The REDTOP experiment: Rare Eta Decays To Explore New Physics

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Fermilab

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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

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

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

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^o \pi^+ \pi^-$
- CP Violation (Type I – P and T odd , C even): $\eta \to 4\pi^o \to 8\gamma$
- CP Violation (Type II - C and T odd , P even): $\eta \to \pi^o \ell^+ \ell^-$ **and** $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+ \mu^-$
- Test of CP invariance via γ^* polarization studies: $\eta \to \pi^+ \pi^- e^+ e^-$ and $\eta \to \pi^+ \pi^- \mu^+ \mu^-$
- Test of CP invariance in angular correlation studies: $\eta \to \mu^+ \mu^- e^+ e^-$
- Test of T invariance via μ transverse polarization: $\eta \to \pi^o \mu^+ \mu^-$ and $\eta \to \gamma \mu^+ \mu^-$
- CPT violation: μ polariz. in $\eta \to \pi^+ \mu \nu$ vs $\eta \to \pi \mu^+ \nu$ and γ polarization 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 : $\eta \to \pi\pi \mathbf{a}_{17}$ with $\mathbf{a}_{17} \to e^+e^-$
- New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^o$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
- Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$
- Lepton Universality

Other discrete symmetry violations

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

Other Precision Physics measurements

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

Non-η/η' based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: qqbar → A'/a → l^+l^-
- ALP's searches in Primakoff processes: p Z → p Z a → l^+l^- (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: $\pi^o \to \gamma A' \to \gamma e^+e^-$

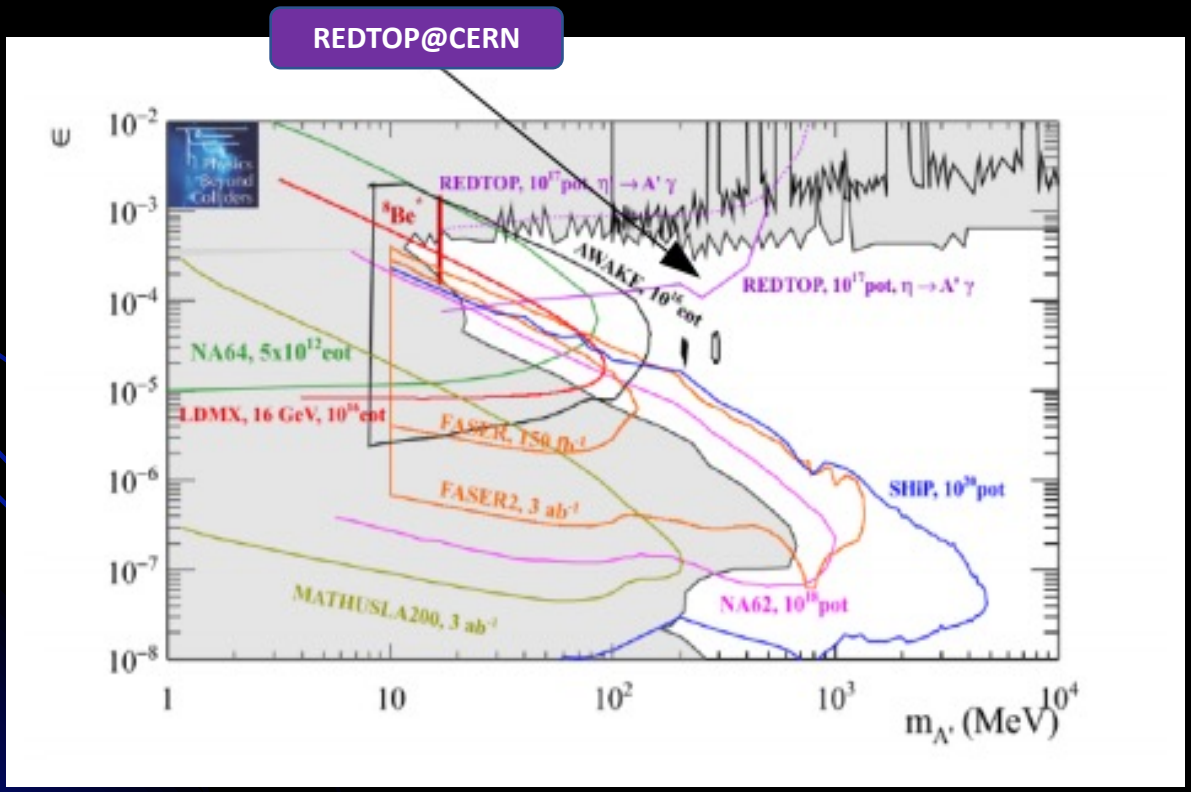
High precision studies on medium energy physics

