Rare $\eta$ Decays with a $T_{\text{pc}}$ for Optical $\gamma$ Photons

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For the REDTOP Collaboration
SM is showing its age

- SM matter: Dark matter:Dark energy=5%:25%:70%
- Baryon Asymmetry of the Universe
- Expansion of the universe is accelerating (hint to more forces)

New physics is elusive: probability of processes where new physics is coupled to SM physics is low

LHC found no hint of new physics at high energy so far

- New physics could be at much lower energy
- Colliders have insufficient luminosity ($\mathcal{L}(10^{41})$ cm$^{-2}$ vs $\mathcal{L}(10^{44})$ cm$^{-2}$ for 1-mm fixed target)

Newest theoretical models prefer gauge bosons in MeV-GeV mass range as “...many of the more severe astrophysical and cosmological constraints that apply to lighter states are weakened or eliminated, while those from high energy colliders are often inapplicable” (B. Batell, M. Pospelov, A. Ritz – 2009)

High intensity-low energy experiments are growing in popularity (Fixed target and beam dump)
It is a Goldstone boson

Symmetry constrains its QCD dynamics

It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^+$

It can be used to test C and CP invariance.

All its additive quantum numbers are zero

$Q = I = j = S = B = L = 0$

Its decays are not influenced by a change of flavor (as in K decays) and violations are “pure”

All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.

It is a very narrow state ($\Gamma_\eta = 1.3$ KeV vs $\Gamma_\rho = 149$ MeV)

Contributions from higher orders are enhanced by a factor of $\sim 100,000$

EM decays are forbidden in lowest order by C invariance and angular momentum conservation

Excellent for testing invariances

The $\eta$ decays are flavor-conserving reactions

Decays are free of SM backgrounds for new physics search

$\eta$ is an excellent laboratory to search for physics Beyond Standard Model
C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \rightarrow \pi^+ \pi^+ \pi^-$
- CP Violation (Type I – P and T odd, C even): $\eta \rightarrow 4\pi^0 \rightarrow 8\eta$
- CP Violation (Type II - C and T odd, P even): $\eta \rightarrow \pi^0 \pi^0 \pi^0$ and $\eta \rightarrow 3\pi$
- Test of CP invariance via $\mu$ longitudinal polarization: $\eta \rightarrow \mu^+ \mu^-$
- Test of CP invariance via $\gamma*$ polarization studies: $\eta \rightarrow \pi^+ \pi^- \pi^0 e^-$ and $\eta \rightarrow \pi^+ \pi^- \pi^0 \mu^-$
- Test of CP invariance in angular correlation studies: $\eta \rightarrow \mu^+ \mu^- e^- e^-$
- Test of T invariance via $\mu$ transverse polarization: $\eta \rightarrow \pi^+ \mu^- e^-$ and $\eta \rightarrow \gamma \mu^+ \mu^-$
- CPT violation: $\mu$ polariz. in $\eta \rightarrow \pi^+ \mu^- \nu \eta \rightarrow \pi^+ \mu^- \nu$ and $\gamma$ polarization in $\eta \rightarrow \gamma \gamma$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \rightarrow \mu^+ e^- + c.c.$
- Double lepton Flavor Violation: $\eta \rightarrow \mu^+ \mu^- e^- e^- + c.c.$

Non-$\eta/\eta'$ based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: $\bar{q}q \rightarrow A'/a \rightarrow l^+l^-$
- ALP’s searches in Primakoff processes: $p Z \rightarrow p Z a \rightarrow l^+l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ e^- e^- e^-$ and $K^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ e^- e^-$
- Neutral pion decay: $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \rightarrow \pi^0 H$ with $H \rightarrow e^+ e^-$ and $H \rightarrow \mu^+ \mu^-$
- Dark photon searches: $\eta \rightarrow \gamma A' \rightarrow e^+ e^-$
- Protophobic fifth force searches: $\eta \rightarrow \gamma X_{17}$ with $X_{17} \rightarrow e^+ e^-$
- New leptophobic baryonic force searches: $\eta \rightarrow \mu^+ \mu^-$ and $\eta \rightarrow e^+ e^-$
- Search for true muonium: $\eta \rightarrow \gamma (\mu^+ \mu^-)^2_{2M_\mu} \rightarrow \gamma e^+ e^-$

Other discrete symmetry violations

- Proton radius anomaly: $\eta \rightarrow \gamma \mu^+ \mu^- vs \eta \rightarrow \gamma e^+ e^-$
- All unseen leptonic decay mode of $\eta / \eta'$ (SM predicts $10^{-6} - 10^{-9}$)

Non-$\eta/\eta'$ based BSM Physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for $g-2$)

High precision studies on medium energy physics

Assume a yield $\sim 10^{13}$ $\eta$ mesons/yr and $\sim 10^{11}$ $\eta'$ mesons/yr

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Dark photon searches:

$\eta \rightarrow \gamma A' \text{ with } A' \rightarrow \mu^+ \mu^- \text{ and } e^+ e^-$

- Studied within the “Physics Beyond Collider” program at CERN for $10^{17}$ POT
- FNAL and BNL can provide 10x more POT
- Only “bump hunt analysis”. Adding vertexing improve the sensitivity to physics BSM by 10x (K. Maamary summer project)
Searches for light scalar mesons

\[ \eta \rightarrow \pi^0 H \text{ with } H \rightarrow \mu^+ \mu^- \text{ and } e^+ e^- \]

- Studied within the “Physics Beyond Collider” program at CERN for $10^{17}$ POT
- FNAL and BNL can provide $10x$ more POT
- Only “bump hunt analysis”. Adding vertexing improve the sensitivity to physics BSM by $1000x$ (K. Maamary summer project)
\eta \rightarrow \pi^0 \pi^0 \alpha \text{ and } \eta \rightarrow \pi^+ \pi^- \alpha \text{ with } \alpha \rightarrow \mu^+ \mu^- \text{ and } e^+ e^-

- Studied within the “Physics Beyond Collider” program at CERN for $10^{17}$ POT
- FNAL and BNL can provide 10x more POT
- Only “bump hunt analysis”. Will add vertexing to the analysis.
Beam emitted ALP’s from the following processes:

- **Drell-Yan processes**: \( qqbar \to A'/a \to l^+l^- \)
- **Proton bremsstrahlung processes**: \( p N \to p N A'/a \) with \( A'/a \to l^+l^- \) (J. Blümlein and J. Brunner)
- **Primakoff processes**: \( p Z \to p Z a \to l^+l^- \) (F. Kahlhoefer, et. Al.)

