Nuclear Theory for New Physics - a DOE Topical Collaboration

2023 Jefferson Lab Users Organization Annual Meeting

June 26-29, JLab

André Walker-Loud

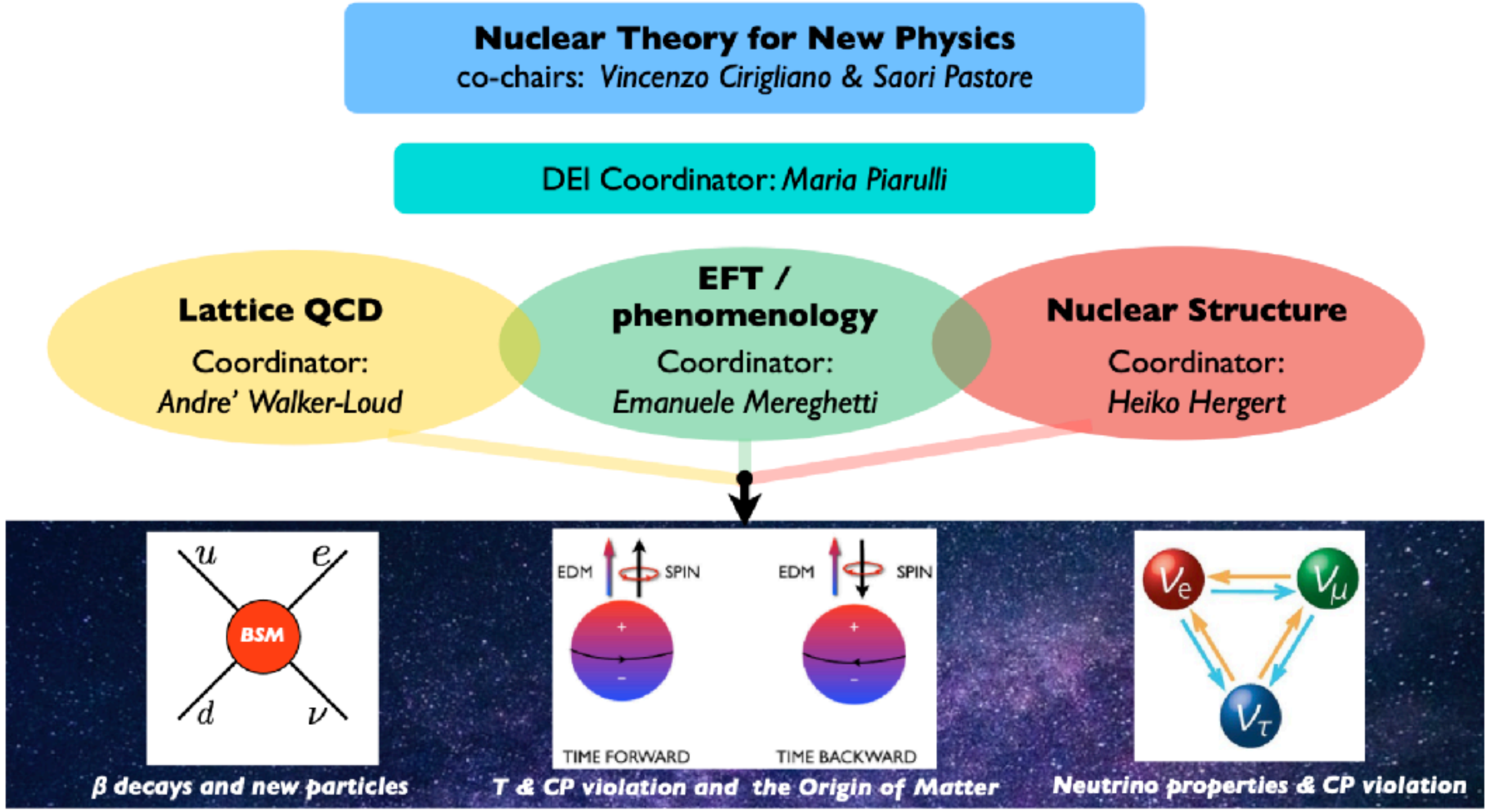
NTNP (Nuclear Theory for New Physics)

NTNP   Home   science   people   meetings   Code of Conduct

https://a51.lbl.gov/~ntnp/TC/

Nuclear Theory for New Physics

- About Us
- Commitment to Diversity
- Funding Acknowledgement

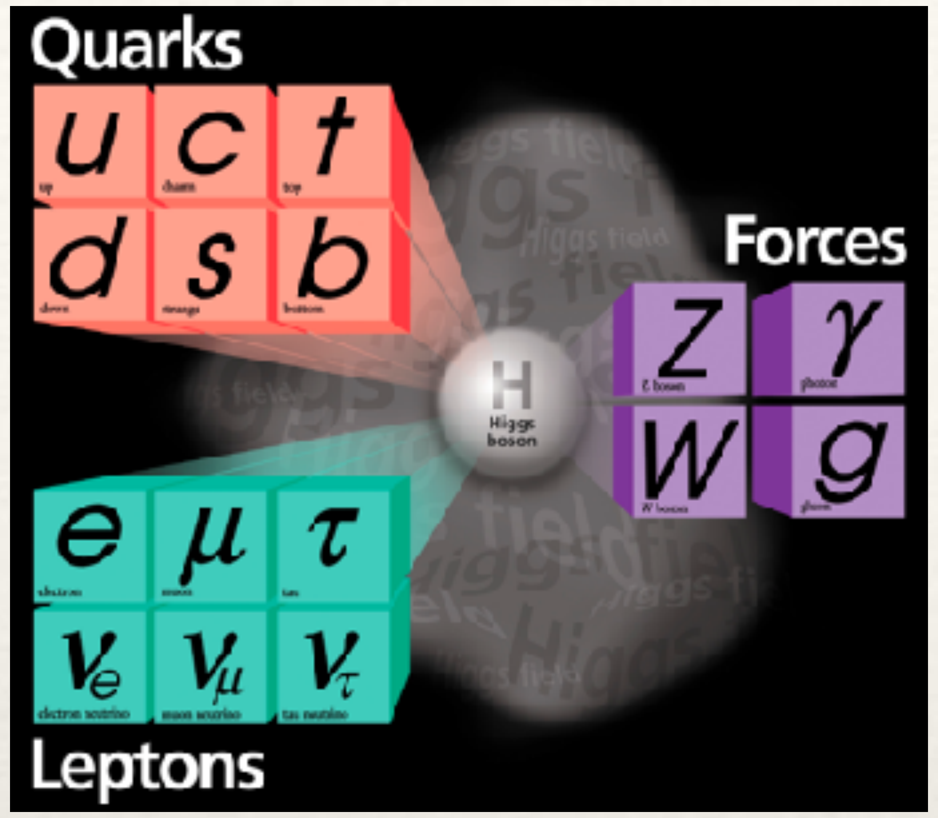


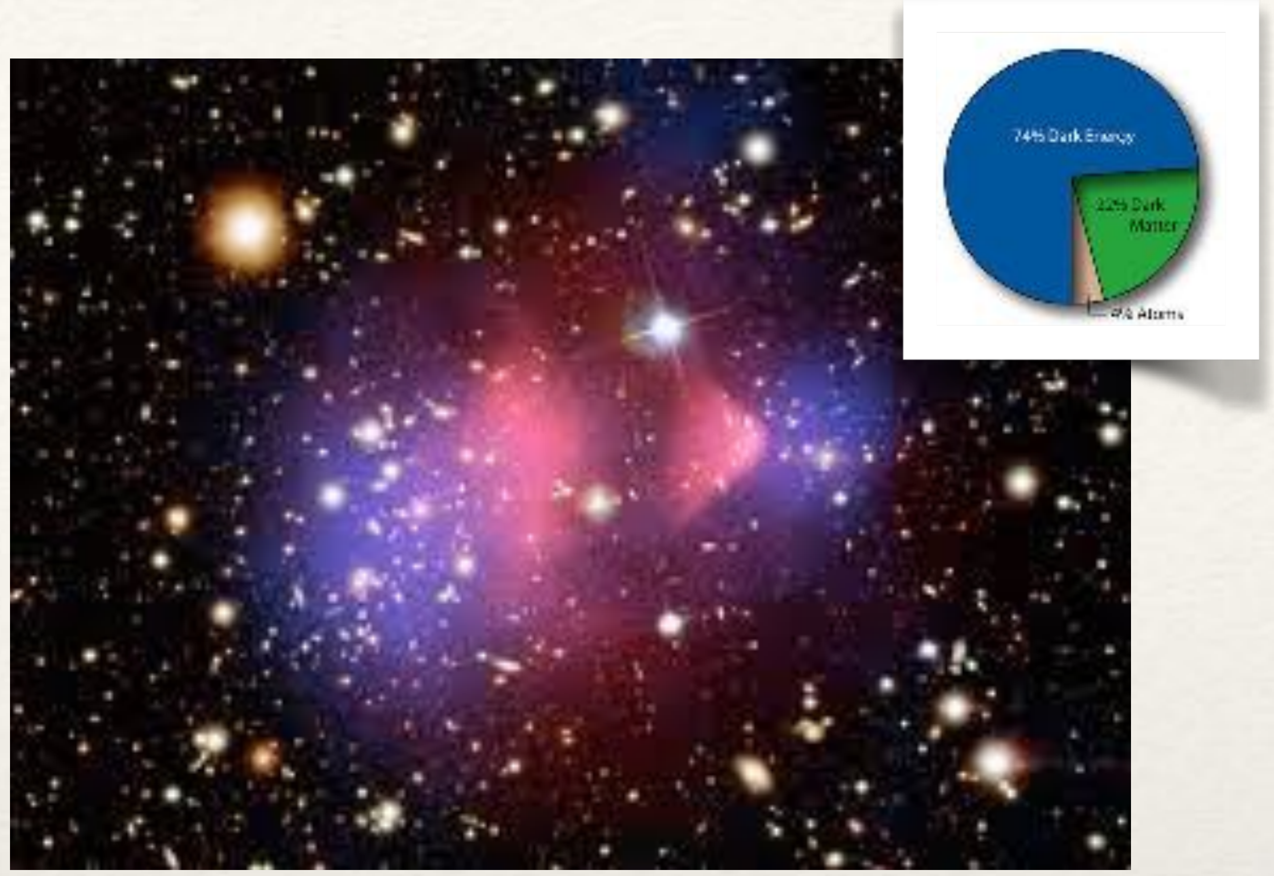
U.S. DEPARTMENT OF ENERGY | Office of Science

- We are a new DOE Topical Collaboration
- We are jointly funded by the Offices of Nuclear and High Energy Physics

NTNP: What Science Questions are we Investigating?

- The Standard Model is remarkably successful, but it is at best incomplete





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

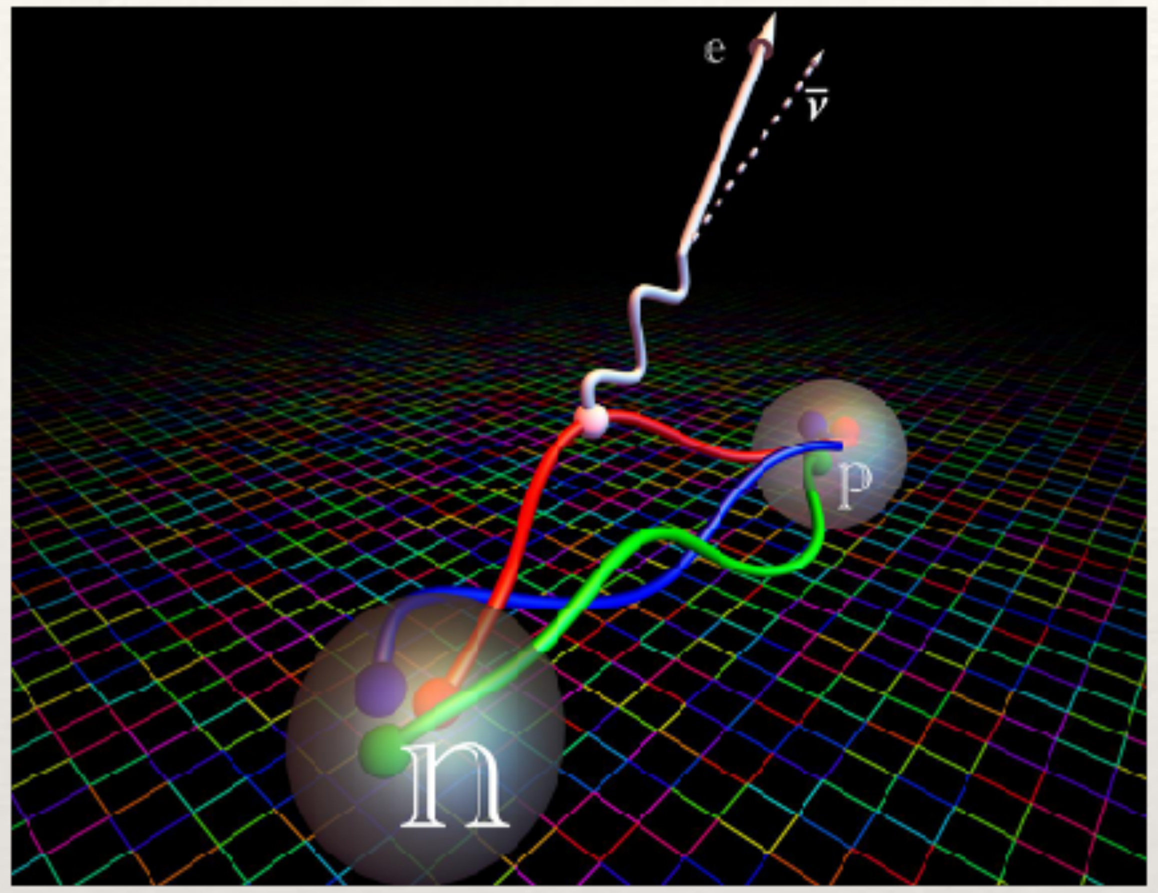
- Low-energy experiments can reveal new physics through precision measurements of SM-allowed processes or by observing SM-suppressed processes

- Nuclear physics plays an important role in the search for new physics through a "targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model" (2015 NSAC LRP)

NTNP: What Science Questions are we Investigating?

