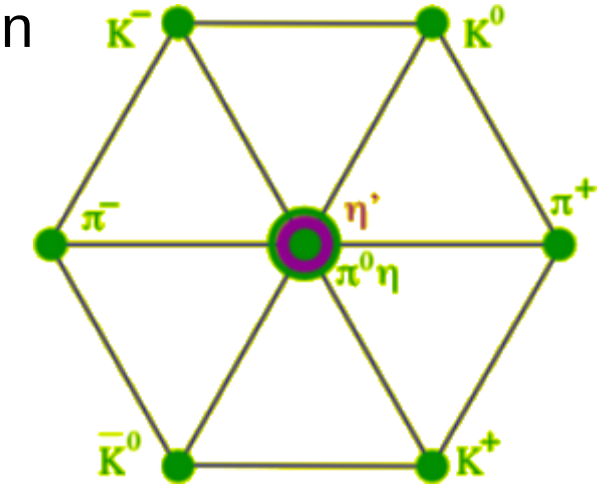
# Overview of recent and upcoming experiments using meson decays to probe low-energy QCD, fundamental symmetries and BSM physics

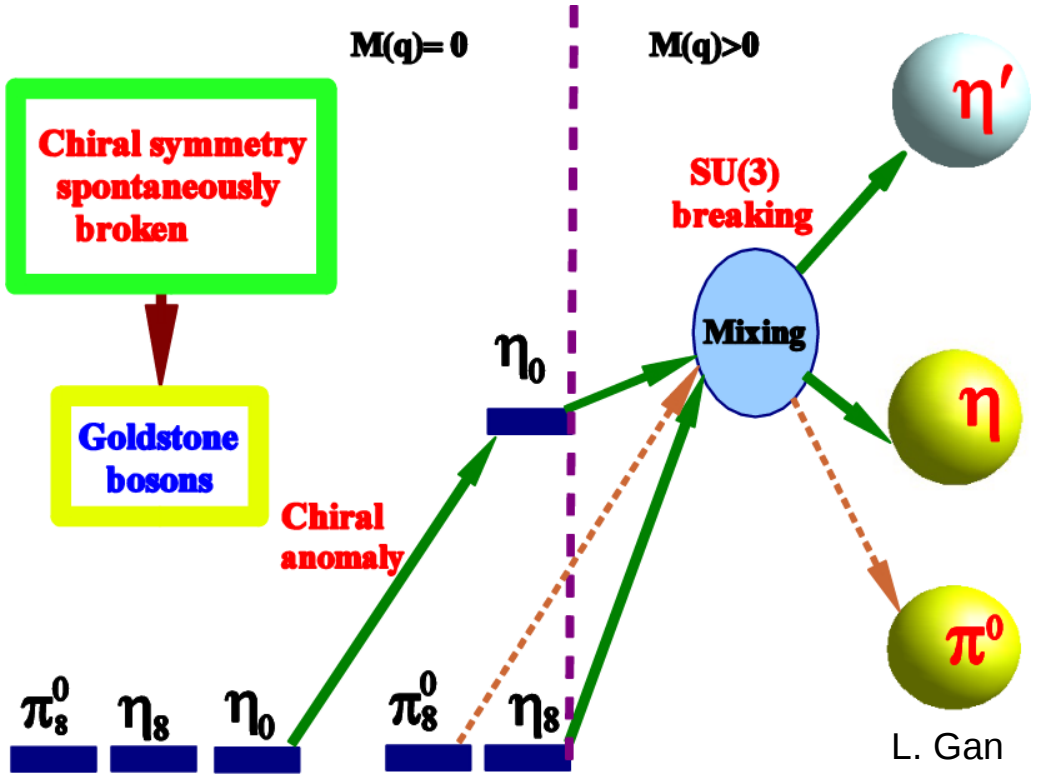
Simon Taylor / Jefferson Lab for the GlueX collaboration

- Introduction to the low-lying pseudoscalar mesons
- Highlights of recent experimental results
- The GlueX experiment and JEF
- Summary

# Light pseudoscalar mesons

- QCD Lagrangian: symmetry $U(3)_L \times U(3)_R$ for $m_q=0$ spontaneously broken
  $\Rightarrow$ $SU(3)_L \times SU(3)_R \times U(1)_B \times U(1)_A$
  - Goldstone bosons: octet ($\pi^0$, $\pi^\pm$, $K^\pm$, $K^0$, $\bar{K}^0$, $\eta_8$) + singlet ($\eta_0$)
  - $m_q \neq 0 \Rightarrow$ chiral symmetry explicitly broken $\Rightarrow$ massive goldstone bosons




- Chiral anomaly: $U(1)_A$ explicitly broken for $m_q=0$
  - $\eta_0$ is massive
  - Responsible for two-photon decays of $\pi^0$, $\eta$, $\eta'$
- Broken SU(3) symmetry $\Rightarrow$ mixing between $\pi^0$, $\eta$, $\eta'$

L. Gan

# Physics processes from η decays

- Light quark mass ratio, chiral anomaly, chiral perturbation theory, P/CP violation, physics beyond the Standard model, ...

| 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 $O(p^6)$, 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) |
| $\eta \to 4\gamma$ | $< 2.8 \times 10^{-4}$ | $< 10^{-11}$ |
| $\eta \to \pi^+\pi^-\pi^0$ | 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 |

| Channel | Expt. branching ratio | Discussion |
|---|---|---|
| $\eta \to \mu^+\mu^-$ | $5.8(8) \times 10^{-6}$ | 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 |
| $\eta \to \pi^+\pi^-$ | $< 4.4 \times 10^{-6}$ | $P/CP$ 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 |

Phys.Rept. 945 (2022) 1-105

# Physics processes from η′ decays

- Light quark mass ratio, chiral anomaly, chiral perturbation theory, P/CP violation, physics beyond the Standard model, ...

| Channel | Expt. branching ratio | Discussion |
|---|---|---|
| $\eta' \to \eta\pi^+\pi^-$ | 42.6(7)% | large-$N_c$ $\chi$PT, light Higgs scalars |
| $\eta' \to \pi^+\pi^-\gamma$ | 28.9(5)% | chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, $P/CP$ violation |
| $\eta' \to \eta\pi^0\pi^0$ | 22.8(8)% | large-$N_c$ $\chi$PT |
| $\eta' \to \omega\gamma$ | 2.489(76)% | theory input for singly-virtual TFF and $(g-2)_\mu$ |
| $\eta' \to \omega e^+e^-$ | $2.0(4)\times10^{-4}$ | theory input for doubly-virtual TFF and $(g-2)_\mu$ |
| $\eta' \to 2\gamma$ | 2.331(37)% | chiral anomaly, $\eta$–$\eta'$ mixing |
| $\eta' \to 3\pi^0$ | 2.54(18)% $^{(\star)}$ | $m_u - m_d$ |
| $\eta' \to \mu^+\mu^-\gamma$ | $1.09(27)\times10^{-4}$ | theory input for $(g-2)_\mu$, dark photon |
| $\eta' \to e^+e^-\gamma$ | $4.73(30)\times10^{-4}$ | theory input for $(g-2)_\mu$, dark photon |
| $\eta' \to \pi^+\pi^-\mu^+\mu^-$ | $< 2.9\times10^{-5}$ | theory input for doubly-virtual TFF and $(g-2)_\mu$, $P/CP$ violation, dark photon, ALPs |
| $\eta' \to \pi^+\pi^-e^+e^-$ | $2.4(^{+1.3}_{-1.0})\times10^{-3}$ | theory input for doubly-virtual TFF and $(g-2)_\mu$, $P/CP$ violation, dark photon, ALPs |
| $\eta' \to \pi^0\pi^0\ell^+\ell^-$ | | $C/CP$ violation, ALPs |
| $\eta' \to \pi^+\pi^-\pi^0$ | $3.61(17)\times10^{-3}$ | $m_u - m_d$, $C/CP$ violation, light Higgs scalars |

| Channel | Expt. branching ratio | Discussion |
|---|---|---|
| $\eta' \to 2(\pi^+\pi^-)$ | $8.4(9)\times10^{-5}$ | theory input for doubly-virtual TFF and $(g-2)_\mu$ |
| $\eta' \to \pi^+\pi^-2\pi^0$ | $1.8(4)\times10^{-4}$ | |
| $\eta' \to 2(\pi^+\pi^-)\pi^0$ | $< 1.8\times10^{-3}$ | ALPs |
| $\eta' \to K^\pm\pi^\mp$ | $< 4\times10^{-5}$ | weak interactions |
| $\eta' \to \pi^\pm e^\mp\nu_e$ | $< 2.1\times10^{-4}$ | second-class current |
| $\eta' \to \pi^0\gamma\gamma$ | $3.20(24)\times10^{-3}$ | vector and scalar dynamics, $B$ boson, light Higgs scalars |
| $\eta' \to \eta\gamma\gamma$ | $8.3(3.5)\times10^{-5}$ | vector and scalar dynamics, $B$ boson, light Higgs scalars |
| $\eta' \to 4\pi^0$ | $< 4.94\times10^{-5}$ | ($S$-wave) $P/CP$ violation |
| $\eta' \to e^+e^-$ | $< 5.6\times10^{-9}$ | theory input for $(g-2)_\mu$, BSM weak decays |
| $\eta' \to \mu^+\mu^-$ | | theory input for $(g-2)_\mu$, BSM weak decays |
| $\eta' \to \ell^+\ell^-\ell^+\ell^-$ | | theory input for $(g-2)_\mu$ |
| $\eta' \to \pi^+\pi^-\pi^0\gamma$ | | $B$ boson |
| $\eta' \to \pi^+\pi^-$ | $< 1.8\times10^{-5}$ | $P/CP$ violation |
| $\eta' \to 2\pi^0$ | $< 4\times10^{-4}$ | $P/CP$ violation |

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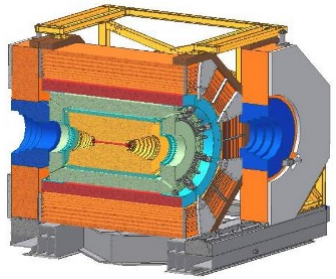
# The experimental landscape

