Prospects for rare η and η' decays

Emilie Passemar (Indiana University)

Topical group RF2: weak decays of light & strange quarks
Conveners: Emilie Passemar (epassema@indiana.edu),
Evgueni Goudzovski (goudzovs@cern.ch)
Web: https://snowmass21.org/rare/weaksud
Mailing list: SNOWMASS-RPF-02-LIGHT-QUARKS@FNAL.GOV
Slack channel: rpf-02-light-quarks

Kickoff Meeting of Rare and Precision Frontier
27 July 2020

Outline :

1. Physics Opportunities in studying rare η and η' decays
2. JEF project
3. REDTOP project
4. First-row CKM unitarity tests
5. Summary

1. Physics Opportunities in studying rare η and η' decays

Gan, Kubis, E.P., Tulin, arXiv:2007.00664

1.1 Introduction and Motivation

- Studying η and η' decays gives an unique opportunity:
  - Study of beyond Standard Model Physics
  - Extract fundamental parameters of the Standard Model: ex: light quark masses
  - Test chiral dynamics at low energy

$M_\eta = 547.862(17)$ **MeV**

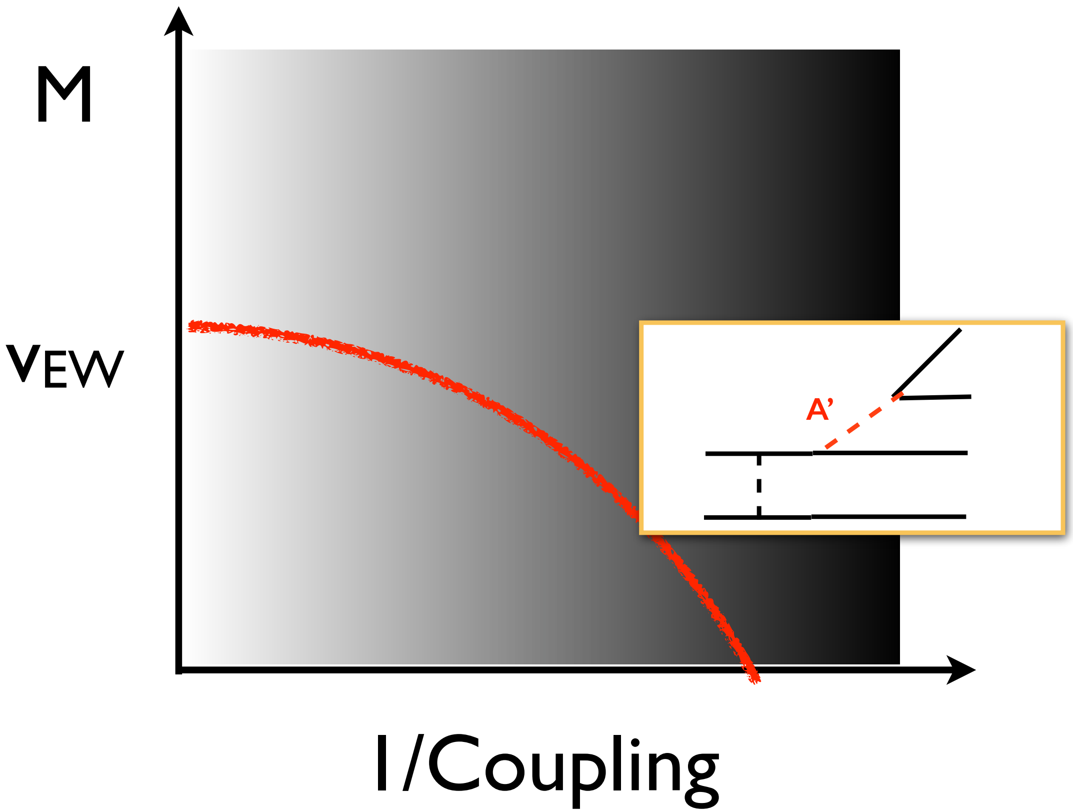
$M_{\eta'} = 957.78(6)$ **MeV**

Decay channel	Standard Model	Discrete symmetries	Light BSM particles
$\eta \to \pi^+\pi^-\pi^0$	light quark masses	C/CP violation	scalar bosons (also η')
$\eta^{(\prime)} \to \gamma\gamma$	η–η' mixing, precision partial widths		
$\eta^{(\prime)} \to \ell^+\ell^-\gamma$	$(g-2)_\mu$		Z' bosons, dark photon
$\eta \to \pi^0\gamma\gamma$	higher-order χPT, scalar dynamics		$U(1)_B$ boson, scalar bosons
$\eta^{(\prime)} \to \mu^+\mu^-$	$(g-2)_\mu$, precision tests	CP violation	
$\eta \to \pi^0\ell^+\ell^-$		C violation	scalar bosons
$\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$	$(g-2)_\mu$		ALPs, dark photon
$\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$		C violation	ALPs

1.2 New Light Particles beyond the SM

- EFT for SM-neutral light dark sector: dominated by "portals"

$$\mathcal{L} \sim O_{\rm portals} + O\left(\frac{1}{\Lambda}\right)$$



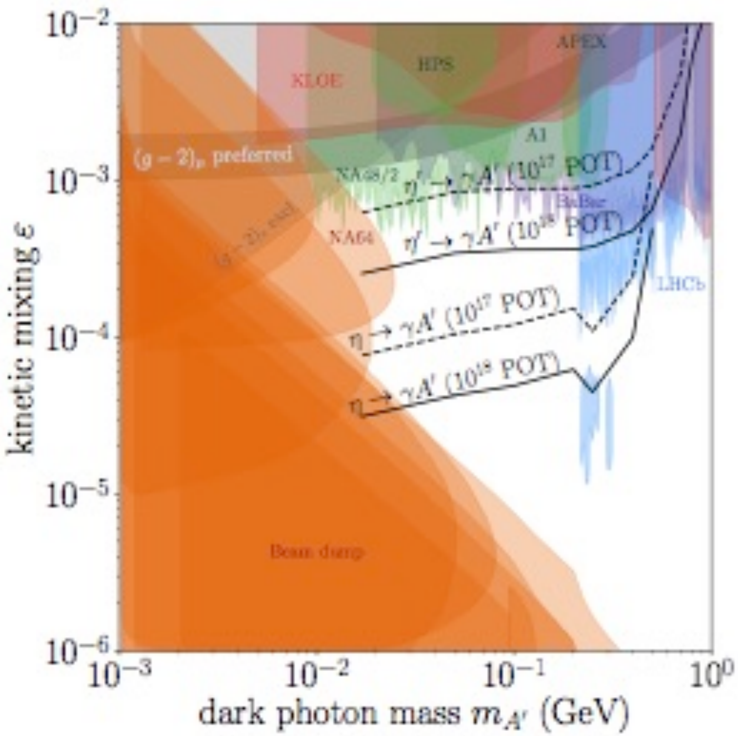
$$O_{\rm Vector} = -\frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu}$$
$$O_{\rm Neutrino} = -Y_N^{ij} \bar{L}_i H N_j$$
$$O_{\rm Higgs} = -H^\dagger H \left(A\,S + \lambda\,S^2\right)$$

See e.g. Fayet'07, Reece & Wan'09, Bjorken et al.'09, Batell et al.'09

Dark photons and other hidden vector bosons

$$\mathcal{B}(\eta \to A'\gamma) = 2\varepsilon^2 \mathcal{B}(\eta \to \gamma\gamma) \left|\bar{F}_{\eta\gamma^*\gamma^*}(m_{A'}^2, 0)\right|^2 \left(1 - m_{A'}^2/M_\eta^2\right)^3 .$$

- Resonances in the dilepton invariant mass spectrum for $\eta^{(\prime)} \to \ell^+\ell^-\gamma$



Projected sensitivies for visibly-decaying A′ from η, η′ decays at REDTOP for:

