JÜLICH FORSCHUNGSZENTRUM

Studying η-Meson Decays with WASA-at-COSY

03.06.2016 | Daniel Lersch for the WASA-at-COSY collaboration

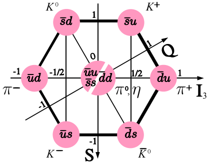
Institute for Nuclear Physics - Jülich Research Center

From Quarks to Mesons

$$\mathscr{L}_{QCD}(\bar{q},q,g) = \sum_{f=u,d,s,c,b,t} \bar{q}_f(i\gamma^\mu D_\mu - m_f)q_f - \frac{1}{4}G^a_{\mu\nu}G_{a\mu\nu}$$

	General	Chiral Limit
Energy	$\gtrsim$ MeV	$\sim$ GeV
Quark mass	$m_u, m_d, m_s, ..., \neq 0$	$(m_u, m_d, m_s) \to 0$
L- and R-Quarks	coupled via m_f	decoupled
Symmetry	$SU(3)$ colour	chiral symmetry*
Theory	Full QCD	Full QCD $\to$ ChPT
Lagrangian	$\mathscr{L}_{QCD}(\bar{q},q,g)$	$\mathscr{L}_{eff}(\pi, K, \eta) = \mathscr{L}_{2N} + \mathbf{L_{WZW}} + ...$

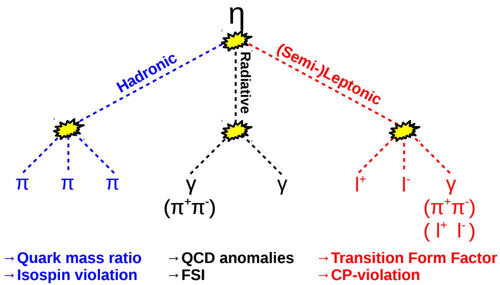
- $*$ spontaneously broken in ground state
  Goldstone Theorem $\Longrightarrow$
- massless bosons $\Leftrightarrow$
  8 pseudoscalar* mesons: π, K, η
  $\star\ J = \ell = s = 0$



One Meson, many Opportunities

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

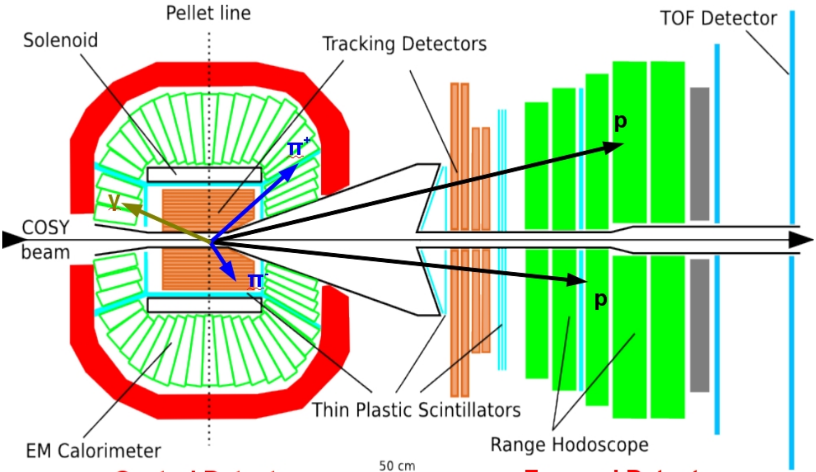
⇒ **Access to rare decay processes**



η-Meson production at WASA-at-COSY:

1. $pd \to {}^3\mathrm{He}\eta[\eta \to ...] \parallel \sigma(\eta) = (0.412 \pm 0.016)\,\mu\mathrm{b}$ at $T_{beam} = 1\,\mathrm{GeV}$
2. $pp \to pp\eta[\eta \to ...] \parallel \sigma(\eta) = (9.8 \pm 1)\,\mu\mathrm{b}$ at $T_{beam} = 1.4\,\mathrm{GeV}$

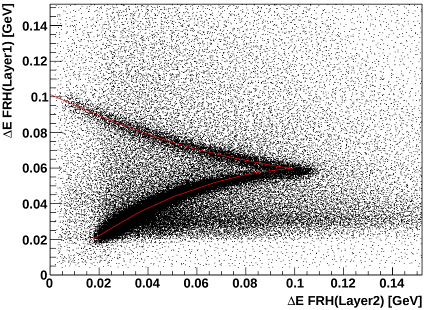
Wide Angle Shower Apparatus - WASA

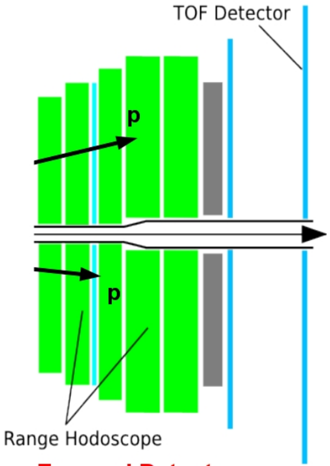


Central Detector:
meson decay products
(pions,electrons,photons)