Collider experiments



BESIII

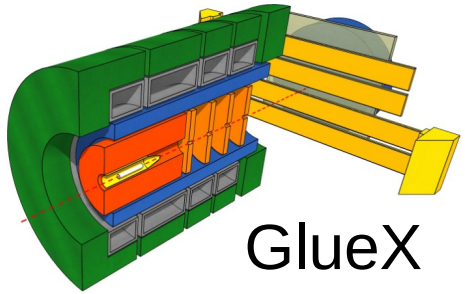
KLOE/KLOE-2

Fixed target experiments

Crystal Ball

Wide Angle Shower Apparatus
WASA@COSY

High Acceptance Di-Electron Spectrometer
HADES@GSI

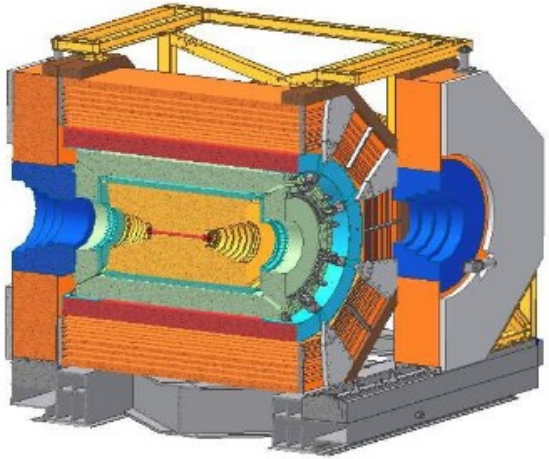


GlueX

Future experiments: **JEF**, **REDTOP**

# Facilities for $\eta(')$ physics

## BES III



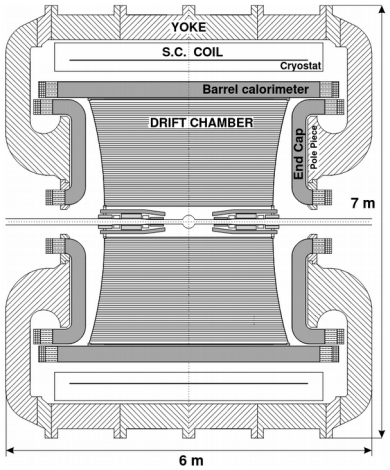
- BEPCII: $e^+e^-$ collider
  - $\sqrt{s}$=2-4.6 GeV
- 10 billion J/ψ events
- Sources of η/η′ events:
  - $J/\psi \to \gamma\eta/\eta'$:

    $1\times10^7$ η, $5.2\times10^7$ η′
  - $J/\psi \to \phi\eta/\eta'$:

    $4\times10^6$ η, $2.5\times10^6$ η′

Shuang-shi Fang, “Light Meson Decays at BESIII”, QNP22

## KLOE/KLOE-2



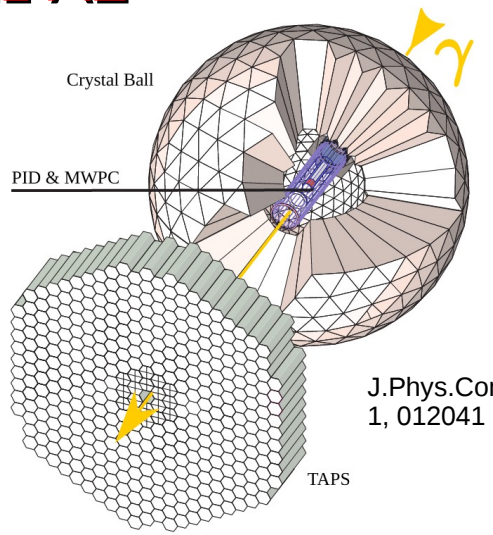

Nucl.Instrum.Meth.A 488 (2002) 51-73

- DAΦNE: $e^+e^-$ collider
  - $\sqrt{s}=M_\Phi$ =1019.4 MeV
- Source of η events: $\Phi \to \gamma\eta$

$N_\Phi=2.4\times10^{10} \rightarrow N_\eta = 3\times10^8$

PoS (ICHEP2022) 791.

## Mainz A2




J.Phys.Conf.Ser. 587 (2015) 1, 012041

- Electron beam, $E_e \leq 1.6$ GeV

  → energy-tagged bremsstrahlung photon beam
- Fixed target
- Almost 4π acceptance for final-state photons

Full data set from $\gamma p \to p\eta$:
$N_\eta=6\times10^7$



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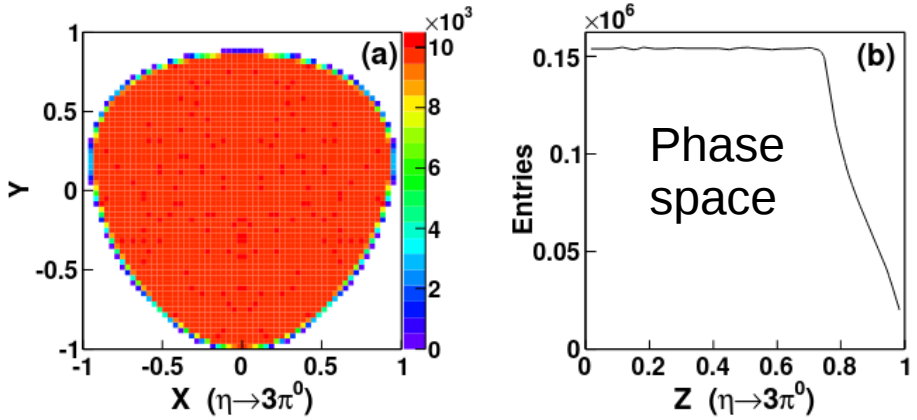
# Light quark masses and cusp effects: $\eta \to 3\pi^0$

- Quark masses are fundamental QCD parameters
  - $\eta \to 3\pi$ provides direct way to constrain light quark masses
- QCD Lagrangian: isospin violation amplitude $A$ proportional to $m_u - m_d$

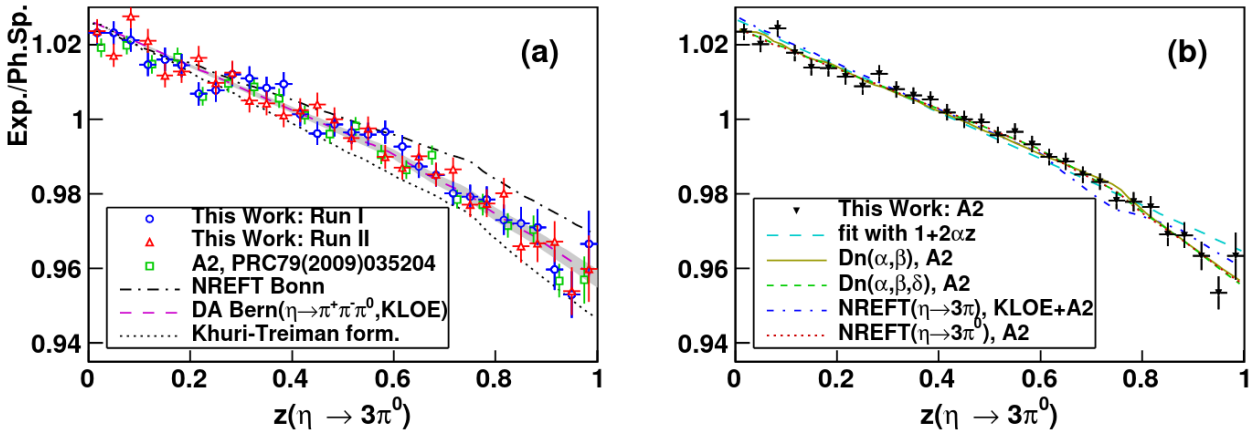
$$\Gamma_n(X,Y) = |\mathcal{A}_n(s,t,u)|^2 \propto 1 + 2\alpha Z + 2\beta Y\left(3X^2 - Y^2\right) + 2\gamma Z^2 + \ldots$$

$$Z = X^2 + Y^2$$



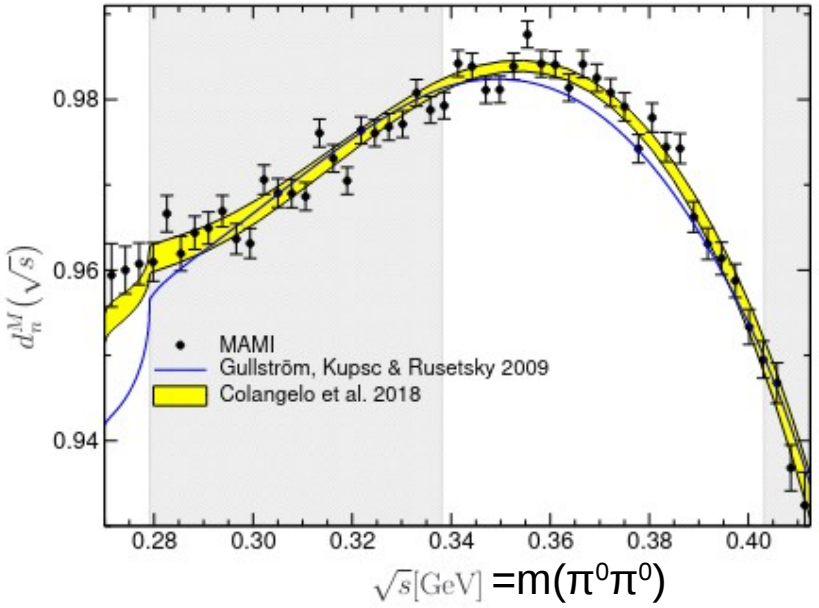

Phys. Rev. C 97, 065203 (2018)

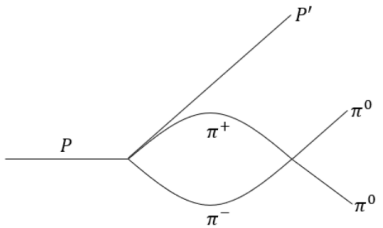
- Dalitz plot distribution almost flat: $\alpha \sim -0.03$




Phys. Rev. C 97, 065203 (2018)

- Cusp effect expected near $m(\pi^0\pi^0)=m(\pi^+\pi^-)$
  - $\pi^+\pi^- \to \pi^0\pi^0$ transition




Phys.Rept. 945 (2022) 1-105



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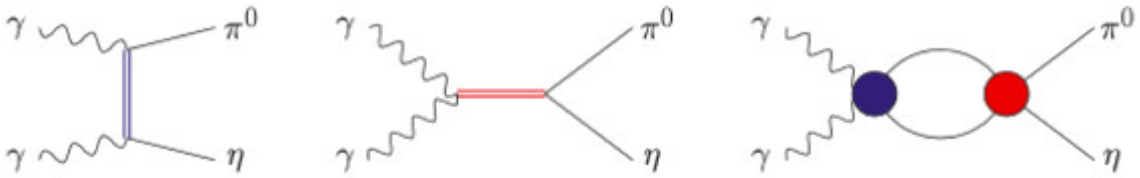
# Rare decay: $\eta \to \pi^0\gamma\gamma$

