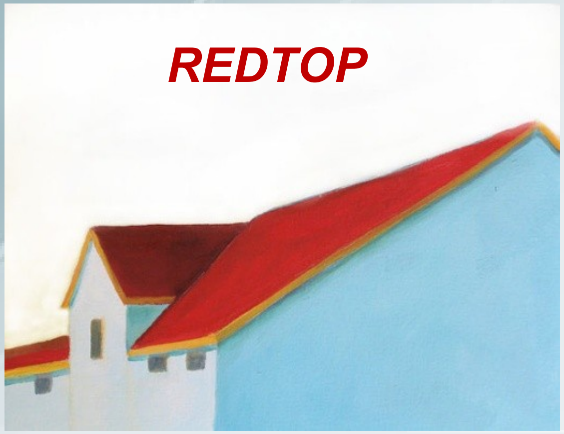
The REDTOP experiment: a η/η' factory to explore dark matter and physics beyond the Standard Model



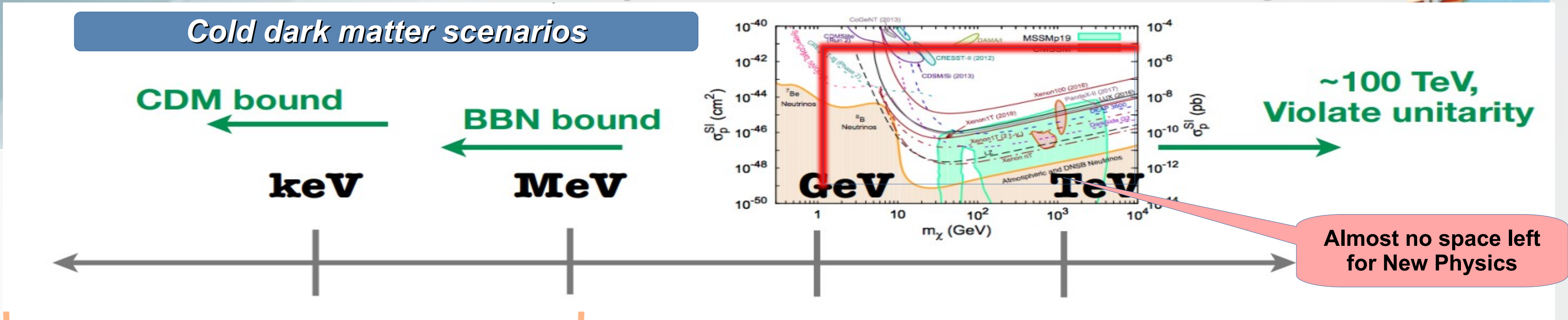
Rare Eta Decays
TO Probe New Physics

Corrado Gatto

INFN Napoli and Northern Illinois University

Rationale for an η/η′ Factory

REDTOP



Bound by cosmological observations	Mostly unconstrained	Disfavorite by LHC/Direct detection	Requires new facilities

"Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders" [G. Krnjaic RF6 Meeting, 8/2020]

- The only known particles with all-zero quantum numbers: Q = I = J = S = B = L = 0 are the **η/η′ mesons** and the **Higgs boson (also the vacuum!)** ->very rare in nature
- The η meson is a Goldstone boson (the η′ meson is not!)
- The η/η′ decays are flavor-conserving reactions

Experimental advantages:

- Hadronic production cross section is quite large (~ 0.1 barn) → easy to produce
- Strong & EM decays are forbidden in lowest order by discrete symmetry invariance. BR of processes from New Physics are enhanced compared to SM.

A η/η′ factory is equivalent to a low energy Higgs factory and an excellent laboratory to probe New Physics below 1 GeV

REDTOP Key Points

REDTOP: η/η′ yielding ~10^{14}(10^{12}) mesons

$\mathcal{O}(10^5)$ the existing world sample with a 3-yr run

Hadro-produced mesons: requires a 30W (55W) CW proton beam

Pion beam also well suited

Designed to search for BSM physics in the MeV-GeV region

Main search fields: dark matter and CP-violation

Sensitive to 17MeV resonances

Moderate cost:

$55M excl. contingency and labor

Main Physics Goals of REDTOP

Test of CP invariance via Dalitz plot mirror asymmetry: $\eta \to \pi^o \pi^+ \pi^-$

Search for asymmetries in the dalitz plot with very high statistics

Test of CP invariance via μ polarization studies: $\eta \to \pi^o \mu^+ \mu^-$, $\eta \to \gamma \mu^+ \mu^-$, $\eta \to \mu^+ \mu^-$,

Measure the angular asymmetry between spin and momentum

Dark photon searches: $\eta \to \gamma A'$, with $A' \to \mu^+ \mu^-$, $A' \to e^+ e^-$

Need excellent vertexing and particle ID

QCD axion and ALP searches: $\eta \to \pi\pi a$, with $a \to \gamma\gamma$, $a \to \mu^+ \mu^-$, $a \to e^+ e^-$

Dual (or triple!) calorimeters and vertexing

Dark scalar searches: $\eta \to \pi^o H$, with $H \to \mu^+ \mu^-$, $H \to e^+ e^-$

Dual (or triple!) calorimeters and particle ID

Lepton Flavor Universality studies: $\eta \to \mu^+ \mu^- X$, $\eta \to e^+ e^- X$

Need excellent particle ID

Detecting BSM Physics with REDTOP (η/η′ factory)

Assuming a yield ~10^{14} η mesons/yr and ~10^{12} η′ mesons/yr

C, T, CP-violation

- *CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^o \pi^+\pi^-$*
- *CP Violation (Type I – P and T odd , C even): $\eta \to 4\pi^o \to 8\gamma$*
- *CP Violation (Type II - C and T odd , P even): $\eta \to \pi^o \ell^+\ell^-$ **and** $\eta \to 3\gamma$*
- *Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$*
- *CP inv. via γ* polarization studies: $\eta \to \pi^+\pi^-e^+e^-$ & $\eta \to \pi^+\pi^-\mu^+\mu^-$*
- *CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-e^+e^-$*
- *CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-\pi^+\pi^-$*
- *CP invariance in μ polar. in studies: $\eta \to \pi^o \mu^+\mu^-$*
- *T invar. via μ transverse polarization: $\eta \to \pi^o\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$*
- *CPT violation: μ polr. in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ - γ polar. in $\eta \to \gamma\gamma$*

Other discrete symmetry violations

- *Lepton Flavor Violation: $\eta \to \mu^+e^- + c.c.$*
- *Radiative Lepton Flavor Violation: $\eta \to \gamma\mu^+e^- + c.c.$*
- *Double lepton Flavor Violation: $\eta \to \mu^+\mu^+e^-e^- + c.c.$*

Non-η/η′ based BSM Physics

- *Neutral pion decay: $\pi^o \to \gamma A' \to \gamma e^+e^-$*
- *ALP's searches in Primakoff processes: $p\,Z \to p\,Z\,a \to l^+l^-$*
- *Charged pion and kaon decays: $\pi+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$*
- *Dark photon and ALP searches in Drell-Yan processes: $qqbar \to A'/a \to l^+l^-$*

New particles and forces searches

- *Scalar meson searches (charged channel): $\eta \to \pi^o H$ with $H \to e^+e^-$ and $H \to \mu^+\mu^-$*
- *Dark photon searches: $\eta \to \gamma A'$ with $A' \to \ell^+\ell^-$*
- *Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to \pi^+\pi^-$*
- *QCD axion searches : $\eta \to \pi\pi \boldsymbol{a}_{17}$ with $\boldsymbol{a}_{17} \to e^+e^-$*
- *New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^o$*
- *Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$*
- *Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$*
- *Lepton Universality*
- *$\eta \to \pi^o H$ with $H \to \nu N_2$, $N_2 \to h'N_1$, $h' \to e^+e^-$*

Other Precision Physics measurements

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

High precision studies on medium energy 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)*

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- T invar. via μ transverse polarization: $\eta \to \pi^o\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ polar. in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ - γ polar. in $\eta \to \gamma\gamma$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+e^- + c.c.$
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- Dark photon searches: $\eta \to \gamma A'$ with $A' \to l^+l^-$
- Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to \pi^+\pi^-$
- QCD axion searches : $\eta \to \pi\pi a_{17}$ with $a_{17} \to e^+e^-$
- New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^o$
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- Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$
- Lepton Universality
- $\eta \to \pi^o H$ with $H \to \nu N$, $N \to$ [illegible] e^+e^-

Other Precision Physics measurements

- Proton radius anomaly: $\eta \to \gamma\mu^+\mu^-$ vs $\eta \to \gamma e^+e^-$
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Only experiment, along with SHIP, sensitive to all four BSM portals

The physics case for REDTOP

Physics case presented in 176-pp White Paper. Sensitivity studies based on ~10^{14} η mesons (3.3×10^{18} POT and 3-yr run), >30×10^{6} CPU-Hr on OSG+NICADD

15 processes fully simulated and reconstructed – 20 theoretical models benchmarked

- Four BSM portals
- Three CP violating processes requiring no μ-polarization measurement
- A fourth CP violating processes under study
- Three CP violating processes requiring μ-polarization measurement
- Two lepton flavor universality studies
- Two lepton flavor violation studies

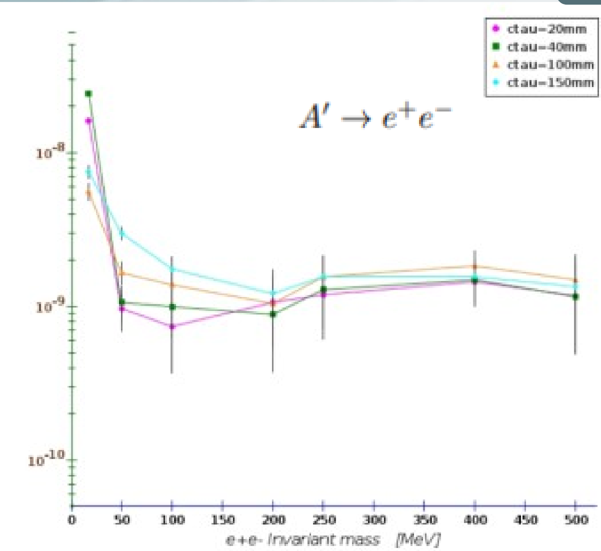
Key detector parameters

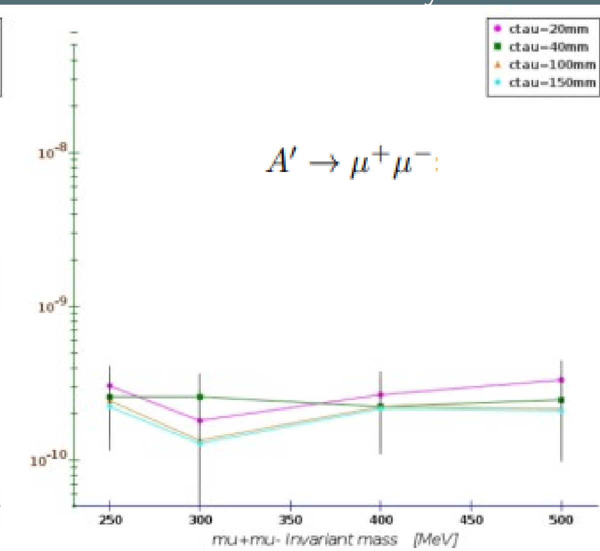
- Large sensitivity to <17 Mev mass resonances (compared to WASA and KLOE)
- Tracking capable to reconstruct detached verteces up to ~100 cm
- Sensitivity to BR ~$\mathcal{O}(10^{-11})$ (~$\mathcal{O}(10^{-12})$ with pion beam)
- Detector optimization under way

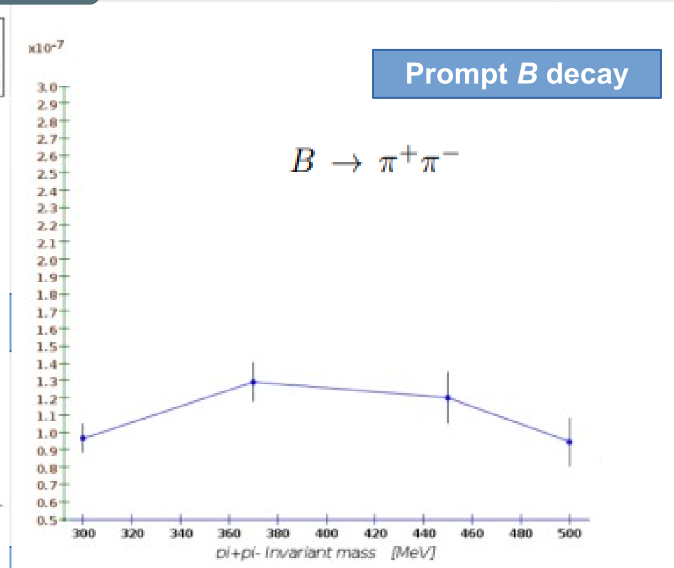
Vector Portal: $\eta \to \gamma A'$ with $A' \to l^+l^-$ or $\pi^+\pi^-$

REDTOP

Some BR sensitivity curves







Sensitivity curves for Minimal Dark Photon Model

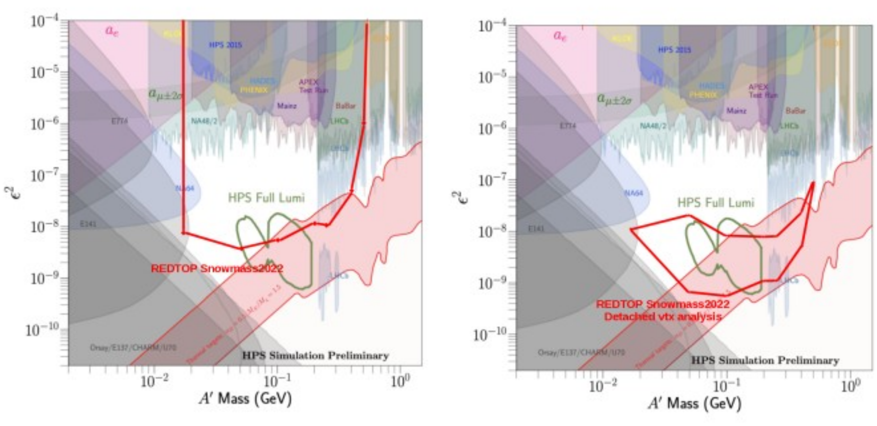


FIG. 36. Sensitivity to to ε^2 for the processes $\eta \to \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

Theoretical Models considered

- *Minimal dark photon model*
  - *Most popular model*
- *Leptophobic B boson Model*
- *Protophobic Fifth Force*
  - *Explains the Atomki anomaly*

New particles & forces

Pseudoscalar Portal: $\eta \rightarrow \pi^0 \pi^0 a$ & $\eta \rightarrow \pi^+ \pi^- a$ with $a \rightarrow \gamma\gamma$, $\mu^+\mu^-$ and $e^+ e^-$

