Probe Fundamental Physics via the η and η' Decays

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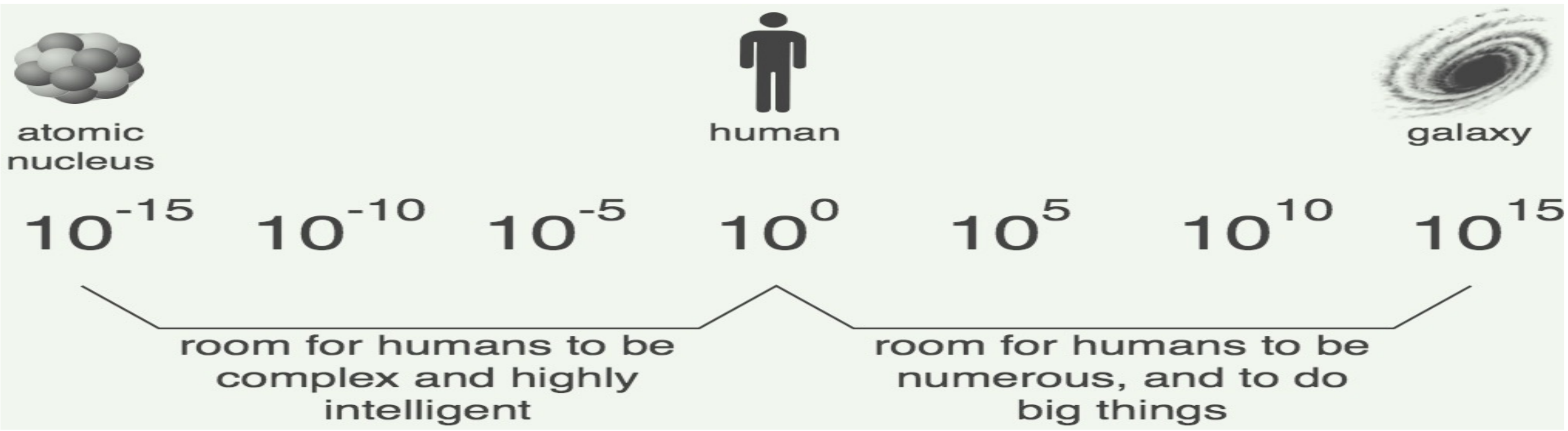
Outline

1. Overview of η and η' Physics
2. Standard Model Tests
   - JLab Primakoff experimental program
3. BSM Physics Search: Symmetry and Dark Sector
   - JLab Eta Factory (JEF) experiment
   - A new proposal: REDTOP
4. Summary

Challenges in Physics



Confinement QCD

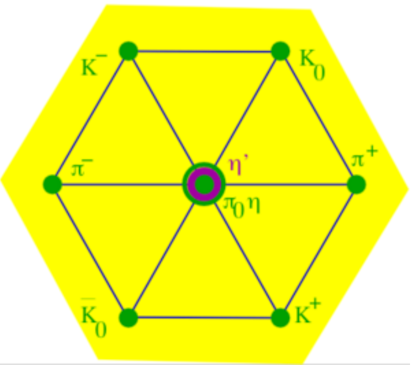
- Nature of QCD confinement
- Its relationship to the dynamical chiral symmetry breaking

New physics beyond the Standard Model (SM)

- New sources of CP violation
- Dark matter
- Dark energy

η and η' decays provide sensitive probes to explore both fundamental issues

Why η is a unique probe for QCD and BSM physics?



- A Goldstone boson due to spontaneous breaking of QCD chiral symmetry
  → η is one of key mesons bridging our understanding of low-energy hadron dynamics and underlying QCD

- All its possible strong and EM decays are forbidden in the lowest order so that η has narrow decay width (Γ_η =1.3KeV compared to Γ_ω=8.5 MeV)
  → Enhance the higher order contributions (by a factor of ~7000 compared to ω decays). Sensitive to weakly interacting forces.

- Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
  → tests for C, CP

- Its quantum numbers are the same as Higgs or vacuum (except parity) and its decays are flavor-conserving
  → effectively free of SM backgrounds for new physics search.

Rich η (and η') Physics

Standard Model Tests:

- Chiral symmetry and anomalies
- Extract η-η' mixing angle and quark mass ratio
- Theory inputs to HLbL for $(g-2)_\mu$
- QCD scalar dynamics

Fundamental Symmetry Tests:

- C, CP violations
- P, CP violations
- Lepton flavor violations

BSM Physics in Dark Sector:

- Vector bosons (B boson, dark photon and X boson)
- Dark scalars
- Pseudoscalars (ALPs)
- BSM weak decays

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [54]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^+e^-\bar{\nu}_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [55]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

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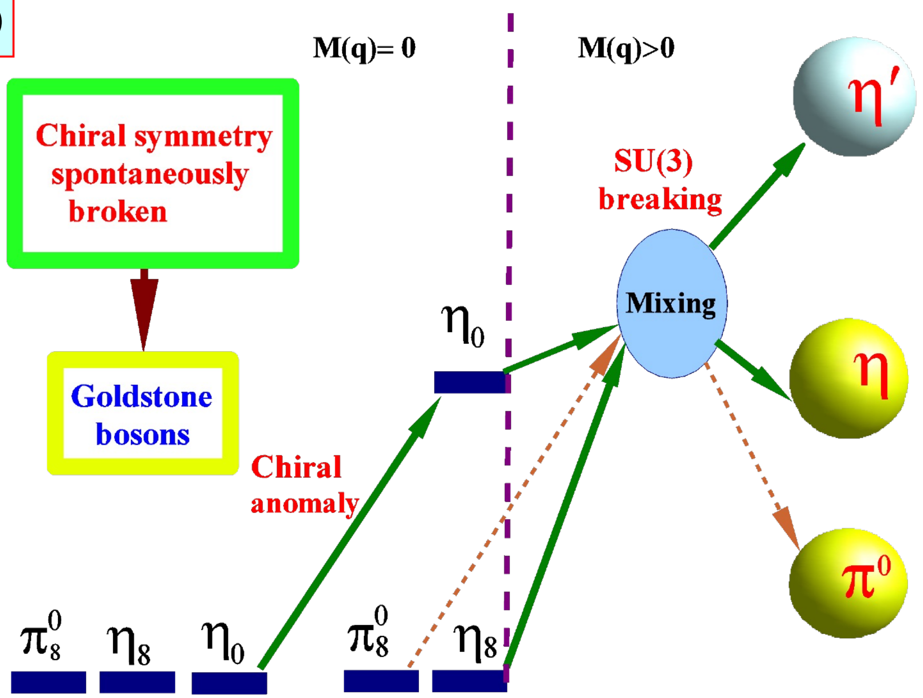
Low-Energy QCD Symmetries and Light Mesons

- QCD Lagrangian in Chiral limit ($m_q \to 0$) is invariant under:

$$SU_L(3) \times SU_R(3) \times U_A(1) \times U_B(1)$$

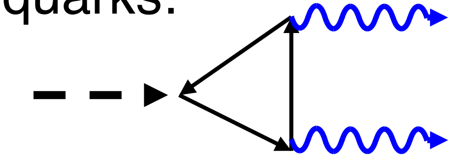
- Chiral symmetry $SU_L(3)xSU_R(3)$ spontaneously breaks to SU(3)
  - 8 Goldstone Bosons (GB)
- $U_A(1)$ is explicitly broken:
  (Chiral anomalies)
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
  - Non-zero mass of η_0
- $SU_L(3)xSU_R(3)$ and SU(3) are explicitly broken:
  - GB are massive
  - Mixing of π^0, η, η'



The π^0, η, η' system provides a rich laboratory to study the symmetry structure of QCD at low energies.

Axial Anomaly and $\Gamma(P \to \gamma\gamma)$

- $P \to \gamma\gamma$ decay proceeds primarily via the chiral anomaly in QCD.
- The chiral anomaly prediction is exact for massless quarks:



$$\Gamma(P \to \gamma\gamma) = \frac{\pi\, \alpha_{em}^2 M_P^3}{4} \left| F_{P\gamma\gamma} \right|^2 \qquad F_{P\gamma\gamma} \equiv F_{P\gamma^*\gamma^*}(0,0)$$

For π^0: $$\Gamma\left(\pi^0 \to \gamma\gamma\right) = \frac{\alpha^2 N_c^2 m_\pi^3}{576\pi^3 F_\pi^2} = 7.760\ eV$$

- $\Gamma(\pi^0 \to \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely at ~1% level to higher orders! It offers the most sensitive test to chiral anomaly

- $\Gamma(\eta^{(\prime)} \to \gamma\gamma)$ is sensitive to the mixing angle due to SU(3) breaking

$$F_{\eta\gamma\gamma} = \frac{1}{4\sqrt{3}\cos(\theta_8 - \theta_0)\pi^2} \left[\frac{\cos\theta_0}{F_8} - \frac{2\sqrt{2}\sin\theta_8}{F_0} \right],$$

$$F_{\eta'\gamma\gamma} = \frac{1}{4\sqrt{3}\cos(\theta_8 - \theta_0)\pi^2} \left[\frac{\sin\theta_0}{F_8} + \frac{2\sqrt{2}\cos\theta_8}{F_0} \right]$$

Transition Form Factor and $(g-2)_\mu$

important hadronic light-by-light contribution:

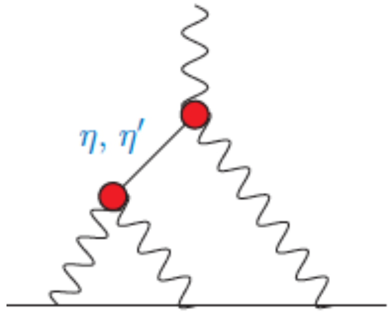
$\eta^{(\prime)}$ pole terms

singly / doubly virtual
transition form factors (TFFs)

$F_{\eta^{(\prime)}\gamma^*\gamma^*}(q^2,0)$ and $F_{\eta^{(\prime)}\gamma^*\gamma^*}(q_1^2,q_2^2)$

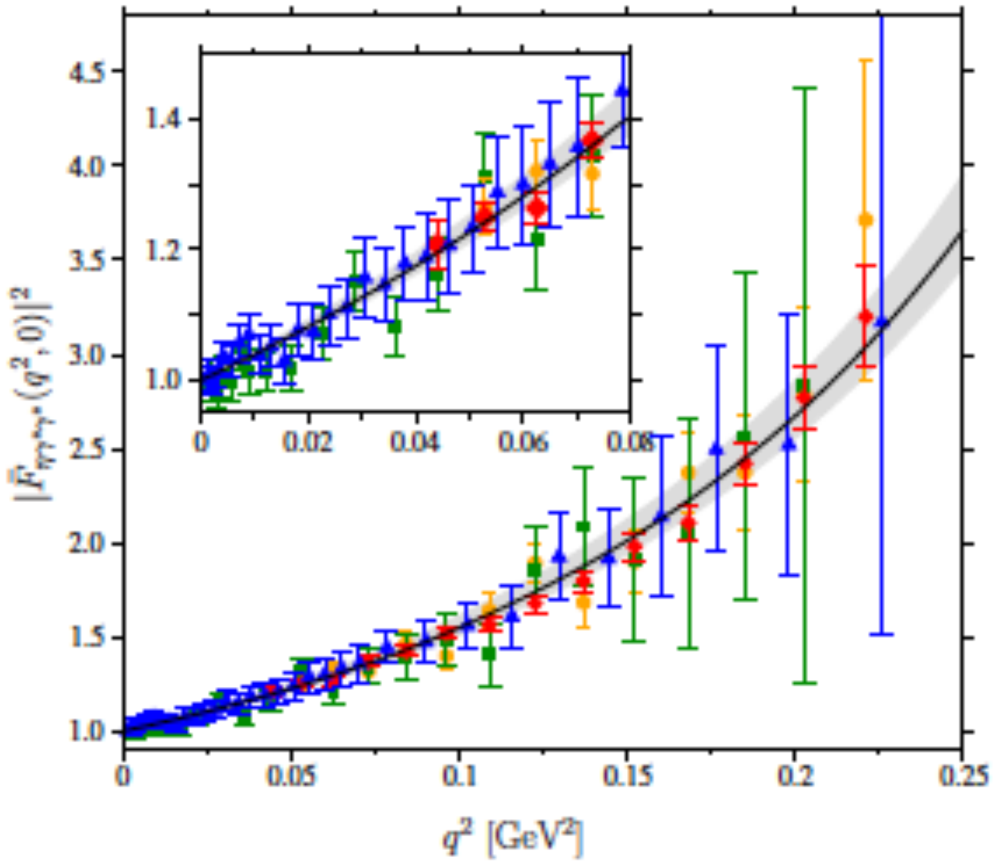
normalisation fixed by WZW anomaly

$\longrightarrow$ I. Jaeglé

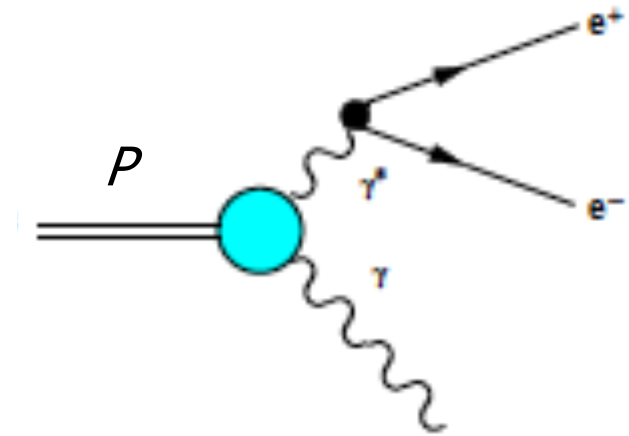


HLbL

Time-like Transition Form Factor $\eta^{(\prime)} \to \gamma^{*}\gamma$



data: NA60 2009, '16; A2 2014, '17

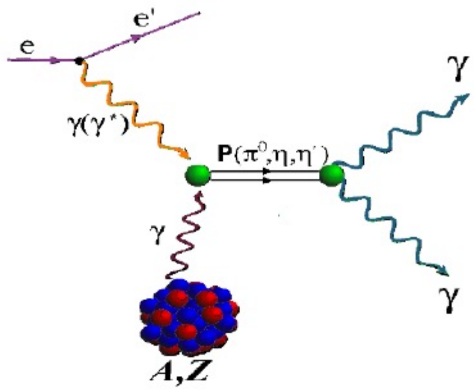


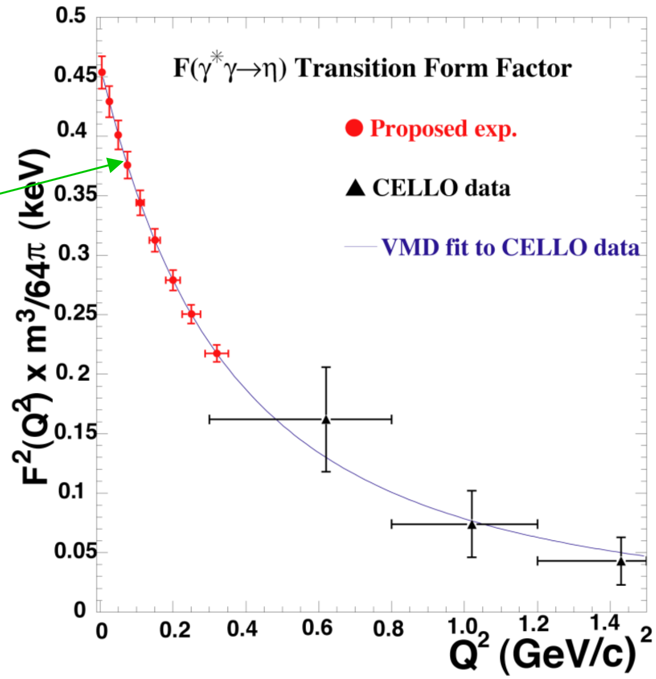
$$4m_l^2 < q^2 < M_P^2$$

Space-like Transition Form Factor $\eta^{(\prime)} \to \gamma^* \gamma$

Experimental approaches:

