The REDTOP experiment: A super-η/η' Factory to Explore Dark Matter and Physics Beyond the Standard Model

Corrado Gatto

INFN Napoli and Northern Illinois University

Part I:

Current physics landscape in HEP

Shortfalls of the Standard Model

Where to search for New Physis

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

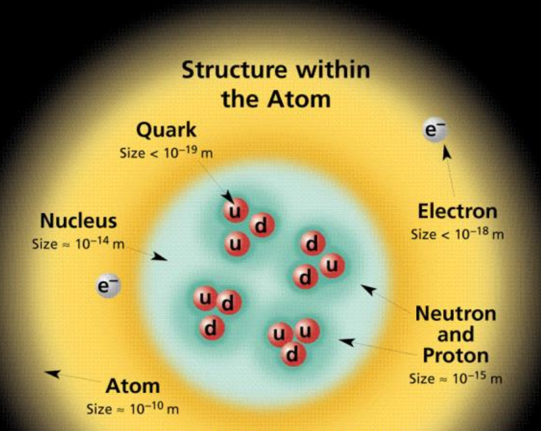
Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ — Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

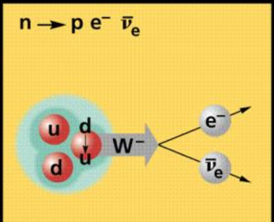
Mesons $q\bar{q}$ — Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

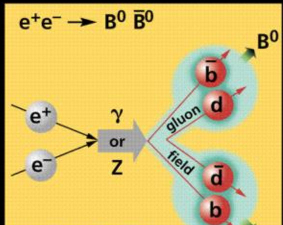
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

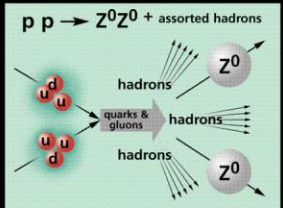
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

This chart has been made possible by the generous support of:

U.S. Department of Energy
U.S. National Science Foundation
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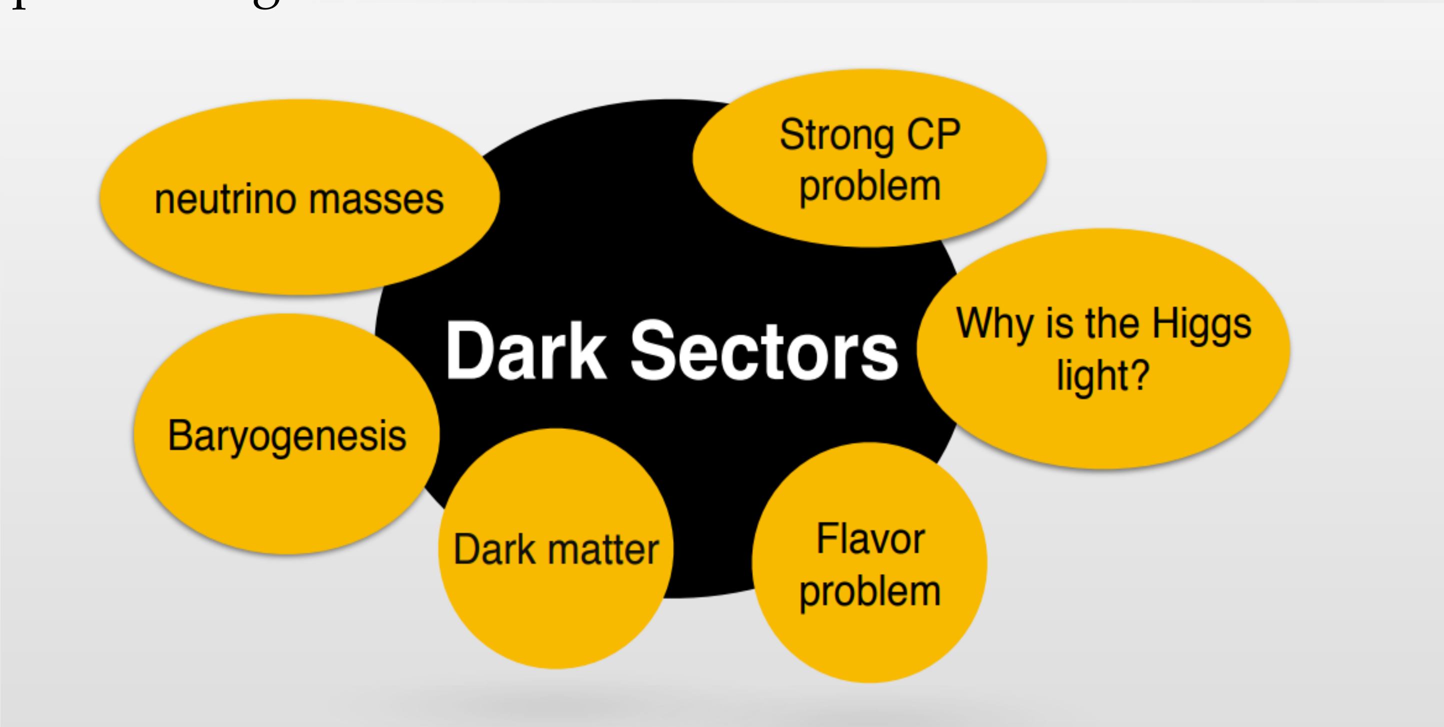
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

The Shortfalls of The Standard Model

- The Standard Model has served us well for 50 years
- Recent measurements indicates it can't be the final answer
- Six categories of problems have arisen
  - Type 1: Disagreement between theory and experiment
  - Type 2: Inelegant or ad-hoc rules



Type-1 anomaly

Anomalies of the Standard Model - I

Baryon asymmetry of the universe (BAU)

Necessary ingredients are:

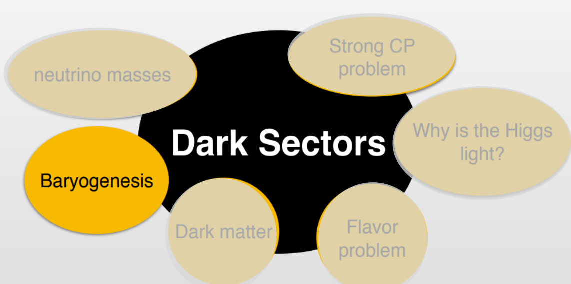
- Baryon number violation
- Thermal non-equilibrium
- C and CP violation

Sakarov - conditions

All of these ingredients were present in the early Universe!

- Do we understand the cause of CP violation in particle interactions?
- Can we calculate the BAU from first principles?

1975 Nobel Peace Prize



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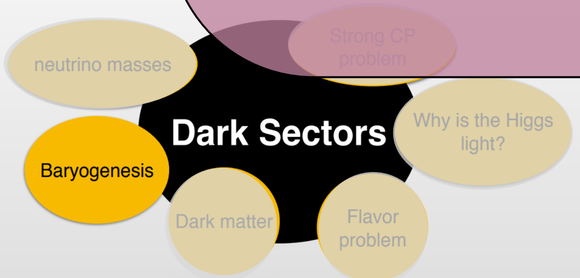
CP Violation in SM not sufficient to explain BAU

Baryon Number Violation still not observed



Anomalies of the Standard Model - II

Hubble Constant (describing the expansion of the universe)

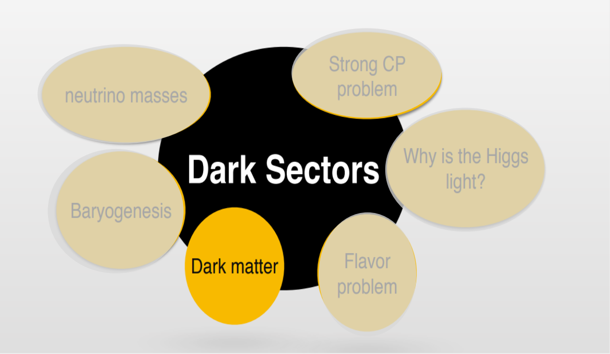
Latest measurements diverge from Standard Cosmology Model

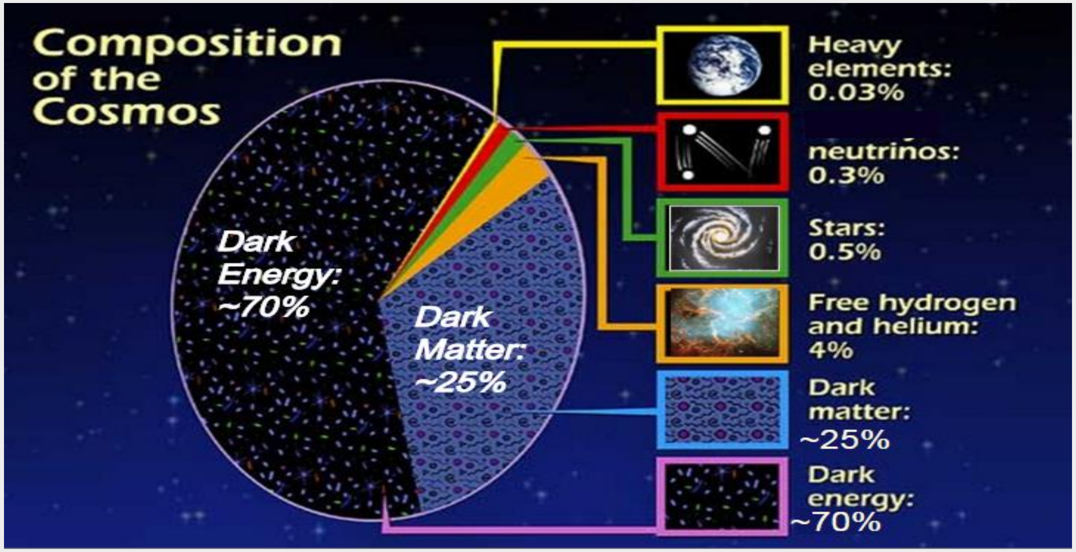
Expansion of the universe is accelerating

- Indicates large amounts of "dark energy" (~ 70% of total energy)
- Cosmologists have included a repulsive dark energy in their model of cosmic evolution

Galactic rotation curves and clusters

- Indicates large amounts of "dark matter" (~ 5x standard matter)
- Presence of dark matter inferred via gravitational effects only





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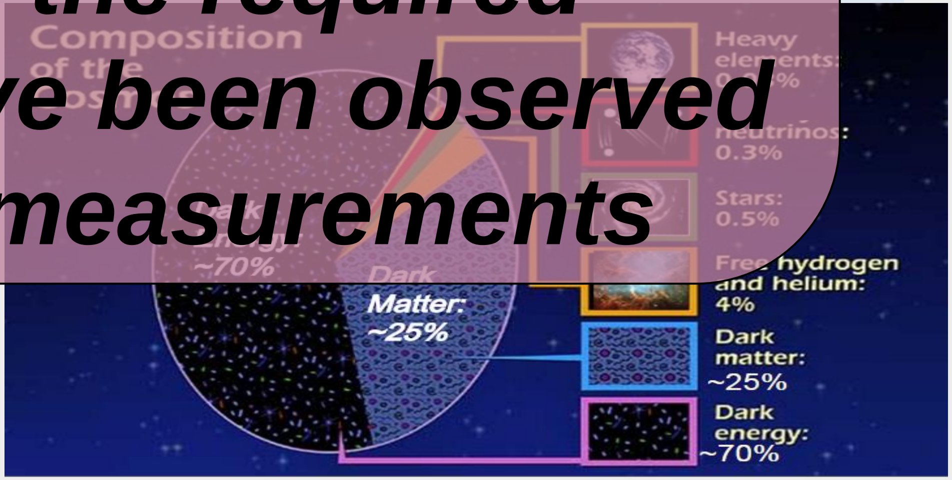
- Indicates large amounts of "dark matter" (~ 5x standard matter)
- Presence of dark matter inferred via gravitational effects only
- No dark matter with the required properties still observed

Neither Dark Matter or Dark Energy exists in the Standard Model

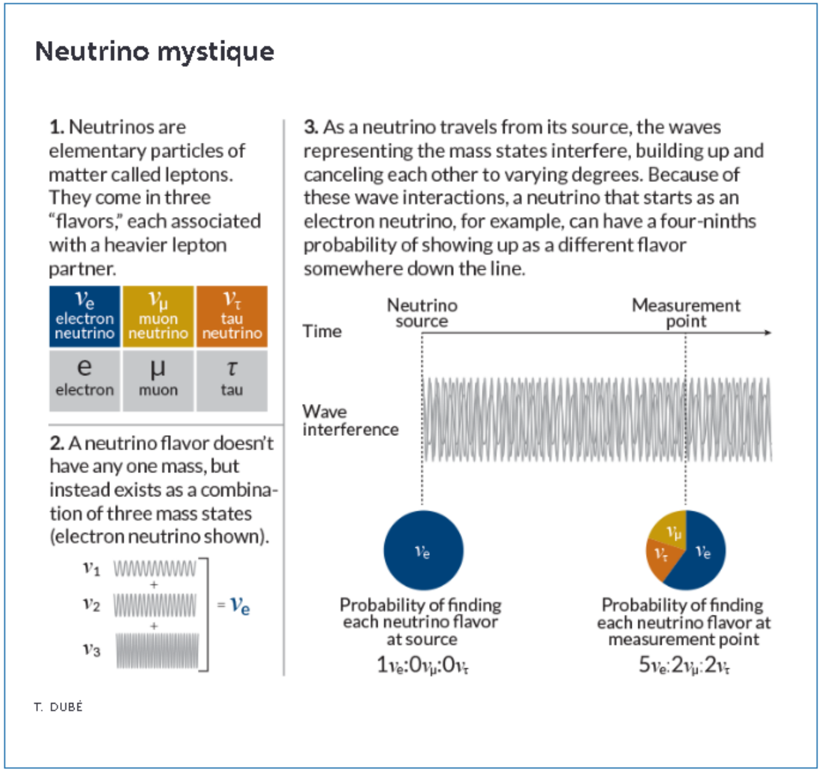
None with the required properties have been observed with direct measurements

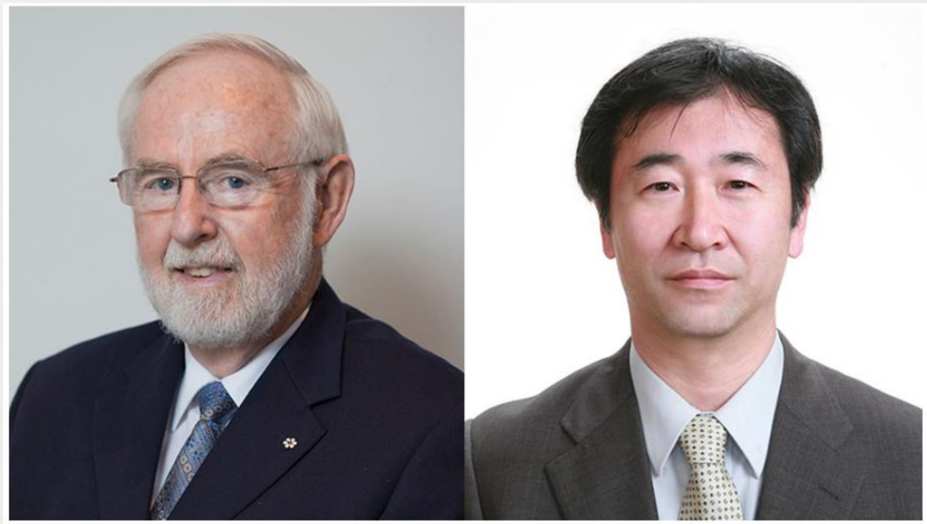


Type-1 anomaly

Anomalies of the Standard Model - III

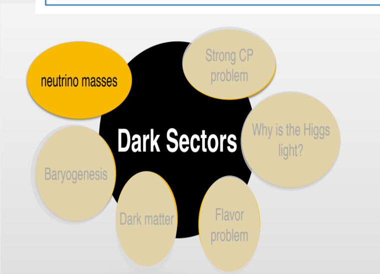
Super-Kamiokande and SNO demonstrated that neutrino mass ≠ 0 as they oscillate





NEUTRINO NOBEL Arthur McDonald (left) and Takaaki Kajita shared the Nobel Prize in physics for the discovery that neutrinos oscillate between different types, which demonstrates that the particles have mass.

2015 Nobel Prize



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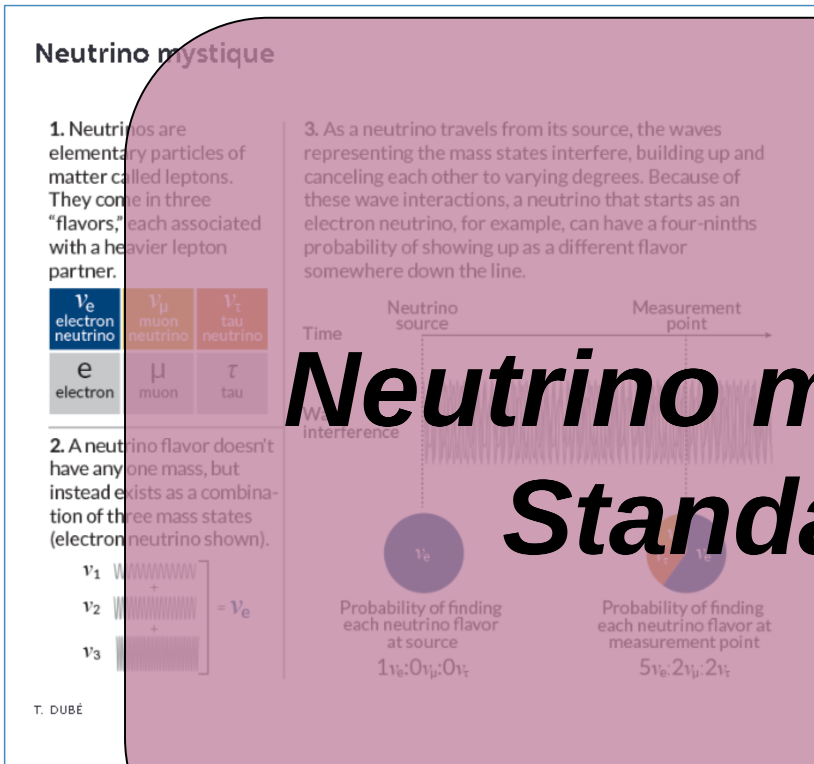

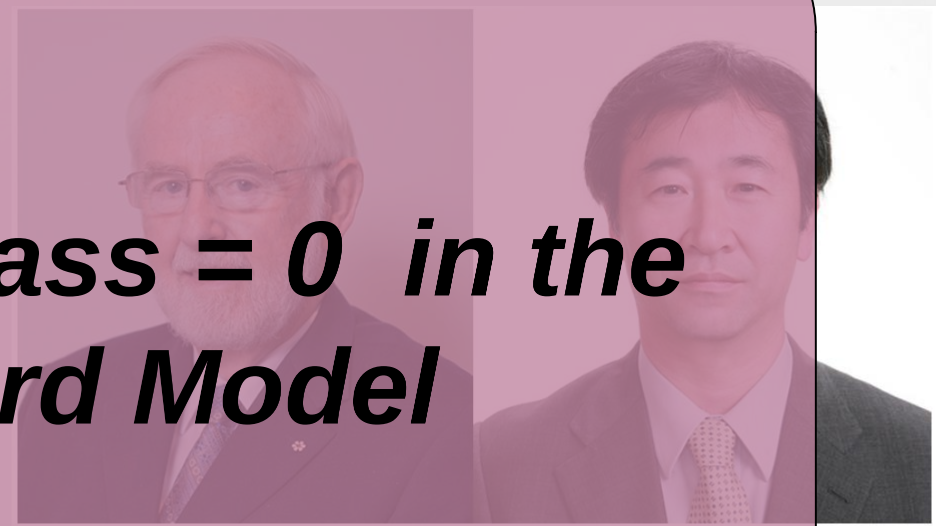

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Neutrino mass = 0 in the Standard Model

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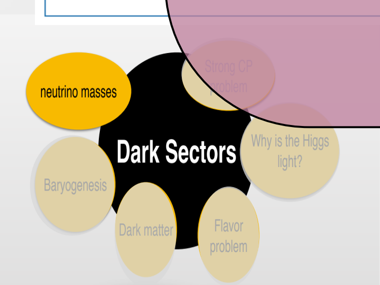


Theoretical Problems of the SM - I

The strong CP problem

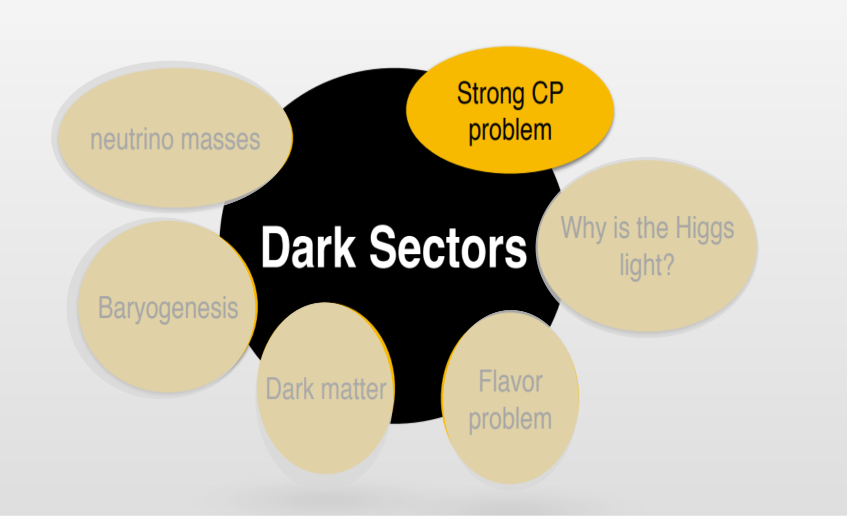
Why does QCD seem to preserve CP-symmetry?

CP-symmetry could be violated in strong interactions. However, no such violation has ever been observed in any experiment involving only the strong interaction.

It could be a fine-tuning problem (but very unnatural) or a hint of New Physics

There are several solutions being proposed

The existence of a Peccei-Quinn axion is the most famous



Type-2 anomaly

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Several experiment are searching for the QCD axion

It has not been found yet

Type-2 anomaly

Theoretical Problems of the SM - II

❐ The hierarchy problem

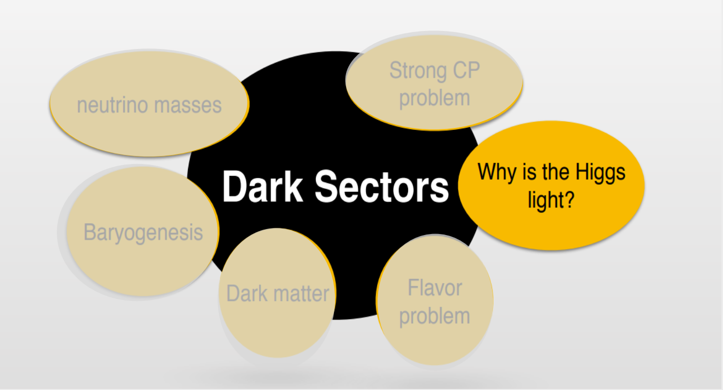
- It is the huge difference in the strength of fundamental forces or the wide range in mass for the elementary particles.
- Why is there such a wide spectrum of masses among the building blocks of matter? Imagine having a Lego set containing bricks as disparate in size as that!

❐ The hierarchy problem is also related to the Higgs boson mass.

