The REDTOP experiment: A Precision η/η' Factory for New Physics in the MeV–GeV Range

Corrado Gatto

INFN Napoli and Northern Illinois University

On behalf of REDTOP Collaboration

ESS STAP Meeting

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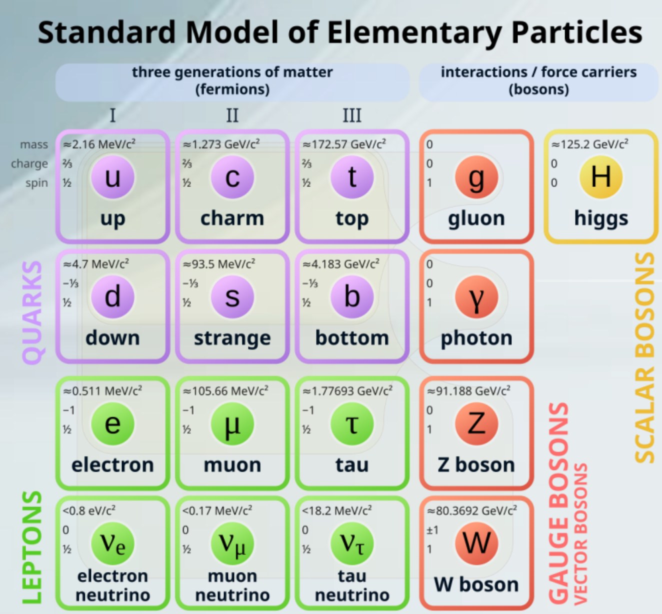
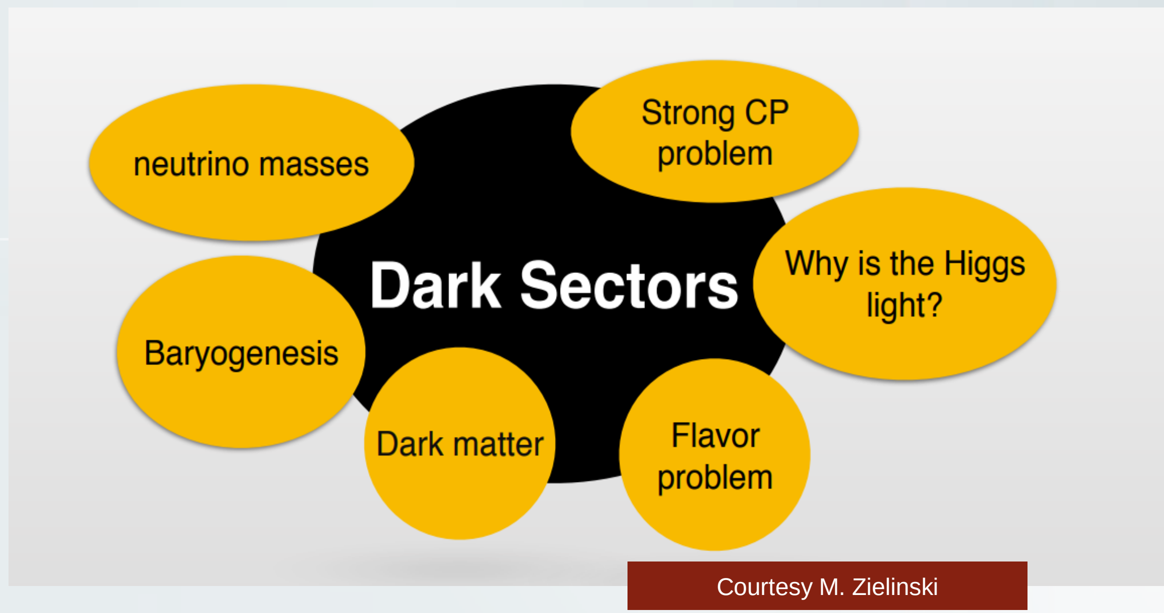
General motivation

Status of Standard Model in HEP:

- **The Standard Model has served us well for 50 years!**
- **Recent measurements indicates SM can't be the final answer.**
- **Six categories of problems have arisen in SM.**





General motivation

Examples of experimentally observed anomalies:

Muonic puzzle

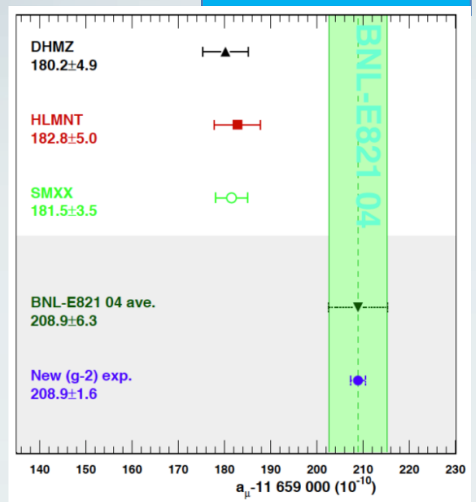
$(g-2)_\mu$

Latest measurement at Fermilab

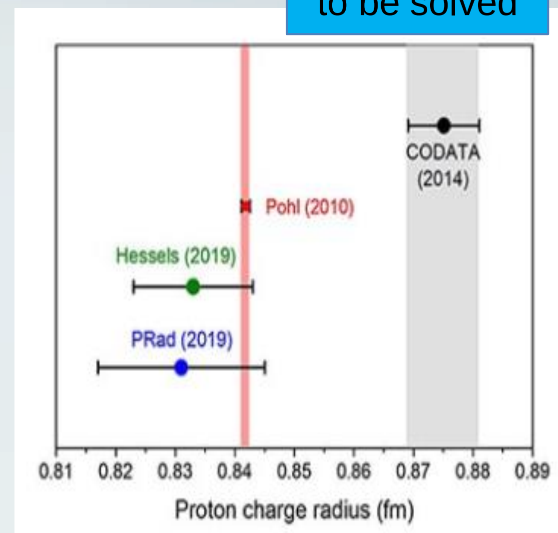
Proton radius

Energy levels in muonic hydrogen are different than standard hydrogen

4.2σ effect



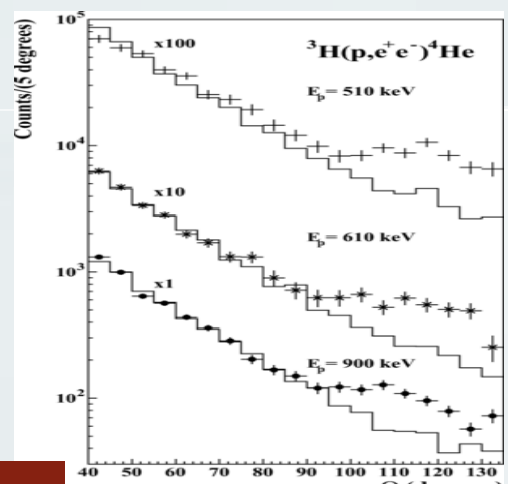
Maybe close to be solved



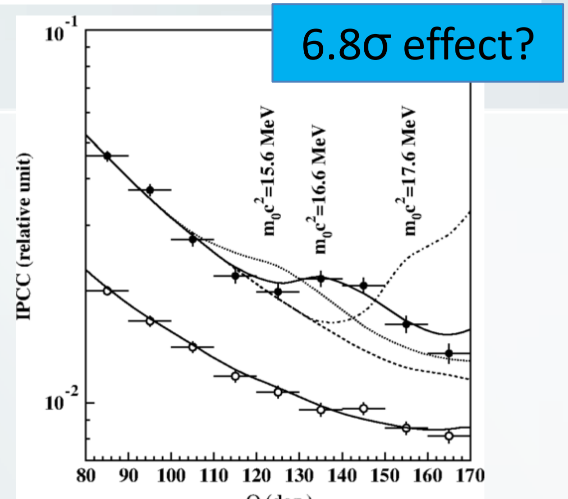
X_{17} in the e^+e^- spectra

X_{17}

„Bumblike" structure in the emission spectra of openning angles for e^+e^- pairs in the isoscalar magnetic transitions of ^8Be and ^4He nuclei



6.8σ effect?

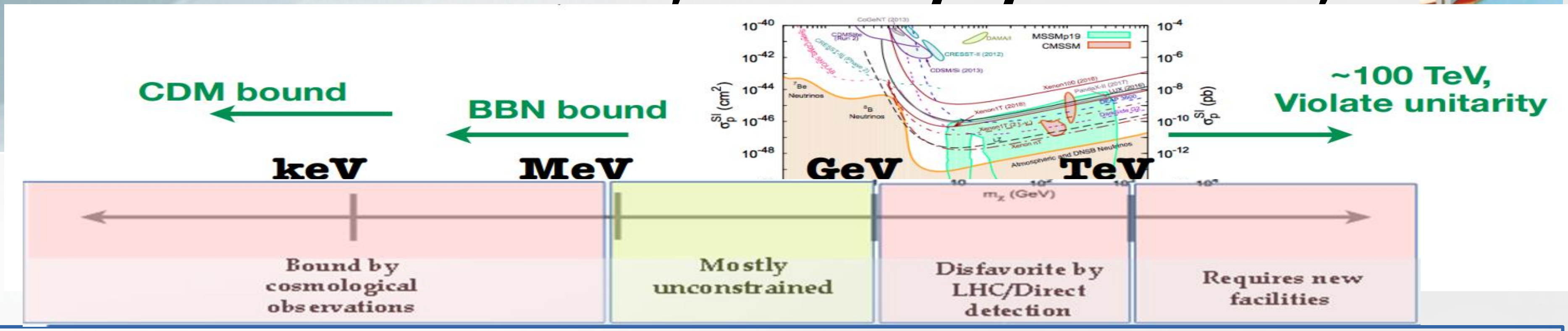


Courtesy M. Zielinski

Current Status of HEP

- *SM ingredients are insufficient to explain the nature. Most likely we need:*
  - *new forces (with adequate CP violation)*
  - *new particles*
- *We don't have a clue of what's Beyond the Standard Model*
- *Mass of possible New Physics spans 40 order of magnitude*
- *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*

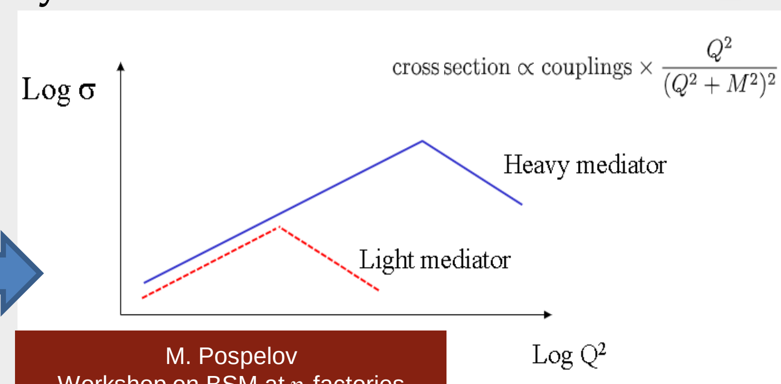
Rationale for an η/η′ Factory



"Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders" [G. Krnjaic RF6 Meeting, 2020] & *"requires new interactions"* [N. Toro, FIPS2022]

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

  → laboratory for symmetry tests
- Light particles induced interactions do not benefit from going to large √s the same way as e.g. interactions from heavy particles



M. Pospelov
Workshop on BSM at η-factories
(Lund 5/2025)

Experimental advantages:

- Hadronic production cross section is quite large (~ 0.1 barn) → easy to produce
- Strong & EM decays are forbidden in lowest order $\mathcal{O}((m_u - m_d)^2)$ or $\mathcal{O}(\alpha^2_{em})$ by discrete symmetry invariance → Window to BSM physics

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

REDTOP Key Points

Designed to search for BSM physics in the MeV-GeV region with a medium energy beam

- Main search fields: dark matter and CP-violation
- Background is much reduced compared to High Energy experiments
- Sensitive to 17MeV resonances

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

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

Hadro-produced mesons: requires a 30W (55W) CW proton beam or $\mathcal{O}$(10 W) pion beam

Moderate cost:

Less than $100M (excluding labor)

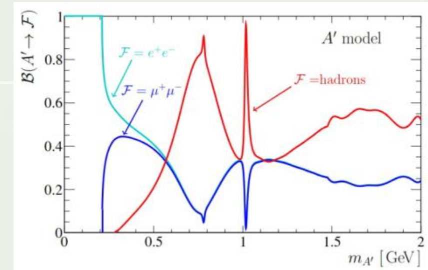
Main Physics Goals of REDTOP

Searches of new fields and forces

Dark photon searches:

$\eta \rightarrow \gamma A'$, with $A' \rightarrow \mu^+\mu^-$, $A' \rightarrow e^+e^-$

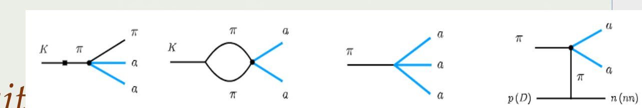
- *Sensitivity to multiple models*



F. Kahlhofer

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

- *Various single production of axions are suppressed by $(\theta_{\pi 0a})^2$.*
- *Exception is η/η' decays.*
- *Double and triple production of a is not suppressed. Current limit*



M. Hostert, M. Pospelov (2020)

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

- Important to differentiate between ***Minimal Scalar Models*** and ***Leptophilic Scalar Models***

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: $\eta \rightarrow \pi^0\mu^+\mu^-$, $\eta \rightarrow \gamma\mu^+\mu^-$, $\eta \rightarrow \mu^+\mu^-$

Violation of discrete symmetries+

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

- Need excellent particle ID

Displaced verteces in $\mu^+\mu^-$, e^+e^-, $\pi^+\pi^-$ events

- No long-lived SM are produced at REDTOP beam energy

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

REDTOP

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 $\gamma*$ polarization studies: $\eta \to \pi^+\pi^- e^+e^-$ & $\eta \to \pi^+\pi^-\mu^+\mu^-$
- CP invariance in angular correlation studies: $\eta \to \mu^+\mu^- e^+e^-$
- CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-\pi^+\pi^-$
- CP invariance in μ polar. in studies: $\eta \to \pi^o \mu^+\mu^-$
- T invar. via μ transverse polarization: $\eta \to \pi^o\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ 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)

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

Assuming a yield $\sim 10^{14}$ η mesons and $\sim 10^{12}$ η' mesons

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

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): $\eta \to 4\pi^o \to 8\gamma$
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- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+ \mu^-$
- CP inv. via γ^* polarization studies: $\eta \to \pi^+ \pi^- e^+ e^-$ & $\eta \to \pi^+ \pi^- \mu^+ \mu^-$
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- CPT violation: μ polar in $\eta \to \pi^+ \mu^- \nu$ vs $\eta \to \pi^- \mu^+ \nu$ ... polar in ...

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+ e^- + c.c.$
- Radiative Lepton Flavor Violation: $\eta \to \gamma \mu^+ e^- + c.c.$
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- Lepton Universality
- $\eta \to$ ... $\to h' N_1$, $h' \to e^+ e^-$

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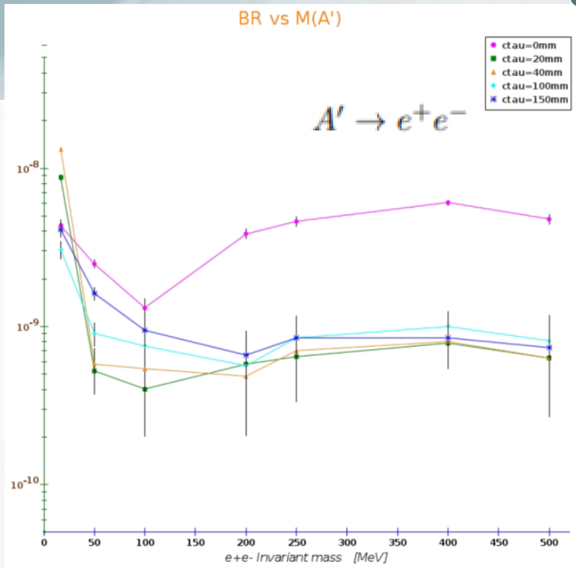
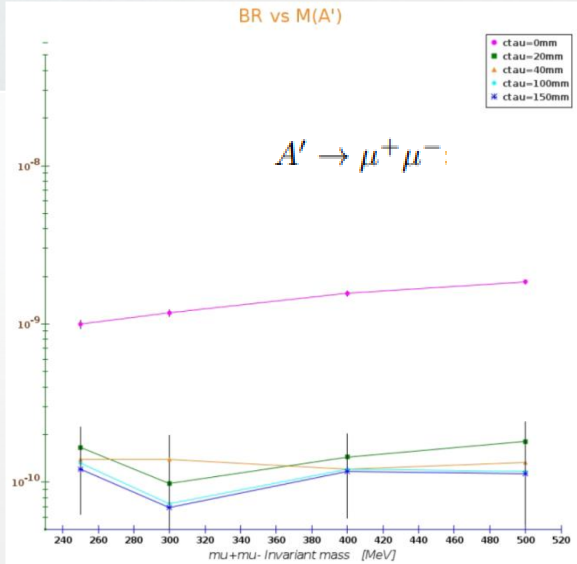
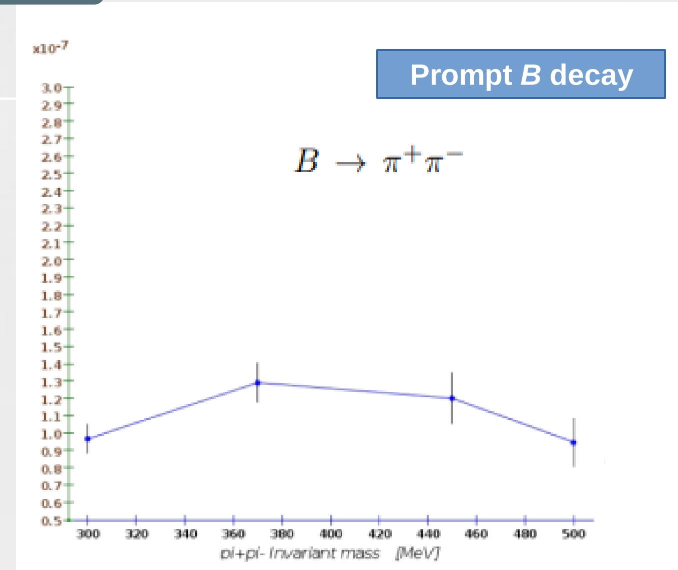
Vector Portal: $\eta \to \gamma A'$ with $A' \to l^+ l^-$ or $\pi^+\pi^-$