- 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

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

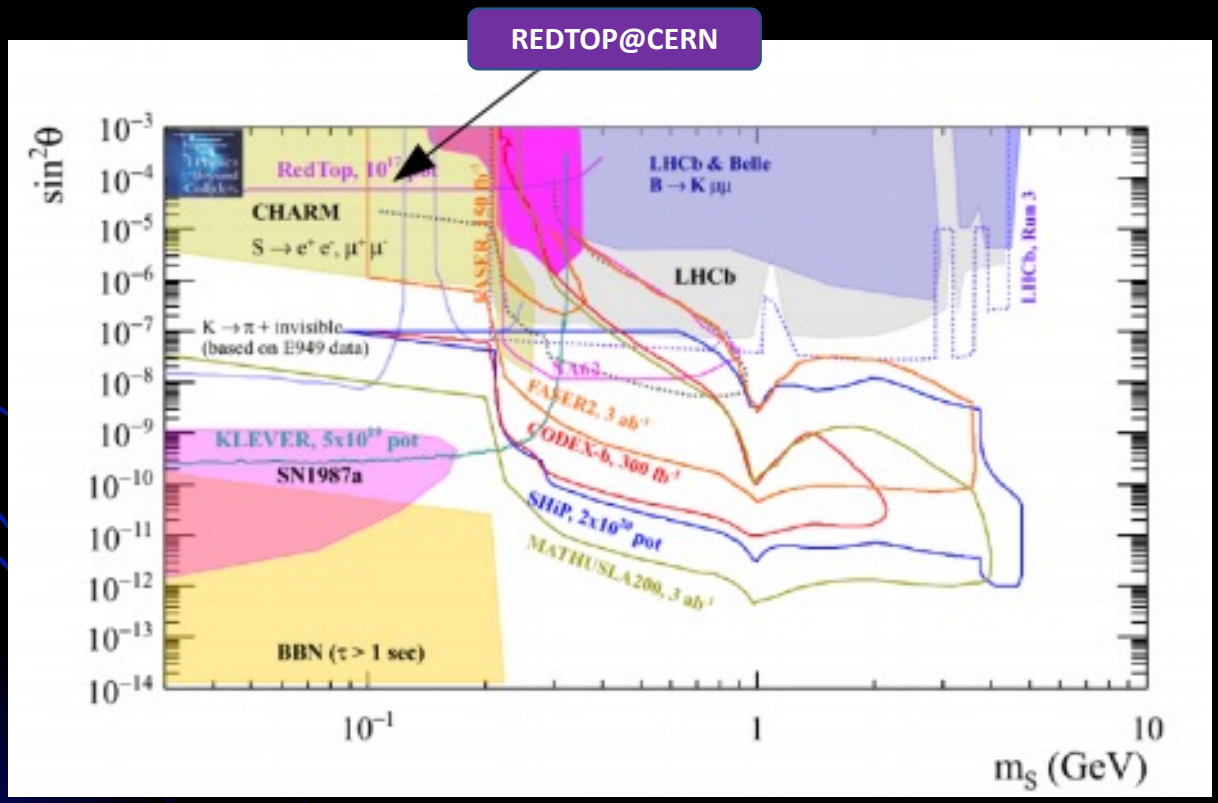
- *Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT*
- *FNAL and BNL can provide 10x more POT*
- *Only "bump hunt analysis". Adding vertexing improve the sensitivity to physics BSM by 10x*
- *A protophobic gauge boson might explain the* 17 MeV anomaly in Beryllium nuclear decays *https://arxiv.org/abs/1608.03591*



Searches for light scalar mesons

$$\eta \rightarrow \pi^o H \quad with\ H \rightarrow \mu^+\mu^- \ and \ \ e^+e^-$$

- *Viable DM candidate (in certain circumstances) coupling to Higgs portal - M. Pospelov, A. Ritz and M. Voloshin, Phys. Rev. D 78, 115012 (2008)*
- *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". Adding vertexing improve the sensitivity to physics BSM by 1000x*



