Rare η and η' Decay Program at Hall D / Jefferson Lab

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On Behalf of the GlueX Collaboration

University of Regina [1]

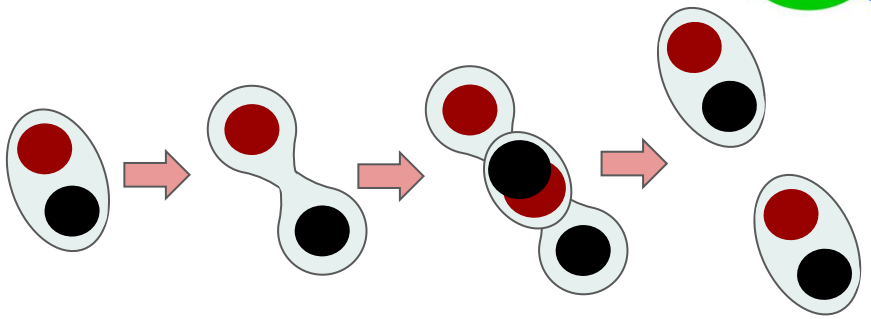
Jefferson Lab
Exploring the Nature of Matter [2]

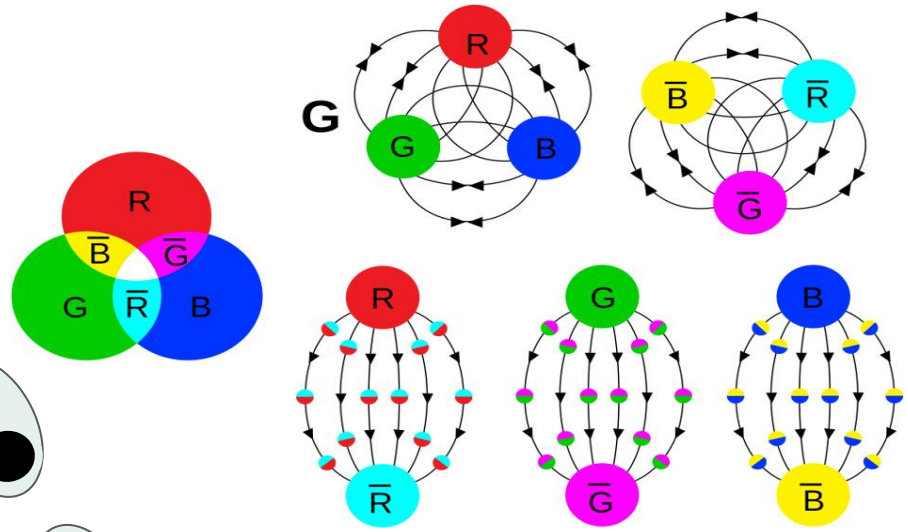
Quantum Chromodynamics (QCD)

Properties
- Color confinement
- Asymptotic freedom
- Chiral symmetry breaking

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

Use Mesons
- Ground states → mesons
- Excited states → hybrid mesons
- Chiral perturbation theory





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

Richness of η Standard Model Physics

The nature of QCD confinement poses challenges in SM

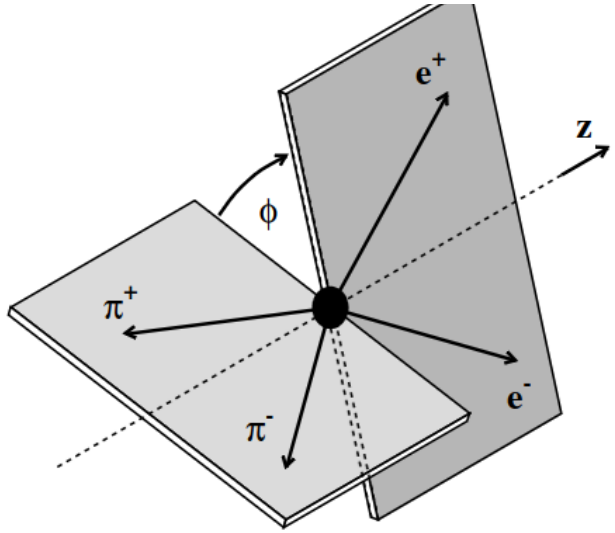
$$\mathcal{A}_\phi = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}}$$

TRANSITION FORM FACTORS (TFFs)

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

DISCRETE SYMMETRIES

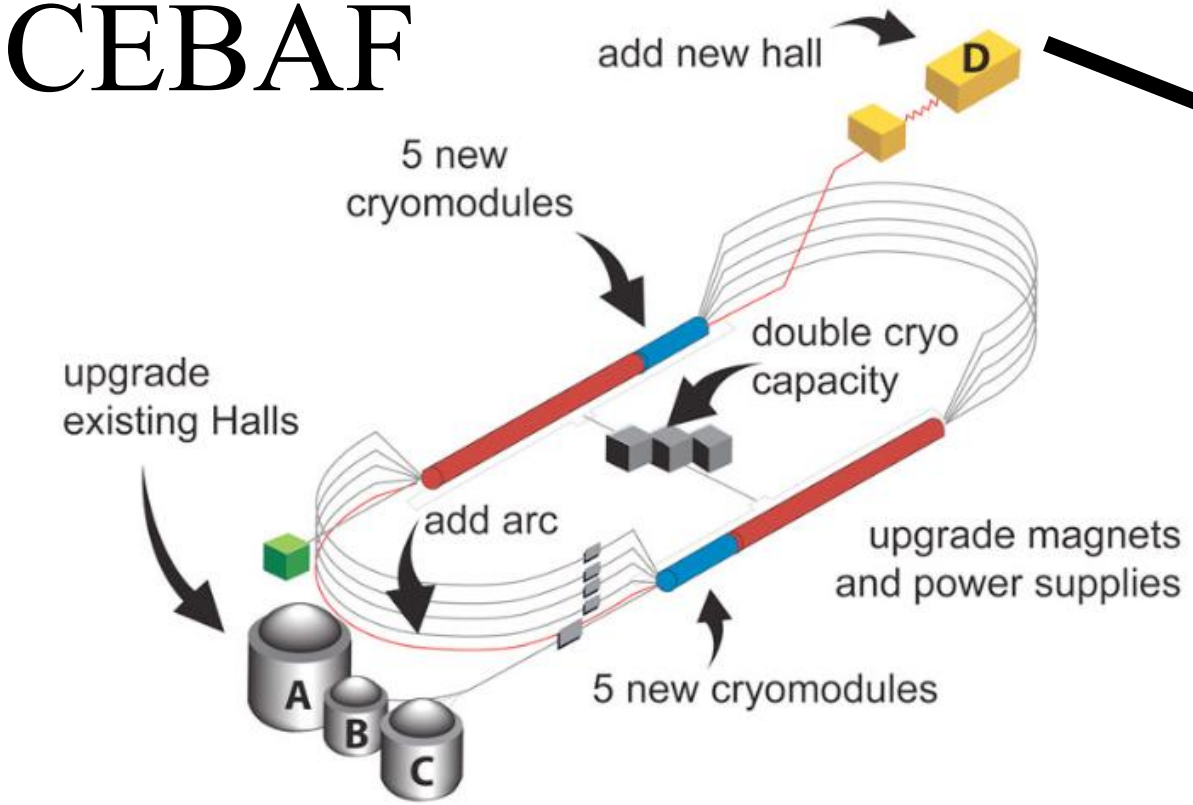
- ***P*** and ***CP*** are violated, while ***C*** is conserved
- (i) CP-violating dynamics in strong interactions
- (ii) CP-violating dynamics in quark-lepton interactions

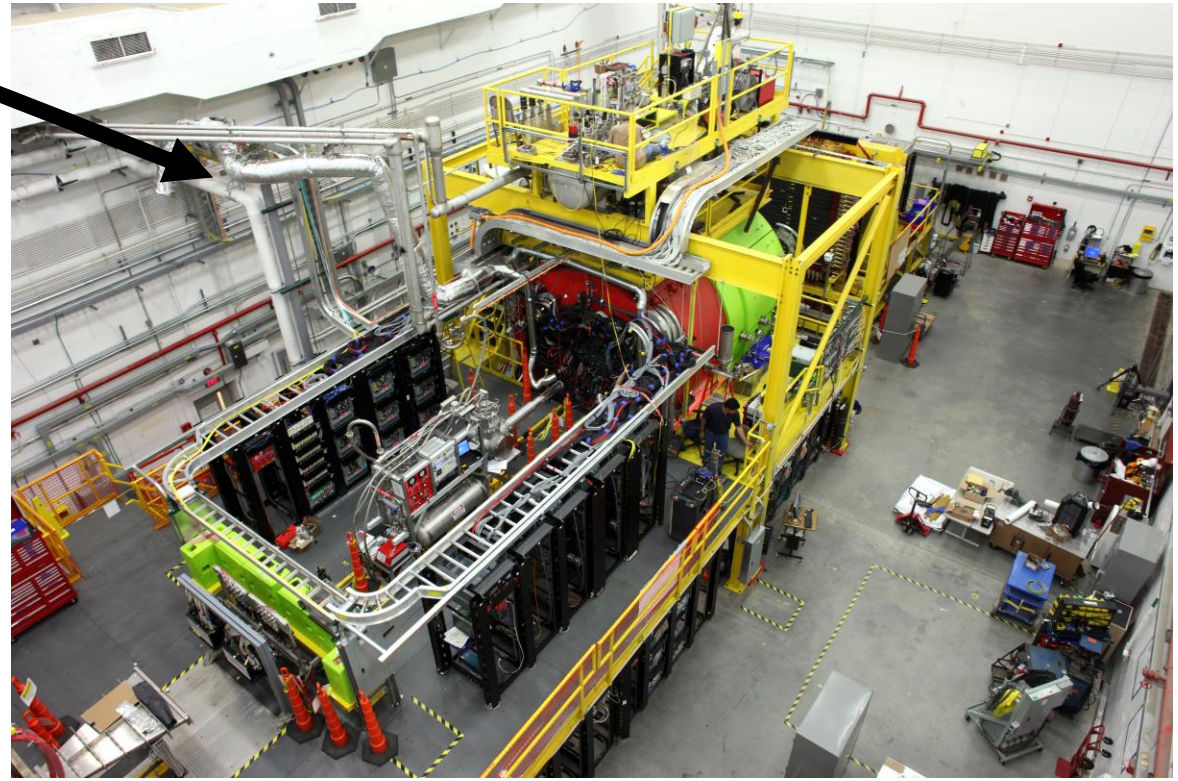


[1]

