JÜLICH
FORSCHUNGSZENTRUM

Radiative and Hadronic Decay modes of the η-Meson with CLAS and WASA-at-COSY

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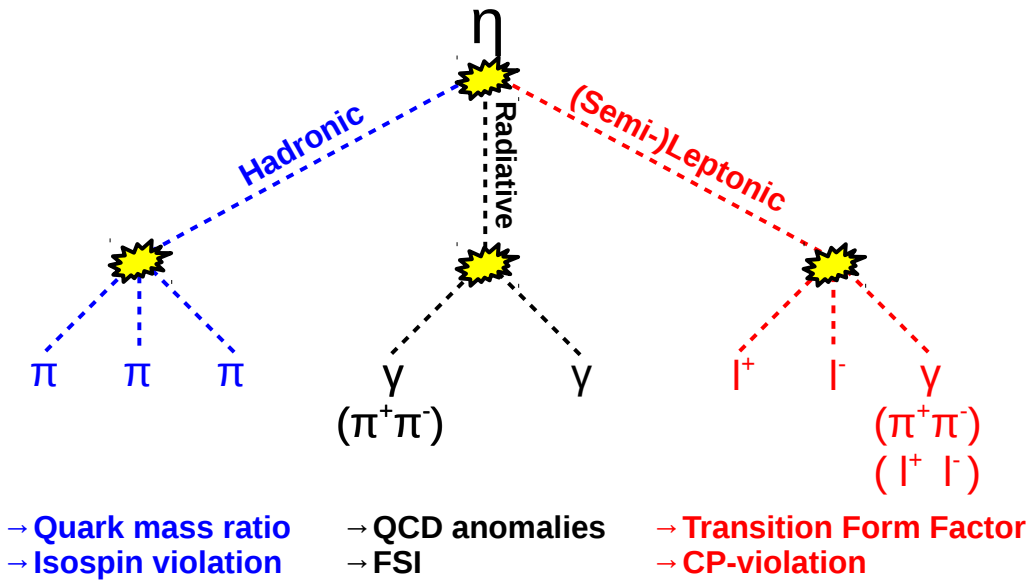
One Meson, two Decays and two Experiments

The η-Meson: A unique tool

- $m_\eta = 0.5478\,\mathrm{GeV/c^2}$
- $\Gamma_\eta = (1.31 \pm 0.05)\,\mathrm{keV}$
- $\bar{\tau} \approx 5 \cdot 10^{-19}\,\mathrm{s}$
- $J^{PC} = 0^{-+} \Longrightarrow \eta$-meson is:
  C-, *P*-, *G*- and *CP*- eigenstate
- All strong and electromagnetic decays are forbidden to first order

⇒ **Access to rare decay processes**



Focus of this talk:

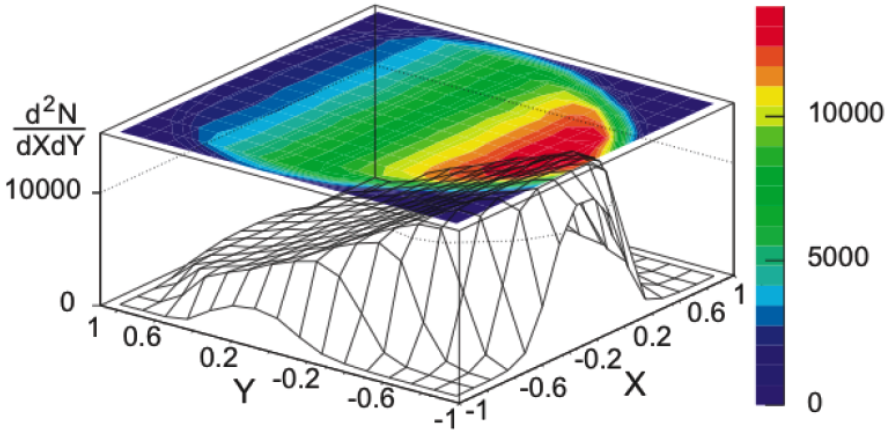
1. $\eta \to \pi^+\pi^-\pi^0$ || Measured in $\gamma p \to p\eta[\eta \to ...]$ with CLAS
2. $\eta \to \pi^+\pi^-\gamma$ || Measured in $pp \to pp\eta[\eta \to ...]$ with WASA

η-Decays with CLAS and WASA-at-COSY

Decay mode	Issue
$\eta' \to \pi^+\pi^-\eta$	Dalitz plot analysis
$\eta \to \pi^+\pi^-\pi^0$	Dalitz plot analysis
$\eta^{(\prime)} \to \pi^+\pi^-\gamma$	Box anomaly, $\pi^+\pi^-$ FSI
$\eta^{(\prime)} \to e^+e^-\gamma$	Single-off-shell transition form factor
$\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$	CP-Violation
$\eta \to e^+e^-e^+e^-$	Double-off-shell transition form factor
$\eta \to \pi^0e^+e^-$	C-Violation

