
Rare η Decay Signal and Background Generation for JEF
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WNPPC 2025
NSERC CRSNG
University of Regina
JEF D

AGENDA

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**

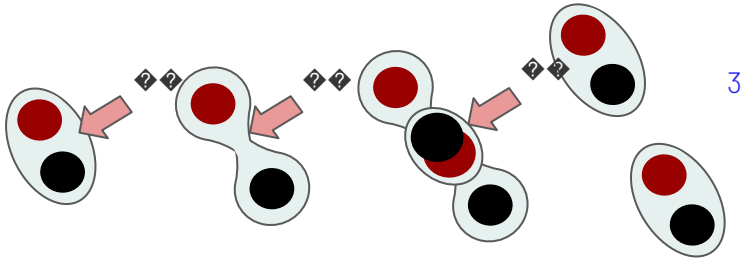
$\pi^0\gamma\gamma$ Signal and Background removal
$\pi^+\pi^-e^+e^-$ Signal and Background removal
Asymmetry Factor

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

- The ground state denotes the formation of a meson, while excited states correspond to hybrid mesons
- SU(3):

$$\eta_1 = \frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right) \qquad \eta_8 = \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

- Great! We can just calculate everything we need to know...
- Chiral perturbation theory

Richness of η SM Physics

The nature of QCD confinement still poses challenges in the process of fully understanding the aspects of the SM

CHIRAL PERTURBATION THEORY (ChPT)

- Effective field theories → significant step towards computing scattering amplitudes
- $SU(N_f)_L \times SU(N_f)_R$
- Constraints studied in detail up to $O(p^6)$
- Compared to LQCD
- **Strong precision test for non-perturbative QCD**

$\pi^0\gamma\gamma$

TRANSITION FORM FACTORS (TFFs)

$$\mathcal{M}(\eta \to \gamma^*(q_1)\gamma^*(q_2)) = -ie^2\epsilon_{\mu\nu\alpha\beta}q_1^\mu q_2^\nu \varepsilon_1^\alpha \varepsilon_2^\beta F_{\eta^{(\prime)}\gamma^*\gamma^*}(q_1^2, q_2^2)$$

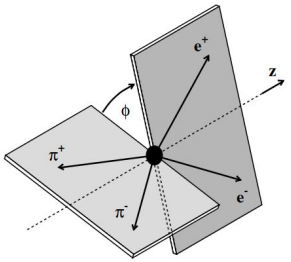
- Electromagnetic transition form factors $F_{\eta^{(\prime)}\gamma^*\gamma^*}$
- **Quark and gluon structure**
- **Anomalous magnetic moment of the muon $(g-2)_\mu$**
- Measure experimentally with low systematic uncertainty

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

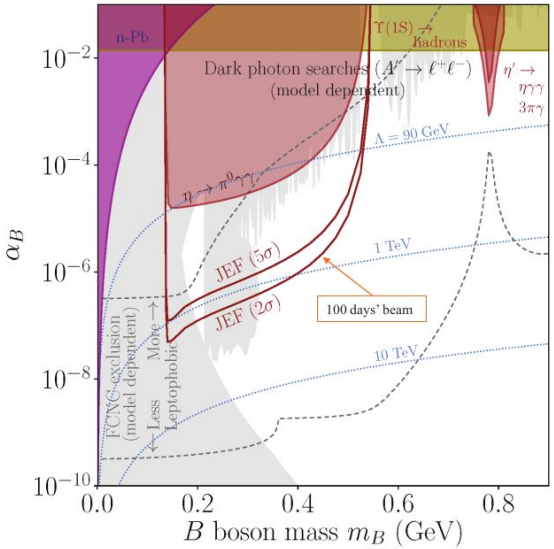
DISCRETE SYMMETRIES

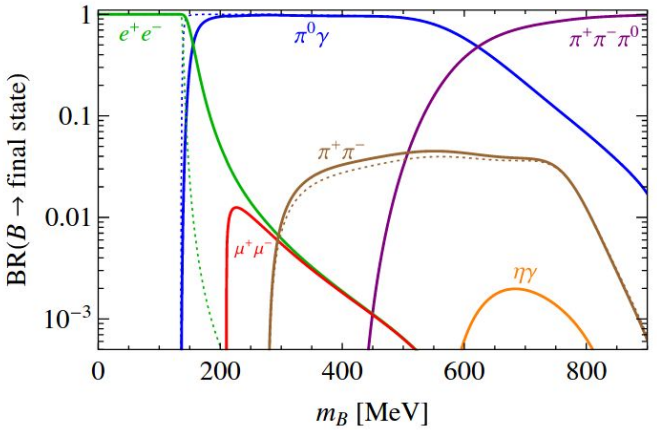
- ***P*** and ***CP*** are violated, while ***C*** is conserved
- Asymmetry factor defined by the pion and lepton decay planes
- Highly suppressed within the SM

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



[1]

