The REDTOP experiment
An eta/eta' factory to explore
Physics Beyond the Standard Model

*R*are *E*ta *D*ecays with a
*T*pc for *O*ptical *P*hotons

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Rationale for an η/η‘ Factory

- Recent LHC results suggest that the next search for New Physics should be in the MeV-GeV mass range with high-luminsity experiments (ex. Fixed target)
- "…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).
- "*…Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders…*" [G. Krnjaic RF6 Kickoff Meeting, August 12, 2020]
- The only known particles with all-zero quantum numbers are the η/η' mesons and the Higgs boson
- The structure of the η/η' mesons has never been fully understood: it might very well contain a non-quark (BSM) component
- All electromagnetic and strong decays of the neutral and long-lived and ' are suppressed at first order and weak decays have branching ratios of order 10^{-11}. Branching Ratio of processes from New Physics are enhanced compared to SM and easier to detect.

An η/η' factory could be considered a low-energy Higgs factory

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

Assume a yield ~10^{13} η mesons/yr and ~10^{11} 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: $\eta \to \mu^+\mu^-e^+e^-$
- T invariance via μ transverse polarization: $\eta \to \pi^o\mu^+\mu^-$ or $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ polar. in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi\mu^+\nu$ and γ polar. in $\eta \to \gamma\gamma$

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 $X_{17} \to e^+e^-$**
- **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**

Other discrete symmetry violations

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

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})

Non-η/η′ based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: qqbar → A′/a → l^+l^-
- **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 $K^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$
- Neutral pion decay: $\pi^o \to \gamma A' \to \gamma e^+e^-$

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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See also A. Mazzacane's talk

Other disc

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Present & Future η Samples

	Technique	$\eta \to 3\pi^o$	$\eta \to e^+e^-\gamma$	Total η
CB@AGS	$\pi^- p \to \eta n$	9×10^5		10^7
CB@MAMI-B	$\gamma p \to \eta p$	1.8×10^6	5000	2×10^7
CB@MAMI-C	$\gamma p \to \eta p$	6×10^6		6×10^7
KLOE	$e+e- \to \Phi \to \eta\gamma$	6.5×10^5		5×10^7
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 (just started)	$\gamma_{12\ GeV} p \to \eta X \to$ neutrals			5.5×10^7/yr
JEF@JLAB (recently approved)	$\gamma_{12\ GeV} p \to \eta X \to$ neutrals			3.9×10^5/day
REDTOP@FNAL (proposing)	$p_{1.8\ GeV} Li \to \eta X$	10^{12}	6×10^9	2.5×10^{13}/yr

The REDTOP Program

- REDTOP is more than an experiment: it is a program of BSM physics exploration through multiple running phases

Phase – Ia: Untagged 10^{13} η mesons (Delivery Ring)

- *Medium energy low intensity proton beam:* ***~2 GeV - 30 W***
- ***Near-4π central detector***

Phase – Ib: Untagged 10^{11} η′ mesons (Delivery Ring)

- *Medium energy low intensity proton beam:* ***~4 GeV - 60 W***
- ***Same detector as in Phase-Ia***

Phase – II: Tagged 10^{13} η mesons (PIP-II)

- *Low energy high intensity proton beam:* ***~0.9 GeV - 1 MW***
- ***Same detector as in Phase-Ia + fwd tagging detector***

Phase – III: Tagged 10^{13} η′ mesons (Booster upgrade)

- *Low energy high intensity proton beam:* ***~2 GeV - 1 MW***
- ***Same detector as in Phase-II***

Possible More Phases

- *Reuse REDTOP detector with different beam species (K, μ, π)*

REDTOP Beam Requirements

Phase – I: Untagged 10^{13} η/η′ mesons

Fermilab Delivery ring

- *CW beam:* ~2 GeV (η)– ~4(η′) GeV
- *Low intensity :* 10^{11} POT/sec or 10^{18} POT/yr on solid target
- *Multiple (10) thin* Li or Be *targets to disentangle event pileup*

vs LHCb@40 MHz

Inelastic interaction rate: ~ 0.5 GHz
Average event multiplicity ≈
4 charged + 4 neutral
η/η′ production rate: ~ 2.3 MHz