- Collider: $e^- e^+ \to \eta^{(\prime)}\ e^- e^+$
- Virtual Primakoff: $e^- A \to \eta^{(\prime)}\ e^- A$



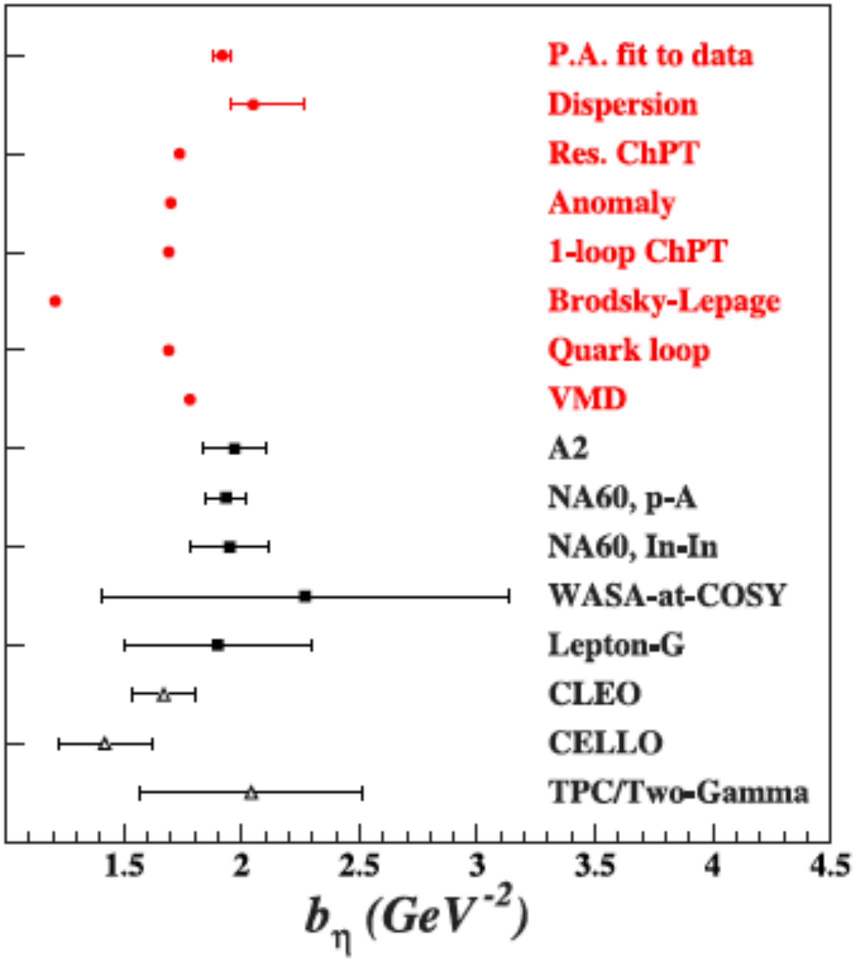


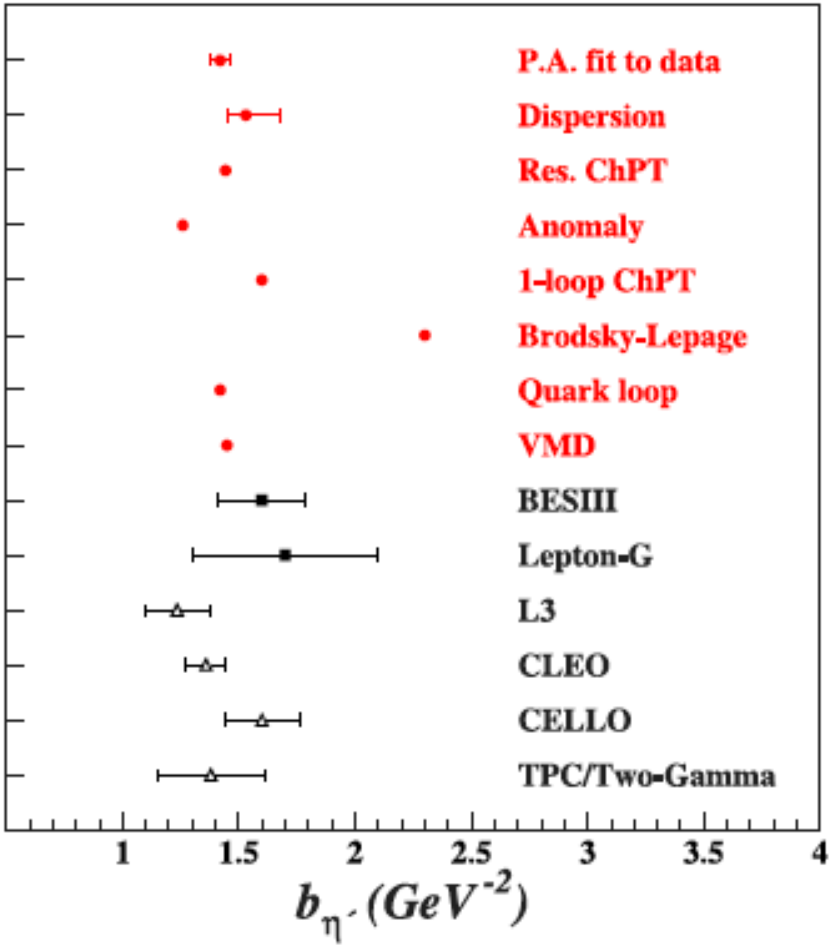
$$F_{P\gamma^*\gamma}(q^2) = F_{P\gamma\gamma}\left[1 + b_P q^2 + \mathcal{O}(q^4)\right],$$

Slope: $b_P = \frac{1}{F_{P\gamma\gamma}} \frac{dF_{P\gamma^*\gamma}(q^2)}{dq^2}\Big|_{q^2=0}$

$Q^2 = -q^2$

Status of TFF Slope Parameters





SM allowed $\eta \to \pi^0 \gamma\gamma$

→ A rare window to probe interplay of VMD & scalar resonances in ChPT to calculate $O(p^6)$ LEC's in the chiral Lagrangian

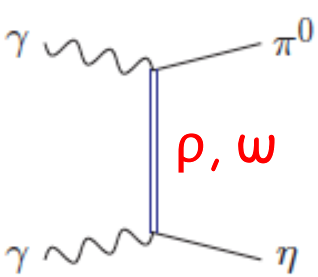
- The major contributions to $\eta \to \pi^0 \gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian → an unique probe for the high order ChPT.

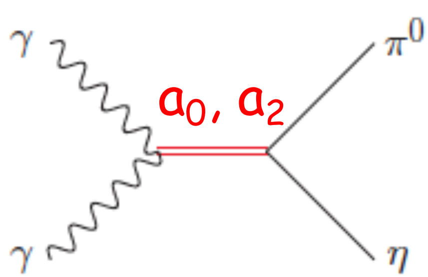
  L. Ametller, J, Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

- Shape of Dalitz distribution is sensitive to the role of scalar resonances.

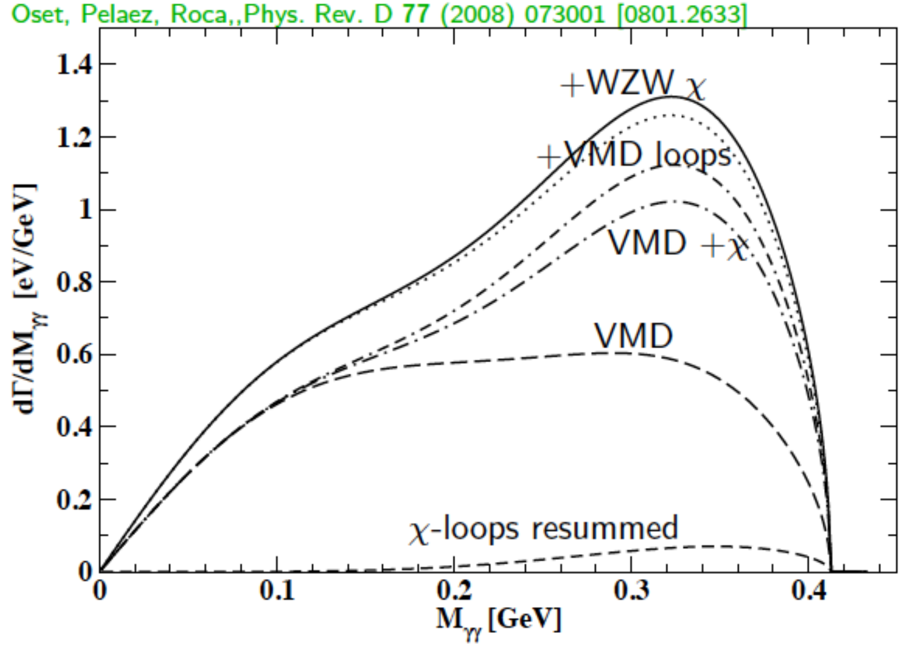
LEC's are dominated by resonances

Gasser, Leutwyler 84; Ecler, Gasser, Pich, de Rafael1989
Donoghue, Ramirez, Valencia 1989



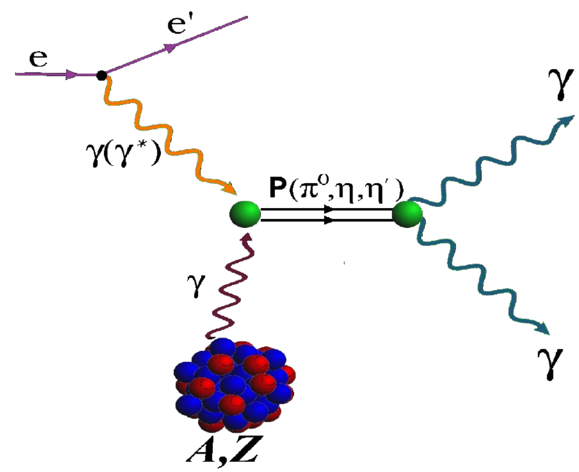


Oset, Pelaez, Roca,,Phys. Rev. D 77 (2008) 073001 [0801.2633]



Primakoff Program at JLab 6 & 12 GeV

Precision measurements of electromagnetic properties of π^0, η, η' via Primakoff effect



a) Two-Photon Decay Widths:

1) $\Gamma(\pi^0 \to \gamma\gamma)$ @ 6 GeV
2) $\Gamma(\eta \to \gamma\gamma)$
3) $\Gamma(\eta' \to \gamma\gamma)$

Input to Physics:

- precision tests of chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle
- input to calculate HLbL in $(g-2)_\mu$

b) Transition Form Factors at Q^2 of 0.001-0.3 GeV^2/c^2:

$F(\gamma\gamma^* \to \pi^0)$, $F(\gamma\gamma^* \to \eta)$, $F(\gamma\gamma^* \to \eta')$

Input to Physics:

- π^0,η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?
- input to calculate HLbL in $(g-2)_\mu$

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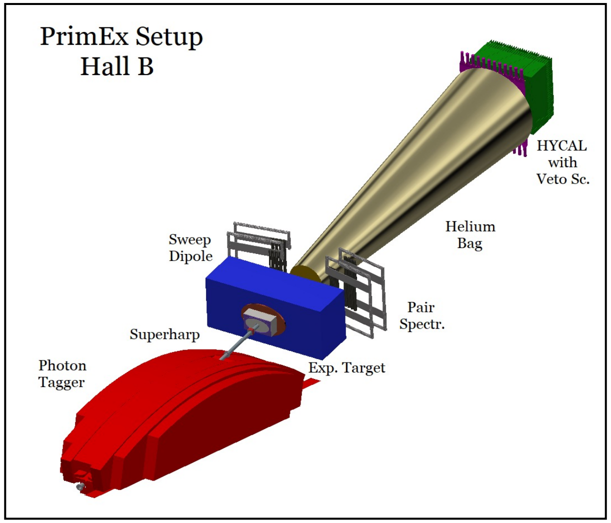

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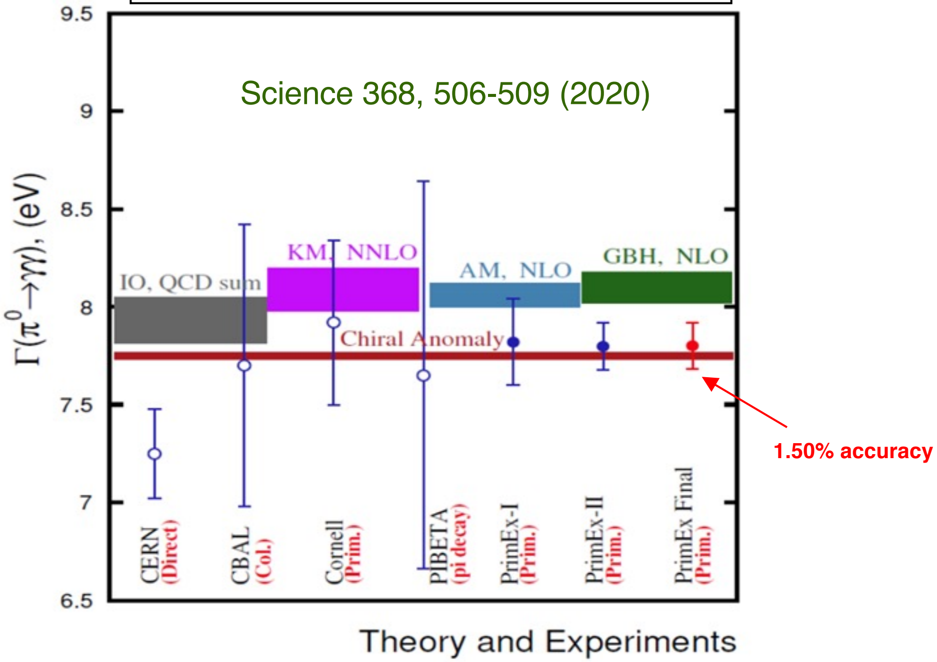

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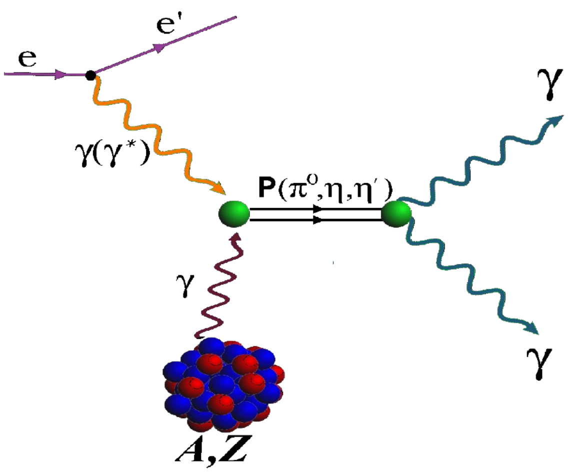

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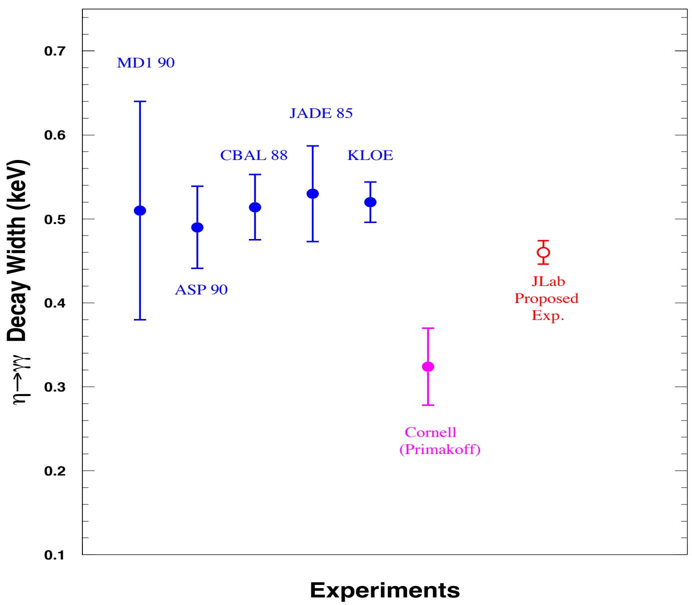
On-Going PrimEx-eta experiment