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

The GlueX Experiment and Experimental Hall D





Electron Accelerator 12 GeV

Feeds Four Halls Simultaneously

Key Features of Jefferson η Factory (JEF)

- η/η’ production: 8.4-11.7 GeV tagged γ beam; η, η’ energy boost
- produce & detect η/η’ simultaneously; rare exclusive channels:

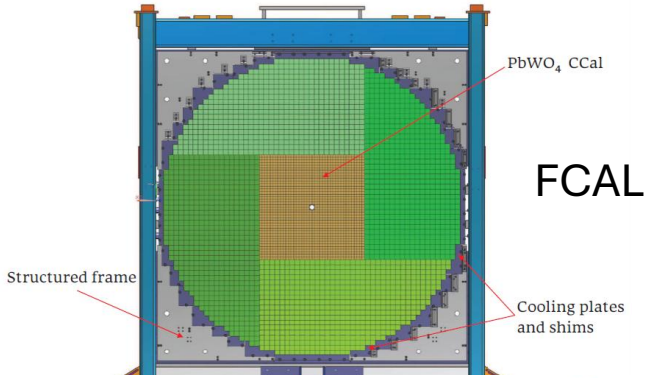
$$\gamma p \rightarrow p(\eta/\eta')$$
$$\eta/\eta' \rightarrow \gamma\gamma, \pi^0\gamma\gamma \ldots$$

- Reduce non-coplanar backgrounds by detecting recoil protons

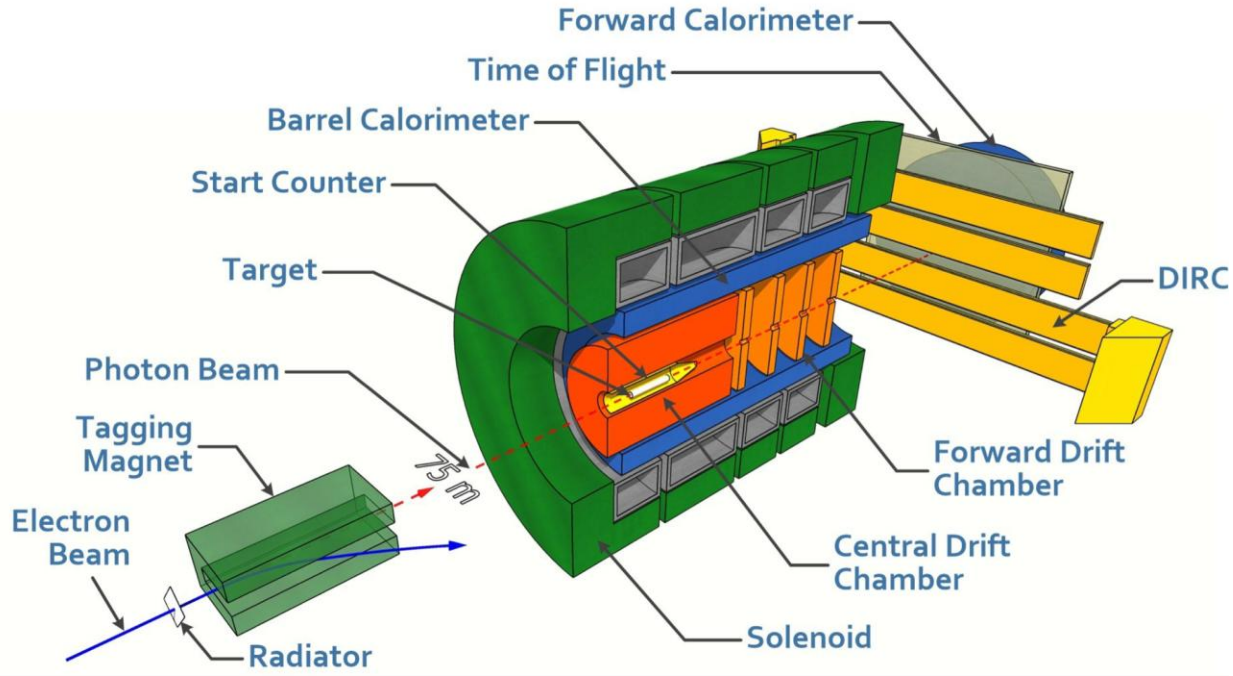
This Talk:

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

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



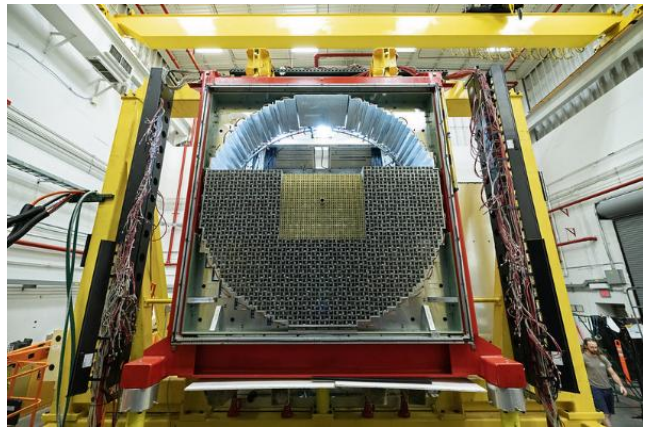
FCAL 2 Design



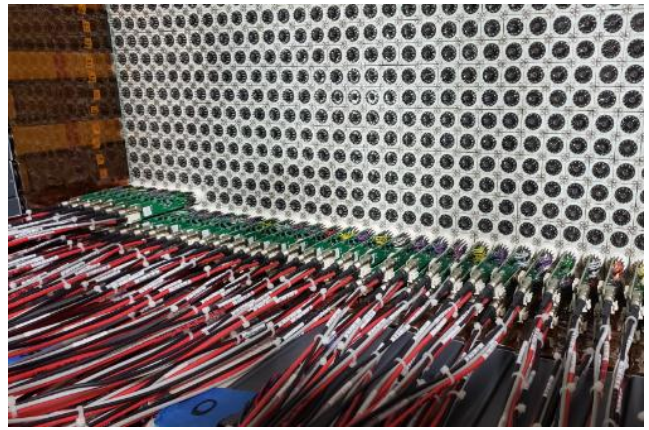
JEF and the Forward Calorimeter

- Photoproduction → η and η'
- Reconstruction four-momenta
- Kept 2400 Lead glass blocks + FEU 84-3 PMTs

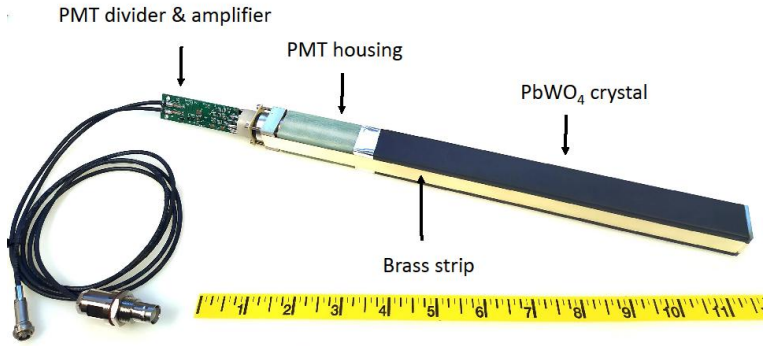
- FCAL2 upgrade
  ->Smaller, radiation-resistant, higher-resolution lead tungstate modules
  ->1600 Lead Tungstate scintillating material + Hamamatsu PMT 4125