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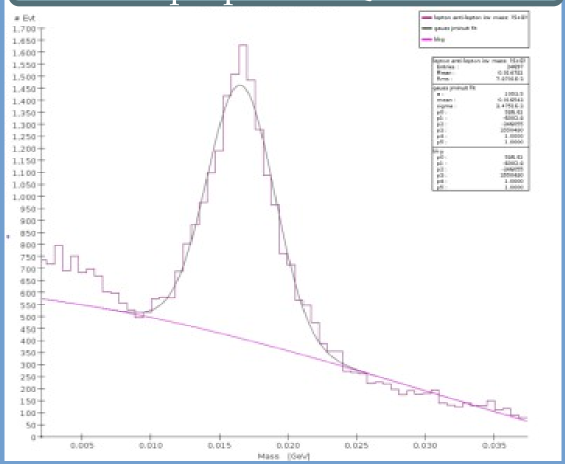
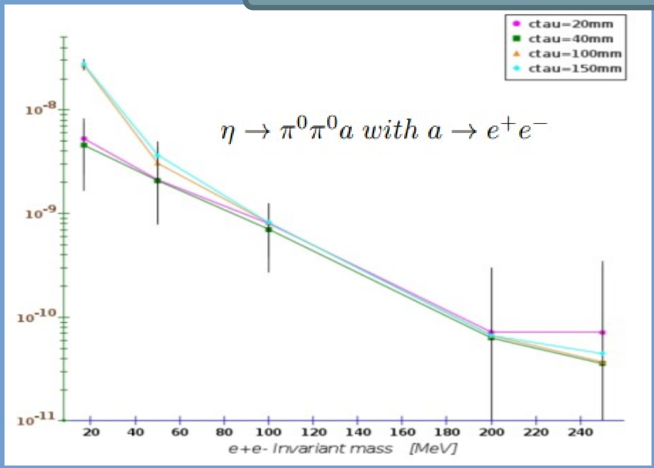
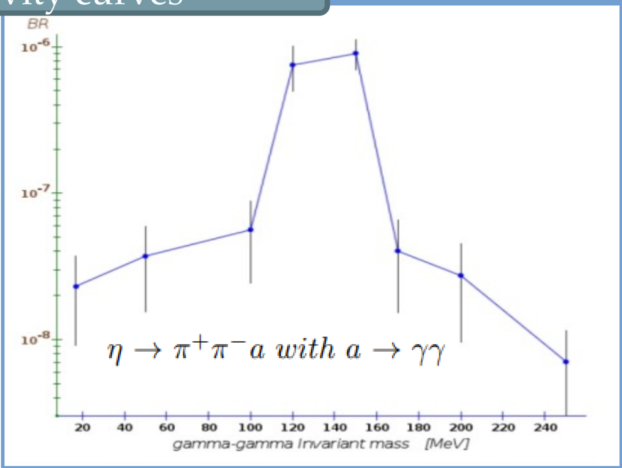
17 MeV piophobic QCD axion

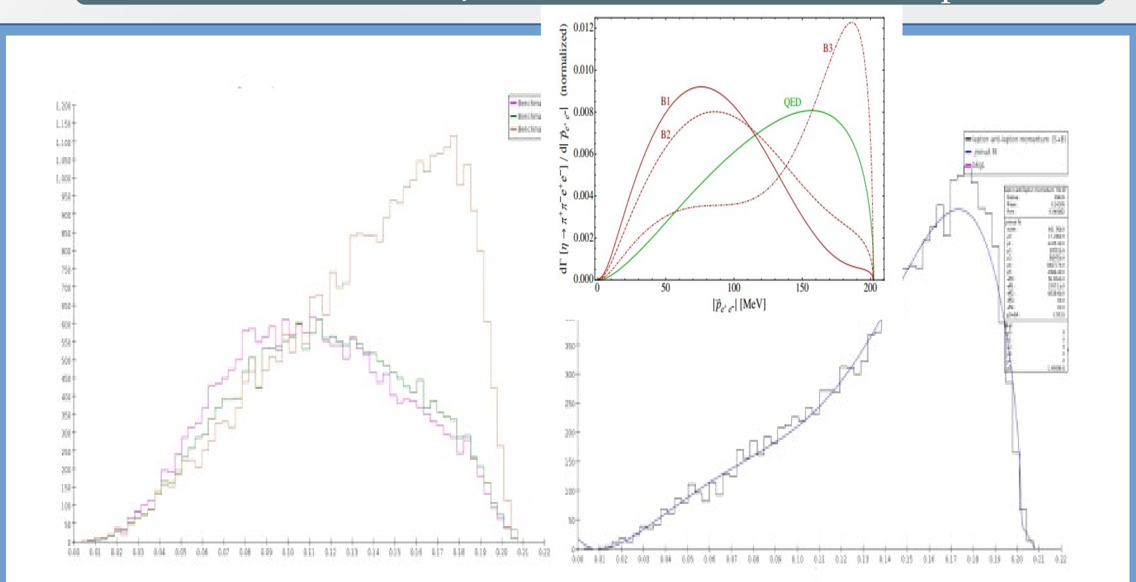


Some BR sensitivity curves





Differential rate for $\eta \rightarrow \pi^+\pi^- a$ for three benchmark params

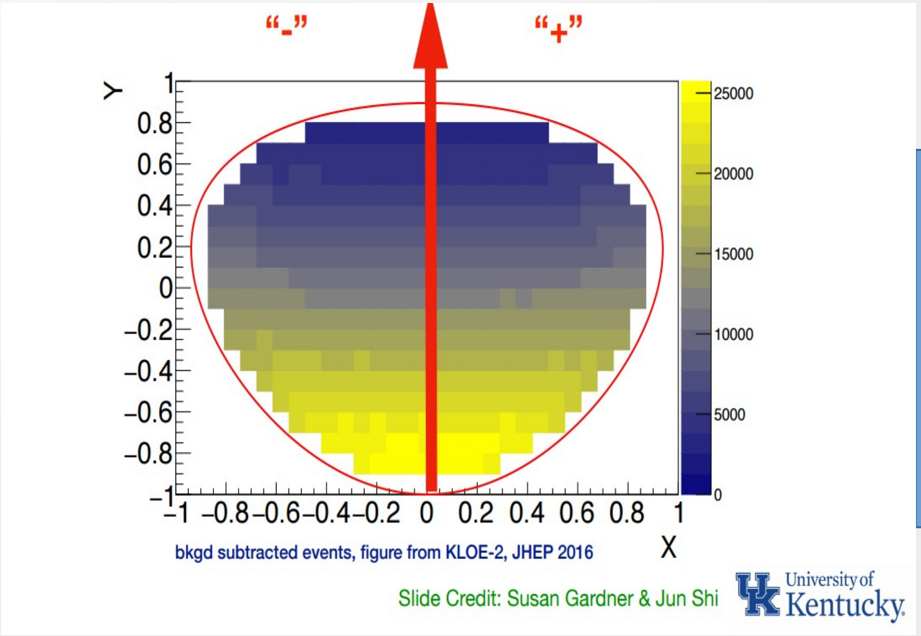


Theoretical models considered

- ***Piophobic QCD axion model*** *(D. S. M. Alves)*
  - *Below KLOE sensitivity*
  - *the CELSIUS/WASA Collaboration observed 24 evts with SM expectation of 10*
- ***Heavy Axion Effective Theories***

CP Violation from Dalitz plot mirror asymmetry in $\eta \to \pi^+\pi^-\pi^o$

- *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*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi) based on* https://arxiv.org/abs/1903.11617

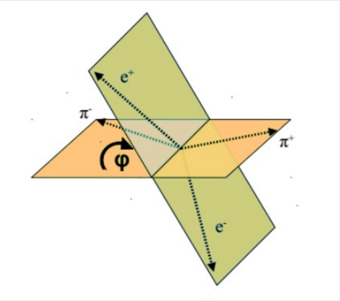


REDTOP sensitivity to model parameters

#Rec. Events	Re(α)	Im(α)	Re(β)	Im(β)	p-value
10^8 (no-bkg)	3.3×10^{-1}	3.7×10^{-1}	4.4×10^{-4}	5.6×10^{-4}	17%
Full stat. (no-bkg)	1.9×10^{-2}	2.1×10^{-2}	2.5×10^{-5}	3.2×10^{-5}	17%
Full stat. (100%-bkg)	2.3×10^{-2}	3.0×10^{-2}	3.5×10^{-5}	4.5×10^{-5}	16%

CP Violation from the asymmetry of the decay planes in $\eta \to \mu^+\mu^- e^+e^-$ and $\eta \to \pi^+\pi^- e^+e^-$

- See: Dao-Neng Gao, /hep-ph/0202002 and P. Sanchez-Puertas, JHEP 01, 031 (2019)
- *Requires the measurement of angle between pions and leptons decay planes*



CP violation is related to asymmetries in $\eta \to \mu^+\mu^- e^+e^-$

$$A_{sin\Phi cos\Phi} = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$

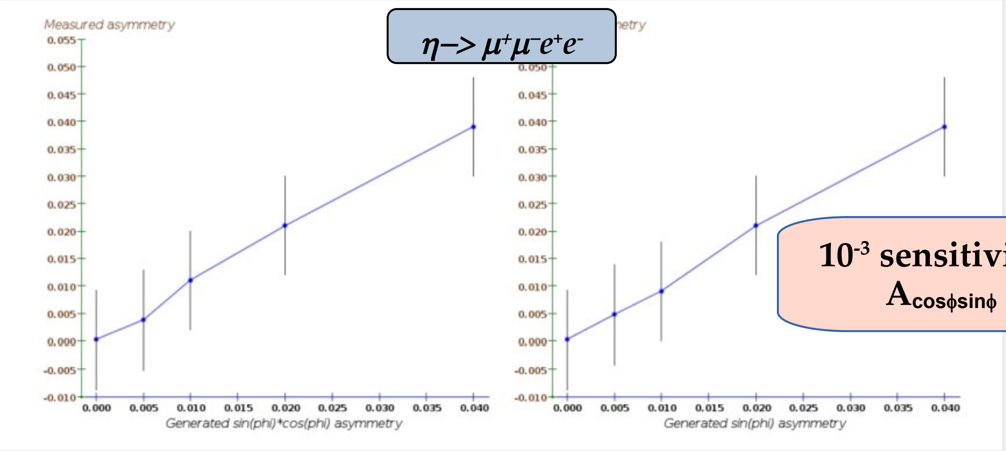
$$A_{sin\Phi} = \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)}$$

through Wilson coefficients

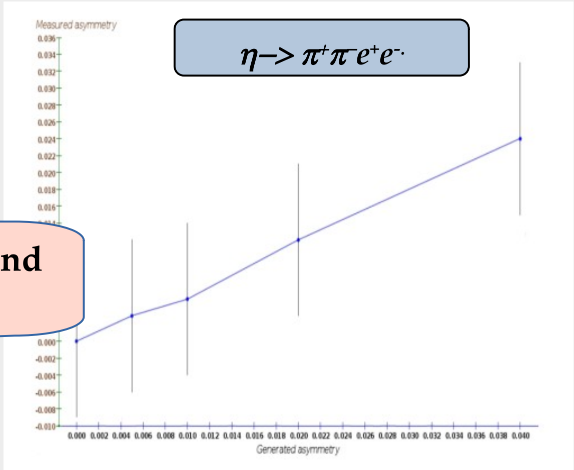
$$A_{\sin\phi\cos\phi} = \mathrm{Im}[1.9 c^{2222}_{\ell edq} - 1.3(c^{(1)2211}_{\ell equ} + c^{1122}_{\ell edq})] \times 10^{-5} - 0.2\epsilon_1 + 0.0003\epsilon_2$$

CP violation is related to asymmetries in $\eta \to \pi^+\pi^- e^+e^-$

$$A_\phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$



10^{-3} sensitivity to and $A_{\cos\phi\sin\phi}$ $A_{\sin\phi}$



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CP Violation in $\eta \to (\gamma,\pi^o)\mu^+\mu^-$

From model: P. Masjuan and P. Sanchez-Puertas, JHEP 08, 108 (2016), 1512.09292 & JHEP 01, 031 (2019), 1810.13228.

- *Requires the measurement of μ–polarization to form the following asymmetries*

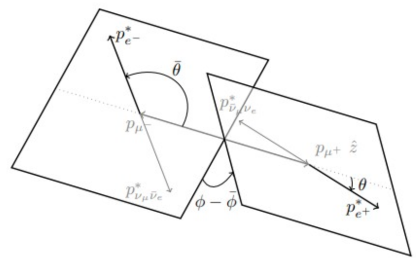


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar{\nu}$ system. The $\hat{z}$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

$$A_L = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N} = \mathrm{Im}[4.1 c^{2222}_{\ell edq} - 2.7(c^{(1)2211}_{\ell equ} + c^{2211}_{\ell edq})] \times 10^{-2}, \quad (47)$$

$$A_\times = \frac{N(\sin\Phi > 0) - N(\sin\Phi < 0)}{N} = \mathrm{Im}[2.5 c^{2222}_{\ell edq} - 1.6(c^{(1)2211}_{\ell equ} + c^{2211}_{\ell edq})] \times 10^{-3}, \quad (48)$$

REDTOP sensitivity to Wilson CP violating Wilson coeffiecients

Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction + analysis*	**Total**	Branching ratio sensitivity
$\eta \to \mu^+\mu^-$	66.3%	16.3%	51.9%	69.6%	3.9%	$2.7 \times 10^{-8} \pm 3.0 \times 10^{-10}$
Urqmd	21.7%	1.7%	22.2%	8.6×10^{-3}%	7.0×10^{-6}%	-

$$\Delta(c^{1122}_{\ell equ}) = 0.1 \times 10^{-1}, \quad \Delta(c^{1122}_{\ell edq}) = 0.1, \quad \Delta(c^{2222}_{\ell edq}) = 6.6 \times 10^{-2},$$

Lepton Universality Studies

REDTOP

~~LHCb latest results using $B^+ \to \mu^+\mu^- K^+$ vs $e^+e^- K^+$: 3.1σ discrepancy vs SM~~

REDTOP statistical error for ~10^{11} POT

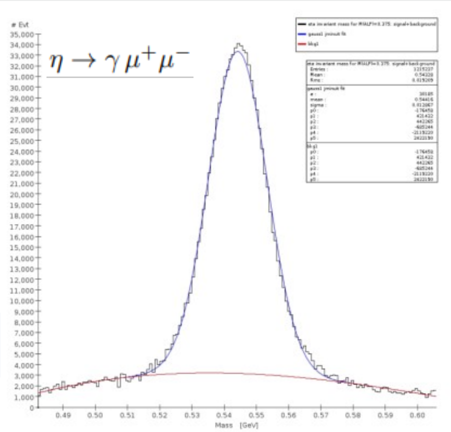
$\eta \to \gamma\, \mu^+ \mu^-$ vs $\gamma\, e^+ e^-$

Process	POT	Signal events	Background events	$\frac{S}{\sqrt{B}}$	**Statistical err**
$\eta \to \gamma e^+e^-$	1.38×10^{11}	2.13×10^6	2.52×10^4	1.3×10^4	**0.09%**
$\eta \to \gamma \mu^+\mu^-$	1.38×10^{11}	8.84×10^5	6.5×10^3	3.5×10^3	**0.14%**

TABLE XLII. Statistical error from the fit of $\eta \to \gamma$ *lepton − antilepton* and Urqmd ge background using a gaussian and a 5th-order polynomial, for 1.38×10^{18} POT