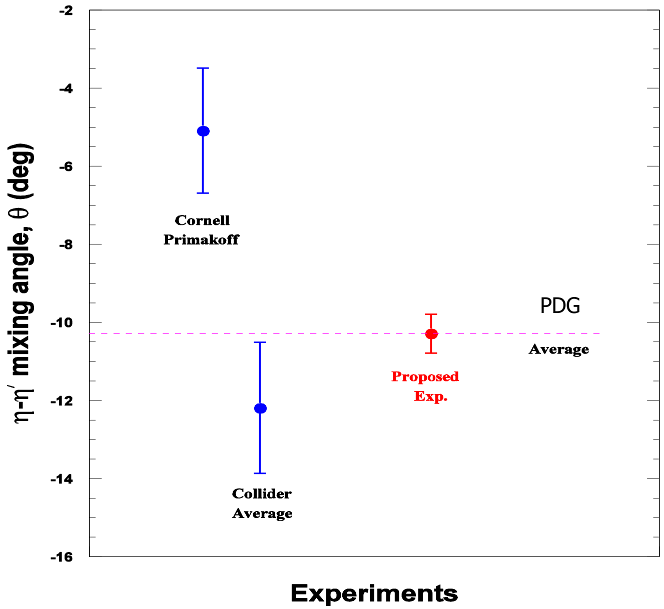
- Two data sets were collected in 2019 and in 2021.
- The third run is scheduled for 2022

Physics for $\Gamma(\eta\rightarrow\gamma\gamma)$ Measurement

1. Resolve long standing discrepancy between previous collider and Primakoff measurements:



2. Extract η-η′mixing angle:



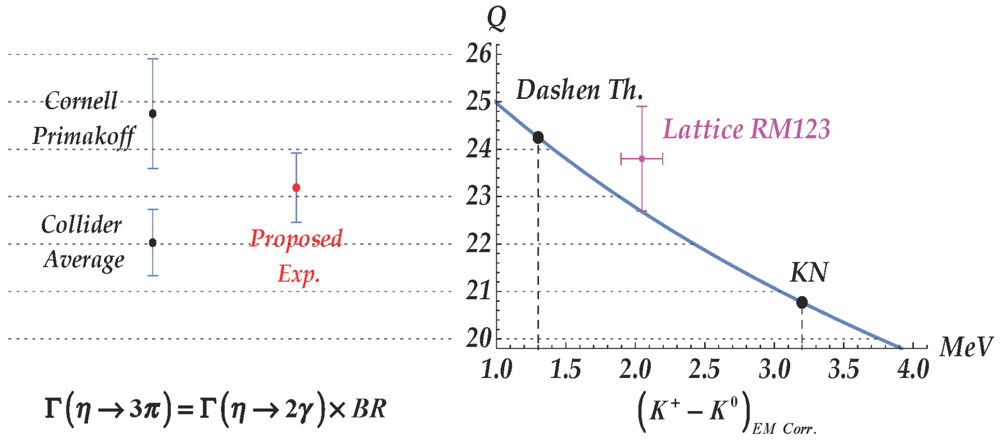
3. Improve calculation of the η-pole contribution to Hadronic Light-by-Light (HLbL) scattering in $(g\text{-}2)_\mu$

4. Improve all partial decay widths in the η-sector

Precision Determination Light Quark Mass Ratio

A clean probe for quark mass ratio: $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$, where $\hat{m} = \frac{1}{2}(m_u + m_d)$

- $\eta \rightarrow 3\pi$ decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em}A_2$
- α_{em} is small
- Amplitude: $A(\eta \rightarrow 3\pi) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$



$\Gamma(\eta \rightarrow 3\pi) = \Gamma(\eta \rightarrow 2\gamma) \times BR$

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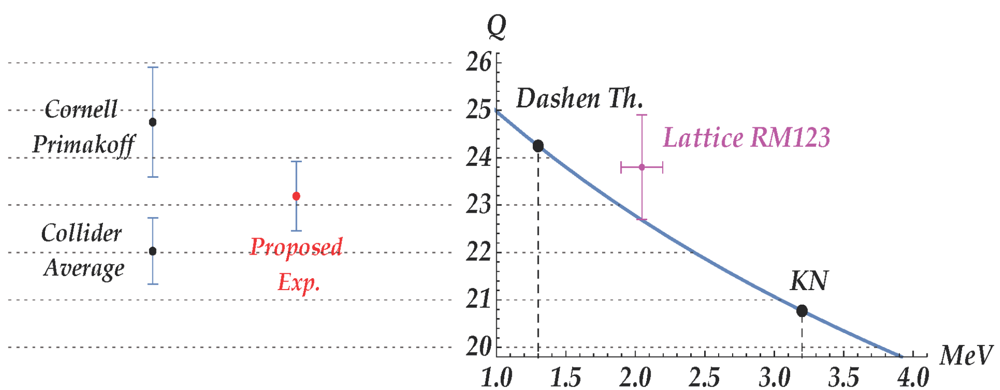

$\Gamma(\eta \to 3\pi) = \Gamma(\eta \to 2\gamma) \times BR$

- Critical input to extract Cabibbo Angle, $V_{us} = \sin(\theta_c)$ from kaon or hyperon decays.
- V_{us} is a cornerstone for test of CKM unitarity:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

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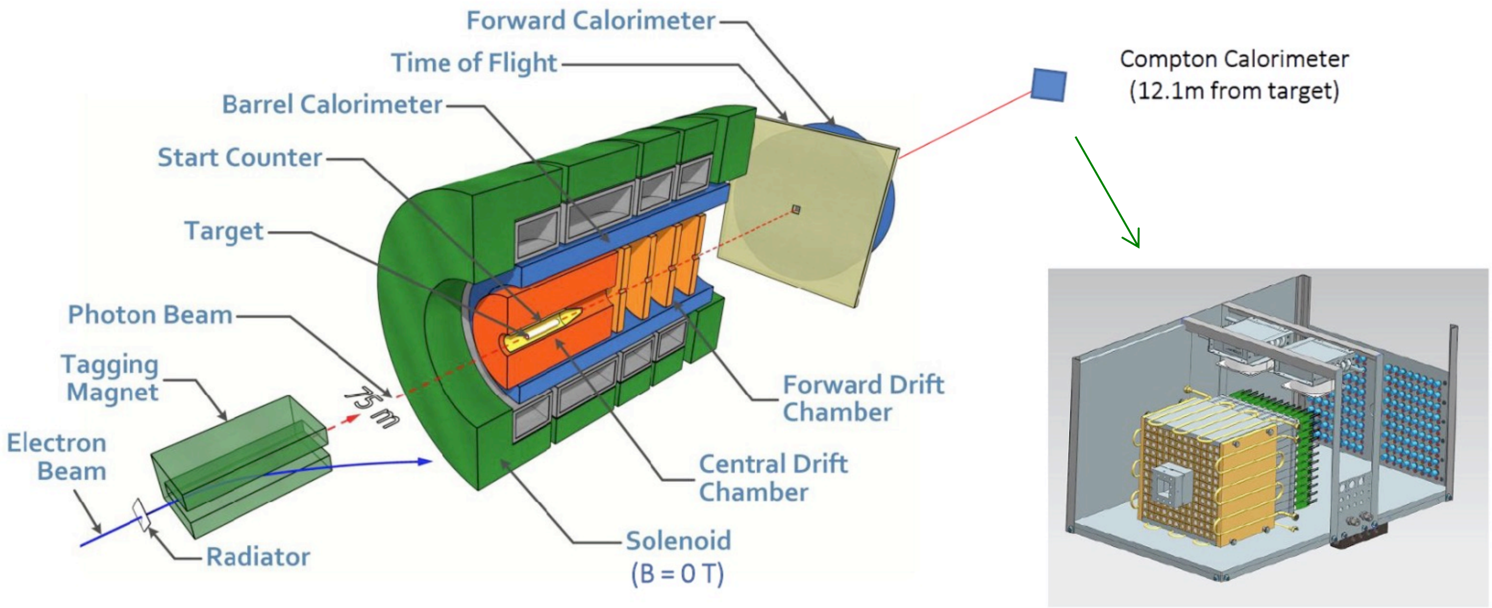
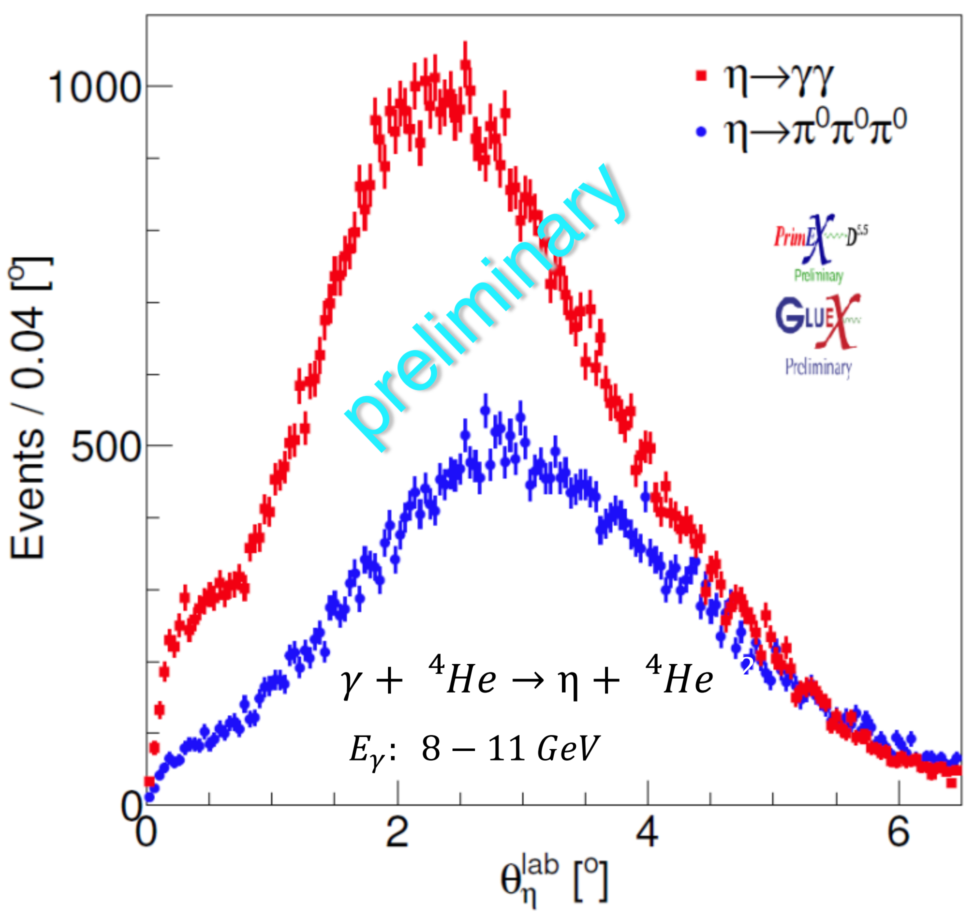
PrimEx-eta Experiment on $\Gamma(\eta\to\gamma\gamma)$ in Hall D



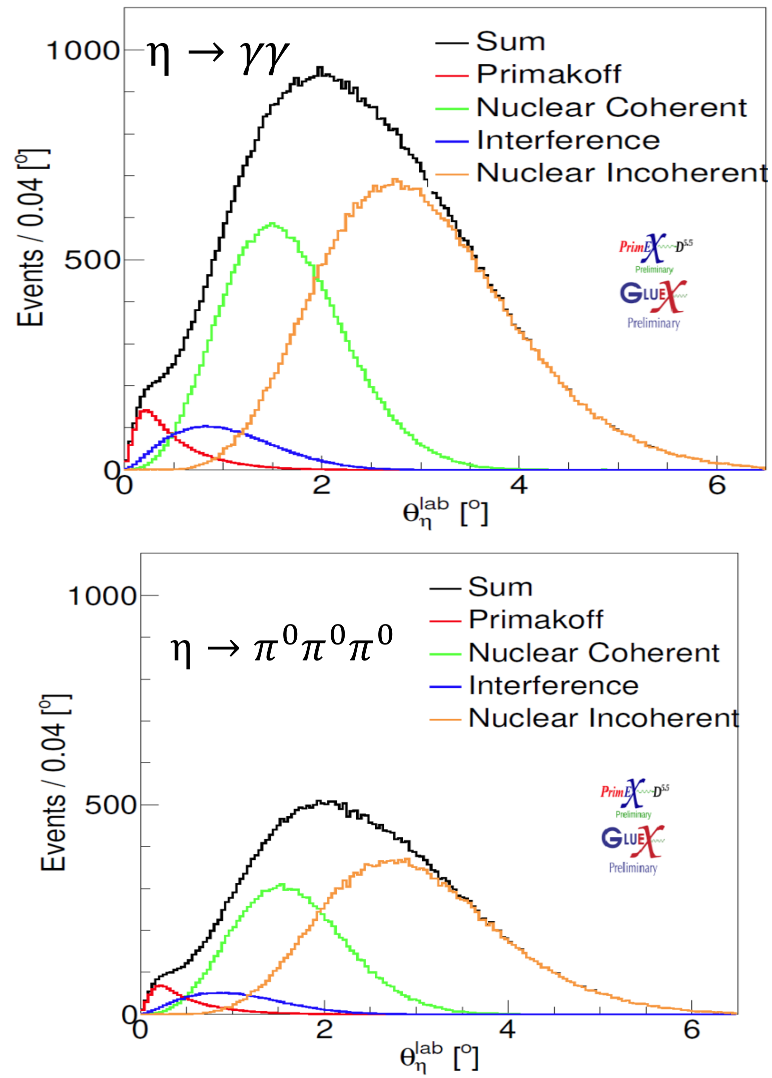
- Tagged photon beam (~8.0-11.7 GeV).
- Pair spectrometer and a TAC detector for the photon flux control.
- Liquid Hydrogen (3.5% R.L.) and ^{4}He targets (~4% R.L.)
- The η decay photons are detected by Forward Calorimeter (FCAL); the charged decay particles of η are detected by the GlueX spectrometer.
- CompCal and FCAL to measure electron Compton scattering for control of overall systematics.