- Corrections to the Higgs mass are proportional to the mass of the contributing quark
- The top quark being the heaviest particle, it adds such a large correction to the *theoretical* Higgs boson mass that theorists wonder how the *measured* Higgs boson mass can be as small as it was found.

❐ The naturalness problem (hint: it is a consequence of the hierarchy problem)

- the cosmological constant [often referred to as "dark energy"] is amazingly small, compared to what you'd naturally expect.



Type-2 anomaly

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No explenation has been found within the Standard Model for the hierarchy and the naturalness problems

The naturalness problem (hint: it is a consequence of the hierarchy problem)

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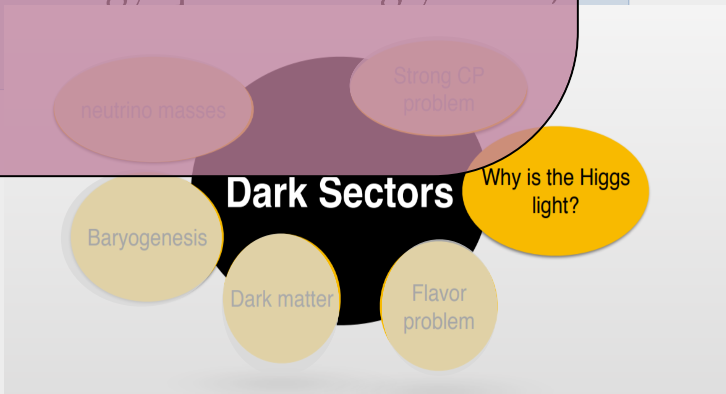

Theoretical Problems of the SM - III

- **Number of parameters**
  - The Standard Model depends on 19 numerical parameters
  - Their value is know from the experiments, but their origin is unknown
  - Any attempt to find a relationship among different parameters has failed

- **Quantum triviality**
  - Suggests that it might not be possible to create a quantum field theory involving elementary scalar Higgs particles

- No full theory of gravitation as described in the general relativity
  - Simply adding a graviton to the SM does not reproduce the experimental observations
  - SM is widely considered *incompatible* with the current general relativity

Type-2 anomaly

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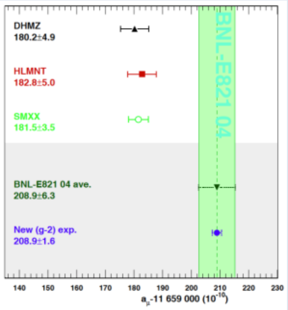
Plank's limit: the Standard Model is only a "low energy" approximation to a more fundamental theory

Outstanding Anomalies in HEP - I

Muonic puzzle



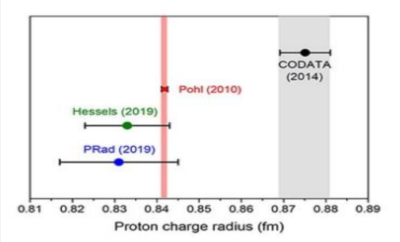
4.2σ effect

- $(g-2)_\mu$

    Latest measurement at Fermilab

- *Proton radius*

    Energy levels in muonic hydrogen are different than standard hydrogen



Maybe close to be solved

Lepton Flavor Non-Universality in charged currents

$$R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)},$$

$$R(D^*) = (1.25 \pm 0.07) \times R(D^*)_{\rm SM},$$
$$R(D) = (1.32 \pm 0.16) \times R(D)_{\rm SM},$$

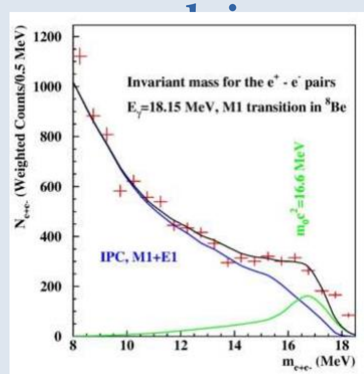
4σ effect

$$R_K = \frac{\mathrm{BR}\,(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}\,(B^+ \to K^+e^+e^-)}, \quad R_{K^*} = \frac{\mathrm{BR}\,(B \to K^*\mu^+\mu^-)}{\mathrm{BR}\,(B \to K^*e^+e^-)}.$$

~~3.1σ effect~~

Outstanding Anomalies in HEP - II

X_{17} in the e^+e^- emission spectra of isoscalar magnetic transitions of ^{8}Be and ^{4}He



6.8σ effect

W mass from CDF vs SM prediction

$$M_W|_{\text{CDF}} = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80,433.5 \pm 9.4\,\text{MeV}$$

7σ effect

CKM Matrix

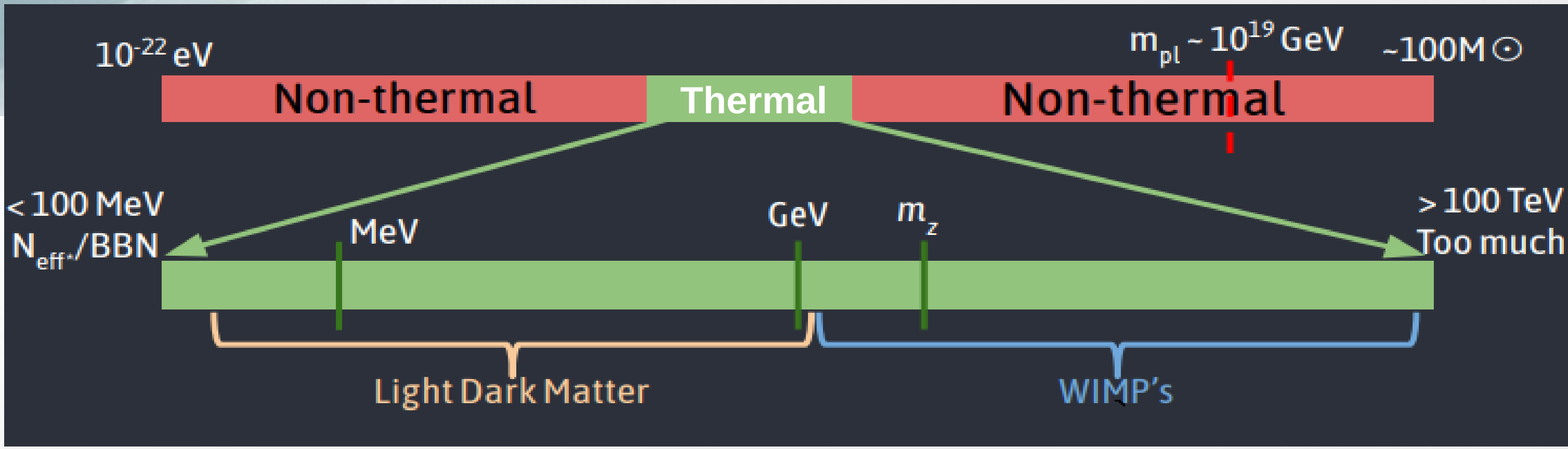
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9969 \pm 0.0024.$$

1-2σ effect

Current Status of HEP

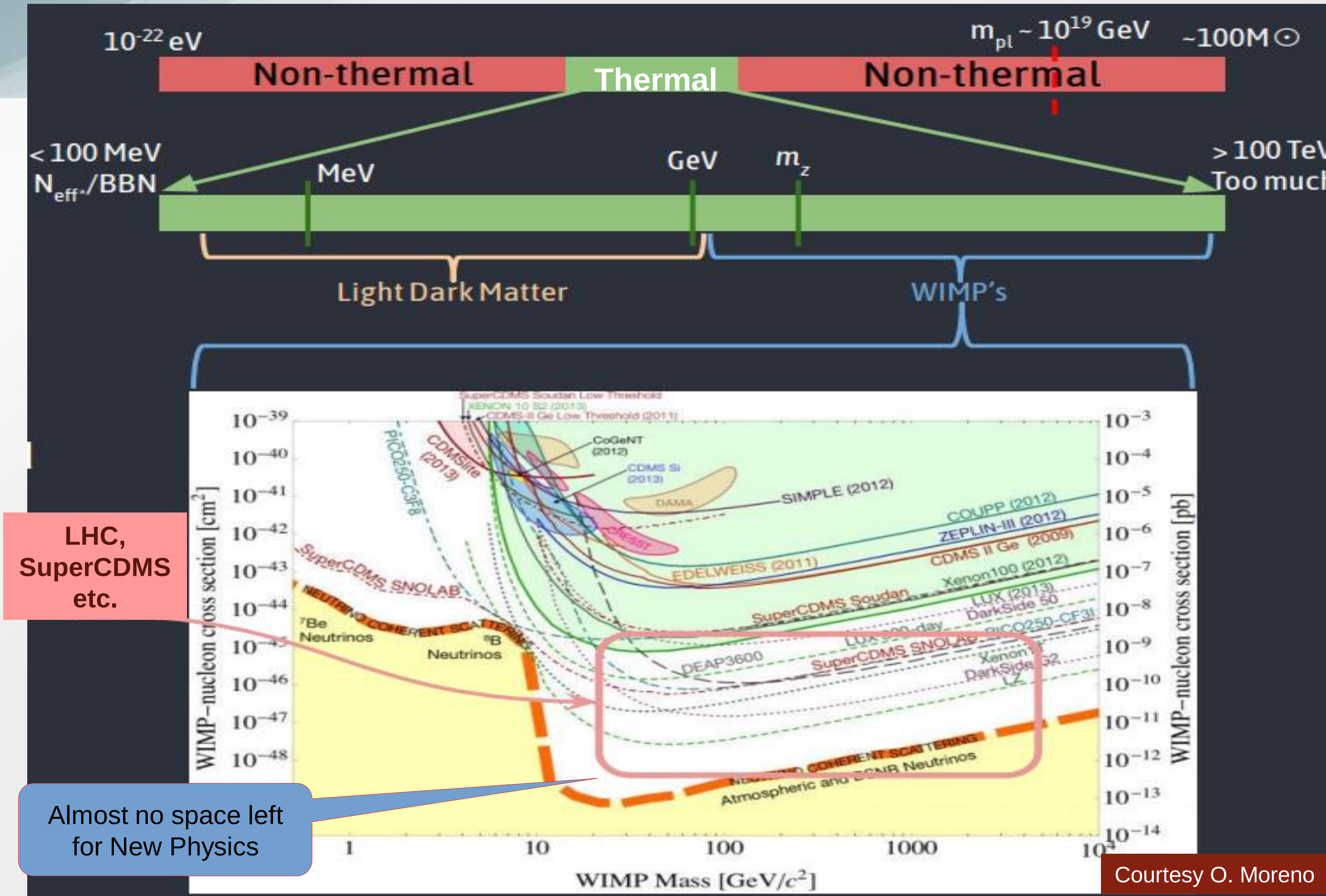
- *SM ingredients are insufficient to explain the nature. Most likely we need:*
  - *new forces (with adequate CP violation)*
  - *new particles*
- *Mass of possible New Physics spans 40 order of magnitude*
- *We don't have a clue of what's beyond the Standard Model*
- *Parameter space for New Physics at High Energy is running out (from LHC results)*
- *Scientists are hard pressed to design new experiments for understanding what's going on*
- *We are in a rare (and exciting time) when discoveries will set the stage for the next 30-50 years*

The Quest for Dark Matter



Courtesy O. Moreno

The Quest for Dark Matter



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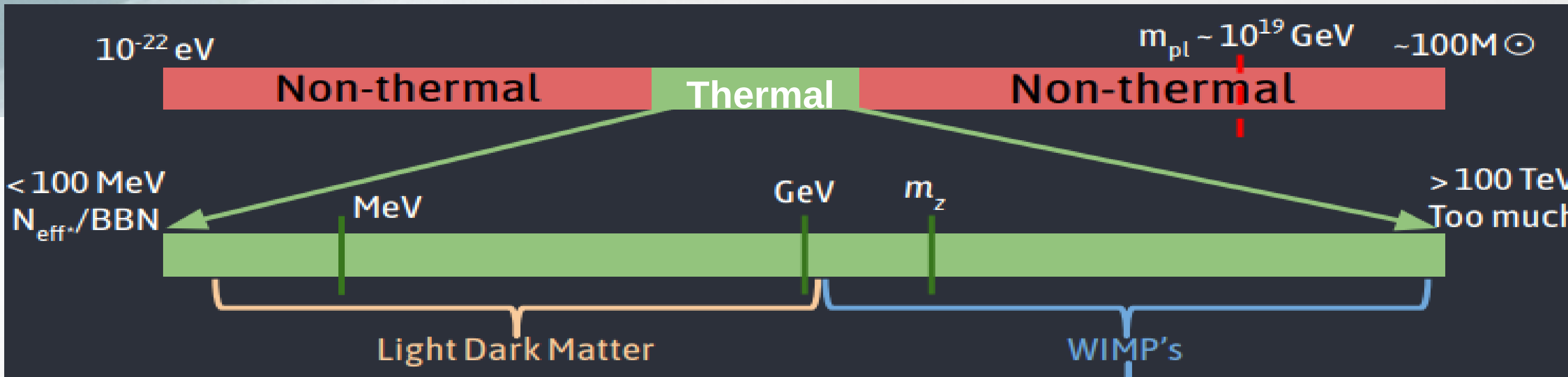


Need new mediator!

$$G_X > G_F$$

$$G_X = \frac{g_X^{SM} g_X^{DM}}{m_X^2}$$

Sub-GeV thermal DM requires stronger than G_{fermi} interactions!

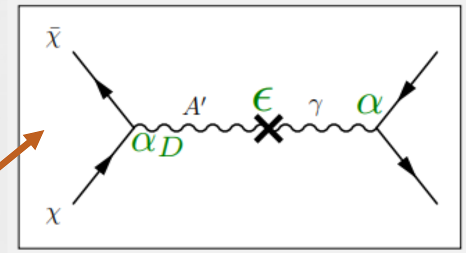
*Newest theoretical models prefer gauge bosons in MeV-GeV mass range as "…**many of the more severe astrophysical and cosmological constraints** that apply to lighter states **are weakened or eliminated**, while **those from high energy colliders are often inapplicable**" (B. Batell , M. Pospelov, A.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

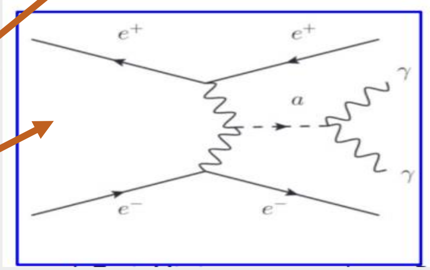
New mediator is expected to couple to SM stronger than G_F

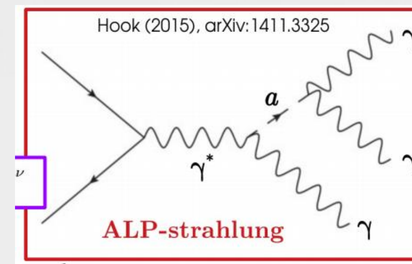
Courtesy O. Moreno

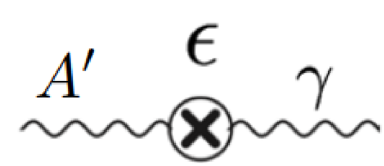
Connection between Standard and Dark Matter

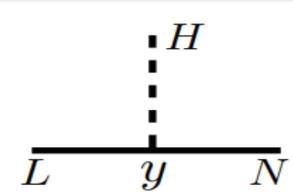
Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu} \widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$











New Physics talk to Standard Model particles through four portals

Experimental Signatures

Invisible, non-SM

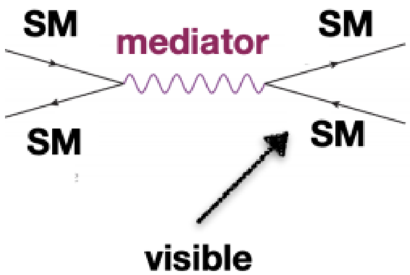
Dark Matter production

Producing stable particles that could be (all or part of) Dark Matter

Visible, SM

Production of portal-mediators that decay to SM particles

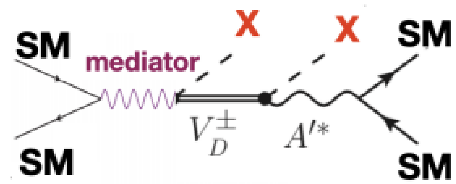
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

Production of “rich” dark sectors

Testing the structure of the dark sector



Stefania Gori, Mike Williams

High intensity meson factories

Current Experimental Searches

- Direct searches
- Proton beam dump
- Electron beam dump
- Fixed target electron scattering
- **Fixed target p/π experiments**
- Colliders

Cosmic rays

Higher Luminosity Accelerator

Lower Luminosity Accelerator

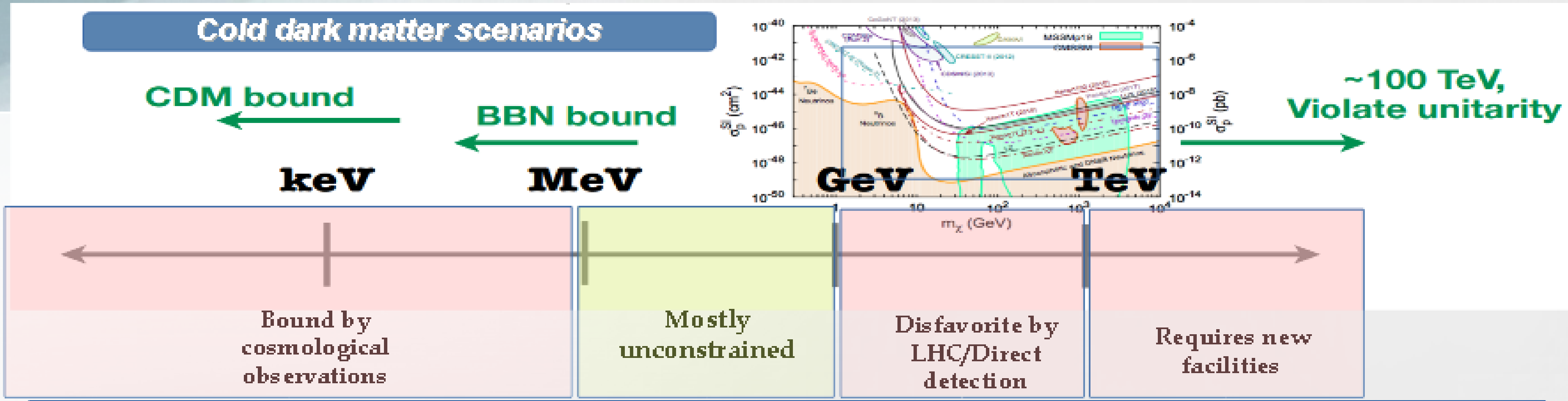
Part II:

REDTOP

Rare Eta/Eta' Decays
TO Explore New Physics

Searching for Light Cold DM with
η/η' rare meson decays

Rationale for an η/η‘ Factory



"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 the only mesons with **flavor-conserving** reactions
- **20%-40% of is NOT made of quarks**

Experimental advantages:

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

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

Main Physics Goals of REDTOP

Assuming a yield ~10^{14} η mesons and ~10^{12} η' mesons

Test of CP invariance via Dalitz plot mirror asymmetry: $\eta \rightarrow \pi^0\pi^+\pi^-$

Search for asymmetries in the dalitz plot with very high statistics

Test of CP invariance via μ polarization studies: $\eta \rightarrow \pi^0\mu^+\mu^-$, $\eta \rightarrow \gamma\mu^+\mu^-$, $\eta \rightarrow \mu^+\mu^-$,

Measure the angular asymmetry between spin and momentum

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

Need excellent particle ID

Violation of discrete symmetries+

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

Dual (or triple!) calorimeters and vertexing

Dark scalar searches: $\eta \rightarrow \pi^0 H$, with $H \rightarrow \mu^+\mu^-$, $H \rightarrow e^+e^-$

Dual (or triple!) calorimeters and particle ID

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

Need excellent vertexing and particle ID

Searches of new fields and forces

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

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

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

Other discrete symmetry violations

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

Non-η/η′ based BSM Physics

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

New particles and forces searches

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

Other Precision Physics measurements

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

High precision studies on medium energy physics

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

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C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^o \pi^+\pi^-$
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- QCD axion searches : $\eta \to \pi\pi a_{17}$ with $a_{17} \to e^+e^-$
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- Lepton Universality
- $\eta \to \pi^o H$ with $H \to \gamma a_2$, $a_2 \to l_1 l_2$, $l_1 \to e^+e^-$

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)

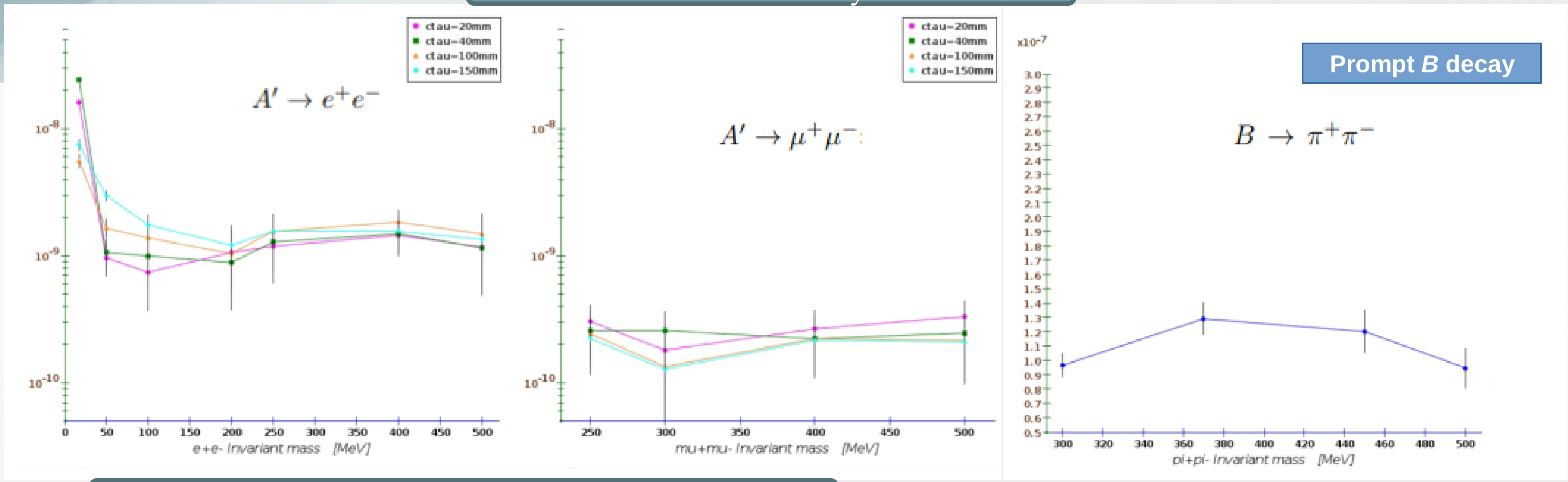
Only experiment, along with SHIP, sensitive to all four BSM portals