LHCb @ 4.2% with 1640 evts

LHCb @ 1.8% with 3850 evts



$\eta \to \mu^+\mu^-\mu^+\mu^-$, $e^+e^-\mu^+\mu^-$, $e^+e^-e^+e^-$

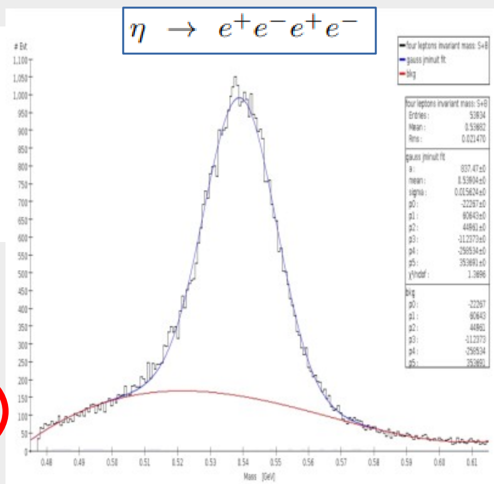
- *Theoretical calculations at the 10^{-3} precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018))*

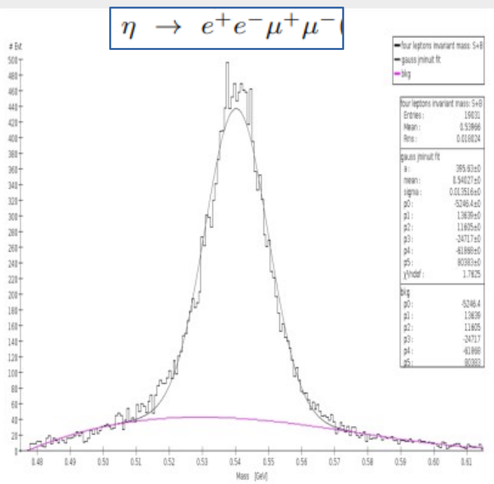
REDTOP reconstruction efficiency

Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction*	*Analysis*	**Total**
$\eta \to e^+e^-e^+e^-$	96.1%	80.7%	15.5%	63.3%	61.2%	4.5%
$\eta \to e^+e^-\mu^+\mu^-$	80.4%	57.0%	20.4%	16.6%	52.8%	0.8%
$\eta \to \mu^+\mu^-\mu^+\mu^-$	45.1%	31.9%	25.5%	61.3%	40.5%	0.9%
Urqmd	21.7%	1.7%	22.2%	$0.9 - 8.2 \times 10^{-4}$%	17.6%-30.7%	$0.7 - 6.7 \times 10^{-7}$%

REDTOP statistical error for various POT

Process	POT	Signal events	**Statistical error**
$\eta \to e^+e^-e^+e^-$	4.4×10^{14}	53,934	**0.5%**
$\eta \to e^+e^-\mu^+\mu^-$	1.6×10^{15}	18,841	**0.8%**
$\eta \to \mu^+\mu^-\mu^+\mu^-$	2.2×10^{18}	10,548	**1.0%**





Present & Future η Samples

	Technique	$\eta \to 3\pi^o$	$\eta \to e^+e^-\gamma$	Total η mesons
CB@AGS	$\pi^- p \to \eta\, n$	9×10^5		10^7
CB@MAMI C&B	$\gamma p \to \eta\, p$	1.8×10^6	5000	$2\times10^7 + 6\times10^7$
BES-III	$e^+e^- \to J/\psi \to \eta\gamma + \eta$ hadrons	6×10^6		$1.1\times10^7 + 2.5\times10^7$
KLOE-II	$e+e- \to \Phi \to \eta\gamma$	6.5×10^5		$\sim10^9$
WASA@COSY	$pp \to \eta\, pp$ $pd \to \eta\, ^3He$			$>10^9$ (untagged) 3×10^7 (tagged)
CB@MAMI 10 wk (proposed 2014)	$\gamma p \to \eta\, p$	3×10^7	1.5×10^5	3×10^8
Phenix	$d\, Au \to \eta\, X$			5×10^9
Hades	$pp \to \eta\, pp$ $p\, Au \to \eta\, X$			4.5×10^8
Near future samples				
GlueX@JLAB (running)	$\gamma_{12\ GeV} p \to \eta\, X \to$ neutrals			5.5×10^7/yr
JEF@JLAB (approved)	$\gamma_{12\ GeV} p \to \eta\, X \to$ neutrals			3.9×10^5/day
REDTOP (proposing)	$p_{1.8\ GeV} Li \to \eta\, X$			3.4×10^{13}/yr

Beam Options for 10^{14} η mesons

Baseline option – medium-energy CW proton beam

- proton beam on thin Li/Be target : ~1.8 GeV - 30 W (10^{11} POT/sec)
- Low-cost, readily available (BNL, ESS, FNAL, GSI, HIAF)
- η : inelastic background = 1:200
- Untagged η production

vs LHCb@40 MHz

Inelastic interaction rate: ~ 0.7 GHz
Average event multiplicity ≈
4 charged + 4 neutral
η/η′ production rate: ~ 2.3 MHz

Preferred option – low-energy pion beam

- π^+ on Li/Be or π^- on LH: ~750 MeV - 2.5x10^{10} πOT/sec
- More expensive but lower background (ESS, FNAL(?), FAIR, HIAF, ORNL)
- η : inelastic background = 1:50 → sensitivity to BSM increased by > 2x
- Semi-tagged η production

Inelastic interaction rate: ~ 0.1GHz
η/η′ production rate: ~ 2.3 MHz

Ultimate option: Tagged 10^{13} η mesons

- high intensity proton beam on De target: ~0.9 GeV ; 0.1-1 MW
- Less readily available: (ESS, FAIR, CSNS, ORNL, PIP-II)
- Required fwd tagging detector for He_3^{++}
- Fully tagged production from nuclear reaction: $p+De \rightarrow \eta + He_3^{+}$

Inel. interaction rate: ~ 13 - 130 GHz
η/η′ production rate: ~ 0.1 - 1 MHz

Beam Options for 10^{14} η mesons

vs LHCb@40 MHz

Baseline option – medium-energy CW proton beam

- proton beam on thin Li/Be target : ~1.8 GeV - 30 W (10^{11} POT/sec)
- Low-cost, readily available (BNL, ESS, FNAL, GSI, HIAF)
- η : inelastic background = 1:200
- Untagged η production

Inelastic interaction rate: ~ 0.7 GHz
Average event multiplicity ≈ 4 charged + 4 neutral
η/η' production rate: ~ 2.3 MHz

Only ~1% of the proton or pion beam interacts with REDTOP

Remaining beam can be used for a downstream pion and/or muon precision experiment

Preferred option – low-energy pion beam

- π^+ on Li/Be or π^- on LH: ~750 MeV - 2.5×10^{10} πOT/sec
- More expensive but lower background (ESS, FNAL(?), FAIR, HIAF, ORNL)
- η : inelastic background = 1:50 → sensitivity to BSM increased by > 2x
- Semi-tagged η production

Inelastic interaction rate: ~ 0.1GHz
η/η' production rate: ~ 2.3 MHz

Ultimate option: Tagged 10^{13} η mesons

- high intensity proton beam on De target: ~0.9 GeV ; 0.1-1 MW
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- Required fwd tagging detector for He_3^{++}
- Fully tagged production from neclear reaction: $p+De \rightarrow \eta + He_3^{++}$

Inel. interaction rate: ~ 13 - 130 GHz
η/η' production rate: ~ 0.1 - 1 MHz

Detector Requirements and Technology

- *Sustain up to 0.7 GHz event rate with avg final state multiplicity of ~8 particles*
- *Calorimetric $\sigma(E)/E \sim 2\text{-}3\%/\sqrt{E}$*
- *High PID efficiency: 98/99% (e,γ), 95% (μ), 95% (π), 99.5%(p,n)*
- $\sigma_{tracker}(t) \sim 30psec$, $\sigma_{calorimeter}(t) \sim 80psec$, $\sigma_{TOF}(t) \sim 50psec$
- *Low-mass vertex detector*
- *Near-4π detector acceptance (as the η/η' decay is almost at rest).*

charged tracks detection

LGAD Tracker

- *4D track reconstruction for multihadron rejection*
- *Material budget < 0.1% r.l./layer*

EM + had calorimeter

- *ADRIANO2 calorimeter (Calice+T1604)*
- *ADRIANO3 rear section with Fe absorbers*
- *PFA + Dual-readout+HG*
- *Light sensors: SiPM or SPADs*
- *96.5% coverage*

Vertex reconstruction

Option 1: Fiber tracker (LHCb style)

- *Established and low-cost technology*
- *~70μm vertex resolution in x-y. Stereo layers*

Option 2: HV-MAPS (Mu3e style)

- *Low material budget (0.11%/layer)*
- *~40μm vertex resolution in 3D*

Cerenkov Threshold TOF

Option 1: Quartz tiles

- *Established and low-cost technology*
- *~50psec timing with T1604 prototype*

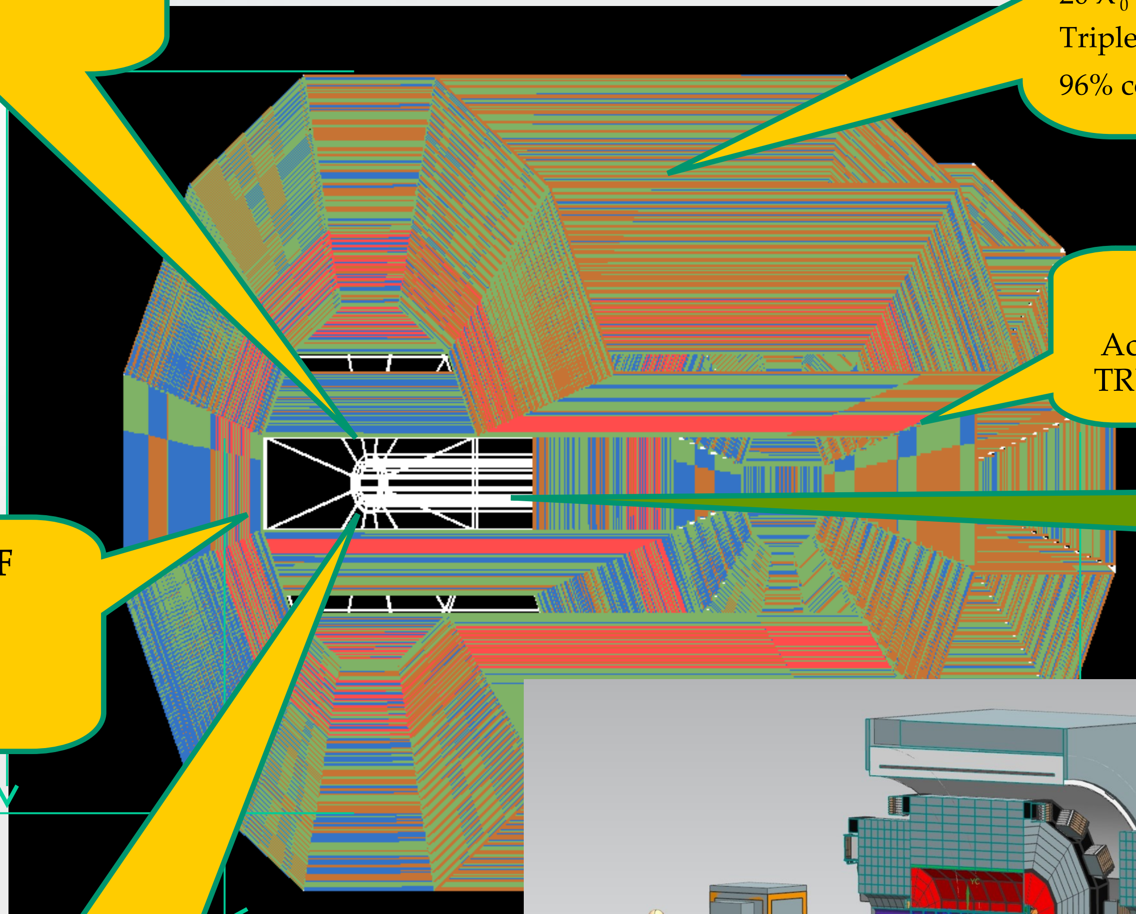
Option 2: EIC-style LGAD

- *~30-40 psec timing, but expensive*

REDTOP detector

Central Tracker
~ 1m x 1.5 m
Thin LGAD
98% coverage

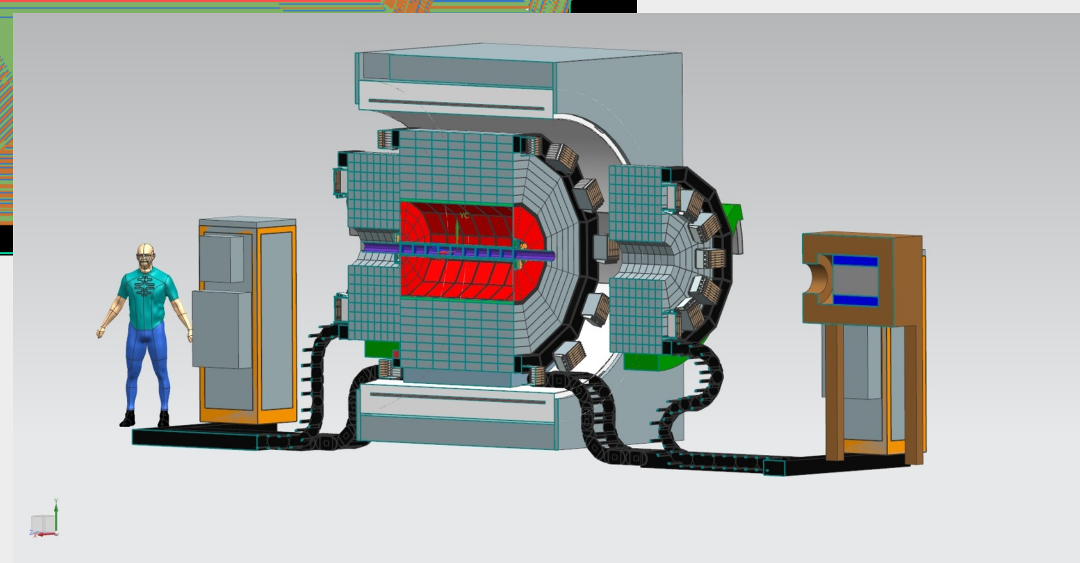
ADRIANO2(3) Calorimeter (tiles)
Scint. + heavy glass sandwich + RPC
20 X_0 (~ 64 cm deep)
Triple-readout +PFA
96% coverage