Searches for light scalar mesons

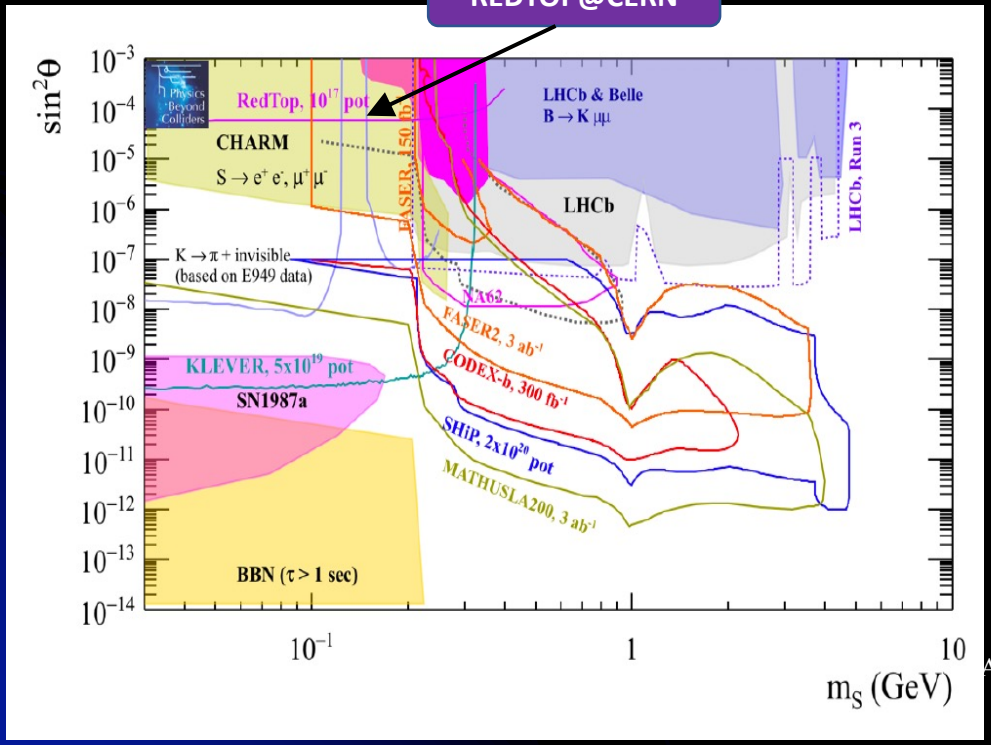
MINIMAL SM HIGGS EXTENSION

- *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

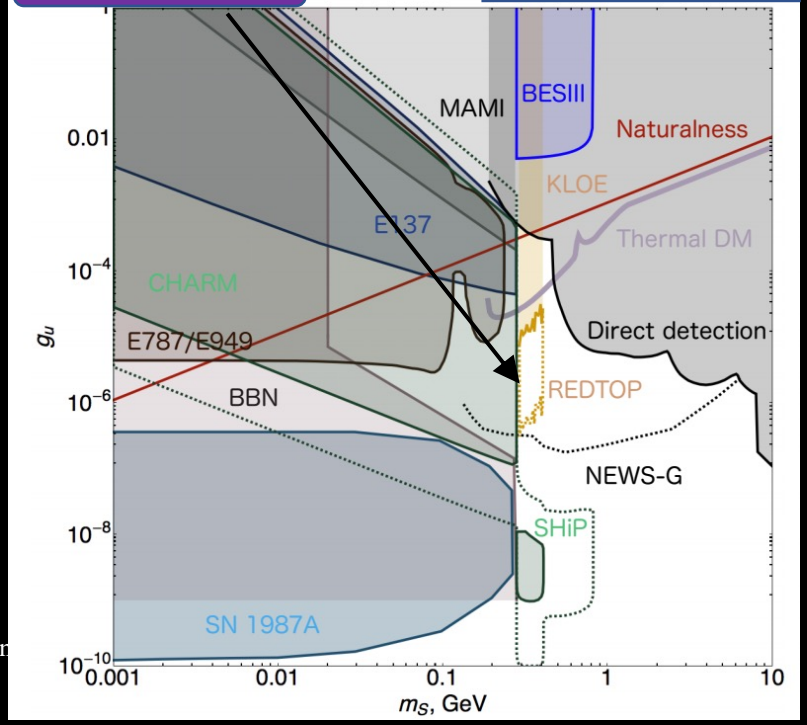
- *Studied in arXiv:1812.05103*
- *Only "bump hunt", no vertexing*

REDTOP@CERN



REDTOP@FNAL

arXiv:1812.05103



Searches for ALPs with fermion or gluon coupling

- *Beam emitted ALP's from the following processes:*
  - *Drell-Yan processes: qqbar → A'/a → l^+l^-*
  - *Proton bremsstrahlung processes: p N → p N A'/a with A'/a → l^+l^- (J. Blümlein and J. Brunner)*
  - *Primakoff processes: p Z → p Z a → 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).*

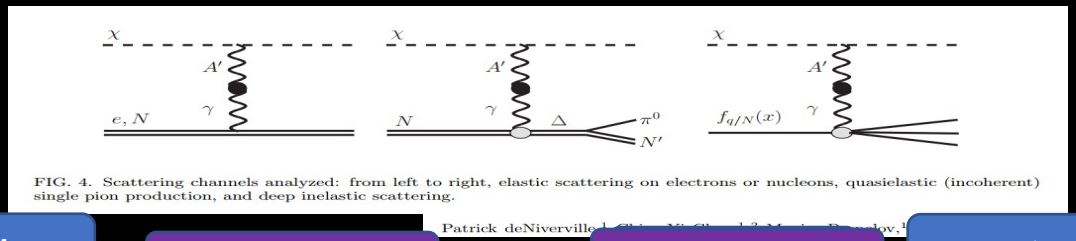
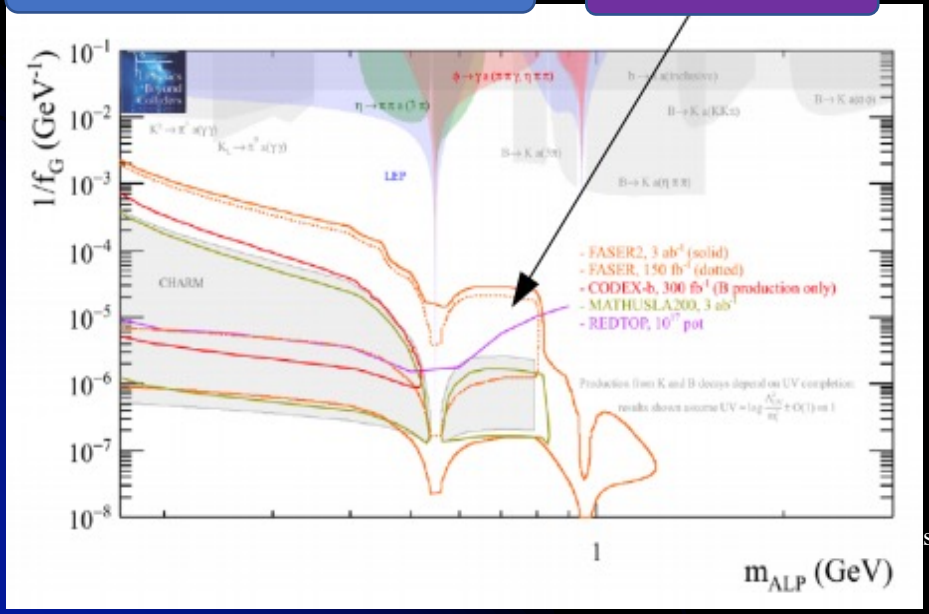