- Dashed: expected flux 10^{17} POT
- Solid: : expected flux 10^{18} POT

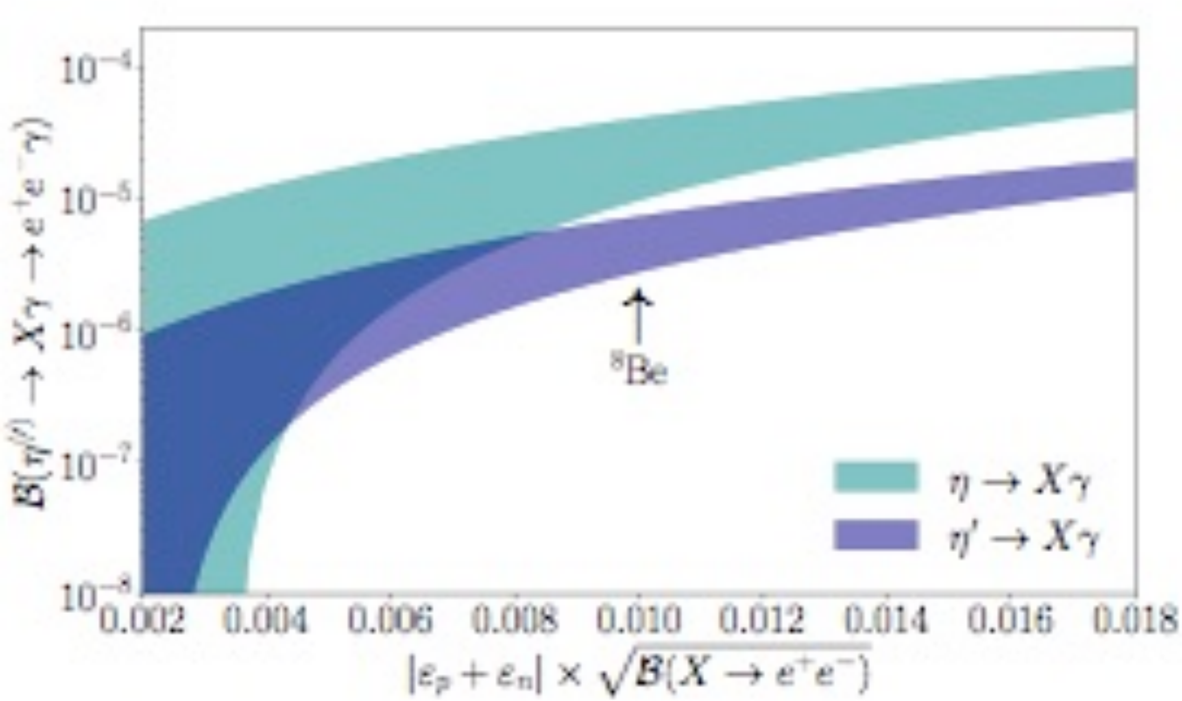
Dark shaded band is preferred to explain $(g-2)_\mu$ anomaly, while other shaded regions are exclusions.

1.2 New Light Particles beyond the SM

Dark photons and other hidden vector bosons

- Search for protophobic X boson related to the ^{8}Be anomaly
  5σ for a 16.7 MeV boson in $^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, X \to {}^8\mathrm{Be}\, e^+e^-$ *Krasznahorkay et al.'16*

  with $B(\eta \to X\gamma \to \gamma e^+e^-) \approx 10^{-5}$



$$|\varepsilon_p + \varepsilon_n| \approx \frac{0.01}{\sqrt{\mathcal{B}(X \to e^+e^-)}}$$

$$|\varepsilon_p| < \frac{0.0012}{\sqrt{\mathcal{B}(X \to e^+e^-)}}$$

Constraints on ε_P comes from null searches in $\pi^0 \to X\gamma \to e^+e^-\gamma$

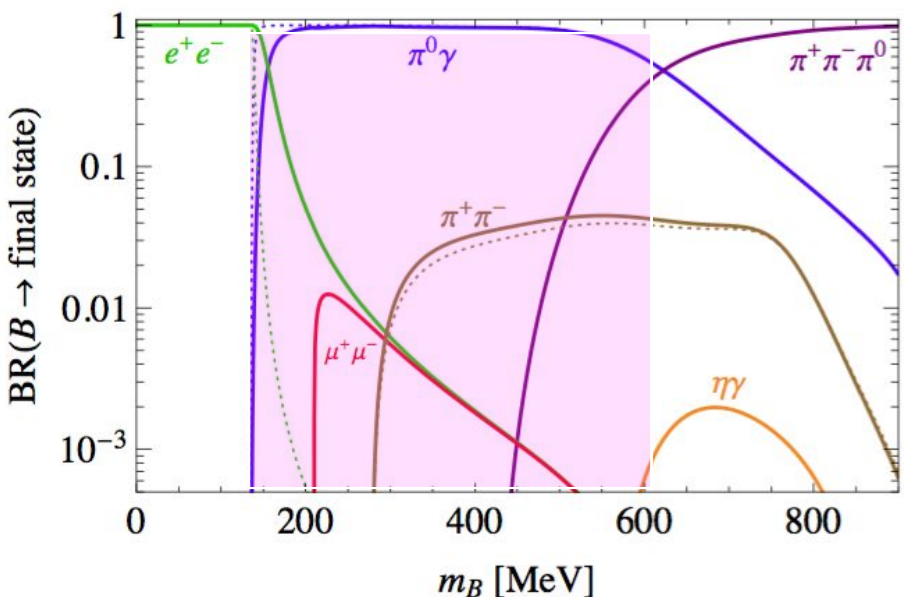
NA48/2

1.2 New Light Particles beyond the SM

Dark photons and other hidden vector bosons

- Leptophobic vector bosons: B boson from gauged $U(1)_B$ symmetry

  ⇨ non-leptonic signatures, e.g., *$\pi^0\gamma$ resonance* in $\eta \to B\gamma \to \pi^0\gamma\gamma$



Leptophobic B′
(dark ω, γ_B , or Z′): $\frac{1}{3} g_B \bar{q}\gamma^\mu q B_\mu$

Gauged baryon symmetry $U(1)_B$

Lee and Yang'55

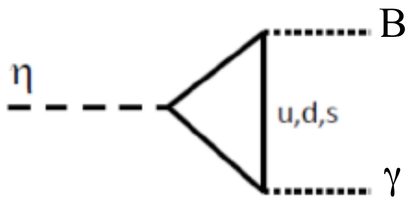
- $m_B < m_\pi$ is strongly constrained by long-range forces searches
- $m_B > 50$ GeV investigated by collider experiments.
- GeV-scale domain is nearly untouched:

  ⇨ a *discovery opportunity*!

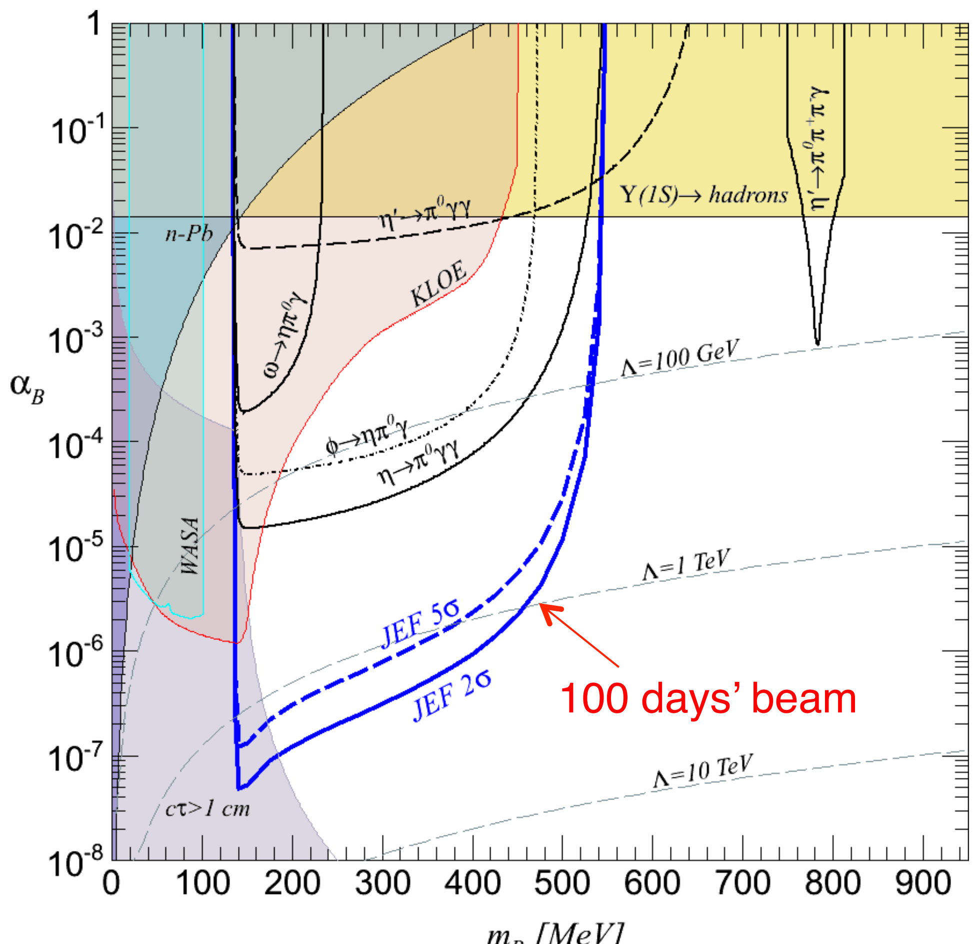
JEF Experimental Reach for B

From L. Gan

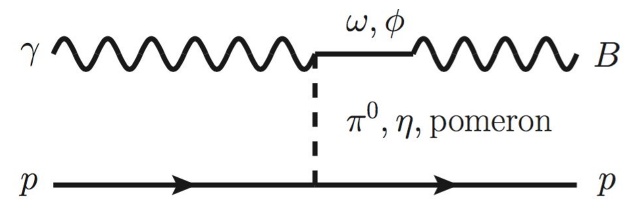
1. Meson decay $\eta \to B\gamma \to \pi^0\gamma\gamma$

