The REDTOP experiment: Rare Eta Decays to Explore new Physics

Rare **E**ta **D**ecays with a
Tpc for **O**ptical **P**hotons

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Rationale for an η/η‘ Factory

- Recent LHC results suggest that the next search for New Physics should be in the MeV-GeV mass range with high-intensity beams.

  "…Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders…" [G. Krnjaic RF6 Kickoff Meeting, August 12, 2020]

- The only known particles with all-zero quantum numbers are the η/η′ mesons and the Higgs boson

- All electromagnetic and strong decays of the neutral and long-lived and ′ are suppressed at first order and weak decays have branching ratios of order 10^{-11}. Branching Ratio of processes from New Physics are enhanced compared to SM.

- *"….The physics sectors which can be probed at REDTOP range from the violation of discrete symmetries to the search for new particles…"* [S. Tulin et al. https://arxiv.org/abs/2007.00664]

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

Assuming a yield ~10^{13} η mesons/yr and ~10^{11} η′ mesons/yr

C, T, CP-violation

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

New particles and forces searches

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

Other discrete symmetry violations

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

Other Precision Physics measurements

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

Non-η/η′ based BSM Physics

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

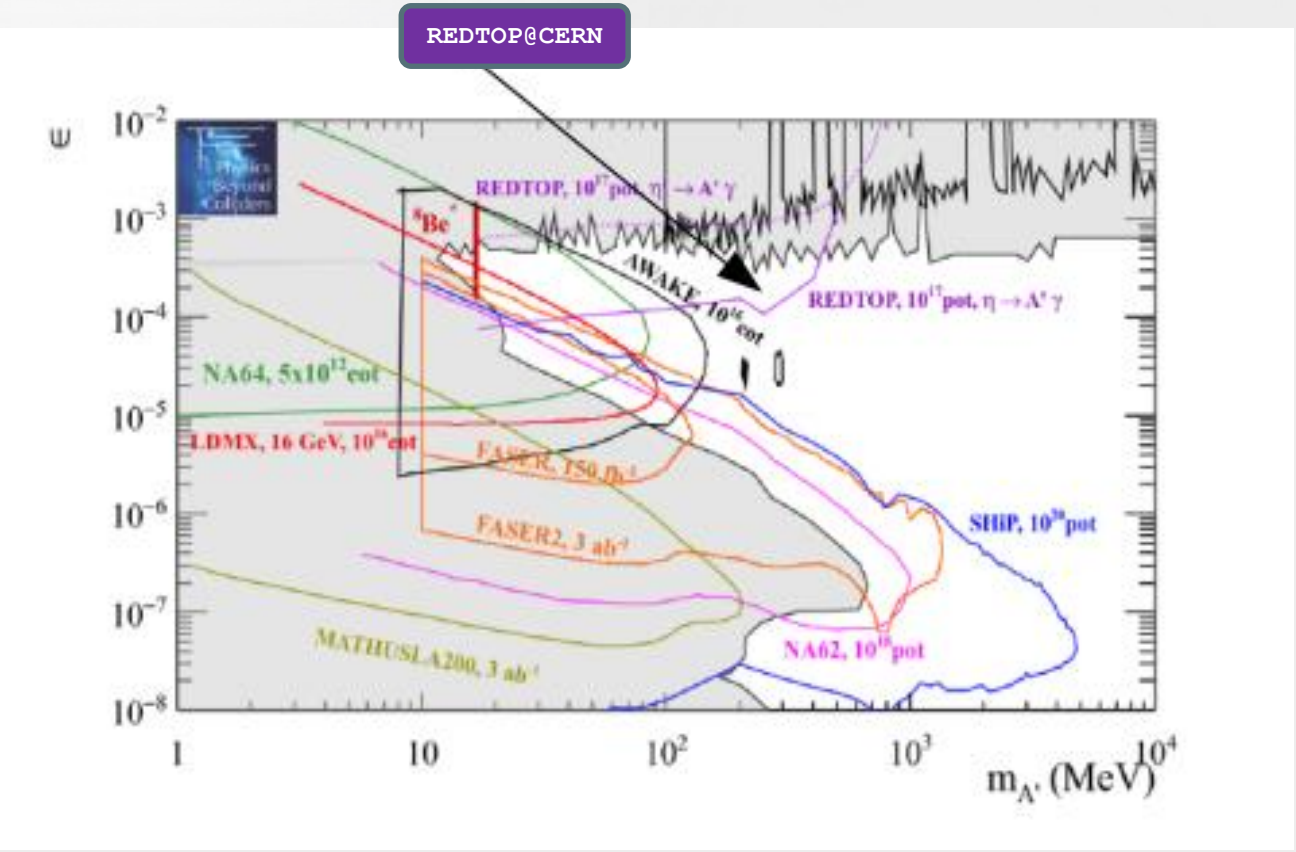
High precision studies on medium energy physics

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

Dark photon searches:

$$\eta \rightarrow \gamma A' \ \text{with} \ A' \rightarrow \mu^+\mu^- \ \text{and} \ e^+e^-$$

- *Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT*
- *Other laboratories can provide 10x more POT*
- *Only "bump hunt analysis". Vertexing being added in studies for Snowmass2021 to improve the sensitivity to physics BSM by 10x*



