

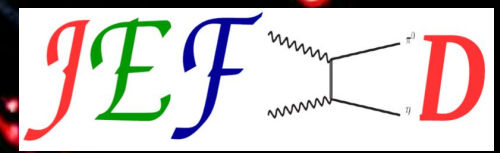
η η η

Rare η Decay Signal and Background Generation for JEF

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Co-supervisor: Dr. Cristiano Fanelli



01 BACKGROUND

Quantum Chromodynamics
Richness of η SM Physics
BSM η Physics

02 OPPORTUNITY

The GlueX Experiment and
Experimental Hall D
Jefferson eta Factory and
the Forward Calorimeter

03 SIMULATIONS

Monte Carlo Simulations

04 RESULTS

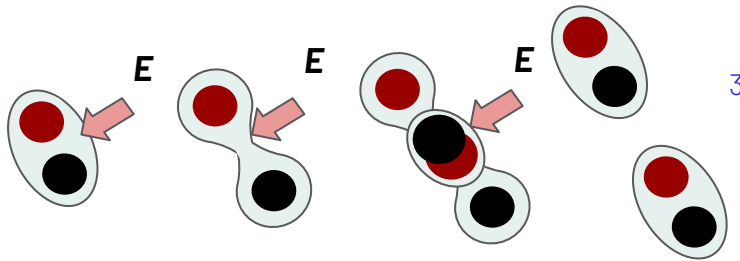
$\pi^0\gamma\gamma$ Signal and
Background removal
 $\pi^+\pi^-e^+e^-$ Signal and
Background removal
Asymmetry Factor

05 CLOSING

Thank You
Questions

Quantum Chromodynamics (QCD)

Theory of the strong interaction between quarks mediated by gluons
Non-abelian gauge theory with symmetry group SU(3)



Properties

- Color confinement
- Asymptotic freedom
- Chiral symmetry breaking

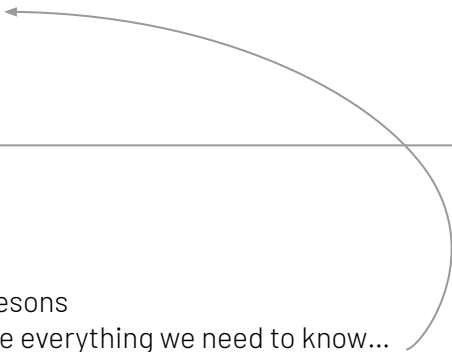
Weaknesses

- Non-perturbative Regime
- Confinement
- Strong CP Problem
- ...

Formation of Mesons

Channel	Expt. branching ratio
$\eta \rightarrow 2\gamma$	39.41(20)%
$\eta \rightarrow 3\pi^0$	32.68(23)%
$\eta \rightarrow \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$
$\eta \rightarrow \pi^+\pi^-\pi^0$	$2.68(11) \times 10^{-4}$

- Ground states \rightarrow mesons
- Excited states \rightarrow hybrid mesons
- Great! We can just calculate everything we need to know...
- Chiral perturbation theory



Richness of η SM Physics

CHIRAL PERTURBATION THEORY (ChPT)

- Effective field theories \rightarrow significant step towards computing scattering amplitudes
- Constraints studied in detail up to $\mathcal{O}(p^6)$
- Compared to LQCD
- **Strong precision test for non-perturbative QCD**

$$\pi^0 \gamma \gamma$$

TRANSITION FORM FACTORS (TFFs)

$$\mathcal{M}(\eta \rightarrow \gamma^*(q_1) \gamma^*(q_2)) = -ie^2 \epsilon_{\mu\nu\alpha\beta} q_1^\mu q_2^\nu \epsilon_1^\alpha \epsilon_2^\beta F_{\eta^{(\prime)} \gamma^* \gamma^*}(q_1^2, q_2^2)$$

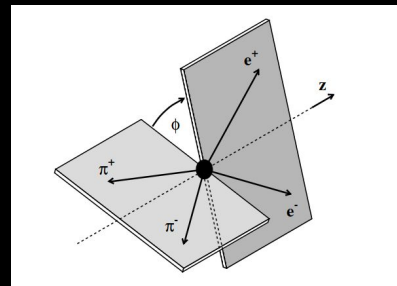
- Electromagnetic transition form factors $F_{\eta^{(\prime)} \gamma^* \gamma^*}$
- Quark and gluon structure
- **Anomalous magnetic moment of the muon ($g-2$) $_\mu$**

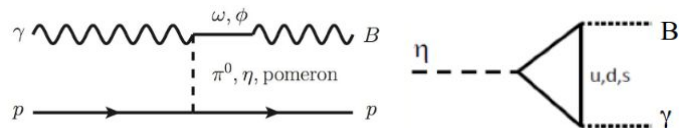
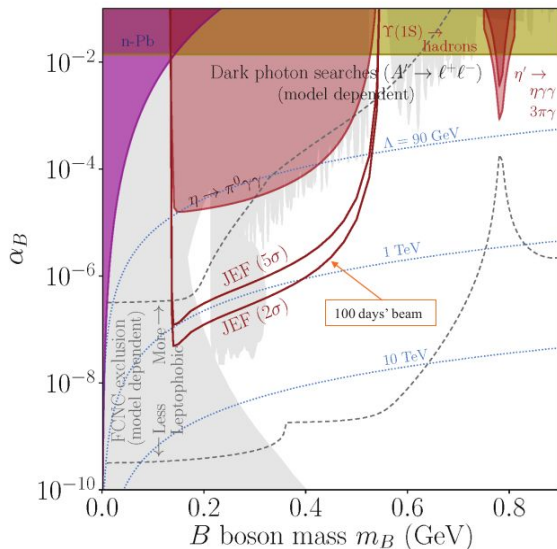
$$\pi^+ \pi^- e^+ e^-$$

DISCRETE SYMMETRIES

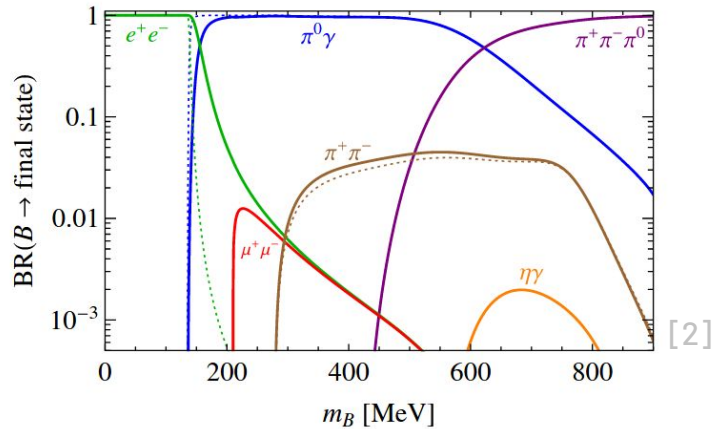
- **P** and **CP** are violated, while **C** is conserved
- (i) CP-violating dynamics in strong interactions \rightarrow nonzero form factor
- (ii) CP-violating dynamics in quark-lepton interactions