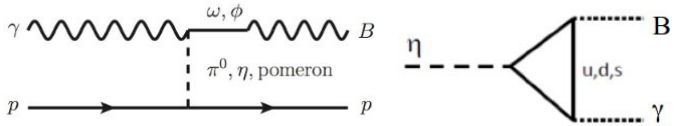




[2]

BSM η Physics

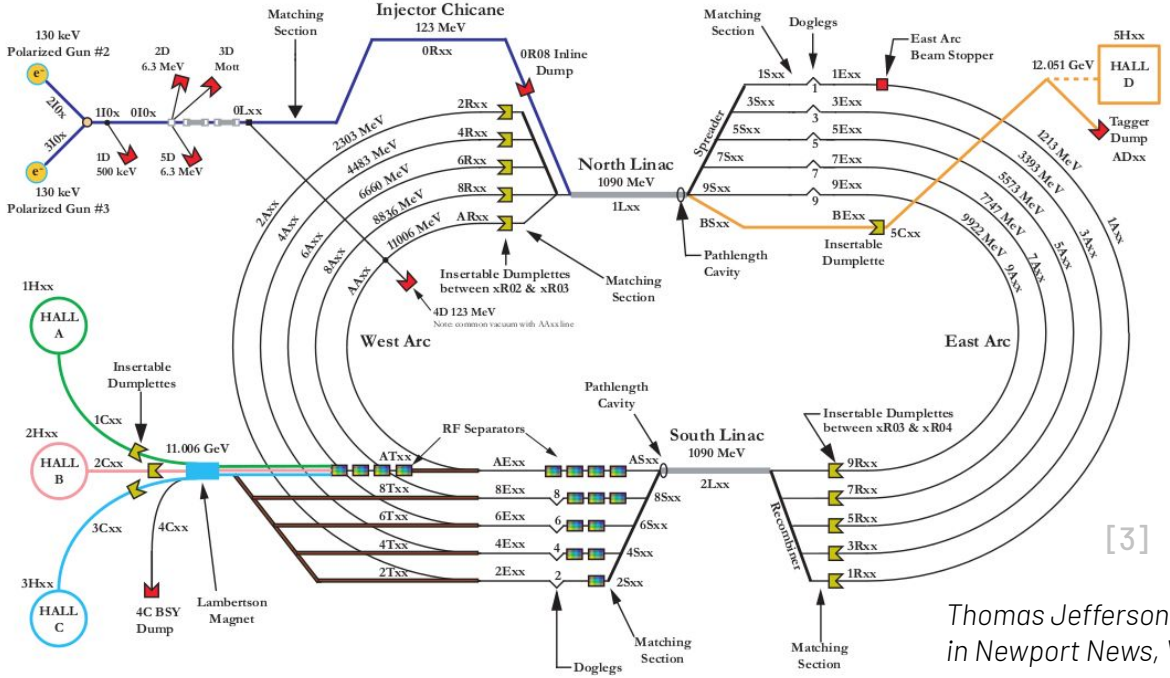
$$\mathcal{L}_{INT} = (\frac{1}{3}g_B + \epsilon Q_q e)\bar{q}\gamma^\mu q B_\mu - \epsilon e \bar{l}\gamma^\mu l B_\mu$$



JEF Experiment Goals		
Channel	**Branching Ratio**	**Physics of Interest**
$\gamma + B$	BSM	leptophobic vector boson
$\pi^0 + \phi'$	BSM	electrophobic scalar boson
$\pi^0\gamma\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	ChPTB at $\mathcal{O}(p^6)$
$\pi^0\pi^0\pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$
$\pi^+\pi^-\pi^0$	$(22.7 \pm 0.3)\%$	$m_u - m_d$, C violation sector
$\gamma\gamma\gamma$	$< 1.6 \times 10^{-5}$	C violation sector, C and P violation sector

- Various models → **connection with SM physics** -> massive resonances that decay almost instantly into SM final-states
- Large SM backgrounds
- Interesting model: New force introduced, mediated by ``dark photons" ⇆ weakly interact with SM photons through electrically charged particles
- Gauge boson that decays leptonically
- Gauge ***B***-boson which interacts with SM quarks and arises from a redefined ***U(1)*** $_B$ gauge symmetry
- $\pi^0\gamma\gamma$ **measurable link** between DM and the SM: $\eta \to B\gamma \to \pi^0\gamma\gamma$

