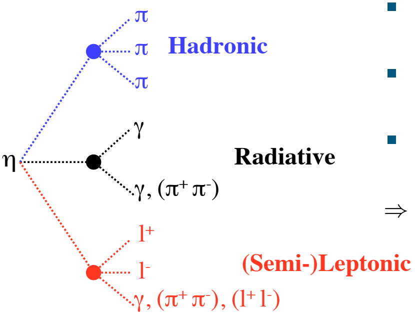
# The $\eta$-Meson Decay Program at WASA-at-COSY

15.09.2015 | Daniel Lersch for the WASA-at-COSY collaboration

XVI International Conference on Hadron Spectroscopy

# The $\eta$-Meson




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

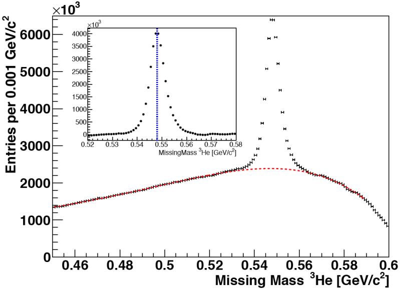
$\Rightarrow$ **Access to rare decay processes:**

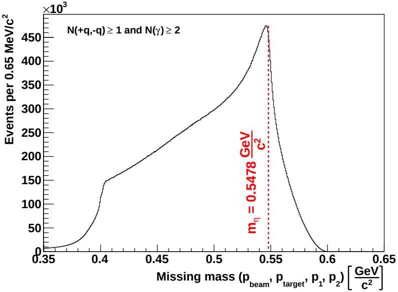
- Explore anomalous sector of QCD
- Determine electromagnetic transition form factors
- Study of symmetry-breaking-phenomena

$\eta$-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 $T_{beam} = 1.4\,\mathrm{GeV}$

# The data sets



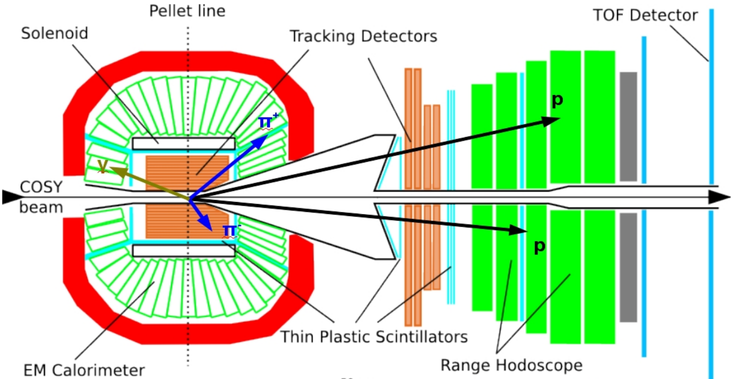




- Reconstruct $\eta$-meson via missing mass: $|\mathbf{P}_{\text{in}} - \mathbf{P}_{\text{out}}|$
- Background contributions from direct pion production reactions: $pd \rightarrow {}^3\mathrm{He}X$, $pp \rightarrow ppX$
  $X = \pi^+\pi^-$, $X = \pi^0\pi^0$ and $X = \pi^+\pi^-\pi^0$

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

# Wide Angle Shower Apparatus - WASA

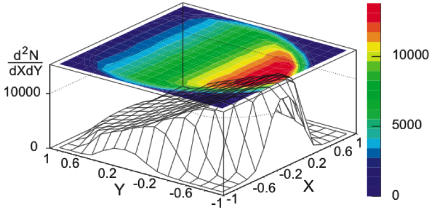
**Example:** $pp \rightarrow pp\eta[\eta \rightarrow \pi^+\pi^-\gamma]$




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

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

# $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot analysis



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

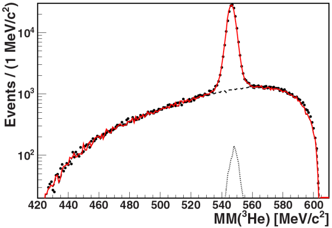
  $\to$ *c*, *e* and *h* would imply C-violation