- CLAS: (Thomas Jefferson Laboratory, Newport News, USA)
  - Access to variety of light meson decays via: $\gamma p \to pX$
  - Light Meson Decay program with focus on: π^0, η, ω, η' and Φ-decays
- WASA-at-COSY: (Forschungszentrum Jülich, Germany)
  - η-Decay program with data sets: $pd \to {}^3\mathrm{He}\eta$ and $pp \to pp\eta$
  - Analyses of π^0- and ω-decays were also performed

$\eta \to \pi^+\pi^-\pi^0$ The Dalitz Plot



(a) KLOE coll., *JHEP*, 05, (2008)

Dalitz plot variables:

$$X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{T_{\pi^+} + T_{\pi^-} + T_{\pi^0}}$$

$$Y = \frac{3T_{\pi^0}}{T_{\pi^+} + T_{\pi^-} + T_{\pi^0}}$$

- Decay via strong isospin violation: $\Gamma_{meas} = \left(\frac{Q_D}{Q}\right)^4 \bar{\Gamma}$
  - $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$, $\hat{m} = \frac{1}{2}(m_u + m_d)$
  - $\bar{\Gamma}$ calculated with ChPT at Dashen limit: $Q_D = 24.2$
- Dalitz plot analysis: $\frac{d\Gamma}{dXdY} \propto (1 + aY + bY^2 + dX^2 + fY^3 + gX^2Y + ...)$
  $\to$ *c*, *e* and *h* would imply C-violation

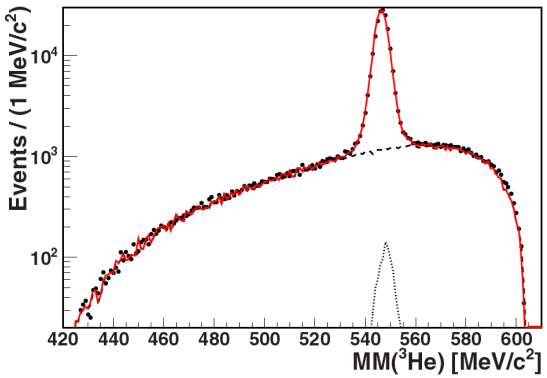
$\eta \to \pi^+\pi^-\pi^0$ Recent Measurements and Theoretical Predictions

	Parameter:	$-a$	b	d	f
Theor.	ChPT (NNLO)[b]	1.271(75)	0.394(102)	0.055(57)	0.025(160)
	NREFT[c]	1.213(14)	0.308(23)	0.050(3)	0.083(19)
	PWA[e]	1.116(32)	0.188(12)	0.063(4)	0.091(3)
Exp.	KLOE[a]	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
	WASA[d]	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)

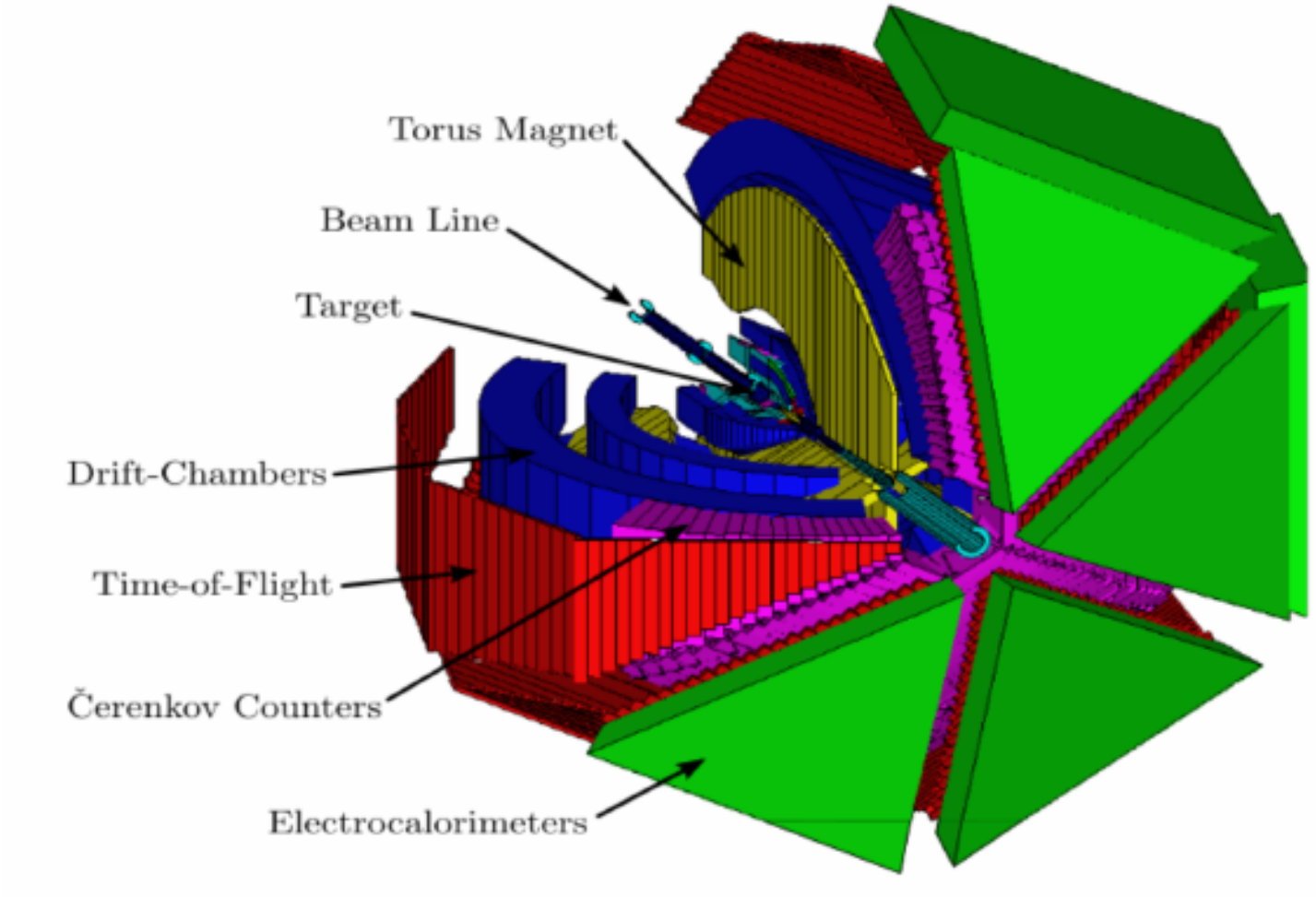
(a) KLOE coll., *JHEP*, 05, (2008) (b) J. Bijnens and K. Ghorbani., *JHEP*, 11, (2007) (c) S- P. Schneider et al., *JHEP*, 028, (2011)

