Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Theoretical particle & astrophysics

Stephen Parke

Fermilab Institutional Review

11 February 2015

Our Vision

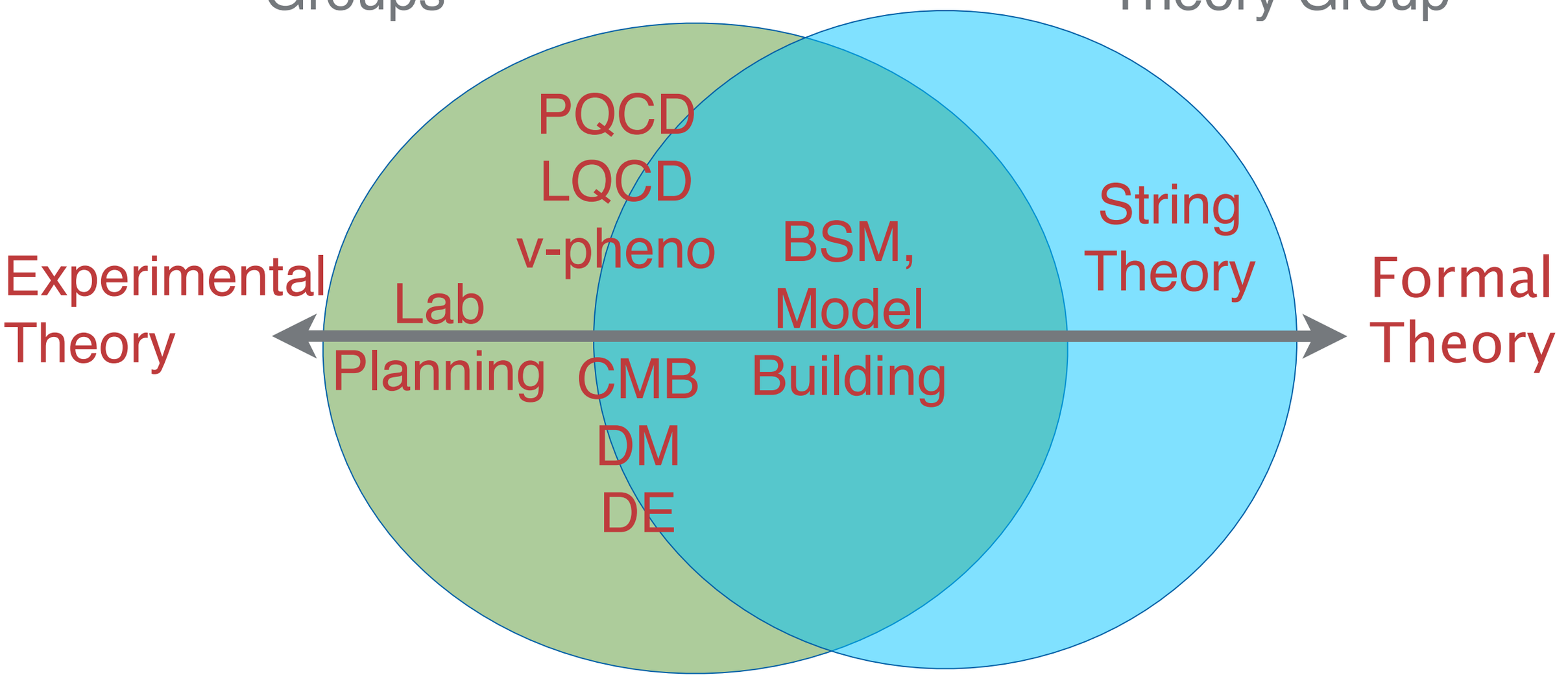
- Conduct world-class theoretical particle-physics and astrophysics research.
- Focus effort and core strength in key research areas directly related to U.S. and worldwide experimental programs.
- Influence and motivate the design of experiments, data analyses, and their interpretation.
- Train next generation of theorists in data-rich environment and educate young experimentalists.
- Provide a national resource for university physicists.
- Foster an intellectually vibrant atmosphere.

Overlapping, complementary and synergistic with
Laboratory experimental program &
University theory research program

Where are we?

Fermilab Theory Groups

Typical University Theory Group



Theoretical Physics Department: Members

Associate Scientist:

Ruth Van de Water (9/12) (LQCD)

Scientists I–III:

John Campbell (pQCD/Collider Physics)

Marcela Carena (BSM)

Estia Eichten (muon collider)

Keith Ellis (pQCD/Collider Physics)

Paddy Fox (BSM)

Walter Giele (pQCD/Collider)

Roni Harnik (BSM)

Christopher Hill (scale symmetry; axions)

Andreas Kronfeld (LQCD)

Joe Lykken (7/2014 became Deputy Director)

Paul Mackenzie (LQCD)

Bogdan Dobrescu (BSM)

Stephen Parke (Neutrinos, Top Quark)

Chris Quigg (SM, Quarkonium)

Jim Simone (1/2 FTE – LQCD)

Retired Scientists:

Bill Bardeen (2010) — Emeritus

Boris Kayser (2013) — Emeritus guest

http://theory.fnal.gov

Theoretical Physics Department: Research Associates

FY15 (8+1):

Prateek Agrawal (→Harvard) (BSM)

Pilar Coloma (Neutrinos)

Claudia Frugiuele (→Weizmann) (BSM)

Elisabetta Furlan (pQCD)

Jack Kearny (BSM)

Daniel Mohler (→Mainz) (LQCD/pheno)

Raoul Rontsch (→Karlsruhe) (pQCD)

Ran Zhou (LQCD)

Katrin Gemmler* (pheno)

New FY16 (→9)

Kiel Howe (BSM)

Seyda Ipek (BSM)

Ye Li (pQCD)

Zhen Liu (BSM)

Aarti Veenala (LQCD)

Our Post Docs work closely with faculty members as well as frequently write papers without senior collaborators → path to independent researchers!

* funded by German Fellowship

http://theory.fnal.gov/people/ellis/alumni.html

Theoretical Astrophysics Group

Scientists I–III: 5

Scott Dodelson (DE, DM, EU, CC, ν's)

Joshua Frieman* (DE, EU)

Nick Gnedin (DE, CC)

Daniel Hooper (DM, ν's)

Albert Stebbins (DE, EU)

Research Associates: 2 FY15→3 FY16

Ilias Cholis (DM) (→John Hopkins)

Elise Jennings (DE)

Gordon Krnjaic (DM) (new Schramm Fellow in Fall)

Irshad Mohammed (DE) (new in Fall)

*Director of the Dark Energy Survey

Research Associate mentoring success rate:

56 alumni: 46 faculty level, 3 postdoc, 1 science writer

http://www-astro-theory.fnal.gov

DE: dark energy DM: dark matter EU: early universe ν's: neutrinos in astrophysics CC: cosmological computing

Honors and awards

APS Fellows: 12 Particle / 4 Astro AAAS Fellows: 6 / 1

American Academy of Arts and Sciences: Bardeen

Honorary Fellow Royal Astronomical Society: Frieman

Institute of Astrophysics of Paris Medal: 2014 Stebbins

J.J. Sakurai Prize: 2011 Eichten & Quigg
2009 Ellis
1996 Bardeen

National Academy of Science: Bardeen

Royal Society of London: Ellis

Alexander Von Humboldt Foundation Senior Scientist: 2011–2015 Carena
2007–2011 Quigg

Hans Fischer Senior Fellowship at TUM-IAS: 2014–2017 Kronfeld

Simons Distinguished Scholar (KITP, UCSB): 2013 Carena

Neutrino & muon programs:
Synergistic activities

Laboratory activities

- Fermilab theorists devote significant energy to help formulate and evaluate possible future programs for Fermilab
  - Rotating permanent slot on Fermilab PAC Eichten (current), Parke, Kayser, ...
  - Parke & Kayser contributed to numerous studies for both Short- and Long-Baseline Neutrino programs
- Theoretical Physics Department hosts weekly Joint Experimental-Theoretical Physics ("Wine & Cheese") Seminar
- Harnik & Quigg organized academic lecture series "The Allure of UltraSensitive Experiments."
  - Pedagogical lectures included 4 talks on g-2, 4 on LFV, 13 on neutrinos, ...
  - Fermilab theorists Agrawal (RA), Altsmanshoffer (former RA), Dodelson, Fox, Harnik, Kayser, Kronfeld, Parke, Stebbins, gave talks.
- Kronfeld & Quigg proposed Project X Physics Study which culminated in the physics part of the Project X Physics Book (Kronfeld co-editor).
  - Lays broad experimental program that could be mounted with a new intense proton source at Fermilab, including Mu2e, g-2, EDMs, ELBNF, ...
- Eichten studied physics and detector issues of a possible Muon Collider
  - Active in Muon Accelerator Project (MAP) and Muon Accelerator Staging Study (MASS) group.

Community leadership

- Fermilab theorists authors on 18 Snowmass reports. In particular:
  - Harnik gave several talks on charged-lepton physics.
  - Kayser co-convener Neutrino WG on Anomalies and New Physics
  - Van de Water spoke on lattice-QCD status and prospects for g-2.
  - Van de Water co-convener of Lattice Field Theory/Computing Frontier WG, and co-convener of Lattice QCD task force of the Quark Flavor/Intensity Frontier WG
- Fermilab theorists serve on numerous domestic and international scientific councils and advisory boards. In particular:
  - Parke chair of the International Neutrino Commission and custodian of the International Conference on Neutrino Physics and Astrophysics
  - Kayser on Program Advisory Committee of Sanford Underground Research Facility
- Fermilab theorists organized numerous conferences and workshops related to neutrino and muon physics including:
  - Kronfeld, Mackenzie (chair), & Van de Water co-organized the 2014 "Lattice Meets Experiment" workshop. Topics included g-2, Mu2E, and neutrinos.
  - Fox & Harnik (with Batell) organized "New approaches in the Search for Dark Matter." Topics included searches for light DM and light mediators with neutrino beams.
  - Eichten co-chaired 2011 Muon Collider workshop. Hill organized and co-convened physics and detector WGs.