New particles & forces

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

REDTOP

Some BR sensitivity curves



Sensitivity curves for Minimal Dark Photon Model

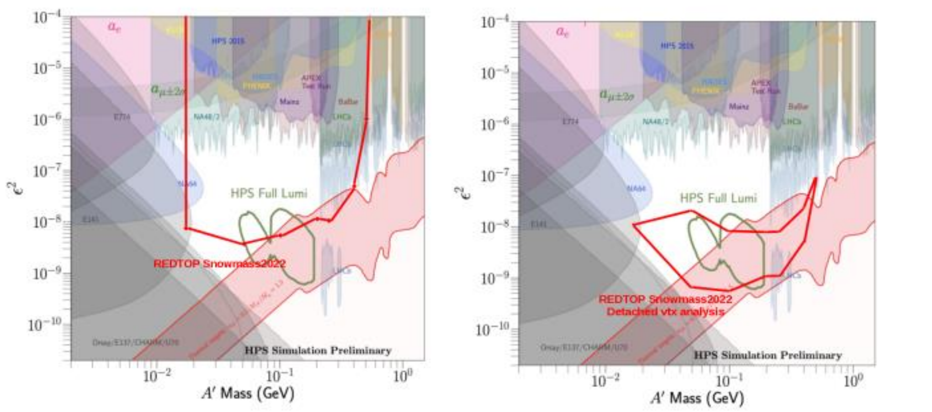


FIG. 36. Sensitivity to to ε^2 for the processes $\eta \to \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

Theoretical Models considered

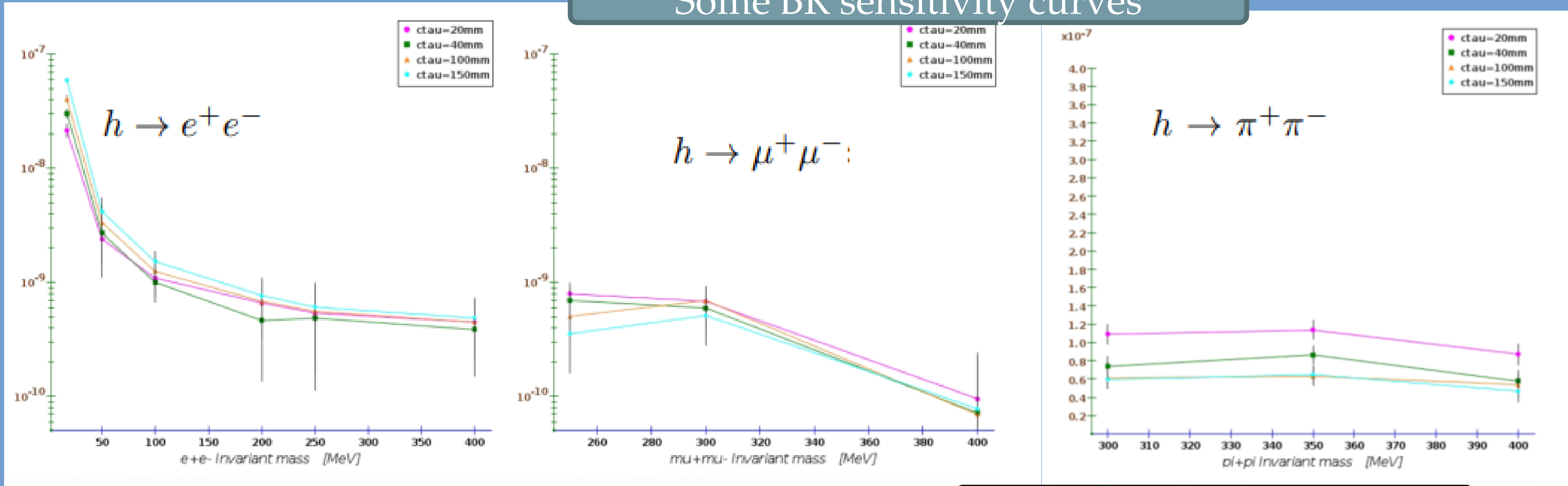
- *Minimal dark photon model*
  - *Most popular model*
- *Leptophobic B boson Model*
- *Protophobic Fifth Force*
  - *Explains the Atomki anomaly*

New particles & forces

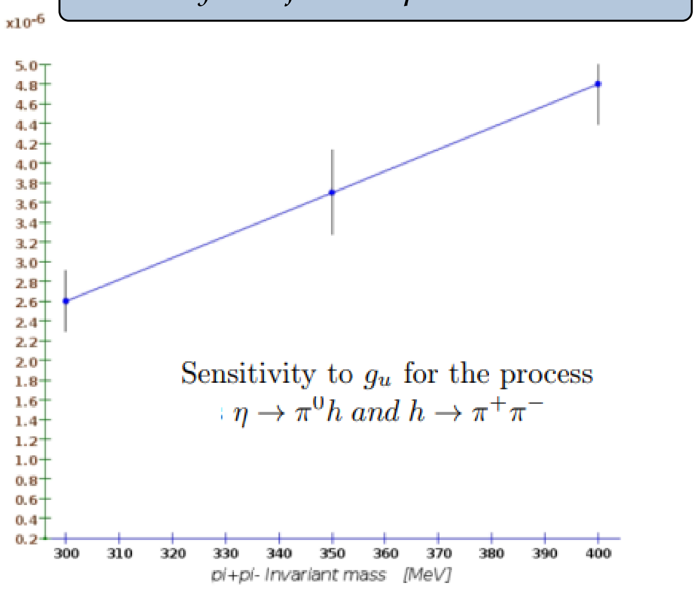
Scalar Portal searches: $\eta \rightarrow \pi^0 h$ with $h \rightarrow \mu^+\mu^-, \pi^+\pi^-, e^+e^-$

REDTOP

Some BR sensitivity curves



Sensitivity curve for Hadrophilic Mediator model



Sensitivity for Two-Higgs doublet model

Process	m_S	Analysis	$(\lambda_u - \lambda_d)^2$ sensitivity
$\eta \rightarrow \pi^0 S$; $S \rightarrow e^+e^-$	17 MeV	bump hunt	2.0×10^{-13}
$\eta \rightarrow \pi^0 S$; $S \rightarrow \mu^+\mu^-$	17 MeV	detached vertex	3.2×10^{-13}

TABLE XXV. Sensitivity to $(\lambda_u - \lambda_d)^2$ for the process $\eta \rightarrow \pi^0 S$ and $S \rightarrow e^+e^-$ and $S \rightarrow \mu^+\mu^-$.

Theoretical models considered

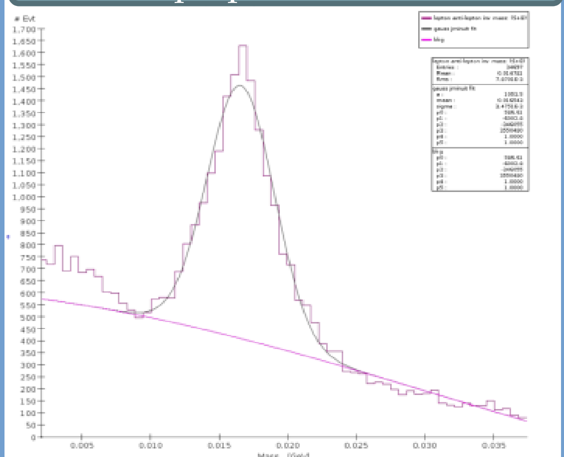
- ***Hadrophilic Scalar Mediator*** *(B. Batell, A. Freitas, A. Ismail, D. McKeen)*
- ***Spontaneous Flavor Violation*** *(D.Egana-Ugrinovic, S. Homiller, P. Meade)*
- ***Two-Higgs doublet model*** *(W. Abdallah, R. Gandhi, and S. Roy)*
- ***Minimal scalar model*** *(C.P. Burgess, M. Pospelov, T. ter Veldhuis)*

New particles & forces

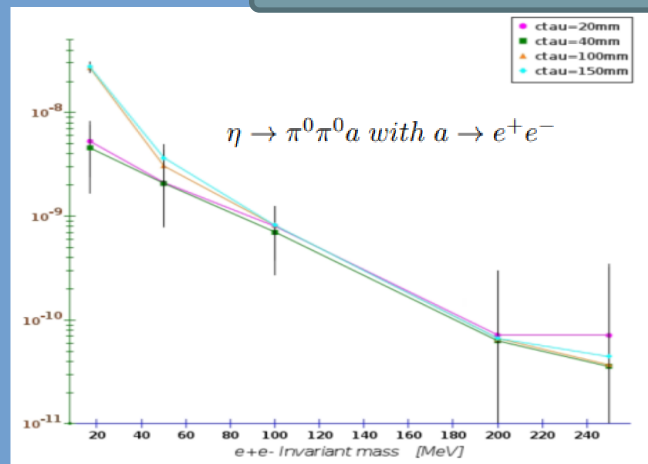
Pseudoscalar Portal: $\eta \to \pi^0 \pi^0 a$ & $\eta \to \pi^+ \pi^- a$ with $a \to \gamma\gamma$, $\mu^+ \mu^-$ and $e^+ e^-$

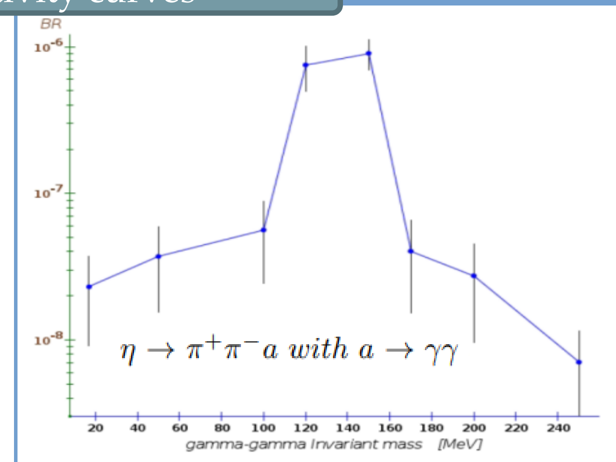
REDTOP

17 MeV piophobic QCD axion

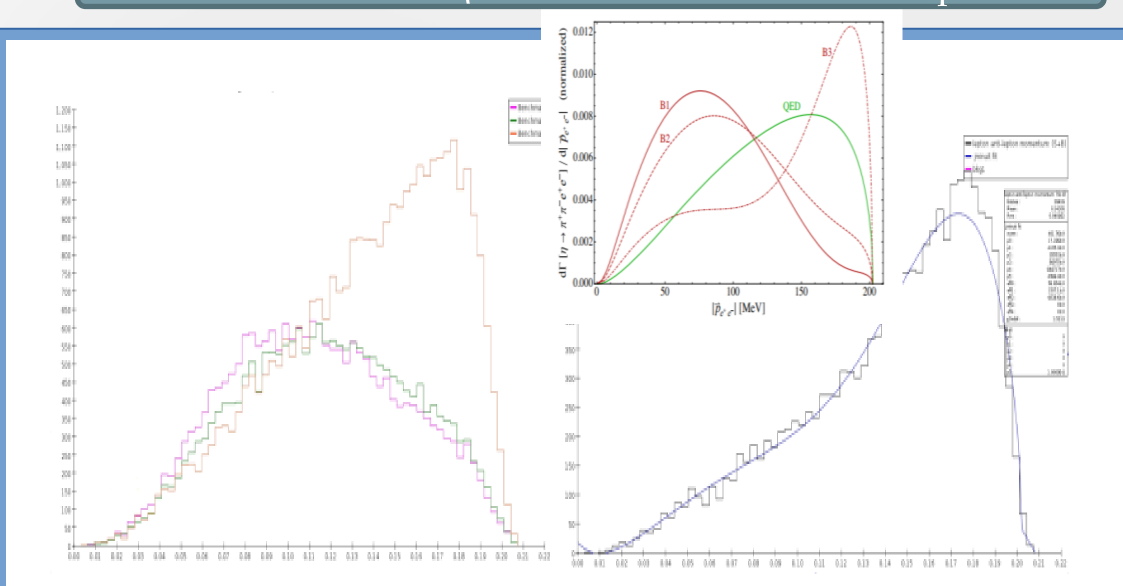


Some BR sensitivity curves





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



Theoretical models considered

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

New particles & forces

Heavy Neutral Lepton Portal: $\eta \to \pi^0 H$; $H \to \nu N_2$; $N_2 \to N_1 h_0$; $h_0 \to e^+e^-$

REDTOP

Model considered for Snowmass

- *Two-Higgs doublet model (W. Abdallah, R. Gandhi, and S. Roy) with the following benchmark parameters:*

m_{N_1}	m_{N_2}	m_{N_3}	$y^{h'}_{e(\mu)}\times 10^4$	$y^{H}_{e(\mu)}\times 10^4$
85 MeV	130 MeV	10 GeV	0.23(1.6)	2.29(15.9)
$m_{h'}$	m_H	$\sin\delta$	$y^{h'(H)}_{\nu_{12}}\times 10^3$	$\lambda^{h'(H)}_{N_{12}}\times 10^3$
17 MeV	250 MeV	0.1	1.25(12.4)	74.6(−7.5)

TABLE XXVIII. Benchmark parameters for REDTOP.

REDTOP sensitivity to model parameters

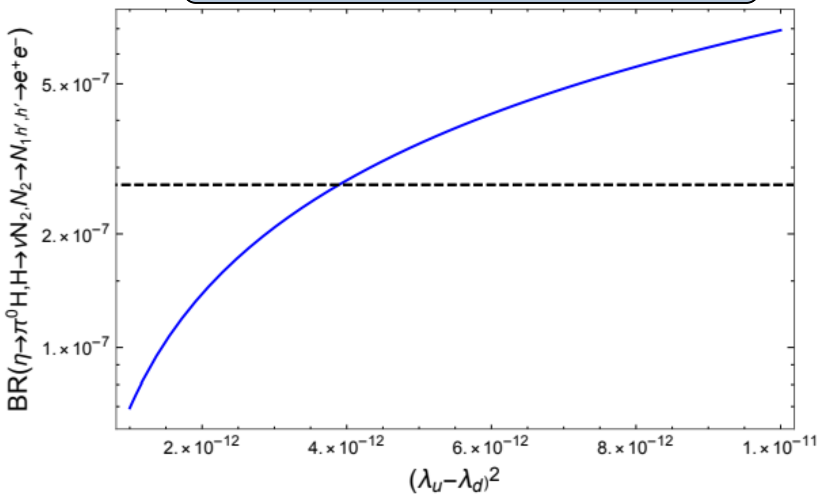


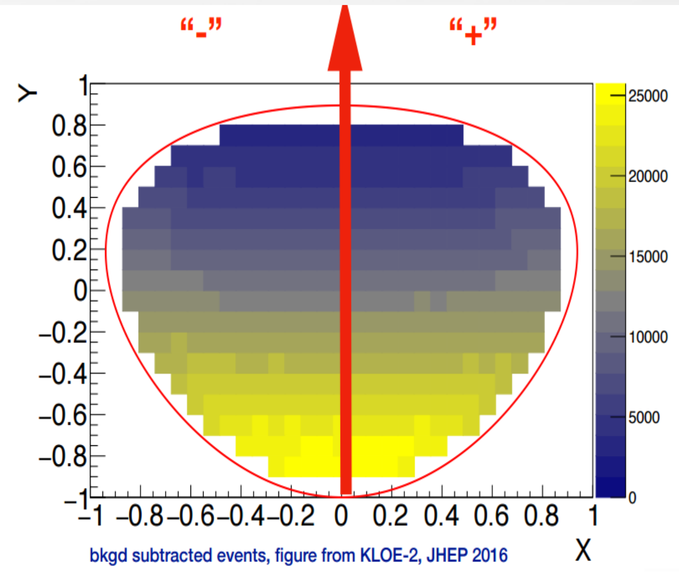
FIG. 61. Branching ratio for the process $\eta \to \pi^0 H$; $H \to \nu N_2$; $N_2 \to N_1 h'$; $h' \to e^+e^-$ predicted by the Two Higgs Doublet model [51] as a function of $(\lambda_u - \lambda_d)^2$. The dashed line corresponds to the experimental limit for REDTOP with an integrated luminosity of 3.3×10^{18} POT.

Test of discrete symmetries

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

REDTOP

- *CP-violation from this process is not bounded by EDM as is the case for the $\eta \rightarrow 4\pi$ process.*
- *Complementary to EDM searches even in the case of T and P odd observables, since the flavor structure of the eta is different from the nucleus*
- *Current PDG limits consistent with no asymmetry*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi) based on* https://arxiv.org/abs/1903.11617



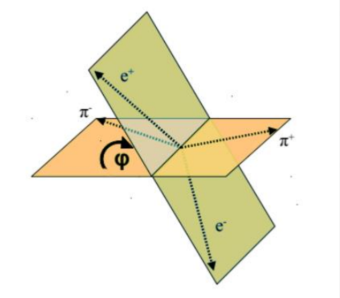
REDTOP sensitivity to model parameters

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

Physics analysis by A. Kupsc – Uni-Uppsala

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

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



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

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

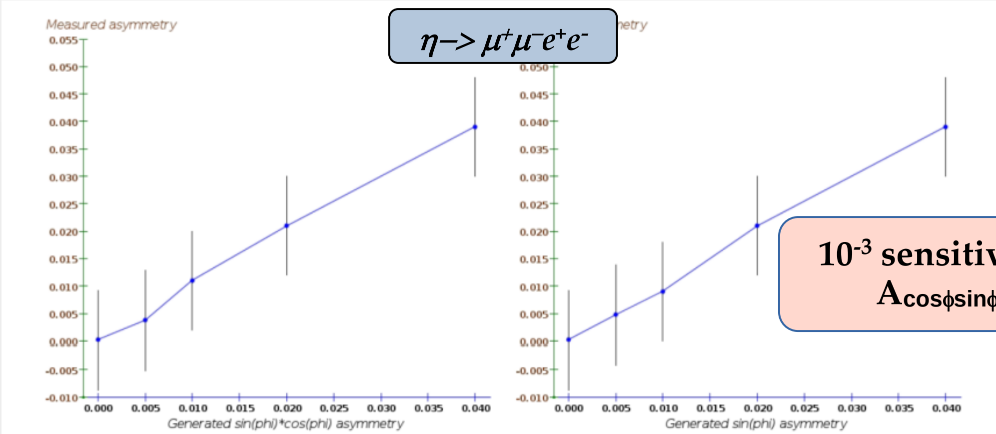
$$A_{sin\Phi} = \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)}$$

through Wilson coefficients

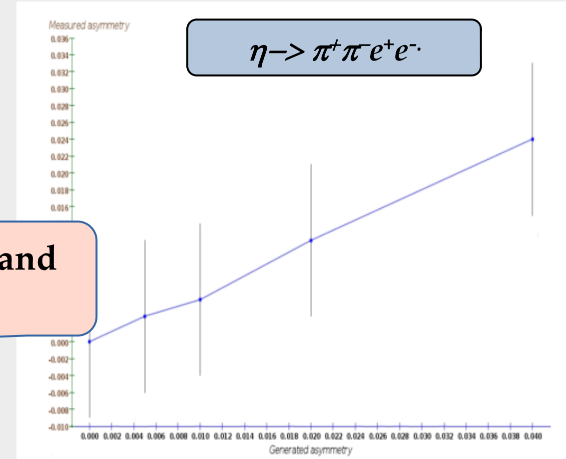
$$A_{\sin\phi\cos\phi} = \mathrm{Im}[1.9c^{2222}_{\ell edq} - 1.3(c^{(1)2211}_{\ell equ} + c^{1122}_{\ell edq})] \times 10^{-5} - 0.2\epsilon_1 + 0.0003\epsilon_2$$

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

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



$\eta \rightarrow \mu^+\mu^- e^+e^-$



$\eta \rightarrow \pi^+\pi^- e^+e^-$.

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

CP-violation from μ–polarization

CP Violation in $\eta \to (\gamma,\pi^0)\mu^+\mu^-$

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

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

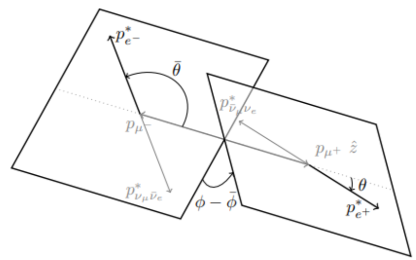


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar{\nu}$ system. The $\hat{z}$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

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

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

REDTOP sensitivity to Wilson CP violating Wilson coeffiecients

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

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

LF-universality

REDTOP

Lepton Universality Studies

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

$\eta \rightarrow \gamma \mu^+ \mu^-$ vs $\gamma e^+ e^-$

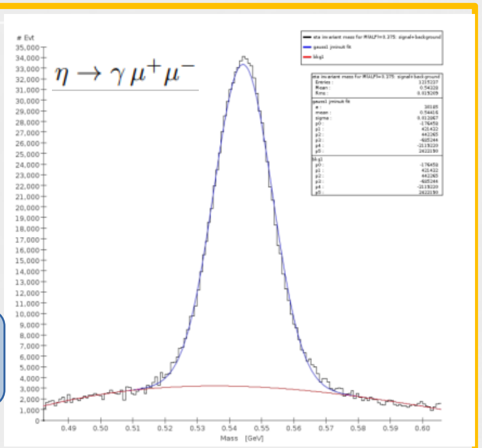
REDTOP statistical error for ~10^{11} POT

Process	POT	Signal events	Background events	$\frac{S}{\sqrt{B}}$	Statistical err
$\eta \rightarrow \gamma e^+e^-$	1.38×10^{11}	$.13 \times 10^6$	2.52×10^4	1.3×10^4	**0.09%**
$\eta \rightarrow \gamma \mu^+\mu^-$	1.38×10^{11}	$.84 \times 10^5$	6.5×10^3	3.5×10^3	**0.14%**

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

LHCb @ 4.2% with 1640 evts

LHCb @ 1.8% with 3850 evts



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

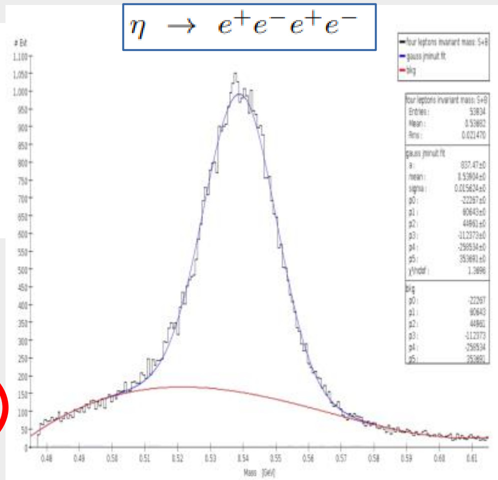
- *Theoretical calculations at the 10^{-3} precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018))*

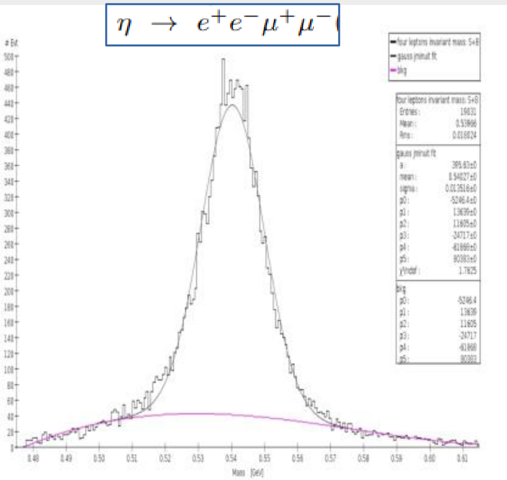
REDTOP reconstruction efficiency

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

REDTOP statistical error for various POT

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





Present & Future η Samples

REDTOP

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

REDTOP Running Modes for 10^{14} η mesons

REDTOP

Baseline option – medium-energy CW proton beam

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

vs LHCb@40 MHz

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

Preferred option – low-energy pion beam

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

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

Ultimate option: Tagged 10^{13} η mesons

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

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

REDTOP Running Modes for 10^{14} η mesons

REDTOP

vs LHCb@40 MHz

Baseline option – medium-energy CW proton beam

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

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

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

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

Preferred option – low-energy pion beam

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

Inelastic interaction rate: ~ ...1GHz
η/η′ production rate: ~ 2.3 MHz

Ultimate option: Tagged 10^{13} η mesons

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

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

Accelerator scheme for Run-I at FNAL (M. Syphers)

