Of course having separate summary talks for particle physics and cosmology goes against the whole philosophy of this meeting.

So Professor Turner and I agreed on a different approach:
Alphabetical division of themes

A – M
(Turner)

N – Z
(me)
### Alphabetical division of themes

<table>
<thead>
<tr>
<th>A – M (Turner)</th>
<th>N – Z (me)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrophysics</td>
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<tr>
<td>Axions</td>
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<td>Baryogenesis</td>
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<td>BSM models</td>
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<td>CMB</td>
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<td>Cosmology</td>
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<td>Dark energy</td>
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<td>Dark matter</td>
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<td>Future colliders</td>
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<td>Higgs</td>
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<td>LHC</td>
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### Alphabetical division of themes

**A – M**
*Turner)*

- Astrophysics
- Axions
- Baryogenesis
- BSM models
- CMB
- Cosmology
- Dark energy
- Dark matter
- Future colliders
- Higgs
- LHC

**N – Z**
*me)*

- Neutrinos
Outline

• Science drivers and connections
• Excitement and confusion
• Windows to higher scales:
  – Proton decay
  – Charged lepton flavor violation
• Speculation about prospects for
  – Neutrinos
  – Dark matter
Science Drivers of Particle Physics (from P5)

Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles
Science drivers are intertwined: e.g. Higgs connections

- Is the Higgs boson connected to supersymmetry or other naturalness-preserving new physics
- Does the Higgs field destabilize the vacuum
- How does the Higgs talk to neutrinos
- Are there more Higgs-like bosons and a “Higgs sector”
- Is there a Higgs portal to dark matter
- Is the Higgs sector related to baryogenesis
- Extra credit: Is the Higgs related to inflation or dark energy
Another example: neutrino connections

• How do neutrinos talk to the Higgs boson
• How are tiny neutrino masses related to the origin of particle masses in general
• Are neutrinos responsible for leptogenesis/baryogenesis
• Are neutrinos related to superhigh energy scales and unification
• How are neutrinos related to dark matter
• Extra credit: are neutrinos related to dark energy
Particle physics connections to other fields

- **Cosmology**: probes dark matter, dark energy, the number of types of neutrinos and their masses, primordial inflation and the superhigh energy scale associated with it.

- **Nuclear physics**: Majorana nature of neutrino mass, neutrino-nuclear physics underlying neutrino oscillation experiments, nuclear recoil physics for dark matter experiments, nuclear astrophysics connects to solar and supernova neutrino fluxes, heavy ion collisions as probes of quark-gluon plasma and gluon structure of the nucleon.

- **Astrophysics**: dark matter indirect detection, neutrinos as probes of supernovae, cosmic accelerators, etc.

- **Condensed matter**: theory connections (Higgs mechanism, string theory, entanglement, ...
We live in *exciting* times for particle physicists

- The Higgs boson / Higgs field is a completely new kind of beast
  - We have just scratched the surface of the Higgs sector
- LHC 13 TeV has begun!
  - Anything new will be a revolution in particle physics
- Neutrino science is both maturing and ramping up fast
  - Answers to many of our basic questions appear within reach
  - Could confirm anomalies or discover new surprises
- Dark matter direct detection could be just around the corner
  - The most (?) interesting region for WIMPS is being probed soon
  - Could also detect signs of a dark mediator
We live in *exciting* times for particle physicists

Surprises may arise from a variety of experiments that explore the unknown:

• Flavor surprises:
  – muon to electron conversion and other CLFV processes
  – flavor-violating Higgs decays (a hint already?)
  – in B decays at BELLE II or LHCb
  – Lepton non-universality (CMS eejj excess, LHCb $B \rightarrow K \ell^+ \ell^-$)

• Other potential surprises:
  – muon g-2
  – electric dipole moments or other EM anomalies
  – production and decay of heavy neutral leptons
  – proton decay!

