The Intensity Frontier

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The Project X Physics Study
will engage theorists, experimenters,
and accelerator scientists in establishing
and documenting a comprehensive vision
of the physics opportunities at Project X,
and integrating these opportunities within a
coherent plan for development of detector
capabilities and the accelerator complex.

Working Groups
Long-Baseline Neutrinos
Short-Baseline Neutrinos
Muon Experiments
Kaon Experiments
Electric Dipole Moments
Neutron-Antineutron Oscillations
Lattice QCD
High Rate Precision Photon Calorimetry
Very Low-Mass High-Rate Charged Particle Tracking
Time-of-Flight System Performance Below 10 psec
High-Precision Measurement of Neutrino Interactions
Large-Area Cost Effective Detector Technologies

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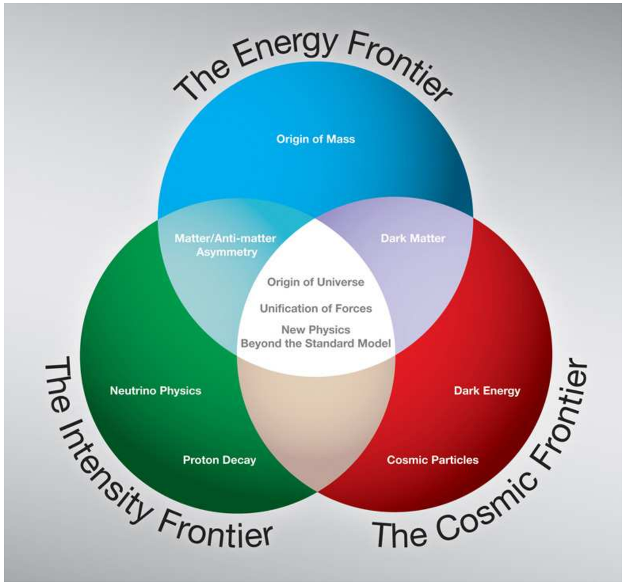


The big picture

Not my best quote ever, but now I have a chance to explain:

> Unlike everyone else, for us one plus one is not one, for us it is more like four

Together is better

Outline

- Introduction: The big picture
- Baryogenesis: CMB, LHC, Mesons, neutrinos, EDM
- Specific processes and their connections (partial list!)
  - $K \to \pi\nu\bar{\nu}$
  - CPV in charm
  - EDMs
  - Proton and dinucleon decays
  - $n - \bar{n}$ oscillation
  - μ to e
  - Neutrino oscillations and NSI
- Conclusions

The Big Picture

What is HEP

Very simple question

$$\boxed{\mathcal{L} = ?}$$

Not a very simple answer

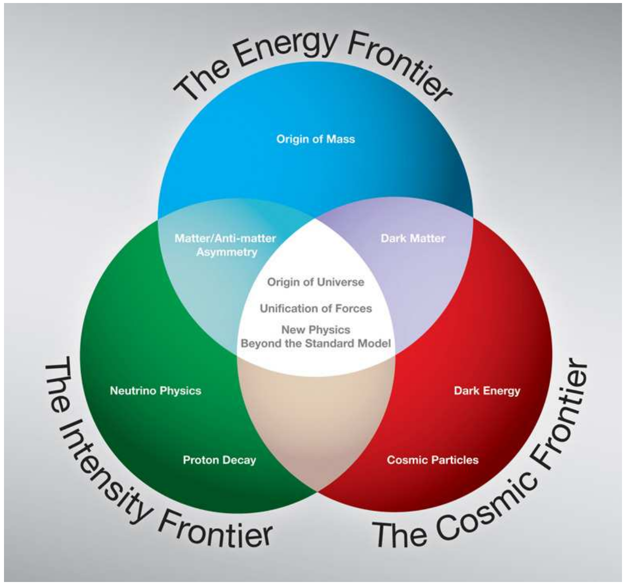
- The SM works great! (in fact too well)
- Still some open issues that we are after

Open problems (not a full list!)