(d) WASA-at-COSY coll., *Phys. Rev.*, C90(045207), 2014 (e) Peng Guo et al., *Phys. Rev.*, D92(05016), (2015)

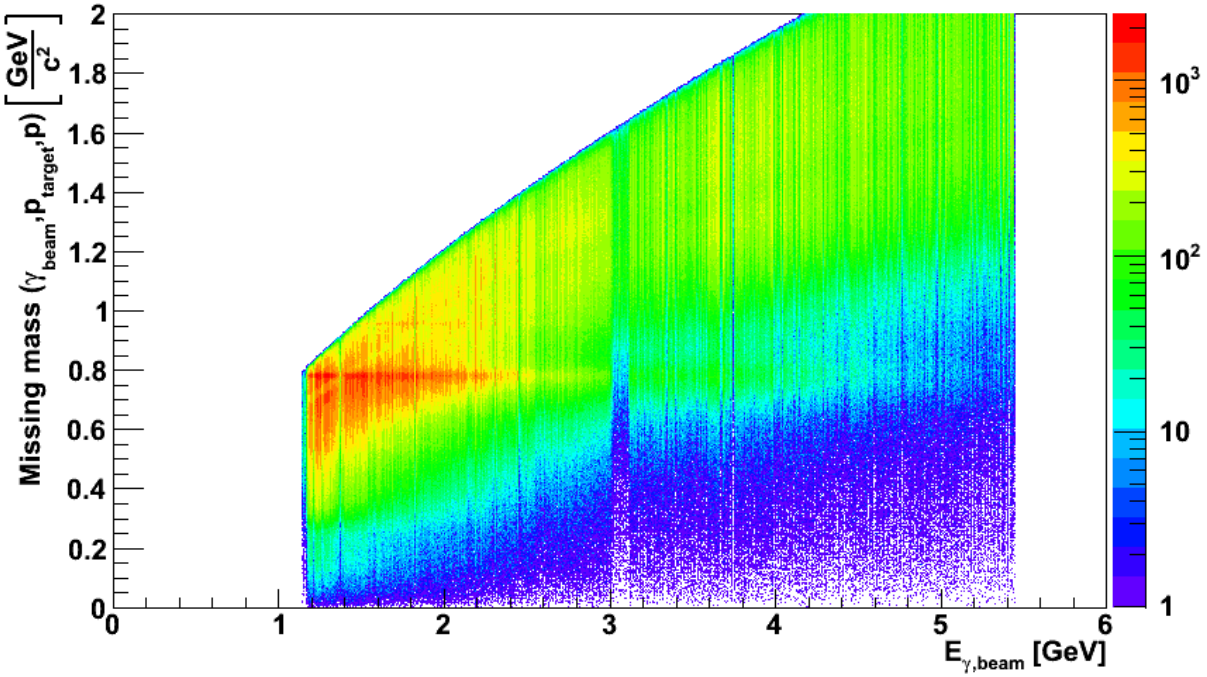
- $\approx 120\,\mathrm{k}\ \eta \to \pi^+\pi^-\pi^0$ events in the final WASA-at-COSY event sample
- Partial Wave Analysis from JPAC group: $Q = 21.4 \pm 0.4_{\mathrm{stat}}$[e]
- **Dalitz plot analysis for $\gamma p \to p\eta[\eta \to \pi^+\pi^-\pi^0]$ with CLAS**