• And there could be signals from the “unknown unknowns”
We live in *confusing* times for particle physicists

For the past 30 years, particle theorists have used the idea of naturalness to argue that a relatively light Higgs boson implies superpartner particles with mass below a TeV

- Light Higgs boson discovered, but no sign of superpartners
- No sign of any other new particles at LHC either!
- Precision measurements (almost) all agree with Standard Model predictions, with frightening regularity
- Meanwhile the pattern of masses and mixings of Standard Model particles are a total mystery
Hints from LHC Run 1

- High mass di-boson resonance searches with boson-tagged jets at $\sqrt{s} = 8$ TeV (arXiv:1506.00962)
  - Di-boson resonances are predicted in several extensions to the SM, such as
    - technicolor
    - warped extra dimensions
    - Grand Unified Theories
  - Production of $W, Z$ bosons from decay of the massive resonance together with large transverse momentum relative to their mass:
    - each boson is reconstructed in a single large-radius jet
    - looking for resonance structure on a smoothly falling dijet invariant mass spectrum

Can’t get too excited, since some fluctuations have to be there

On the other hand, you cannot get to 5 sigma without passing through 2.5 sigma on the way...

- Results:
  - Most significant discrepancy with the background-only model occurs around 2 TeV in WZ channel with local significance of $3.4\sigma$
  - Global significance with entire mass range in all three channels (WZ, WW, ZZ) of $2.5\sigma$

Catrin Bernius PPC2015
Hints from LHC Run 1 (my favorite)

Excesses around 2 TeV in three different channels:
- Boosted VV -> dijet (ATLAS and CMS)
- Boosted HV -> bbenu (CMS only)
- $W_R$ -> eejj (CMS only)

Talk by M. Pierini
Fermilab Users Meeting

Could be:
- Gauged B-L (impact on baryogenesis)
- Leptoquarks
- Colorons or other techni-style resonances

U. Sarkar PPC2015
What is all this telling us?

Mass hierarchy?

Mixing hierarchy?

why 3 generations?

origin of neutrino mass?

Joe Lykken | PPC2015, Deadwood
July 03 2015
What is the underlying dynamics of flavor?

Saying that the Standard Model with the Higgs mechanism is a successful theory of fermion masses is like saying that the Periodic Table is a successful theory of atoms.
My view (also a prediction):

Flavor (broadly defined) is a big over-arching challenge of particle physics for the first half of this century

- What are the dynamical origins of fermion masses, mixings, and CP violation?
- What are the scales associated with this dynamics?
- What are the symmetries and symmetry breakings?
- What is the complete Higgs sector and how does it work?
- How are quark and lepton flavor related?
- What other flavor sectors are accessible, e.g.
  - superpartners
  - dark sector
Today we are confused but nature is surely following some logic

A. Strumia, Moriond 2015

Natural solution: Napoli = Salerno. But not supported by geo data
Anthropic solution: mafia sells signposts. Plausible but untestable
Or think different
Thinking different is a healthy exercise

• Maybe superpartners are there, but heavier than we thought
• Maybe lots of new physics with $O(1)$ flavor violation at 10-100 TeV, out of reach of the LHC
• Dark matter sector may be much richer, more complicated than vanilla WIMPs
• Maybe the neutrino sector is richer and neutrino mass generation is a more complicated story
• Maybe a lot of the seemingly arbitrary features of the Standard Model are explained by the multiverse and the anthropic principle (not my favorite...)
The naturalness argument: how far are you willing to go?

$m_H \ll M_P$?

Towards naturalness

Supersymmetry

"fermionizing" the Higgs

"marrying" a fermion:
Higgsino

Compositeness

Relaxation mechanism?

Multiverse

The "transvestite" Higgs:

new TeV-physics

H = \begin{array}{c}
\bar{u} \\
u
\end{array}

No new TeV-physics

A. Pomarol, WIN2015

H = \begin{array}{c}
\bar{u} \\
u
\end{array}

arXiv:1504.07551
After EWSB: $\epsilon = \nu_{\text{SM}}/f$ and precision data demands $f > 500$ GeV

More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics.

Other global symmetry patterns allow for additional Higgs Bosons in the spectrum.
Composite pNGB Higgs Models predict light Fermions

Pair production, single production, or exotic Higgs production of vector-like fermions [masses in the TeV range and possibly with exotic charges: $Q = 2/3, -1/3, 5/3, 8/3, -4/3$]

Large variety of signatures, many with energetic leptons

M.C., Da Rold, Ponton’14

Talk by M. Carena

LHC exclusion for $M_f < 800$ GeV
SUSY: a balance between natural and “special”?

WHAT WENT WRONG?

★ Perhaps $\delta m_{h}^{2} < m_{h}^{2}$ is too stringent? Many examples of accidental cancellations in nature of one or two orders of magnitude.