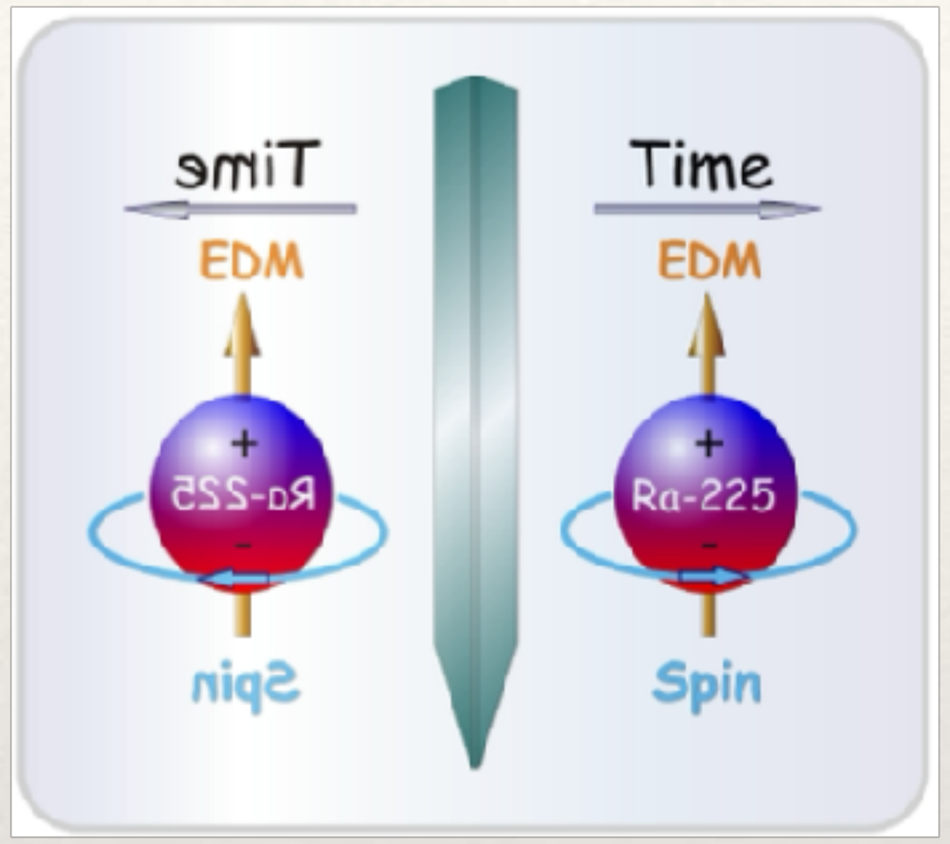
- NTNP focuses on selected aspects of the targeted program, with the goal of providing state-of-the-art predictions with quantified uncertainties.

Image credit: Evan Berkowitz



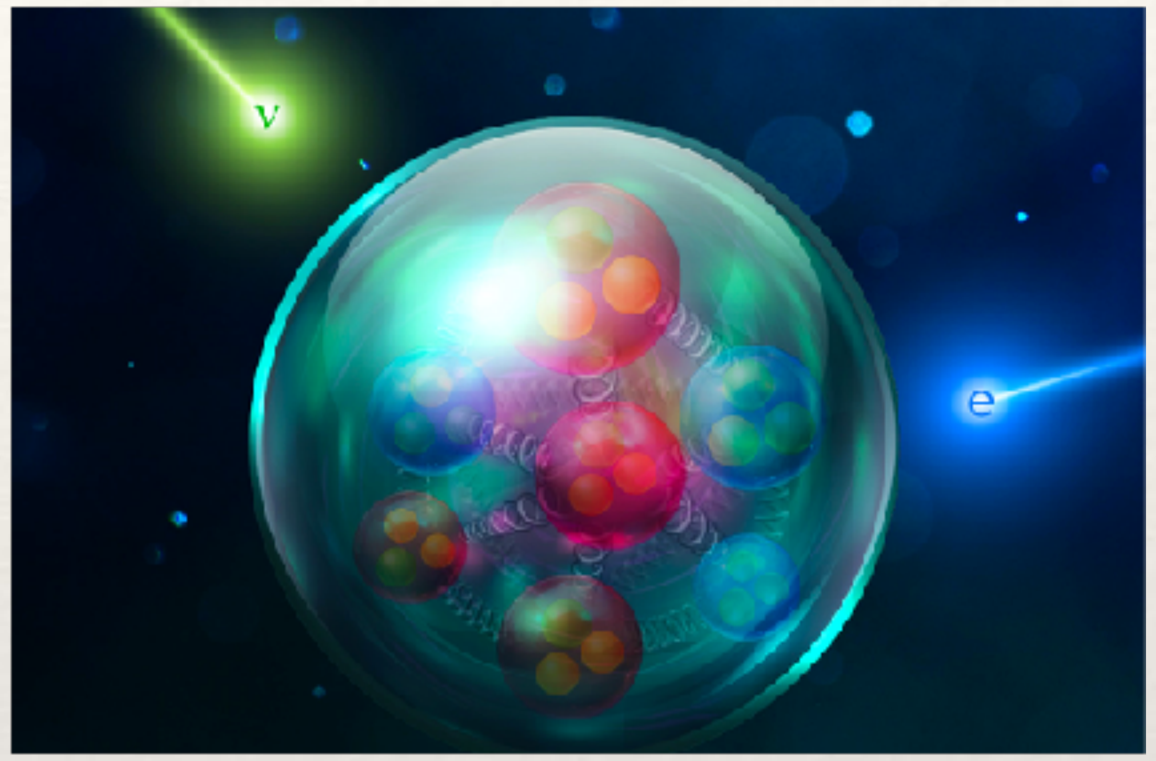
Precision studies of neutron and nuclear beta decays are exquisite probes of the electroweak interactions and can uncover new physics.
NTNP: radiative corrections to neutron & nuclear decays and implications for new physics

Image credit: R. Holt, Z. T. Lu, W. Korsch, P. Muller, J. Singh



The discovery of permanent EDMs would point to a microscopic 'arrow of time', with major implications for the origin of the baryon asymmetry.
NTNP: ab-initio calculations of Schiff moments of ^{129}Xe, ^{199}Hg, ^{225}Ra

Image credit: Jefferson Lab



Neutrino-nucleus scattering is a chief tool to learn about neutrino properties in oscillation experiments: connection to DUNE program (HEP).
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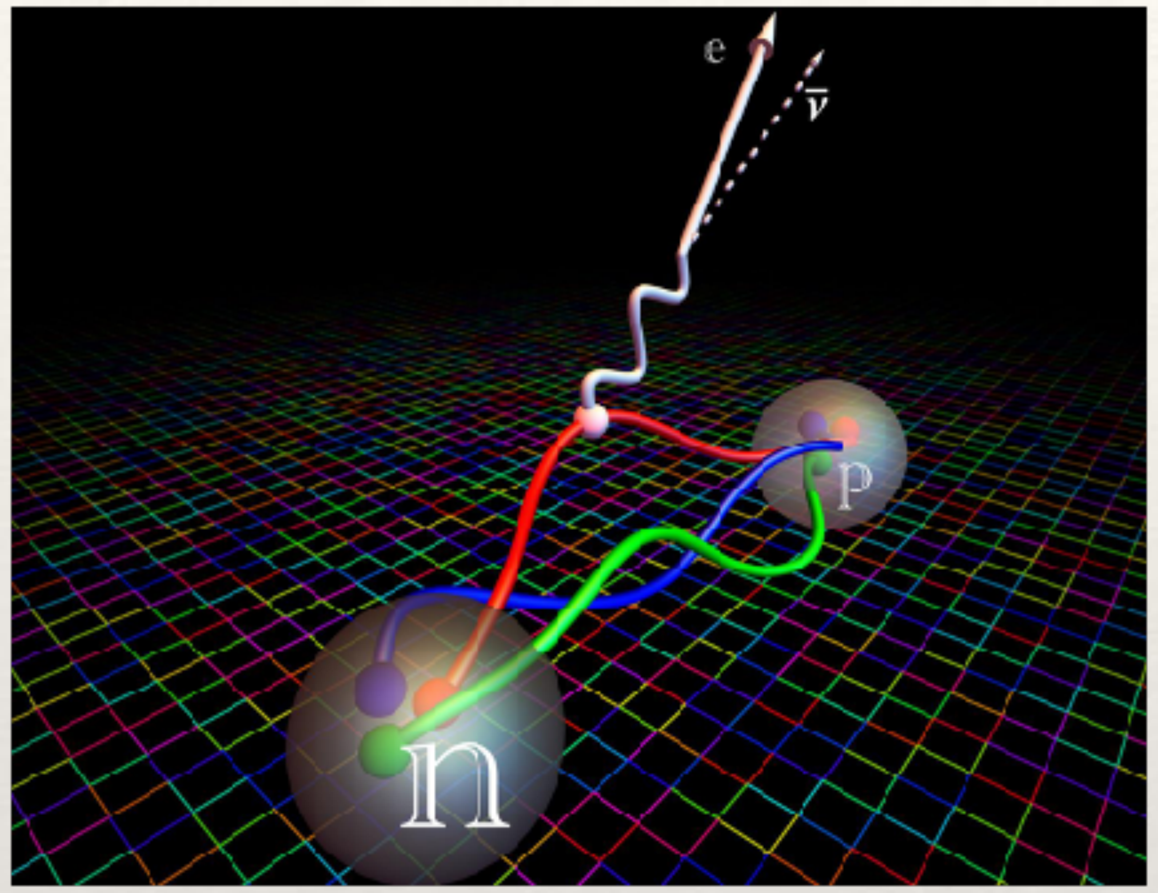

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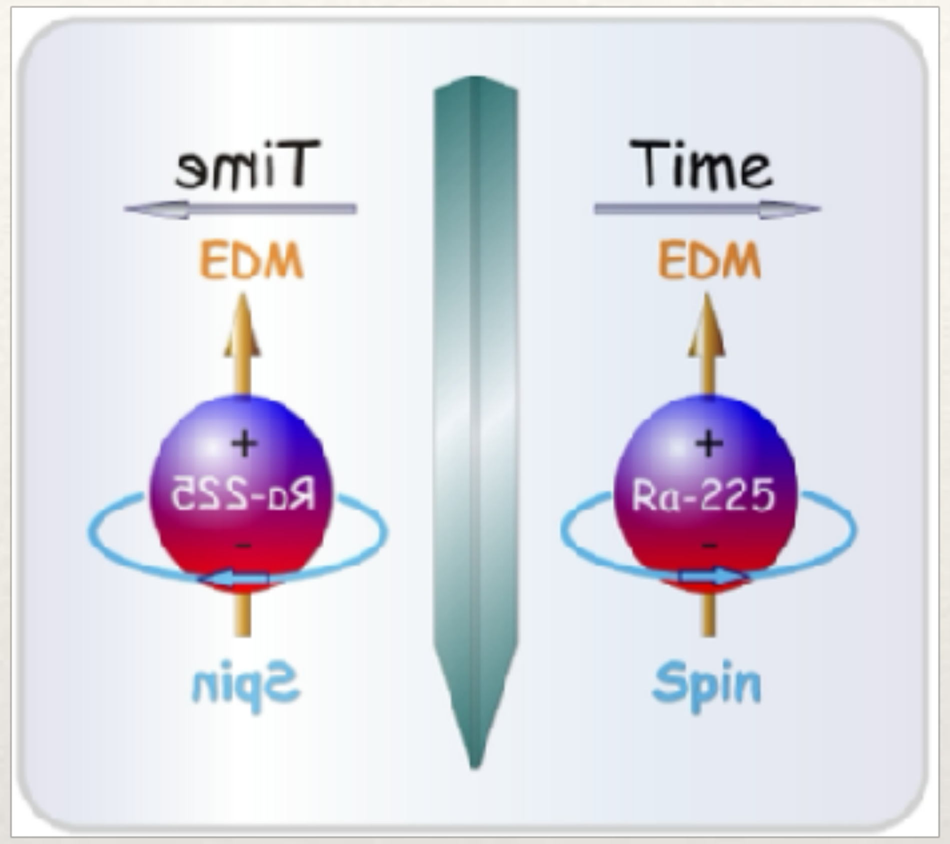