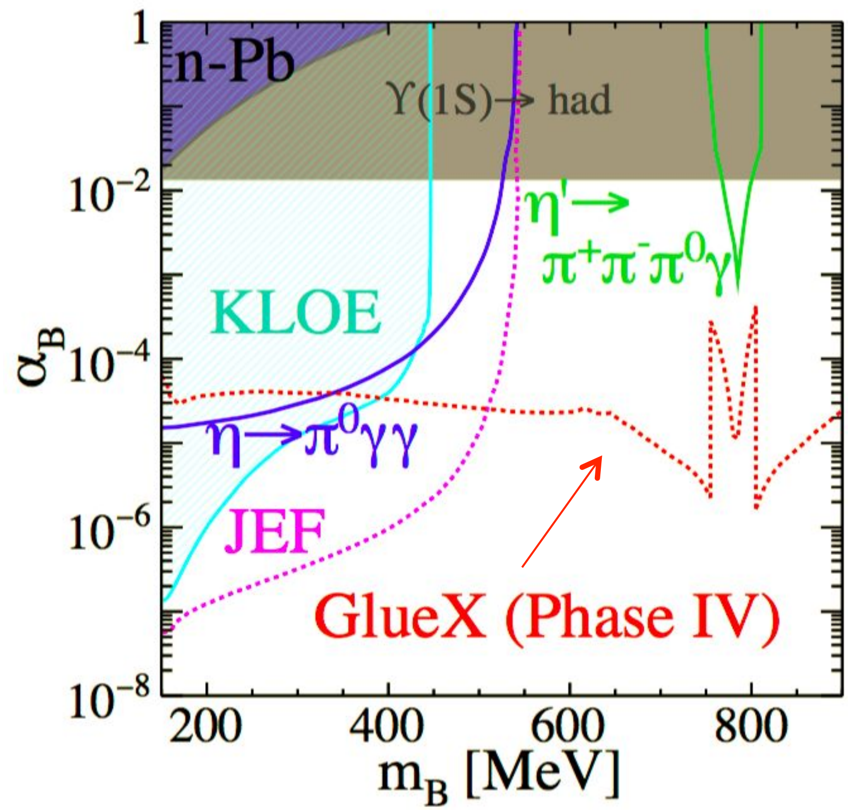


PL, B221, 80 (1989)
PR,D89,114008



2. Photoproduction $\gamma p \to Bp$





arXiv:1605.07161

1.2 New Light Particles beyond the SM

Scalar particles

- η(′) decays ⇒ the strongest limits on a scalar *S* coupling to *light quarks* instead of heavy quarks
  - For leptophobic scalar, signal channels are:
    $\eta(') \to \pi^0\gamma\gamma$ or $\eta(') \to 3\pi$ with S a *γγ* or *2π resonance*.
  - For more general models, S can be discovered as a *dilepton resonance* in $\eta^{(')} \to \pi^0 \ell^+ \ell^-$ channel motivated mainly for C and CP searches

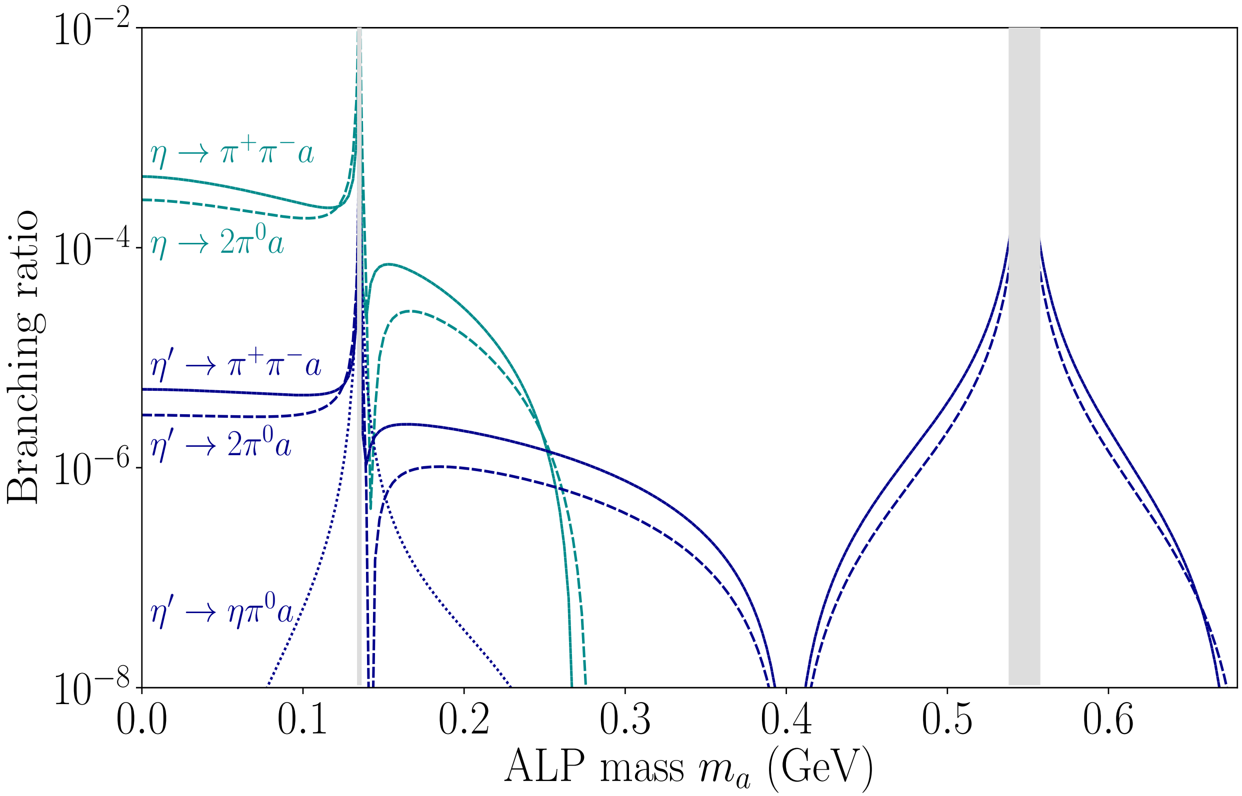
⇒ Work remains to be done:

- Map out the more general parameter space for these decays
- Compute the transition form factors for η′ decays needed to access a wider range of m_S

Axion Like Particles (ALPs)

See e.g. Aloni et al'19, Landini & Meggiolaro'20

- ALP searches in η(′) decays new and potentially rich avenue not widely studied in the literature.



Branching ratios for ALP production in

- η decays (light blue)
- η′ decays (dark blue)

No direct quark-ALP coupling (c_q = 0) has been assumed

$B \sim 1/f_a^2$ and here f_a = 10 GeV, equivalent to an effective mass scale ≈ 3 TeV.

1.2 New Light Particles beyond the SM

Axion Like Particles (ALPs)

- ALP searches in η(′) decays new and potentially rich avenue not widely studied in the literature.

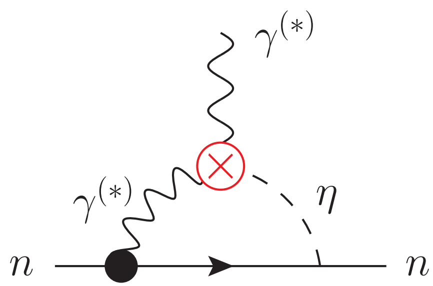
⇨ Need collaboration between BSM phenomenologists, χPT theorists and experimentalists

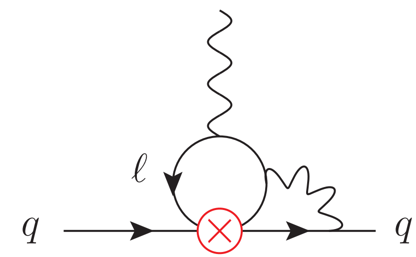
- Key questions:
  - Which among the at least 4 η and 11 η′ signal channels—all with four- and five-body final states, several of which have never been studied before in any context—are *most promising* to measure from both theoretical and experimental points of view?
  - What are the *predicted branching ratios* in light of existing ALP constraints?
  - LO formulae known for these decay rates but *NLO corrections* are likely large and would need to be included for robust predictions

1.3 Discrete symmetry tests and lepton flavor violation

P and CP violation

- A large number of P,CP-violating η(′) decays indirectly excluded from extremely stringent neutron EDM bounds





- The only exception: investigation of the *muon polarization asymmetries* in η→μ+μ− : EDM constraints at 2 loop order