Phase – II: Tagged 10^{12} – 10^{13} η/η′ mesons

Fermilab PIP-II

- *CW beam:* ~0.9 GeV (η) and ~1.7(η′) GeV
- *High intensity beam :* 10^{21}-10^{22} POT/yr on De gaseous target

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

Detector Requirements and Technology

- *Calorimetric $\sigma(E)/E < 5\%/\sqrt{E}$*
- *High PID efficiency: 98/99% (e,γ), 95% (μ), 95% (π), 99.5%(p,n)*
- *$\sigma_{tracker}(t)$ ~50psec, $\sigma_{calorimeter}(t)$ ~80psec, $\sigma_{Rich}(t)$ ~80psec*
- *Low-mass vertex detector*
- *Near 4π detector acceptance (as the η/η' decay is almost at rest).*

charged tracks detection

Option 1: Optical-TPC

- *Barions and most pions are below threshold*
- *Electrons and most muons are detected and reconstructed*

Option 2: Ultra-light LGAD Tracker

- *4D track reconstruction for multihadron rejection*
- *Complemented with outer quartz tiles for TOF measurements*
- *<150μm total layer thickness*

γ/e detection

- ***ADRIANO2** tile calorimeter*
- *Calice and T1604*
- *PFA + Dual-readout+HG*
- *PID from scintillation vs Cerenkov*
- *Light sensors: SiPM or SPADs*
- *96.5% coverage*

***Fiber tracker** (LHCB style) for rejection of background from γ-conversion and reconstruction of secondary vertices (~70μm resolution)*

