# Precision tests of fundamental physics with light meson decays

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*Susan Schadmand, FFN-Hadron*

# Review article: Precision tests of fundamental physics with η and η′ mesons

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$\pi^0\gamma\gamma$ →

TFF →

| Channel | Expt. branching ratio | Discussion |
|---|---|---|
| $\eta \to 2\gamma$ | 39.41(20)% | Chiral anomaly, $\eta$–$\eta'$ mixing |
| $\eta \to 3\pi^0$ | 32.68(23)% | $m_u - m_d$ |
| $\eta \to \pi^0\gamma\gamma$ | $2.56(22) \times 10^{-4}$ | $\chi$PT at $\mathcal{O}(p^6)$, leptophobic $B$ boson, light Higgs scalars |
| $\eta \to \pi^0\pi^0\gamma\gamma$ | $<1.2 \times 10^{-3}$ | $\chi$PT, axion-like particles (ALPs) |
| $\eta \to 4\gamma$ | $<2.8 \times 10^{-4}$ | $<10^{-11}$[55] |
| $\eta \to \pi^+\pi^-\pi^0$ | 22.92(28)% | $m_u - m_d$, $C/CP$ violation, light Higgs scalars |
| $\eta \to \pi^+\pi^-\gamma$ | 4.22(8)% | Chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, $P/CP$ violation |
| $\eta \to \pi^+\pi^-\gamma\gamma$ | $<2.1 \times 10^{-3}$ | $\chi$PT, ALPs |
| $\eta \to e^+e^-\gamma$ | $6.9(4) \times 10^{-3}$ | Theory input for $(g-2)_\mu$, dark photon, protophobic $X$ boson |
| $\eta \to \mu^+\mu^-\gamma$ | $3.1(4) \times 10^{-4}$ | Theory input for $(g-2)_\mu$, dark photon |
| $\eta \to e^+e^-$ | $<7 \times 10^{-7}$ | Theory input for $(g-2)_\mu$, BSM weak decays |
| $\eta \to \mu^+\mu^-$ | $5.8(8) \times 10^{-6}$ | Theory input for $(g-2)_\mu$, BSM weak decays, $P/CP$ violation |
| $\eta \to \pi^0\pi^0\ell^+\ell^-$ | | $C/CP$ violation, ALPs |
| $\eta \to \pi^+\pi^-e^+e^-$ | $2.68(11) \times 10^{-4}$ | Theory input for doubly-virtual TFF and $(g-2)_\mu$, $P/CP$ violation, ALPs |
| $\eta \to \pi^+\pi^-\mu^+\mu^-$ | $<3.6 \times 10^{-4}$ | Theory input for doubly-virtual TFF and $(g-2)_\mu$, $P/CP$ violation, ALPs |
| $\eta \to e^+e^-e^+e^-$ | $2.40(22) \times 10^{-5}$ | Theory input for $(g-2)_\mu$ |
| $\eta \to e^+e^-\mu^+\mu^-$ | $<1.6 \times 10^{-4}$ | Theory input for $(g-2)_\mu$ |
| $\eta \to \mu^+\mu^-\mu^+\mu^-$ | $<3.6 \times 10^{-4}$ | Theory input for $(g-2)_\mu$ |
| $\eta \to \pi^+\pi^-\pi^0\gamma$ | $<5 \times 10^{-4}$ | Direct emission only |
| $\eta \to \pi^\pm e^\mp \nu_e$ | $<1.7 \times 10^{-4}$ | Second-class current |
| $\eta \to \pi^+\pi^-$ | $<4.4 \times 10^{-6}$ [56] | $P/CP$ violation |
| $\eta \to 2\pi^0$ | $<3.5 \times 10^{-4}$ | $P/CP$ violation |
| $\eta \to 4\pi^0$ | $<6.9 \times 10^{-7}$ | $P/CP$ violation |

KLOE-II
*WASA-at-COSY*
CLAS

PrimeX
GlueX-JEF
CLAS12

MAMI A1, A2
BESIII
*REDTOP*

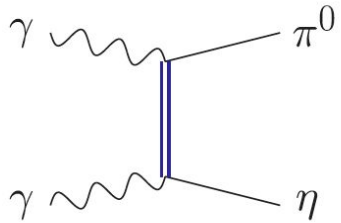
# Light Meson Decays: Rare decay $\eta \to \pi^0 \gamma\gamma$

