THE REDTOP EXPERIMENT

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

Corrado Gatto
INFN Napoli and NIU
For the REDTOP Collaboration

REDTOP Experiment Key Points

- ***A near-4π, fixed target detector sensitive to leptons and γ's***
  - Optical-TPC, Multiple-readout calorimeter, Active Muon Polarimeter (all novel technologies)
  - Very fast (Cerenkov and scintillating light only) to sustain event rates in next generation of High Intensity experiments
  - Blind to barions
  - Not terribly expensive
- ***A CW proton beam with user selectable energy***
  - All energies in 1.5-8 GeV available
  - Extraction line from Delivery Ring to AP50
  - Reuses components already available at Fermilab
- ***The experiment will yield 2×10^{13} η mesons/year and 2×10^{11} η' mesons/year***

More details at: http://redtop.fnal.gov

BSM Physics Program (η and η' factory)

C, T, CP-violation

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

Other discrete symmetry violations

- *Lepton Flavor Violation:* $\eta \rightarrow \mu e$
- *Double lepton Flavor Violation:* $\eta \rightarrow \mu \mu e e$

New particles and forces searches

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

BSM Physics Program (η and η' factory)

Other Precision Physics measurements

- *Proton radius anomaly:* $\eta \to \gamma \mu^+ \mu^-$ *vs* $\eta \to \gamma e^+ e^-$

Non-η/η' based BSM Physics

- *Dark photon and ALP searches in Drell-Yan processes:* $qqbar \to A' / \mathrm{a} \to l^+ l^-$
- *ALPS searches in Primakoff processes:* $p\, Z \to \mathrm{p\, Z\, a} \to l^+ l^-$
- *Charged pion and kaon decays:* $\pi+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$ *and* $K+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$
- *Neutral pion decay:* $\pi^0 \to \gamma A' \to \gamma e^+ e^-$

Non-BSM Physics Program (η and η' factory)

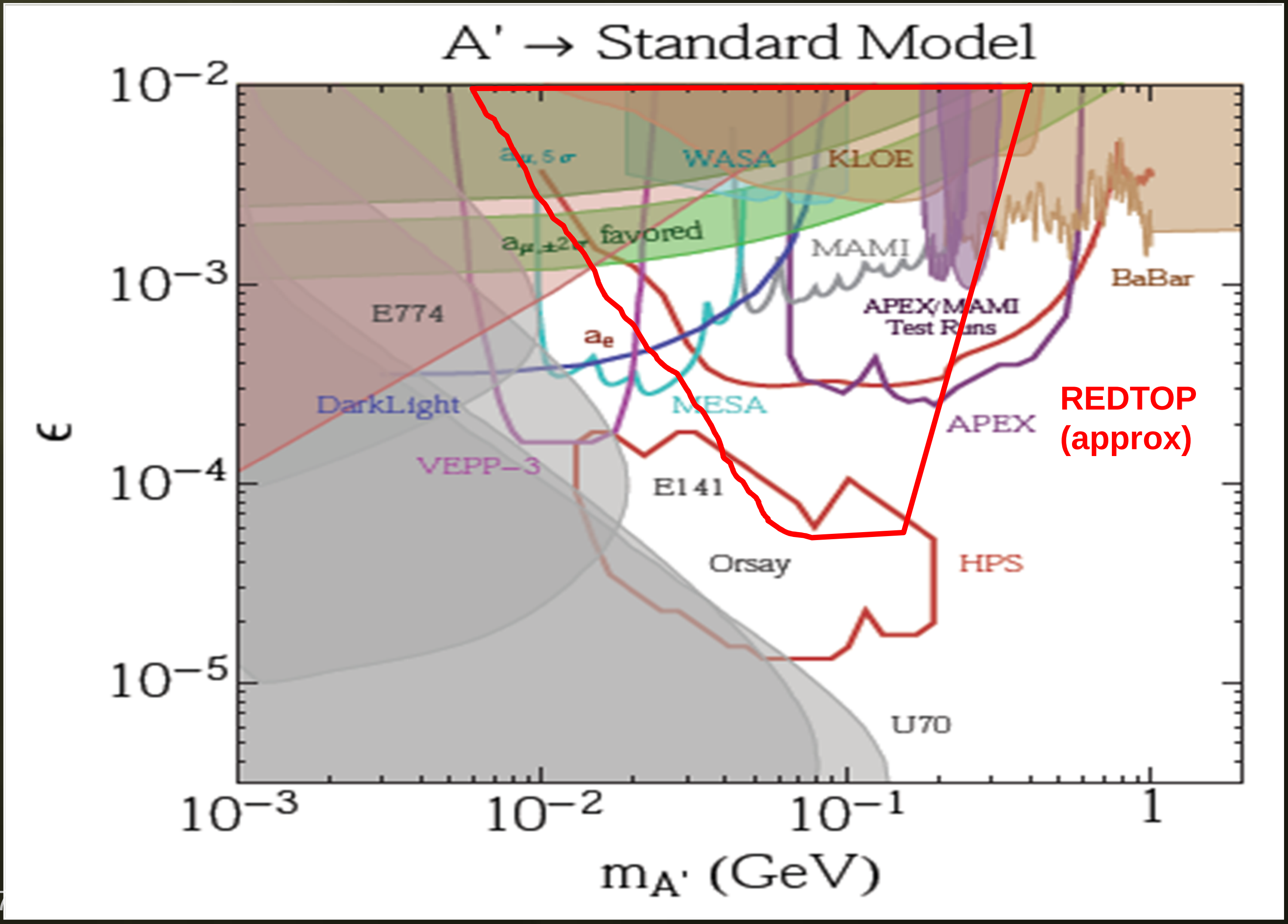
High precision studies on low energy physics

- *Nuclear models*
- *Chiral perturbation theory*
- *Non-perturbative QCD*
- *Isospin breaking due to the u-d quark mass difference*
- *Octet-singlet mixing angle*
- *$\pi\pi$ interactions*
- *Electromagnetic transition form-factors (important input for g-2)*
- *Lots of other bread&butter physics*

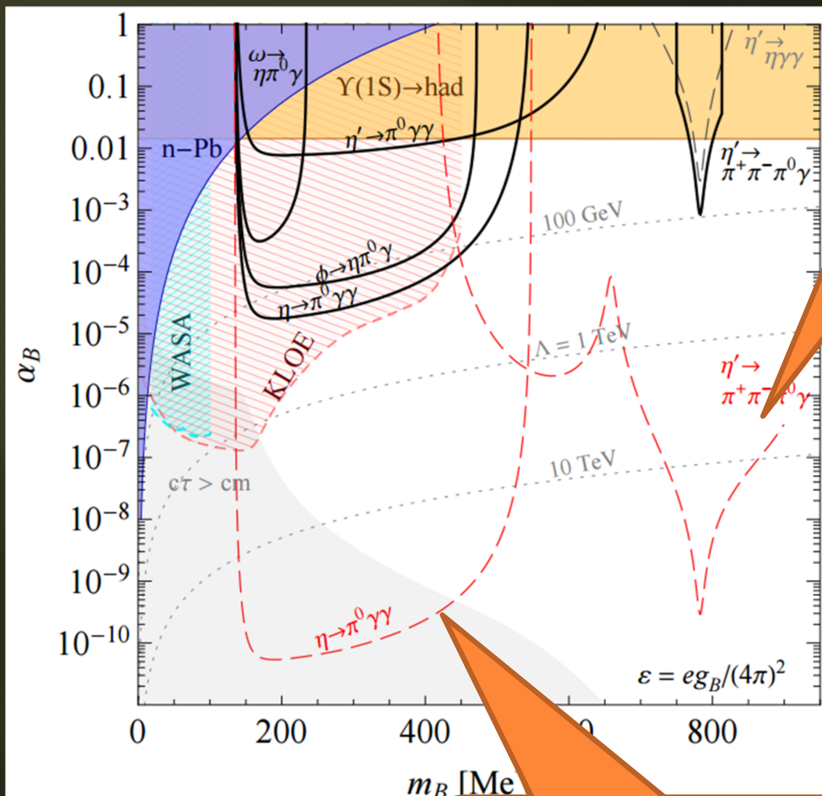
Dark photon searches with 10^{13} η mesons

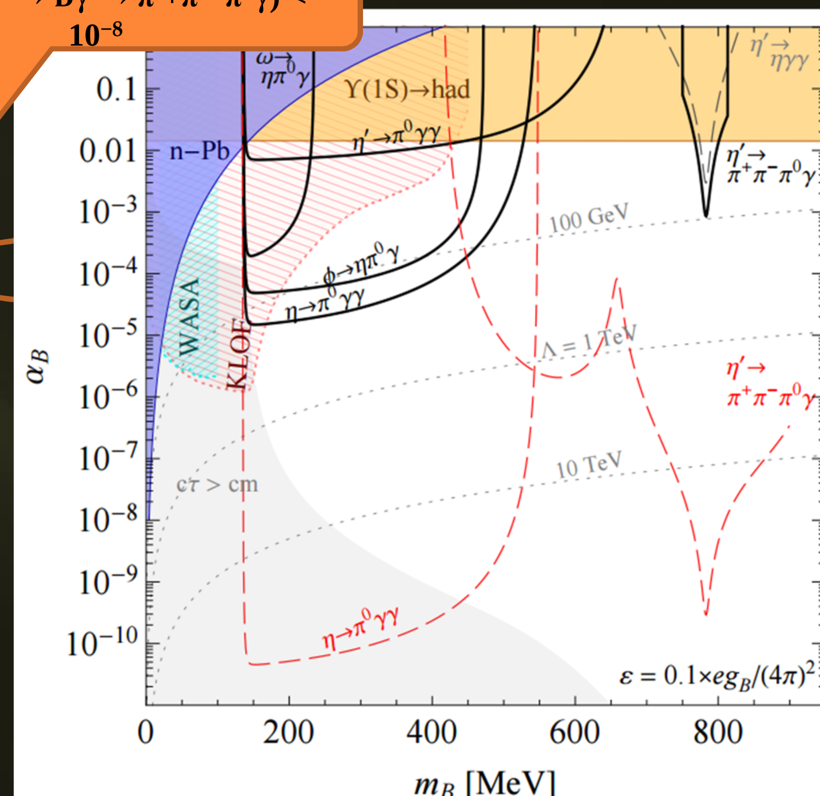
$$\eta \to \gamma A' \to 3\gamma \text{ or } \gamma + \ell^+\ell^-$$

Essig et al (2013)



REDTOP Constraints on a new baryonic force (courtesy of S. Tulin – U. York)





REDTOP constraints at the level of BR($\eta' \to B\gamma \to \pi^+\pi^-\pi^0\gamma$) < 10^{-8}

REDTOP constraints at the level of BR($\eta \to B\gamma \to \pi^0\gamma\gamma$) < 3×10^{-9}

Based on 2.5×10^{13} η meson produced and 1×10^{11} η′ meson produced

Present η Samples

	Technique	$\eta\to3\pi^0$	$\eta\to e^-e^+\gamma$	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	$e^+e^-\to\phi(1020)\to\eta\gamma$	6.5×10^5	????	5×10^7
WASA@COSY	$pp\to\eta pp$ $pd\to\eta\ {}^3He$			$>10^9$ 3×10^7
CB@MAMI (proposed)	$\gamma p\to\eta p$	3×10^7	1.5×10^5	3×10^8

Near future η Samples

GlueX@JLAB (just started) $\gamma_{12\,\mathrm{GeV}}p \to \eta\, p \to$ neutrals 4.5×10^7/yr

JEF@JLAB $\gamma_{12\,\mathrm{GeV}}p \to \eta\, X \to$ neutrals 3.9×10^5/day

(proposing – not yet approved)

REDTOP@FNAL $p_{1.9\,\mathrm{GeV}}p \to \eta\, pp$ 2.5×10^{13}/yr

(proposing) $p_{1.9\,\mathrm{GeV}}n \to \eta\, pp$

REDTOP Running Phases

- Phase I: η-factory
  - Beam: protons
  - T_{beam}: 1.8-2.1 GeV
  - Detector: baseline
- Phase II: η'-factory
  - Beam: protons
  - T_{beam}: 3.5-4.5 GeV (to be optimized)
  - Detector: baseline (change O-TPC gas pressure, probably the Aerogel section)
- Phase III: Muon Scattering Experiment **(optional)**
  - Beam: muons
  - T_{beam}: 0.2< <0.8 GeV (to be optimized)
  - Detector: baseline + front graphite target
- Phase IV: Rare Kaon Decays: $K^+ \to \pi^+ \nu \underline{\nu}$ **(optional)**
  - Beam: kaons
  - T_{beam}: from 8 GeV protons
  - Detector: might need upgrade target and central tracker, add range stack

All based on 1-yr of running

Beam and Target Requirements

- Phase I: η-factory. Goal is 2.5 x 10^{13} η /yr
  - T_{beam}: 1.8-2.1 GeV
  - Power: 30 W
  - Target: 10 x 0.33 mm Be
- Phase II: η ′-factory. Goal is ~ 10^{11} η′ /yr
  - T_{beam}: 3.5-4.5 GeV (to be optimized)
  - Power: 60 W
  - Target: 10 x 0.33 mm Be
- Phase III: Muon Scattering Experiment. Goal is > 2.0 ×10^{12} μ/yr
  - T_{beam}: 0.2< <0.8 GeV (to be optimized)
  - Muon muon yield: >1.6 ×10^{-8} μ/p
  - Target: 1 x 100 mm graphite
- Phase IV: Rare Kaon Decays: $K^+ \rightarrow \pi^+ \nu \underline{\nu}$ Goal is > 1 ×10^{14} KOT/yr
  - T_{beam}: K^+ from 8 GeV protons
  - K^+/π yield: 1 /13 (neglecting very soft pions - factor 1.8 better than p@p2 GeV)
  - Target: primary (PT: for K production) + secondary (active: scintillating plastics)

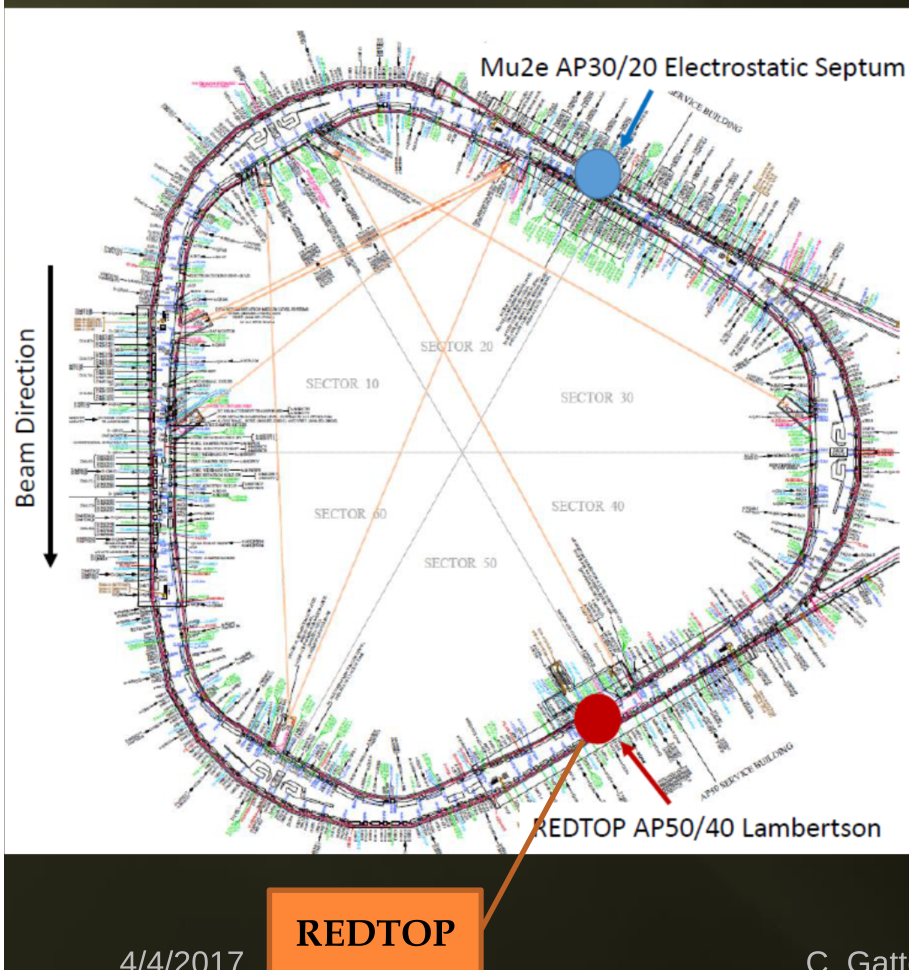
Very preliminary

Acceleration Scheme (M. Syphers)

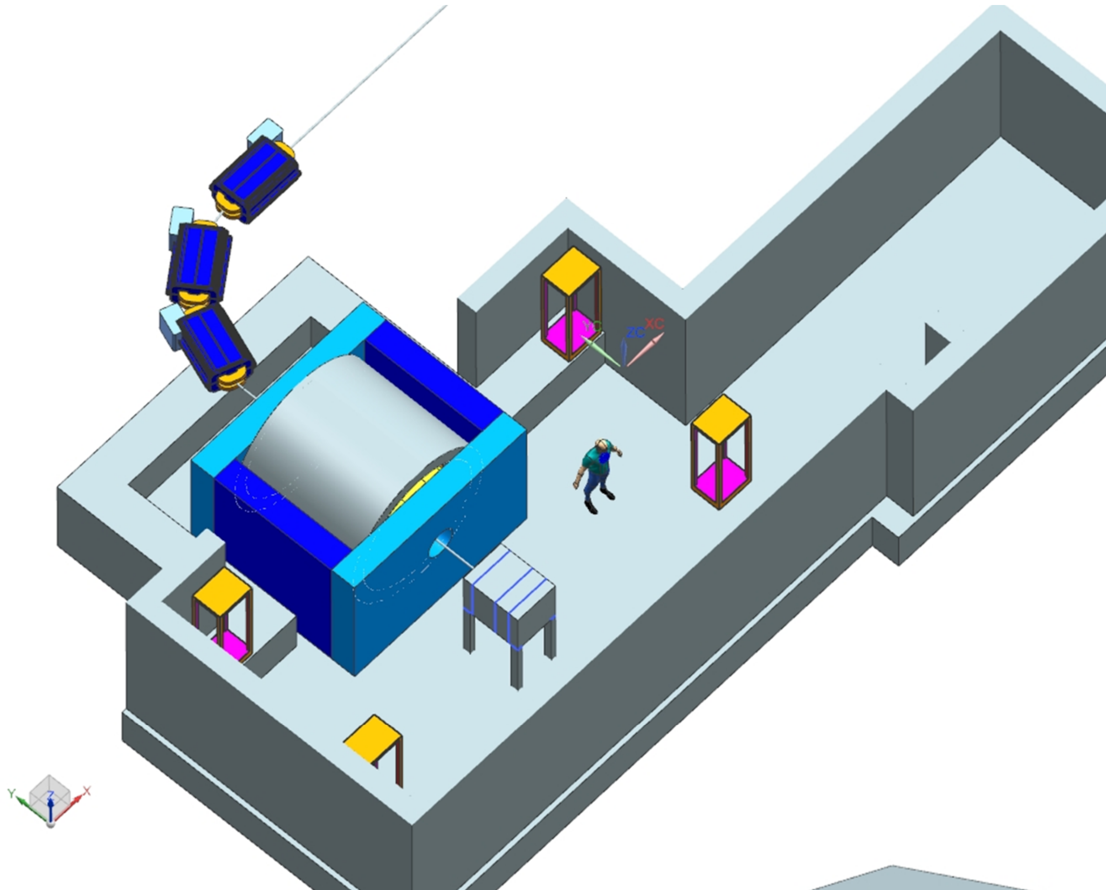
- ***Single p pulse from booster*** *($\leq 4x10^{12}$ p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)*
- *Energy is removed by adding 1-2 RF cavities identical to the one already planned for mu2e (J. Dey). Transitionless deceleration scheme by J. Johnstone (requires MADX confirmation)*
- *Spare RF cavities already existing (owned by mu2e and AD)*
- *Debunching occurs adiabatically inside the DR*
- *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.* ***A DEDICATED SEPTUM IS NOT REQUIRED***
- *Total time to decelerate-debunch-extract: 51 sec: duty cycle ~80%*

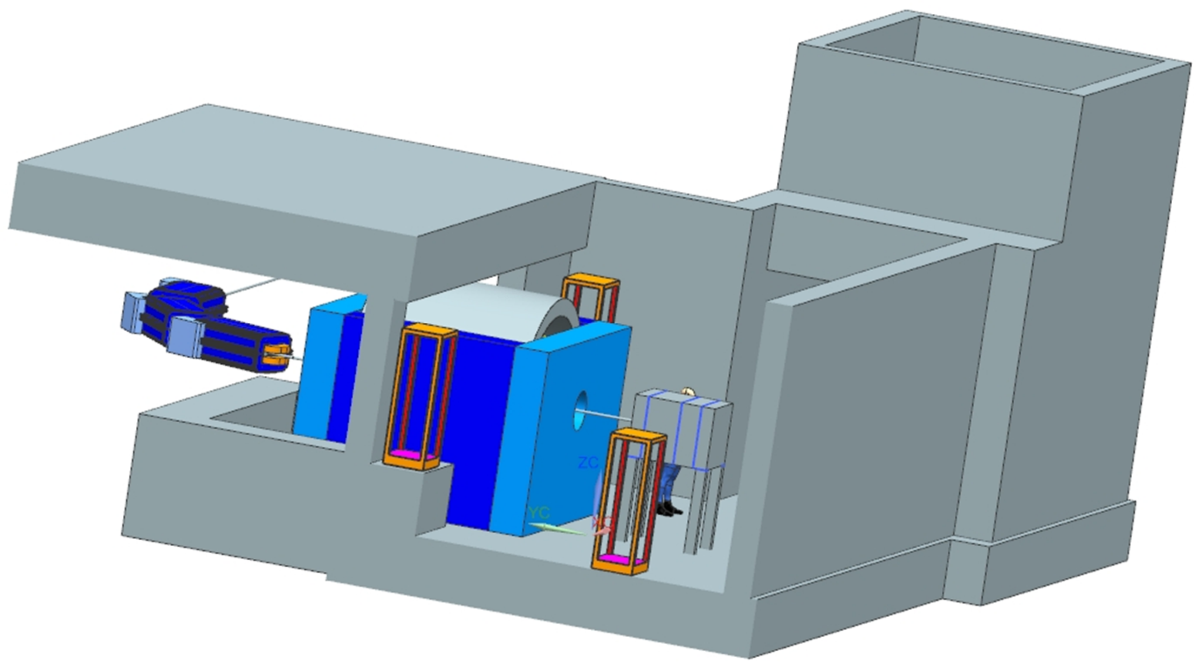
Accelerator complex for REDTOP Fermilab Option: AP50 hall

- Use delivery ring and extract beam at AP50
- Decelerate the 8 GeV beam to desired energy.