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Fiber tracker *and*

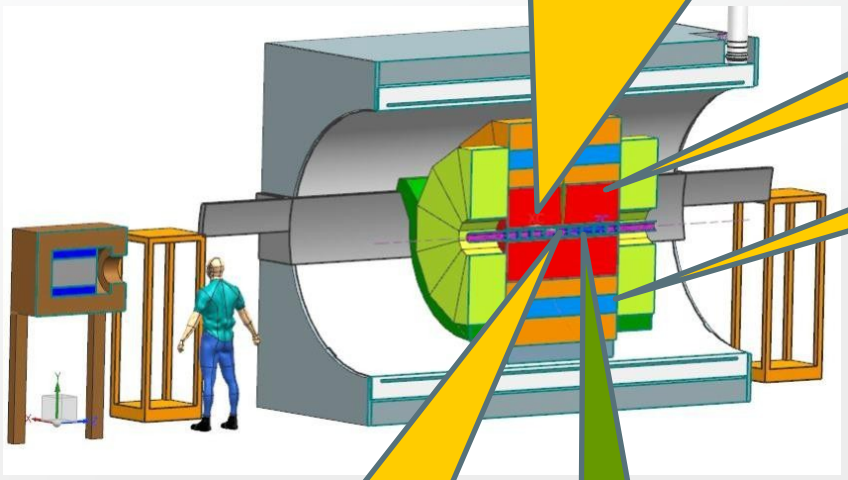
instru

All new detector techniques need to be developed

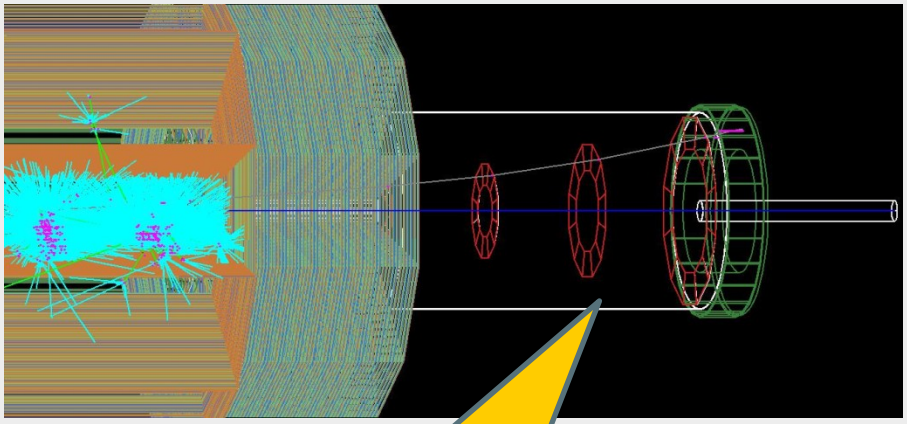
The REDTOP Detector

Optical-TPC
For slow background rejection
or
LGAD Tracker surrounded by Quartz cells
For 4D track reconstruction and TOF measurements

5D- Calorimeter: ADRIANO2 (Dual-readout +PFA)
Sci and Cer light read by SiPM or SPAD