Searches for light scalar mesons

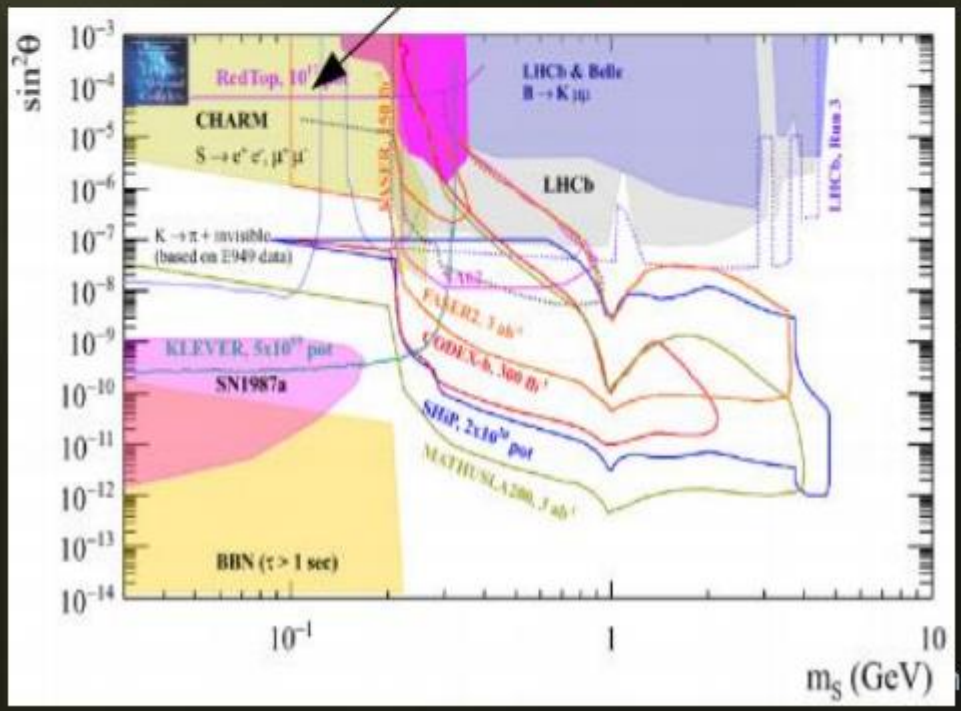
Minimal SM Higgs extension

- *Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT*
- *FNAL and BNL can provide 10x more POT*
- *Only "bump hunt analysis". Vertexing add 10x more sensitivity*

Hadrophilic Scalar Mediator

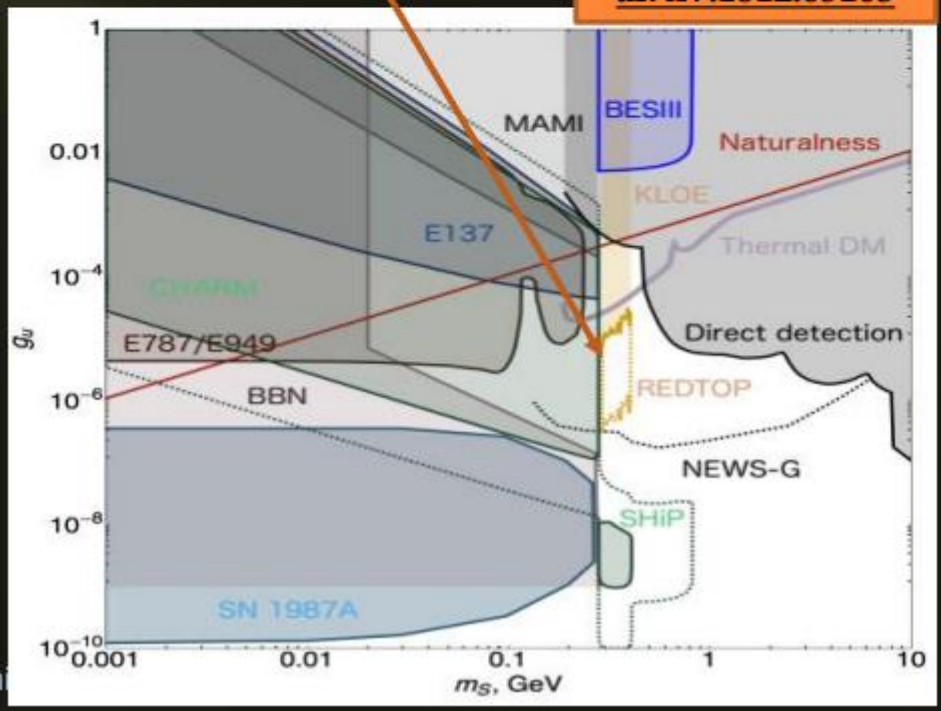
- *Studied in arXiv:1812.05103*
- *Only bump hunt - no vertexing*

REDTOP@CERN



REDTOP@Fermilab

arXiv:1812.05103



Searches for ALPs with fermion or gluon coupling

- *Beam emitted ALP's from the following processes:*
  - *Drell-Yan processes:* $qqbar \rightarrow A'/a \rightarrow l^+l^-$
  - *Proton bremsstrahlung processes:* $p\ N \rightarrow p\ N\ A'/a$ *with* $A'/a \rightarrow l^+l^-$ *(J. Blümlein and J. Brunner)*
  - *Primakoff processes:* $p\ Z \rightarrow p\ Z\ a \rightarrow l^+l^-$ *(F. Kahlhoefer, et. Al.)*
- *Only "bump hunt analysis" with 10^{17} POT (CERN). Will add vertexing+timing to the analysis.*
- *Redtop@PIP-II will provide x100 sensitivity (ALPACA study).*

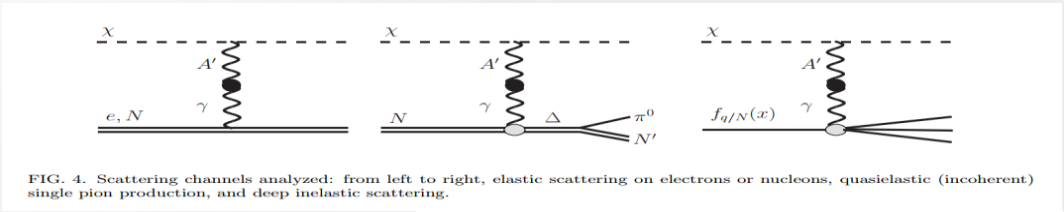


FIG. 4. Scattering channels analyzed: from left to right, elastic scattering on electrons or nucleons, quasielastic (incoherent) single pion production, and deep inelastic scattering.