Neutrino program: scientific research

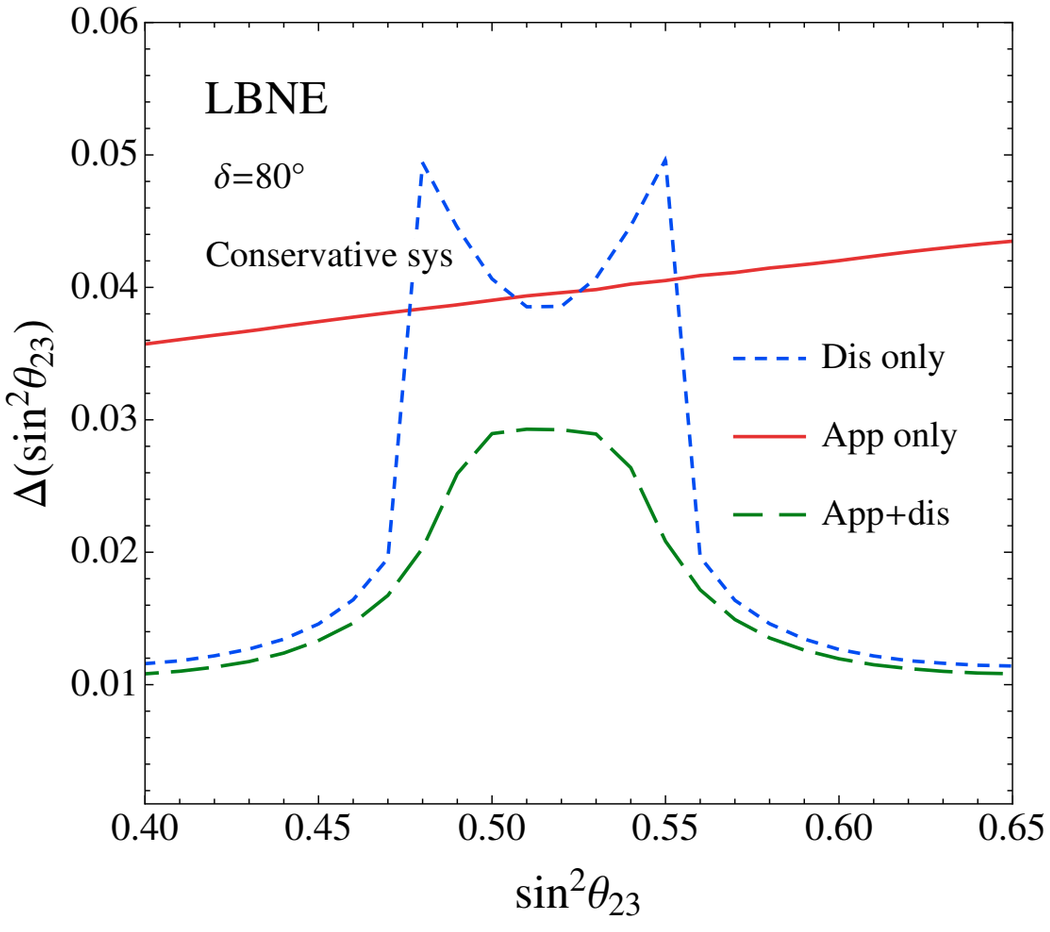
Neutrino Phenomenology: Research summary

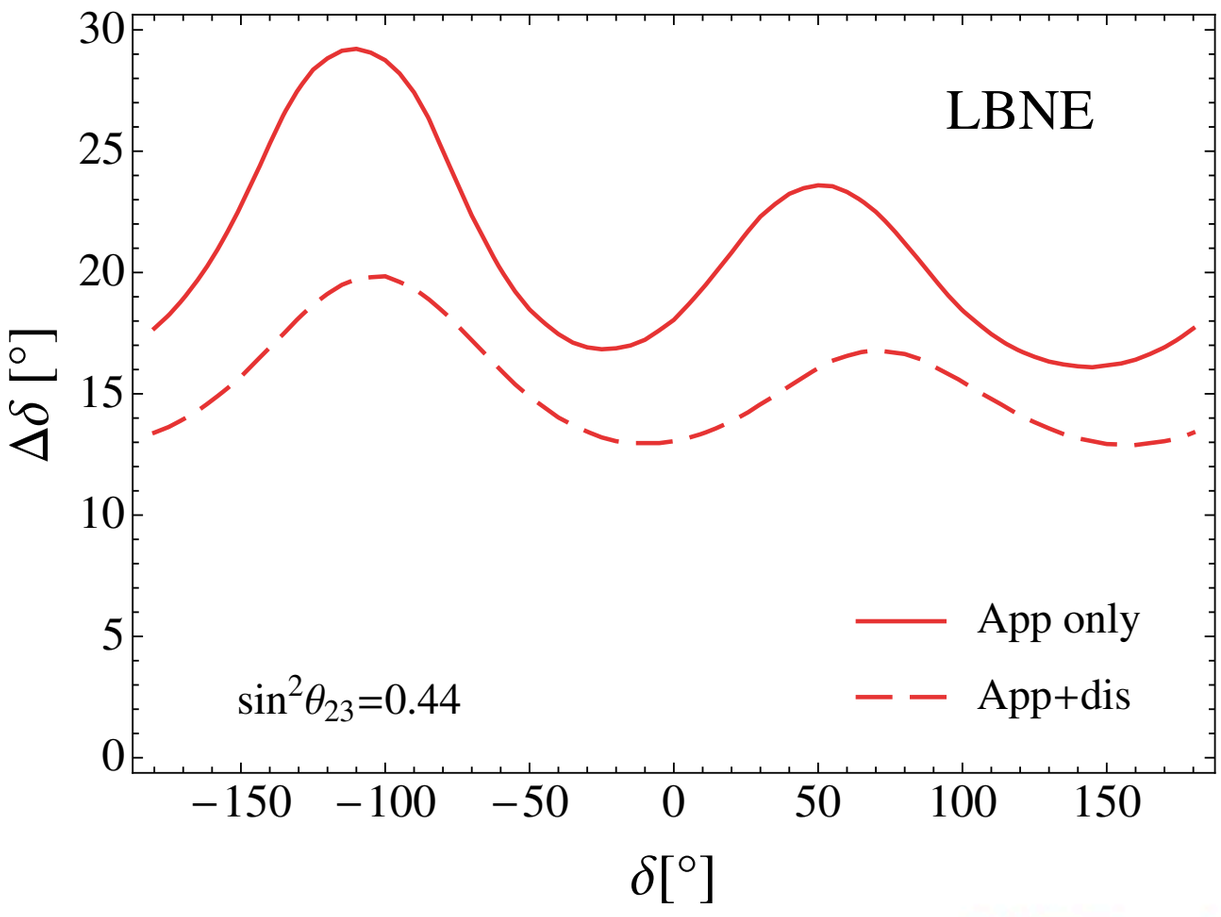
- Develop strategies for precision studies of the Standard 3-neutrino paradigm
- Assess the stated sensitivities of present and proposed experiments
- Study the impact of light sterile neutrinos, should they exist, on long-baseline oscillation experiments
- Suggest new kinds of experiments to probe the existence and explore the physics of light sterile neutrinos
- Explore the possible existence and impact of non-Standard-Model neutrino interactions of a kind not considered before
- Help develop proposals for future experiments
- Participate in experimental collaborations
- Consider the possible connection of CP violation in neutrino oscillation to the matter-antimatter asymmetry of the universe
- Confront the subtle quantum mechanics underlying neutrino oscillation
- Determine nuclear effects on the measurement of neutrino oscillation parameters

Long-baseline neutrino papers

- Long Baseline Neutrino Program: MINOS, MINO+, NOvA & ELBNF
  - Many papers over last 15 years
- Determination of θ_{23} using appearance and disappearance channels and the impact of θ_{23} on determination of CP-violating parameter δ [Coloma, Minakata, Parke]

[1406.2551]





Long-baseline neutrino studies

- Many long-baseline studies over the years
  - E.g. LBNE reconfiguration circa 2012 (pre-P5)

Physics Working Group Report to the LBNE Reconfiguration Steering Committee

J. Appel[1], M. Bass[2], M. Bishai[3], S. Brice[1], E. Blucher[4], D. Cherdack[2], M. Diwan[3], B. Fleming[5], G. Gilchriese[6], Z. Isvan[3], B. Lundberg[1], W. Marciano[3], M. Messier[7], S. Parke[1], J. Reichanadter[8], G. Rameika[1], K. Scholberg[9], M. Shochet[4], J. Thomas[10], R. Wilson[2], E. Worcester[3], C. Young[8], G. Zeller[1],

(Dated: August 6, 2012)

This document summarizes the physics capabilities of a long-baseline neutrino experiment employing a liquid argon detector and fed by an intense neutrino beam from Fermilab. The locations considered for the detector are at the Homestake mine in South Dakota, the Soudan mine in Minnesota, and the Ash River, Minnesota site of the NOvA detector. The experimental reach as a function of detector mass is given for the neutrino mass hierarchy and CP violation phase as well as for proton decay, atmospheric neutrino studies, and neutrinos from supernova explosions.

This is the “10 ktons on surface at Homestake” study!