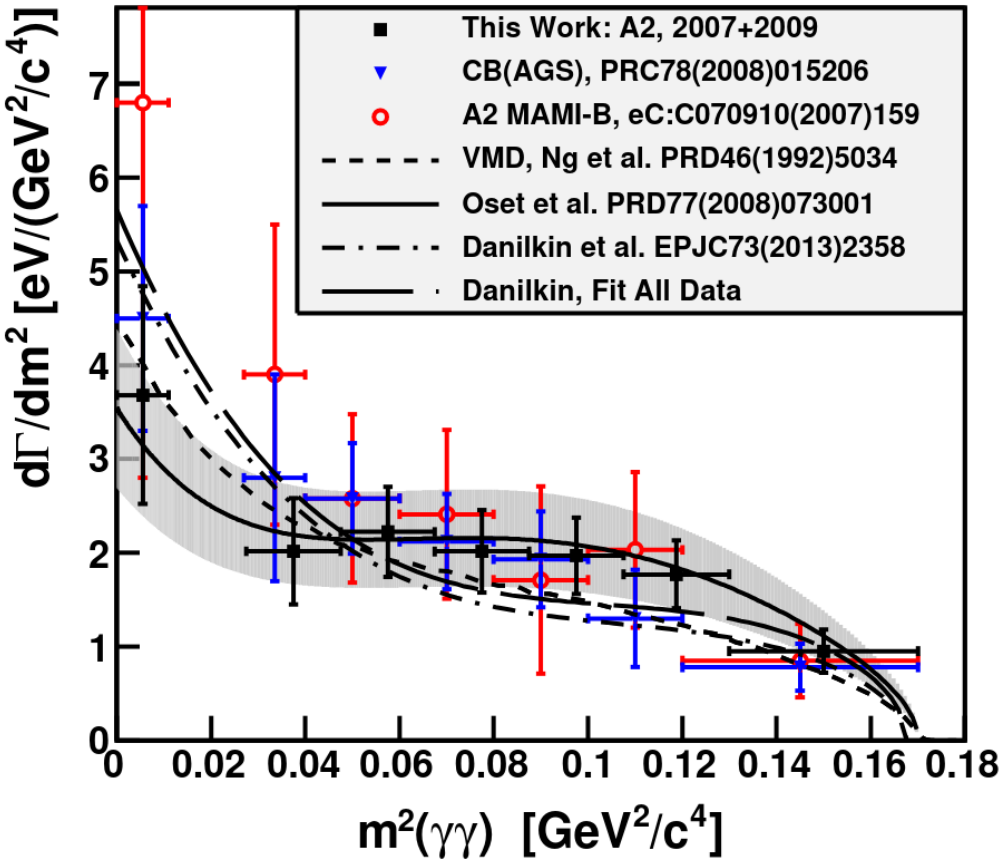
- Unique probe for high order Chiral Perturbation Theory ($\chi$PT)
  - Tree level amplitudes $O(p^2)$ and $O(p^4)$ vanish
  - First sizeable contributions to $\eta \to \pi^0\gamma\gamma$ : two $O(p^6)$ counter-terms in chiral Lagrangian

    Ametller, Bijnens, Bramon, and Cornet, Phys. Lett., B276, 185 (1992)

  - Access two Low Energy Constants
- Shape of Dalitz distribution ($M^2_{\gamma\gamma}$) sensitive to role of scalar resonances

  Gasser, Leutwyler 1984; Ecler, Gasser, Pich, de Rafael 1989; Donoghue, Ramirez, Valencia 1989




$$\Gamma(\eta \to \pi^0\gamma\gamma) = (0.330 \pm 0.030_{\mathrm{tot}})\ \mathrm{eV}$$

Phys. Rev. C 90, 025206 (2014)



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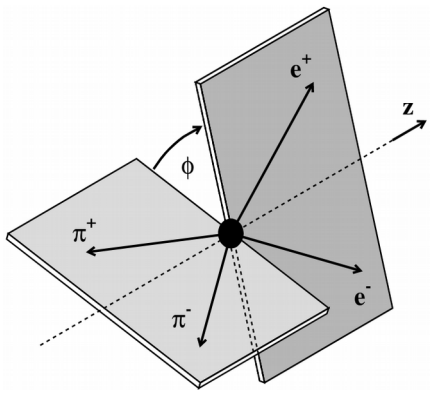
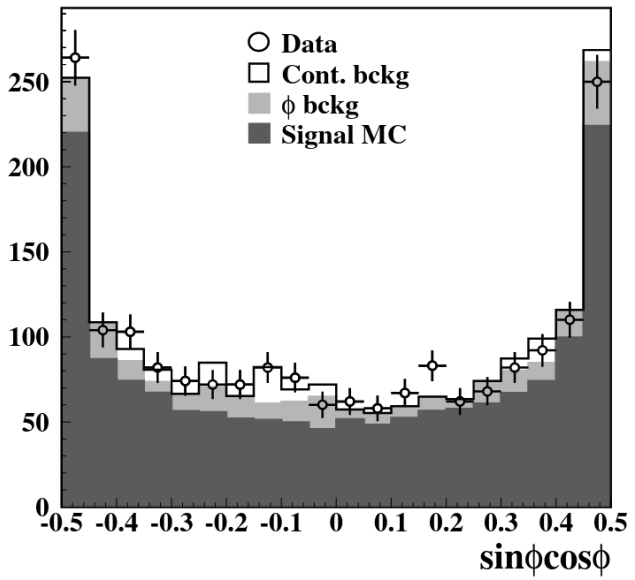
# Decays involving lepton pairs and rare radiative decays

- $\eta \to \pi^+\pi^-e^+e^-$: sensitivity to CP-violating mechanism beyond the Standard Model

$$\mathcal{A}_\phi = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}}$$

$$\mathcal{A}_\phi = (-0.6 \pm 2.5\ _{Stat.} \pm 1.8\ _{Syst.}) \times 10^{-2}$$



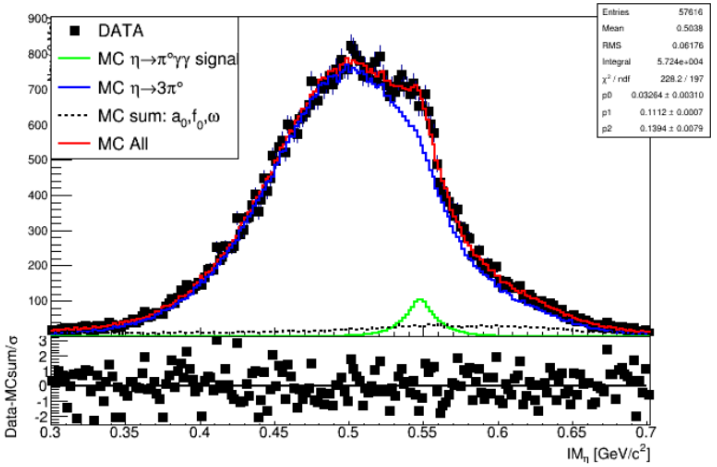



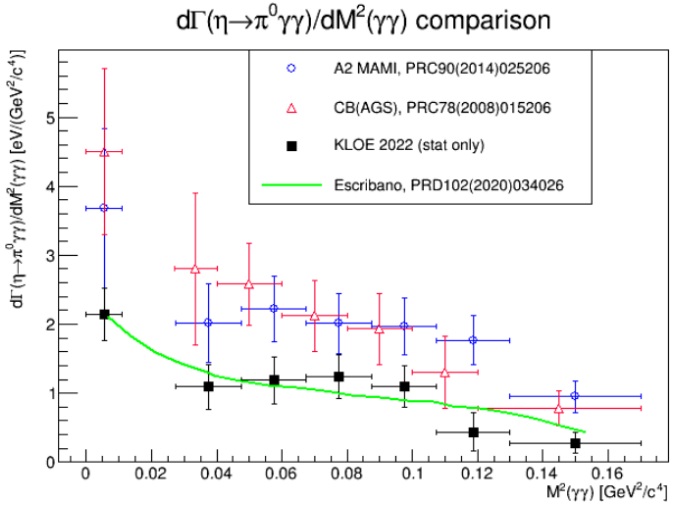

Phys.Lett.B675:283-288,2009

- $\eta \to \pi^0\gamma\gamma$: $\Gamma$=0.334±0.028 eV (BR=(2.55±0.22)x$10^{-4}$)

Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

  - Test higher-order chiral perturbation theory
  - Search for Beyond Standard Model physics




PoS (ICHEP2022) 791.

- Preliminary result:

BR=(1.21±0.13$_{stat}$±0.28$_{syst}$)x$10^{-4}$

*… a factor of 2 smaller than previous measurements ...*



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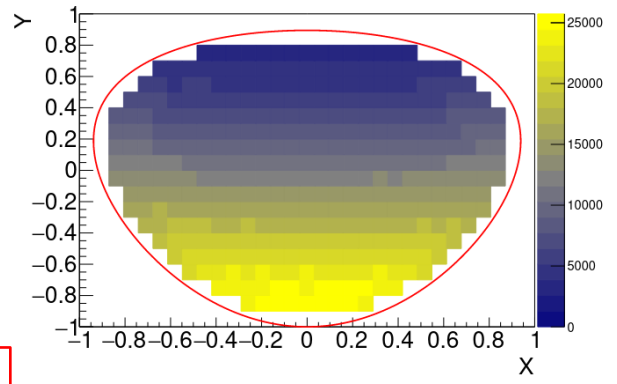
# Light quark mass ratio: $\eta \to \pi^+\pi^-\pi^0$

- Quark masses are fundamental QCD parameters
  - $\eta \to \pi^+\pi^-\pi^0$ provides direct way to constrain light quark masses and source term for isospin violation
- QCD Lagrangian: isospin violation amplitude *A* proportional to $m_u - m_d$

$$A = (m_u - m_d)A_1 + \alpha_{em}A_2$$ ← small

- Quark mass ratio:

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \quad \hat{m} = \frac{m_u + m_d}{2}$$




$$X = \sqrt{3}\frac{T_+ - T_-}{Q_\eta}$$

$$Y = \frac{3T_0}{Q_\eta} - 1$$

$$Q_\eta = m_\eta - 2m_{\pi^+} - m_{\pi^0}$$

- Decay width:

$$\Gamma(\eta \to 3\pi) \propto \int \mathrm{d}s\,\mathrm{d}u |\mathcal{A}_{\eta\to 3\pi}(s,t,u)|^2 \propto \frac{1}{Q^4}$$

- Measure Dalitz plot distribution for $\eta \to \pi^+\pi^-\pi^0$
  - Charge conjugation symmetry: $c = e = h = l = 0$

$$\Gamma_c(X,Y) = |\mathcal{A}_c(s,t,u)|^2 \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + \ldots$$

JHEP 1605, 019 (2016)

$$a = -1.095 \pm 0.003^{+0.003}_{-0.002}$$
$$b = +0.145 \pm 0.003 \pm 0.005$$
$$d = +0.081 \pm 0.003^{+0.006}_{-0.005}$$
$$f = +0.141 \pm 0.007^{+0.007}_{-0.008}$$
$$g = -0.044 \pm 0.009^{+0.012}_{-0.013}$$