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

| | Parameter: | $-a$ | b | d | f |
|---|---|---|---|---|---|
| Theo. | 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) |
| 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) |

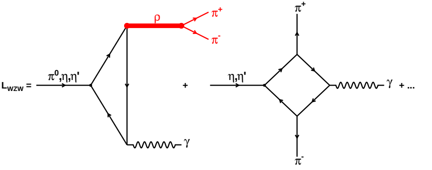
(a) KLOE coll., *JHEP*, 05, (2008)
(b) J. Bijnens and K. Ghorbani., *JHEP*, 11, (2007)
(c) S- P. Schneider et al., *JHEP*, 028, (2011)
(d) WASA-at-COSY coll., *Phys. Rev.*, C90(045207), 2014

- $\sim 1.2 \cdot 10^5$ $\eta \to \pi^+\pi^-\pi^0$ events selected via a kinematic fit for the final event sample
- Dalitz plot analysis for $pp \to pp\eta[\eta \to \pi^+\pi^-\pi^0]$ in progress



# $\boxed{\eta \to \pi^+\pi^-\gamma}$ The box anomaly and $\pi^+\pi^-$ FSI

## Beyond chiral limit:




- Include $\pi^+\pi^-$ Final State Interactions
- Modification of decay amplitude:[(a)]

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

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

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

*Input from theory

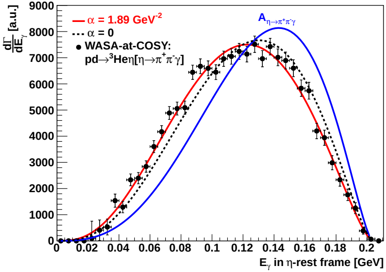
- $\Gamma^{\text{Theory}}(\eta \to \pi^+\pi^-\gamma) = 35.7\,\text{eV}^{(b)}$
- $\Gamma^{\text{Exp.}}(\eta \to \pi^+\pi^-\gamma) = (55.3 \pm 2.4)\,\text{eV}^{(c)}$

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

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

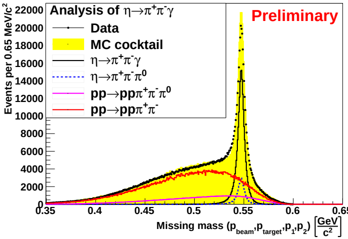
- Photon energy distribution $E_\gamma$:[(d)]

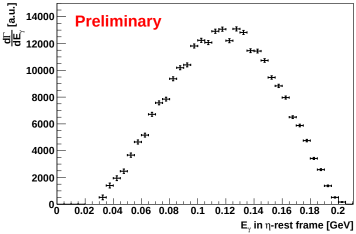
(d) WASA-at-COSY coll. *Phys. Lett.*, B707:243-249, 2012




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

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



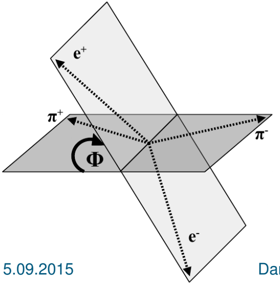




- $\sim 209\,\mathrm{k}\ \eta \to \pi^+\pi^-\gamma$ events reconstructed
  i) Rejection of wrongly reconstructed photons $\Rightarrow$ Reduce background from $pp \to pp\pi^+\pi^-$
  ii) Kinematic fit $\Rightarrow$ Further reduction of multi pion background and improvement of $E_\gamma$ resolution
- $E_\gamma$ distribution after background correction from direct pion production
- Next steps (ongoing):
  1.) Include efficiency corrections for different assumptions on $\alpha$
  2.) Calculate $\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)}$ and determine $\alpha$

# $\eta \to \pi^+\pi^- e^+ e^-$ CP-Violation

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

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




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

- Look at asymmetry $A_\Phi$[a] of angle $\Phi$ between decay planes of electrons and pions:

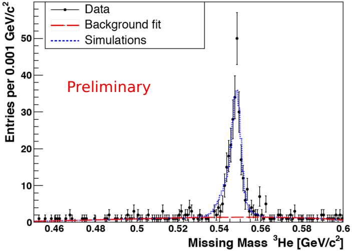
$$A_\Phi = \frac{N(\sin[\Phi]\cos[\Phi]>0) - N(\sin[\Phi]\cos[\Phi]<0)}{N(\sin[\Phi]\cos[\Phi]>0) + N(\sin[\Phi]\cos[\Phi]<0)}$$

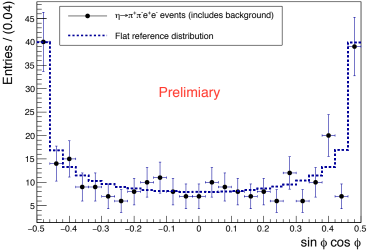
- Upper limit predicted by theory[a]: $\sim 1\%$
- Results found by KLOE:[b]
  1.) $A_\Phi = (-0.6 \pm 2.5_{stat} \pm 1.8_{sys}) \cdot 10^{-2}$
  2.) $\frac{\Gamma(\eta\to\pi^+\pi^-e^+e^-)}{\Gamma_\eta} = (2.68 \pm 0.09_{stat} \pm 0.07_{sys}) \cdot 10^{-4}$

(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* $\to {}^3\mathrm{He}\eta$




- $251 \pm 17$ $\eta \to \pi^+\pi^- e^+ e^-$ events in the final sample
  - i) Rejection of photon conversion events $\Rightarrow$ Reduce contributions from $\eta \to \pi^+\pi^-\gamma$ / $\eta \to \pi^+\pi^-\pi^0$
  - ii) Identification of $\pi^\pm$ and $e^\pm$ in the mixed final state $\Rightarrow$ Crucial for the determination of $A_\Phi$
  - iii) Kinematic fit $\Rightarrow$ Reduction of $\eta \to \pi^+\pi^-\pi^0[\pi^0 \to e^+e^-\gamma]$
- Preliminary:
  1.) $A_\Phi = (-1.1 \pm 6.6_{stat} \pm 0.2_{sys}) \cdot 10^{-2}$
  2.) $\frac{\Gamma(\eta\to\pi^+\pi^-e^+e^-)}{\Gamma_\eta} = (2.7 \pm 0.2_{stat} \pm 0.2_{sys}) \cdot 10^{-4}$
- Need more statistics $\Rightarrow$ *pp*$\eta$ data set

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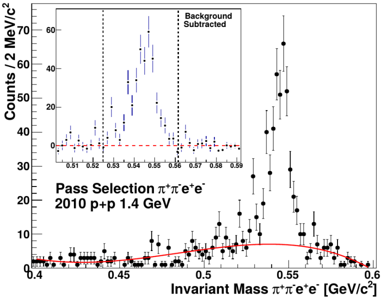
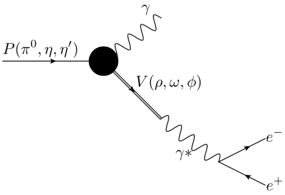
# $\boxed{\eta \to \pi^+\pi^- e^+ e^-}$ Status in $pp \to pp\eta$

- Analysis procedure shown above done for a fraction of 2010 $pp \to pp\eta$ data set:$^{(c)}$
  - $\sim 220$ $\eta \to \pi^+\pi^- e^+ e^-$ 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 $F(q^2)$

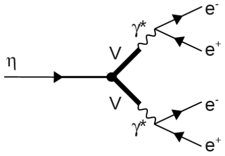
- $\frac{d\Gamma}{dq^2} = \left[\frac{d\Gamma}{dq^2}\right]_{QED} \cdot |F(q^2)|^2$
- Observables to test: $\frac{\Gamma(\eta \to e^+e^-\gamma)}{\Gamma_\eta}$ and Dilepton mass
- Recent result: $\frac{\Gamma(\eta \to e^+e^-\gamma)}{\Gamma_\eta} = (6.9 \pm 0.4) \cdot 10^{-3}$ (a)