- Studied within the “Physics Beyond Collider” program at CERN for \( 10^{17} \) POT
- FNAL and BNL can provide 10x more POT
- Only “bump hunt analysis”. Will add vertexing to the analysis.
- Redtop@PIP-II will provide x100 sensitivity (ALPACA study)
CP Violation from Dalitz plot mirror asymmetry in $\eta \to \pi^+ \pi^- \pi^0$

- CP-violation from this process is not bounded by EDM as is the case for the $\eta \to 4\pi$ process.
- Complementary to EDM searches even in the case of T and P odd observables, since the flavor structure of the eta is different from the nucleus.
- Current PDG limits consistent with no asymmetry.
- REDTOP will collect $4 \times 10^{11}$ such decay (factor 100 in stat. error).
### Present & Future $\eta$ Samples

<table>
<thead>
<tr>
<th>Technique</th>
<th>Technique</th>
<th>$\eta \rightarrow 3\pi^0$</th>
<th>$\eta \rightarrow e^+e^-\gamma$</th>
<th>Total $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB@AGS</td>
<td>$\pi^-p \rightarrow \eta n$</td>
<td>9x10^5</td>
<td></td>
<td>10^7</td>
</tr>
<tr>
<td>CB@MAMI-B</td>
<td>$\gamma p \rightarrow \eta p$</td>
<td>1.8x10^6</td>
<td>5000</td>
<td>2x10^7</td>
</tr>
<tr>
<td>CB@MAMI-C</td>
<td>$\gamma p \rightarrow \eta p$</td>
<td>6x10^6</td>
<td></td>
<td>6x10^7</td>
</tr>
<tr>
<td>KLOE</td>
<td>$e^+e^- \rightarrow \Phi \rightarrow \eta \gamma$</td>
<td>6.5x10^5</td>
<td></td>
<td>5x10^7</td>
</tr>
<tr>
<td>WASA@COSY</td>
<td>$pp \rightarrow \eta pp$</td>
<td></td>
<td></td>
<td>&gt;10^9 (untagged)</td>
</tr>
<tr>
<td></td>
<td>$pd \rightarrow \eta ^3He$</td>
<td></td>
<td></td>
<td>3x10^7 (tagged)</td>
</tr>
<tr>
<td>CB@MAMI 10 wk (proposed 2014)</td>
<td>$\gamma p \rightarrow \eta p$</td>
<td>3x10^7</td>
<td>1.5x10^5</td>
<td>3x10^8</td>
</tr>
<tr>
<td>Phenix</td>
<td>$d Au \rightarrow \eta X$</td>
<td></td>
<td></td>
<td>5x10^9</td>
</tr>
<tr>
<td>Hades</td>
<td>$pp \rightarrow \eta pp$</td>
<td></td>
<td></td>
<td>4.5x10^8</td>
</tr>
<tr>
<td></td>
<td>$p Au \rightarrow \eta X$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Near future samples**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Technique</th>
<th>$\gamma_{12\text{GeV}}p \rightarrow \eta X \rightarrow$ neutrals</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>GlueX@JLAB (just started)</td>
<td></td>
<td></td>
<td>$5.5\times10^7$/yr</td>
</tr>
<tr>
<td>JEF@JLAB (recently approved)</td>
<td></td>
<td></td>
<td>$3.9\times10^5$/day</td>
</tr>
<tr>
<td>REDTOP@FNAL (proposing)</td>
<td>$p_{1.8\text{GeV}}Be \rightarrow \eta X$</td>
<td></td>
<td>$2.5\times10^{13}$/yr</td>
</tr>
</tbody>
</table>
Medium energy proton beam 1.5 – 4 GeV

- $10^{17}$ POT/yr (10^{18} POT/yr better-FNAL and BNL)

- Produce $\sim 10^{13} \eta$ mesons/yr – reco eff $> 10\%$

- Produce $\sim 10^{11} \eta'$ mesons/yr– reco eff $> 10\%$

- Efficient detection of the leptonic decays of the $\eta$

- Blind to protons and low energy charged pions.

- Near 4$\pi$ detector acceptance.
### Experimental Techniques - $\eta/\eta'$ production + detection

- Incident proton energy \(~1.8~\text{GeV} (3.5~\text{GeV for } \eta')\)
- CW beam, $10^{17}-10^{18}~\text{POT/yr (depending on the host laboratory)}$
- $\eta/\eta'$ hadro-production from inelastic scattering of protons on Li or Be targets (vs Nb as Hades-like experiments)
- Use multiple thin targets to minimize combinatorics background

#### Charged Tracks Detection
- Use Cerenkov effect for tracking charged particles
- Baryons and most pions are below Č threshold
- Electrons and most muons are detected and reconstructed in an Optical-TPC

#### $\gamma$ Detection
- Use ADRIANO calorimeter for reconstructing EM showers
- $\sigma_E/E < 5%/\sqrt{E}$
- PID from dual-readout to disentangle showers from $\gamma/\mu$/hadrons
- 96.5% coverage

- Fiber tracker (LHCB style) for rejection of background from $\gamma$-conversion and reconstruction of secondary vertices (~70\,$\mu$m resolution)
**Optical TPC**
- ~ 1m x 1.5 m
- CH₄ @ 1 Atm
- 5x10⁵ Sipm/Lappd
- 98% coverage

**ADRIANO2 Calorimeter (tiles)**
- Scint. + heavy glass sandwich
- 20 X₀ (~ 64 cm deep)
- Triple-readout + PFA
- 96% coverage

**μ-polarizer**
Active version (from TREK exp.) - optional

**Aerogel**
Dual refractive index system

**Fiber tracker**
for rejection of g-conversion and vertexing

**10x Be or Li targets**
- 0.33 mm thin
- Spaced 10 cm
- Single p pulse from booster ($\leq 4 \times 10^{12}$ p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)
- Energy is removed by adding 1-2 RF cavities identical to the one already planned (~5 seconds)
- Slow extraction to REDTOP over ~40 seconds.
- The 270° of betatron phase advance between the Mu2e Electrostatic Septum and REDTOP Lambertson is ideal for AP50 extraction to the inside of the ring.
- Total time to decelerate-debunch-extract: 51 sec; duty cycle ~80%
Accelerator Physics Issues