The GlueX Experiment and Experimental Hall D

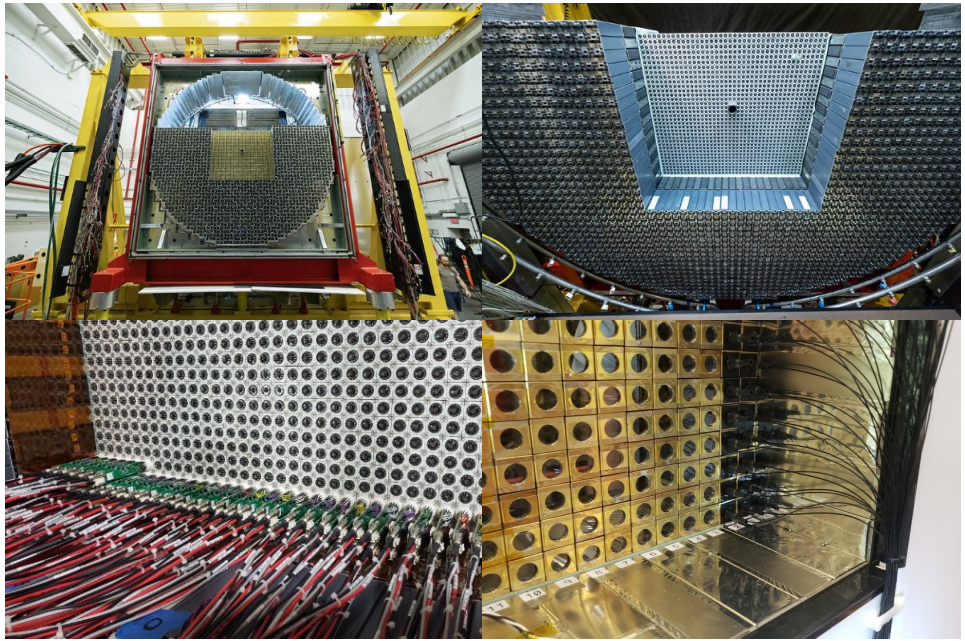


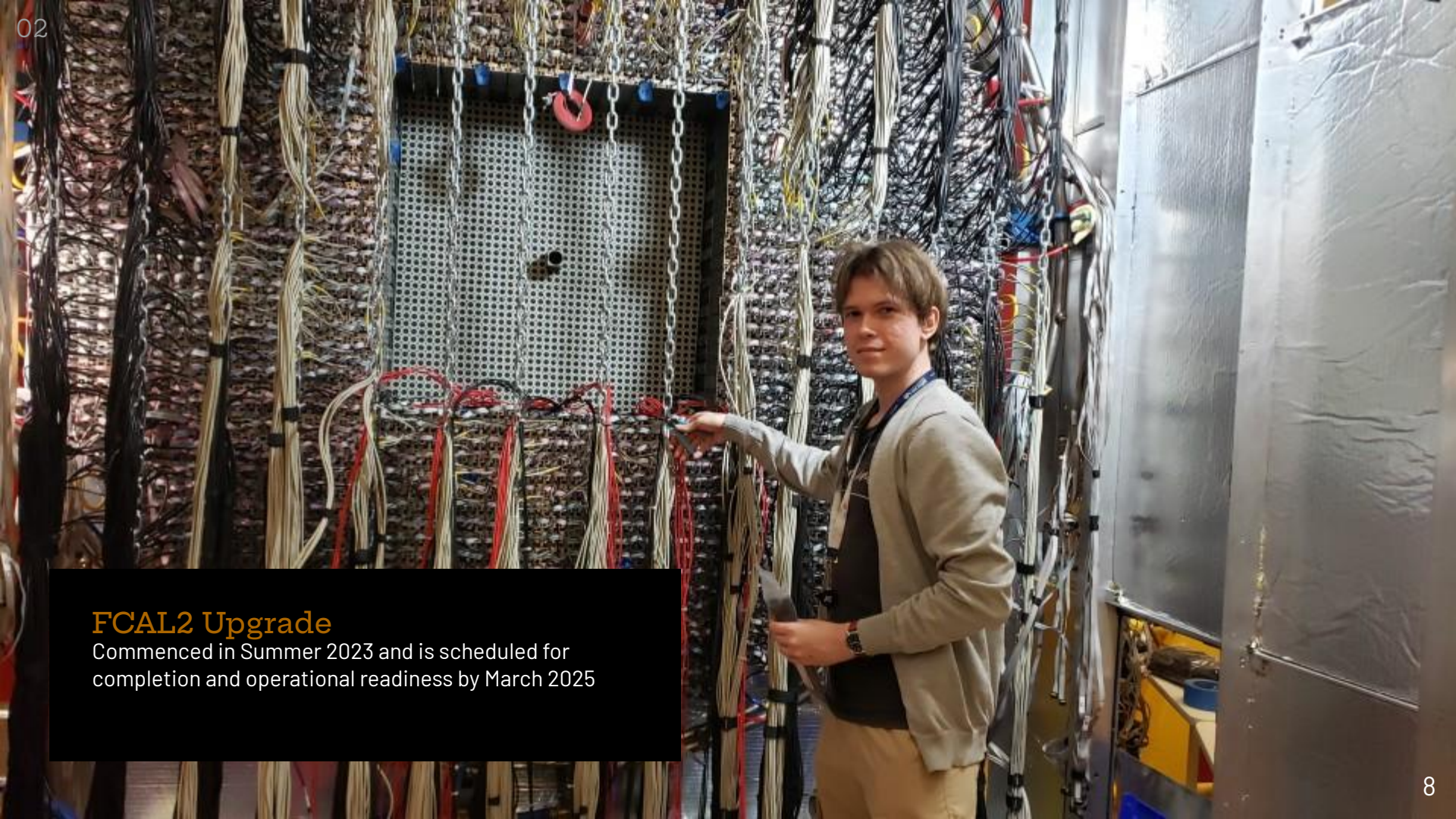
[3]