Different kinds of “problems”

- Hierarchy problems
  - The cosmological constant problem
  - The weak hierarchy problem
  - The strong CP problem
  - The flavor problem
- Unexplained experimental facts (too many explanations)
  - Fermion and gauge boson masses (?!)
  - Baryogenesis
  - Dark matter
  - Dark energy
  - Neutrino masses

How to “answer” these problems



- Energy frontier: high energies with colliders
- Intensity frontier: rare processes and small effects
- Cosmic frontier: look up the sky

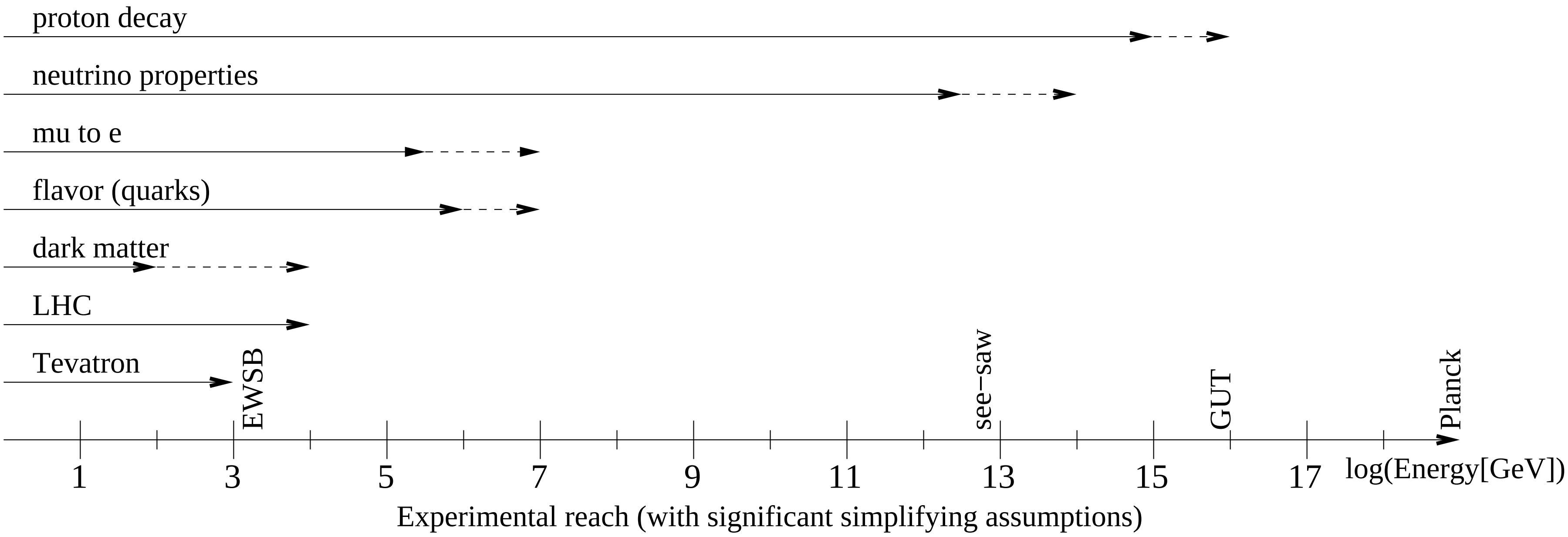
How can we make the picture more technical?

How do we answer these questions?