CEBAF Large Acceptance Spectrometer - CLAS

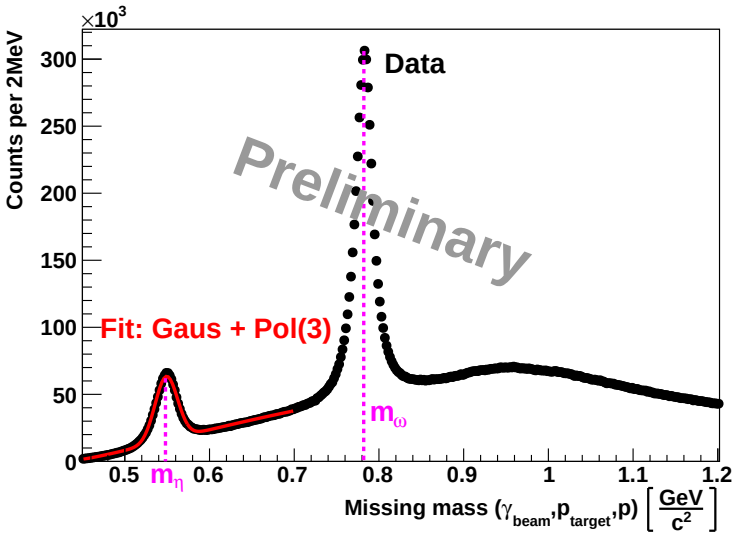


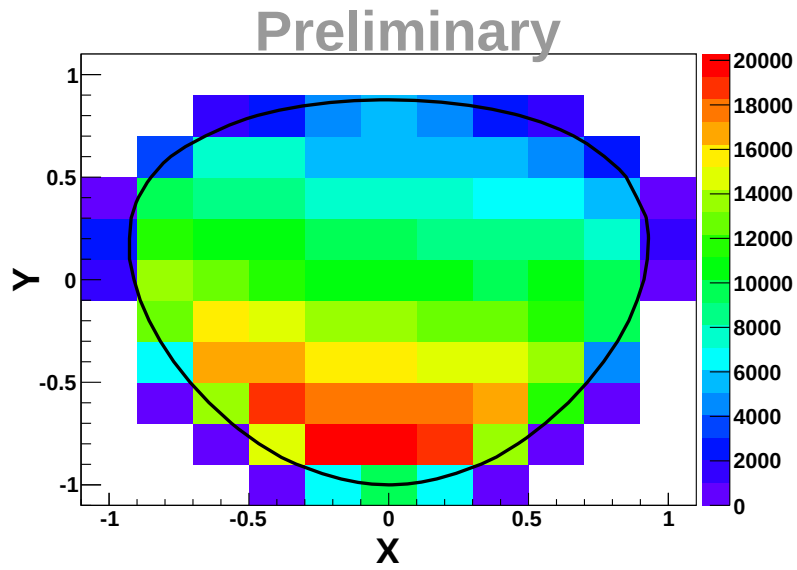
The CLAS $\gamma p \to pX$ Data Set



- Photon beam: $E_{\gamma,\text{beam}} \in [1.1\,\text{GeV}, 5.45\,\text{GeV}]$
- (Main) Contributions from:
  - Direct pion production (e.g. $\gamma p \to p\pi^+\pi^-\pi^0$)
  - π^0, η, ω and ρ decays
- Use missing mass: $|\mathbf{P}_{\gamma,\text{beam}} + \mathbf{P}_{\text{target}} - \mathbf{P}_{\text{proton}}|$ to monitor analysis

$\eta \to \pi^+\pi^-\pi^0$ Analysis and Results



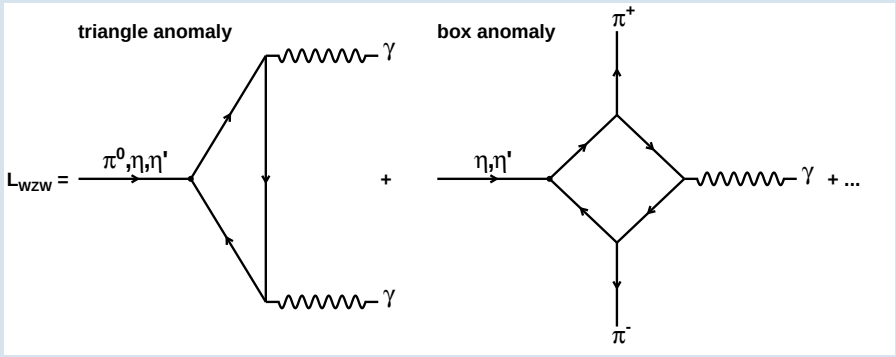


→ Use kinematic fit and kinematic limits of $M(\pi^+, \pi^-)$ to suppress background

- $\approx 770\,\mathrm{k}\ \eta \to \pi^+\pi^-\pi^0$ events reconstructed for 2/3 of CLAS data set
- Performed side-band subtraction for each Dalitz Plot bin
- To do:
  - i) Efficiency correction and correction for $\eta \to \pi^+\pi^-\gamma$ events
  - ii) Include partial wave analysis
  - iii) Determine Dalitz Plot parameters and Q

$\eta \to \pi^+\pi^-\gamma$ The Box Anomaly and $\pi^+\pi^-$ FSI

Chiral limit:[a],[b]