Detector Stacking



Fiber light monitoring system



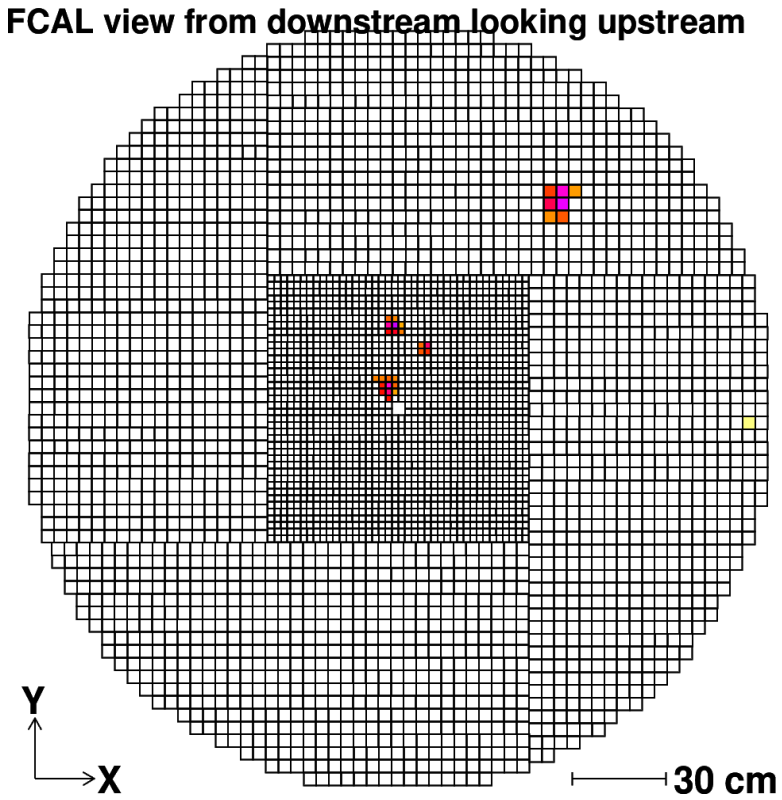
Detector Assembly

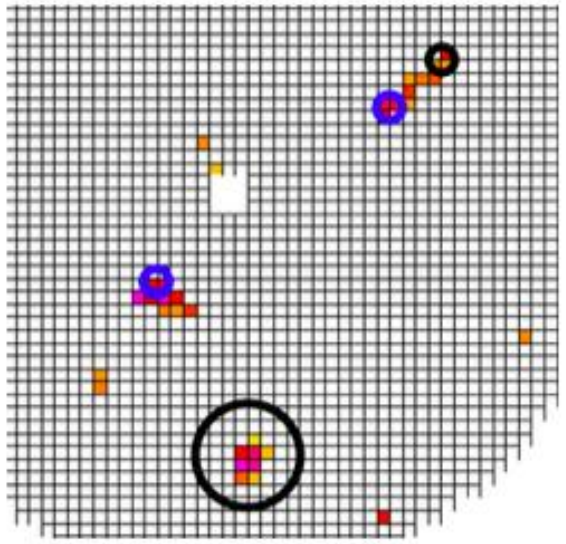
Monte Carlo Simulations

MCWrapper

- Event Generation
- Simulated Detector Hits
- Data Smearing

Explicit physics symmetry not included





We Observe Photon Shower Patterns

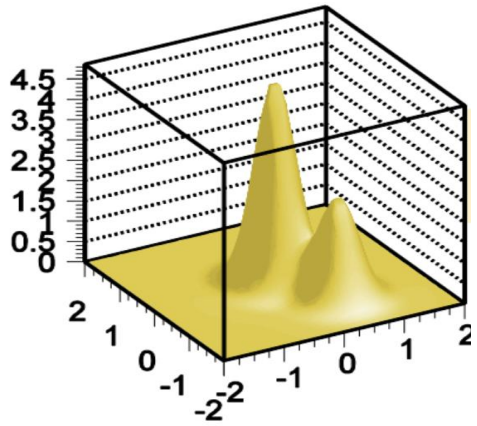
Photon Separation

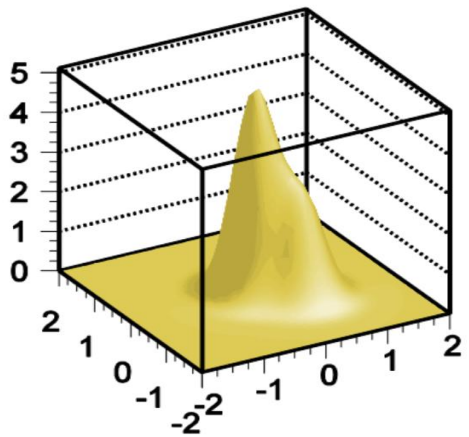
Clusterizer & Reconstruction:

- Default Algorithm adapted from RADPHI (NIM A 570 (2007) 384–398)
- Island Algorithm adapted from GAMS (A. A. Lednev, IHEP preprint 93-153)

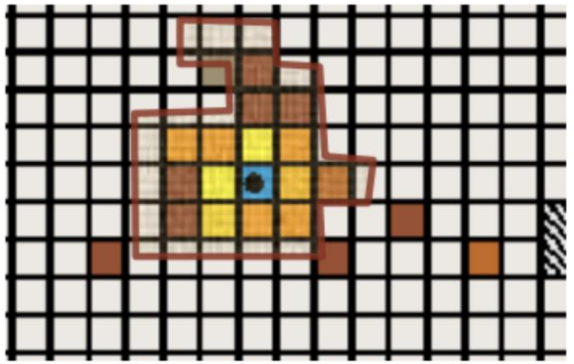
Studies:

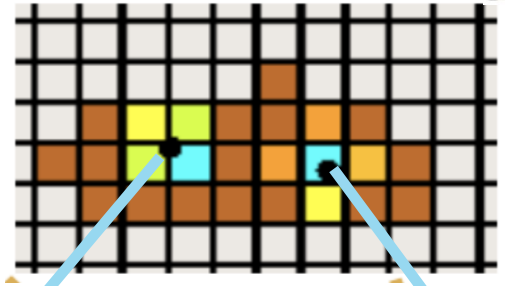
- evaluate as function(energy, photon opening angle)
- "Stitch" boundary region between PbW04 and LGD