Preliminary Results on the η Yield

η Yield from phase I data:

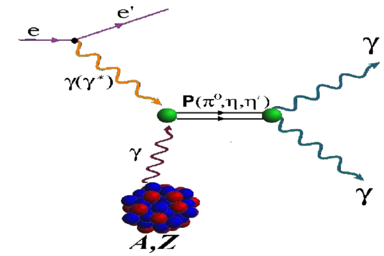


Simulations:

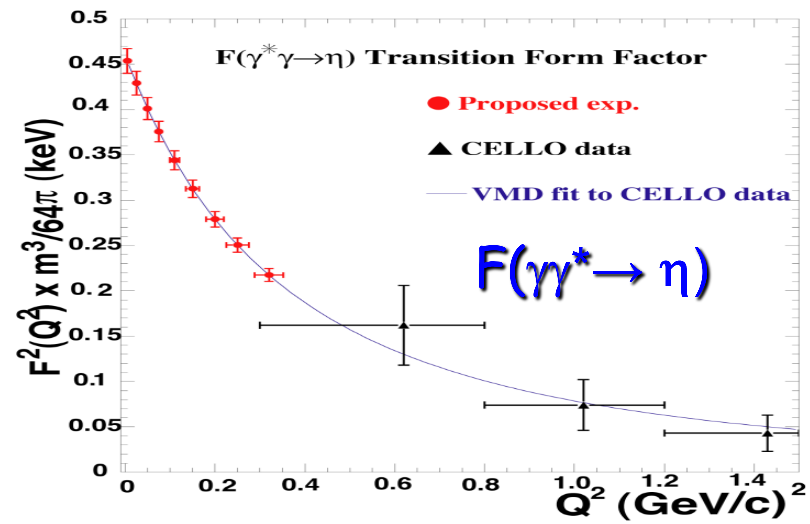


More details presented by Igal Jaegle, **Y07.00003**

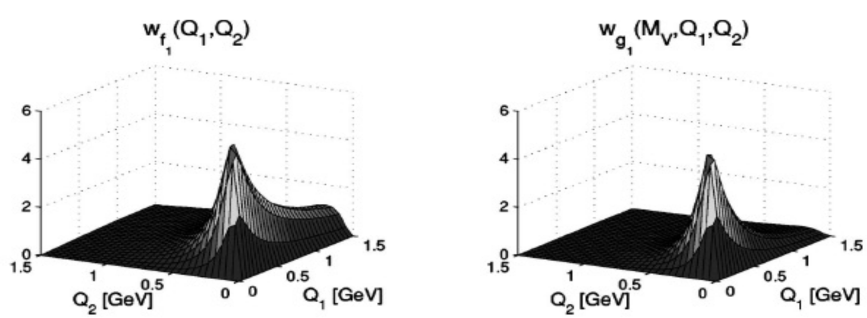
Space-Like Transition Form Factors
(Q^2 : 0.001-0.3 GeV^2/c^2)



- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^* P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



- Input for hadronic light-by-light calculations in muon (g-2)



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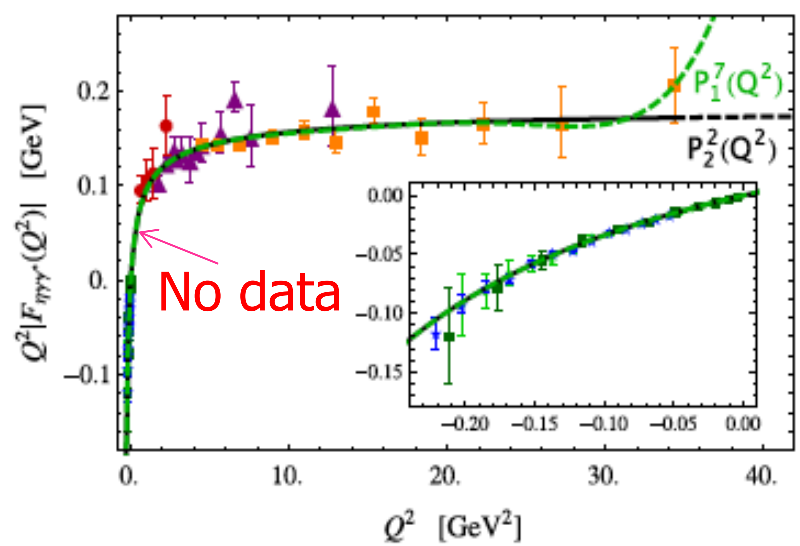

Eur.Phys.J. C75, 414 (2015)

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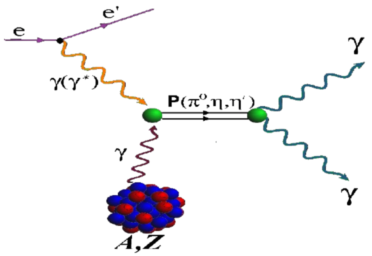

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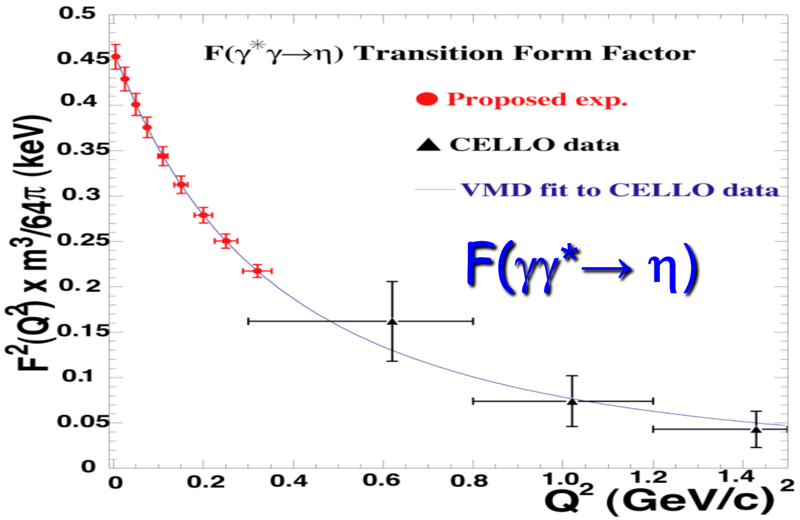

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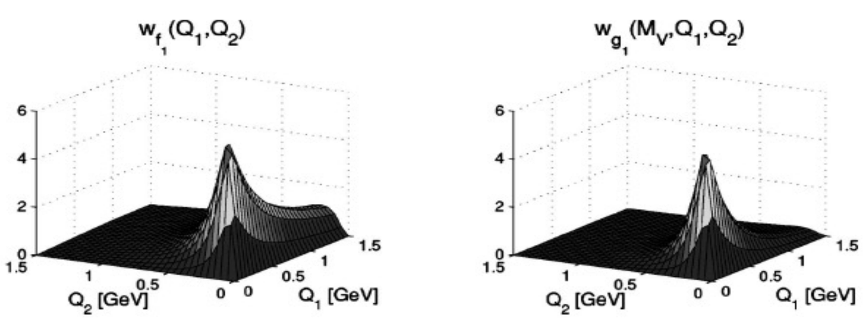

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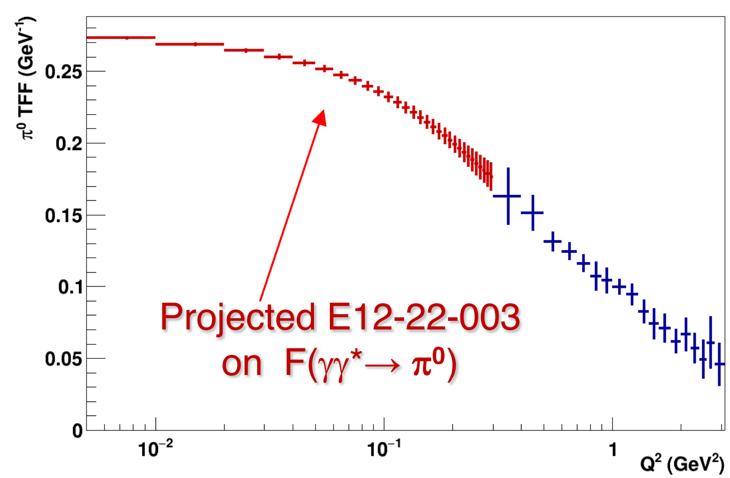


Discrete Symmetries

Class	Violated	Conserved	Interaction
0		C, P, T, CP, CT, PT, CPT	strong, electromagnetic
I	C, P, CT, PT	T, CP, CPT	(weak, with no KM phase or flavor-mixing)
II	P, T, CP, CT	C, PT, CPT	
III	C, T, PT, CP	P, CT, CPT	
IV	C, P, T, CP, CT, PT	CPT	weak

- class II: *P*-, *CP*-violation
  - ▷ QCD θ-term; in general: electric dipole moments
  - ▷ $\eta^{(\prime)}$ decay examples: $\eta^{(\prime)} \to 2\pi$, $\eta^{(\prime)} \to \pi^+\pi^-\gamma^{(*)}$
- class III: *C*-, *CP*-violation
  - ▷ far less discussed; in SMEFT, start at dimension 8 only
  - ▷ $\eta^{(\prime)}$ decay examples: $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to \pi^0\gamma^* \ldots$

❖ A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee Phys. Rev.,139, B1650 (1965)

Class III has much weaker experimental constraint, offer a opportunity for new physics search.

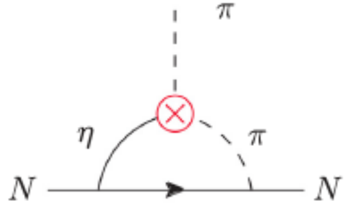
Class II: P-, CP-Violation in $\eta^{(\prime)} \to \pi\pi$

- $\eta \to \pi\pi$: class II, *P*-, *CP*-violating
  ($\pi\pi$ *S*-wave: $J^{PC} = 0^{++}$, η: $J^{PC} = 0^{-+}$)
- θ-term induces such a decay:

$$\mathcal{B}(\eta \to \pi^+\pi^-) = \frac{\bar{g}^2_{\eta\pi\pi}}{16\pi M_\eta \Gamma_\eta}\sqrt{1 - \frac{4M^2_{\pi^\pm}}{M^2_\eta}}, \quad \bar{g}_{\eta\pi\pi} = \frac{2\bar{\theta} M^2_\pi m_u m_d}{\sqrt{3}F_\pi (m_u + m_d)^2}$$

Crewther et al. 1979, Pich, de Rafael 1991

- experimental limit $\mathcal{B}(\eta \to \pi^+\pi^-) < 4.4 \times 10^{-6}$ $\longrightarrow$ E. Pérez del Rio
  implies $\bar{\theta} < 4 \times 10^{-4}$ KLOE 2020
- problem: neutron EDM constraint much stronger, $|\bar{\theta}| \lesssim 10^{-10}$
  $\eta \to \pi\pi$ via θ-term suppressed beyond all experimental reach



Class II: P-, CP-Violation via Strange-Quark-Muon Operators

- new class of *CP*-tests in Sánchez-Puertas 2019

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

$$\eta \to \pi^0\mu^+\mu^- \qquad \eta \to \pi^+\pi^-\mu^+\mu^-$$

E. Royo

Zillinger, BK, Sánchez-Puertas

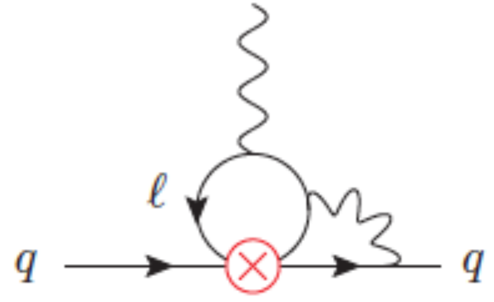
- quark–lepton four-fermion operators (scalar–pseudoscalar):

$$\mathcal{L}_{\text{eff}} = \frac{1}{2v^2} \text{Im}\, c_{\ell edq}^{2222} \Big[(\bar{\mu}\mu)(\bar{s}i\gamma^5 s) - (\bar{\mu}i\gamma^5\mu)(\bar{s}s) \Big] + [u\text{-}, d\text{-quarks}]$$

- EDMs only generated at two loops

  constraint for strange quarks weakest:

$$|\text{Im}\, c_{\ell edq}^{2222}| < 0.04$$

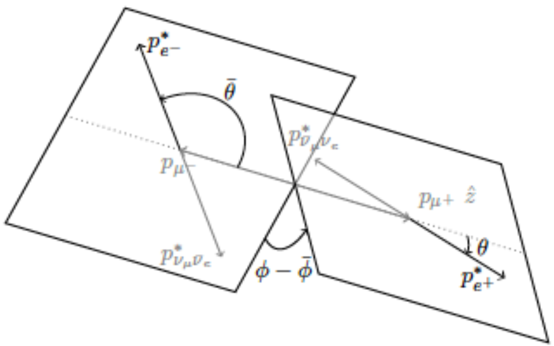


- Offer good opportunities for P-, CP-violation tests

Class II: P-, CP-Violation via Scalar Operators (cont.)

- μ-polarization asymmetry in $\eta^{(\prime)} \to \mu^+ u^-$, $\eta^{(\prime)} \to \gamma \mu^+ u^-$, $\eta^{(\prime)} \to \pi^0 \mu^+ u^-$

  JHEP 01, 031 (2019)
  hep-ph/0202002



$$A_L = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N}$$

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

- Angular asymmetry in decay planes:

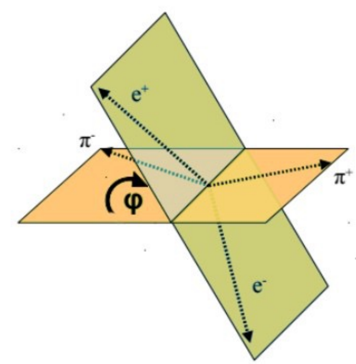
$\eta^{(\prime)} \to \mu^+ u^- e^+ e^-$

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

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

$\eta^{(\prime)} \to \pi^+ \pi^- e^+ e^-$

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



Class III: C- and CP-Violation

- $\eta^{(\prime)}$ are $C = +1$ eigenstates: opportunity to test C-violation!

Channel	Branching ratio	Note
$\eta \to 3\gamma$	$< 1.6 \times 10^{-5}$	
$\eta \to \pi^0\gamma$	$< 9 \times 10^{-5}$	Violates angular momentum conservation or gauge invariance
$\eta \to \pi^0 e^+ e^-$	$< 7.5 \times 10^{-6}$	C, CP-violating as single-γ process
$\eta \to \pi^0 \mu^+ \mu^-$	$< 5 \times 10^{-6}$	C, CP-violating as single-γ process
$\eta \to 2\pi^0\gamma$	$< 5 \times 10^{-4}$	
$\eta \to 3\pi^0\gamma$	$< 6 \times 10^{-5}$	

- example ops.: Khriplovich 1991; Ramsey-Musolf 1999; Kurylov et al. 2001

$$\frac{1}{\Lambda^3}\bar{\psi}_f\gamma_5 D_\mu\psi_f\,\bar{\psi}_{f'}\gamma^\mu\gamma_5\psi_{f'} + \text{h.c.}\,, \qquad \frac{1}{\Lambda^3}\bar{\psi}_f\sigma_{\mu\nu}\lambda_a\psi_f G_a^{\mu\lambda}F_\lambda^\nu$$

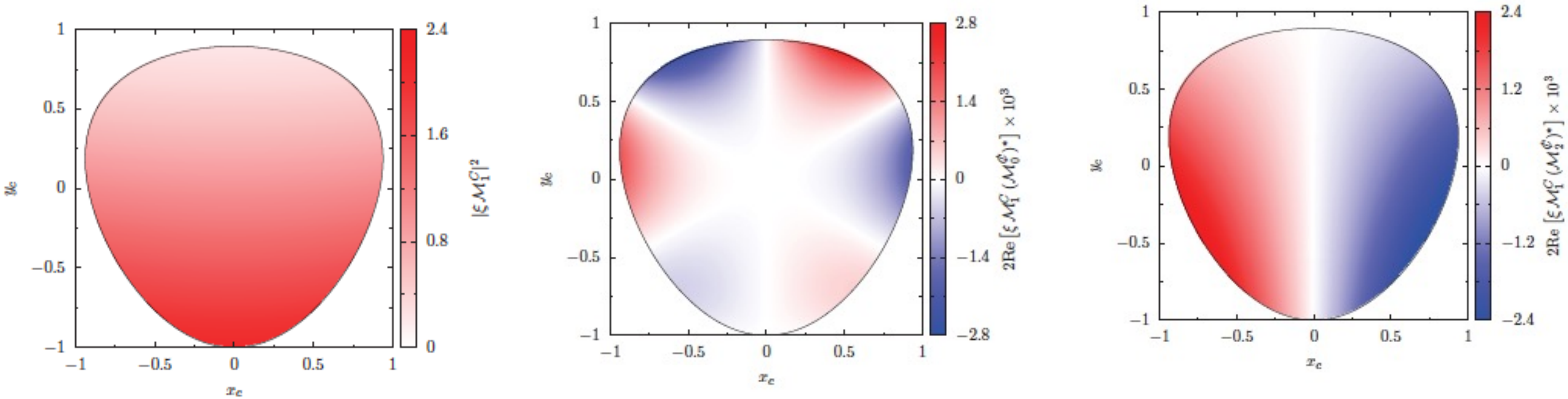
$\longrightarrow$ require helicity flip, actually dimension-8 in SMEFT

- electroweak radiative corrections mix class II and class III
  still weaker EDM constraints

Class III: C- and CP-Violation in $\eta^{(\prime)} \to \pi^+\pi^-\pi^0,\ \eta' \to \pi^+\pi^-\eta$

- Dalitz plot decomposition (central fit result)

$$|\mathcal{M}_c|^2 \approx |\mathcal{M}_1^C|^2 + 2\mathrm{Re}\left[\mathcal{M}_1^C\,(\mathcal{M}_0^{\not C})^*\right] + 2\mathrm{Re}\left[\mathcal{M}_1^C\,(\mathcal{M}_2^{\not C})^*\right]$$



- $\mathcal{M}_0^{\not C}$ and $\mathcal{M}_2^{\not C}$ lead to different interference patterns

- CP-violation from these processes is not bounded by EDM.