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

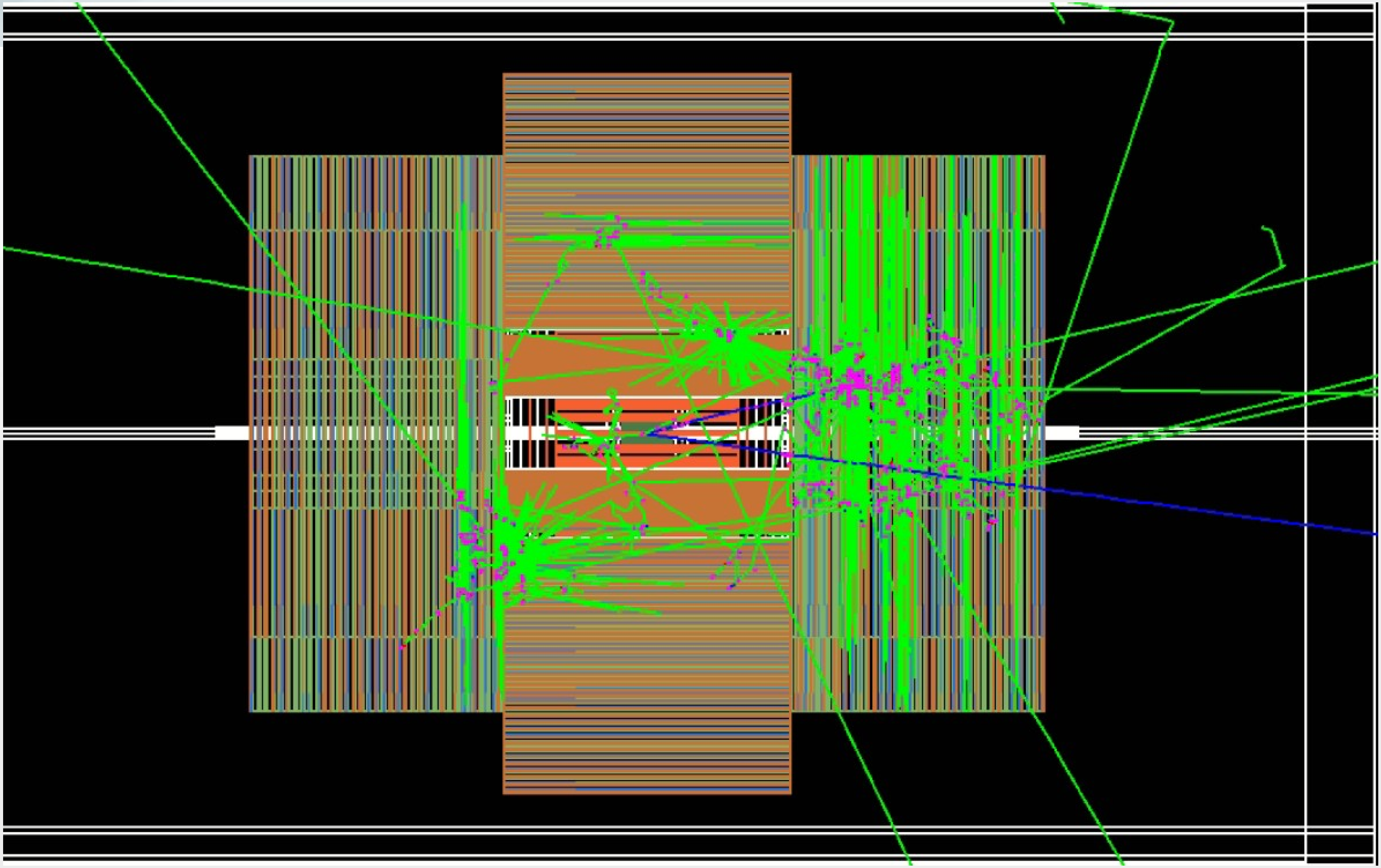
10x Be or Li targets
•0.33 mm thin
•Spaced 10 cm

Cerenkov TOF
~ 1m x 1.5 m
Fused quartz tiles
98% coverage



Fiber tracker or HV-MAPS
for rejection of γ-conversion and vertexing

$\eta \rightarrow \gamma A'$ with $A' \rightarrow e^+ e^-$ event in REDTOP



Cost estimate ($2022)

Preliminary

- Three funding scenarios considered
- Largest cost uncertainties
  - ADRIANO2 SiPM's ($2x10^6 – 4x10^6$)
  - LGAD mechanics
- **No labor considered (usually, 1/3 of the total)**

	Baseline option	Optimized option	Expensive option
Target+beam pipe	0.5	0.5	0.9
Vtx detector	0.93	3.11	25.4
LGAD tracker	18.5	18.5	19.6
CTOF	0.6	1.3	3.0
ADRIANO2	47.7	23.9	47.7
Solenoid	0.2	0.2	0.2
Supporting structure	1	1	1
Trigger	1.3	1.3	5
DAQ	5	5	5
Total	**69.7**	54.8	**101.8**
Contingency 50%	34.9	27.4	50.9
Grand total	**104.6**	82.2	**152.7**

Cost estimate ($2022)

Preliminary

- Three funding scenarios considered
- Largest cost uncertainties
  - ADRIANO2 SiPM's ($2x10^6$ – $4x10^6$)
  - LGAD mechanics
- No labor considered (usually, 1/3 of the total)

Cost optimization is in progress
Based on sensitivity studies for Snowmass 2022

	[illegible] option	[illegible] option	[illegible] option
Target+beam pipe	0.5	[illegible]	0.9
Vtx detector	0.93	3.11	25.4
LGAD tracker	[illegible]	[illegible]	19.6
CTOF	0.6	1.3	3.0
ADRIANO2	47.7	23.9	47.7
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Supporting structure	1	1	1
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Grand total	**104.6**	**82.2**	**152.7**

REDTOP Collaboration

REDTOP

J. Elam, A. Mane
Argonne National Laboratory, (USA)

J. Comfort, P. Mauskopf, D. McFarland, L. Thomas
Arizona State University, (USA)

I. Pedraza, D. Leon, S. Escobar, D. Herrera, D Silverio
Benemérita Universidad Autónoma de Puebla, (Mexico)

W. Abdallah
Faculty of Science, Cairo University, Giza, (Egypt)

D. Winn
Fairfield University, (USA)

A. Alqahtani
Georgetown University, (USA)

W. Abdallah
Cairo University, Cairo (Egypt)

A. Kotwal
Duke University, (USA)

M. Spannowski
Durham University, (UK)

A. Liu
Euclid Techlabs, (USA)

J. Dey, V. Di Benedetto, B. Dobrescu, D. Fagan, E. Gianfelice-Wendt, E. Hahn, D. Jensen, C. Johnstone, J. Johnstone, J. Kilmer, G.Krnjaic, T. Kobilarcik, A. Kronfeld, K. Krempetz, S. Los, M. May, A. Mazzacane, N. Mokhov, W. Pellico, A. Pla-Dalmau, V. Pronskikh, E. Ramberg, J. Rauch, L. Ristori, E. Schmidt, G. Sellberg, G. Tassotto, Y.D. Tsai

Fermi National Accelerator Laboratory, (USA)

J. Shi
Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, I, Guangzhou 510006, (China)

R. Gandhi
Harish-Chandra Research Institute, HBNI, Jhunsi (India)

S. Homiller
Harvard University, Cambridge, MA (USA)

E. Passamar
Indiana University (USA)

P. Sanchez-Puertas
IFAE – Barcelona (Spain)

X. Chen, Q. Hu
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou (China)

C. Gatto[1†]
Istituto Nazionale di Fisica Nucleare – Sezione di Napoli, (Italy)

W. Baldini
Istituto Nazionale di Fisica Nucleare – Sezione di Ferrara, (Italy)

R. Carosi, A. Kievsky, M. Viviani
Istituto Nazionale di Fisica Nucleare – Sezione di Pisa, (Italy)

W. Krzemień, M. Silarski, M. Zielinski
Jagiellonian University, Krakow, (Poland)

D. Guadagnoli
Laboratoire d'Annecy-le-Vieux de Physique Théorique, (France)

D. S. M. Alves, S. Gonzalez-Solis de la Fuente, S. Pastore
Los Alamos National Laboratory, (USA)

M. Berlowski
National Centre for Nuclear Research – Warsaw, (Poland)

G. Blazey, A. Dychkant, K. Francis, M. Syphers, V. Zutshii, P. Chintalapati, T. Malla, M. Figora, T. Fletcher
Northern Illinois University, (USA)

A. Ismail
Oklahoma State University, (USA)

D. Egaña-Ugrinovic
Perimeter Institute for Theoretical Physics – Waterloo, (Canada)

S. Roy
Physical Research Laboratory, Ahmedabad – Ahmedabad, (India)

Y. Kahn
Princeton University – Princeton, (USA)

D. McKeen
TRIUMF (Canada)

Z. Ye
Tsinghua University, (China)

P. Meade
Stony Brook University – New York, (USA)

A. Gutiérrez-Rodriguez, M. A. Hernandez-Ruiz
Universidad Autónoma de Zacatecas, (Mexico)

R. Escribano, P. Masjuan, E. Royo
Universitat Autònoma de Barcelona, Departament de Física and Institut de Física d'Altes Energies, (Spain)

J. Jaeckel
Universität Heidelberg, (Germany)

B. Kubis
Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik (Theorie) and Bethe Center for Theoretical Physics, (Germany)

C. Siligardi, S. Barbi, C. Mugoni
Università di Modena e Reggio Emilia, (Italy)

L. E. Marcucci*
Universita' di Pisa, (Italy)

M. Guida[3]
Università di Salerno, (Italy)

S. Charlebois, J. F. Pratte
Université de Sherbrooke, (Canada)

L. Harland-Lang
University of Oxford, (UK)

J. M. Berryman
University of California Berkeley, (USA)

S. Gori
University of California Santa Cruz, (USA)

R. Gardner, P. Paschos
University of Chicago, (USA)

J. Konisberg
University of Florida, (USA)

C. Mills[5]
University of Illinois Chicago, (USA)

M. Murray, C. Rogan, C. Royon, Nicola Minafra, A. Novikov, F. Gautier, T. Isidori
University of Kansas, (USA)

S. Gardner, X. Yan
University of Kentucky, (USA)

Y. Onel
University of Iowa, (USA)

B. Batell, A. Freitas, M. Rai
University of Pittsburgh, (USA)

M. Pospelov
University of Minnesota, (USA)

D. Gao
University of Science and Technology of China, (China)

K. Maamari
University of Southern California, (USA)

A. Kupsc, Maja Olvegård
University of Uppsala, (Sweden)

B. Fabela-Enriquez
Vanderbilt University, (USA)

S. Tulin
York University, (Canada)

15 Countries
58 Institutions
128 Collaborators

Future Prospects for REDTOP

REDTOP

Baseline detector layout defined (with options for vtx and μpol detectors)

- Sensitivity studies helped to consolidate the detector requirements and to drive cost optimization
- VTX Fiber Tracker replaced by HV-MAPS detector
- Muon polarimeter requires further studies

Next steps:

- **Initial funding from US agencies (mid-RI proposal – $2-10M)**
- Prepare a CDR to support the proposal of the experiment to one (or more) of the interested laboratories
- Consolidate the detector R&D (ongoing)

Conclusions

- *HEP in the next 10 years will focus strongly on the MeV-GeV region*
- *All meson factories: LHCb, B-factories, Dafne, J/psi - have produced a broad spectrum of nice physics. An η /η′ factory will do the same*
- *REDTOP has been designed expressely to study rare processes and to discover physics BSM in the MeV-GeV mass region*
- *Only experiment (with SHIP) sensitive to all four DM portals*
- *Very large physics reach for NP as well*
- *New detector techniques benefit the next generation of high intensity experiments*
- *Beam requirements could be met by several labs in US, Europe, and Asia*
  - *Before 2030: HIAF and GSI*
  - *After 2030: Fermilab and ESS*

More details: https://redtop.fnal.gov and https://arxiv.org/abs/2203.07651

Backup Slides

Why the η meson is special?

- 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.
- EM decays are forbidden in lowest order by C invariance and angular momentum conservation
  - It is a very narrow state (Γ_η=1.3 KeV vs Γ_ρ=149 MeV)
  - Contributions from higher orders are enhanced by a factor of ~100,000
  - Excellent for testing invariances
- The η decays are flavor-conserving reactions
  - Decays are free of SM backgrounds for new physics search

η is an excellent laboratory to search for physics Beyond Standard Model

η/η' yield and background evaluation

Inelastic p-Li scattering probability (percentage):

Model	p-Li cross section [cm^{-2}]	p-Li interaction prob.	p-Target interaction prob.
Wellisch & Axen	2.01×10^{-25}	0.710	0.719
Tripathi Light	1.96×10^{-25}	0.693	0.702
Incl++	1.60×10^{-25}	0.567	0.574
Sihver et. al	1.51×10^{-25}	0.535	0.543
Barashenkov	1.73×10^{-25}	0.612	0.620
Shen et. al	2.0×10^{-25}	0.707	0.715
Kox et. al	2.98×10^{-25}	1.06	1.07
Average	$1.98 \pm 0.48 \times 10^{-25}$	0.70 ± 0.17	0.71 ± 0.17

Inelastic interaction rate: ~ 0.7 GHz

Evaluation of η/η′ yield for 3.3x10[18] POT (3.3 years running at 1x10[18] POT/yr)

Nuclear collision model	p+Li η yield
Urqmd [208]	0.49%
Incl++ v6.2 [209]	1.48%
Gibuu v2019 [210]	0.74%
PHSD v 4.0 [211]	0.67%
Jam v1.9 [212]	0.26%
Average	$(0.73 \pm 0.46)\%$

	Total yield for E_{kin}=1.8 GeV
N_η	1.1×10^{14}
$N_{\eta'}$	0
N_{ni}	2.5×10^{16}

	Total yield for E_{kin}=3.6 GeV
N_η	5.9×10^{14}
$N_{\eta'}$	7.9×10^{11}
N_{ni}	3.2×10^{16}

η/η′ production rate: ~ 2.3 MHz

Simulation Framework For Physics&Detector Studies

Event generator: GenieHad

- Proprietary (not yet public) package interfacing standalone generators to genie

Package	Model	Type
Urqmd [210]	QMD	Microscopic many body approach
Incl++ v6.2 [211]	INCL	Intranuclear cascade
Gibuu v2019 [212]	BUU	time evolution of Kadanoff–Baym-equations
PHSD v 4.0 [213]	HSD	covariant transport with NJL-type Lagrangian
Jam v1.9 [214]	Cascade/RQMD.RMF/BUU	Multi-model - hybrid approach
Dpmjet-III [240]	Dual Parton/ perturbative QCD	Multi-model approach
Pythia 7, 8[239]	LUND	string hadronization model
IAEA tables[241]	LUT of measured cross sections	Look-up tables based on ENDF (by IAEA)
Intranuke[242]	Parametric	
ALPACA[243]	Alpaca	Bremsstrahlung of Axion-Like-Particles (ALPs)

Simulation: slic

- Geant4 interface from SLAC
- Proprietary adds-on for REDTOP specific detectors

Digitization, reconstruction, analysis: lcsim

- Java package from ILC and HPS (jlab)
- Geometry adds-on for REDTOP specific detectors, beam components, and magnetic fields
- Histograms and fitting in Jas3, Jas4app

Some Signal vs Background Acceptance

- *Values from White Paper*
- *QCD background at TL2: $8x10^{-4}$*
- *Efficiencies and BR sensitivities calculated after reconstruction and analysis*
- *Values are very dependence on BSM mass and width*