- Wess-Zumino-Witten Lagrangian

(a) Wess, Zumino, *Phys. Lett*, B37(95), 1971

(b) Witten, *Nucl. Phys.*, B223:422-432, 1983

- Decay amplitude $A_{\eta\to\pi^+\pi^-\gamma}$ is sensitive to box anomaly[c]:

$$A_{\eta\to\pi^+\pi^-\gamma} \propto \frac{e}{4\sqrt{3}\pi^2 F_\pi^3}\left(\frac{F_\pi}{F_8}\cos\theta - \sqrt{2}\frac{F_\pi}{F_0}\sin\theta\right)$$

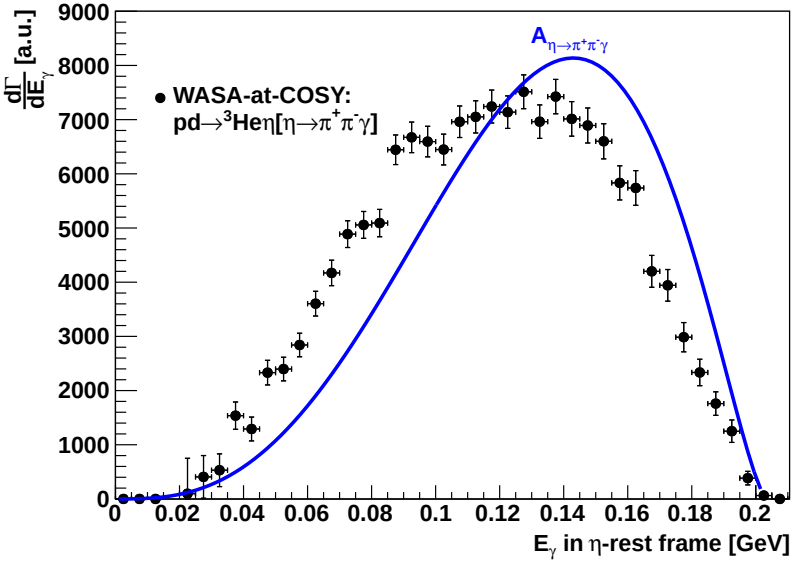
- $\Gamma^{\text{Theory}}(\eta \to \pi^+\pi^-\gamma) = 35.7\,\text{eV}$[c]
- $\Gamma^{\text{Exp.}}(\eta \to \pi^+\pi^-\gamma) = (55.3 \pm 2.4)\,\text{eV}$[d]

(c) B.R. Holstein, *Phys. Scripta*, T99:55-67, 2002

(d) PDG, *Chin. Phys.*, 090001, 2014

- Photon energy distribution E_γ:[e]

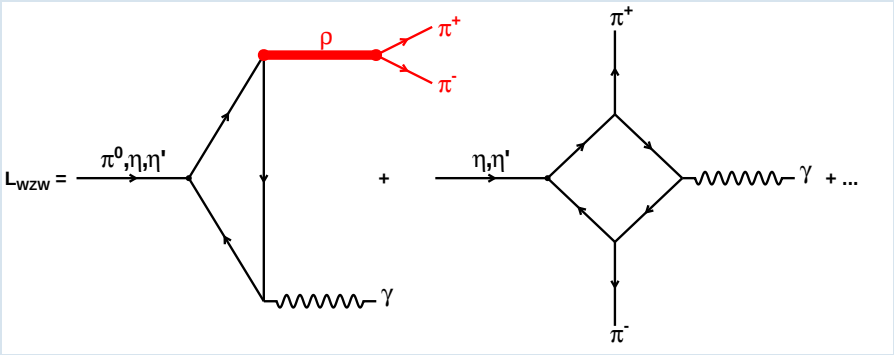
(e) WASA-at-COSY coll. *Phys. Lett.*, B707:243-249, 2012



$$E_\gamma(s_{\pi\pi}) = \frac{1}{2}\cdot\left(m_\eta - \frac{s_{\pi\pi}}{m_\eta}\right)$$

$\eta \to \pi^+\pi^-\gamma$ The Box Anomaly and $\pi^+\pi^-$ FSI

Beyond chiral limit:



- Wess-Zumino-Witten Lagrangian & $\pi^+\pi^-$ Final State Interactions
- Modification of decay amplitude:[a]

(a) F.Stollenwerk et al., *Phys. Lett.*, B707:184-190, 2012

$$A_{\eta\to\pi^+\pi^-\gamma} \times [F_{PV}(s_{\pi\pi}) \cdot (1 + \alpha s_{\pi\pi})]$$

$\Rightarrow$ Description of FSI: $\begin{cases} \text{by } F_{PV} & \alpha = 0 \\ \text{reaction specific}^* & \alpha \neq 0 \end{cases}$

*Input from theory

- $\Gamma^{\text{Theory}}(\eta \to \pi^+\pi^-\gamma) = 35.7\,\text{eV}$[b]
- $\Gamma^{\text{Exp.}}(\eta \to \pi^+\pi^-\gamma) = (55.3 \pm 2.4)\,\text{eV}$[c]

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- Photon energy distribution E_γ:[d]