For excellent energy , position resolution and PID



-polarimeter (optional)
sandwich of fused silica and Si-pixel
for measurement of muon polarization



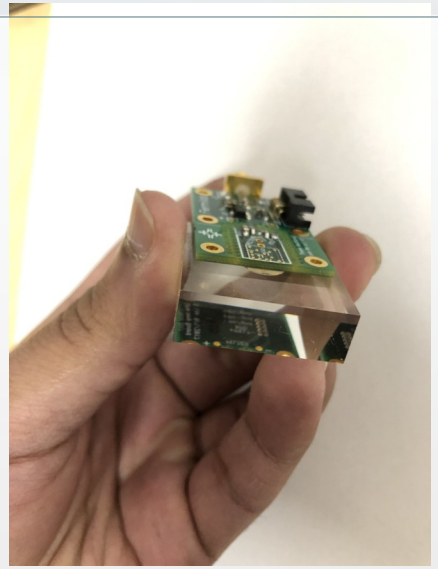
Vertex Fiber tracker
for rejection of -conversion and identifying displaced vertices from long lived particles

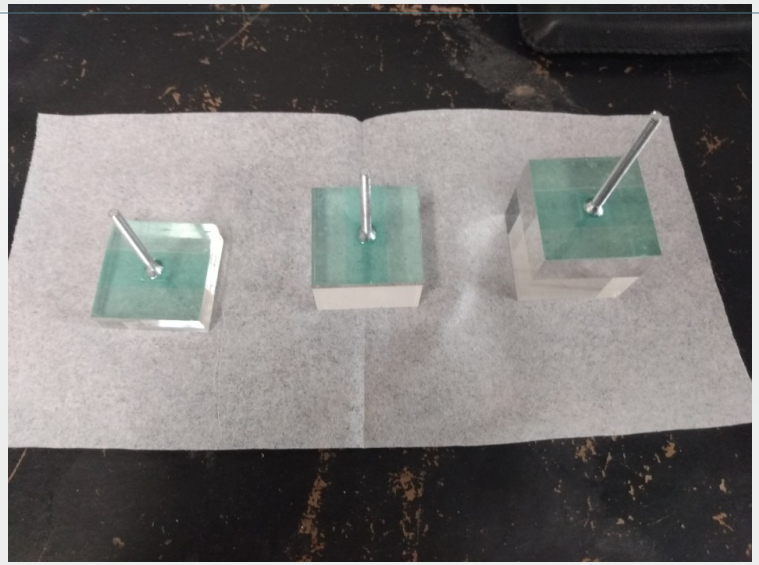
10x Be or Li targets

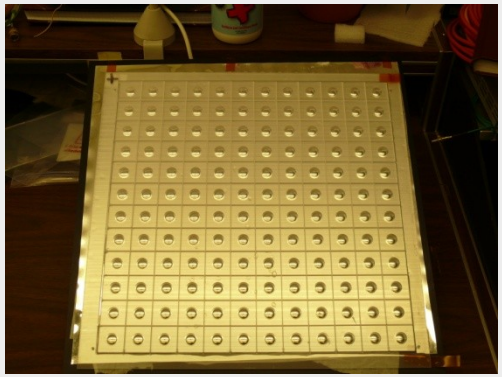
Forward Detector for Phase-2
for tagging $^{3}He^{++}$ ions