Process	Eff(Bkg)	Eff(signal)	BR sensitivity
$\eta \to \gamma A'$; $A' \to e^+e^-$	$3x10^{-10}$ - $4x10^{-7}$	8%-22%	$1x10^{-9}$-$2x10^{-8}$
$\eta \to \gamma A'$; $A' \to \mu^+\mu^-$	$1x10^{-11}$-$6x10^{-8}$	6%-42%	$1x10^{-10}$-$2x10^{-9}$
$\eta \to \pi^0 h$; $h \to e^+e^-$	$3x10^{-11}$ - $^{8}x10^{-8}$	1%-16%	$4x10^{-10}$-$7x10^{-8}$
$\eta \to \pi^0 h$; $h \to \mu^+\mu^-$	$2x10^{-11}$-$1x10^{-8}$	6%-18%	$7x10^{-11}$-$4x10^{-9}$
$\eta \to \pi^0\pi^0$alp ; alp $\to e^+e^-$	$2x10^{-11}$-$1x10^{-10}$	0.2%-2.8%	$2x10^{-11}$-$2.7x10^{-8}$
$\eta \to \pi^+\pi^-$axion(17 MeV) ; axion $\to e^+e^-$	$2.3x10^{-8}$	3.0%-3.7%	$1.6x10^{-8}$-$2.1x10^{-8}$
$\eta \to \pi^+\pi^-$alp ; alp $\to \gamma\gamma$	$1x10^{-10}$-$4x10^{-8}$	0.6%-1.4%	$7x10^{-9}$-$5x10^{-8}$
$\eta \to \pi^0 H$; $H \to \nu N_2$; $N_2 \to N_1 h$; $h \to e^+e^-$	$6.8x10^{-7}$	1.2%	$2.7x10^{-7}$

η/η’ yield and background evaluation

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η/η′ production rate: ~ 2.3 MHz

Montecarlo generation of QCD background

Generators comparison

- *Generate and reconstruct ~2x10^9 p+li→ X inelastic events with Incl++ (v6) and Urqmd (v5.3)*
- *Results where within statistical uncrtainties*
- *Urqmd was selected for its higher reliability at ~2-3 GeV*

QCD Production

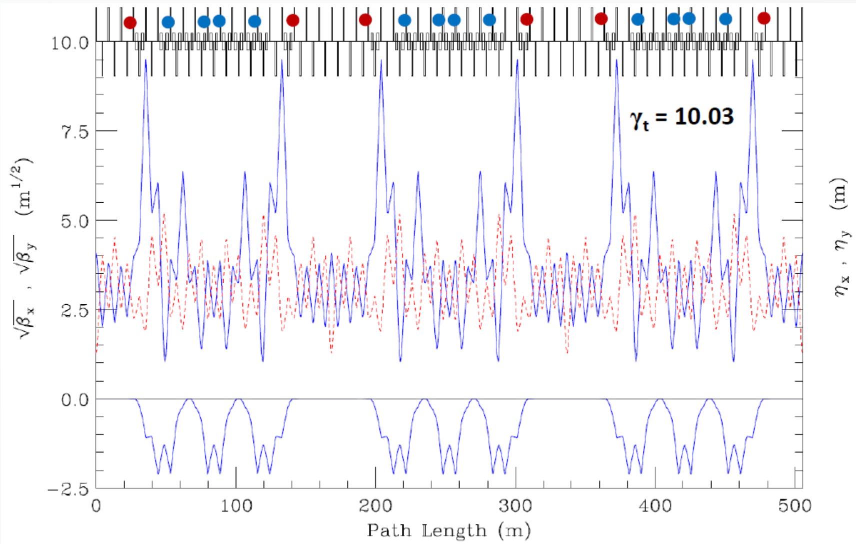
- *5x10^{10} events where generated for the White Paper*
- *50x10^6 wall-hr cpu over a two-year period (mostly on the OSG)*

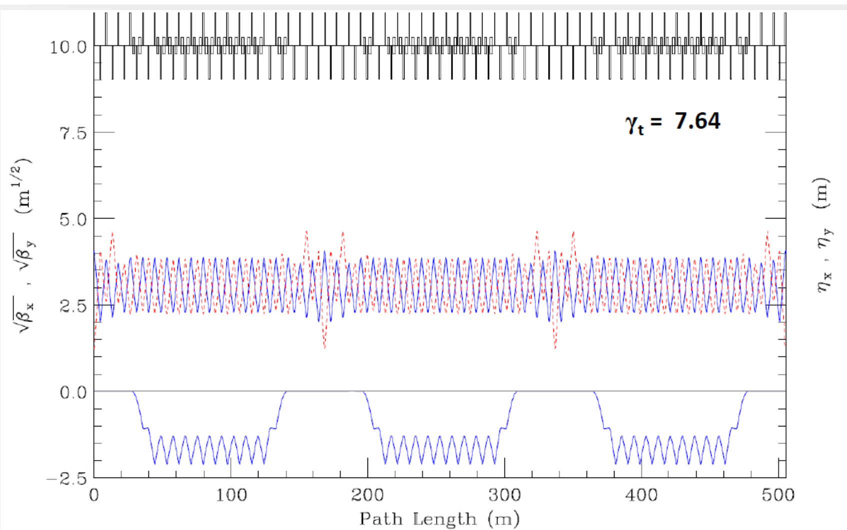
Source	Storage	#core available	Jobs/yr	Wall hr/yr	Fraction
OSG	100 TB (with peaks of 140 TB)	opportunistic	7x10^6	14x10^6	72%
NICADD	15 TB	500-690	4x10^6	5x10^6	26%
Fermilab-AD	200 TB	350	300K	600K	2%

Ring Optics through Deceleration (J. Johnstone)

Transition is avoided by using select quad triplets to boost γt above beam γ by 0.5 units throughout deceleration until γ_t = 7.64 and beam γ = 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 γ_t quad triplets.

p (GeV/c)	8.89	8.33	7.76	7.20	6.63
KE (GeV)	8.00	7.45	6.88	6.32	5.76
γ_{BEAM}	9.53	8.93	8.33	7.74	7.14
$\gamma_{transition}$	10.03	9.43	8.83	7.74	7.64
β_{max} (m)	94.9	72.5	49.5	30.1	15.1
q (m^{-1})	.0697	.0573	.0416	.0236	0.0
3σ (mm)	15.0	13.6	11.6	9.4	6.9

Variation of , β_{max}, and the 15π 99% beam envelope through deceleration

"J.Johnstone, M.Syphers, NA-PAC, Chicago (2016)"

Acceleration Scheme for Run-I (M. Syphers)

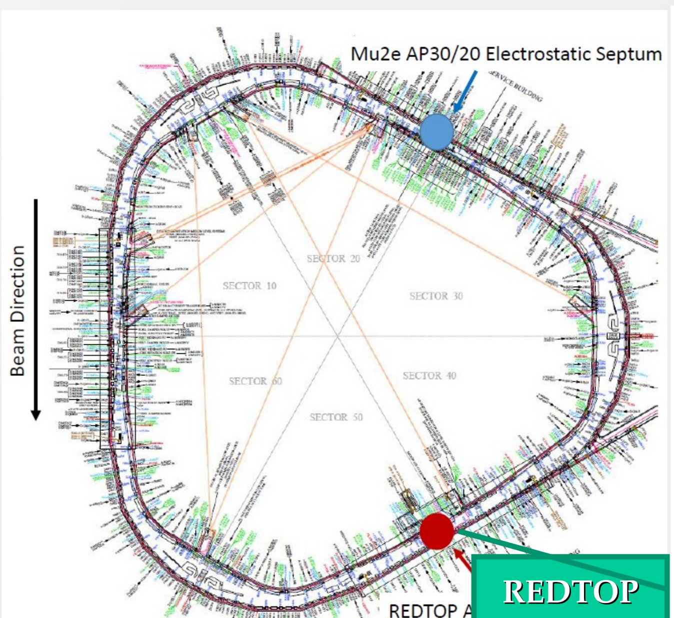
Single p pulse from booster (≤4x10¹² p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)

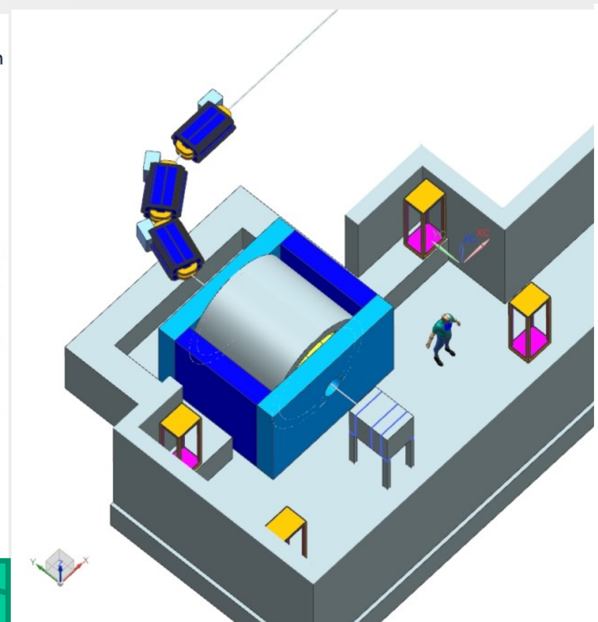
Energy is removed by inserting 1 or 2 RF cavities identical to the one already planned (~5 seconds)

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.

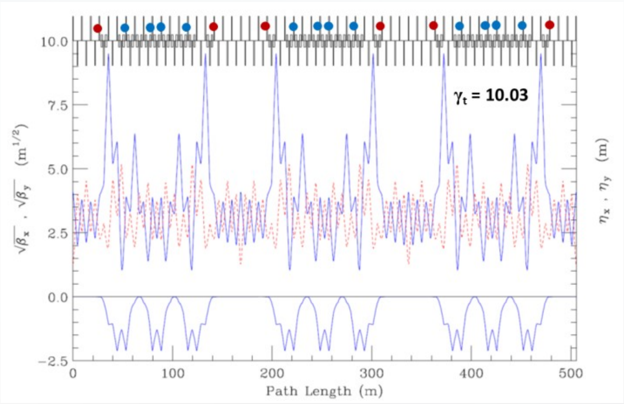
Total time to decelerate-debunch-extract: 51 sec: duty cycle ~80%

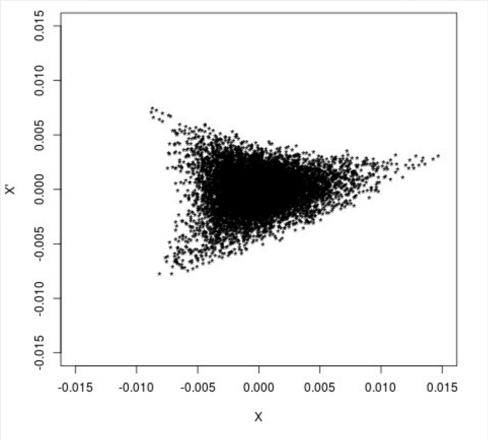




C. Gatto - INFN & NIU

Accelerator Physics Issues





- *Transition Energy*
  - γ_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
    - Johnstone and Syphers, *Proc. NA-PAC 2016*, Chicago (2016).
- *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

Beam Options at GSI/FAIR (near future)

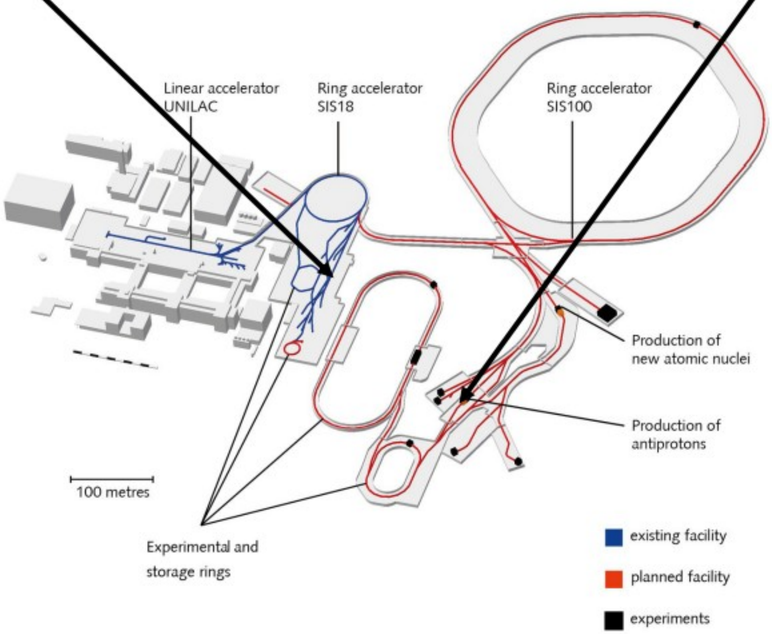
Opportunities as fixt target exp.

FAIR GSI

OPTION A
Fixt target (SIS18)

- HEST towards pion target
- 1e11 p/spill (time structure flexible) at SIS18

- Residual beam might be used for Hades pion program
- Additional shielding and cave need to be evaluated
- High intensity needs exclusive proton operation



OPTION B
Fixt target (SIS100)

- p-bar target area
- 2e12 p/spill (time structure flexible) at SIS100

- Parallel operation possible due to p-LINAC
- Shielding and cave need to be evaluated
- Actual timeline beyond 2028

Beam intensity: 1.8 GeV protons with 1e11/s

Daniel Severin

Beam Options at GSI (far future)

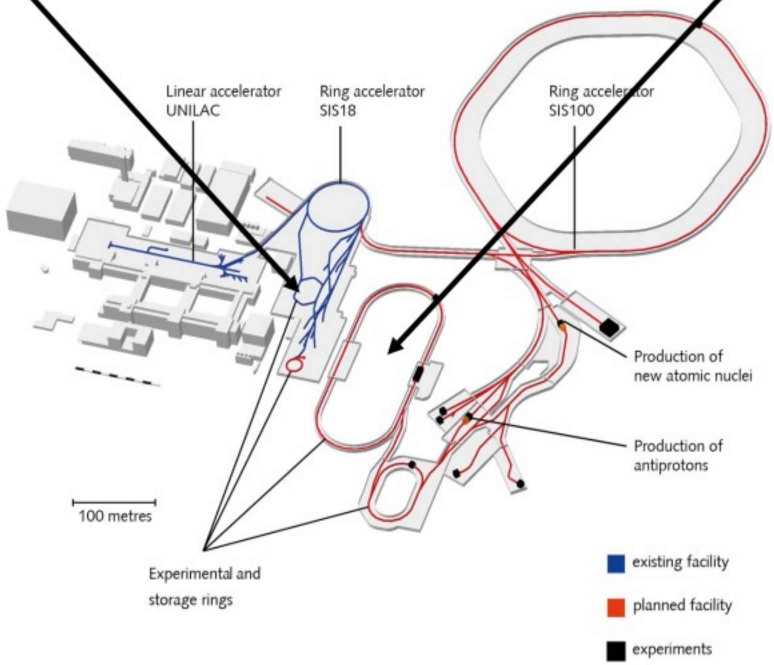
Opportunities as in-ring target exp.