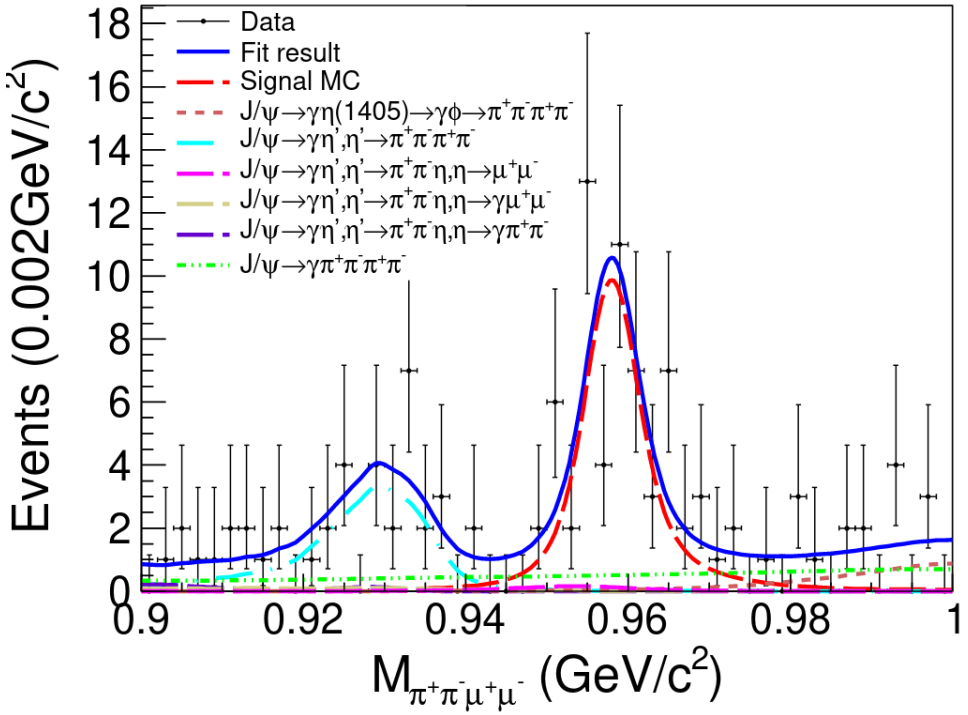
- Dalitz plot parameters (*a*, *b*, *d*, ...): compute from theory (χPT, dispersion analysis)

# Decays involving lepton pairs

- Allow access to doubly-virtual transition form factors
- Sensitivity to box anomaly contribution
- Test the possibility of double vector meson dominance

- First observation of $\eta' \to \pi^+\pi^-\mu^+\mu^-$

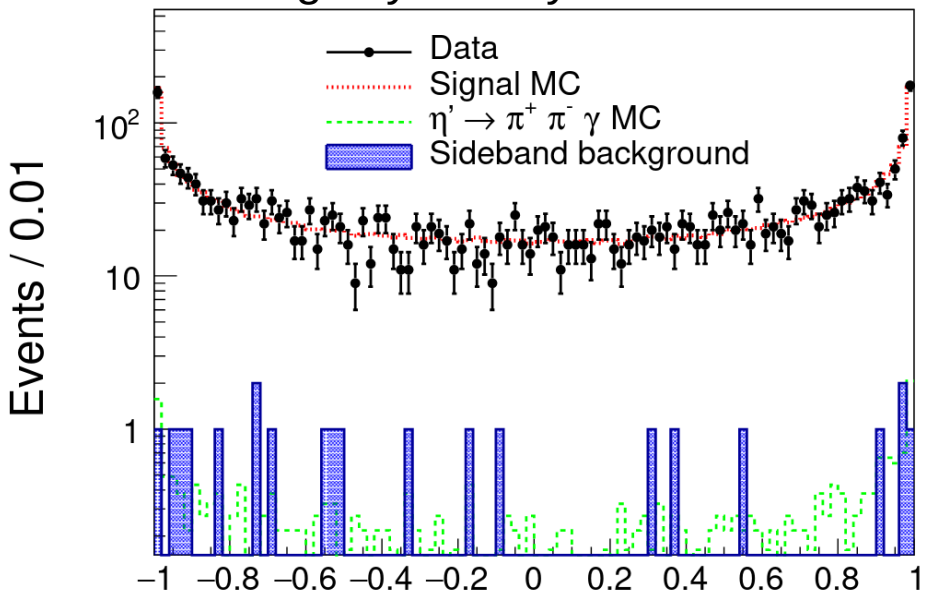
$$\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-) = (1.97 \pm 0.33(\text{stat}) \pm 0.19(\text{syst})) \times 10^{-5}$$




Phys. Rev. D 103, 072006 (2021)

- $\eta' \to \pi^+\pi^-e^+e^-$: sensitivity to CP-violating mechanism due to possible new electric dipole-type transition

CP-violating asymmetry=2.9±3.7±1.1 %




Phys.Rev.D 103 (2021) 9, 092005



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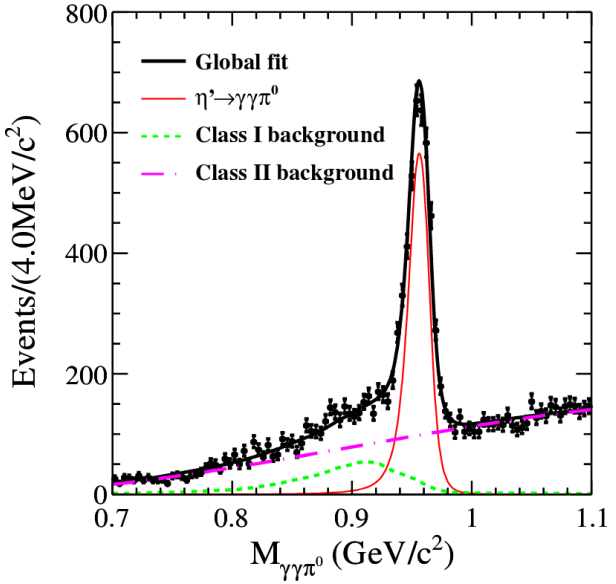
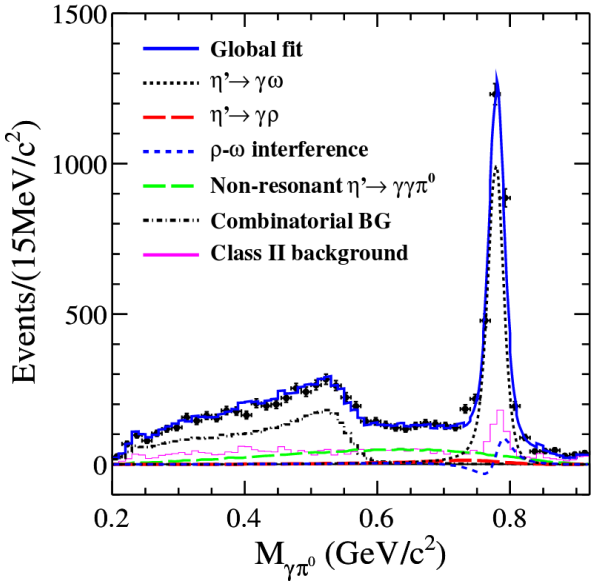
# Rare decays: $\eta' \to \pi^0 \gamma\gamma$ and $\eta' \to \eta \gamma\gamma$

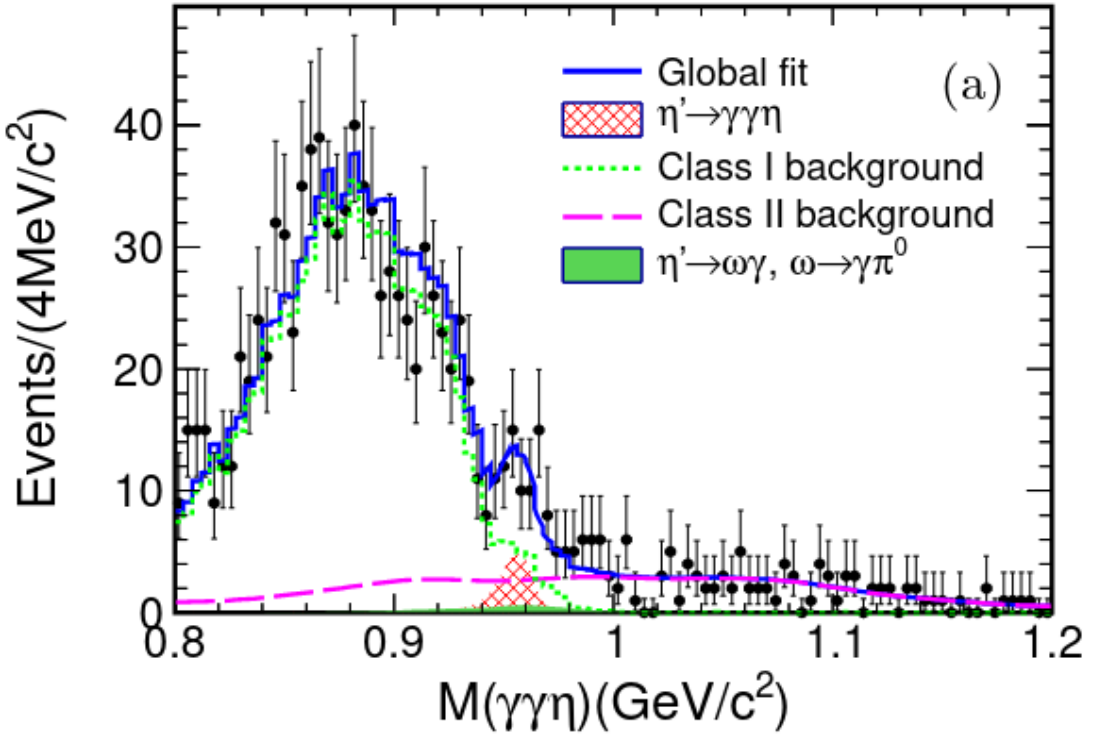
- $\eta' \to \pi^0 \gamma\gamma$ previously seen via $\eta' \to \gamma\omega$, $\omega \to \gamma\pi^0$
- Non-resonant contribution measured for first time
  - BR(inclusive)=3.20±0.07(stat)±0.23(sys))×$10^{-3}$
  - BR(non-resonant)=(6.16±0.64(stat)±0.67(sys))×$10^{-4}$




Phys. Rev. D 96, 012005

- $\eta' \to \eta\gamma\gamma$ never observed before
  - At 2.6σ level, BR=(8.25±3.41±0.72)×$10^{-5}$
  - Upper limit: BR<1.33×$10^{-4}$ at 90% CL




Phys. Rev. D 100, 052015 (2019)