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

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

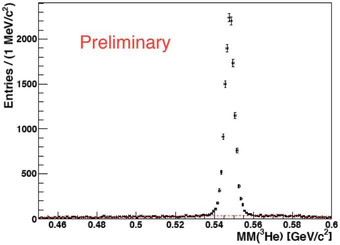
- Different approaches for calculation of $F$ (b)
- Observable to test: $\frac{\Gamma(\eta \to e^+e^-e^+e^-)}{\Gamma_\eta}$
- Current result measured by KLOE: (c)
  $\frac{\Gamma(\eta \to e^+e^-e^+e^-)}{\Gamma_\eta} = (2.4 \pm 0.2_{stat} \pm 0.1_{sys}) \cdot 10^{-5}$

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

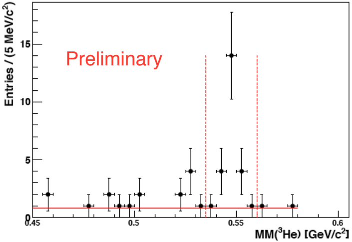


# $\eta \to e^+e^-\gamma$ and $\eta \to e^+e^-e^+e^-$

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




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

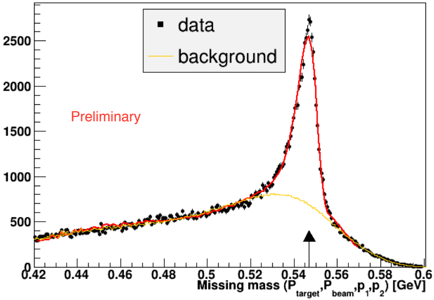



- $18 \pm 5$ $\eta \to e^+e^-e^+e^-$ events reconstructed
- Preliminary: $\frac{\Gamma(\eta \to e^+e^-e^+e^-)}{\Gamma_\eta} =$ $(3.2 \pm 0.9_{stat} \pm 0.5_{sys}) \cdot 10^{-5}$
- Need more statistics $\Rightarrow$ $pp\eta$ data set

Challenges in analysis:

i) Dilepton pairs from conversion events at the beam pipe
ii) Handling of large pion background

# $\eta \to e^+e^-\gamma$ Status in $pp \to pp\eta$

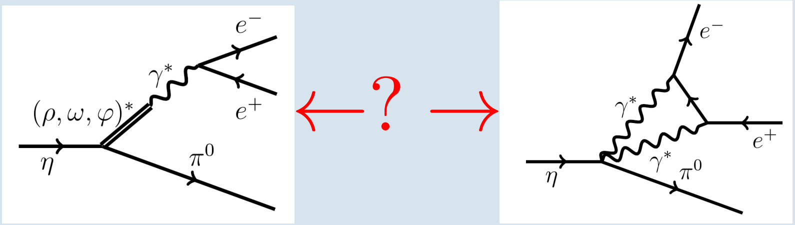



- Reduce uncertainty of $F(q^2)$ at high $q^2$: Increase statistics $\Rightarrow$ $pp\eta$ data set
- $\sim 29\,\mathrm{k}\ \eta \to e^+e^-\gamma$ events reconstructed in current $pp \to pp\eta[\eta \to e^+e^-\gamma]$ analysis
  - i) PID $\Rightarrow$ Reduction of pions
  - ii) Rejection of conversion events $\Rightarrow$ Suppression of $\eta \to \gamma\gamma$
  - iii) Check for energy and momentum conservation
- In preparation:
  1.) Calculation of $\frac{\Gamma(\eta \to e^+e^-\gamma)}{\Gamma_\eta}$
  2.) Dilepton invariant mass distribution $\Rightarrow F(q^2)$