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

Wide Angle Shower Apparatus - WASA





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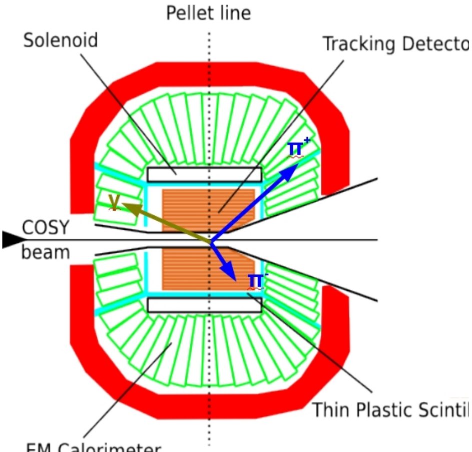
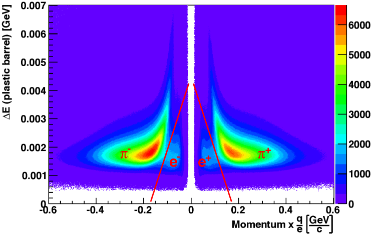
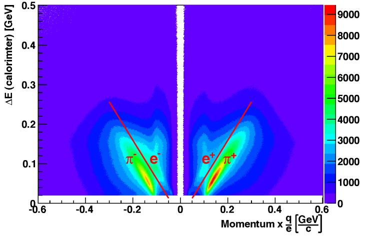
recoil particles (e.g. protons)

Wide Angle Shower Apparatus - WASA

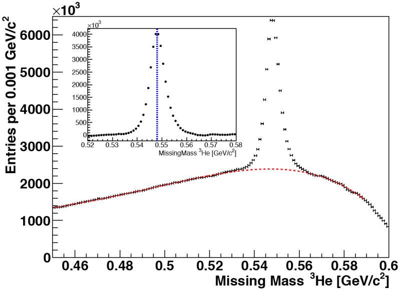


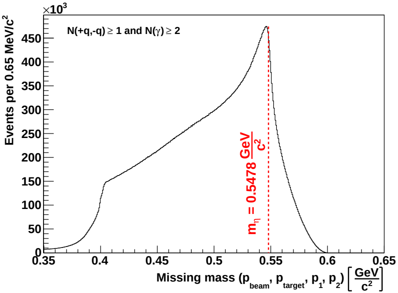
Central Detector:
meson decay products
(pions,electrons,photons)





The Data Sets

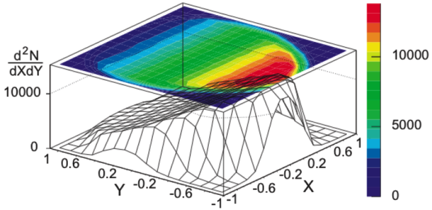




- Reconstruct η-meson via missing mass: $|\mathbf{P}_{in} - \mathbf{P}_{out}|$
- Background contributions from direct pion production reactions: $pd \rightarrow {}^3\mathrm{He}X$, $pp \rightarrow ppX$ with: $X = \pi^+\pi^-$, $X = \pi^0\pi^0$ and $X = \pi^+\pi^-\pi^0$

	$pd \rightarrow {}^3\mathrm{He}\eta$		$pp \rightarrow pp\eta$		
Data taken in	2008	2009	2008	2010	2012
Duration of beam time	4 weeks	8 weeks	2 weeks	7 weeks	8 weeks
$\#\eta$ detected (pd) / produced (pp)	$\sim 1 \cdot 10^7$	$\sim 2 \cdot 10^7$	$\sim 1 \cdot 10^8$	$\sim 4 \cdot 10^8$	$\sim 5 \cdot 10^8$

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



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

Dimensionless 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: $\frac{d^2\Gamma}{dXdY} \propto (1 + aY + bY^2 + dX^2 + fY^3 + gX^2Y + ...)$

  $\rightarrow$ *c*, *e* and *h* would imply C-violation

$\eta \to \pi^+\pi^-\pi^0$ Results from *pd* $\to {}^3\mathrm{He}\eta$

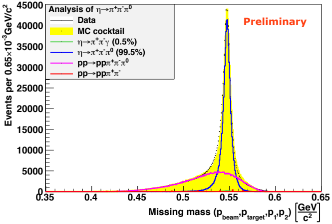
	Parameter:	$-$a	b	d	f
Theor.	ChPT (NNLO)[(b)]	1.271(75)	0.394(102)	0.055(57)	0.025(160)
	NREFT[(c)]	1.213(14)	0.308(23)	0.050(3)	0.083(19)
	PWA[(e)]	1.116(32)	0.188(12)	0.063(4)	0.091(3)
Exp.	KLOE (08)[(a)]	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
	WASA[(d)]	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)
	KLOE (16)[(f)]	1.104(3)(2)	$0.142(3)(^{5}_{-4})$	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$

(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)
(f) KLOE coll., *JHEP*, 019, (2016)