REDTOP detector in AP50





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

(Many thanks to K. Krempetz, as well)

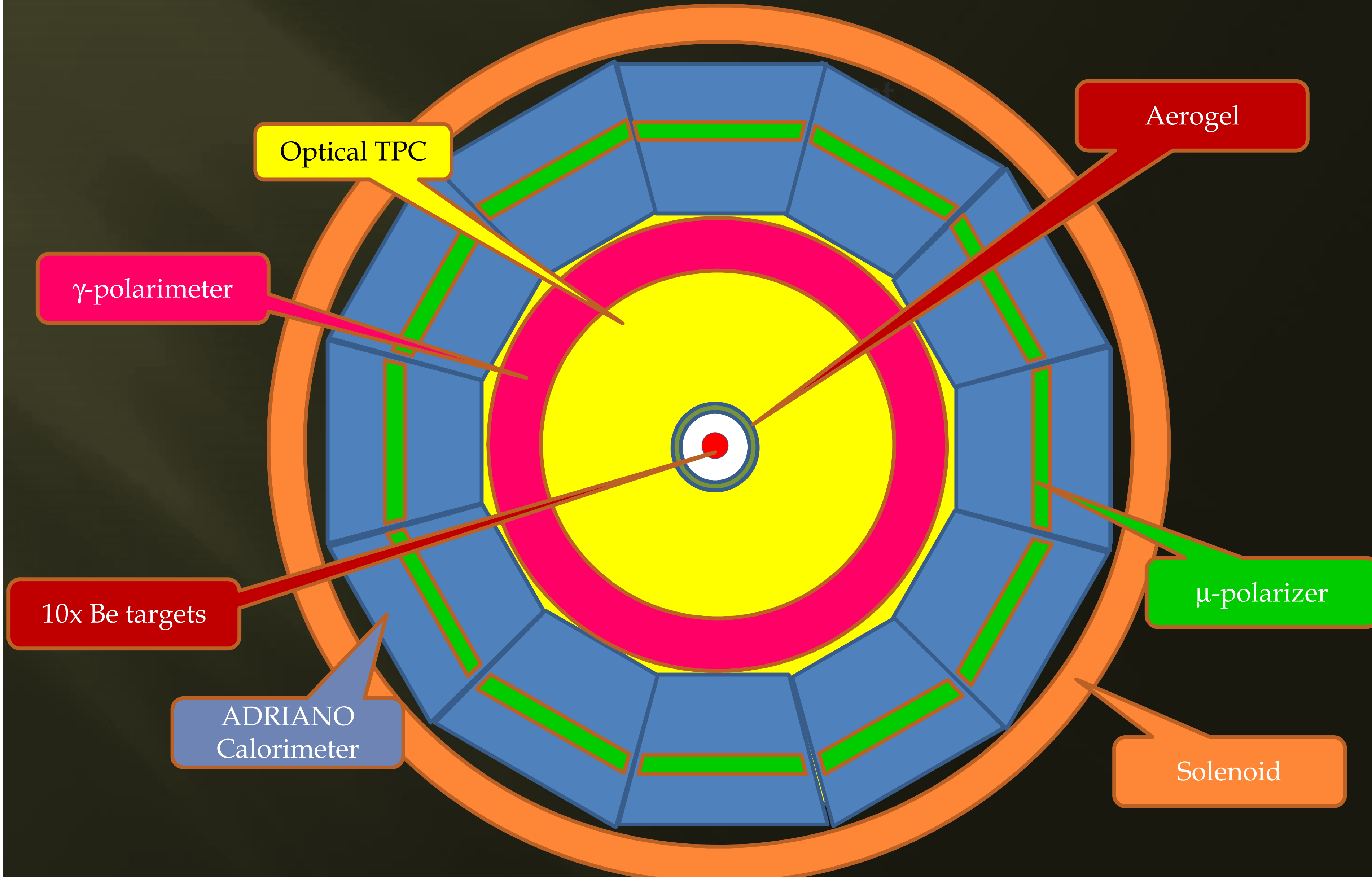
4/4/2017

The Experimental Apparatus

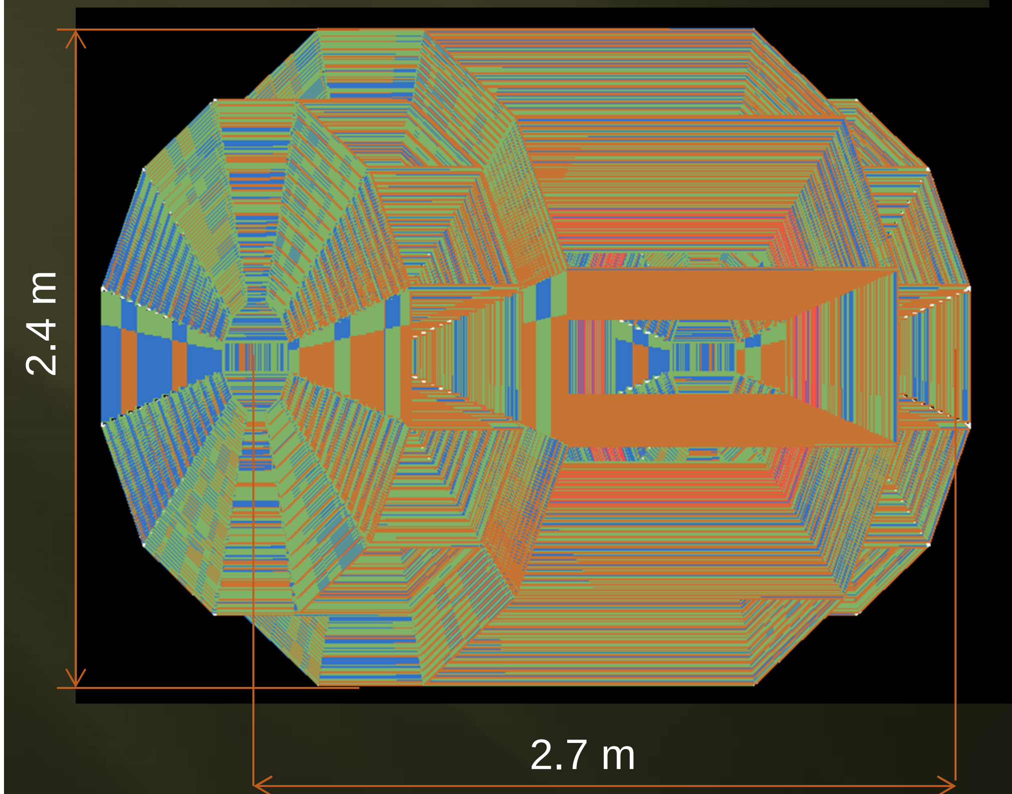
Baseline detector

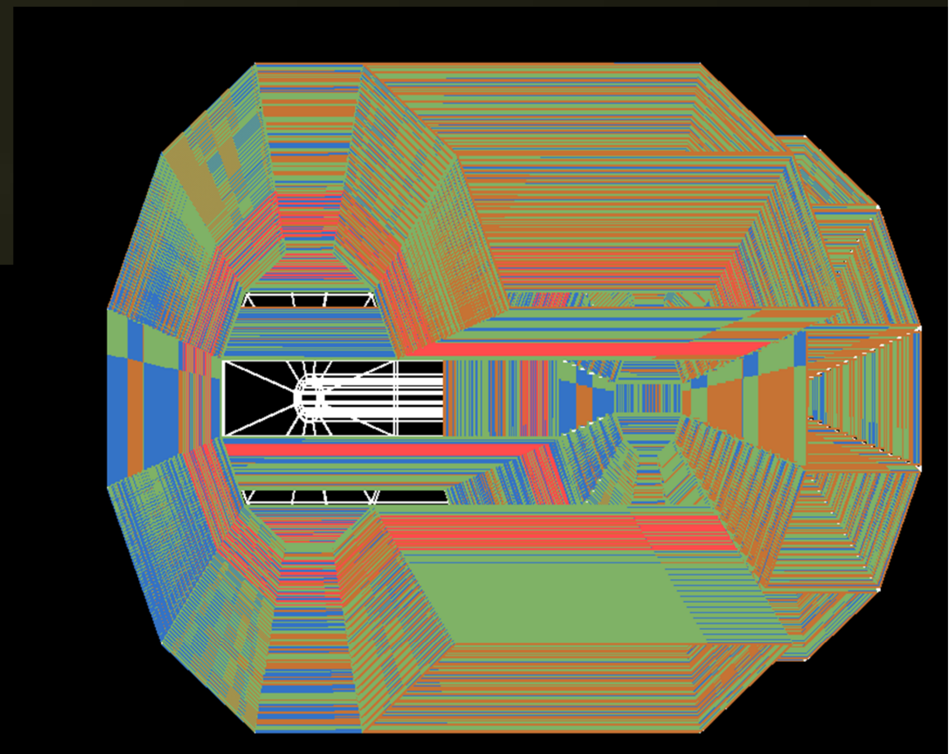
- *Beryllium or carbon fiber beam pipe, 10 cm dia x 1.5 m long*
- *1 cm dia targets disk inside the pipe, spaced 10 cm apart*
- *Multi-Aerogel around the beam pipe, 3cm thick (for most muons and fast pions detection)*
- *Optical-TPC 1m diameter x 1.5 m long*
- *γ-polarimeter in the rear section of the Optical-TPC (optional)*
- *ADRIANO calorimeter: ~20 Xo (same as ORKA) or 64 cm deep. Inner and outer sections to accommodate the μ-polarimeter in between*
- *Total detector dimensions: 2.2 m dia x 2.7 m long*
- *2.7 m long solenoid run at 0.6 T (2.4 m inner diameter) – E. Barzi helping with the design. Asymmetric yoke required*
- *AP50 cryogenics already in place*
- *Potential interest from CERN-Geant4 group on instrumenting the fwd and bkg detector regions (for G4 validation of new hadronic models)*

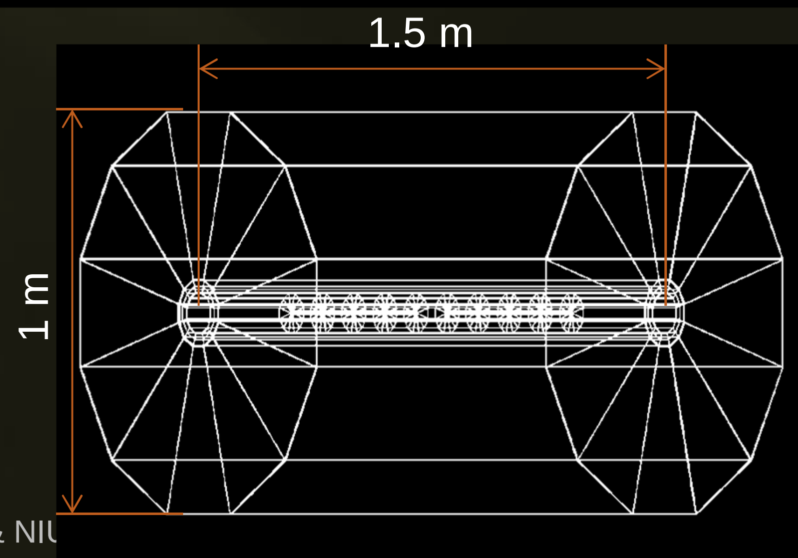
The REDTOP Detector



REDTOP detector

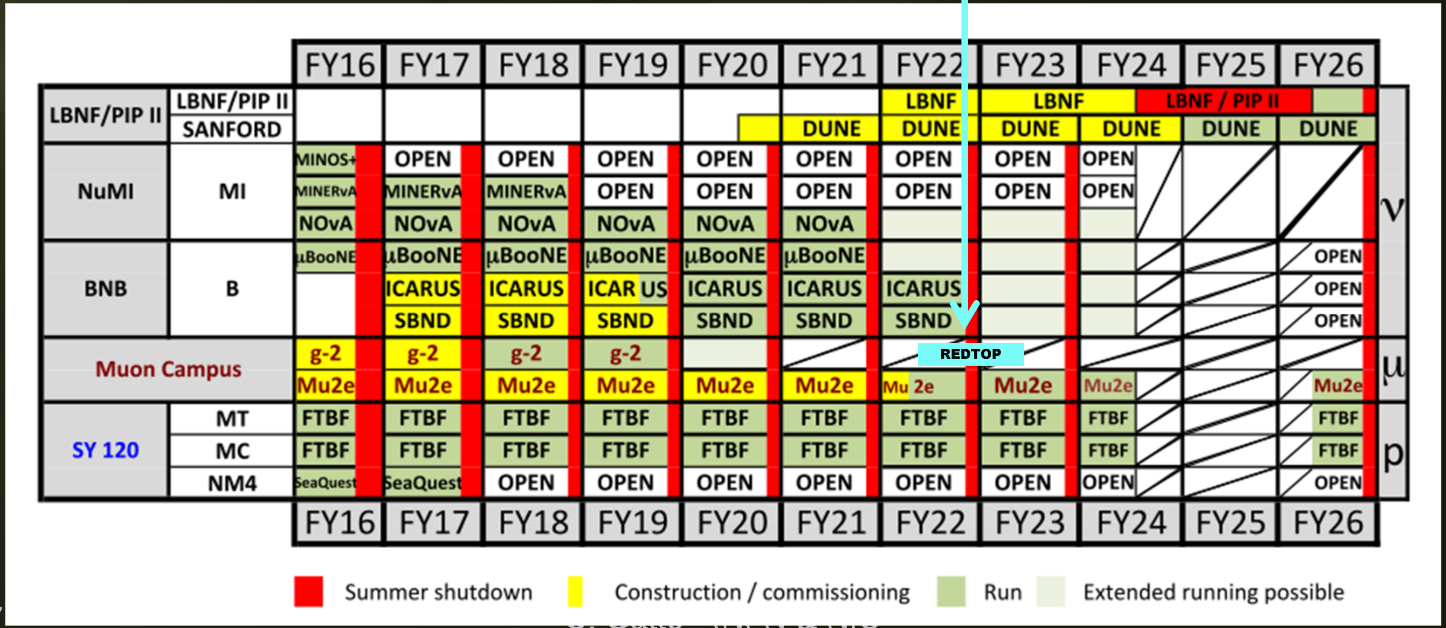






Status and Plans

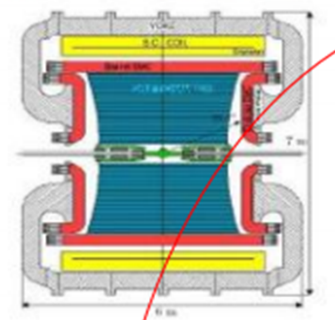
- *CY 2016-1017: Collaboration forming and studies for the Proposal*
- *Dec. 2017: proposal to PAC (Fermilab for now)*
- *CY 2018-2020: Detector R&D (could be shorter)*
- *CY 2021: Detector construction + engineering run*
- *CY 2022: Start physics run for Phase-I*
- *Successive phases contingent to results of phase I, occupancy of the experimental hall and of the beam*



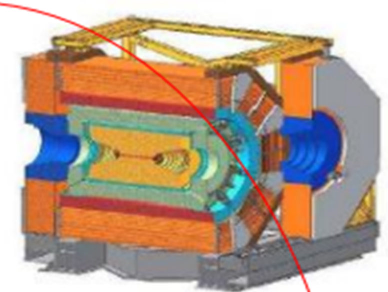
REDTOP Competitors

e+e- Collider

KLOE-2 at DAΦNE



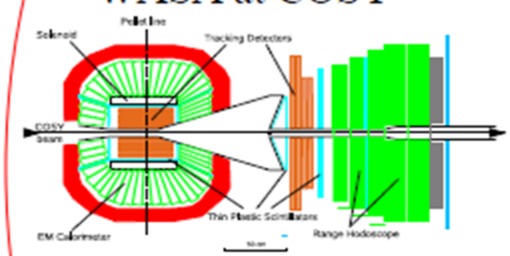
BESIII at BEPCII



Low energy η-facilities

Fixed-target

WASA at COSY

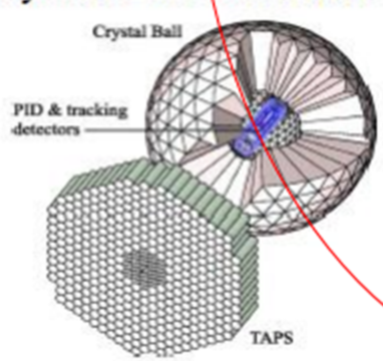


hadroproduction

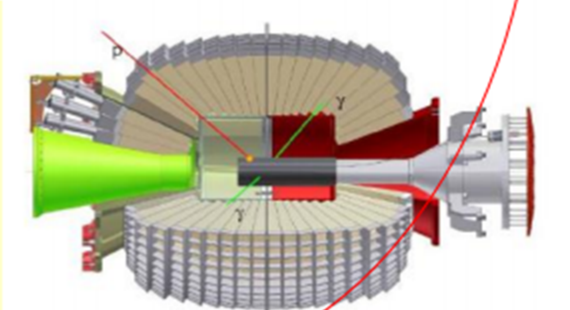
High energy η-facility

photoproduction

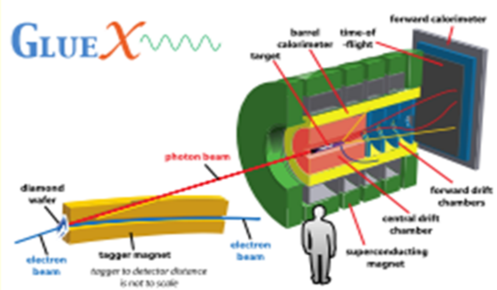
Crystall Ball at MAMI



CBELSA/TAPS at ELSA



JEF at Jlab



L. Gan, APS13

Backup slides

Final Considerations

- *REDTOP physics case is strongly supported by theorists*
- *A new accelerator facility available at hosting lab:*
  - *an energy-variable, CW beam [1.8-8 GeV]*
- *Pre-PIP II detector: will shape the way for a new generation of experiments*
  - *All-new technology detectors*
- *Multiple years running plan:*
  - *Run I: 1.8 GeV beam for η –factory*
  - *Run II: 3.5-4.5 GeV for η' –factory (after mu2e or before if time slot available)*
  - *Run III: with muon beam for a muon scattering experiment*
  - *Run IV: kaon beam for rare kaons decays studies*
- *Attractive to Universities and graduate students for quick physics and considerable detector R&D*
- *Total cost: < 30 M$ (depending on re-use of existing infra-structure)*

Summary & Prospects (I)

- *The η meson is a fantastic laboratory for studying rare processes*
- *Existing world sample not sufficient for breaching into decays violating conservation laws*
- *REDTOP goal is to produce >2 x 10^{13} η mesons/yr in phase I*
- *Three more phases could extend the lifetime of the experiment considerably*
- *Three golden processes will be studied:*
  - *CP Violation via Dalitz plot mirror asymmetry: $\eta \rightarrow \pi^o \pi^+ \pi^-$*
  - *Dark photon searches (charged channel): $\eta \rightarrow \gamma A'$ with $A' \rightarrow e^+e^-$ and $A' \rightarrow \mu^+\mu^-$*
  - *New baryonic force searches (charged channel): $\eta \rightarrow \gamma X$ with $X \rightarrow e^+e^-$*
  - *Scalar meson searches (charged channel): $\eta \rightarrow \pi^o H$ with $H \rightarrow e^+e^-$ and $H \rightarrow \mu^+\mu^-$*
- *Many other processes also within reach*
- *Fermilab is strongly preferred by the collaboration as hosting lab. BNL has, also, expressed considerable interest*

REDTOP Key Points

The experiment will yield 2×10^{13} η mesons/year and 2×10^{11} η' mesons/year

That is a consequence of the relatively large η production cross section (10-20 mbar in the 2 GeV beam energy region)

Requires a detector blind to protons and slow charged pions

4π-detector can be used with beams of different energy and/or particles

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 → 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

REDTOP Key Points

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Requires a detector blind to protons and slow charged pions

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REDTOP Physics Program (I)

CP Violation (Type I – P and T odd , C even):

$$\eta \to 4\pi^o \rightarrow 8\gamma$$

- *Expected background from p+Be* $\rightarrow 4\pi^o + X < 10^{-10}$
- *Highly over-constrained decay*
- *Current PDG limits:* $<2.8 \times 10^{-10}$ CL=*90%* *(from* $K_L \rightarrow \pi^o + \ell^+ \ell^-$ *) ???*
- *CP violation with the* η *has no strangeness changing currents involved*
- *REDTOP sensitivity:* 10^{-11} - 10^{-10}

Charge conjugation (C), Parity (P),
Charge conjugation × Parity (CP), or
Lepton Family number (LF) violating modes

Γ_{24}	$\pi^0\gamma$	C		<9	$\times 10^{-5}$	CL=90%
Γ_{25}	$\pi^+\pi^-$	P,CP		<1.3	$\times 10^{-5}$	CL=90%
Γ_{26}	$2\pi^0$	P,CP		<3.5	$\times 10^{-4}$	CL=90%
Γ_{27}	$2\pi^0\gamma$	C		<5	$\times 10^{-4}$	CL=90%
Γ_{28}	$3\pi^0\gamma$	C		<6	$\times 10^{-5}$	CL=90%
Γ_{29}	3γ	C		<1.6	$\times 10^{-5}$	CL=90%
Γ_{30}	$4\pi^0$	P,CP		<6.9	$\times 10^{-7}$	CL=90%
Γ_{31}	$\pi^0 e^+ e^-$	C	[a]	<4	$\times 10^{-5}$	CL=90%
Γ_{32}	$\pi^0 \mu^+ \mu^-$	C	[a]	<5	$\times 10^{-6}$	CL=90%
Γ_{33}	$\mu^+ e^- + \mu^- e^+$	LF		<6	$\times 10^{-6}$	CL=90%