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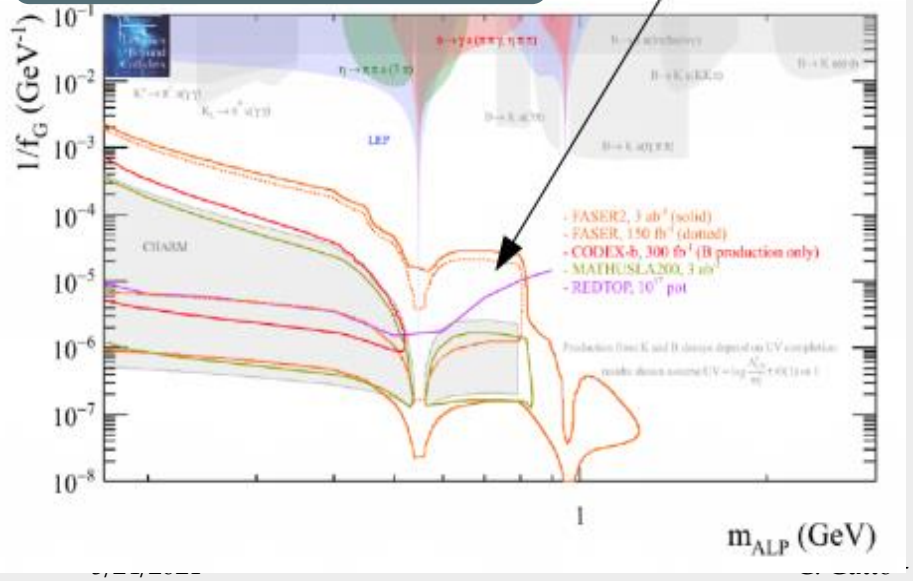
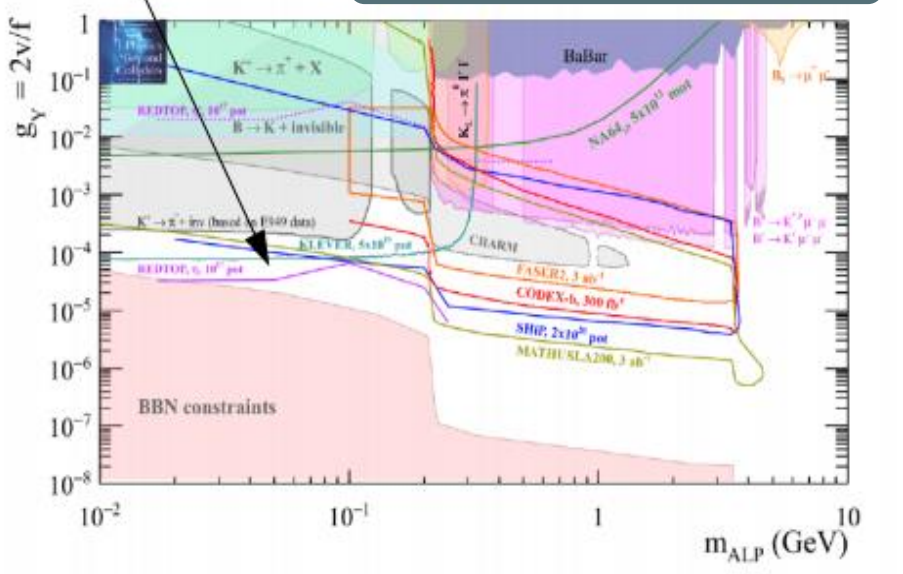
$p\ N \rightarrow p\ N\ a$ *with* $a \rightarrow l^+l^-$

REDTOP@CERN



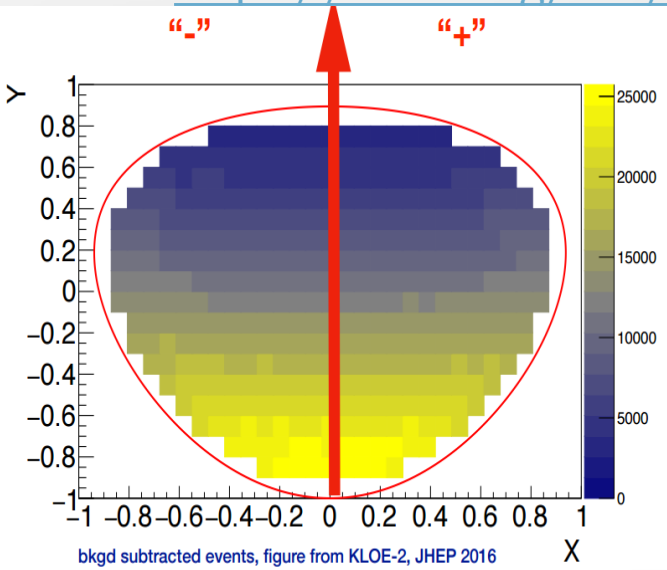
REDTOP@CERN

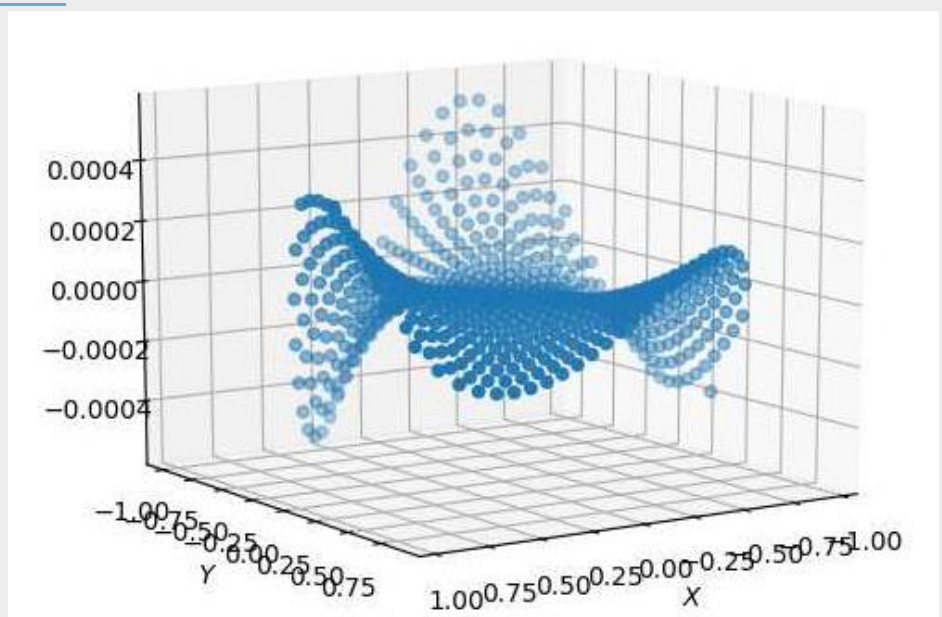
$\eta \rightarrow \pi^+\ \pi^-\ a$ *with* $a \rightarrow l^+l^-$



