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

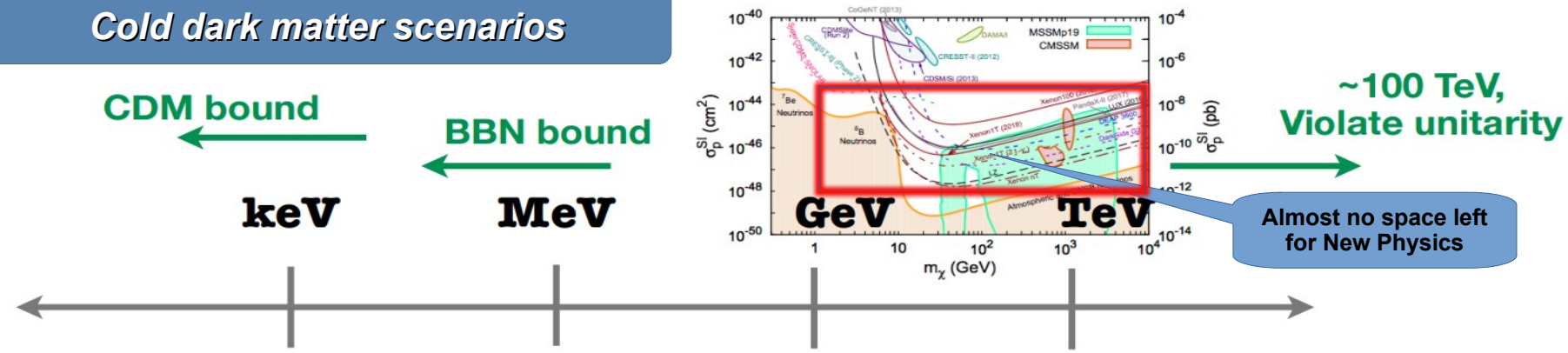
*R*are *E*ta *D*ecays
*TO P*robe New Physics

Corrado Gatto

INFN Napoli and Northern Illinois University

Motivations for an η/η' Factory

Cold dark matter scenarios



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
- **Only <80%(70%) of the η(η') is made of quarks**

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

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 → p Z a → 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 → A′/a → 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 : $\eta \to \pi\pi a_{17}$ with $a_{17} \to e^+e^-$*
- *New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^o$*
- *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*
- *HNL searches: $\eta \to \pi^o H$ 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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REDTOP

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- *CP invariance in [illegible]*
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- *[illegible]*
- *Lepton Universality*
- *[illegible]*

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Only experiment, along with SHIP, sensitive to all four BSM portals

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

REDTOP Running Modes for 10^{14} η/η′ mesons

RUN I

Baseline option – medium-energy CW proton beam at Delivery Ring

- *CW proton beam on thin Li/Be target : ~2 and 4 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: ~ 0.5 GHz
Average event multiplicity ≈
4 charged + 4 neutral
η/η′ production rate: ~ 2.3 MHz

RUN II

High sensitivity option: Tagged 10^{13} η mesons (PIP-II)

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

Inelastic interaction rate: ~ 13 - 130 GHz
η production rate: ~ 0.1 - 1 MHz

RUN III

High sensitivity option: Tagged 10^{13} η mesons (ACE)

- *high intensity proton beam on De target: ~1.7 GeV - 2 MW*
- *Less readily available: (also FAIR, ESS)*
- *Required fwd tagging detector for He_3*
- *Fully tagged production from reaction: $p+De \rightarrow \eta'+He_3^{++}$*

