolution could be achieved by using a deuterium target and detecting a slow spectator in solid state telescopes.