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

- *CP-violation from this process is not bounded by EDM as is the case for the $\eta \to 4\pi$ 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*
- *REDTOP will collect $4x10^{11}$ such decay (factor 100 in stat. error vs PDG)*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi – UK) based on* https://arxiv.org/abs/1903.11617

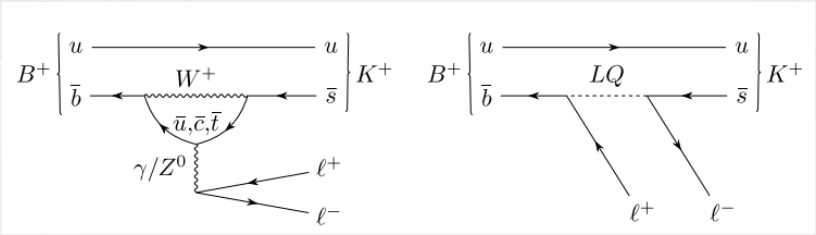




Lepton Universality Test

LHCb latest results: with $B^+ \to \mu^+\mu^- K^+$ vs $e^+e^- K^+$

- *Based on 3850 vs 1640 evts ($BR_{SM} = 10^{-6}$)*
- *3.1σ discrepancy vs SM*



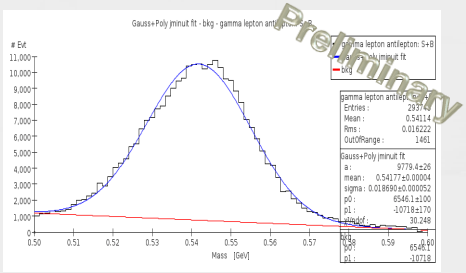
η/η' factories are especially important to confirm the anomaly

- *If new particle has a mass close to $2xM_{\mu}$ the m-e non-universality could be due to a phase space effect rather than a non-universal coupling*
- *Low energy experiments are more sensitive to that mass scale*
- *Several processes under study:*
  - $\eta \to \gamma\, \mu^+ \mu^-$ *vs* $\gamma\, e^+ e^-$
  - $\eta \to \mu^+ \mu^- \mu^+ \mu^-$ *vs* $e^+ e^- \mu^+ \mu^-$ *vs* $e^+ e^- e^+ e^-$
  - $\eta \to \pi^o \mu^+ \mu^-$ *vs* $\pi^o e^+ e^-$
- *The most rare of the processes involving leptons could have as much as several 10^4 SM events ($BR_{SM} \sim 10^{-8}$)*

Lepton Universality Test: REDTOP

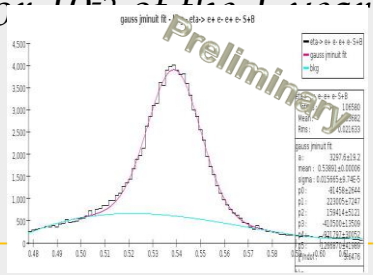
$\eta \to \gamma \mu^+ \mu^-$ vs $\gamma e^+ e^-$

- *Preliminary studies based on $3x10^{10}$ POT ($9x10^7$ η mesons) or 10^{-5} of the 1-year run statistics*
- *Background rejection from $\eta \to \gamma\gamma$ using high-resolution energy measurement (ADRIANO2) and vertex reconstruction*
- *Preliminary stat uncertainty:*
  - *< 0.3% for $\eta \to \gamma e^+ e^-$ (cfr LHCb @ 4.2%)*
  - *< 0.9% for $\eta \to \gamma \mu^+ \mu^-$ (cfr LHCb @ 1.8%)*



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

- *Theoretical calculations at the 10^{-3} precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018)) – hard photon corrections need to be included*
- *Preliminary studies based on $3x10^{10}$ POT ($9x10^7$ η mesons) c[illegible] run statistics*
- *Preliminary stat uncertainty: ~ 0.5%*



QCD axion studies

- *Based on D. Alves model (PR D 103, 055018 (2021))*

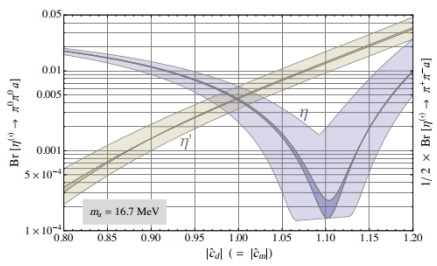


FIG. 3. Estimated branching ratios for $\eta^{(\prime)} \to \pi\pi a$ as a function of the scalar octet couplings to the light pseudoscalar mesons, cf. (45), (48), and (50). The bands result from varying the masses and widths of the scalar resonances, a_0 and f_0, within their experimental uncertainties. For the dark narrow bands, their masses are fixed to $m_{a_0} = m_{f_0} = 980$ MeV, and their widths are varied within the ranges $\Gamma_{a_0} = (40\text{–}100)$ MeV, $\Gamma_{f_0} = (10\text{–}200)$ MeV. The broader bands result from additionally vary-