Inelastic interaction rate: ~ 13 - 130 GHz
η′ production rate: ~ 0.01 – 0.1 MHz

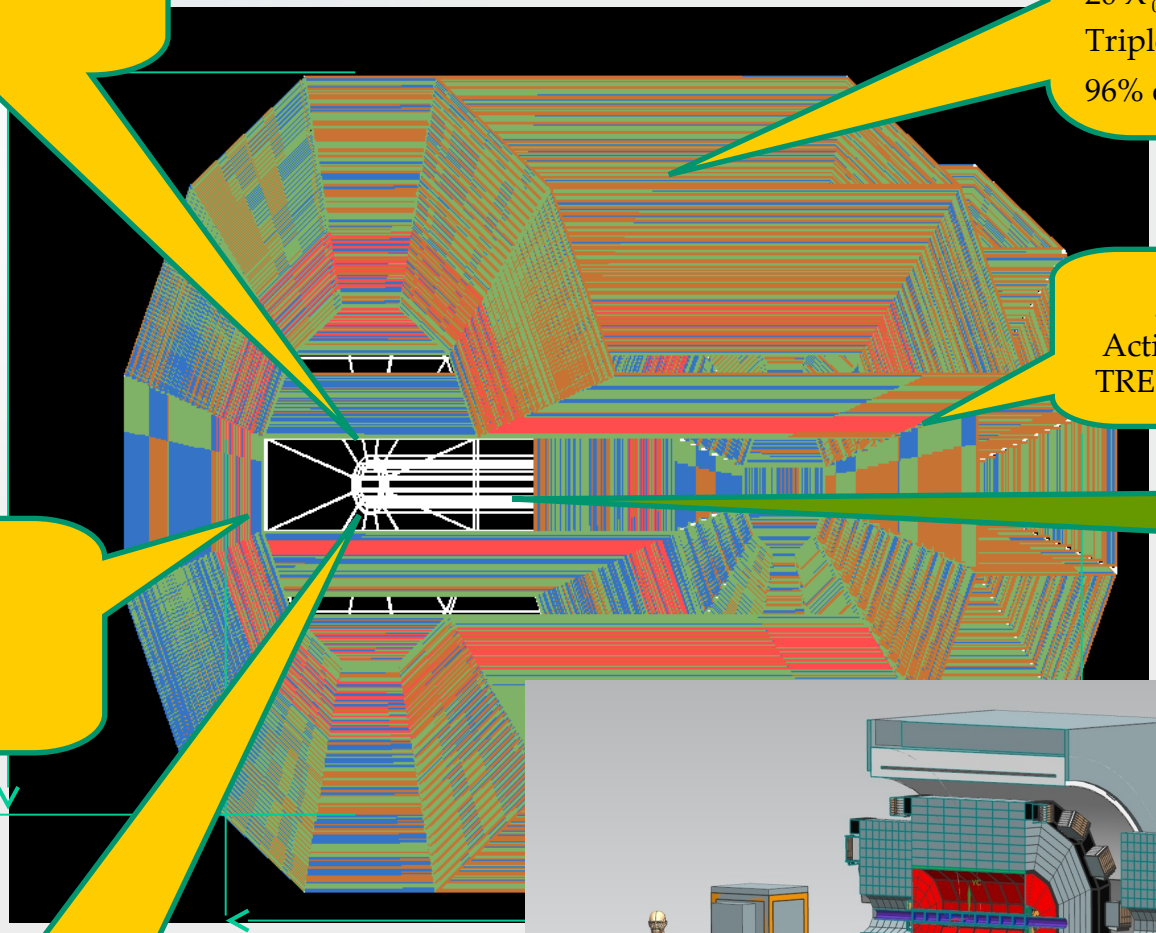
REDTOP detector

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

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

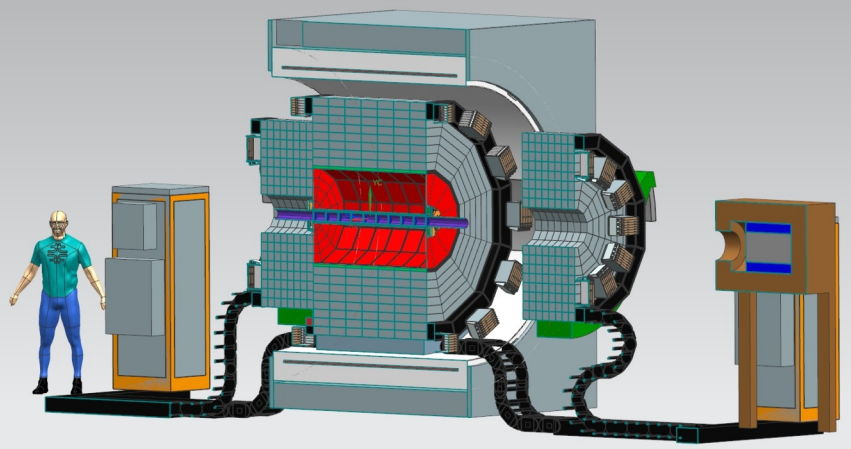
μ-polarizer
Active version (from TREK exp.) - optional

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



RICH
~ 1m x 1.5 m
Lead-glass tiles
98% coverage

Fiber tracker or ITS3
for rejection of γ-conversion and vertexing



Conclusions

- *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 four DM portals*
- *Very large physics reach for NP as well*
- *New detector techniques benefit the next generation high intensity experiments*
- *Beam requirements could be met by several labs in US, Europe, and Asia*
  - *Before 2030: HIAF and GSI (Delivery Ring @ Fermilab?)*
  - *After 2030: Fermilab and ESS, FAIR*
- *Moderate cost: ~100 M$ (including contingency and labor)*