- **Transition Energy**
  - $\gamma_t$ is where $\Delta f/f = 1/\gamma^2 - \langle D/\rho \rangle = 0$; synchrotron motion stops momentarily, can often lead to beam loss
  - beam decelerates from $\gamma = 9.5$ to $\gamma = 3.1$
  - original Delivery Ring $\gamma_t = 7.6$
  - a re-powering of 18 quadrupole magnets can create a $\gamma_t = 10$, thus avoiding passing through this condition

- **Resonant Extraction**
  - Mu2e will use $1/3$-integer resonant extraction
  - REDTOP can use same system, with use of the spare Mu2e magnetic septum
  - initial calculations indicate sufficient phase space, even with the larger beam at the lower energies

- **Vacuum**
  - REDTOP spill time is much longer than for Mu2e
  - though beam-gas scattering emittance growth rate 3 times higher at lower energy, still tolerable level
Transition is avoided by using select quad triplets to boost $\gamma_t$ above beam $\gamma$ by 0.5 units throughout deceleration until $\gamma_t = 7.64$ and beam $\gamma = 7.14$ (5.76 GeV kinetic). Below 5.76 GeV the DR lattice reverts to the nominal design configuration.

8 GeV injection energy (top) and <5.8 GeV (bottom)

- Blue & red circles indicate sites of the $\gamma_t$ quad triplets.

<table>
<thead>
<tr>
<th>$p$ (GeV/c)</th>
<th>8.89</th>
<th>8.33</th>
<th>7.76</th>
<th>7.20</th>
<th>6.63</th>
</tr>
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<tbody>
<tr>
<td>KE (GeV)</td>
<td>8.00</td>
<td>7.45</td>
<td>6.88</td>
<td>6.32</td>
<td>5.76</td>
</tr>
<tr>
<td>$\gamma_{\text{BEAM}}$</td>
<td>9.53</td>
<td>8.93</td>
<td>8.33</td>
<td>7.74</td>
<td>7.14</td>
</tr>
<tr>
<td>$\gamma_{\text{transition}}$</td>
<td>10.03</td>
<td>9.43</td>
<td>8.83</td>
<td>7.74</td>
<td>7.64</td>
</tr>
<tr>
<td>$\beta_{\text{max}}$ (m)</td>
<td>94.9</td>
<td>72.5</td>
<td>49.5</td>
<td>30.1</td>
<td>15.1</td>
</tr>
<tr>
<td>$q$ (m$^{-1}$)</td>
<td>0.0697</td>
<td>0.0573</td>
<td>0.0416</td>
<td>0.0236</td>
<td>0.0</td>
</tr>
<tr>
<td>$3\sigma$ (mm)</td>
<td>15.0</td>
<td>13.6</td>
<td>11.6</td>
<td>9.4</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Variation of $\gamma_t$, $\beta_{\text{max}}$, and the 15π 99% beam envelope through deceleration

"J. Johnstone, M. Syphers, NA-PAC, Chicago (2016)"
Assume: $1 \times 10^{11}$ POT/sec – CW

- Beam power @ 3 GeV: $10^{11} \text{ p/sec} \times 1.9 \text{ GeV} \times 1.6 \times 10^{-10} \text{ J/GeV} = 30 \text{ Watts (48 W for } \eta')$

Target system: 10 x 0.33mm Be or 0.5 mm Li foils, spaced 10 cm apart

- Be is thinner (better vertex resolution) but makes more primary hadrons (final state hadron multiplicity $\approx A^{1/3}$)
- $\text{Prob}(p + \text{target} \rightarrow X) \sim 0.5\%$ or $5 \times 10^8 \text{ p-Be inelastic collisions per second}$

- $p$-inelastic production: $5 \times 10^8 \text{ evt/sec (1 interaction/2 nsec in any of the 10 targets)}$
- Probability of 2 events in the same target in 2 nsec: 7%
- $\eta$ production: $2.5 \times 10^6 \eta/\text{sec (2.5 x 10^4 } \eta' /\text{sec})$ or $2.5 \times 10^{13} \eta/\text{yr (2.5 x 10^{11} } \eta' /\text{yr})$
The REDTOP Detector

**Optical TPC**
- ~ 1m x 1.5 m
- CH$_4$ @ 1 Atm
- 5x10$^5$ Sipm
- 98% coverage

**10x Li/Be targets**
- 0.33 mm thin
- Spaced 10 cm

**ADRIANO2 Calorimeter**
- Scint. + heavy glass sandwich
- 20 X$_0$ (~ 64 cm deep)
- Triple-readout mode
- 96% coverage

**Solenoid**
- 0.6-0.8 T

**Aerogel**
- Dual refractive index system

**μ-polarizer (optional)**
- Active version (from TREK exp.)

**Fiber tracker**
The ADRIANO2 Calorimeter

- Sandwich of Pb-glass and scintillating plastic tiles with direct SiPM reading
  - Evolution of ADRIANO dual-readout calorimeter (A Dual-Readout Integrally Active Non-segmented Option)
- Triple-readout obtained from waveform analysis

- Rationale for multiple readout calorimetry at $\eta$-factory
  - Particle identification (see next)
  - Integrally active (no sampling)
  - Prompt Cerenkov light fed to L) trigger
  - Good granularity helps disentangling overlapping showers
Triple-readout adds the measurement of the neutron component improving the energy resolution even further.
ADRIANO PID @ 100MeV

- pions
- p/n
- e/γ
- muon
**ADRIANO Light Yield and Resolution**

**Integrally Active with Double side readout (ADRIANO)**

<table>
<thead>
<tr>
<th>Pitch [mm²]</th>
<th>Diameter</th>
<th>Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2</td>
<td>1mm</td>
<td>1053</td>
</tr>
<tr>
<td>3x3</td>
<td>1mm</td>
<td>430</td>
</tr>
<tr>
<td>4x4</td>
<td>1mm</td>
<td>254</td>
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<tr>
<td>5x5</td>
<td>1mm</td>
<td>163</td>
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<tr>
<td>6x6</td>
<td>1mm</td>
<td>124</td>
</tr>
<tr>
<td>4x4</td>
<td>1.4mm</td>
<td>500</td>
</tr>
<tr>
<td>4x4</td>
<td>2mm</td>
<td>110</td>
</tr>
<tr>
<td>4x4 capillary</td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>5x5</td>
<td>1mm</td>
<td>200</td>
</tr>
<tr>
<td>6x6</td>
<td>1mm</td>
<td>7.5</td>
</tr>
</tbody>
</table>

**Baseline configuration**

**1-side readout**

**ILCroot simulations**

Fiber pitches: 2mmx2mm through 6mmx6mm

- Fiber diameter: 1mm – 1.4mm – 2mm

**All numbers include the effect of photodetector QE**
Neutron contribution

\[ E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S} + \eta_n \cdot E_{neutrons} \]

**Time history of the scintillation signal in ADRIANO for \( \pi @40 \text{ GeV} \).**

The contribution after 35 ns is from neutrons only. The distribution has been fitted with a triple exponential function.