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





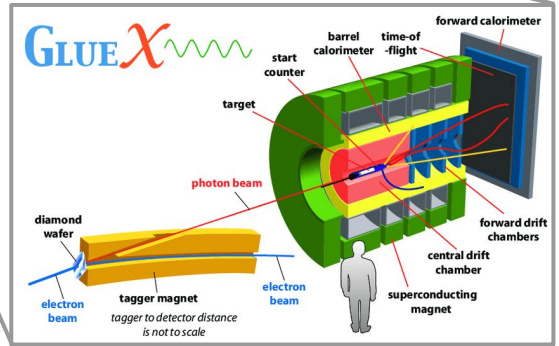
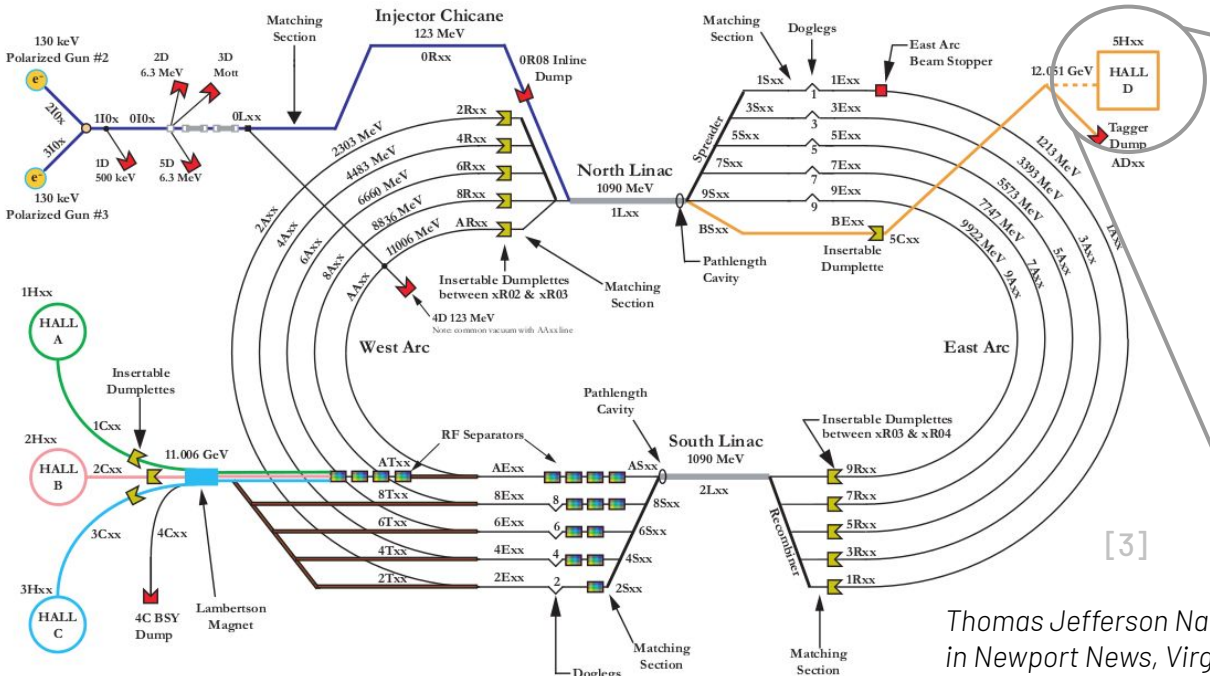
Channel	Branching Ratio	Physics of Interest
$\gamma + B$	BSM	leptophobic vector boson
$\pi^0 \gamma \gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	ChPT at $\mathcal{O}(p^6)$
$\pi^+ \pi^- e^+ e^-$	$(2.7 \pm 0.1) \times 10^{-4}$	CP violation, TFFs, $(g-2)_\mu$
$\pi^0 \pi^0 \pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$



BSM η Physics $\mathcal{L}_{INT} = \left(\frac{1}{3}g_B + \epsilon Q_q e\right) \bar{q} \gamma^\mu q B_\mu - \epsilon e \bar{l} \gamma^\mu l B_\mu$

- Primary decay modes 2-4 orders of magnitude larger than $\pi^0 \gamma \gamma$ and $\pi^+ \pi^- e^+ e^-$
- Various models \rightarrow **connection with SM physics** \rightarrow massive resonances that decay almost instantly into SM final-states
- Interesting model: New force mediated by "dark photons"
 \Leftrightarrow weakly interact with SM photons through electrically charged particles
- Gauge **B**-boson interacts with SM quarks
 \rightarrow redefined **$U(1)_B$** gauge symmetry
- $\pi^0 \gamma \gamma$ **measurable link** between DM and the SM: $\eta \rightarrow B \gamma \rightarrow \pi^0 \gamma \gamma$

The GlueX Experiment and Experimental Hall D



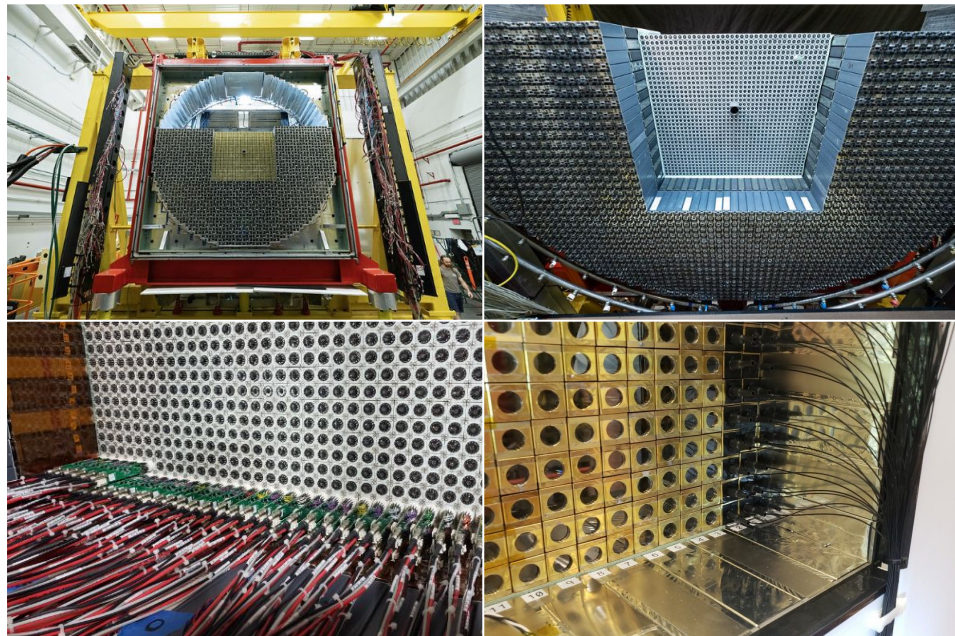
[3]