FAIR GSI

OPTION C
ESR (SIS18)

- ESR
- 1e6 p/injection (1-2 MHz revolution rate)
- Full beam usage

- Lower intensity
- Parallel operation of UNILAC and SIS18 exp. possible
- Standard ESR exp. area needs to be dismounted
- Major disruption for the already approved program



OPTION D
HESR (SIS100)

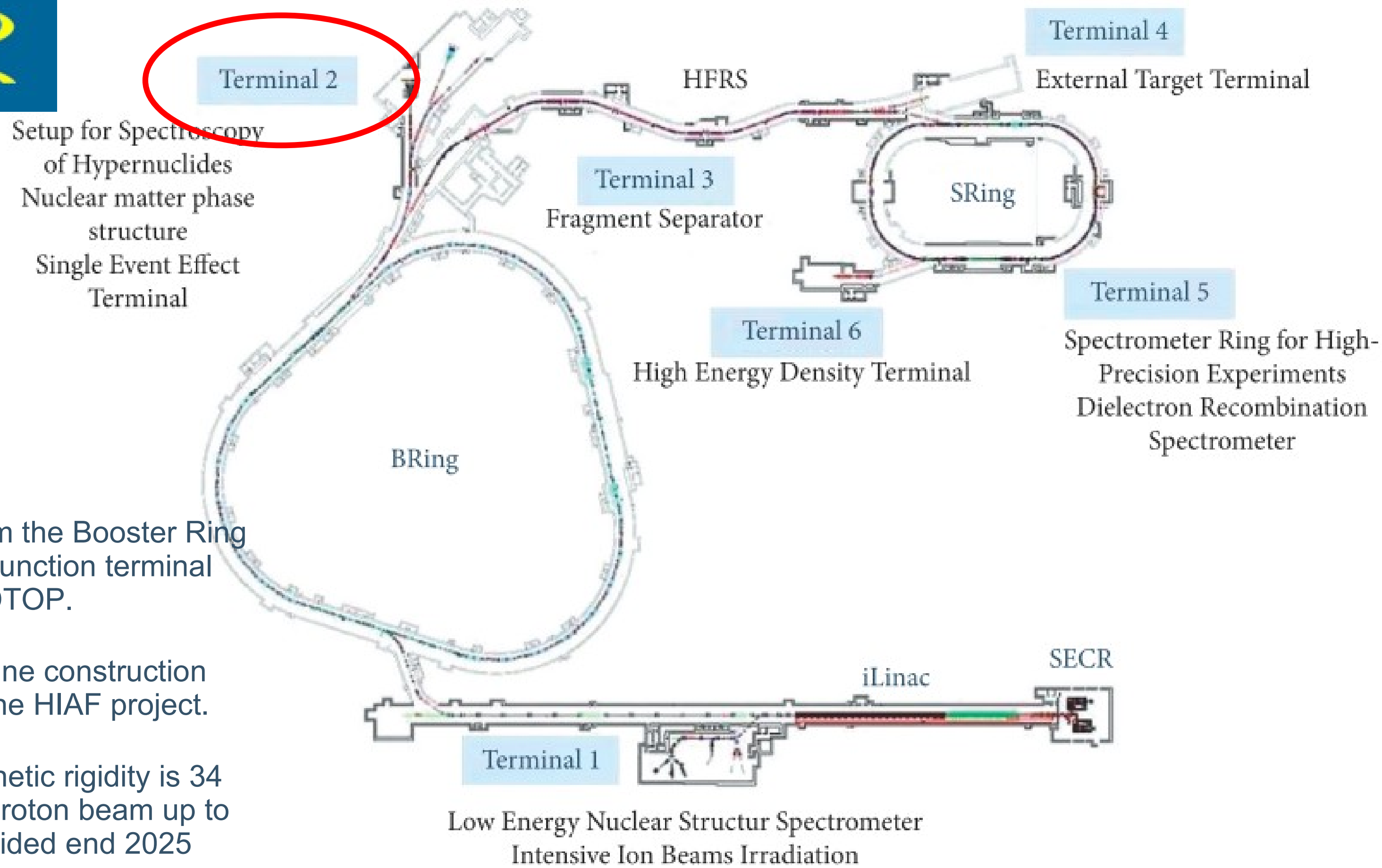
- HESR or CR
- Intensity fully flexible
- Full beam usage

- Parallel operation possible due to p-LINAC
- Standard installation needs to be discussed
- Actual timeline beyond 2030

Daniel Severin

Beam intensity: 1.8 GeV protons with 1e11/s

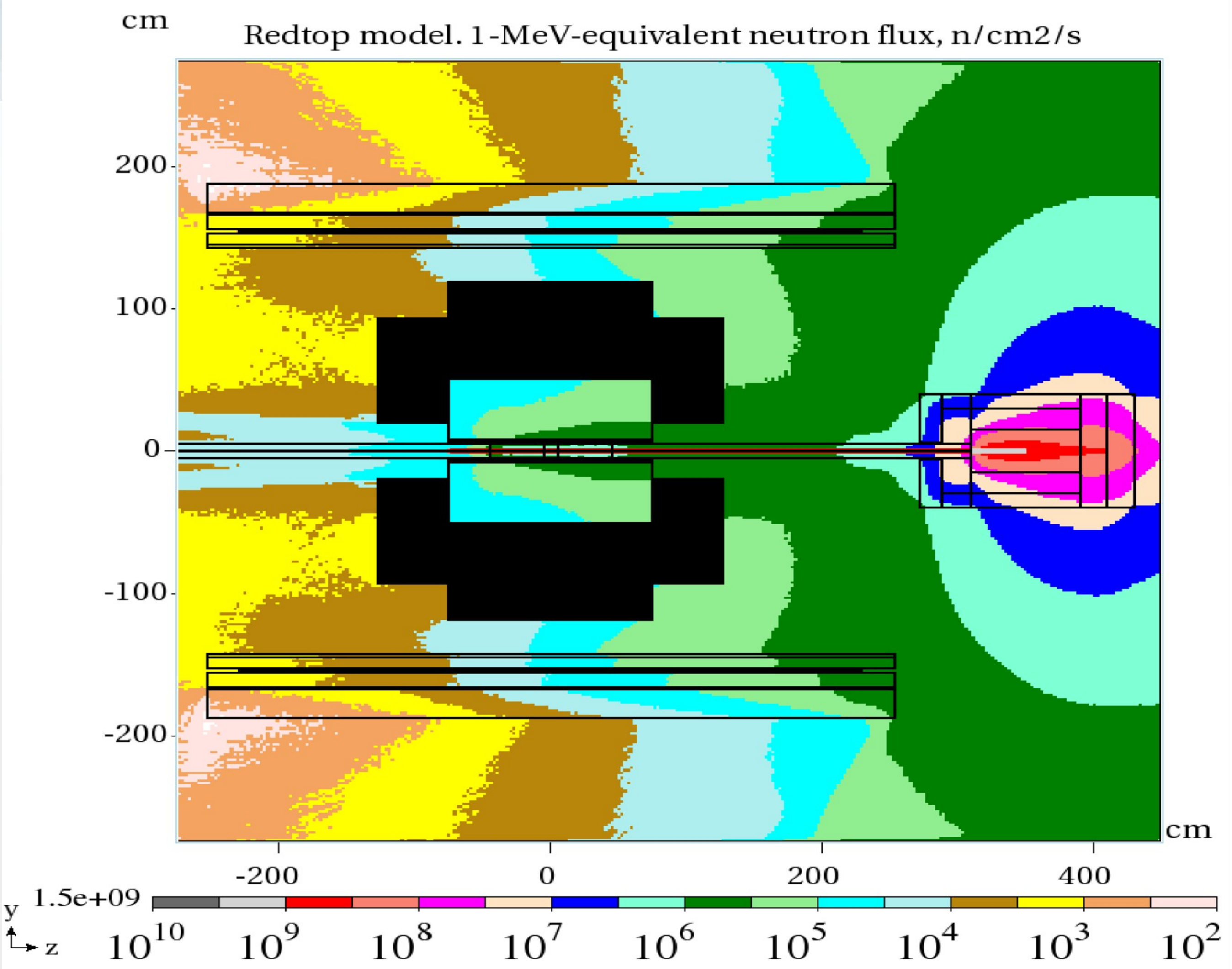
Beam Options at HIAF (near future)



- Beam extracted from the Booster Ring (BRing) to the Multi-function terminal ans be used for REDTOP.
- The transfer beam line construction already included in the HIAF project.
- The maximum magnetic rigidity is 34 Tm which means a proton beam up to 9.3 GeV can be provided end 2025

*Beam intensity: 0.5 ~1.0x10^{13} ppp (1~5*1x10^{13} pps) in Terminal 2 . $10^{(18\text{-}19)}$ POT /yr*
Energy from 2.0 to 9 GeV around 2028 – 2030
Plans are to combine REDTOP with an experiment on hypernuclei

MARS15 Shielding Assesment



Beam dump: dia-30 x 80 cm Al + 15 cm HDPE +5% B + 10 cm Barite

Detector Requirements: BSM physics driven

LFU: Tagged lepton production from flavor-conserving decays

- excellent e/π/μ separation

QCD axion

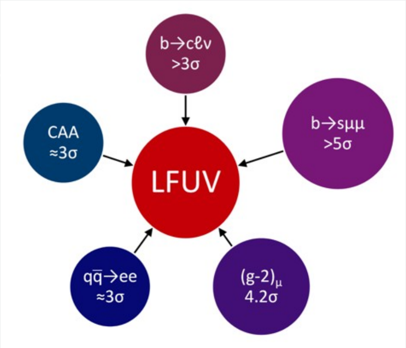
- *Calorimetric sensitivity to M(γγ)~30MeV*

17 MeV e^+e^- state (Atomki experiment)

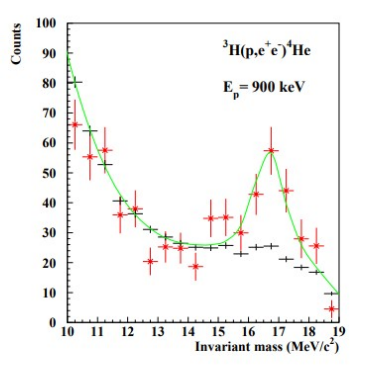
- *Tracker sensitivity to M(e^+e^-)~ 20 MeV*
- *Electron ID at very low energy*

CP violation with muons

- *Muon polarimeter or high-granularity calorimeter*



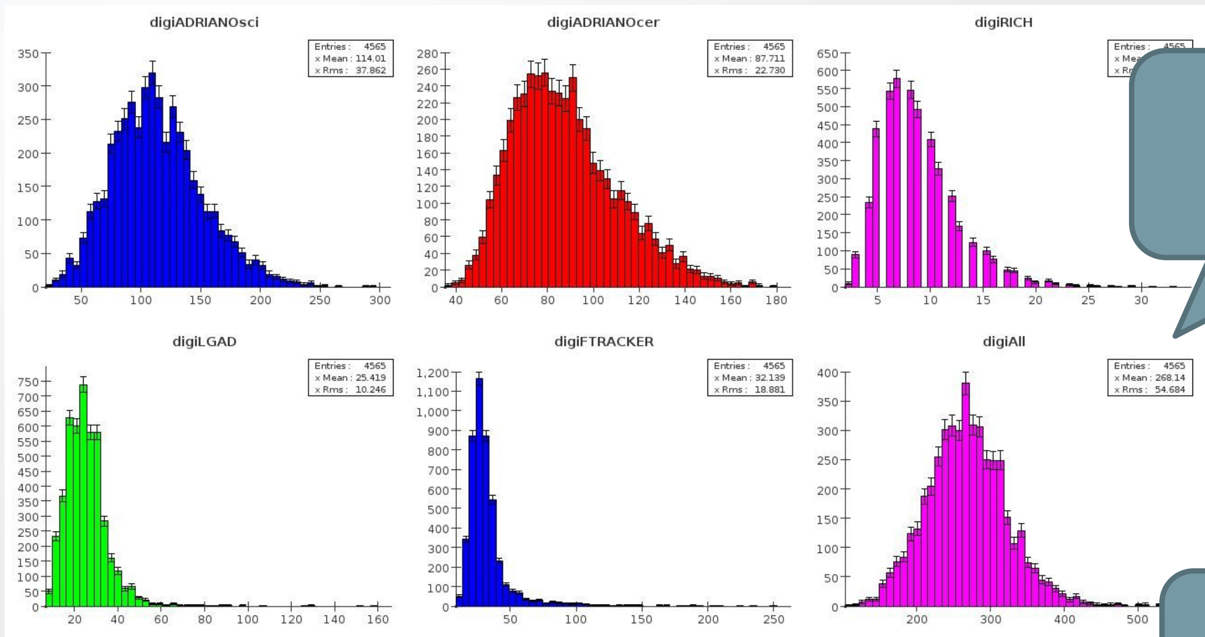
Mounting Evidence for the Violation of Lepton Flavor Universality https://arxiv.org/pdf/2111.12739.pdf (A. Crivellin, M. Hoferichter)



REDTOP Trigger Requirement

Untagged 10^{14} η/η' mesons

Hits from subdetectors



Total channel occupancy:
270 ± 50 /evt

Trigger rejection factors

18x LHCb

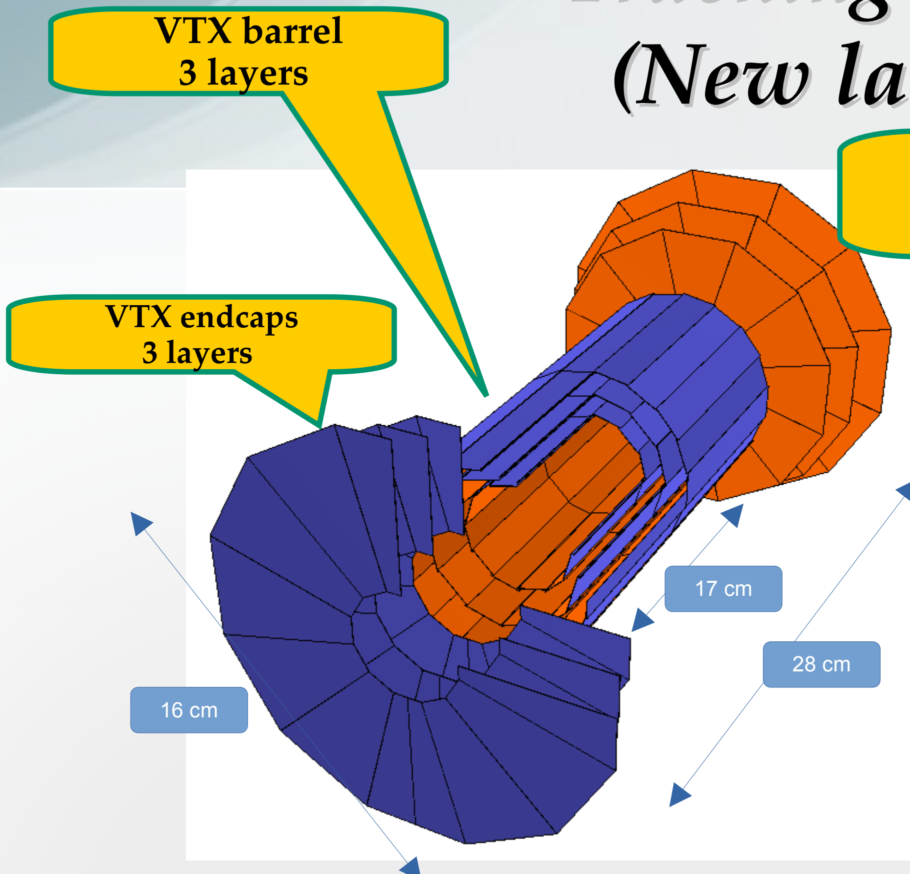
Trigger stage	Input event rate Hz	Event size bytes	Input data rate bytes/s	Event rejection
Level 0	$7. \times 10^8$	1.4×10^3	9.8×10^{11}	~4
Level 1	1.5×10^8	1.5×10^3	2.3×10^{11}	60
Level 2	2.5×10^6	1.5×10^3	3.8×10^9	~4.5
Storage	0.56×10^6	1.6×10^3	0.9×10^9	