★ Argument applies only to superpartners with large couplings to the EWSB sector (not, e.g. to first generation squarks and gluinos probed at the LHC).

★ Most importantly, once we understand the SUSY breaking mechanism, almost certainly we will find that contributions from the various superpartners are correlated, leading to the possibility of automatic cancellations. Ignoring this, will overestimate the UV sensitivity of any model.

X. Tata, PPC2015
Is the Standard Model (almost) all there is?

Maybe the naturalness argument applied to the Higgs is just wrong (well, it was apparently wrong for the vacuum energy too)

- The Standard Model plus some TeV scale renormalizable additions (like dark matter) might be all there is
- The Standard Model itself, or with such modest additions, is completely natural
- Usual counterargument involves the putative Planck scale and unification thresholds, but this is speculative
- An unsatisfying scenario, leaving many questions unanswered, but has a certain minimalist appeal…
The canonical Beyond the Standard Model paradigm

- Superpartners at the LHC
- Dark matter from supersymmetry, axions
- “Grand” or similar unification of matter and gauge forces somewhere around $10^{16}$ or $10^{17}$ GeV
- Tiny neutrino masses from a see-saw related to the new physics at superhigh energies
- Superstrings at the Planck scale with lots of extra structure to explain flavor structure, primordial inflation, etc.

There are lots of good arguments for this picture
The canonical **Beyond the Standard Model** paradigm

The experimental program that goes with this paradigm is pretty clear:

- Find superpartners, map properties
- Nail down the physics of the Higgs
- Close the circle of dark matter between direct detection, indirect detection, LHC production, and large scale structure
- Nail down the neutrino sector including CP violation and Majorana mass
- Find proton decay and possibly charged lepton flavor violation
- Cosmic Microwave Background probes primordial inflation
- **Use all these clues to extract a more concrete picture of the unified theory at superhigh energies**
Proton decay

- Supersymmetric Grand Unified Models have exotic particles related to the Higgs that induce proton decay
- Long known to be trouble for minimal supersymmetric SU(5): lower limits on the proton are already very strong!

![Proton decay lifetime limits](image-url)
Split SUSY and proton decay

- Lifting some superpartner masses to ~100 TeV or higher gives an extra suppression that revives minimal supersymmetric SU(5)
- This kind of “split SUSY” has become the most popular first line of retreat for advocates of supersymmetry worried about naturalness

Even better, such models will actually produce a proton decay signal at DUNE and HyperK
More upper limits on proton decay

$$m_{\tilde{q}_{1,2}} = 21122 \text{ GeV} \quad m_{\tilde{t}_3} = 3115 \text{ GeV}$$
$$m_{\tilde{t}_1} = 735.02 \text{ GeV}, \quad m_{\tilde{t}_2} = 1503.2 \text{ GeV}$$
$$m_{\tilde{\tau}} = 3227.6 \text{ GeV} \quad \mu = 759.6 \text{ GeV}$$

Neutralinos:  \( m(\tilde{\chi}^0_i) \simeq (653 - 1295) \text{ GeV} \)
Charginos:  \( m(\tilde{\chi}^{\pm}_i) \simeq (759 - 1295) \text{ GeV} \)

Varying SUSY spectrum with reasonable naturalness & using the inverse correlation (A) → Get theoretical upper limits:

\[
\tilde{\Gamma}'(p \to e^+\pi^0)^{\text{th}} \lesssim (2 - 10) \times 10^{34} \text{ yrs}
\]
\[
\tilde{\Gamma}'(p \to \bar{\nu}K^+)^{\text{th}} \lesssim (1 - 8) \times 10^{34} \text{ yrs}
\]

* Badziak, Dudas, Olechowski, Pokorski, Arxiv: 1205.1675

**SO(10) × U(1) × Z_2 → Desired Superpotential**

\[ \rightarrow \text{D-T splitting via DW absolutely stable} \]

J. Pati, PPC2015

SO(10) models with *somewhat heavy* SUSY giving upper bounds on proton lifetime within the reach of DUNE and HyperK
SUSY GUTs with gluinos accessible to LHC
Another window to BSM: charged LFV

\[ \mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L) \]

If one is to hope to ever reconstruct the seesaw Lagrangian and test leptogenesis, LFV needs to be measured.