Short-baseline neutrino studies

- Short Baseline Neutrino Program: MiniBooNE, MicroBooNE, LAr X, (NuSTORM)
  - Parke and Kayser involved in many studies over the years

FERMILAB-FN-0947
June 7, 2012

SHORT-BASELINE NEUTRINO FOCUS GROUP

REPORT

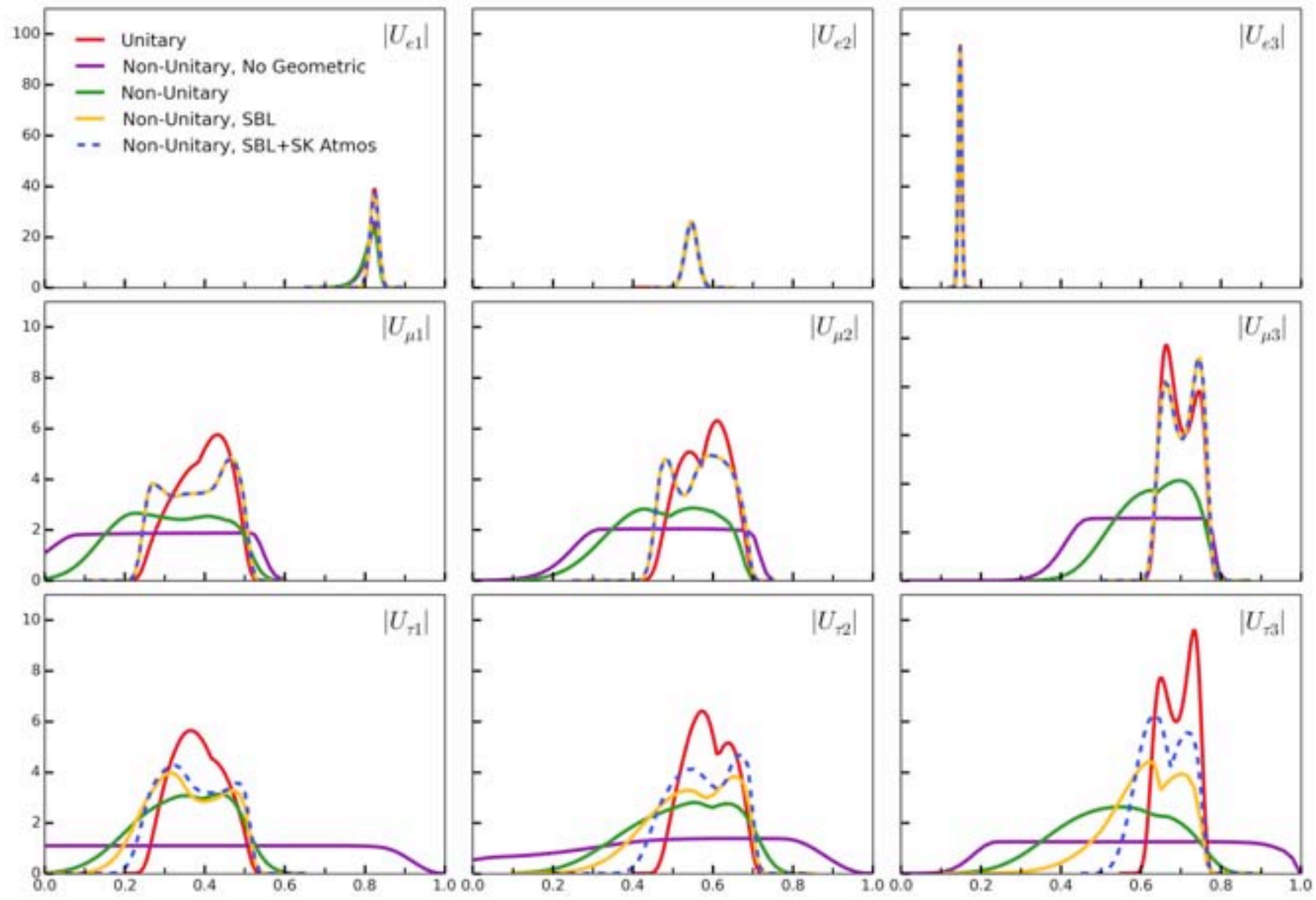
S. J. Brice (FNAL), B. Fleming (Yale), S. Geer (FNAL), A. de Gouvea (NW), D. Harris (FNAL), P. Huber (Virginia Tech), B. Kayser (FNAL), G. Mills (LANL), K. Nishikawa (KEK), S. Parke (FNAL), C. Polly (FNAL), A. Rubbia (Zurich), R. Tschirhart (FNAL), R. Van de Water (LANL), G. Zeller (FNAL), R. Zwaska (FNAL)

Light sterile neutrino sensitivity at the nuSTORM facility

D. Adey,[1] S.K. Agarwalla,[2] C.M. Ankenbrandt,[3,*] R. Asfandiyarov,[4] J.J. Back,[5] G. Barker,[5] E. Baussan,[6] R. Bayes,[7,†] S. Bhadra,[8] V. Blackmore,[9] A. Blondel,[4] S.A. Bogacz,[10] C. Booth,[11] S.B. Boyd,[5] S.G. Bramsiepe,[7] A. Bravar,[4] S.J. Brice,[1] A.D. Bross,[1] F. Cadoux,[4] H. Cease,[1] A. Cervera,[12] J. Cobb,[9] D. Colling,[13] P. Coloma,[14] L. Coney,[15] A. Dobbs,[13] J. Dobson,[13] A. Donini,[12] P. Dornan,[13] M. Dracos,[6] F. Dufour,[4] R. Edgecock,[16] M. Geelhoed,[1] M.A. Uchida,[13] T. Ghosh,[12] J.J. Gómez-Cadenas,[12] A. de Gouvêa,[17] A. Haesler,[4] G. Hanson,[15] P.F. Harrison,[5] M. Hartz,[8,‡] P. Hernández,[12] J.A. Hernando Morata,[18] P. Hodgson,[11] P. Huber,[14] A. Izmaylov,[12] Y. Karadzhov,[4] T. Kobilarcik,[1] J. Kopp,[19] L. Kormos,[20] A. Korzenev,[4] Y. Kuno,[21] A. Kurup,[13] P. Kyberd,[22] J.B. Lagrange,[23] A. Laing,[12] A. Liu,[1] J.M. Link,[14] K. Long,[13] K. Mahn,[24] C. Mariani,[14] C. Martin,[4] J. Martin,[25] N. McCauley,[26] K.T. McDonald,[27] O. Mena,[12] S.R. Mishra,[28] N. Mokhov,[1] J. Morfín,[1] Y. Mori,[23] W. Murray,[16] D. Neuffer,[1] R. Nichol,[29] E. Noah,[4] M.A. Palmer,[1] S. Parke,[1] S. Pascoli,[30] J. Pasternak,[13] R. Plunkett,[1] M. Popovic,[1] P. Ratoff,[20] M. Ravonel,[4] M. Rayner,[4] S. Ricciardi,[16] C. Rogers,[16] P. Rubinov,[1] E. Santos,[13] A. Sato,[21] T. Sen,[1] E. Scantamburlo,[4] J.K. Sedgbeer,[13] D.R. Smith,[22] P.J. Smith,[11] J.T. Sobczyk,[31] L. Søby,[32] F.J.P. Soler,[7] M. Sorel,[12] P. Snopok,[33,§] P. Stamoulis,[12] L. Stanco,[34] S. Striganov,[1] H.A. Tanaka,[35] I.J. Taylor,[5] C. Touramanis,[26] C. D. Tunnell,[9,¶] Y. Uchida,[13] N. Vassilopoulos,[6] M.O. Wascko,[13] A. Weber,[9] M.J. Wilking,[24] E. Wildner,[32] and W. Winter[36]
(The nuSTORM Collaboration)

Global PMNS Fits without Unitarity [Parke, Ross-Lonergan]

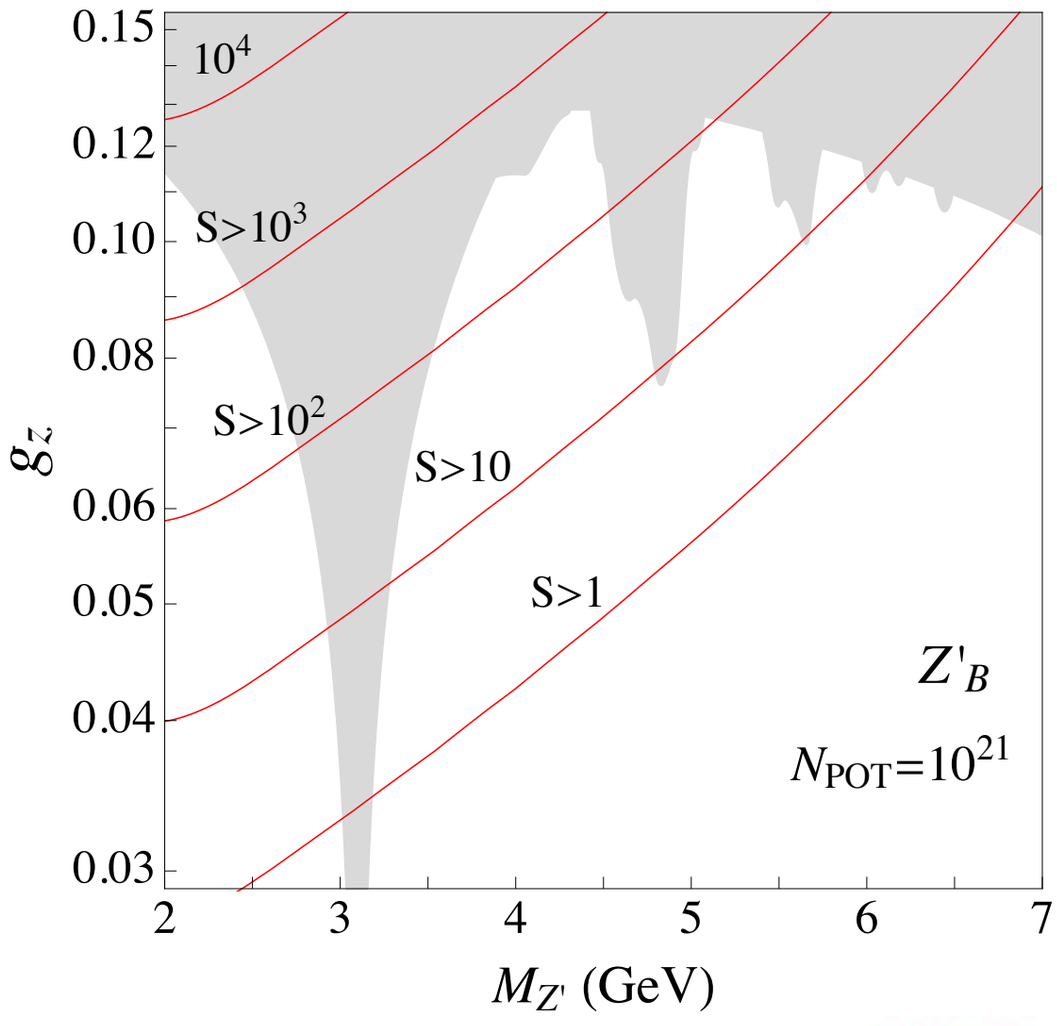
- What do we really know about the PMNS matrix? (in preparation)
  - with Mark Ross-Lonergan (graduate student, Durham U. via Invisibles Network)



Dark matter in neutrino experiments

- Fermilab ν-beams are also intense fixed target facilities.
  - Can take part in the search for dark sectors.
- April 2014: Fermilab Theory hosted a workshop on search for DM at low energy beams and other novel DM searches.