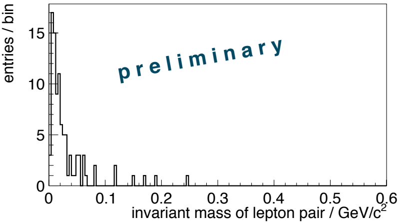
Analysis of $pp \to pp\eta[\eta \to e^+e^-e^+e^-]$ in preparation

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

## Different decay models:




- Forbidden by SM:
  $BR(\eta \to \pi^0 e^+ e^-) < 4 \cdot 10^{-5}$ (a)
- Investigate existing upper limit *BR* with hight statistics $pp \to pp\eta$ data set




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

# Summary and Outlook

| Decay mode | $\Gamma(\eta \to \ldots)/\Gamma_\eta$ [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 |
| $\eta \to \pi^0e^+e^-$ | $< 4 \cdot 10^{-5}$ | C-Violation |
| $\eta \to e^+e^-$ | $< 5.6 \cdot 10^{-6}$ | Physics beyond the SM |

1. $pd \to {}^3\mathrm{He}\eta[\eta \to \ldots]$
2. $pp \to pp\eta[\eta \to \ldots] \Rightarrow$ Analysis ongoing

(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 preparation**

$\Rightarrow$ More fun with $\eta$-decays: See talk by M. Kunkel (1F1)

# Contents

# Backup

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

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- Theoretical Predictions and Recent Measurements
- Analysis (Split-off rejection)
- Analysis (Kinematic fit)
- Determining the $E_\gamma$-distribution

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

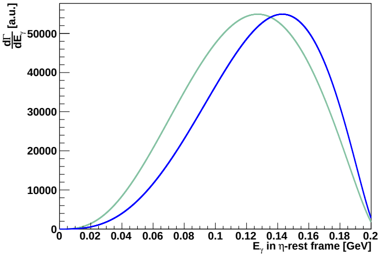
- Form factor $F(q^2)$
- Theoretical predictions for $\Gamma(\eta \to e^+e^-e^+e^-)/\Gamma(\eta)$

- Conversion events
- $\eta$ Production mechanisms
- Preselection of the $pp \to pp\eta$ data set
- PID at WASA

# $\boxed{\eta \to \pi^+\pi^-\gamma}$ 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: $\left[\frac{1+0.5m_\rho^2 s_{\pi\pi}}{D_1(s_{\pi\pi})}\right]$



# $\boxed{\eta \to \pi^+\pi^-\gamma}$ Theoretical Models

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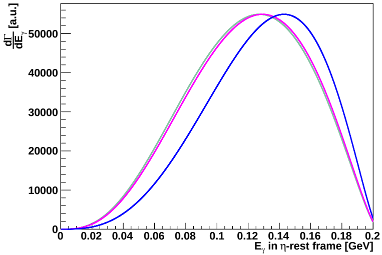
- HLS (Hidden Local Symmetries)-Model:[b)]
  - $\gamma - V$ Transitions
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with: $\left[1 + \frac{3m_\rho^2}{D_\rho(s_{\pi\pi})}\right]$

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

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



# $\boxed{\eta \to \pi^+\pi^-\gamma}$ Theoretical Models

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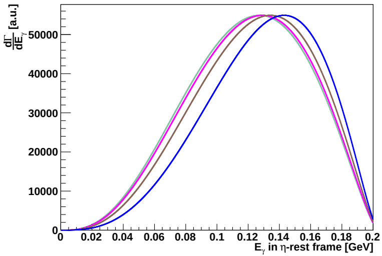
- HLS (Hidden Local Symmetries)-Model:[b)]
  - $\gamma - V$ Transitions
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with: $\left[1+\frac{3m_\rho^2}{D_\rho(s_{\pi\pi})}\right]$
- $O(p^6) + 1 -$ loop-Modell:[c)]
  - Higher momentum orders $O(p^6)$ and one loop chiral corrections
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$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