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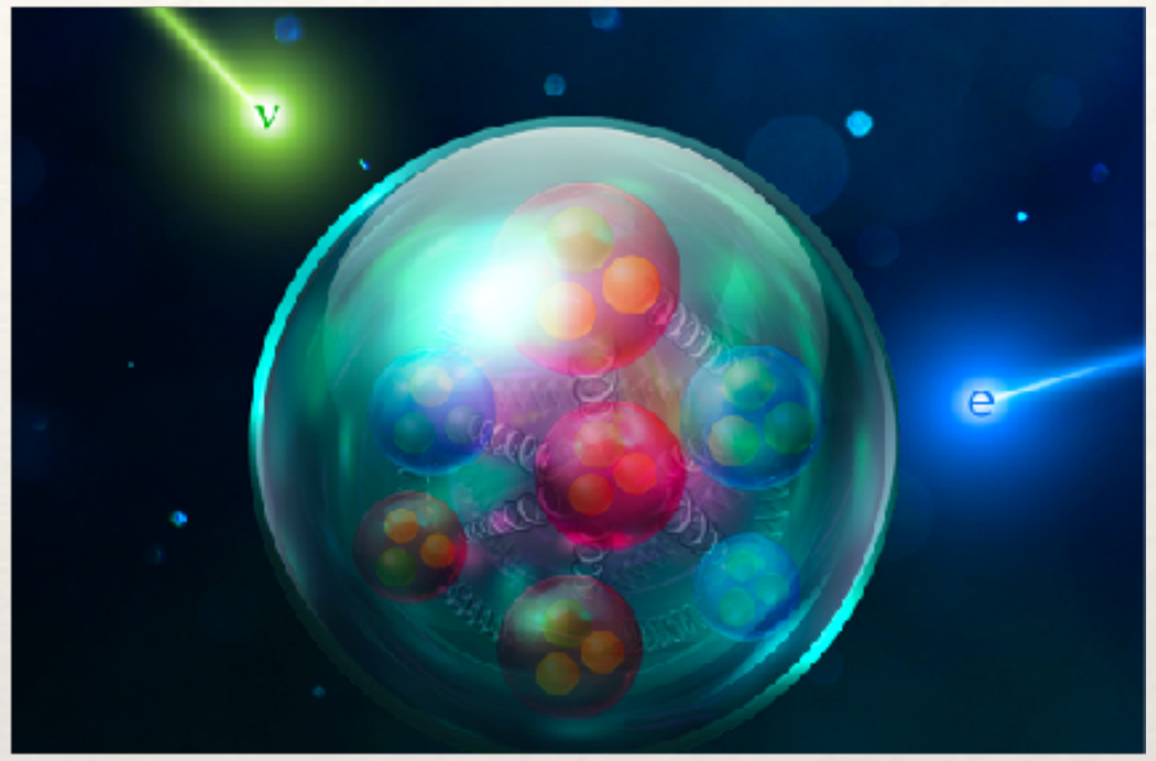

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NTNP: ab-initio calculations of neutrino-nucleus scattering in

This theoretical work is essential to turn experimental measurements into discovery tools

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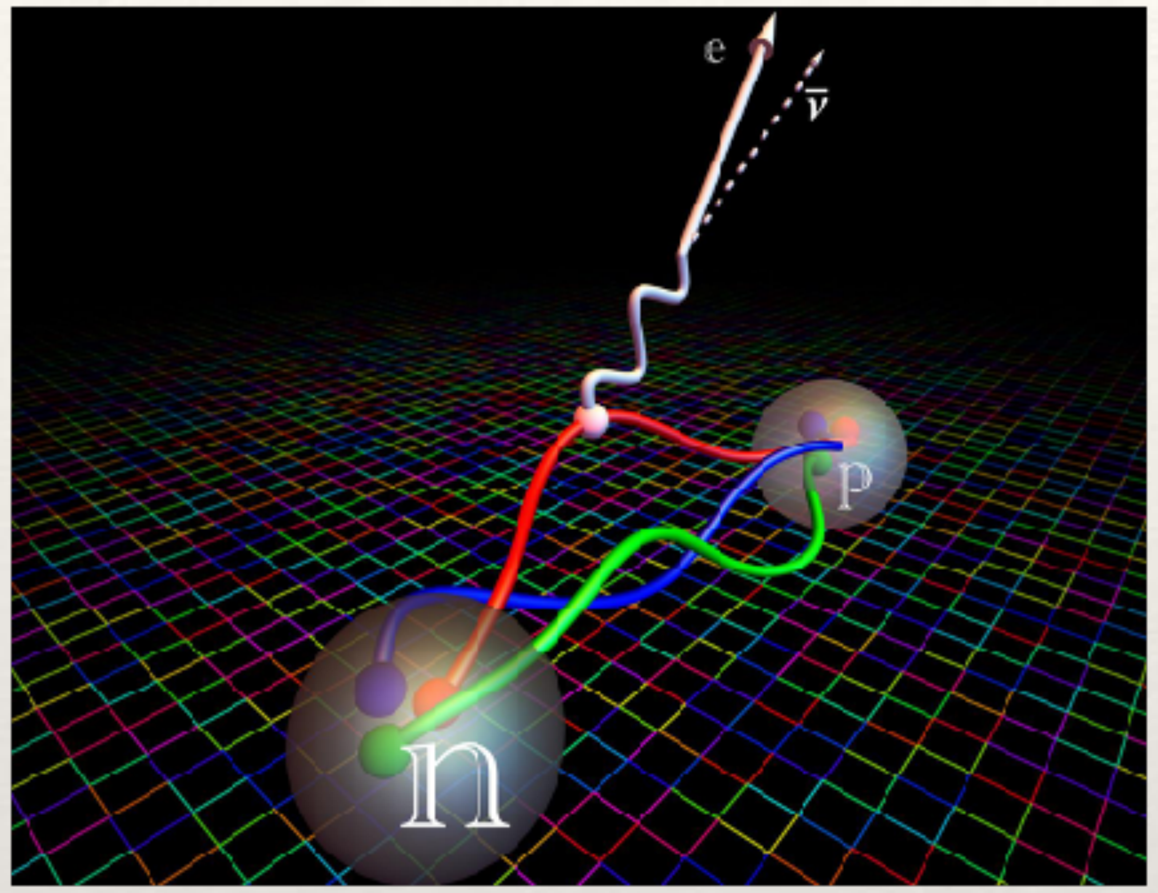

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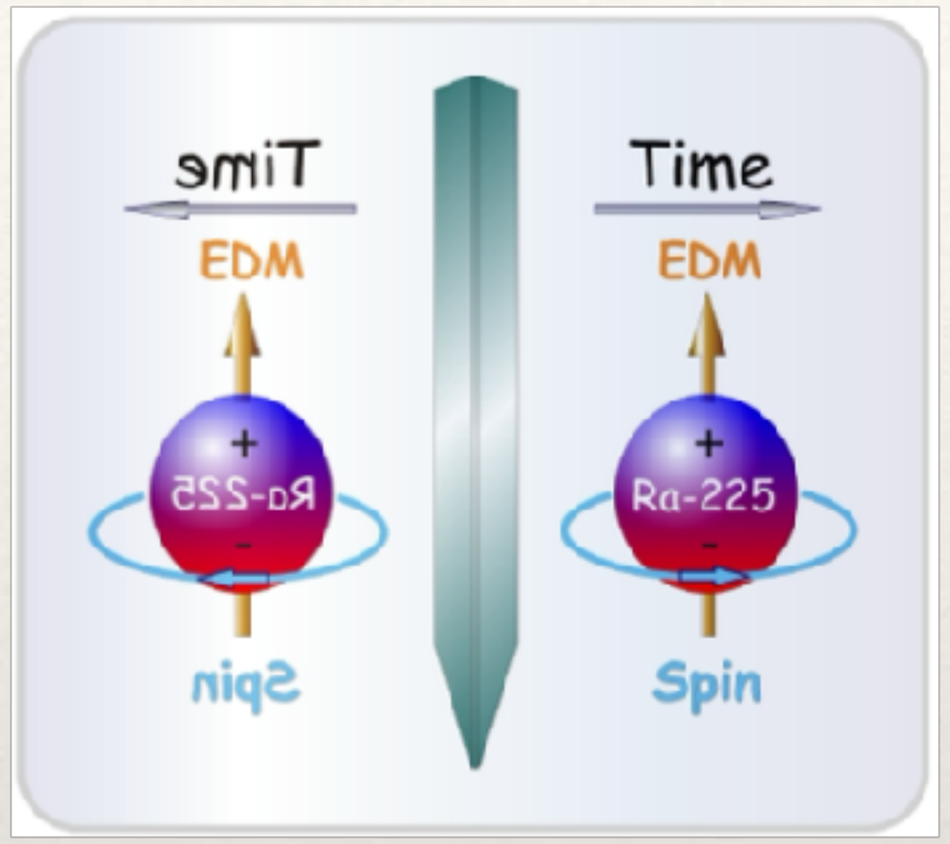

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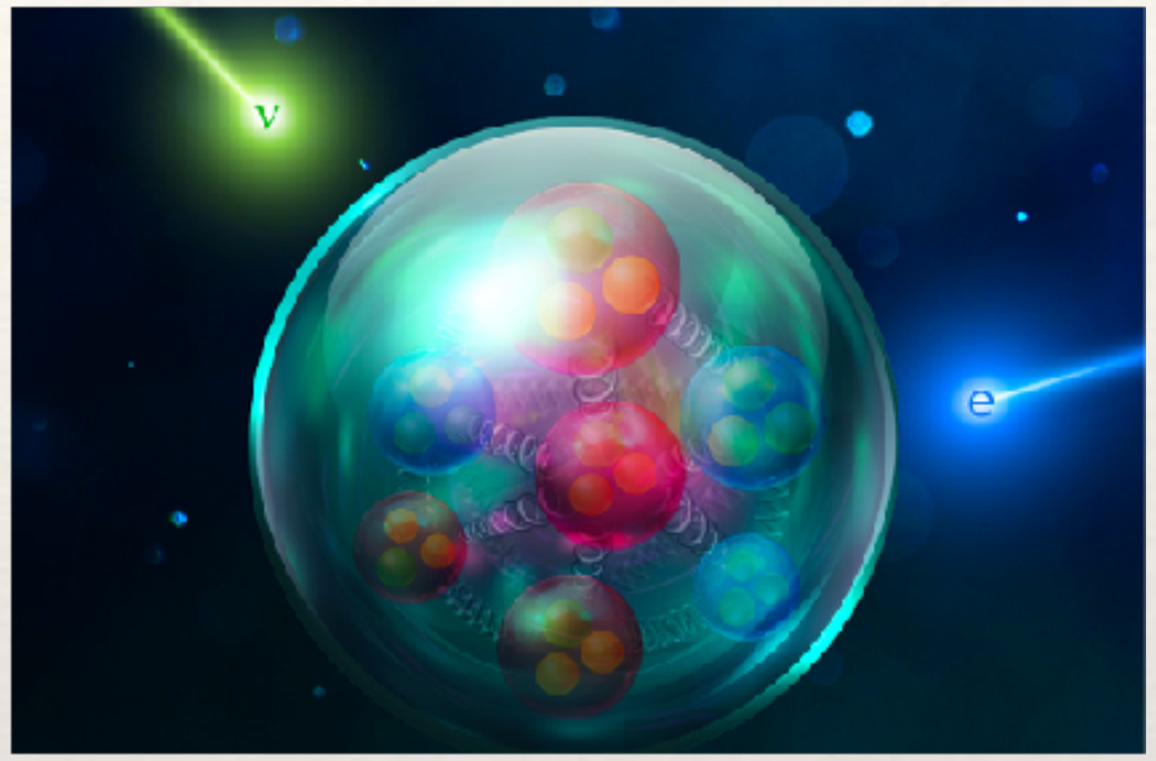

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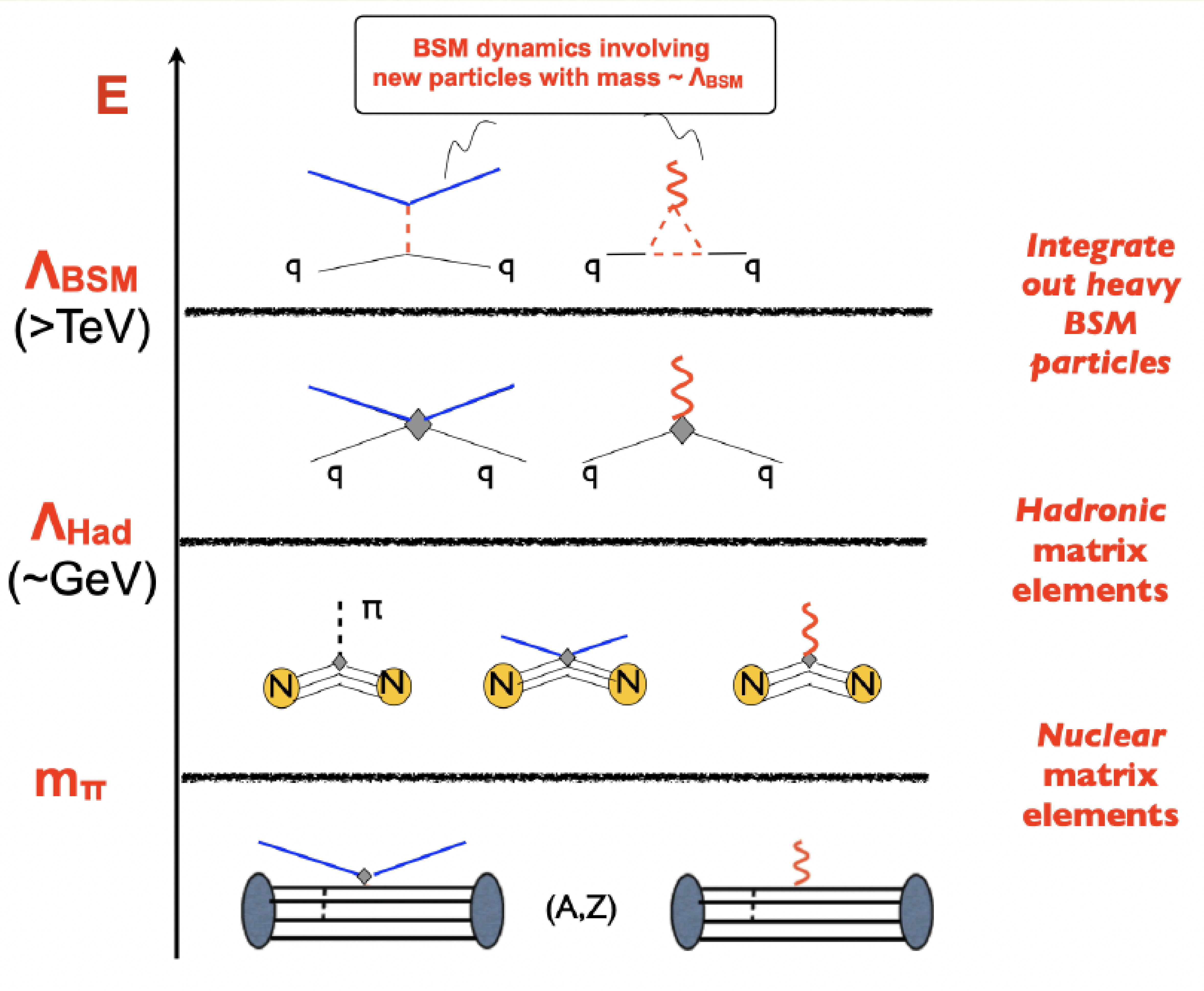
The three areas share challenges (multi-scale problems!), techniques, and infrastructure
Need synergy of EFT / phenomenology, lattice QCD, nuclear structure.