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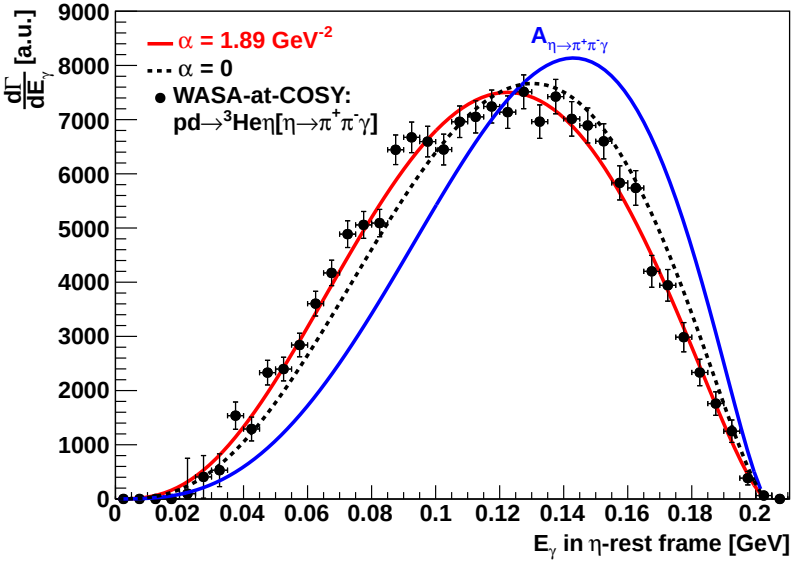

$$E_\gamma(s_{\pi\pi}) = \frac{1}{2} \cdot \left(m_\eta - \frac{s_{\pi\pi}}{m_\eta}\right)$$

$\eta \to \pi^+\pi^-\gamma$ Recent Measurements and Theoretical Predictions

		$\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$	$\alpha\ [\mathrm{GeV}^{-2}]$
Experiment	Gormley et al.	0.202 ± 0.006	1.8 ± 0.4
	Thaler et al.	0.209 ± 0.004	-
	Layter et al.	-	-0.9 ± 0.1
	GAMS-200*	-	2.7 ± 0.1
	CRYSTAL BARREL*	-	1.8 ± 0.53
	CLEO	0.175 ± 0.013	-
	WASA-at-COSY	Preliminary: 0.206 ± 0.011	1.89 ± 0.86
	KLOE	0.1856 ± 0.003	1.32 ± 0.2
	CLAS	Analysis ongoing for η and η'	-
Theory	N/D	0.2188 ± 0.0088	0.64 ± 0.02
	HLS	0.1875 ± 0.0094	0.23 ± 0.01
	$(O(p^6) + 1 - \text{loop})$	0.1565 ± 0.0063	-0.7 ± 0.1
	Box anomaly	0.119 ± 0.0048	-1.7 ± 0.02

*Measured $\eta' \to \pi^+\pi^-\gamma$

$\Longrightarrow$Determine $\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)}$ and α via E_γ-distribution in $pp \to pp\eta[\eta \to \pi^+\pi^-\gamma]$