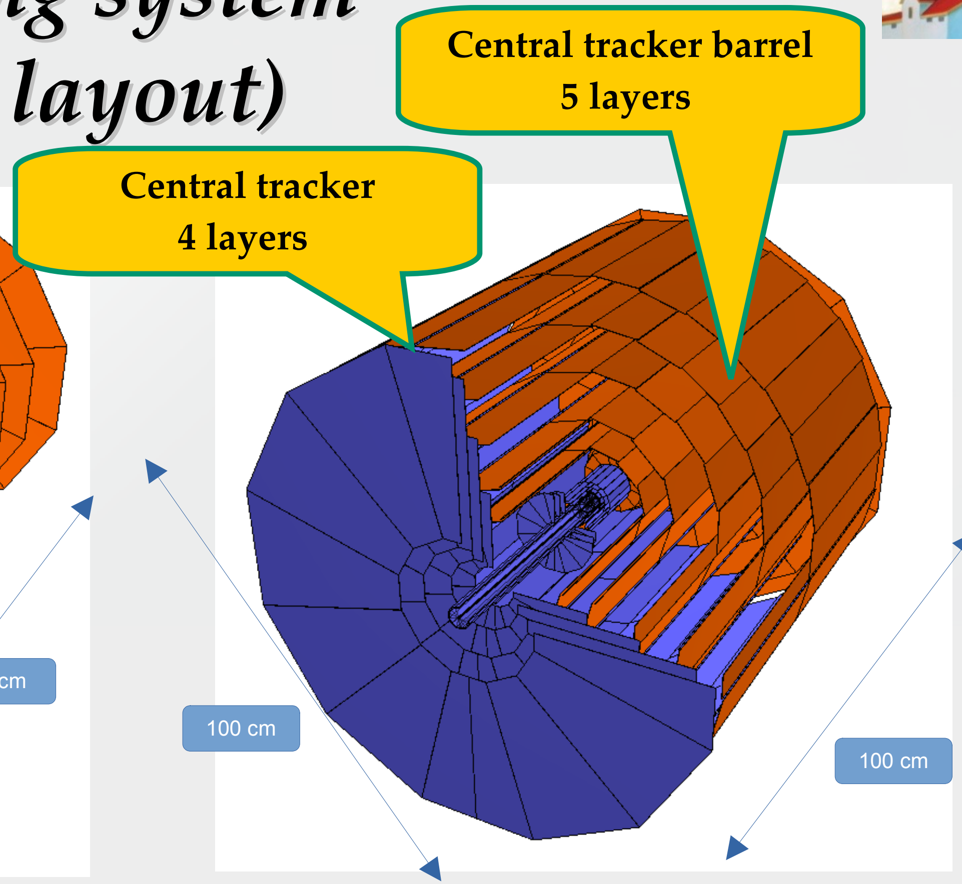
Hardware

Software

~9 PB/year to tape
(1.6 kb event size)

Tracking system (New layout)





Vertex detecor

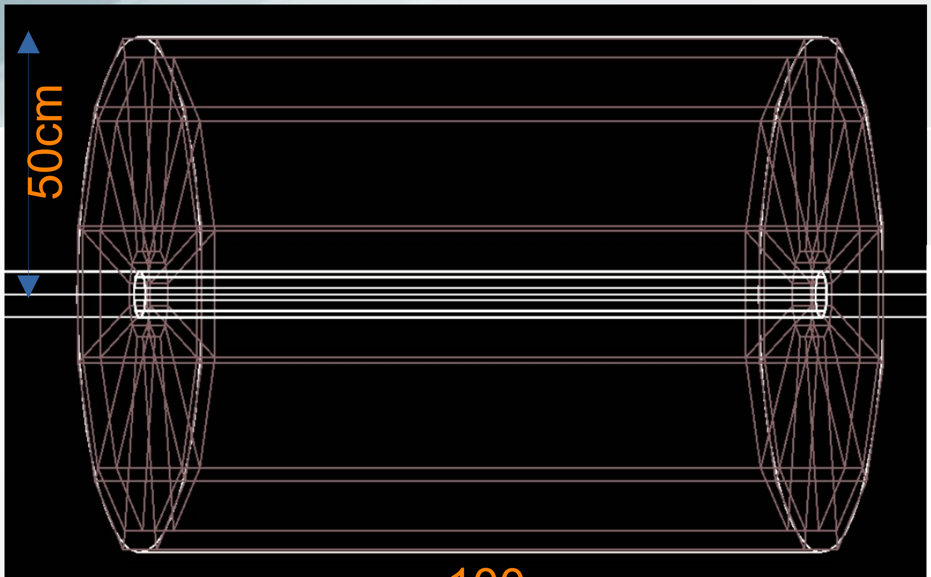
- *MuMAPS (Mu3e style)*
- *Rin = ~2 cm   L=10 cm*
- *Material budget (0.33%)*
- *80μm pixel pitch*
- *6 nsec timing resolution*

Central tracker

- *AC-LGAD (CMS style)*
- *Passive cooling*
- *Rin = ~50 cm   L=100 cm*
- *~35 psec timing resolution*
- *Material budget ~ 0.5% r.l./layer*
- *1.3 mm pixel pitch*

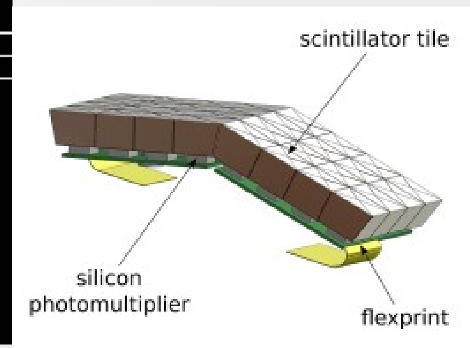
C. Gatto - INFN & NIU

Threshold Cerenkov - TOF



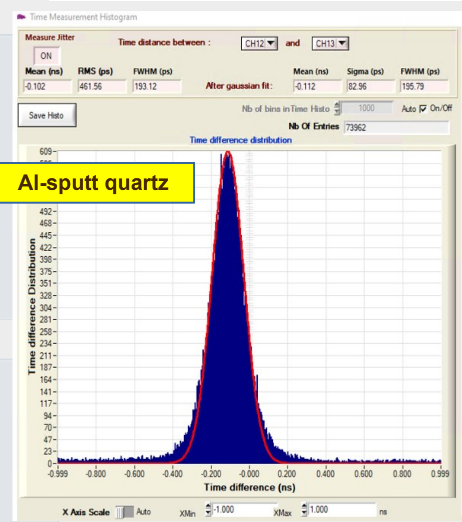
Requirements

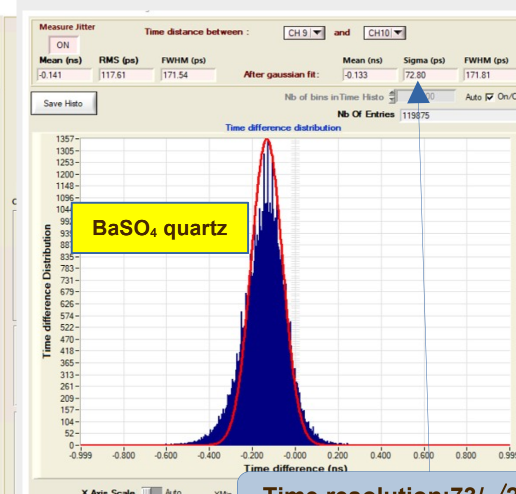
- ❑99% efficiency
- ❑Rad-hard <1x10[5] 1 MeV-neq n/cm2/sec
- ❑Timing resolution: <50 psec



Option 1: Small tiles of JGS1 & on-tile SiPM

- – Two layers 3x3cm tiles
- – Similar technologies: CMS' BTL (lyso) and Mu3e tile detector (scint. plastics)
- – Well established TOFHIR2 Asic (LIP)





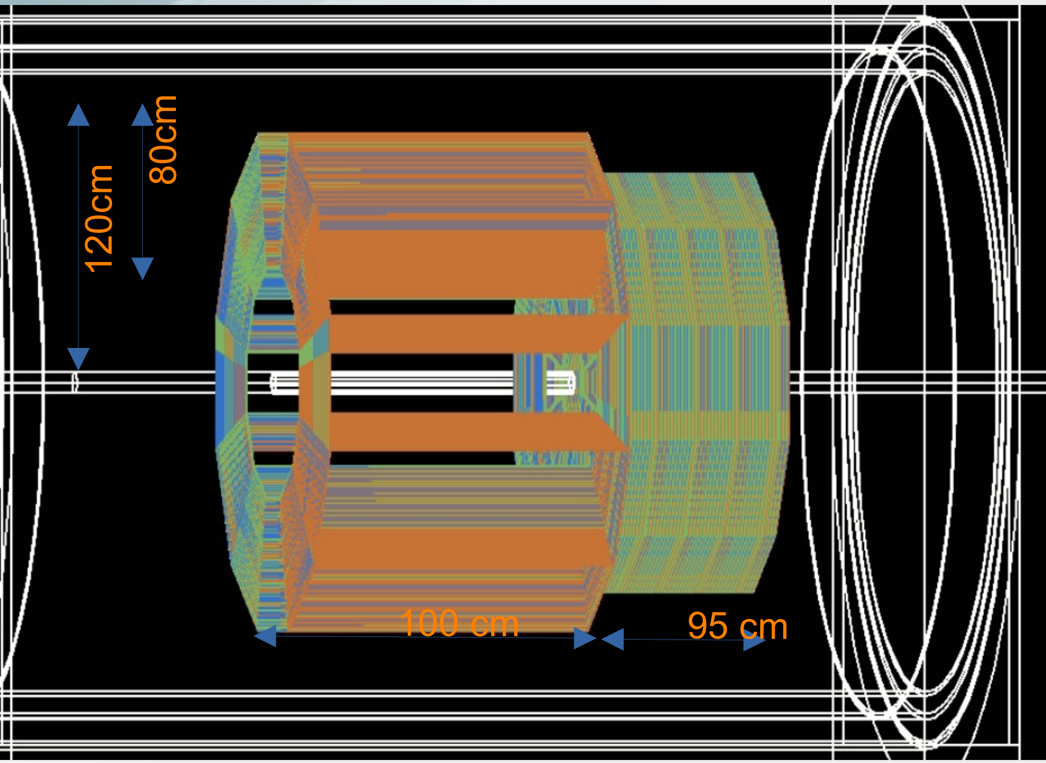
Time resolution:73/$\sqrt{2}$ psec

Option 2: LGAD

- – REDTOP vs CMS's ETL: 51% area
- – Extra cost justified by position measurement, but loose energy measurement

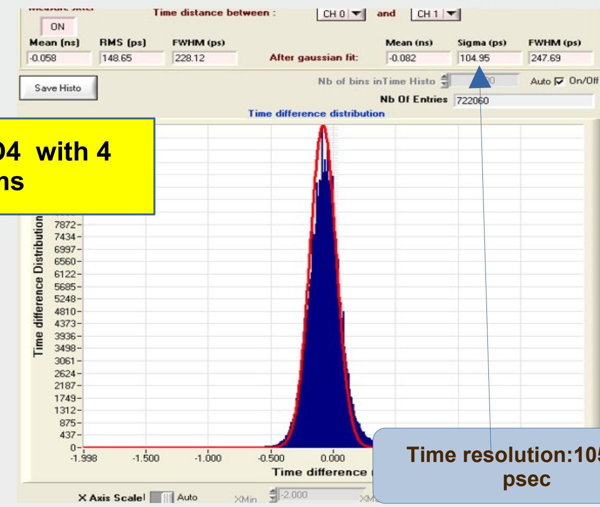
~50 psec/cell already achieved by T1604 Collaboration

CALORIMETERS



Requirements

- ❑ $\sigma_E/E \sim 2\text{-}3\%/\sqrt{E}$
- ❑ ~80 psec/cell timing resolution for MIPs.
- ❑ No active cooling
- ❑ Rad-hard ~5x10^4 1 MeV-neq n/cm2/sec



EM: dual-readout ADRIANO2

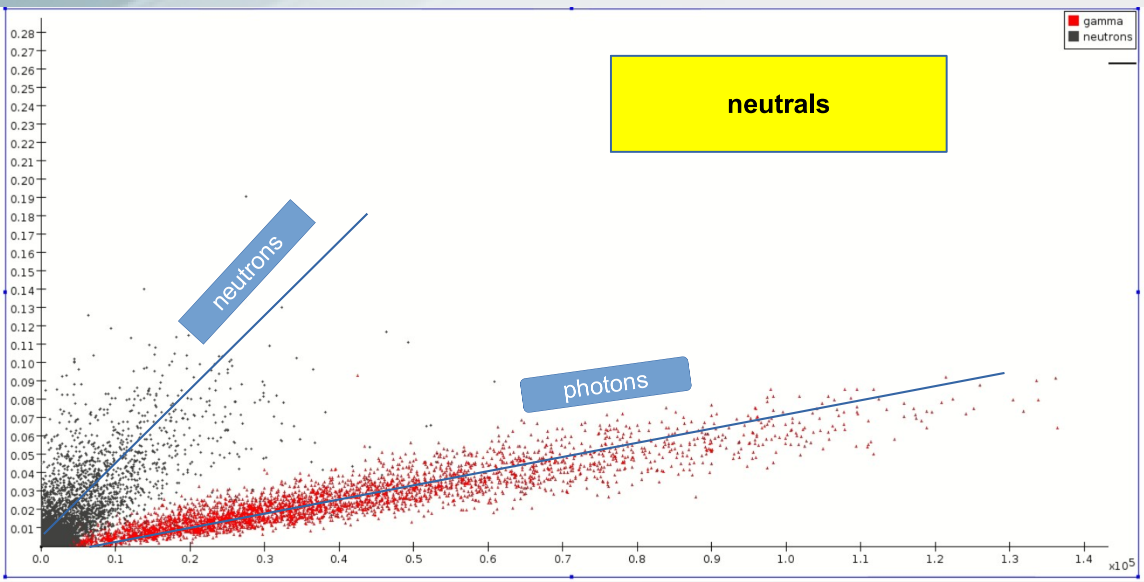
- Inner section: Pb-glass and scint. Tiles interleaved
- Barrel 12 layers (17 cm) – 8 X0 / 0.6 λ_I
- Endcap 20 layers (28 cm) – 13 X0 / 1.1 λ_I
- 195,00 tile-pairs
- Same plastic tiles as CMS' HGCAL
- FEE from Weeroc+Omega (costing being discussed) or TOFPET2