Sanchez-Puertas'19

$$\mathcal{L}_{\text{eff}} = -\frac{1}{2v^2}\Big\{\text{Im}\, c_{\ell equ}^{(1)2211}\big[(\bar{\mu}\mu)(\bar{u}i\gamma^5 u) + (\bar{\mu}i\gamma^5\mu)(\bar{u}u)\big] - \text{Im}\, c_{\ell edq}^{2211}\big[(\bar{\mu}\mu)(\bar{d}i\gamma^5 d) - (\bar{\mu}i\gamma^5\mu)(\bar{d}d)\big] - \text{Im}\, c_{\ell edq}^{2222}\big[(\bar{\mu}\mu)(\bar{s}i\gamma^5 s) - (\bar{\mu}i\gamma^5\mu)(\bar{s}s)\big]\Big\}$$

➡ probe flavour-conserving CP-violation in the second generation possible with REDTOP statistics

1.3 Discrete symmetry tests and lepton flavor violation

C and CP violation

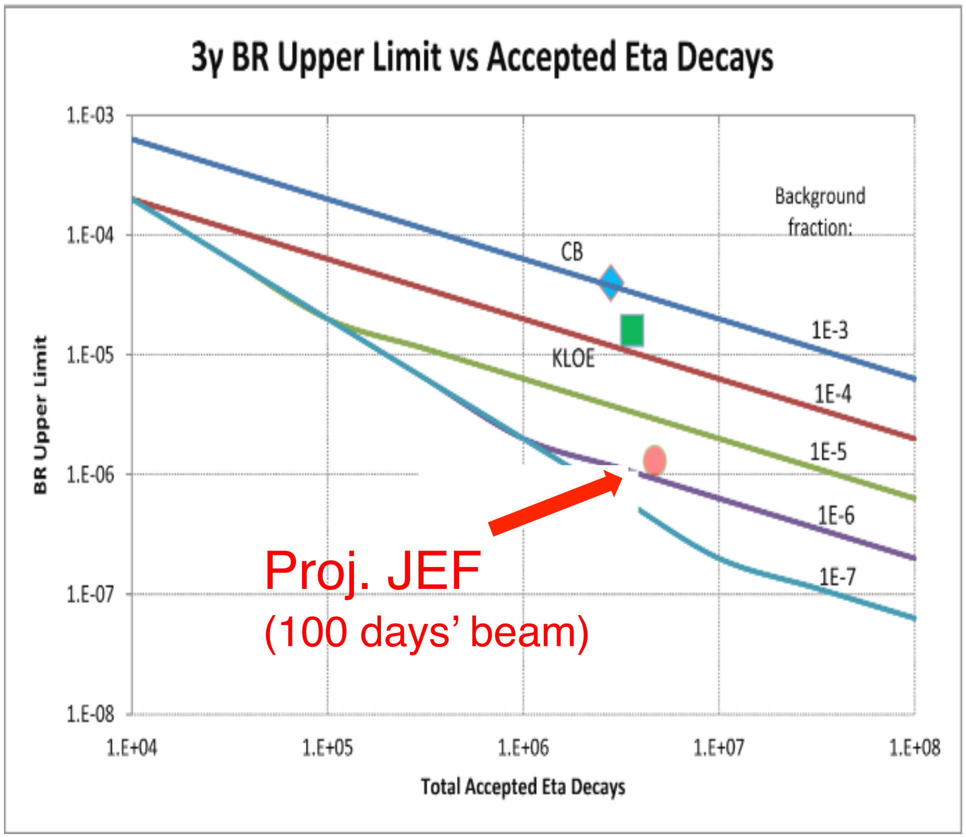
- Not much work done in this direction:
  ⇨ theoretical studies remain to be done to motivate experimental searches:
  - BSM operators need to be identified
  - their contributions to η(′) decays, as well as indirect limits from EDMs, need to be quantified.

- η(‘)→3γ : *C*, *P*-violating but *CP*-conserving.

1.3 Discrete symmetry tests and lepton flavor violation

C and CP violation

- $\eta(')\to 3\gamma$: *C*, *P*-violating but *CP*-conserving.



JEF could Improve the BR upper limit by one order of magnitude

1.3 Discrete symmetry tests and lepton flavor violation

C and CP violation

- Not much work done in this direction:
  ⇨ theoretical studies remain to be done to motivate experimental searches:
  – BSM operators need to be identified
  – their contributions to $\eta(')$ decays, as well as indirect limits from EDMs, need to be quantified.

- $\eta(') \to 3\gamma$: *C*, *P*-violating but *CP*-conserving.

- C- and CP-violating asymmetries in the $\eta \to \pi^+\pi^-\pi^0$ Dalitz-plot *Gardner & Shi'20*

- C- and CP-violating channels used to search for new light particles:
  $\eta(') \to \pi^0 l^+ l^-$ and $\eta(') \to 2\pi^0 l^+ l^-$

1.3 Discrete symmetry tests and lepton flavor violation

Lepton Flavour Violation

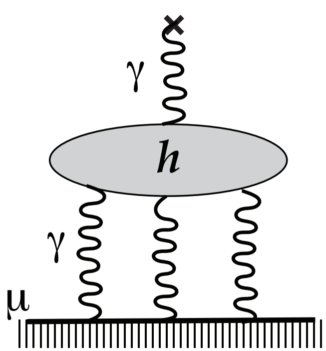
- In light of strong constraints on $\mu \to e$ conversion on nuclei, further theoretical study is needed to motivate searching for $\eta(') \to e^{\pm}\mu^{\mp}$

- But decays that violate charged lepton flavour by two units, $\eta(') \to e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$ are worth investigated since they are not similarly constrained

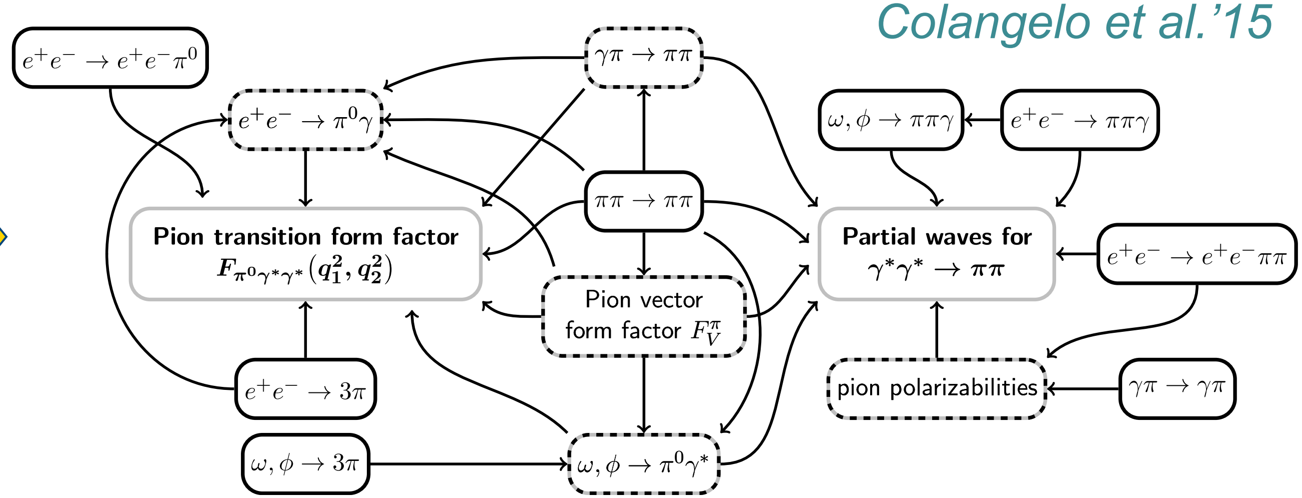
1.4 Standard Model studies

- Extraction of fundamental parameters of the SM: *light quark masses* from η(′)→3π.