Ideas from the Intensity frontier, then directly from the Energy frontier

- Past examples: charm and top. First via kaon and B mixing, then directly
- present example: Higgs. First EWPM, now(?) directly
- future example: (maybe) $g-2$, CPV in charm, ...
- Never example: (maybe) Neutrino masses, GUT

The Zoltan plot



Disclaimer: This is a very rough cartoon

Connections and Complementarity

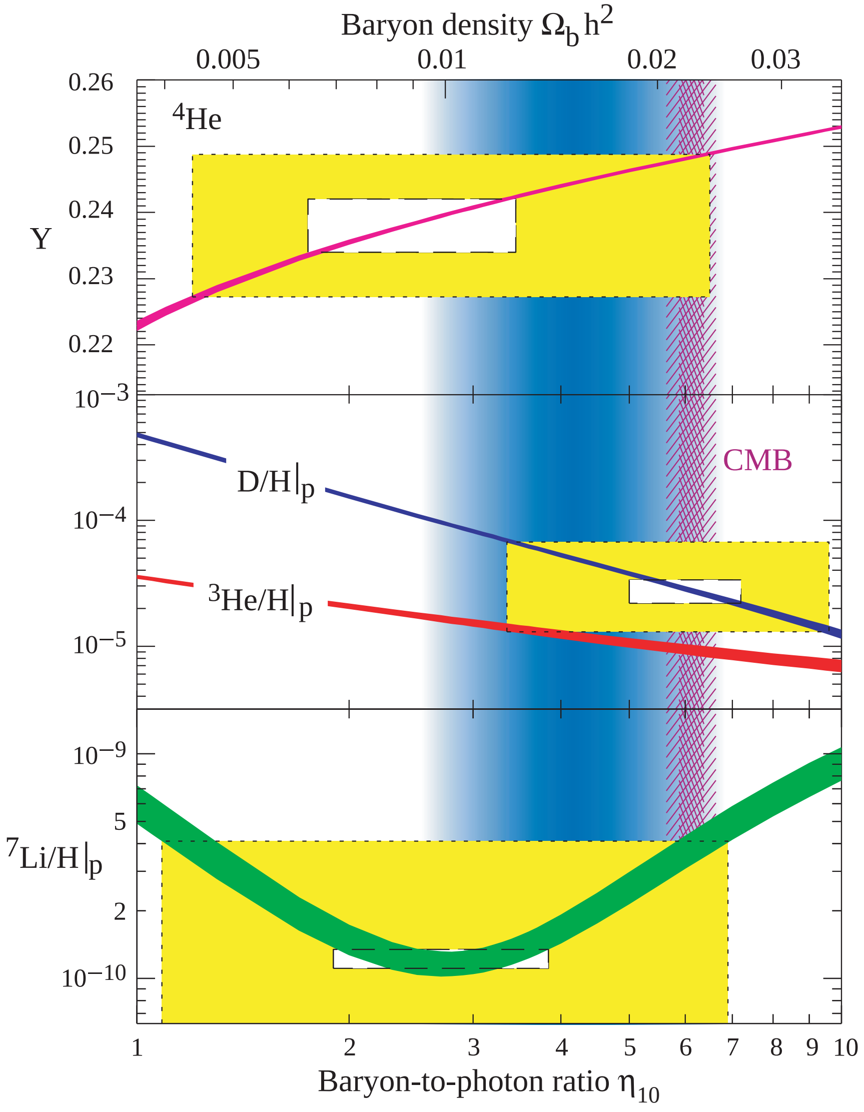
We all have limitations:

- Energy frontier: Can find new particles. Yet, limited by energy
- Intensity frontier: Can find new physics up to very high scale, but can never tell all their properties
- The more information we get, more we can pin down the new physics

Lets get intense!

Baryogenesis

Cosmology and particle physics



- Particle physics and cosmology are connected
- BBN and CMB tell us

$$\eta = \frac{n_B}{n_\gamma} \sim 10^{-10}$$

Sakharov's conditions

Sakharov's conditions for dynamically generated baryon asymmetry

- Baryon number violating process

$$X \to p^+ e^-$$

- C and CP violation

$$\Gamma(X \to p^+ e^-) \neq \Gamma(\overline{X} \to p^- e^+)$$

- Deviation from thermal equilibrium

$$\Gamma(X \to p^+ e^-) \neq \Gamma(p^+ e^- \to X)$$

SM baryogenesis

The three Sakharov conditions are satisfied in the SM

- Baryon number violating process: sphalerons
- The weak interaction violates C and CP
- Out of equilibrium at the electroweak phase transition

The SM, however, predicts not enough baryons

$$\eta_{\rm SM} \sim 10^{-20} \ll 10^{-10}$$

Baryogenesis: The problem

- The SM cannot explain the data
- The problem: too many solutions!
  - GUT
  - SUSY
  - Other new states at the TeV
  - leptogenesis

How can we tell?