Thomas Jefferson National Accelerator Facility in Newport News, Virginia

Jefferson η Factory (JEF) and the Forward Calorimeter

- Photoproduction → sample of η and η' with statistical precision comparable to or surpassing that of other facilities worldwide
- Cherenkov light
- Reconstruction four-momenta → timing information, energy, and shower position
- Energy resolution: $5.6\%/\sqrt{E[GeV]}+3.6\%$
- Positional resolution: $6.4mm/\sqrt{E[GeV]}$
- 2,800 ``blocks" containing FEU 84-3 PMTs
- FCAL2 upgrade → **smaller, higher-resolution lead tungstate modules**
- *$PbWO_4$* scintillating material connected to a Hamamatsu PMT 4125

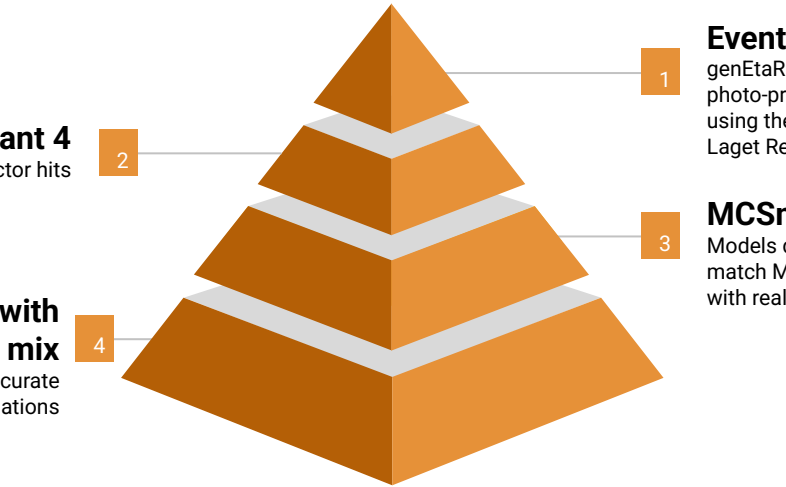




FCAL2 Upgrade

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

Monte Carlo Simulations

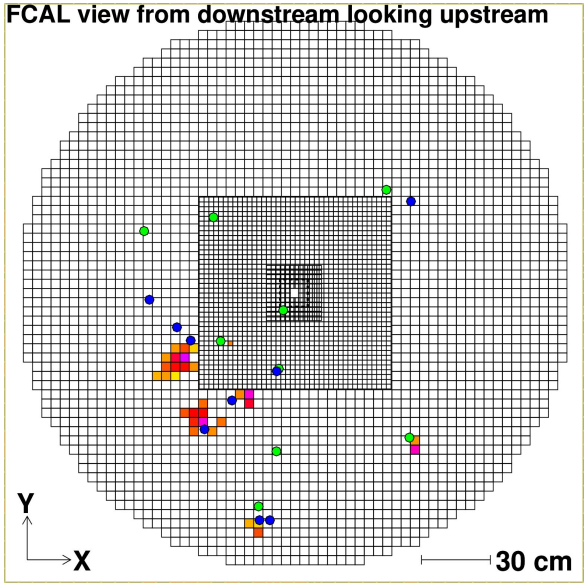


Event Generators
genEtaRegge - generates η photo-production events using the Laget Regge model