- $\sim 120\,\mathrm{k}\ \eta \to \pi^+\pi^-\pi^0$ events in the final event sample
- Calculation from JPAC⋆ group:
  $Q = 21.4 \pm 0.4$[(e)]

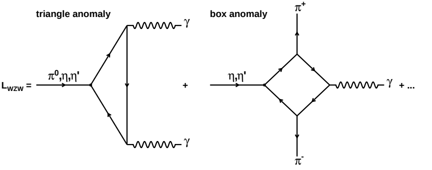
  ⋆ Interactive web page: http://www.indiana.edu/ jpac/index.html

  (e) Peng Guo et al., *Phys. Rev.*, D92(05016), (2015)
- Dalitz plot analysis for
  pp $\to$ *pp*$\eta[\eta \to \pi^+\pi^-\pi^0]$ in progress



$\eta \to \pi^+\pi^-\gamma$ 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):

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

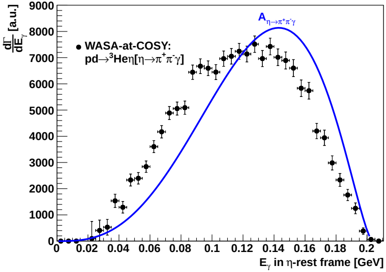
- $\Gamma^{\text{Theory}}(\eta \to \pi^+\pi^-\gamma) = 35.7\,\text{eV}^{(c)}$
- $\Gamma^{\text{Exp.}}(\eta \to \pi^+\pi^-\gamma) = (55.3 \pm 2.4)\,\text{eV}^{(d)}$

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

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

- Photon energy distribution E_γ: (e)

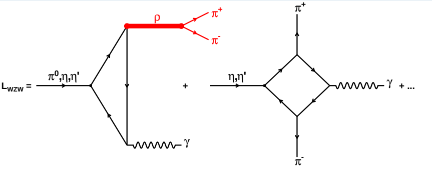
  (e) WASA-at-COSY coll. *Phys. Lett.*, B707:243-249, 2012



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

$\eta \to \pi^+\pi^-\gamma$ 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

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

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

*Input from theory

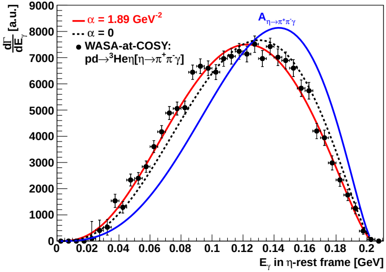
- $\Gamma^{\text{Theory}}(\eta \to \pi^+\pi^-\gamma) = 35.7\,\text{eV}$(b)
- $\Gamma^{\text{Exp.}}(\eta \to \pi^+\pi^-\gamma) = (55.3 \pm 2.4)\,\text{eV}$(c)

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

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

- Photon energy distribution E_γ:(d)

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



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

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

		$\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$	α [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	$1.32^{\star} \pm 0.2$
	CLAS	See talk by M.C. Kunkel (Session B)	-
	BESIII	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 $\eta' \to \pi^+\pi^-\gamma$ / $\star$ Include effects of a_2: Kubis and Plenter, Eur. Phys. J., C75: 283, 2015

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

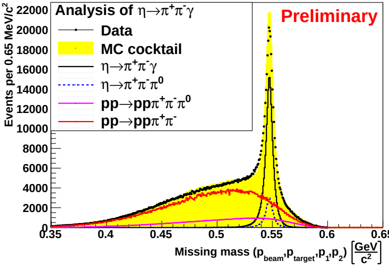
$\eta \to \pi^+\pi^-\gamma$ Theoretical Predictions and Recent Measurements

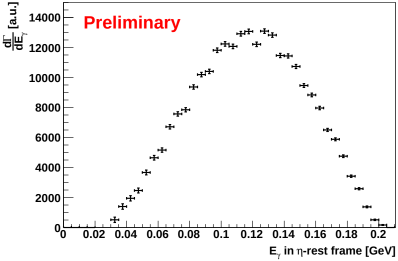
		$\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$	α [GeV^{-2}]
Experiment	*Phys. Rev.,D2:501-505, 1970*	0.202 ± 0.006	1.8 ± 0.4
	Phys. Rev.,D7:2569-2571, 1973	0.209 ± 0.004	-
	Phys. Rev.,D7:2565-2568, 1973	-	-0.9 ± 0.1
	Phys.,C50:451-454, 1991 *	-	2.7 ± 0.1
	Phys. Lett.,B402:195, 1997 *	-	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
	Phys. Scripta, T99:55-67, 2002	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 $pp \to pp\eta[\eta \to \pi^+\pi^-\gamma]$

$\eta \to \pi^+\pi^-\gamma$ Status in *pp* $\to$ *pp*η



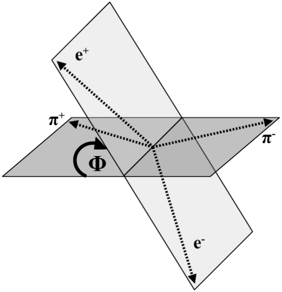


- $\sim$ 209 k $\eta \to \pi^+\pi^-\gamma$ events reconstructed
- E_γ-distribution after background correction from direct pion production
- Ongoing steps:
  i) Systematic checks $\Leftrightarrow$ Include efficiency corrections
  ii) Calculate $\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)}$ and α