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

Backup Slides

REDTOP Key Points

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

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

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

Pion beam also well suited

Detector 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

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57 Institutions
126 Collaborators

The physics case for REDTOP

Physics case presented in 176-pp White Paper. Sensitivity studies based on ~10^{14} η mesons ($3.3x10^{18}$ POT and 3-yr run), >$30x10^{6}$ 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

Acceleration Scheme for Run-I (M. Syphers)

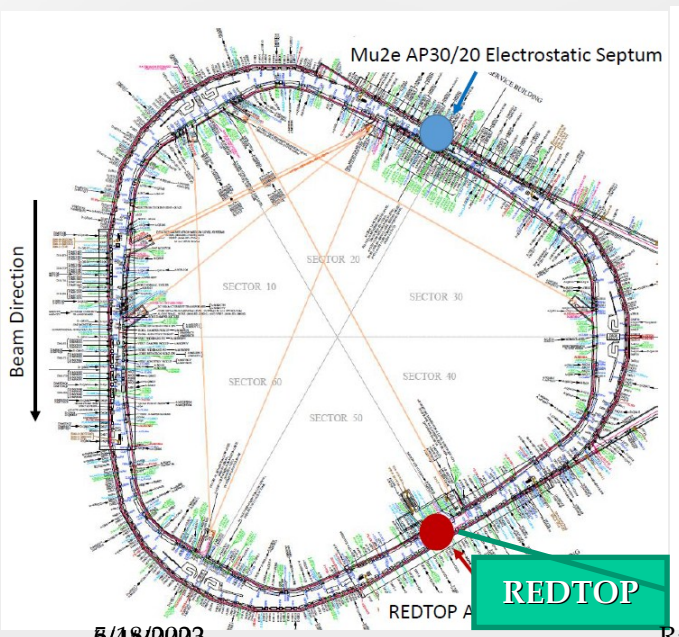
Single p pulse from booster (≤4x10^{12} p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)

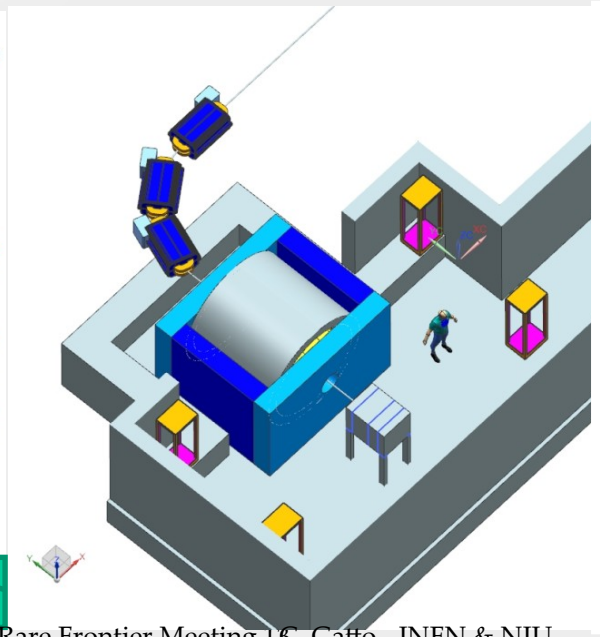
Energy is removed by inserting 1 or 2 RF cavities identical to the one already planned (~5 seconds)

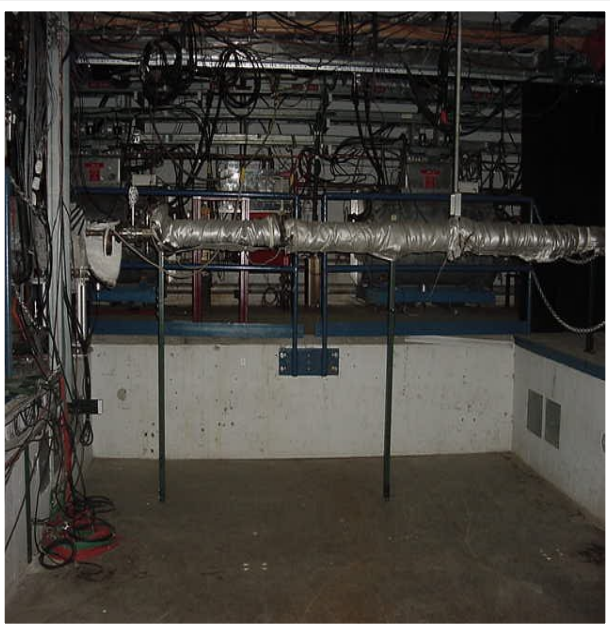
Slow extraction to REDTOP over ~40 seconds.

The 270^{o} 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%







Cost estimate

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**