NTNP: How are we investigating these open questions?

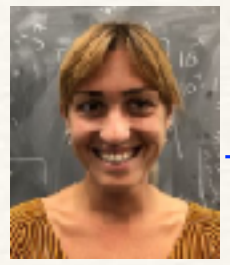


- ❑ A coordinated, multi-scale theory effort is required
- ❑ Effective Field Theory (EFT) and Phenomenology to understand how to couple BSM physics, to a Standard Model EFT (embed high-mass scale BSM physics in short-distance higher-dimensional operators)
- ❑ Also use EFT to couple this SM-EFT to a hadronic-level EFT of pions and nucleons
- ❑ Use lattice QCD to compute hadronic-level matrix elements in terms of quark and gluon degrees of freedom
- ❑ Could hadronic EFT to many-body nuclear effective theory to perform calculations with nuclei
- ❑ Use EFT to couple few-body nuclear EFT to no-core shell model methods in order to compute properties of medium and large nuclei

This multi-scale problem requires a coordinated effort with a broad set of expertise including Effective Field Theory & Phenomenology, lattice QCD and many-body nuclear methods

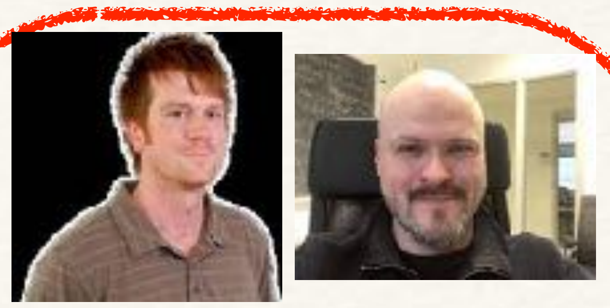
NTNP: Who are we?

UW/INT
Vincenzo Cirigliano
Wouter Dekens
Chien-Yeah Seng
Ayala Glick Magid
Maria Dawid

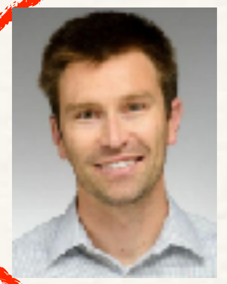


FNAL
Noemi Rocco

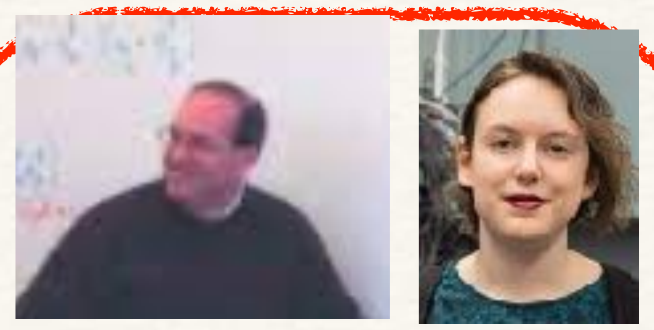
ANL
Alessandro Lovato
Robert Wiringa



MSU (& FRIB)
Scott Bogner
Heiko Hergert



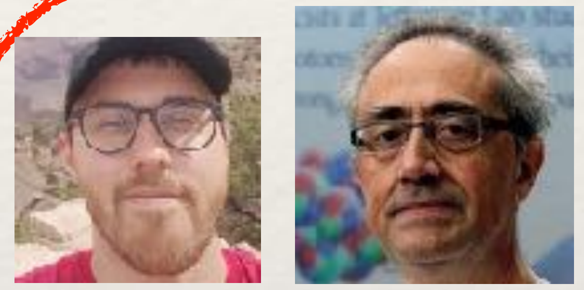
Notre Dame
Ragnar Stoberg



Carnegie Mellon University
Colin Morningstar
Sarah Skinner

UMass Amherst
Michael Ramsey-Musolf

UC Berkeley/LBNL
Wick Haxton
André Walker-Loud
Andrea Shindler
Lukáš Gráf
Zack Hall



ODU/JLab
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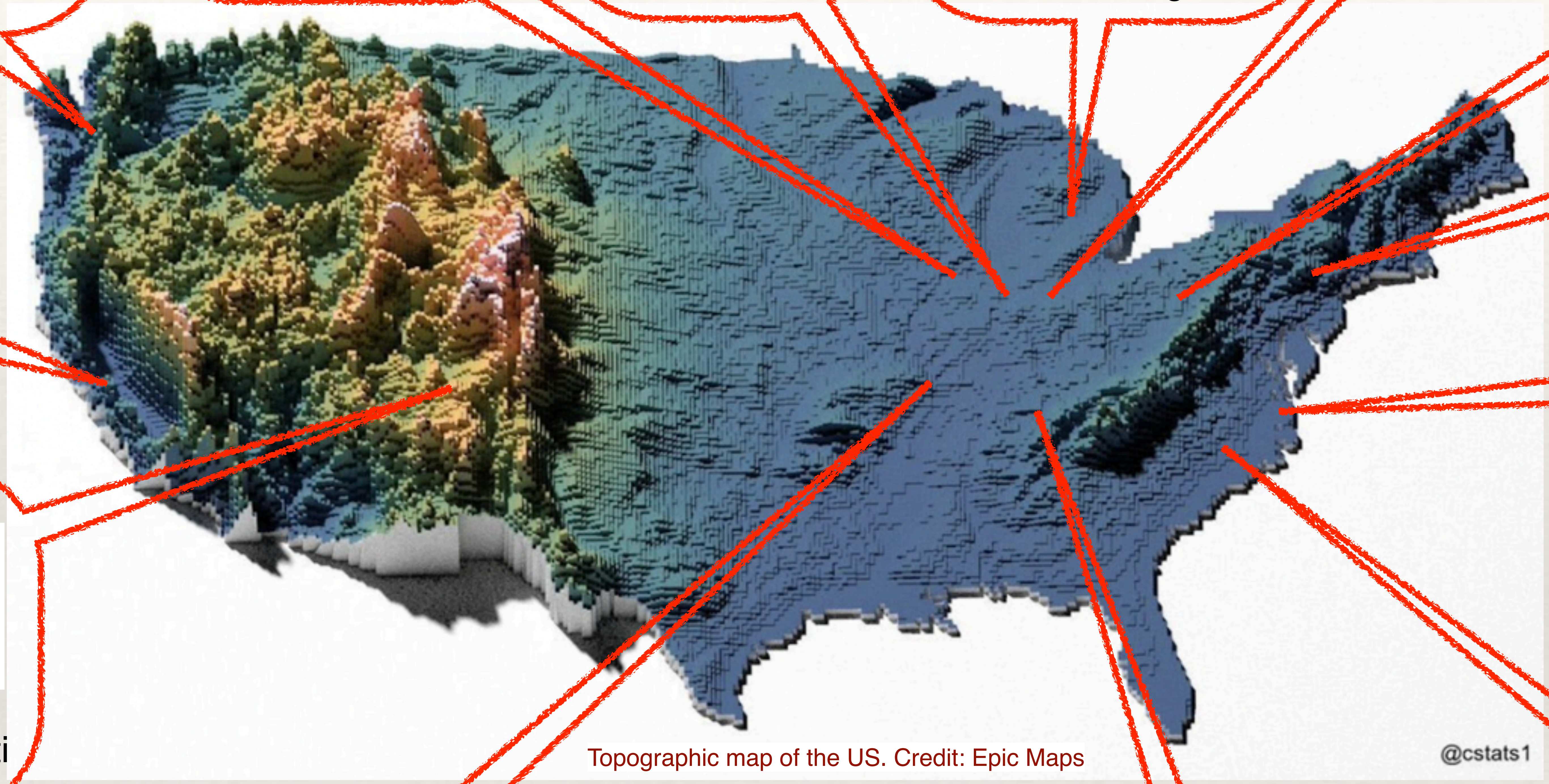
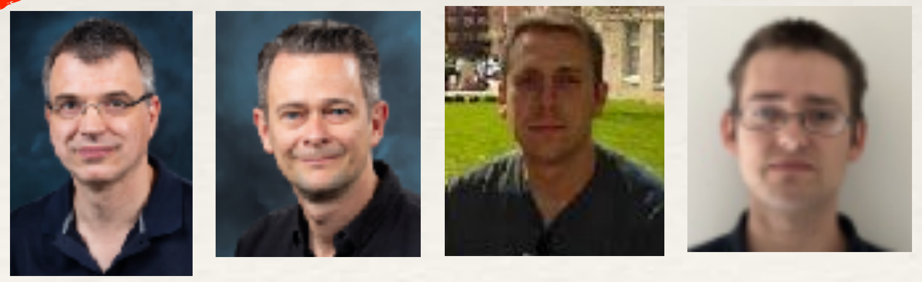
Rocco Schiavilla



Topographic map of the US. Credit: Epic Maps

LANL
Joseph Carlson
Stefano Gandolfi
Emanuele Mereghetti
Ingo News

Wash. U. St Louis
Pupal Dev
Saori Pastore
Maria Piarulli
Anna McCoy
Lorenzo Andreoli
Garrett King
Jason Bub



University of Tennessee/ORNL
Gaute Hagen
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Lucas Platter
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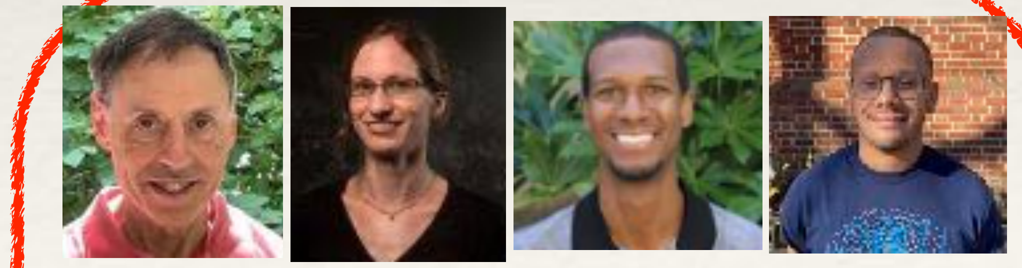

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Jon Engel
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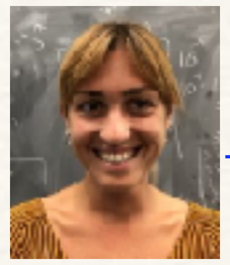

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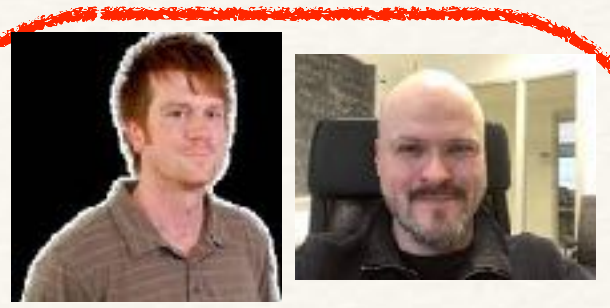

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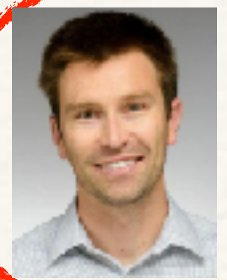

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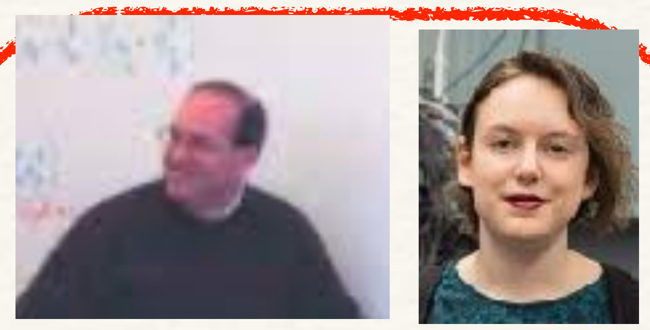

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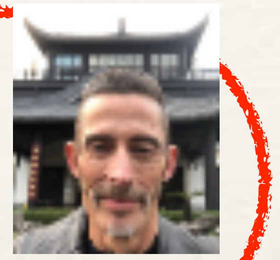

