Teilchenphysik:

Lecture 24: What's Next?

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So, what are the big themes in research going forward?

- Understanding strong interactions better
- Understanding neutrino oscillations better
- Are there new heavy particles beyond the Standard Model?
- What is the Dark Matter?
- Are baryons really stable?

2: Dealing with QCD

The least-well understood part of the SM is Quantum Chromodynamics
The problem is that the coupling is so large in the IR – can't "solve"
Important! Poor understanding stands in the way of all other experimental goals

- Problems at low energies (particle spectrum, f_π, etc):
  Lattice QCD to numerically "solve" QCD at strong coupling
- Problems at high energies (high-energy scattering, "jets")
  Factorization divides problem in 3 parts
  - **Parton Distribution Functions**: finding q, g in hadron
  - **High-order Scattering calculations** for how they collide
  - **Fragmentation functions** how q, g turn into "jets" of particles

  Requires mixture of Pert. Theory, data, fitting, ...

Recent advances:

- Lattice QCD now a 1% endeavor for some quantities
- PDFs and fragmentation to high perturbative orders
- Scattering calculations with multiple legs at loop level,
  via very sophisticated analyticity techniques

But you didn't come here to hear about SM physics!

3: Neutrino oscillations

Recent + ongoing measurements:

- Measure Δm^2_{12} and θ_{12} with more precise solar and reactor neutrino studies
- Measure Δm^2_{13} and θ_{23} with neutrino beams and more precise atmospheric neutrino studies (PINGU)
- Measure θ_{13} with high-statistics precision reactor neutrino studies at 1-2 km distance

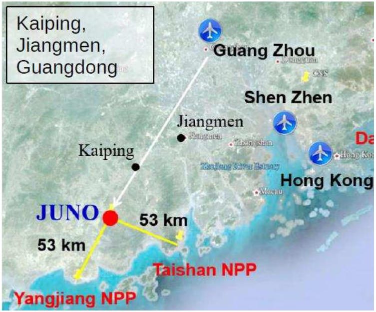
Last big advance was in 2012 when θ_{13} was measured (Daya Bay)

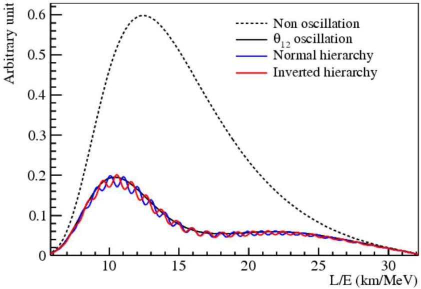
What's next?

- Better beams (larger, more distant detectors) to get δ
- Very large 60km baseline reactor neutrino detectors

4: JUNO

20Kton detector, 53km from 10(!) nuclear reactor cores!





With $<$ 3% energy resolution, can make out "wiggles" and determine all mass splittings and angles precisely, as well as "hierarchy" (if $m_1 < m_3$ or $m_1 > m_3$)

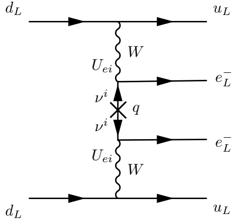
5: The other PMNS elements

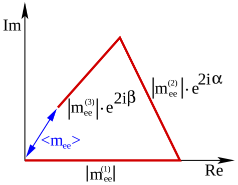
The "real" PMNS matrix for neutrino oscillations is:

$$U_{ai} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{bmatrix}$$

The phases α, β are overall phases for ν_2, ν_3.
They play *no* role in oscillation phenomena – they always cancel.
But they *play a role* in neutrinoless double-beta:

$$\Gamma_{0\nu\beta\beta} \propto \left| m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2 \right|^2$$





6: Limitations of double-beta

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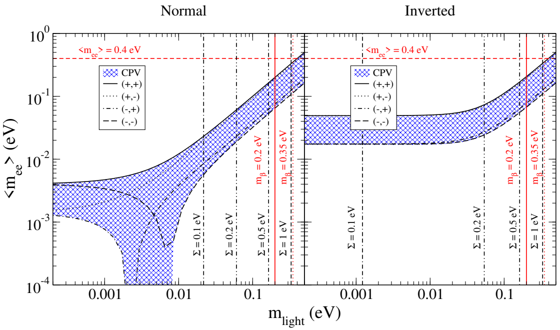
If nature is very mean, the $e^{i\alpha}$, $e^{i\beta}$ phases can conspire to make double-beta cancel.



We will never measure m_1 this way because of the width of the band, and because the nuclear matrix elements have $\sim$ 100% uncertainties. So we only learn whether neutrinos are Majorana – unlikely to learn α, β, m_1

7: Change gears: new physics!

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If there were a new heavy particle, mass M, what could it do?