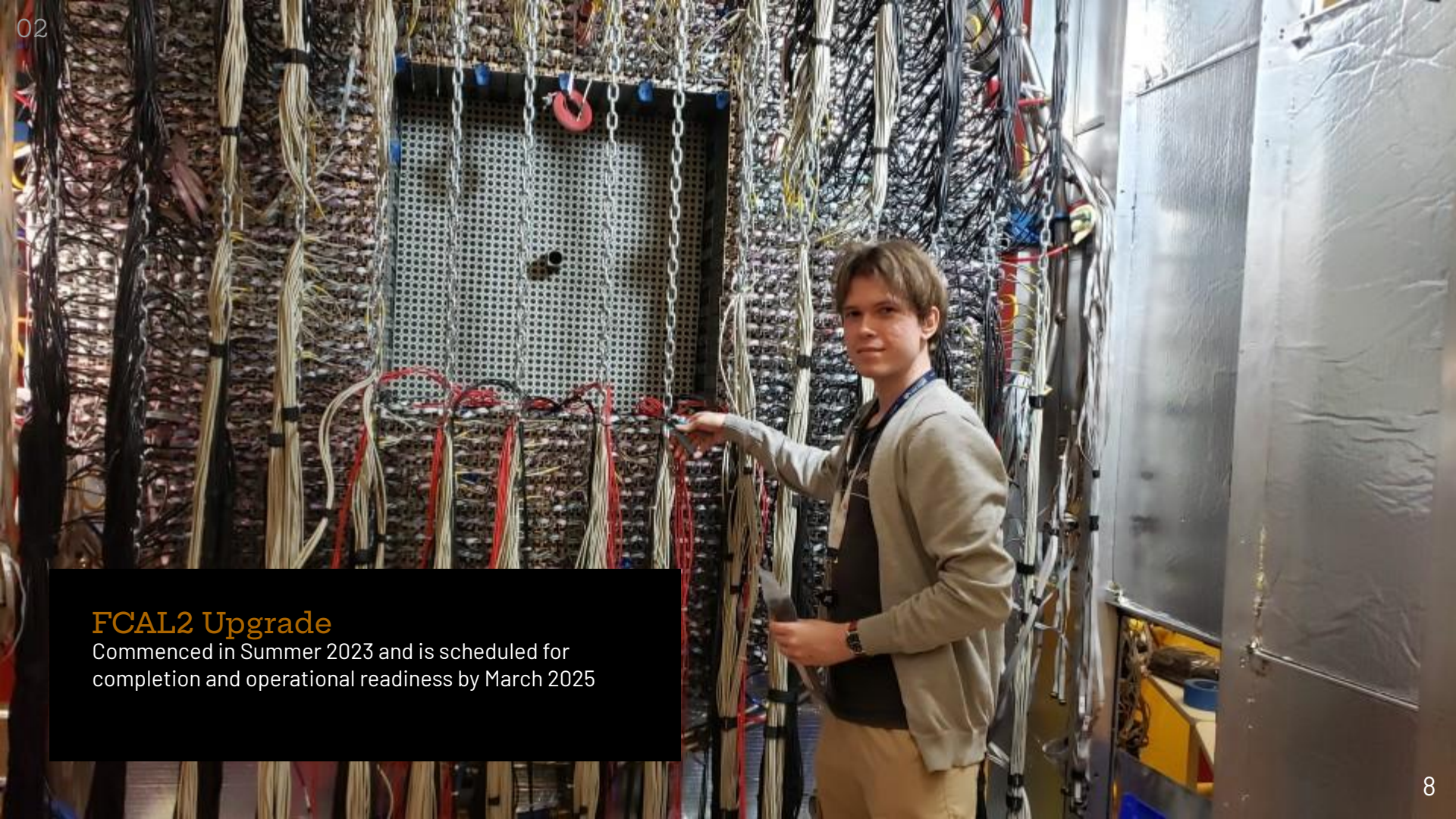
[4]

Thomas Jefferson National Accelerator Facility
in Newport News, Virginia

Jefferson η Factory (JEF) and the Forward Calorimeter

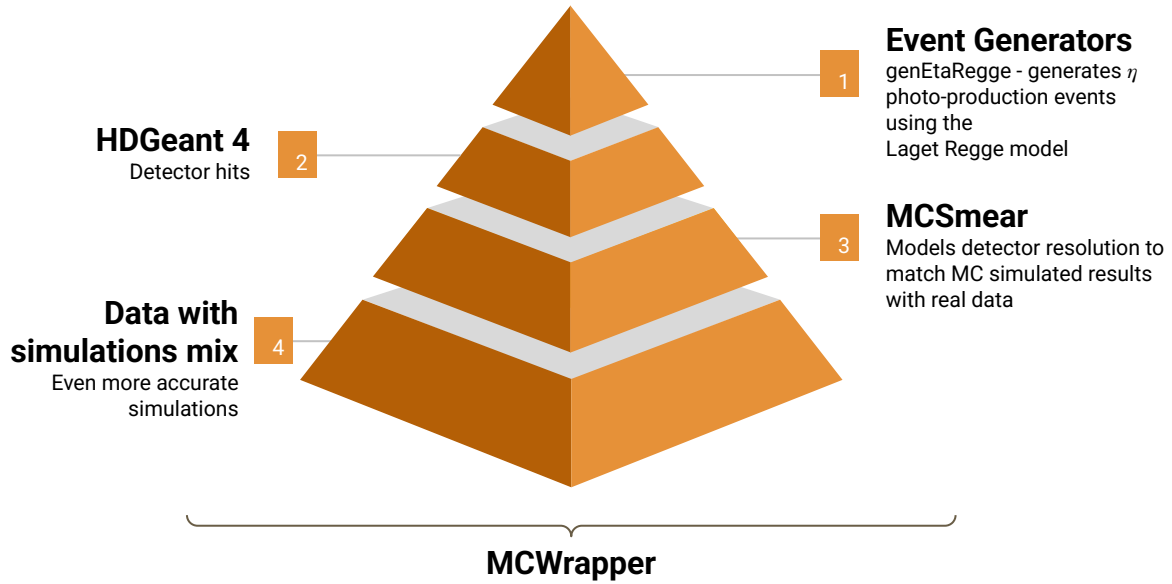
- Photoproduction $\rightarrow \eta$ and η'
- Reconstruction four-momenta \rightarrow timing information, energy and shower position
- Lead glass connected to FEU 84-3 PMTs
- FCAL2 upgrade
 \rightarrow **smaller, radiation-resistant, higher-resolution lead tungstate modules**
- $PbWO_4$ scintillating material connected to a Hamamatsu PMT 4125



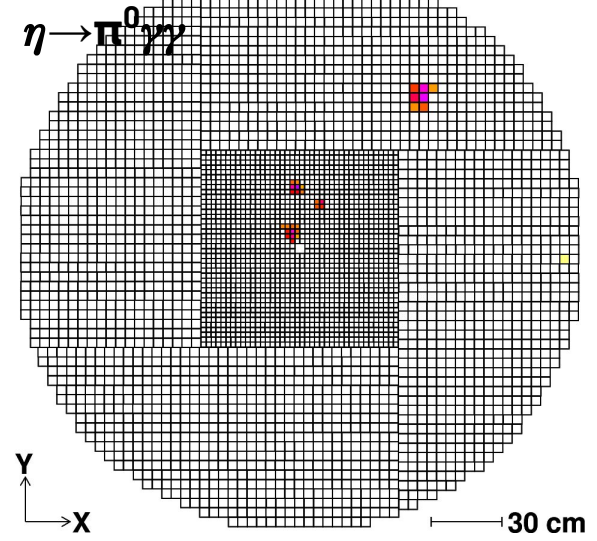


FCAL2 Upgrade
Commenced in Summer 2023 and is scheduled for completion and operational readiness by March 2025