- Complementary to nEDM searches even in the case of T and P odd observables, since the flavor structure of the η is different from the nucleus

Lepton Flavor violations

- $\eta^{(\prime)} \rightarrow \mu^+ e^- + c.c.$
- $\eta^{(\prime)} \rightarrow \gamma\mu^+ e^- + c.c.$
- $\eta^{(\prime)} \rightarrow \mu^+ \mu^+ e^- e^- + c.c.$

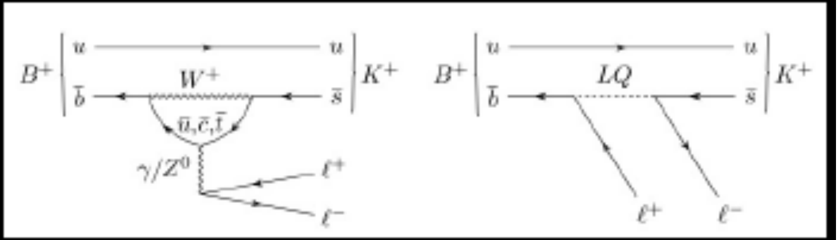
PDG limit:

$$\mathcal{B}(\eta \rightarrow \mu^+ e^- + \mu^- e^+) < 6 \times 10^{-6},$$
$$\mathcal{B}(\eta' \rightarrow \mu^+ e^- + \mu^- e^+) < 4.7 \times 10^{-4}$$

Lepton Universality Tests

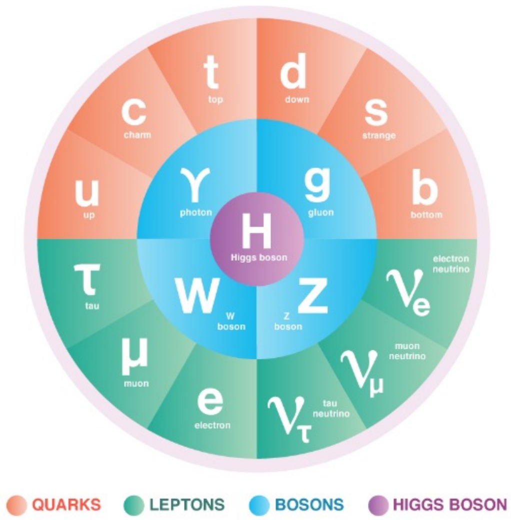
LHCb latest results: with $B+ \to \mu^+\mu^- K^+$ vs $e^+e^- K^+$

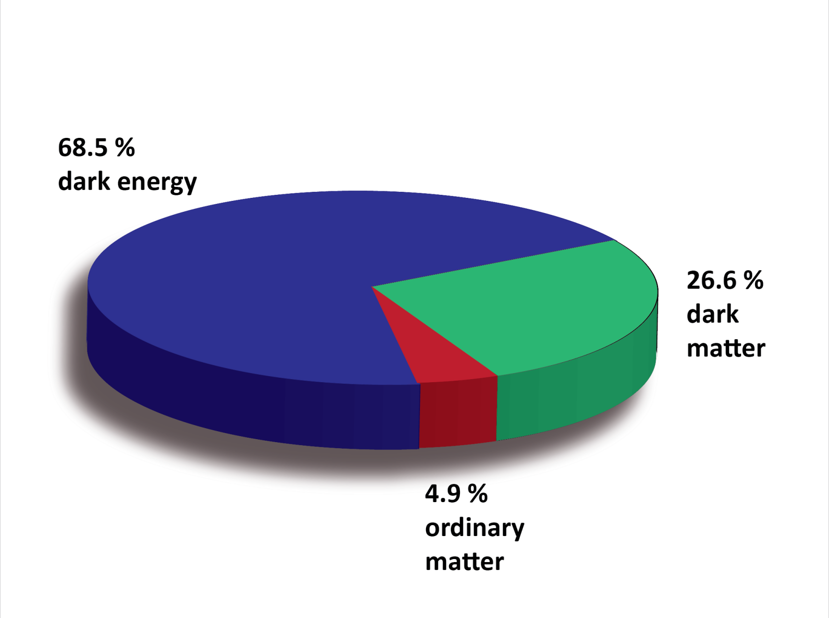
- *Based on 3850 vs 1640 evts ($BR_{SM} = 10^{-6}$)*
- *3.1σ discrepancy vs SM*



- $\eta \to \gamma\mu^+\mu^-$ vs $\eta \to \gamma e^+e^-$
- $\eta \to \mu^+\mu^-\mu^+\mu^-$ vs $\eta \to e^+e^-\mu^+\mu^-$
- $\eta \to \pi^0\mu^+\mu^-$ vs $\eta \to \pi^0 e^+e^-$

BSM Physics in Dark Sector

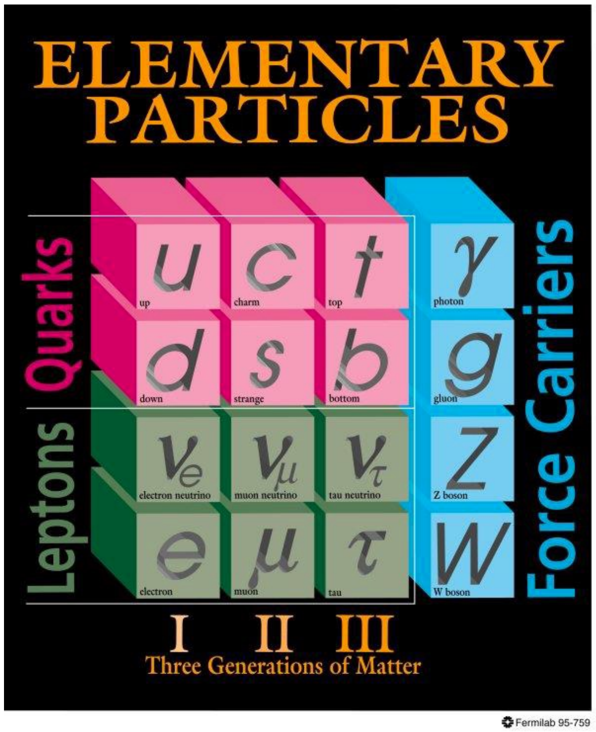




Open questions:

- What is dark matter?
- How is the matter-antimatter asymmetry generated?
- What dynamics is responsible for neutrino masses?
- What physics underlies the Higgs sector and sets the weak scale?
- Why is CP conserved by the strong interactions?

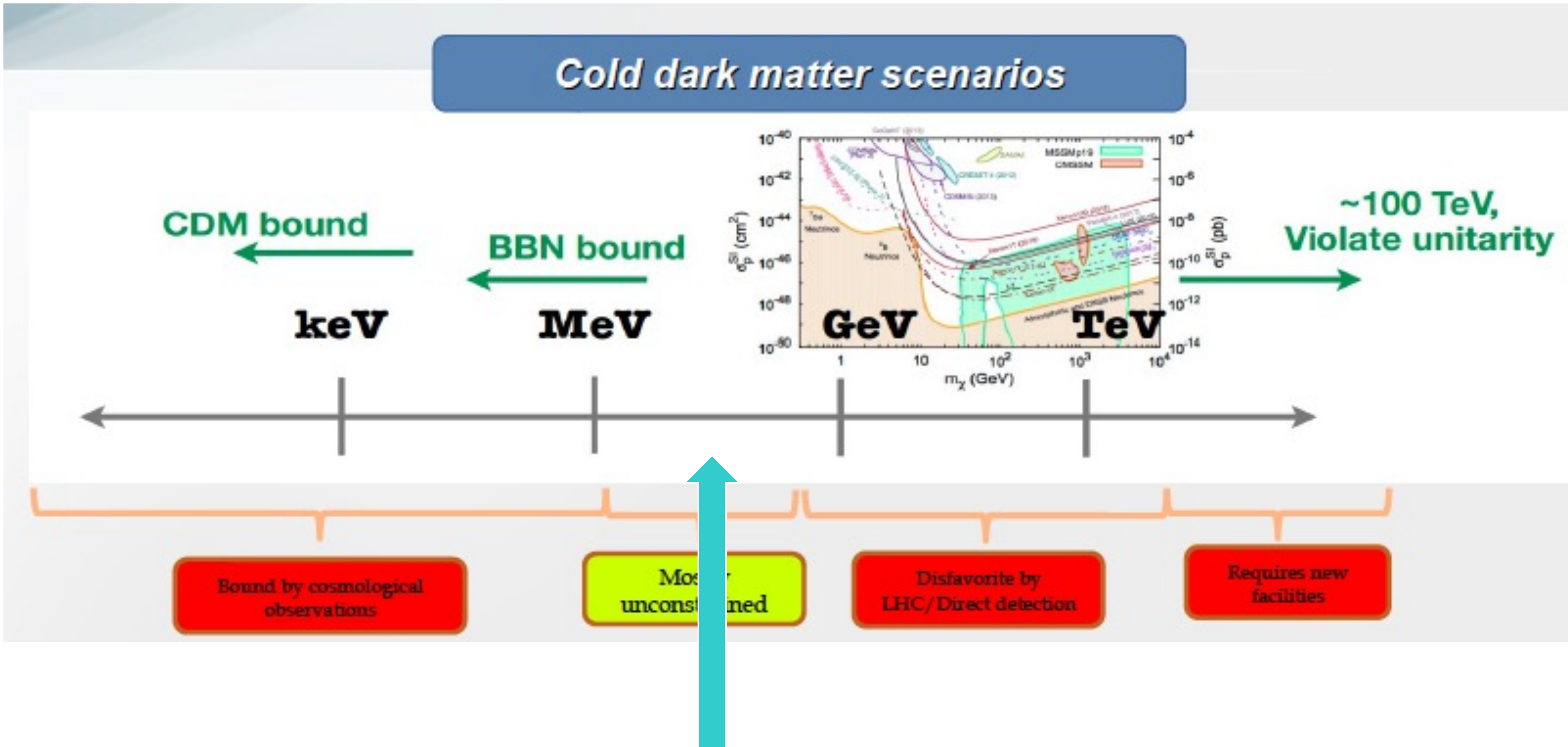
Motivation for New Physics



Dark Sector

- New gauge forces, bosons and fermions beyond SM.
- The stability of dark matter can be explained by the dark charge conservation.

Where to Search for Dark Matter?

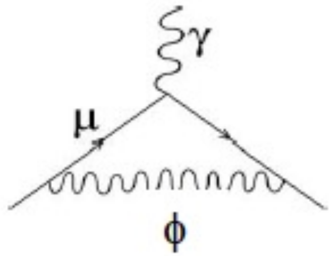


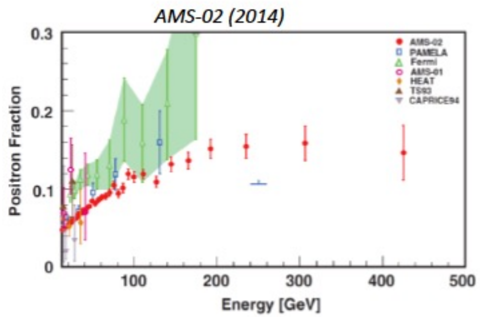
Sub-GeV region represents a good discovery opportunity

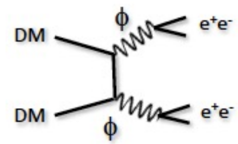
Motivation for sub-GeV New Physics

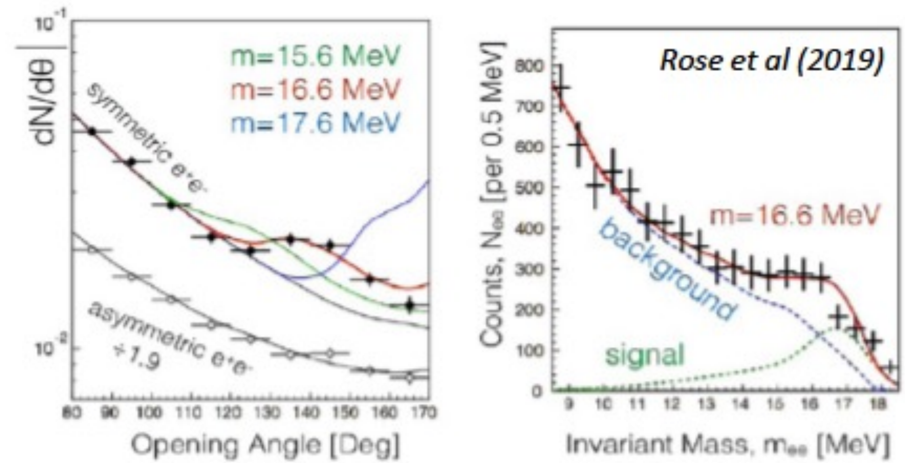
$(g-2)_\mu$ anomaly

Pospelov (2008)

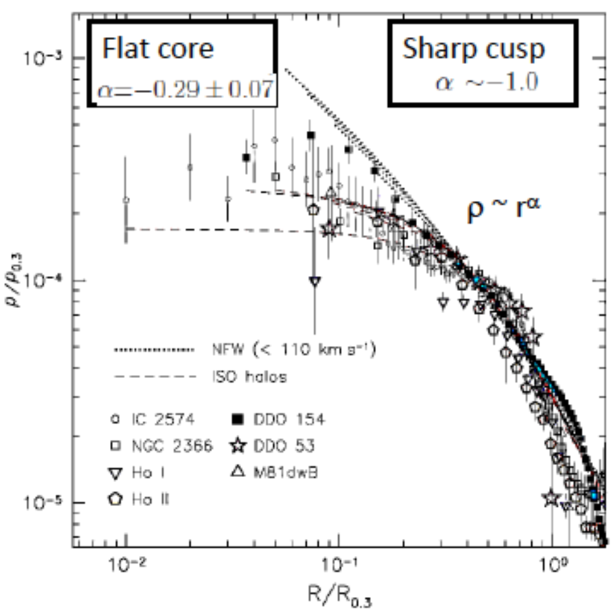


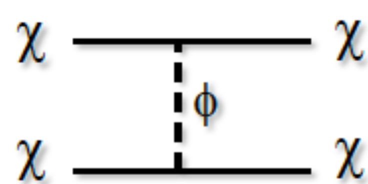






THINGS (dwarf galaxy survey) - Oh et al. (2011)





