REU Mentors Presentations July 1 2024

Searching for New Physics at the "precision frontier"

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- Introduction: the Standard Model and the quest for new physics
- The 'precision frontier' and the role of Nuclear Science
- Selected topics from my research
- My career path

Spin 1/2: ordinary matter + 2 heavier generations

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$$
\mathcal{L}_I(x) \sim J_\mu(x)\,A^\mu(x)\,\Big|\,
$$

Spin 0: Higgs boson

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Massive EW gauge bosons (short range weak force)

New physics: why?

• The Standard Model is remarkably successful, but … 74% Dark Energy **Quarks** Hot gas (X rays) X **Forces** Higgs
boson Dark Matter (gravitational lensing) **Leptons**

No Baryonic Matter, no Dark Matter, no Dark Energy, no Neutrino Mass

Do forces unify at high E? What is the origin of families? ...

Addressing these puzzles requires new physics

New physics: where?

• Where is the new physics? Is it Heavy? Is it Light & weakly coupled?

Two complementary paths to search for new physics

1/Coupling

The Precision Frontier cuts across AMO, HEP & NP Nuclear Physics plays a key role in this endeavor, through unique probes with high discovery potential

• Probes of new physics at the precision frontier can be grouped in three classes, pushing the boundary in qualitatively different ways and at different mass scales

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> 1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_{α}): 0νββ decay, EDMs, n-nbar oscillations, μ→e conversion, ep→τX, …

2. Precision measurements of SM-allowed processes: β-decays (mesons, neutron, nuclei), muon g-2, PV electron scattering, …

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2. Precision measurements of SM-allowed processes: β-decays (mesons, neutron, nuclei), muon g-2, PV electron scattering, …

3. Searches / characterization of light and weakly coupled particles: active v's, sterile v's, dark sector particles and mediators, axions, …

(Strong connection with astrophysics)

Precision probes cluster around four interconnected questions

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Origin of neutrino mass

Baryogenesis requires (Sakharov)

- **B** (L) violation
- C and CP violation
- Departure fro equilibrium

Baryogenesis does not work in the Standard Model

Baryon asymmetry (violation of B, L, CP)

Precision probes cluster around four interconnected questions

Origin of neutrino mass

Baryon asymmetry (violation of B, L, CP)

Are there new forces, weaker than the weak force?

Precision probes cluster around four interconnected questions

Origin of neutrino mass

Baryon asymmetry (violation of B, L, CP)

Portals to the dark sector: Neutrino, Vector, Higgs, Axion, …

Are there new forces, weaker than the weak force?

Nature of dark matter

Precision probes cluster around four interconnected questions

Precision frontier and BSM

- Three classes of probes
	- Searches for rare / SM-forbidden processes
	- Precision measurements of SM-allowed processes
	- Search / characterization of light weakly coupled particles
- Shedding light on four interconnected scientific questions
	- Why is there more matter than antimatter in the present universe?
	- How do neutrinos get their masses and what are their values?
	- Are there new forces in nature, weaker than the weak force?
	- What is the nature of dark matter?

Precision frontier and BSM

• Three classes of probes

Topics from my research: precision tests of weak interaction

- Searches for rare / SM-forbidden processes
- Precision measurements of SM-allowed processes
- Search / characterization of light weakly coupled particles
- Shedding light on four interconnected scientific questions
	- Why is there more matter than antimatter in the present universe?
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Precision tests of the Standard Model with beta decays

- Beta decays have played a central role in the development of the SM
- Nowadays: tool to challenge the SM & probe possible new physics

In the SM, W exchange \Rightarrow universality relations

Cabibbo-Kobayashi-Maskawa (unitary) matrix

In the SM, W exchange \Rightarrow universality relations

(unitary) matrix

Cabibbo universality

$$
|V_{ud}|^2 + |V_{us}|^2 + |\mathbf{W}_{\mathbf{W}}|^2 = 1
$$

$$
[G_F]_e / [G_F]_\mu = 1
$$

Lepton Flavor Universality (LFU)

In the SM, W exchange \Rightarrow universality relations

Probing Cabibbo universality

Extract V_{ud} =Cos θ_c and V_{us} =Sin θ_c from various decays and check their squares sum to 1

CKM element Hadronic matrix element Radiative corrections: (a/π) ~ 2. \times 10⁻³ and smaller effects

Input from *many* experiments and theory papers

β decays and CKM unitarity β decays and CKM unitarity

rs, a rs, and radiative \mathbf{Q} \mathbf{Q} \mathbf{Q} ons, are **Voltaint Moulson 2208.11707** *A***C-Critical Activities 2208.11707** *AC***-Critical Activities 2208.11707** *AC* inated by experiment [22]. A uires a dedicated experimental ONEER ϵ fperiment $\overline{26}$. Vu comes from kaon decays, K_{22} = v_{ℓ} . The former is typically anacays [27], leading to a constraint ive direct access to V_{us} when the rovided from lattice QCD [28]. on decays, as well as the input

 V_{us}

$$
\left\{ \begin{array}{l} \left(42 \right)_{F_K/F_\pi} (16)_{\text{IB}} [51]_{\text{total}}, \\ \left(39 \right)_{f_+} (8)_{\text{IB}} [59]_{\text{total}}, \end{array} \right\} \tag{7}
$$

on *Vus*/*Vud*, while *K*`³ decays give direct access to *Vus* when the $\frac{g}{v}$ co v_{ud} ,
mth for decay constants, form factors, and radiative corrections, are α on V_{us} can be derived from τ \sum_{u} , these \sum_{u} \sum_{v} a ten- V_{ud} , these bands give rise to the ment, lattice input for the matrix g corrections, respectively. To-**EKM** unitarity, but another tenon decays, is due to the fact that tersect away from the unitarity e larger errors $[31, 32]$ we will ector.