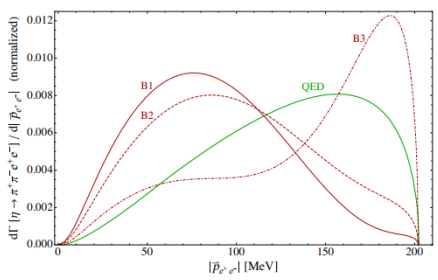
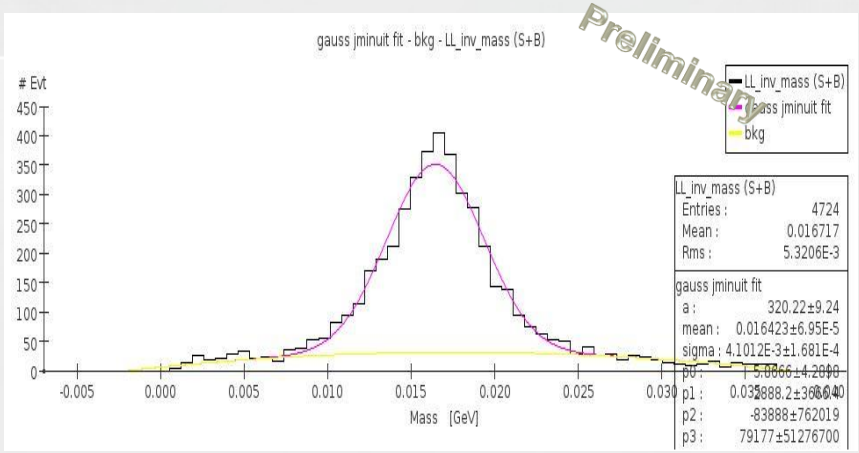


FIG. 4. The differential rate for $\eta \to \pi^+\pi^- a$ as a function of $|\vec{p}_{e^+e^-}| \equiv |\vec{p}_{e^+} + \vec{p}_{e^-}| = \vec{p}_a$, for three benchmark choices of RχT parameters specified in Table I. For comparison, we also show the differential rate of the SM process $\eta \to \pi^+\pi^- e^+ e^-$, labeled "QED."

reconstructed e^+e^- vertex was within a 2.5 cm distance

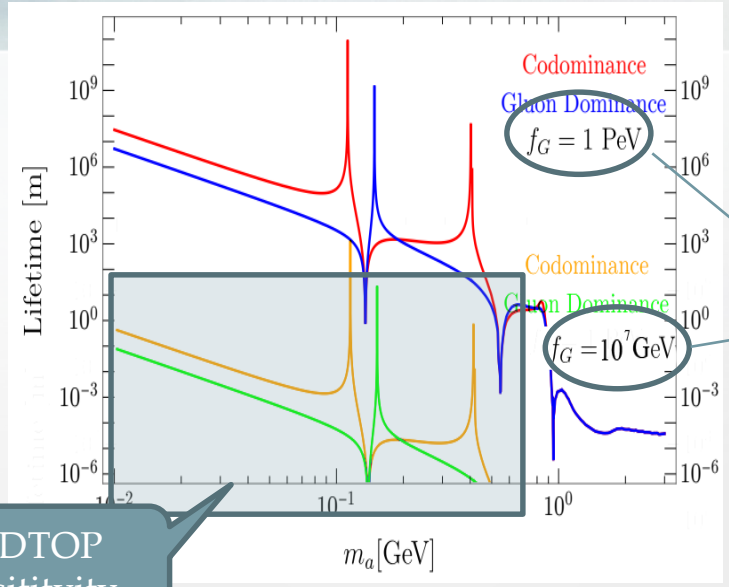


- *Assume the axion is the 17 MeV anomaly observed in Atomki experiment*
- *Below KLOE sensitivity*
- *the CELSIUS/WASA Collaboration observed 24 evts with SM expectation of 10*

- *Preliminary studies based on $3x10^{10}$ POT ($9x10^7$ η mesons) or 10^{-5} of the 1-year run statistics*
- *Main background $\eta \to \pi^0 \pi^+ \pi^-$ $\eta \to \gamma \pi^+ \pi^-$ with ensuing gamma-conversion. Rejected with high resolution ADRIANO2 and vertexing*
- *Large statistics to disentangle the six parameters of the model*

More ALPs studies

- *Based on [Gan et al (2020) , Kelly et al (2020)]*



REDTOP sensititvity

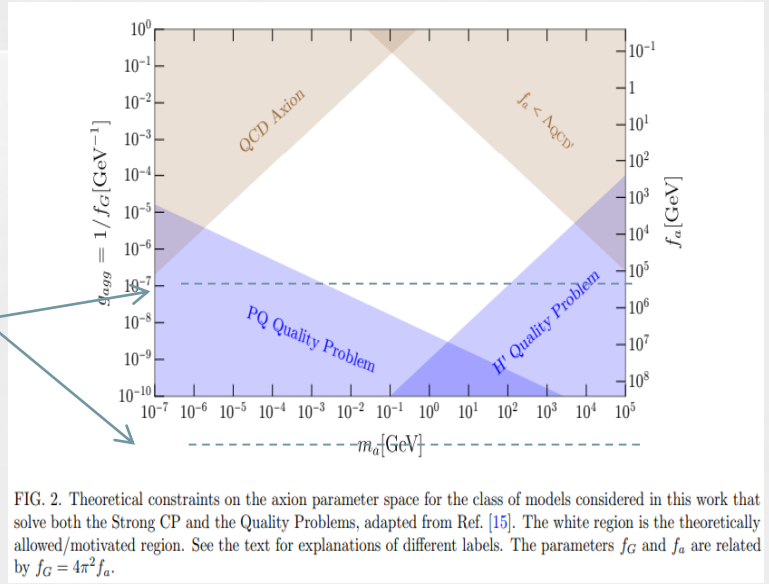
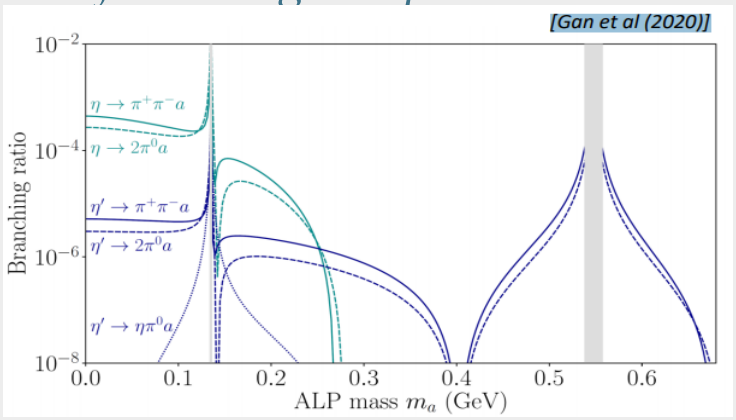


FIG. 2. Theoretical constraints on the axion parameter space for the class of models considered in this work that solve both the Strong CP and the Quality Problems, adapted from Ref. [15]. The white region is the theoretically allowed/motivated region. See the text for explanations of different labels. The parameters f_G and f_a are related by $f_G = 4\pi^2 f_a$.