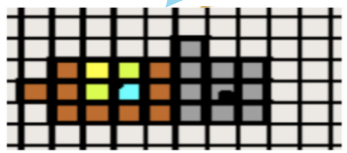


Single photon candidate



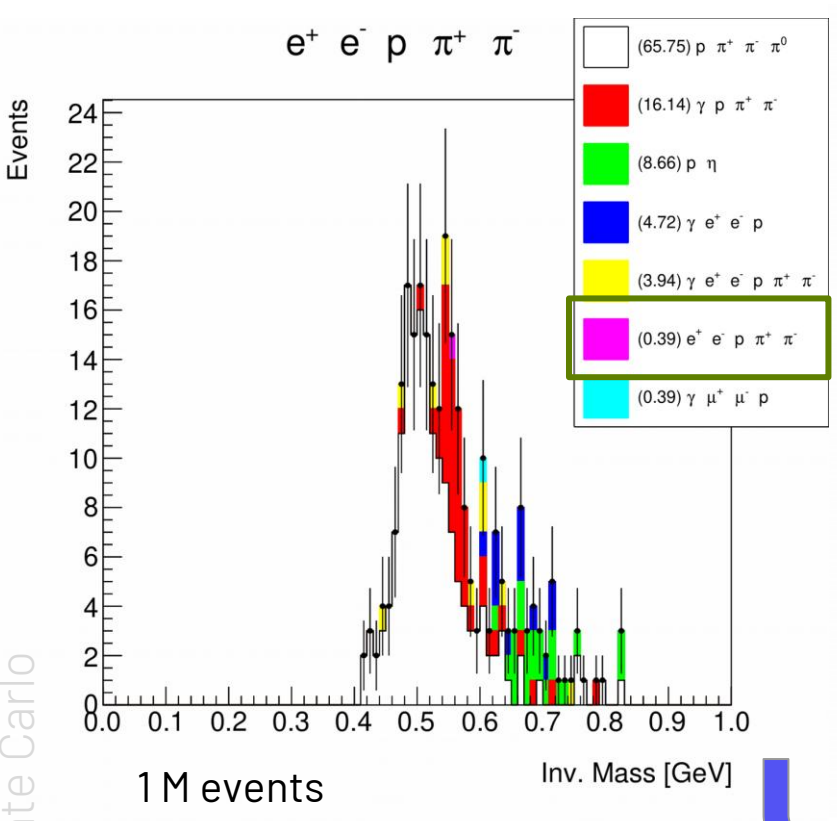


Double photon candidate

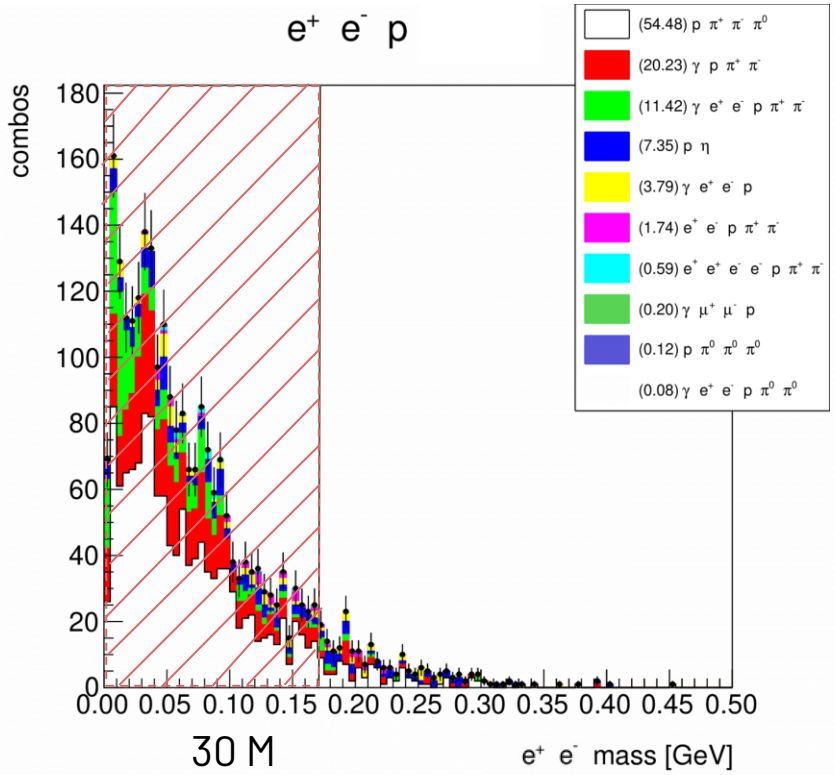


I. Larin, JLab

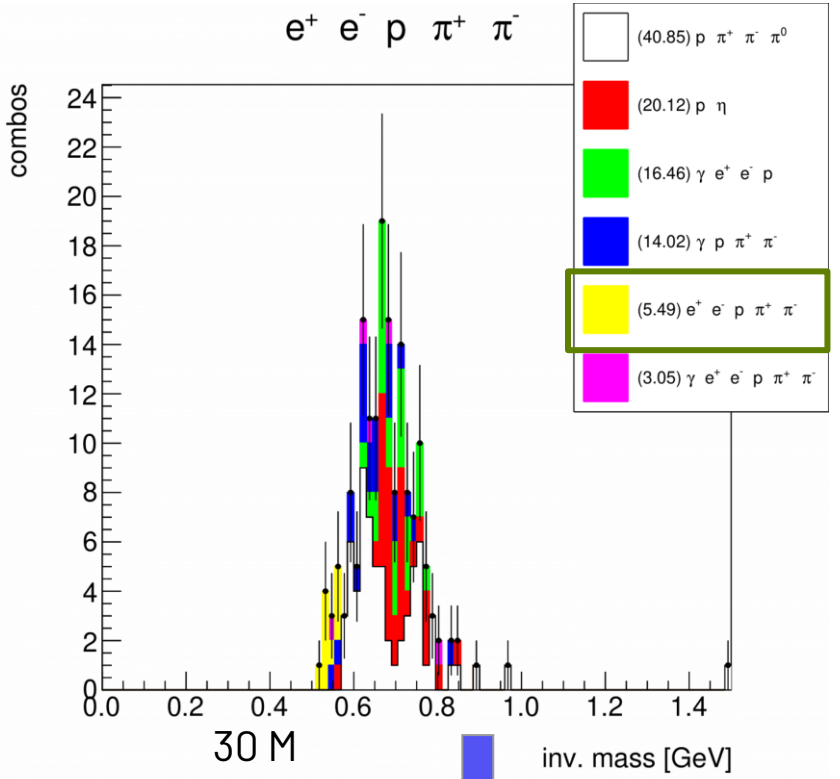
Signal Generation



1 M events

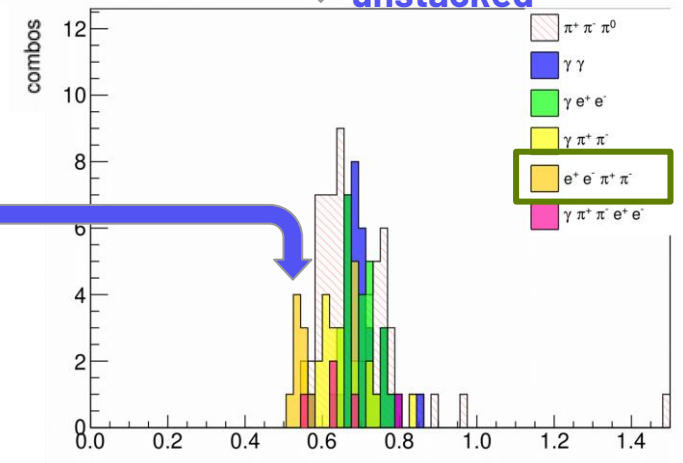


30 M events



30 M events

unstacked



Invariant Mass Plots

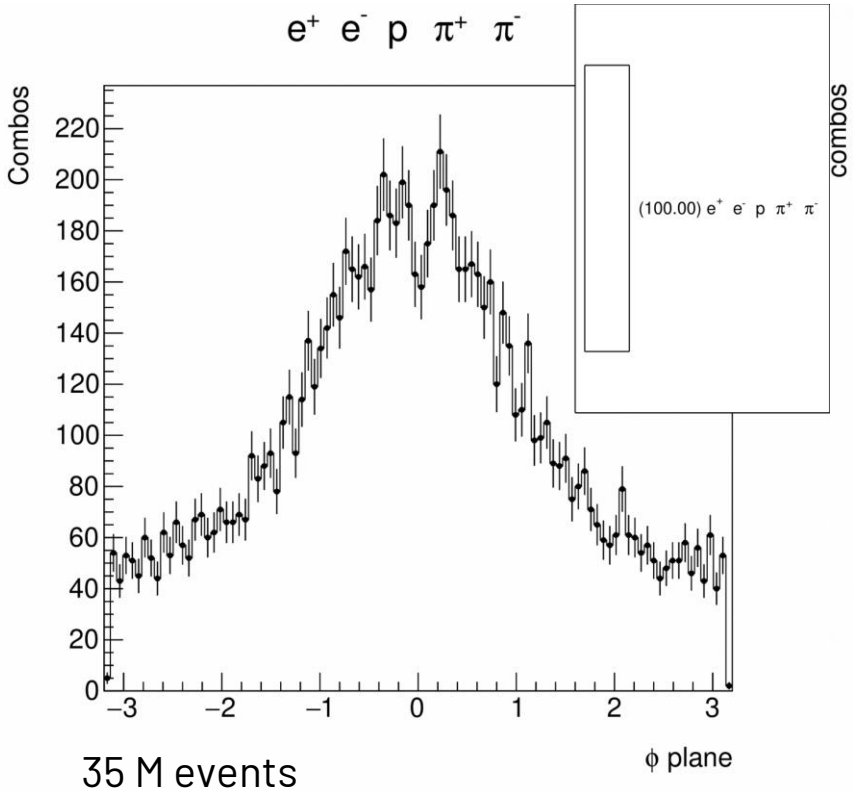
Simulation Settings:
Reaction: $\gamma + p \rightarrow \eta + p$
Decay: $\eta \rightarrow \pi^+ + \pi^- + e^+ + e^-$
Post Processing: **evtgen**

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

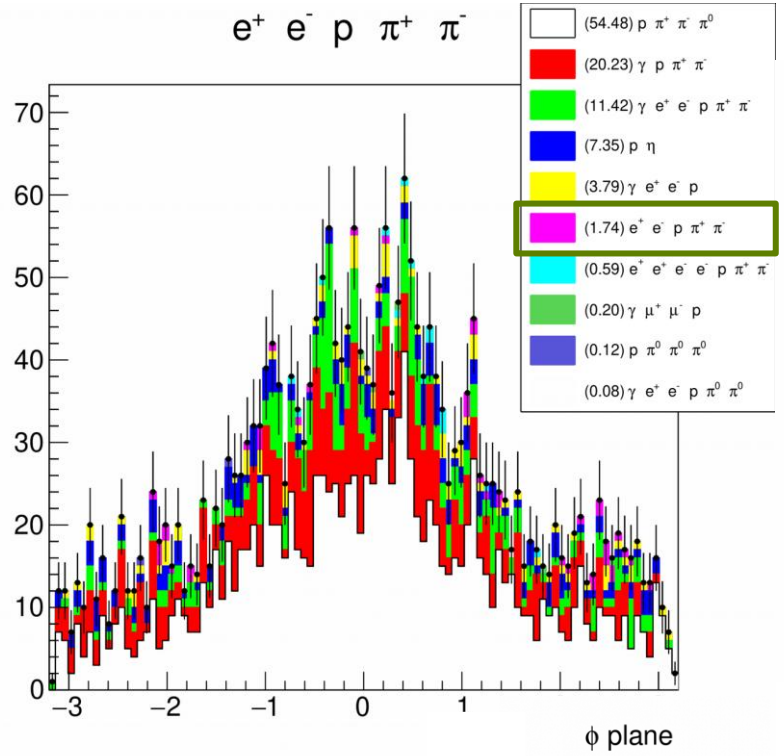
Eliminating e+e- conversion events
M(e^+, e^-) > 0.19 GeV

Signal almost completely isolated!

Signal Generation (*)

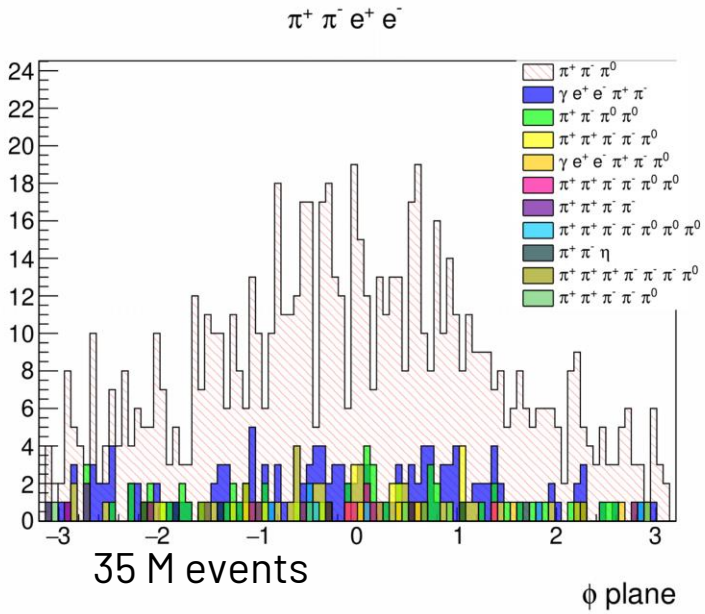


35 M events



30 M events

Background Generation (**)



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Asymmetry Plots

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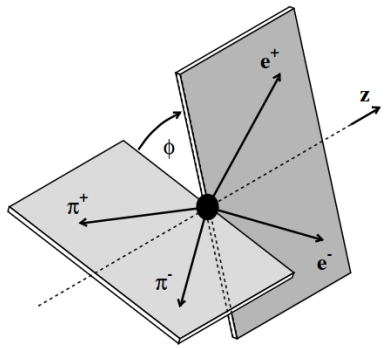
$$\mathcal{A}_\phi = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}}$$