How to find why we are here?

- Looking for CPV in super-flavor factories...
- With the emerging value of θ_{13}, CPV experiments...
- Looking for light stops is very important and...
- Proton decay experiments, can be used to probe the physics of baryon number violation and...
- EDM experiments are looking for flavor diagonal CPV effects. As such, they...
- $n-\bar{n}$ oscillation and dinucleon decay are sensitive to baryon number violation and...

can shed light on baryogenesis

We need it all!

Baryogenesis is an example of a deep question that we probe from all directions

- From cosmology we get the number, and other cosmological parameters that may be related (like DM)
- From the energy frontier we probe EW baryogenesis. We look for new particles that can be used to get the phase transition and CPV
- In the Intensity frontier we look for low energy CPV in mesons, neutrinos and EDMs

We need it all to probe this question

Relation to hadrons and energy frontier

The NP flavor problem

There is tension:

- The hierarchy problem $\Rightarrow\ \Lambda \sim 1$ TeV
- Flavor bounds $\Rightarrow\ \Lambda \gtrsim 10^4$ TeV

This tension is the NP flavor problem

Any TeV scale NP has to deal with the flavor bounds

$$\Downarrow$$

Such NP cannot have a generic flavor structure

Solution to the NP flavor problem

- No NP at the TeV
- There must be a structure in the TeV NP
  - Degeneracy
  - Alignment
  - Only top partners are light