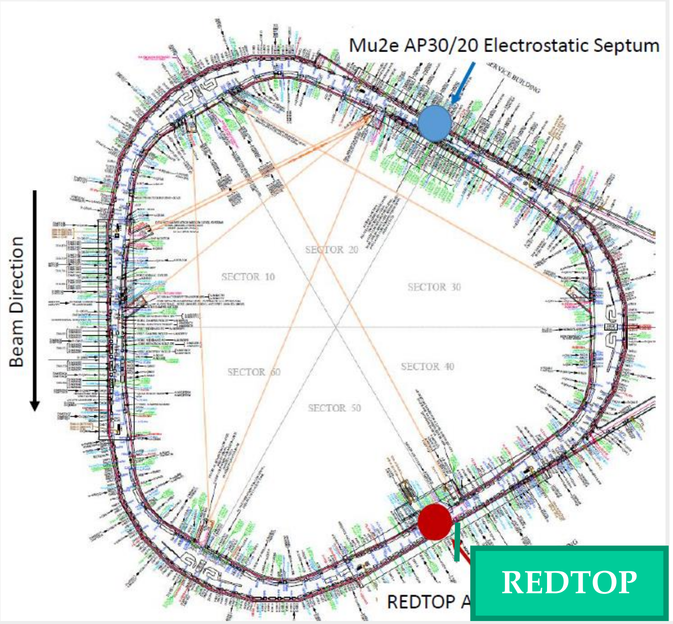
Single p pulse from booster (≤4x10^{12} p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)

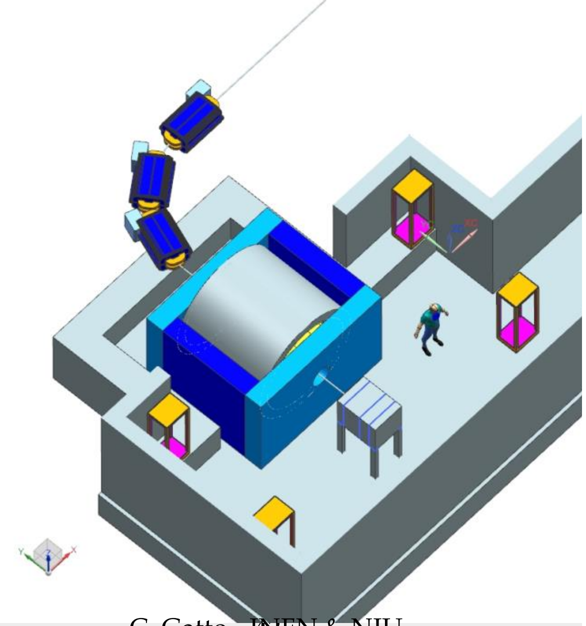
Energy is removed by inserting 1 or 2 RF cavities identical to the one already planned (~5 seconds)

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%





Beam Options at GSI/FAIR (near future)

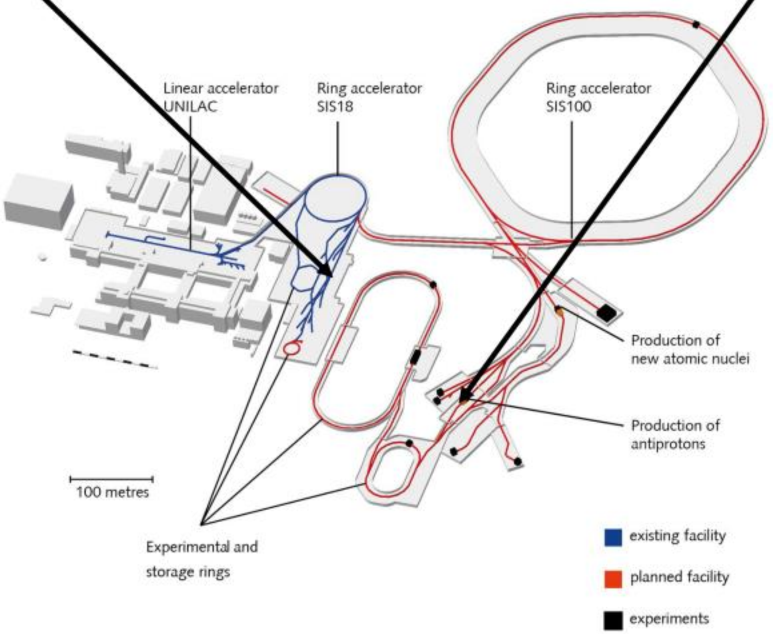
FAIR GSI

Opportunities as fixt target exp.

OPTION A
Fixt target (SIS18)

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

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



OPTION B
Fixt target (SIS100)

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

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

FAIR GmbH | GSI GmbH

Beam intensity: 1.8 GeV protons with 1e11/s

Daniel Severin

GSI option

Beam Options at GSI (far future)

REDTOP

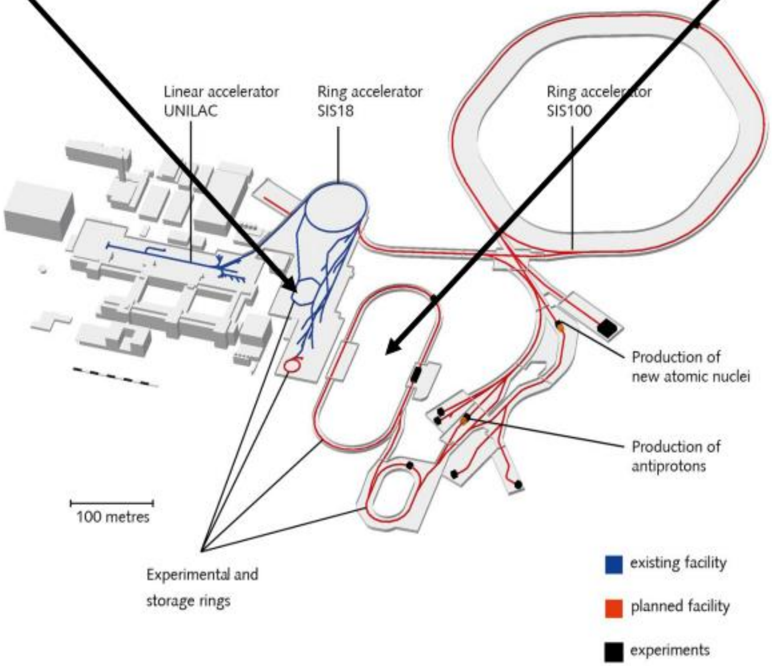
Opportunities as in-ring target exp.

FAIR GSI

OPTION C
ESR (SIS18)

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

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



OPTION D
HESR (SIS100)

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

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

FAIR GmbH | GSI GmbH

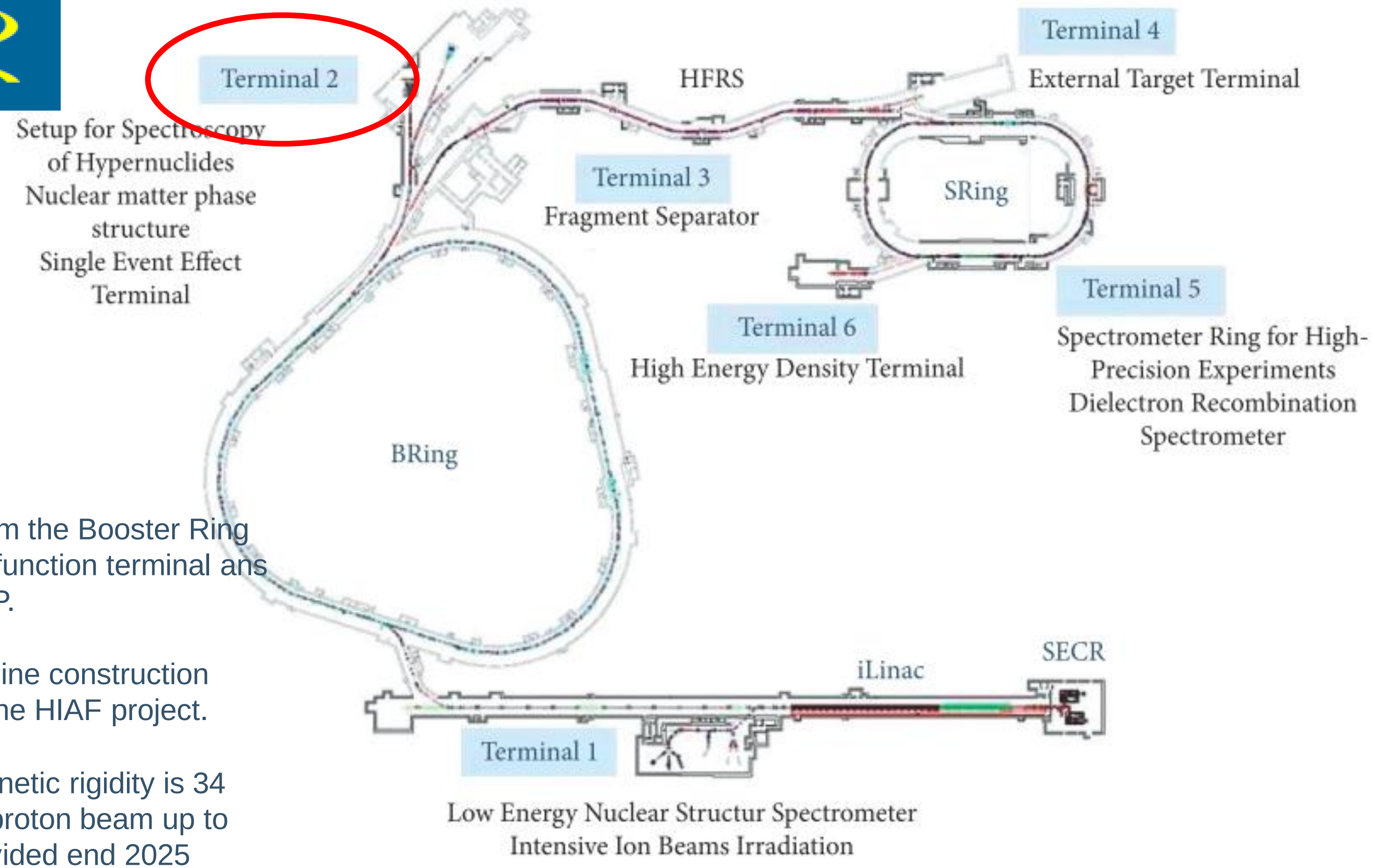
Beam intensity: 1.8 GeV protons with 1e11/s

Daniel Severin

Beam Options at HIAF (near future)

REDTOP

HIAF



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

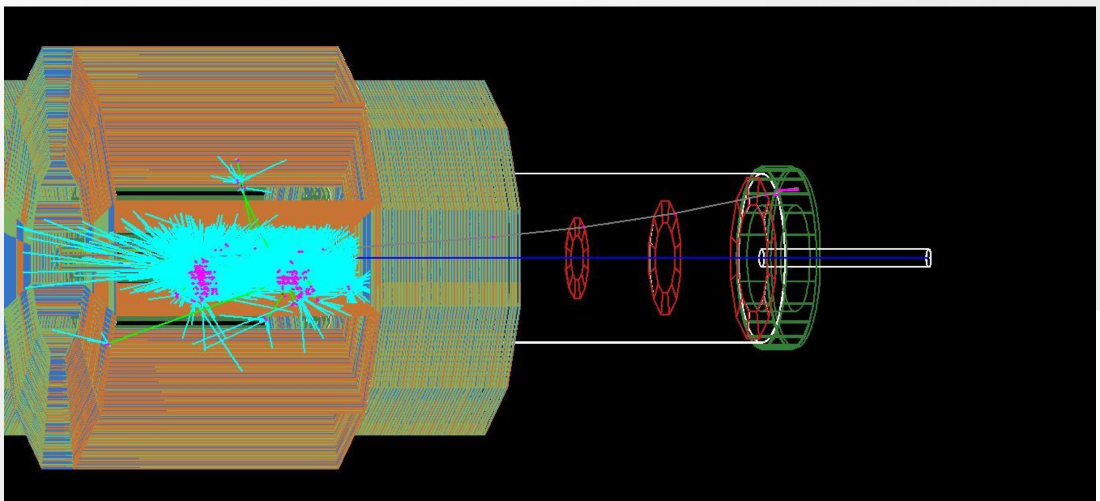
*Beam intensity: 0.5 ~1.0x10^{13} ppp (1~5*1x10^{13} pps) in Terminal 2 . $10^{(18-19)}$ POT /yr*
Energy from 2.0 to 9 GeV around 2028 – 2030
Plans are to combine REDTOP with an experiment on hypernuclei

REDTOP

Beam Options at ESS

Option #1: Tagged η–factory

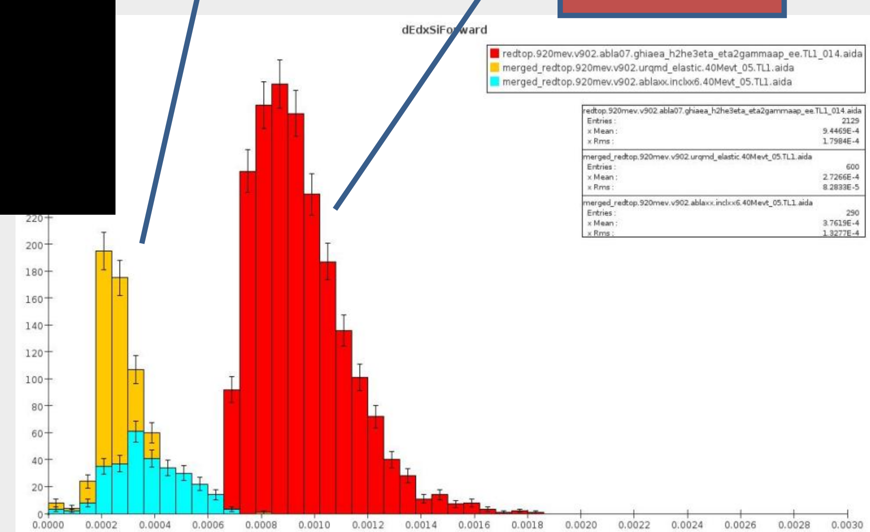
- *Fully tagged production from nuclear reaction: p+De → η +He₃⁺⁺*
- *η production cross sec: ~ μbarn; bkg cross sec: ~ 100 mbarn -> 5 orders of magnitude!*
- *Requires fwd tagging detector for He₃⁺⁺*
- *high intensity proton beam on De target: ~0.8-**0.9 GeV ; 0.1-1 MW***



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

background

η signal



Signal/background separation achievable with a properly designed fwd tagger and trigger

Beam Options at ESS

REDTOP

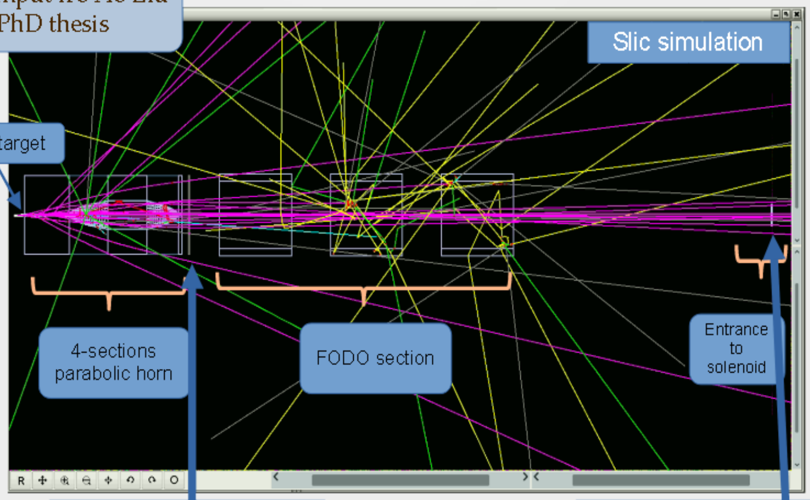
Option #2: Semi-tagged η–factory

- *Semi-tagged production from reactions:*
  - π^+ + Li/Be → η +X (large x-sec) → non-tagged
  - $\pi^+ + d \rightarrow \eta + p + p$ → 2p-tagged
  - $\pi^- + p \rightarrow \eta + n$ → neutron-tagged
  - $\pi^- + He_3 \rightarrow \eta + t$ → tritium tagged
- *η production xsec: ~ 10 mbarn; bkg cross sec: ~ 100 mbarn -> 1 order of magnitude!*
- *Requires pion beam ~750 MeV with >2.5x10^{10} πOT/sec*
- *Medium intensity proton beam on Ti or W target: ~1.3 GeV ; ~15 KW*

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

Pion beams with modified Longhin Magnetic Horn

With input fro Ao Liu PhD thesis



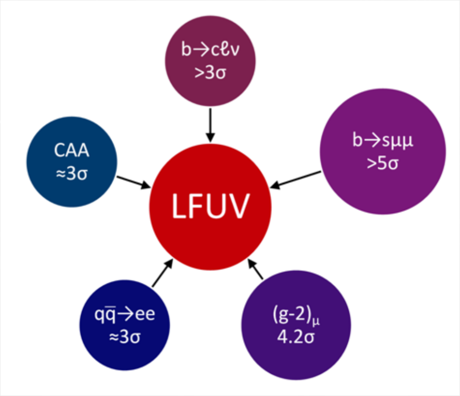
Longhin magnetic Horns are expensive.
With ESS beam power, LAMPF-style horns could be used
(see Patrik Simion thesis. Uni-Uppsala, 2019)

Detector Requirements: BSM physics driven

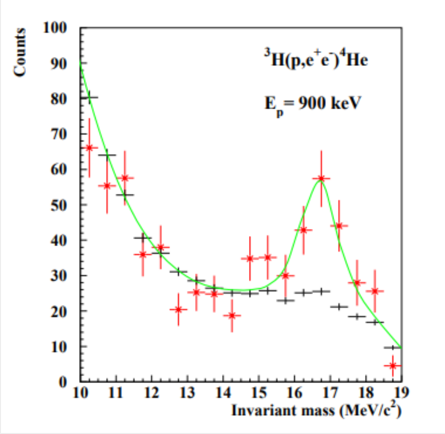
LFU: Tagged lepton production from flavor-conserving decays

- excellent e/π/μ separation

- *QCD axion*
  - *Calorimetric sensitivity to M(γγ)~30MeV*
- *17 MeV e^+e^- state (Atomki experiment)*
  - *Tracker sensitivity to $M(e^+e^-)$~ 20 MeV*
  - *Electron ID at very low energy*
- *CP violation with muons*
  - *Muon polarimeter or high-granularity calorimeter*
- *Sustain a 700 MHz event rate*
  - *New generation trigger*



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



Detector Requirements and Technology

REDTOP

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

charged tracks detection

LGAD Tracker

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

EM + Had calorimeter

- *ADRIANO2/3 calorimeter (T1041+T1604)*
- *Rear section with Fe absorber and Gd-doped RPC*
- *PFA + Dual-readout+HG*
- *96.5% coverage*

Vertex reconstruction

HV-MAPS (Mu3e style)

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

Cerenkov Threshold TOF

Option 1: Quartz tiles

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

Option 2: EIC-style LGAD

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

Detector Requirements and Technology

- *Sustain 0.7 GHz event rate with avg final state multiplicity of 8 particles*
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- *Low-mass vertex detector*
- *Near-4π detector acceptance (as the η/η' decay is almost at rest).*

All next generation detector technologies

charged tracks detection

LGAD Tracker

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

EM + had calorimeter

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

Vertex reconstruction

HV-MAPS (Mu3e style)

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

Cerenkov Threshold TOF

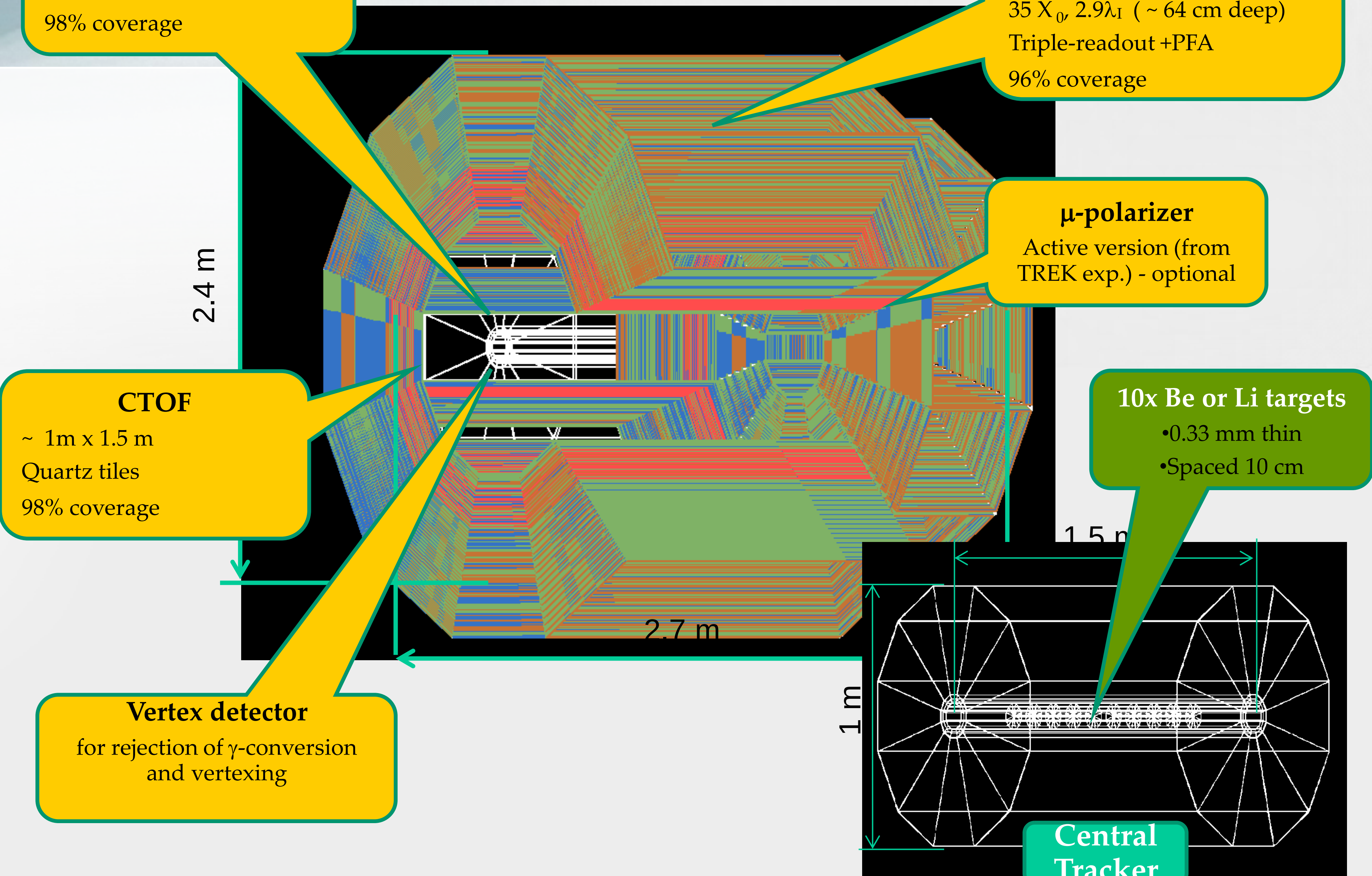
Option 1: Quartz tiles

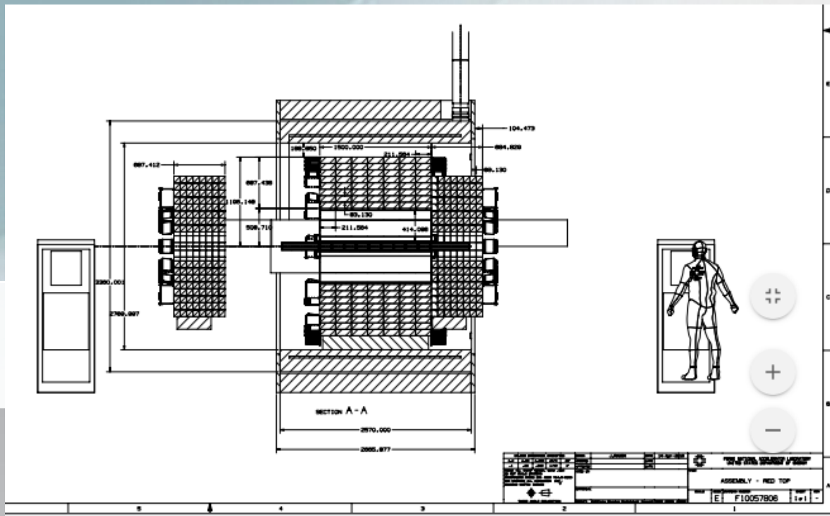
- *Established and low-cost technology*
- *~50psec timing with T1604 prototype*