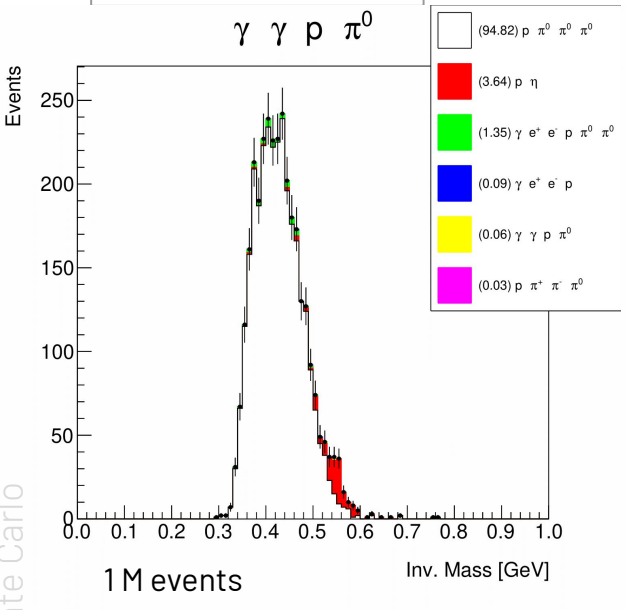
HDGeant 4
Detector hits

MCSmear
Models detector resolution to match MC simulated results with real data

Data with simulations mix
Even more accurate simulations

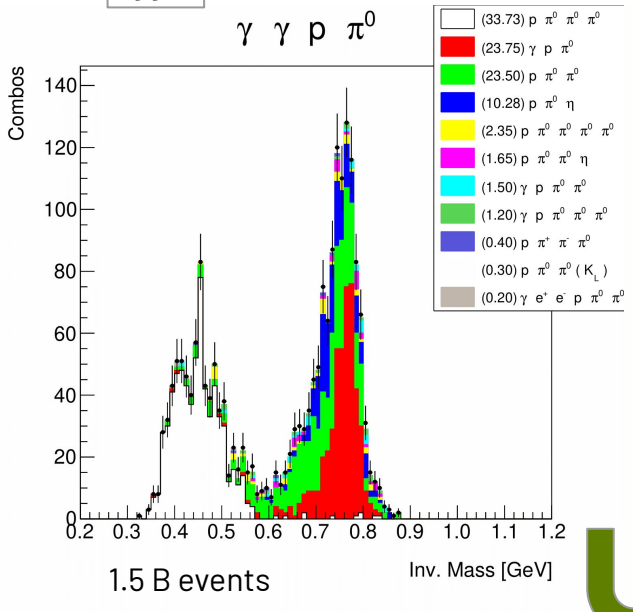


genEtaRegge + evtgen



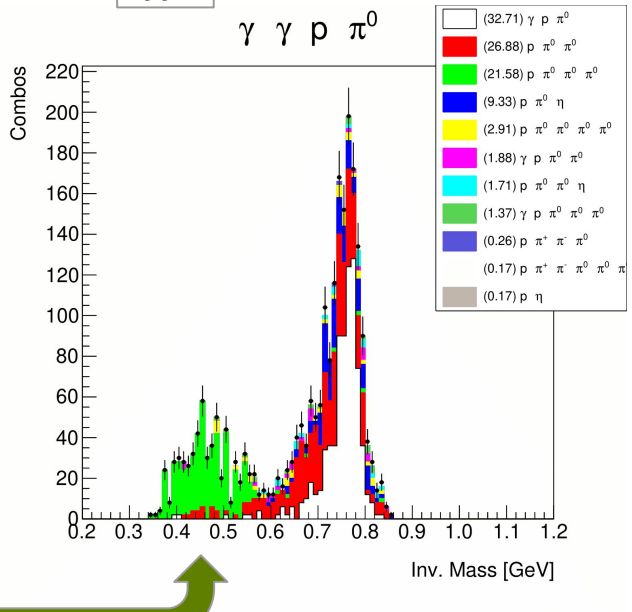
1 M events

bggen



1.5 B events

bggen



Background removal

$|(m(\gamma,\gamma[\text{decay}])-0.135|>0.015$

Invariant Mass Plots

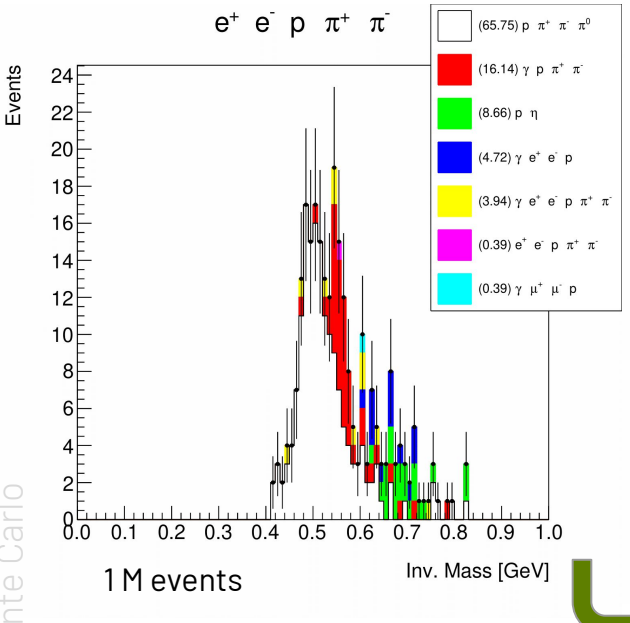
Simulation Settings:
Reaction: $\gamma + p \rightarrow \eta + p$
Decay: $\eta \rightarrow \gamma + \gamma + \pi^0$
Post Processing: **evtgen**

Analysis Cuts:
χ^2DOF < 10
Best χ^2 (|RFDeltaT|<2)