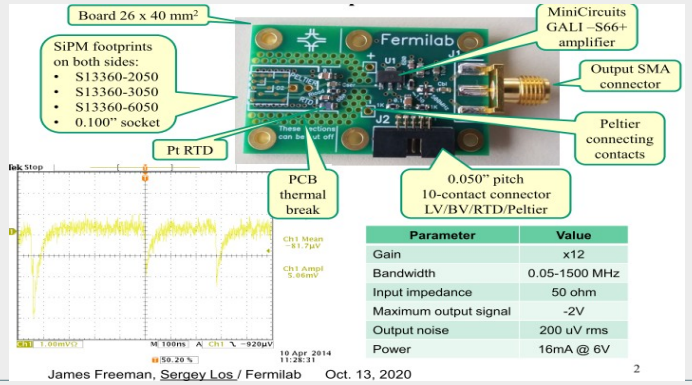
ADRIANO2 R&D: T1604 and CALICE

Sandwich of Pb-glass and scintillating tiles for dual-readout technique









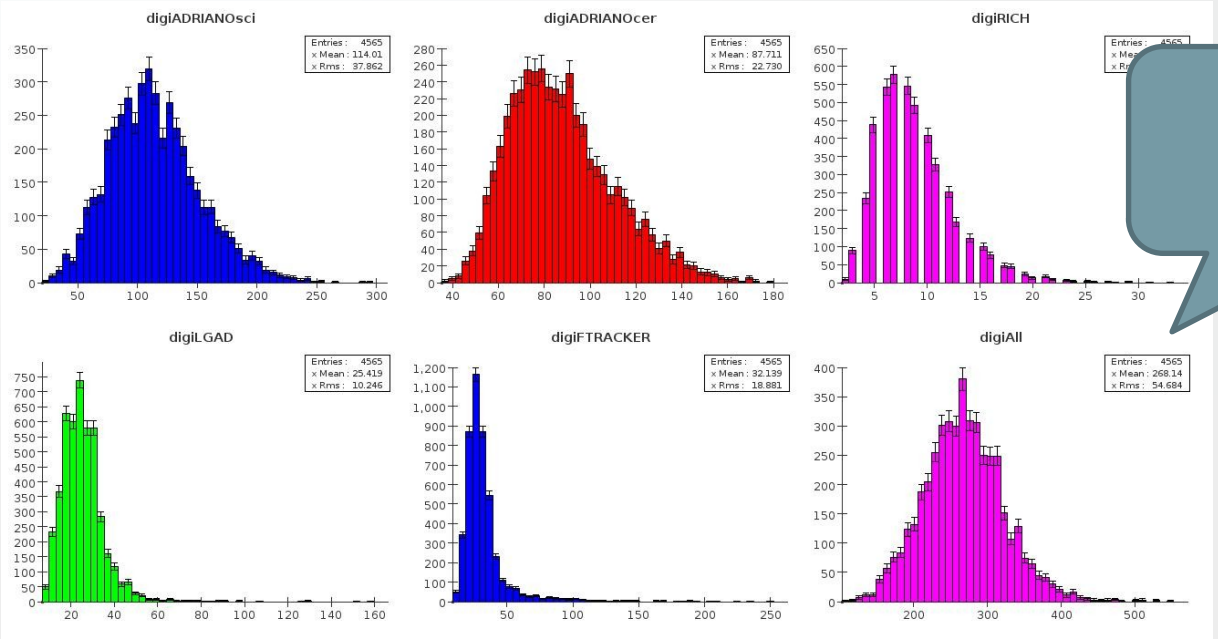
Parameter	Value
Gain	x12
Bandwidth	0.05-1500 MHz
Input impedance	50 ohm
Maximum output signal	-2V
Output noise	200 uV rms
Power	16mA @ 6V