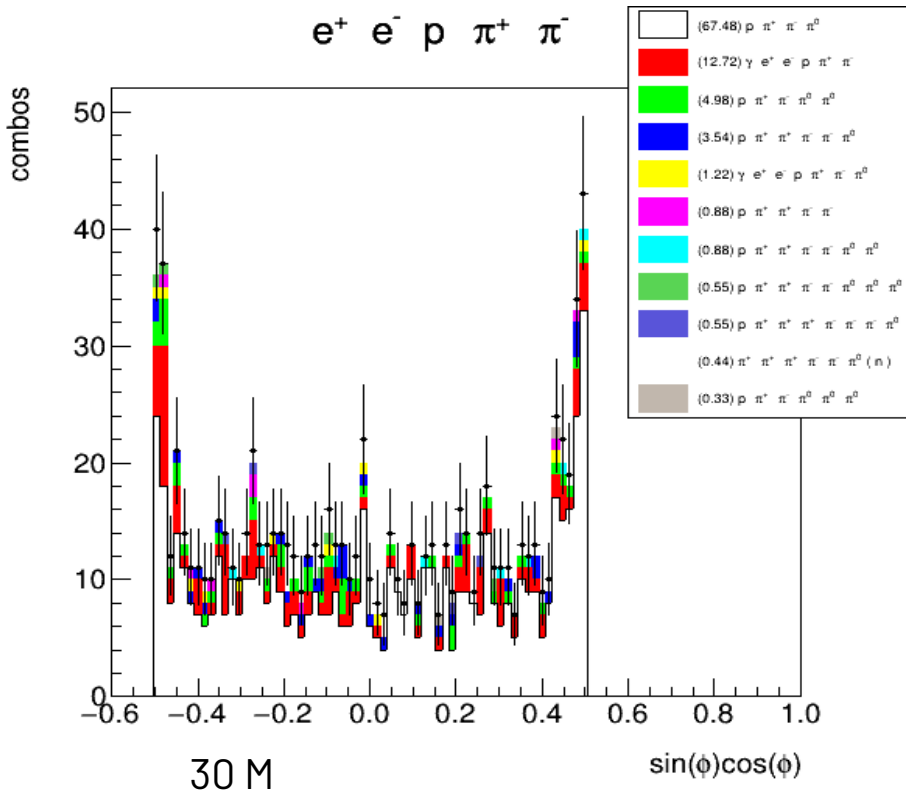
(*) $\rightarrow$ Aφ = (0.4 +/- 2.0 (stat.)) x 10^{-2}

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



Newly Generated Monte Carlo

Signal Generation (*)



30 M events

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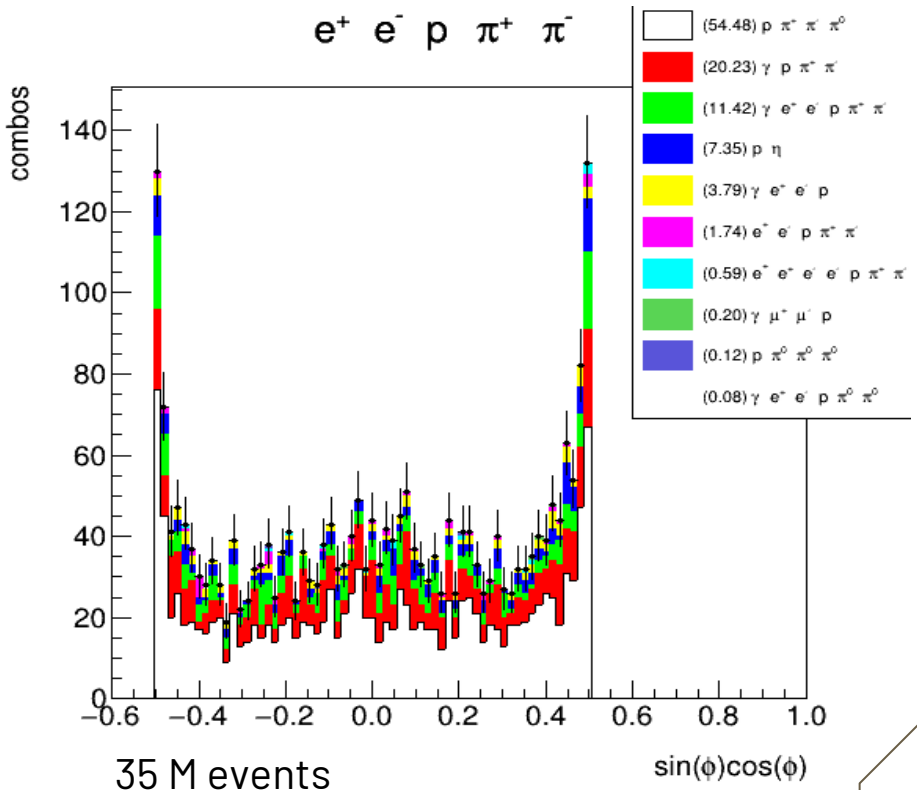

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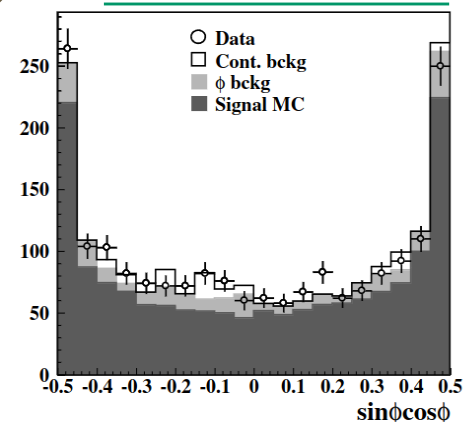
KLOE Collaboration



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

Conclusions

JEF

- - Signal and background plots give insight into future measurements in JEF
- - Rare decays simulated and analyzed
- - Cut evaluation done with two generators

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

- - Possible BSM indications and input for TFFs
- - Signal almost completely isolated
- - Asymmetry Factor calculated and verified that the Detector does not contribute to asymmetry

Thank You
Merci

Thanks to the GlueX Collaboration

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

[3] R.T. Jones et. Al. Performance of RADPHI detector and trigger in a high rate tagged photon beam, NIM A 570 (2007) 384–398

[4] A. A. Lednev, IHEP preprint 93-153

Bland, et. al., Instruments and Experimental Techniques 5,1342-350

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[2] logbooks.jlab.org

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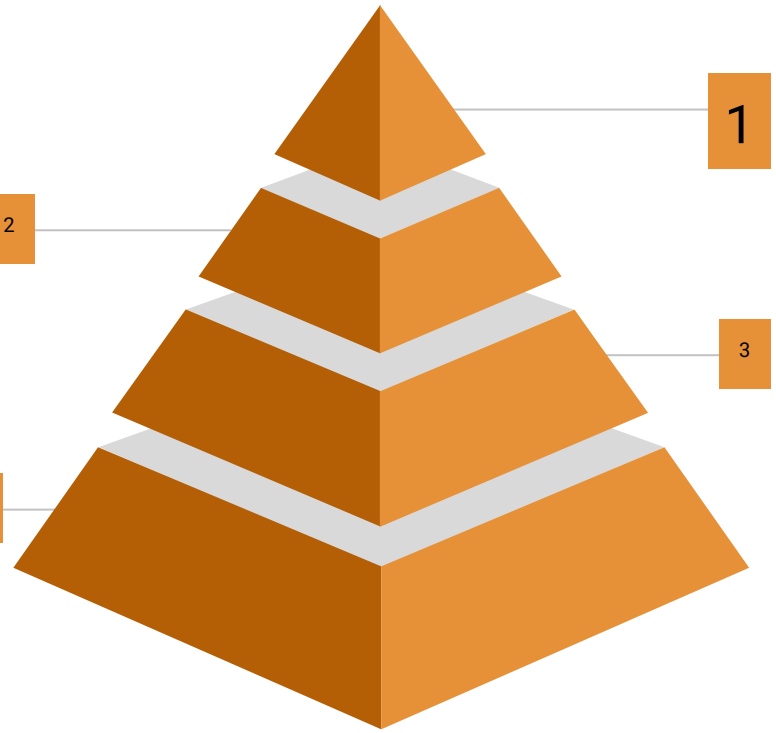