- Inputs for our understanding of *hadronic light-by-light scattering* in the anomalous magnetic moment of the muon from
  - η(′)→γγ
  - Transition form factors from $\eta'\to 2(\pi^+\pi^-)$, $\eta'\to\pi^+\pi^-e^+e^-$, $\eta'\to\omega e^+e^-$



Colangelo et al.'15



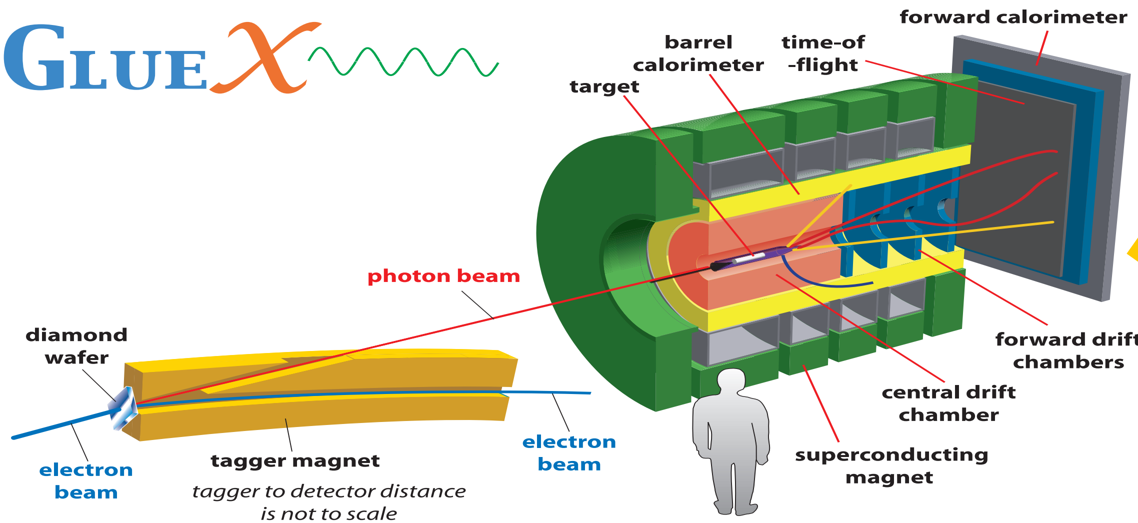
- Understanding of QCD dynamics $\eta\to\pi^0\gamma\gamma$ and similar η′ decays

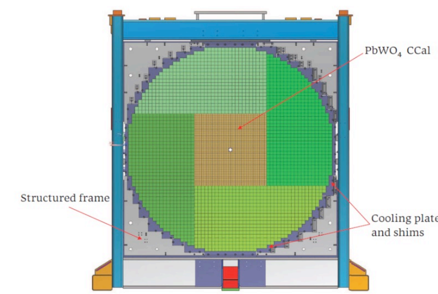
2. Jefferson Eta Factory (JEF) Program

2. JEF program

- The ongoing JLab Eta Factory experiment will open a new avenue for precision measurements of various decays of η and η' in one setting, with unprecedented low backgrounds in rare decays, particularly in neutral modes.

2. JEF program





FCAL-II

Simultaneously measure η/η' decays: $\eta\to\pi^0\gamma\gamma$, $\eta\to3\gamma$, and …

- η/η' produced on LH_2 target with 8.4-11.7 GeV tagged photon beam:
  $\gamma+p \to \eta/\eta'+p$
- 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 decays

2. JEF program

- The ongoing JLab Eta Factory experiment will open a new avenue for precision measurements of various decays of η and η' in one setting, with unprecedented low backgrounds in rare decays, particularly in neutral modes.

- Highly boosted η and η' by a~12 GeV photon beam will help reducing the experimental systematics, offering complementary cross checks on the results from A2, BESIII, KLOE-II, WASA-at-COSY, and future REDTOP experiments, where the produced mesons have relatively small kinetic energies in the lab frame.

2. JEF program

Time line

- The data collection for non rare decays has been in progress since fall 2016. A significant improvement on the light quark mass ratio will be achieved in the next 3-4 years by a combination of a new Primakoff measurement of the η radiative decay width and the improvements in the Dalitz distributions of $\eta \to 3\pi$ for both charged and neutral channels.

- The second phase of JEF will run with an upgraded forward calorimeter:
  - 2018 - 2023, development of an upgraded forward calorimeter (FCAL-II) with a PWO crystal insert
  - 2024: first run with an upgraded FCAL-II for rare decays expected

- Within 100 days of beam time for the phase II, JEF will have sufficient precision to explore the role of scalar meson dynamics in chiral perturbation theory, to search for sub-GeV dark gauge bosons (vector, scalar, and axion-like particles) by improving the existing bounds by two orders of magnitude

3. Redtop Program

See: https://redtop.fnal.gov/

3. REDTOP program

- Proposed REDTOP experiment at FNAL:
  Projected η production rate at the level of 2×10^{12} (a factor of ten more forphase II) per year.

- Expected backgrounds in REDTOP about several orders of magnitude higher than in the JEF experiment compensated for by an enormous η yield.

- The recoil detection technique considered for phase II will help further reducing the backgrounds.

- The proposed muon polarimeter (and an optional photon polarimeter) for the REDTOP apparatus will offer additional capability to measure the longitudinal polarization of final-state muons (and possibly photons), which are not available in most other experiments, including JEF.

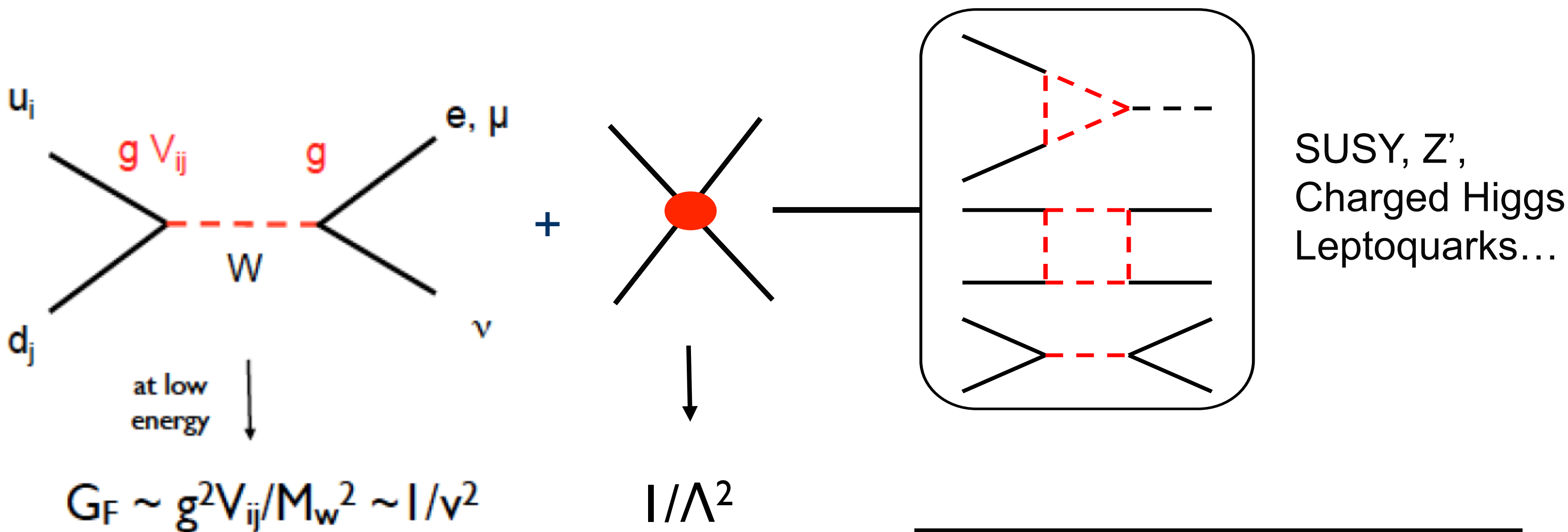
- In the foreseeable future, REDTOP will offer the most sensitive probes for the rare charged decay channels, while the JEF experiment will remain leading in the rare neutral decays because of lower backgrounds and higher experimental resolutions

- The JEF and REDTOP experiments are complementary to each other, promising a new exciting era for η(′) physics.

4. First-row CKM unitarity tests

V_{us} and Unitarity of the CKM matrix

- Stringent test of the SM and new physics with unitarity of the first row of CKM matrix
- In the SM, W exchange ⇒ V-A currents, universality