Option 2: EIC-style LGAD

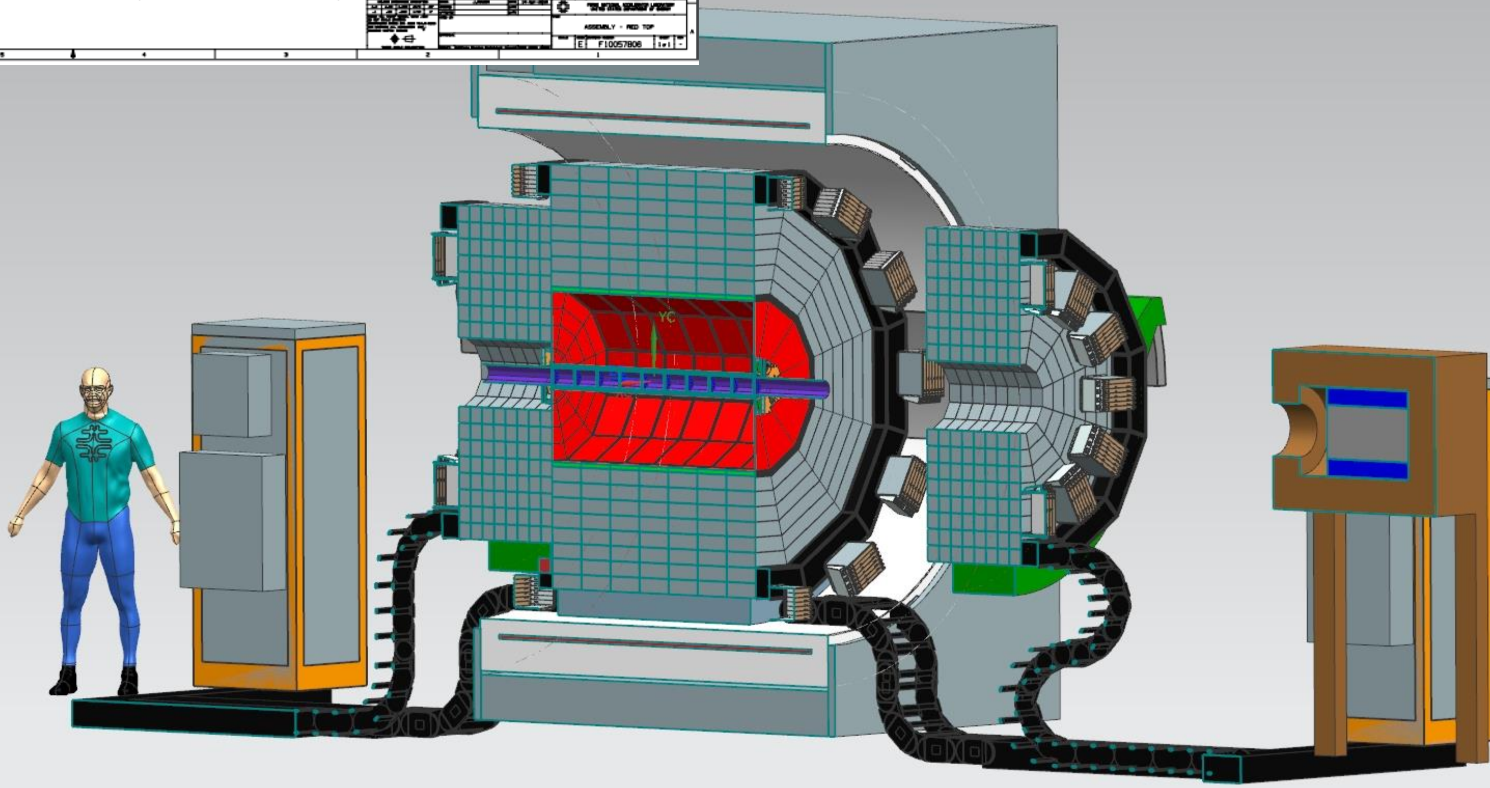
- *~30-40 psec timing, but expensive*

REDTOP detector



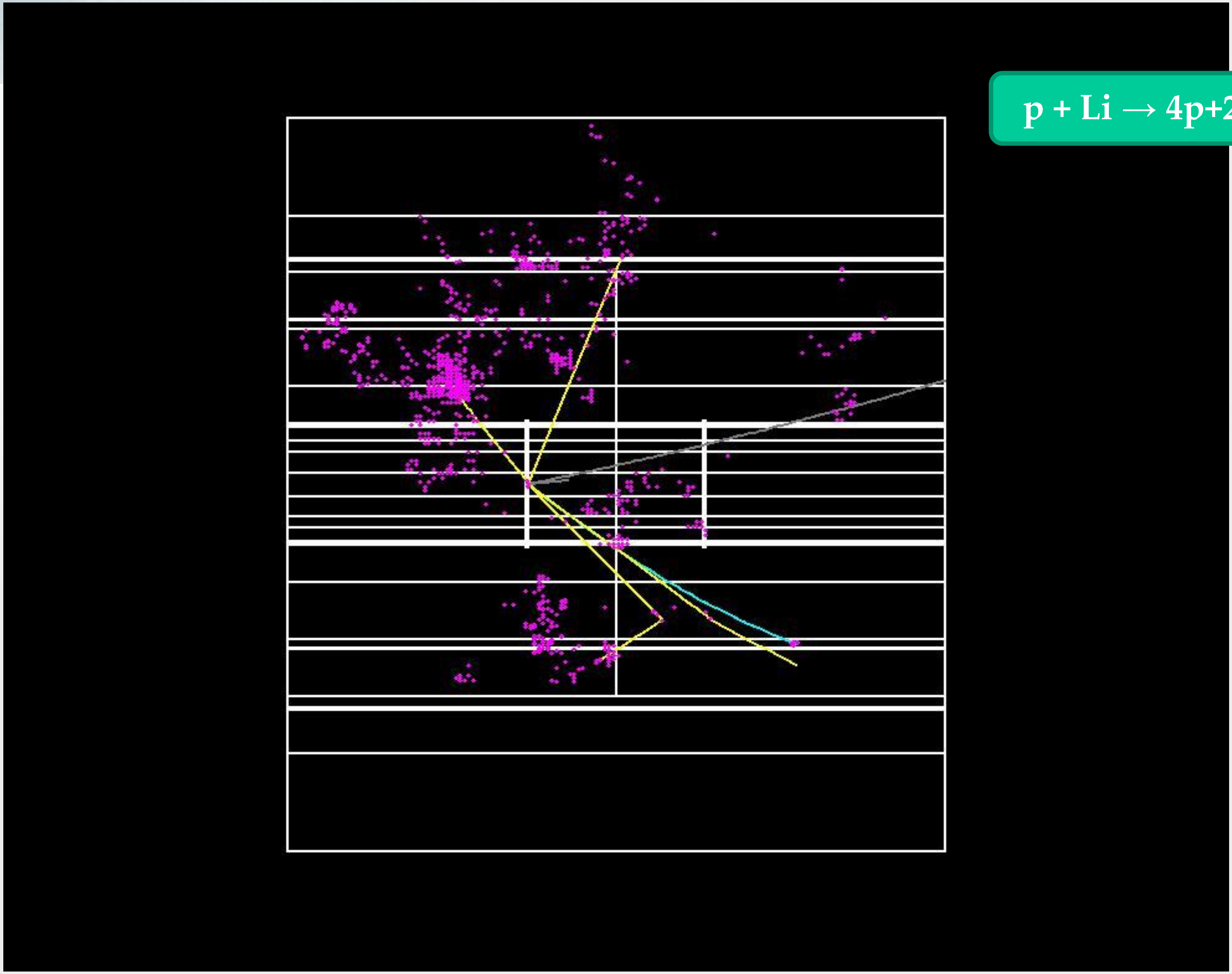


REDTOP Detector + Finuda Magnet



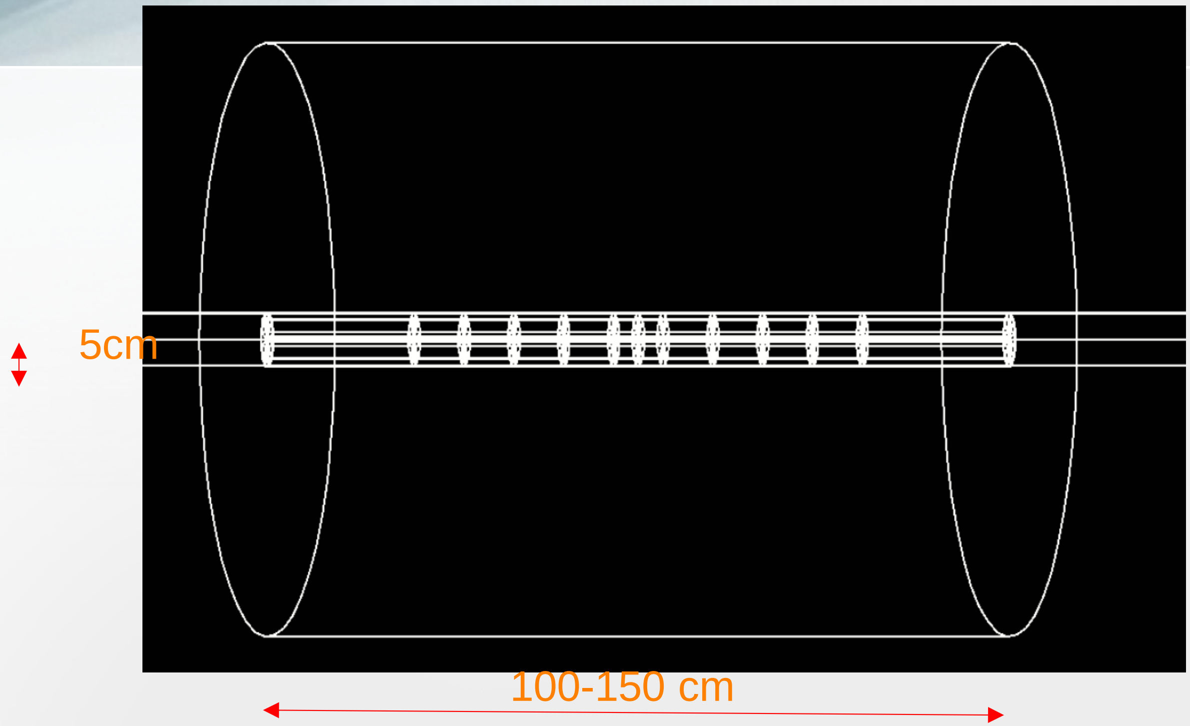
J. Kilmer – J. Rauch

Event Display @ 1.8 GeV



p + Li → 4p+2n+1π+ De

Target Systems



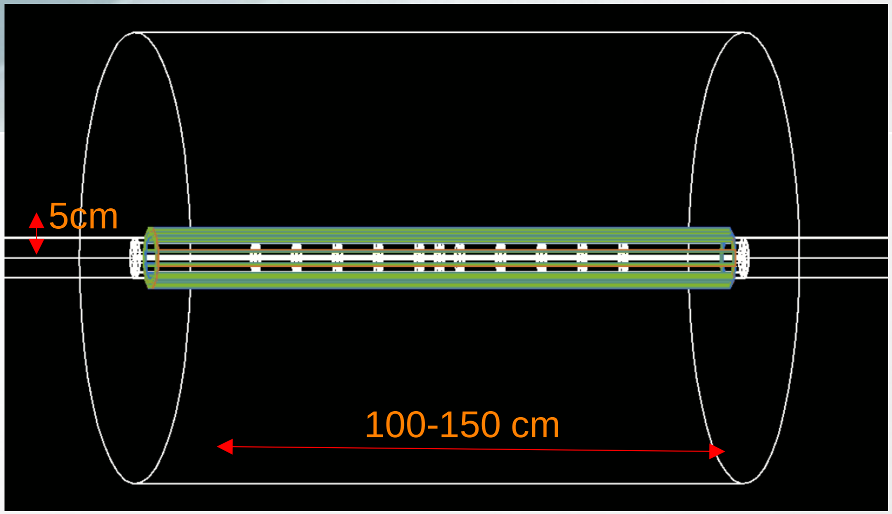
Target for p and π^+ beams: 10x 0.78 mm Li or Be foil

–For p and π^+ beams
–Inexpensive, but more background
–Untagged/semi-tagged η/η□ production

Target for π^- beams: : LH_2 (pellets or fluid)

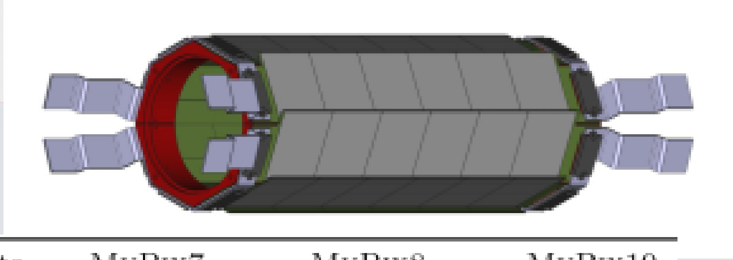
– For π^- beams only
– More expensive, but less background
– Tagged η/η□ production: π^- p→η/η□ n

Vertex Detector



Requirements

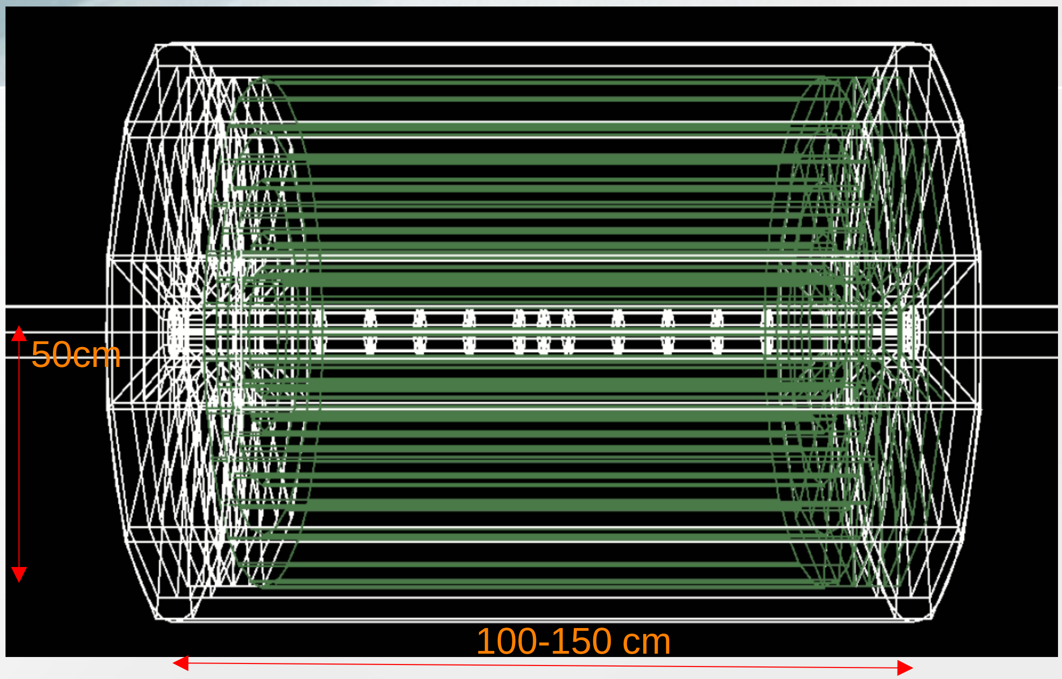
- <0.5% X0
- <=70μm vertex resolution in x-y.
- No active cooling
- Rad-hard ~5x10^5 1 MeV-neq n/cm2/sec
- Timing: ~10 nsec



MuPix10 (Mu3e vtx technology)

	Requirements	MuPix7	MuPix8	MuPix10
pixel size [μm^2]	80×80	103×80	81×80	80×80
sensor size [mm^2]	20×23	3.8×4.1	10.7×19.5	20.66×23.18
active area [mm^2]	20×20	3.2×3.2	10.3×16.0	20.48×20.00
active area [mm^2]	400	10.6	166	410
sensor thinned to thickness [μm]	50	50, 63, 75	63, 100	50, 100
LVDS links	$3+1$	1	$3+1$	$3+1$
maximum bandwidth§ [Gbit/s]	3×1.6	1×1.6	3×1.6	3×1.6
timestamp clock [MHz]	≥ 50	62.5	125	625
RMS of spatial resolution [μm]	≤ 30	≤ 30	≤ 30	≤ 30
power consumption [mW/cm^2]	≤ 350	$\approx 300^{\dagger}$	$250-300$	≈ 200
time resolution per pixel [ns]	≤ 20	≈ 14	≈ 13 (6^*)	not meas.‡
efficiency at 20 Hz/pix noise [%]	≥ 99	99.9	99.9	99.9
noise rate at 99 % efficiency [Hz/pix]	≤ 20	< 10	< 1	< 1

LGAD Tracker



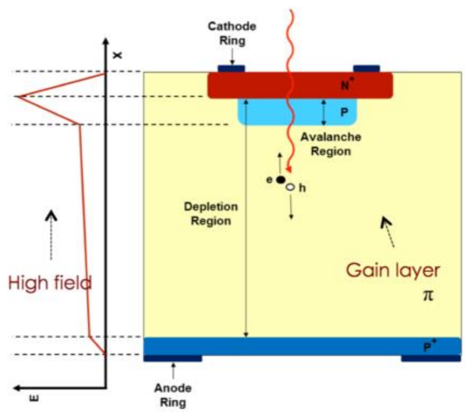
Requirements

- *<1% X0*
- *30 psec timing resolution.*
- *No active cooling*
- *Rad-hard ~1x10^5 1 MeV-neq n/cm2/sec*
-

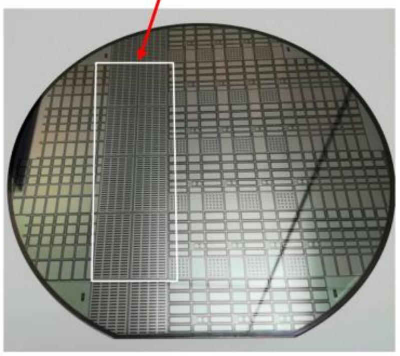
Adaptation of CMS's ETL

- –REDTOP vs CMS' ETL: 87.5% area
- –use pixel upgrade for the mechanics
- –5-layer barrel
- –4-layer endcaps
- –SID layout

- Demonstrated time resolution ~30 ps up to 1x10^{15} n_{eq}/cm^2, and about 40 psec up to 2x10^{15} n_{eq}/cm^2