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

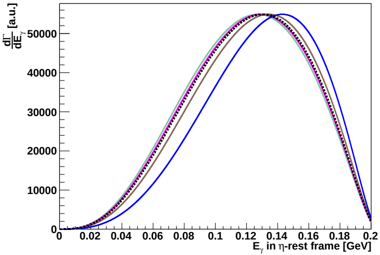
- N/D-Model:[a)]
  - One-loop chiral corrections and VMD
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with: $\left[\frac{1+0.5m_\rho^2 s_{\pi\pi}}{D_1(s_{\pi\pi})}\right]$
- HLS (Hidden Local Symmetries)-Model:[b)]
  - $\gamma - V$ Transitions
  - Modify $A_{\eta\to\pi^+\pi^-\gamma}$ with: $\left[1+\frac{3m_\rho^2}{D_\rho(s_{\pi\pi})}\right]$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

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

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

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

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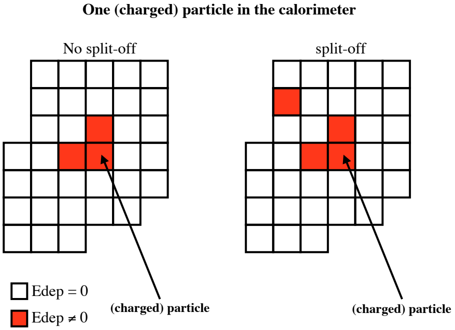
# $\boxed{\eta \to \pi^+\pi^-\gamma}$ Theoretical Predictions and Recent Measurements

| | | $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$ | $\alpha$ [GeV$^{-2}$] |
|---|---|---|---|
| **Experiment** | *Phys. Rev.,D2:501-505, 1970* | $0.202 \pm 0.006$ | $1.8 \pm 0.4$ |
| | *Phys. Rev.,D7:2569-2571, 1973* | $0.209 \pm 0.004$ | - |
| | *Phys. Rev.,D7:2565-2568, 1973* | - | $-0.9 \pm 0.1$ |
| | *Phys.,C50:451-454, 1991* * | - | $2.7 \pm 0.1$ |
| | *Phys. Lett.,B402:195, 1997* * | - | $1.8 \pm 0.53$ |
| | *Phys. Rev. Lett.,99(122001), 2007* | $0.175 \pm 0.013$ | - |
| | *Phys. Rev. Lett.,B707:243-249, 2013* | - | $1.89 \pm 0.86$ |
| | *Phys. Lett.,B718:910-914, 2013* | $0.1856 \pm 0.003$ | $1.32 \pm 0.2$ |
| | *Chin. Phys.*, 090001, 2014 | $0.1847 \pm 0.003$ | - |
| **Theory** | *Phys. Scripta*, T99:55-67, 2002 | $0.2188 \pm 0.0088$ | $0.64 \pm 0.02$ |
| | *Europ. Phys. Journal*, C31:525-547, 2003 | $0.1875 \pm 0.0094$ | $0.23 \pm 0.01$ |
| | *Phys. Lett.*, B237:488-494, 1990 | $0.1565 \pm 0.0063$ | $-0.7 \pm 0.1$ |
| | *Phys. Scripta*, T99:55-67, 2002 | $0.119 \pm 0.0048$ | $-1.7 \pm 0.02$ |