- Direct effects: none unless you achieve $\sqrt{s} \geq M$!
- Loop effects: effects on “standard” couplings already incorporated in our measurements
- Loop effects: new “high-dimension” operators suppressed by E/M (ν-mass) or E^2/M^2 (all others)
- Loop effects: shifts the Higgs mass by ... $\sim \alpha M^2$.

8: Hierarchy problem

New physical scales contribute to the Higgs mass by an amount $\sim \alpha M^2$.
How are v, m_h "so small"? Hierarchy problem.

Proposed solution: protect m_h with a symmetry which would make it 0, if it weren't (spontaneously / softly explicitly) broken...

Supersymmetry!

9: Supersymmetry

Long theoretical development, but short version is:

- For each fermion we know, there is a spin-0 “superpartner”
  $e^- \rightarrow$ selectron. $u \rightarrow$ up squark or ’sup. $t \rightarrow$ top squark or “stop”
- For each scalar we know, there is a spin-$\frac{1}{2}$ superpartner
  Higgsino. (Actually, need 2 Higgs fields, 2 Higgsinos)
- For each vector boson, there is a spin-$\frac{1}{2}$ superpartner
  $g \rightarrow$ Gluino. $W \rightarrow$ Wino. $\gamma \rightarrow$ Photino. $Z \rightarrow$ Zino.

If SUSY were true, these would have *same* masses, charges, couplings.
SUSY breaking: M heavier, charges same, couplings same in UV.

“solves” hierarchy problem if $M < 10 m_h$ (roughly)

10: Supersymmetric Standard Model

- Add the SUSY partners
- Add all possible low-dimension (soft) SUSY breaking terms
- That includes masses for all SUSY partners
- About 105 new parameters (!)

Generically, severely spoils flavor physics, smallness of CP violation
For instance, $\tilde{u}, \tilde{c}, \tilde{t}$ mass matrix need not be diagonal in (u, c, t) basis, leading to rapid flavor violation.
Some assumptions needed to avoid these problems and reduce parameter freedom.

Wide range of proposals, no experimental evidence to help (yet)

11: Where are the superpartners?

Some theorists have been confidently predicting that we are about to discover SUSY – for the past 25-30 years.
Limits keep getting tighter (LHC has seen nothing, bounds some superpartners to few-TeV mass range)

Theory “hard to kill” but the higher the bounds become, the less motivated it becomes. Current bounds, and m_h value, mean that if SUSY exists, it still requires substantial “tuning” to explain Higgs mass.

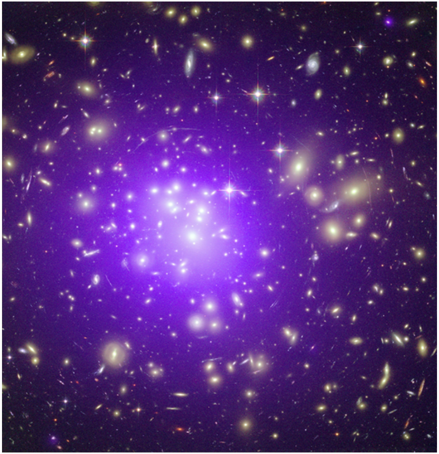
But SUSY has one interesting extra consequence... WeaklyInteractingMassiveParticles

12: Lightest supersymmetric partner

The SUSY partners have an interesting property:
There is a discrete symmetry (R-parity) under which they are "odd" and "ordinary" particles are even

- No tree-level effects, only appear in loops
- SUSY partners produced in pairs
- SUSY partner decay always produces at least one new SUSY partner
- *Lightest SUSY partner is stable!*

if lightest SUSY partner is colorless and neutral (weakly interacting), it could be the **Dark Matter**



Rich cluster of galaxies.
So massive, it distorts background light.
Glows in X-rays.
What is the mass of this cluster?

There is more than one way to measure mass.
Also, I can measure **Total** mass, or mass of **Ordinary matter**

14: Mass measurements

How do I go about measuring mass? There are multiple ways!

Measure *Total mass:*

- Temperature of *x*-rays
- Amount it distorts background galaxies

Measure *Mass of Normal Matter*

- Intensity of *x*-rays
- Amount it *rescatters* microwave background (image not shown)

The “total mass” measurements are in agreement with each other
The “normal matter mass” measurements also agree
The total mass is 5$\times$ more than the normal matter mass
This is seen *repeatedly* for *many* clusters.

15: Other lines of evidence

There are *several* lines of evidence for dark matter.
The strongest is from microwave sky, but it's too complicated to explain in 1 overhead, so I will skip it.

Maybe we don't understand gravity correctly? Doubtful.
Alternative gravity theories proposed, but few are internally self-consistentc and none can explain all data, especially microwave sky.