REDTOP

Some BR sensitivity curves







Sensitivity curves for Minimal Dark Photon Model

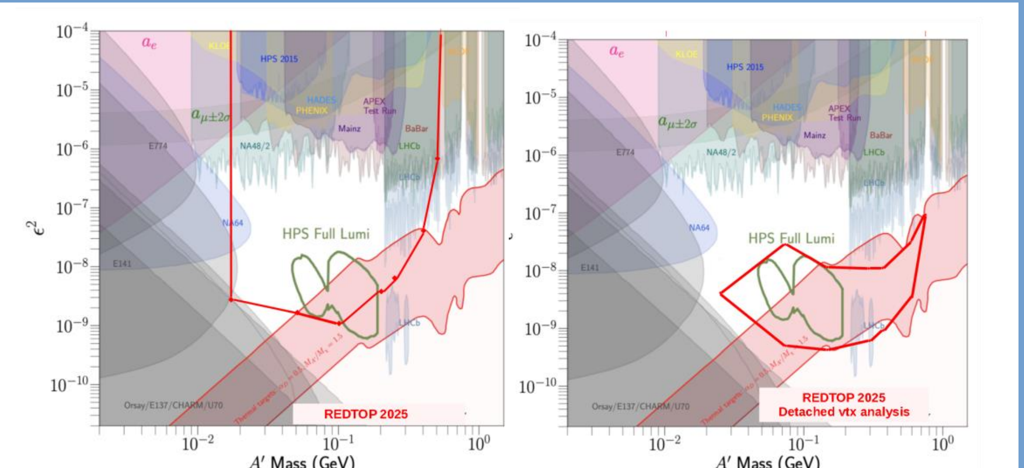


FIG. 36. Sensitivity to to ε^2 for the processes $\eta \to \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

Theoretical Models studied

- *Minimal dark photon model*
  - *Most popular model:*
- *Leptophobic B boson model*
  - *1– boson coupled to quarks but not to leptons (Escribano, González-Solís, and Royo (2022))*
- *Protophobic Fifth Force*
  - *Explains the Atomki anomaly*

The physics case for REDTOP

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

https://arxiv.org/abs/2203.07651

15 processes fully simulated and reconstructed – 20 theoretical models benchmarked

- Four BSM portals
- Three CP violating processes requiring no μ-polarization measurement
- Four 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

Present & Future η Samples

	Technique	$\eta \to 3\pi^o$	$\eta \to e^+e^-\gamma$	Total η mesons
CB@AGS	$\pi^- p \to \eta\, n$	9×10^5		10^7
CB@MAMI	$\gamma p \to \eta\, p$	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
HHAS (proposing)	$p_{1.8\,GeV}\ N \to \eta\, X$			$\sim 10^{13}$/yr
REDTOP (proposing)	$p_{1.8\,GeV}\ Li/Be \to \eta\, X$			3.4×10^{13}/yr

REDTOP Running Modes for 10^{14} η mesons

REDTOP

Baseline option – medium-energy CW proton beam

vs LHCb@40 MHz

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

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

Preferred option – low-energy pion beam

- ***π^+ on Li/Be or π^- on LH:*** *~750* ***MeV - $2.5\mathrm{x}10^{10}$ πOT/sec***
- *More expensive but lower background (**ESS**, FAIR, ORNL)*
- *η : inelastic background = 1:50 → higher sensitivity to BSM*
- *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 ; 0.05-1 MW*
- *Less readily available: (**ESS**, FAIR, 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: ~ 7 - 130 GHz
η/η' production rate: ~ 0.1 - 1 MHz

REDTOP Running Modes for 10^{14} η mesons

REDTOP

Baseline option – medium-energy CW proton beam

vs LHCb@40 MHz

- 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)

Inelastic interaction rate: ~ 0.7 GHz

Average event multiplicity ≈

η/η' production rate: ~ 2.3 MHz

ESS is the only laboratory capable of providing beam for all three running modes

Preferred option – low-energy pion beam

- More expensive but lower background (ESS, FAIR, ORNL)
- Semi-tagged η production

Inelastic interaction rate: ~ 0.1GHz

η/η' production rate: ~ 2.3 MHz

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

Ultimate option: Tagged 10^{13} η mesons

- Less readily available: (ESS, FA
- 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

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

Detector Requirements: BSM physics driven

LFU: Tagged lepton production from flavor-conserving decays

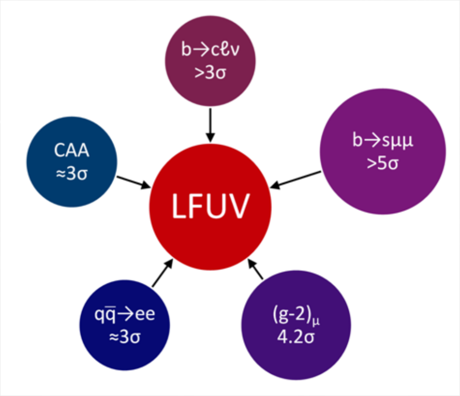
- excellent e/π/μ separation

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

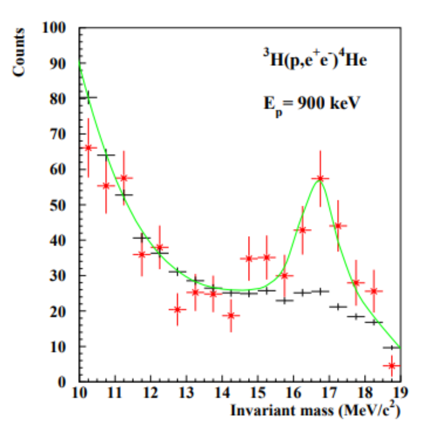
- *17 MeV e^+e^- state (Atomki experiment)*
  - *Tracker sensitivity to $M(e^+e^-)$~ 10 MeV*
  - *Electron ID at very low energy*

- *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

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

charged tracks detection

Option 1: LGAD Tracker

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

Option 2: Mu3e Phase2 HV-MAPS

- *100 psec/layer timing resolution*
- *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/layer timing with T1604 prototype*

Detector Requirements and Technology

REDTOP

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- *Calorimetric $\sigma(E)/E \sim 2\text{-}3\%/\sqrt{E}$*
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- *$\sigma_{tracker}(t) \sim 30$psec, $\sigma_{calorimeter}(t) \sim 80$psec, $\sigma_{TOF}(t) \sim 50$psec*
- *Low-mass vertex detector*
- *Near-4π detector acceptance (as the η/η' decay is almost at rest).*

All last 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

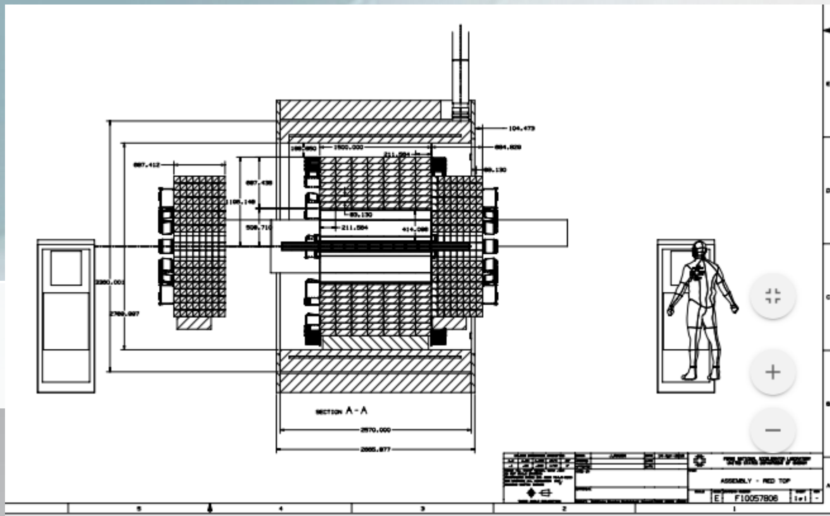
Option 1: Quartz tiles

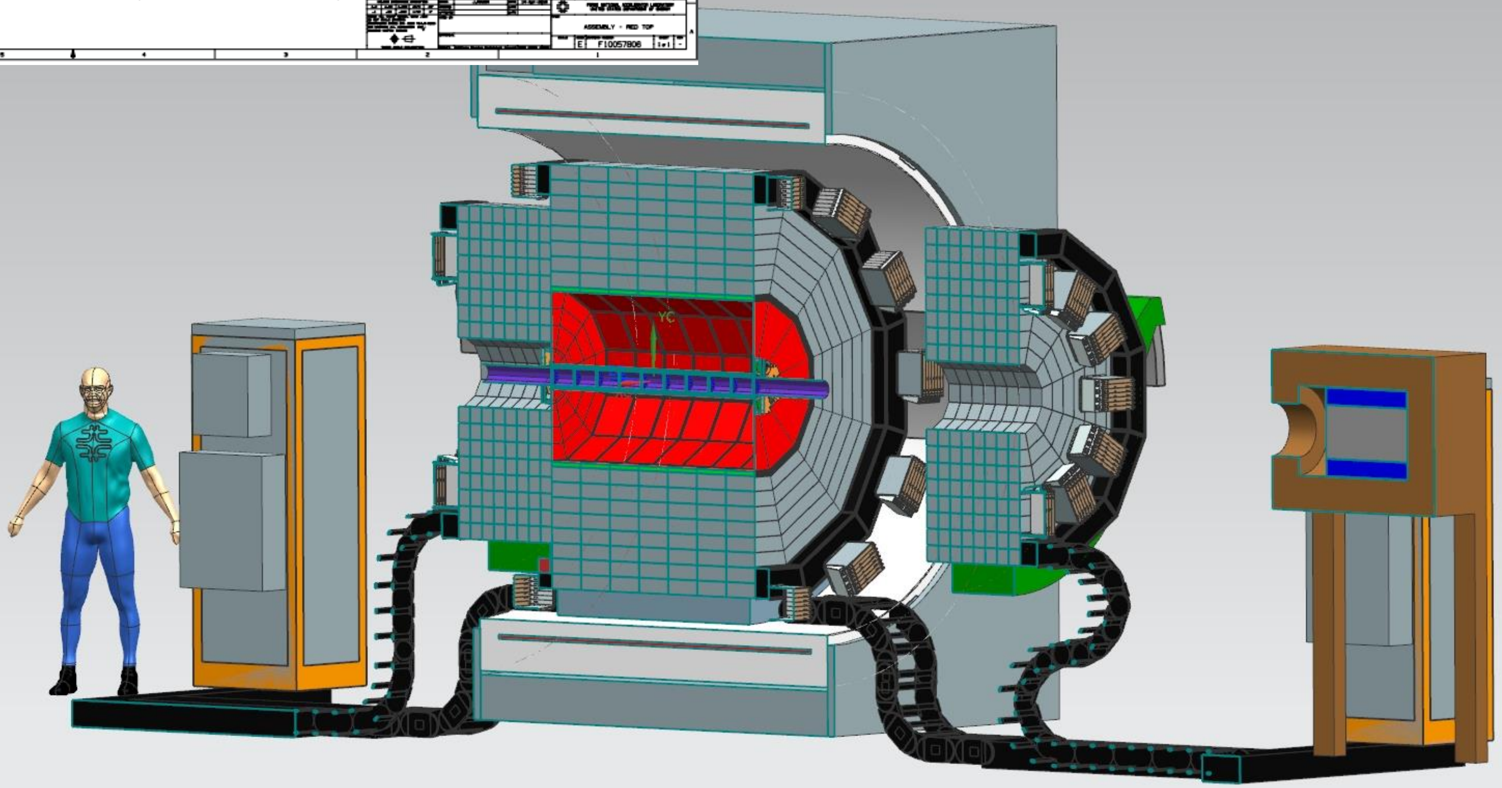
- *Established and low-cost technology*
- *~50psec timing with T1604 prototype*

Option 2: EIC-style LGAD

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

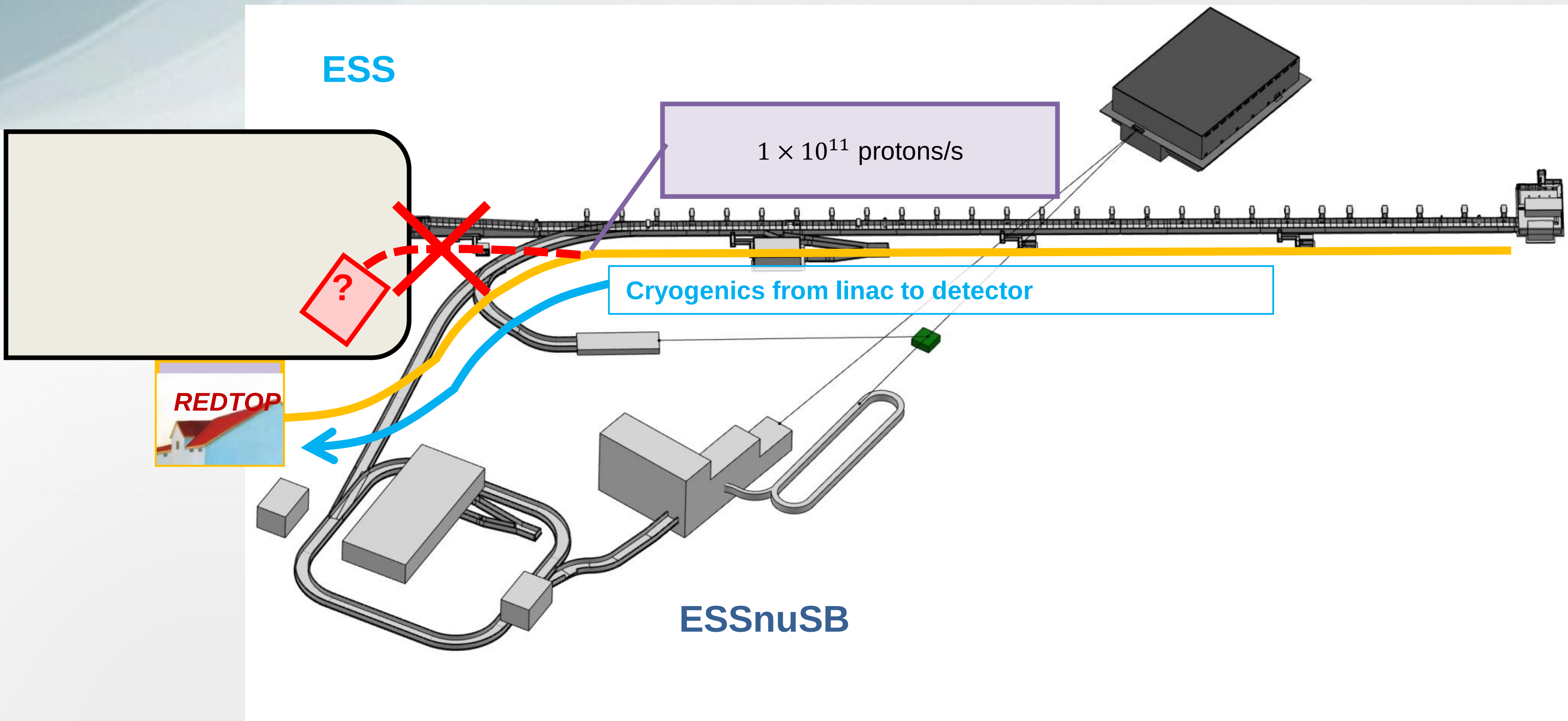
REDTOP Detector + Finuda Magnet





J. Kilmer – J. Rauch

Location at the ESS



Proton Beam option

- Pulsed extraction dipole magnet with long top-off (2.8 ms):
- full linac pulse at low repetition rate
- Extract low intensity pulses at 14 Hz.

Option 1: Solid target

Extract 10^{11} protons/s at 1.8-2.0 GeV kinetic Energy, 30 W

Option 3: De target

Extract 2.5×10^{14} protons/s at 0.9 GeV kinetic Energy, 50KW – 1 MW

Pion Beam option

Option 2: Solid or liquid target

- Extract protons at energy >1.3 GeV (~ 100-200 KW)
- Convert protons to pions
- Focus pions onto secondary solid target

Courtesy M. Olvegard

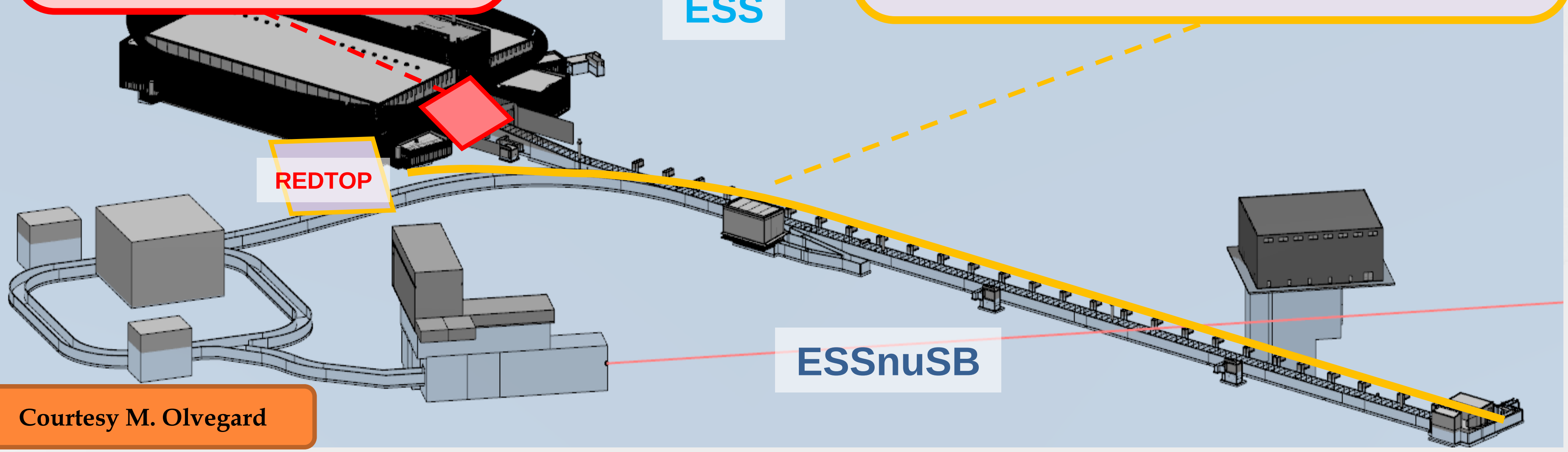
Courtesy M. Olvegard

Location at the ESS

REDTOP

Placement of REDTOP in the experimental hall has been discarded. Impossible to bring the proton beam here.