- *Original work (tailored for beam dump experiments) assume $f_G = 10^{12}$ GeV*
- *More realistic assumption for f_G indicate that a fixed target experiment is way more suited than a beam dump*
- *Expect 10^5-10^9 events at REDTOP*



More Studies for Snowmass2021

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

- *Based on the work by Pere Masjuan and Pablo Sanchez-Puertas* [JHEP 1608, 108 (2016)]
- *Ultra rare process: very sensitive to physics BSM , in particular new couplings (necessarily SU(2) breaking), or lepton flavor violating (LFV) models*
- *One operator inducing CP-violation not baound by EDM measurements [arXiv:1909.07491]*

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

- *Based on the work by D. N. Gao* [arXiv:hep-ph/0202002].
- *Study of the angular correlation of the $e^+ e^-$ and $\pi^+ \pi^-$ planes due to the interference between the magnetic and electric decay amplitudes.*

More alps studies from rare π^0 and η decays

- *Based on the work by Stefania Gori, Wolfgang Altmannshofer , Lucian Harland-Lang Joerg Jaeckel, and Michael Spannowsky, Felix Kahlhoefer. Et al.*
- *Uses interface between GenieHad and ALPCA event generator [* arXiv:1902.04878 **[hep-ph]***]*

Muon polarization studies

- *Independent window on CPviolation*
- *Require implementation of polarimetry in the ADRIANO2 calorimeter*

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-B	$\gamma p \to \eta p$	1.8×10^6	5000	2×10^7
CB@MAMI-C	$\gamma p \to \eta p$	6×10^6		6×10^7
KLOE	$e+e- \to \Phi \to \eta\gamma$	6.5×10^5		5×10^7
WASA@COSY	$pp \to \eta pp$ $pd \to \eta\, ^3He$			$>10^9$ (untagged) 3×10^7 (tagged)
CB@MAMI 10 wk (proposed 2014)	$\gamma p \to \eta p$	3×10^7	1.5×10^5	3×10^8
Phenix	$d\,Au \to \eta X$			5×10^9
Hades	$pp \to \eta pp$ $p\,Au \to \eta X$			4.5×10^8
Near future samples				
GlueX@JLAB (just started)	$\gamma_{12\ GeV} p \to \eta X$ → neutrals			5.5×10^7/yr
JEF@JLAB (recently approved)	$\gamma_{12\ GeV} p \to \eta X$ → neutrals			3.9×10^5/day
REDTOP (proposing)	$p_{1.8\ GeV} Li \to \eta X$			2.5×10^{13}/yr

REDTOP Requirements

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

- *Medium energy proton beam:* ~2 GeV (η)– ~4(η') GeV
- *Low intensity beam:* 10^{18} POT/yr on Li or Be solid target
- *Calorimetric* $\sigma(E)/E \sim 5\%/\sqrt{E}$ (ADRIANO2 dual readout)
- *High PID efficiency: 98/99% (e,γ), 95% (μ), 95% (π), 99.5%(p,n)*
- $\sigma_{tracker}(t) \sim 80psec$, $\sigma_{calorimeter}(t) \sim 80psec$, $\sigma_{Rich}(t) \sim 80psec$
- *Low-mass vertex detector (fiber tracker LHCb-style)*
- *Near -4π detector acceptance (as the η/η' decay is almost at rest).*

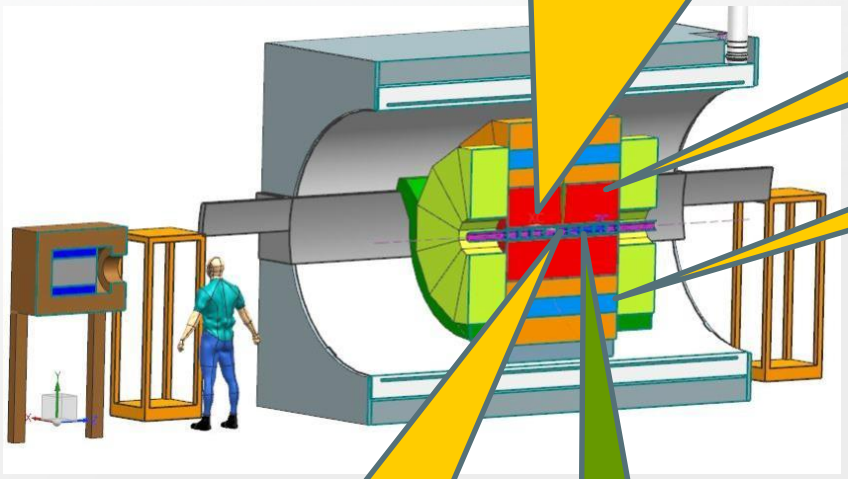
Phase – II: Tagged ~10^{13} η/η' mesons

- *Low energy proton beam:* ~0.9 GeV (η)– ~1.7(η') GeV
- *High intensity beam:* 10^{18} POT/yr on De gaseous target
- *Same detector as Phase-I + forward tagger*