recto
er is ne n
v of .
ithe erms base $\frac{[33]}{[}$ lays
nizo the **K**³
and **K**³ by of $K_{\ell 2}$ and $K_{\ell 2}$ or Ω or Ω or Ω . O.965 0.970 0.975 mized by a new measurement of er is that given the various tenere is urgent need for additional ingled *in K*₂ and *K*₂₃ data *R*₂ and *K*₂₃ data *K*₂ and *K*₂₃ data *R*₂ and *K*₂₃ data *K*₂ and *K*₂₃ data *K*₂₃ data *K*₂₃ data *K*₂₃ data *K*₂₃ data *K*₂₃ dans *K*₂₃ dans *K*₂₃ dans erms of physics beyond the SM base for $K_{\ell 2}$ is completely dom-[33], and at the same time the lays a relatively poor fit quality. x at the *level* of a few permil of

 $\Delta_{\rm CEM}$ Cated experimental $\Delta_{\rm CKM} = |V_{\rm ud}|^2 + |V_{\rm us}|^2 + |V_{\rm ub}|^2 - 1 = -15(5) \times 10^{-4}$

Vud

K→ π*l***ν (0.25%) unitarity** it deviate**s** from **the colosity line by 2.8.** Note that the significance tends to increase**Neutror (0.043%)** uded. Figure 1: Constraints in the $V_{ud}-V_{us}$ plane. The partially overlapping vertical bands correspond to $V_{ud}^{0^+\to0^+}$ (leftmost, red) and $V_{ud}^{\text{h, best}}$ (rightmost, violet). The horizontal band (green) corresponds to $V_{u,s}^{K_{\ell 3}}$. The diagonal band (blue) corresponds to $(V_{us}/V_{ud})_{K_{\ell 2}/\pi_{\ell 2}}$. The unitarity circle is denoted by the black solid line. The 68% C.L. ellipse from a fit to all four constraints is depicted in yellow (*V_{ud}* = 0.97378(26), *V_{us}* = 0.22422(36), $\sqrt{2}$ dof = 6.4/2, *p*-value 4.1%),

Table 1, where, however, the value for V_{us} from $K_{\ell 3}$ decays in-
cludes all charge channels, accounting for correlations among a new measurement of sive parameterization from Ref. [71], constrained by data from of the parameterization from Ref. [71], constrained by data from
28. **Refs.** [72–78]. This leaves form-factor normalizations, decay Table 1, where, however, the value for V_{us} from $K_{\ell 3}$ decays inthem. The extraction of V_{us} from $K_{\ell 3}$ decays requires further input on the respective form factors, which are taken in the disper-

- Two *'anomaly'* points toward vertex
	- At face value point toward vertex d to corrections when A-1 City (hard to probe even at the HI-LUMI LHC)

ental opportunities in

decay, nuclear decays, $π & K$ decays, all with clear target goals

• Theory opportunities: fully controlled uncertainties in radiative corrections to neutron and nuclear decays

Pion decay and Lepton Flavor Universality

David Hertzog

Pion decay and Lepton Flavor Universality

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My career path

- Undergrad + graduate school at University of Pisa, Italy
- Visiting grad. student at UMass Amherst
- Postdoc at Vienna (Austria) + Valencia (Spain) (1.5 years each), as part of a European Training Network
- Postdoc at Caltech (2.5 years)
- Scientist at Los Alamos National Laboratory (16 years)
- Faculty at INT & UW Physics (2.5 years)

Concluding comments

Precision frontier: vibrant particle and nuclear physics program (experiment and theory) probing uncharted territory in the search for new physics **Shedding light on big questions**

1/Coupling

Sheds light on several unsolved mysteries about our universe

Thank you!

T. D. Lee in a drawing by Bruno Touschek

Backup

More on the precision frontier

- Practical definition: searches for new phenomena through precision measurements or the study of rare processes at low energy
- Important feature: can probe new physics originating at very high mass scale
- How so? Through quantum mechanical effects

1/Coupling

How does it work?

- Key point: particles of mass M affect physics at E << M by inducing
	- a shift in coupling constants of known interactions
	- new local interactions suppressed by powers of E/M

How does it work?

- Key point: particles of mass M affect physics at $E \leq N$ by inducing
	- a shift in coupling constants of known interactions
	- new local interactions suppressed by powers of E/M

You are familiar with this concept from perturbation theory in QM

 (0)

 (0)

 (0)

$$
H = H_0 + \lambda V \qquad H|n^{(0)}\rangle = E_n^{(0)}|n^{(0)}\rangle
$$

$$
E_n(\lambda) = E_n^{(0)} + \lambda \langle n^{(0)} | V | n^{(0)} \rangle + \lambda^2 \sum_{k \neq n} \frac{|\langle k^{(0)} | V | n^{(0)} \rangle|^2}{E_n^{(0)} - E_k^{(0)}} + O(\lambda^3)
$$

$$
|n(\lambda)\rangle = |n^{(0)}\rangle + \lambda \sum_{k \neq n} |k^{(0)}\rangle \frac{\langle k^{(0)} | V | n^{(0)} \rangle}{E_n^{(0)} - E_k^{(0)}} + O(\lambda^2)
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Sensitivity to high-energy states through sum over complete set of states