Note that this is VERY ambitious, and we need to get lucky a few times:

- Weak scale SUSY has to exist;
- “Precision” measurement of \( \mu \to e, \tau \to \mu, \tau \to e \);
- “Precision” measurement of SUSY masses;
- Very good understanding of mechanism of SUSY breaking;
- There are no other relevant degrees of freedom between the weak scale and \( > 10^9 \) GeV;

A. de Gouvea, PPC2015
The dipole effective operators that mediate $\mu \rightarrow e\gamma$ and contribute to $a_\mu$ are virtually the same:

$$\frac{m_\mu}{\Lambda^2} \bar{\mu} \sigma^{\mu\nu} \mu F_{\mu\nu} \times \theta_{e\mu} \frac{m_\mu}{\Lambda^2} \bar{\mu} \sigma^{\mu\nu} e F_{\mu\nu}$$

<table>
<thead>
<tr>
<th>$g - 2$</th>
<th>CLFV</th>
<th>What Does it Mean?</th>
</tr>
</thead>
<tbody>
<tr>
<td>YES</td>
<td>YES</td>
<td>New Physics at the TeV Scale; Some Flavor Violation</td>
</tr>
<tr>
<td>YES</td>
<td>NO</td>
<td>New Physics at the TeV Scale; Tiny Flavor Violation</td>
</tr>
<tr>
<td>NO</td>
<td>YES</td>
<td>New Physics Above TeV Scale; Some Flavor Violation – How Large?</td>
</tr>
<tr>
<td>NO</td>
<td>NO</td>
<td>No New Physics at the TeV Scale; CLFV only way forward?</td>
</tr>
</tbody>
</table>

A. de Gouvea, PPC2015
• Muon g-2 ring is cold and almost fully powered (3,000 amps)
• Will get beam in 2017
• Mu2e starts in 2020
Neutrino Outlook

Paha Sapa, as seen from Mt. Roosevelt
Pressing Questions for Neutrinos

Talk by K. Babu

- Are neutrinos their own antiparticles?
- Is there CP violation in neutrino oscillations?
- Is the mass hierarchy normal or inverted?
- Are there light sterile neutrinos?
- What is the scale of neutrino mass generation?
- What explains the pattern of neutrino mixings?
- Can neutrinos be unified with quarks?
- Is neutrino CP violation related to baryon asymmetry?

Can be addressed strongly with current and planned experiments

Very interesting and very important, but also very hard to address experimentally
The ordering of neutrino masses may as well come from a global fit to different data.

Blennow, Schwetz, 1306.3988 [hep-ph]
(see also Li et al, 1303.6733 [hep-ph], for instance)
The appeal of the Type I neutrino see-saw

Prototype: Type I seesaw

right-handed neutrinos: $Y_{ij} L_i \nu_{Rj} H + M_{Rij} \nu_{Ri} \nu_{Rj}^c$

$\mathcal{M}_\nu = \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$

$m \sim O(100 \text{ GeV})$

$M \gg m$

$m_1 \sim \frac{m^2}{M}$

$m_2 \sim M \gg m_1$

$\nu_{1,2} \sim \nu_{L,R} + \frac{m}{M} \nu_{R,L}$

advantages: naturalness, connection to grand unification, leptogenesis,...

disadvantage: testability (even at low scales)

L. Everett, PPC2015
Neutrino mass: a complicated story

3x3 matrix

\[
\begin{pmatrix}
\bar{\nu}_L & \bar{\nu}_R^c \\
\end{pmatrix}
\begin{pmatrix}
M_L & m_D \\
M_D & M_R \\
\end{pmatrix}
\begin{pmatrix}
\nu_L^c \\
\nu_R \\
\end{pmatrix}
\]

Usually:
- \(M_L\) tiny or 0, \(M_R\) heavy
- \(\rightarrow\) see-saw & variants
- light sterile: F-symmetries...

Now:
- \(M_L, M_R\) may have any value:
- \(\rightarrow\) diagonalization: \(3+N\) EV
- \(\rightarrow\) 3x3 active almost unitary

<table>
<thead>
<tr>
<th>(M_L=0, m_D = M_W), (M_R=)high: see-saw</th>
<th>(M_R) singular singular-SS</th>
<th>(M_L = M_R = 0) Dirac</th>
<th>(M_L = M_R = \epsilon) pseudo Dirac</th>
</tr>
</thead>
</table>

sterile

active
How little we know: which see-saw? what scale?