FIG. 4. Scattering channels analyzed: from left to right, elastic scattering on electrons or nucleons, quasielastic (incoherent) single pion production, and deep inelastic scattering.

Patrick deNiverville

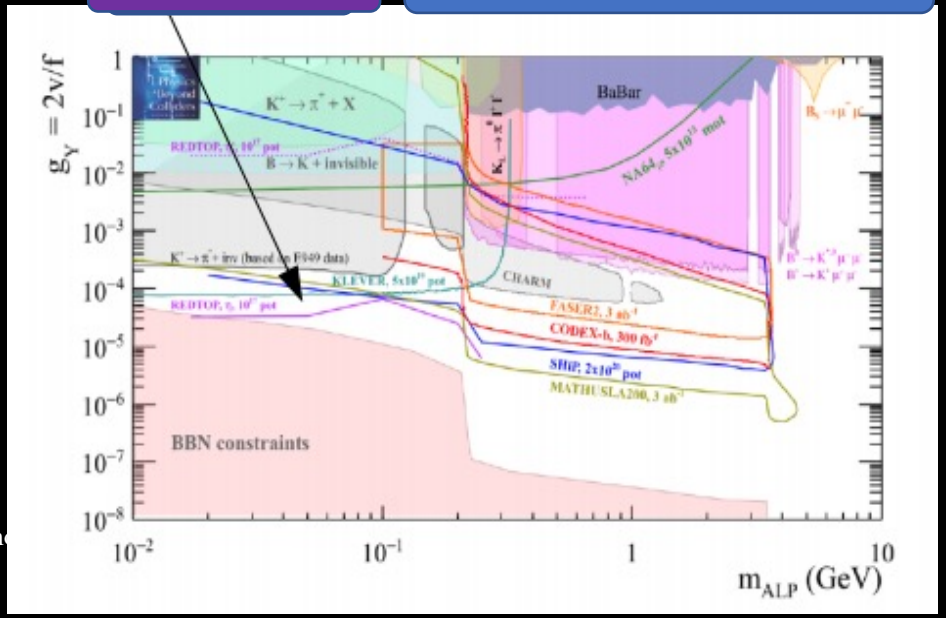
p N → p N a with a → l^+l^-

REDTOP@CERN



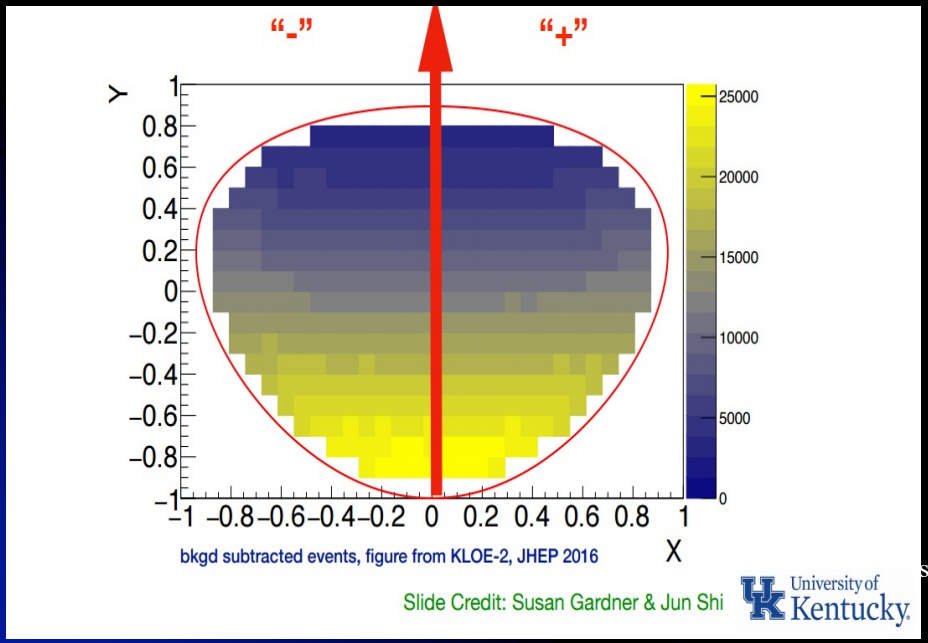
REDTOP@CERN

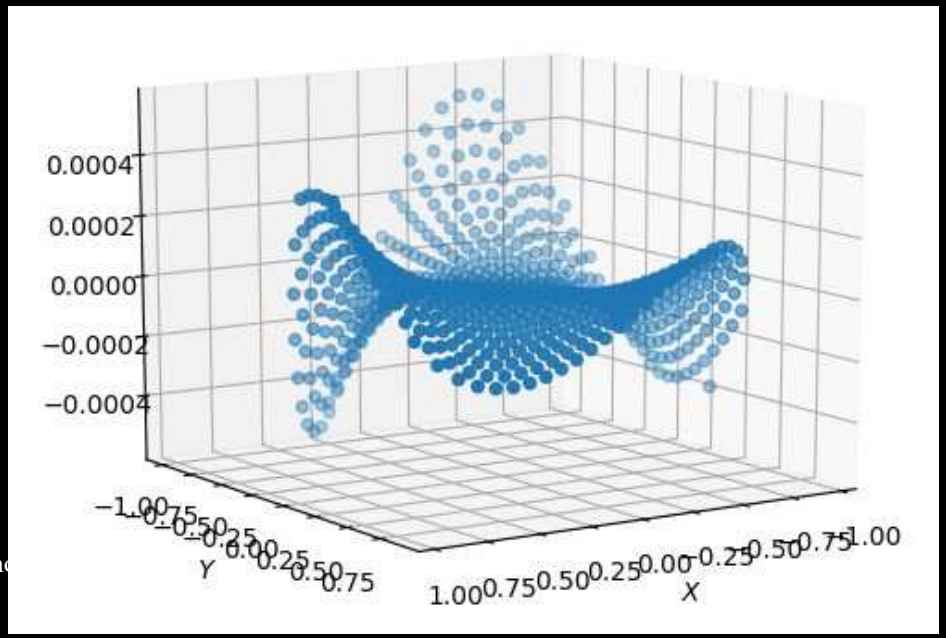
$\eta \to \pi^+ \pi^-$ a with a → l^+l^-



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*
- *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)*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi – UK) based on* PHYSICAL REVIEW D 101, 115038 (2020)

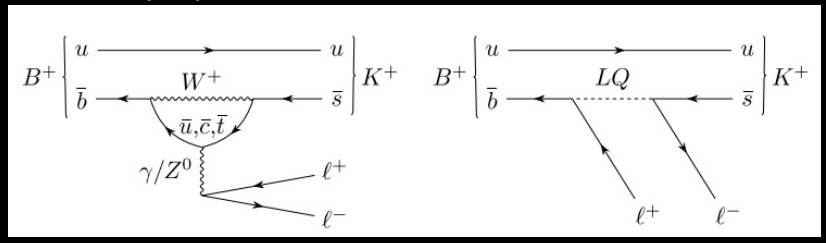




Lepton Universality Test

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*