Existence of additional massive particle is best and most conservative explanation

16: WIMP as DM candidate

If SUSY is true, there is a heavy, stable particle: L$_{\text{ightest}}$S$_{\text{upersymmetric}}$P$_{\text{article}}$

Charged? Colored? strongly experimentally excluded. That leaves

- Sneutrino: experimentally excluded :-(
- neutral Higgsino
- Zino or Photino
- Linear-combination of Higgsino, Zino, Photino: Neutralino

The Higgsino, Zino, Photino generically mix.
That makes coupling + mass unknown and “tuneable”

17: Looking for WIMP Dark Matter

WIMP scattering	WIMP production	WIMP annihilation

Massive underground detectors, accelerators, and astroparticle observations.

18: Underground detection

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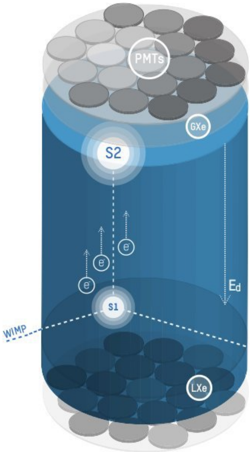

Detector in “deep” lab (no CosmicRay background)
Large (currently, 3.5 Ton) liquid Xenon bath
Free of radiation, and “self-shielding”
Dense (3.6g/cc), pure (noble), efficient scintillator
Wire up to provide uniform electric field.
Scattering produces scintillation light + charges
Light read out promptly by PhotoMultiplierTubes
Charges “drift” To surface, escape, cascade
Second light flash – 3D event reconstruction

Sensitive down to few KeV energy – needed, as $E \sim mv^2$ and $v/c \sim 10^{-3}$

19: Other Dark Matter candidates?

Of course! There are plenty!

- Huge range of non-SUSY WIMP candidates
- Axions – my favorite. 20 μeV mass, coherent Bose condensate. Solves a problem with QCD. Active observational campaign
- ALP – axion-like particle. Less-motivated generalization
- WIMPzilla – superheavy WIMP. Almost unobservable
- Gravitino – extremely weak interactions
- Q-balls . . . don't ask
- Primordial black holes? Actually almost ruled out!
- Your Favorite Candidate Here

20: Grand Unified Theories

Standard model is strange: $SU(3) \times SU(2) \times U(1)$ product group.
In a Grand Unified Theory, they merge together into a big but simple group, $SU(5)$.

$$SU(5): \quad \begin{bmatrix} g & g & g & Y & X \\ g & g & g & Y & X \\ g & g & g & Y & X \\ Y & Y & Y & W & W \\ X & X & X & W & W \end{bmatrix}$$

Gluons are 3×3 block, W are 2×2, B is on diagonal, and *new, colored and flavored* bosons X, Y fill in the other 12 spots. Couple a quark to a quark or lepton!

$$u \to \overline{d} Y^{+1/3}, \quad Y^{+1/3} \to \overline{u} e^{+}$$

Allows, eg, $p \to e^{+} \pi^{+} \pi^{-}$

21: Proton lifetime?

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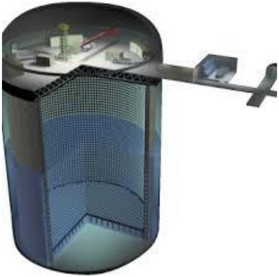
Feynman diagram a lot like W-mediated decay:

$$\Gamma \sim \frac{\alpha^2 m_p^5}{192\pi M_Y^4} \sim \left(\frac{10^{15}\ \mathrm{GeV}}{M_Y}\right)^4 \frac{1}{10^{33}\ \mathrm{years}}$$

If M_Y is 10^3 GeV, proton decays in nanoseconds.
For 10^{14} GeV, the scale we saw in neutrino oscillations, it's 10^{29} years.
Sounds safe, but it isn't!

22: Proton stability?

Introducing the SuperKamiokande Experiment!



50,000 tons of ultrapure water, 1km under mountain, with photodetectors.
Looks for Ćerenkov flashes from high-energy particles.
Sees gammas, cosmic ray μ, ν, and p-instability decay products.
Limits: $p \to e^+\pi^0$ lifetime $\tau > 1.6 \times 10^{34}$ years.

23: Summary for today

Important avenues to improve our understanding of Standard Model:

- Get better at handling QCD, at low and at high energies
- Improve understanding of neutrino masses and oscillations

Physics which is *not* in the Standard Model?

- There must be! Robust evidence of Dark Matter
- Motivation: Hierarchy problem. Why isn't Higgs boson heavier?
- Supersymmetry: interesting structure, no experimental evidence
- WIMP: generic prediction and good Dark Matter candidate
- Plethora of other Dark Matter candidates
- Grand Unified Theory and Proton decay: still untested ideas.

24: My Thank-You

You have been more than patient with me through the semester

I know I tried to do too much. But somehow you hung on.

I hope you learned something

I look forward to meeting you all IN PERSON some day, maybe late summer?