1

Event Generators

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

2

HDGeant 4

Detector hits

3

MCSmear

Models detector resolution to match MC simulated results with real data

4

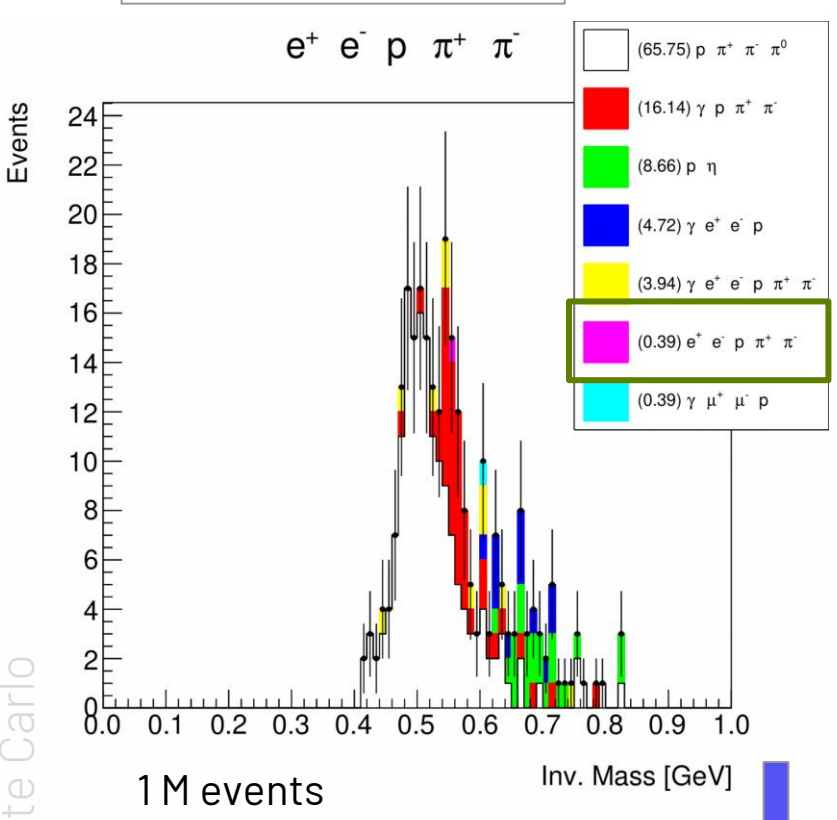
Data with simulations mixing

Even more accurate simulations

MCWrapper

Signal Generation

genEtaRegge + evtgen



1 M events

Signal Generation

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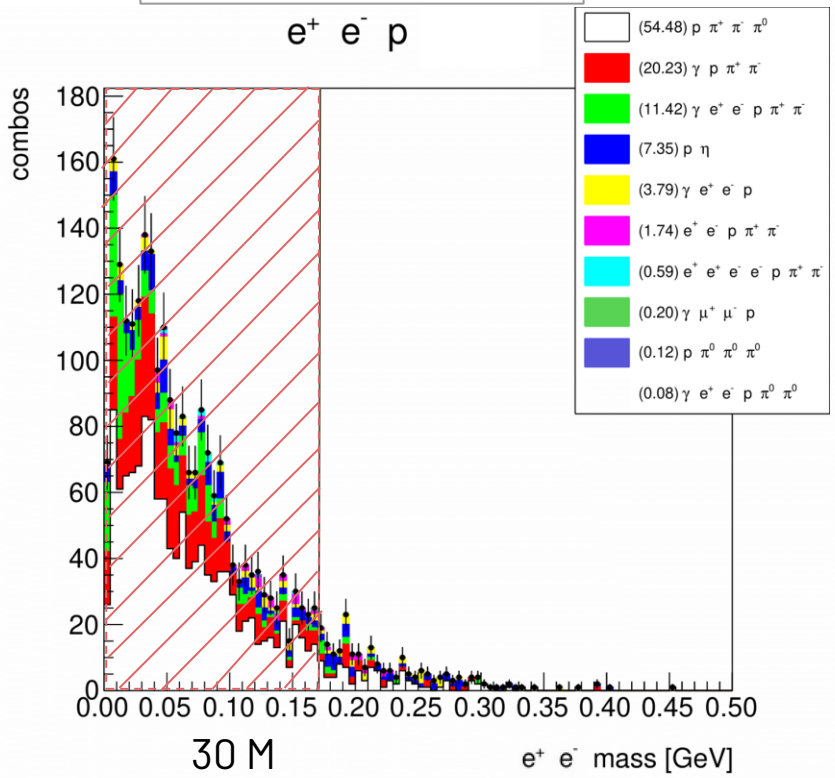

30 M events

Signal Generation

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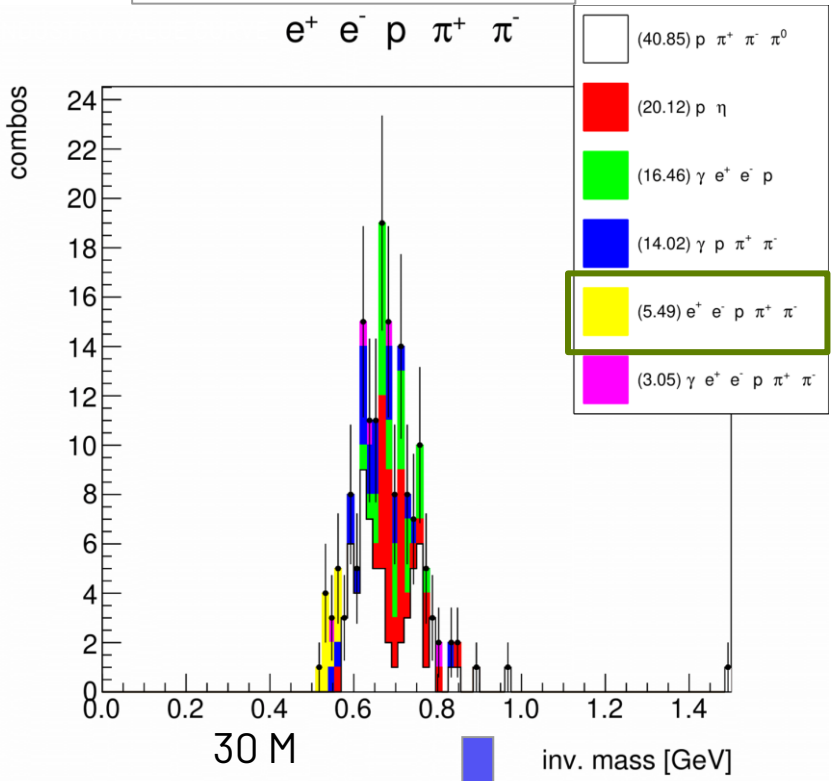
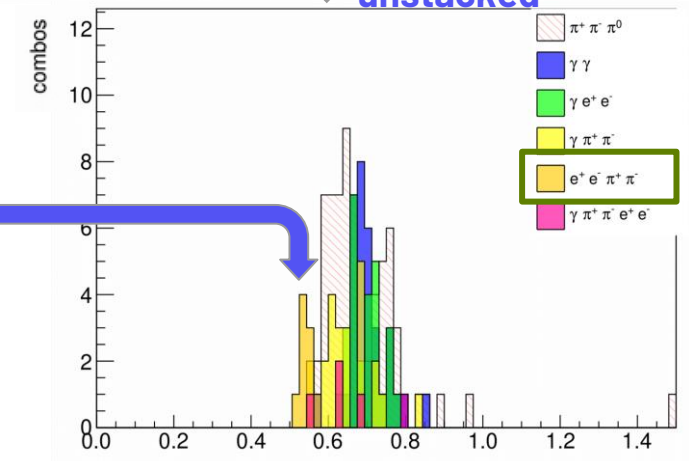


30 M events

unstacked



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Signal Generation

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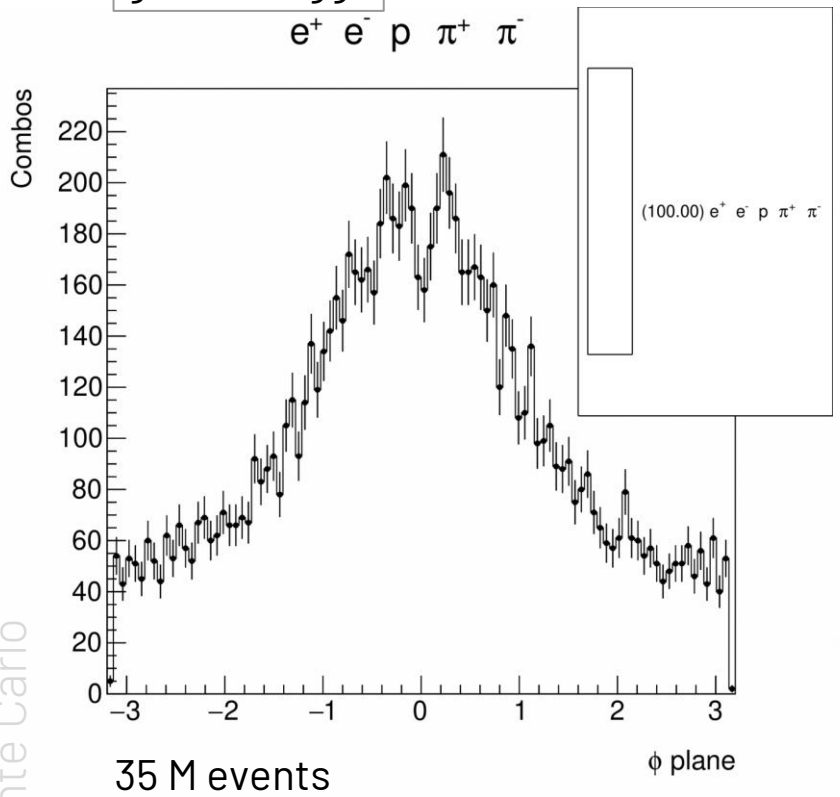
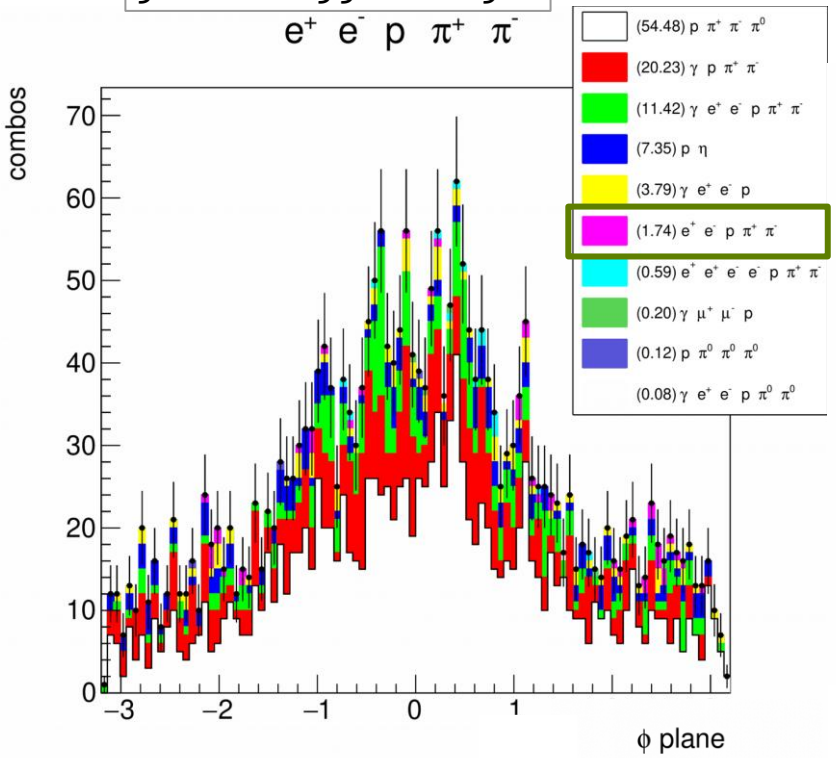