Smallness of neutrino mass can be “explained” by:

⇒ High scale: Large $\Lambda$
  “classical” seesaw

⇒ Loop factor: $n \geq 1$
  + “smallish” $Y \sim \mathcal{O}(10^{-3} - 10^{-1})$

⇒ Higher order: $d = 7, 9, 11$

⇒ Nearly conserved $L$,
  i.e. small $\epsilon$ ("inverse seesaw")

⋯ or combination thereof
How little we know: sterile neutrinos

S. King

Sterile neutrinos = right-handed neutrinos (no SM charges)

There may be 0,1,2,3,...n sterile neutrinos

$M_{GUT}$

Classic See-Saw (Leptogenesis)

TeV

Low Scale See-Saw (LHC)

GeV

Nu-MSM

BAU

MeV

WDM

keV

eV

LSND, Reactor Anomaly,...

meV

Extra radiation (Planck)

S. Horiuchi, PPC2015
sterile neutrinos: tensions on short and long scales

There is a strong tension between app and disapp data

Gallium and reactor anomalies are ok with all null experiments

MiniBooNE and LSND anomalies are consistent among themselves but in tension with the rest

3+1 and 3+2: poor fits

1+3+1: better fit, but sum of $\nu$ masses gets dangerously higher...

Up to now, there is no satisfactory explanation for these anomalies. The existence of sterile neutrinos remains an open question. See also Maltoni Schwetz 2007, Kopp

Can it be avoided by secret interactions on the sterile sector?

See for instance Chu Dasgupa Kopp 2015 and Saviano Pisanti Mangano Mirizzi 2014

number of relativistic species : $N_{\text{eff}} = 3.15 \pm 0.23$
(standard value : 3.046)
Good news: neutrino mass affects the observed universe

What a remarkable cosmic coincidence that we can strongly constrain and perhaps measure $\sum m_{\nu_i}$ from the effect of neutrinos on large-scale structure!
Good news / bad news: $0\nu\beta\beta$

**Majorana $\nu$-masses or other $\Delta L=2$ physics:** $\Rightarrow$ 2 electrons $0\nu\beta\beta$

- **Good news:** observation of neutrinoless double beta decay would be a huge discovery, violation of an important symmetry
- **Bad news:** doesn’t *necessarily* mean that the decay is driven by Majorana masses of neutrinos
- **Good news:** the “loopholes” are themselves interesting for LHC etc
Good news / bad news: leptogenesis

Good news: not the only possibility to explain the baryon asymmetry, but looking very attractive!

Bad news: many possibilities, how will you ever sort it out?

P. di Bari PPC2015

New stage in early Universe history:

- $T_{\text{RH}}$?
- Inflation
- Leptogenesis
- $T = 100 \text{ GeV}$
- EWSSB
- $0.1$ - $1 \text{ MeV}$
- BBN
- $0.1$ - $1 \text{ eV}$
- Recombination
Good news / bad news: CP violation in oscillations

- Good news: observation of CP violation in long-baseline neutrino oscillations would be a huge discovery, violation of an important symmetry
- Bad news: doesn’t *necessarily* mean that the observed CPV is the CPV of leptogenesis, or even that leptogenesis occurs
- Good news: a point in favor of the canonical BSM paradigm, will focus the attention of the community
- We are not trying to match onto a *generic* high scale theory; the high scale theory is *special*
Low energy phases can be the only source of CP violation
(Nardi et al.’06; Blanchet, PDB’06; Pascoli, Petcov, Riotto ’06; Anisimov, Blanchet, PDB ’08)

- Assume real \( \Omega \Rightarrow \varepsilon_1 = 0 \Rightarrow \varepsilon_{1\alpha} = P_{1\alpha}^0 \varepsilon_1 + \frac{\Delta P_{1\alpha}}{2} \)

\[ \Rightarrow N_{\text{B-L}} \Rightarrow 2\varepsilon_1 K_{1\alpha}^{\text{fin}} + \Delta P_{1\alpha} (K_{1\alpha}^{\text{fin}} - K_{1\beta}^{\text{fin}}) \quad (\alpha = \tau, e+\mu) \]