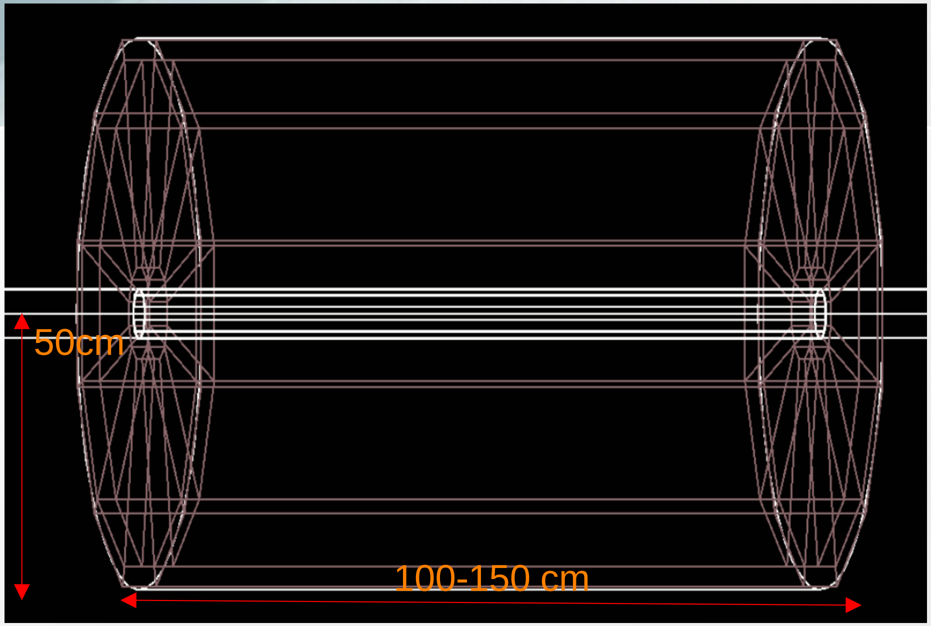


CMS-designed 96-channel sensors



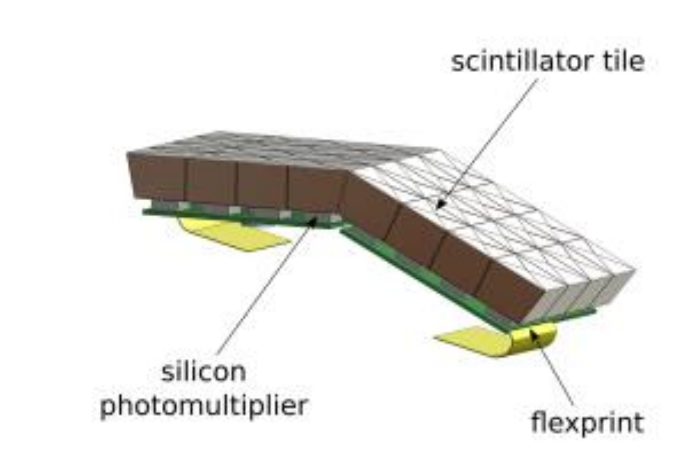
FBK wafer with CMS- and ATLAS- sensors

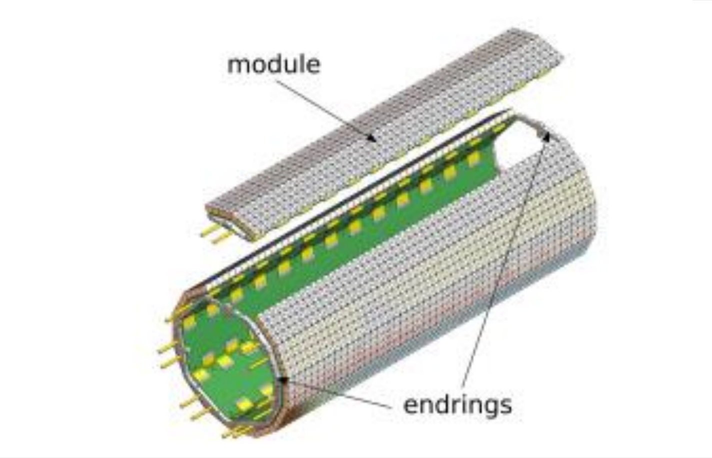
Threshold Cerenkov - TOF



Requirements

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





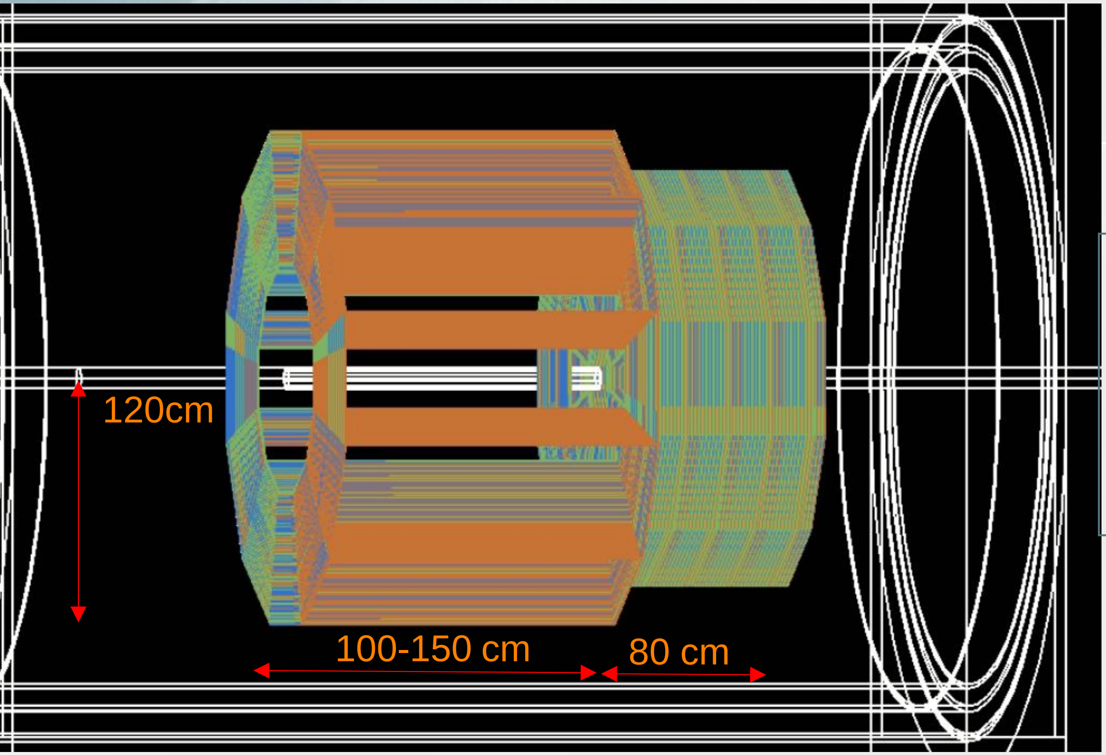
Option 1: Small tiles of JGS1 & on-tile SiPM

- Different options: #layers and tile size
- Similar technologies: CMS' BTL (lyso) and Mu3e tile detector (scint. plastics)
- Well established TOFHIR2 Asic (LIP)

Option 2: LGAD

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

CALORIMETERS



Requirements

- $\sigma_E/E \sim 2\text{-}3\%/\sqrt{E}$
- ~80 psec/cell timing resolution for MIPs.
- No active cooling
- Rad-hard ~5×10^4 1 MeV-neq n/cm2/sec

EM: dual-readout ADRIANO2

- Inner section: Pb-glass and scint. Tiles interleaved
- 10 layers – 6.6 X0 / 0.55 λ_I
- 120,00 tile-pairs
- Same plastic tiles as CMS' HGCAL
- FEE from Weeroc+Omega (costing being discussed) or TOFPET2

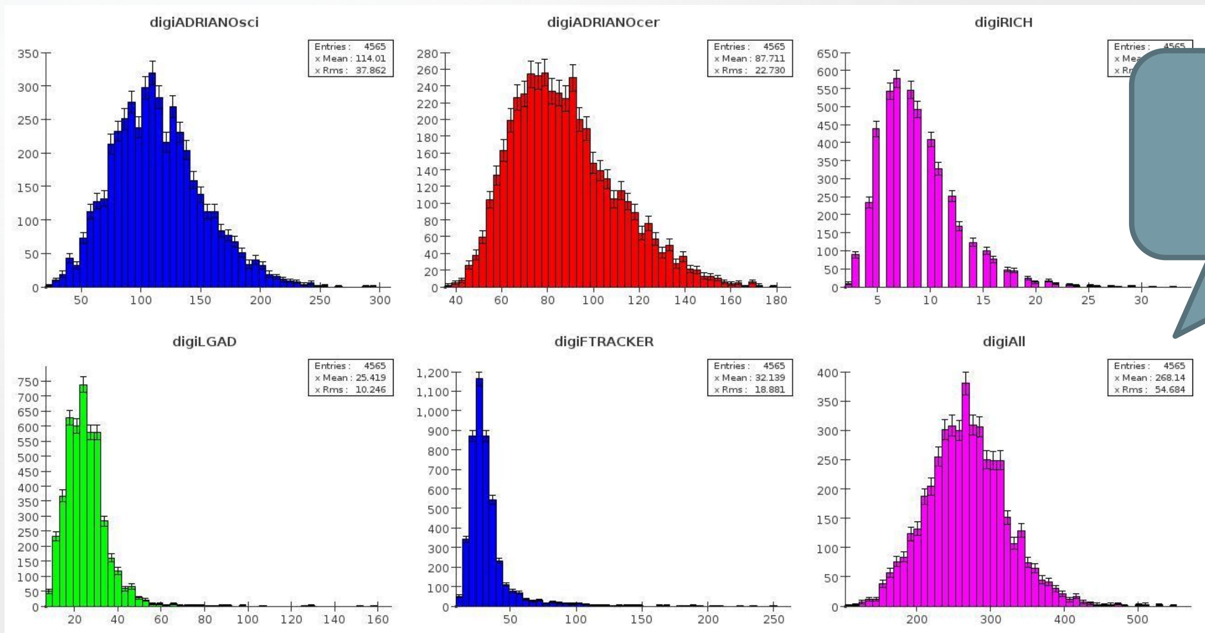
HAD: triple-readout ADRIANO3

- Outer section: Pb-glass + scint. + thin RPC + Fe
- 25 layers – 22 X0 / 2.7 λ_I
- Longer λ_I for better hadron shower containement
- 390,00 tile-pairs
- Heatsink: pyrolitic foil

REDTOP Trigger Requirement

Untagged 10^{14} η/η' mesons

Hits from subdetectors



Total channel occupancy:
270 ± 50 /evt

18x LHCb

Trigger rejection factors

Trigger stage	Input event rate Hz	Event size bytes	Input data rate bytes/s	Event rejection
Level 0	$7. \times 10^8$	1.4×10^3	9.8×10^{11}	$\sim$4.6
Level 1	1.5×10^8	1.5×10^3	2.3×10^{11}	$\sim$60
Level 2	2.5×10^6	1.5×10^3	3.8×10^9	$\sim$4.5
Storage	0.56×10^6	1.6×10^3	0.9×10^9	

Hardware

Software

Cost estimate

Preliminary 2023

REDTOP

- 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 (White paper)	GSI option	Expensive option
Target+beam pipe	0.5	**0.1**	0.9
Vtx detector	0.93	**2.1**	25.4
LGAD tracker	18.5	**22.5**	19.6
CTOF	0.6	**0.75**	3.0
ADRIANO2	47.7	**22.5**	47.7
Solenoid	0.2	**0.3**	0.2
Supporting structure	1.3	**1.3**	1.3
Trigger	1.3	**2.4**	5
DAQ	1.1	**1.1**	5
Computing	0.4	**0.4**	0.4
Total	**69.7**	**54.8**	**101.8**
Contingency 50%	34.9	**26.7**	50.9
Grand total	**104.6**	**80.2**	**152.7**

REDTOP Collaboration

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

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

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

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

D. Winn
Fairfield University, (USA)

A. Alqahtani
Georgetown University, (USA)

W. Abdallah
Cairo University, Cairo (Egypt)

A. Kotwal
Duke University, (USA)

M. Spannowski
Durham University, (UK)

A. Liu
Euclid Techlabs, (USA)

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

Fermi National Accelerator Laboratory, (USA)

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

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

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

E. Passamar
Indiana University (USA)

P. Sanchez-Puertas
IFAE – Barcelona (Spain)

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

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

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

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

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

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

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

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

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

A. Ismail
Oklahoma State University, (USA)

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

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

Y. Kahn
Princeton University – Princeton, (USA)

D. McKeen
TRIUMF (Canada)

Z. Ye
Tsinghua University, (China)

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

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

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

J. Jaeckel
Universität Heidelberg, (Germany)

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

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

L. E. Marcucci[4]
Universita' di Pisa, (Italy)

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

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

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

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

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

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

J. Konisberg
University of Florida, (USA)

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

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

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

Y. Onel
University of Iowa, (USA)

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

M. Pospelov
University of Minnesota, (USA)

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

K. Maamari
University of Southern California (USA)

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

B. Fabela-Enriquez
Vanderbilt University, (USA)

S. Tulin
York University, (Canada)

15 Countries
58 Institutions
127 Collaborators

Future Prospects for REDTOP

REDTOP

Physics case presented in White Paper and Snowmass Summer Meeting (July 2022)

- Sensitivity to 15 processes fully simulated and reconstructed
- 20 theoretical models benchmarked

Baseline detector layout defined

- Sensitivity studies helped to consolidate the detector requirements
- Muon polarimeter requires further studies

LOI submitted to GSI (November 2023)

- Should know the outcome in June 2024
- Sensitivity studies to GSI detector are ongoing

Next steps:

- Explore other laboratories (in particular, the ESS and HIAF)
- Prepare the CDR to support the proposal of the experiment
- Continue the BSM sensitivity studies (New MC campaign started – 5×10^{10} SM events)
- Strengthen the collaboration and the detector R&D
- Broad nuclear and intermediate physics program available to new groups

What about REDTOP at the ESS

- *Sweden has put a large investment into the ESS*
- *At present, the facility is ~100% utilized for Material Science research*
- *New HEP initiatives started by Swedish Universities would be welcomed by Funding Agencies in Sweden.*
- *REDTOP could be one of such initiatives*
- *Good coordination between Swedish Universities is necessary (Uppsala, Lund, etc.)*

Conclusions

- *Next 10-20 years will bring crucial discoveries in HEP*
- *All meson factories: LHCb, B-factories, Dafne, J/psi factories - have produced a broad spectrum of nice physics*
- *The η/η' meson is a excellent laboratory for studying rare processes and physics BSM at a lower mass scale and LCDM searches*
- *REDTOP only experiment (with SHIP) sensitive to four DM portals*
- *New detector techniques for next generation precision experiments*
- *Beam requirements could be met by labs in US, Europe, and Asia*
- *Strong competition mounting from China (HIAF)*
- *Simulation machinery ready for high-level studies/optimization*

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

also https://redtop.fnal.gov/wp-content/uploads/2023/09/REDTOP_LOI_2023-4.pdf

Backup slides

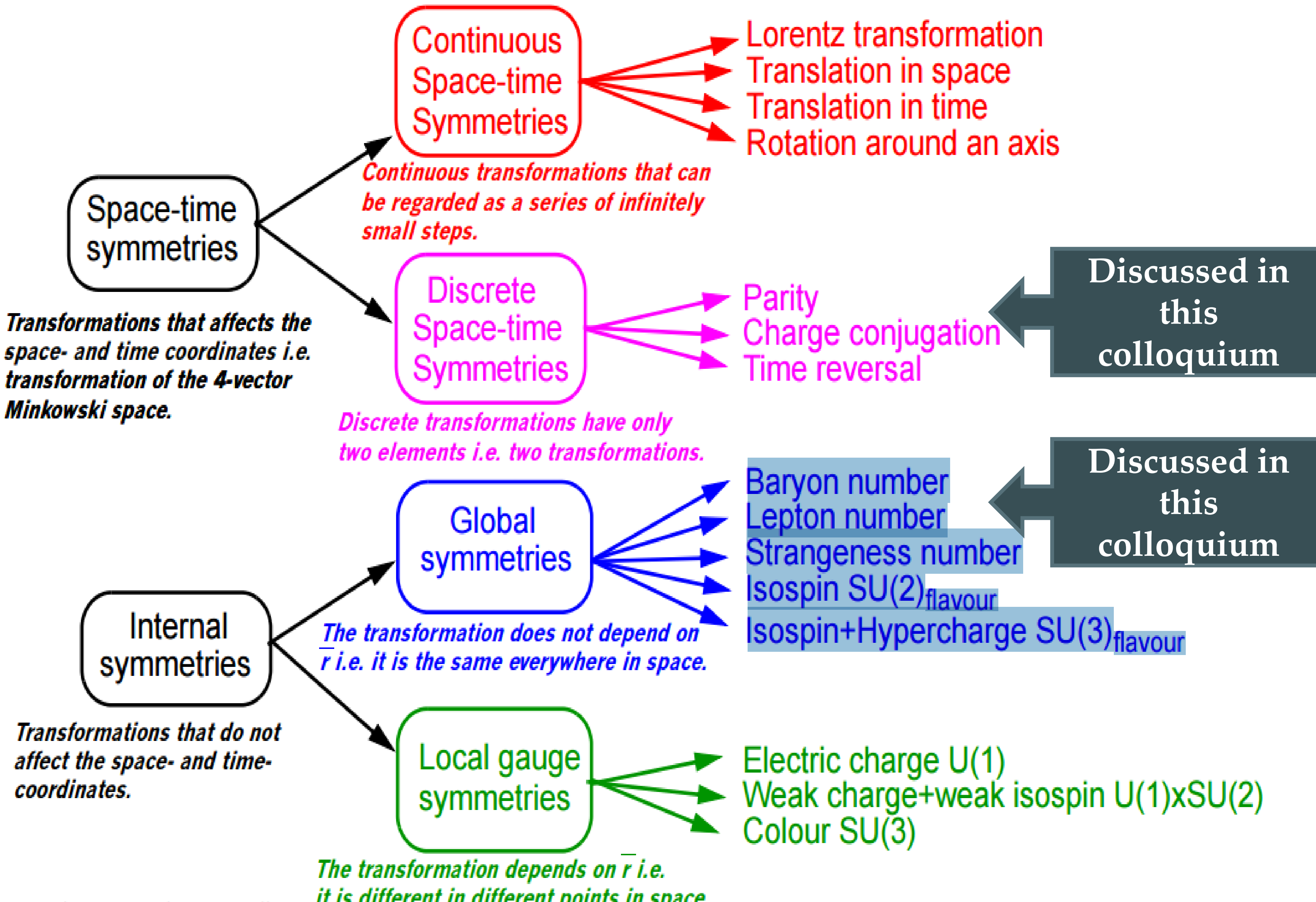
Importance of symmetries in the universe

- If the universe was not (mostly) symmetric then its laws would be different from one place or time to another (not very elegant!)

- Existence of symmetries implies that there is a framework of predictability in the Universe independent of initial conditions of space, rotation, and time

- A perfectly symmetric universe would be very different from ours (hint: life could not even exist)

Symmetries Classification



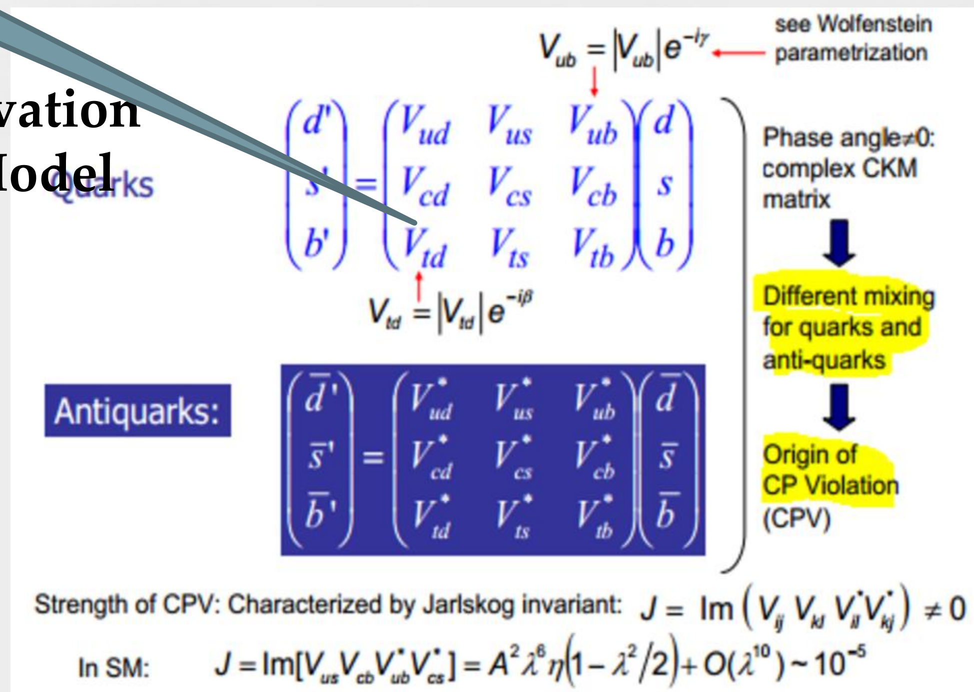
Discrete Space-time Symmetries of the Standard Model

- In the Standard Model, CP violation is described by a unique physical phase in the CKM quark mixing matrix

CP violating phase

Symmetry conservation in the Standard Model

Forces	P	C	CP	T	CPT
Gravity	√	√	√	√	√
Electromagnetic	√	√	√	√	√
Strong	√	√	√	√	√
Weak	×	×	×	×	√



Baryon & Lepton Numbers in the Standard Model

- Empirical observations indicate that the number of baryons (fermions with masses ≥ the M_{proton}) minus the number of antibaryons is conserved
- Therefore, we define a "***baryon number***": B ≡ (# baryons) - (# antibaryons) as a conserved quantity
- The same has been assumed to be true for Leptons

Particle	Symbol	Antiparticle	Baryon Number	Strangeness Number	Mass (MeV/C^2)
Proton	p	$\overline{p}$	1	0	938.3
Neutron	n	$\overline{n}$	1	0	939.6
Sigma	Σ^+	Σ^-	1	-1	1189
	Σ^0	Σ^0	1	-1	1193
	Σ^-	Σ^+	1	-1	1197
Xi	Ξ^0	Ξ^0	1	-2	1315
	Ξ^-	Ξ^+	1	-2	1321
Lambda	Λ^0	$\overline{\Lambda^0}$	1	-1	1116
Omega	Ω^-	Ω^+	1	-3	1672

Baryon & Lepton Number Symmetries of the Standard Model

- In any process, the total lepton and baryon number before and after is the same.
- This is the consequence of two global, continuous, gauge symmetries of the SM interactions
- Conservation of B and L means that protons and electrons don't decay (so matter is stable) and baryons don't mix with leptons.