35 M events

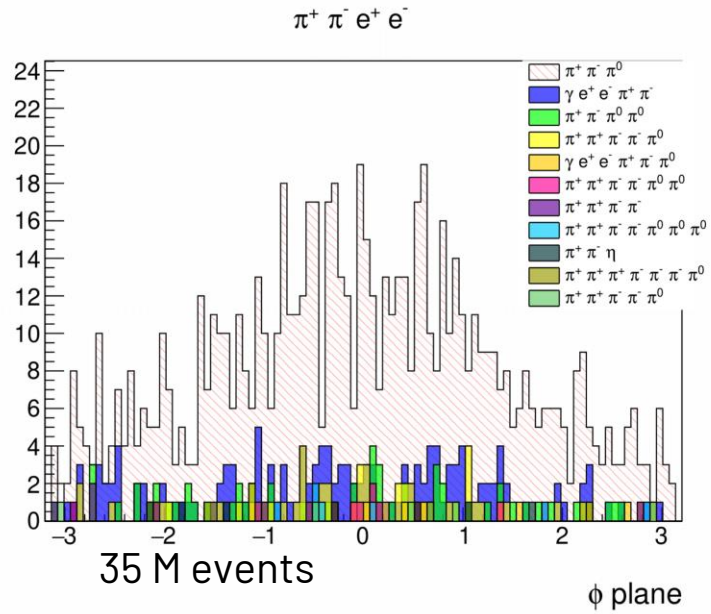
genEtaRegge + evtgen (*)



30 M events

Background Generation

bggen (**)



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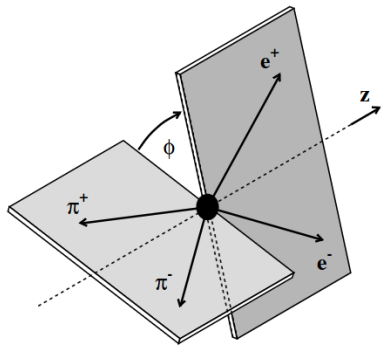
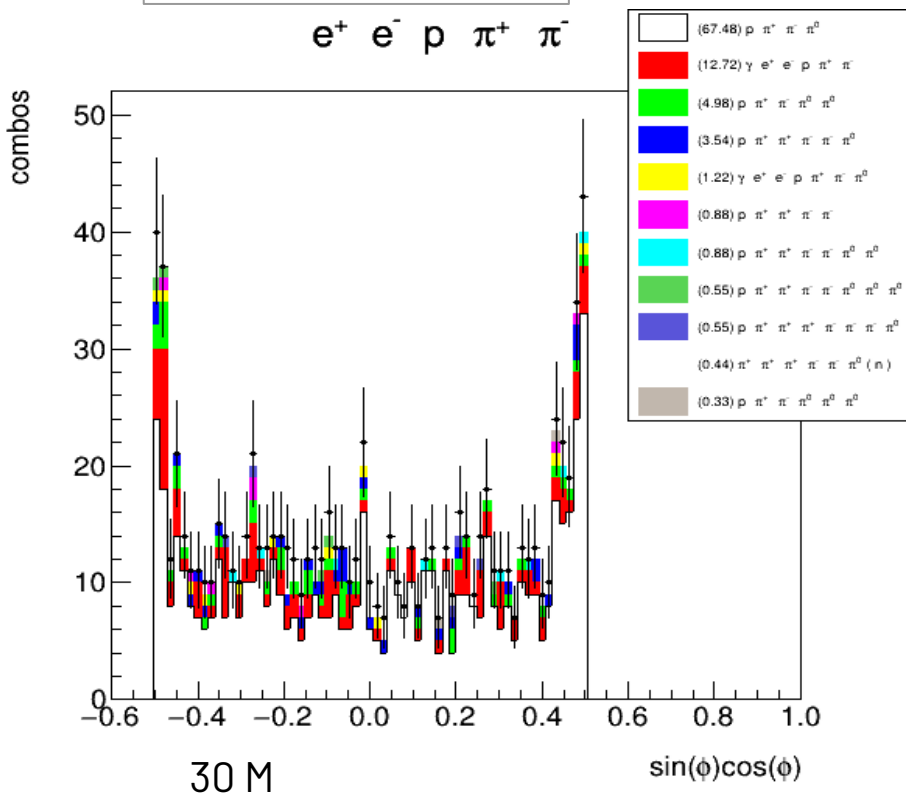


Newly Generated Monte Carlo

(ii) CP-violating dynamics in quark-lepton interactions

Signal Generation

genEtaRegge + evtgen (*)



30 M events

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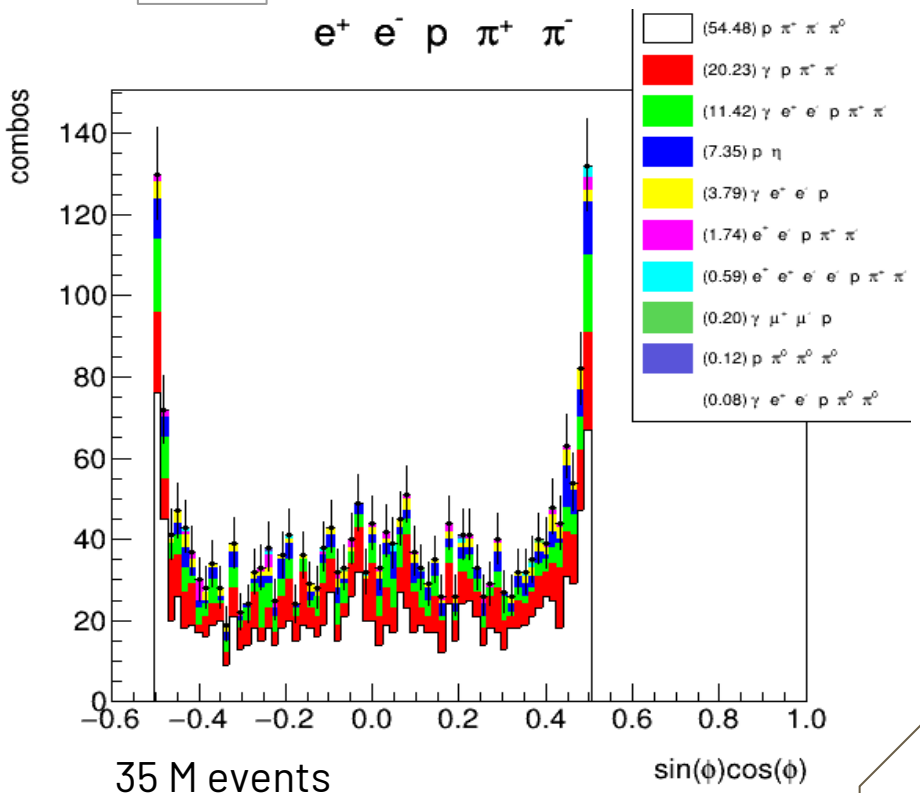

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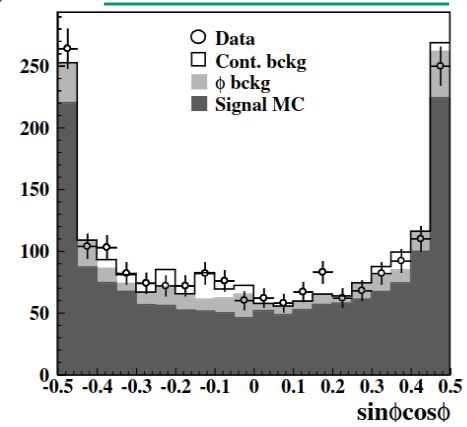