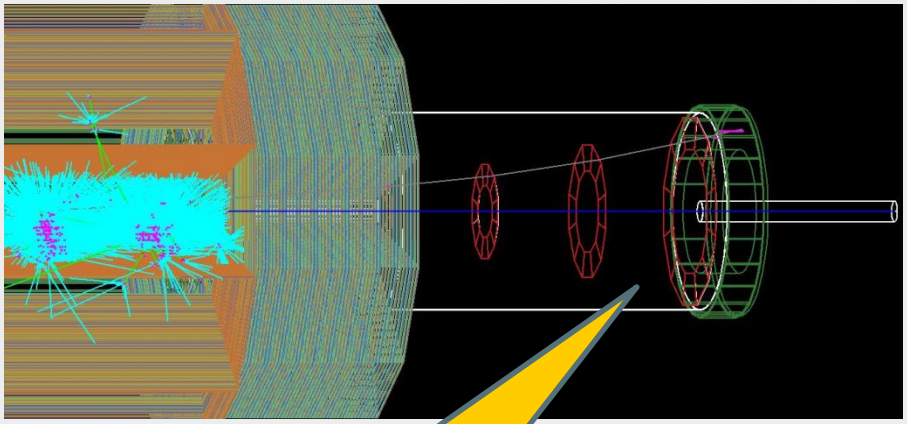
REDTOP detector

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

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



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



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

10x Be or Li targets

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

REDTOP Collaboration

11 Countries, 35 Institutions, 92 Collaborators

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Summary

- *All meson factories: LHCb, B-factories, Dafne, J/psi factories - all 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*
- *Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles*
- *REDTOP goal is to produce ~10^{13} untagged η mesons/yr and ~ 10^{11} η' /year in Phase-I and ~10^{13} tagged mesons in Phase-II*
- *Relatively low beam requirements could be met by several laboratories in US and Asia*
- *Fermilab is the only laboratory with beam for Phase-I (Delivery Ring) and Phase-II (PIP-II)*

Backup slides

Why the η meson is special?

- It is a Goldstone boson → Symmetry constrains its QCD dynamics
- It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^{-+}$ → It can be used to test C and CP invariance.
- All its additive quantum numbers are zero
  $Q = I = j = S = B = L = 0$ → 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

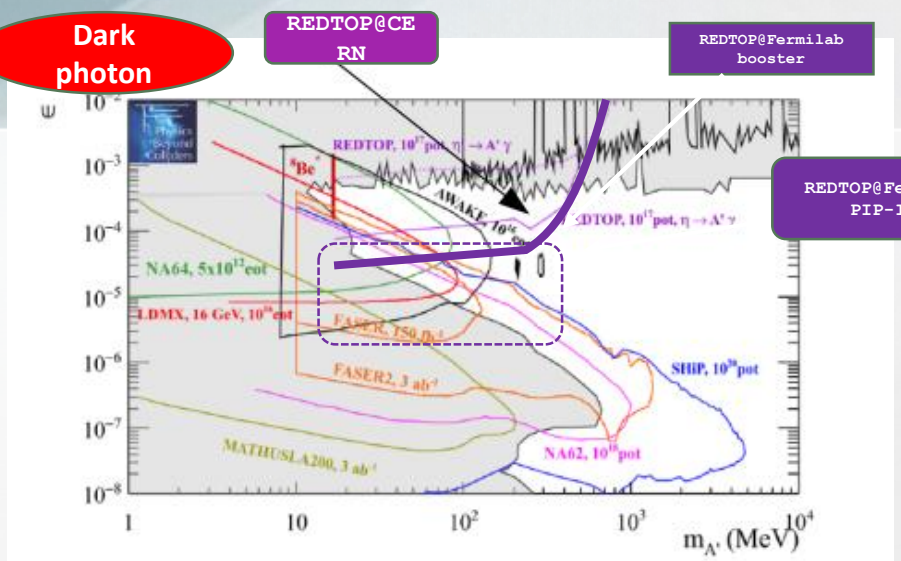
Excellent for testing invariances

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

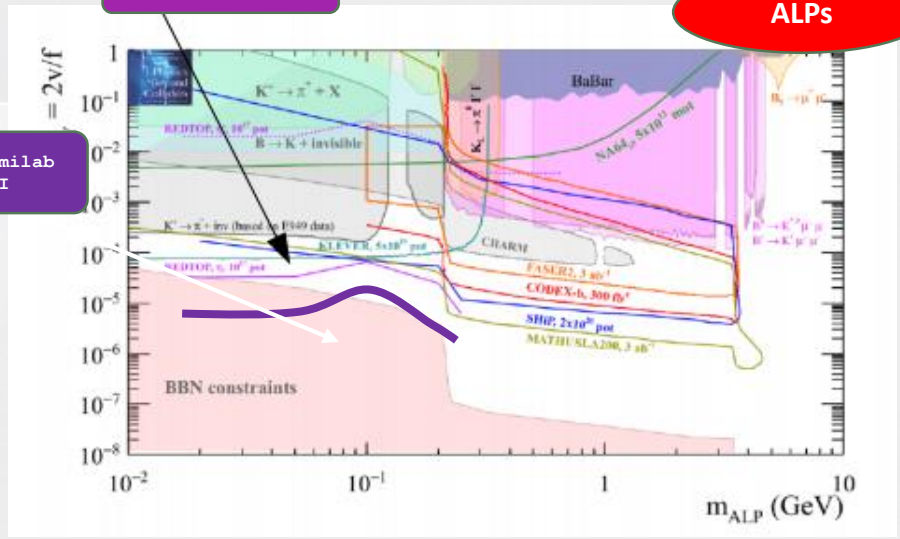
η is an excellent laboratory to search for physics Beyond Standard Model