Even if we find NP at the LHC, we have a problem

The inverse LHC problem

The inverse LHC problem

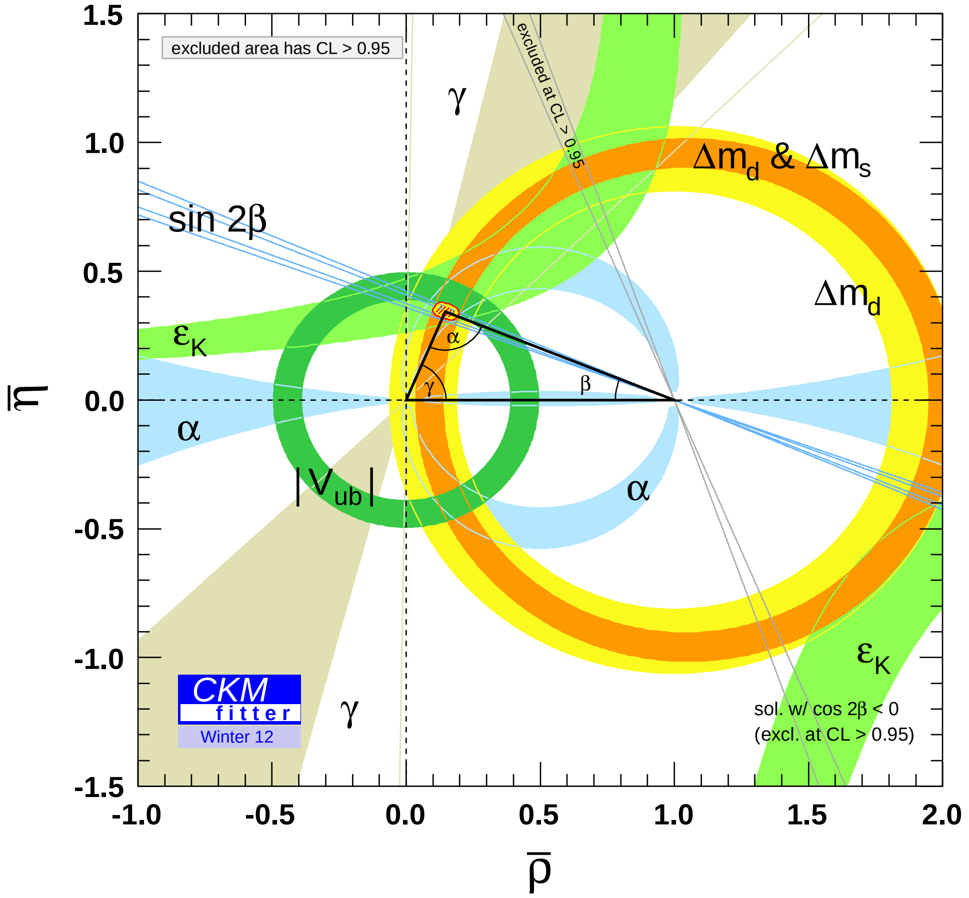
A scenario

- The LHC finds NP :-)
- There are many more models than data points
- We still do not know the right model :-(
- Intensity frontier can help! More points to pin down the NP :-))

- $g-2$ as an example
- The prime example of indirect probe of new physics
- Complementary to energy frontier. LHC and $g-2$ can give much better control of $\tan\beta$

Within quarks

The UT: working together



The overall goal for the future

- Overconstraining the UT and looking for disagreement
- B: looking of γ via $B \to DK$
- Kaon: β via $K \to \pi\nu\bar{\nu}$
- Charm: CPV is SCS decay. Is it SM or NP?

$K \to \pi\nu\bar{\nu}$

- Very clean process (well, nothing to see...)
- Sensitive to CPV in the $K_L \to \pi^0\nu\bar{\nu}$ decay
- The combination can give us β
- Different sensitivity compare to B physics. NP could affect them differently

CPV in charm

The biggest news from the LHC came from charm

$$\mathcal{A}_{CP}(D \to f) \equiv \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

The data:

$$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(D \to K^+K^-) - \mathcal{A}_{CP}(D \to \pi^+\pi^-)$$

$$= (-0.656 \pm 0.154)\%$$ World average

$\sim 4\sigma$ from zero

Systematic? Statistics? NP? SM?

Baryons

Proton decay

I feel it in my bones

Is it?

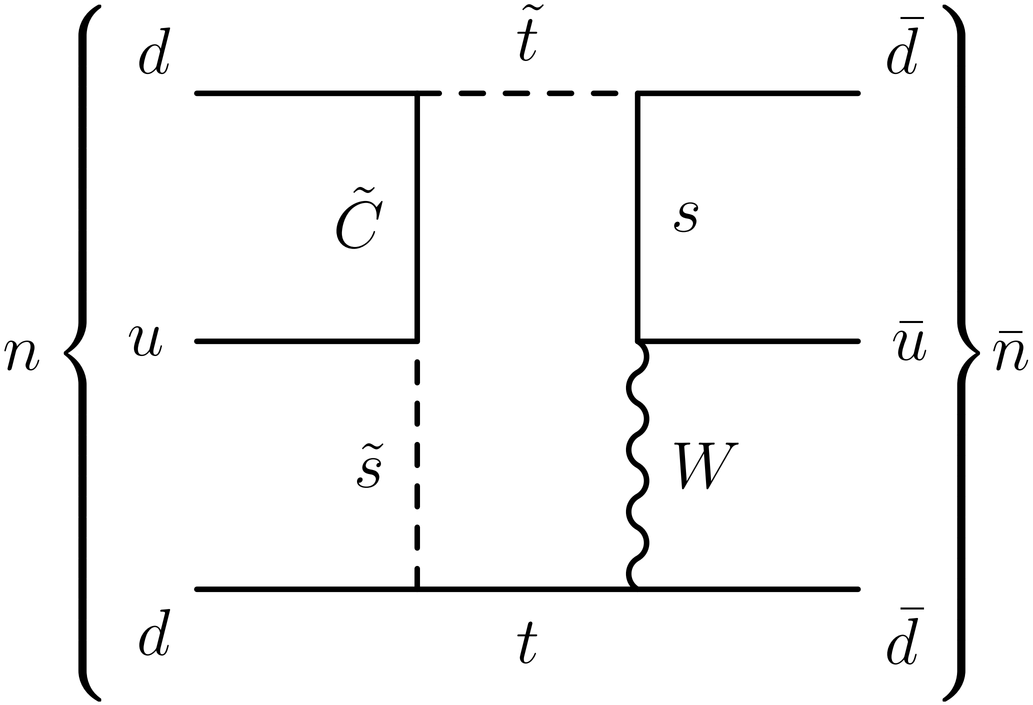
- A sign that baryon number is conserved
- A sign that baryon number is violated