Example: Antimuon decaying into a positron, muon antineutrino and electron neutrino

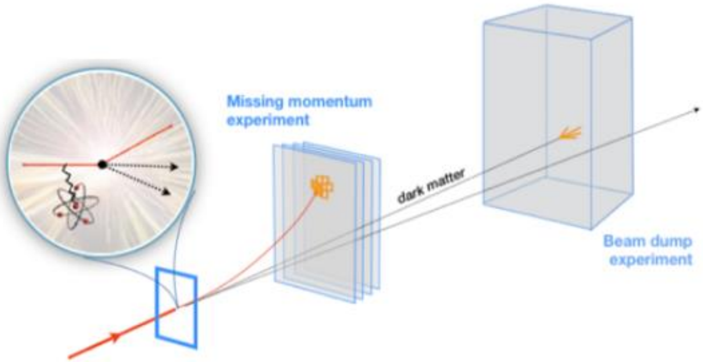
$$\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e$$

Table 1 *The decay of the antimuon (interaction is weak)*

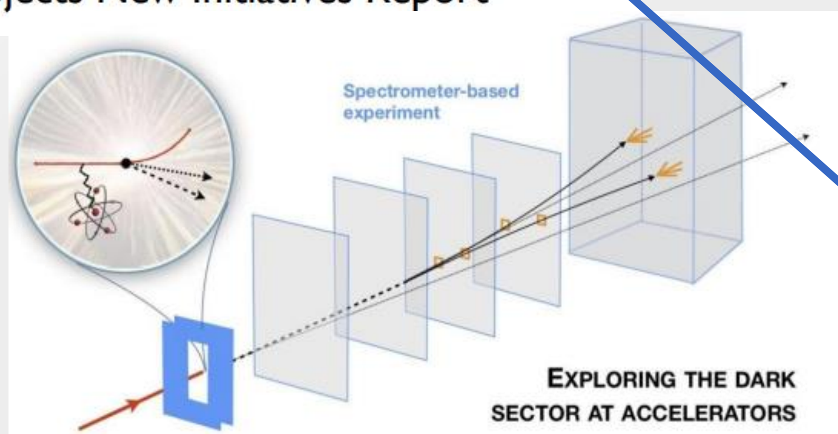
	μ^+	e^+	ν_e	$\bar{\nu}_\mu$
charge	+1	+1	0	0
muon lepton number	−1	0	0	−1
electron lepton number	0	−1	+1	0

Experimental Techniques

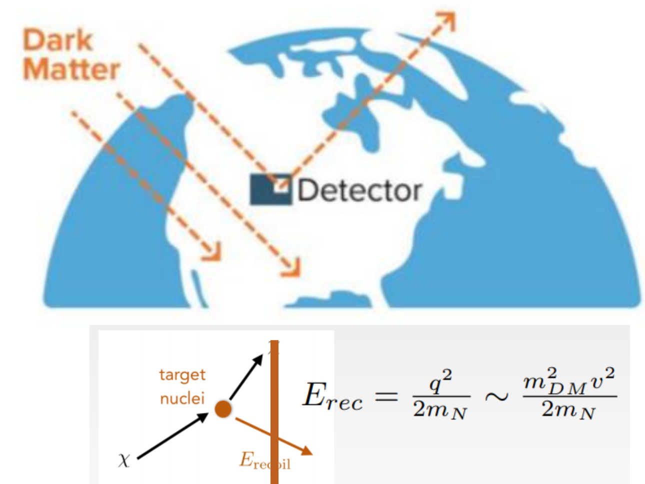
Accelerators

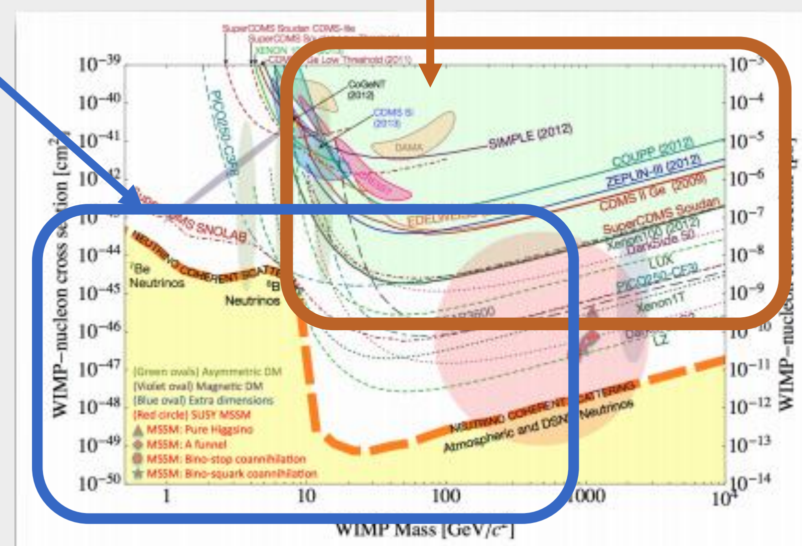


From Dark Matter Small Projects New Initiatives Report



Direct Detection





Complementary approach

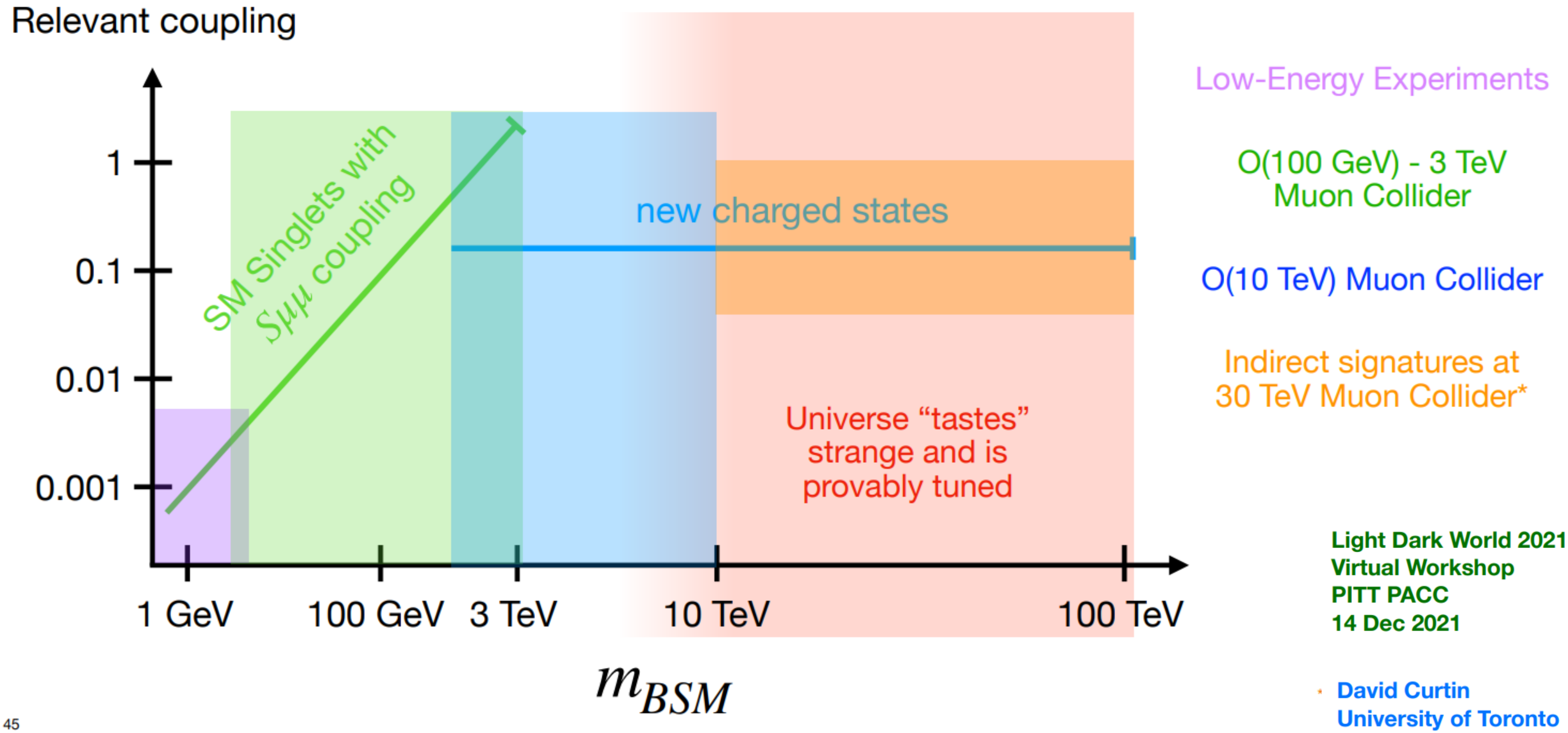
Both are required for a full understanding of the structure of the dark sector

$(g\text{-}2)_\mu$ Driven Paradigm of Physics BSM

Model-agnostic theorem based on very general assumptions (unitarity, naturalness, Minimal Flavour Violation, etc.)

–**New Physics is a SM singlet, with mass <GeV→ low energy experiments**

–**New Physics is a SM charged doublet, with mass 10 – 100 TeV→ >20 TeV collider**



Why the η meson is special?

REDTOP

- It is a Goldstone boson → Symmetry constrains its QCD dynamics
- It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^{-+}$ → It can be used to test C and CP invariance.
- All its additive quantum numbers are zero: $Q = I = j = S = B = L = 0$ → Its decays are not influenced by a change of flavor (as in K decays) and violations are "pure"
- All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.
- EM decays are forbidden in lowest order by C invariance and angular momentum conservation

→ It is a very narrow state (Γ_η=1.3 KeV vs Γ_ρ=149 MeV)

Contributions from higher orders are enhanced by a factor of ~100,000

Excellent for testing invariances

- The η decays are flavor-conserving reactions → Decays are free of SM backgrounds for physics search

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

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

See: https://arxiv.org/pdf/2203.07651.pdf

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

REDTOP

CP Violation in $\eta \to \gamma\mu^+\mu^-$

- *From model: P. Sanchez-Puertas, JHEP 01, 031 (2019), 1810.13228.*
- *Requires the measurement of μ–polarization to form the following asymmetries*

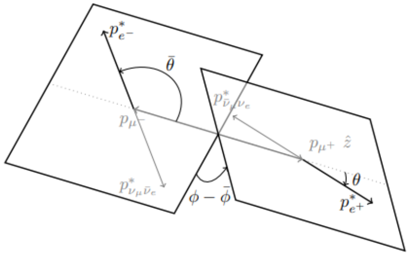


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar{\nu}$ system. The $\hat{z}$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

$$A_L^{\eta\to\pi^0\mu^+\mu^-} = -0.19(6)\,\mathrm{Im}\,c^{(1)2211}_{\ell equ} - 0.19(6)\,\mathrm{Im}\,c^{2211}_{\ell edq} - 0.020(9)\,\mathrm{Im}\,c^{2222}_{\ell edq}\,,$$

$$A_\times^{\eta\to\pi^0\mu^+\mu^-} = 0.07(2)\,\mathrm{Im}\,c^{(1)2211}_{\ell equ} + 0.07(2)\,\mathrm{Im}\,c^{2211}_{\ell edq} + 7(3)\times 10^{-3}\,\mathrm{Im}\,c^{2222}_{\ell edq}$$

REDTOP sensitivity to Wilson CP violating Wilson coeffiecients

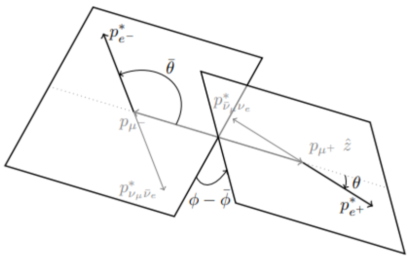
Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction + analysis*	**Total**	Branching ratio sensitivity
$\eta \to \gamma\mu^+\mu^-$	80.6%	64.6%	94.3%	92.9%	45.6%	$1.93 \times 10^{-9} \pm 0.9 \times 10^{-11}$
Urqmd	21.7%	1.7%	22.2%	4.7×10^{-3}%	4.7×10^{-6}%	-

$$\Delta(c^{1122}_{\ell equ}) = 2.6, \quad \Delta(c^{1122}_{\ell edq}) = 2.6, \quad \Delta(c^{2222}_{\ell edq}) = 1.7.$$

REDTOP

CP Violation in $\eta \to \pi^0 \mu^+ \mu^-$

- *From model: R. Escribano, et. al., JHEP 05 (2022) 147.*
- *Requires the measurement of μ–polarization to form the following asymmetries*



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$$A_\times^{\eta\to\pi^0\mu^+\mu^-} = 0.07(2)\,\mathrm{Im}\,c^{(1)2211}_{\ell equ} + 0.07(2)\,\mathrm{Im}\,c^{2211}_{\ell edq} + 7(3)\times 10^{-3}\,\mathrm{Im}\,c^{2222}_{\ell edq}$$

REDTOP sensitivity to Wilson CP violating Wilson coeffiecients

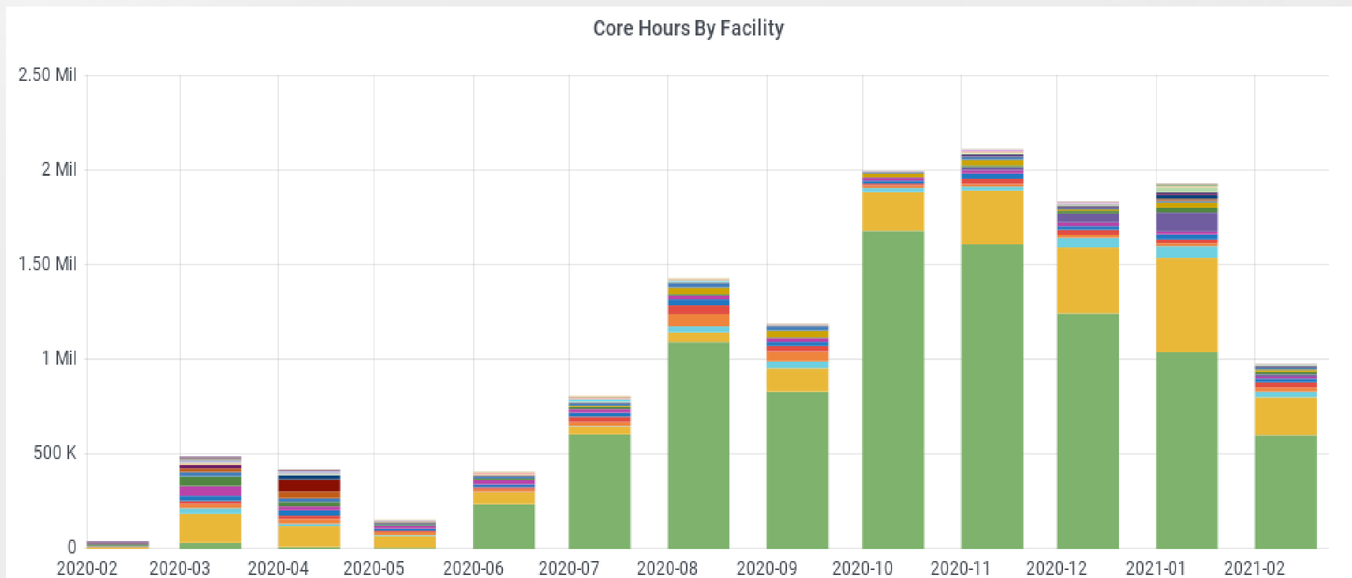
Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction + analysis*	**Total**	Branching ratio sensitivity
$\eta \to \pi^0\mu^+\mu^-$	64.1%	36.7%	91.4%	73.2%	15.7%	$9.4\times10^{-9} \pm 1.3\times10^{-10}$
Urqmd	21.7%	1.7%	22.2%	1.6×10^{-2}%	1.3×10^{-5}%	-

$$\Delta(c^{1122}_{\ell equ}) = 21, \quad \Delta(c^{1122}_{\ell edq}) = 21, \quad \Delta(c^{2222}_{\ell edq}) = 200.$$

REDTOP OSG Yearly Usage Statistics

	total
SU ITS	9 Mil
MWT2 ATLAS UC	2 Mil
GLOW	303 K
TCNJ - ELSA	293 K
FSU_HNPGRID	267 K
BNL ATLAS Tier1	264 K
UConn-OSG	250 K
UConn-HPC	178 K
UColorado_HEP	174 K
OU ATLAS	173 K
ASU Research Computing	163 K
Nebraska-Omaha	75 K
ICC-SLATE-HTC	69 K
New Mexico State Discovery	61 K
NWICG_NDCMS	42 K
Clemson-Palmetto	41 K
AMNH	40 K
UPRM_HEP	34 K
FermiGrid	34 K
cinvestav	31 K

- Time range: Feb 2020 – Feb 2021
- Total Core Hours: 13.8 million
- Total jobs: 7.15 million



LGAD Central Tracker R&D

Goals

- σ_t<30 psec
- ¼ the material budget of LGAD's for LHC
- Spatial resolution lower priority

Motivations

- 4D reconstruction of tracks
- Disentangle overlapping tracks from protons interacting in different targets
- Fast information for L0 trigger
- Contribute to TOF measurement
- Assist VTX detector for vertex reconstruction
- New generation of Central Tracker for High Intensity experiments

Organization

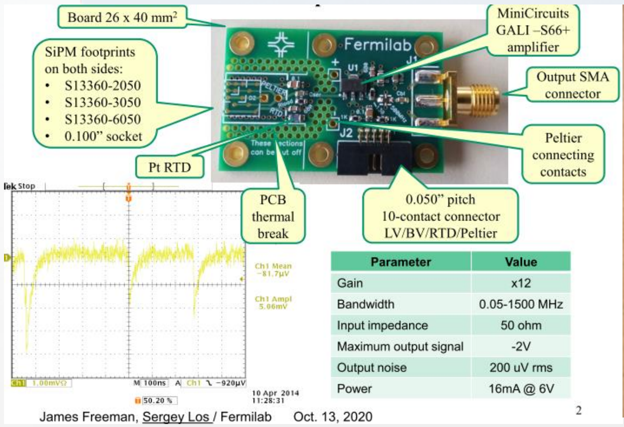
- Collaboration is forming (Group Leader: C. Mill, UIC)
- Funding proposal to DOE in October
- New collaborators are welcome

Slide from Calor2022

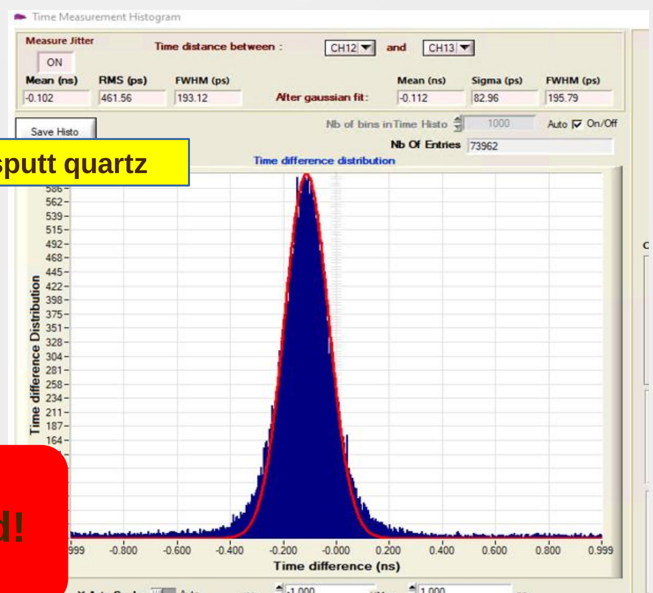
Cerenkov TOF in T1604

Test beam with 3x3x1 cm^3 JS1 tiles with UV coating

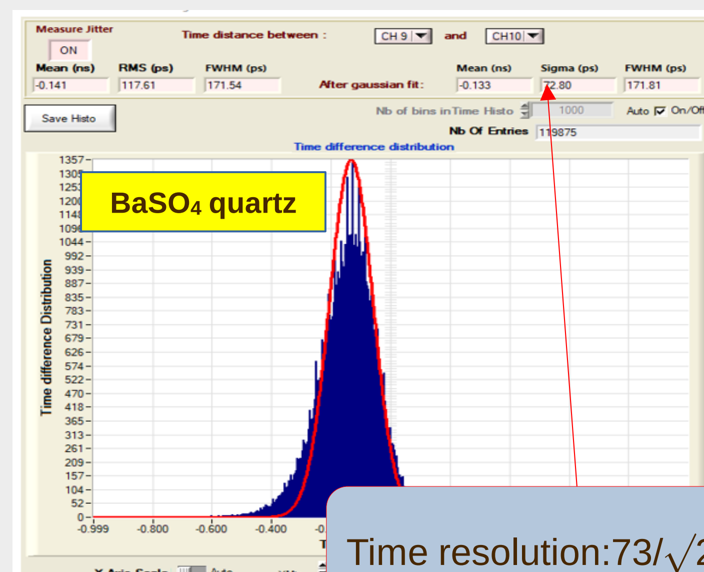
- S14160-5060 Sipm
- Porka FEE and Sampic TDC digitizer



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



Al-sputt quartz



BaSO$_4$ quartz

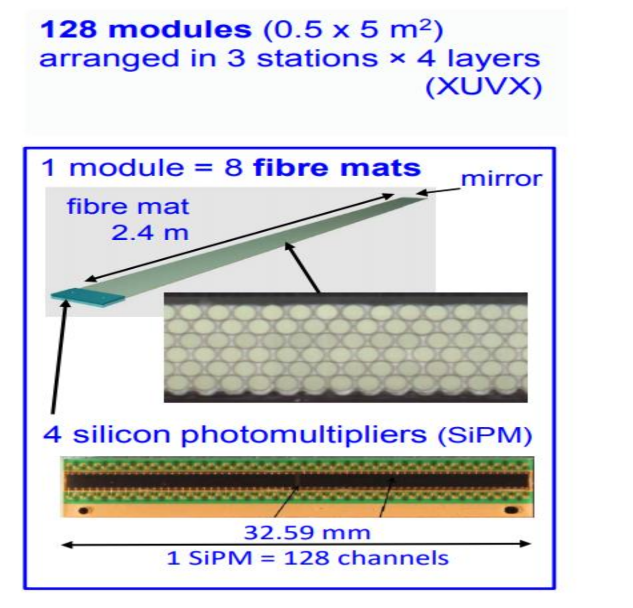
Goal achieved!

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

Vertex Detector R&D

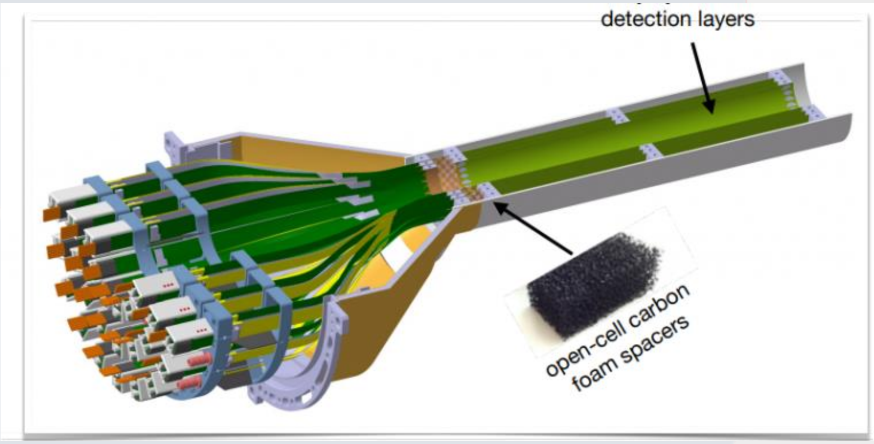
Option 1: LHCb-stile Fiber Tracker

- Established and simple technology – no R&D required
- Active surface is about 0.24 m^2 vs 360 m^2 for LHCb
- Readout channels is about 18,000 vs 590k for LHCB
- Cheap, but no z-measurement nor TOF



Option 2: ALICE-stile ITS3

- curved wafer-scale ultra-thin silicon sensors
- arranged in perfectly cylindrical layers pions
- unprecedented low material budget of 0.05% X0 per layer
- Will be the standard of most new generation lower-energy trackers



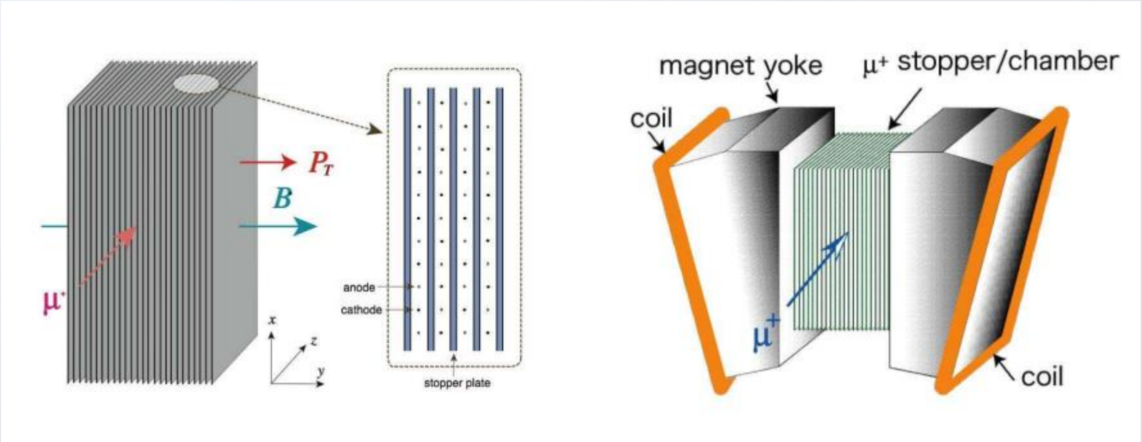
Organization

- REDTOP groups will join existing EIC consortia

Muon Polarimeter R&D

Option 1: TREK-style active polarimeter

- To be inserted between the EM and Hadronic sections of ADRIANO2
- High efficiency, but requires a separate detector
- Benefit from R&D in E-246 Collaboration



Option 2: Implement special layers in ADRIANO2

- Lead-glass or quartz are OK since the do not change the muon polarization
- Requires higher granularity to reconstruct the electron direction
- Two possible solutions:
- Silicon pixel/strips layers between lead glass tiles
- Smaller lead-glass or quartz tiles

Organization

- Simulation needed to select baseline option.