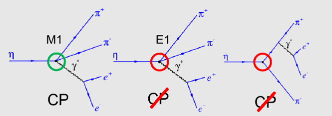
$\eta \rightarrow \pi^+\pi^-e^+e^-$ CP-Violation

$\eta \rightarrow \pi^+\pi^-\gamma$

- CP-conserving for M_1 and E_2 transitions
- Access to CP-violation:
  - ⇒ Measure E_1 transition
  - ⇒ Need information about polarisation of single photon



$\eta \rightarrow \pi^+\pi^-\gamma^*[\gamma^* \rightarrow e^+e^-]$



CP-allowed, and possible CP-forbidden amplitudes

- Look at asymmetry A_Φ [(a)] of angle Φ between decay planes of electrons and pions:

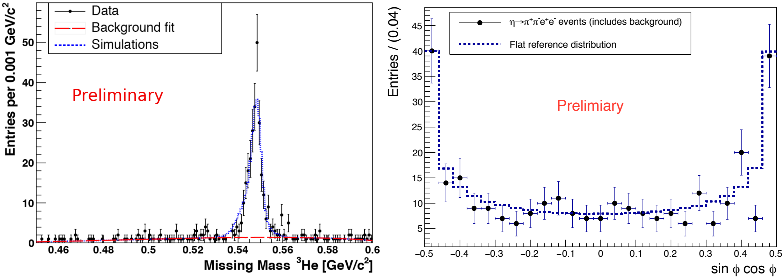
$$A_\Phi = \frac{N(\sin[\Phi]\cos[\Phi]>0) - N(\sin[\Phi]\cos[\Phi]<0)}{N(\sin[\Phi]\cos[\Phi]>0) + N(\sin[\Phi]\cos[\Phi]<0)}$$

- Upper limit predicted by theory[(a)]: $\sim 1\%$
- Results found by KLOE:[(b)]
  1.) $A_\Phi = (-0.6 \pm 2.5_{stat} \pm 1.8_{sys}) \cdot 10^{-2}$
  2.) $\frac{\Gamma(\eta \rightarrow \pi^+\pi^-e^+e^-)}{\Gamma_\eta} = (2.68 \pm 0.09_{stat} \pm 0.07_{sys}) \cdot 10^{-4}$

(a) D. Gao. *Mod. Phys. Lett.*, A17:1583-1588, 2002

(b) KLOE coll. *Phys. Lett.*, B675:283-288-914, 2009

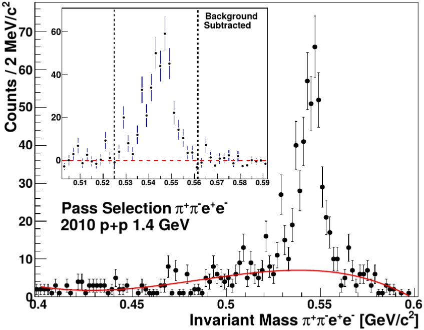
$\eta \to \pi^+\pi^-e^+e^-$ Results from $pd \to {}^3\mathrm{He}\eta$



- 251 ± 17 $\eta \to \pi^+\pi^-e^+e^-$ events in the final sample
- Preliminary:
  1.) $A_\Phi = (-1.1 \pm 6.6_{stat} \pm 0.2_{sys}) \cdot 10^{-2}$
  2.) $\frac{\Gamma(\eta \to \pi^+\pi^-e^+e^-)}{\Gamma_\eta} = (2.7 \pm 0.2_{stat} \pm 0.2_{sys}) \cdot 10^{-4}$
- More statistics $\Rightarrow$ $pp\eta$ data set

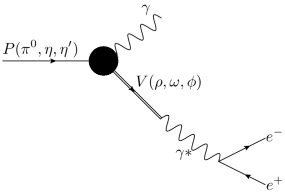
$\eta \to \pi^+\pi^-e^+e^-$ Status in $pp \to pp\eta$

- Analysis done for a fraction of 2010 $pp \to pp\eta$ data set:$^{(c)}$
  - ~ 220 $\eta \to \pi^+\pi^-e^+e^-$ events reconstructed
  - $\sim 1,000$ events expected for full $pp \to pp\eta$ data sample
- Analysis in $pp \to pp\eta$ needs to be continued



(c) D. Coderre, *PhD Thesis*, 2012

$\eta \to e^+e^-\gamma$ and $\eta \to e^+e^-e^+e^-$ Dalitz Decays



Single off-shell transition form factor $F(q^2)$

- $\frac{d\Gamma}{dq^2} = \left[\frac{d\Gamma}{dq^2}\right]_{QED} \cdot |F(q^2)|^2$
- Observables to test: $\frac{\Gamma(\eta \to e^+e^-\gamma)}{\Gamma_\eta}$ and Dilepton mass
- Recent result: $\frac{\Gamma(\eta \to e^+e^-\gamma)}{\Gamma_\eta} = (6.9 \pm 0.4) \cdot 10^{-3}$ (a)