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**Triple Readout aka Dual Readout with time history readout**
**ADRIANO in Triple Readout configuration**

Fiber pitches: 2mmx2mm through 6mmx6mm

- 2x2
- 3x3
- 4x4
- 5x5
- 6x6

Baseline configuration

<table>
<thead>
<tr>
<th>Fiber Diameter</th>
<th>Layer Type</th>
<th>Energy Resolution ($\sigma_{E/E}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1mm – 1.4mm – 2mm</td>
<td>4x4</td>
<td>$0.2787 \pm 0.002618$</td>
</tr>
<tr>
<td></td>
<td>4x4.2</td>
<td>$0.2834 \pm 0.002592$</td>
</tr>
<tr>
<td></td>
<td>4x4.3</td>
<td>$0.2611 \pm 0.002393$</td>
</tr>
<tr>
<td></td>
<td>4x4.4</td>
<td>$0.2398 \pm 0.00225$</td>
</tr>
</tbody>
</table>

ILCroot simulations

$\sigma_{E/E} = 28\% / \sqrt{E} \pm 1\%$

Pion beams

$\sigma_{E/E} = 24\% / \sqrt{E} \pm 1\%$

Compare to ADRIANO in Double Readout configuration

$\sigma_{E/E} = 33\% / \sqrt{E} \pm 2\%$

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Two versions built: scifi and scintillating plates

10 x 8 x105 cm³ long prototypes, about 50 Kg each

4 cells total, front and back readout

Hopefully, we will be able to test the dual-readout concept with integrally active detectors

ADRIANO 2014A: 8 grooves

ADRIANO 2014B: 23 grooves
ADRIANO for High Energy
Nov. 2015 test Beam at Fermilab
Evolution of ADRIANO: log layout->tiles
Sandwich of 3mm scintillating plastics and 10 mm Pb-glass (10cm x 10cm transverse size)
WLS light capture -> SiPM directly coupled to glass and plastic
Prompt Cerenkov signal used in L0 trigger
Granularity can be made extremely fine
16 layers – prototype (64 ch) under construction at NIU
Will be tested in Fall 2019 at FTBF
At present, Fermilab-INFN-NIU-UMN Collaboration
Glass preparation
Polishing
Coating and testing
Rationale for an Optical-TPC

- At 1 GHz inelastic interaction rate, a conventional, gas detector is suboptimal
- Hadronic particles (p, ion remnants, slow pions, etc.) will clutter the tracker
- Use the Cerenkov effect to detect the fast (leptons and fast pions) tracks
- Prompt signal is also fed to the L0 trigger for fast selection of event with leptons
Electron Detection

$n_D(N_2@2.7\text{psi})=1.000145$

Č threshold for $e^-$ in $N_2$: $P=40\text{ mev}$

$n_D(\text{aerogel1})=1.12$

$n_D(\text{aerogel2})=1.22$
Electrons are recognized by:

1. A large (>30 cm dia) circle of photons generated in the aerogel
2. A sweep of photons circles with dia < 1cm and several cm long (depends on $P_t$)
3. An EM shower in ADRIANO (identified by Č vs S)
Muon/pion Detection

- $n_D(\text{aerogel}) = 1.22/1.12$
- Č threshold for muons: $P = 160$ mev
- Č threshold for pions: $P = 200$ mev

Dual-readout: Č vs $S$ for $\mu$ and $\pi$ with $P = 500$ MeV

- 95 MeV muon
- 120 MeV muon

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$\eta \rightarrow \pi^+ \pi^- \pi^0$
Improvement with timing (~10 nsec)

- **Uncertainty on the photon origin**

- **Two-track separation**
Detector R&D: OTPC

Fnal -T1059 (H. Frisch, E. Oberla)

- Successful proof of principle in 2015 at FTBF
- Instrumented with an MCP photo-detector, three boards each with thirty channels of 10 GSPS waveform digitizing readout

It requires a robust and dedicated R&D (LDRD)
The Fiber Tracker – LHCb design

128 modules (0.5 x 5 m²)
arranged in 3 stations x 4 layers
(XUVX)

1 module = 8 fibre mats

mirror

fibre mat
2.4 m

4 silicon photomultipliers (SiPM)

32.59 mm
1 SiPM = 128 channels

Light yield for 6-layer mat:
16–20 photo-electrons
(for particles near mat mirror)
Layout for LHCb vs REDTOP

Input parameters:
- ~360 m² vs 0.24 m²
- 1152 mats vs 36 mats
- 524,000 vs 18,000 channels

Performance:
- peak PDE = 48% (at 3.5 V)
- direct cross-talk = 3%
- delayed cross-talk = 2.5%
- afterpulses < 0.1%

Dark count rate per channel after neutron irradiation:

Goal: <100 μm resolution over a total active surface of ~340 m²
Results from LHCb Test Beam