Monte Carlo Simulations

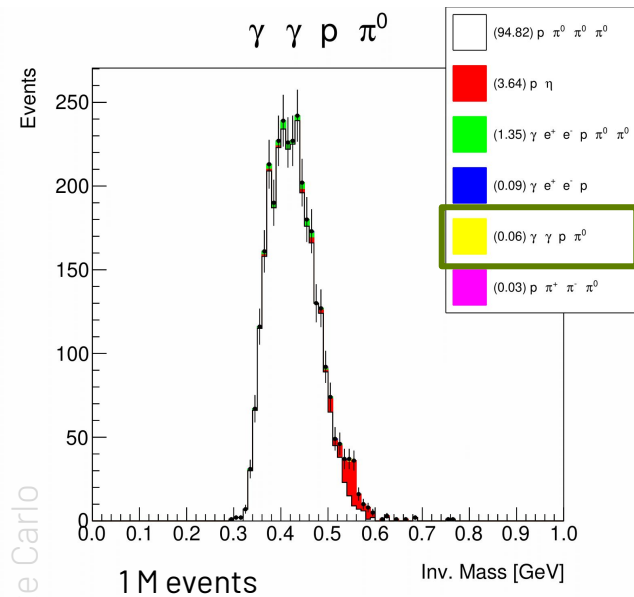


FCAL view from downstream looking upstream



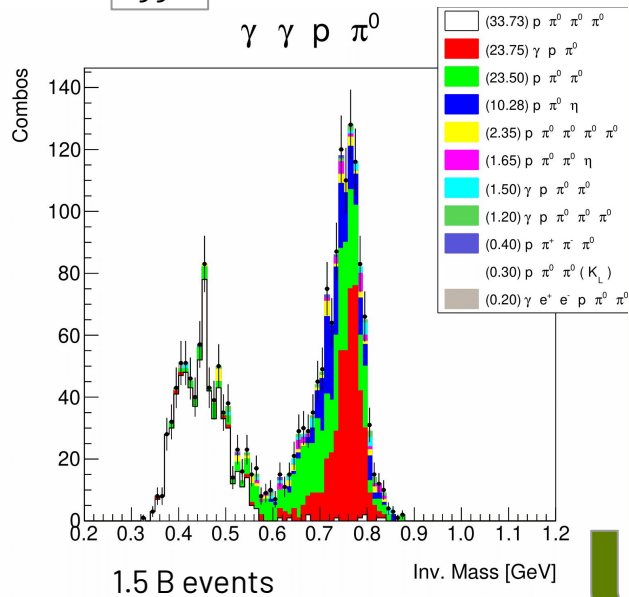
Signal Generation

genEtaRegge + evtgen



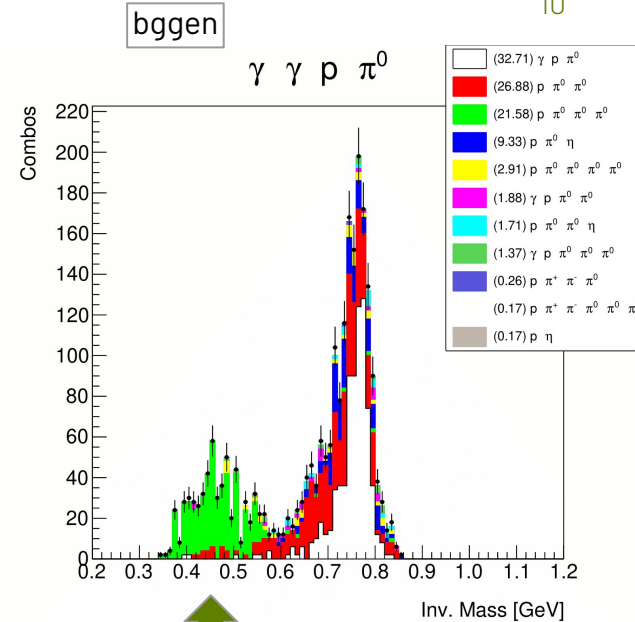
Background Generation

bggen



Background Generation

10



Invariant Mass Plots

Simulation Settings:

Reaction: $\gamma + \rho \rightarrow \eta + \rho$ **Decay:** $\eta \rightarrow \gamma + \gamma + \pi^0$ Post Processing: **evtgen**

Analysis Cuts:

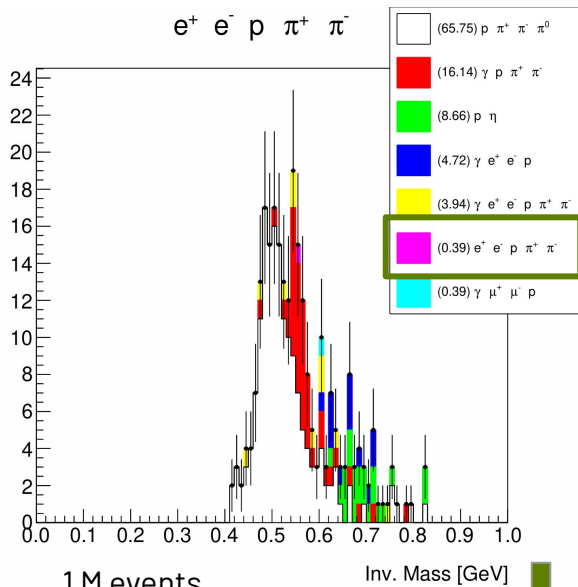
 $\chi^2 \text{DOF} < 10$ Best χ^2 ($|\text{IRF}\Delta T| < 2$)Reduction in the $3\pi^0$ background

Signal Generation

genEtaRegge + evtgen

 $e^+ e^- p \pi^+ \pi^-$

Events



1 M events

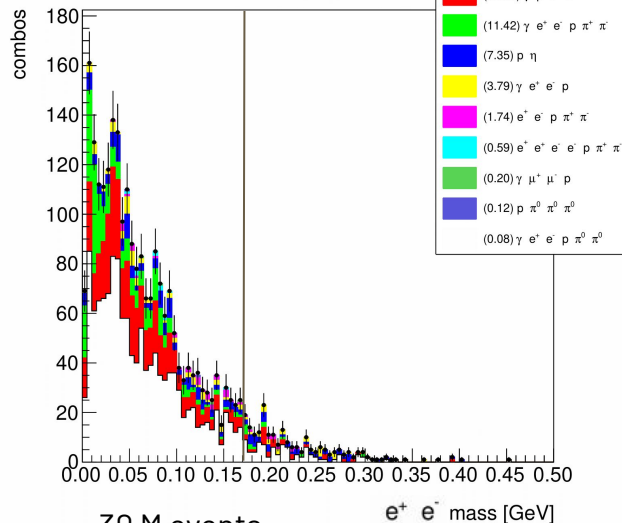
Inv. Mass [GeV]