Reduction in the $3\pi^0$ background

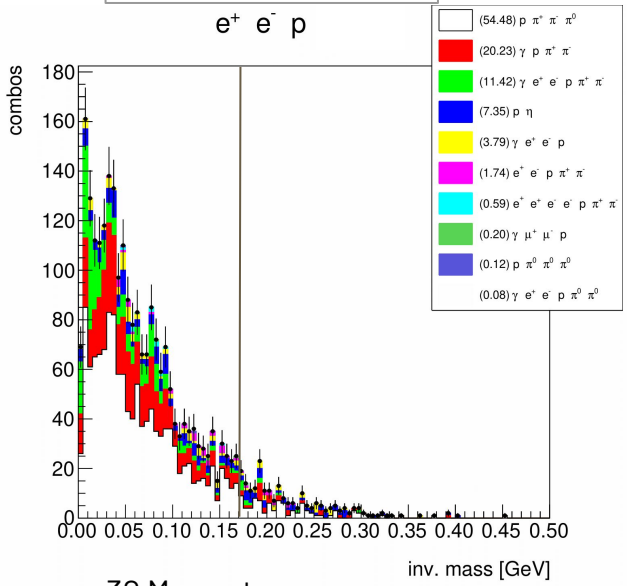
Newly Generated Monte Carlo

genEtaRegge + evtgen



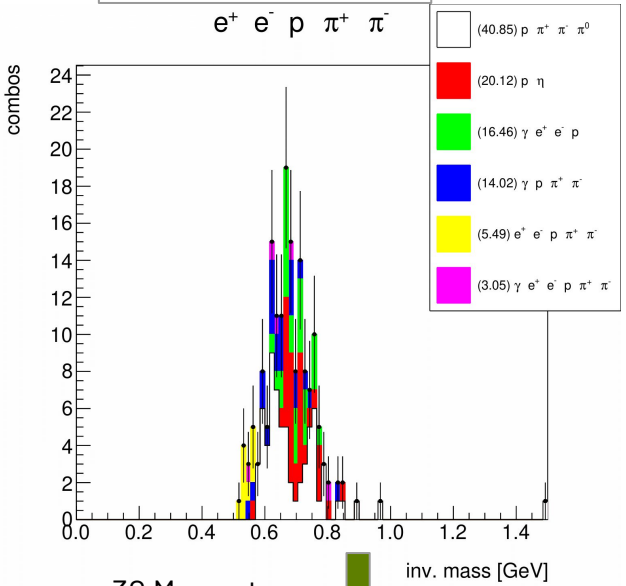
1 M events

genEtaRegge + evtgen

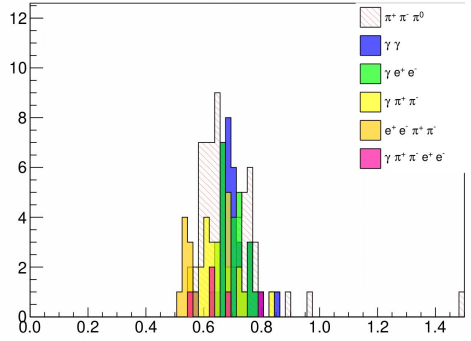


30 M events

genEtaRegge + evtgen



30 M events



Invariant Mass Plots

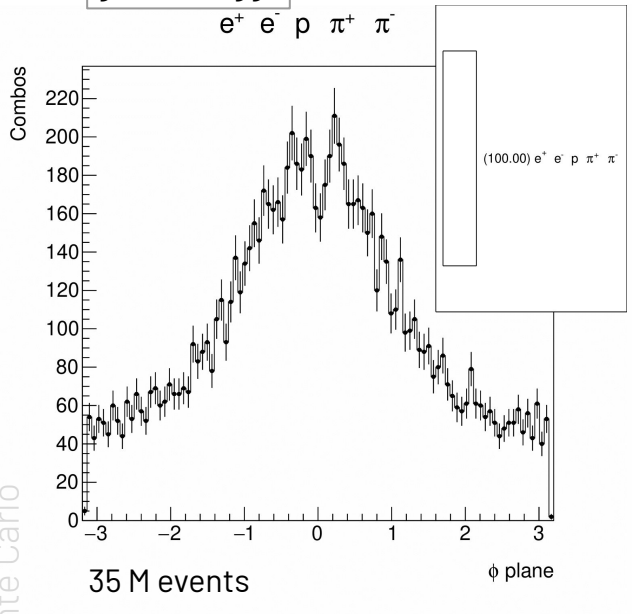
Simulation Settings:
Reaction: $\gamma + p \rightarrow \eta + p$
Decay: $\eta \rightarrow \pi^+ + \pi^- + e^+ + e^-$
Post Processing: **evtgen**

Analysis Cuts:
χ^2DOF < 10
Best χ^2 (|RFDeltaT|<2)

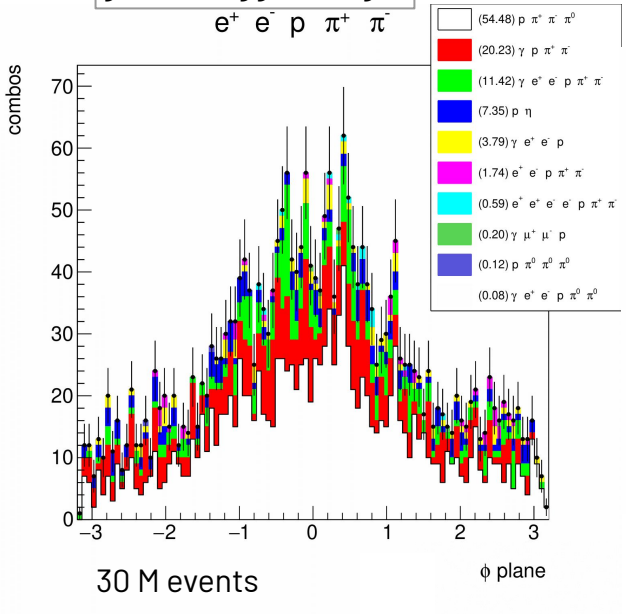
Eliminating e+e- conversion events
$M(e^+, e^-) > 0.19$ GeV

Signal almost completely isolated!