- Protons extracted from the end of the linac
  - (at 2.5 GeV point in the ESSnuSB design)
- Cryogenics for the detector magnet tapped from the central cooling system



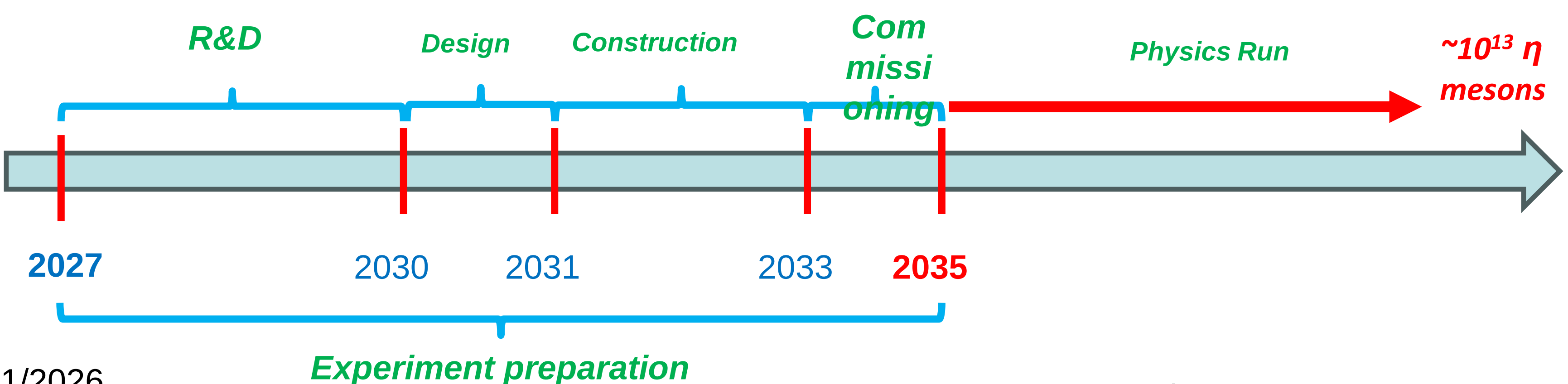
Courtesy M. Olvegard

- *Only preliminary investigation on the location*
- *Feasibility has been studied within ESSnuSB.*
- *Thanks to V. Santoro, M. Olvegard and I. Pavelic*
- *A more robust assessment of the location of the experiment needs the involvement of the ESS staff*
- *6-months of an engineer has been requested in the proposal*

Timeline

- One approved at a laboratory, REDTOP needs:
  - 2-3 years for detector R&D
  - 1 year for design
  - 2 years for construction
- **Running time – based on $3x10^{18}$ pOT or $3x10^{17}$ πOT**
  - **1 year for commisioning + 1 year engineering run**
  - **3 year for physics run**
  - **1 year for contingency**

In total:
~11 years



Cost estimate

REDTOP

Preliminary 2023

- Three funding scenarios considered
- Largest cost uncertainties
  - ADRIANO2 SiPM's ($2 \times 10^6 - 4 \times 10^6$)
  - LGAD mechanics
- **No labor considered (usually, 1/3 of the total)**

	Baseline option (White paper)	ESS 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

15 Countries
62 Institutions
138 Collaborators

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

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

B. Bilki[6]
Beykent University, (Turkey)

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, (Egypt)

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

Fermi National Accelerator Laboratory, (USA)

A. Belias, Y. Litvinov
GSI Helmholtz Center for Heavy Ion Research, 64291, Darmstadt, (Germany)

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

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

S. Homiller
Cornell University, Ithaca, NY, (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[11]
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)

J. M. Berryman
Lawrence Livermore Laboratory, (USA)

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, (India)

Y. Kahn
Princeton University (USA)

J. Friese
Technical University of Munich (Germany)

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)

M. Lucente[4], S. Pascoli[4], F. Sala[4]
Università di Bologna, (Italy)

L. E. Marcucci[7]
Universita' di Pisa, (Italy)

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

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

L. Harland-Lang
University College London, (UK)

Y.D. Tsai
University of California Irvine, (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)

V. Santoro
University of Lund, (Sweden)

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. Petrov
University of Southern Carolina, (USA)

D. Milstead
University of Stockholm, (Sweden)

M. Wolke, A. Kupsc, M. Olvegård
University of Uppsala, (Sweden)

B. Fabela-Enriquez
Vanderbilt University, (USA)

S. Tulin
York University, (Canada)

Status and Prospects

- *The design of the experiment is very mature: only minimal R&D is required before engaging in a Technical Design Report*
- *The Collaboration plans to bring its own funding for the construction of the detector*
- *The hosting lab is expected to sustain the infrastructure and operation costs, possibly, contribute to the installation*
- *ESS can meet the beam requirements of REDTOP exceptionally well for all three running modes.*
- *Unique beam opportunity, partially shared by Oak Ridge.*
- *The infrastructures built for REDTOP could become a long-term asset for future HEP and nuclear-physics experiments at ESS (for example, a super Kaon factory if E_{beam} ~ 2.5 GeV).*

Conclusions

REDTOP

- *All past and present meson factories: LHCb, B-factories, Dafne, J/psi factories - have delivered broad and impactful physics programs.*
- *Neither the high-energy frontier nor the traditional low-energy frontier has yet revealed clear evidence of New Physics; the MeV–GeV region is now regarded as one of the most promising discovery domains.*
- *The η / η' meson is a excellent laboratory for studying rare processes and physics BSM at the MeV–GeV region*
- *REDTOP is among the very few proposed experiments, together with SHiP and HHaS, with sensitivity to all four Dark Matter portals.*
- *REDTOP relies on innovative detector concepts with broad relevance for the next generation of precision experiments.*
- *Now shows-stoppers found so far to running REDTOP at the ESS*
- *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

Outstanding Anomalies in HEP - I

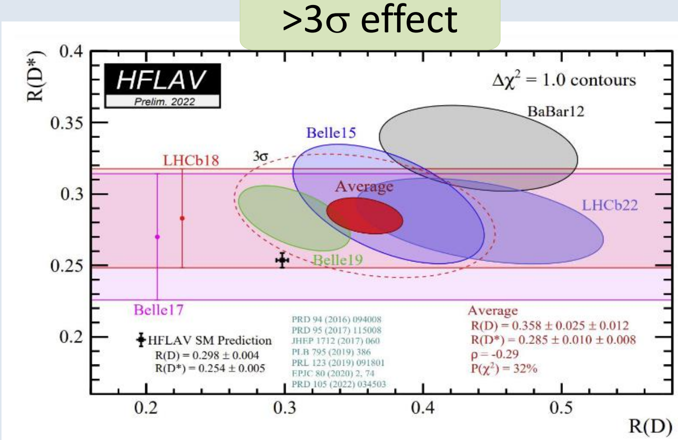
Hadronic meson decays

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

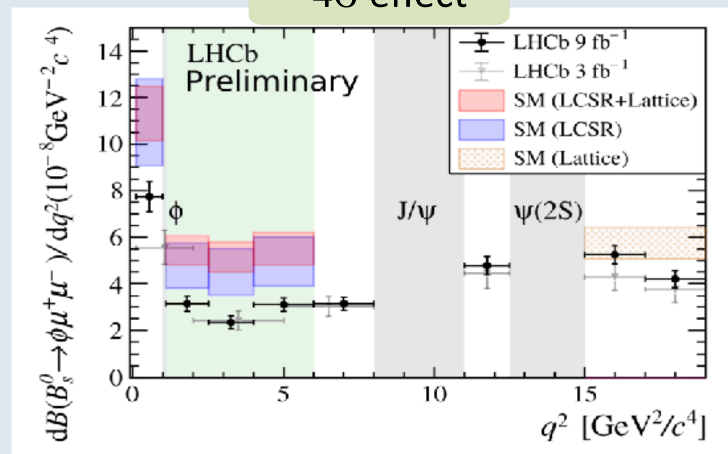
$$R(D^*) = (1.25 \pm 0.07) \times R(D^*)_{\rm SM},$$
$$R(D) = (1.32 \pm 0.16) \times R(D)_{\rm SM},$$

$B \to K^{(*)}\mu\mu$ and $B_s \to \phi\mu\mu$

>3σ effect



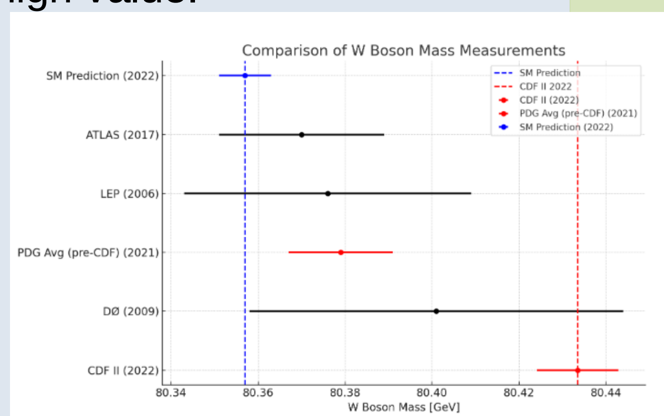
~4σ effect



W mass from CDF vs SM prediction

7σ effect

- ATLAS and LEP data do not support such a high value.
- More measurements (e.g. from CMS, LHCb) are essential to resolve the tension



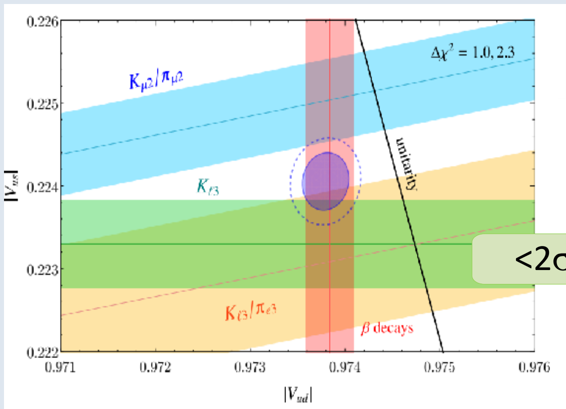
$$M_W|_{\rm CDF} = 80,433.5 \pm 6.4_{\rm stat} \pm 6.9_{\rm syst} = 80,433.5 \pm 9.4 \text{ MeV}$$

Outstanding Ano

Nuclear β-decays anomalies

1st row of CKM Matrix

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



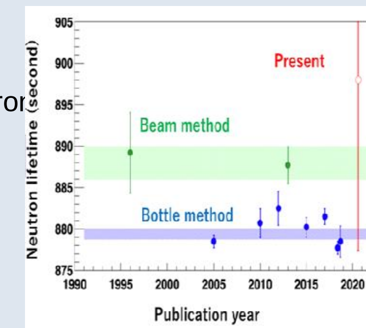
<2σ effect

Tension in neutron lifetime (beam vs bottle)

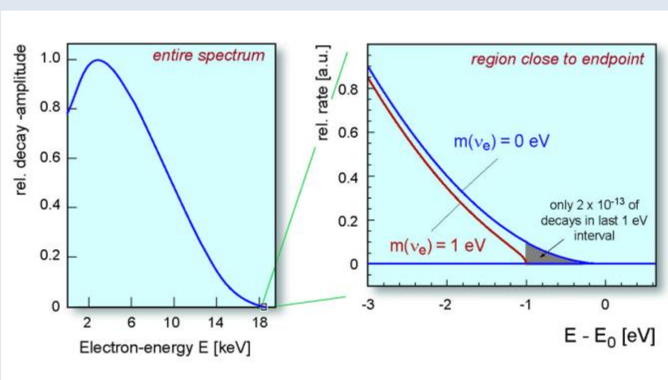
Bottle experiments: trap ultracold neutrons and measure the total number over time (~879 seconds)

Beam experiments: count decay products (e.g. protons) in a cold neutron beam (~888 seconds)

~4σ effect

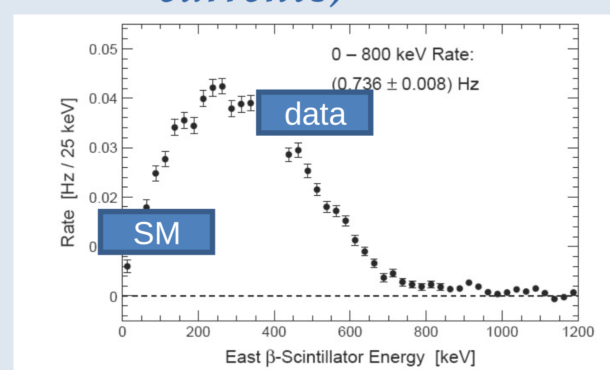


β-decay spectrum &Endpoint



KATRIN experiment near the endpoint for tritium decay

Fierz Interference Term (non purely V-A currents)



UCNA collaboration: beta-decay-spectrum-of-free-neutrons-below-150-kev

Courtesy A. Crivellin

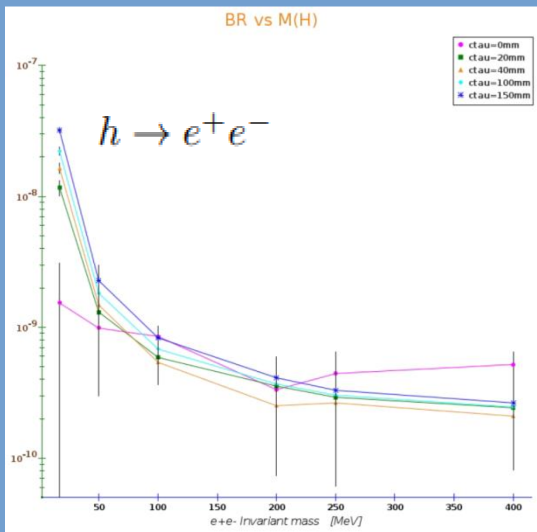
New particles & forces

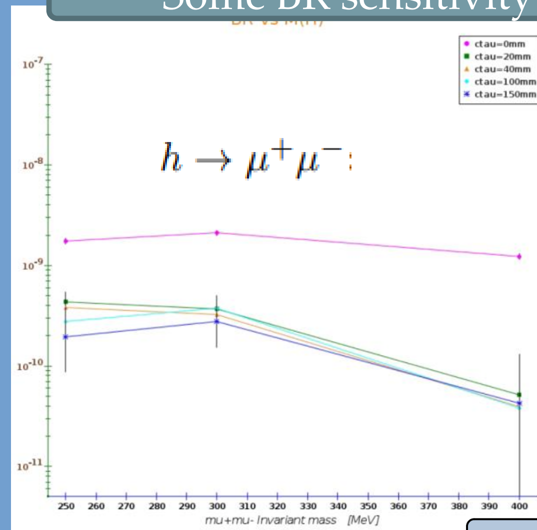
REDTOP

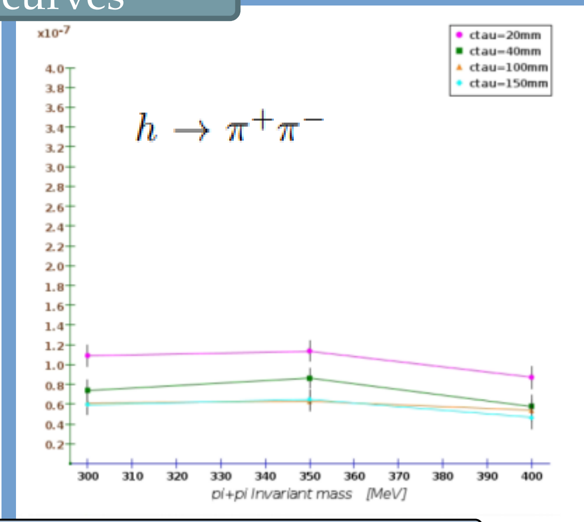
Scalar Portal searches:

$\eta \rightarrow \pi^0 h$ with $h \rightarrow \mu^+\mu^-, \pi^+\pi^-$, e^+e^-

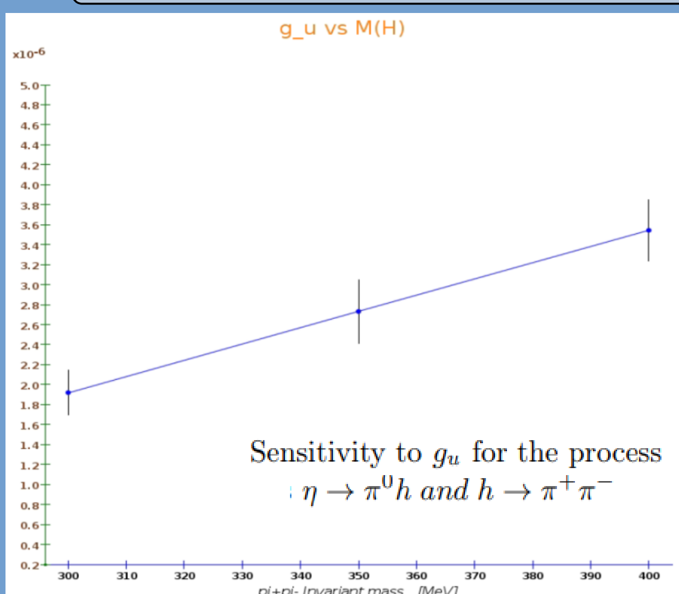
Some BR sensitivity curves







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 $S \rightarrow \mu^+\mu^-$.

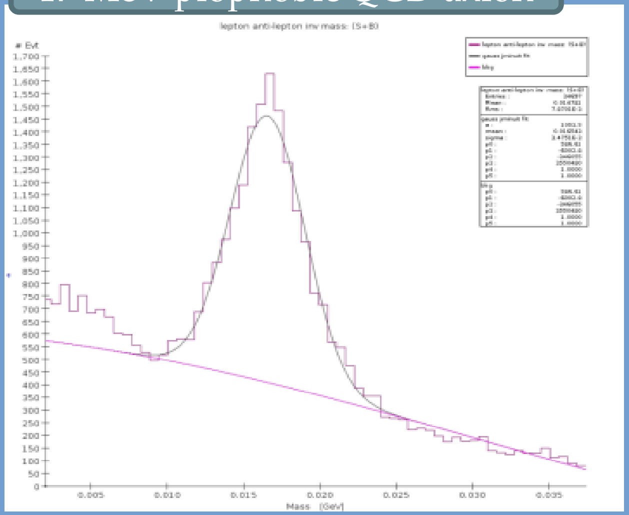
Theoretical models considered

- ***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)*

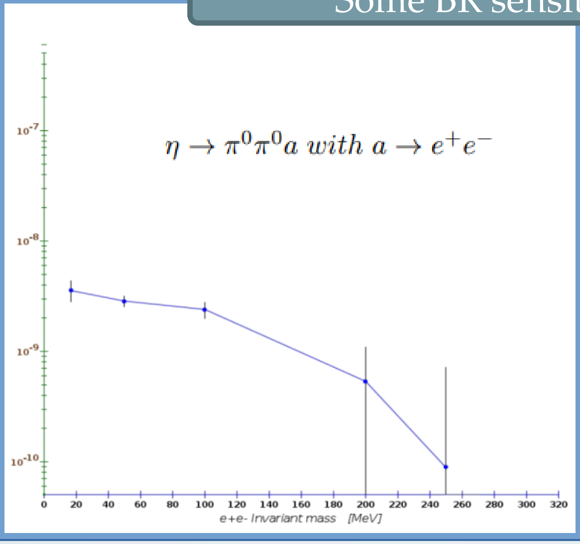
Pseudoscalar Portal: $\eta \rightarrow \pi^o \pi^o a$ & $\eta \rightarrow \pi^+ \pi^- a$ with $a \rightarrow \gamma\gamma$, $\mu^+ \mu^-$ and $e^+ e^-$