CP violation with η mesons

- ***Standard model (Jarlskog & Shabalin 1995)***
  - *CKM phase:* $BR(\eta \to \pi^o \pi^o) < 10^{-27}$
  - θ_{QCD} *phase:* $BR(\eta \to \pi^o \pi^o) < 10^{-18} \times (\theta_{QCD}/10^{-10})^2$
- ***Any contribution to*** $BR(\eta \to \pi^o \pi^o)$ ***also generates a nonzero n-EDM***
- ***Gorchtein bound: (Gorchtein 2008)***
  - $BR(\eta \to \pi^o \pi^o) < 3.5 \times 10^{-14}$ *for* $d(n) < 2.9 \times 10^{-26}$ *e cm neutron EDM. Can use neutron EDM to limit* $BR(\eta \to \pi^o \pi^o)$
  - *Independent of particle physics model*
- ***However: bound is approximate (order of magnitude only)***
- n_{EDM} *and* $BR(\eta \to \pi^o \pi^o)$ *sensitive to different linear combinations of new physics CPV phases*
- ***Can have fine-tuned cancellations between phases contributing to*** d_n ***but not*** $BR(\eta \to \pi^o \pi^o)$
  - 10^{-5} *cancellation in* $d_n \to BR < 3.5 \times 10^{-4}$
  - 10^{-4} *cancellation in* $d_n \to BR < 3.5 \times 10^{-6}$

S. Tulin - University of Michigan

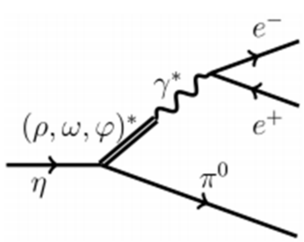
REDTOP Physics Program (II)

CP Violation (Type II –C and T odd , P even):

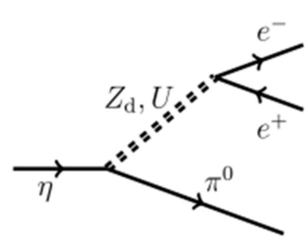
$$\eta \to \pi^0 \ell^+\ell^- \quad \text{and } \eta \to 3\gamma$$

- *A new kind of CP violation, which is also a C violation, could solve the cosmological problem of the known baryon excess over antibaryons by ten orders of magnitude. The known CP violation in K_o decay is not sufficient for this purpose.*
- *A new kind of C and CP violation could help to explain a peculiar asymmetry of the Stand ard Model, namely, that the basic constituents of the SM are left handed doublets and right handed singlets quarks and leptons. (B. Nefkens)*
- *SM decay occurs via 2-photon exachange: highly suppressed*
- *Current PDG limits:* <3.1 x10^{-8} CL=90% *(from $\eta \to 3\gamma$)*
- *REDTOP sensitivity:* 10^{-11} *from $\eta \to \pi^0 \ell^+\ell^-$ and* 10^{-10} *from $\eta \to 3\gamma$*

C -violating



via dark photon



Charge conjugation (C), Parity (P), Charge conjugation × Parity (CP), or Lepton Family number (LF) violating modes

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Γ_{28}	$3\pi^0\gamma$	C		< 6	$\times 10^{-5}$	CL=90%
Γ_{29}	3γ	C		< 1.6	$\times 10^{-5}$	CL=90%
Γ_{30}	$4\pi^0$	P,CP		< 6.9	$\times 10^{-7}$	CL=90%
Γ_{31}	$\pi^0 e^+ e^-$	C	[a]	< 4	$\times 10^{-5}$	CL=90%
Γ_{32}	$\pi^0 \mu^+ \mu^-$	C	[a]	< 5	$\times 10^{-6}$	CL=90%
Γ_{33}	$\mu^+ e^- + \mu^- e^+$	LF		< 6	$\times 10^{-6}$	CL=90%

REDTOP Physics Program (III)

More CP Violation :

Dalitz plot mirror asymmetry in

$\eta \rightarrow \pi^+\pi^-\pi^0$

- *S. Gardner and J. Tandean, Phys.Rev. D69 (2004) 034011*
- *Any mirror-asymmetry in the Dalitz plot is an indication of* ***CP and C*** *violation.*
- *Such asymmetry does not arise from SM operators at tree level, nor can the operators that generate EDMs contribute to it (at tree level).*
- *Consequently, the violation of discrete symmetry resulting from studying this process is not bounded by EDM as is the case for the* $\eta \rightarrow 4\pi$ *process.*
- *Furthermore, this measurement is 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*
- *Largest data sample: WASA (*1.2×10^7 *– 2014)*
- *Stat. error of violating parameter is comparable with the measured value*
- *REDTOP will collect* 4×10^{11} *such decay (factor 100 in stat. error)*

REDTOP Physics Program (VI)

Test of CP invariance via γ polarization studies*

$$\eta \rightarrow \pi^+ \pi^- e^+ e^- \quad \textit{and} \quad \eta \rightarrow \pi^+ \pi^- \mu^+ \mu^-$$

- *CP violation could be investigated by looking at E1 transitions of the photon in the decay $\eta \rightarrow \pi^+ \pi^- \gamma$.This require the measurement of photon polarization.*
- *If the photon is virtual and it decays decaying into a e+ e– pair:*

$$\eta \rightarrow \pi^+ \pi^- \gamma \rightarrow \pi^+ \pi^+ l^+ l^-$$

- *The following asymmetry is an open window on CP violation:*

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

- *Φ is the angle between the decay planes of the electron-positron pair and the two charged pions*

Charged modes

Γ_8	charged modes	(28.10 ± 0.34) %	S=1.2
Γ_9	$\pi^+ \pi^- \pi^0$	(22.92 ± 0.28) %	S=1.2
Γ_{10}	$\pi^+ \pi^- \gamma$	(4.22 ± 0.08) %	S=1.1
Γ_{11}	$e^+ e^- \gamma$	$(6.9 \pm 0.4) \times 10^{-3}$	S=1.3
Γ_{12}	$\mu^+ \mu^- \gamma$	$(3.1 \pm 0.4) \times 10^{-4}$	
Γ_{13}	$e^+ e^-$	$< 2.3 \times 10^{-6}$	CL=90%
Γ_{14}	$\mu^+ \mu^-$	$(5.8 \pm 0.8) \times 10^{-6}$	
Γ_{15}	$2e^+ 2e^-$	$(2.40 \pm 0.22) \times 10^{-5}$	
Γ_{16}	$\pi^+ \pi^- e^+ e^- (\gamma)$	$(2.68 \pm 0.11) \times 10^{-4}$	
Γ_{17}	$e^+ e^- \mu^+ \mu^-$	$< 1.6 \times 10^{-4}$	CL=90%
Γ_{18}	$2\mu^+ 2\mu^-$	$< 3.6 \times 10^{-4}$	CL=90%
Γ_{19}	$\mu^+ \mu^- \pi^+ \pi^-$	$< 3.6 \times 10^{-4}$	CL=90%

REDTOP Physics Program (V)

Searches for light scalar mesons :

$$\eta \rightarrow \pi^o H \quad ; H \rightarrow \mu^+ \mu^- \ vs \quad e^+ e^-$$

- *Viable DM candidate (in certain circumstances) coupling to Higgs portal - M. Pospelov, A. Ritz and M. Voloshin, Phys. Rev. D 78, 115012 (2008)*
- *Occuring in the SM via a two-photon exchange diagram with a branching ratio of the order of 10^{-9}.*
- *The existence of a light scalar particle coupling the muons to the quarks will change the dynamics of the process by increasing its probability of occurrence even by several orders of magnitude.*
- *REDTOP's expected sensitivity is greater that 10^{-10} .*
- *A precision measurement of the BR, along with unitarity constraints and with the measurements from $\eta \to \pi^o \gamma\gamma$ will reveal if there is any "abnormality" in the two photon channel. It will also provide strong constraints on new physics models where a light new particle mediates interactions.*
- *Postulated scalar meson H could solve the R_p anomaly*

Charge conjugation (C), Parity (P), Charge conjugation × Parity (CP), or Lepton Family number (LF) violating modes

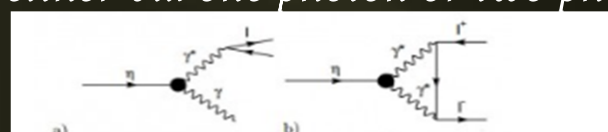
Γ_{24}	$\pi^0\gamma$	C		$<$	9	$\times 10^{-5}$	CL=90%
Γ_{25}	$\pi^+\pi^-$	P,CP		$<$	1.3	$\times 10^{-5}$	CL=90%
Γ_{26}	$2\pi^0$	P,CP		$<$	3.5	$\times 10^{-4}$	CL=90%
Γ_{27}	$2\pi^0\gamma$	C		$<$	5	$\times 10^{-4}$	CL=90%
Γ_{28}	$3\pi^0\gamma$	C		$<$	6	$\times 10^{-5}$	CL=90%
Γ_{29}	3γ	C		$<$	1.6	$\times 10^{-5}$	CL=90%
Γ_{30}	$4\pi^0$	P,CP		$<$	6.9	$\times 10^{-7}$	CL=90%
Γ_{31}	$\pi^0 e^+ e^-$	C	[a]	$<$	4	$\times 10^{-5}$	CL=90%
Γ_{32}	$\pi^0 \mu^+ \mu^-$	C	[a]	$<$	5	$\times 10^{-6}$	CL=90%
Γ_{33}	$\mu^+ e^- + \mu^- e^+$	LF		$<$	6	$\times 10^{-6}$	CL=90%

REDTOP Physics Program (VI)

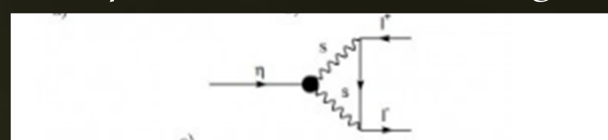
Proton radius anomaly:

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

- *Conventional methods (levels of muonic atoms and elastic scattering experiments) find a discrepancy of about 7σ.*
- *Those processes occur mainly trough the exchange of one virtual photon.*
- $\eta \to \gamma l^+l^-$ *can occur either via one photon or two photons*



- *A new light scalar particle S which couples differently to electrons and muons, could mediate the process via a third diagram*



Consequently, a precise measurement of the branching ratios of the latter might help in explaining the R_p anomaly.

Charged modes

Γ_8	charged modes	(28.10 ± 0.34) %	S=1.2
Γ_9	$\pi^+\pi^-\pi^0$	(22.92 ± 0.28) %	S=1.2
Γ_{10}	$\pi^+\pi^-\gamma$	(4.22 ± 0.08) %	S=1.1
Γ_{11}	$e^+e^-\gamma$	$(6.9\pm0.4)\times10^{-3}$	S=1.3
Γ_{12}	$\mu^+\mu^-\gamma$	$(3.1\pm0.4)\times10^{-4}$	

REDTOP Physics Program (VII)

Dark photon searches:

$$\eta \rightarrow \gamma A' \rightarrow 3\gamma \text{ or } \gamma + \ell^+\ell^-$$

- *Motivated from many directions:*
  - *possible cosmic ray excesses from dark matter annihilation (ex. Pamela, AMS, etc),*
  - *self interacting DM and explaining small scale structure anomalies in dwarf galaxies: Pospelov and Ritz (2008), Arkani-Hamed et al. (2008)*
  - *the muon g−2 anomaly.*
- *Most accredited model has A′ weakly-coupled to the SM via kinetic mixing and has mass in the MeV – GeV range.*
- *Kinetic mixing can naturally arise if there are states charged under both U(1)s, even if such states are very heavy.*
- *It couples to the Standard Model charged particles with a strength* $\leq 10^{-3} - 10^{-4}$ *of that of the photon This is the natural size of this coupling if we assume it originates from loops of heavy particles*
- *The A′ also couples to the SM weak neutral current, with a strength further suppressed by a factor of* $(m_{A'}/m_Z)^2$.

REDTOP Physics Program (VII)

Dark photon searches:

$$\eta \to \gamma A' \to 3\gamma \text{ or } \gamma + \ell^+\ell^-$$

- *The probe of the coupling scales* $\varepsilon \propto n^{1/4}$

$$\frac{S}{\sqrt{B}} \approx \sqrt{n_X}\frac{\epsilon^2 \times \mathrm{BR}(X \to Y+\gamma) \times \mathrm{BR}(U \to \ell^+\ell^-)}{\sqrt{\mathrm{BR}(X \to Y+\gamma^* \to Y+\ell^+\ell^-)}}\sqrt{\frac{m_U}{\delta m}\log\left(\frac{m_X - m_Y}{2m_\ell}\right)}.$$

- *Searched in different ways:*
- *Low energy colliders (Babar, Belle, Cleo, Kloe, etc) -> not enough statistics*
- *Meson decays*

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	$\mathrm{BR}(X \to Y+\gamma)$	$\mathrm{BR}(X \to Y+\ell^+\ell^-)$	$\epsilon \le$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

[a]Branching ratio $\mathrm{BR}(K^+ \to \mu^+ \nu e^+ e^-)$ for $m_{e^+e^-} > 145$ MeV [39]

Matthew Reece[1,*] and Lian-Tao Wang[2,†]

- *Complements the new experiments at JLAB and Frascati with γ and e^- beams in the MeV-GeV energy range*
- *η and A' mass constraints help to reject the background*
- *Requires > 10^{11} eta/eta′ mesons*

REDTOP Physics Program (VIII)

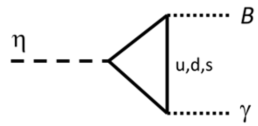
New leptophobic baryonic force searches:

$$\eta \to \gamma B \quad \text{with } B \to \gamma \pi^o \text{ or } B \to \gamma\, e^+ e^-$$

- *Mediates a new force which couples to the baryonic number (predominantly to quarks over leptons) and arises from a new $U(1)_B$ gauge symmetry*
- *$U(1)_B$ is anomalous (given the fermion content of the SM)*
- *Consistency of the quantum theory therefore requires introducing new heavy baryonic fermions with electroweak quantum numbers to cancel the anomalies.*

REDTOP Physics Program (VIII)

$\eta \rightarrow B\gamma$ decay ($m_B < m_\eta$)

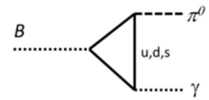


Triangle diagram

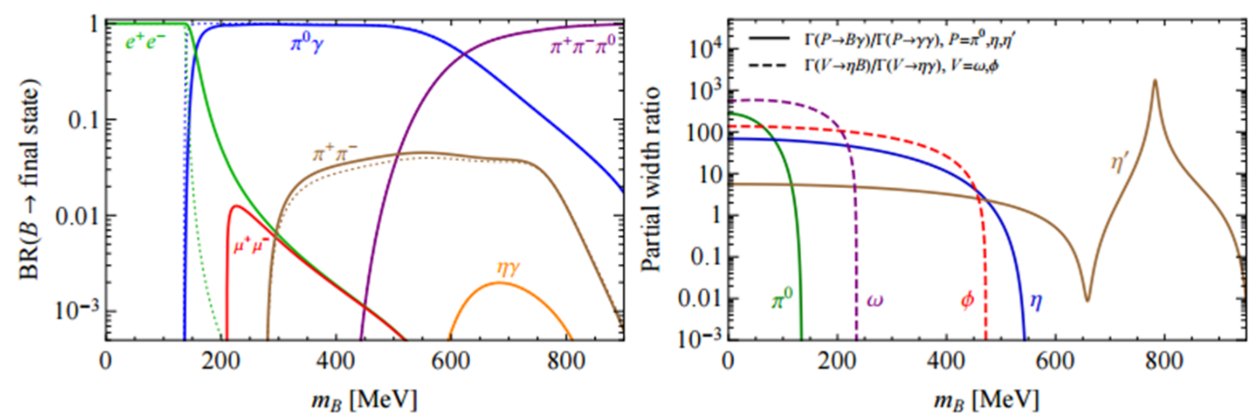
$3m_\pi < m_B <$ ~GeV : $B \rightarrow \pi^+ \pi^- \pi^0$

$m_\pi < m_B < 3m_\pi$: $B \rightarrow \pi^0 \gamma$

$MeV < m_B < m_\pi$: $B \rightarrow e^+e^-, \gamma\gamma\gamma$



- *Preferred B decays depends on its mass:*



Decay → / Production ↓	$B \to e^+e^-$ $m_B \sim 1 - 140$ MeV	$B \to \pi^0\gamma$ 140 – 620 MeV	$B \to \pi^+\pi^-\pi^0$ 620 – 1000 MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	–	–	–
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	–	–
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	–	–
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	–	

TABLE I: Summary of rare light meson decays induced by B gauge boson.

S. Tulin
arXiv:1404.4370v1 - 2014

- *$B \rightarrow \pi\pi$ forbidden by G parity (1^- state)*

Anomaly Cancellation

There a variety of constructions exist in the literature for anomy free UV completions of a local $U(1)_B$ symmetry

B. Batell, M. Pospelov, et. al., arXiv:1405.7049
M. William, C.P. Burgess, et., al., JHEP 08, 106 (2011)

The simplest model is a 4th generation of fermions that is vector-like under the SM gauge symmetries and chiral under $U(1)_B$.

M. Duerr and P. F. Perez, Phys.Lett. B732 (2014) 101-104
P. F.Perez and M.B. Wise, Phys.Rev. D82 (2010) 011901

Having the extra states heavy enough to evade direct constraints does imply a additional bound on B-boson from the collider data $m_B/\Lambda \gtrsim g_B/(4\pi)$

B.A. Dobrescu and C. Frugiuele, arXiv:1404.3947
S. Tulin, Phys.Rev. D89 (2014) 114008

REDTOP Physics Program (VI)

Lepton Flavor Violation:

$$\eta \rightarrow \mu e$$

- *Current PDG limits:* $<5.7 \times 10^{-13}$ CL=90% (*from* $\mu^- \rightarrow e^- \gamma$)
- *Lower sensitivity, but different systematics*
- *REDTOP sensitivity:* $\sim 10^{-13}$

Charge conjugation (C), Parity (P),
Charge conjugation × Parity (CP), or
Lepton Family number (LF) violating modes

Γ_{24}	$\pi^0\gamma$	C	$<$	9	$\times 10^{-5}$	CL=90%
Γ_{25}	$\pi^+\pi^-$	P,CP	$<$	1.3	$\times 10^{-5}$	CL=90%
Γ_{26}	$2\pi^0$	P,CP	$<$	3.5	$\times 10^{-4}$	CL=90%
Γ_{27}	$2\pi^0\gamma$	C	$<$	5	$\times 10^{-4}$	CL=90%
Γ_{28}	$3\pi^0\gamma$	C	$<$	6	$\times 10^{-5}$	CL=90%
Γ_{29}	3γ	C	$<$	1.6	$\times 10^{-5}$	CL=90%
Γ_{30}	$4\pi^0$	P,CP	$<$	6.9	$\times 10^{-7}$	CL=90%
Γ_{31}	$\pi^0 e^+ e^-$	C	[a] $<$	4	$\times 10^{-5}$	CL=90%
Γ_{32}	$\pi^0 \mu^+ \mu^-$	C	[a] $<$	5	$\times 10^{-6}$	CL=90%
Γ_{33}	$\mu^+ e^- + \mu^- e^+$	LF	$<$	6	$\times 10^{-6}$	CL=90%

REDTOP Physics Program (VII)

Double Lepton Flavor Violation:

$$\eta \rightarrow \mu^+ \mu^+ e^- e^- \quad + \quad c.c.$$

- *This is expected a very rare process to occur.*
- *Nonetheless, if it occurs within the sensitivity of the experiment, it will be easily detected has it carries a very unique signature.*

REDTOP Physics Program (X)

Leptoquark searches:

$$\eta \to \mu^+\mu^- \text{ and } \eta \to e^+e^-$$

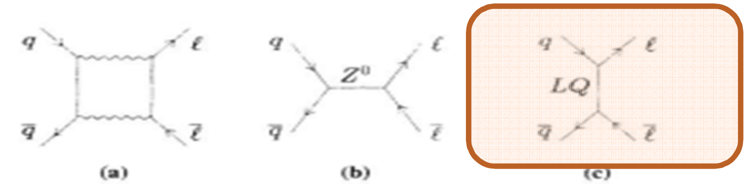


FIG. 1. Diagrams for the decay $P^0 \to \ell^+\ell^-$: (a) QED contribution, (b) weak interaction contribution, and (c) hypothetical leptoquark contribution.