Signal Generation

genEtaRegge + evtgen

 $e^+ e^- p$

combos



30 M events

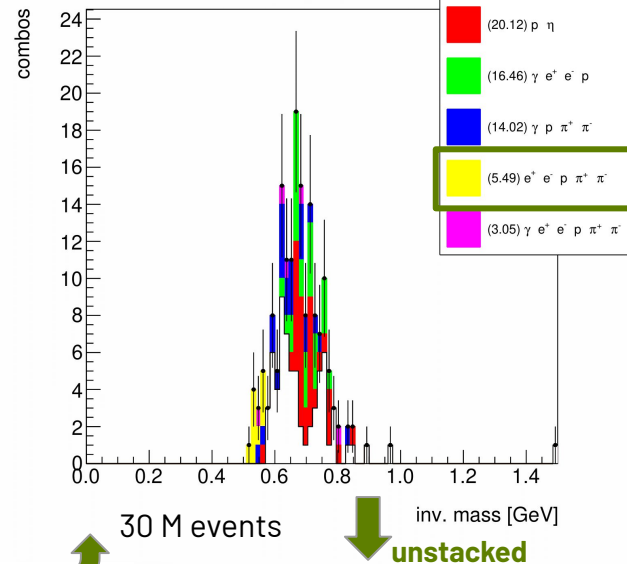
 $e^+ e^-$ mass [GeV]

Signal Generation

genEtaRegge + evtgen

 $e^+ e^- p \pi^+ \pi^-$

combos



30 M events

inv. mass [GeV]

unstacked

Invariant Mass Plots

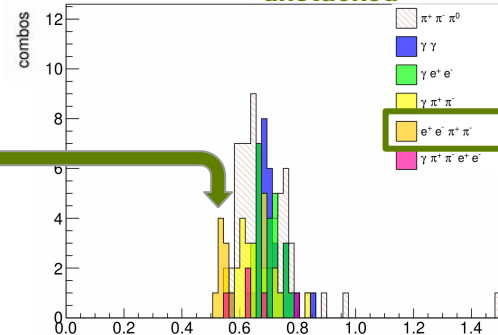
Simulation Settings:

Reaction: $\gamma + p \rightarrow \eta + p$ **Decay:** $\eta \rightarrow \pi^+ + \pi^- + e^+ + e^-$ Post Processing: **evtgen**

Analysis Cuts:

 χ^2 DOF < 10Best χ^2 (|IRFΔT|<2)Eliminating e^+e^- conversion events $M(e^+, e^-) > 0.19$ GeV

Signal almost completely isolated!

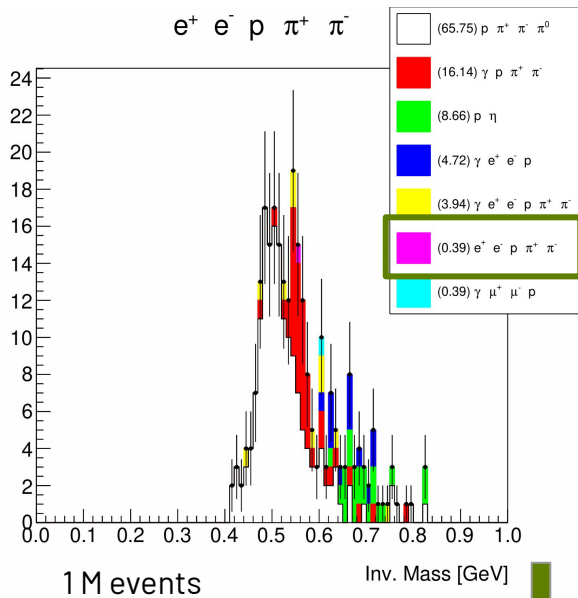


Signal Generation

genEtaRegge + evtgen

 $e^+ e^- p \pi^+ \pi^-$

Events

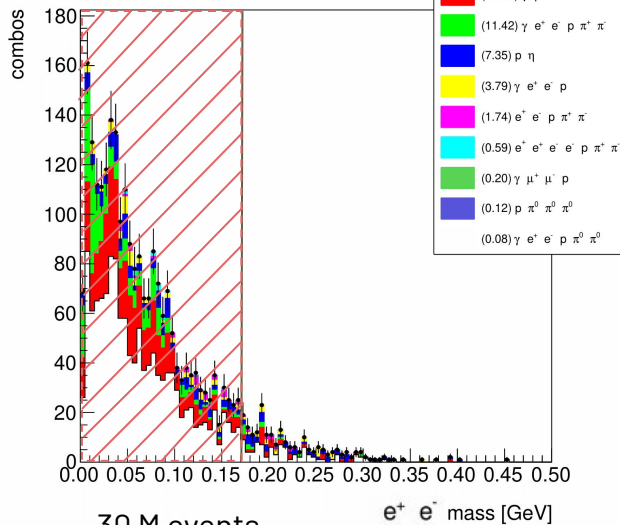


Signal Generation

genEtaRegge + evtgen

 $e^+ e^- p$

combos

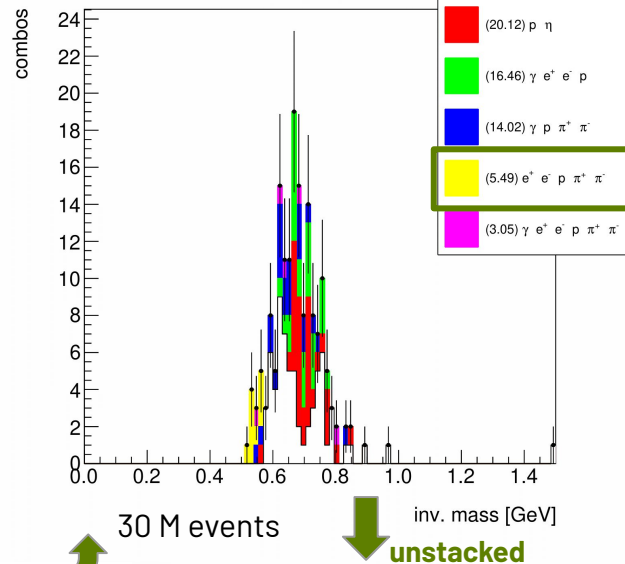


Signal Generation

genEtaRegge + evtgen

 $e^+ e^- p \pi^+ \pi^-$

combos



12

unstacked

Invariant Mass Plots

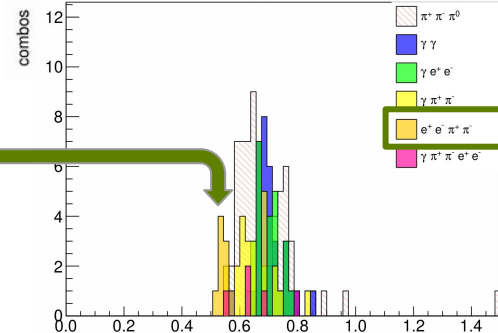
Simulation Settings:

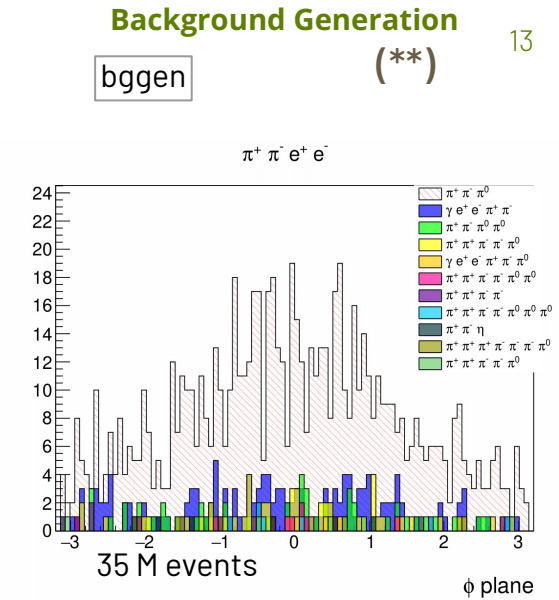
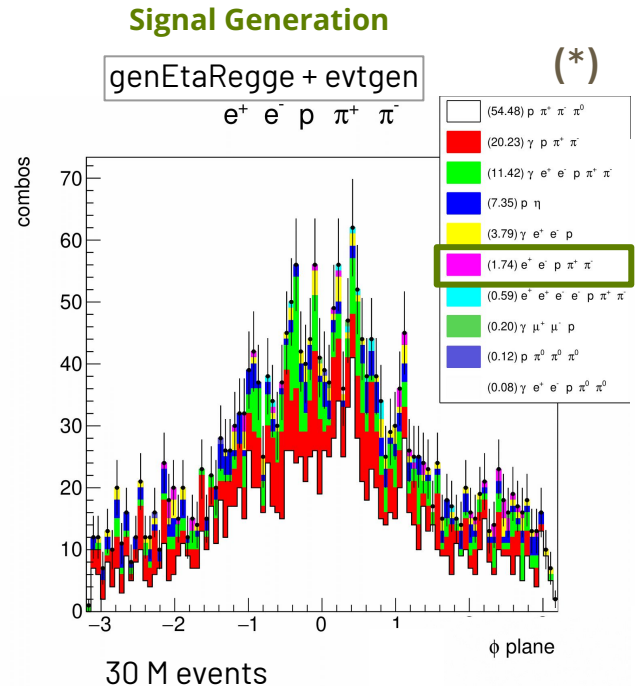
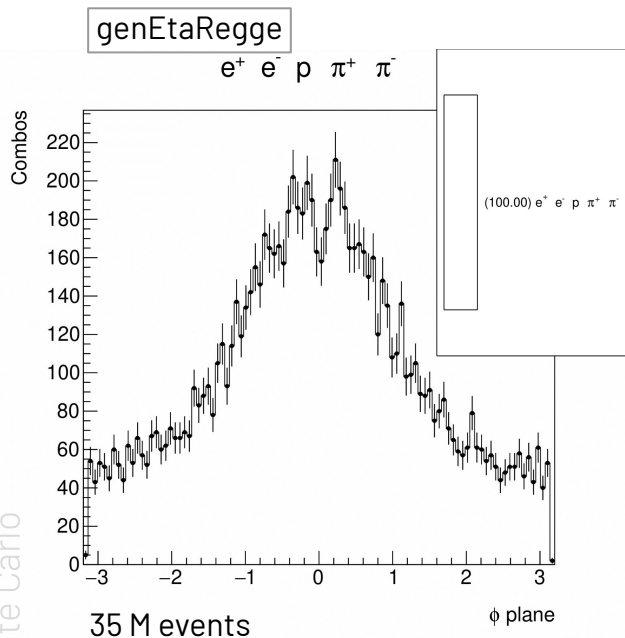
Reaction: $\gamma + p \rightarrow \eta + p$ **Decay:** $\eta \rightarrow \pi^+ + \pi^- + e^+ + e^-$ Post Processing: **evtgen**

Analysis Cuts:

 $\chi^2 \text{DOF} < 10$ Best χ^2 ($|\text{IRF}\Delta T| < 2$)Eliminating e^+e^- conversion events $M(e^+, e^-) > 0.19 \text{ GeV}$

Signal almost completely isolated!





Asymmetry Plots

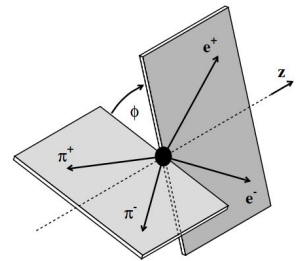
$$A_\phi = \frac{N_{\sin \phi \cos \phi > 0} - N_{\sin \phi \cos \phi < 0}}{N_{\sin \phi \cos \phi > 0} + N_{\sin \phi \cos \phi < 0}}$$

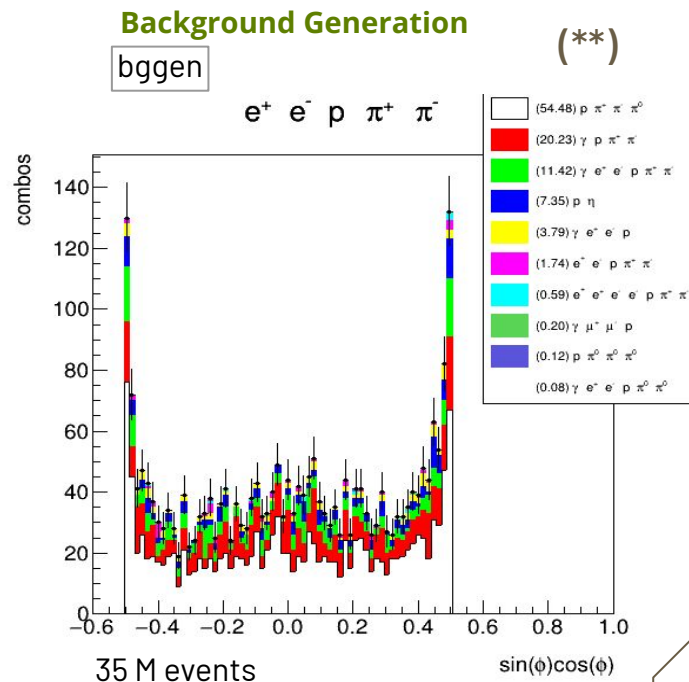
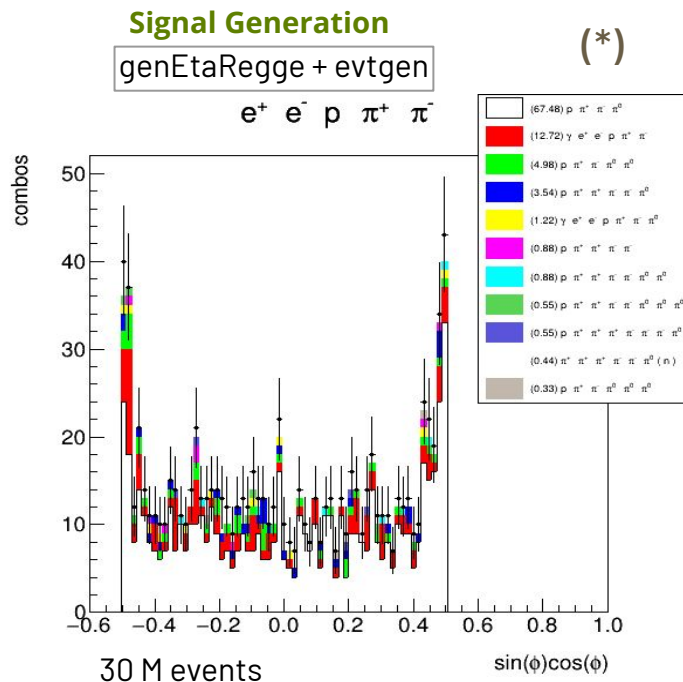
Simulation Settings:
Reaction: $\gamma + p \rightarrow \eta + p$
Decay: $\eta \rightarrow \pi^+ + \pi^- + e^+ + e^-$
 Post Processing: **evtgen**