**higher order Chiral Perturbation Theory**

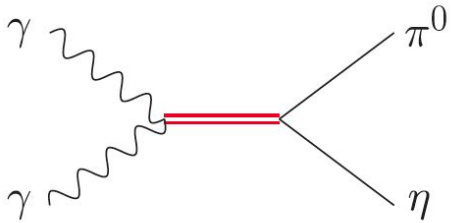
**Dalitz distribution Mγγ** sensitivity to scalars

**MAMI:** γp→ηp ($E_{\gamma,max}$= **1.402 GeV**) 1200 η→π0 γγ decays

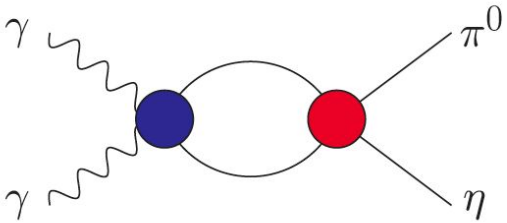
*B. M. K. Nefkens, S. Prakhov et al. (A2 Collaboration at MAMI) Phys.Rev.C 90 (2014) 2, 025206*




t-channel resonance exchange
(e.g. vectors)




s-channel resonance exchange
(a0(980) and a2(1320))

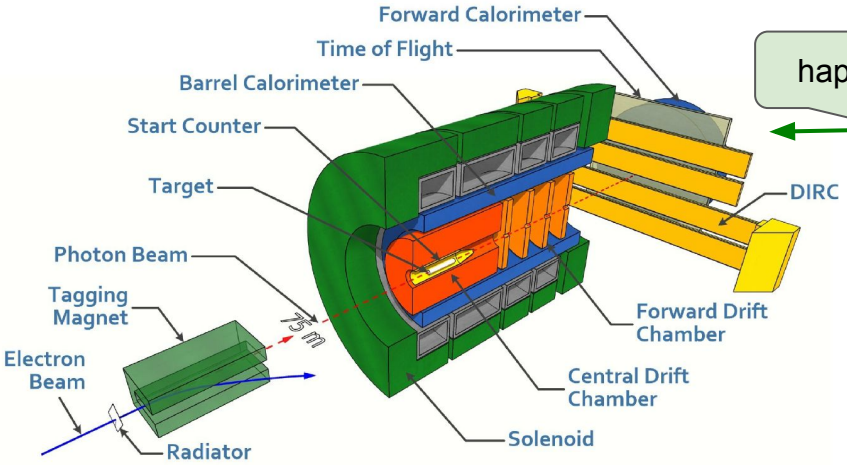



generic loop diagram/rescattering mechanism

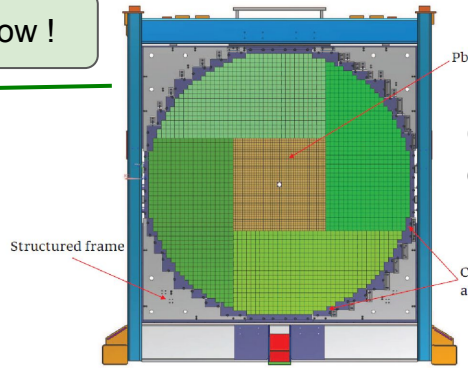
**GlueX JEF experiment**

- **Hall D 12 GeV, energy tagged photon beam**
- **upgraded calorimeter FCAL-II**

# JLab Eta Factory (JEF) Experiment γ+p → η/η'+p




happening now !




FCAL-II
GlueX upgraded forward calorimeter
$PbWO_4$ insert

## η/η' radiative decays

- ★ 8.4 - 11.7 GeV tagged photon beam and $LH_2$ target
- ★ detect recoil protons with GlueX detector
- ★ detect multi photon final states with FCAL-II
- ★ high resolution, high granularity, **highly suppressed background**