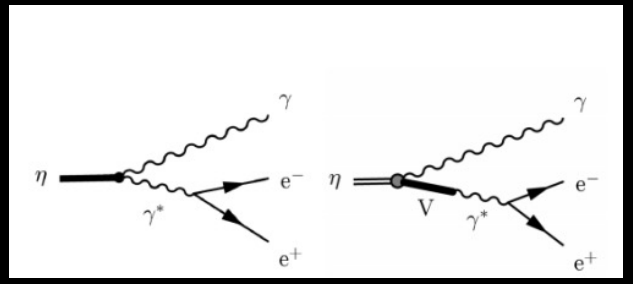
η/η' factories are especially important to confirm the anomaly

- *If new particle has a mass close to 2xM_μ the μ-e non-universality could be do to a phase space effect rather than a different coupling*
- *Low energy experiments are more sensitive to that mass scale (MeV-GeV)*
- *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 $\pi^o e^+ e^-$

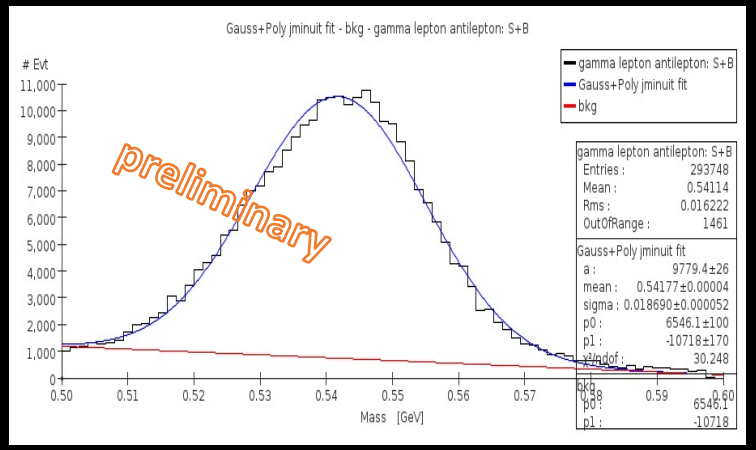
Lepton Universality Test: REDTOP

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

- *Preliminary studies based on $3x10^{10}$ POT ($9x10^7$ η mesons) or 10^{-5} of the 1-year run statistics*
- *Main background: η and $\pi^0 \rightarrow \gamma\gamma$ with ensuing gamma-conversion*