Analysis Cuts:
 $\chi^2 \text{DOF} < 10$
 Best χ^2 ($|\text{IRF}\Delta T| < 2$)

(*) $\rightarrow A_\phi = (0.4 \pm 2.0 \text{ (stat.)}) \times 10^{-2}$

(**) $\rightarrow A_\phi = -0.06 \pm 0.03 \text{ (stat.)}$





Asymmetry Plots

Simulation Settings:

Reaction: $\gamma + p \rightarrow \eta + p$

Decay: $\eta \rightarrow \pi^+ + \pi^- + e^+ + e^-$

Post Processing: **evtgen**

Analysis Cuts:

χ^2 D0F < 10

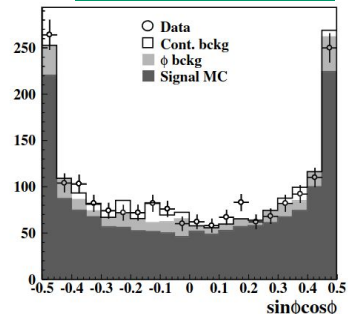
Best χ^2 (|IRFΔT|<2)

$$A_\phi = \frac{N_{\sin \phi \cos \phi > 0} - N_{\sin \phi \cos \phi < 0}}{N_{\sin \phi \cos \phi > 0} + N_{\sin \phi \cos \phi < 0}}$$

(*) $\rightarrow A_\phi = 0.05 \pm 0.02$ (stat.)

(**) $\rightarrow A_\phi = -0.02 \pm 0.03$ (stat.)

KLOE Collaboration



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

Conclusions

Signal and background plots give insight into future measurements in JEF

Rare decays simulated and analyzed

Cut evaluation done with two generators

JEF

Important feedback for ChPT and BSM physics

Significant reduction in the $3\pi^0$ background

Will be a very challenging channel to reconstruct

$\pi^0\gamma\gamma$

Possible BSM indications and input for TFFs

Signal almost completely isolated

Asymmetry Factor calculated and compared to KLOE

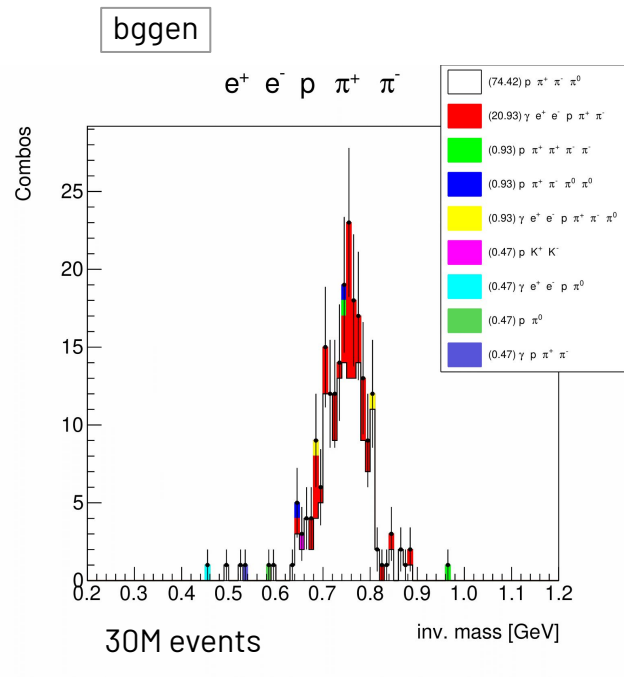
$\pi^+\pi^-e^+e^-$

Expected defense in June 2025

THANK YOU

REFERENCES

- [1] F. Ambrosino et. al. (KLOE Collaboration), Measurement of the branching ratio and search for a CP violating asymmetry in the $\eta \rightarrow \pi^+\pi^-e^+e^-(\gamma)$ decay at KLOE, *Physics Letters B*, 675, 283-288, 2009
- [2] G. Liping et. al., Precision tests of fundamental physics with η and η' mesons, *Physics Reports*, 945, 1-105, 2022
- [3] I. Neththikumara et al., Beam study on low dispersion CEBAF arcs, *WEPL055*, 3240-3243, 2023
- [4] H. Al Ghouli et al. (The GlueX Collaboration), First results from the GlueX experiment, *AIP Conf. Proc.* 1735, 020001, 2016
- [5] logbooks.jlab.org



Does not overlap
the signal!

Invariant Mass Plots

Simulation Settings:

Reaction: $\gamma + p \rightarrow \eta + p$

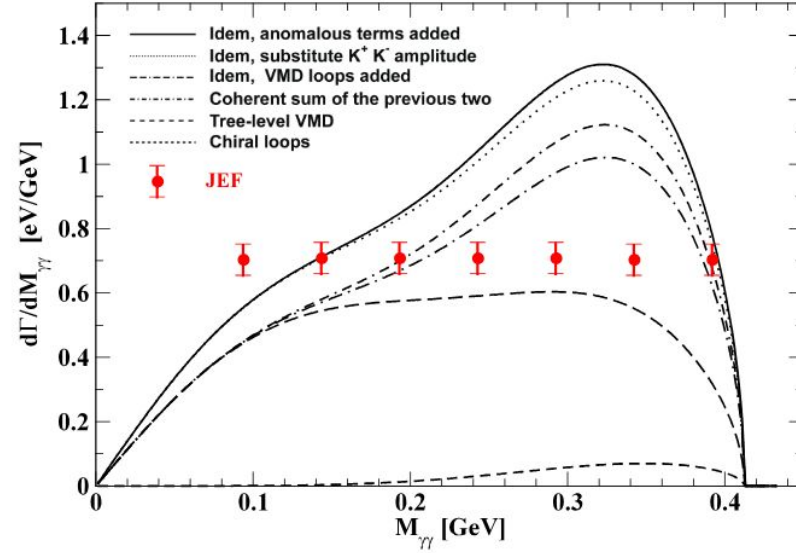
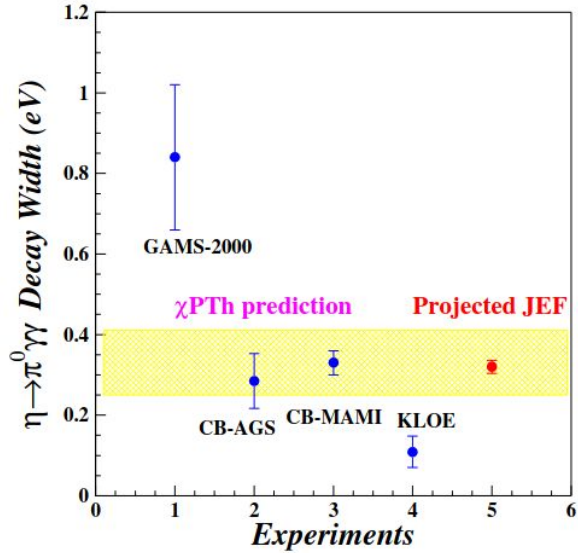
Decay: $\eta \rightarrow \pi^+ + \pi^- + e^+ + e^-$