We do not talk much about it. Yet, the motivation for looking for it is there. Our best probe of GUT

$n - \bar{n}$ oscillation

- Sensitive to $\Delta B = 2$ operators
- Unlike proton decay, no need to violate lepton number
- Complementary to proton decay
- Two kinds of experiments: “free” neutrons and “bound” neutrons
- Different mixing angle and different lifetime
  - free: large mixing, short lifetime
  - bound: small mixing, long lifetime

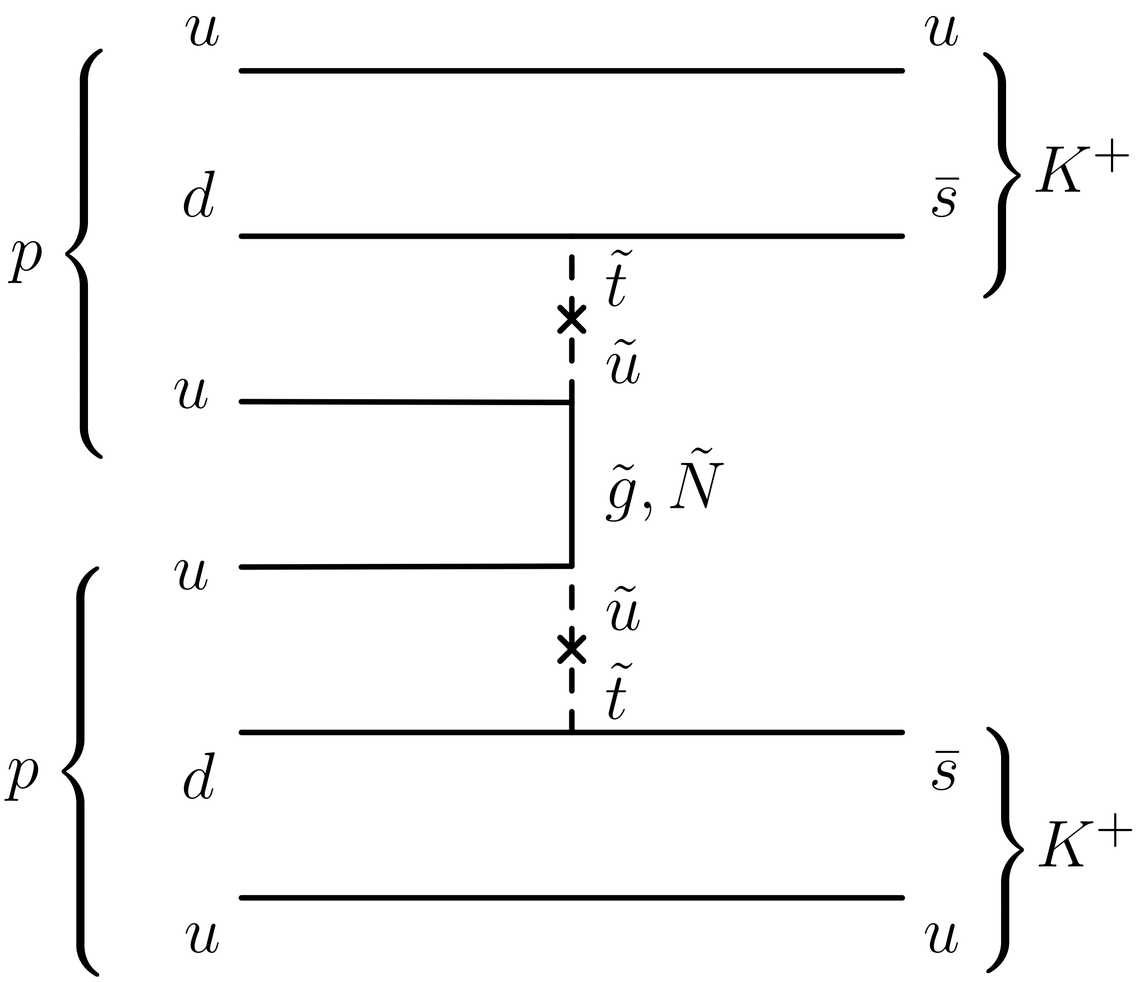
$n - \bar{n}$ oscillation



Dinucleon decay

- $\Delta B = 2$ and lepton number conservation
- In terms of physics similar to $n - \bar{n}$ oscillation
- Yet, again, complementary. Can involve different operators and flavors
- Nuclear physics (hadronic) uncertainties

Dinucleon decay



EDMs

- EDM of elementary particles violate CP
- Flavor diagonal CPV: Complementary to mesons CPV
- Can be generated by TeV states: Complementary to the LHC
- Even if we find such states at the LHC, it will be very hard to probe their CPV phase.
- Many elementary particles, and thus many EDMs to look for

Leptons

Interplay within the charged leptons

- There are many operators. Each mode is sensitive to a different set of them
- Example: $\mu \to e\gamma$ vs $\mu \to eee$
  - If the only diagram is photon exchange

$$\frac{\Gamma(\mu \to eee)}{\Gamma(\mu \to e\gamma)} \propto \alpha$$

  - Yet, $\mu \to eee$ can also be mediated at tree level.

Discriminating power

Neutrino oscillations