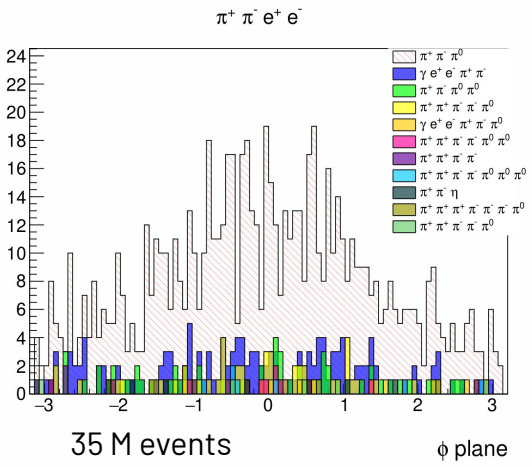
genEtaRegge



genEtaRegge + evtgen (*)



bggen (**)



Asymmetry Plots

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

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

Analysis Cuts:
χ^2DOF < 10
Best χ^2

(*) $\rightarrow$ Aφ = (0.4 +/- 2.0 (stat.)) x 10^{-2}

(**) $\rightarrow$ Aφ = −0.06 +/- 0.03 (stat.)

KLOE Collaboration

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

Newly Generated Monte Carlo

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

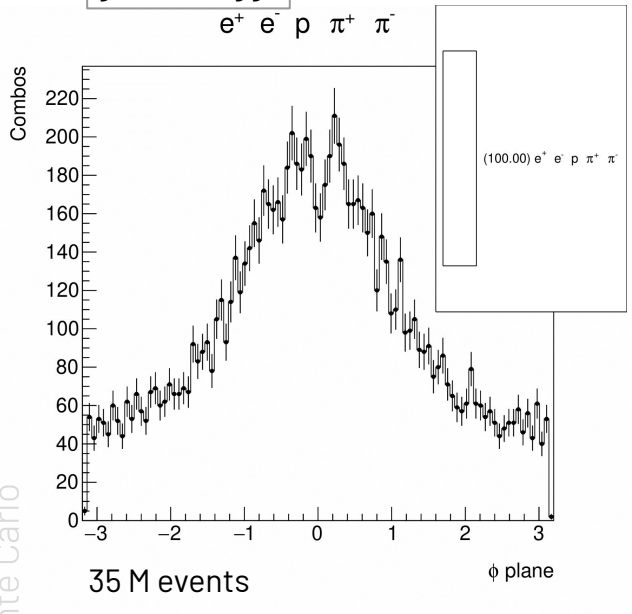
[1] F. Ambrosino et. al. (KLOE Collaboration), Measurement of the branching ratio and search for a CP violating asymmetry in the η→π+π−e+e−(γ) decay at KLOE, Physics Letters B, 675, 283-288, 2009

[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

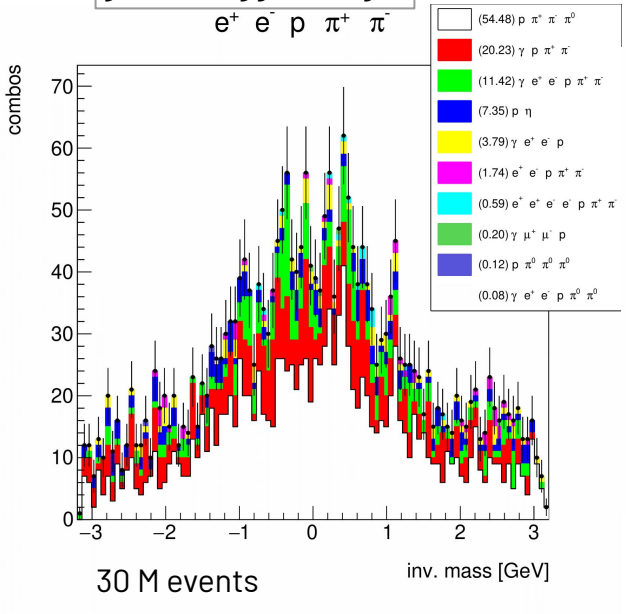
[4] logbooks.jlab.org

genEtaRegge



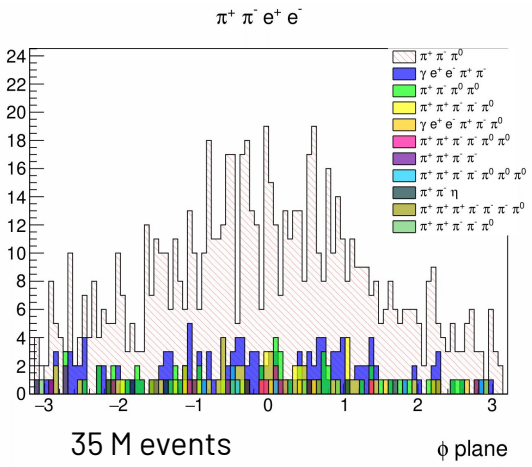
35 M events

genEtaRegge + evtgen (*)