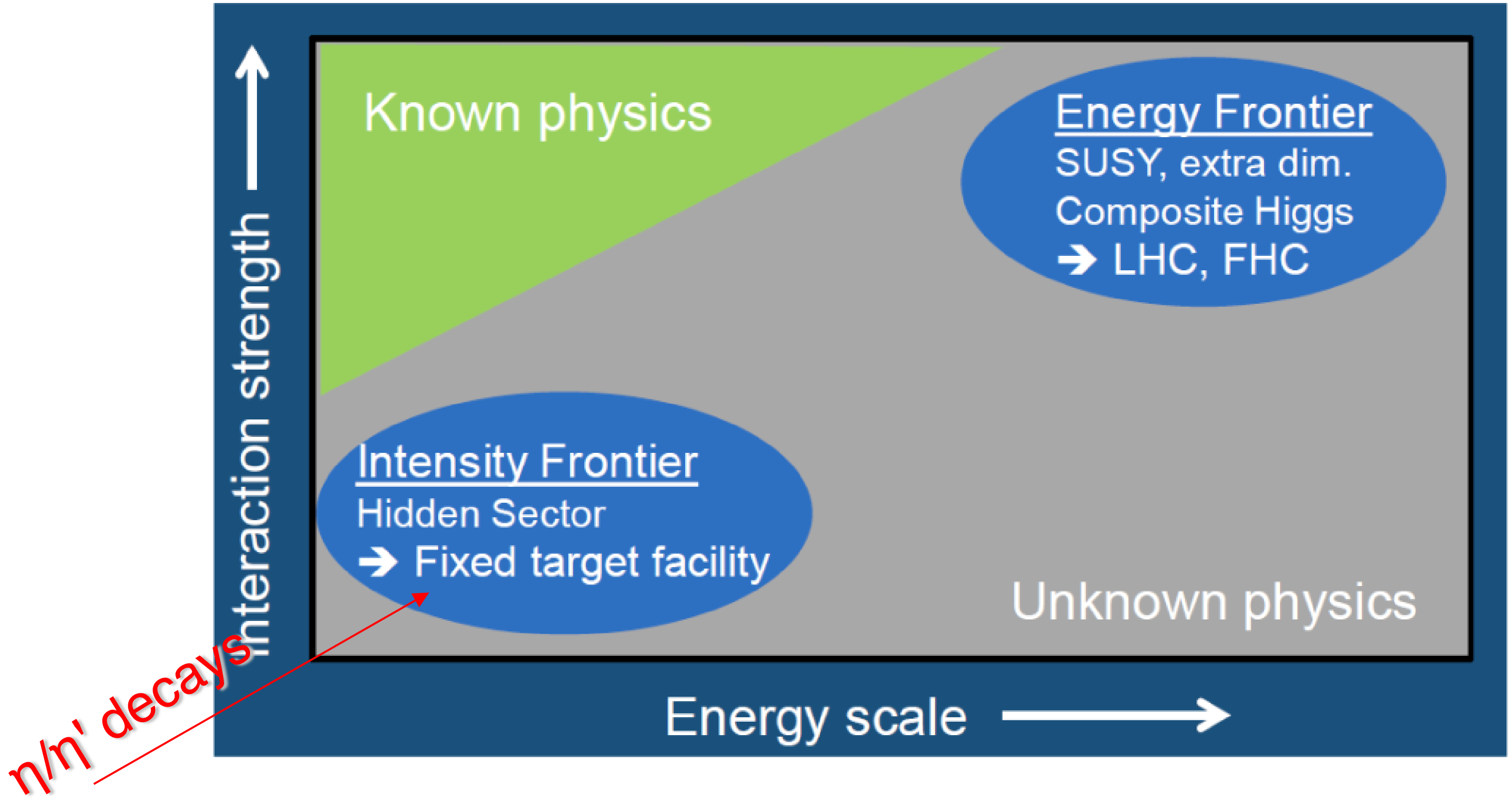
self-interaction

Self-interactions solve core-vs-cusp

Particles get scattered out of dense halo centers

If these anomalies are interpreted in terms of new physics, all point to new forces with mediator particles in the MeV–GeV mass range!

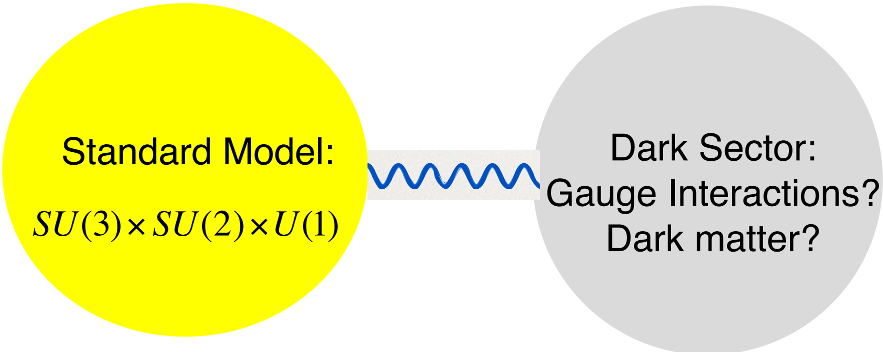
Landscape of BSM Physics Search



arXiv:1504.04855

Complementary to other types of experiments, η/η' decays offer unique sensitivity for sub-GeV new physics that are flavor-conserving, light quark-coupling, PC-conserving.

Portals Coupling SM and Dark Sector



vector:

- Leptophobic vector B'
  $\eta,\eta' \to B'\gamma \to \pi^0\gamma\gamma$, $(0.14 < m_{B'} < 0.62\ \text{GeV})$;
  $\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma$, $(0.62 < m_{B'} < 1\ \text{GeV})$.
- X boson or dark photon: $\eta,\eta' \to X\gamma \to e^+e^-\gamma$

scalar S: $\eta \to \pi^0 S \to \pi^0\gamma\gamma,\ \pi^0 e^+e^-,\ (10\ \text{MeV} < m_S < 2m_\pi)$;
$\eta,\eta' \to \pi^0 S \to 3\pi,\ \eta' \to \eta S \to \eta\pi\pi,\ (m_S > 2m_\pi)$.

Fermion: $\eta \to \pi^0 H$,
$with\ H \to \nu N_2,\ N_2 \to h' N_1,\ h' \to e^+e^-$

Portals:

vector $\kappa B^{\mu\nu}V_{\mu\nu}$

Scalar $H^+H(\varepsilon S + \lambda S^2)$

Fermion ξLHN

ALP $c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}$

Axion-Like Particles (ALP): $\eta,\eta' \to \pi\pi a \to \pi\pi\gamma\gamma,\ \pi\pi e^+e^-$

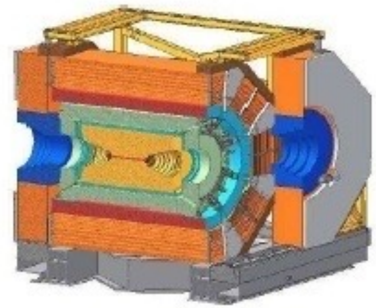
Phys. Rept. 945 (2022) 1-105, arXiv:2207.06905, arXiv:2203.07651

World Competition in η Decays

e+e- Collider

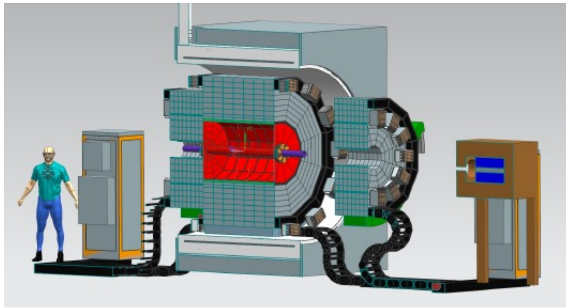
KLOE-2 at DAΦNE

BESIII at BEPCII



New Experiments:

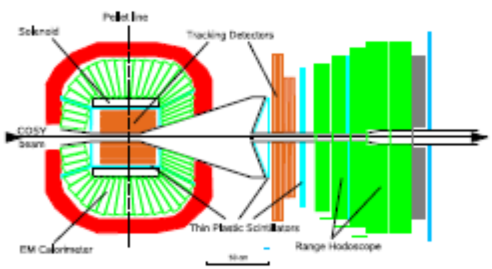
Proposed REDTOP



Fixed-target

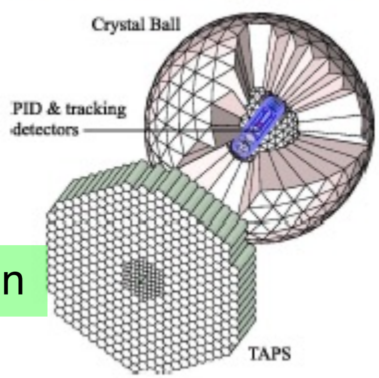
hadroproduction

WASA at COSY

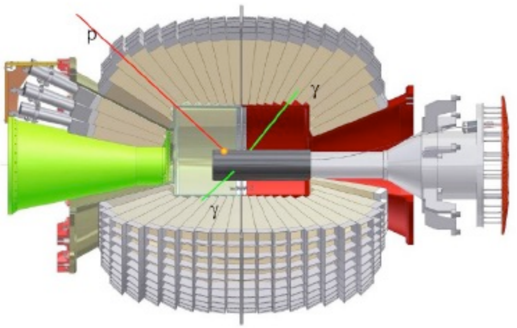


Photoproduction

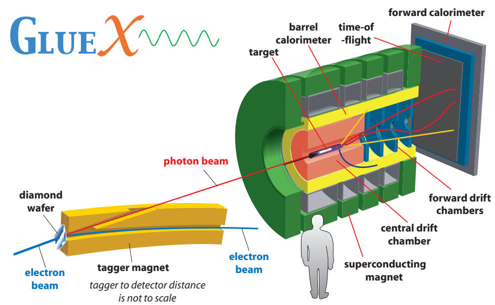
Crystall Ball at MAMI



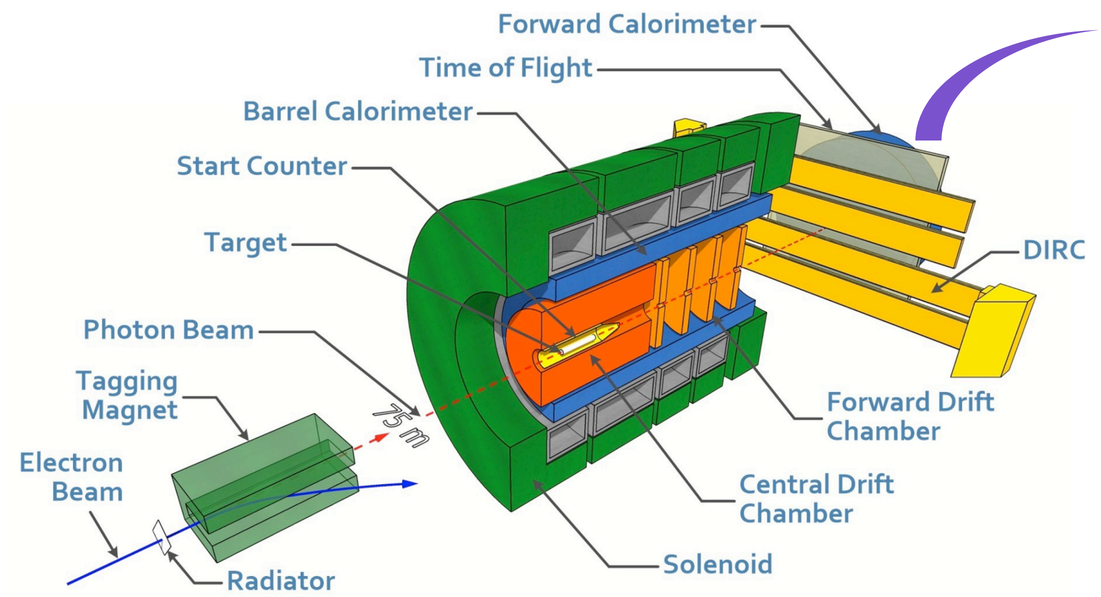
CBELSA/TAPS at ELSA

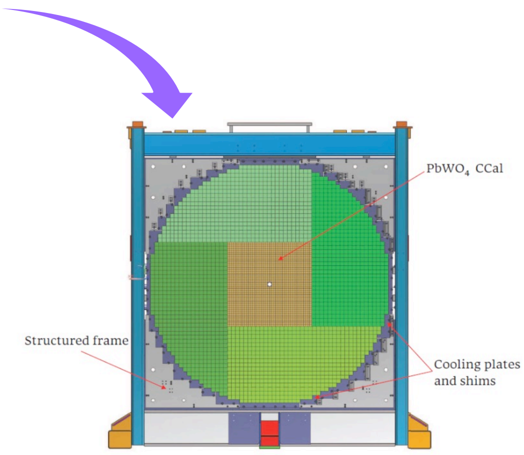


JEF at JLab



JLab Eta Factory (JEF) Experiment





FCAL-II

- Simultaneously produce η/η' on LH_2 target with 8.4-11.7 GeV tagged photon beam via $\gamma+p \rightarrow \eta/\eta'+p$
- Reduce non-coplanar backgrounds by detecting recoil protons with GlueX detector
- Upgraded Forward Calorimeter with High resolution, high granularity PWO insertion (FCAL-II) to detect multi-photons from the η/η' decays
- The GlueX detector will detect the charged products from the η/η' decays

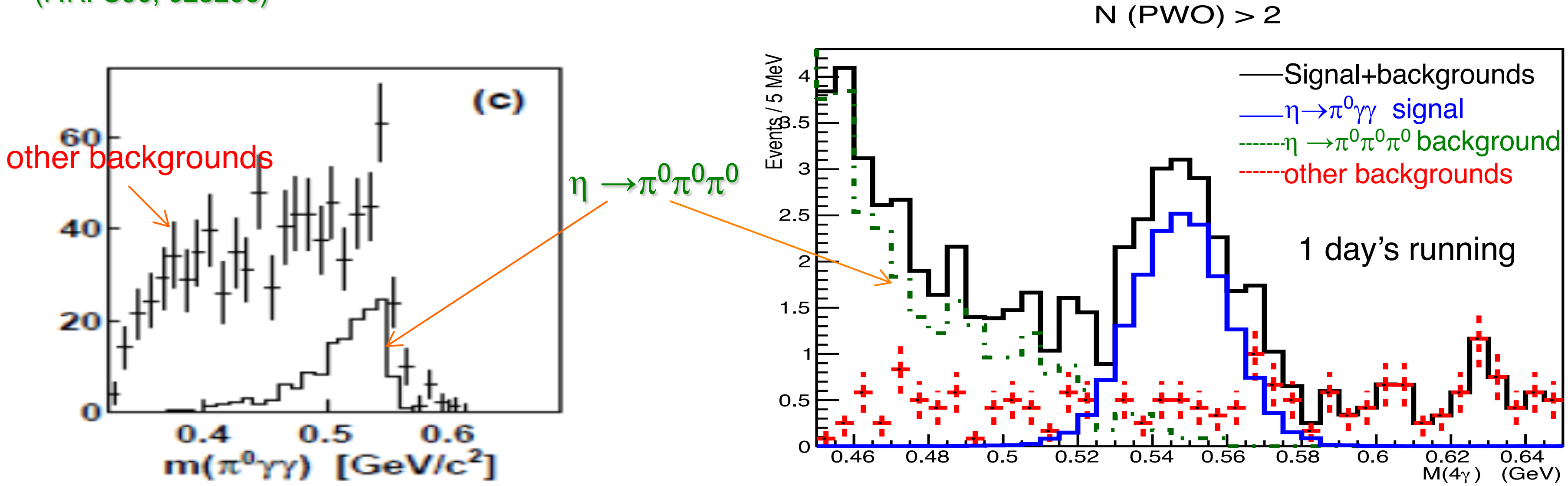
Uniqueness of JEF Experiment

1. Two-orders of magnitude background suppression comparing to all other experiments:

   a) η/η′ energy boost; b) FCAL-II; c) exclusive detections

A2 at MAMI: $\gamma p \rightarrow \eta p$ (E_γ=1.5 GeV) (P.R. C90, 025206)