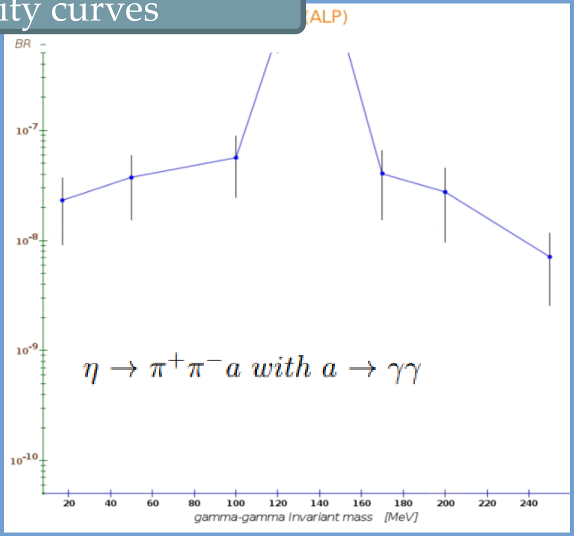
REDTOP

17 MeV piophobic QCD axion

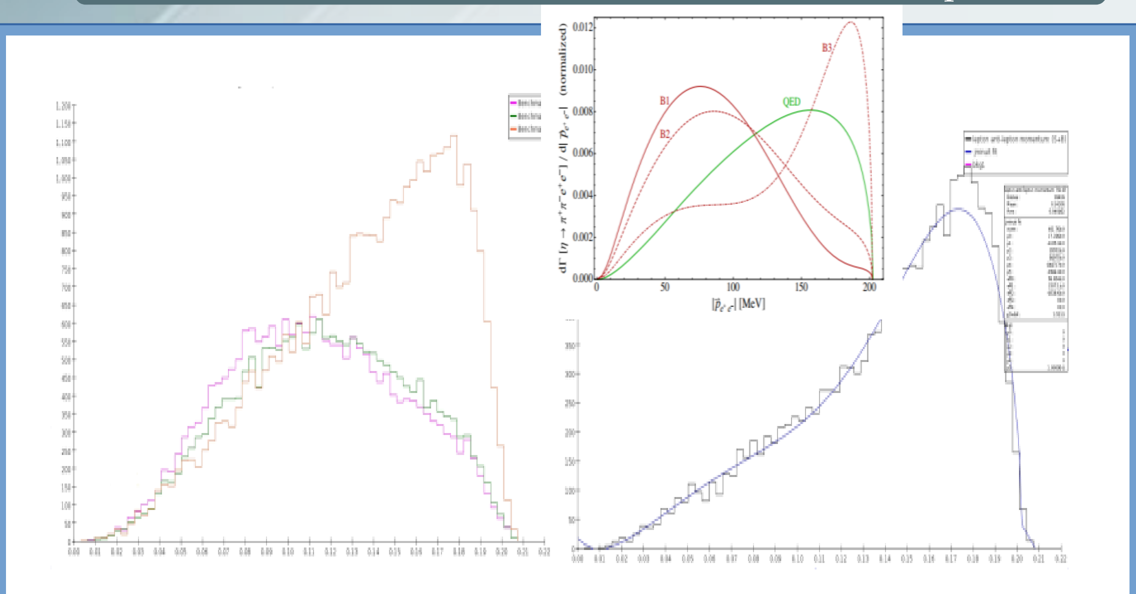


Some BR sensitivity curves





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



Theoretical models considered

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

New particles & forces

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

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	$\sin\delta$	$y^{h'(H)}_{\nu_2} \times 10^3$	$\lambda^{h'(H)}_{N_{12}} \times 10^3$
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

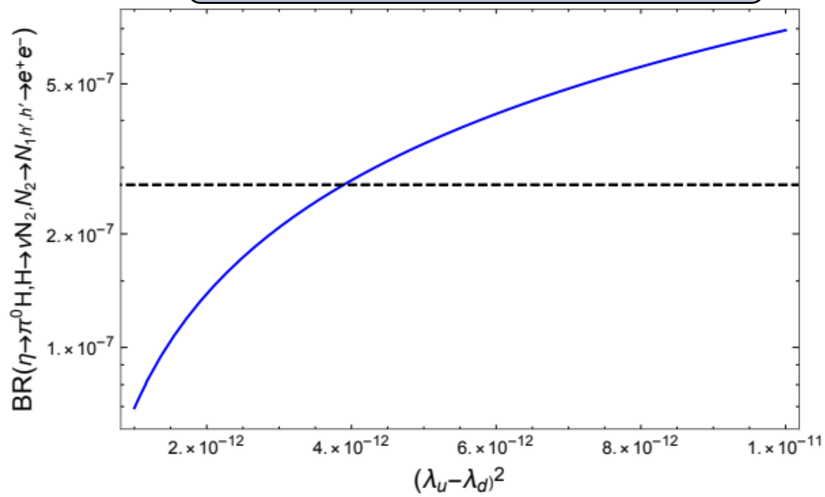


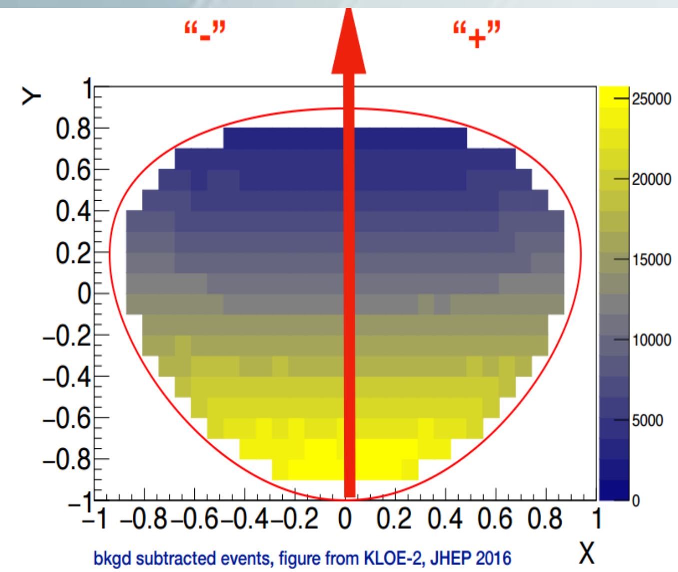
FIG. 61. Branching ratio for the process $\eta \rightarrow \pi^0 H$; $H \rightarrow \nu N_2$; $N_2 \rightarrow N_1 h'$; $h' \rightarrow e^+e^-$ predicted by the Two Higgs Doublet model [51] as a function of $(\lambda_u - \lambda_d)^2$. The dashed line corresponds to the experimental limit for REDTOP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

Test of discrete symmetries

CP Violation from Dalitz plot mirror asymmetry in $\eta \rightarrow \pi^+\pi^-\pi^0$

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*



bkgd subtracted events, figure from KLOE-2, JHEP 2016

Slide Credit: Susan Gardner & Jun Shi

University of Kentucky

REDTOP sensitivity to model parameters

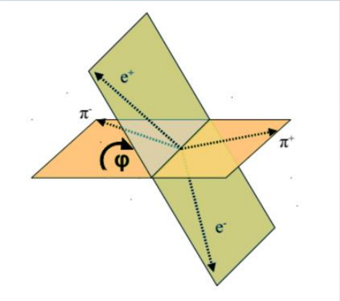
#Rec. Events	Re(α)	Im(α)	Re(β)	Im(β)	p-value
10^8 (no-bkg)	3.3×10^{-1}	3.7×10^{-1}	4.4×10^{-4}	5.6×10^{-4}	17%
Full stat. (no-bkg)	1.9×10^{-2}	2.1×10^{-2}	2.5×10^{-5}	3.2×10^{-5}	17%
Full stat. (100%-bkg)	2.3×10^{-2}	3.0×10^{-2}	3.5×10^{-5}	4.5×10^{-5}	16%

Physics analysis by A. Kupsc – Uni-Uppsala

Test of discrete symmetries

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

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



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

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

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

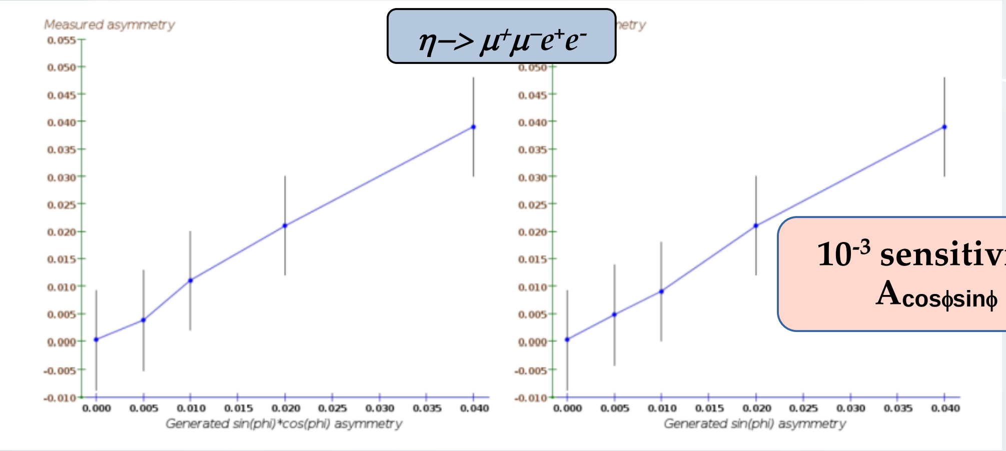
through Wilson coefficients

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

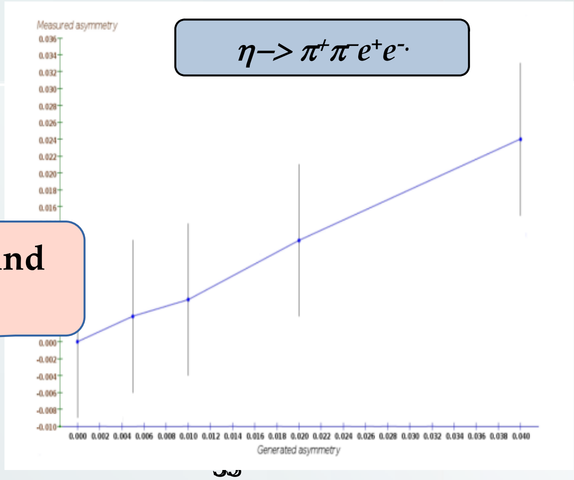
CP violation is related to asymmetries in $\eta \to \pi^+\pi^-e^+e^-$

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

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



$\eta \to \pi^+\pi^-e^+e^-$



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

CP-violation from μ–polarization

REDTOP

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

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

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

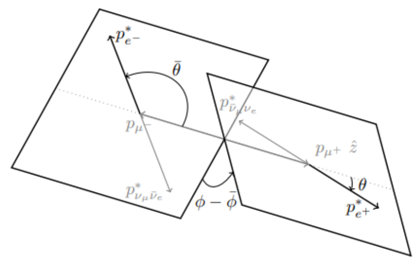


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar\nu$ system. The $\hat z$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

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

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

REDTOP sensitivity to 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%	$2.7\times10^{-8}\pm3.0\times10^{-10}$
Urqmd	21.7%	1.7%	22.2%	8.6×10^{-3}%	7.0×10^{-6}%	-

$$\Delta(c^{1122}_{\ell equ}) = 0.1\times10^{-1}, \quad \Delta(c^{1122}_{\ell edq}) = 0.1, \quad \Delta(c^{2222}_{\ell edq}) = 6.6\times10^{-2},$$

CP violating Wilson coefficient

LF-universality

Lepton Universality Studies

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

REDTOP statistical error for ~10^{11} POT

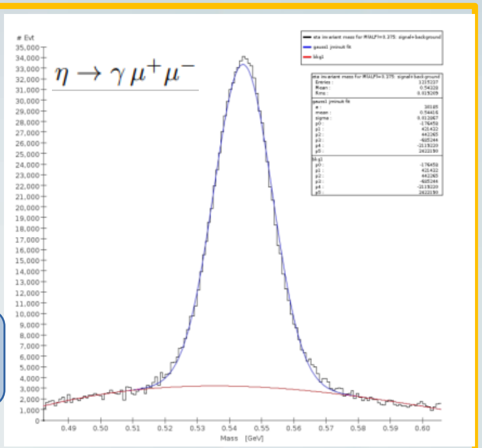
$\eta \rightarrow \gamma \mu^+ \mu^-$ vs $\gamma e^+ e^-$

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



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

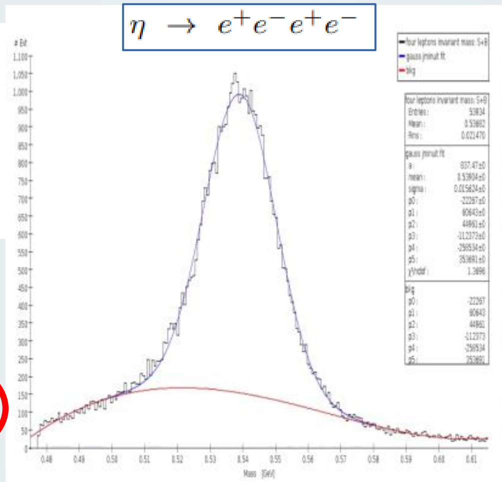
- Theoretical calculations at the 10^{-3} precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018))

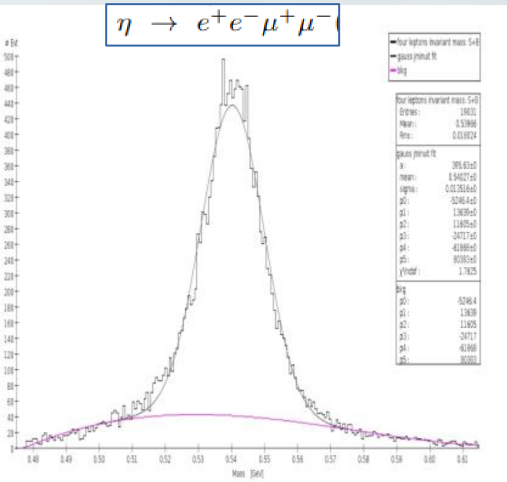
REDTOP reconstruction efficiency

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%**





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

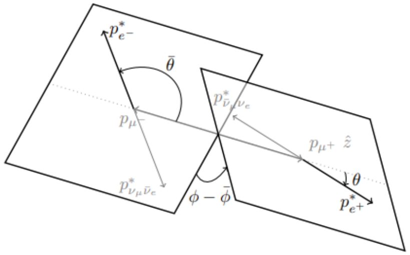


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar\nu$ system. The $\hat z$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

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

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

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%	$1.93\times10^{-9} \pm 0.9\times10^{-11}$
Urqmd	21.7%	1.7%	22.2%	4.7×10^{-3}%	4.7×10^{-6}%	-

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

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*

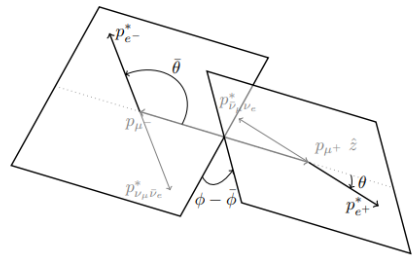


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar\nu$ system. The $\hat z$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

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

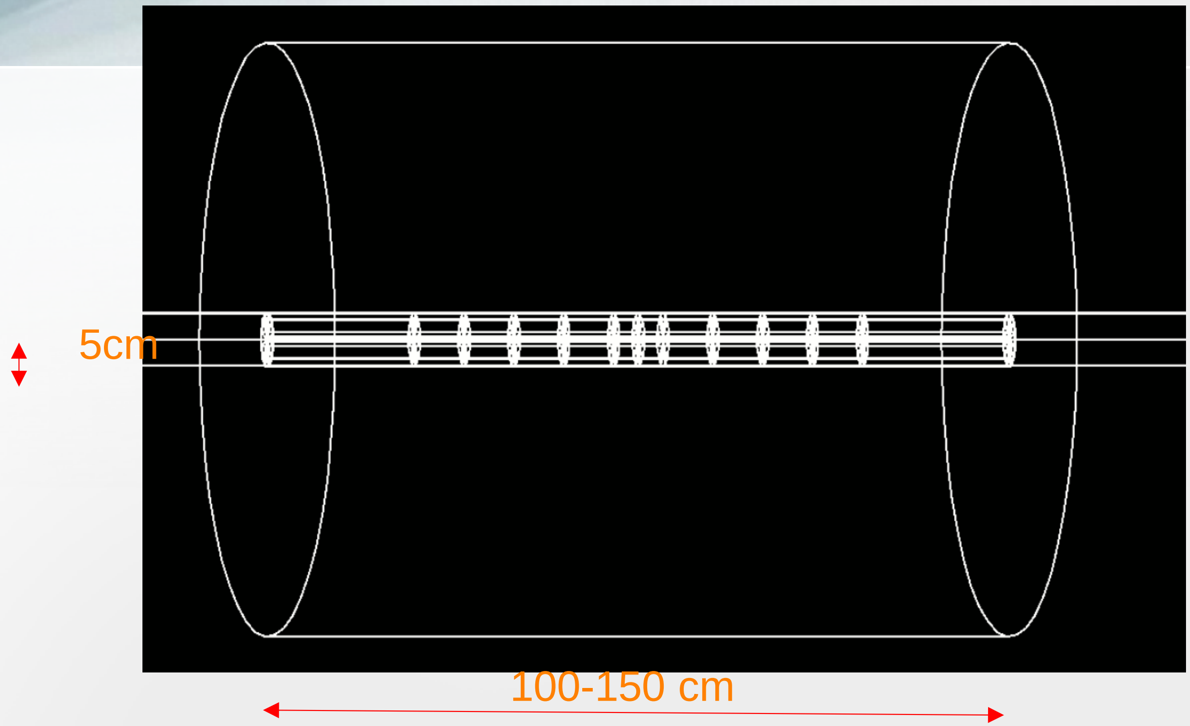
$$A_\times^{\eta\to\pi^0\mu^+\mu^-} = 0.07(2)\,\mathrm{Im}\,c^{(1)2211}_{\ell equ} + 0.07(2)\,\mathrm{Im}\,c^{2211}_{\ell edq} + 7(3)\times 10^{-3}\,\mathrm{Im}\,c^{2222}_{\ell edq}$$

REDTOP sensitivity to Wilson CP violating Wilson coeffiecients

Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction + analysis*	**Total**	Branching ratio sensitivity
$\eta \to \pi^0\mu^+\mu^-$	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}%	-

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

Target Systems



MUSE LH_2 target

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

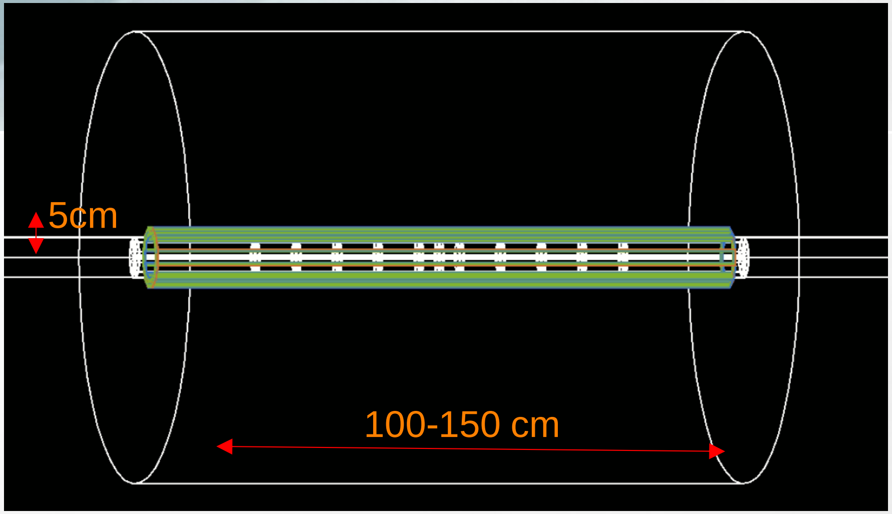
Target for π^- beams: LH_2 (pellets or fluid)