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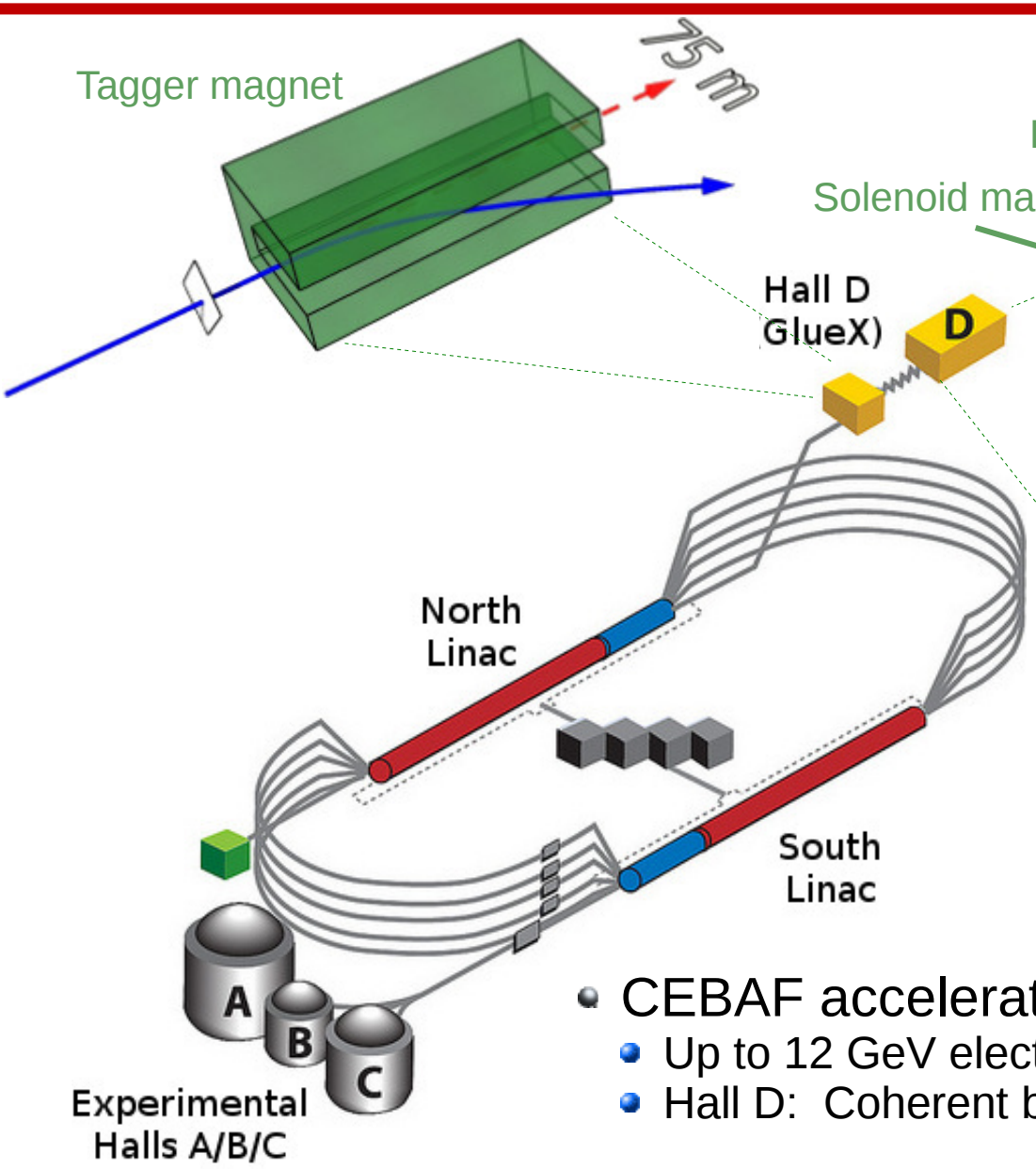
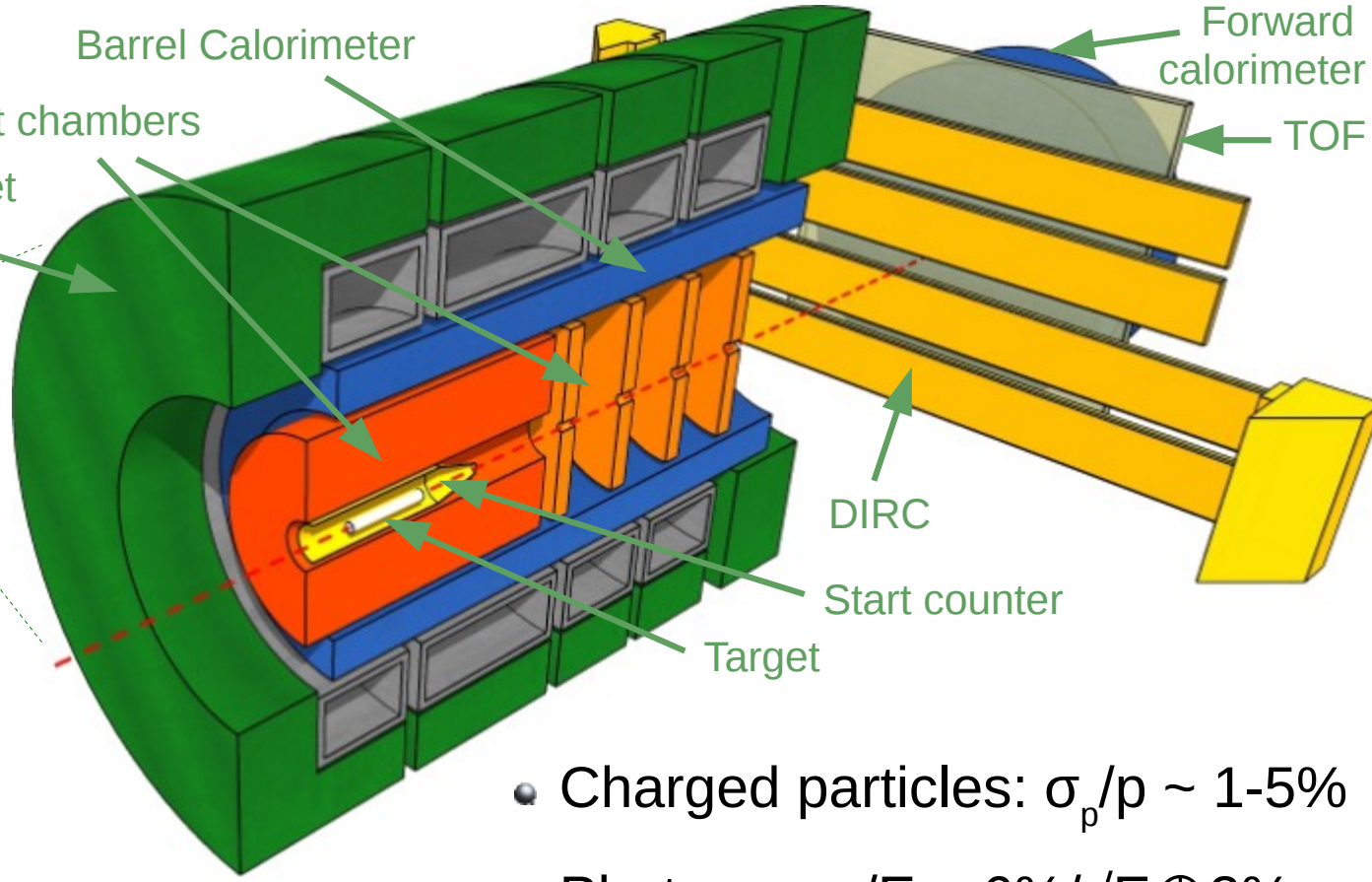
# Hall D and the GlueX detector at Jefferson Lab




- Charged particles: $\sigma_p/p \sim 1\text{-}5\%$
- Photons: $\sigma_E/E \sim 6\%/\sqrt{E} \oplus 2\%$
- Acceptance: $\theta = 1\text{–}120°$

- CEBAF accelerator:
  - Up to 12 GeV electron beam
  - Hall D: Coherent bremsstrahlung photon beam, ~9 GeV peak energy



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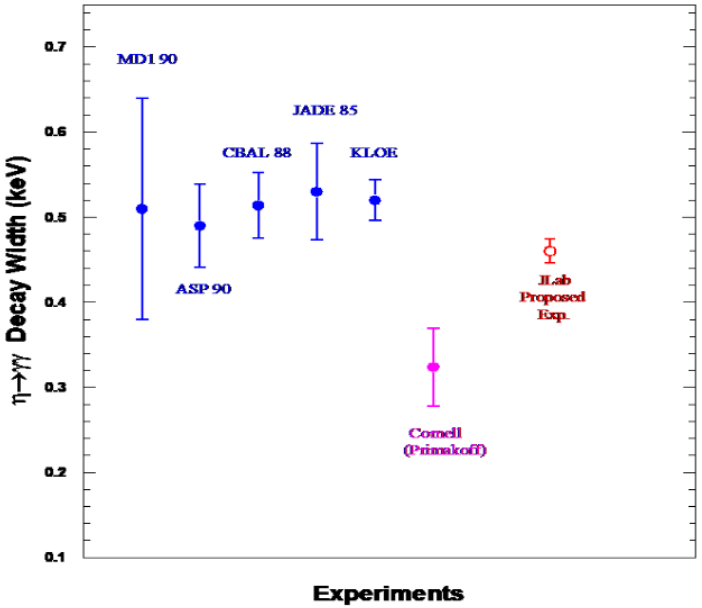
# Measuring $\Gamma(\eta\to\gamma\gamma)$ in Hall D at Jefferson Lab

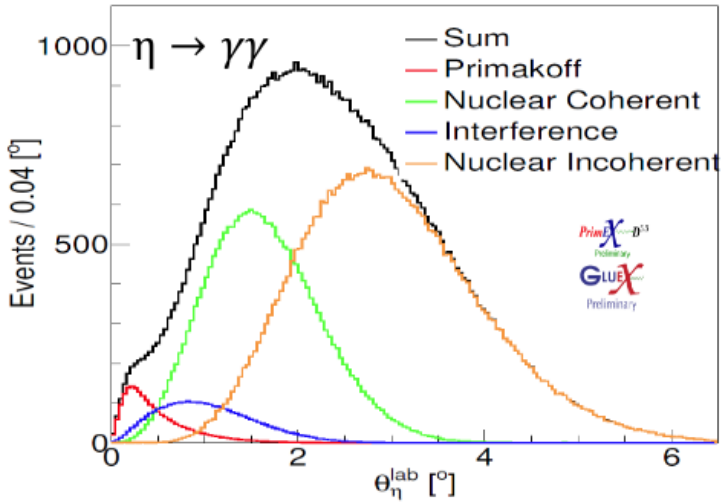
- Photoproduction off a Helium target: $\gamma^4\text{He}\to\eta^4\text{He}$
- Primakoff cross section proportional to $\Gamma(\eta\to\gamma\gamma)$

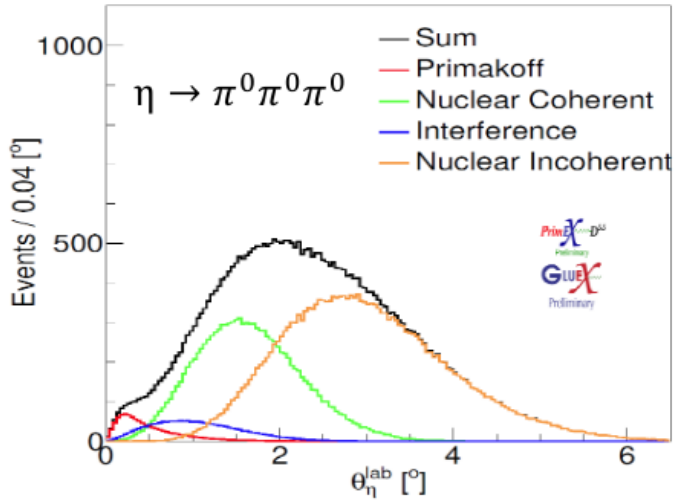
$$\frac{d\sigma_P}{d\Omega} = \Gamma(P\to\gamma\gamma)\frac{8\alpha_{em}Z^2}{M_P^3}\frac{\beta^3E^4}{Q^4}\left|F_{em}(Q^2)\right|^2\sin^2\theta$$