Detection efficiency 5 Layers

Charge-weighted residual

<table>
<thead>
<tr>
<th>Seed</th>
<th>Neighbour</th>
<th>Sum</th>
<th>Hit Eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9993 ± 0.0001</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>0.9990 ± 0.0001</td>
</tr>
<tr>
<td>2.0</td>
<td>1.5</td>
<td>2.0</td>
<td>0.9972 ± 0.0002</td>
</tr>
<tr>
<td>2.5</td>
<td>1.5</td>
<td>2.5</td>
<td>0.9946 ± 0.0003</td>
</tr>
<tr>
<td>3.0</td>
<td>1.5</td>
<td>3.0</td>
<td>0.9990 ± 0.0004</td>
</tr>
<tr>
<td>3.5</td>
<td>1.5</td>
<td>3.5</td>
<td>0.9817 ± 0.0005</td>
</tr>
<tr>
<td>4.0</td>
<td>1.5</td>
<td>4.0</td>
<td>0.9693 ± 0.0006</td>
</tr>
<tr>
<td>4.5</td>
<td>1.5</td>
<td>4.5</td>
<td>0.9540 ± 0.0007</td>
</tr>
<tr>
<td>2.5</td>
<td>1.5</td>
<td>4.0</td>
<td>0.9866 ± 0.0004</td>
</tr>
</tbody>
</table>

at the mirror | centre | 50 cm from SiPM

$\sigma_{\text{eff,charge}} [\mu m]$ | 66.78 ± 0.23 | 65.93 ± 0.18 | 61.22 ± 0.21
$\sigma_{\text{eff,Pacific}} [\mu m]$ | 73.27 ± 0.26 | 73.18 ± 0.20 | 73.64 ± 0.20
Fiber Tracker Radiation Hardness

- 3 m long SCSF-78 fibres (Ø 0.25 mm), embedded in glue (EPOTEK H301-2)
- irradiated at CERN PS with 24 GeV protons (+ background of 5 \cdot 10^{12} \text{n/cm}^2)

Expected irradiation at REDTOP

- Worst case (forward detector): \(~10^{13} \text{n/cm}^2\)
- Average: \(~10^{12} \text{n/cm}^2\)
Input parameters

- $\sim 5 \times 10^8$ p-Be inelastic collisions per second
- $\sim 2.5 \times 10^6 (10^4)$ produced $\eta (\eta')$ per second

Trigger requirements (L. Ristori)

<table>
<thead>
<tr>
<th>Level</th>
<th>Algo</th>
<th>Detectors</th>
<th>Hardware</th>
<th>Rejection factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>$\Sigma$ OTPC &amp; ADRIANO-Cer</td>
<td>OTPC, ADRIANO</td>
<td>Fast sum</td>
<td>100</td>
</tr>
<tr>
<td>L1</td>
<td>identification of a pair of leptons, $\gamma$-conversion rejection</td>
<td>OTPC, ADRIANO, Fiber Tracker</td>
<td>FPGA</td>
<td>100</td>
</tr>
<tr>
<td>L2</td>
<td>Reco</td>
<td>All</td>
<td>2000 CPU-cores</td>
<td>$&gt;100$</td>
</tr>
</tbody>
</table>

Expected data rates

- About 100 Hz to be stored on tape
- $\sim 1$ MB/sec from L2
- $\sim 5$ PB/year to tape (assume 5 kb event size)
### Cost (estimate for ESPP)

- **In kind contribution from INFN**
  - Solenoid (from Finuda experiment at Frascati)
  - $\frac{3}{4}$ of Pb-glass (from NA62)

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoid</td>
<td>0.2</td>
</tr>
<tr>
<td>Refurbishing, shipping</td>
<td>0.2</td>
</tr>
<tr>
<td>Supporting structure</td>
<td>1.0</td>
</tr>
<tr>
<td>Target + beam pipe</td>
<td>0.5</td>
</tr>
<tr>
<td>Fiber tracker</td>
<td>0.93</td>
</tr>
<tr>
<td>Fiber mats</td>
<td>0.01</td>
</tr>
<tr>
<td>Tooling</td>
<td>0.45</td>
</tr>
<tr>
<td>SiPM array</td>
<td>0.1</td>
</tr>
<tr>
<td>Front-end electronics</td>
<td>0.12</td>
</tr>
<tr>
<td>Back-end electronics</td>
<td>0.05</td>
</tr>
<tr>
<td>Mechanics and cooling</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Optical-TPC</strong></td>
<td>10.0</td>
</tr>
<tr>
<td>Vessel</td>
<td>0.5</td>
</tr>
<tr>
<td>Aerogel</td>
<td>1.0</td>
</tr>
<tr>
<td>Photo-sensors (LAPPD option)</td>
<td>6.0</td>
</tr>
<tr>
<td>Front-end electronics</td>
<td>1.8</td>
</tr>
<tr>
<td>Back-end electronics</td>
<td>0.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADRIANO2</td>
<td>16.0</td>
</tr>
<tr>
<td>Pb-glass</td>
<td>2.7</td>
</tr>
<tr>
<td>Cast scintillator</td>
<td>0.75</td>
</tr>
<tr>
<td>Tile fabrication</td>
<td>0.6</td>
</tr>
<tr>
<td>SiPM</td>
<td>6.0</td>
</tr>
<tr>
<td>Front-end electronics</td>
<td>4.0</td>
</tr>
<tr>
<td>Back-end electronics</td>
<td>1.5</td>
</tr>
<tr>
<td>Mechanics and cooling</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Trigger</strong></td>
<td>1.2</td>
</tr>
<tr>
<td>L0 + L1</td>
<td>1.0</td>
</tr>
<tr>
<td>L2 farm + networking</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>DAQ</strong></td>
<td>5.0</td>
</tr>
<tr>
<td>Digitizer</td>
<td></td>
</tr>
<tr>
<td>Networking</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contingency</td>
<td>Pre</td>
</tr>
<tr>
<td>50% Contingency</td>
<td>17.0</td>
</tr>
<tr>
<td><strong>Total REDTOP</strong></td>
<td>51.3</td>
</tr>
</tbody>
</table>

- **For Fermilab**
  - Add labor and accelerator (R.F.cavities and EM septum are available at Fermilab)
  - Adjust contingency from 50% to 25%
History of the Project

Dec. 2014
- Born at FTBF (A. M., C. G., H. F.)

Sept. 2017
- LOI submitted to Fermilab’s PAC in Sept. 2017
  - PAC recommendation: “The PAC finds that the science goals of the experiment are very interesting….., the PAC does not recommend that the Laboratory invest resources into furthering the REDTOP proposal at this time.”
  - Fermilab’s Director recommended a two-year waiting period (still ongoing).