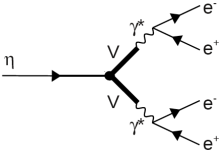
(a) K. Olive et al. *Chin. Phys.*, C38, 090001, 2014

Double off-shell transition form factor $F(q_1^2, q_2^2)$

- Different approaches for calculation of F (b)
- Observable to test: $\frac{\Gamma(\eta \to e^+e^-e^+e^-)}{\Gamma_\eta}$
- Current result measured by KLOE: (c)

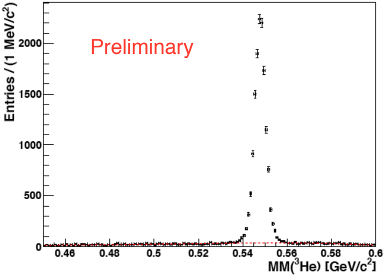
$\frac{\Gamma(\eta \to e^+e^-e^+e^-)}{\Gamma_\eta} = (2.4 \pm 0.2_{stat} \pm 0.1_{sys}) \cdot 10^{-5}$

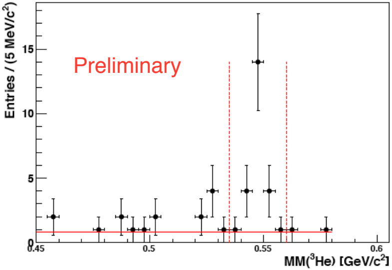
(b) J. Bijnens et al. *arXiv:hep-ph/0106130v1*, 2001 (c) KLOE coll. *Phys. Lett.*, B702:324-328, 2011



$\eta \to e^+e^-\gamma$ and $\eta \to e^+e^-e^+e^-$

Results from $pd \to {}^3\mathrm{He}\eta$





- $14,040 \pm 120$ events $\eta \to e^+e^-\gamma$ events reconstructed
- Preliminary: $\frac{\Gamma(\eta \to e^+e^-\gamma)}{\Gamma_\eta} = (6.72 \pm 0.07_{stat} \pm 0.31_{sys}) \cdot 10^{-3}$

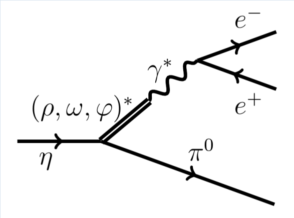
- 18 ± 5 $\eta \to e^+e^-e^+e^-$ events reconstructed
- Preliminary: $\frac{\Gamma(\eta \to e^+e^-e^+e^-)}{\Gamma_\eta} = (3.2 \pm 0.9_{stat} \pm 0.5_{sys}) \cdot 10^{-5}$

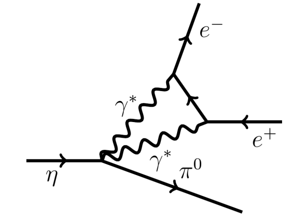
Status of those decays in $pp \to pp\eta$:

See talk by Anktia Goswami at the end of this session

$\eta \to \pi^0 e^+ e^-$ C-Violation

Possible Realisations of this Decay:





- Forbidden by SM:
  $BR(\eta \to \pi^0 e^+ e^-) < 4 \cdot 10^{-5}$ [(a)]
- Investigate existing upper limit BR in $pd \to {}^3\mathrm{He}\eta$ and $pp \to pp\eta$ data set

$\Rightarrow$ See poster by Kay Demmich on 04.06.2016

(a) K. Olive et al. *Chin. Phys.*, C38, 090001, 2014

Summary and Outlook

Decay mode	$\Gamma(\eta \to ...)/\Gamma_\eta$ [a]	Issue
$\eta \to \pi^0\pi^0\pi^0$ (b)	$(32.68 \pm 0.23)\%$	Dalitz plot analysis
$\eta \to \pi^+\pi^-\pi^0$ (c)	$(22.92 \pm 0.28)\%$	Dalitz plot analysis
$\eta \to \pi^+\pi^-\gamma$ (d)	$(4.22 \pm 0.08)\%$	Box anomaly, $\pi^+\pi^-$ FSI
$\eta \to e^+e^-\gamma$ (e)	$(0.69 \pm 0.11)\%$	Single-off-shell transition form factor
$\eta \to \pi^0\gamma\gamma$	$(2.7 \pm 0.5) \cdot 10^{-4}$	Test of ChPT
$\eta \to \pi^+\pi^-e^+e^-$ (e)	$(2.68 \pm 0.11) \cdot 10^{-4}$	CP-Violation
$\eta \to e^+e^-e^+e^-$ (e)	$(2.40 \pm 0.22) \cdot 10^{-5}$	Double-off-shell transition form factor
$\eta \to \pi^0 e^+e^-$	$< 4 \cdot 10^{-5}$	C-Violation
$\eta \to e^+e^-$	$< 5.6 \cdot 10^{-6}$	Physics beyond the SM