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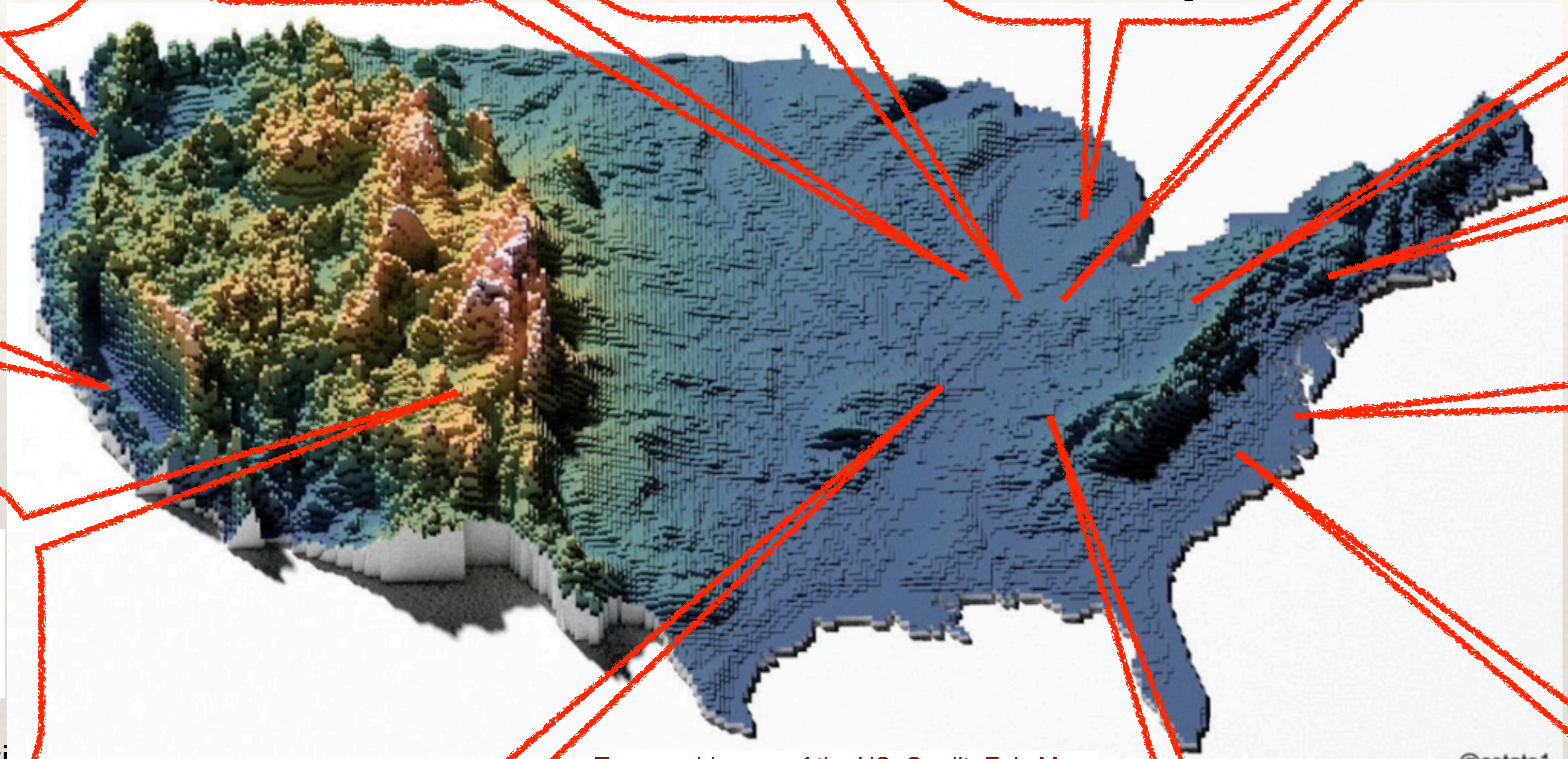

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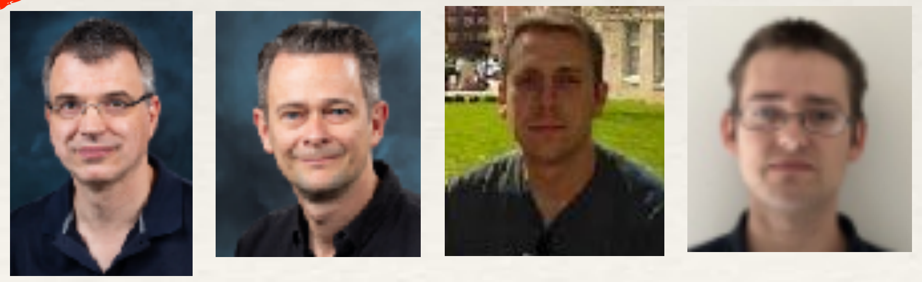

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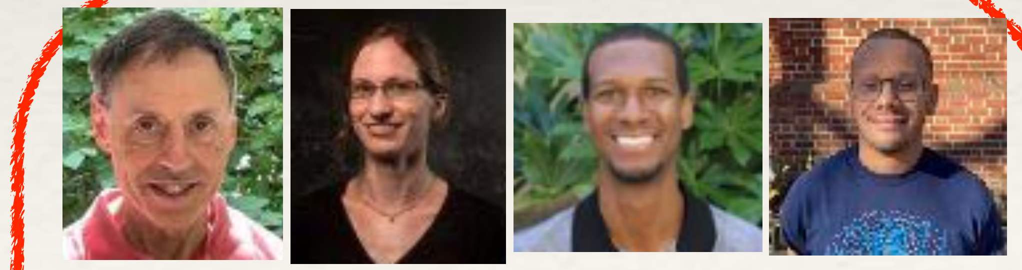

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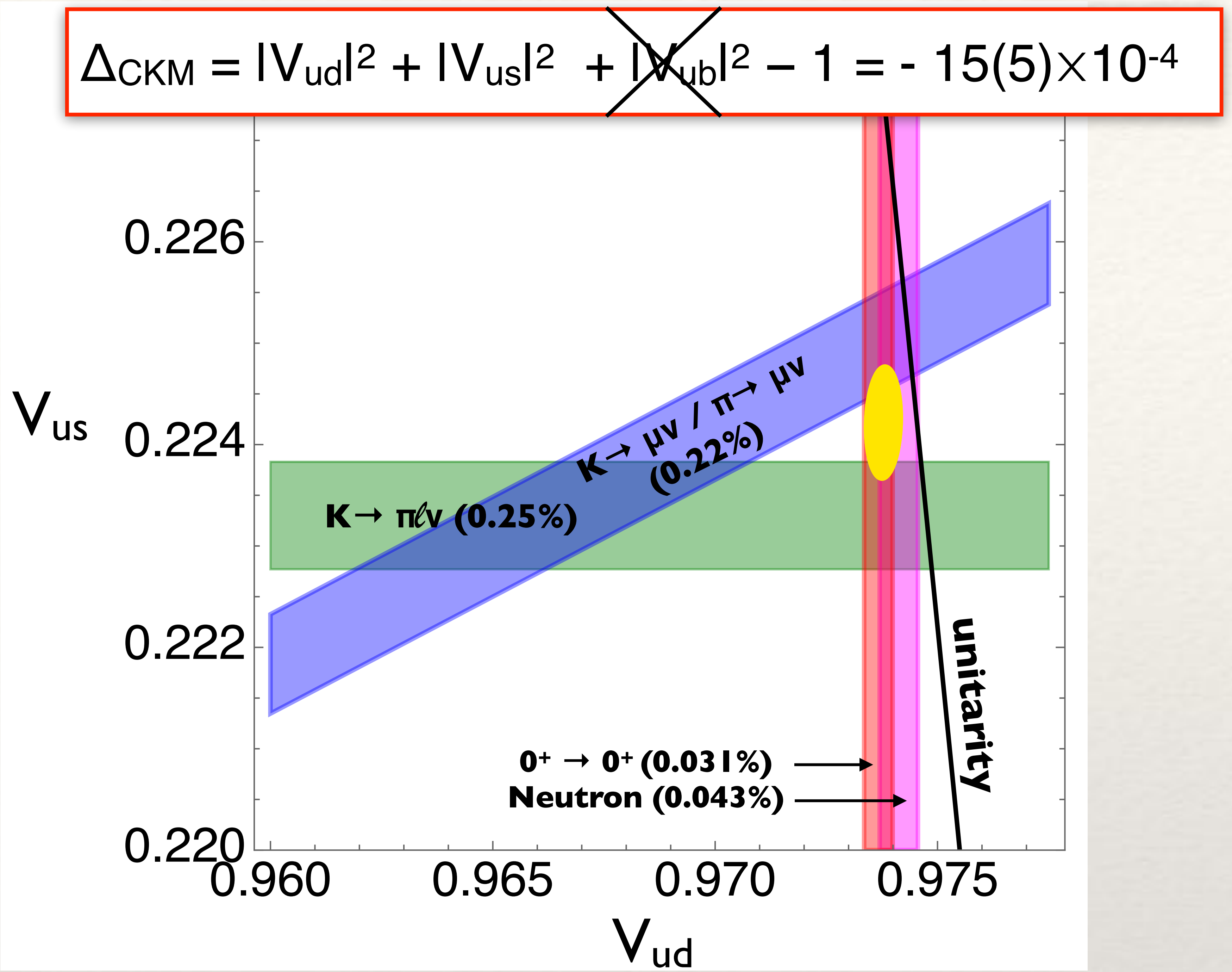
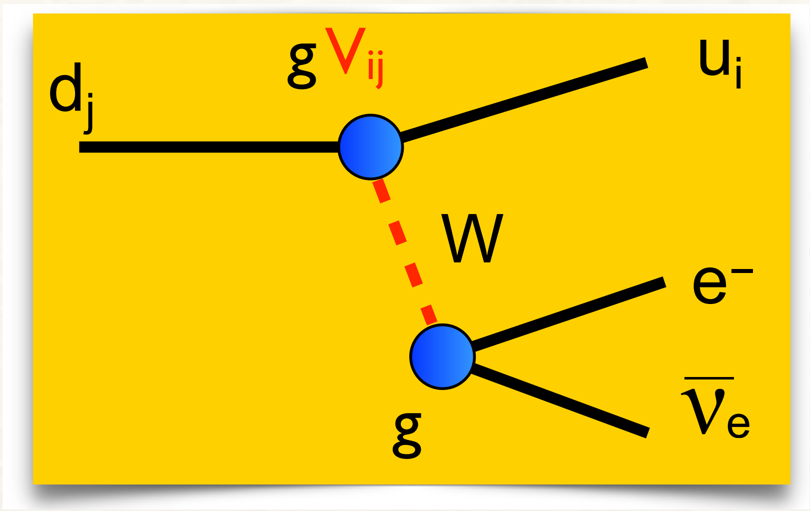
Two selective topics that we are working on

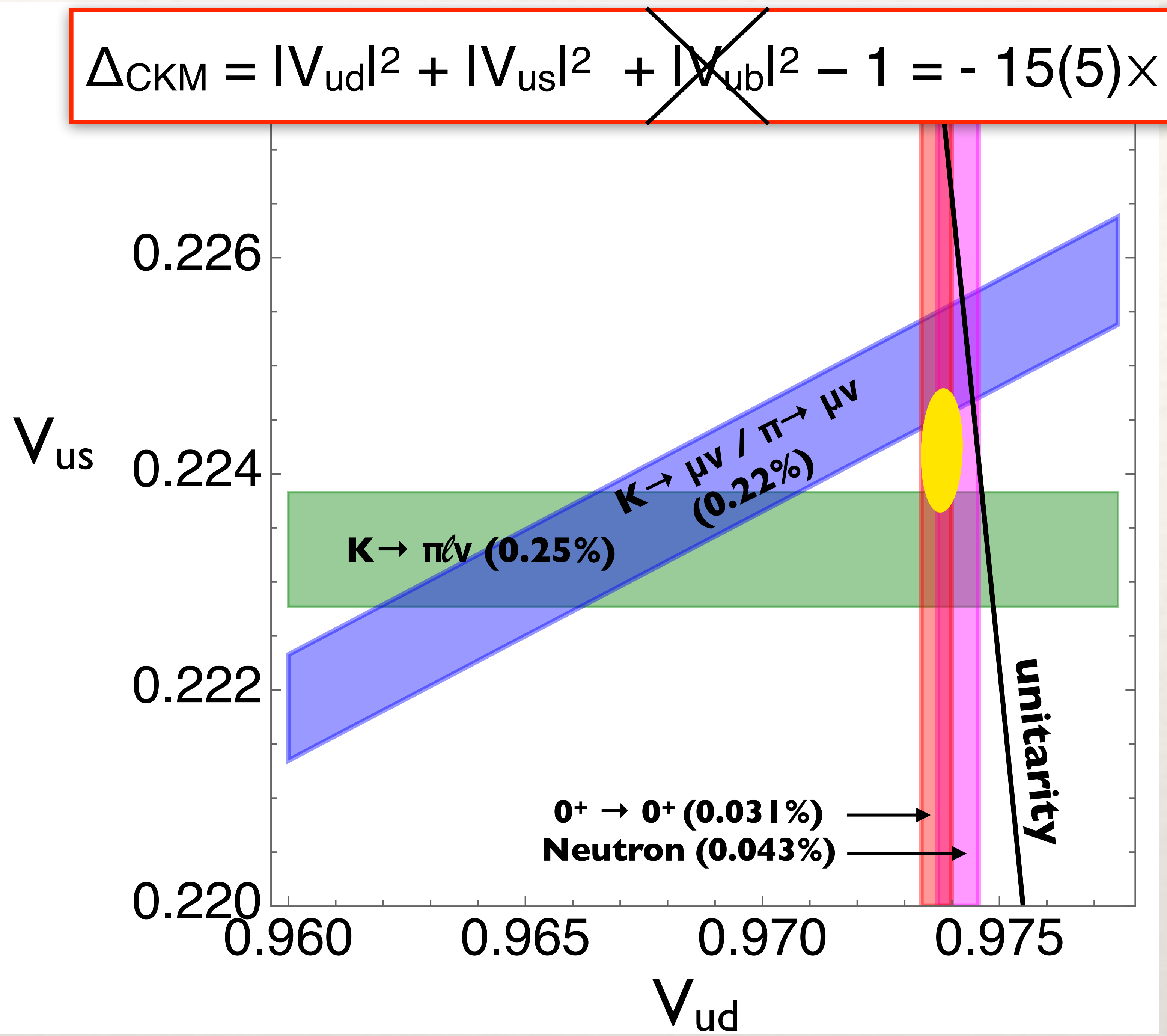
Precision β decays

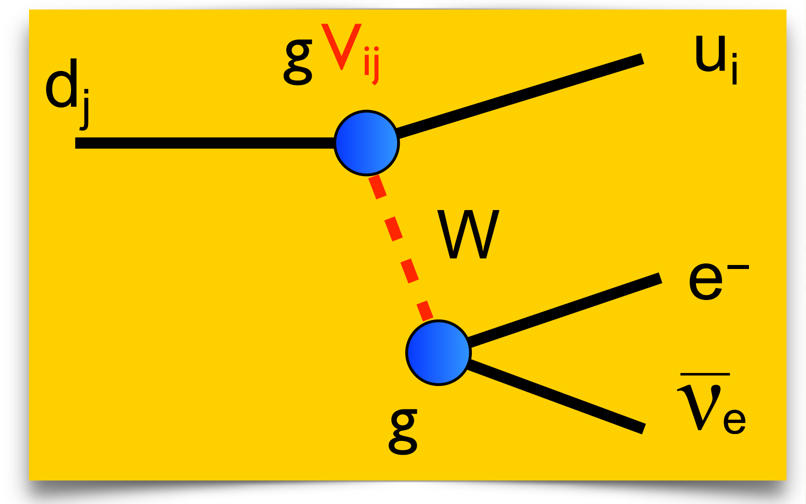




- Two tantalizing 'anomalies'
- At face value point toward vertex corrections with $\Lambda_{BSM}\sim10$ TeV (hard to probe even at the HI-LUMI LHC)