Charged modes

Γ_8	charged modes	(28.10 ± 0.34) %	S=1.2
Γ_9	$\pi^+\pi^-\pi^0$	(22.92 ± 0.28) %	S=1.2
Γ_{10}	$\pi^+\pi^-\gamma$	(4.22 ± 0.08) %	S=1.1
Γ_{11}	$e^+e^-\gamma$	$(6.9\pm0.4)\times10^{-3}$	S=1.3
Γ_{12}	$\mu^+\mu^-\gamma$	$(3.1\pm0.4)\times10^{-4}$	
Γ_{13}	e^+e^-	$<2.3\times10^{-6}$	CL=90%
Γ_{14}	$\mu^+\mu^-$	$(5.8\pm0.8)\times10^{-6}$	
Γ_{15}	$2e^+2e^-$	$(2.40\pm0.22)\times10^{-5}$	
Γ_{16}	$\pi^+\pi^-e^+e^-(\gamma)$	$(2.68\pm0.11)\times10^{-4}$	
Γ_{17}	$e^+e^-\mu^+\mu^-$	$<1.6\times10^{-4}$	CL=90%
Γ_{18}	$2\mu^+2\mu^-$	$<3.6\times10^{-4}$	CL=90%
Γ_{19}	$\mu^+\mu^-\pi^+\pi^-$	$<3.6\times10^{-4}$	CL=90%
Γ_{20}	$\pi^+e^-\bar{\nu}_e$ + c.c.	$<1.7\times10^{-4}$	CL=90%
Γ_{21}	$\pi^+\pi^-2\gamma$	$<2.1\times10^{-3}$	
Γ_{22}	$\pi^+\pi^-\pi^0\gamma$	$<5\times10^{-4}$	CL=90%
Γ_{23}	$\pi^0\mu^+\mu^-\gamma$	$<3\times10^{-6}$	CL=90%

Most decays of the η meson into 2 or more prongs need to be measured

REDTOP Physics Program (XI)

μ polarization studies - test of T invariance:

$\eta \to \mu^+\mu^-$; $\eta \to \pi^0\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$

- *CP invariance does not allow the muons in $\eta \to \mu^+\mu^-$ to be longitudinally polarized. Any polarization requires a CP violating lepton-quark current.*
- *The existence of an extra Higgs boson the polarization of the μ^+ in $\eta \to \mu^+\mu^-$ would be as high as 10^{-2} . In minimal SM , the polarization is not observable.*
- *Since T invariance requires a null transverse polarization of μ in $\eta \to \gamma\,\mu^+\mu^-$ and $\eta \to \pi^0\mu^+\mu^-$ decays, any polarization observed is a direct violation of T invariance*

Charged modes

Γ_8	charged modes	(28.10 ± 0.34) %	S=1.2
Γ_9	$\pi^+\pi^-\pi^0$	(22.92 ± 0.28) %	S=1.2
Γ_{10}	$\pi^+\pi^-\gamma$	$(\ 4.22\pm0.08)$ %	S=1.1
Γ_{11}	$e^+e^-\gamma$	$(\ 6.9\ \pm0.4\ ) \times 10^{-3}$	S=1.3
Γ_{12}	$\mu^+\mu^-\gamma$	$(\ 3.1\ \pm0.4\ ) \times 10^{-4}$	
Γ_{13}	e^+e^-	$< 2.3 \times 10^{-6}$	CL=90%
Γ_{14}	$\mu^+\mu^-$	$(\ 5.8\ \pm0.8\ ) \times 10^{-6}$	
Γ_{15}	$2e^+2e^-$	$(\ 2.40\pm0.22) \times 10^{-5}$	
Γ_{16}	$\pi^+\pi^-e^+e^-(\gamma)$	$(\ 2.68\pm0.11) \times 10^{-4}$	
Γ_{17}	$e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	CL=90%
Γ_{18}	$2\mu^+2\mu^-$	$< 3.6 \times 10^{-4}$	CL=90%
Γ_{19}	$\mu^+\mu^-\pi^+\pi^-$	$< 3.6 \times 10^{-4}$	CL=90%
Γ_{20}	$\pi^+e^-\overline{\nu}_e$ + c.c.	$< 1.7 \times 10^{-4}$	CL=90%
Γ_{21}	$\pi^+\pi^-2\gamma$	$< 2.1 \times 10^{-3}$	
Γ_{22}	$\pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	CL=90%
Γ_{23}	$\pi^0\mu^+\mu^-\gamma$	$< 3 \times 10^{-6}$	CL=90%
Γ_{32}	$\pi^0\mu^+\mu^-$	$< 5 \times 10^{-6}$	CL=90%

REDTOP Physics Program (XII)

Search for true muonium:

$$\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+ e^-$$

- *This state has not been observed yet.*
- *Detection of true muonium would be an important discovery and would represent a further important test of QED.*
- *If the branching ratio of η decaying into true muoniom is larger than about 10-^{9}, it will be relatively easy to observe since REDTOP targets are very thin (< 240 μm) and the electron positron pairs in the final state will leave the nuclear matter mostly undisturbed.*

REDTOP Physics Program (XIV)

test of CPT invariance:

$$\eta \rightarrow \pi^{+} \mu^{-} \nu \ \textit{vs} \ \eta \rightarrow \pi \mu^{+} \nu$$

$$\eta \rightarrow \pi^{0} \mu^{+} \mu^{-} \ \textit{and} \ \eta \rightarrow \gamma \mu^{+} \mu^{-}$$

- *CPT invariance implies that the muons have opposite transverse polarization: $P^T(\mu^+) = -P^T(\mu^-)$*
- *The $\eta_{\pi 3}$ decay has not been observed yet.*

test of CPT invariance in models with non-hermitian $\mathscr{L}$:

Circular photon polarization in

$$\eta \rightarrow \gamma\gamma \ \textit{and} \ \pi \rightarrow \gamma\gamma$$

- *CPT invariance and hermiticity of the lagrangian implies that the photons have null circular polarization*
- *It is also a test of hermiticity of the lagrangian*

REDTOP Physics Program (XVI)

Non η-decays:

- *Drell-Yan: qqbar → A′ → **l^+l^-***
  - *Cross sections expected to be comparable to ccomparable to fixed target experiment with e- beams*
  - *Easy signature: di-lepton with vertex detached from any target*

REDTOP Physics Program (XV)

π-decays:

- *$\pi^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$ and $K^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$*
  - *$>10^{15}$ pions produced per year while the kaons would be produce when running at the η'*
  - *Very easy signature: a bump in the di-lepton mass and a detached vertex*

TABLE I: Branching ratios of the SM background in the range of $m_X - \frac{\delta m}{2} < m_{e^+e^-} < m_X + \frac{\delta m}{2}$, where $m_X = 16.7$ MeV, for different experimental schemes.

	Scheme 1	Scheme 2	Scheme 3
$\Delta \mathrm{BR}_{\gamma^*}(K^+ \to \mu^+ \nu e^+ e^-)$	2.54×10^{-7}	1.29×10^{-6}	2.70×10^{-6}
$\Delta \mathrm{BR}_{\gamma^*}(\pi^+ \to \mu^+ \nu e^+ e^-)$	1.61×10^{-10}	8.69×10^{-10}	2.21×10^{-9}

C. W. Chiang and P.Y. Tseng : arXiv:1612.06985v1 [hep-ph] - Dec 2016

- *$\pi^0 \to \gamma A' \to \gamma e^+ e^-$*
  - *Largest data sample from WASA: 5×10^5 **(2013)***
  - *REDTOP will produce 10^{15} pions per year*
  - *Very easy signature: a bump in the di-lepton mass and a detached vertex*

P. Adlarson et al.: arXiv:1304.0671v2 [hep-ex]

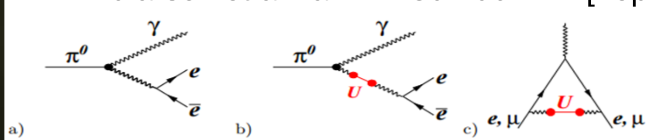


Figure 1: Feynman diagrams for a) the lowest order electromagnetic $\pi^0 \to e^+e^-\gamma$ decay and a possible contribution of U vector boson to: b) $\pi^0 \to e^+e^-\gamma$ and c) lepton $g-2$.

REDTOP Physics Program (XVII)

Low energy η physics

- *Nuclear models*
- *Chiral perturbation theory*
- *Non-perturbative QCD*
- *Isospin breaking due to the u-d quark mass difference*
- *Octet-singlet mixing angle*
- *$\pi\pi$ interactions*
- *Electromagnetic transition form-factors (important input for g-2)*
- *Lots of other bread&butter physics*

Experimental Techniques

η/η' production

- *η/η' hadro-production from inelastic scattering of protons on Nb (same as Hades experiment) or Be targets*
- *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*

γ detection

- *Use ADRIANO calorimeter for reconstructing EM showers*

↓

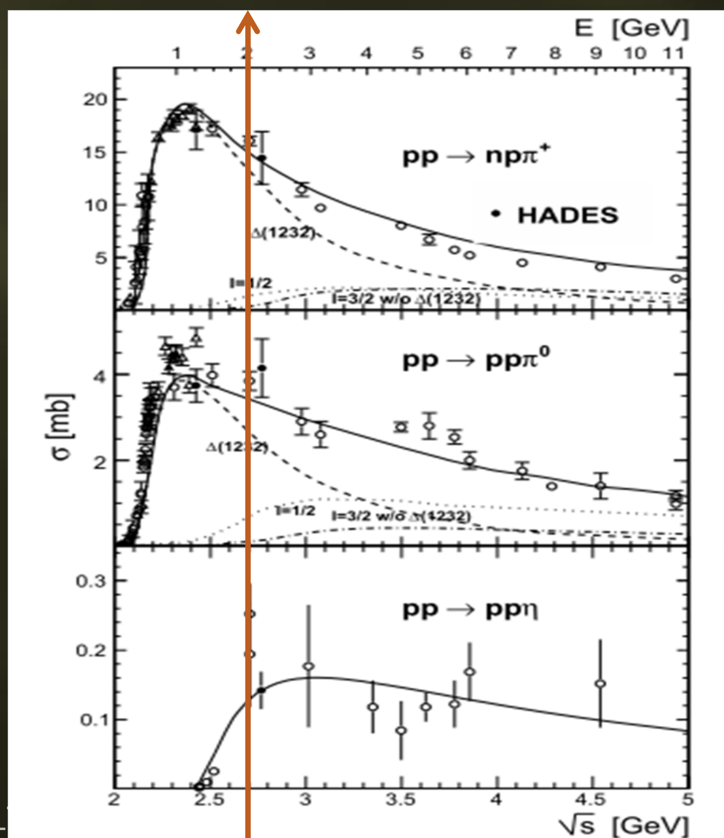
- $\sigma_E/E < 5\%/\sqrt{E}$
- *PID from dual-readout to disentangle showers from γ/μ/hadrons*
- *96.5% coverage*

Beam Requirements for η-factory (1)

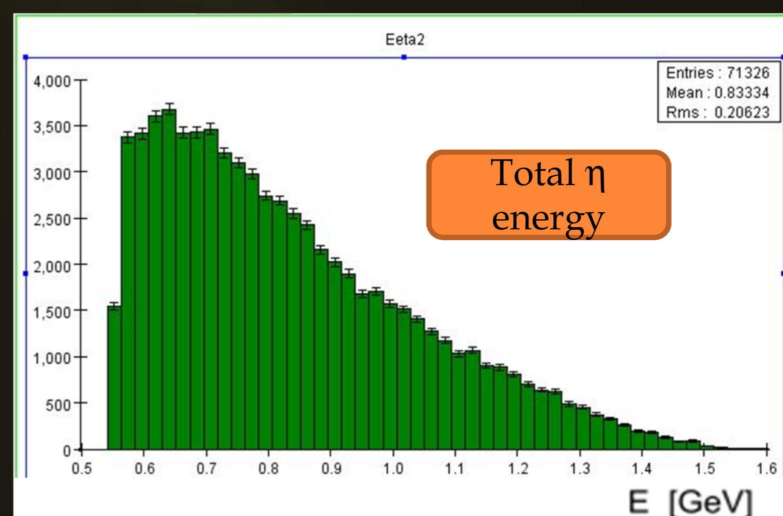
Beam energy

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

G. Agakishiev et al.
PHYSICAL REVIEW. C, NUCLEAR PHYSICS 2012, 48, 74-1



Total cross sections @ 2 GeV
$pp \rightarrow pp\eta$
140 μbarn
Total inelastic cross sections @ 2 GeV
About 200x

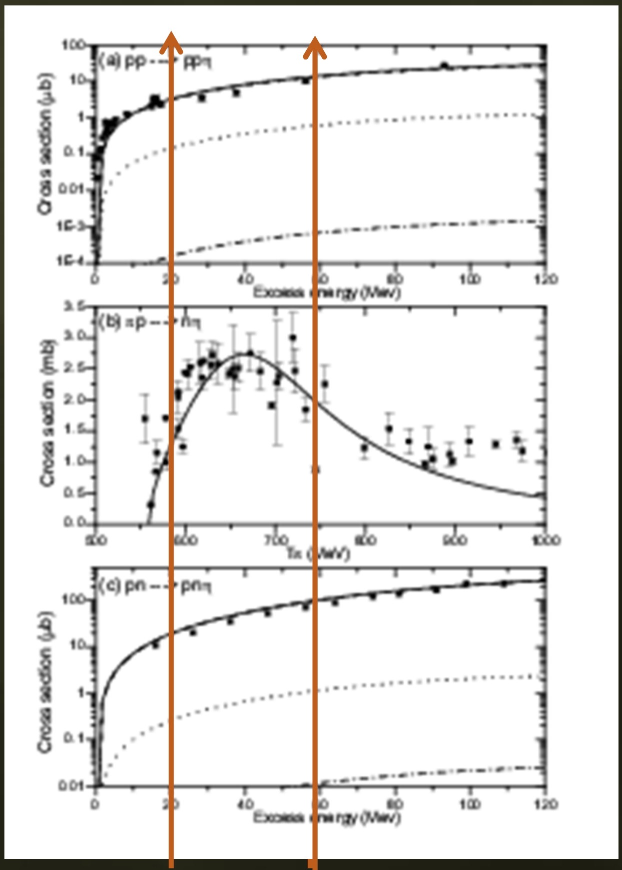


Expected η Yield

- *Assume: 1×10^{11} POT/sec – CW*
  - *Beam power @ 1.9 GeV: 10^{11} p/sec × 1.9 GeV × 1.6 × 10^{-10} J/GeV = 30 Watts*
- *Target system : 10 x 0.1mm Nb or 10 x 0.33mm Be foils, spaced 10 cm apart*
  - *Nb is thinner (better vertex resolution) but makes more primary hadrons (final state hadron multiplicity ≈ $A^{1/3}$)*
  - *Prob(p + target → X) = 0.5%*
- *Power dissipated from target:*
  - *150 mW total*
  - *15 mW per target foil*
- *p-inelastic production: 5×10^8 evt/sec (1 interaction/2 nsec in the targets)*
- *Probability of 2 events in the same target in 20 nsec: 70%*
- *η production: 2.5×10^6 η/sec or 2.5×10^{13} η/yr*
- *Charged mode (1% acceptance) : 1 L0 trigger/200 nsec or 5×10^{13} trigger/yr*
- *Neutral mode (10% acceptance) : 1 L0 trigger/20 nsec or 5×10^{14} trigger/yr*

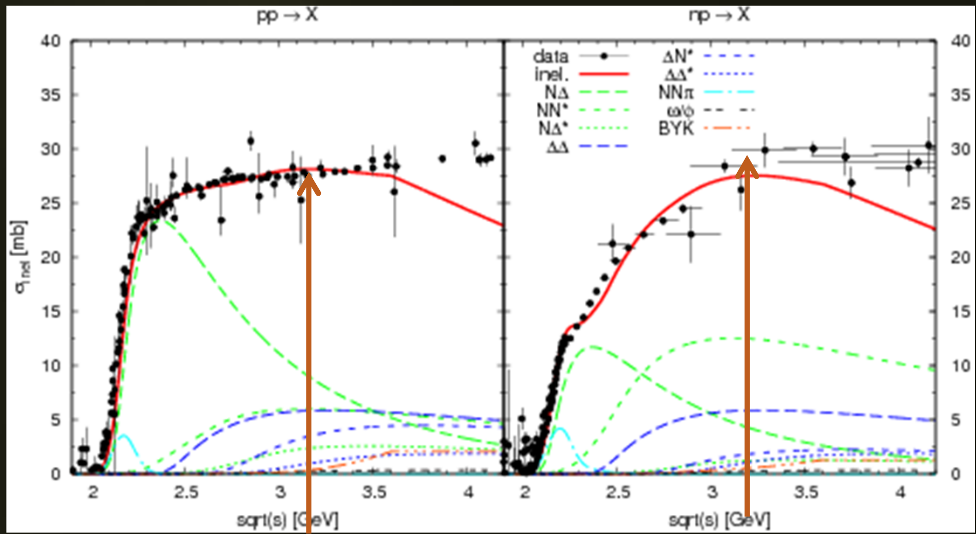
Beam Considerations for η' -factory

- *Constraints:*
  - *Same as for η-factory*
- E_{beam} = 3.5 – 4.5 GeV *(yet to be optimized)*
- $R_{\eta'}=\sigma(pp \rightarrow pn\eta')/\sigma(pp \rightarrow pp\eta')$ slightly lower than R_η



Xu Cao and Xi-Guo Lee
Phys. Rev. C 78, 035207 –2008

Total cross sections @ 3.8 GeV
$pp \rightarrow pp\eta'$
1 μbarn
Total inelastic cross sections @ 2 GeV
About 25,000x



Expected η' Yield

- *Assume: 1×10^{11} POT/sec – CW*
  - *Beam power @ 1.9 GeV: 10^{11} p/sec × 1.9 GeV × 1.6 × 10^{-10} J/GeV = 30 Watts*
- *Target system : 10 x 0.1mm Nb or 10 x 0.33mm Be foils, spaced 10 cm apart*
  - *Nb is thinner (better vertex resolution) but makes more primary hadrons (final state hadron multiplicity ≈ $A^{1/3}$)*
  - *Prob(p + target → X) = 0.5%*

- *p-inelastic production: 5 x 10^{8} evt/sec (1 interaction/20 nsec in any of the 10 targets)*
- *Probability of 2 events in the same target in 20 nsec: 70%*
- *η' production: 1.5 x 10^{4} η'/sec or 1.5 x 10^{11} η' /yr*
- *Expect similar trigger rate as with η-factory: ~ 10^{13} trigger/yr*

Accelerator Studies at FNAL

- Fermilab's AD has been supportive of the project
  - enhances use of the Muon Campus for additional program
  - selectable energy can create new opportunities for future experiments
  - standard accelerator technologies, techniques

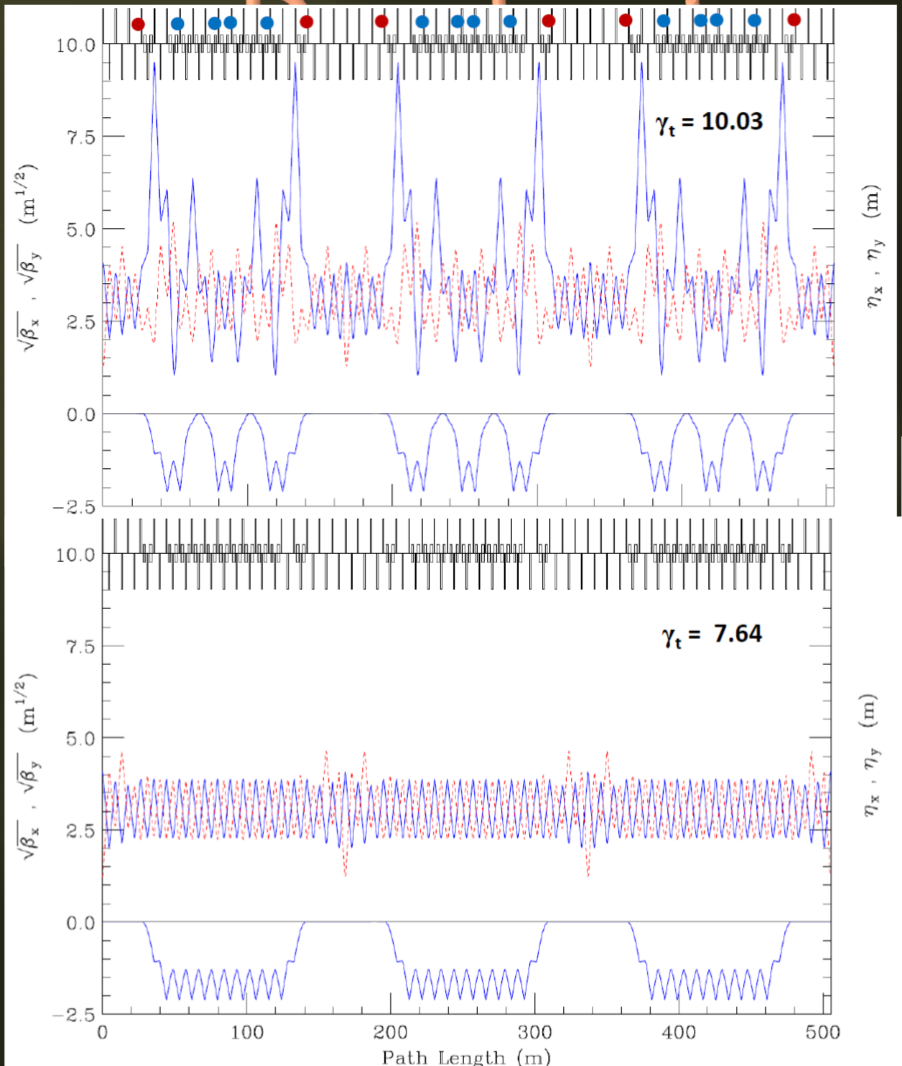
- Two working groups:
- Accelerator/beamline, coordinated by M. Syphers (NIU/FNAL): Y. Alexahin, E. Gianfelice, J. Johnstone (APC/AD) and C. Johnstone (EB/AD)
  - potential showstoppers in the beam deceleration and delivery (reversing current in shunt, beam disruption through transition, etc.)
- MARS15 : N. Mokhov and V. Pronskikh (APC/AD)
  - General radiation and background studies
  - Shielding
  - Beam dump

- Support for 2017 is under discussion - Remaining question marks:
  - simulations of deceleration, extraction at ~2 GeV with enhanced optics (Y. Alexahin, E. Gianfelice)
  - extraction and transport line development (C. Johnston)
  - MARS15 simulations of AP50 area and beam dump (V. Pronskikh)

Transitionless Deceleration in the Delivery Ring
J. Johnstone

- Large beam losses will occur if beam is decelerated from injection @ 8 GeV (γ = 9.53) to 2 GeV (γ = 3.13) through the DR natural transition energy γ_t = 7.64.
- Transition is avoided by using select quad triplets to boost γ_t 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
- Optical perturbations are localized within each triplet
- Straight sections are unaffected thereby keeping

Ring Optics through
- J.Johnstone



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

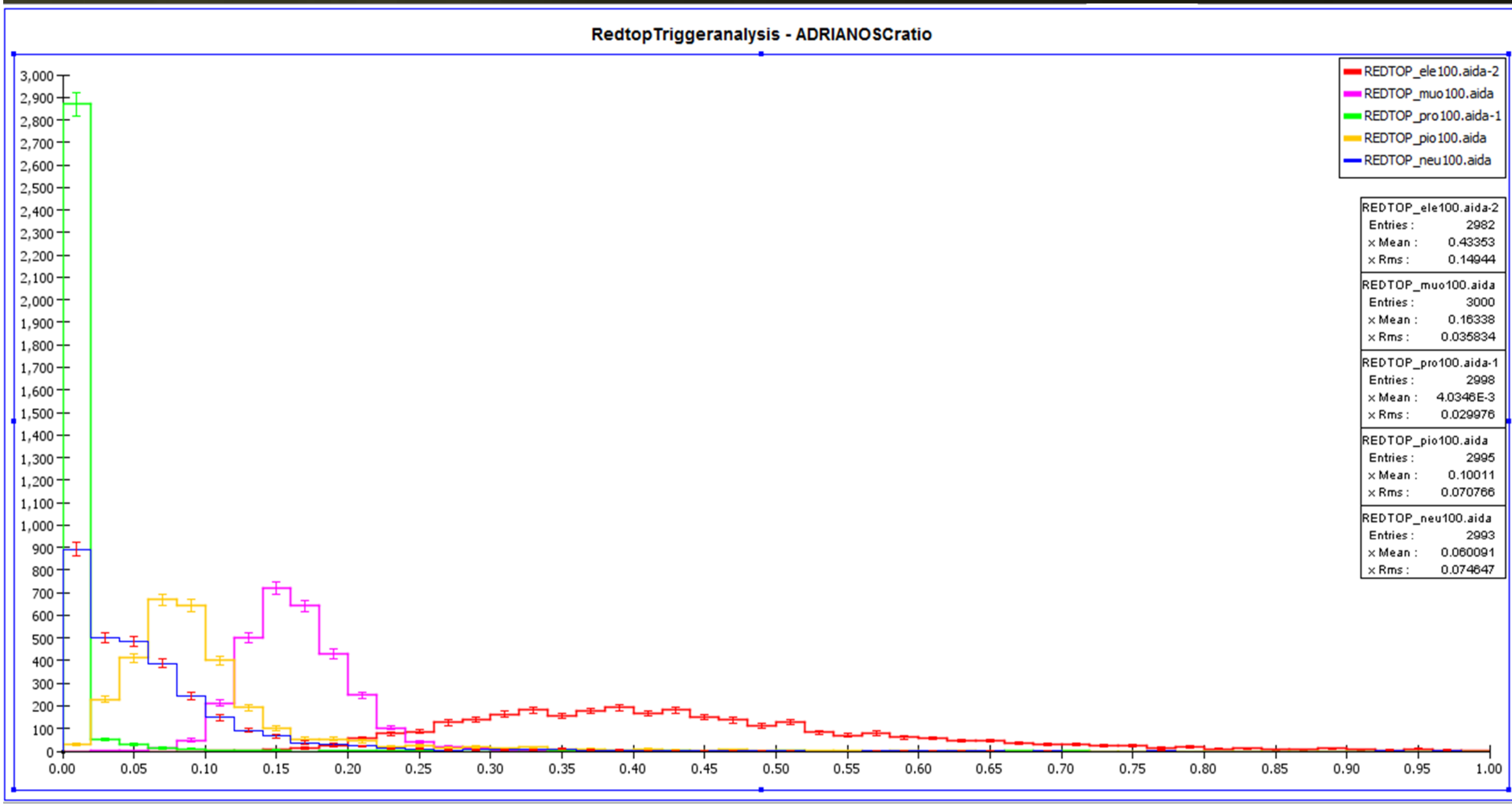
- Blue & red circles indicate sites of the γ_t quad triplets.