- Assume even vanishing Majorana phases

\[ \Rightarrow \delta \text{ with non-vanishing } \theta_{13} (J_{\text{CP}} \neq 0) \text{ would be the only source of CP violation} \]

(and testable)

Green points:
only Dirac phase
with \( \sin \theta_{13} = 0.2 \)
\( |\sin \delta| = 1 \)

Red points:
only Majorana phases

• No reasons for these assumptions to be rigorously satisfied
• In general this contribution is overwhelmed by the high energy phases
• But they can be approximately satisfied in specific scenarios for some regions
• It is in any case by itself interesting that CP violation in neutrino mixing could be sufficient to have successful leptogenesis
The actual unified theory is highly constrained

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<td>$edm_e \times 10^{-30} (\text{e cm})$</td>
<td>-1.403</td>
<td>-3.305</td>
<td>-1.763</td>
<td>-5.886</td>
</tr>
</tbody>
</table>

S. Raby, PPC2015
Cabibbo haze?

ideas of quark-lepton complementarity and “Cabibbo haze”

Raidal ’04, Minakata+Smirnov, many others...
(“haze” terminology from Datta, L.E., Ramond ’05)

Long before measurement, conjecture that $\theta_{13}$ is a Cabibbo effect

$$
\theta_{13} \sim \frac{\lambda_C}{\sqrt{2}} \sim \lambda_C \cos \theta_{23}^0
$$

Ramond, others...

(general idea often called “charged lepton corrections”) $U_{\text{MNSP}} \sim U_{\text{CKM}} W$

good fit to data! but nontrivial to implement...

one reason: now $\sim \lambda_C$ corrections floating around

L. Everett, PPC2015
some neutrino news from Fermilab
SBN Program – Three detectors with one mission

- **ν_μ** Disappearance
- **ν_e** Appearance

**ICARUS**
- Fewer ν_μ?
- More ν_e?

**MicroBooNE**
- Fewer ν_μ?
- More ν_e?

**SBND**
- ν_μ ~1% ν_e

**Produce**
- ν_μ ~1% ν_e

Distance:
- 110m
- 470m
- 600m
SBN program...growing and roaring ahead

Sunday, April 26, 2015 9:42 AM

Dear Colleagues,

this is to let know that all the ICARUS participating groups have been formally consulted and have unanimously agreed to extend the ICARUS collaboration to you and your teams. Argonne National Laboratory, Colorado State University, Los Alamos National Laboratory, FermiLab, University of Pittsburgh and SLAC are presently new participants in the Collaboration.

Welcome in ICARUS!

Sincerely

Carlo Rubbia
Prospecting for gold at Homestake

• Already one Nobel prize awarded for a neutrino experiment in the Homestake mine
• Why not more?
A new era begins: LBNF and DUNE

LBNF/DUNE will be the first truly international “mega science” project hosted by the U.S.
A new era begins: LBNF and DUNE

CD-3a review this year for far site construction start in 2017
Scale of one cryostat = Building 156 at CERN
Embarkment allows placement of the target close to grade to reduce risk of tritium production in the aquifer.
Deep Underground Neutrino Experiment

A growing global science collaboration:
- 776 members
- 144 institutions
- 26 countries

Spokesperson:
- André Rubbia
  ETH

Spokesperson:
- Mark Thomson
  Cambridge

Technical Coordinator:
- Eric James
  FNAL

Resource Coordinator:
- Chang Kee Jung
  Stony Brook

see M. Marshak PPC2015
DUNE/LBNF…rapid progress

• This is a special year: support from U.S. government is strong
• Next milestone is July 14-16 CD-1 refresh review
  – Full scope cost and schedule to be presented
• Nov 2015: CD-3a review for far site…this is baseline and construction start for the caverns in South Dakota
• Single and dual phase LAr TPC prototypes will test at CERN
• First 10 kt fiducial module to begin installation by end of 2021
• Cascading schedule to complete full scope around 2026:
  – > 40 kt fiducial of LAr TPCs deep underground
  – Megawatt beam from Fermilab sensitive to both 1st & 2nd oscillation maximum
  – Fine-grained near detector
“The sky is full of ghosts” – William Herschel (1813)

- 650 light-centuries to the far side of the Milky Way
- Neutrinos from ~2000 supernovae are already on their way here
Neutrinos from core collapse supernovae

- Core collapse supernovae very complicated, neutrino signal carries unique information
- The neutrino gas itself is a many body system driven by weak interactions
- Can we detect the ~10 ms neutronization burst?
- Can we see a neutrino cutoff after a few seconds due to a black hole event horizon enveloping the neutrinospheres?
- Dip in neutrino spectrum from resonant scattering off light DM?