$\eta \to \pi^+\pi^-\gamma$ Recent Measurements and Theoretical Predictions

		$\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$	$\alpha\ [\mathrm{GeV}^{-2}]$
Experiment	*Phys. Rev.,D2:501-505, 1970*	0.202 ± 0.006	1.8 ± 0.4
	Phys. Rev.,D7:2569-2571, 1973	0.209 ± 0.004	-
	Phys. Rev.,D7:2565-2568, 1973	-	-0.9 ± 0.1
	Phys.,C50:451-454, 1991 *	-	2.7 ± 0.1
	*Phys. Lett.,B402:195, 1997**	-	1.8 ± 0.53
	Phys. Rev. Lett.,99(122001), 2007	0.175 ± 0.013	-
	Phys. Rev. Lett.,B707:243-249, 2013	-	1.89 ± 0.86
	Phys. Lett.,B718:910-914, 2013	0.1856 ± 0.003	1.32 ± 0.2
	-	-	-
Theory	*Phys. Scripta*, T99:55-67, 2002	0.2188 ± 0.0088	0.64 ± 0.02
	Europ. Phys. Journal, C31:525-547, 2003	0.1875 ± 0.0094	0.23 ± 0.01
	Phys. Lett., B237:488-494, 1990	0.1565 ± 0.0063	-0.7 ± 0.1
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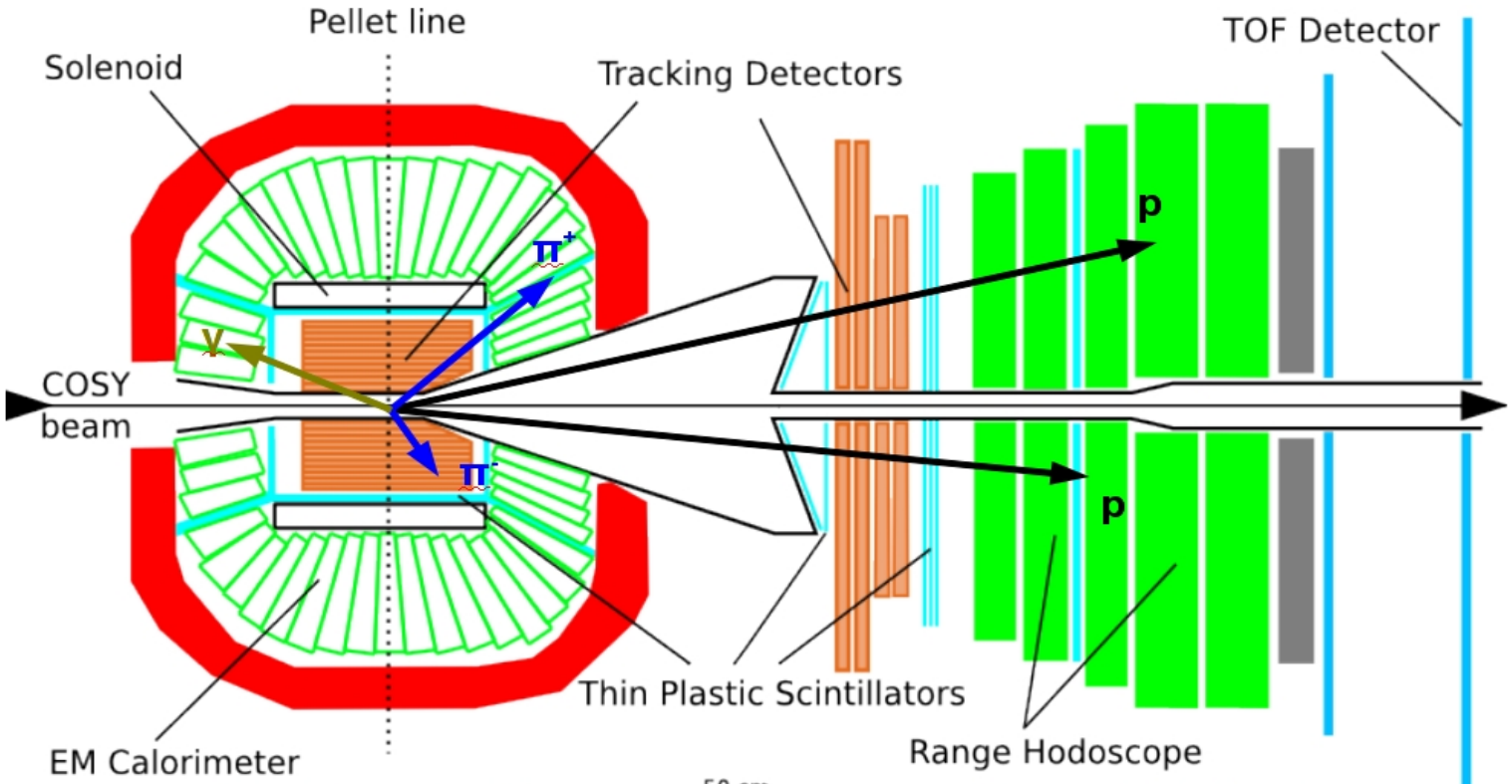
* Measured $\eta' \to \pi^+\pi^-\gamma$

$\Longrightarrow$ Determine $\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)}$ and α via E_γ-distribution in $pp \to pp\eta[\eta \to \pi^+\pi^-\gamma]$

Wide Angle Shower Apparatus - WASA

Example: $pp \rightarrow pp\eta[\eta \rightarrow \pi^+\pi^-\gamma]$

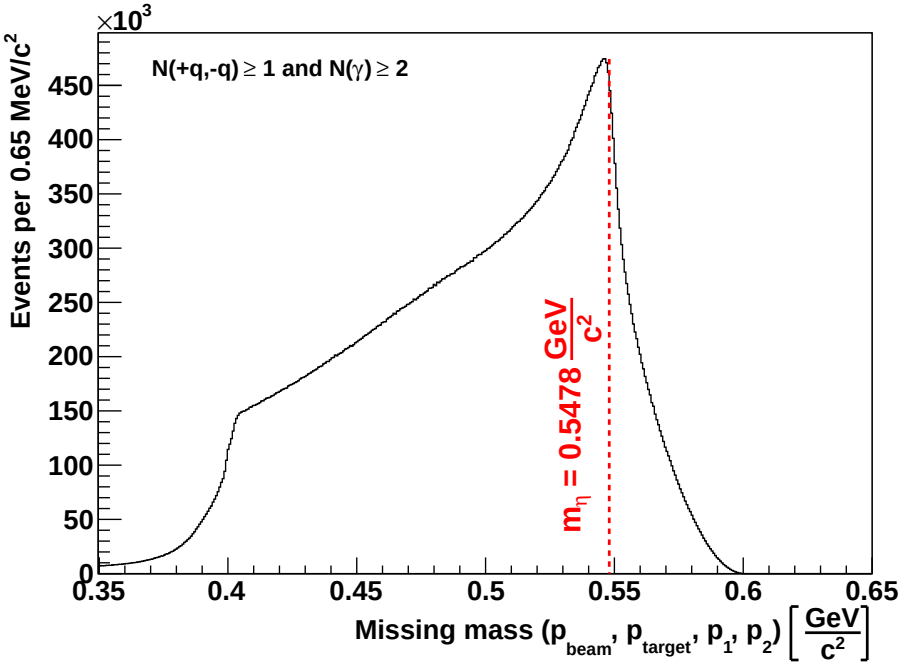


Central Detector:
meson decay products
(pions,electrons,photons)