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

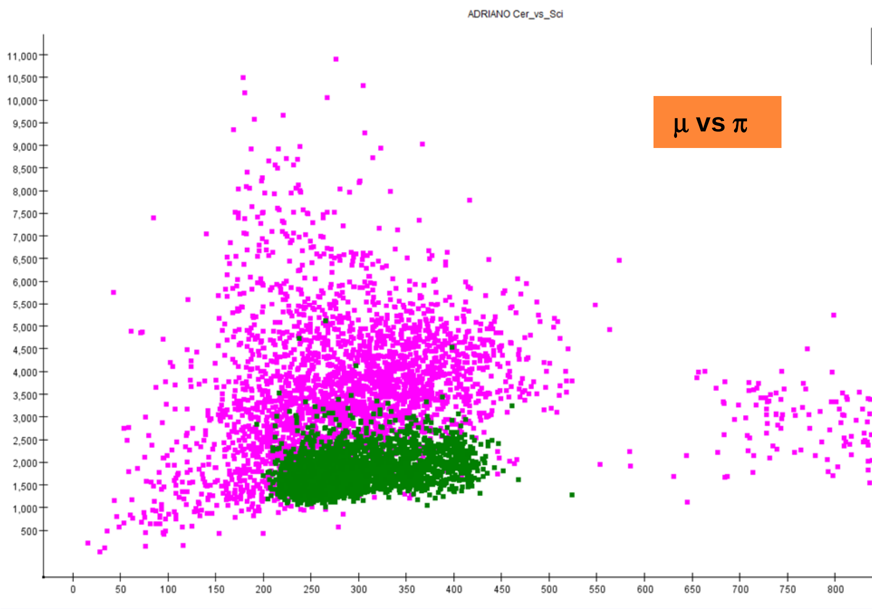
Variation of γ_t, β_{max}, and the 15π 99% beam envelope through deceleration

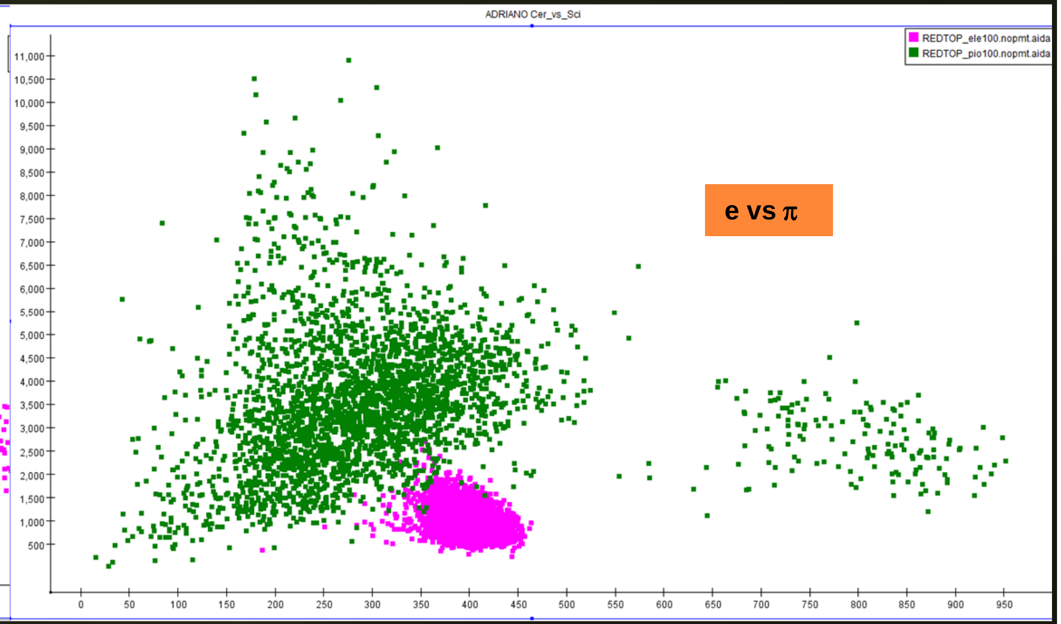
"J.Johnstone, M.Syphers, NA-PAC, Chicago (2016)"

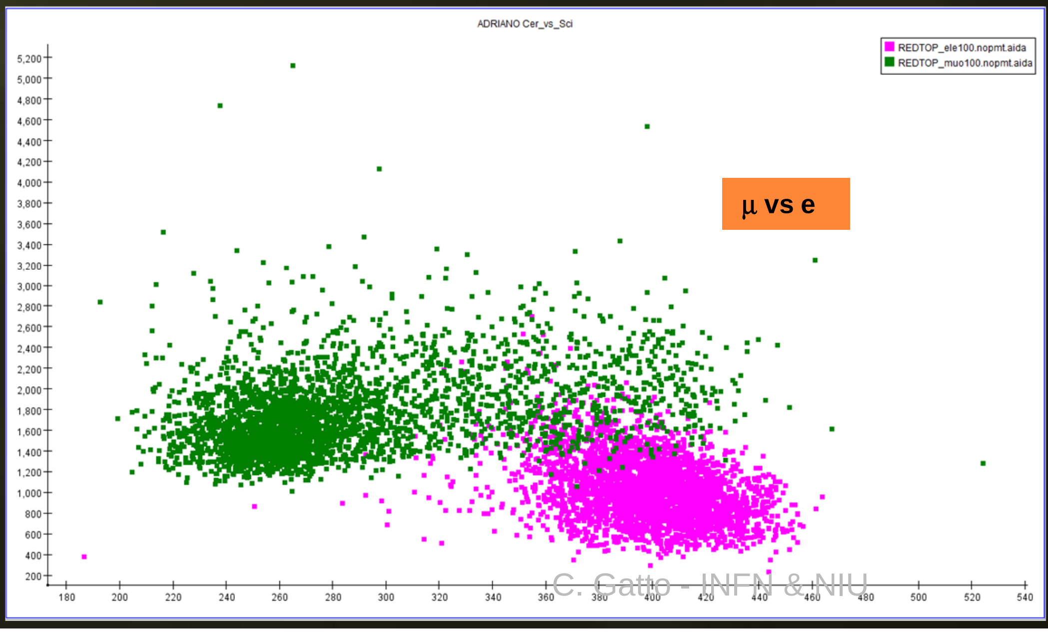
Scintillation-Cerenkov Ratio in ADRIANO



ADRIANO Particle ID @ 100MeV

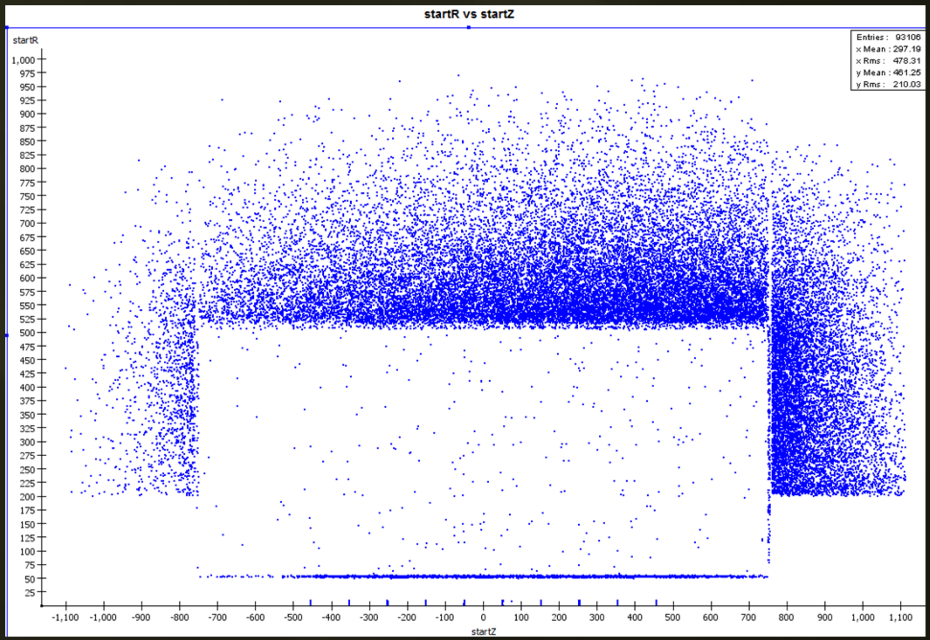






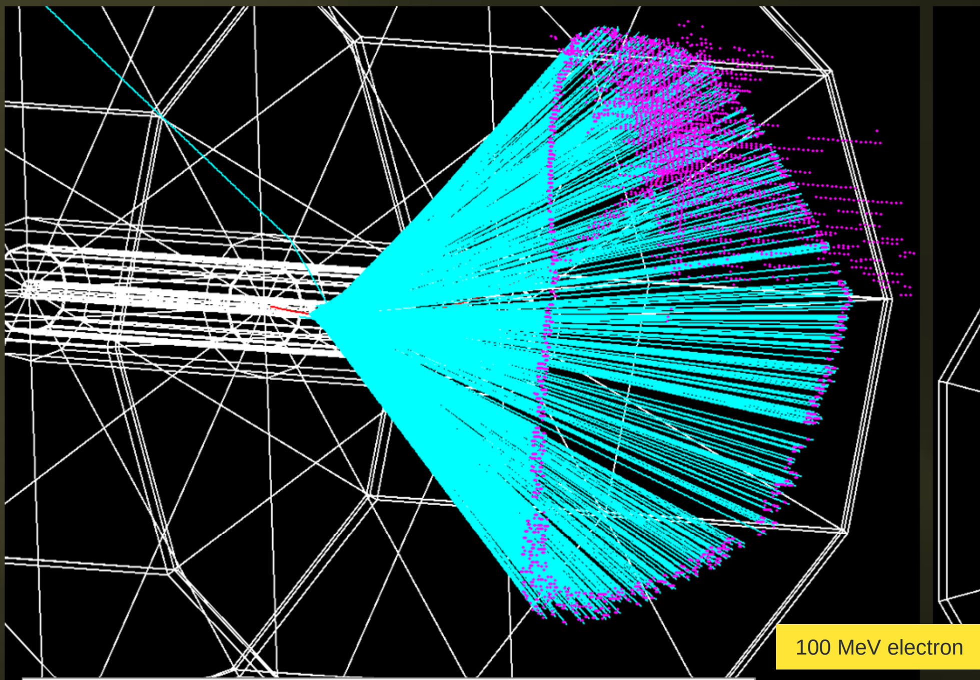
Background rejection (ctd)

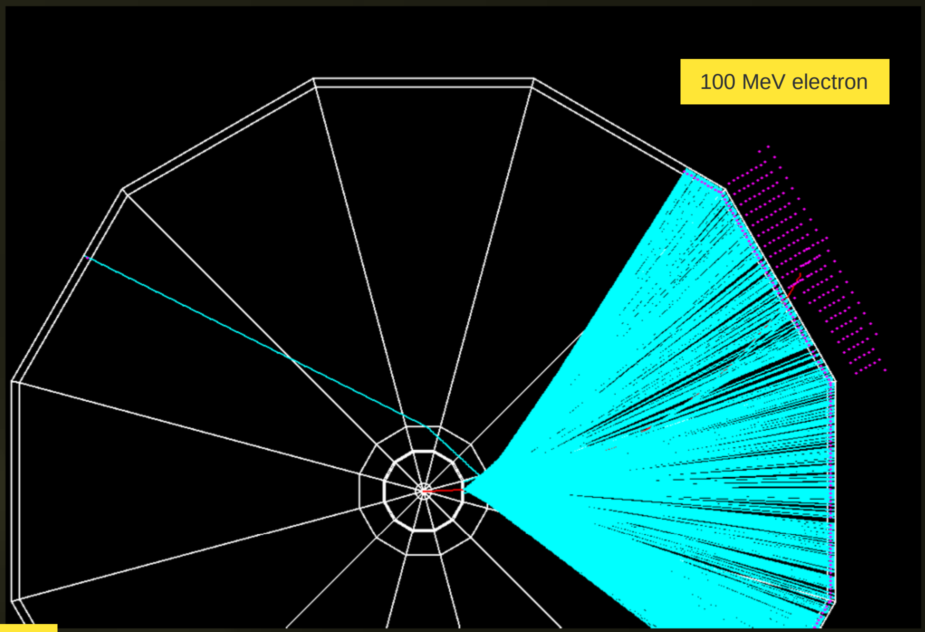
- Backsplash from ADRIANO is particularly nasty
- Possible solutions (under investigation):
  - Current detector has a diameter of only 2.2m (to contain costs)
  - Available space in CDF solenoid is 3 m
  - A more efficient ADRIANO design could help in limiting the backsplash of charged particles

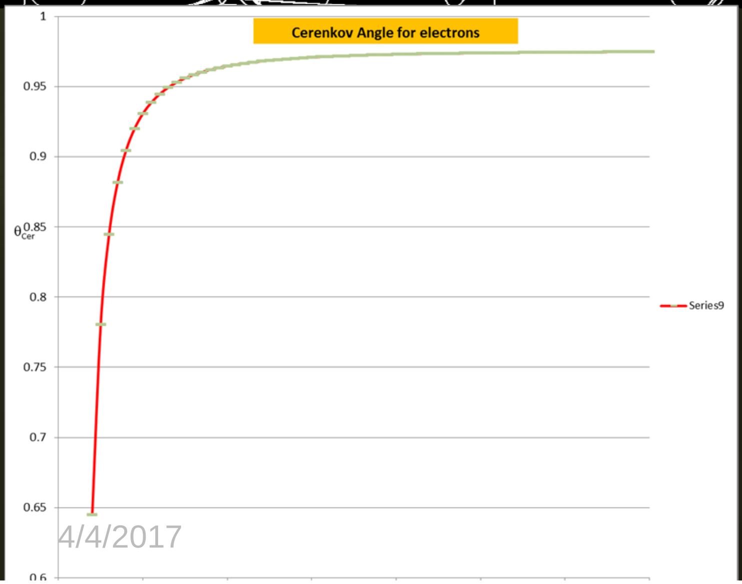


Secondary neutrons point of origin

Electron Detection







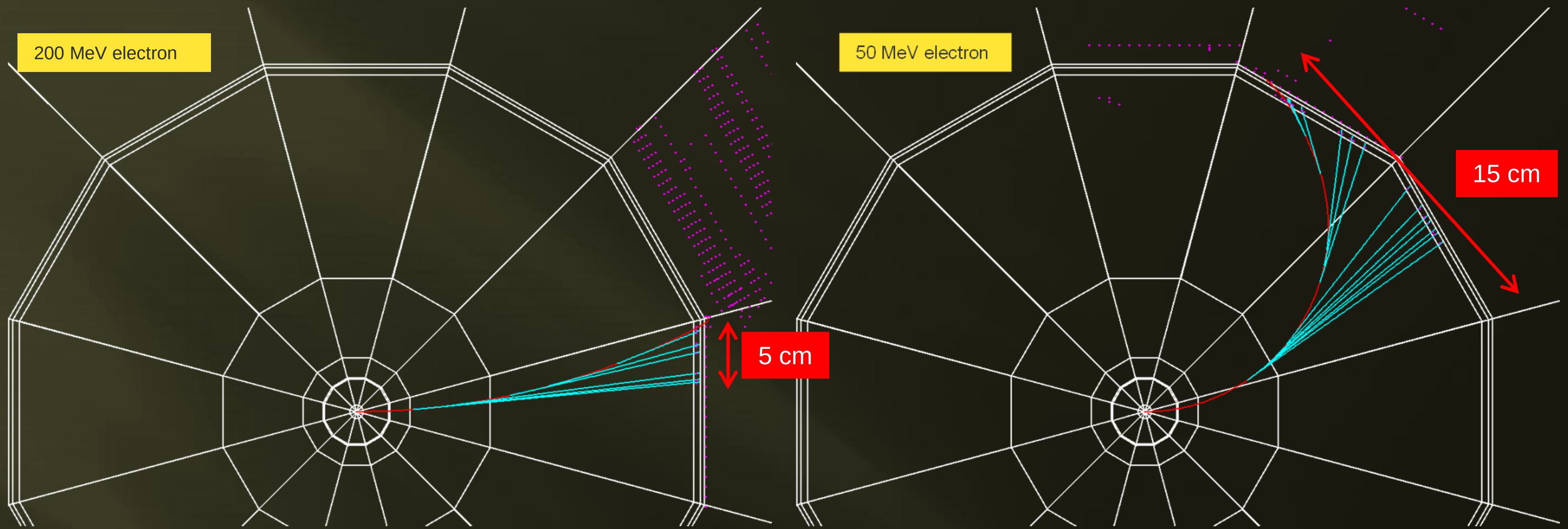
$n_D(N_2@2.7psi)=1.000145$

Č threshold for e- in N_2: P=40 mev

$n_D(aerogel1)=1.12$

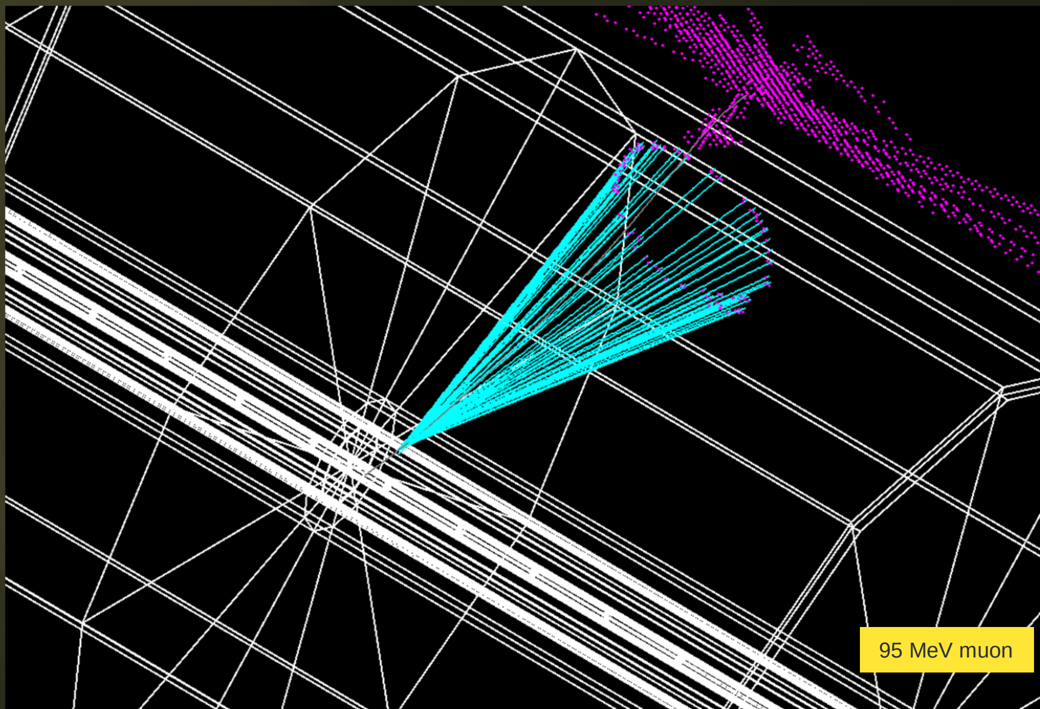
$n_D(aerogel2)=1.22$

Electron Momentum Reconstruction

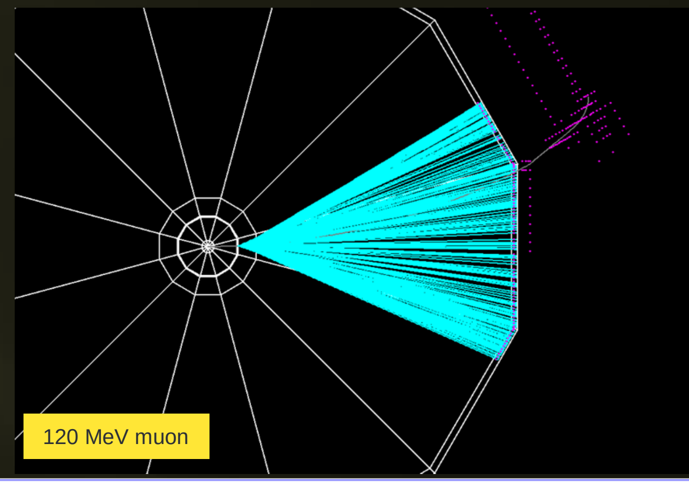


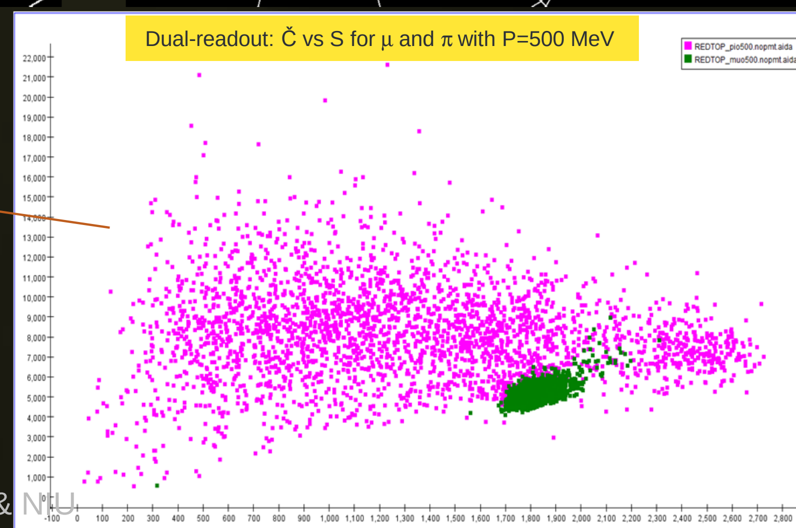
- Electrons are recognized by:
  1. a large (>30 cm dia) circle of photons generated in the aerogel
  2. A sweep of photons circles with dia < 1cm and several cm long (depends on P_t)
  3. An EM shower in ADRIANO (identified by Č vs S)