Storage & CPU

Expected data rates from the experiment

- About 500 kHz to be stored on tape
- ~0.9 GB/sec from L2
- ~6 PB/year to tape (assume 1.6 kb event size)

Data from DAQ and Montecarlo

- Data from experiment: ~6 PB/year to tape
- Processed data (reco, calib. Analysis, etc) : ~1.0 PB/year (tape and disk)
- Montecarlo (~10^{11} events): ~0.5 PB/run (tape and disk)
- ***Total: 7.5 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)

Overall Computing Usage

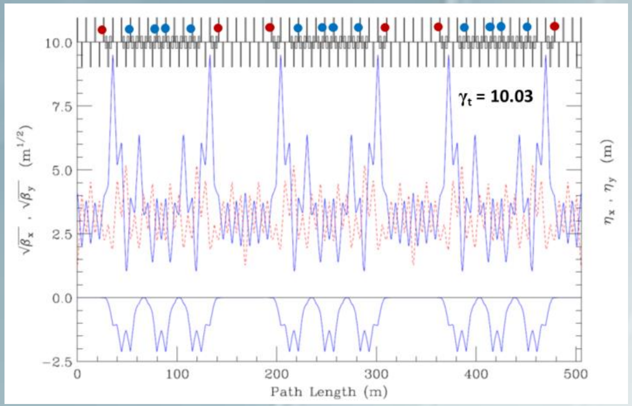
- *Computing resources for REDTOP are from three sources:*
  - *OSG: CPU and stash storage*
  - *NICADD/NIU: CPU and permanent storage*
  - *Fermilab (private farm hosted by AD) : CPU and permanent storage*

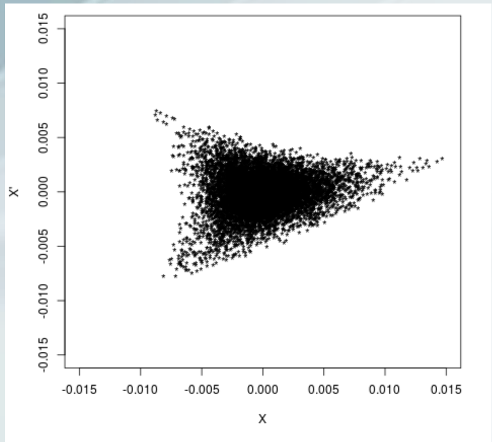
Summary of computing

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	200 TB	350	300K	600K	2%

FNAL option

Accelerator Physics Issues





- ***Transition Energy***
  - γ_t is where $\Delta f/f = 1/\gamma2$ - <D/ρ> = 0; synchrotron motion stops momentarily, can often lead to beam loss
  - beam decelerates from γ = 9.5 to γ = 3.1
  - original Delivery Ring γ_t = 7.6
  - a re-powering of 18 quadrupole magnets can create a γ_t = 10, thus avoiding passing through this condition
    - Johnstone and Syphers, *Proc. NA-PAC 2016*, Chicago (2016).
- ***Resonant Extraction***
  - Mu2e will use 1/3-integer resonant extraction
  - REDTOP can use same system, with use of the spare Mu2e magnetic septum
  - initial calculations indicate sufficient phase space, even with the larger beam at the lower energies
- ***Vacuum***
  - REDTOP spill time is much longer than for Mu2e
  - though beam-gas scattering emittance growth rate 3 times higher at lower energy, still tolerable level

FNAL option

Accelerator Physics Issues

- *Transition Energy*
  - γ_t is where $\Delta f/f = 1/\gamma 2 - \langle D/\rho \rangle = 0$; synchrotron motion stops momentarily, can often lead to beam loss
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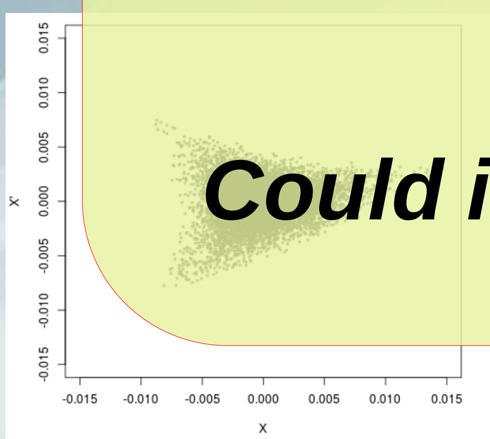
  - REDTOP spill time is much longer than for Mu2e
  - though beam-gas scattering emittance growth rate 3 times higher at lower energy, still tolerable level



No showstoppers to run at Fermilab

All needed accelearator component on site

Could install in AP50 immediately

GSI option

REDTOP

Beam Options at GSI (far future)

Opportunities as in-ring target exp.

FAIR GSI

OPTION C ESR (SIS18)	OPTION D HESR (SIS100)
• ESR	• HESR or CR
• 1e6 p/injection (1-2 MHz revolution rate)	• Intensity fully flexible
• Full beam usage	• Full beam usage
• Lower intensity	• Parallel operation possible due to p-LINAC
• Parallel operation of UNILAC and SIS18 exp. possible	• Standard installation needs to be discussed
• Standard ESR exp. area needs to be dismounted	• Actual timeline beyond 2030
• Major disruption for the already approved program	

GSI an excellent option

Proposal submitted to GSI'Directorate in Fall 2023

FAIR GmbH | GSI GmbH

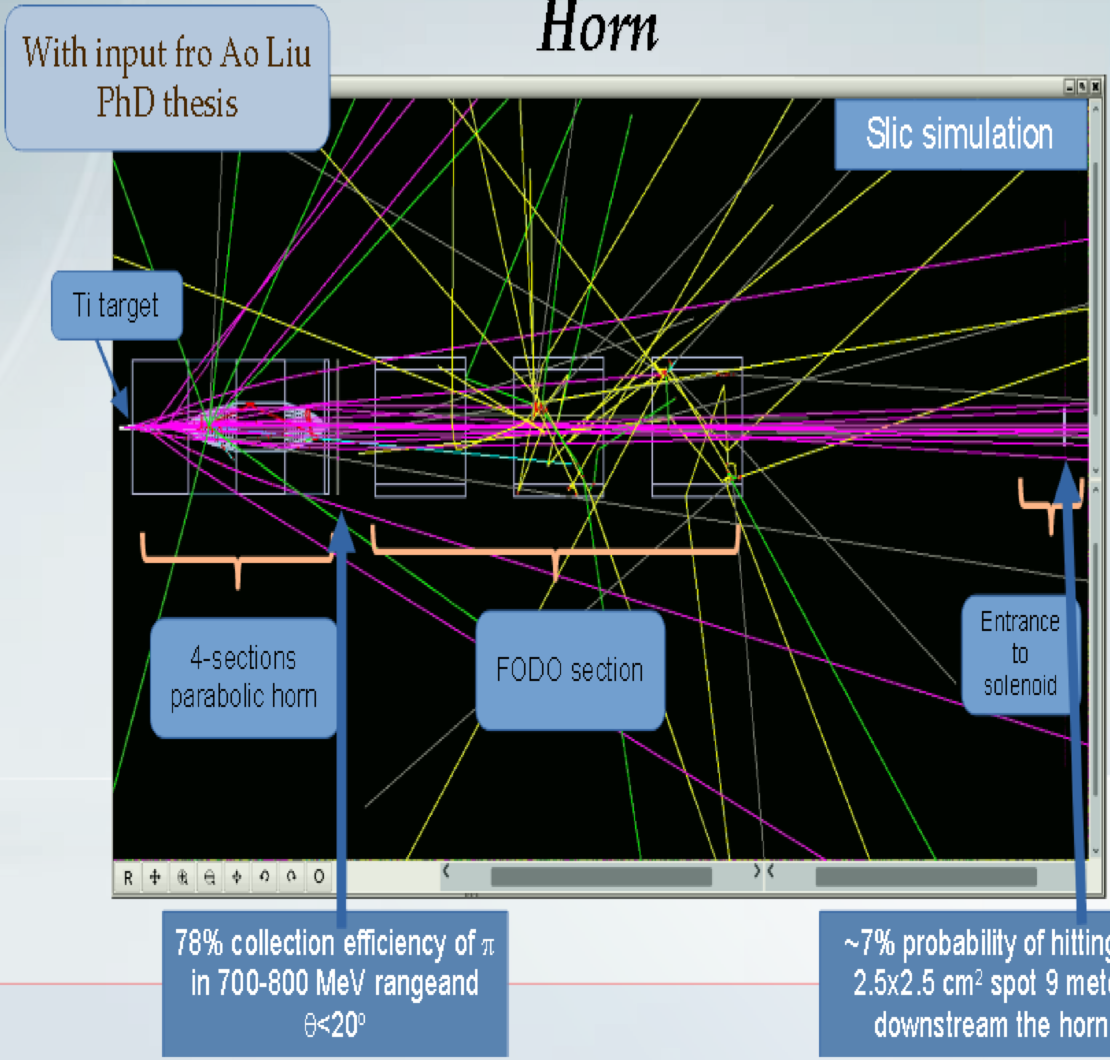
Beam intensity: 1.8 GeV protons with 1e11/s

Daniel Severin

REDTOP

Beam Options at ESS

Pion beams with modified Longhin Magnetic Horn

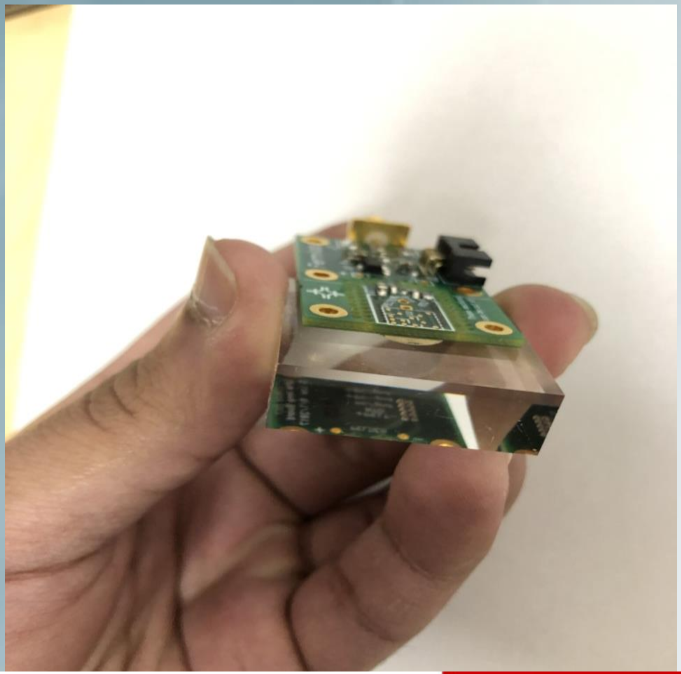


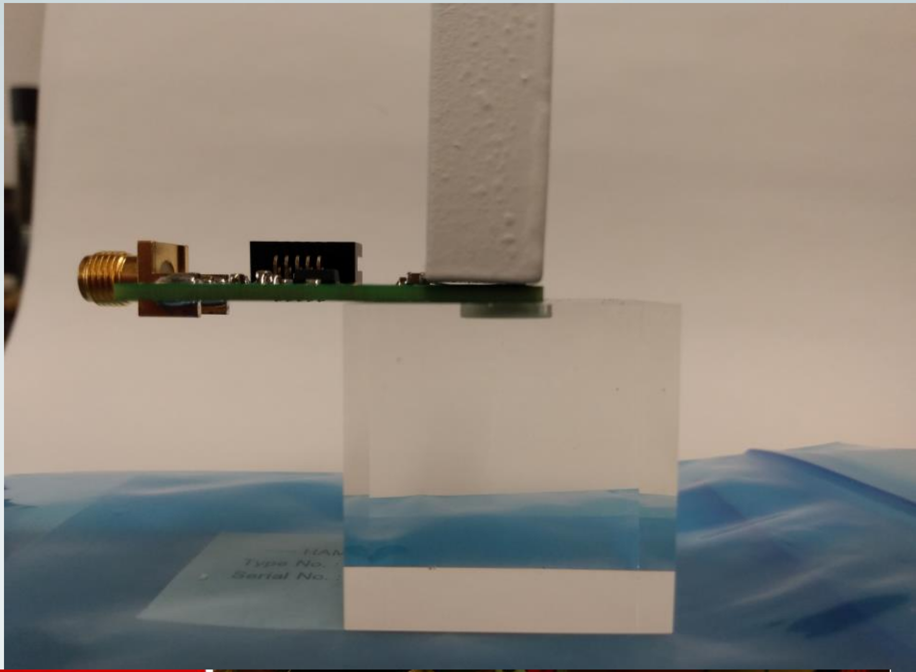
•A 1.3 GeV proton beam hitting a tungsten target has a 2% probability of generating a pion in the right energy range. A HPSP-style (CERN's neutrino superbeam) double horn would funnel about 78% probability of funneling them into a parallel beam, with a ~7% probability of hitting a 2.5x2.5 cm^2 spot 9 meter downstream (with just 3 quads for focusing). In summary, REDTOP would use less than 2% of a 2 MW proton beam.

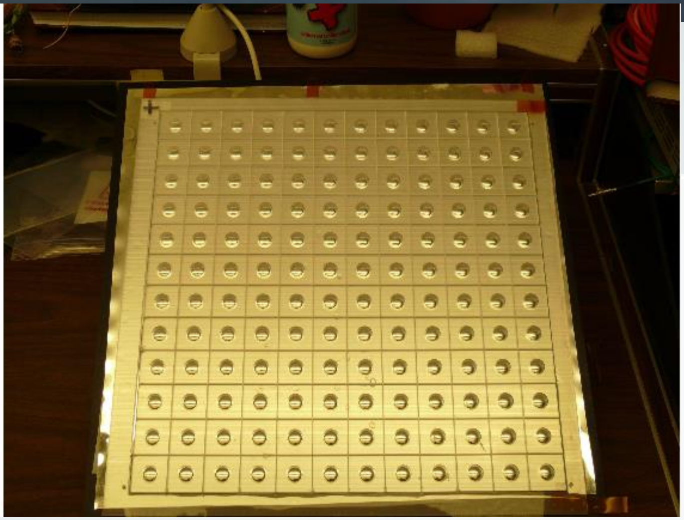
Beam intensity

Slide from Calor2022

FEE + Tiles with dimple





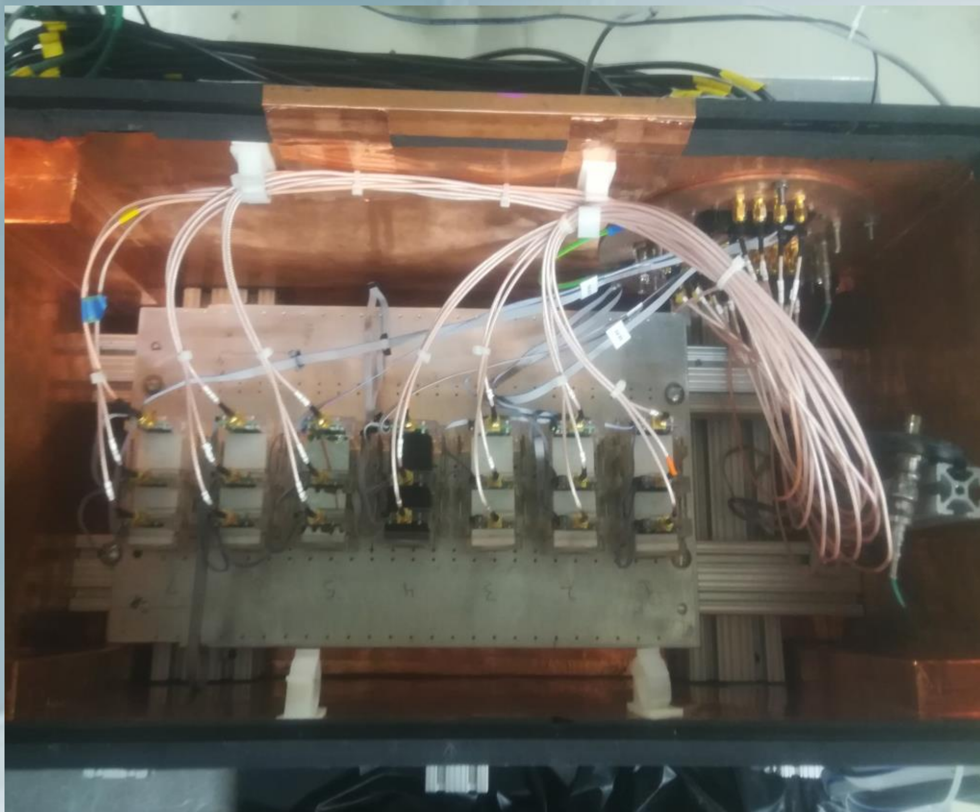


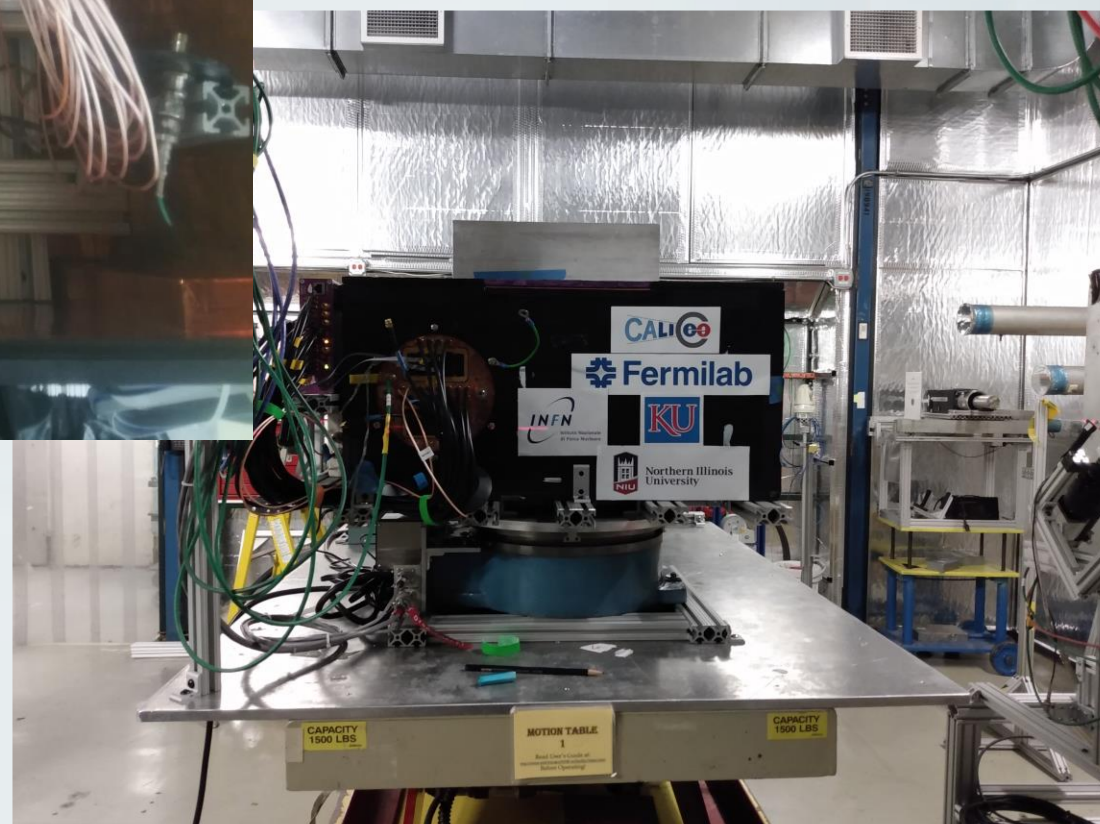
Slide from Calor2022

ADRIANO2 at FTBF

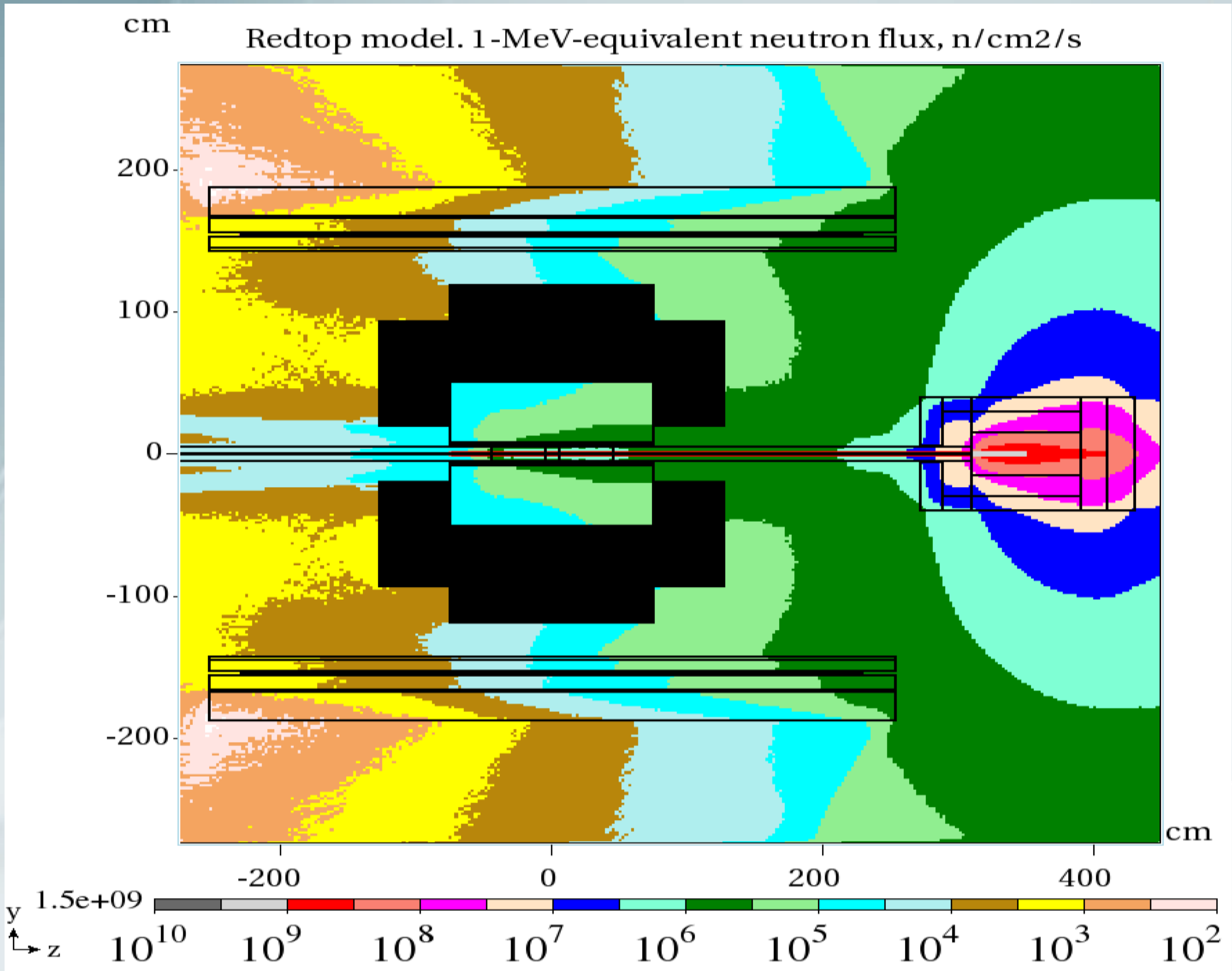
- Three test beam completed
- Tiles organized in triplet of three sizes
- Final test beam planned for Winter 2024
- Final test beam with 64 channels and ASIC DAQ : CAEN 5500 with petiroc-2

(University of Kansas)





Radiation flux with MARS15



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