- [x] Analysis of $pd \to {}^3\mathrm{He}\eta[\eta \to ...]$ (e)
- [ ] Analysis of $pp \to pp\eta[\eta \to ...]$

(a): PDG, *Chin. Phys.*, 090001, 2014

(b): WASA-at-COSY coll., *Phys. Lett.*, **B677:24-29, 2009**

(c): WASA-at-COSY coll., *Phys. Rev.*, **C90(045207), 2014**

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

(e): Publication in progress

Picture found at: http://www.sunexpressnews.com/wp-content/ uploads/2011/12/MTG_Apocalypse-Hydra.jpg

Contents

Backup

$\eta \to \pi^+\pi^-\gamma$

- Theoretical Models
- Analysis (Split-off rejection)
- Analysis (Kinematic fit)
- Determining the E_γ-distribution

$\eta \to e^+e^-\gamma$ and $\eta \to e^+e^-e^+e^-$

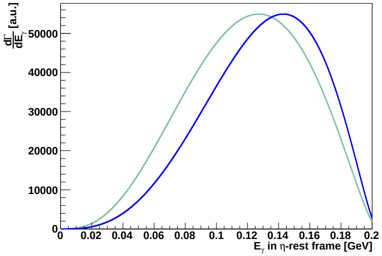
- Form factor $F(q^2)$
- Theoretical predictions for $\Gamma(\eta \to e^+e^-e^+e^-)/\Gamma(\eta)$

- Conversion events
- η Production mechanisms
- Preselection of the $pp \to pp\eta$ data set

$\eta \to \pi^+\pi^-\gamma$ Theoretical Models

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

- N/D-Model:[a)]
  - One-loop chiral corrections and VMD
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with: $\left[\frac{1+0.5m_\rho^2 s_{\pi\pi}}{D_1(s_{\pi\pi})}\right]$



$\eta \to \pi^+\pi^-\gamma$ Theoretical Models

- N/D-Model:[a)]
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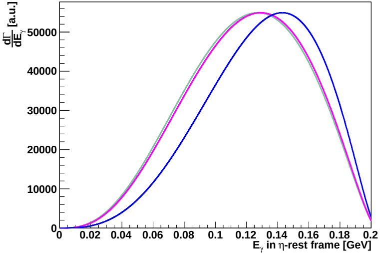
- HLS (Hidden Local Symmetries)-Model:[b)]
  - $\gamma - V$ Transitions
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with: $\left[1 + \frac{3m_\rho^2}{D_\rho(s_{\pi\pi})}\right]$

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

b) M.Benayoun et al., *Europ. Phys. Journal*, C31:525-547, 2003



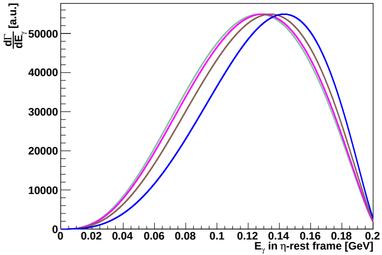
$\eta \rightarrow \pi^+\pi^-\gamma$ Theoretical Models

- N/D-Model:[a)]
  - One-loop chiral corrections and VMD
  - Modify $A_{\eta\rightarrow\pi^+\pi^-\gamma}$ with: $\left[\frac{1+0.5m_\rho^2 s_{\pi\pi}}{D_1(s_{\pi\pi})}\right]$
- HLS (Hidden Local Symmetries)-Model:[b)]
  - $\gamma - V$ Transitions
  - Modify $A_{\eta\rightarrow\pi^+\pi^-\gamma}$ with: $\left[1+\frac{3m_\rho^2}{D_\rho(s_{\pi\pi})}\right]$
- $O(p^6)+1-$loop-Modell:[c)]
  - Higher momentum orders $O(p^6)$ and one loop chiral corrections
  - Modify $A_{\eta\rightarrow\pi^+\pi^-\gamma}$ with:
    $\left[1+C^{\text{loops}}+\frac{3}{2m_\rho^2}(p_{\pi^+}+p_{\pi^-})^2\right]$