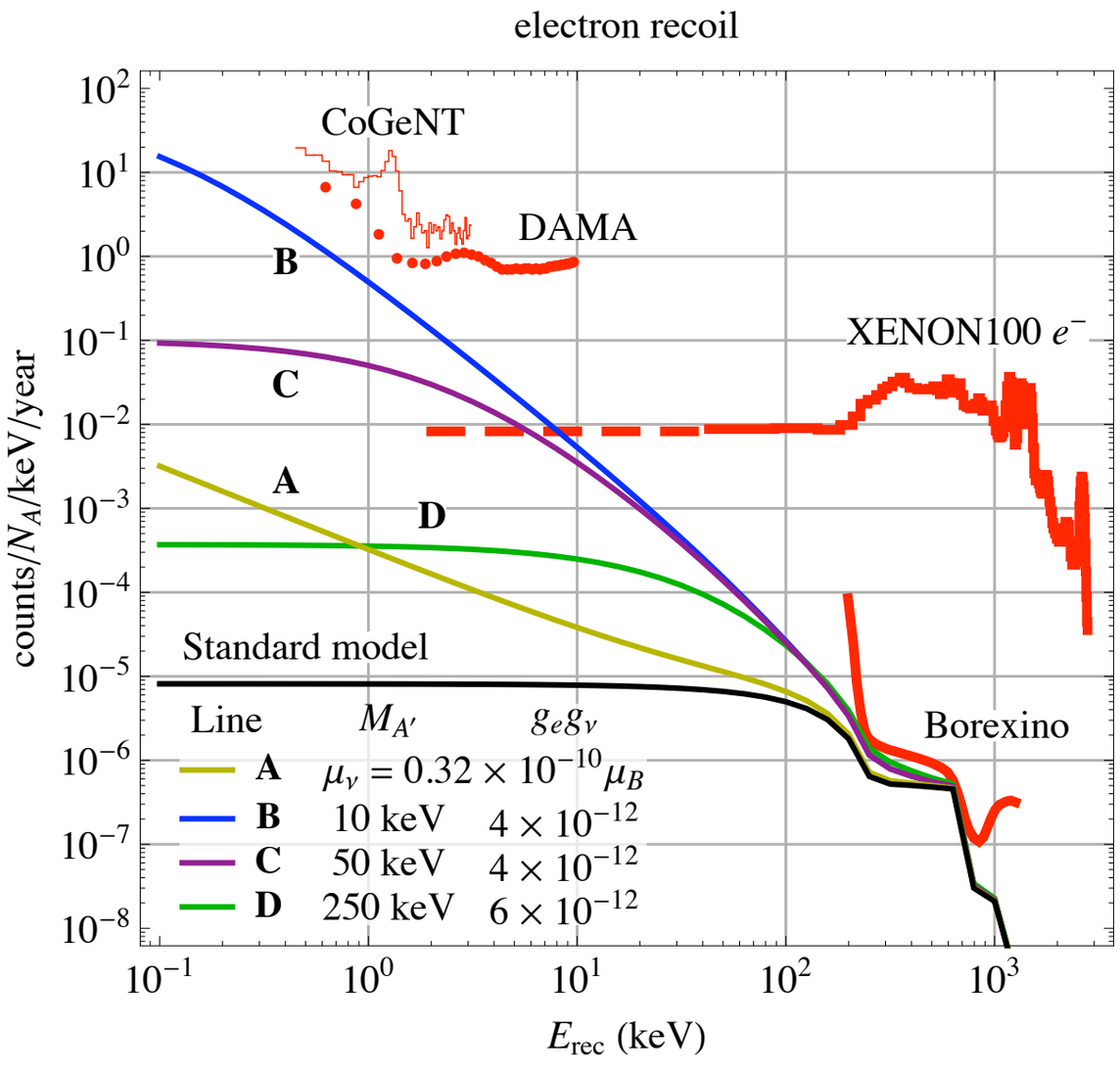
Dobrescu & Frugiuele (2014):
NOvA can search for GeV DM.



Neutrinos on dark-matter experiments

- DM Experiments are within striking distance of "Solar Neutrino floor".
- New Physics in the neutrino sector can raise this floor. ν's can fake DM.
- Can discover light gauge bosons, sterile ν's, or ν dipole moments.
- CONNIE (Coherent Neutrino-Nucleus Interaction) reactor experiment (J. Estrada, Fermilab LDRD) will probe this model space

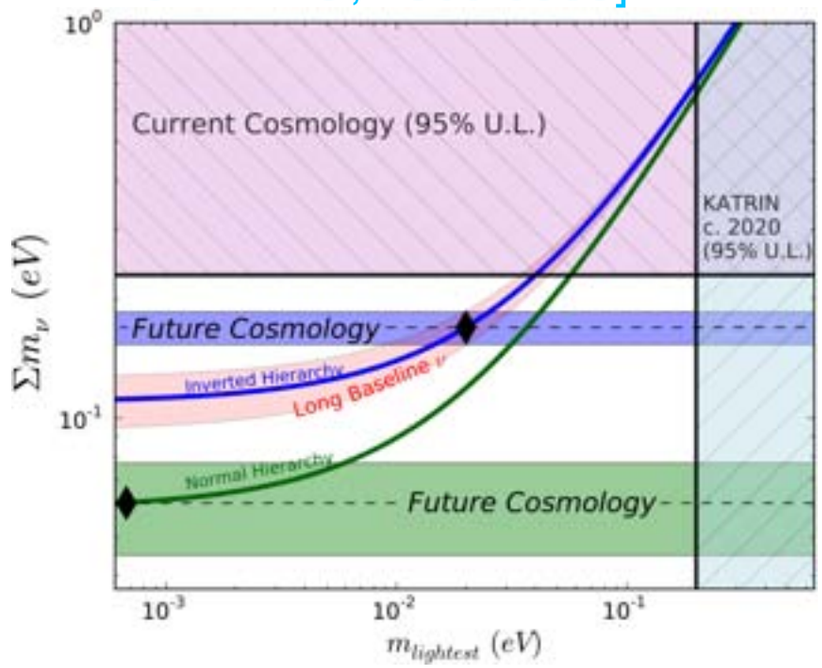
Harnik, Kopp (RA),
Machado (Latin American student – 2011)

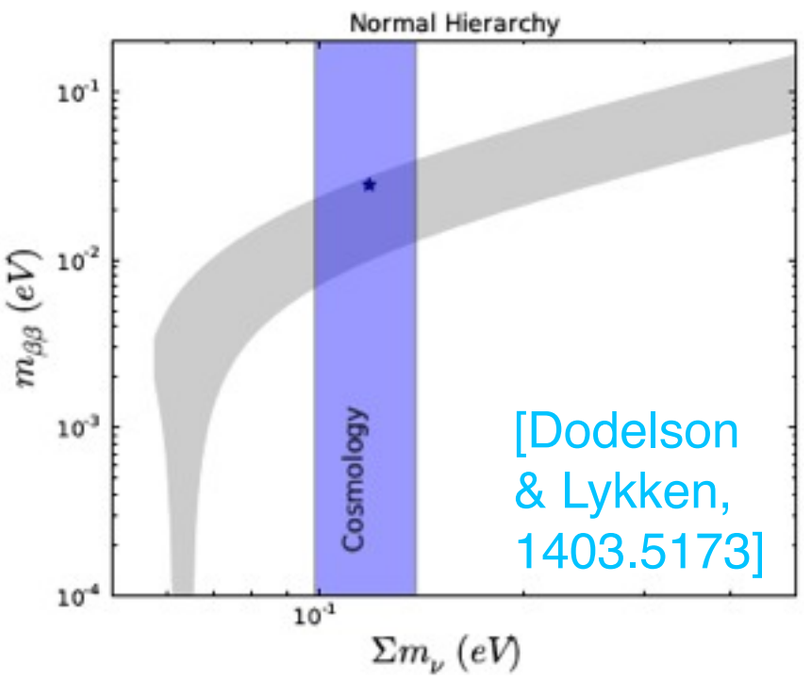


Neutrinos constraints from the cosmos [Stebbins; Dodelson, Lykken]

- Large-scale structure simultaneously constrains sum of neutrino masses.
- Neutron star coalescence may explain fast radio bursts, associated 10-50 MeV ν's could constrain neutrino masses.
- Cosmological constraints inform ν-less ββ decay:
  - Could provide lower limit on rate
  - Could jointly constrain Majorana phase.