First ADRIANO2 protoype succesfully tested at FTBF in June 2021

REDTOP Trigger Requirement

Phase – I: Untagged 10^{13} η/η′ mesons

Hits from subdetectors



Total channel occupancy: 270 +/- 50 /evt

Trigger requirements (L. Ristori, A. Kotwal)

Level	Algo	Detectors	Hardware	Rejection factor
L0	Σ LGAD, RICH & ADRIANO-Cer	LGAD, RICH, ADRIANO	Fast sum	100
L1	identification of a pair of leptons, γ-conversion rejection, TOF	LGAD, RICH, ADRIANO Fiber Tracker	FPGA	100
L2	Reco	All	2000 CPU-cores	>100

Storage & CPU

Expected data rates from the experiment

- About 100 Hz to be stored on tape
- ~0.25 MB/sec from L2
- ~2.5 PB/year to tape (assume 2.5 kb event size)

Data from DAQ and Montecarlo

- Data from experiment: ~2.5 PB/year to tape
- Processed data (reco, calib. Analysis, etc) : ~2.0 PB/year (tape and disk)
- Montecarlo (~10^{11} events): ~0.5 PB/run (tape and disk)
- ***Total: 5 PB/year***

CPU for Reconstruction Analysis and Montecarlo

- 55 million core-hours for Monte Carlo jobs
- 35 million core-hours for data reconstruction jobs
- Total: ~ 90 million core-hours /year

(estimate by projecting current OSG usage)

REDTOP Collaboration

11 Countries, 39 Institutions, 94 Collaborators

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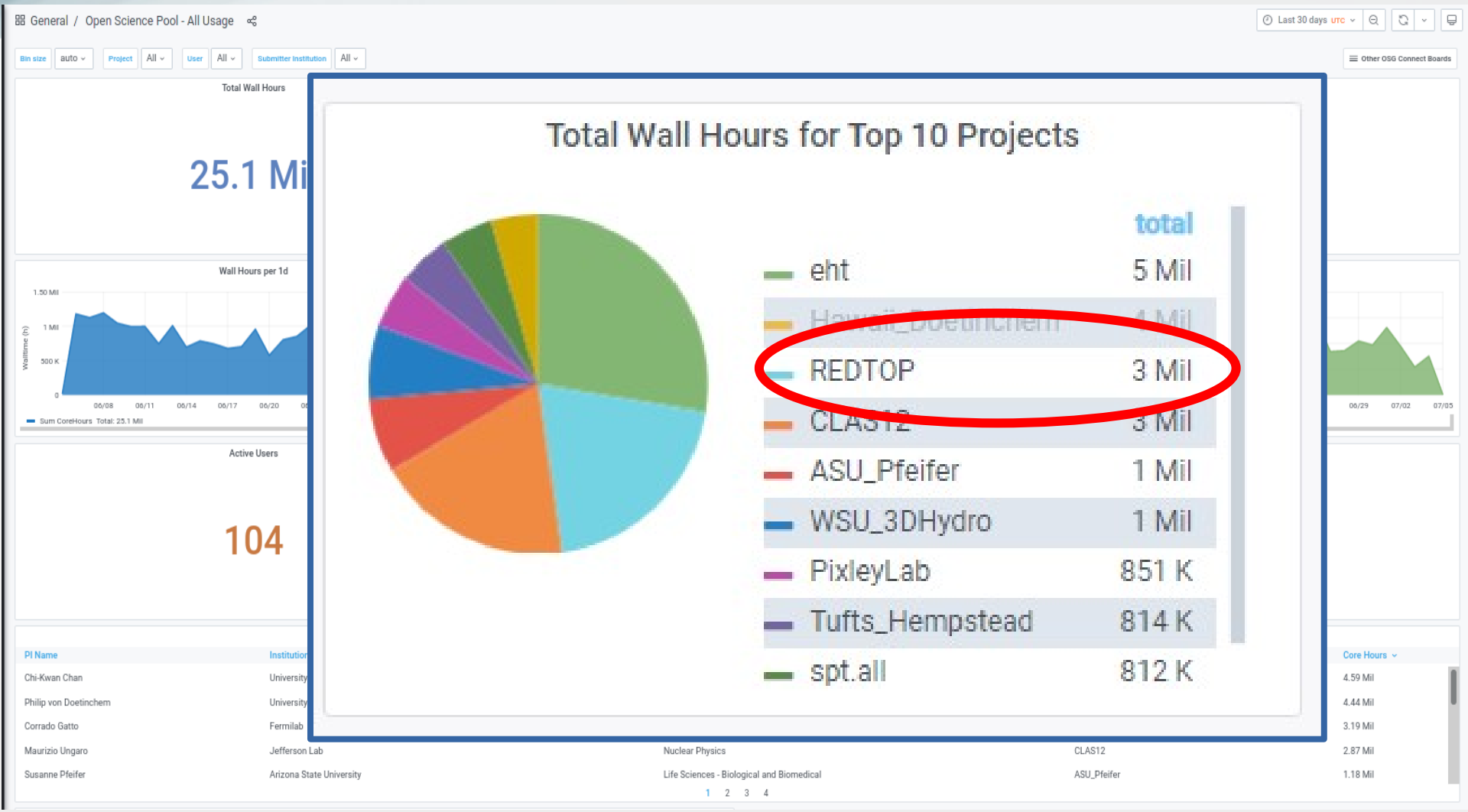
Summary