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

b) M.Benayoun et al., *Europ. Phys. Journal*, C31:525-547, 2003

c) J.Bijnens et al., *Phys. Lett.*, B237:488-494, 1990



$\eta \to \pi^+\pi^-\gamma$ Theoretical Models

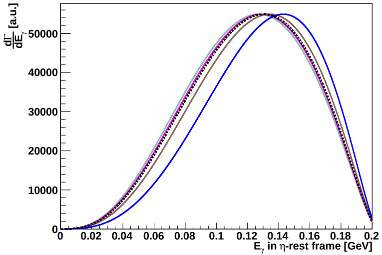
- N/D-Model:[a)]
  - One-loop chiral corrections and VMD
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with: $\left[\frac{1+0.5m_\rho^2 s_{\pi\pi}}{D_1(s_{\pi\pi})}\right]$
- HLS (Hidden Local Symmetries)-Model:[b)]
  - $\gamma - V$ Transitions
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with: $\left[1 + \frac{3m_\rho^2}{D_\rho(s_{\pi\pi})}\right]$
- $O(p^6) + 1 -$ loop-Modell:[c)]
  - Higher momentum orders $O(p^6)$ and one loop chiral corrections
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with:
    $\left[1 + C^{\text{loops}} + \frac{3}{2m_\rho^2}(p_{\pi^+} + p_{\pi^-})^2\right]$
- Pion-Vektor-Formfactor:[d)]
  - $\pi^+\pi^-$-interactions (universal)
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with:
    $F_{PV}(s_{\pi\pi}) \approx a \cdot s_{\pi\pi}^3 + b \cdot s_{\pi\pi}^2 + c \cdot s_{\pi\pi} + d$

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

b) M.Benayoun et al., *Europ. Phys. Journal*, C31:525-547, 2003

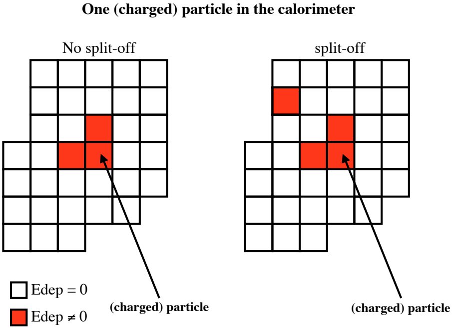
c) J.Bijnens et al., *Phys. Lett.*, B237:488-494, 1990

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



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

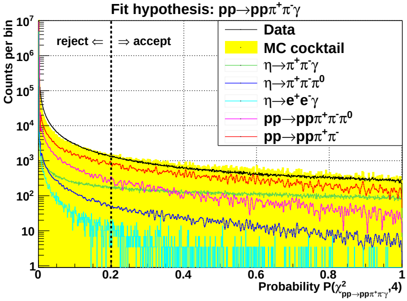
i) Rejection of split-offs



- Hit in calorimeter is assigned to a cluster
- Split-off: Satellite cluster with close distance to primary cluster $\rightarrow$ low energy fake photon
- Predominant background: $pp \rightarrow pp\pi^+\pi^-(\gamma)$
- Reject low energy fake photons with close distance to primary cluster

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

ii) Kinematic fit



- Least squares fit:

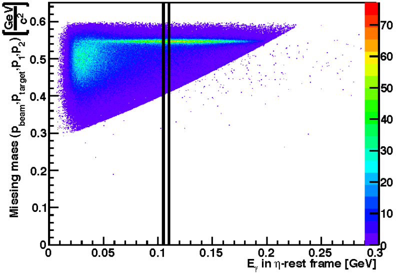
$$\chi^2 = \sum_{i=1}^{N_p}\sum_{j=1}^{N_v}\left(\frac{v_{ij}^{fit} - v_{ij}^{meas}}{\sigma_{ij}^{meas}}\right)^2 + 2\cdot\sum_{\mu}\lambda_\mu F_\mu(v_{11}^{fit}, \ldots, v_{N_pN_v}^{fit})$$

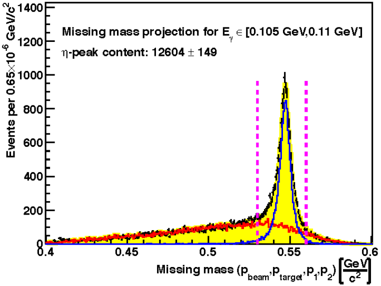
- F_μ: energy and momentum conservation $\to$ 4 constraints
- $$P(\chi^2, N) = \frac{1}{\sqrt{2^N \cdot \Gamma(\frac{1}{2}N)}} \int_{\chi^2}^{\infty} e^{-\frac{t}{2}} \cdot t^{\frac{1}{2}N-1} dt$$

Use kinematic fit to:

a) Improve resolution
b) Suppress background

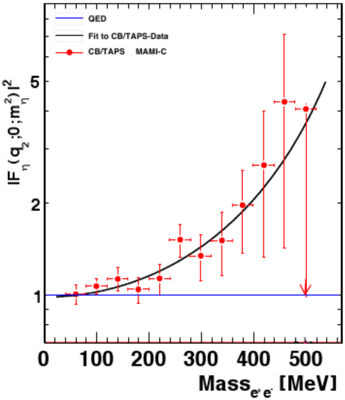
$\eta \to \pi^+\pi^-\gamma$ Determining the E_γ-distribution

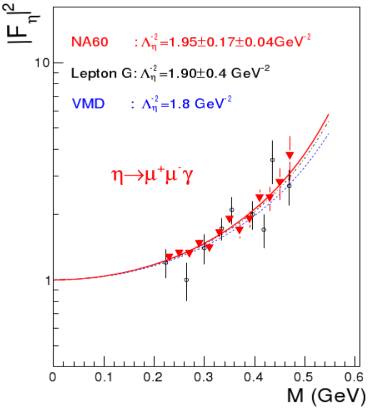




- Scan two proton missing mass distribution in E_γ-intervals
- Subtract background for each E_γ-interval
- Obtain number of $\eta \to \pi^+\pi^-\gamma$ events