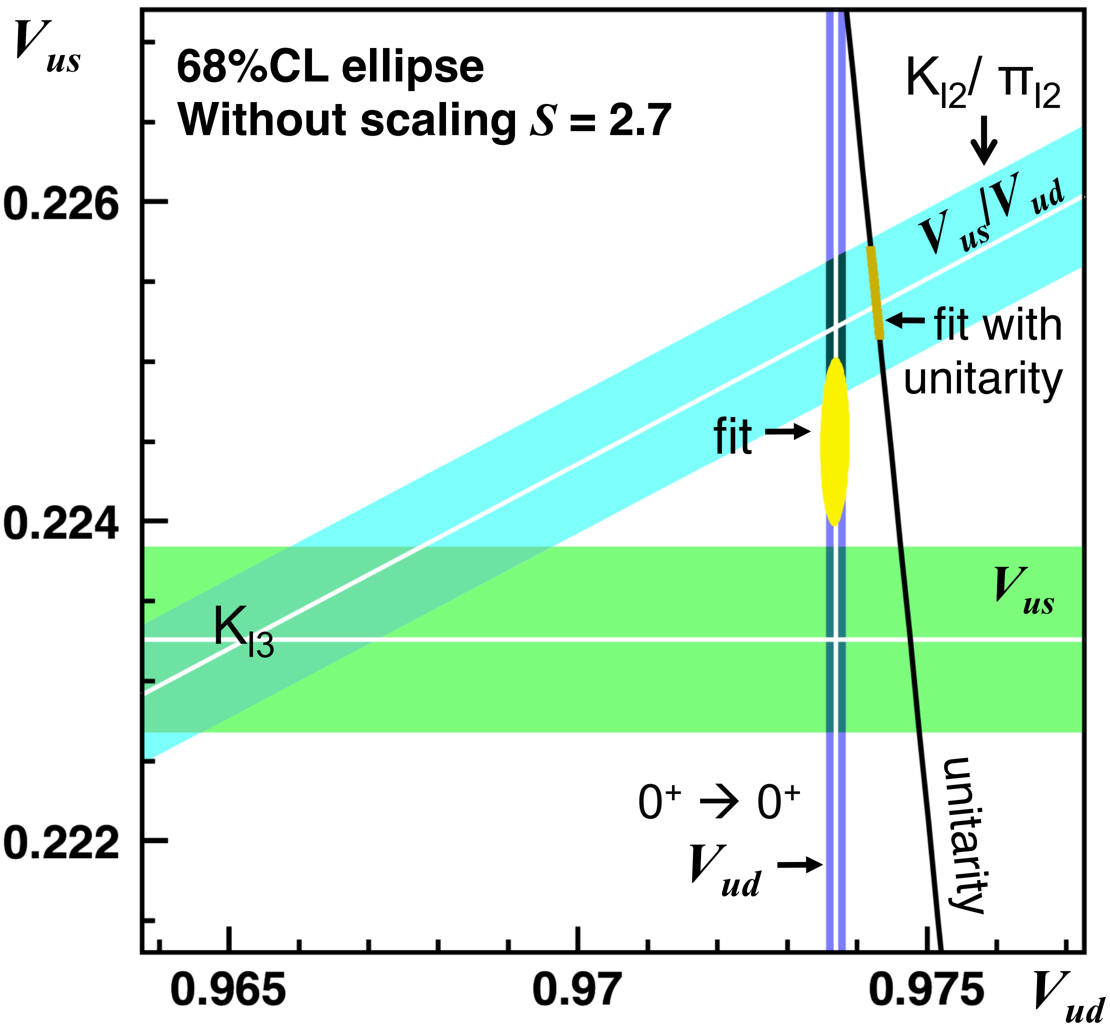
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM}$$

- Broad sensitivity to BSM scenarios :

$$\Delta \sim \frac{c_n}{g^2}\frac{M_W^2}{\Lambda^2} \leq 10^{-2} - 10^{-3} \longleftrightarrow \Lambda\text{~1-10 TeV}$$

V_{us} and Unitarity of the CKM matrix

- Recent discrepancy with CKM unitarity:



$|V_{ud}| = 0.97370(14)$

$|V_{us}| = 0.2233(6)$

$|V_{us}|/|V_{ud}| = 0.2313(5)$

Fit results, no constraint

$V_{ud} = 0.97368(14)$

$V_{us} = 0.22450(35)$

χ^2/ndf = 7.2/1 (0.7%)

$\Delta_{CKM} = -0.00154(32)$

-4.8σ

V_{us} and Unitarity of the CKM matrix

- Recent discrepancy with CKM unitarity: -4.8σ

- Due to change in theory inputs:
  - $f_+(0)$ from lattice QCD:
    2σ inconsistency between K_{l3} and K_{l2} results for V_{us}
    V_{us} from K_{l2} consistent with unitarity up to new V_{ud} evaluation

  - V_{ud} side: new radiative corrections to 0+ → 0+ superallowed beta decays: 2.9σ - 4.8σ discrepancy with unitarity

V_{ud} and New Radiative Corrections

$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q)\,(1+RC) \longrightarrow f\,t\,(1+RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$

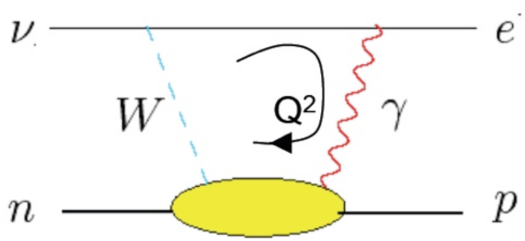
$$(1+RC) = (1-\delta_C)\,(1+\delta_R)\,(1+\Delta_R)$$

$\langle f|\tau_+|i\rangle = \sqrt{2}\,(1-\delta_C/2)$
Coulomb distortion of wave-functions

Nucleus-dependent rad. corr.
(Z, E^{max}, nuclear structure)

Nucleus-independent short distance rad. corr.

- New calculation based on Dispersion Relations



Inputs needed: DIS of neutrino on nucleon but also quasi elastic neutrino nucleon data

$$|V_{ud}| = 0.97418(10)_{Ft}(18)_{\Delta_R^V}$$

Marciano & Sirlin'06

~1.8σ smaller

$$|V_{ud}| = 0.97370(10)_{Ft}(10)_{\Delta_R^V}$$

Seng, Gorchtein, Patel & Ramsey-Musolf'18

V_{ud} and New Radiative Corrections

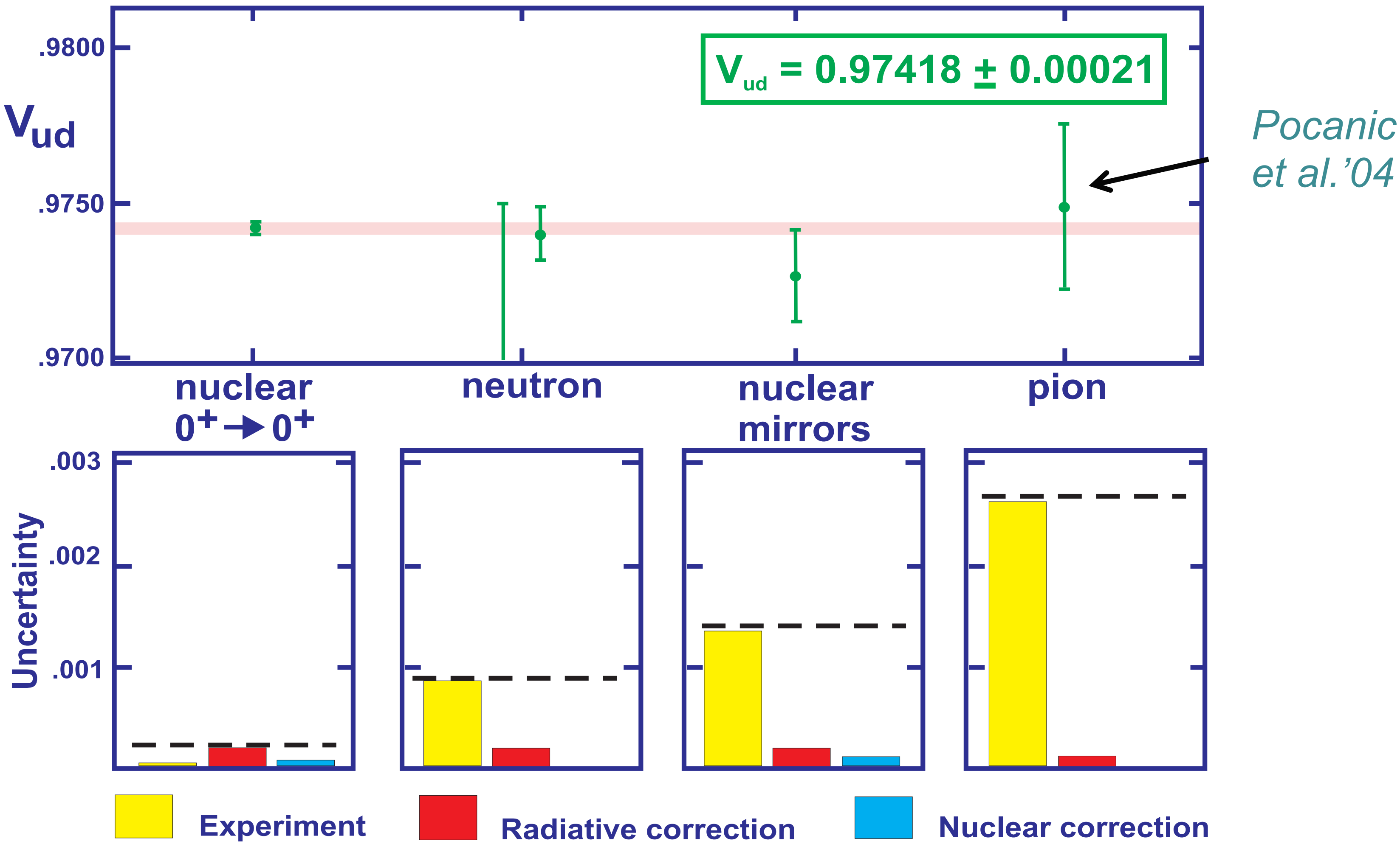
- With new calculation of radiative corrections: 2.9σ - 4.8σ discrepancy with unitarity ⇒ calculations need to be checked and model dependence understood

- Quantity can be computed on the lattice, see *Seng & Meissner'19*
  e.g. by *Roma-Southampton group, CalLat*

- Can we extract V_{ud} differently?