- *All meson factories: LHCb, B-factories, Dafne, J/ψ factories - have generated a broad spectrum of nice physics*
- *Existing world sample of η/η' mesons not sufficient for breaching into decays violating conservation laws or searching for new particles*
- *REDTOP goal is to produce >10^{13} untagged η mesons/yr and ~10^{11} η'/yr in Phase-I and ~10^{13} tagged η mesons in Phase-II (x10^4 existing world sample)*
- *Complementary to JEF η -factory at JLAB*
- ***No similar experiment being proposed worldwide***
- *Novel detector techniques are required to cope with high interaction rate and background. Sub-nsec timing is essential.*
- *Relatively low beam requirements could be met by several laboratories in US, Europe and Asia*
- *Fermilab only laboratory with beam for Phase-I (Delivery Ring) and Phase-II (PIP-II).*
- ***More details: https://redtop.fnal.gov***

Backup slides

REDTOP OSG Monthly Usage Statistics



Overall Computing Usage

- *Computing resources for REDTOP are from three sources:*
  - *OSG: CPU and stash storage*
  - *NICADD/NIU: CPU and permanent storage*
  - *Fermilab (private farm hosted by AD) : CPU and permanent storage*

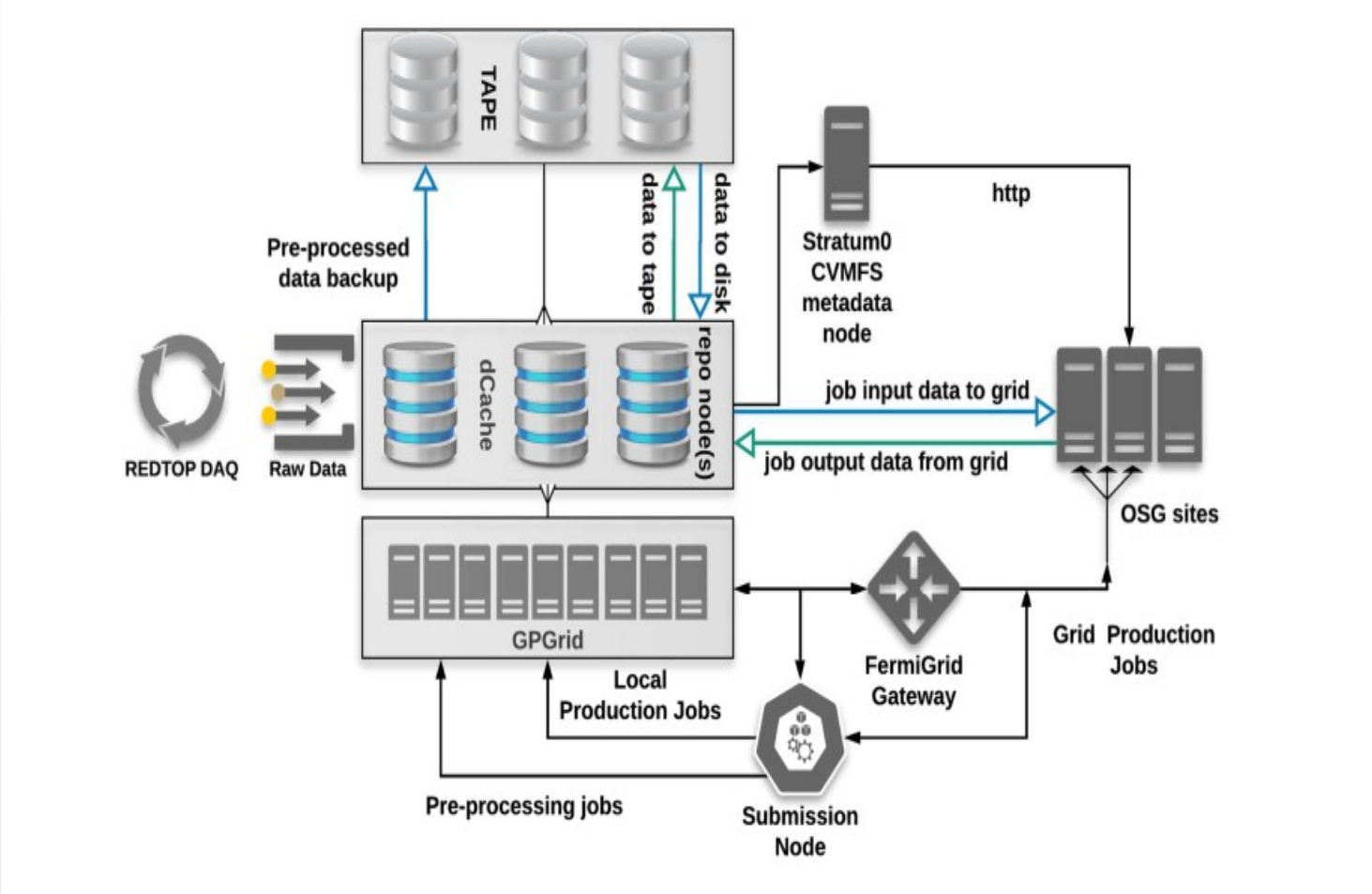
Summary of computing

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%

REDTOP Computing Model

- *Model architecture:*
  - *Single-core computational workflow has proven to be well suited for the distributed High Throughput Computing (DHTC) environment of the OSG.*
  - *Model already adopted by other small Collaborations (IceCube, XENON, et. al.)*
- *Storage:*
  - *DataStream from the L-2 farm will be staged at (FNAL) dCache storage and sent to tape (or wherever is cheaper when the experiment runs: FNAL at present)*
  - *Stratum-0 server hosts a CVMFS repository of the REDTOP software*
- *CPU:*
  - *Any (dedicated or opportunistic) OSG working node*
  - *Member institutions can join the OSG federation and accept jobs from OSG's GlideinWMS job factory via a HostedCE deployment.*

REDTOP Baseline Computing Model



For more details: http://redtop.fnal.gov/wp-content/uploads/2020/05/redtop-compute_v3.pdf