Jan. 2018
- REDTOP admitted into the “Physics Beyond Colliders” program to explore a possible implementation at CERN
- Near full simulations studies indicate very good sensitivity studies to physics BSM for 3 out of 4 “portals”
- Final report from PBC indicate that the experiment is feasible at CERN, but with lower (1/10x) beam luminosity and larger impact on existing physics program cfr. FNAL

Dec. 2018
- EOI submitted to European Strategy for Particle Physics
Phase I: \( \eta \)-factory. Goal is \(~10^{13} \eta \)/yr
- \( T_{\text{beam}} \): 1.8-2.1 GeV
- Power: 30 W
- Target: 10 x 0.33 mm Be

Phase II: \( \eta' \)-factory. Goal is \(~10^{11} \eta' \)/yr
- \( T_{\text{beam}} \): 3.5-4.5 GeV (to be optimized)
- Power: 60 W
- Target: 10 x 0.33 mm Be

Phase III: Dark photons radiating form muons. Goal is \( >1.0 \times 10^{13} \mu \)/yr
- (G. Krnjaic and Y. Kahn)
- \( T_{\text{beam}} \): 1< 3 GeV (to be optimized)
- Target: \( \text{H}_2 \) gas

Phase IV: Muon Scattering Experiment. Goal is \( >2.0 \times 10^{12} \mu \)/yr
- \( T_{\text{beam}} \): 0.2< 0.8 GeV (to be optimized)
  - Muon yield: \( >1.6 \times 10^{-8} \mu /p \)
  - Target: 1 x 100 mm graphite

Phase V: tagged REDTOP. Goal is \( >2.0 \times 10^{13} \eta \)/yr
- \( T_{\text{beam}} \): 1.2 GeV at PIP-II
  - Muon muon yield: \( >1.6 \times 10^{-8} \mu /p \)
  - Target: \( ^3 \text{H} \)

Phase VI: Rare Kaon Decays: \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) Goal is \( >1 \times 10^{14} \text{KOT} /\text{yr} \)
- \( T_{\text{beam}} \): \( K^+ \) from 8 GeV protons
  - \( K^+/\pi \) yield: \( 1/13 \) (neglecting very soft pions – factor 1.8 better than \( p@92 \text{GeV} \))
  - Target: primary (PT: for \( K \) production) + secondary (active: scintillating plastics)

It could be made unnecessary by NA62+ and JPARC
Intermediate Phases

*Pre-REDTOP with OTPC only*

- $p^7 Li \rightarrow ^8 Be^* \rightarrow e^+ e^- X$
  - At 2.5 MeV IOTA proton source (Fermilab)
  - Confirm 17 MeV bump found in Prague experiment
- $p D \rightarrow ^3 He e^+ e^- \ (M. Viviani, L. E. Marcucci and A. Kievsky)$
  - At 40 MeV Fermilab p linac (Fermilab) or ATLAS facility (ANL)
- $p^9 Be \rightarrow ^8 Be^* + X \rightarrow e^+ e^- X$
  - At MCenter 2 GeV p beam (Fermilab)
- $\mu^+$ Nucleus scattering in fixed target mode
  - 1.5-3 GeV muon campus – Fermilab
- $\mu^+$ Nucleus in beam dump mode
- $e^- Nucleus in fixed target mode$
  - 250-500 MeV, 50 mA IOTA facility – Fermilab
- $e^- Nucleus in beam dump mode$
- OTPC test with 2 GeV protons dumped by g-2 - Fermilab
### The REDTOP collaboration

<table>
<thead>
<tr>
<th>Countries</th>
<th>Institutions</th>
<th>Collaborators</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>23</td>
<td>67</td>
</tr>
</tbody>
</table>

- J. Confort, P. Mauskopf, D. McFarland, L. Thomas
  Arizona State University, (USA)
- I. Pedraza, D. Leon, S. Escazur, D. Herrera, D Silverio
  Benemérita Universidad Autónoma de Puebla, (Mexico)
- A. Alqahtani
  Brown University, (USA)
- F. Ignatov
  Budker Institute of Nuclear Physics – Novosibirsk, (Russia)
  Fermi National Accelerator Laboratory, (USA)
- P. Sánchez-Oquera
  IFAE – Barcelona, (Spain)
- C. Gatto
  Instituto Nazionale di Fisica Nucleare – Sezione di Napoli, (Italy)
- W. Badini
  Instituto Nazionale di Fisica Nucleare – Sezione di Ferrara, (Italy)
- R. Carosi, A. Kievsky, M. Viviani
  Instituto Nazionale di Fisica Nucleare – Sezione di Pisa, (Italy)
- W. Krzemień, M. Sliarzki, M. Zieliński
  Jagiellonian University, Krakow, (Poland)

- S. Pastore
  Los Alamos National Laboratory, (USA)
- M. Berliowski
  National Centre for Nuclear Research – Warsaw, (Poland)
- G. Blazey, M. Syphers, V. Zutshi, P. Chintalapati, T. Maila, M. Figora
  Northern Illinois University, (USA)
- M. Pospelov
  Perimeter Institute for Theoretical Physics – Waterloo, (Canada)
- Y. Kahn
  Princeton University – Princeton, (USA)
- A. Gutiérrez-Rodriguez, M. A. Hernandez-Ruiz
  Universidad Autónoma de Zacatecas, (Mexico)
- B. Fabela-Enriquez
  Vanderbilt University, (USA)
- C. Siligardi, S. Barbi, C. Mugoni
  Università di Modena e Reggio Emilia, (Italy)
- L. E. Marcuccio
  Università di Pisa, (Italy)
- M. Guida
  Università di Salerno, (Italy)
- J. Konisberg
  University of Florida, (USA)
- S. Gardner, J. Shi, X. Yan
  University of Kentucky, (USA)
- R. Rusack
  University of Minnesota, (USA)
- A. Kupsc
  University of Uppsala, (Sweden)

- Potential hosting laboratories: BNL, CERN, FNAL (either DR and/or PIP-II)
Event generation

- GenieHad (Genie add-on) event generator interfaces to: Urqmd, Gibuu, Phsd, Abla, Gemini, SMM, G4EM processes, Incl+++, IAEA tables, LELAPS

- New interfaces to JAM (JPARC) and ALPS (for PIP-II simulations) in preparation

Simulation, digitization, reconstruction and analysis

- Based on ILC frameworks (slic, lcsim and ilcroot)

- Full simulation in place (except for OTPC-reco and vertexing)

Detector optimization and sensitivity studies are ongoing

- Improvement on BSM physics from detached vertices
Ongoing activities – detector R&D