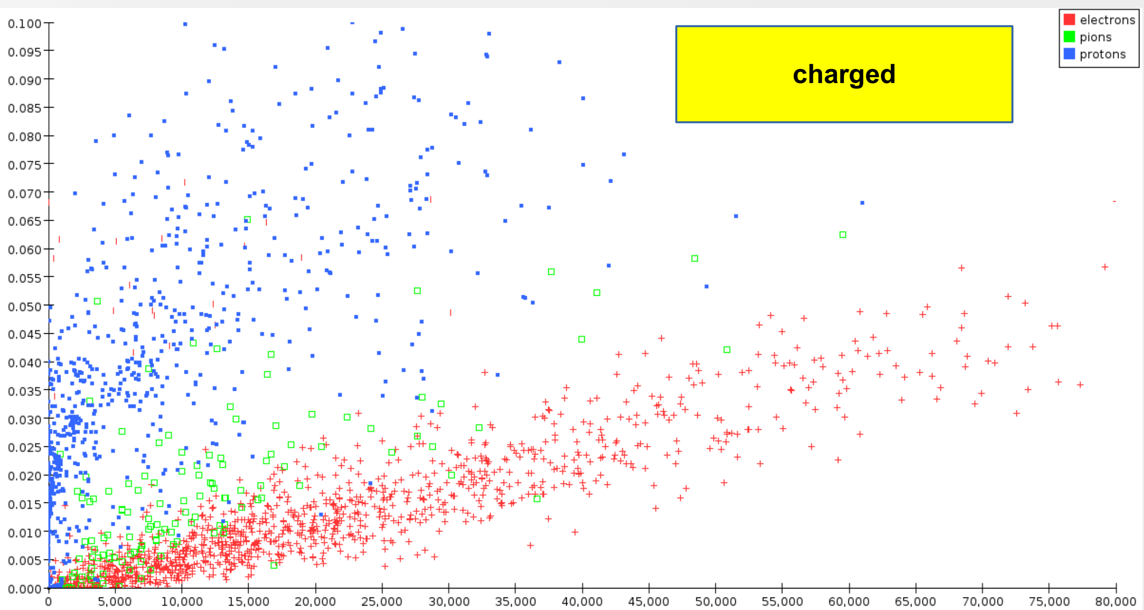
HAD: triple-readout ADRIANO3

- Outer section: Pb-glass + scint. + thin RPC + Fe
- Barrel: 20 layers (53) – 17 X0 / 2.2 λ_I
- Endcap: 25 layers (67)– 22 X0 / 2.9 λ_I
- Longer λ_I for better hadron shower containement
- 365,00 tile-pairs
- Heatsink: pyrolitic foil

Why dual-readout: PID

REDTOP



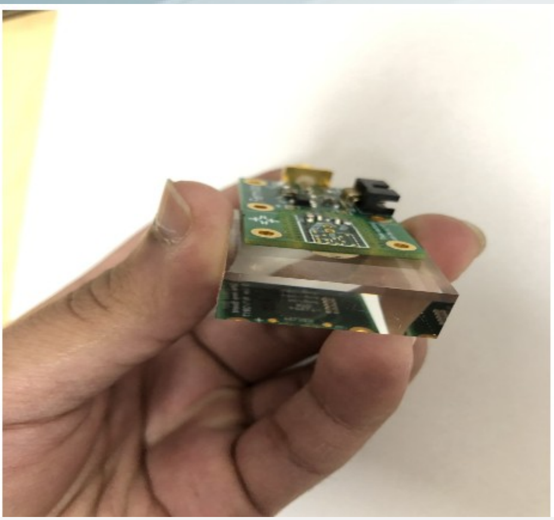


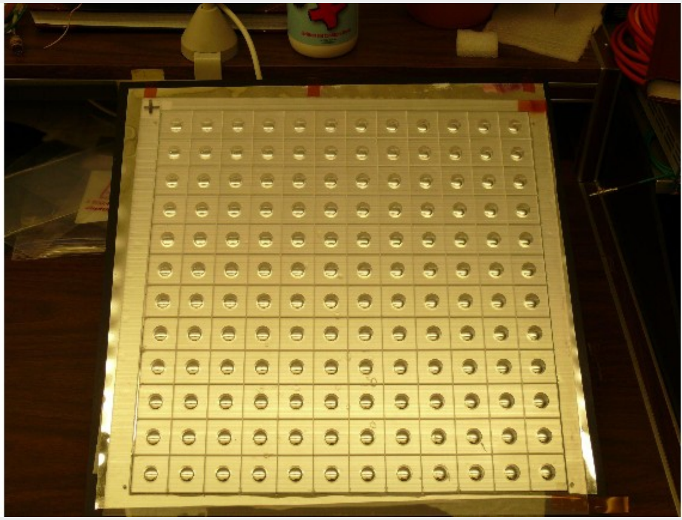
Simulate:

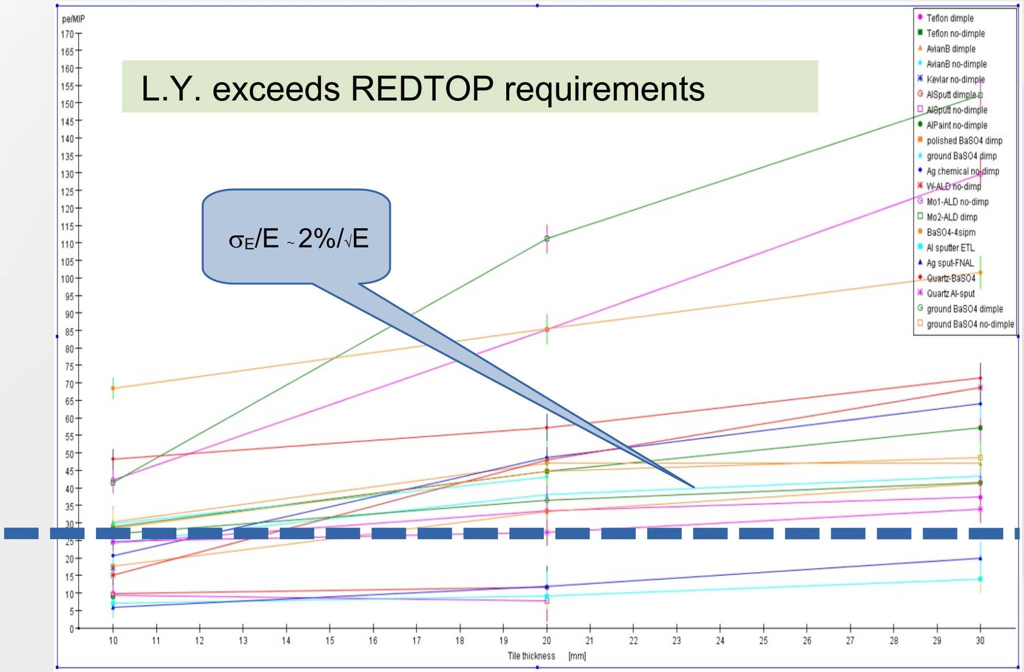
- $\eta \rightarrow \gamma A_{17}' \rightarrow \gamma e^+e^-$
- *Urqmd*
- *ADRIANO2 dual-readout calorimeter*

EM vs hadrons separated at 5σ

ADRIANO2 *vs* ADRIANO3







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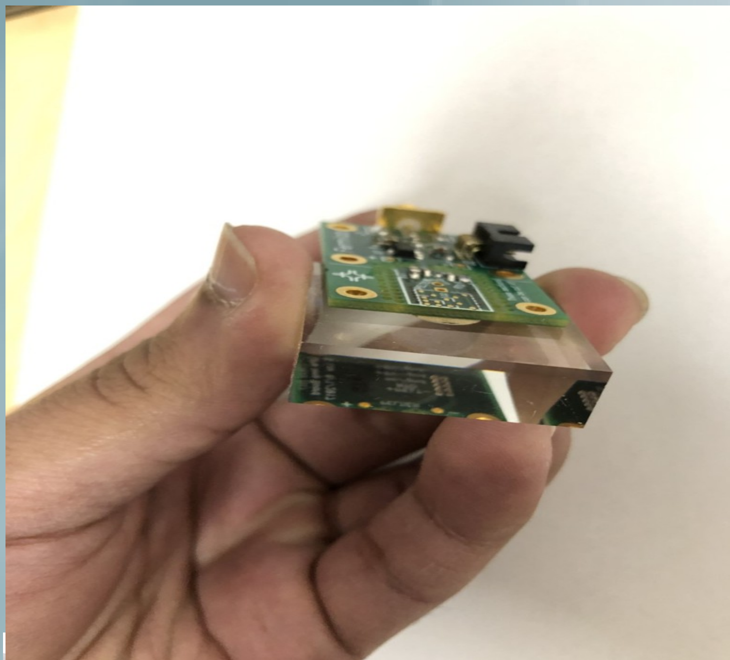
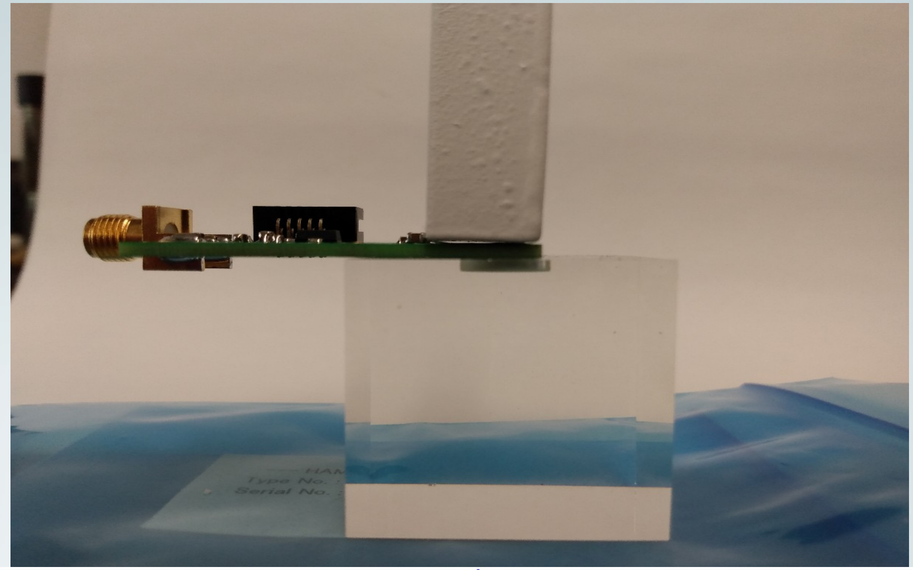
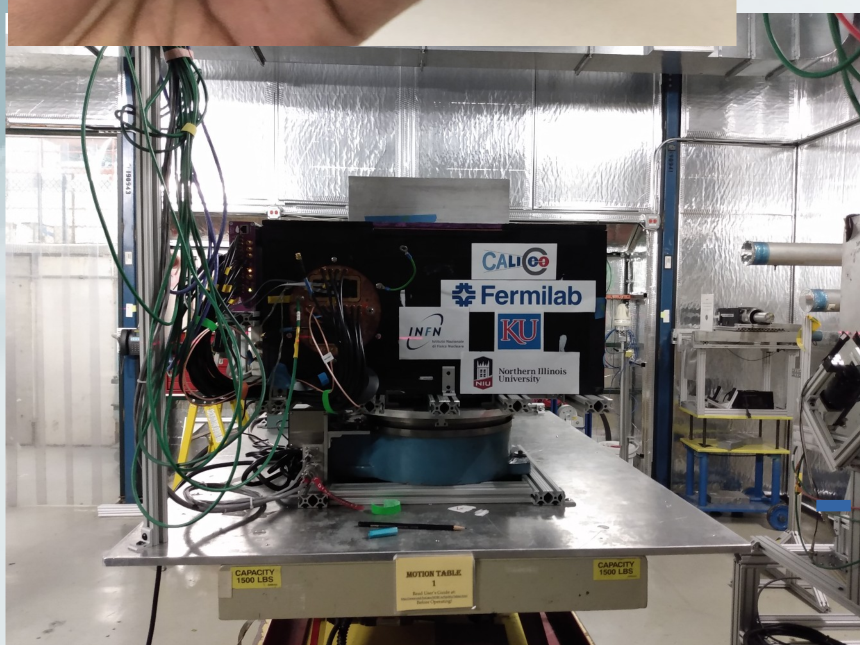
- Longer λ_I for better hadron shower containement
- 365,00 tile-pairs
- Heatsink: pyrolitic foil

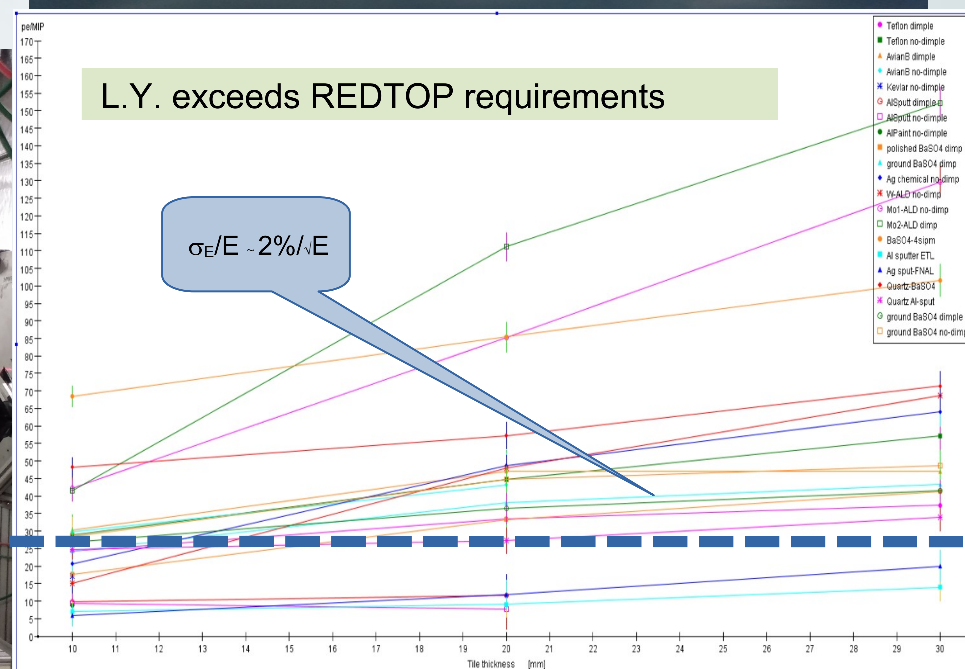
Slide from Calor2022

R&D on ADRIANO2 (from T1604)









Subdetector Technologies

	Baseline (White paper)	Options
Target	Li foils: 10x 0.78mm	LH_2 11 cm
VTX	LHCb fiber tracker. REDTOP: 0.24m^2 vs LHCb: 360m^2	CMOS (ITS3) or hybrid (fiber+1 layer CMOS)
Central tracker	LGAD 100μm/layer eq., no active cooling (30 psec/layer). REDTOP: 14m^2 vs CMS: 16m^2	LGAD 120μm/layer eq., no active cooling (42 psec/layer)
TOF	1 layer 30x30x10 mm^3 JGS1 + Petiroc (50 psec/layer). Area: 3.7 m^2	2 layers, 30x30x10 or 20x20x10 mm^3 JGS1 + Liroc+Tsinghua TDC/PicoTDC (<30 psec/layer). Area: 9.4 m^2
Calorimeter	ADRIANO2: 53 layers 30x30x14 mm^3 SF57/cast scint (80 psec/cell) 800,000 tile pairs	ADRIANO2: 30 layers 30x30x14 mm^3 ZF2/ scint + 23 layers JGS1/Cu/scint (80 psec/cell) 400,000 tile pairs
μ-polarimeter	Not implemented	TBD