Muon/pion Detection

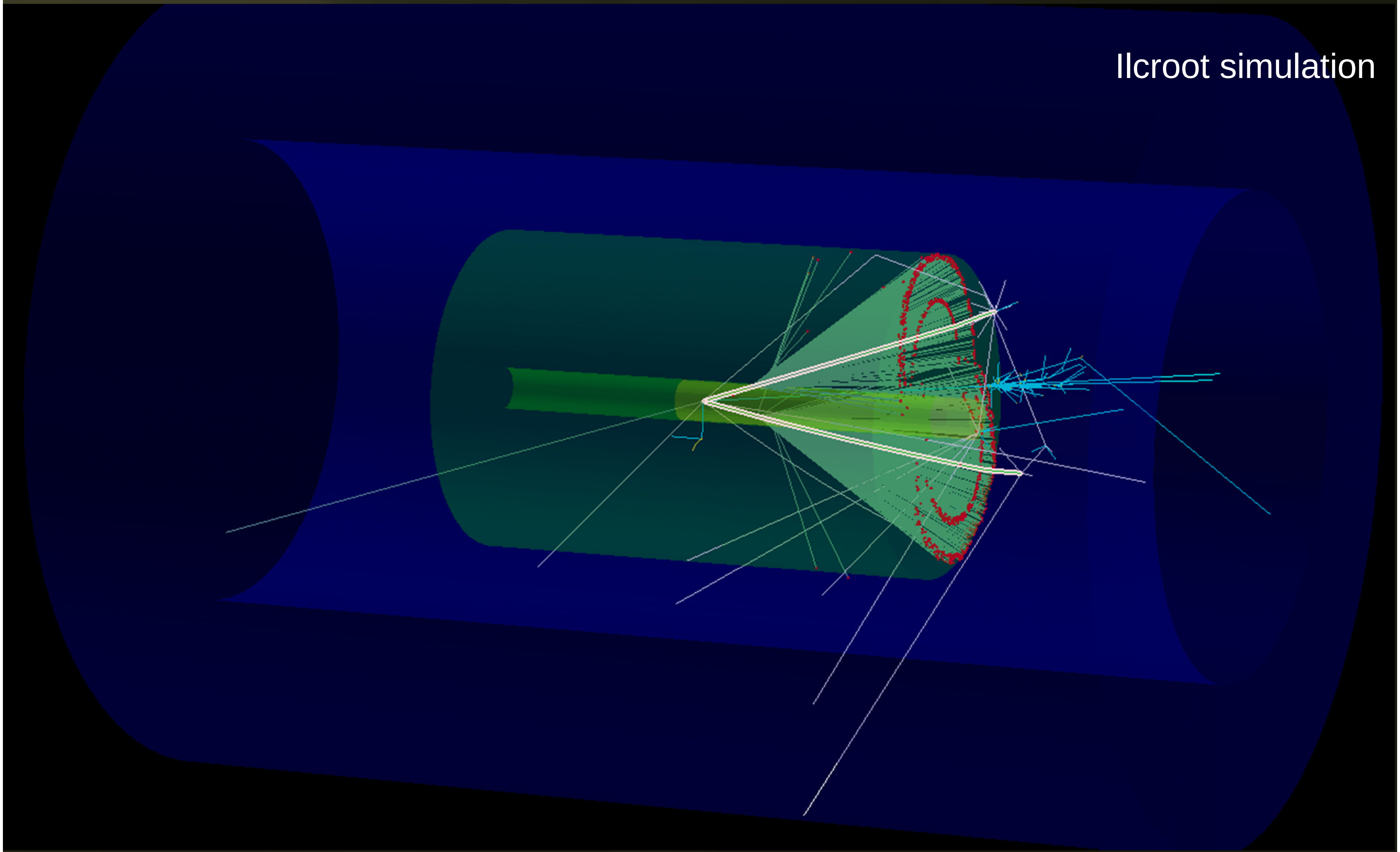


- n_D(aerogel)=1.22/1.12
- Č threshold for muons: P=160 mev
- Č threshold for pions: P=200 mev

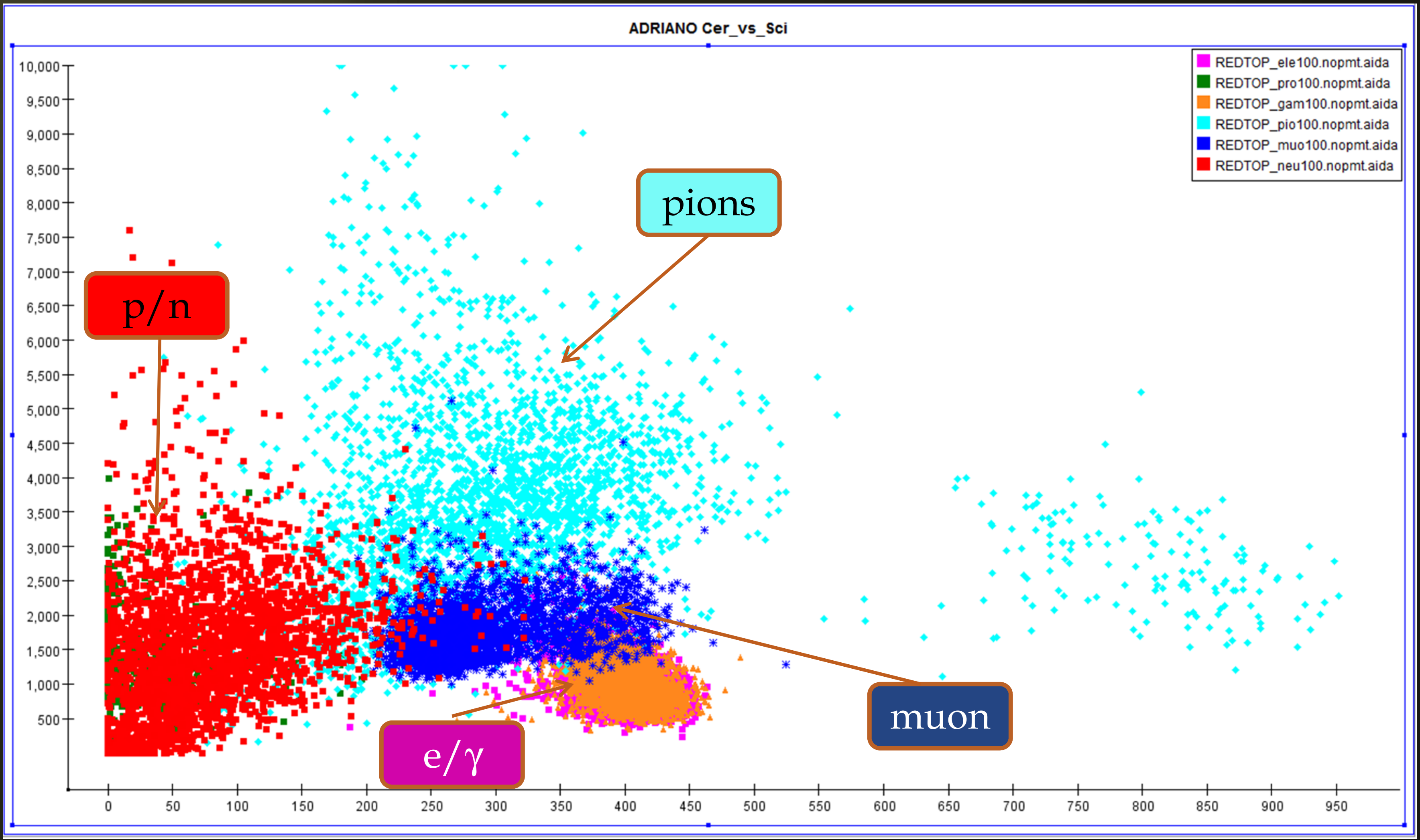




$\eta \rightarrow \pi^+ \pi^- \pi^0$



ADRIANO PID @ 100MeV



Preliminary Urqmd-Geant4 Simulation

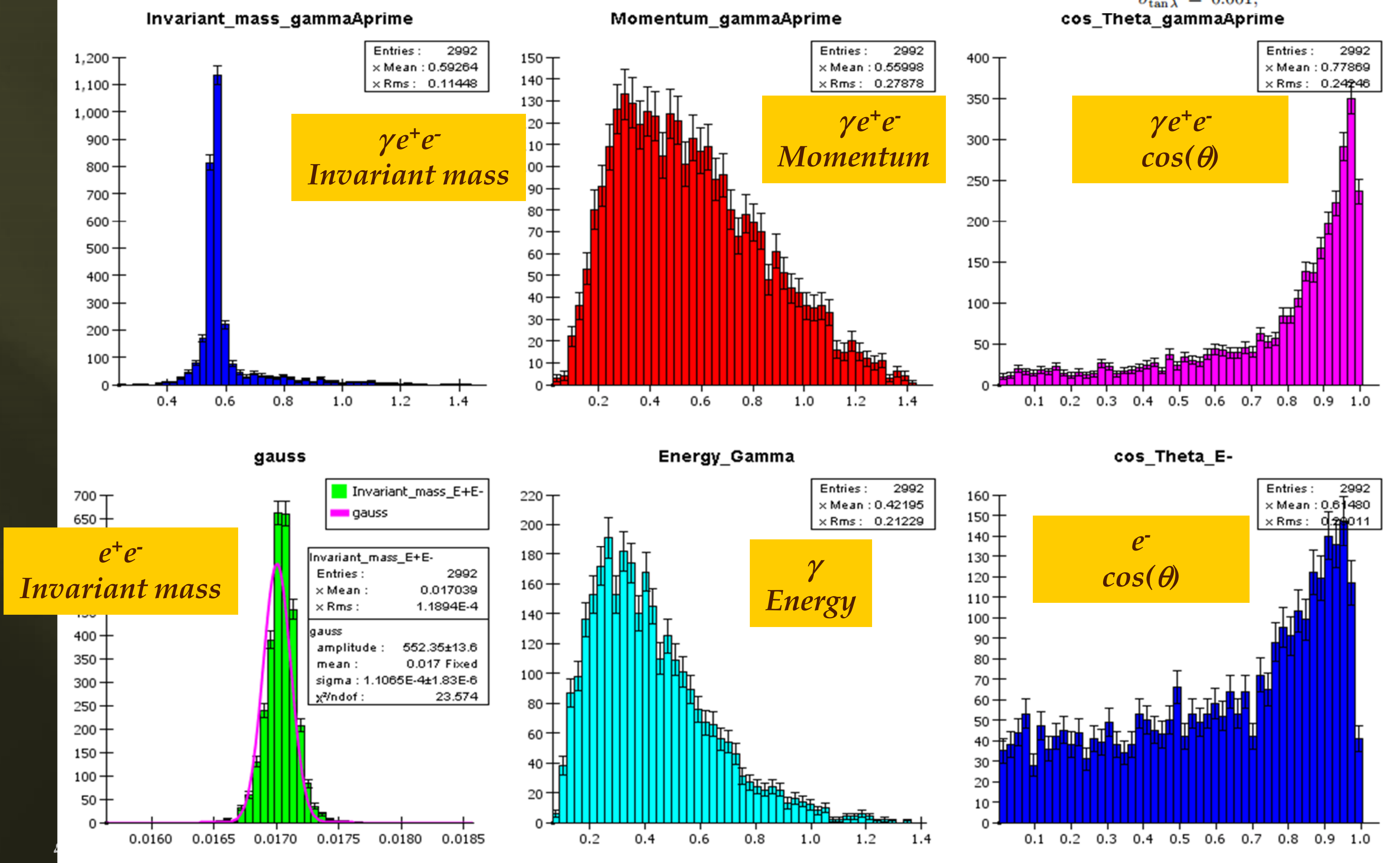
- $\eta \rightarrow \gamma Z_{17} \rightarrow \gamma + e^{+}e^{-}$

Photons

$$\frac{S}{E} = \frac{5\%}{\sqrt{E}} + 3\%$$

Charged tracks

$$\sigma_{p_t}/p_t = 0.13\% \times p_t + 0.45\%,$$
$$\sigma_{\phi} = 1 \text{ mrad},$$
$$\sigma_{\tan\lambda} = 0.001,$$



The Experimental Apparatus Triggers

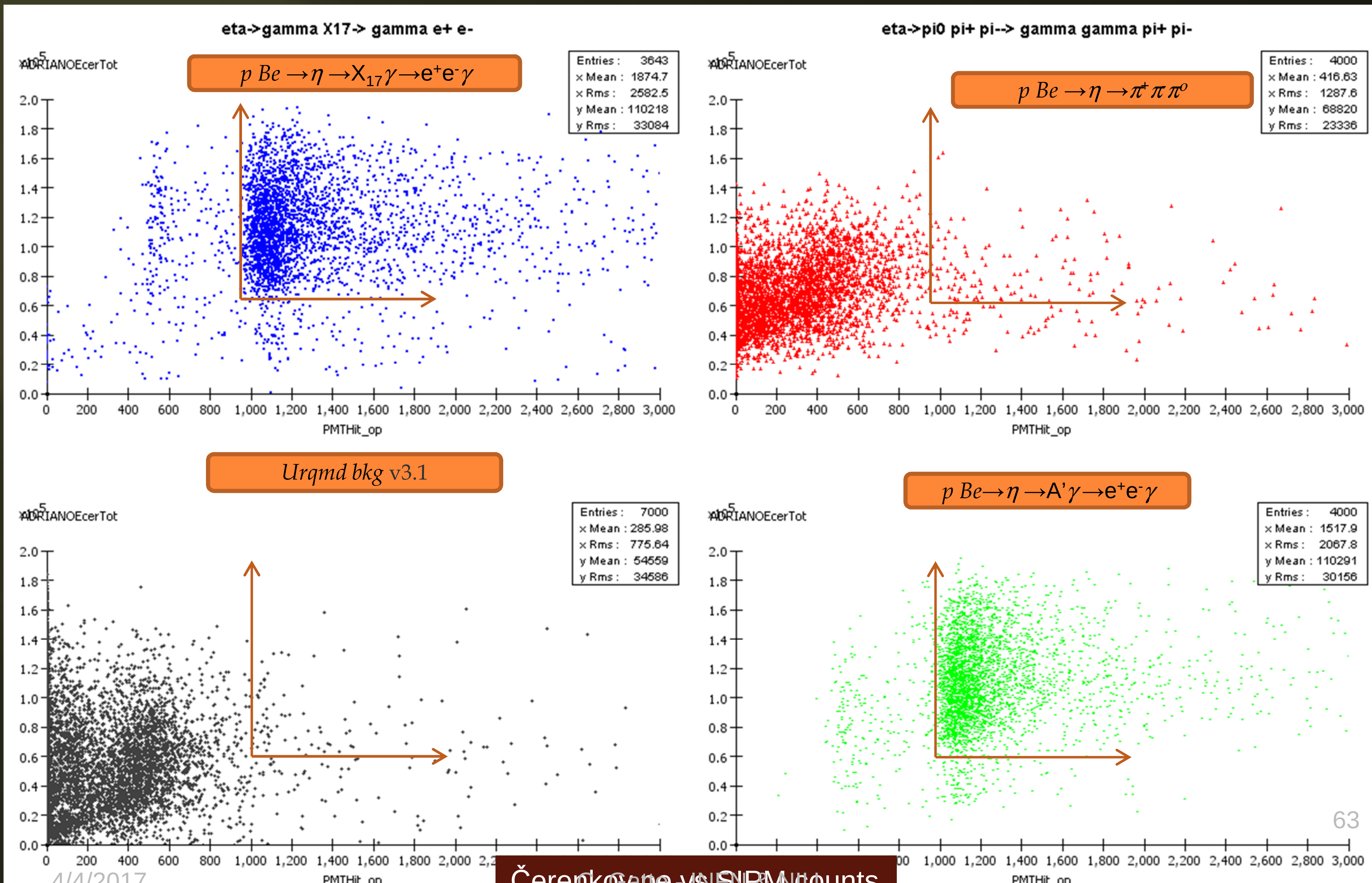
Charged mode

- *LF-violation: 1$e^{\pm}$ and 1 muon in the photo-sensors*
- *Heavy photon/baryonic field : 1γ > 50 MeV in ADRIANO and e^+e^- pair in the photo-sensors*
- *C-violation with electrons: 2γ > 30 MeV in ADRIANO and e^+e^- in the photo-sensors*
- *C-violation with muons: 2γ > 30 MeV in ADRIANO and $\mu^+\mu^-$ in the photo-sensors*
- *Add η, π^0 and A′ mass constraints*
- *Expected: 1 L0 trigger/μsec (still under optimization)*

Neutral mode

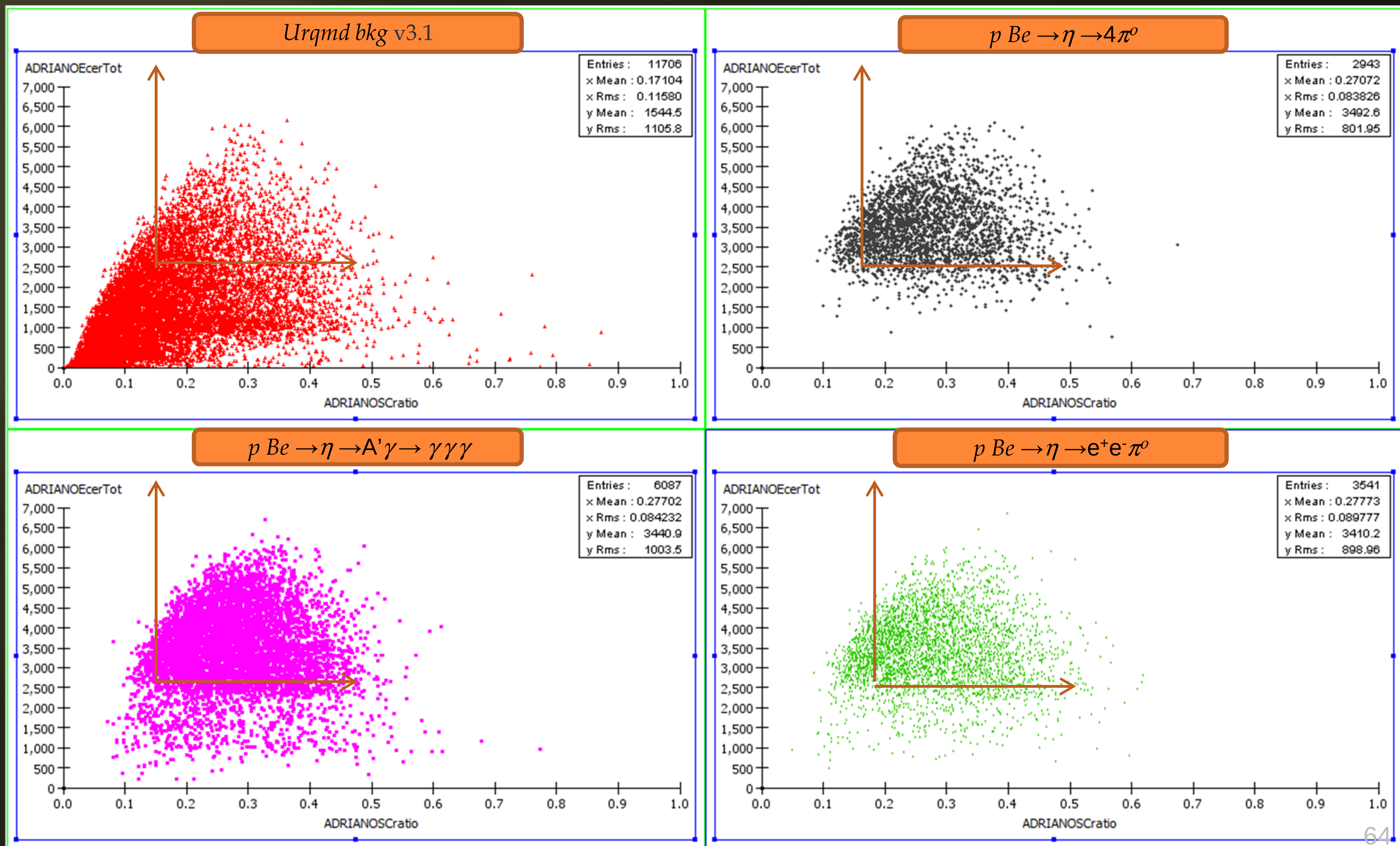
- *CP-violation: >8γ showers in ADRIANO or 4γ showers + $\pi^+\pi^-$*
- *Heavy photon/baryonic field : 3γ > 50 MeV in ADRIANO*
- *Add η, π^0 and A′ mass constraints*
- *Expected: 5 L0 trigger/μsec (still under optimization)*