- **ADRIANO**
  - ADRIANO2 prototype under construction at NIU (INFN-NIU-UMN collaboration). FNAL probably joining (J. Freeman)
  - Inherits from 10+ years R&D by T1015

- **O-TPC**
  - UC (H. Frish) only existing prototype
  - Requires a more structured collaboration

- **Fiber tracker**
  - No R&D needed: technology is exact copy of LHCB’s new tracker
  - In talk with Aachen-RWTH for joining
  - Otherwise, technology&tools transfer to REDTOP
Once approved and funded, REDTOP needs about 2-3 years detector R&D + 1 year detector construction

- Solenoid and 3/4 of Pb-Glass for ADRIANO in-kind contributions from INFN (Finuda and NA64 experiments)

Accelerator mods requires:

- BNL: <1yr (only requiring a new electronics for the extraction line (C4))
- CERN: need further studies
- FNAL: ~1yr (add a SC cavity to the DR and build an extraction line)
Future Prospects

- The Collaboration is currently engaged in the ESPP and P5-Snowmass processes

- Endorsement by the community and/or laboratories is needed to fund detector R&D activities

- Current activities aim at the preparation of a full proposal in about 2-3 years (corresponding to the ESPP conclusion)
  - Fermilab best: either DR or PIP-II (tREDTOP)
  - Detector optimization and sensitivity studies
  - Detector R&D

- Competition from several other experiments (LHCB, et. Al.)
  - However, experimental techniques are quite different

- More details: https://redtop.fnal.gov
The $\eta/\eta'$ meson is a fantastic laboratory for studying rare processes and physics BSM

Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles

REDTOP goal is to produce $\sim 10^{13} \eta$ mesons/yr in phase I and $\sim 10^{11} \eta'$ /year in phase II

More running phases could use different beam species:

- PIP-II for a tagged-$\eta$ experiment

Several labs could host the experiment (FNAL is the most optimal)

New detector technique would set the stage for next generation High Intensity experiments

Moderate cost

C. Gatto - INFN & NIU 54
Backup slides
Beam Requirements for $\eta$-factory (1)

Beam energy

- **Constraints:**
  - Beam energy large enough to get $\Gamma(\eta)/\Gamma(pX) \sim 1\%$
  - Beam energy low enough to make slow baryons (minimize background)
  - $\eta$ meson energy low enough to make slow pions
  - $T_{\text{beam}} = 1.8 - 2.1$ GeV (still under optimization but 1.9 GeV seems preferred)

**Total cross sections @ 2 GeV**

$pp \to pp\eta$

140 $\mu$barn

Total inelastic cross sections @ 2 GeV

About 200x
Constraints:

- Same as for $\eta$-factory
- $E_{\text{beam}} = 3.0 - 4.0$ GeV (yet to be optimized)
- $R_\eta = \sigma(pp \rightarrow p\eta')/\sigma(pp \rightarrow pp\eta')$ slightly lower than $R_\eta$

Total cross sections @ 3.8 GeV
- $pp \rightarrow pp\eta'$
  - 1 $\mu$barn
Total inelastic cross sections @ 2 GeV
  - About 25,000x
Large beam losses will occur if beam is decelerated from injection @ 8 GeV (\(\gamma = 9.53\)) to 2 GeV (\(\gamma = 3.13\)) through the DR natural transition energy \(\gamma_t = 7.64\).

Transition is avoided by using select quad triplets to boost \(\gamma_t\) above beam \(\gamma\) by 0.5 units throughout deceleration until \(\gamma_t = 7.64\) and beam \(\gamma = 7.14\) (5.76 GeV kinetic).

Below 5.76 GeV the DR lattice reverts to the nominal design configuration.

Optical perturbations are localized within each triplet.

Straight sections are unaffected thereby keeping the nominal M3 injection beamline tune valid.
Non-gaussian Dual readout calorimeter is two distinct calorimeters sharing the same absorber. Measured energy is gaussian because of compensation event by event.

\[ E_{HCAL} = \eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1) \]

\[ \eta_C = \left( \frac{e}{h} \right)_C \quad \eta_S = \left( \frac{e}{h} \right)_S \]

From calibration @ 1 Energy only

6/11/2019 C. Gatto - INFN & NIU
Dual Readout Calorimetry from a Different Perspective

\[ E_{\text{HCAL}} = \frac{\eta_s \cdot E_s \cdot (\eta_c - 1) - \eta_c \cdot E_c \cdot (\eta_s - 1)}{\eta_c - \eta_s} \]

\[ \begin{align*}
\eta_s &= \left( \frac{e}{h} \right)_s \\
\eta_c &= \left( \frac{e}{h} \right)_c
\end{align*} \]

If \( \eta_s \neq \eta_c \) then the system can be solved for \( E_{\text{HCAL}} \)

Dual Readout is nothing but a rotation in \( E_S - E_C \) plane

\[ E_S = \left[ \text{fem} + \frac{(1 - \text{fem})}{\eta_s} \right] \cdot E_{\text{HCAL}} \]

\[ E_C = \left[ \text{fem} + \frac{(1 - \text{fem})}{\eta_c} \right] \cdot E_{\text{HCAL}} \]
The major source of fluctuations: \textit{fem}

<table>
<thead>
<tr>
<th>Scintillating signal</th>
<th>40 Gev $\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^\pm, p, n$</td>
<td>$e^\pm, \pi^0, \gamma, \eta$</td>
</tr>
<tr>
<td>total</td>
<td>total</td>
</tr>
</tbody>
</table>
Dual Readout is nothing but a rotation in E_S - E_C plane

$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$

$$\eta_s = \left( \frac{e}{h} \right)_s, \quad \eta_c = \left( \frac{e}{h} \right)_c$$

$$\begin{cases} E_S = \left[ fem + \frac{(1 - fem)}{\eta_S} \right] \cdot E_{HCAL} \\ E_C = \left[ fem + \frac{(1 - fem)}{\eta_C} \right] \cdot E_{HCAL} \end{cases}$$

If $\eta_s \neq \eta_c$ then the system can be solved for $E_{HCAL}$
**Figures of Merit for Dual-Readout Calorimeter**

- **Large pe/GeV**: must be much greater than 45 pe/GeV (corresponding to 15% theoretical limit contribution to stochastic term)

- System is solvable only when $\eta_S \neq \eta_C$. The larger the compensation asymmetry the better. Aka, $\tan(\theta_{S/Q})$ much different from 1

\[
\sigma_{E_{corr}}^2 = \left(\frac{1}{1-\chi}\right)^2 \sigma_S^2 + \left(\frac{\chi}{1-\chi}\right)^2 \sigma_Q^2
\]

\[
\chi \equiv \tan(\theta_{S/Q}) = \frac{1-1/\eta_C}{1-1/\eta_S}
\]

- **Small $\Gamma$** = photodetector area/calorimeter area. $\Gamma_{\text{DREAM}} = 24\%$. $\Gamma_{4\text{th}} = 21\%$. Goal is $\Gamma < 10\%$.