[Snowmass Dark Energy and CMB WG, 1309.5383]

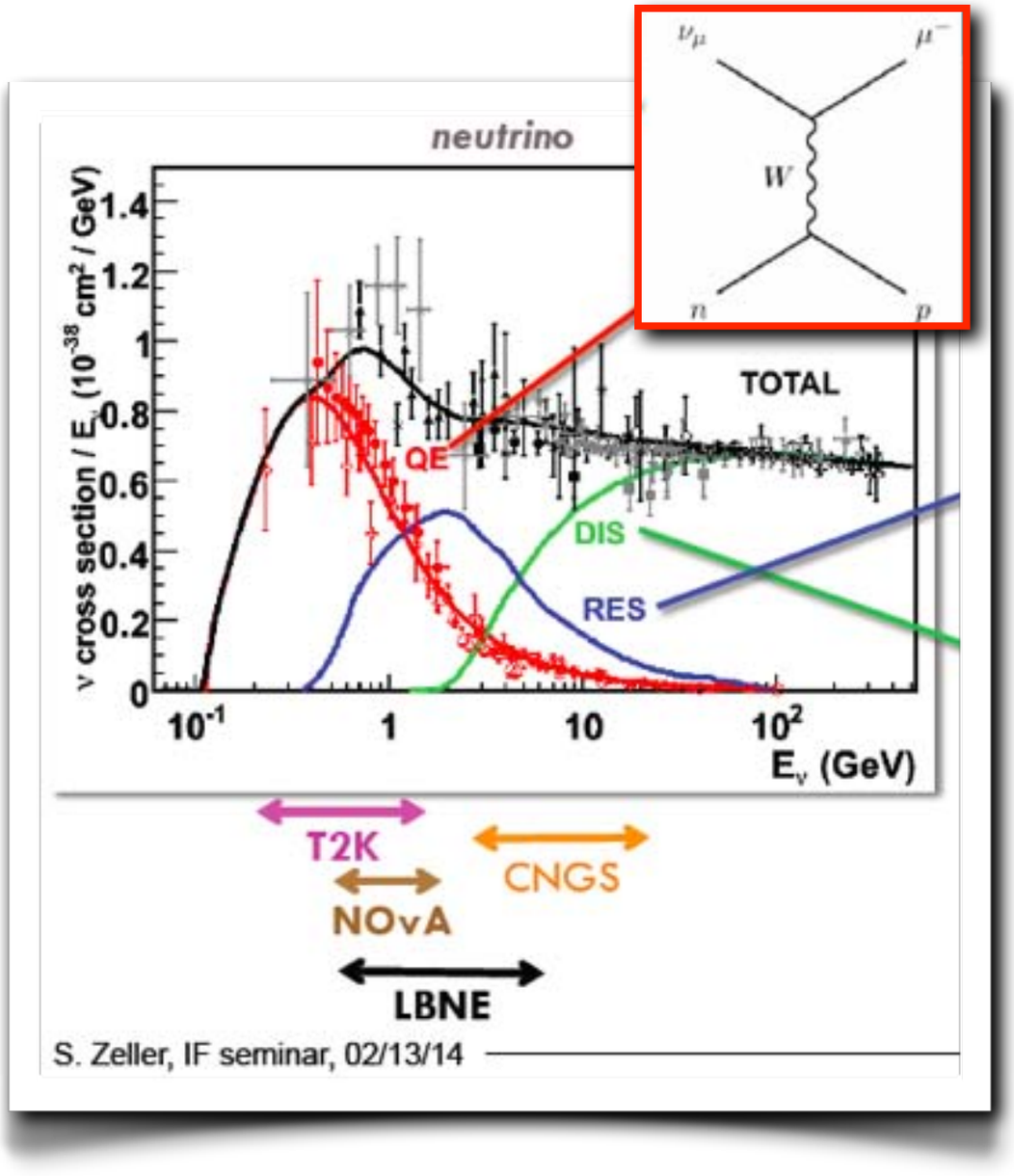




[Dodelson & Lykken, 1403.5173]

Nucleon axial-vector form factor from lattice QCD

- Nucleon axial-vector form factor important input into determination of CCQE X-section, which gives largest contribution to signal sample in many accelerator-based neutrino experiments (T2K, NOvA, ELBNF)
- Kronfeld co-supervising U. Chicago student Aaron Meyer★ on first-principles calculation of $F_A(q^2)$ merging analyticity constraints with lattice QCD
  - Completed work implementing z-parameterization & external QCD input into standard GENIE Monte Carlo
  - Beginning lattice calculation with physical-mass pions to avoid large chiral-extrapolation errors of other works
  - Engagement and interest from MINERvA, MicroBooNE, and other experiments



★ Received URA Visiting Scholars' Award for this research in 2015, and DOE Office of Science Graduate Student Research Award to complete it in 2015-2016.

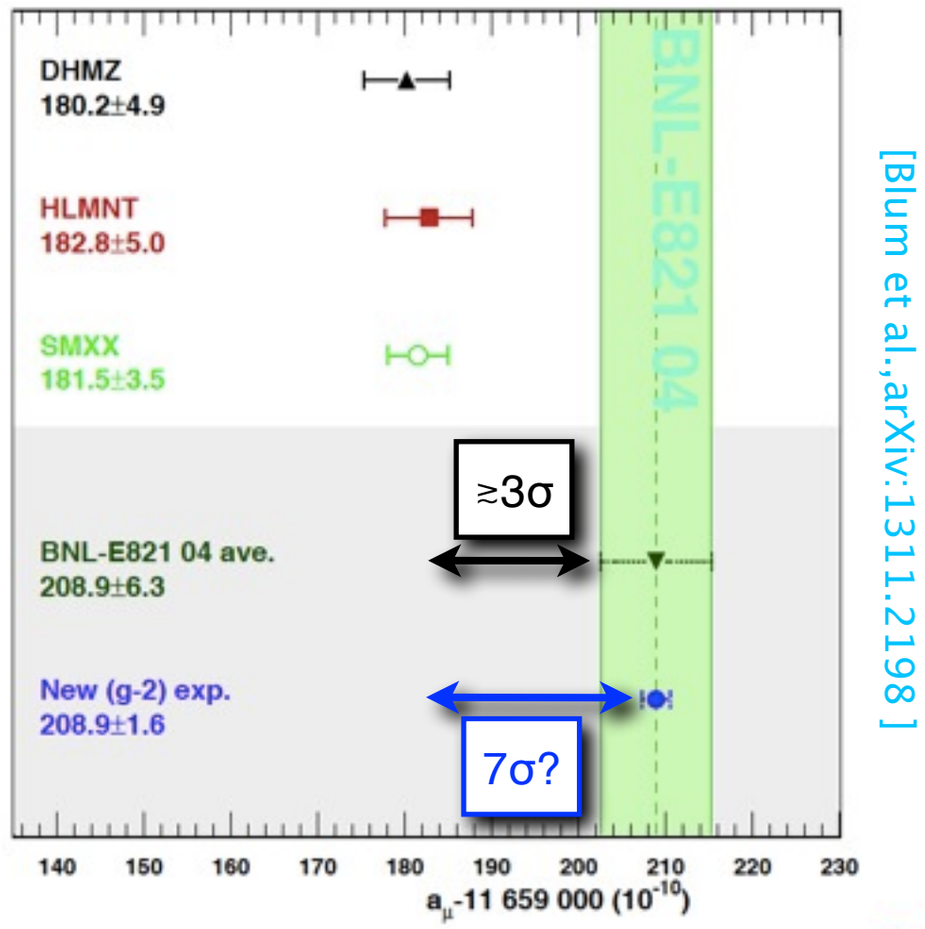
Neutrino theory visitors

- Andre de Gouvea (Northwestern) spends about one day a week at Fermilab
- Collaborators spend many person-weeks a year here, in particular:
  - Hisakazu Minakata (Sao Paulo)
  - Others include Hiroshi Nunokawa, Renata Zukanovich Funchal, ...
- Invisibles Network (Europe): Silvia Pascoli (Durham) spends between one and two months at the Lab and frequently brings students and RAs. Also member of Fermilab PAC.
- Providing partial support to nuclear theorists
  - Luis Alvarez-Ruso (Valencia) to interface between nuclear theory and Monte Carlos used in neutrino experiments
  - Joe Carlson (LANL) in Fall (will bring two RAs)
- Neutrino visitors complement expertise of group members.

Muon program: scientific research

Hadronic vacuum polarization contribution to $(g-2)_\mu$

- To leverage anticipated 4x reduction in experimental error from Muon g-2 Experiment, must reduce Standard-Model theory uncertainty on hadronic contributions to $\delta(a_\mu^{HVP})\sim 0.2\%$ and $\delta(a_\mu^{HLbL})\sim 15\%$
- Van de Water,★ Kronfeld, & Mackenzie (with HPQCD & MILC) now undertaking first complete four-flavor lattice-QCD calculation of a_μ^{HVP} using a new method that enables a significantly more precise determination than the traditional approach [Chakraborty et al. (HPQCD), 1403.1778]
  - Key new ingredients w.r.t. proof-of-principle calculation will be the light-quark & quark-disconnected contributions, both of which require gauge-field ensembles with very high statistics
  - Anticipate determining a_μ^{HVP} to 1% or better with existing 4-flavor ensembles
  - Direct inclusion of isospin-breaking and EM should bring errors to needed precision