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

# $\boxed{\eta \to \pi^+\pi^-\gamma}$ Analysis

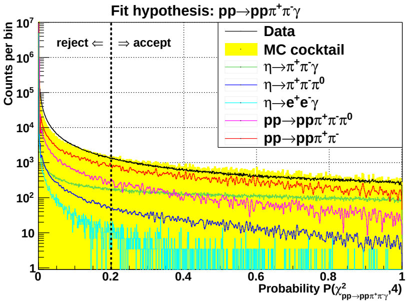
## i) Rejection of split-offs




- 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

# $\boxed{\eta \to \pi^+\pi^-\gamma}$ Analysis

## ii) Kinematic fit

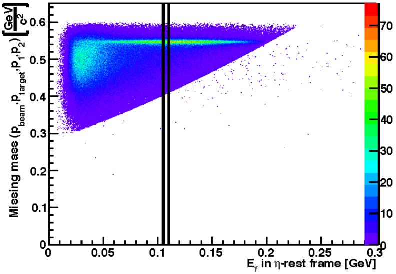


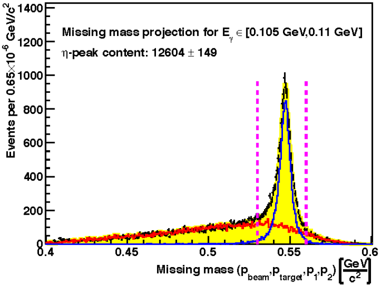

Use kinematic fit to:

a) Improve resolution
b) Suppress background

- Least squares fit:
  $$\chi^2 = \sum_{i=1}^{N_p}\sum_{j=1}^{N_v}\left(\frac{v_{ij}^{fit} - v_{ij}^{meas}}{\sigma_{ij}^{meas}}\right)^2 + 2 \cdot \sum_{\mu} \lambda_\mu F_\mu(v_{11}^{fit}, \ldots, v_{N_pN_v}^{fit})$$
- $F_\mu$: energy and momentum conservation
  $\to$ 4 constraints
- $$P(\chi^2, N) = \frac{1}{\sqrt{2^N \cdot \Gamma(\frac{1}{2}N)}} \int_{\chi^2}^{\infty} e^{-\frac{t}{2}} \cdot t^{\frac{1}{2}N-1} dt$$

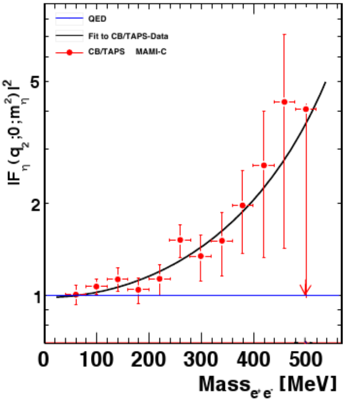
# $\boxed{\eta \to \pi^+\pi^-\gamma}$ Determining the $E_\gamma$-distribution

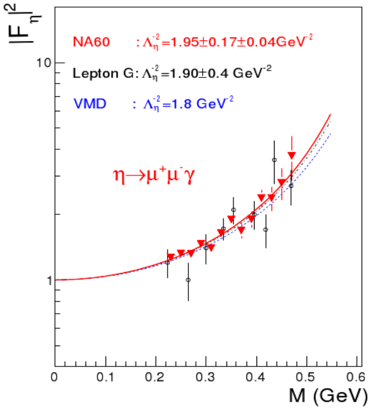



- Scan two proton missing mass distribution in $E_\gamma$-intervals
- Subtract background for each $E_\gamma$-interval
- Obtain number of $\eta \to \pi^+\pi^-\gamma$ events

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




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

$\boxed{\eta \to e^+e^-e^+e^-}$

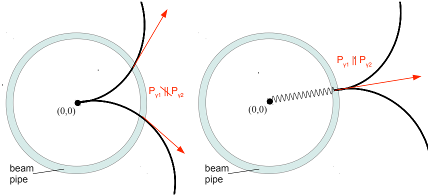
# Theoretical predictions for $\Gamma(\eta \to e^+e^-e^+e^-)/\Gamma(\eta)$

- 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 | $2.52 \pm 0.02$ |
| $\frac{m_\rho^4}{(m_\rho^2 - q_1^2)(m_\rho^2 - q_2^2)}$ | $2.65 \pm 0.02$ |
| $\frac{m_\rho^2}{(m_\rho^2 - q_1^2 - q_2^2)}$ | $2.64 \pm 0.02$ |
| $\frac{m_\rho^4 - \frac{4\pi^2 F_\pi^2}{N_C}(q_1^2 + q_2^2)}{(m_\rho^2 - q_1^2)(m_\rho^2 - q_2^2)}$ | $2.61 \pm 0.02$ |