- Probing the only Dimension 5 operator in the SM $\Rightarrow$ νSM
- Are there sterile neutrinos?
- Maybe our only window to GUT
- NSI - can probe NP of the EW scale!

Is the νSM is the correct description of neutrinos?

Symmetries

- neutrino oscillations imply the breaking of lepton flavor symmetry
- Thus, we must have CLFV
- If all LFV is from m_ν, CLFV is tiny

$$\Gamma(\mu \to e\gamma) \propto \left(\frac{m_\nu}{m_W}\right)^4 \sim 10^{-54}$$

$$\boxed{\text{CLFV probe physics beyond the } \nu\text{SM}}$$

BνSM, CFLV and NSI

If we have BνSM, will it affect neutrino oscillation?

- If the new operators act on the lepton doublet it must be

$$\mathcal{A}(\tau \to \mu) \sim \mathcal{A}(\nu_\tau \to \nu_\mu) = \varepsilon$$

- For neutrino oscillation we have interference

$$\Gamma(\tau \to \mu X) \propto |\varepsilon|^2 \qquad P(\nu_\mu \to \nu_\tau) \propto |\exp(-i\Delta E t) + \varepsilon|^2$$

- For small $x = \Delta m^2 L/(2E)$ we get

$$P(\nu_\mu \to \nu_\tau) \propto |\varepsilon|^2 + x^2 + 2xIm(\varepsilon)$$

NSI in neutrinos and charged leptons

$$P(\nu_\mu \to \nu_\tau) \propto |\varepsilon|^2 + x^2 + 2xIm(\varepsilon) \qquad \Gamma(\tau \to \mu X) \propto |\varepsilon|^2$$

- It affects oscillation experiments by changing the L/E dependence
- Both neutrinos and charged leptons can be relevant (due to the linear vs quadratic)
- tau decays and neutrino oscillations are related
- Same signal if we have “heavy” sterile neutrinos. Again, complementarity

Conclusions

Conclusion: Together is better