– For π^- beams only

– More expensive, but less background

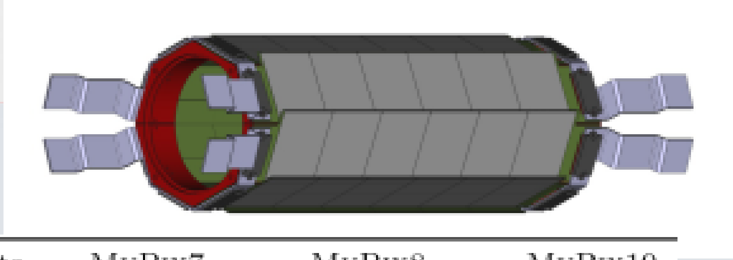
– Tagged η/η' production: $\pi^- p \rightarrow \eta/\eta'\ n$

Vertex Detector



Requirements

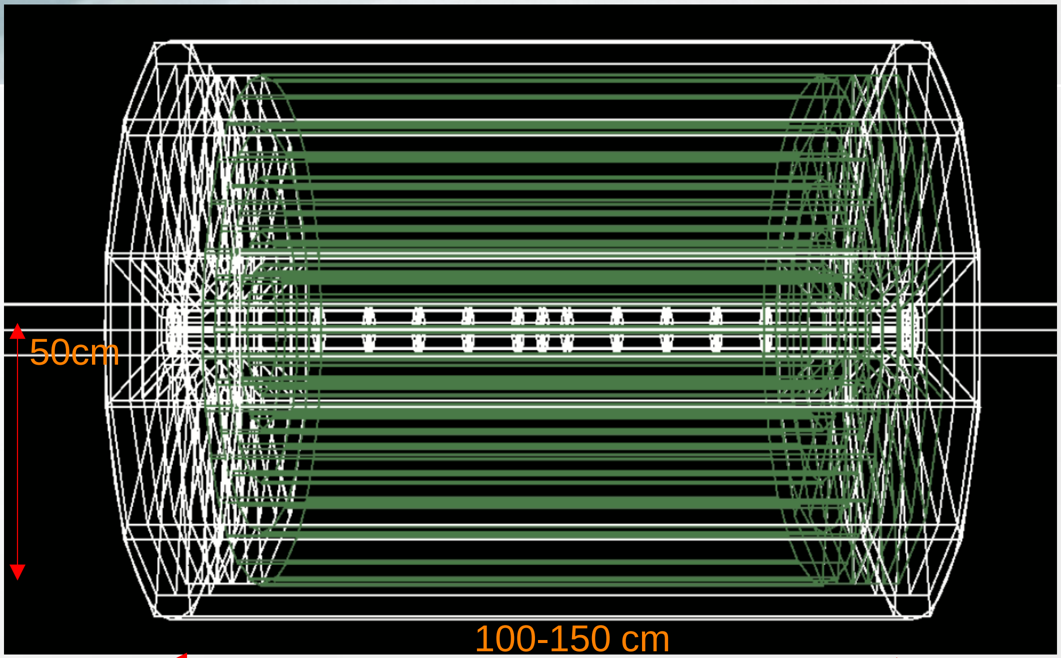
- <0.3% X0
- <=70μm vertex resolution in x-y.
- No active cooling (He cooling)
- Rad-hard ~5x10^5 1 MeV-neq n/cm2/sec
- Timing: ~8 nsec (with timing corrections)



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



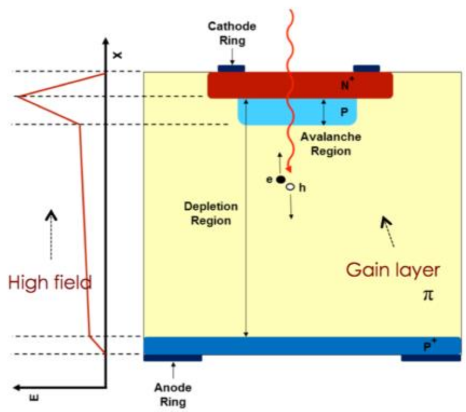
Requirements

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

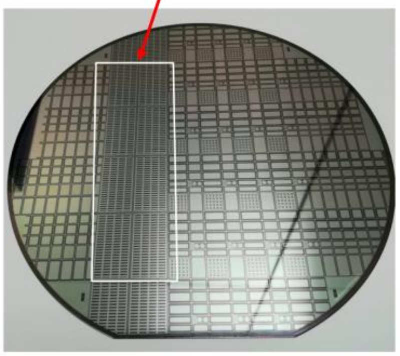
Adaptation of CMS's ETL

- –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

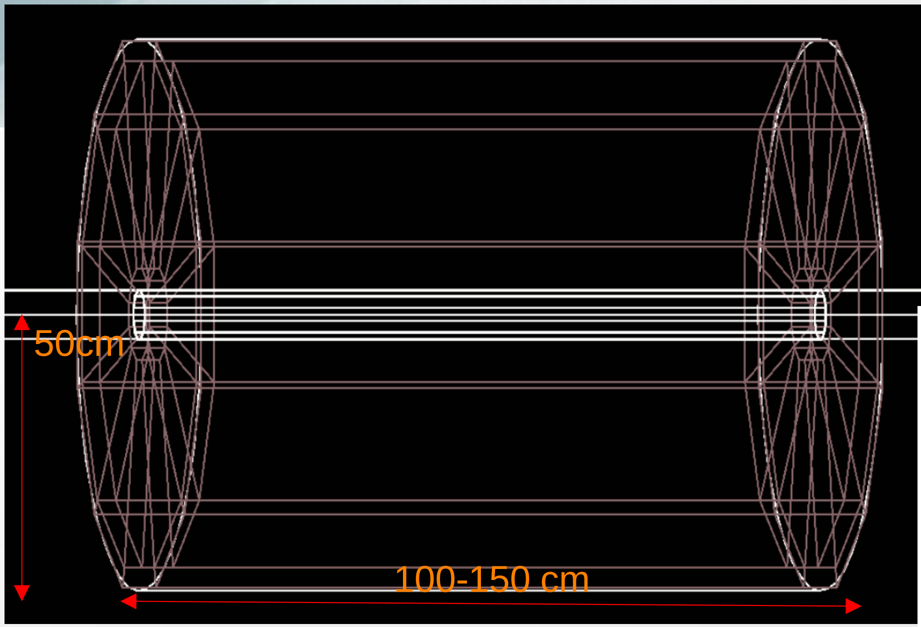


CMS-designed 96-channel sensors



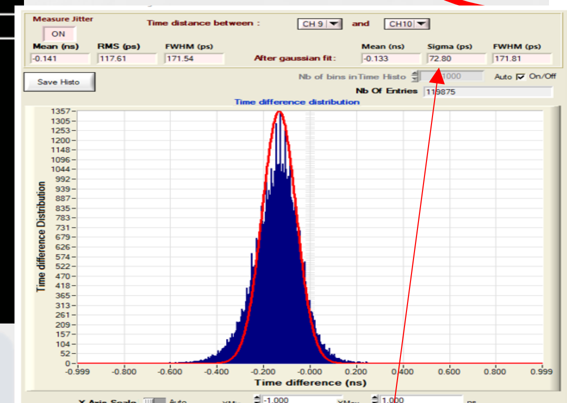
FBK wafer with CMS- and ATLAS- sensors

Threshold Cerenkov - TOF



Requirements

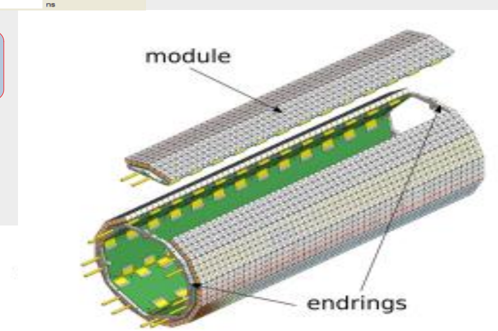
- *99% efficiency*
- *Rad-hard <1x10^5 1 MeV-neq n/cm2/sec*
- *Timing resolution: <50 psec /layer*



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

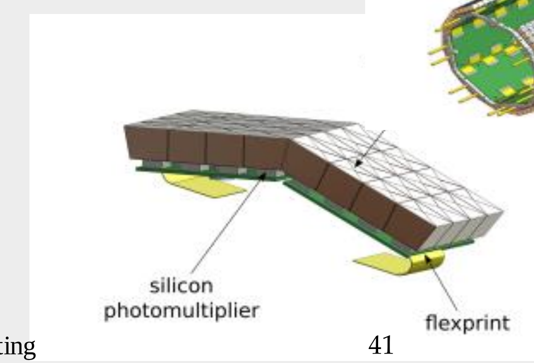
Option 1: Small tiles of JGS1 & on-tile SiPM

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

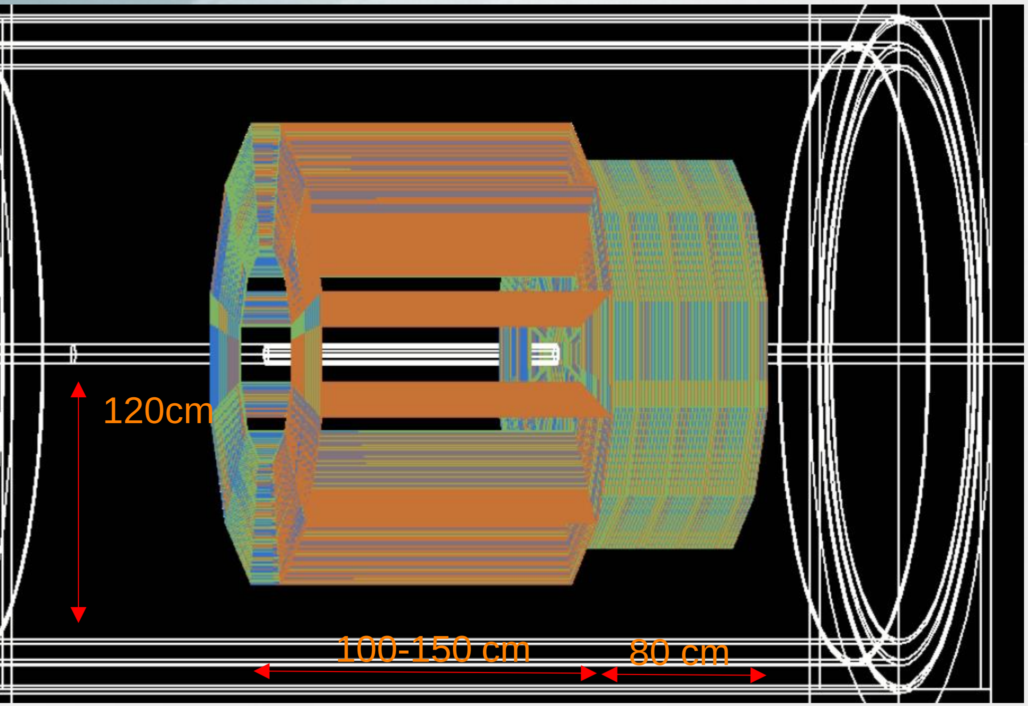


Option 2: LGAD

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

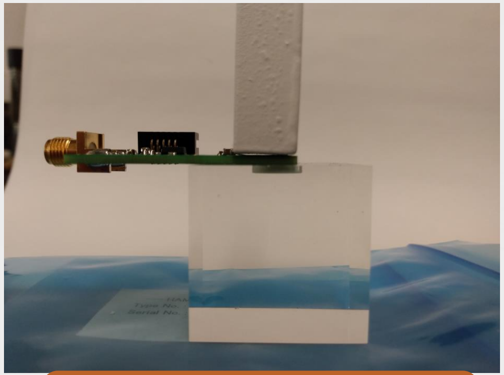


CALORIMETERS



Requirements

- $\sigma_E/E \sim 2\text{-}3\%/\sqrt{E}$
- *~80 psec/cell timing resolution achieved for MIPs.*
- *Lepton/hadron separation >99% Rad-hard ~5x10^4 1 MeV-neq n/cm^2/sec*



Cerenkov tile
FEE from S. Los

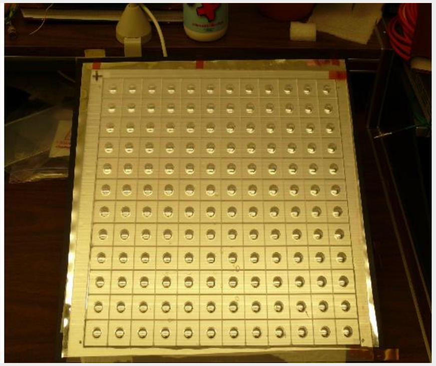
EM: dual-readout ADRIANO2

- 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

Gd-doped glass RPC

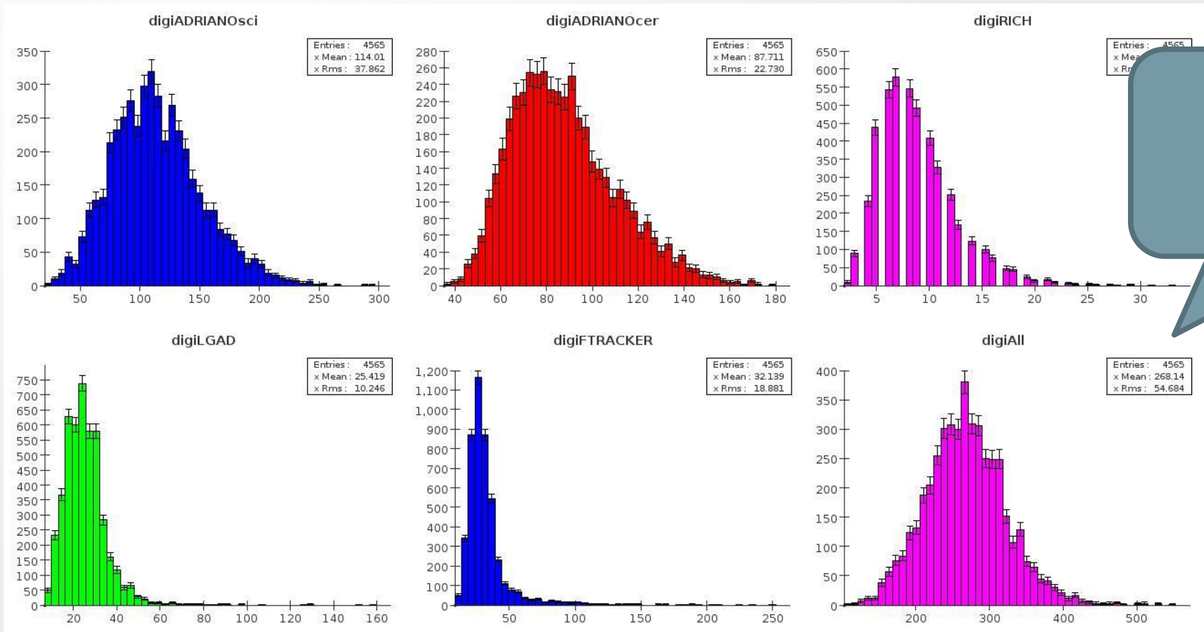


Scintillation tile

REDTOP Trigger Requirement

Untagged 10^{14} η/η' mesons

Hits from subdetectors



Total channel occupancy: 270 ± 50 /evt

Trigger rejection factors

18x LHCb

Trigger stage	*Input event rate Hz*	*Event size bytes*	*Input data rate bytes/s*	*Event rejection*
Level 0	$7. \times 10^8$	1.4×10^3	9.8×10^{11}	$\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	