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Newly Generated Monte Carlo

ECAL insert boundaries

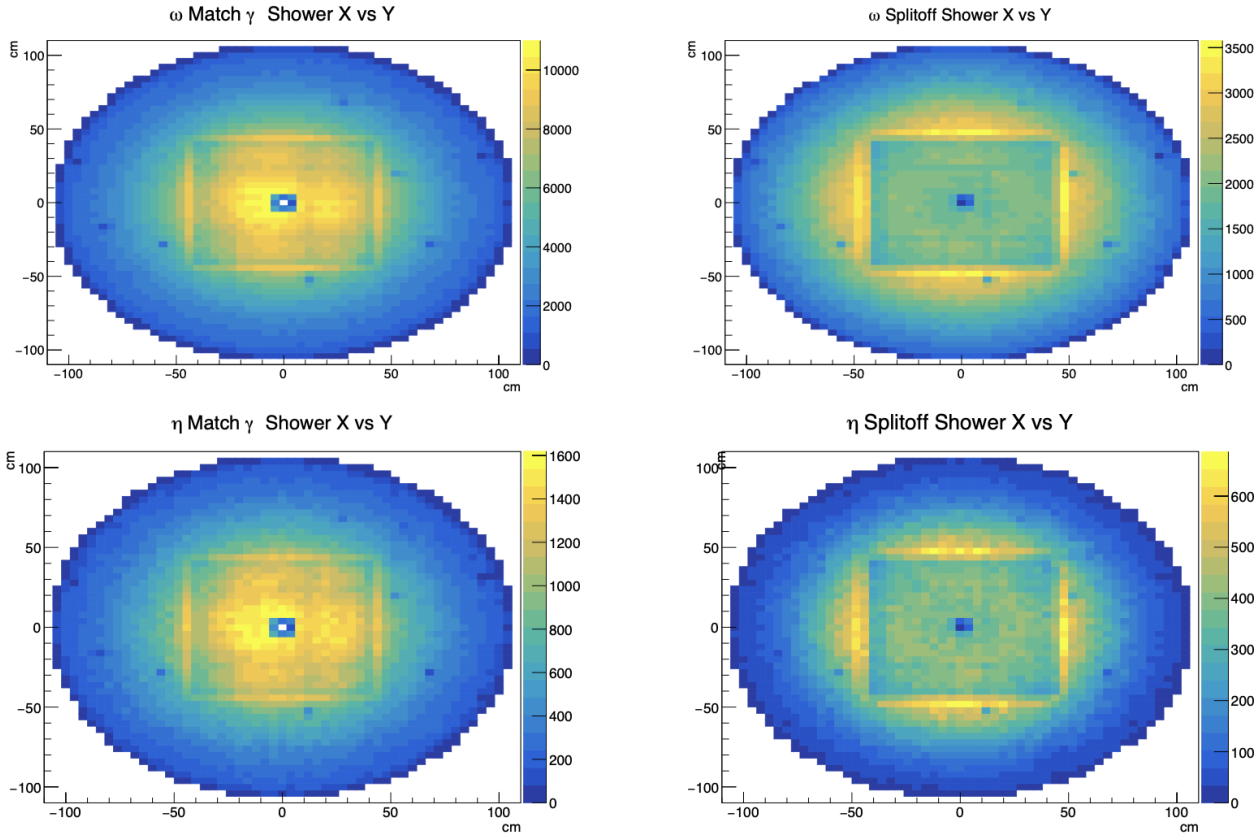
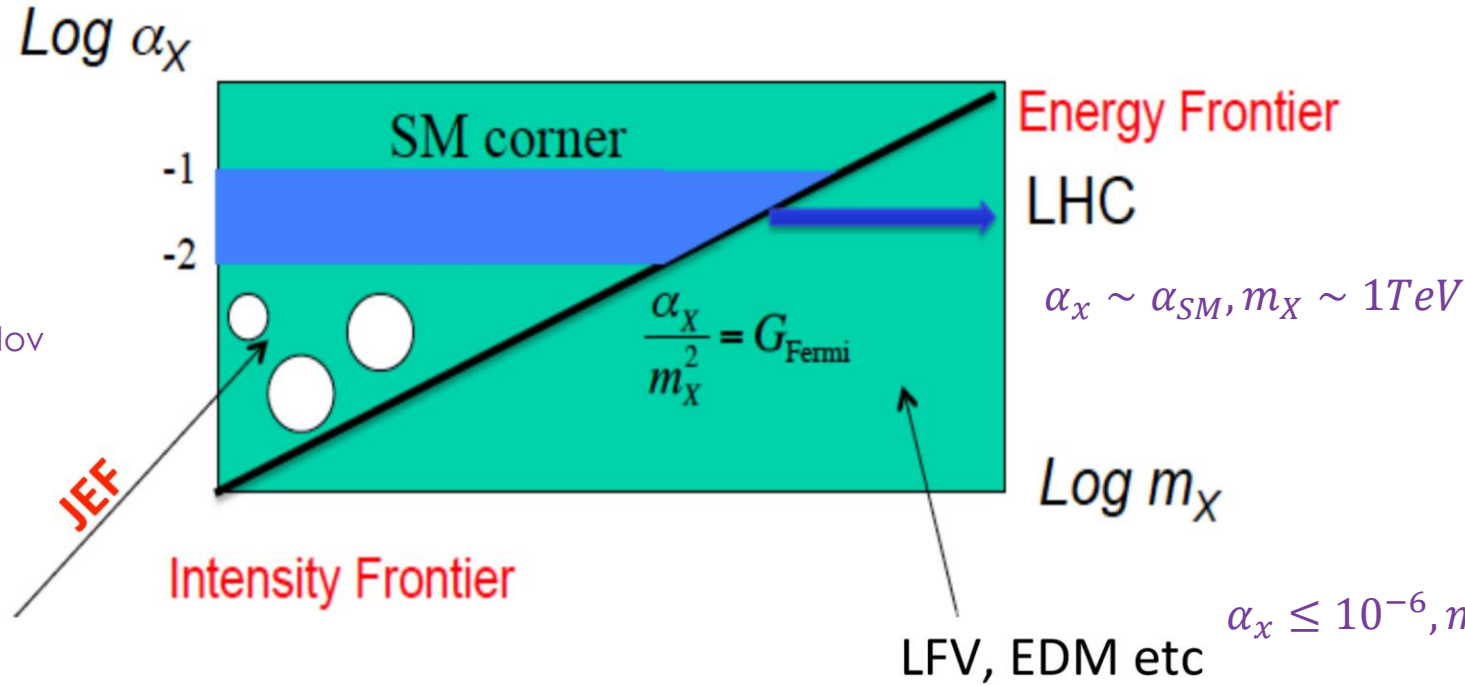


Figure 3.7: The reconstructed position of photons and split-offs on the FCAL face. Top: Photons (left) and split-offs (right) from ω decays, bottom: Photons (left) and split-offs (right) from η decays.

BSM Landscape



η/η' decays offer unique sensitivity for new physics that are flavor-conserving, light quark-coupling, C-violating—P-conserving processes; complementary to other experiments

Simulating Events

Rich physics program at η,η' factories

Standard Model highlights
- Theory input for light-by-light scattering for $(g\text{-}2)_\mu$
- Extraction of light quark masses
- QCD scalar dynamics

Fundamental symmetry tests
- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

Dark sectors (MeV—GeV)
- Vector bosons (dark photon, B boson, X boson)
- Scalars
- Pseudoscalars (ALPs)

(Plus other channels that have not been searched for to date)

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [52]
$\eta \to \pi^+\pi^-\pi^0$	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
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, 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
$\eta \to e^+e^-$	$< 7 \times 10^{-6}$	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
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	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
$\eta \to \pi^+e^-\nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	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

Gan, Kubis, Passemar, ST [arxiv:2007.00664]

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]

JEF - tests/symmetries

2. Directly constrain CVPC new physics:

$$\eta^{(\prime)} \to 3\gamma, 2\pi^0\gamma, \pi^+\pi^-\pi^0$$

3. Precision tests of low-energy QCD:

- Interplay of VMD & scalar dynamics in ChPT: $\eta^{(\prime)} \to \pi^0\gamma\gamma$
- Transition Form Factors of $\eta^{(\prime)}$: $\eta^{(\prime)} \to e^+e^-\gamma$

4. Improve the quark mass ratio via $\eta^{(\prime)} \to 3\pi^0, \pi^+\pi^-\pi^0$

Physics Reports 945 (2022) 1–105
L. Gan, B. Kubis, E. Passemar, S. Tulin
Precision tests of fundamental physics with η and η′ mesons

JEF - sub-GeV

1. Search for sub-GeV, hidden bosons

- vector:
  - Leptophobic vector B'
  - Hidden or dark photon
- scalar:
- Axion-Like Particles (ALP):

mass ranges

$\eta^{(\prime)} \to B'\gamma \to \pi^0\gamma\gamma(0.14 - 0.54GeV)$

$\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma(0.62 - 1.00GeV)$

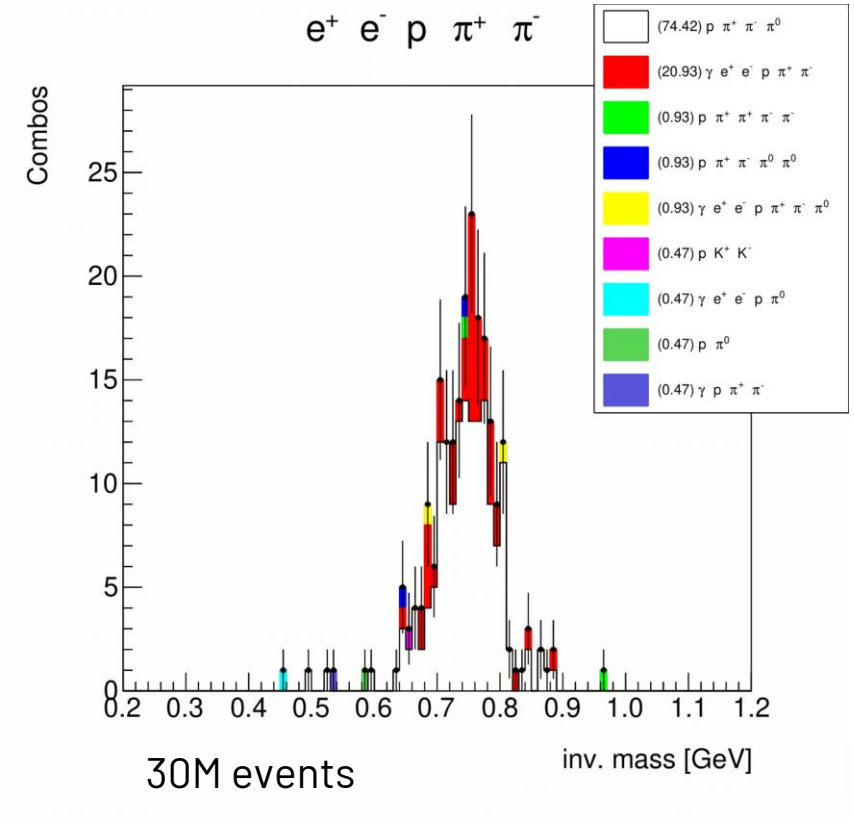
$\eta^{(\prime)} \to A'\gamma \to e^+e^-\gamma$

$\eta \to \pi^0 S \to \pi^0\gamma\gamma, \pi^0 e^+e^-(10MeV < m_S < 2m_\pi)$

$\eta^{(\prime)} \to \pi^0 S \to 3\pi, \eta' \to \eta S \to \eta\pi\pi(m_S > 2m_\pi)$

$\eta^{(\prime)} \to \pi\pi a \to \pi\pi\gamma\gamma, \pi\pi e^+e^-$

bggen



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:
χ^2DOF < 10
Best χ^2 (|RFDeltaT|<2)

Newly Generated Monte Carlo

$$\sin(\phi) = \frac{\mathbf{P_2} \cdot (\mathbf{n_1} \times \mathbf{n_2})}{|\mathbf{n_1}||\mathbf{n_2}|}$$

$$\sin(\phi)\cos(\phi) = \frac{(\mathbf{P_2} \cdot (\mathbf{n_1} \times \mathbf{n_2}))(\mathbf{n_1} \cdot \mathbf{n_2})}{|\mathbf{n_1}|^2|\mathbf{n_2}|^2}$$

$$\phi = \tan^{-1}\left(\frac{\mathbf{P_2} \cdot (\mathbf{n_1} \times \mathbf{n_2})}{\mathbf{n_1} \cdot \mathbf{n_2}}\right)$$

ϕ plane equations