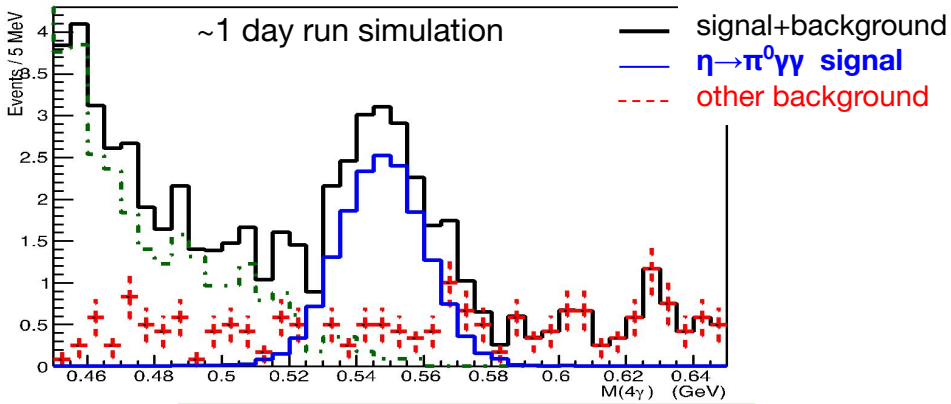
data taking starts 2024 !

| JEF (100 days) | η | η' |
|---|---|---|
| tagged mesons | $6.5 \times 10^7$ | $4.9 \times 10^7$ |

run concurrent with GlueX-II (with DIRC)

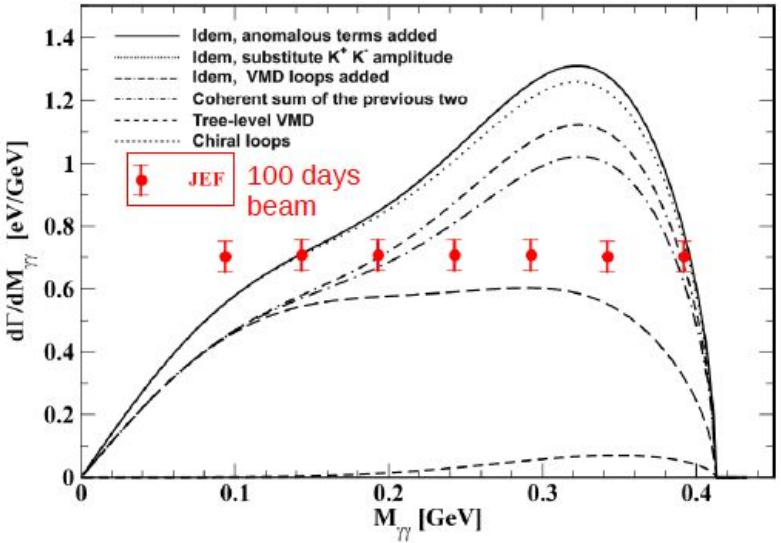
# Light Meson Decays: Rare decay $\eta \to \pi^0 \gamma\gamma$

**JEF:** $\gamma p \to \eta p$ ($E_\gamma$ = 8.4-11.7 GeV)




$\pi^0\gamma\gamma$ analysis of simulated $\eta \to \pi^0\pi^0\pi^0$
**background is small under the η peak**

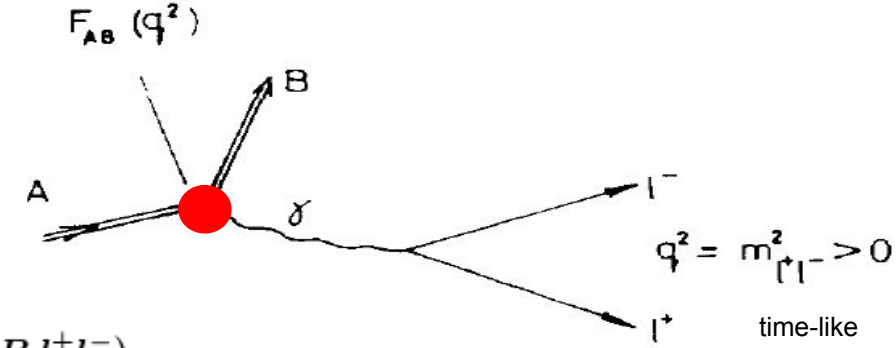
**JEF:** predicted accuracy for **M(γγ)**




E. Oset, J.R. Pelaez, and L. Roca, Phys.Rev.D77:073001,2008

**GlueX JEF experiment**
- **Hall D 12 GeV, energy tagged photon beam**
- **upgraded calorimeter FCAL-II**

# Light Meson Decays: Transition Form Factors




$$\frac{d\Gamma(A \to B\, l^+l^-)}{dq^2 \cdot \Gamma(A \to B\gamma)} = \left|F_{A\to B}(q^2)\right|^2 \cdot |\mathrm{QED}|$$