Charged channels: L0 trigger based on Sipm counts and Č energy



Čerenkov vs SIPM counts

Neutral channels: L0 trigger based on Č energy in ADRIANO only



Čerenkov pe vs Scintillation/Čerenkov ratio

Summary L0 trigger efficiencies

- Charged channels L0

Channels	Eff %
Urqmd bkg v4.1	1%
Incl++ bkg v3.1	1%
$p\ Be \rightarrow \eta \rightarrow \pi^{+}\pi^{-}\pi^{o}$	2%
$p\ Be \rightarrow \eta \rightarrow 4\pi^{o}$	2.9%
$p\ Be \rightarrow \eta \rightarrow e\ \mu$	75.6%
$p\ Be \rightarrow \eta \rightarrow A'\gamma \rightarrow e^{+}e^{-}\gamma$	88.3%
$p\ Be \rightarrow \eta \rightarrow X17\gamma \rightarrow e^{+}e^{-}\gamma$	81.8%
$p\ Be \rightarrow \eta \rightarrow e^{+}e^{-}\pi^{o}$	92.1%
$p\ Be \rightarrow \eta \rightarrow \mu^{+}\mu^{-}\pi^{o}$	21.9%

- Neutral channels L0

Channels	Eff %
Urqmd bkg v3.1	15.1%
Incl++ bkg v3.1	9.7%
Urqmd bkg v2.3	8.56%
$p\ Be \rightarrow \eta \rightarrow 4\pi^{o}$	84.9%
$p\ Be \rightarrow \eta \rightarrow e\ \mu$	50.8%
$p\ Be \rightarrow \eta \rightarrow A'\gamma \rightarrow e^{+}e^{-}\gamma$	80.8%
$p\ Be \rightarrow \eta \rightarrow A'\gamma \rightarrow \gamma\gamma\gamma$	80.4%
$p\ Be \rightarrow \eta \rightarrow e^{+}e^{-}\pi^{o}$	81.5%
$p\ Be \rightarrow \eta \rightarrow \mu^{+}\mu^{-}\pi^{o}$	34.8%

Higher levels trigger will reduce the background much further

Simulation Studies

Event generation: GenieHad

- *Add-on to Genie to use external event generator:*
- *Interfaces available Urqmd, Incl++, PHSD, Gibuu, Abla07 (for nucleus de-excitation and evaporation), G4 electromagnetic, etc.*

Detector simulation and reconstruction: Ilcroot

- *Initially derived from Aliroot*
- *Virtual Montecarlo allow to select tracking engine at run-time (G3, G4, Fluka)*

Detector simulation and reconstruction: Slic-lcsim

- *SLAC software for HPS and SID simulations*
- *Adapted to REDTOP*
- *Java based (lcsim)*

However, a full simulation with MARS15 is mandatory to make the project meaningful

REDTOP Simulation Status

- 3×10^6 background event generated with GenieHad (Urqmd and Incl++ interfaces) and simulated with Geant4
- Plans to reach 10^7 by summer (needed for trigger studies)
- 140 TB available for storage (60 from INFN and 80 from FNAL – thanks to A. Valishev and T. Zingelman)
- All golden processes also available to users
- Collaborating institutions working at analyses for physics and detector studies

Summary Physics Program

Golden processes

- *CP Violation via Dalitz plot mirror asymmetry:* $\eta \rightarrow \pi^o \pi^+ \pi^-$
- *New baryonic force searches (charged channel):* $\eta \rightarrow \gamma X$ *with* $X \rightarrow e^+e^-$
- *Scalar meson searches (charged channel):* $\eta \rightarrow \pi^o H$ *with* $H \rightarrow e^+e^-$ *and* $H \rightarrow \mu^+\mu^-$

Complementary processes

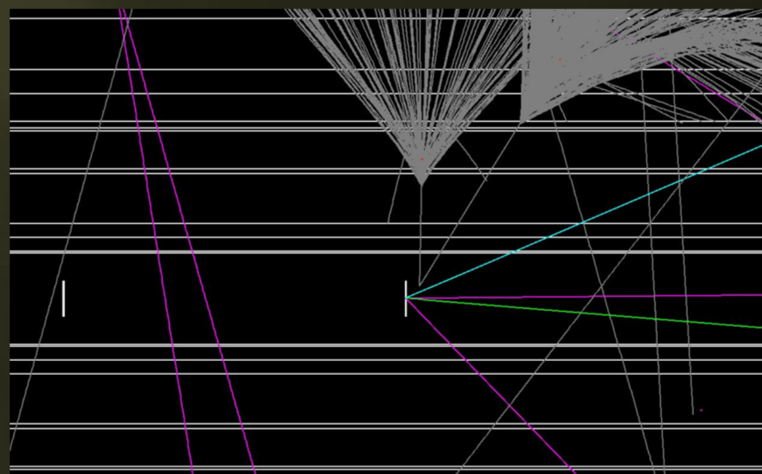
- *Dark photon searches (charged channel):* $\eta \rightarrow \gamma A' \; \gamma + \ell^+\ell^-$
- *Test of T invariance:* $\eta \rightarrow \mu^+\mu^-$; $\eta \rightarrow \pi^o\mu^+\mu^-$ and $\eta \rightarrow \gamma\mu^+\mu^-$
- *CP Violation (Type I):* $\eta \rightarrow 4\pi \rightarrow 8\gamma$
- *Dark photon searches (neutral channel):* $\eta \rightarrow \gamma A' \rightarrow 3\gamma$
- *New baryonic force searches (neutral channel):* $\eta \rightarrow \gamma B$ *with* $B \rightarrow \gamma\gamma\pi^o$
- *Leptoquark searches:* $\eta \rightarrow \mu^+\mu^-$ *and* $\eta \rightarrow e^+e^-$
- *Search for true muonium:* $\eta \rightarrow \gamma(\mu^+\mu^-)|_{2M_\mu} \rightarrow \gamma e^+e^-$
- *CPT violation:* μ *polarization in* $\eta \rightarrow \pi^+\mu^-\nu$ *vs* $\eta \rightarrow \pi^-\mu^+\nu$ *and* γ *polarization in* $\eta \rightarrow \gamma\gamma$
- *Drell-Yan:* $qqbar \rightarrow A' \rightarrow l^+l^-$
- $\pi^+ \rightarrow \mu^+\nu A' \rightarrow \mu^+\nu e^+e^-$ *and* $K^+ \rightarrow \mu^+\nu A' \rightarrow \mu^+\nu e^+e^-$
- $\pi^o \rightarrow \gamma A' \rightarrow \gamma e^+e^-$
- *High precision studies on physics beyond the Standard Model - Low energy* η *physics*
- *Lepton Flavor Violation:* $\eta \rightarrow \mu e$
- *Double lepton Flavor Violation:* $\eta \rightarrow \mu\mu ee$
- *CP Violation (Type II):* $\eta \rightarrow \pi^o \ell^+\ell^-$
- *CP Violation (Type II):* $\eta \rightarrow \pi^+\pi^- \ell^+\ell^-$

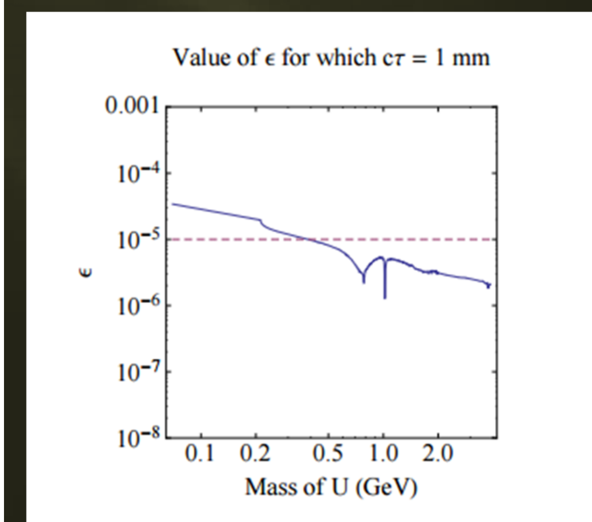
How will we produce enough η's? - How will we detect these rare decays?

Beam Requirements for η-factory

Beam power & Target

- *Constraints:*
  - *η production: > 2×10^{13} η/yr*
  - *Time between inelastic p interaction in one target: ~100 nsec*
  - *Keep down primary multiplicity of hadrons (from p scattering onto the target)*
  - *$R_\eta = \sigma(pp \to pn\eta)/\sigma(pp \to pp\eta) = 6.5$*
  - *Large beam spot size (~ 1 cm), small divergence (< 1^o at first target) but minimal halo*
- *Intensity: >1×10^{11} POT/sec – CW*
  - *Beam power @ 1.9 GeV: 10^{11} p/sec $\times$ 1.9 GeV $\times$ 1.6 $\times$ 10^{-10} J/GeV = 30 Watts*
- *Target: 10 x 0.1mm Nb or 10 x 0.33mm Be foils, spaced 10 cm apart*
  - *Nb is thinner (better vertex resolution) but makes more primary hadrons (final state hadron multiplicity ≈ $A^{1/3}$)*
  - *Prob(p + target → X) = 0.5%*
- *Power dissipated from target:*
  - *150 mW total*
  - *15 mW per target foil*
- *Therefore, no need for target cooling*





$$\ell_0 \equiv \gamma c\tau \simeq \frac{3E_1}{N_{\rm eff}\, m_{A'}^2 \alpha \epsilon^2}$$
$$\simeq \frac{0.8\mathrm{cm}}{N_{\rm eff}} \left(\frac{E_0}{10\mathrm{GeV}}\right)\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{100\,\mathrm{MeV}}{m_{A'}}\right)^2$$

The Experimental Apparatus

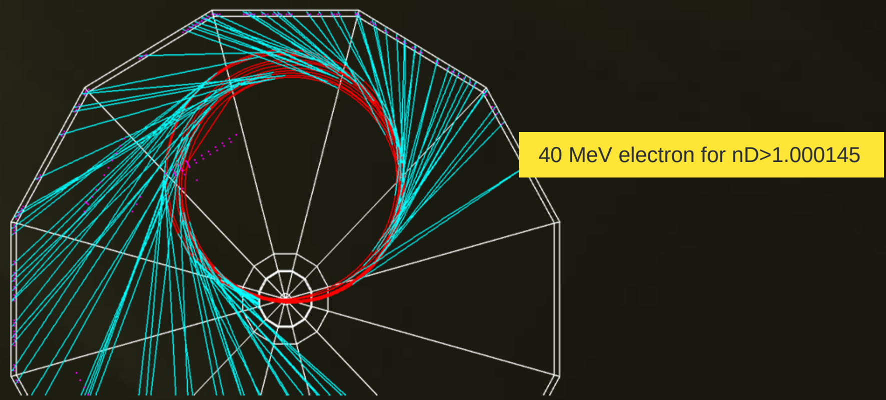
Detector

- *Beryllium or carbon fiber beam pipe, 10 cm dia x 1.5 m long*
- *1 cm dia targets disk inside the pipe, spaced 10 cm apart*
- *Aerogel around the beam pipe, 3cm thick (for most muons and fast pions detection)*
- *Optical-TPC 1m diameter x 1.5 m long*
- *γ-polarimeter in the rear section of the Optical-TPC*
- *ADRIANO calorimeter: ~20 Xo (same as ORKA) or 64 cm deep. Inner and outer sections to accommodate the μ-polarimeter in between*
- *Total detector dimensions: 2.2 m dia x 2.7 m long*
- *CDF solenoid run at 0.6 T (3 m inner diameter x 4.8 m long)*
- *A0 cryogenics infrastructure close to experiment location (Tevatron commissioning transfer tunnel) or existing cryogenics on the muon campus*

- *Potential interest from CERN-Geant4 group on instrumenting the fwd and bkg detector regions (for G4 validation of new hadronic models)*

Background rejection

- Limiting hit counts in the LAPPD is crucial for the experiment
- Background induced LAPPD hits:
  - Cerenkov photons generated in the LAPPD window (1mm quartz) by primary particles and backsplash in the calorimeter
  - Low P_t electrons looping in the OTPC
- Possible solutions (under investigation):
  - Sipm vs LAPPD (no window, but sensitive to any charged particle)
  - Mirrors in the barrel (very nice solution – also costwise, but reco might be complex)
  - Optimize n_D of Cerenkov gas in the OTPC



The Experimental Apparatus

Beam requirements & Target

- E_{beam} = 1.8 ÷ 2.0 GeV (still under optimization)
- Intensity: 1×10^{11} POT/sec – continuous
- Beam power @ 1.8 GeV: 10^{11} p/sec × 1.8 GeV × 1.6 × 10^{-10} J/GeV = 30 Watts
- Target: 10 x 0.1mm Nb or 10 x 0.33mm Be foils, spaced 10 cm apart
- Nb is thinner (better vertex resolution) but makes more primary hadrons (final state hadron multiplicity ≈ $A^{1/3}$)
- Prob(p + target -> X) = 0.5%
- Power dissipated from target:
  - 150 mW total
  - 15 mW per target foil
- Therefore, no need for target cooling

⇓

- p-inelastic production: 5×10^{8} evt/sec (1 interaction/2 nsec in any of the 10 targets)
- η production: 2.5×10^{6} η/sec or 2.5×10^{13} η/yr
- Charged mode (1% acceptance) : 1 L0 trigger/1000 nsec or 5×10^{13} trigger/yr
- Neutral mode (10% acceptance) : 1 L0 trigger/200 nsec or 5×10^{14} trigger/yr

15 Prototypes Performance Summary

Prototype	Year	Glass	gr/cm^3	Cerenkov L. Y./GeV	Notes
5 slices, machine grooved, unpolished, white	2011	Schott SF57HHT	5.6	82	SiPM readout
5 slices, machine grooved, unpolished, white, v2	2011	Schott SF57HHT	5.6	84	SiPM readout
5 slices, precision molded, unpolished, coated	2011	Schott SF57HHT	5.6	55	15 cm long
2 slices, ungrooved, unpolished, white wrap	2011	Ohara BBH1	6.6	65	
5 slices, scifi silver coated, grooved, clear, unpolished	2011	Schott SF57HHT	5.6	64	15 cm long
5 slices, scifi white coated, grooved, clear, unpolished	2011	Schott SF57HHT	5.6	120	
2 slices, plain, white wrap	2011	Ohara	7.5	-	DAQ problem
10 slices, white, ungrooved, polished	2012	Ohara PBH56	5.4	30	DAQ problems
10 slices, white, ungrooved, polished	2012	Schott SF57HHT	5.6	76	
5 slices, wifi Al sputter, grooved, clear, polished	2012	Schott SF57HHT	5.6	30	2 wls/groove
5 slices, white wrap, ungrooved, polished	2012	Schott SF57HHT	5.6	158	Small wls groove
ORKA barrel	2013	Schott SF57	5.6	2500/side	molded
ORKA endcaps	2013	Schott SF57	5.6	4000	molded
10 slices – 6.2 mm thick, scifi version	2014	Schott SF57	5.6	338	molded
10 slices – 6.2 mm thick, sci-plate version	2014	Schott SF57	5.6	354	molded

ADRIANO 2015 (for lepton colliders) is currently in the beam at FTBF

Fermilab's THIN FILM FACILITY at Lab 7

R&D support specialties:

-sputtered & evaporated coatings i.e. fiber mirroring

-plastic optical fiber "ice" polishing

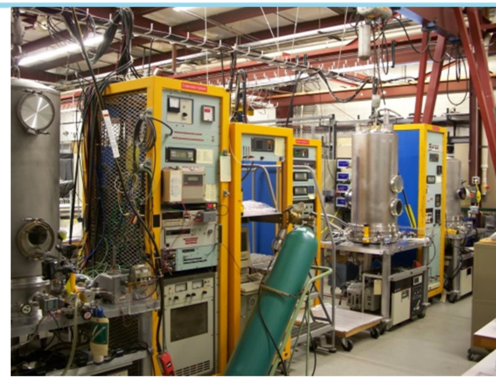
-plastics & aluminum connector polishing

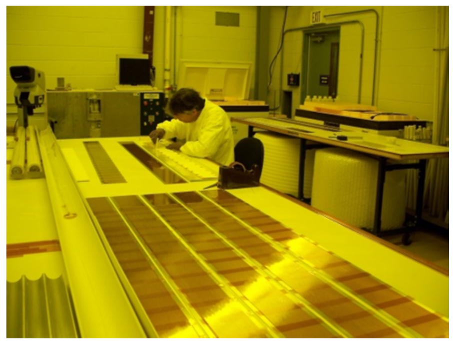
-in vacuum heat treatments up to 1200C

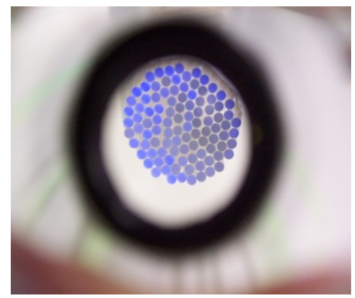
-outgassing/rate of rise tests

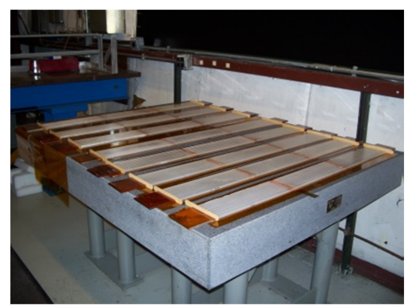
-detector assembly techniques

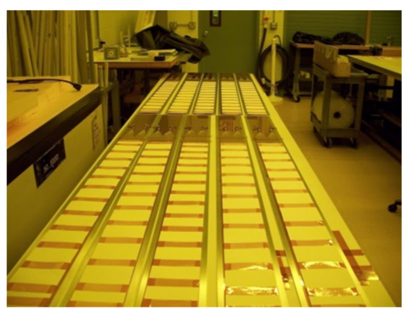
-glues & epoxies

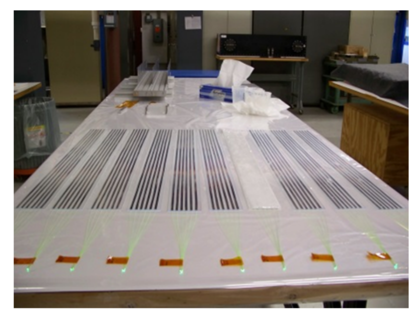












Simulation Studies: event generation

The problem of high intensity – low energy simulations

- *Given the nature of REDTOP experiment, understanding the primary particle production from p-> target is of paramount importance*
- *Inelastic scattering of protons on nuclear matter below 3 GeV occurs mostly via intra-nuclear scattering (binary intra-nuclear cascade) and formation of intra-nuclear baryonic resonances (Δ's, Σ's, etc.)*
- *The physics is non-perturbative: several models have been devised (mostly by nuclear physics theorists) with independent approaches.*
- *Few models have stood up for their completeness and (reasonably) good agreement with the data: LAQGSM, Urqmd, Incl++, PHSD, Gibuu, Abla07 (for nucleus de-excitation and evaporation)*
- *However, almost all of them, suffer from the following limitations:*
  1. *Target nucleus is isolated and in vacuum (no consideration for surronding materials nor for the detector geometry)*
  2. *Final state particles are individual nucleons/mesons (no clusterization nor evaporation of the nuclear remnants)*

REDTOP event generation

- A new event generation framework has been implemented for REDTOP:

1. Use Genie architecture:
   - Geometry-aware through root's Tgeo library (gdml or root files to specify beam+detector geometry)
   - Events are generated in a realistic geometry (primary vertex of the event is generated according to detector geometry and materials)
2. Implement interfaces between Genie's framework and top-of-the line hadronic event generators
   - Currently implemented interfaces: Incl++, PHSD, Urqmd, Gibuu, Abla07, Geant4 electromagnetic models
   - LAQGMS under implementation
3. Add clusterization + de-excitation + evaporation to final state
4. Feed Geant4 with the generated event

However, a full simulation with MARS15 is mandatory (and already planned) to make the project meaningful

REDTOP Simulation Status

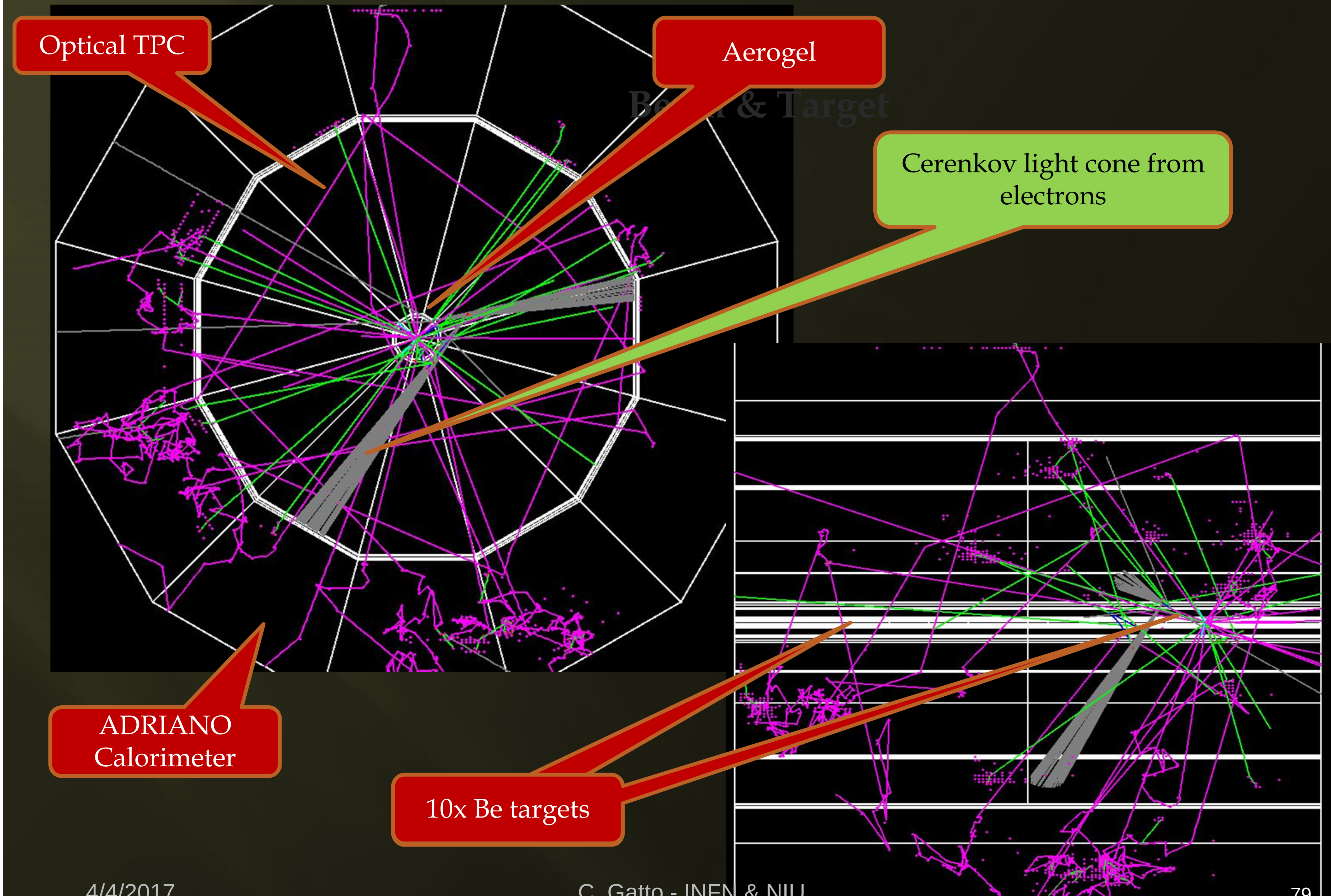
- Several samples of background with multiple detector configurations (target material, LAPPD thickness, etc.)
- Largest sample: 10^5 events with Urqmd and Incl++ with Be targets and 1mm LAPPD quartz window
- Simulated signal channels:

1. $p\,Be \rightarrow \eta \rightarrow 4\pi^o$
2. $p\,Be \rightarrow \eta \rightarrow e\,\mu$
3. $p\,Be \rightarrow \eta \rightarrow A'\gamma \rightarrow e^+e^-\gamma$
4. $p\,Be \rightarrow \eta \rightarrow A'\gamma \rightarrow \gamma\gamma\gamma$
5. $p\,Be \rightarrow \eta \rightarrow e^+e^-\pi^o$
6. $p\,Be \rightarrow \eta \rightarrow \mu^+\mu^-\pi^o$

- More channels will need to be studied (waiting for more collaborators):

1. $p\,Be \rightarrow \eta \rightarrow 2\pi^o\pi^+\pi^-$
2. $p\,Be \rightarrow \eta \rightarrow B\,\gamma \rightarrow \gamma\gamma\gamma$
3. $p\,Be \rightarrow \eta \rightarrow B\,\gamma \rightarrow \gamma\gamma\pi^o$
4. $p\,Be \rightarrow \eta \rightarrow B\,\gamma \rightarrow \gamma\gamma e^+e^-$
5. $p\,Be \rightarrow \eta \rightarrow e^+e^-$
6. $p\,Be \rightarrow \eta \rightarrow \mu^+\mu^-$
7. $p\,Be \rightarrow \eta \rightarrow \mu^+\mu^-\gamma$
8. $p\,Be \rightarrow \eta \rightarrow \mu^+\mu^-\gamma\pi^o$
9. *Bread@butter physics*
10. .