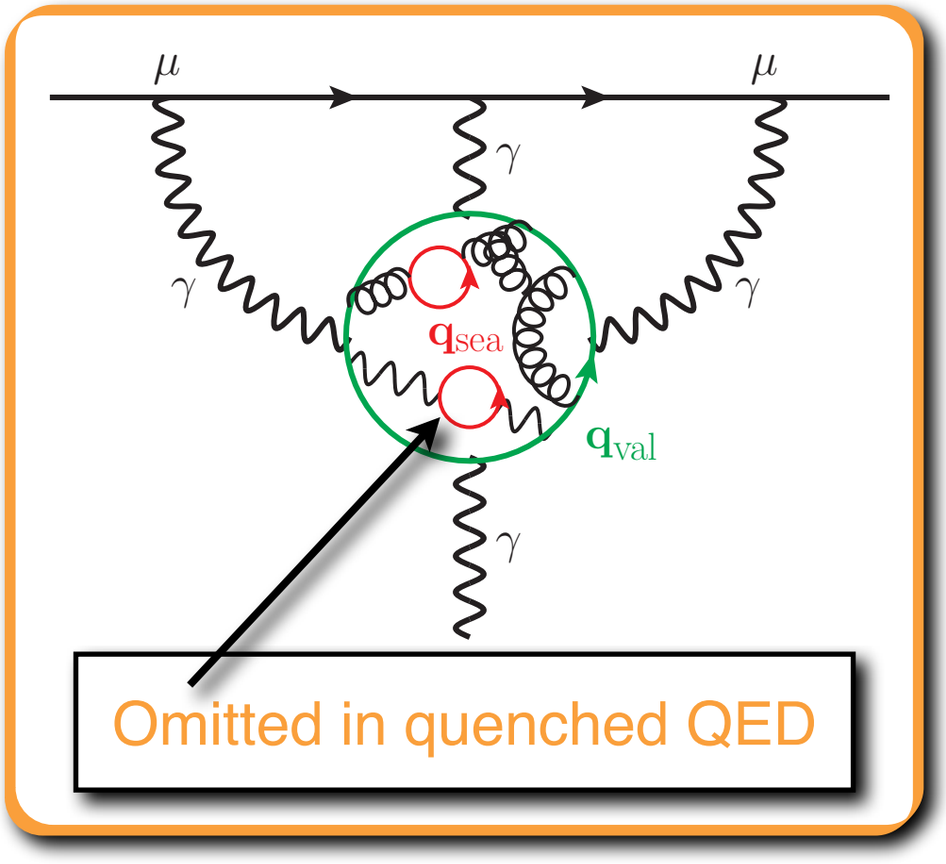


[Blum et al.,arXiv:1311.2198]

★ Submitted DOE Early Career Award to work on $(g-2)_\mu$

Hadronic light-by-light contribution to $(g-2)_\mu$

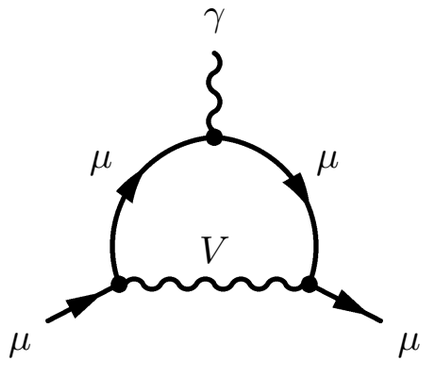
- a_μ^{HLbL} is highest theoretical priority for $(g-2)_\mu$ because error estimate obtained from models is subjective
- A lattice-QCD method for obtaining the light-by-light contribution has not yet been demonstrated, so Fermilab lattice theorists (with MILC colleagues) are studying several approaches
  - Includes promising new strategy we have devised to isolate the desired $O(\alpha^3_{EM})$ contribution without contamination from lower-order (and hence larger) diagrams
  - Will also use new QED+QCD gauge-field ensembles that include dynamical quarks, gluons, and photons to calculate the quark-disconnected contributions omitted from all previous efforts
- Investing significant human & computing resources
  - RA Zhou central to QCD+QED effort
  - Premature to make quantitative error projections, but will sustain effort until needed precision is obtained

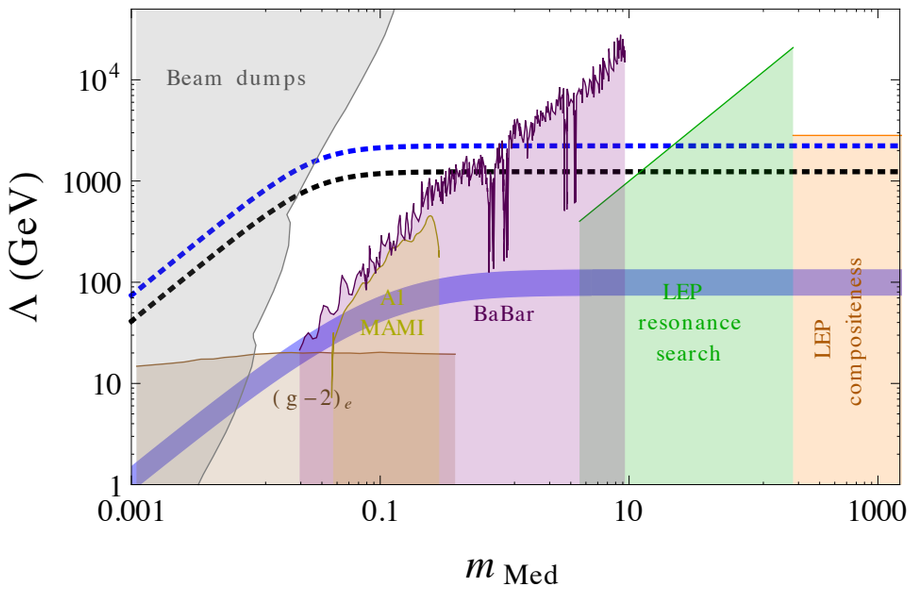


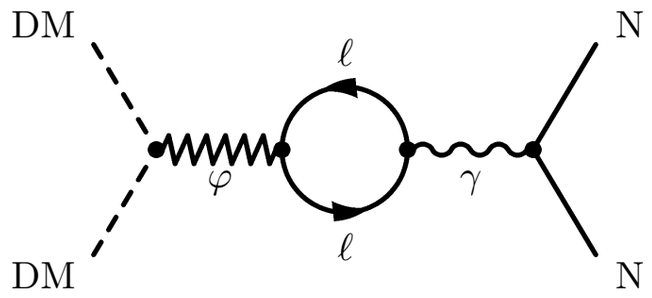
$(g-2)_\mu$ as a Probe of New Physics [Agrawal et al.]

- Exploring a connection between $(g-2)_\mu$ and leptophilic dark matter and dark sectors in simplified models.

$(g-2)_\mu$: $\frac{1}{\Lambda^2} H \bar{\mu} \sigma^{\mu\nu} \mu F_{\mu\nu}$ ⟷ simplified model ⟷ DM: $\frac{1}{\Lambda^2} (\bar{\mu} \Gamma_\nu \mu)(\bar{\chi} \Gamma_\nu \chi)$







- In progress – $(g-2)_\mu$ vs. muon Higgs couplings [Agrawal, Bishara, Yu]:

$(g-2)_\mu$: $\frac{1}{\Lambda^2} H \bar{\mu} \sigma^{\mu\nu} \mu F_{\mu\nu}$ ⟷ simplified model ⟷ modified μ Yukawa: $\frac{1}{\Lambda^2} H^3 \bar{\mu} \mu$

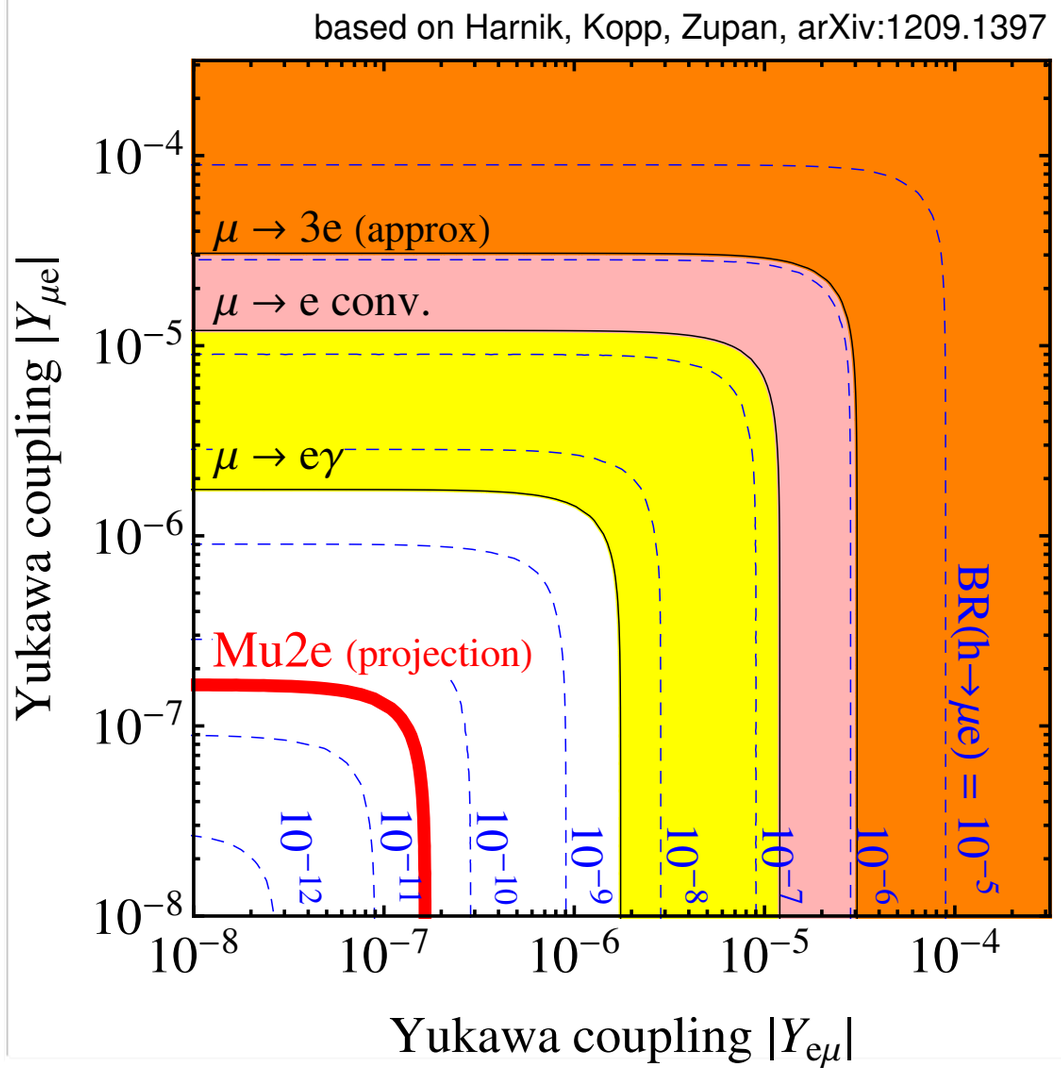
μ2e and the Higgs boson [Harnik, Kopp, Zupan]

- If the Higgs is not the only source of mass in the Universe, Higgs flavor violation is possible.