JEF: $\gamma p \rightarrow \eta p$ (E_γ=8.4-11.7 GeV)



2. Capability of running in parallel with GlueX and other experiments in Hall D
   → high-statistics data set

3. The only facility can simultaneously produce tagged η and η' with similar rates (~5x10^7 per 100 days)

Production Rate

JEF for 100 days of beam:

	η	η'
Tagged mesons	6.5×10^7	4.9×10^7

Previous Experiments:

Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	10^6
WASA-COSY	$\sim3\times10^7$ (p+d), $\sim5\times10^8$ (p+p)	-
KLOE-II	3×10^8	5×10^5
BESIII	$\sim10^7$	$\sim5\times10^7$

JEF offers a competitive η/η' production rate with much cleaner backgrounds

Main JEF Physics Objectives

1. **Search for sub-GeV hidden bosons**

   vector:

   - Leptophobic vector *B '*

     $$\eta, \eta' \to B'\gamma \to \pi^0\gamma\gamma, \ (0.14 < m_{B'} < 0.62 \text{ GeV});$$
     $$\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma, \ (0.62 < m_{B'} < 1 \text{ GeV}).$$

   - Hidden or dark photon: $\eta, \eta' \to X\gamma \to e^+e^-\gamma$.

   scalar S: $\eta \to \pi^0 S \to \pi^0\gamma\gamma, \ \pi^0 e^+e^-, \ (10 \text{ MeV} < m_S < 2m_\pi);$
   $\eta, \eta' \to \pi^0 S \to 3\pi, \ \eta' \to \eta S \to \eta\pi\pi, \ (m_S > 2m_\pi).$

   Axion-Like Particles (ALP): $\eta, \eta' \to \pi\pi a \to \pi\pi\gamma\gamma, \ \pi\pi e^+e^-$

2. **Directly constrain CVPC new physics:** $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to 2\pi^0\gamma$, $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$

3. **Precision tests of low-energy QCD:**
   - Interplay of VMD & scalar dynamics in ChPT: $\eta \to \pi^0\gamma\gamma$ $\eta' \to \pi^0\gamma\gamma$
   - Transition Form Factors of $\eta^{(\prime)}$: $\eta^{(\prime)} \to e^+e^-\gamma$

4. **Improve the quark mass ratio via Dalitz distributions of $\eta \to 3\pi$**

A Key Channel: $\eta \to \pi^0\gamma\gamma$

Phys. Rept. 945 (2022) 1-105

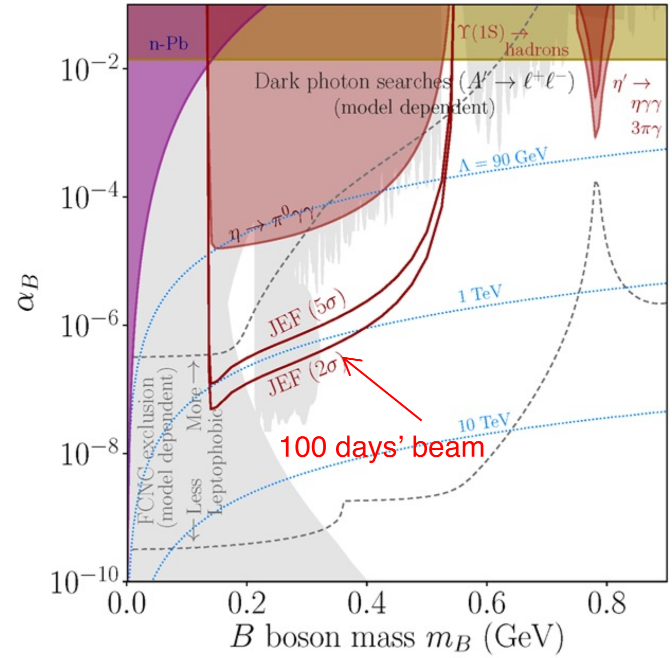
- **Search for sub-GeV gauge bosons**
  - A leptophobic vector B':

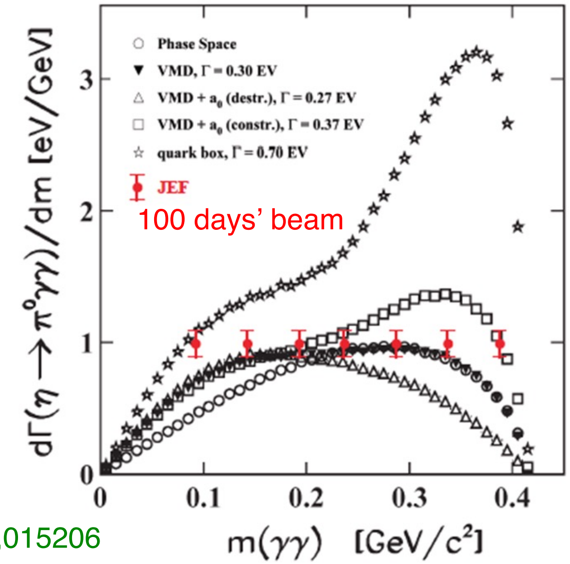
    $\eta \to \gamma B'$, $B' \to \pi^0\gamma$ — PL, B221, 80; PR,D89,114008
  - An scalar S:

    $\eta \to \pi^0 S$, $S \to \gamma\gamma$

    → A 100 keV-100 MeV electrophobic scalar can solve proton radius and $(g\text{-}2)_\mu$ puzzles.

PR,D100,095020; Nucl.Phy.B,114638.





PR,C78,015206

- **A rare window to probe interplay of VMD & scalar resonance in ChPT**

Test Charge Conjugation Invariance

- C is maximally violated in the weak force and is well tested.
- Assumed in SM for electromagnetic and strong forces, but it is not experimentally well tested

(current direct constraint: $\Lambda \geq 1$ GeV)

C Violating η neutral decays

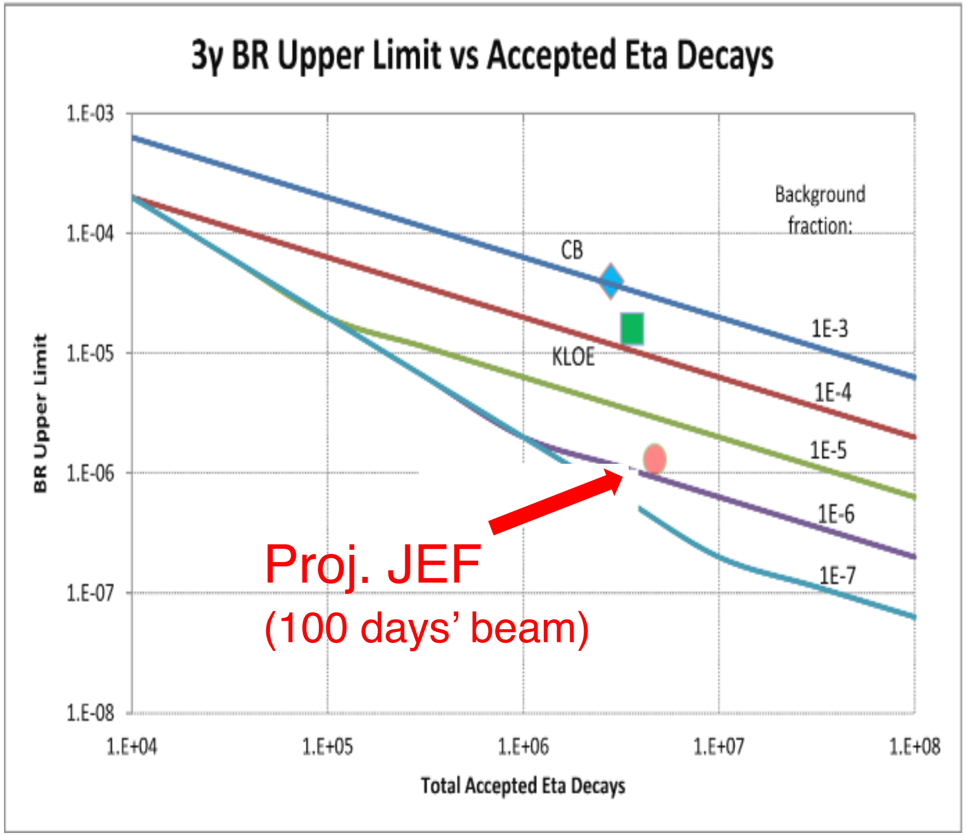
Mode	Branching Ratio (upper limit)	No. γ's
3γ	$< 1.6 \cdot 10^{-5}$	3
$\pi^0\gamma$	$< 9 \cdot 10^{-5}$	
$2\pi^0\gamma$	$< 5 \cdot 10^{-4}$	5
$3\gamma\pi^0$	Nothing published	
$3\pi^0\gamma$	$< 6 \cdot 10^{-5}$	7
$3\gamma 2\pi^0$	Nothing published	

Experimental Improvement on C-violating $\eta \to 3\gamma$

- SM contribution:
  $BR(\eta \to 3\gamma) < 10^{-19}$ via P-violating weak interaction.

- A calculation due to new physics by Tarasov suggests:
  $BR(\eta \to 3\gamma) < 10^{-2}$

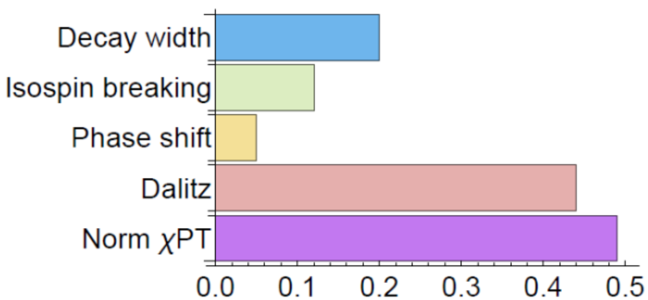
  Sov.J.Nucl.Phys.,5,445 (1967)



Improve BR upper limit by one order of magnitude to directly tighten the constraint on CVPC new physics

Improve Quark-Mass Ratio via $\eta\to3\pi$ Dalitz Distributions

- A clean probe for quark mass ratio: $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\quad \hat{m} = \frac{m_u + m_d}{2}$
  - decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em}A_2$
  - α_{em} is small
  - Amplitude: $A(s,t,u) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$
- Uncertainties in quark mass ratio



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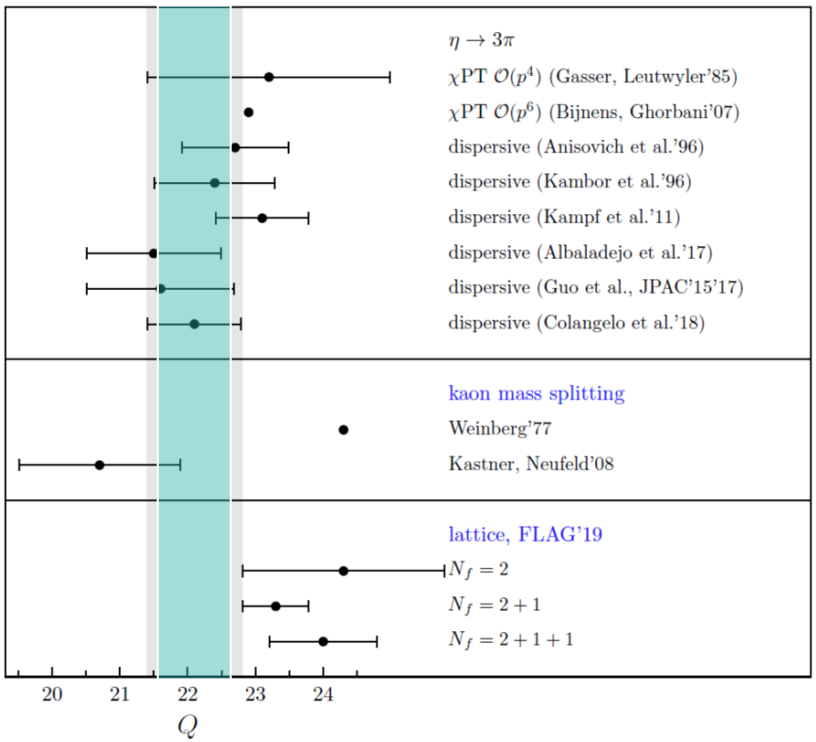
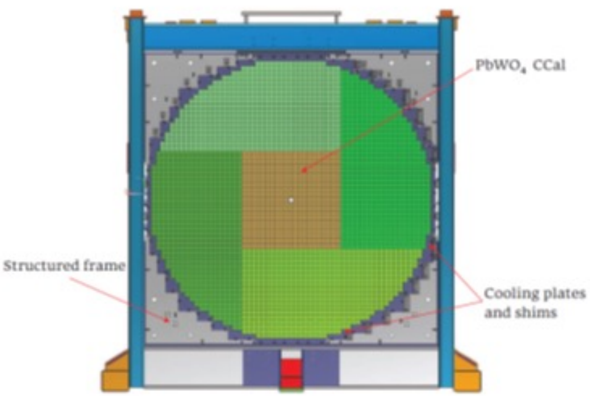


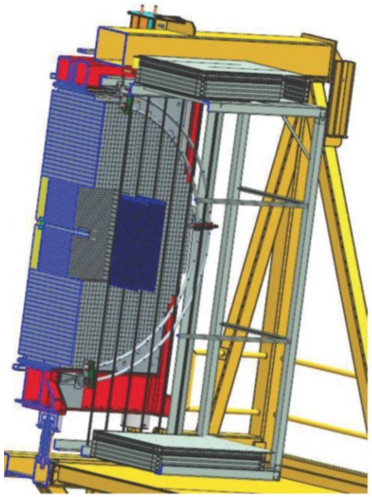
Current Status of the JEF Experiment

1. Non-rare decay data has been collecting with the GlueX spectroscope experiment since 2016.

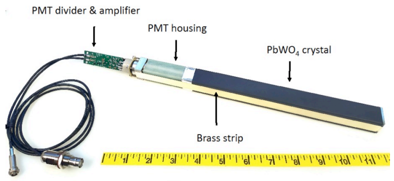
2. A PWO insert to upgrade FCAL is under construction.

- Mass production of 1600 PWO modules is on-going.
- Engineering design for calorimeter frame is finalized.
- Installation of the PWO insert is scheduled for 2023.





PWO module (2x2x20 cm^3)



Undergraduate workforce

3. Rare decay data with FCAL-II is expected in 2024.

A New Proposal: REDTOP

Baseline option – medium-energy CW proton beam

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

vs LHCb@40 MHz

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

Preferred option – low-energy pion beam

- ***π^+ on Li/Be or π^- on LH: ~750 MeV - 2.5×10^9 πOT/sec***
- ***More expensive but lower background (ESS, FNAL(?), FAIR, HIAF, ORNL)***
- ***η : inelastic background = 1:50 $\rightarrow$ sensitivity to BSM increased by > 2x***
- ***Semi-tagged η production***

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

Ultimate option: Tagged 10^{13} η mesons

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

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

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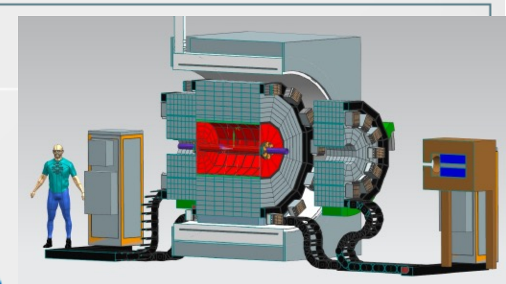
up to ~5x0^{13} η per year!

arXiv:2203.07651

REDTOP Detector

- Calorimetric $\sigma(E)/E \sim 3\text{-}5\%/\sqrt{E}$
- 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

LGAD Tracker

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

EM + had calorimeter

- Use ADRIANO2 calorimeter (Calice+T1604)
- PFA + Dual-readout+HG
- Light sensors: SiPM or SPADs
- 96.5% coverage

Vertex reconstruction

Option 1: Fiber tracker (LHCb style)

- Established and low-cost technology
- ~70μm vertex resolution in x-y. Stereo layers
- Next generation technology

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

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- JEF may still lead in rare neutral decays
- REDTOP will have the best sensitivity for rare charged modes.

