Study of $pp\eta$ dynamics in the $pp \rightarrow pp\eta$ reaction using WASA-at-COSY

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Outline
Motivation
Experimental set-up
Analysis for $pp\eta$ dynamics
Conclusions & outlook
Motivation

- Production of $\eta$-meson in NN collision is not well understood.
- Interaction of eta with nucleons using direct scattering experiments difficult.
- Study interaction by production near kinematical threshold
- Mutual interaction will show up in differential cross-sections.
- $pp\eta$ system can be described by 12 variables, 7 are fixed by E-P conservation and particle masses
- Invariant mass distribution of $pp$ and $p-\eta$ system
- Orientation of the emission plane ($\theta_\eta^*, \phi_\eta^*, \psi_\eta^*$)
### Previous measurements for $pp\rightarrow pp\eta$

<table>
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<th>Excess Energy</th>
<th>Detector</th>
<th>Conclusions</th>
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</table>
| 10, 15.5 MeV  | COSY-11\textsuperscript{1,2} | • Angular distributions $\rightarrow$ isotropic  
• $m^2_{pp}$, $m^2_{p\eta}$ $\rightarrow$ show deviation from phase space  
• Explanation - pp FSI but enhancement at $m^2_{p\eta}$ could not be explained |
| 16, 37 MeV    | PROMICE/WASA\textsuperscript{3} | • Angular distribution of $\eta$ $\rightarrow$ anisotropic  
• Explanation - $S_s/S_d$ interference |
| 16, 41 MeV    | COSY-TOF\textsuperscript{4} | • Angular distributions $\rightarrow$ isotropic  
• $m^2_{pp}$, $m^2_{p\eta}$ $\rightarrow$ show deviation from phase space  
• Can not be explained by pp FSI alone |
| 40, 72 MeV    | CELSIUS/WASA\textsuperscript{5} | • Angular distributions $\rightarrow$ isotropic  
• $m^2_{pp}$, $m^2_{p\eta}$ $\rightarrow$ show deviation from phase space  
• Explanation – contribution from higher partial waves |
| 324, 412, 554 MeV | DISTO\textsuperscript{6} | • Angular distribution of $\eta$ $\rightarrow$ anisotropy at lowest energy  
• Anisotropy disappears as the energy increases  
• Explanation - $N(1535)$ resonance and no need of higher partial waves |

No consistent explanation yet available!

5 H Petren, Thesis 2009  
For $pp\eta$ dynamic study $pp\rightarrow pp\ (\eta\rightarrow 3\pi^0)$ is chosen

- Data taken at beam energy 1.4 GeV ($Q = 56$ MeV)
- Two charged track in the forward detector
- Six neutral clusters in central detector
Identification in forward detector

- Identification of protons by using $\Delta E - E$ technique
- Calibration: Deposited energy $\rightarrow$ Kinetic energy
- Theta and phi from Tracks
- Reconstruct four vectors of each proton

Proton identification
Missing mass of pp

- Missing mass of two protons

\[ MM^2 = (E_{\text{beam}} - E_{p1} - E_{p2})^2 - (P_{\text{beam}} - P_{p1} - P_{p2})^2 \]

Good mass resolution in forward detector helps in \( \eta \) tagging

**Missing Mass of pp data**

Data

Mean = 548.7 MeV/c\(^2\)
sigma = 13.2 MeV/c\(^2\)

**Invariant Mass of \( \eta \)-data**

Mean = 538.1 MeV/c\(^2\)
sigma = 56.5 MeV/c\(^2\)
Kinematic fit

- Kinematic fit is used to improve measured quantities by fitting known values and constraints.

- The measured variables are adjusted within experimental errors so that the constraint equations are satisfied with minimum error.

- **Confidence level:** $CL(\chi^2) = 1 - \int P(\chi^2, n) d\chi^2$

**Probability distribution**

$$ P(\chi^2, n) = \frac{2^{-n/2}}{\Gamma(n/2)} \chi^{n-2} e^{-\chi^2 / 2} $$
Kinematic fit

- **Constraints:**
  - Energy-momentum balance $\rightarrow 4\ \pi^0$ invariant mass $\rightarrow 3$
  - No constraint over $\eta$ mass

**Invariant mass:**

- **Mass widths:**
  - Before kinematic fit $\sigma = 56.5$ MeV/c^2
  - After kinematic fit $\sigma = 5.6$ MeV/c^2
Total cross-section

- Total $9.7 \times 10^6$ events of $\eta \rightarrow 3\pi^0$ from April-2007 data
- We have production cross-section of $\eta$,

$$\sigma = (9.83 \pm 0.03_{\text{stat}} + 3.47_{\text{sys}}) \text{ \(\mu\)b}$$

Normalization is the major source of error.

**Total cross-section as a function of beam KE**
Observables for ppη dynamics

Deviation from Phase space

Conclusions

- Total cross-section for $\eta$ production in pp has been measured.
- The invariant mass squared distributions for pp and $p\eta$ show deviation from phase space.
- Inclusion of pp FSI could not explain the data.

Outlook

- The collaboration is planning to do measurements with polarised beam.
Partial waves

The low energy $pp \rightarrow pp \eta$ amplitude,

$$M = \tilde{A}_{Ss} \phi_i^\dagger \left( \hat{p} \cdot \epsilon_i \right) + A_{Sd} \phi_i^\dagger \left( \hat{p} \cdot k \right) \left( k \cdot \epsilon_i \right) + A_{Ps} \phi_i \left( q \cdot \epsilon_i^\dagger \right) + A_{Ds} \phi_i^\dagger \left( \hat{p} \cdot q \right) \left( q \cdot \epsilon_i \right).$$

- $p$: momentum of initial proton
- $K$: momentum of final $\eta$
- $2q$: relative momentum in the final two proton system
- $\epsilon_i (\epsilon_f)$: spin-one polarization vector of the initial (final) $pp$ pair
- $\phi_i (\phi_f)$: spin-zero functions

The spin averaged matrix element square,

$$|M|^2 = \frac{1}{4} \left[ |\tilde{A}_{Ss}|^2 + 2 k^2 \text{Re}\{\tilde{A}_{Ss}^* A_{Sd}\} \cos^2 \theta_n \right. \left. + 2 q^2 \text{Re}\{\tilde{A}_{Ss}^* A_{Ds}\} \cos^2 \theta_{pp} + q^2 |A_{Ps}|^2 \right].$$

The enhancement factors for $(Ss)^2$, $Ss$-$Sd$ and $Ss$-$Ds$ terms,

$$F_{SS}(q) = 0.440 + \frac{151.7}{1 + q^2/\alpha^2},$$

$$F_{SD}(q) = 0.968 + \frac{11.5}{1 + q^2/\alpha^2},$$

The differential cross-section,

$$d\sigma = \frac{N}{p} \left( F_{SS}(q) + a \frac{k^2}{\mu m_p} F_{SS}(q) \cos^2 \theta_n + b \frac{q^2}{\mu m_p} F_{SD}(q) \cos^2 \theta_{pp} \right) d\text{Lips},$$