Talks by A. Friedland, A.B. Balantekin, D. McKeen, PPC2015
Deadwood as seen from Mt. Moriah cemetery
Dark matter bestiary

- Superpartner particles: Wino, Bino, Higgsino, sneutrino, ...
- Axions
- Kaluza-Klein particles from extra dimensions
- Sterile neutrinos
- Asymmetric dark matter
- WIMPzillas (don’t ask...)
How does dark matter interact with ordinary matter?

via the known weak interactions, like neutrinos?

via the Higgs boson?

via gravity we know

via a neutrino portal?

\[ \mathcal{L} \sim LH \nu_R + \nu_D \eta \nu_R + M \nu_R \nu_R \]

Or: via some exotic unknown “dark forces”?

Talks by Hyun Min Lee, Hai-Bo Yu, PPC2015

Talks by A. Friedland, D. McKeen, PPC2015
The power of the WIMP

Indirect detection

Annihilation

Cosmic density

The power of the WIMP

Direct detection

Production

Scattering

Colliders

Cosmic density

Large scale structure

Talk by P. Gondolo

Michael Turner
(actual size)
Dark matter at the 13 TeV LHC

Talks by X. Tata, T. Kamon, S. Mehlhase, H. Baer, K.C. Kong, B. Thomas PPC2015
Supersymmetry and the WIMP miracle

Table I: Scan ranges for the 19 (20) parameters of the pMSSM with a neutralino (gravitino) LSP. The gravitino mass is scanned with a log prior. All other parameters are scanned with flat priors, though this choice is expected to have little qualitative impact on the results [162–164].

Figure 3: Left: Thermal relic density as a function of the LSP mass in the pMSSM model set, as generated, color-coded by the electroweak properties of the LSP as discussed in the text. Right: Thermal relic density as a function of the LSP mass for all pMSSM models, surviving after all searches, color-coded by the electroweak properties of the LSP.

In the pMSSM approach, one scans over all phenomenologically relevant input parameters and considers all models which pass the existing experimental constraints and have a dark matter candidate which can account for at least a portion of the observed dark matter density [165–167]. The pMSSM parameters and the ranges of values employed in the scans are listed in Table I, where the lower and upper limits were chosen to be essentially consistent with Tevatron and LEP data and to have kinematically accessible sparticles at the LHC, respectively. To study the pMSSM, many millions of model points were generated in this space (using SOFTSUSY [168] and checking for consistency with SuSpect [169], while the decay patterns of the SUSY partners and the extended Higgs sector are calculated using a modified version of SUSY-HIT [170]). These individual models are then subjected to a large set of collider, flavor, precision measurement, dark matter and theoretical constraints [165].

Roughly 225k models with a neutralino LSP survive this initial selection and can then be used for further physics studies. The left panel in Figure 3 shows the thermal relic densities of the Higgsino, ~1.5 TeV, Wino, ~3 TeV, and Pure Bino-Higgsino mixture, closest case to the WIMP Miracle. Pure Bino needs co-annihilation with other quasi-degenerate superpartners. "correct" thermal relic density

M. Cahill-Rowley et al, 1405.6716
Is dark matter like visible matter?

• why should the dark sector be any simpler than the visible sector?
• the visible sector has 5 different massive stable particles (6 if you count the neutron)
• the abundance of visible matter is not a thermal relic abundance, it is set by the unknown process of baryogenesis or leptogenesis
Is dark matter like visible matter?

Talks by C. Trendafilova, Hyun Min Lee, Hai-Bo Yu, Keith Dienes, Brooks Thomas, PPC2015

• perhaps dark matter has several different stable components (a little of this and a little of that)

• perhaps have mass and abundance linked directly to the mass and abundance of visible matter: “asymmetric dark matter”

• perhaps all or some component of DM has significant self-interactions affecting the evolution of structure...

...and killing the dinosaurs?
Thanks to Barbara and all the organizers!

(don’t look down)