Precision β decays





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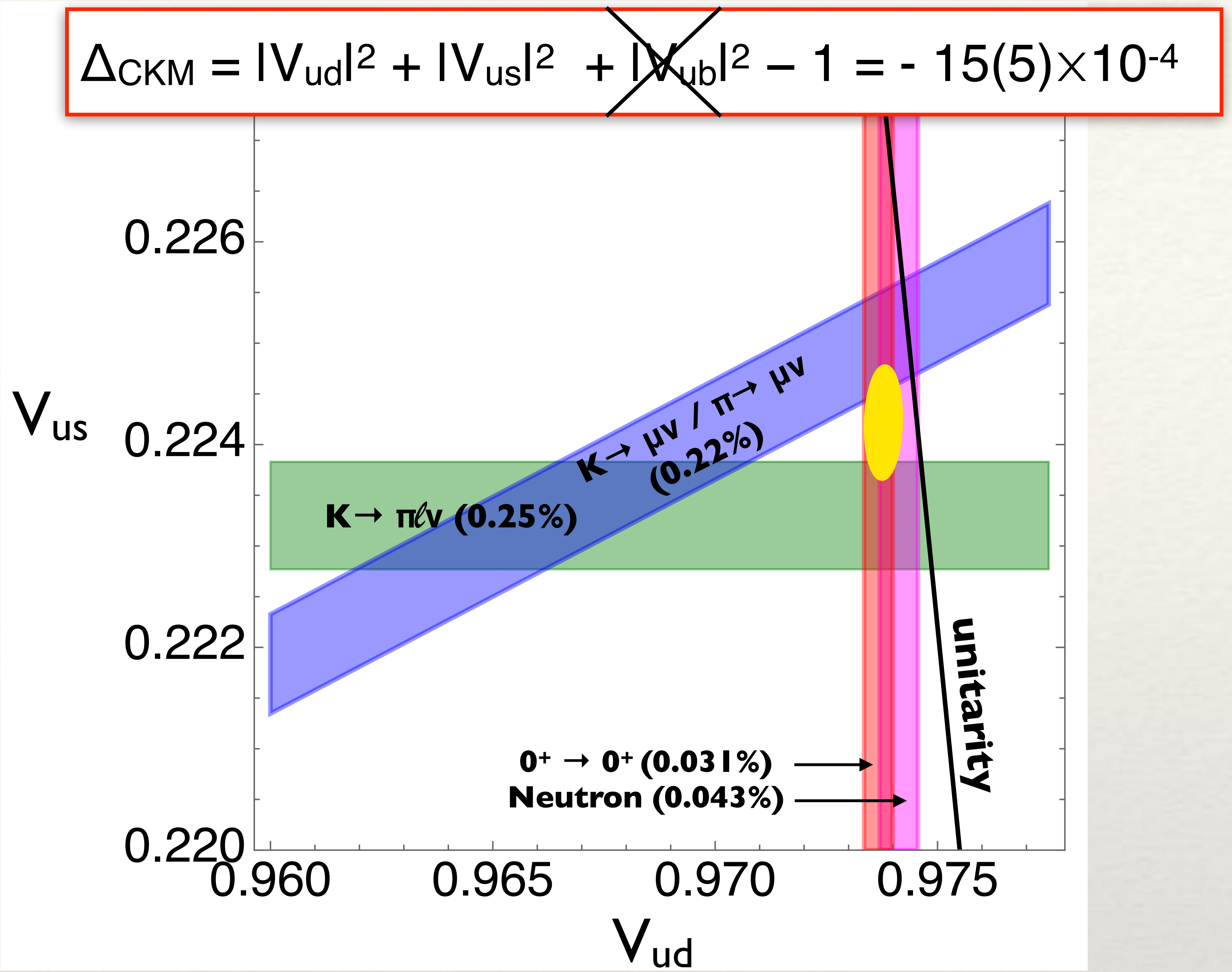
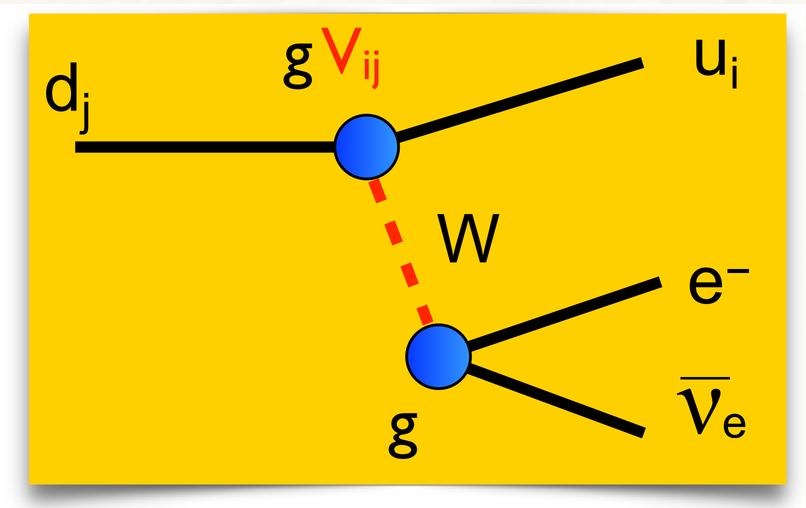
- NTNP objectives:
  - Radiative corrections to neutron decay in Lattice QCD (QED_M)
  - Pion-less and chiral EFT analysis of NN systems to $O(G_F\alpha)$ → input for nuclear structure
  - Radiative corrections to nuclear $0^+ \to 0^+$ decays (A=10, 14, …). Use several ab-initio many-body methods (QMC, CC, IMSRG, HOBET) → controlled uncertainty

Precision β decays





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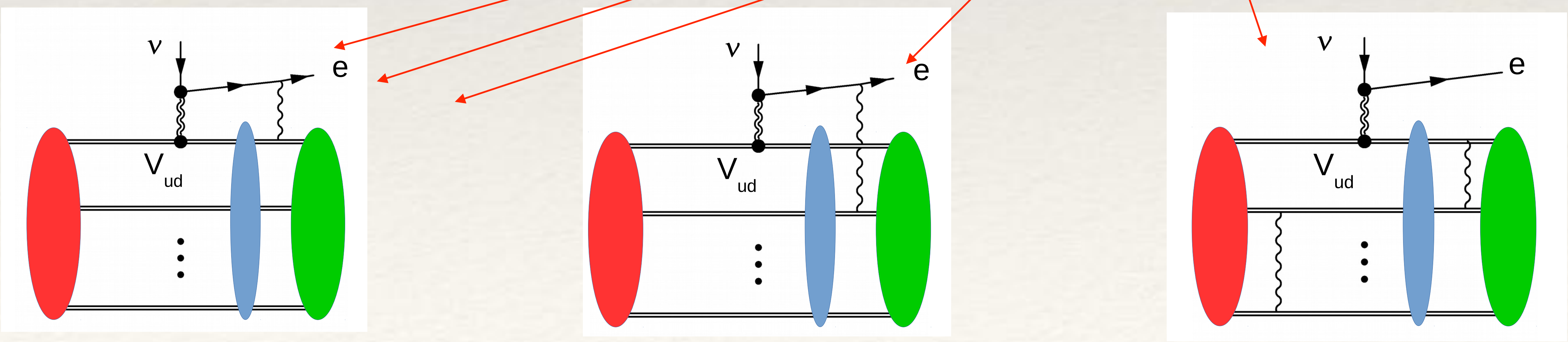
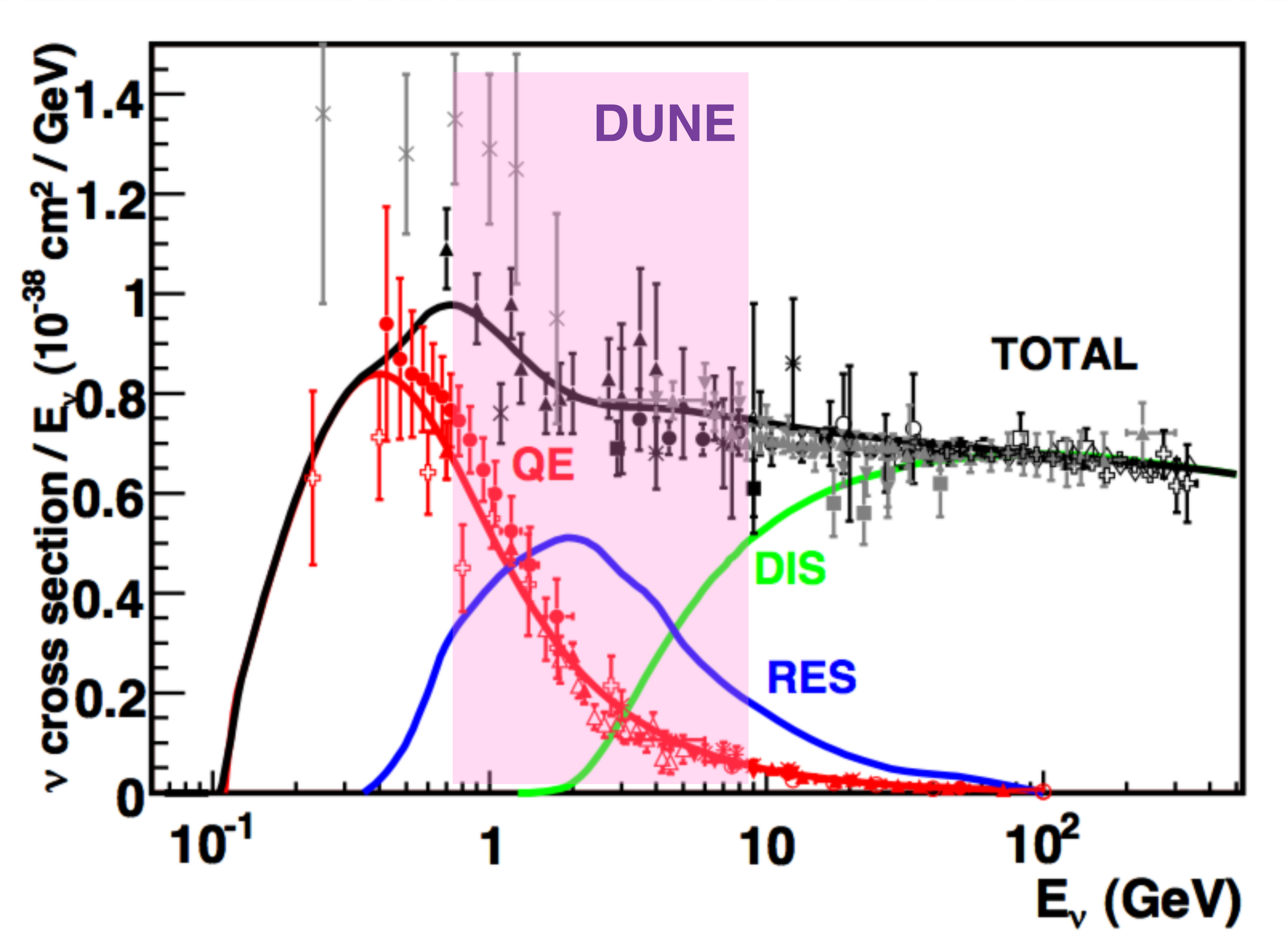
- At face value point toward vertex corrections with Λ_{BSM}~10 TeV (hard to probe even at the HI-LUMI LHC)

$$\frac{\log 2}{ft} = \frac{G_F^2 m_e^5 |V_{ud}|^2}{\pi^3}(1 + \Delta_R^V + \delta_R' + \delta_{NS} - \delta_C)$$