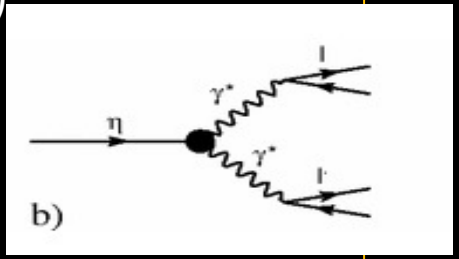
- *Rejected using high-resolution energy measurement (ADRIANO2) and vertex reconstruction*
- ε_{reco} = 26.5% ($\eta \rightarrow \gamma e^+ e^-$)
  18.7% ($\eta \rightarrow \gamma \mu^+ \mu^-$)
- *Errors on ratio of BR's cancel away*
- *Preliminary stat uncertainty:*
  - < 0.3% for $\eta \rightarrow \gamma e^+ e^-$ (cfr LHCb @ 4.2%)
  - < 0.9% for $\eta \rightarrow \gamma \mu^+ \mu^-$ (cfr LHCb @ 1.8%)



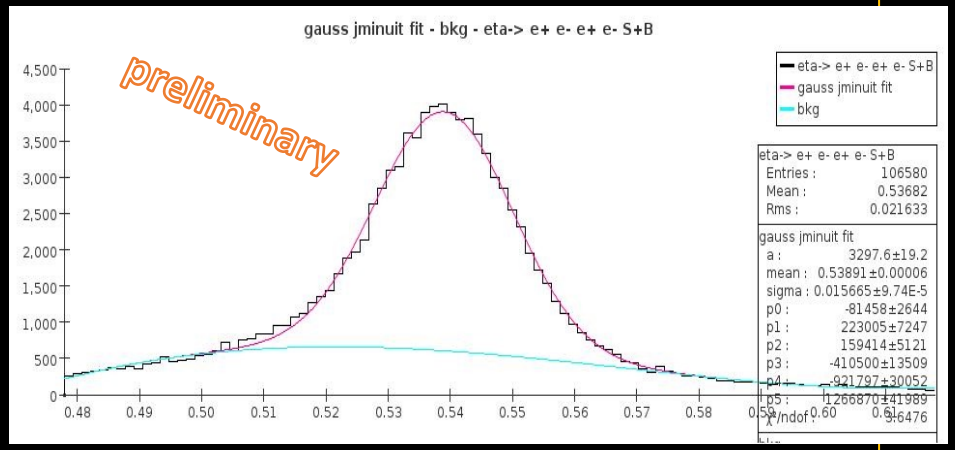
Lepton Universality Test: REDTOP

$\eta \to \mu^+ \mu^- \mu^+ \mu^-$ 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 3×10^{10} POT (9×10^7 η mesons) or 10^{-5} of the 1-year run statistics*



- *Main background $\eta \to \gamma e^+ e^-$ $\eta \to \gamma \mu^+ \mu^-$ with ensuing gamma-conversion*
- *Rejected using high-resolution energy measurement (ADRIANO2) and vertex reconstruction*
- ε_{reco} = *5.1%* ($\eta \to e^+ e^- e^+ e^-$) ,
  1.0% ($\eta \to e^+ e^- \mu^+ \mu^-$)
  1.2% ($\eta \to \mu^+ \mu^- \mu^+ \mu^-$)
- *Preliminary stat uncertainty: ~ 0.5%*



QCD axion studies

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

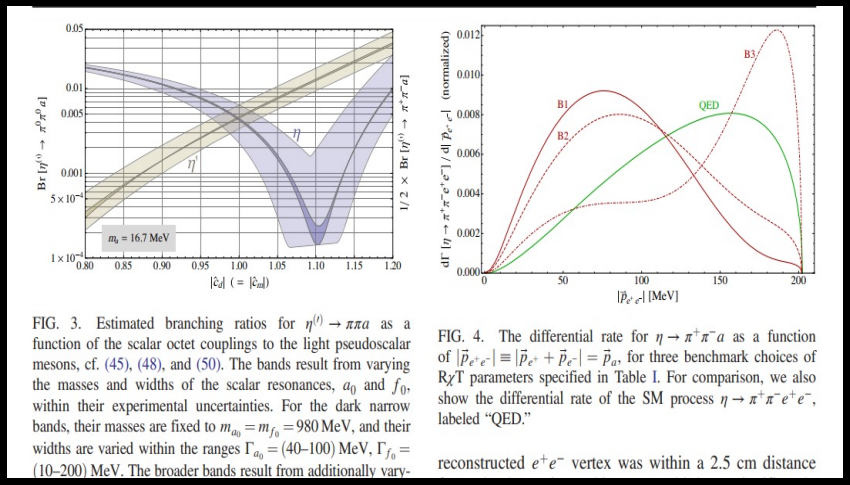
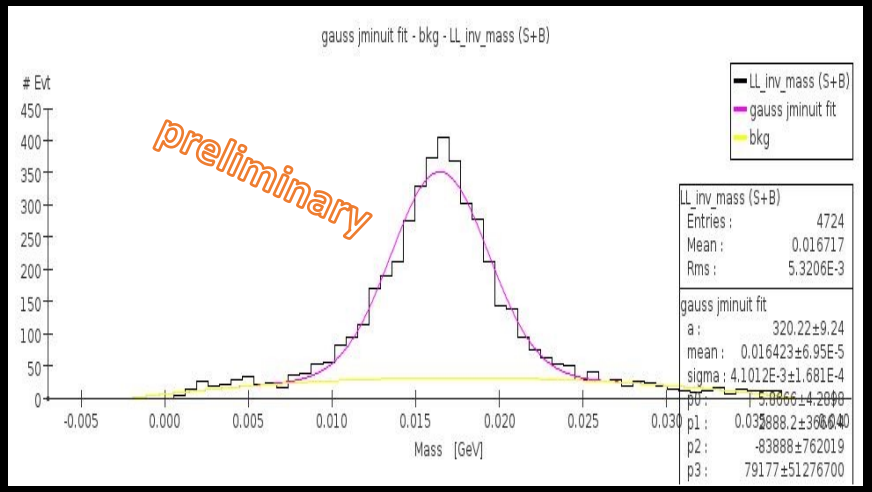