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

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

C, T, CP-violation

- *CP Violation via Dalitz plot mirror asymmetry:* $\eta \to \pi^0 \pi^+ \pi^-$
- *CP Violation (Type I – P and T odd , C even):* $\eta \to 4\pi^0 \to 8\gamma$
- *CP Violation (Type II - C and T odd , P even):* $\eta \to \pi^0 \ell\ell$ *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:* $\eta \to \mu^+\mu^- e^+e^-$
- *CP invariance in angular correlation studies:* $\eta \to \mu^+\mu^- \pi^+\pi^-$
- *CP invariance in* μ *polar. in studies:* $\eta \to \pi^0 \mu^+\mu^-$
- *T invar. via* μ *transverse polarization:* $\eta \to \pi^0\mu^+\mu^-$ *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:* $\pi^0 \to \gamma A' \to \gamma e^+e^-$
- *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):* $\eta \to \pi^0 H$ *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* $X_{17} \to \pi^+\pi^-$
- *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* $B \to \gamma\pi^0$
- *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*
- $\eta \to \pi^0 H$ *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)*

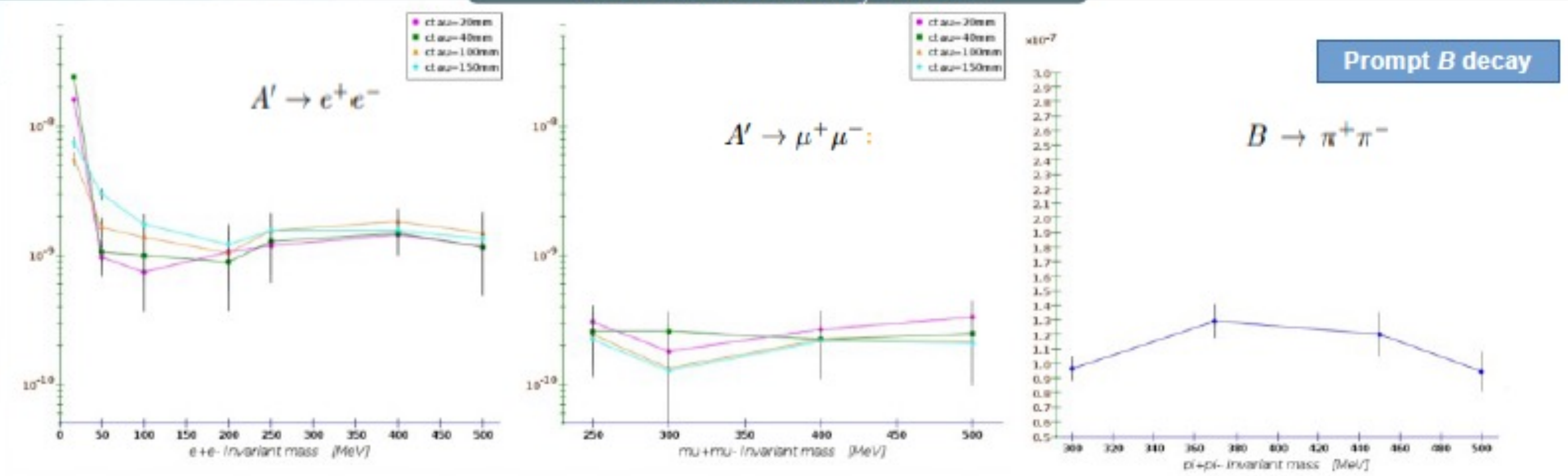
arXiv:2203.07651

New particles & forces

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

REDTOP

Some BR sensitivity curves



Sensitivity curves for Minimal Dark Photon Model

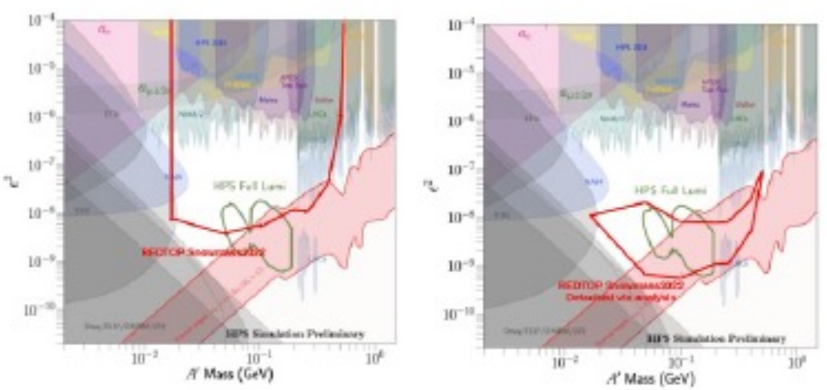


FIG. 36. Sensitivity to to ϵ^2 for the processes $\eta \to \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

Theoretical Models considered

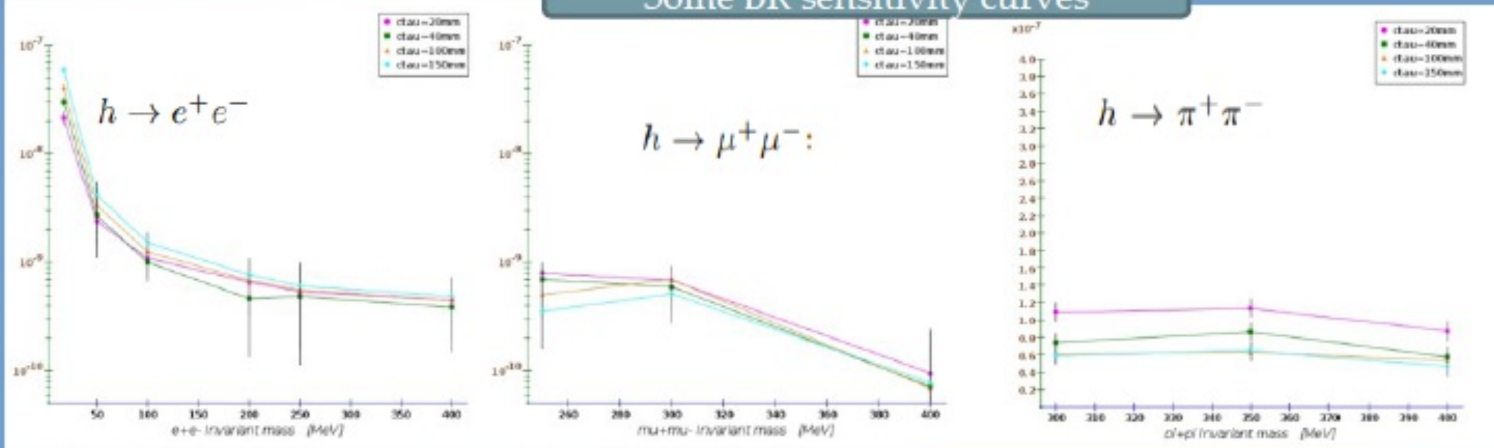
- *Minimal dark photon model*
  - *Most popular model*
- *Leptophobic B boson Model*
- *Protophobic Fifth Force*
  - *Explains the Atomki anomaly*

New particles & forces

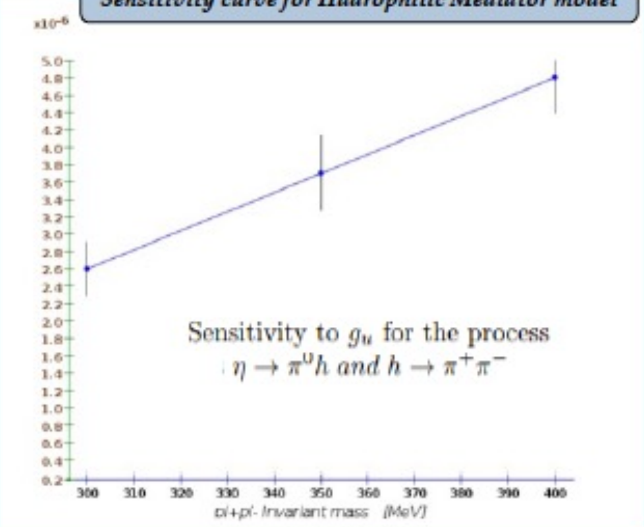
Scalar Portal searches: $\eta \to \pi^0 h$ with $h \to \mu^+\mu^-, \pi^+\pi^-, e^+e^-$

REDTOP

Some BR sensitivity curves



Sensitivity curve for Hadrophilic Mediator model



Sensitivity for Two-Higgs doublet model

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

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

Theoretical models considered

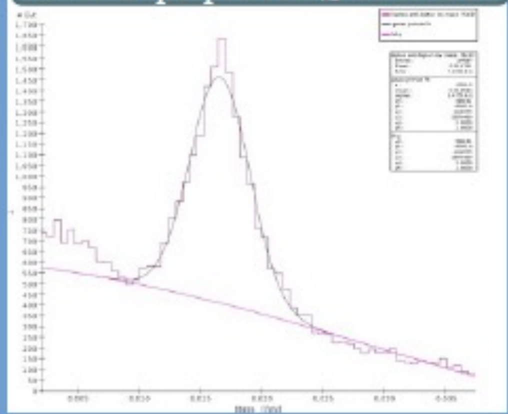
- ***Hadrophilic Scalar Mediator*** *(B. Batell, A. Freitas, A. Ismail, D. McKeen)*
- ***Spontaneous Flavor Violation*** *(D.Egana-Ugrinovic, S. Homiller, P. Meade)*
- ***Two-Higgs doublet model*** *(W. Abdallah, R. Gandhi, and S. Roy)*
- ***Minimal scalar model*** *(C.P. Burgess, M. Pospelov, T. ter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

New particles & forces

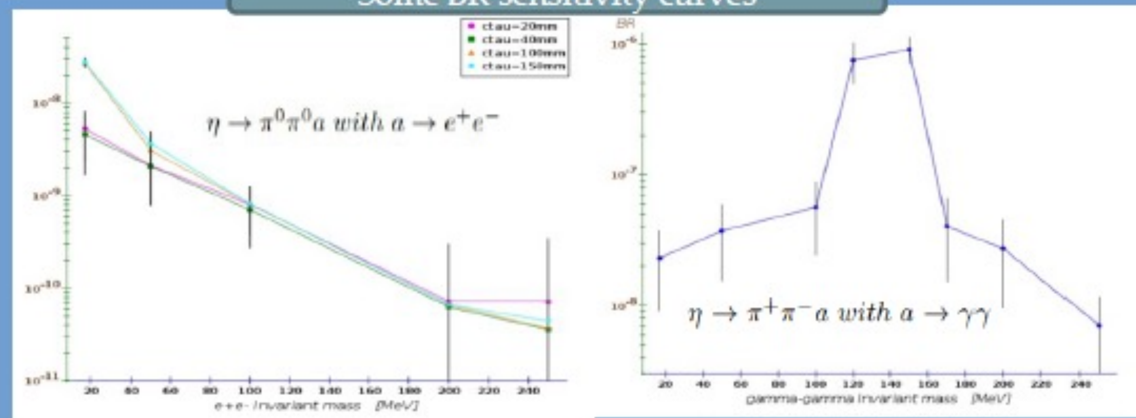
Pseudoscalar Portal: $\eta \to \pi^0 \pi^0 a$ & $\eta \to \pi^+ \pi^- a$ with $a \to \gamma\gamma$, $\mu^+ \mu^-$ and $e^+ e^-$

REDTOP

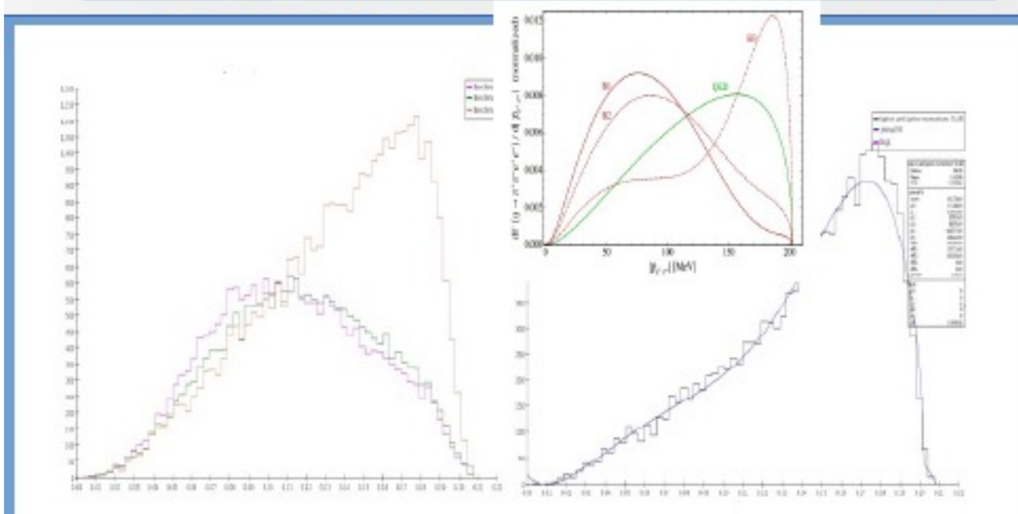
17 MeV piophobic QCD axion



Some BR sensitivity curves



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



Theoretical models considered

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

New particles & forces

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

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	$\sin\delta$	$y^{h'(H)}_{\kappa 2} \times 10^3$	$\lambda^{h'(H)}_{N_{12}} \times 10^3$
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

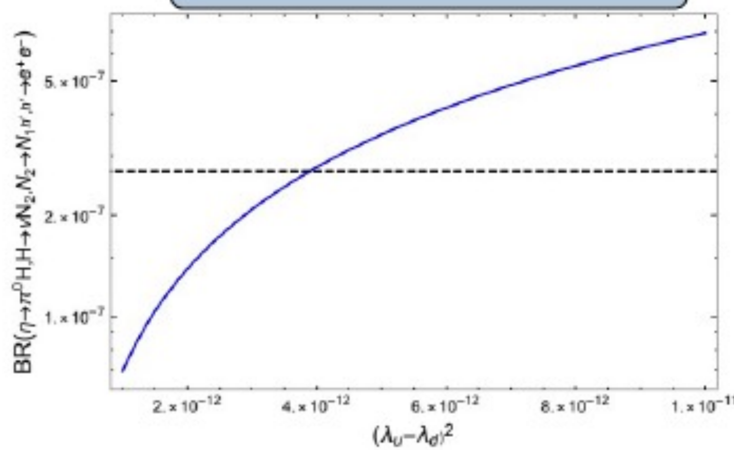


FIG. 61. Branching ratio for the process $\eta \to \pi^0 H$; $H \to \nu N_2$; $N_2 \to N_1 h'$; $h' \to e^+e^-$ predicted by the Two Higgs Doublet model [51] as a function of $(\lambda_u - \lambda_d)^2$. The dashed line corresponds to the experimental limit for REDTOP with an integrated luminosity of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

Summary

- The η/η' decays offer sensitive probes for SM tests and BSM physics searches.
  - Precision tests of SM: chiral anomaly test, the role of scalar dynamics in ChPT; transition form factors of η/η' to calculate HLbL contributions in $(g-2)_\mu$; improve the light quark mass ratio and the η-η' mixing angle
  - Test fundamental symmetries: search for new sources of CP violations
  - Search for sub-GeV hidden forces and hidden particles: vector, scalar, fermion and ALP portals.

- Experimental perspectives:
  - Precision frontier (highly suppressed backgrounds): the JLab Primakoff experimental program and the JEF experiment.
  - High intensity frontier (up to ~5×10^{13} η per year): REDTOP

- A global experimental efforts at different facilities will offer opportunities for discoveries in the η sector.

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