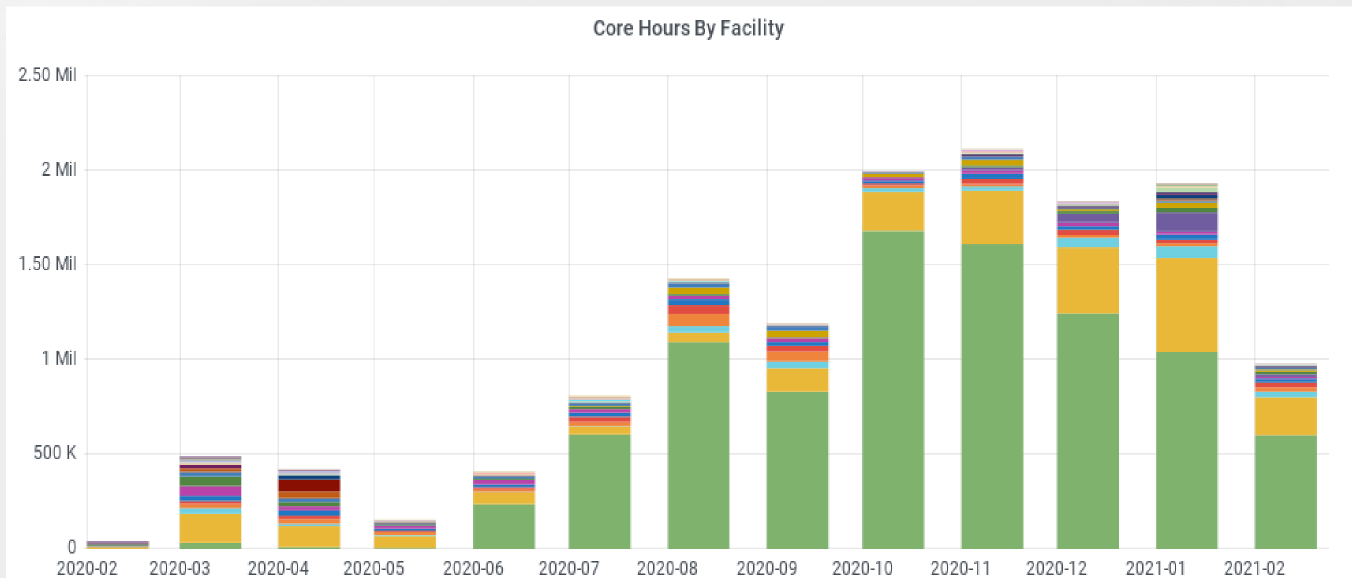
Hardware

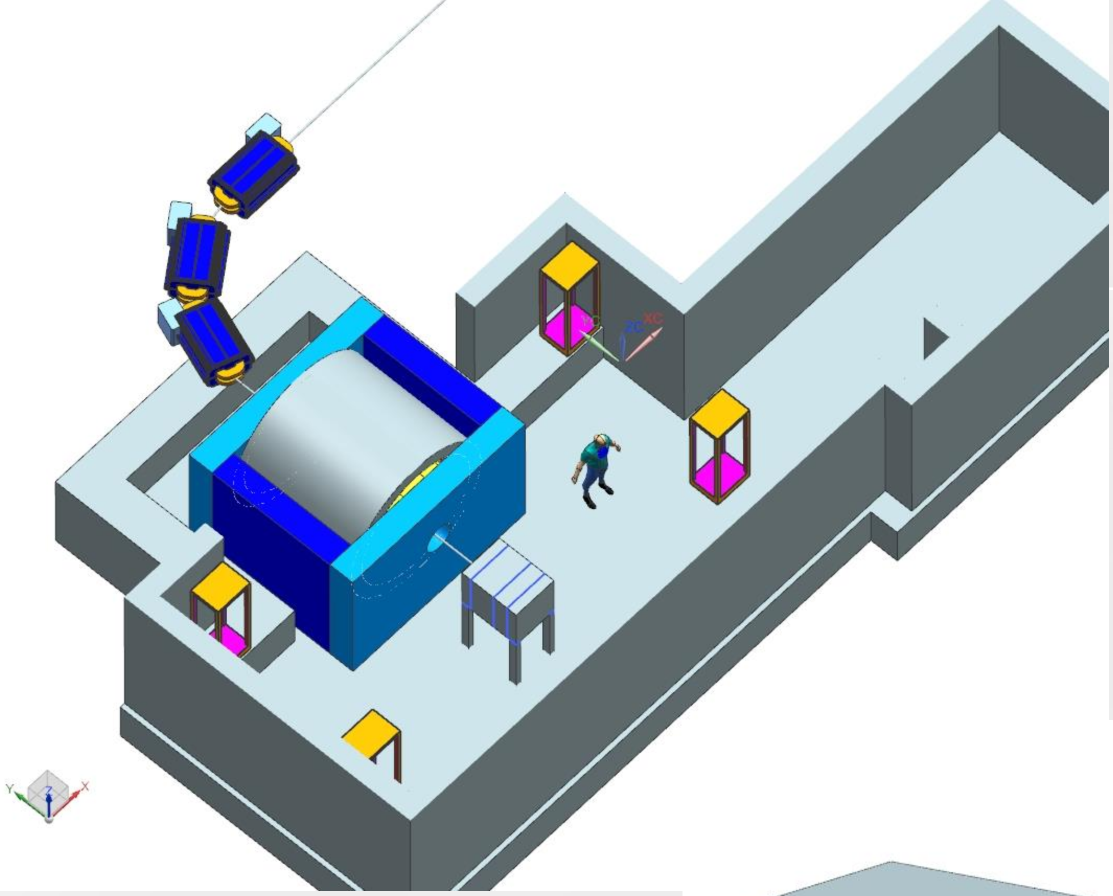
Software

REDTOP OSG Yearly Usage Statistics

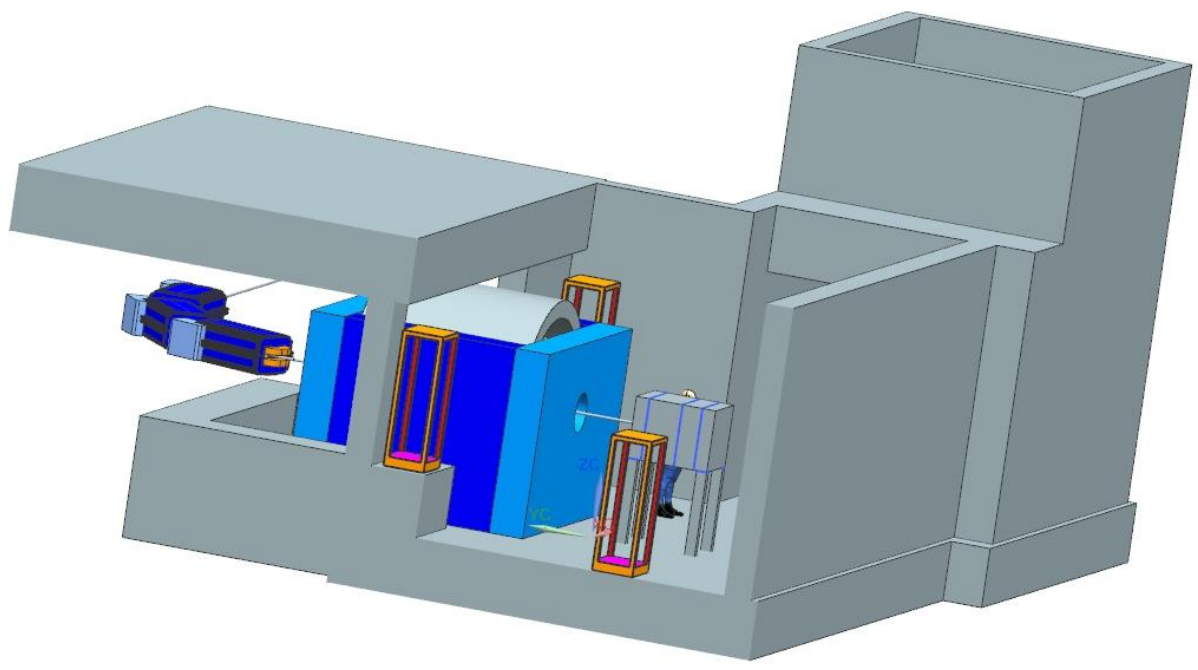
	total
SU ITS	9 Mil
MWT2 ATLAS UC	2 Mil
GLOW	303 K
TCNJ - ELSA	293 K
FSU_HNPGRID	267 K
BNL ATLAS Tier1	264 K
UConn-OSG	250 K
UConn-HPC	178 K
UColorado_HEP	174 K
OU ATLAS	173 K
ASU Research Computing	163 K
Nebraska-Omaha	75 K
ICC-SLATE-HTC	69 K
New Mexico State Discovery	61 K
NWICG_NDCMS	42 K
Clemson-Palmetto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





REDTOP detector in AP50



J. Kilmer
J. Rauch

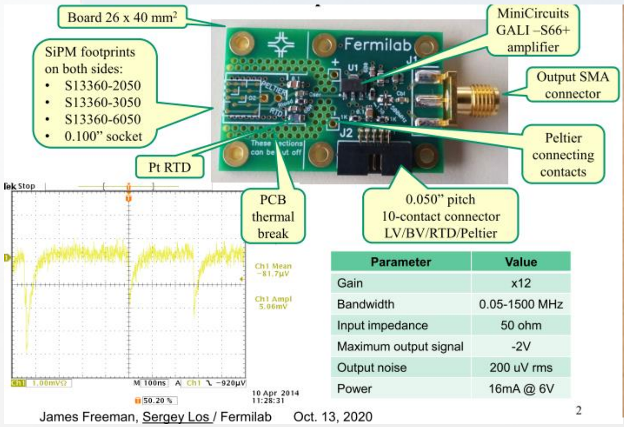
(Many thanks to K. Krempetz, as well)

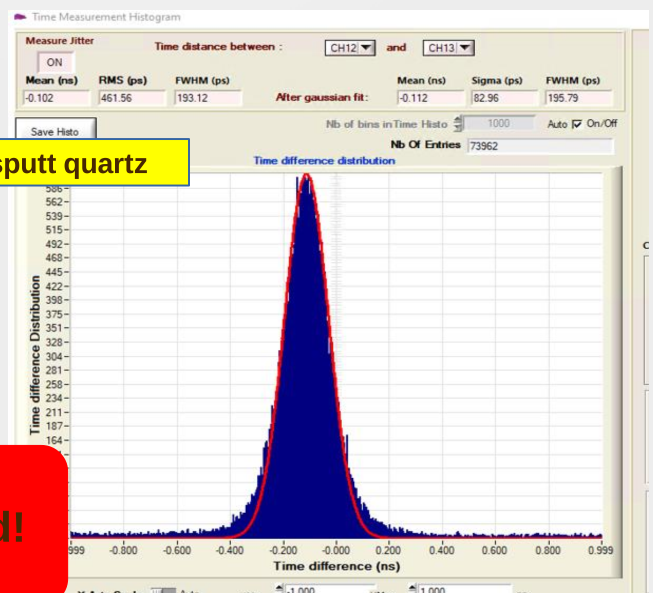
Slide from Calor2022

Cerenkov TOF in T1604

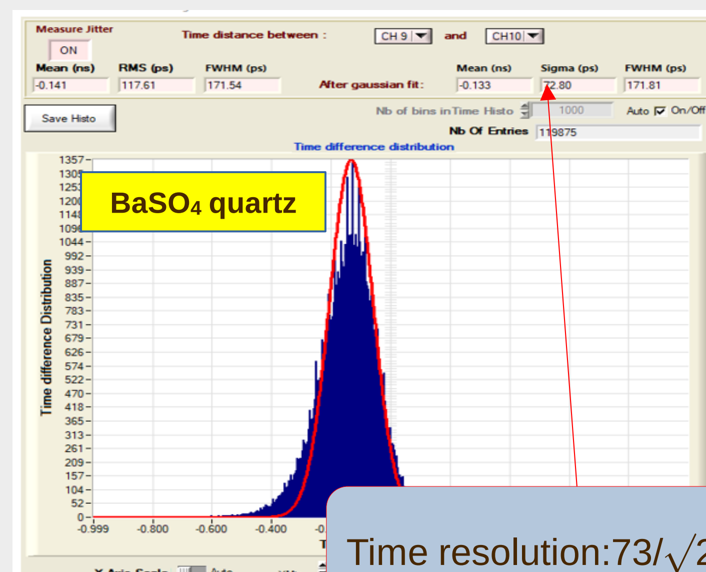
Test beam with 3x3x1 cm^3 JS1 tiles with UV coating

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





Al-sputt quartz



BaSO$_4$ quartz

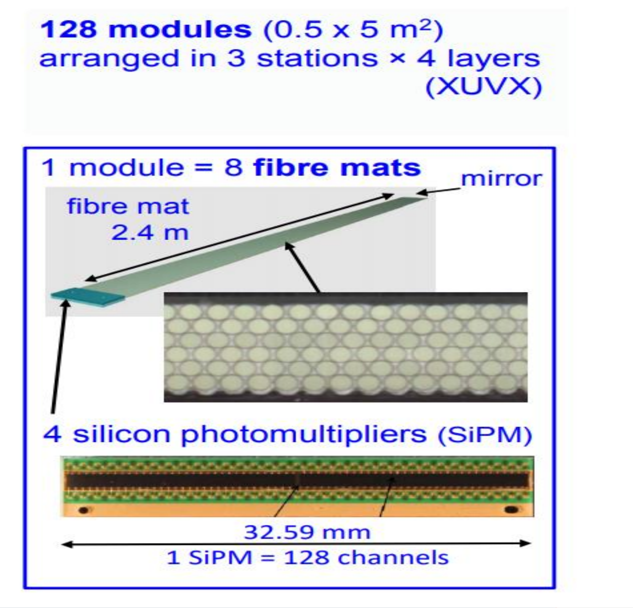
Goal achieved!

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

Vertex Detector R&D

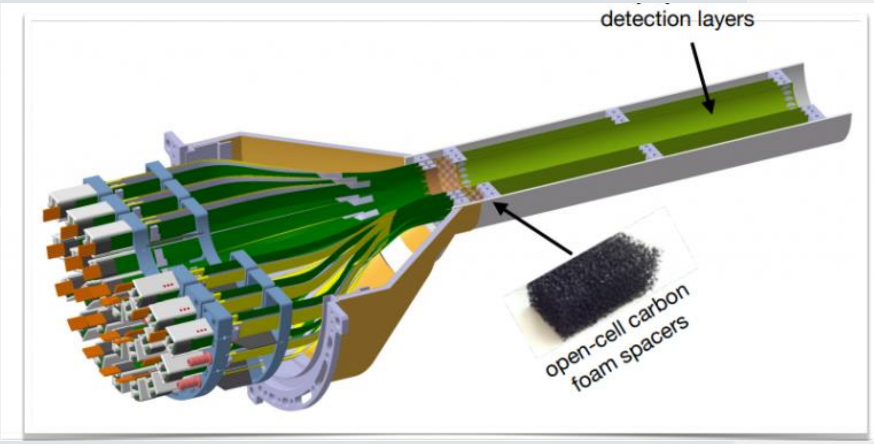
Option 1: LHCb-stile Fiber Tracker

- 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



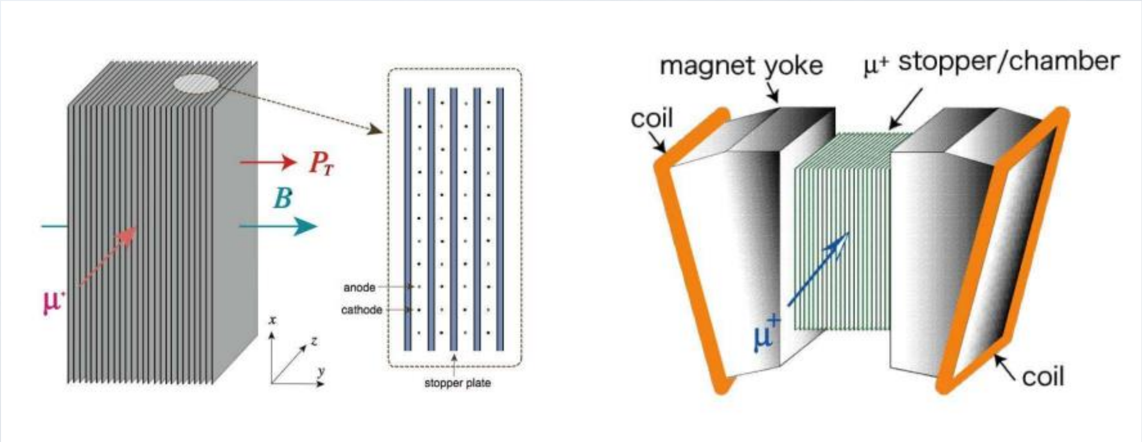
Organization

- 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

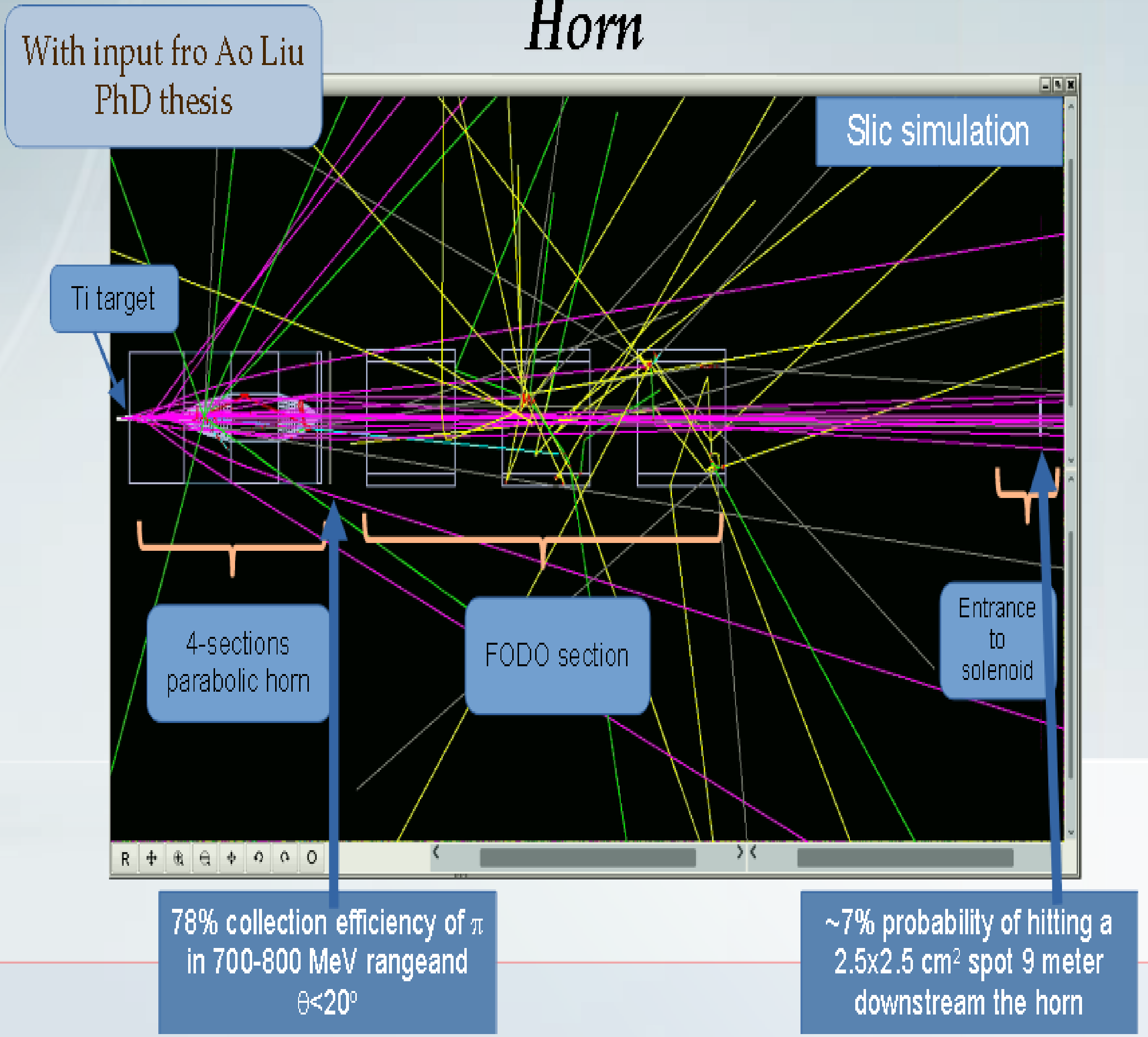
- 55 million core-hours for Monte Carlo jobs
- 35 million core-hours for data reconstruction jobs
- Total: ~ 90 million core-hours /year

(estimate by projecting current OSG usage)

REDTOP

Beam Options at ESS

Pion beams with modified Longhin Magnetic Horn

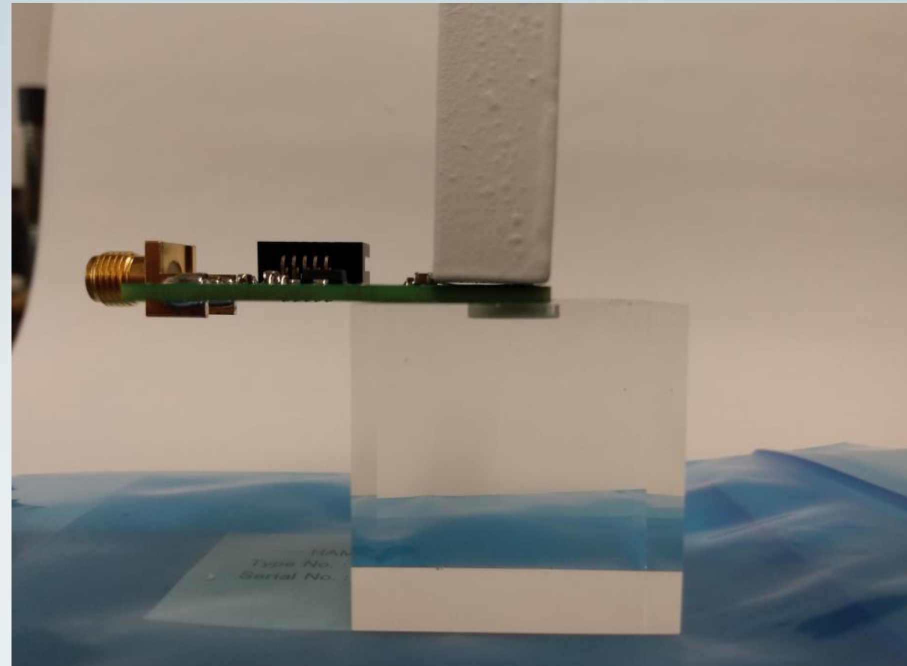


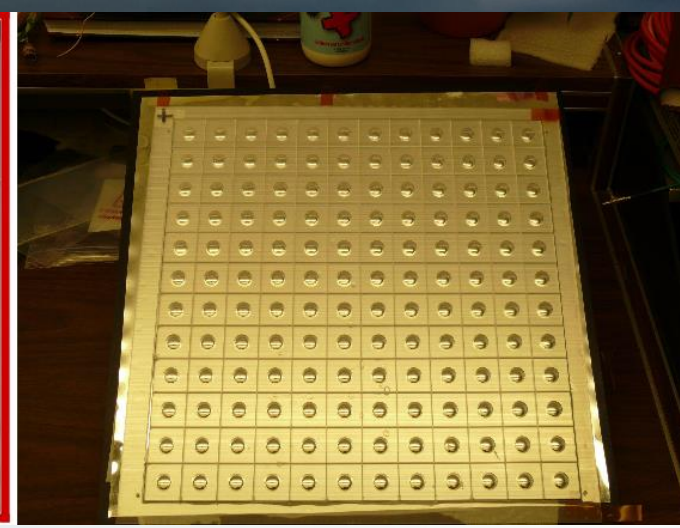
•A 1.3 GeV proton beam hitting a tungsten target has a 2% probability of generating a pion in the right energy range. A HPSP-style (CERN's neutrino superbeam) double horn would funnel about 78% probability of funneling them into a parallel beam, with a ~7% probability of hitting a 2.5x2.5 cm^2 spot 9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