- Goals:
  - Resolve long-standing discrepancy between previous collider and Primakoff measurements
  - Extract η-η′ mixing angle
  - Improve calculation of the η-pole contribution to Hadronic Light-by-Light scattering in $(g\text{-}2)_\mu$
  - Improve all partial decay widths in the η-sector

Simulations:




L, Gan, “The Primakoff Experimental Program at Jefferson Lab”, QNP22



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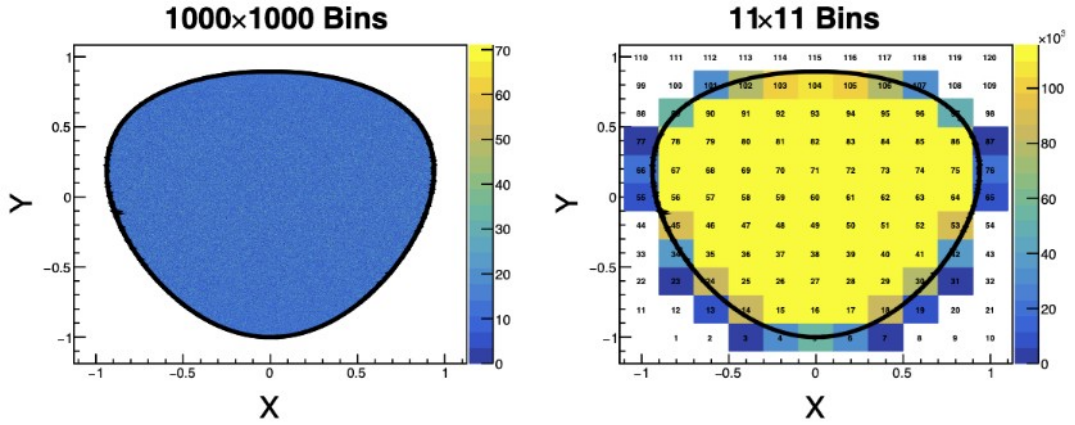
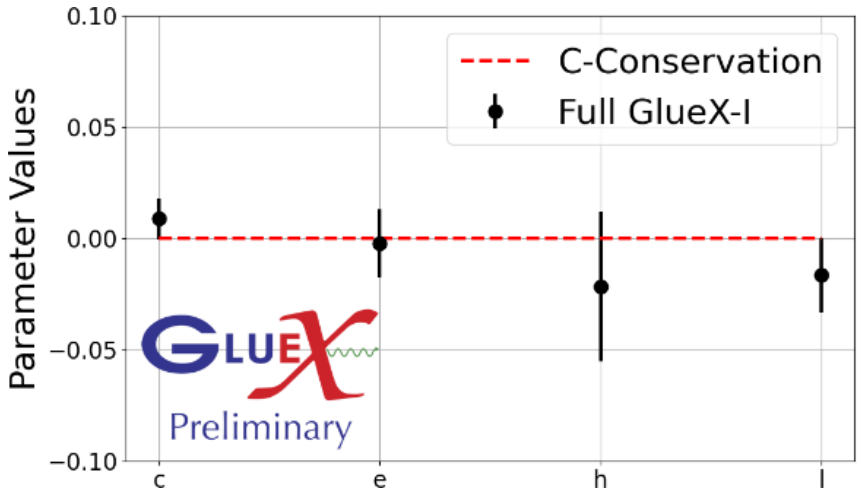
# Dalitz plot analyses using the GlueX detector

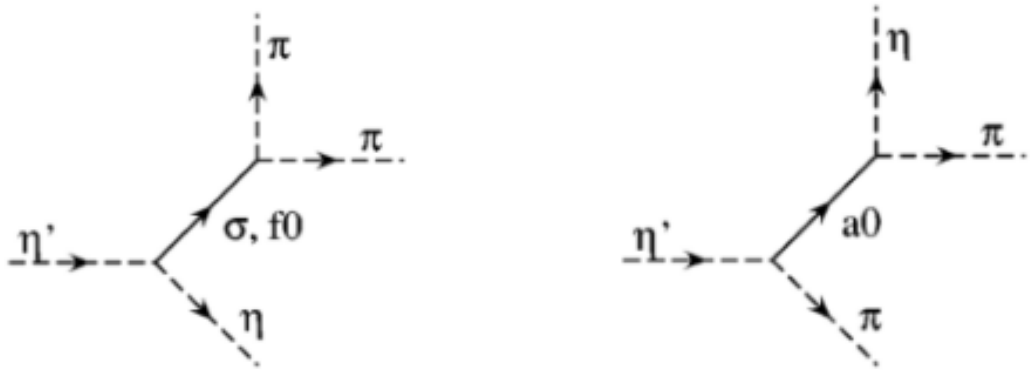
- Measure Dalitz plot distribution for $\eta \to \pi^+\pi^-\pi^0$
  - Charge conjugation symmetry: $c = e = h = l = 0$

$$\Gamma_c(X,Y) = |\mathcal{A}_c(s,t,u)|^2 \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + \ldots$$




- Measure Dalitz plot distribution for $\eta' \to \eta\pi\pi$
- Test extension of chiral perturbation theory theory
- Sensitivity to implicit exchange of scalar resonances $f_0(500)$, $f_0(980)$, $a_0(980)$
- Constrain $\eta\pi$ scattering




- For more information:

Olga Cortes Becerra, “Dalitz Plot Analysis of η′ → ηππ with GlueX Data”



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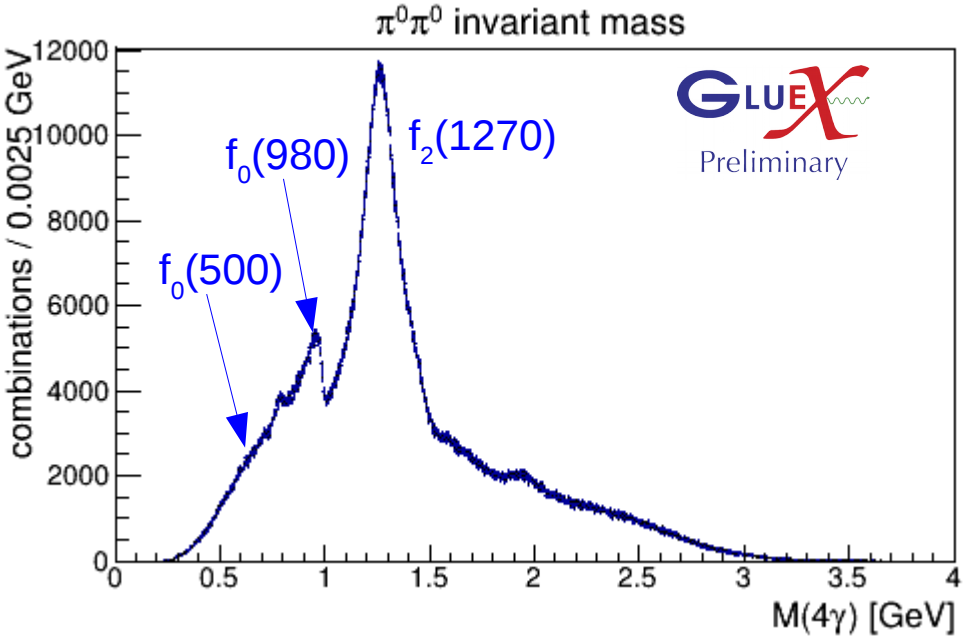
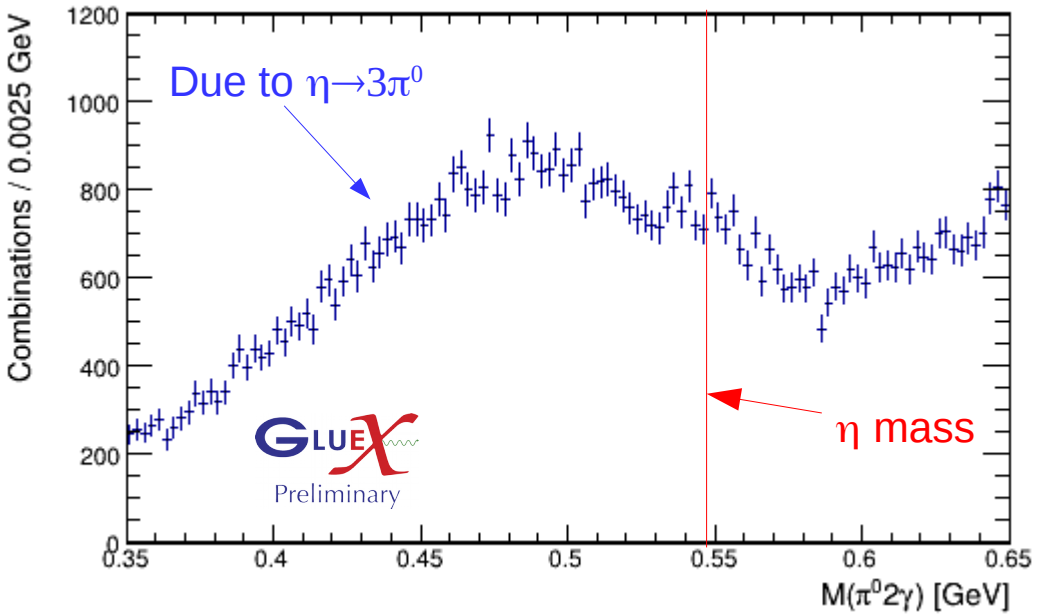
# Looking for $\eta \to \pi^0\gamma\gamma$ with GlueX

- $\gamma p \to p\pi^0\pi^0$: background for $\eta \to \pi^0\gamma\gamma$

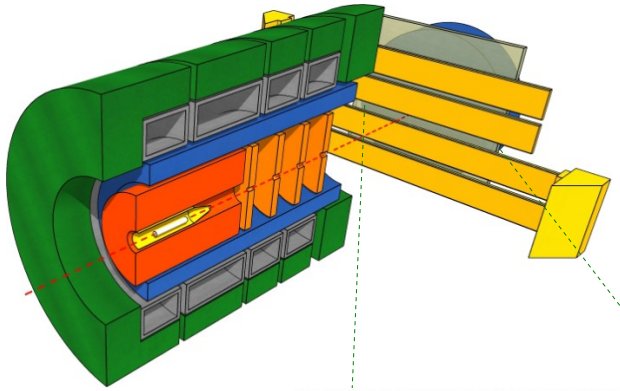



- Another source of significant background:
  $\eta \to 3\pi^0$ with missing/merged photons