30 M events

bggen (**)



35 M events

Asymmetry Plots

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

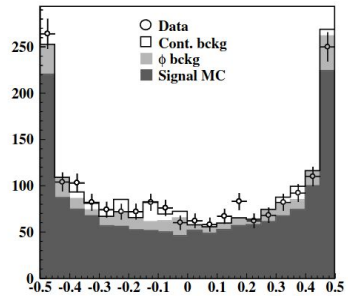
Analysis Cuts:
χ^2DOF < 10
Best χ^2

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

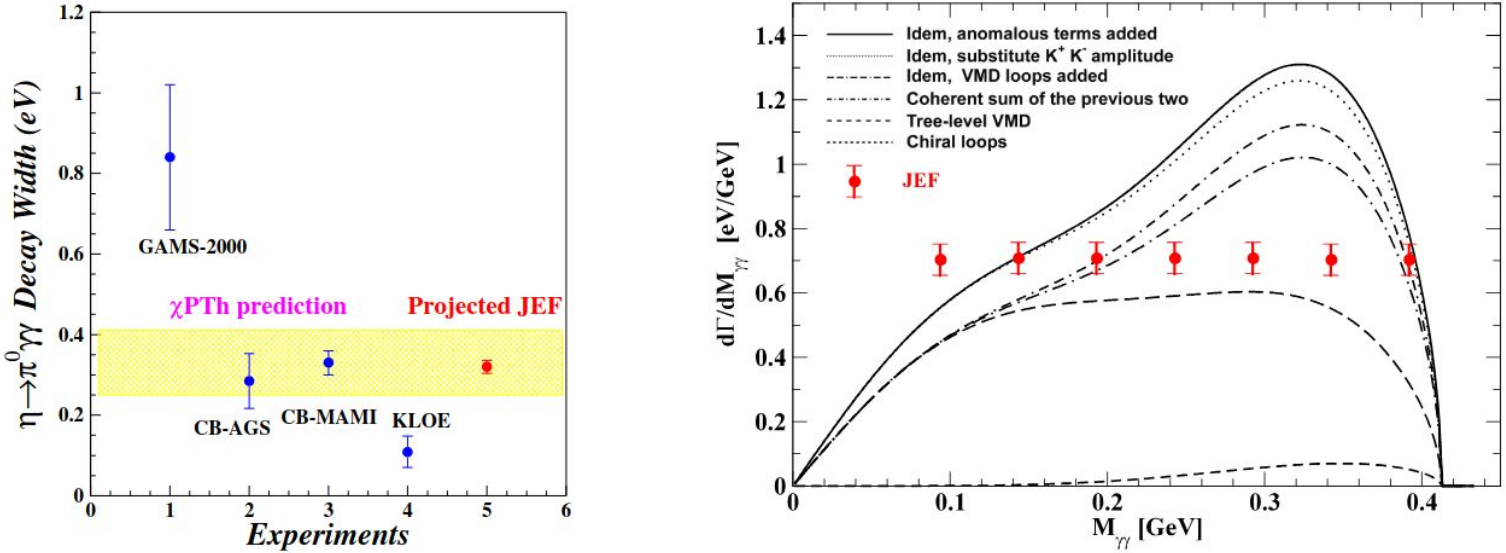
(*) ⟶ Aφ = (0.4 +/- 2.0 (stat.)) x 10^{-2}

(**) ⟶ Aφ = −0.06 +/- 0.03 (stat.)

KLOE Collaboration



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



[2]

Figure 34: *Left:* Experimental results on the decay width of $\eta \to \pi^0\gamma\gamma$ [521, 522, 525, 526]. The yellow band is $\Gamma = 0.33(8)$ eV from the unitarized-χPT 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 $\eta \to \pi^0\gamma\gamma$ 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
$\eta \to \pi^+\pi^-\pi^0$	light quark masses	C/CP violation	scalar bosons (also η')
$\eta^{(\prime)} \to \gamma\gamma$	η–η' mixing, precision partial widths		
$\eta^{(\prime)} \to \ell^+\ell^-\gamma$	$(g-2)_\mu$		Z' bosons, dark photon
$\eta \to \pi^0\gamma\gamma$	higher-order χPT, scalar dynamics		$U(1)_B$ boson, scalar bosons
$\eta^{(\prime)} \to \mu^+\mu^-$	$(g-2)_\mu$, precision tests	CP violation	
$\eta \to \pi^0\ell^+\ell^-$		C violation	scalar bosons
$\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$	$(g-2)_\mu$		ALPs, dark photon
$\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$		C violation	ALPs

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

[2]