**form factor: divide experimental $q^2$ distribution by QED**

$$F_{AB}(q^2) \simeq 1 + q^2[\mathrm{d}F_{AB}/\mathrm{d}q^2]|_{q^2\simeq 0} = 1 + q^2 b_{AB} = 1 + \tfrac{1}{6}q^2\langle r^2_{AB}\rangle$$

$$\Lambda \simeq m_\rho \ (\Lambda^{-2} = b_{AB})$$

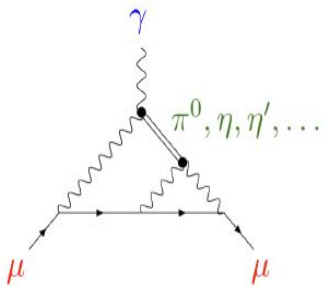
'standard' VMD, b~1.69/GeV$^2$

slope parameter

size (transition region)

- intrinsic structure of hadrons
- hadron coupling to photon
- background for BSM physics

relevance for muon g-2




L.G. Landsberg, Electromagnetic decays of light mesons
PHYSICS REPORTS 128, No. 6 (1985) 301—376.



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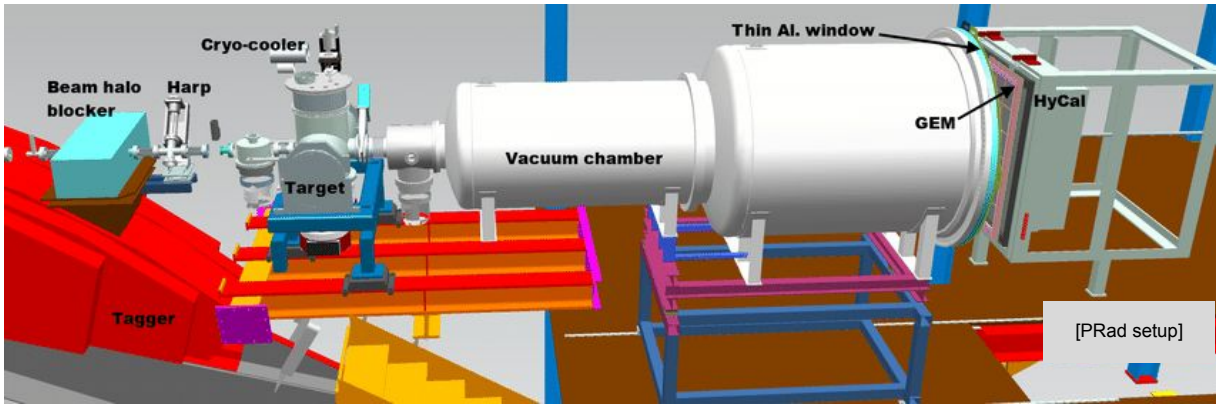
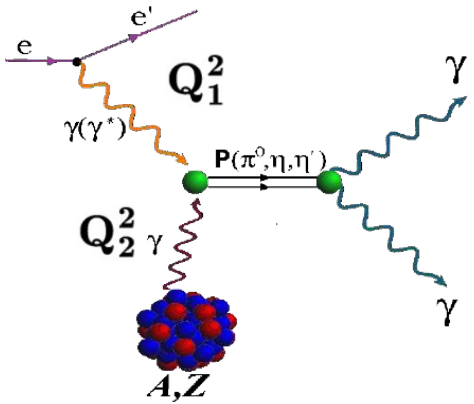
# Jefferson Lab Hall B setup for $\pi^0$ TFF measurement




- ultra-low background
- vacuum chamber
- GEM detector (VETO)
- new solid target
- high resolution electromagnetic calorimeter ($PbWO_4$) for **measuring scattered e' and reconstructing $\pi^0 \to \gamma\gamma$**