- **Small mixing of S and C components**
ADRIANO for ORKA Final Prototypes
High Energy
- Detection of Hadronic and EM showers with large S and Č light production
- Optimized for maximum shower containment (i.e. max detector density)

- Thicker glass
- Thin scintillating fibers or ribbons
- Fewer WLS fibers

High Intensity
- Detection of EM showers only with small S and Č light production
- Optimized for high sensitivity in the 10 MeV range (i.e. max detector granularity)

- Thinner glass
- Thicker scintillator plates
- More WLS fibers
<table>
<thead>
<tr>
<th>Prototype</th>
<th>Year</th>
<th>Glass</th>
<th>gr/cm³</th>
<th>Čerenkov L. Y./GeV</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 slices, machine grooved, unpolished, white</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>82</td>
<td>SiPM readout</td>
</tr>
<tr>
<td>5 slices, machine grooved, unpolished, white, v2</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>84</td>
<td>SiPM readout</td>
</tr>
<tr>
<td>5 slices, precision molded, unpolished, coated</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>55</td>
<td>15 cm long</td>
</tr>
<tr>
<td>2 slices, ungrooved, unpolished, white wrap</td>
<td>2011</td>
<td>Ohara BBH1</td>
<td>6.6</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>5 slices, scifi silver coated, grooved, clear, unpolished</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>64</td>
<td>15 cm long</td>
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<tr>
<td>5 slices, scifi white coated, grooved, clear, unpolished</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>120</td>
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</tr>
<tr>
<td>2 slices, plain, white wrap</td>
<td>2011</td>
<td>Ohara</td>
<td>7.5</td>
<td>-</td>
<td>DAQ problem</td>
</tr>
<tr>
<td>10 slices, white, ungrooved, polished</td>
<td>2012</td>
<td>Ohara PBH56</td>
<td>5.4</td>
<td>30</td>
<td>DAQ problems</td>
</tr>
<tr>
<td>10 slices, white, ungrooved, polished</td>
<td>2012</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>5 slices, wifi Al sputter, grooved, clear, polished</td>
<td>2012</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>30</td>
<td>2 wls/groove</td>
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<tr>
<td>5 slices, white wrap, ungrooved, polished</td>
<td>2012</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>158</td>
<td>Small wls groove</td>
</tr>
<tr>
<td>ORKA barrel</td>
<td>2013</td>
<td>Schott SF57</td>
<td>5.6</td>
<td>2500/side</td>
<td>molded</td>
</tr>
<tr>
<td>ORKA endcaps</td>
<td>2013</td>
<td>Schott SF57</td>
<td>5.6</td>
<td>4000</td>
<td>molded</td>
</tr>
<tr>
<td>10 slices – 6.2 mm thick, scifi version</td>
<td>2014</td>
<td>Schott SF57</td>
<td>5.6</td>
<td>338</td>
<td>molded</td>
</tr>
<tr>
<td>10 slices – 6.2 mm thick, sci-plate version</td>
<td>2014</td>
<td>Schott SF57</td>
<td>5.6</td>
<td>354</td>
<td>molded</td>
</tr>
</tbody>
</table>
On CP violation (CPV) in $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay

Unlike $\eta \rightarrow \pi \pi$ decay, CPV can appear via amplitude interference.

CPV effect would be linear in a CPV parameter.

Multiple observables appear through the Dalitz plot.

- Recall early discussions of C violation, possibly through EM interactions.
- C violation can be discovered through a “charge asymmetry” in the Dalitz plot (difference in the $\pi^+ / \pi^-$ energy spectra).

Note left-right (+/-) asymmetry — and asymmetries to probe if I is non-zero as well.

- New! Note structure of possible CPV interferences in decay rate.

[Note also Layter et al. PRL1972 and, e.g., KLOE-2, JHEP 2016]

On CP violation (CPV) in $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay

Terms in $|A|^2$ that are odd in $X$ generate a charge (±/) asymmetry.
Can also fit Dalitz distribution for these $X$ odd terms.

$|M|^2 = A_0^2 (1 + ay + by^2 + dx^2 + fy^3 + gx^2y + \cdots)$. 

Bkgd subtracted events, figure from KLOE-2, JHEP 2016

Slide Credit: Susan Gardner & Jun Shi
Theoretical Analysis: $\eta \rightarrow \pi^+ \pi^- \pi^0$

C and CP violation poorly constrained in flavor diagonal processes

New way to construct CPV amplitudes in $\eta \rightarrow \pi^+ \pi^- \pi^0$

- Use NLO ChPT result & project it to the isospin basis of two pions (I=0,1,2)

[Gasser & Leutwyler, 1985; note also Anisovich & Leutwyler, 1996; Bijnens & Ghorbani, 2007]

- Add CP violating terms controlled by “a” and “b”

$$A(s,t,u) = M_0(s) + (s-u)M_1(t) + (s-t)M_1(u) + M_2(t) + M_2(u) - \frac{2}{3}M_2(s)$$

$$+a[(s-u)M_1(t) - (s-t)M_1(u)] + b[M_2(t) - M_2(u)]$$

- Expand 8 CPV interferences in $|A(s,t,u)|^2$ in terms of (X, Y)=(0,0)

- Can fit the Dalitz plot to get Re(a), Im(a), Re(b), Im(b) and/or study charge asymmetries

Preliminary analysis shows the largest CPV contributions could come from the interference with $M_0(s)$

J. Kilmer
J. Rauch
E. Barzi (Solenoid and yoke)

(Many thanks to K. Krempetz, as well)
BNL hadron complex
Building 912 AGS Experimental Area (1998)

In use for SRF and ATF-II