Beam intensity

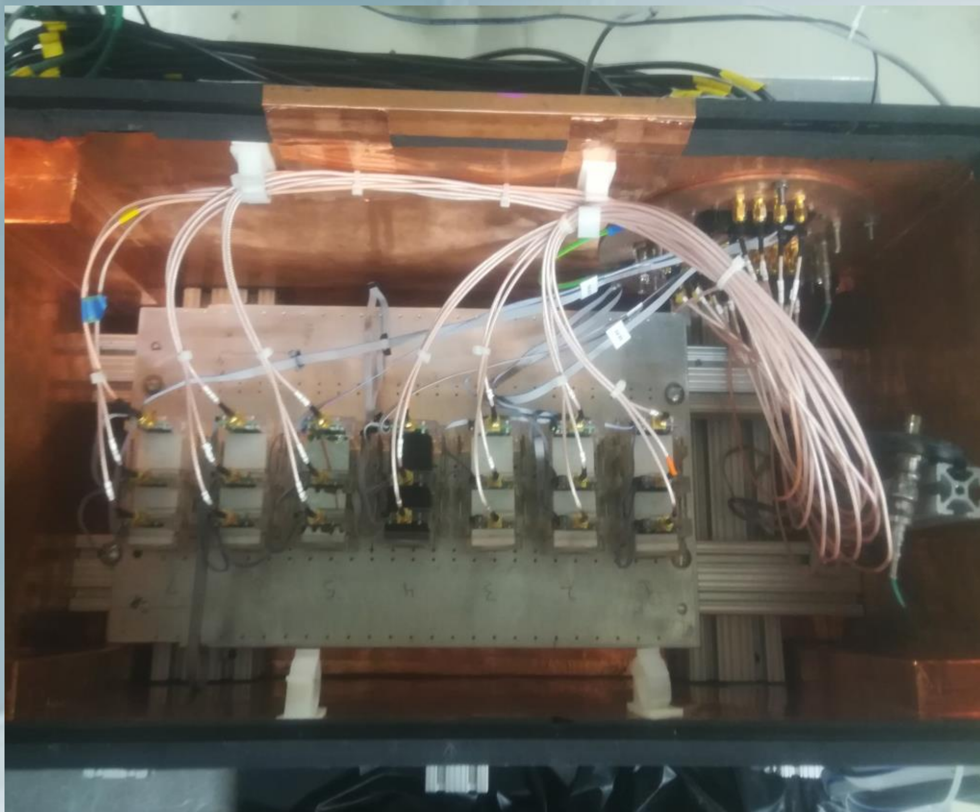
Slide from Calor2022

FEE + Tiles with dimple



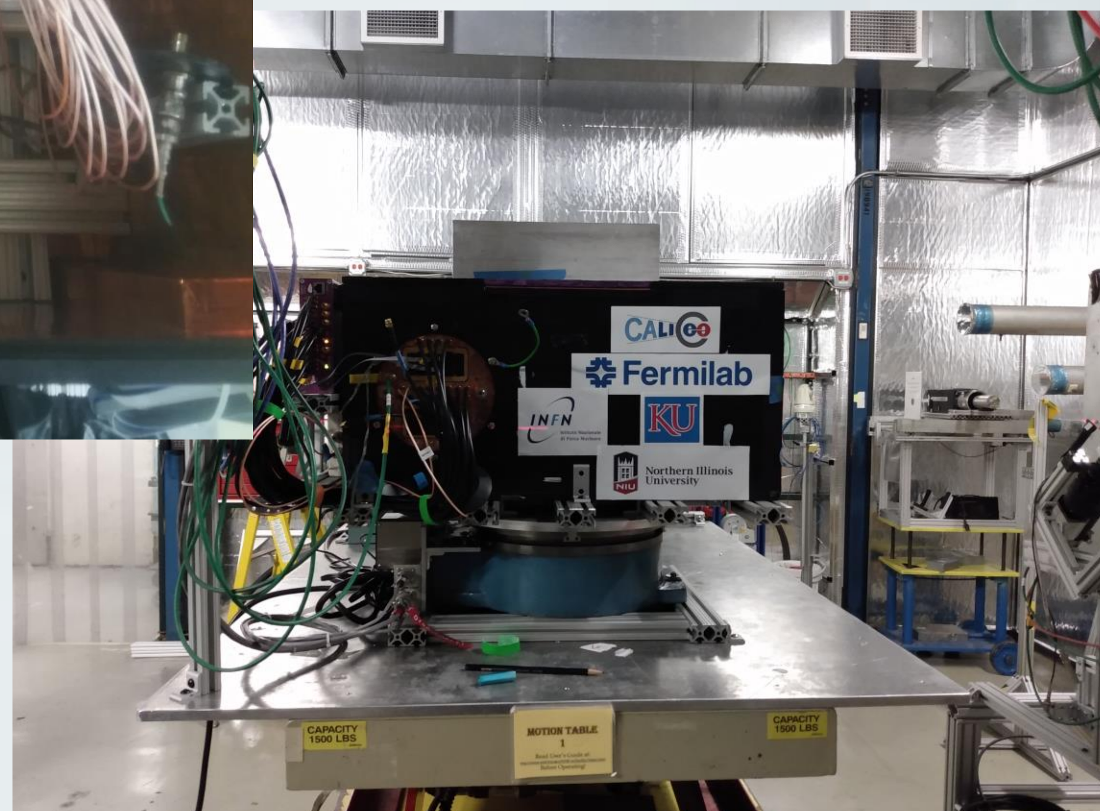


ADRIANO2 at FTBF

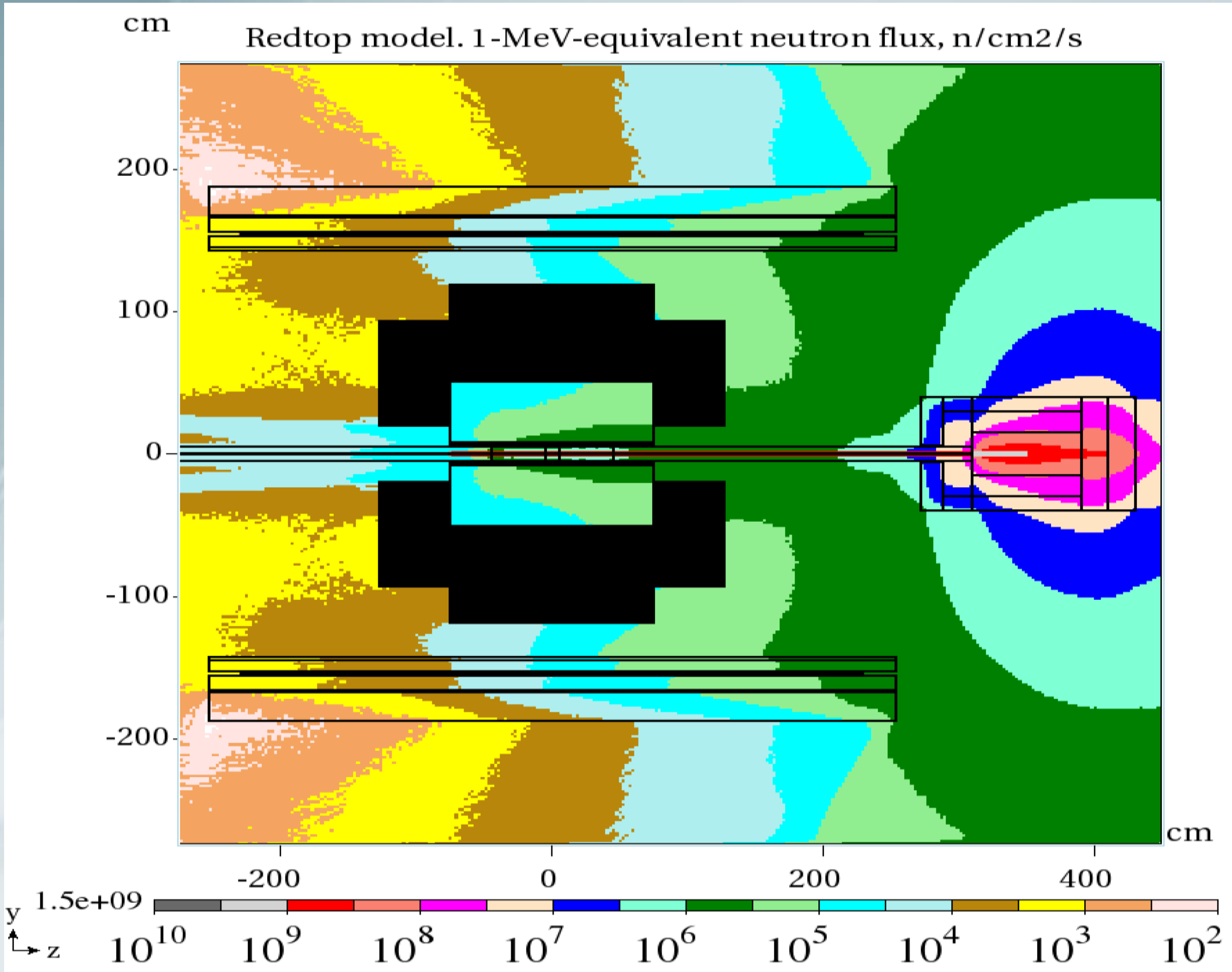


- Three test beam completed
- Tiles organized in triplet of three sizes
- Final test beam planned for Winter 2024
- Final test beam with 64 channels and ASIC DAQ : CAEN 5500 with petiroc-2

(University of Kansas)

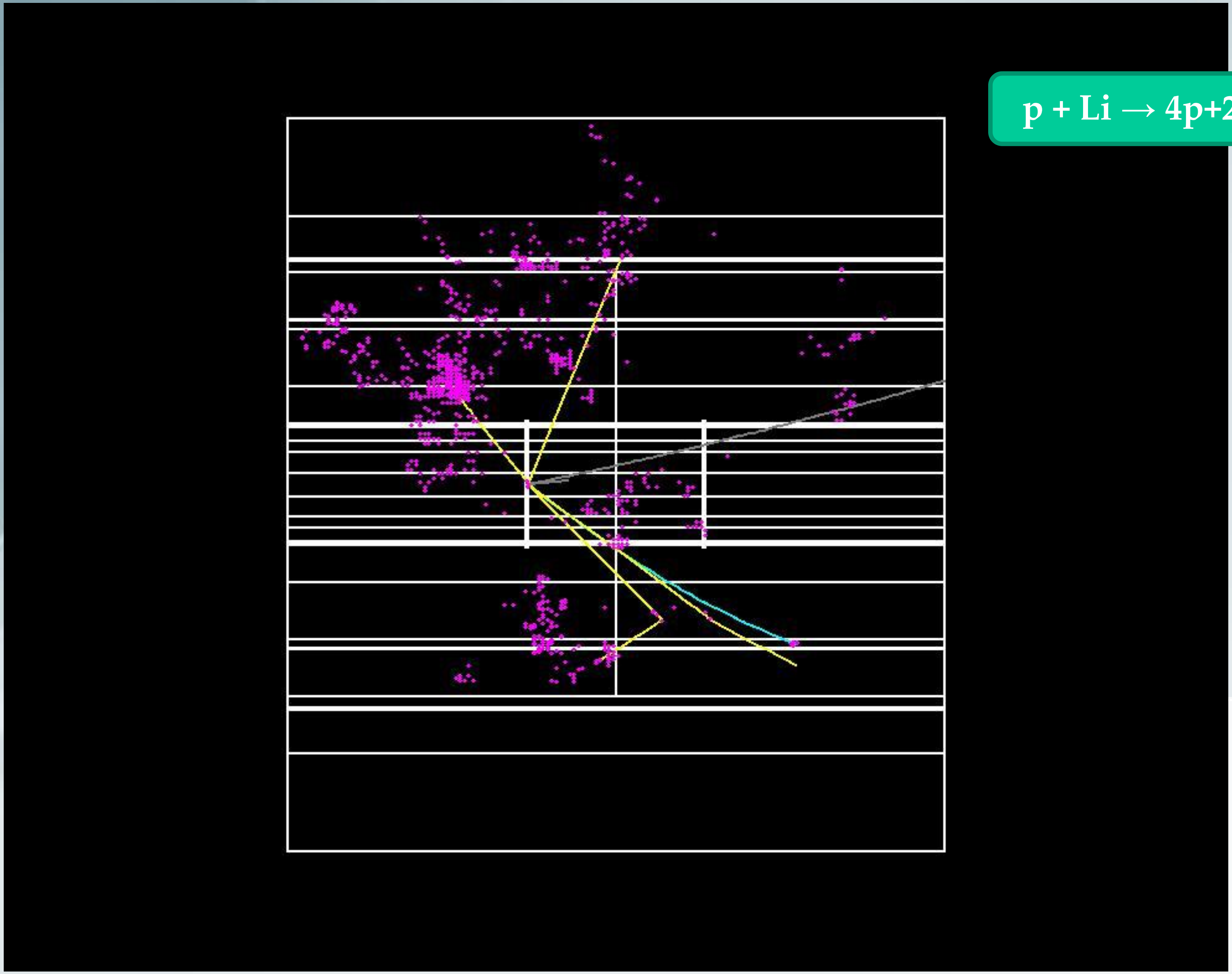


Radiation flux with MARS15



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

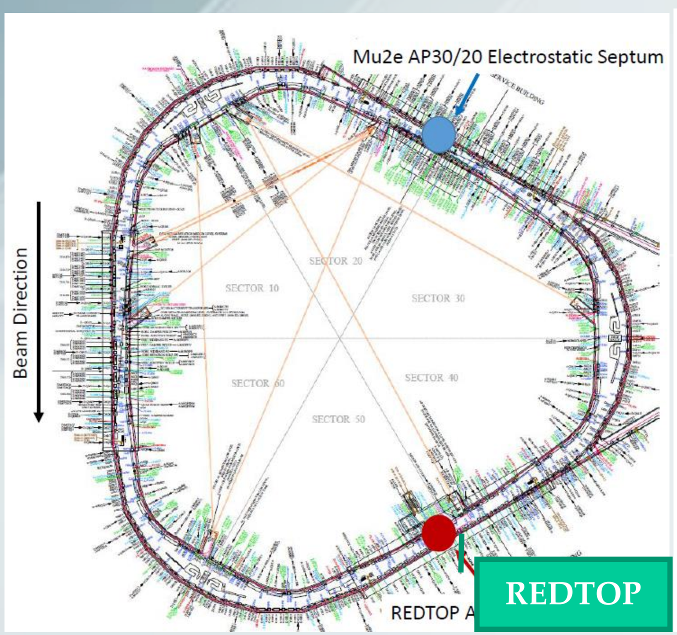
Event Display @ 1.8 GeV

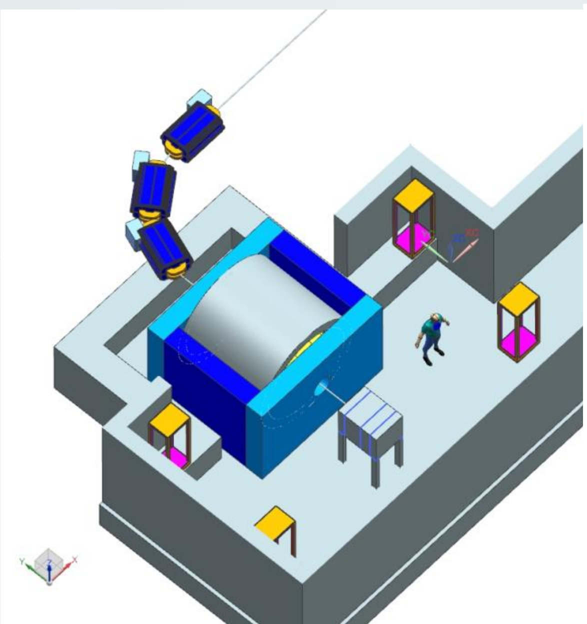


p + Li → 4p+2n+1π+ De

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

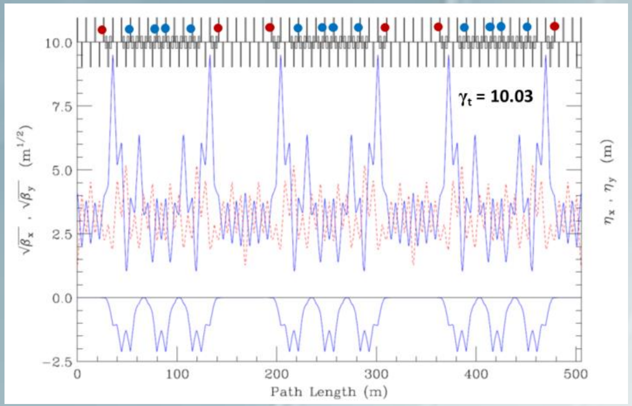
- *Single p pulse from booster (≤4x10^{12} p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)*
- *Energy is removed by inserting 1 or 2 RF cavities identical to the one already planned (~5 seconds)*
- *Slow extraction to REDTOP over ~40 seconds.*
- *The 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%*

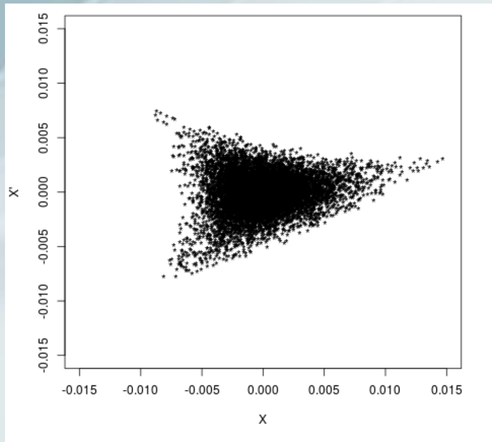




FNAL option

Accelerator Physics Issues





- ***Transition Energy***
  - γ_t is where Δf/f = 1/γ2 - <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

REDTOP

Accelerator Physics Issues

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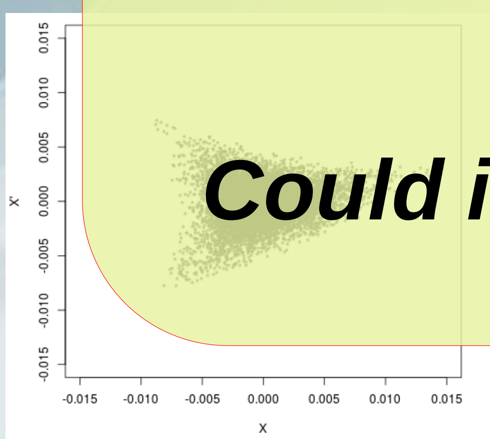
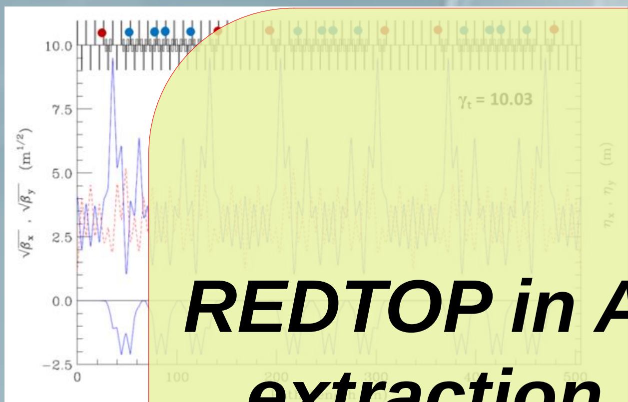


No showstoppers to run at Fermilab

All needed accelearator components on site

Could install in AP50 immediately

Accelerator Physics Issues



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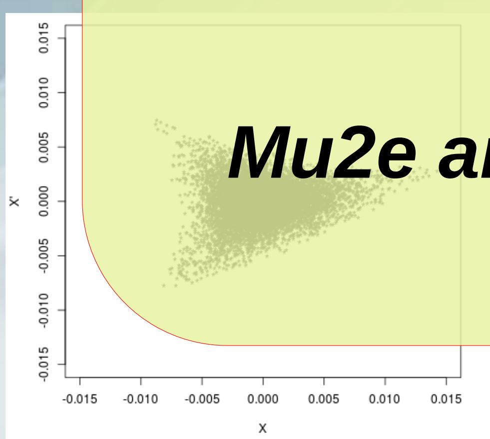

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REDTOP in AP50 uses the same resonance extraction parameters as Mu2e, but in a different location

Mu2e and REDTOP can run togheter!