- μ–e Flavor violation:
Limits from rare muon processes dominate over LHC

- Fermilab μ2e experiment: with 4 order of magnitude leap in limit has the furthest reach

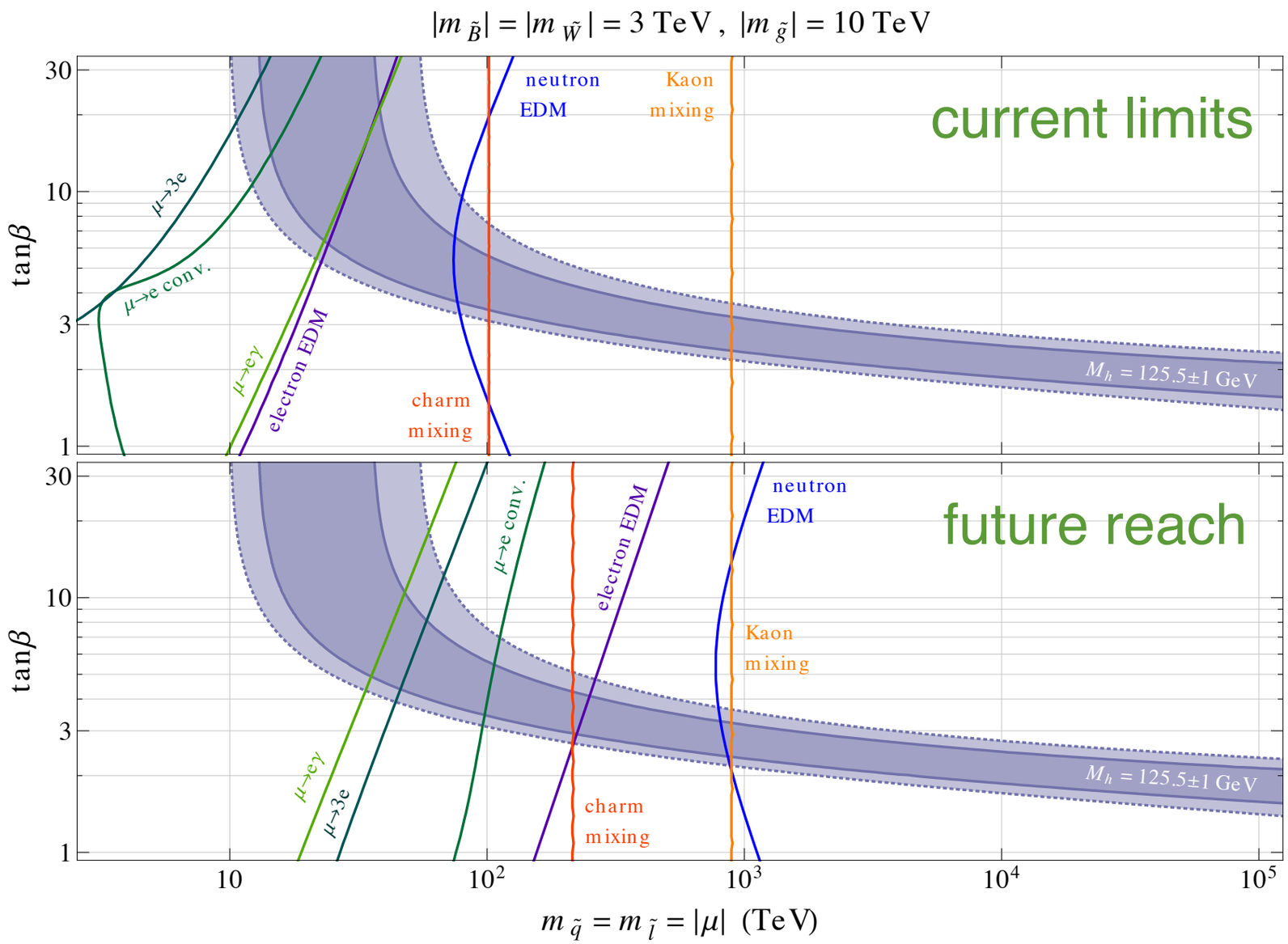
From the μ2e TDR:



μ2e probes PeV-scale SUSY [Altmannshofer, Harnik, Zupan]

- Higgs mass motivates high-scale and supersymmetry.
- Simplest models predict flavor violation at 100-1000 TeV scale
- Low-energy precision probes are key.

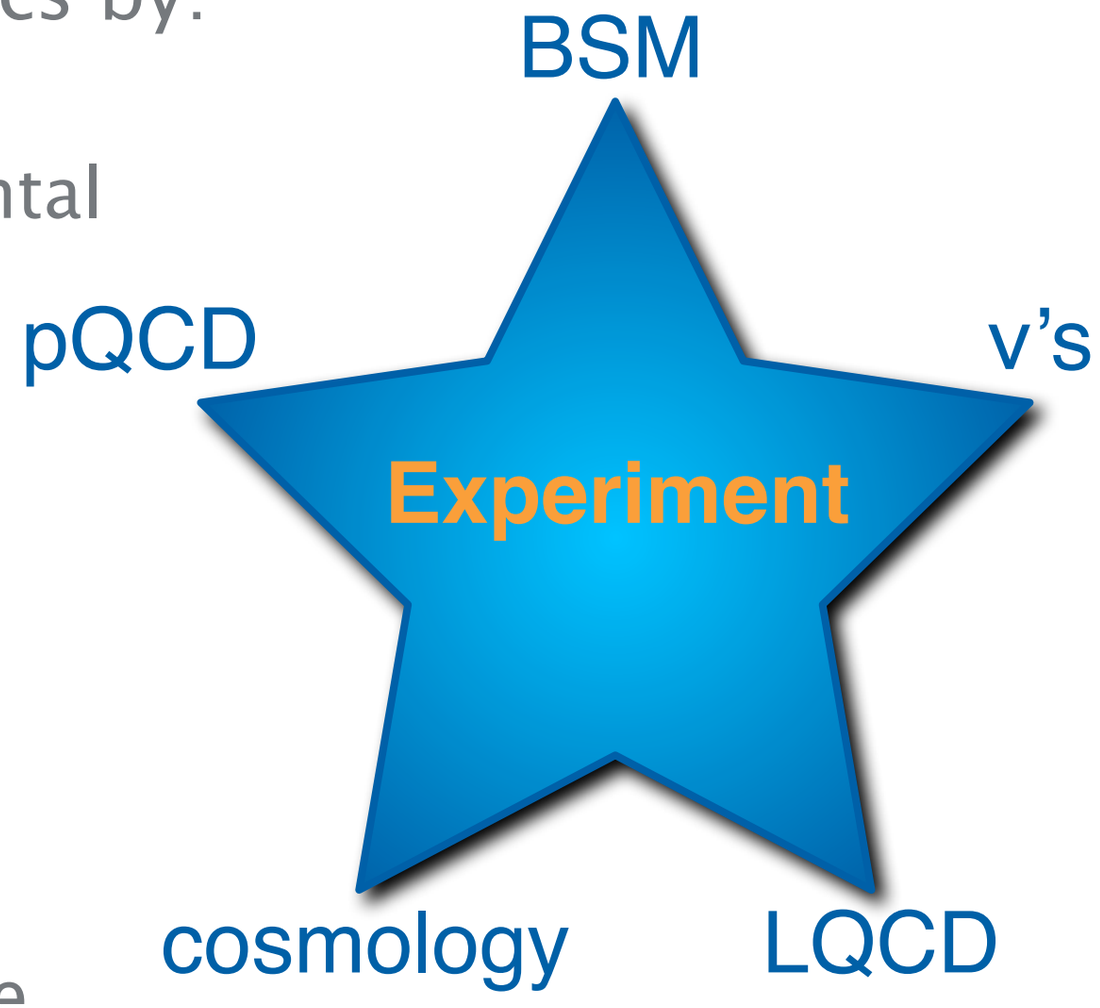
- Fermilab μ2e can probe sleptons at the 100 TeV scale.



Strategic vision

Research vision

- Continue to support and guide Fermilab and worldwide experimental programs to search for new physics by:
  - Providing analytic formulae and numerical tools used in experimental analyses
  - Providing Standard-Model and new-physics predictions
  - Devising new models and search strategies
  - Interpreting experimental data
- Diverse theory expertise enables important connections to be made between subfields
- Close proximity to experiments vital!