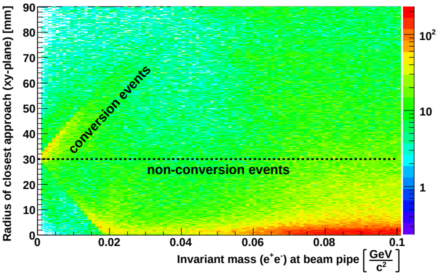
(a) J. Bijnens et al. *arXiv:hep-ph/0106130v1*, 2001

# 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

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# $\eta$ Production mechanisms

| | **pd** $\rightarrow {}^3\mathrm{He}\eta$ | **pp** $\rightarrow$ **pp**$\eta$ |
|---|---|---|
| $T_{beam}$ | 1 GeV | 1.4 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 $\eta$ decays | study of (not-so-) rare $\eta$ decays |
| **Background** | low multi-pion background | high multi-pion background |

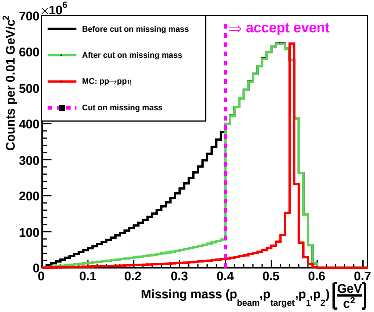
| **Reaction** | $T_{beam}$[GeV] | $\sigma[\mu\mathrm{b}]^{b),c)}$ |
|---|---|---|
| $pd \rightarrow {}^3\mathrm{He}\pi^0\pi^0$ | 0.893 | $2.8 \pm 0.3$ |
| $pd \rightarrow {}^3\mathrm{He}\pi^+\pi^-$ | 0.893 | $5.1 \pm 0.5$ |
| $pp \rightarrow pp\pi^+\pi^-\pi^0$ | 1.36 | $4.6 \pm 1.5$ |
| $pp \rightarrow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

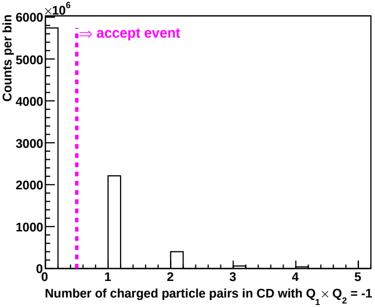
a) R. Bilger et al., *Phys. Rev.*, C65(044608), 2002

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

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

# Preselection of the $pp \rightarrow pp\eta$ data set



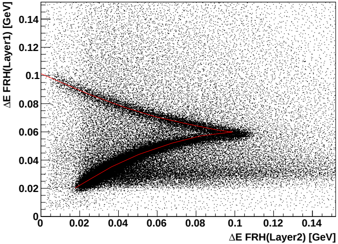




Preselection done in two steps:

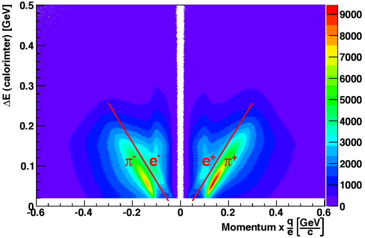
i) Condition on missing mass ⇒ Rejection of multi-pion background

ii) Condition on charged tracks in the Central Detector ⇒ Selection of charged $\eta$ decay modes

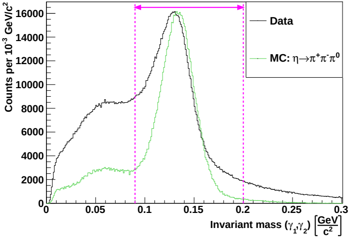
# PID at WASA



ΔE FRH(Layer1) [GeV]
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
ΔE FRH(Layer2) [GeV]

ΔE (calorimter) [GeV]
0.5
0.4
0.3
0.2
0.1
0
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
π-
e-
e+
π+
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Momentum x q/e [GeV/c]

Counts per 10-3 GeV/c2
16000
14000
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Data
MC: η→π+π-π0
Invariant mass (γ1,γ2) [GeV/c2]