Extraction of V_{ud} : summary

Hardy@Amherst'19



5. Summary

Summary

- Studying η and η' decays gives an unique opportunity:
  - Study of beyond Standard Model Physics:
    - New Light Particles beyond the SM: vector, e.g. B boson, scalar, ALPs
    - Discrete symmetries and lepton flavor violation:
      Potential in $\eta(') \to \mu^{\mp}\mu^{\mp}$ and $\eta(') \to e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$
  - Extract fundamental parameters of the Standard Model:
    ex: light quark masses
  - Test chiral dynamics at low energy, TFF inputs for g-2 of the muon

- 2 very interesting experimental proposals: JEF and Redtop pushing the intensity frontier

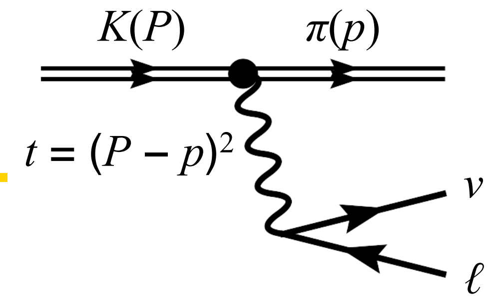
- Work remains to be done theoretically

- First-row CKM unitarity tests: discrepancy at the level of ~4.8σ driven by th:
  - V_{us} from K_{l3}, $f_+(0)$
  - V_{ud}: new radiative corrections

→ to be investigated

6. Back up

2.1 V_{us} from K_{l3} : Master Formula



- Master formula for $K \to \pi l \nu_l$: $K = \{K^+, K^0\}$, $l=\{e,\mu\}$

$$\Gamma\left(K \to \pi l \nu [\gamma]\right) = Br(K_{l3})/\tau = C_K^2 \frac{G_F^2 m_K^5}{192\pi^3} S_{EW}^K \left|V_{us}\right|^2 \left|f_+^{K^0\pi^-}(0)\right|^2 I_{Kl} \left(1 + 2\Delta_{\text{EM}}^{Kl} + 2\Delta_{\text{SU(2)}}^{K\pi}\right)$$

Experimental inputs:

$\Gamma(K_{l3})$ Rates with well-determined treatment of radiative decays
- Branching ratios
- Kaon lifetimes

$I_{Kl}(\lambda_{Kl})$ Integral of form factor over phase space: λs parametrize evolution in $t=q^2$

Inputs from theory:

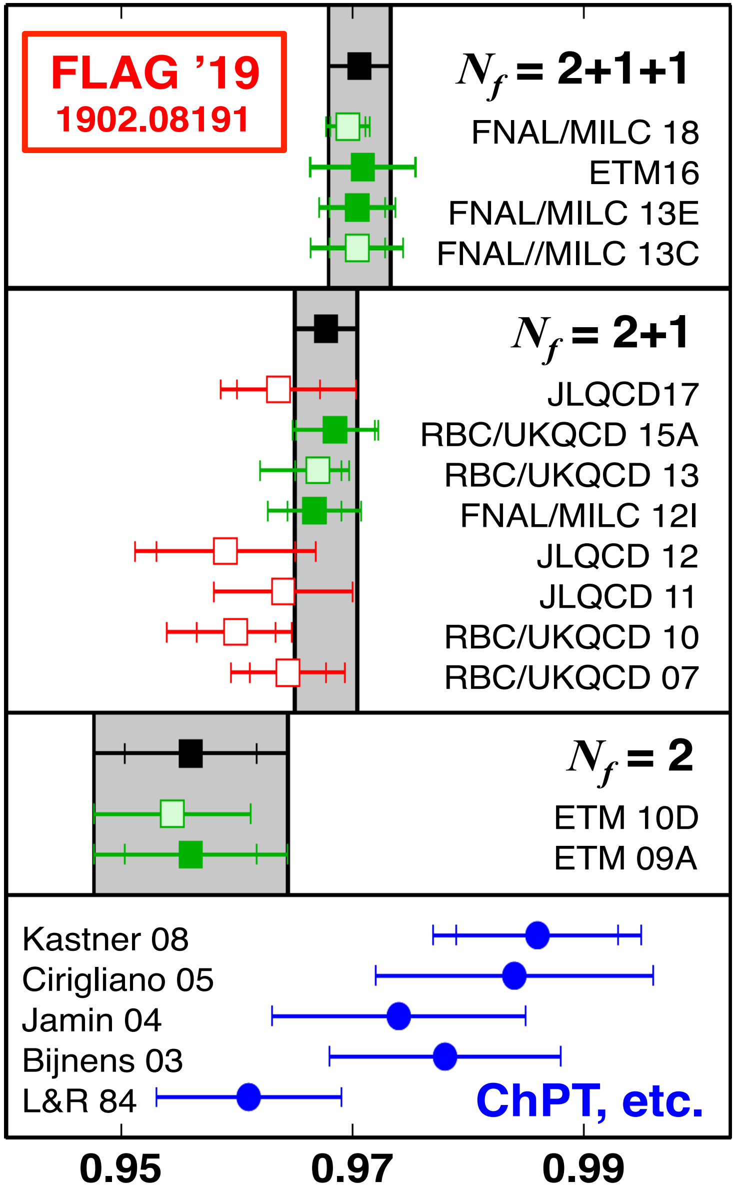
S_{EW}^K Universal short distance EW corrections

$f_+^{K^0\pi^-}(0)$ Hadronic matrix element (form factor) at zero momentum transfer (t=0)

Δ_{EM}^{Kl} Form-factor correction for long-distance EM effects

$\Delta_{\text{SU(2)}}^{K\pi}$ Form-factor correction for SU(2) breaking

2.5 Determination of $f_+(0)$



FLAG '19 averages:

N_f **= 2+1** $f_+(0)$ **= 0.9677(27)**
Uncorrelated average of:
RBC/UKQCD 15A: DWF, $m_\pi \to$ 139 MeV
FNAL/MILC 12I: HISQ, $m_\pi \sim$ 300 MeV

N_f **= 2+1+1** $f_+(0)$ **= 0.9704(32)**
FNAL/MILC 13E: HISQ, $m_\pi \to$ 135 MeV

Recent updates:

N_f **= 2+1** $f_+(0)$ **= 0.9636($^{+62}_{-65}$)** PRD96 (2017)
JLQCD: Overlap, $m_\pi \to$ 300 MeV
Exact chiral symmetry, one lattice spacing

N_f **= 2+1+1** $f_+(0)$ **= 0.9709(44)(9)(11)** PRD 93 (2016)
ETM 16: TwMW, 3sp, $m_\pi \to$ 210 MeV
Full q^2 dependence of f_+, f_0
$f_+(0)$ **= 0.9696(15)(11)** PRD 99 (2019)
FNAL/MILC update 13E

ChPT:

N_f **= 2+1** $f_+(0)$ **= 0.970(8)** Chiral Dynamics 15
Ecker 15: According to Bijnens 03
New LECs from Bijnens, Ecker 14

2019 averages for $f_+(0)$

N_f = 2+1+1

$$f_+(0) = \mathbf{0.9698(17)}$$

FNAL/MILC18 replaces FNAL/MILC13E in FLAG average

ETM16	$0.9709(44)(9)(11)_{ext}$
FNAL/MILC18	0.9696(15)(11)

N_f = 2+1

$$f_+(0) = \mathbf{0.9677(27)}$$

FLAG average, Nov 2016 update

JLQCD17 not included because only 1 lattice spacing used

FNAL/MILC12I	0.9667(23)(33)
RBC/UKQCD15A	0.9685(34)(14)

Phase-I run (Delivery Ring) - Experimental Techniques

From C. Gatto@APS2020

- *Incident proton energy ~1.8 GeV (3.5 GeV for η')*
- *CW beam, 10^{17}-10^{18} POT/yr (depending on the host laboratory)*
- *η/η' hadro-production from inelastic scattering of protons on Li or Be targets*
- *η–production rate: 10^6 Hz (total: 10^{13}/yr) (η' : 10^{11}/yr)*

charged tracks detection

- *Use Cerenkov effect for tracking charged particles*

↓

- *Baryons and most pions are below Č threshold*
- *Electrons and most muons are detected and reconstructed in an Optical-TPC*

γ detection

- *Use ADRIANO2 calorimeter (Calice+T1015) for reconstructing EM showers*

↓

- *$\sigma_E/E < 5\%/\sqrt{E}$*
- *PID from dual-readout to disentangle showers from γ/μ/hadrons*
- *96.5% coverage*

- *Fiber tracker (LHCB style) for rejection of background from γ-conversion and reconstruction of secondary vertices (~70μm resolution)*