$\nu - A$ scattering

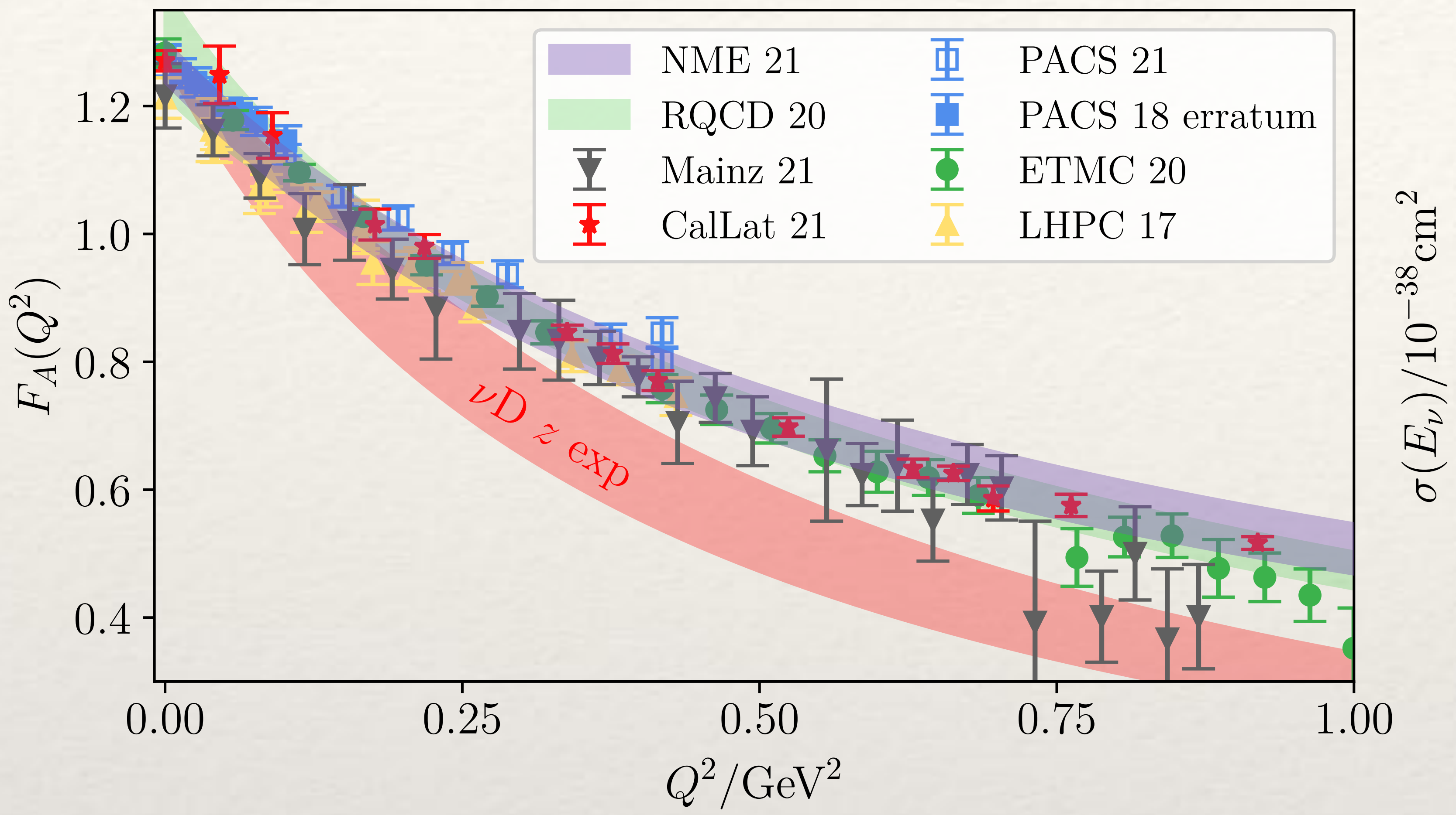
- The success of neutrino oscillations experiments (such as DUNE) requires knowing neutrino-nucleus cross sections at few % level over a broad range of energies (flux determination, ν energy reconstruction , …)

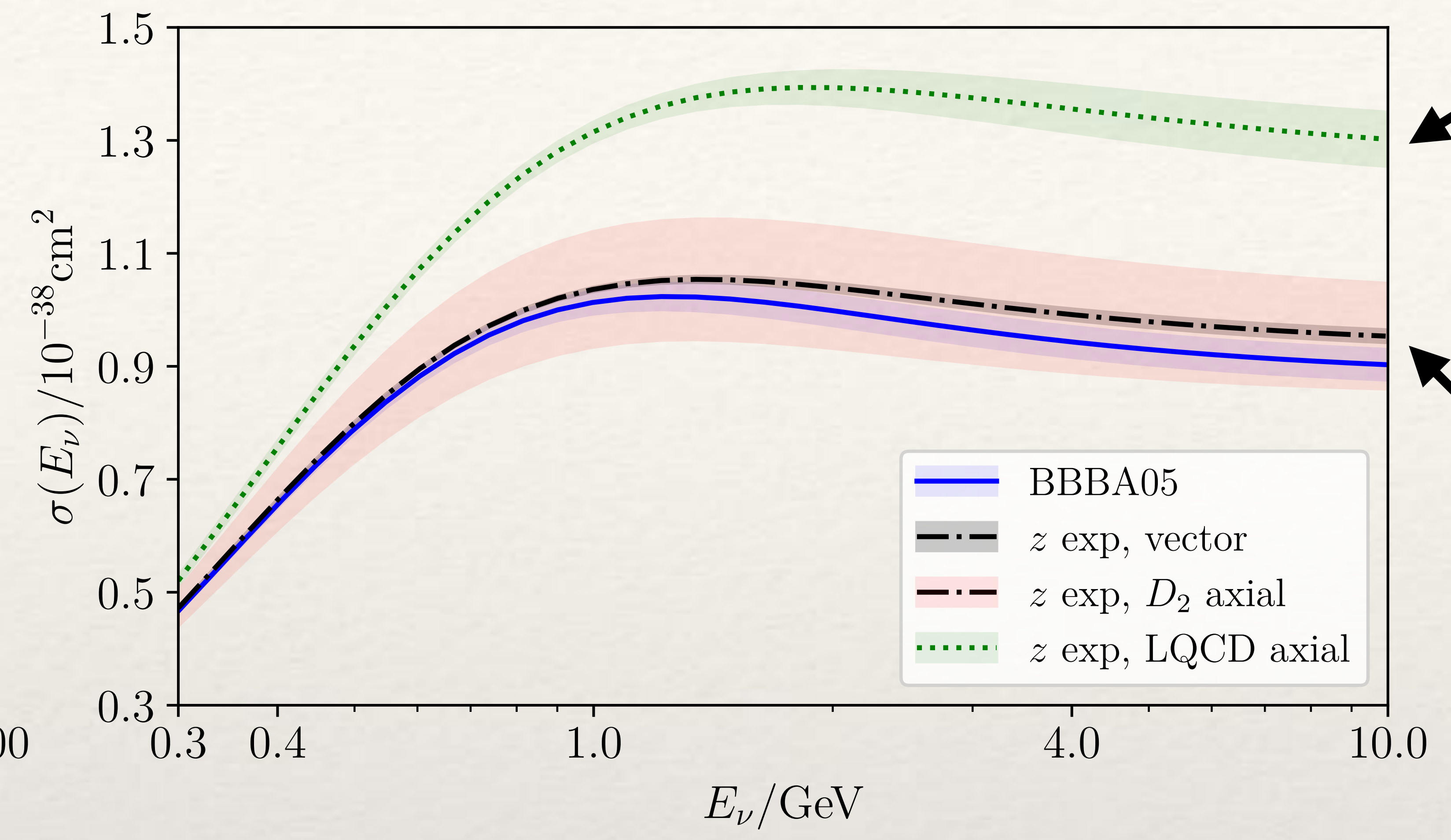


- NTNP objectives: First-principles calculations of inclusive and exclusive cross sections
  - Lattice QCD input on single-nucleon form factors (elastic and not)
  - EFT-based nuclear interactions and currents: retain key many-body correlations
  - Validation: use multiple many-body methods for A=4,12,16,40 & JLAB data on electron scattering

ν-N cross section

Meyer, Walker-Loud, Wilkinson
Ann. Rev. Nucl. Part. Sci. 72 (2022)





This discrepancy impacts the ability to interpret neutrino oscillation parameters

Some of this uncertainty comes from nucleon electromagnetic form factors

- Lattice QCD determination of $F_A(Q^2)$ is inconsistent with older phenomenological extraction

- results in 30% increase in ν-N cross section

ν-N cross section

Meyer, Walker-Loud, Wilkinson
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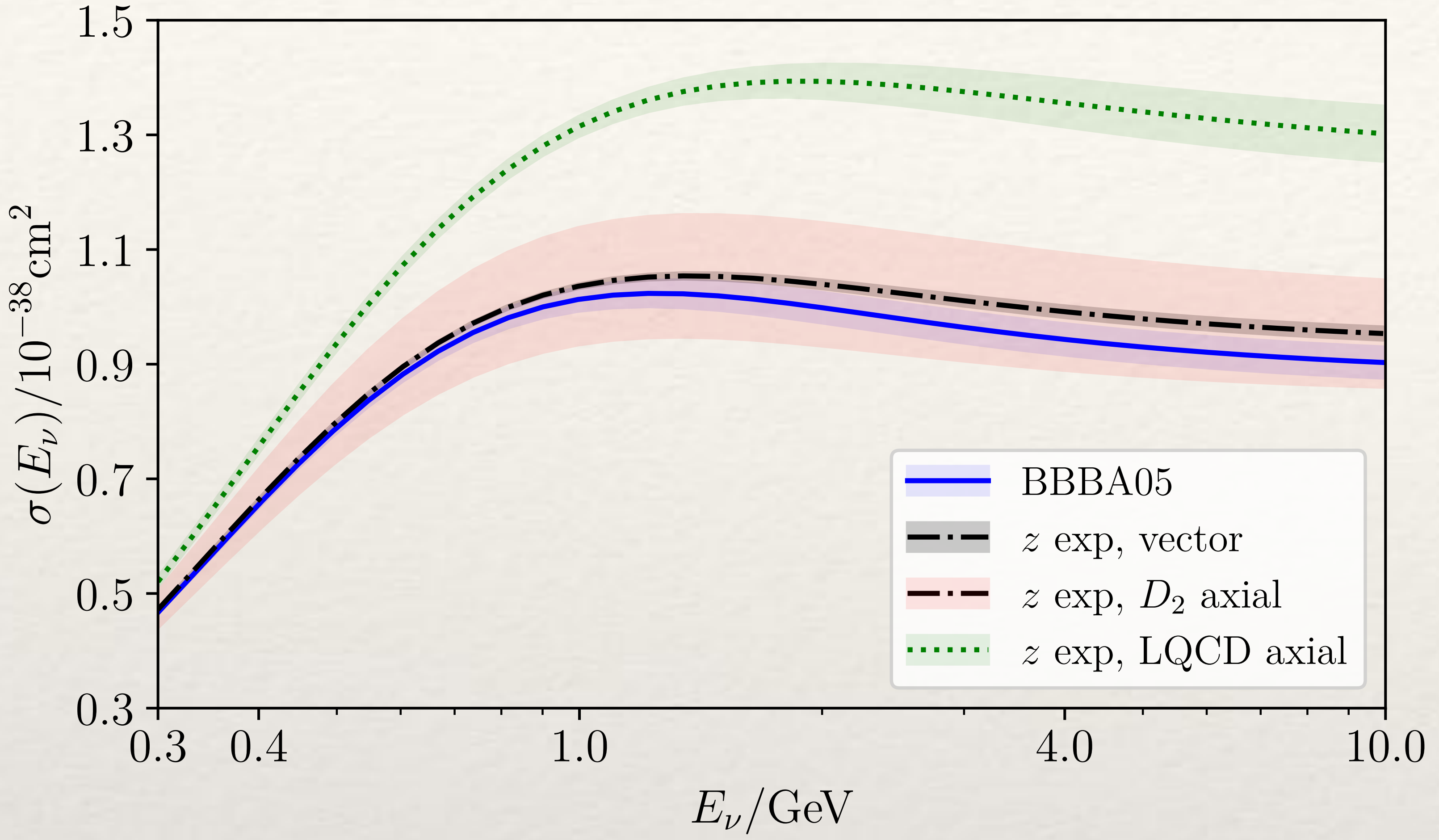
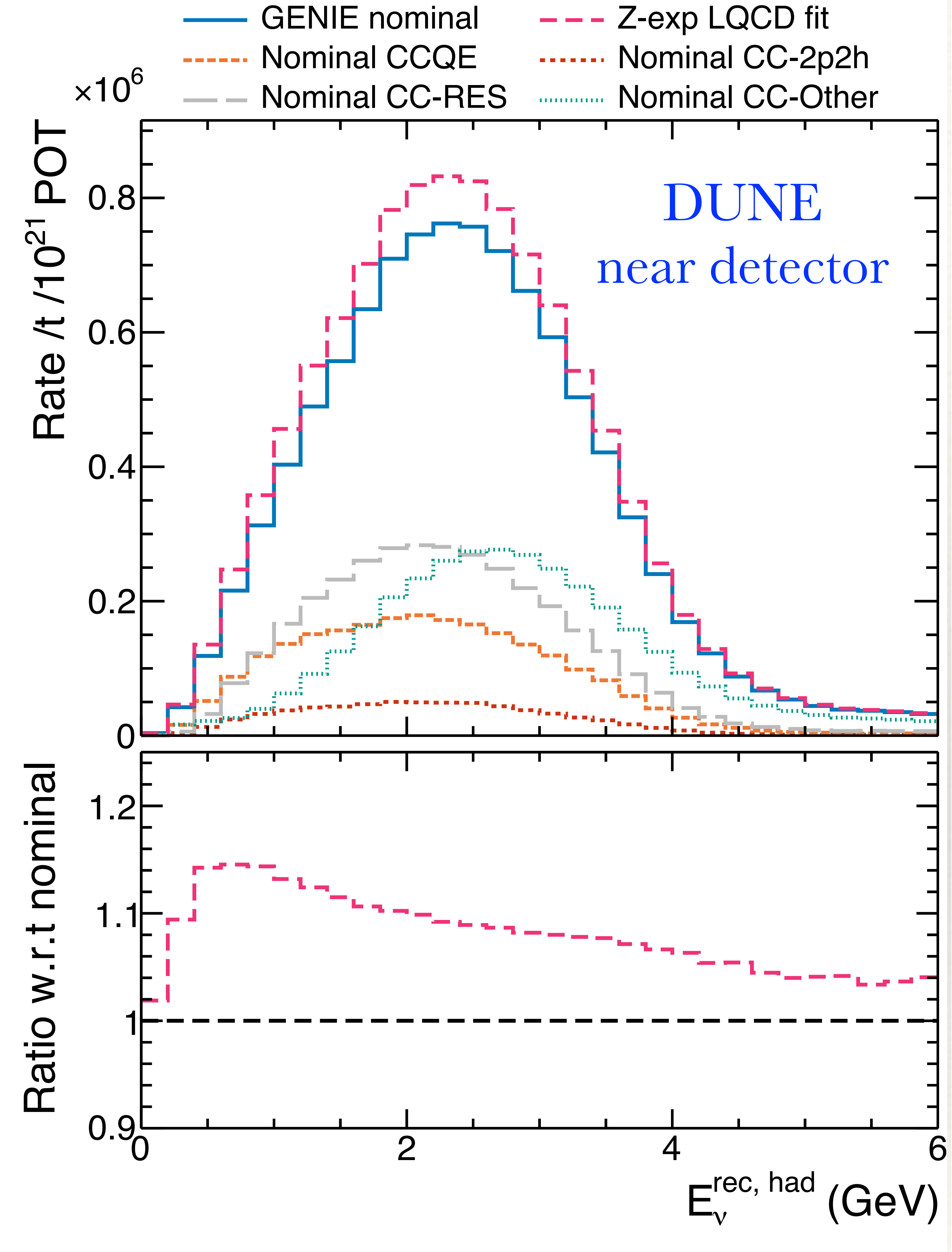
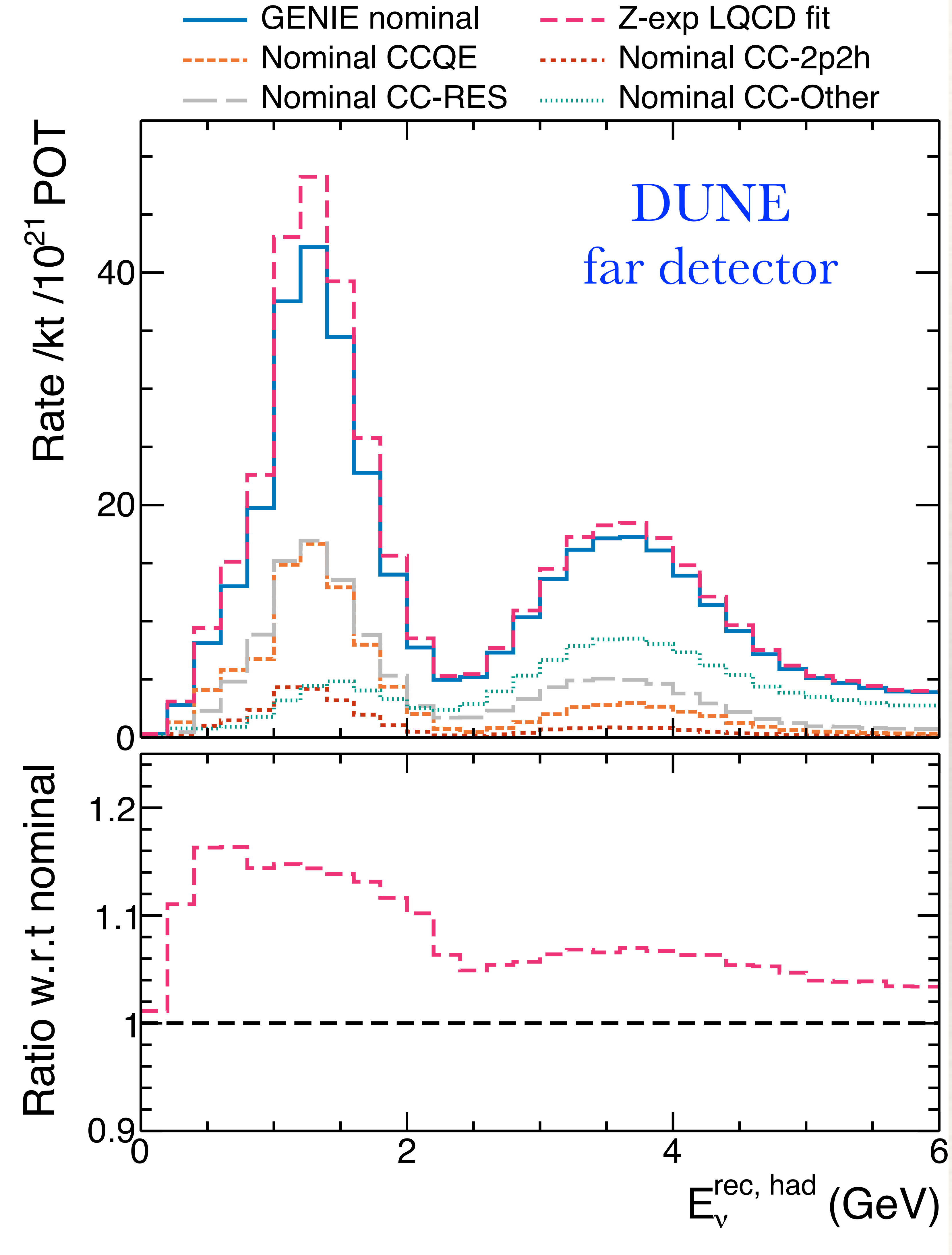