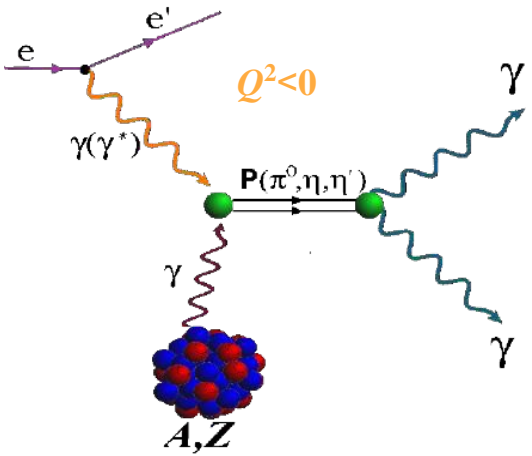

$$F_{\gamma^*\gamma^* \to \pi^0}(-Q_1^2, -Q_2^2)$$

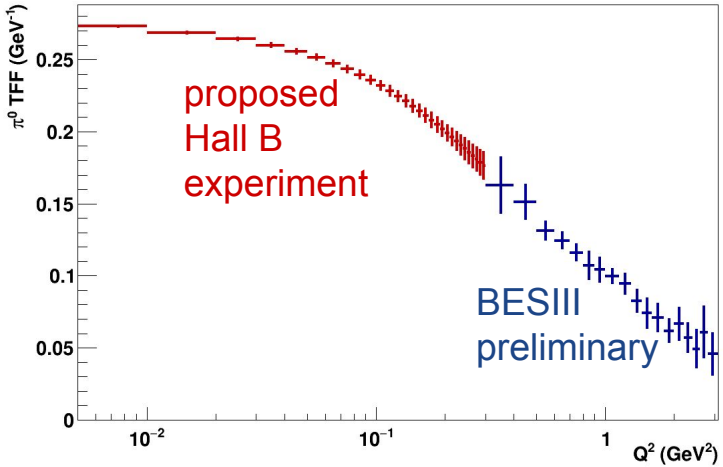
- $Q_1^2$ from scattered e'
- $Q_2^2$ from $\pi^0 \to \gamma\gamma$
  - $Q_2^2 = t = (p_{\gamma^*} - p_{\pi 0})^2$

plan: run >= 2025

# Approved Jefferson Lab Hall B Proposal E12-22-003: "Precision Measurement of the Neutral Pion Transition Form Factor"

***Spokespersons: D.S. Dale, D. Dutta, L. Gan, I. Larin (contact person), R. Miskimen, and E. Pasyuk***




- **space-like $\pi^0$ transition form factor at low $Q^2$**
- **sensitivity to $\pi^0$ radiative decay width**

**At MAMI:** PAC A1-LOI-2020 Measurement of the Electromagnetic Transition Form Factor of the $\pi^0$ in the space-like region via Primakoff Electroproduction
*L. Capozza, M. Gorshteyn, F. Maas, O. Noll, S. Wolff ... plan: pilot run 2024*

# Transition Form Factor of the η′ Meson with CLAS12

Proposal E12-06-108B PAC44 (2016) addition to Hall B Run Group A (**MesonX**)

## CLAS12, the dilepton spectrometer

**BESIII $J/\psi \rightarrow \gamma\eta'$**

- **864 ± 36 $\eta' \rightarrow \gamma ee$**
  **single Dalitz decay**
  based on 1.31 x $10^9$ J/ψ events
  *BESIII PR D92 (2015) 012001*

- **30.1 ± 7.0 $\eta' \rightarrow eeee$**
  **double Dalitz decay**
  based on (10087 ± 44) x $10^6$ J/ψ events
  *BESIII PRD 105 (2022) 112010*

**proposed:**

- **$\eta' \rightarrow \gamma ee$ single Dalitz decay**
  projected 28,200 events / 80 days

- **further objectives**
  - **$\eta \rightarrow \gamma ee$** to show how well it works
  - **$\eta' \rightarrow eeee$** feasibility
  - **$\omega \rightarrow \pi^0$ ee** ω-π transition form factor
  - **$\pi^0 \rightarrow \gamma ee$, $\pi^0 \rightarrow eeee$** can we reach that?

**CLAS12 analysis begins now**

# Precision tests of fundamental physics with light meson decays

## *Light Meson Decays at Jefferson Lab*

1. JLab Eta Factory (JEF) ⚮ GlueX-II
   (combined Jefferson Lab Hall D proposal)
2. Transition Form Factors
   a. Precision Measurement of the Neutral Pion Transition Form Factor
      (Jefferson Lab Hall B, proposal of the PrimeX group)
   b. Transition Form Factor of the η′ Meson
      (Jefferson Lab Hall B, additional proposal to CLAS12 Run Group A)