Phase-II Run: tREDTOP at PIP-II

A tagged eta factory

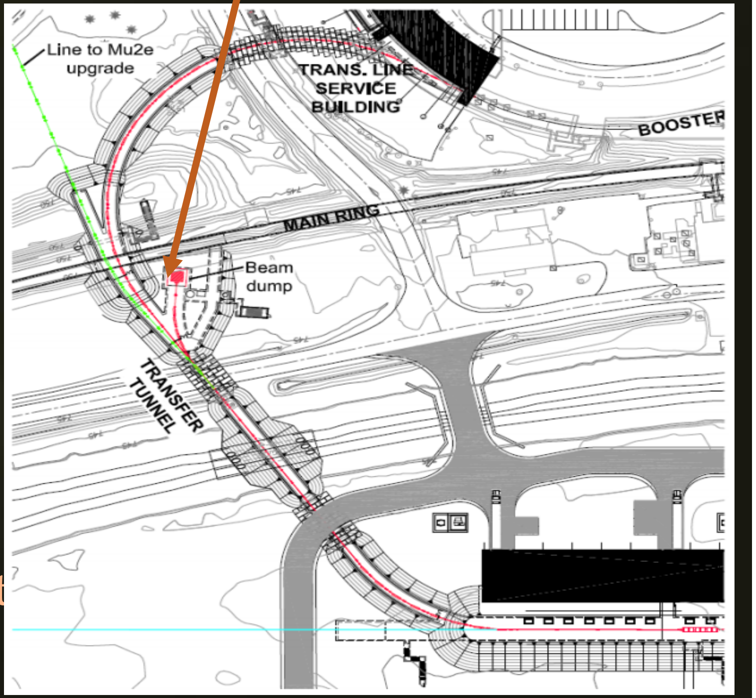
From C. Gatto@APS2020

- Full use of ~1 GeV – CW proton beam provided by PIP-II.

$$p + De \rightarrow \eta + {}^{3}He^{+}$$

- η-meson tagging by detecting the 3He+ ion (higher QCD background rejection)
- Measuring the momentum of the $^{3}He^{+}$ the kinematics is fully closed.
  - Long lived, dark particle escaping detection could be identified using the missing 4-momentum technique.
- The latter is considerably more powerful than the, missing pt or missing energy (proposed at beam-dump or e⁻-fixed target experiments)

tREDTOP



Detector upgrades

New Target: Li foils -> gaseous De

New Central tracker: Optical-TPC -> LGAD tracker

New 3He+ ion detector

Timeline & Costing

From C. Gatto@APS2020

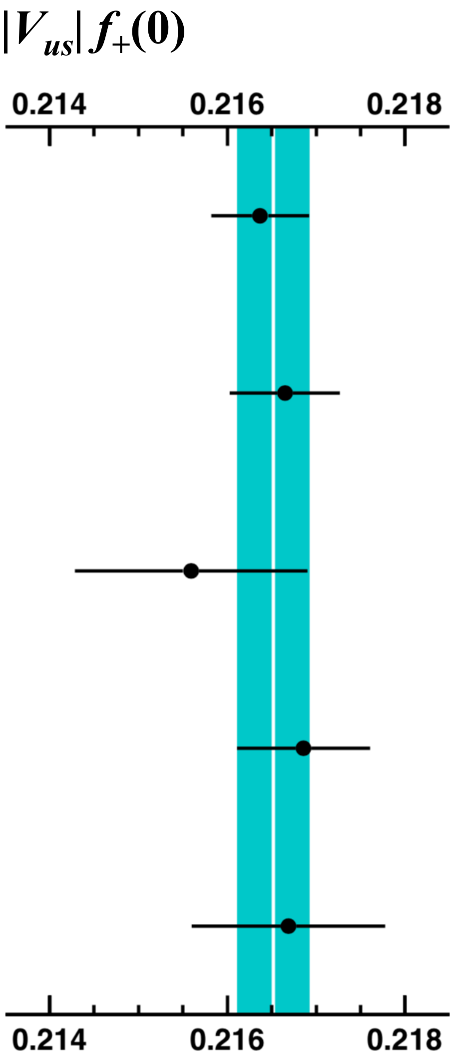
- *Once approved and funded, REDTOP needs:*
  - *2-3 years detector R&D + detector design*
  - *2 yrs construction*
- *Accelerator mods required:*
  - *CERN: need further studies – but beam structure is sub-optimal*
  - *FNAL-DR: ~1yr (add a SC cavity to the DR and build an extraction line*
  - *FNAL-PIPII: new experimental hall required (PIP-III)*
- *R&D required*
  - *ADRIANO2: ongoing*
  - *Fiber tracker: none*
  - *LGAD tracker: piggy-back on existing R&D (ATLAS, EIC)*
  - *O-TPC: very late*

From C. Gatto@APS2020

Future Prospects

- *The Collaboration is currently engaged in the ESPP and the Snowmass2021-P5 processes*
- *Current activities aiming at the preparation of a full proposal in a timeframe consistent with Snowmass2021-P5*
  - *Montecarlo campaign ongoing for Snowmass (Run-I and II)*
  - *~10^{10} events being generated and reconstructed (GenieHad+slic+lcsim)*
  - *(Almost) full reconstruction in place (include track and vertex fitting)*
- *Competition from several other experiments (LHCB, LDMX, etc.)*
  - *But, REDTOP experimental techniques is unique (i.e., missing 4-momentum)*

$|V_{us}| f_+(0)$ from world data: Update



Approx. contrib. to % err from:

		% err	BR	τ	Δ	Int
$K_L e3$	0.2164(6)	0.26	0.09	0.20	0.11	0.05
$K_L \mu 3$	0.2167(6)	0.29	0.15	0.18	0.11	0.07
$K_S e3$	0.2156(13)	0.61	0.60	0.02	0.11	0.05
$K^\pm e3$	0.2169(8)	0.35	0.27	0.06	0.21	0.05
$K^\pm \mu 3$	0.2167(11)	0.50	0.45	0.06	0.21	0.07

Average: $|V_{us}| f_+(0)$ = 0.21652(41) χ^2/ndf = 0.98/4 (91%)

Prospects for new measurements

NA48/2

NA62

Can measure BRs and form-factor parameters for K^+

NA48/2 (2003-2004) recently measured $K_{\ell 3}$ form factors

NA62-RK (2007) has O(10M) $K_{\ell 3}$ decays

NA62 has O(few M) K_{e3} from minimum bias runs (2015-16)

Relative to NA48/2, NA62 has

- Better particle identification π/μ
- Better systematics for t reconstruction:
  - full beam tracking, better σ_p in spectrometer

ISTRA+

OKA

Fixed target experiment at U-70 (Protvino), like ISTRA+

- New beamline with RF-separated K^+ beam

Can measure BRs and form-factor parameters

- Need more analysis of systematics for K_{e3} form factors

Runs from 2010-2013: ~17M $K^+{}_{e3}$ events

- Additional runs in 2016-2018; more planned in future

Prospects for new measurements

KLOE

Can measure all observables: BRs, τs, FFs: $K^{\pm}$, K_L, K_S

5.5 fb^{-1} of data from KLOE-2 running (2015-2018)

- +2 fb^{-1} of original KLOE data not yet analyzed for V_{us}

KLOE-2

Measurements that can be improved with KLOE-2 statistics:

- K_S BRs ($K_S \to \pi e \nu$, but also $K_S \to \pi \mu \nu$)
  See e.g. KLOE-2 measurement of A_S 1806.08654
  70k $K_S \to \pi e \nu$ decays
- $K^{\pm}$, K_L form factors (particularly $K_{\ell 3}$), K_L mean life?

LHCb

Proven capability to measure K_S decays to muons

- 10^{13} K_S/fb^{-1} produced
- EPJC 77 (2017): BR($K_S \to \mu\mu$) < 1.0×10^{-9} 95%CL
  Limited by hardware trigger efficiency ($\varepsilon_{\text{trig}} \sim 1\%$)

Can LHCb measure BR($K_S \to \pi \mu \nu$) to < 1% in Run III?

- Would require dedicated software HLT line

$K_S \to \pi \mu \nu$ never yet measured – a new channel for V_{us}

- τ_S known to 0.04% (vs 0.41% for τ_L, 0.12% for $\tau_{\pm}$)

Prospects for new measurements

KEK-246

⇩

TREK E36

Primary focus is BR($K_{e2}/K_{\mu2}$) to 0.25%

+ Invisible heavy neutrino searches

+ T violation in $K_{\mu3}$ (as E06)

Upgraded KEK-246 setup, moved to J-PARC

- Stopped K^+ in active target
- Toroidal spectrometer surrounding target
- e/μ particle ID by time of flight, Cerenkov counters, lead-glass calorimetry

KEK-246 measured BR($K_{\mu3}/K_{e3}$) and K_{e3} FF, so TREK could potentially use calibration data to measure at least some BRs and FFs of interest for V_{us}