The REDTOP Detector



REDTOP Physics Program (VIII)

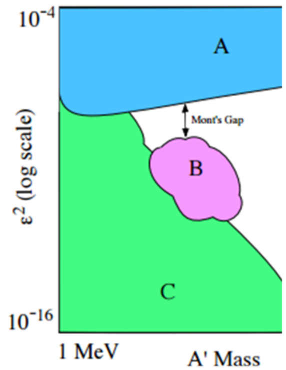
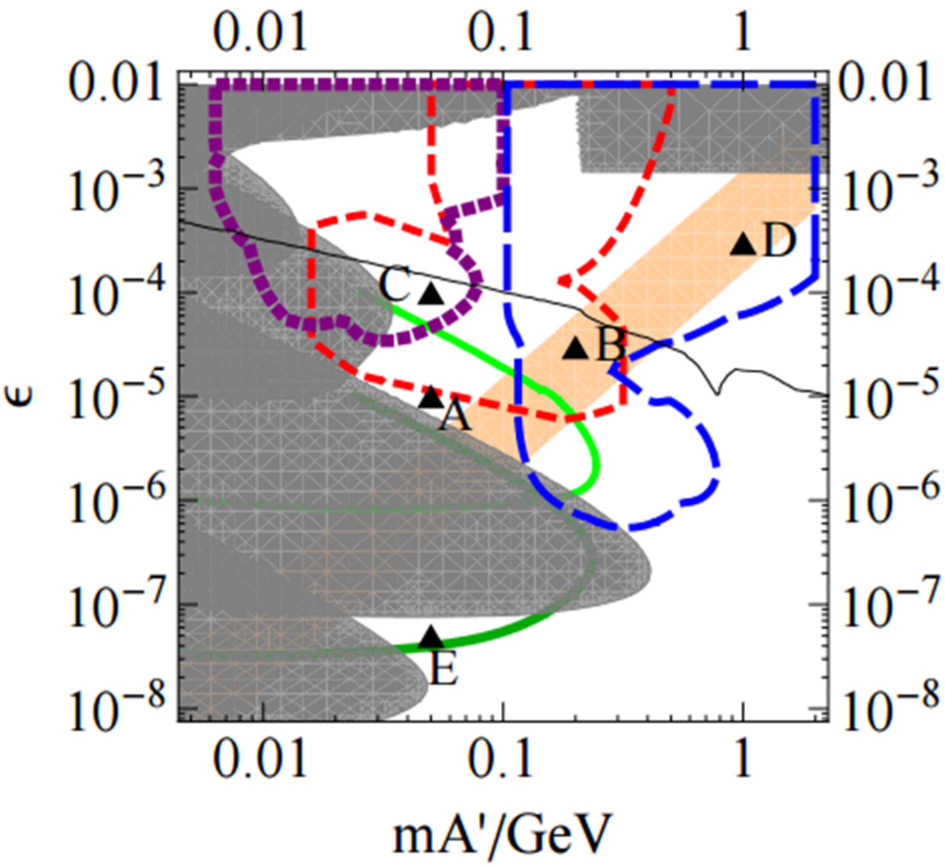


FIG. 2: Cartoon of ε^2 vs. A' mass parameter plane. Re
modes. Region B: displaced vertex searches, short dec
searches, long decay lengths.



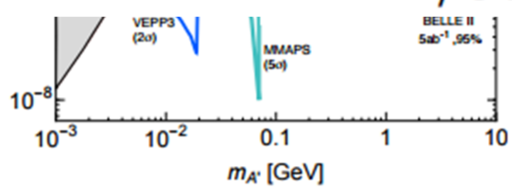


FIG. 3: A' sensitivity for missing-mass experiments, allowing invisible decay modes. Existing exclusions, shown in gray, have been smoothed.

Essig et al (2013)

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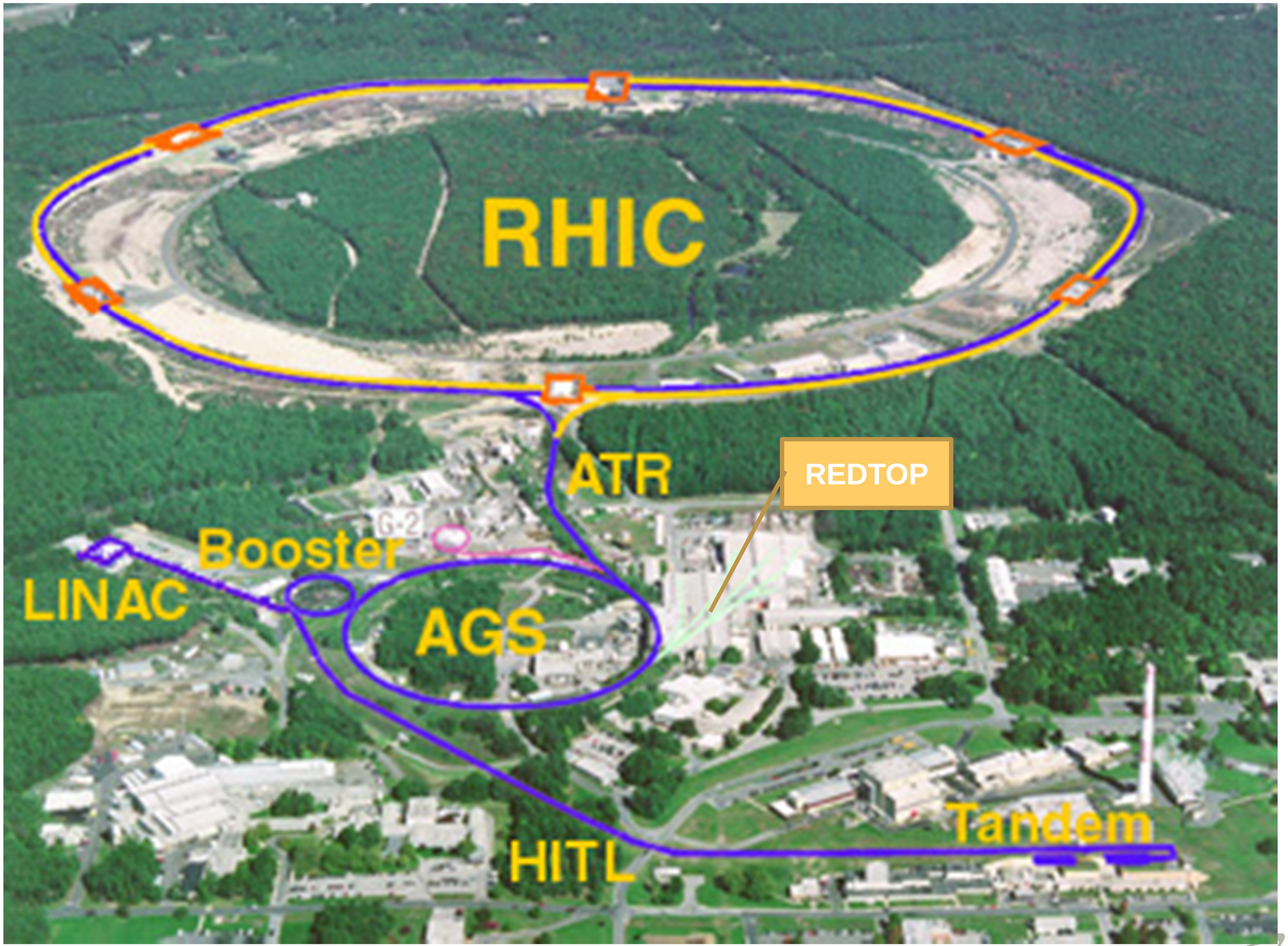
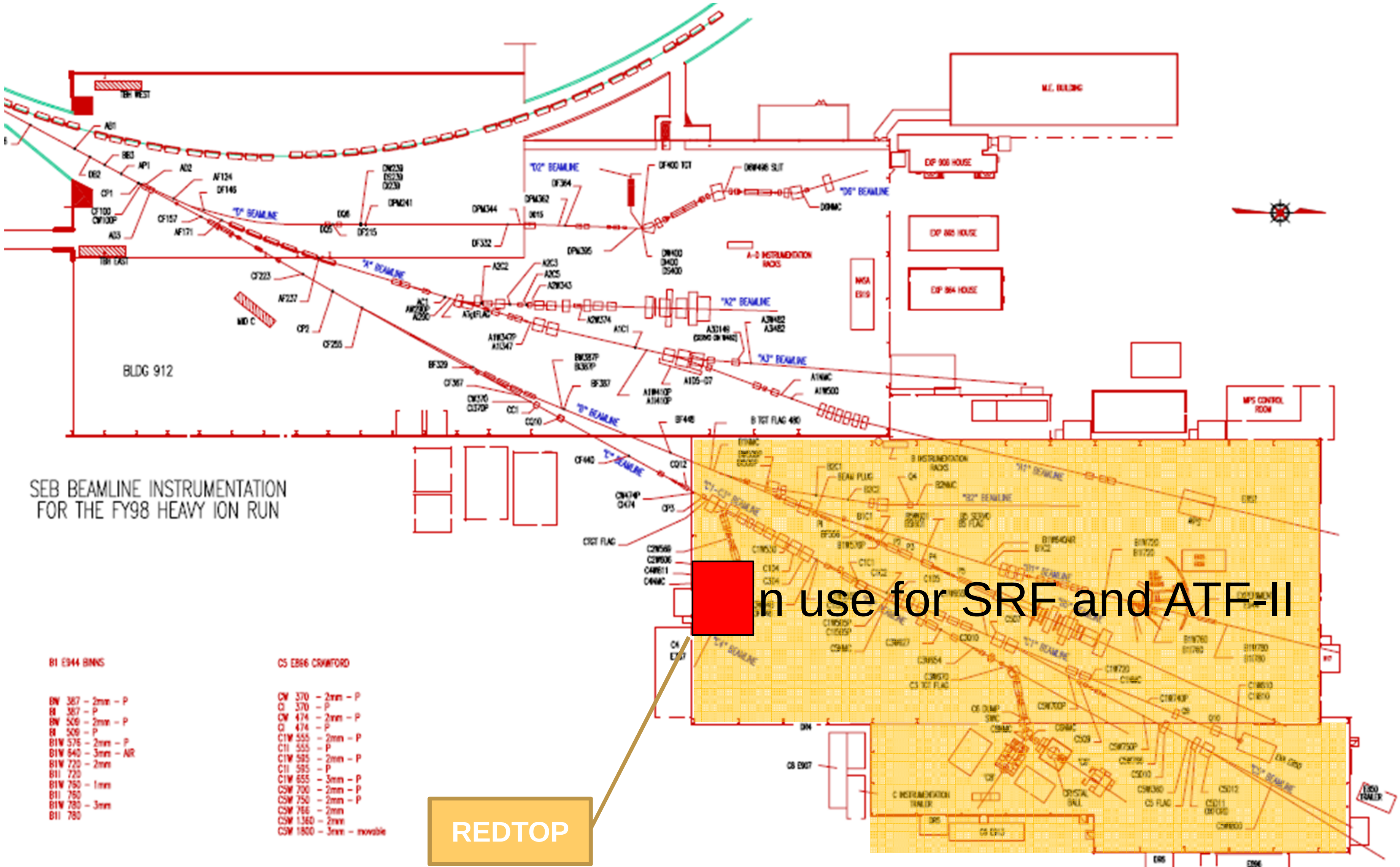
BNL hadron complex



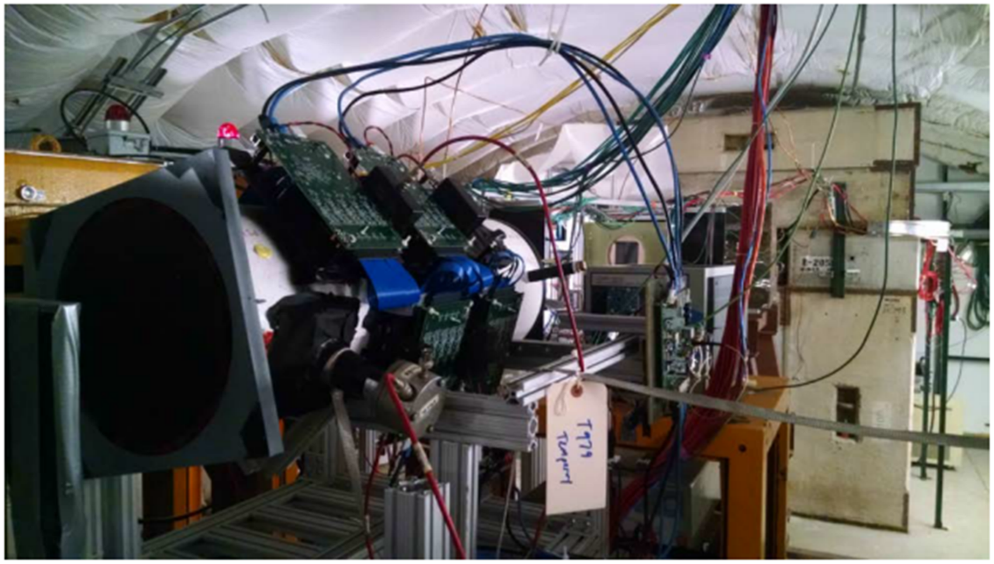
Building 912 AGS Experimental Area (1998)

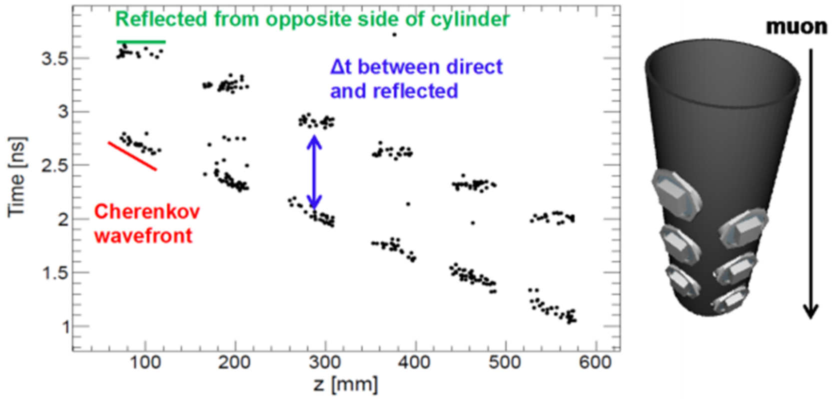


Detector R&D: OTPC

Fnal –T1059 (H. Frisch, E. Oberla)

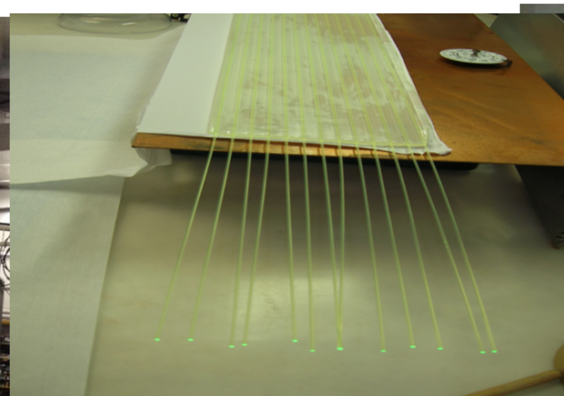
- *Successful proof of principle in 2015 at FTBF*
- *Instrumented with an MCP photo-detector, three boards each with thirty channels of 10 GSPS waveform digitizing readout*
- *http://ppd.fnal.gov/ftbf/TSW/PDF/T1059_tsw.pdf*

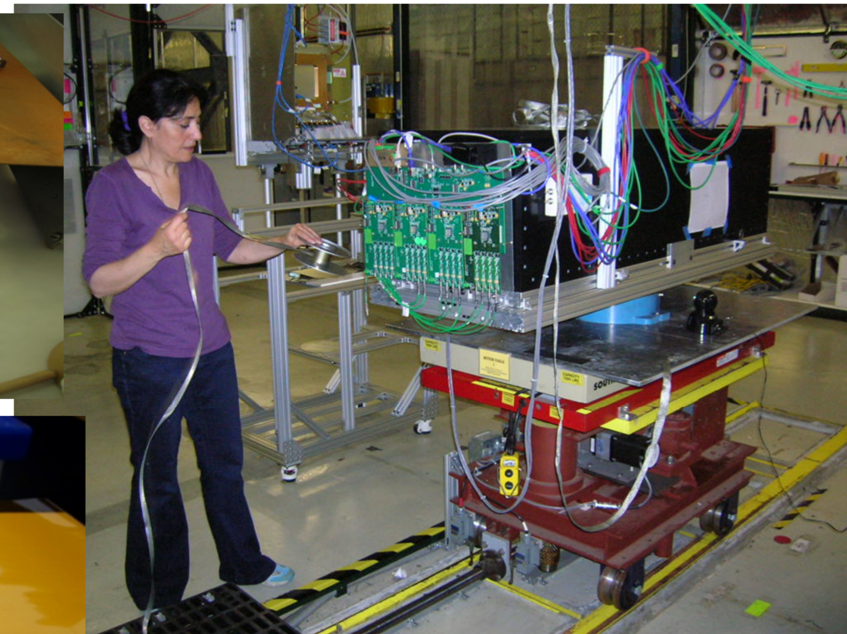


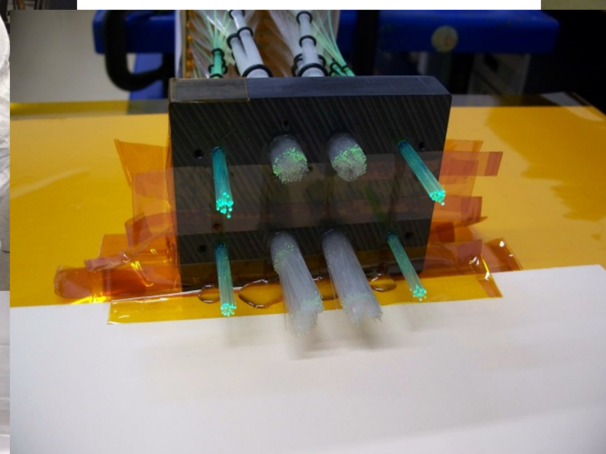


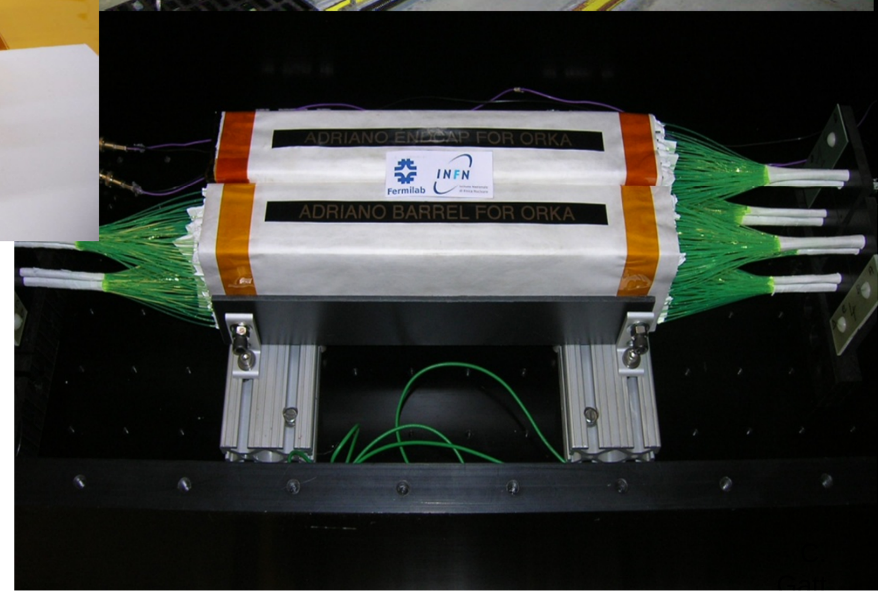
It requires a robust and dedicated R&D

Detector R&D: ADRIANO in T1015
Moving R&D from FNAL to NIU









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