Post Processing: **None**

Analysis Cuts:

$\chi^2 \text{DOF} < 10$

Best χ^2 ($|\text{IRFDeltaT}| < 2$)



[2]

Figure 34: *Left*: Experimental results on the decay width of $\eta \rightarrow \pi^0\gamma\gamma$ [521, 522, 525, 526]. The yellow band is $\Gamma = 0.33(8)$ eV from the unitarized- χ PT calculation of Refs. [510, 511]. The projected JEF measurement with a total error of 5% (in red) for 100 days of beam time is arbitrarily plotted at the CB-MAMI value [522]. *Right*: Predicted two-photon invariant mass distributions from $\eta \rightarrow \pi^0\gamma\gamma$ due to different mechanisms [510, 511] and the projected JEF measurement with 100 days of beam time. Figures reprinted from Ref. [89].

Decay channel	Standard Model	Discrete symmetries	Light BSM particles
$\eta \rightarrow \pi^+ \pi^- \pi^0$	light quark masses	C/CP violation	scalar bosons (also η')
$\eta^{(\prime)} \rightarrow \gamma\gamma$	η - η' mixing, precision partial widths		
$\eta^{(\prime)} \rightarrow \ell^+ \ell^- \gamma$	$(g - 2)_\mu$		Z' bosons, dark photon
$\eta \rightarrow \pi^0 \gamma\gamma$	higher-order χ PT, scalar dynamics		$U(1)_B$ boson, scalar bosons
$\eta^{(\prime)} \rightarrow \mu^+ \mu^-$	$(g - 2)_\mu$, precision tests	CP violation	
$\eta \rightarrow \pi^0 \ell^+ \ell^-$		C violation	scalar bosons
$\eta^{(\prime)} \rightarrow \pi^+ \pi^- \ell^+ \ell^-$	$(g - 2)_\mu$		ALPs, dark photon
$\eta^{(\prime)} \rightarrow \pi^0 \pi^0 \ell^+ \ell^-$		C violation	ALPs

Table 12: Summary of high-priority $\eta^{(\prime)}$ decays with emphasis on synergies across Standard Model and BSM investigations.

JEF for 100 days of beam:

	η	η'
Tagged mesons	6.5×10^7	4.9×10^7

Previous Experiments:

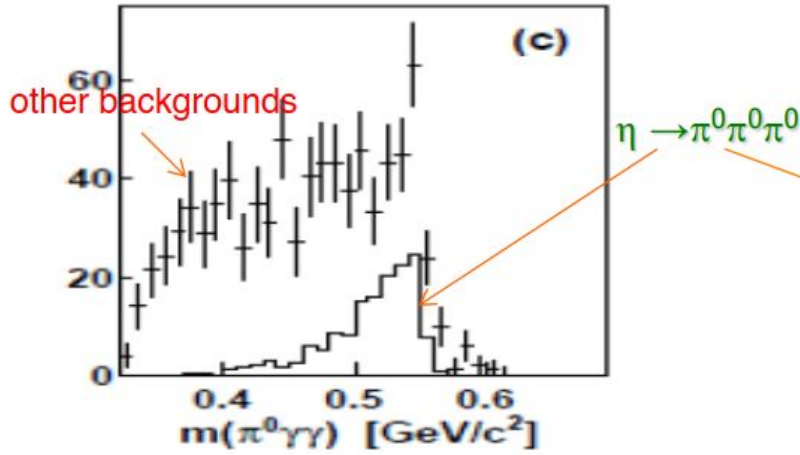
Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	10^6
WASA-COSY	$\sim 3 \times 10^7$ (p+d), $\sim 5 \times 10^8$ (p+p)	-
KLOE-II	3×10^8	5×10^5
BESIII	$\sim 10^7$	$\sim 5 \times 10^7$

[2]

+ Two orders of magnitude background suppression

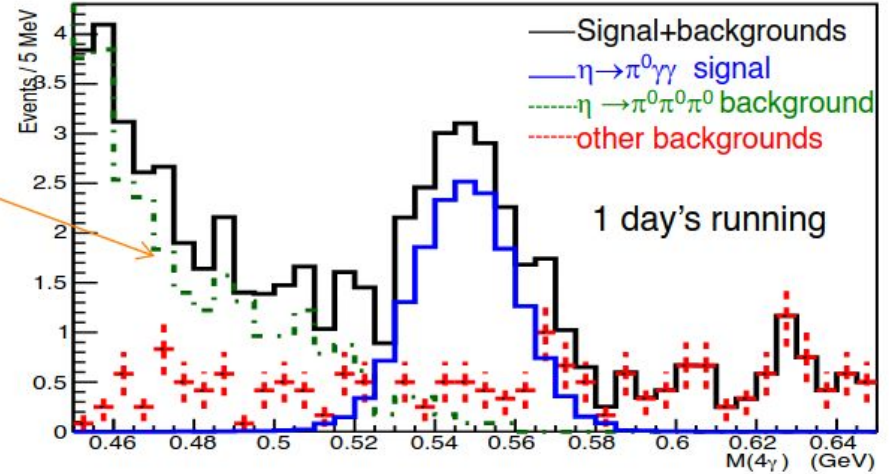
A2 at MAMI: $\gamma p \rightarrow \eta p$ ($E_\gamma = 1.5$ GeV)

(P.R. C90, 025206)



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

$N(\text{PWO}) > 2$



Uniqueness of JEF

- η/η' energy boost
- FCAL-II
- Exclusive detections
- High statistics due to running in parallel with GlueX
- The only facility can simultaneously produce tagged η and η' with similar rates

$$\sin(\phi) = \frac{\mathbf{P}_2 \cdot (\mathbf{n}_1 \times \mathbf{n}_2)}{|\mathbf{n}_1| |\mathbf{n}_2|}$$

$$\sin(\phi) \cos(\phi) = \frac{(\mathbf{P}_2 \cdot (\mathbf{n}_1 \times \mathbf{n}_2))(\mathbf{n}_1 \cdot \mathbf{n}_2)}{|\mathbf{n}_1|^2 |\mathbf{n}_2|^2}$$

$$\phi = \tan^{-1} \left(\frac{\mathbf{P}_2 \cdot (\mathbf{n}_1 \times \mathbf{n}_2)}{\mathbf{n}_1 \cdot \mathbf{n}_2} \right)$$

ϕ plane equations