Forward Detector:
recoil particles (e.g. protons)

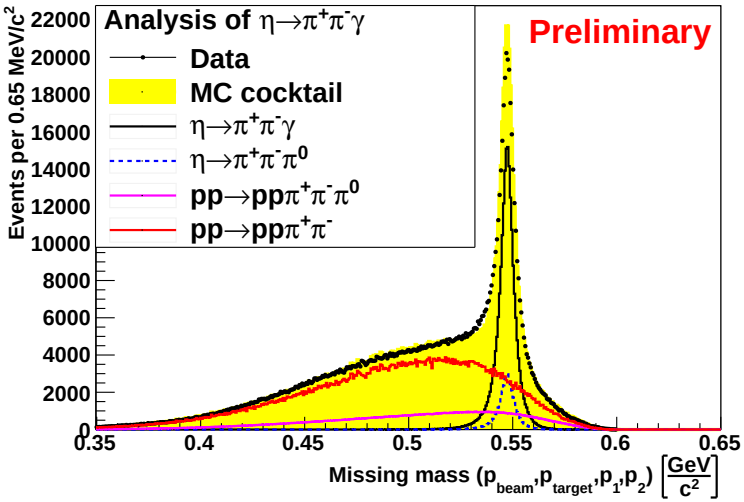
The WASA-at-COSY $pp \to pp\eta$ Data Set

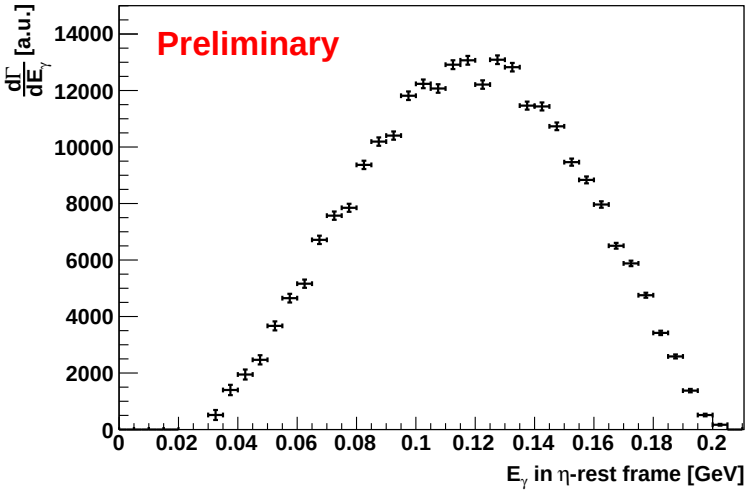
- $\sigma(\eta) = (9.8 \pm 1)\mu\mathrm{b}$ at $T_{beam} = 1.4\,\mathrm{GeV}$
- Background contributions from direct pion production:
  - i) $pp \to pp\pi^+\pi^-$ [σ=(660±100)μb]
  - ii) $pp \to pp\pi^0\pi^0$ [σ=(200±30)μb]
  - iii) $pp \to pp\pi^+\pi^-\pi^0$ [σ=(4.6±1.5)μb]
- After proton identification and requesting an event topology reconstruct η-Meson via Missing mass: $|\mathbf{P}_{\mathrm{beam}} + \mathbf{P}_{\mathrm{target}} - (\mathbf{P}_{\mathrm{proton1}} + \mathbf{P}_{\mathrm{proton2}})|$



$pp \to pp\eta$ data taken in	2008	2010	2012
Duration of beam time	2 weeks	7 weeks	8 weeks
η mesons produced	$\sim 1 \cdot 10^8$	$\sim 4 \cdot 10^8$	$\sim 5 \cdot 10^8$

$\eta \to \pi^+\pi^-\gamma$ Analysis and Results





→ Use kinematic fit and rejection of low energetic satellite clusters in calorimeter to suppress background

- $\approx 209\,\mathrm{k}\ \eta \to \pi^+\pi^-\gamma$ events reconstructed
- E_γ-distribution after background correction from direct pion production
- To do:
  i) Include efficiency corrections
  ii) Calculate $\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)}$ and α

Summary and Outlook

Dalitz Plot analysis of $\gamma p \to p\eta[\eta \to \pi^+\pi^-\pi^0]$:

- ☑ $\approx 770\,\mathrm{k}$ events reconstructed in CLAS
- ☑ Background corrected Dalitz Plot
- ☐ Include simulations into analysis
- ☐ Calculate Dalitz Plot parameters and Q

Box Anomaly and $\pi^+\pi^-$FSI in $pp \to pp\eta[\eta \to \pi^+\pi^-\gamma]$:

- ☑ $\approx 209\,\mathrm{k}$ events reconstructed in WASA
- ☑ Background corrected E_γ-distribution
- ☐ Efficiency correction
- ☐ Extract α and relative branching ratio