Theoretical Physics Staffing

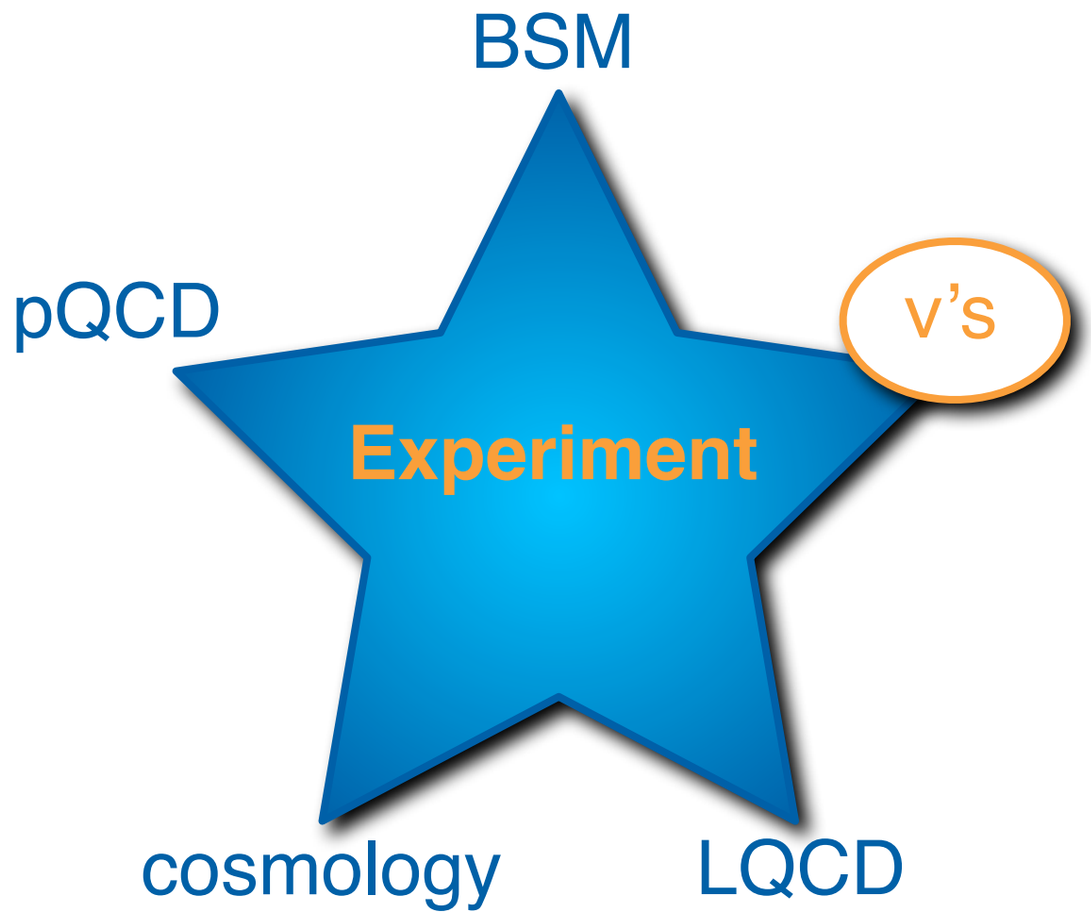
Current:

14.5 staff, 8→9 RAs,
0.5 FTE guests/visitors

Expect ~3 retirements every 5 years
for next 10 years

Within 10 years:

~12 staff, ~12 RAs,
~2 FTE guests/visitors



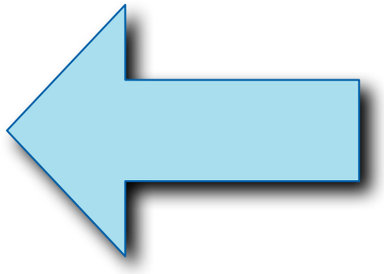
Last Hires:

John Campbell (pQCD, 12/09), Paddy Fox (BSM, 3/07),
Roni Harnik (BSM, 3/10), Ruth Van de Water (LQCD, 9/12)

Last Retirment: Boris Kayser (neutrinos, 12/12)

Neutrino Staff Hire(s)

- Would like to hire at least one additional junior Staff Scientist whose primary interest is neutrino physics
- What kind of neutrino theorist(s)?
  - Neutrino model building
  - Broad phenomenologist (vSM & beyond vSM)
  - Supernova phenomenologist
  - Nuclear theorist for ν-nucleus cross sections



Must be an exceptional physicist
and be able to talk to and interact with
members of the Theoretical Physics Department
AND
the neutrino experimentalists!

Theoretical Astrophysics Staffing

Research Associates:

- Postdocs-to-scientists ratio

  1:1 historically (successful formula)

  2:5 FY2014/15 (historic low)

  3:5 FY2016 ...

➡ Would like to return to 1:1

Scientists:

- Laboratory effort in cosmic program has and continues to increase but scientific staff has remained at 5 since 2005.
- Fermilab's increasing effort in Cosmic Microwave Background would benefit from increased theoretical input as program is still under development.

Theoretical Physics Department Visitors

- In addition to usual guest and visitor program, providing partial support to:
  - Nuclear theorists Luis Alvarez-Ruso & Joe Carlson
  - LPC "Theorist of the week"
- Planning significant addition to the current Theory Visitors' programs involving multi-year commitment to come about one month per year
- Key goals of new program include:
  - Strengthening ties to university community
  - More transparency and inclusiveness
  - Details will be announced soon...

Summary

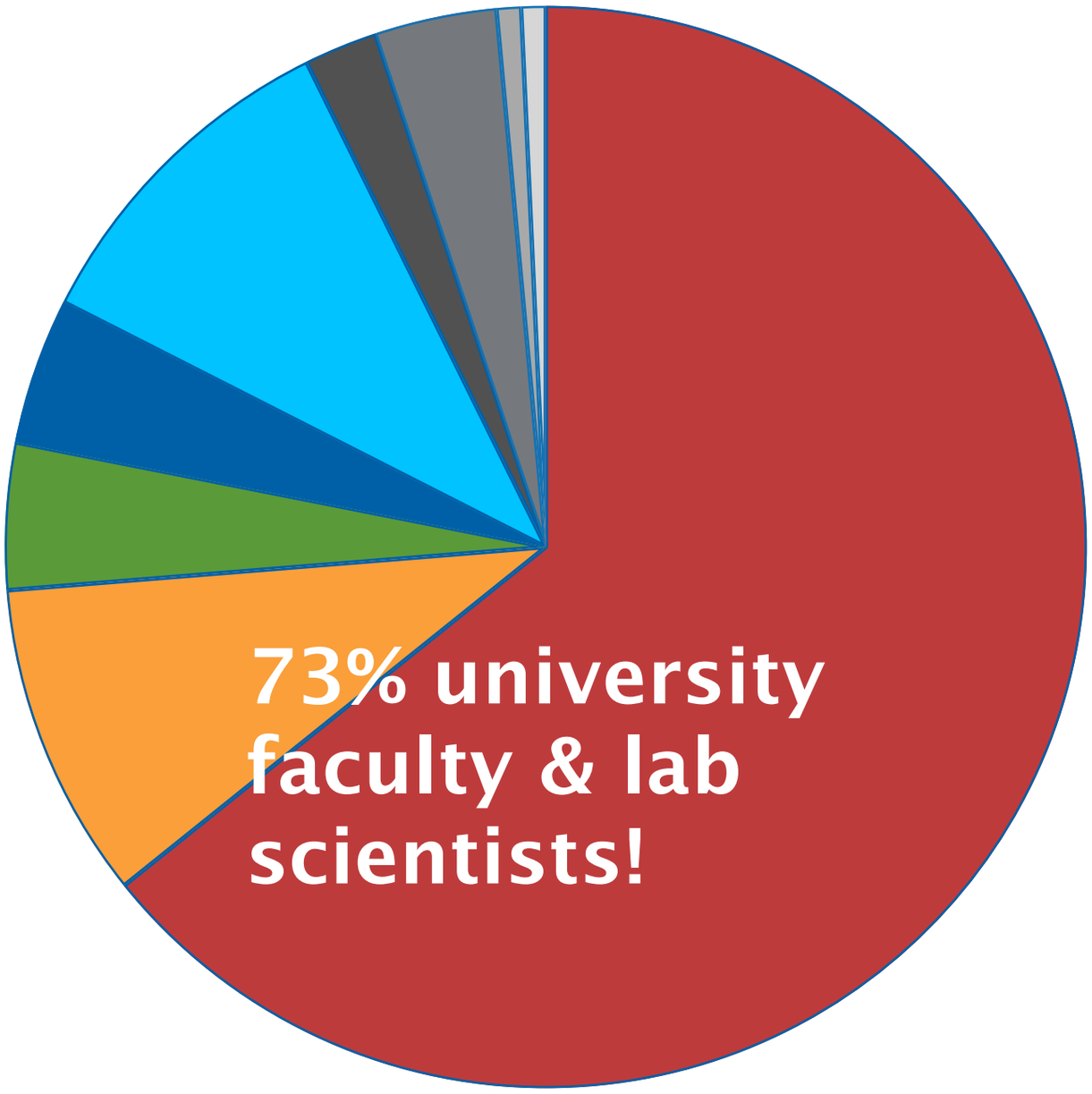
- Theoretical physics and astrophysics groups are essential for vibrant programs in all cross-cut areas.
  - Aligned with OHEP future plans according to P5 priorities.
  - Significant past and current projects have grown out of, or been shaped by, the theory program.
- Proximity to experiment cross-fertilizes both theoretical and experimental research at Fermilab.
  - Engaged with LPC, planned Neutrino Physics Center
  - Broader community benefits: visitors, seminars, conferences.
  - Enlivens intellectual atmosphere.
- Strong service to lab, university, international communities.
- High scientific productivity: research output, program planning, postdoc and student training, future leaders of the field.

Fermilab

Extra material

Current positions of former Theoretical Physics RAs

http://theory.fnal.gov/people/ellis/alumni.html



- University (64%)
- National Lab (9%)
- RA (4%)
- Research (4%)
- Industry (10%)
- Medicine (2%)
- Finance (4%)
- Other (<1%)
- Unknown (<1%)

Current Theoretical Physics Department G&V Program

- For FY2014, spent
  - ~$50K on 39 visitors (9 Summer visitors)
  - ~$23K on theory seminar speakers
  - ~$12K on JETP seminar speakers
- Typical visitor costs are $6K–$7K per person-month

Graduate Student Fellows