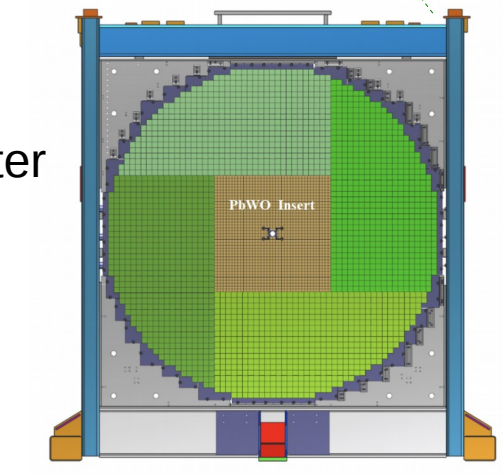



***Resolution of Forward Calorimeter (FCAL) not sufficient to resolve rare decay channel...***

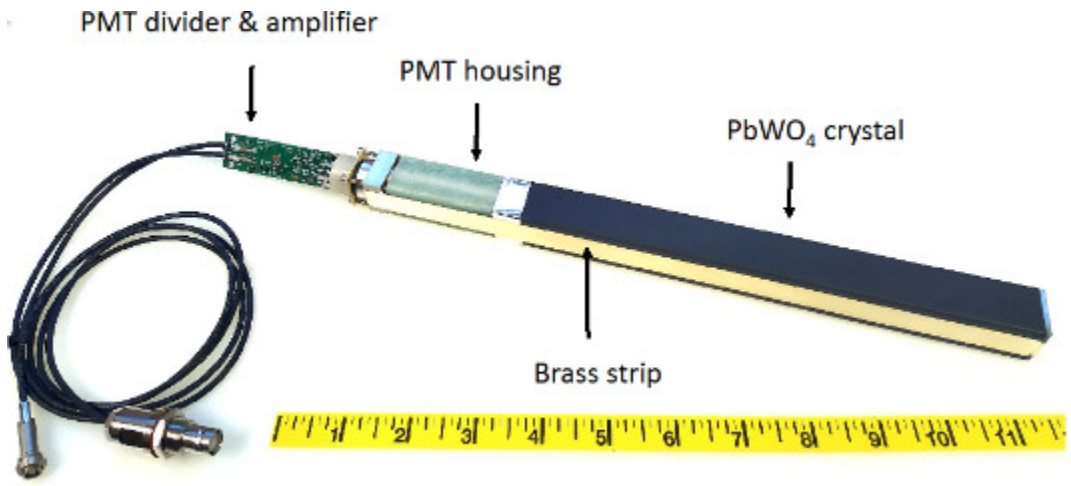
# The Jefferson Lab Eta Factory (JEF) experiment



Forward Calorimeter




- Focus on η/η′ decays with emphasis on rare decay $\eta \to \pi^0\gamma\gamma$
- GlueX detector with Forward Calorimeter upgrade: replace blocks in inner 80×80 cm² region with $PbWO_4$ crystals
  - Outer blocks = 4×4×45 cm³ lead glass
  - Inner blocks = 2×2×20 cm³ lead tungstate




| Property | Improvement factor |
|---|---|
| Energy σ | 2 |
| Position σ | 2 |
| Granularity | 4 |
| Radiation-resistance | 10 |

- Modules ready for installation in 2023
- Planned installation duration: 6-12 months
- Data taking with upgraded Forward Calorimeter expected in 2024



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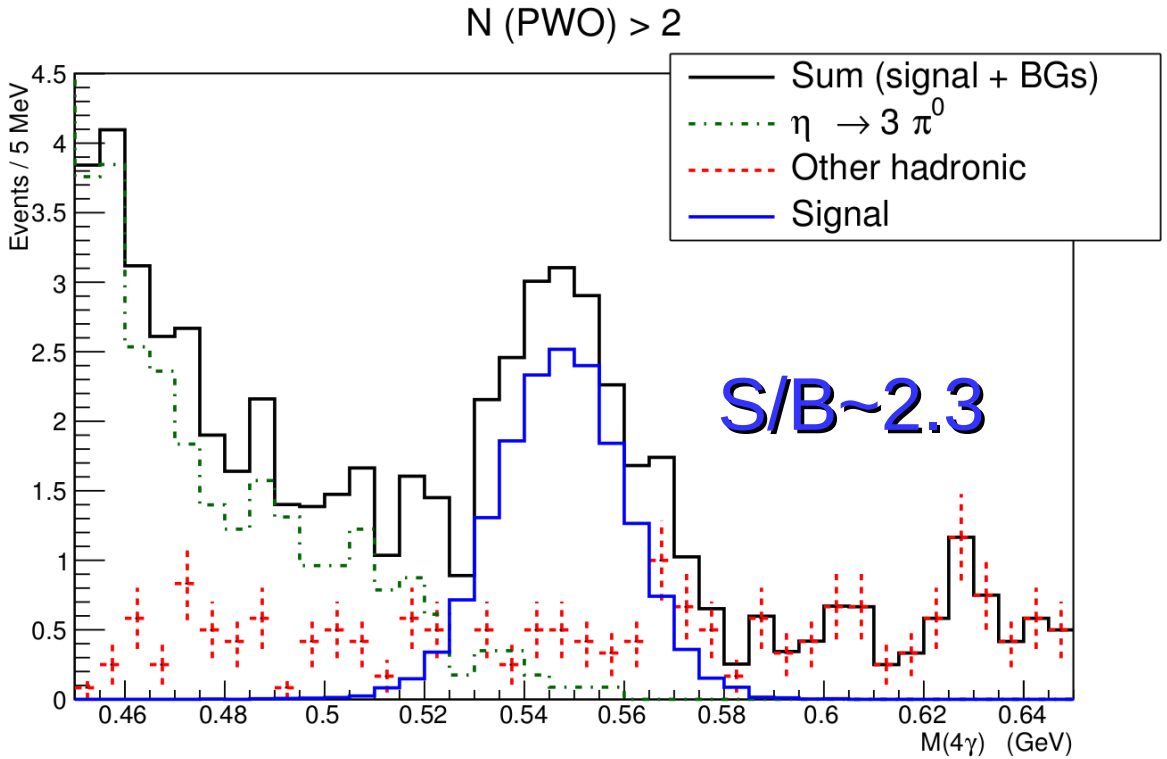
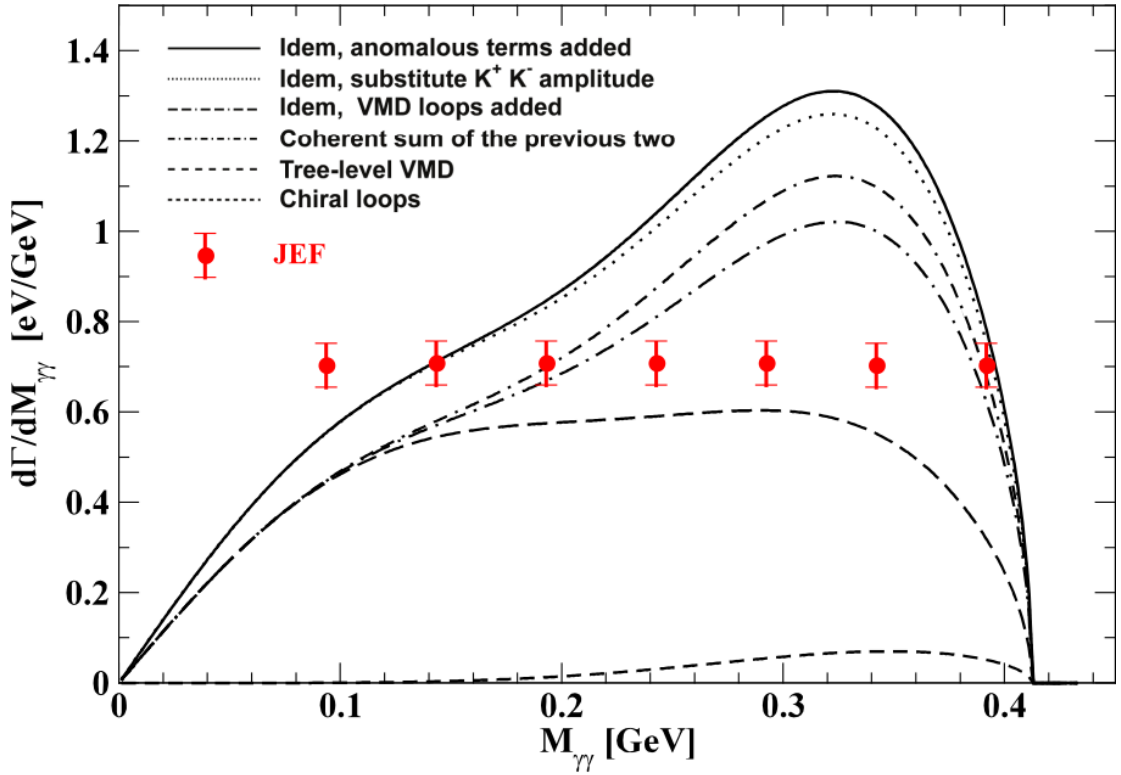
# The rare $\eta \to \pi^0 \gamma\gamma$ decay with JEF

- Reaction: $\gamma p \to \eta p$
- Golden channel: $\eta \to \pi^0 \gamma\gamma$
  - Results of simulation for 1 day of running:
    - Beam energy range: 8.4-11.7 GeV, intensity $N_\gamma \sim 1 \times 10^8$/s




- 100 days of running:
  $N_{\eta,\eta'} \sim 3 \times 10^7$
  (recoil proton required)