FIG. 3. Estimated branching ratios for $\eta^{(\prime)} \to \pi\pi a$ as a function of the scalar octet couplings to the light pseudoscalar mesons, cf. (45), (48), and (50). The bands result from varying the masses and widths of the scalar resonances, a_0 and f_0, within their experimental uncertainties. 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 (Be^8 anomaly)

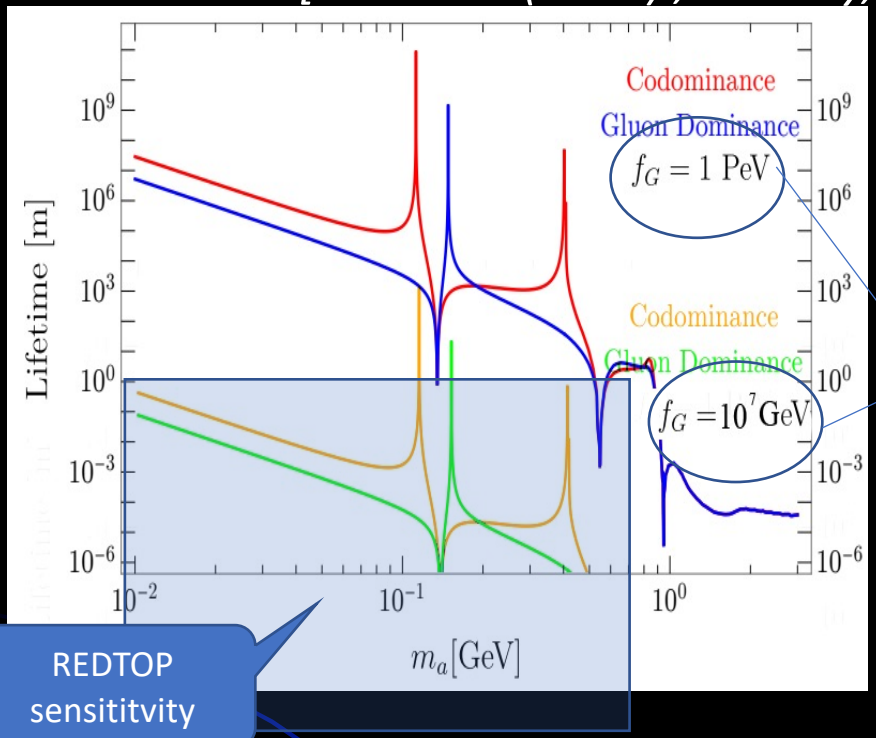
Below KLOE sensitivity

The CELSIUS/WASA Collaboration observed 24 events 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 $\eta \to \pi^o \pi^+ \pi^-$ $\eta \to \gamma \pi^+ p^-$ with ensuing gamma-conversion*
- *Rejected using high-resolution energy measurement (ADRIANO2) and vertex reconstruction*
- *ε_{reco}= 4.8% - Preliminary stat uncertainty: ~ 2.8%*
- *Large statistics to disentangle the six parameters of the model*