GSI option

REDTOP

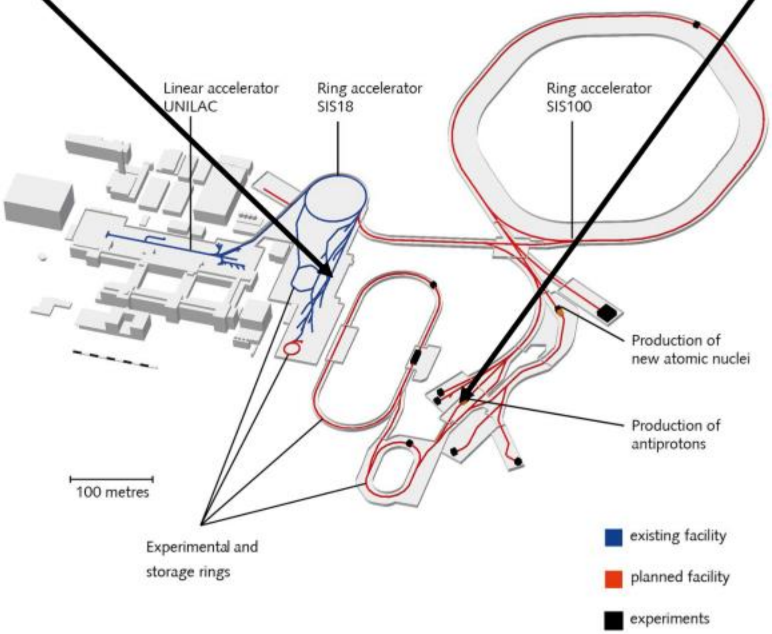
Beam Options at GSI/FAIR (near future)

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

Beam intensity: 1.8 GeV protons with 1e11/s

Daniel Severin

GSI option

Beam Options at GSI (far future)

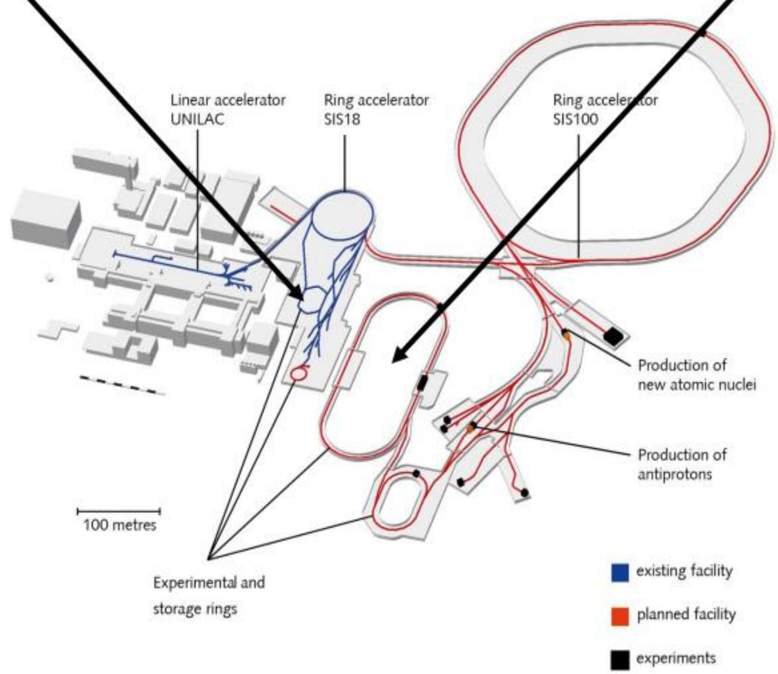
REDTOP

Opportunities as in-ring target exp.

FAIR GSI

OPTION C ESR (SIS18)	OPTION D HESR (SIS100)

- 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



- 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

ESS option

REDTOP

Beam Options at ESS

JAGIELLONIAN UNIVERSITY
IN KRAKOW

REDTOP

Necessary infrastructure at ESS:

- Only 1% of the proton or pion beam interacts with target and can be useful for REDTOP
- Remaining beam can be used for a downstream pion or muon precision experiments.
- ESS could take a staged approach.

- **Proton beam :**
  - extract ~30 W of protons at 1.8 – 2.0 GeV
  - Transport beam line into the experimental hall
- **Pion beam:**
  - Extract ~200 kW of protons > 1.3 GeV
  - Transport beam line to the experimental hall
  - Pion target and pion collector station

Marcin Zieliński,

Beam at ESS: 2 GeV @ 5 MW

π^+/ π^- Beam Options

REDTOP

Semi-tagged η–factory

ESS or PIP-II + Booster or ORNL options

- *Semi-tagged production from reactions:*
  - $\pi^+ + Li/Be \rightarrow \eta + X$ *(large x-sec)* $\rightarrow$ *non-tagged*
  - $\pi^+ + d \rightarrow \eta + p + p \rightarrow$ *2p-tagged*
  - $\pi^- + p \rightarrow \eta + n \rightarrow$ *neutron-tagged*
  - $\pi^- + He_3 \rightarrow \eta + t \rightarrow$ *tritium tagged*
- *η production cross-section: ~ 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

78% collection efficiency of π in 700-800 MeV rangeand θ<20°

~7% probability of hitting a 2.5x2.5 cm² spot 9 meter downstream the horn

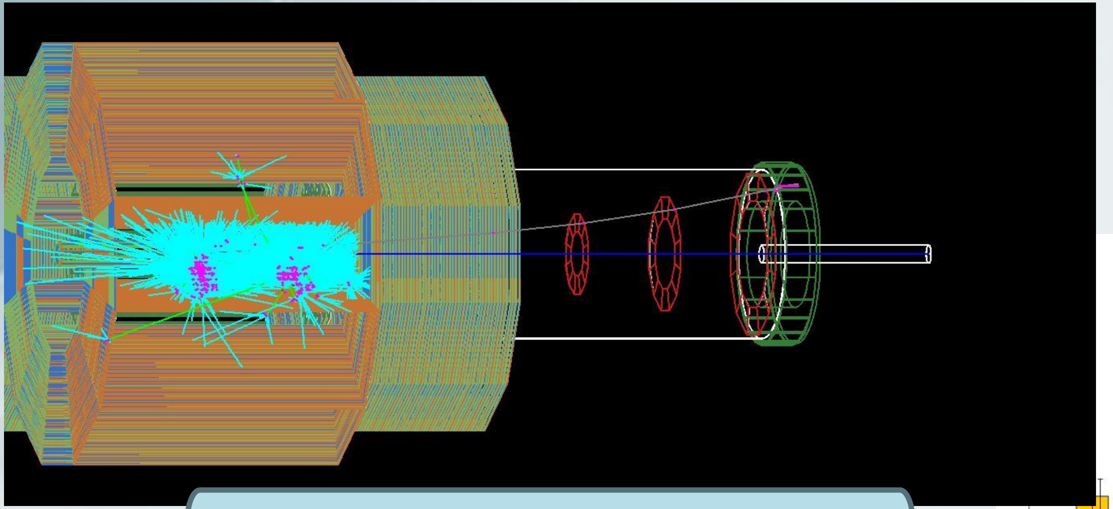
Longhin magnetic Horns are expensive.
With ESS beam power, LAMPF-style horns could be used
(see Patrik Simion thesis. Uni-Uppsala, 2019)

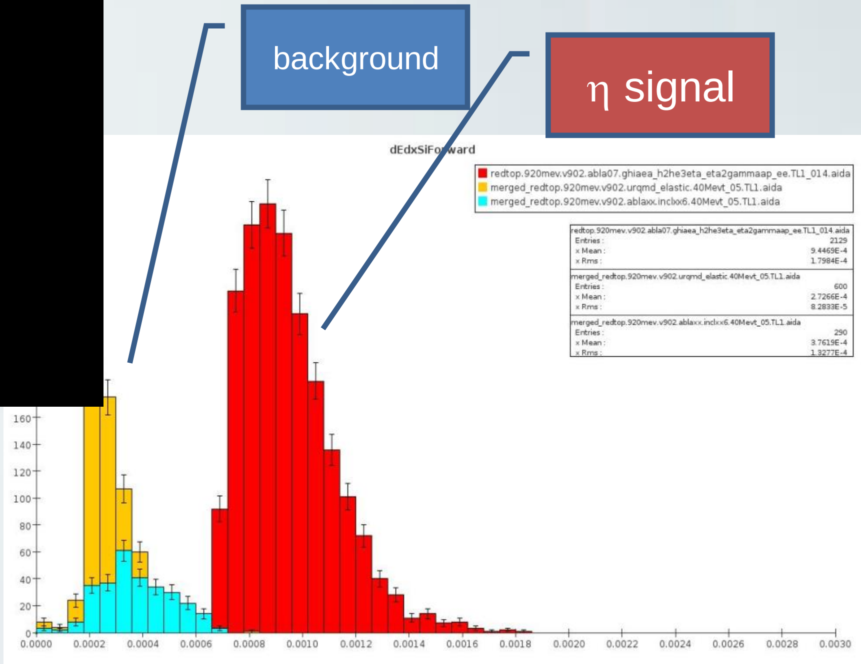
ESS & PIP-II options

Tagged η/η' Factory

- *Fully tagged production from nuclear reaction: p+De $\rightarrow \eta$ +He$_3^{++}$*
- *η production cross sec: ~ μbarn; bkg cross sec: ~ 100 mbarn -> 5 orders of magnitude!*
- *Requires fwd tagging detector for He$_3^{++}$*
- *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



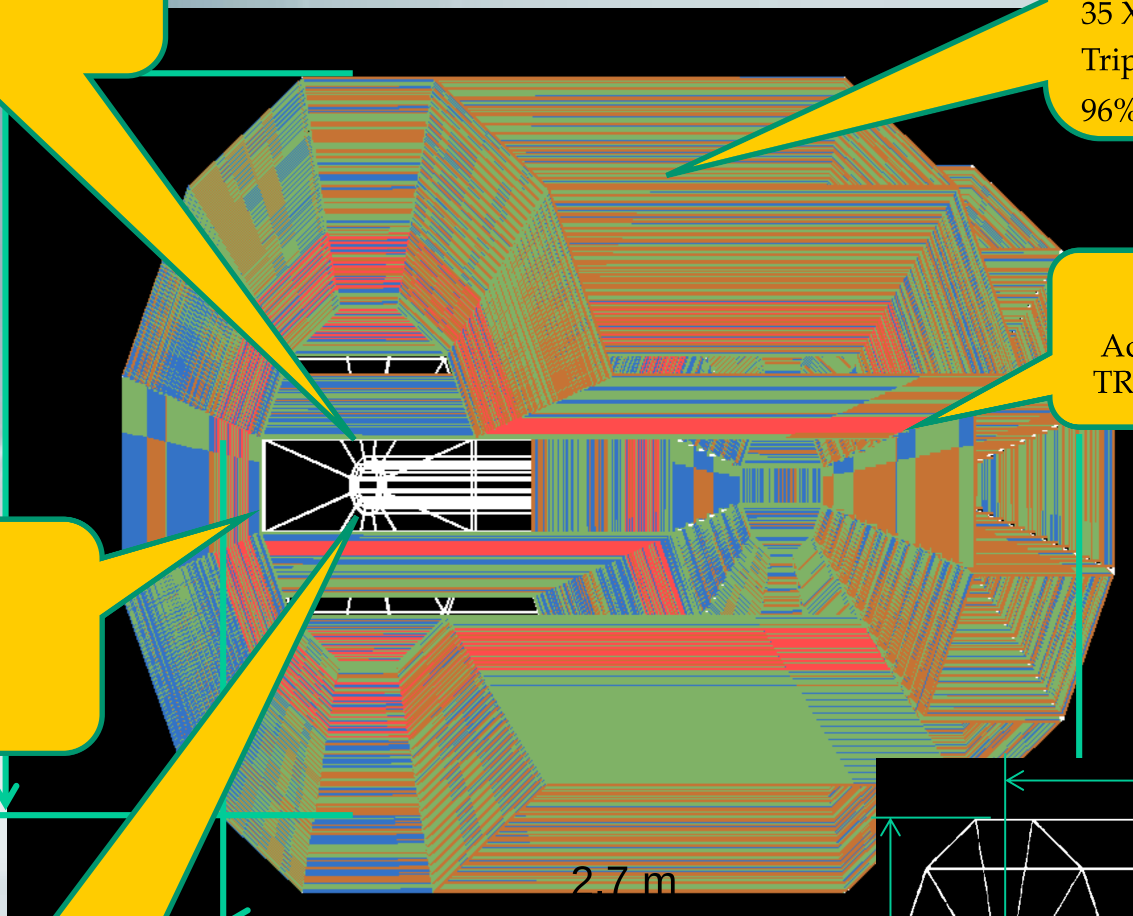


Signal/background separation achievable with a properly designed fwd tagger and trigger

REDTOP detector

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

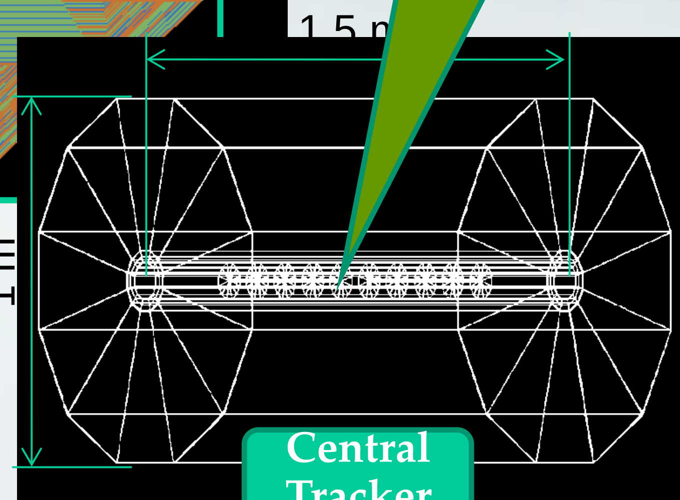
ADRIANO2/3 Calorimeter (tiles + Gd-doped RPC)
Scint. + heavy glass sandwich
35 X_0, 2.9λ_I (~ 64 cm deep)
Triple-readout +PFA
96% coverage



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

CTOF
~ 1m x 1.5 m
Quartz tiles
98% coverage

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



Vertex detector
for rejection of γ-conversion and vertexing

Additional info/questions/comments

The final goal is for ESS to reach 5 MW beam with 2.0 GeV protons at 14 Hz, 2.86 ms pulse length. Average pulse current 62.5 mA.

It is probably possible to ”detune” the last cavities of the linac to slightly reduce the energy for Redtop. Can it be done for one pulse only between two pulses at full energy?

If ESSnuSB is funded, we will co-fund an upgrade of the linac to 2.5 GeV beam energy. The linac will then operate at 28 Hz where every second pulse is a proton pulse and every other is H-. Average pulse current 50 mA, so still 5 MW per beam species.

It is possible to separate the pulses (or parts of a pulse) in time with a kicker. It is much harder and risky to split the beams in transverse space.

Question: Is it possible to produce longer pulses at a lower intensity ? (questionable)

Question: Is it possible to have the occasional proton pulse at a much lower intensity than the nominal 50 mA? (probably yes)

Comment on the extraction at the 2.5 GeV point: The reason I propose to use this one rather than a point further upstream is that the feasibility has been studied within ESSnuSB.

There are ways of extending pulses but it requires time/space; a delay line or so, which would add to the cost.

Status and Prospects

Brief REDTOP history

- 2017 – Proposal submitted to **Fermilab** for running in 2021-22 at the Delivery Ring
  - Declined because Mu2e would be running in those years
- 2018 – Included in PBC@**CERN**
  - Preliminary feasibility study to run at the PS or PSB or LEIR (see next slide)
  - Offered to run at the PS with $\mathcal{O}(10^{17})$ POT/yr. Would consider other labs.
  - See next slide form more details.
- 2022 Physics case presented in White Paper at Snowmass Summer Meeting
  - Sensitivity to 15 processes fully simulated and reconstructed
  - 20 theoretical models benchmarked
- 2022 **GSI** Director (P. Giubellino) solicited a proposal to run at SIS18
  - Offered a beam intensity same order as CERN.
  - Major detector improvements made:
    1. 1) HV-MAPS VTX (rather than LHCb style fiber tracker): precise 3D tracking
    2. 2) Higher granularity innermost layers of ADRIANO2 (better separation)
    3. 3) Two layers of CTOF (timing resolution improvement: 50 ps -> 30 ps)
- 2023 Proposal submitted but GSI's Director quit
- 2025 Started new feasibility studies to run at **CERN** ' PSwith fast extraction
- 2026 Proposal for running at the **ESS** (in preparation)