- Lattice QCD determination of $F_A(Q^2)$ is inconsistent with older phenomenological extraction
- results in 30% increase in ν-N cross section
- Energy dependent change

ν-N cross section

- Need to solidify lattice QCD result
    - one final systematic that must be verified with more sophisticated calculational strategy
      1-2 years

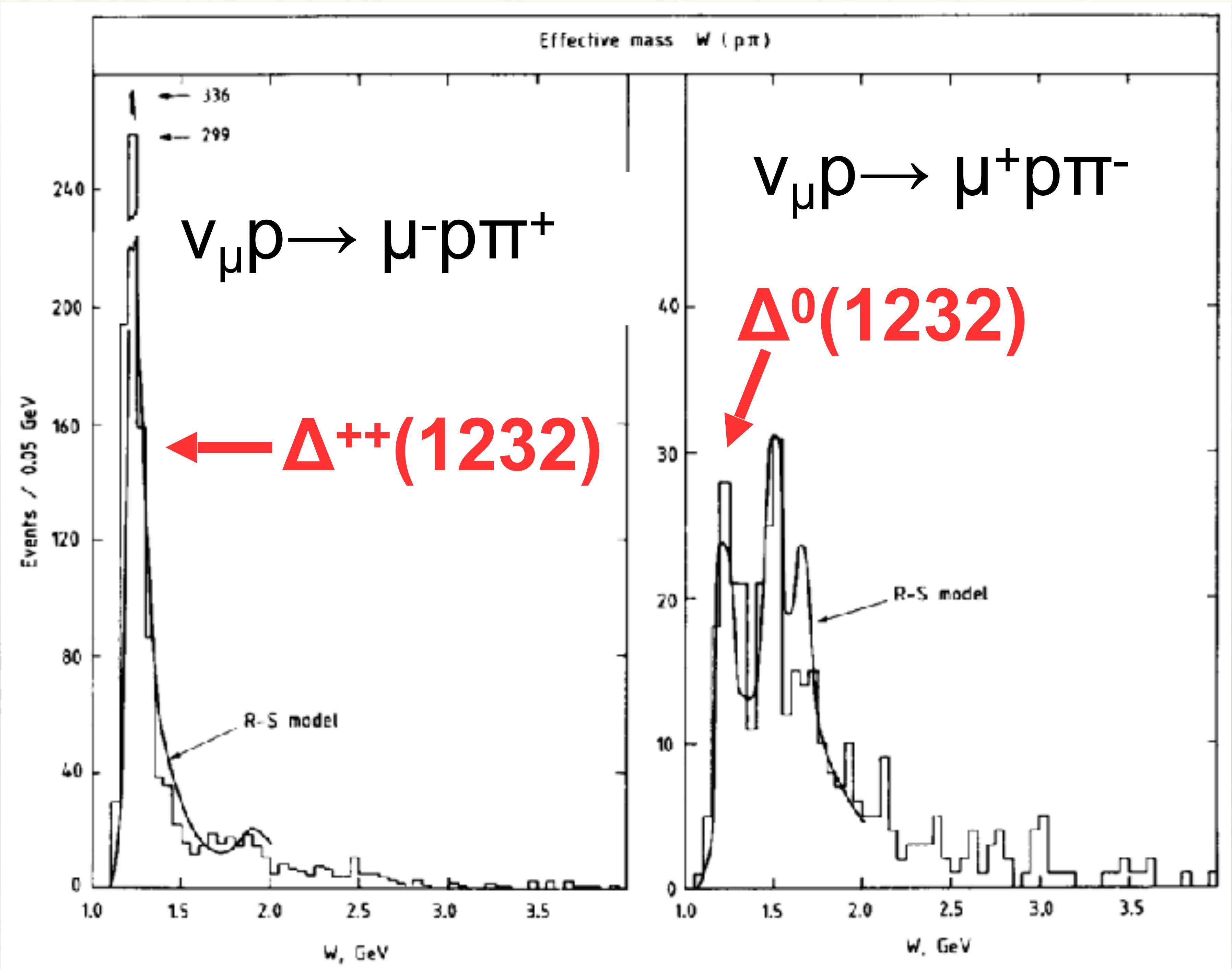
- Need to incorporate modern lattice QCD information into event generators
    - Significant potential for synergy with $e - A$ scattering program @ JLab

- Need to compute resonant inelastic structure, $N \rightarrow \Delta$ and $N \rightarrow N\pi, N \rightarrow N\pi\pi, \ldots$
  starting now - this is a 5+ year effort
    - Results from these more complex processes need to be incorporated into the nuclear many-body calculations
      a major goal of NTNP is to build the pipeline of lattice QCD results to nuclear many-body calculations

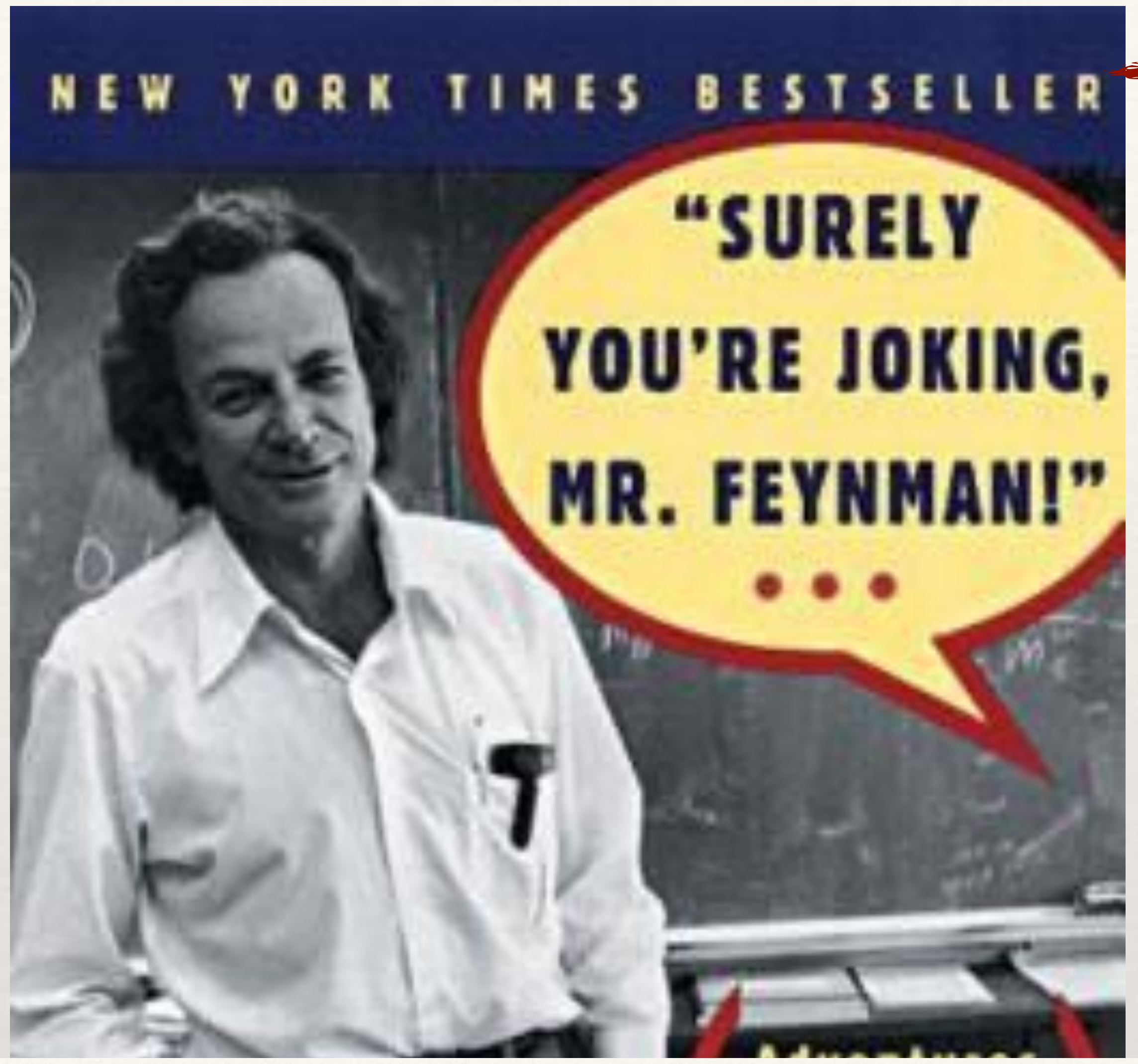
Future directions

2. State of the Field

Nucl. Phys. B264 221 (1986)



$$W^2 = (\Sigma E)^2 - |\Sigma \mathbf{p}|^2$$



Indeed not!

Our pion production model uses a description of resonance production that is "naive and obviously wrong in its simplicity" [F.K.R. PRD3 (1971)]

I trust some bright motivated physicists will fix this soon

- Current models are unsatisfactory:
  - Simplistic description of neutrino-nucleon interaction
  - Unsophisticated description of the nucleus
- Heavy reliance on old data (experiments shut down)
- ~10% uncertainties on effective parameters at best

ν-N cross section

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  - This will also require quantitatively mapping out convergence pattern of baryon chiral perturbation theory
    In order to fully quantify the theory uncertainty, we must start with convergence of single nucleon

Many more research endeavors NTNP is working on…
with many potential connections to JLab Physics Program

Thank You