More ALPs studies

- *Based on [Gan et al (2020) , K. Kelly, S. Kumar, Z. Liu(arXiv:2011.05995)*



REDTOP sensititvity

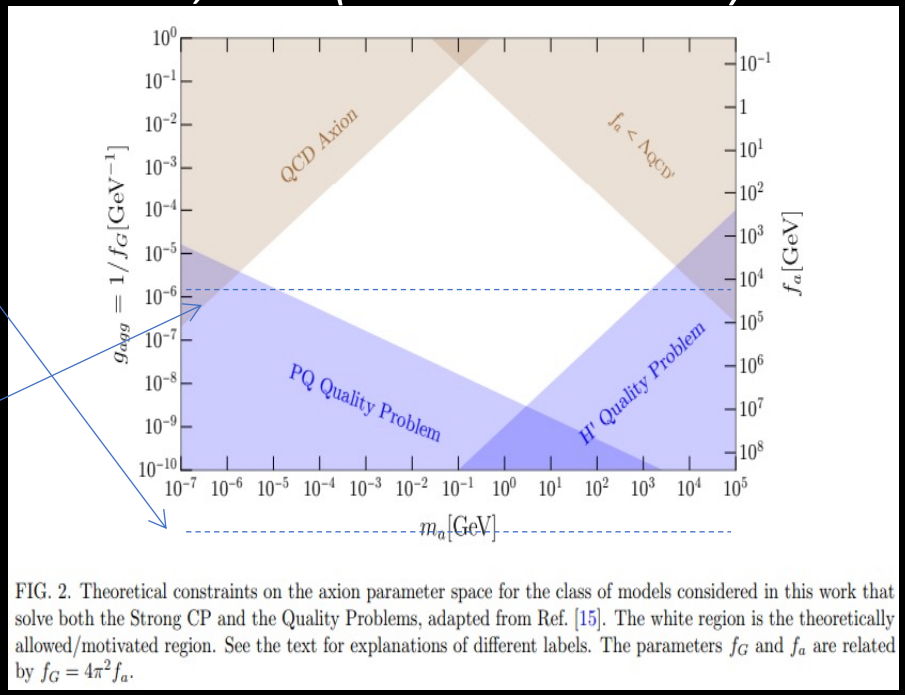


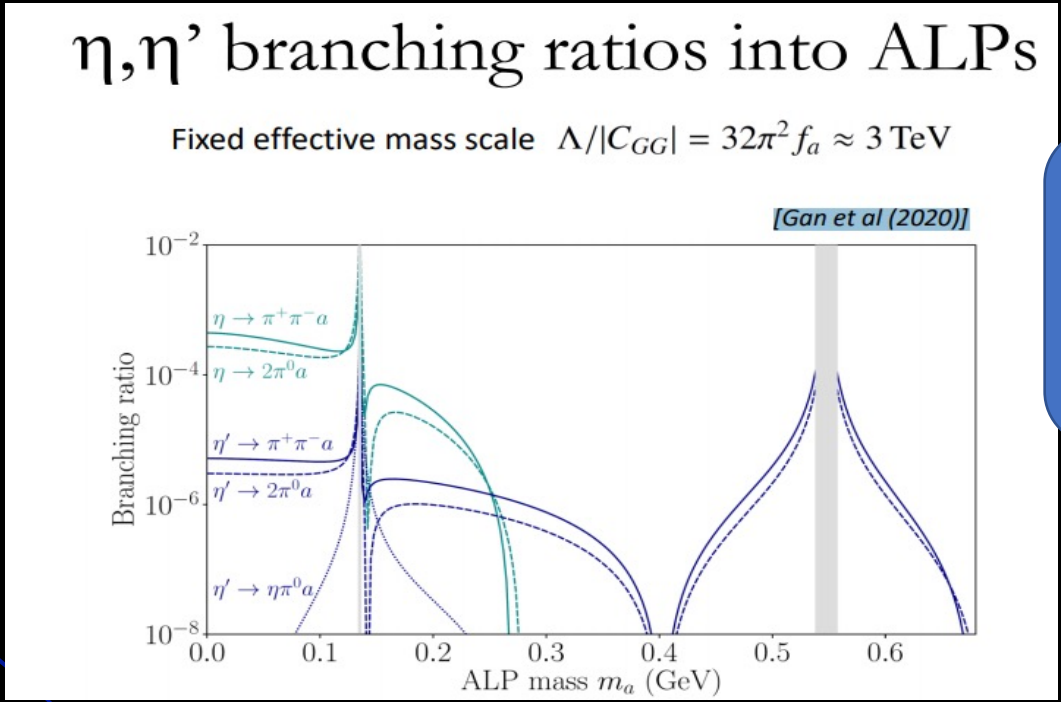
FIG. 2. Theoretical constraints on the axion parameter space for the class of models considered in this work that solve both the Strong CP and the Quality Problems, adapted from Ref. [15]. The white region is the theoretically allowed/motivated region. See the text for explanations of different labels.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

- *Recent work opened interesting parameter space for heavy axions*
- *Original work (tailored for beam dump experiments) assume $f_G = 10^{12}$ GeV*
- *More realistic assumption for f_G indicates that a fixed target experiment is way more suited than a beam dump*

More ALPs studies (cont'd)

It can 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 (*$\eta \rightarrow \pi^o \pi^+ \pi^-$ *and* $\eta \rightarrow \gamma \pi^+ \pi^-$ *)*
- *Expect 10^5-10^9 events , m_a dependent*

More studies for Snowmass 2021

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

- *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 bound by EDM measurements [arXiv:1909.07491]*

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

- *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* [arXiv:1902.04878 hep-ph]

Muon polarization studies

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

Summary

- *All meson factories: LHCb, B-factories, Daphne, J/psi factories - have produced a broad spectrum of physics*
- *The η /η' meson is an excellent laboratory for studying rare processes and physics BSM at a lower small scale*
- *World-wide attention of theorists is growing and broad complementary experimental programs in different high-intensity facilities is flourishing*
- *REDTOP goal is to produce ~10^{13} untagged η mesons/year and ~ 10^{11} η'/year in Phase-I and 10^{13} tagged mesons in Phase-II*
- After PBC at CERN, new studies are ongoing to improve the sensitivity for different (tagged and untagged) running modes.

Thank you

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