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



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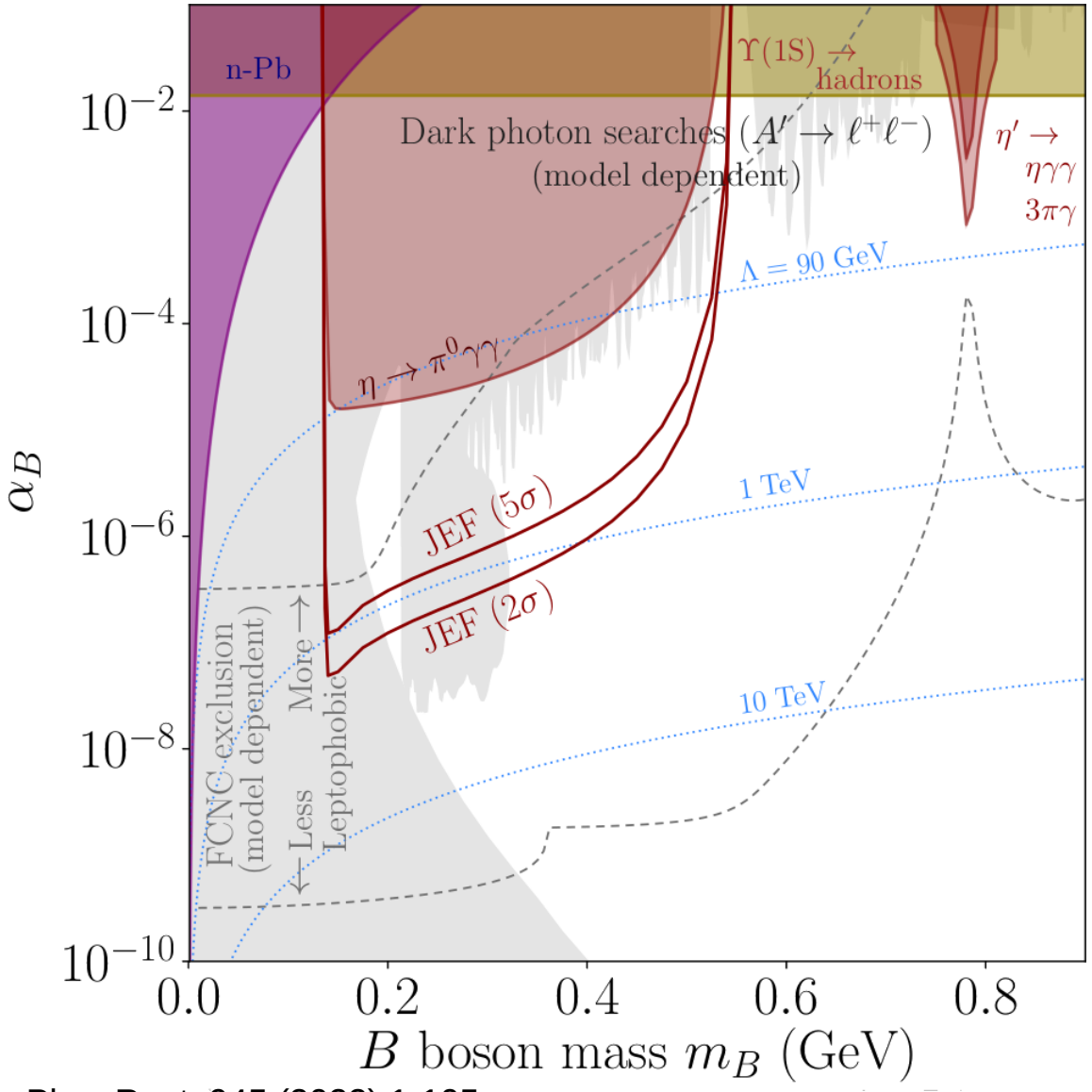
# Portal to dark sector: *B*-boson

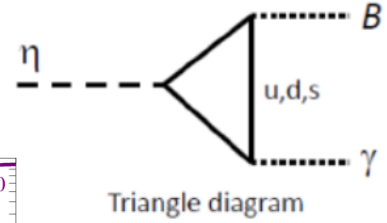



Phys.Rept. 945 (2022) 1-105

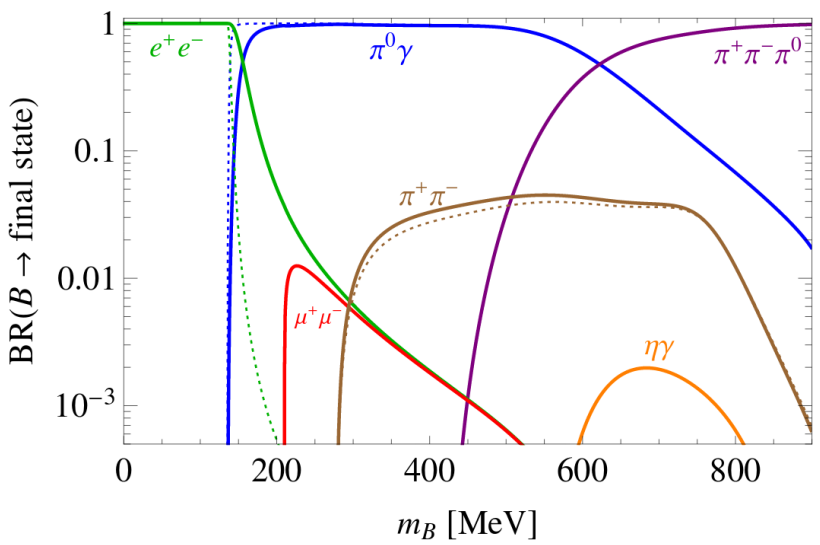
- Leptophobic $U(1)_B$ boson
  - Predominantly couples to quarks
  - Production:

    A.E. Nelson, N. Tetradis,
    Phys. Lett., B221, 80 (1989)

    $\eta \to B\gamma$ decay ($m_B < m_\eta$)




Triangle diagram




S. Tulin,
Phys.Rev. D89,
14008 (2014)

- Look for signals in $\eta \to \gamma B \to \gamma(\pi^0\gamma)$
  - Bump hunt over $M(\pi^0\gamma)$



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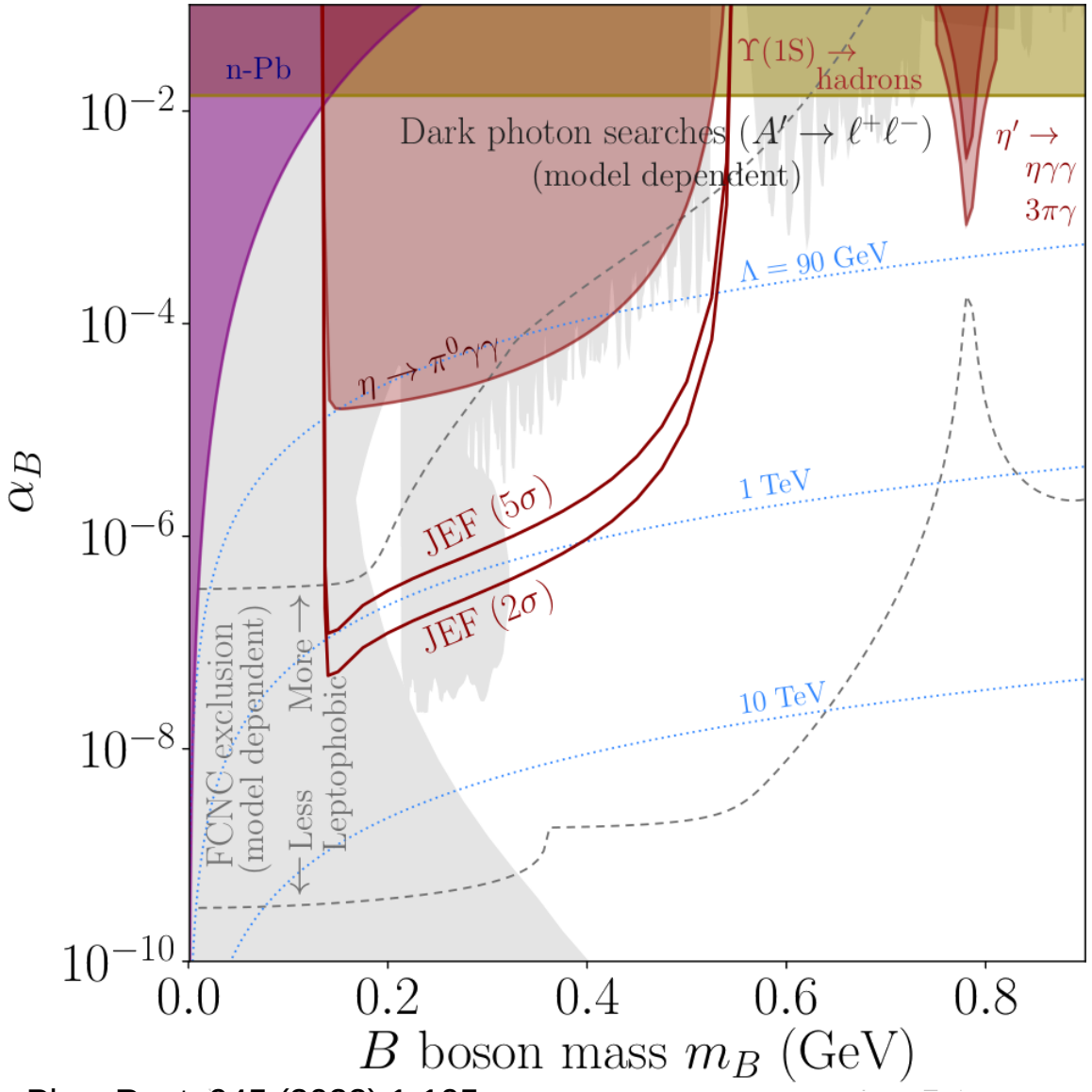
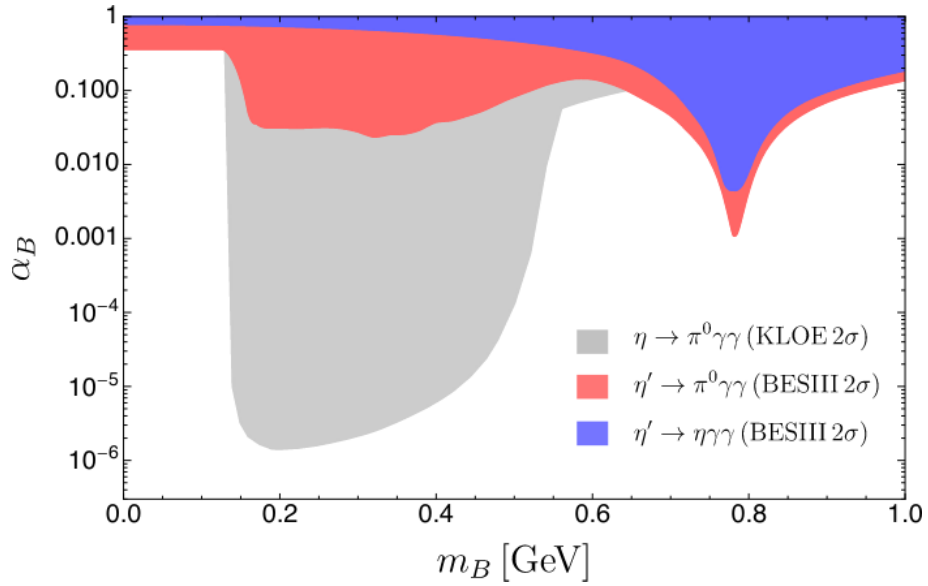
# Portal to dark sector: *B*-boson




Phys.Rept. 945 (2022) 1-105

- Limit from $\eta \to \pi^0\gamma\gamma$ neglects SM contributions
  - KLOE preliminary results not included
- Recent update from Escribano, Gonzales-Solis, and Royo, Phys.Rev.D 106 (2022) 11, 114007
  - Using KLOE preliminary results
  - *B*-boson + SM exchanges



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# Summary

- Light pseudoscalar decays provide a laboratory for probing many physics processes
  - Sensitivity to higher-order chiral perturbation theory
  - Cusp effects from re-scattering
  - Searches for signatures of dark matter
  - Tests of discrete symmetries
- Active field of experimental activity at both fixed-target and collider facilities
  - $e^+e^-$ collisions (BES-III, KLOE), hadron beams (WASA@COSY, HADES), photon beams (MAMI A2, GlueX/JEF)
  - New experiments under construction or being planned

http://www.gluex.org/thanks.html

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