$\eta \to e^+e^-\gamma$ Form factor $F(q^2)$





Single-pole formula: $F_P(q^2) = (1 - b_P^2 q^2)^{-1}$, $b_P \equiv \frac{1}{\Lambda_P}$

$\eta \to e^+e^-e^+e^-$

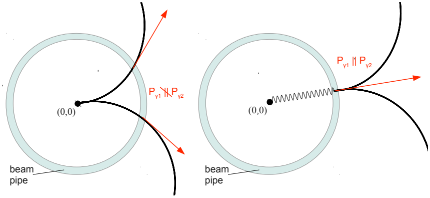
Theoretical predictions for $\Gamma(\eta \to e^+e^-e^+e^-)/\Gamma(\eta)$

- Double transition form factor $F(q_1^2, q_2^2)$
- Different approaches for calculation of $F^{(a)}$:

$F(q_1^2, q_2^2)$	$\Gamma(\eta \to e^+e^-e^+e^-)/\Gamma(\eta)$ $[10^{-5}]$
1	2.52 ± 0.02
$\frac{m_\rho^4}{(m_\rho^2 - q_1^2)(m_\rho^2 - q_2^2)}$	2.65 ± 0.02
$\frac{m_\rho^2}{(m_\rho^2 - q_1^2 - q_2^2)}$	2.64 ± 0.02
$\frac{m_\rho^4 - \frac{4\pi^2 F_\pi^2}{N_C}(q_1^2 + q_2^2)}{(m_\rho^2 - q_1^2)(m_\rho^2 - q_2^2)}$	2.61 ± 0.02

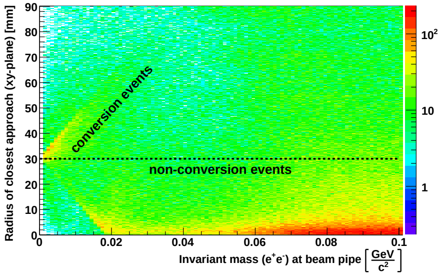
(a) J. Bijnens et al. *arXiv:hep-ph/0106130v1*, 2001

Conversion events



Electrons from Origin

Conversion Event



- Conversion events: small opening angle and origin at beam pipe
- Non-Conversion events: large opening angle and origin at reaction vertex

η Production mechanisms

	pd $\rightarrow {}^{3}\mathrm{He}\eta$	**pp** $\rightarrow$ **pp**η
T_{beam}	$1\,\mathrm{GeV}$	$1.4\,\mathrm{GeV}$
$\sigma(\eta)^{a),b)}$	$(0.412 \pm 0.016)\,\mu\mathrm{b}$	$(9.8 \pm 1)\,\mu\mathrm{b}$
Suited for	study of not-so-rare η decays	study of (not-so-) rare η decays
Background	low multi-pion background	high multi-pion background

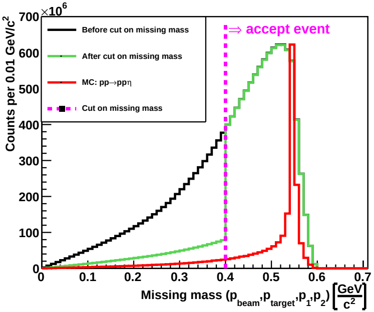
Reaction	$T_{beam}[\mathrm{GeV}]$	$\sigma[\mu\mathrm{b}]^{b),c)}$
$pd \rightarrow {}^{3}\mathrm{He}\pi^{0}\pi^{0}$	0.893	2.8 ± 0.3
$pd \rightarrow {}^{3}\mathrm{He}\pi^{+}\pi^{-}$	0.893	5.1 ± 0.5
$pp \rightarrow pp\pi^{+}\pi^{-}\pi^{0}$	1.36	4.6 ± 1.5
$pp \rightarrow pp\pi^{0}\pi^{0}$	1.36	200 ± 30
$pp \rightarrow pp\pi^{+}\pi^{-}$	1.36	660 ± 100

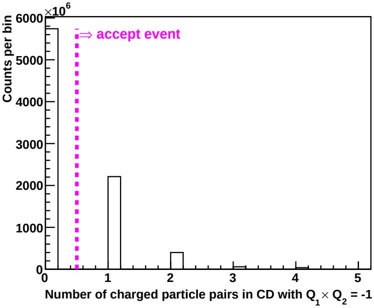
a) R. Bilger et al., *Phys. Rev.*, C65(044608), 2002

b) CELSIUS/WASA coll.., *Phys. Lett.*, B649:122-127, 2007

c) M. Bashkanov et al.., *Phys. Lett.*, B637:223-228, 2006

Preselection of the $pp \to pp\eta$ data set





Preselection done in two steps:

i) Condition on missing mass ⇒ Rejection of multi-pion background

ii) Condition on charged tracks in the Central Detector ⇒ Selection of charged η decay modes