Sensitivity Studies at CERN PBC

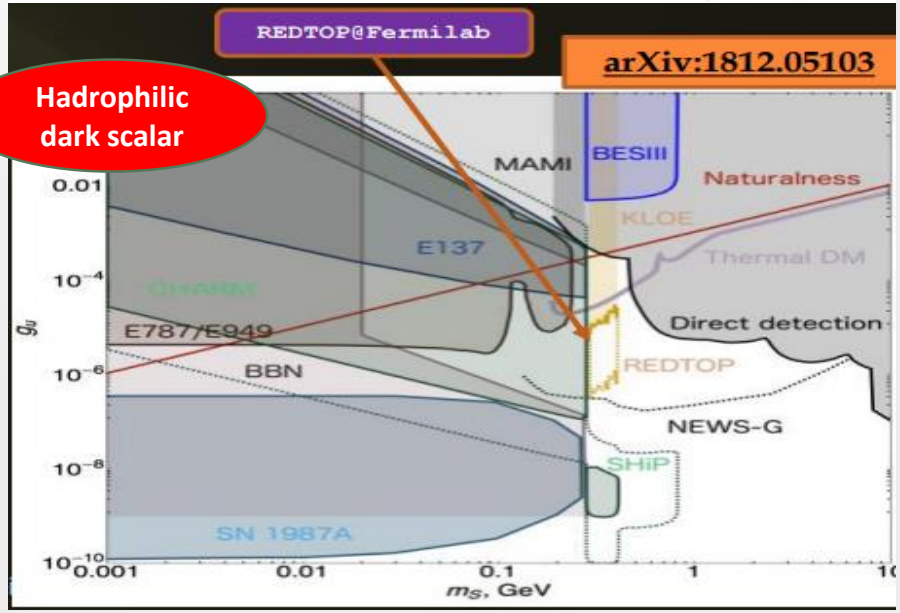
Dark photon



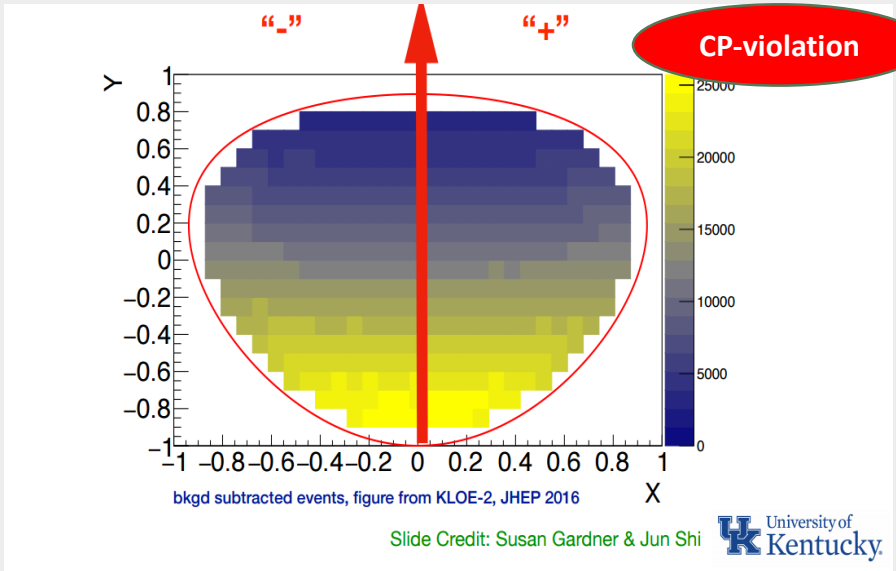
ALPs



Hadrophilic dark scalar



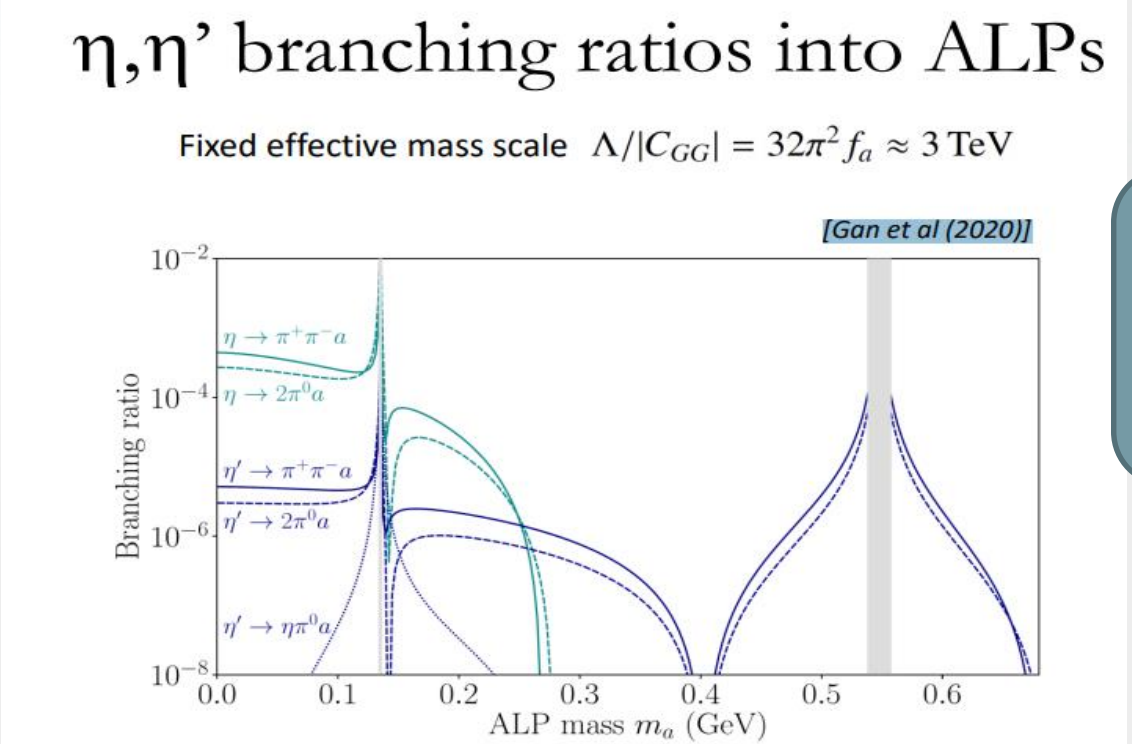
CP-violation



Physics beyond colliders at CERN: beyond the Standard Model working group report:arXiv:1901.09966v2

More ALPs studies

- *It an be searched at REDTOP in* $\eta \rightarrow \pi^+ \pi^- a$ *with* $a \rightarrow \gamma\gamma$ *or* 3π
  - *ALP–η coupling depends on a-η mixing angle*



Dark sectors in η,η′ decays [S. Tulin, Snowmass 2021 RF6 Kickoff meeting]

- *Vertex detector and high energy resolution dual-readout calorimeter help to reject the background* ($\eta \rightarrow \pi^0 \pi^+ \pi^-$ *and* $\eta \rightarrow \gamma \pi^+ \pi^-$)
- *Expect* 10^5-10^9 *events at REDTOP,* (m_a *dependent)*