REU Mentors Presentations
July 1 2024

Searching for New Physics at the "precision frontier"

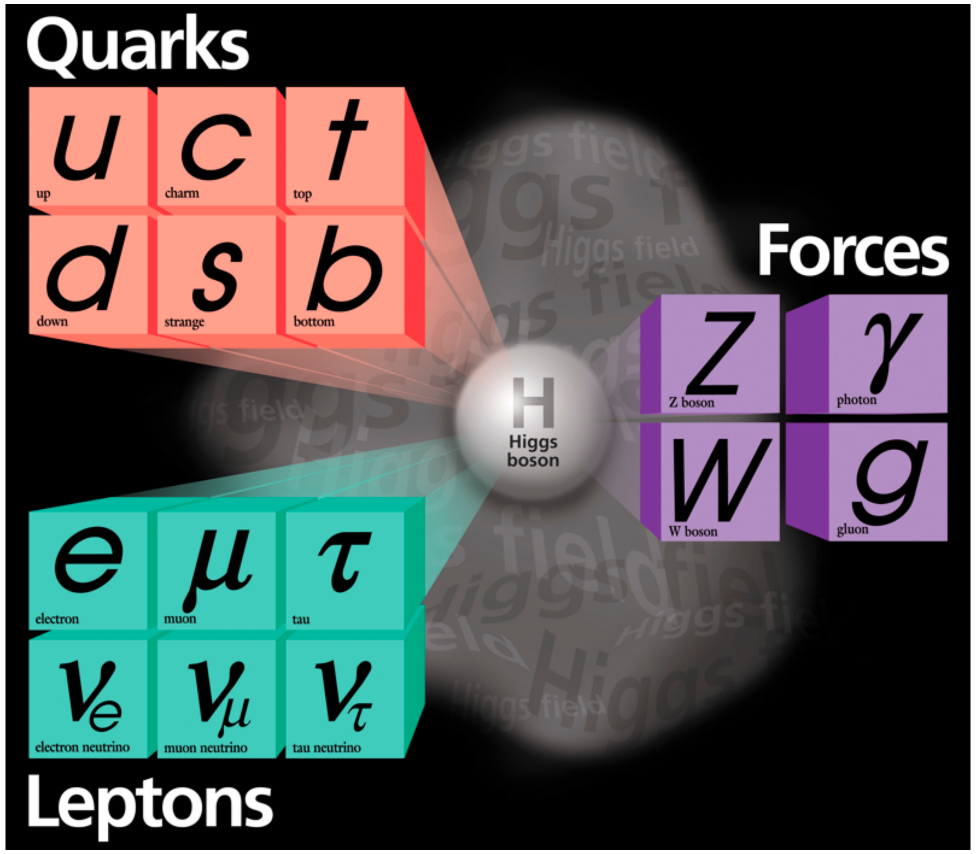
Vincenzo Cirigliano
University of Washington

INSTITUTE for NUCLEAR THEORY

Outline

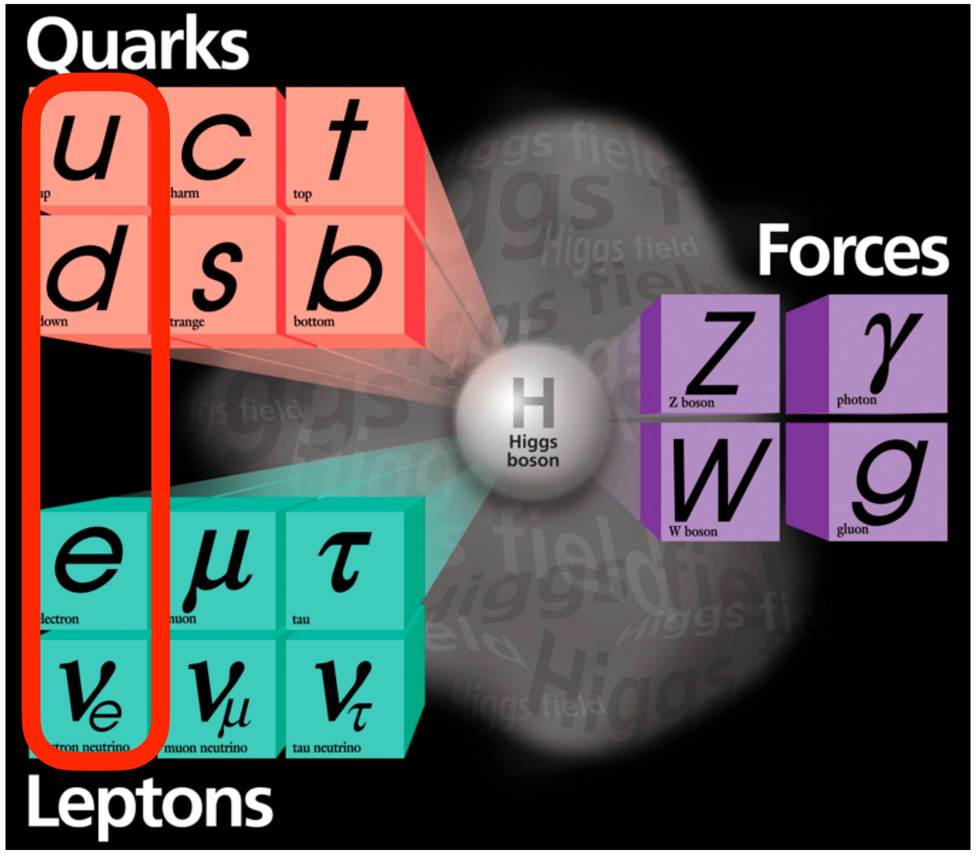
- Introduction: the Standard Model and the quest for new physics
- The ‘precision frontier’ and the role of Nuclear Science
- Selected topics from my research
- My career path

The (known) building blocks of nature



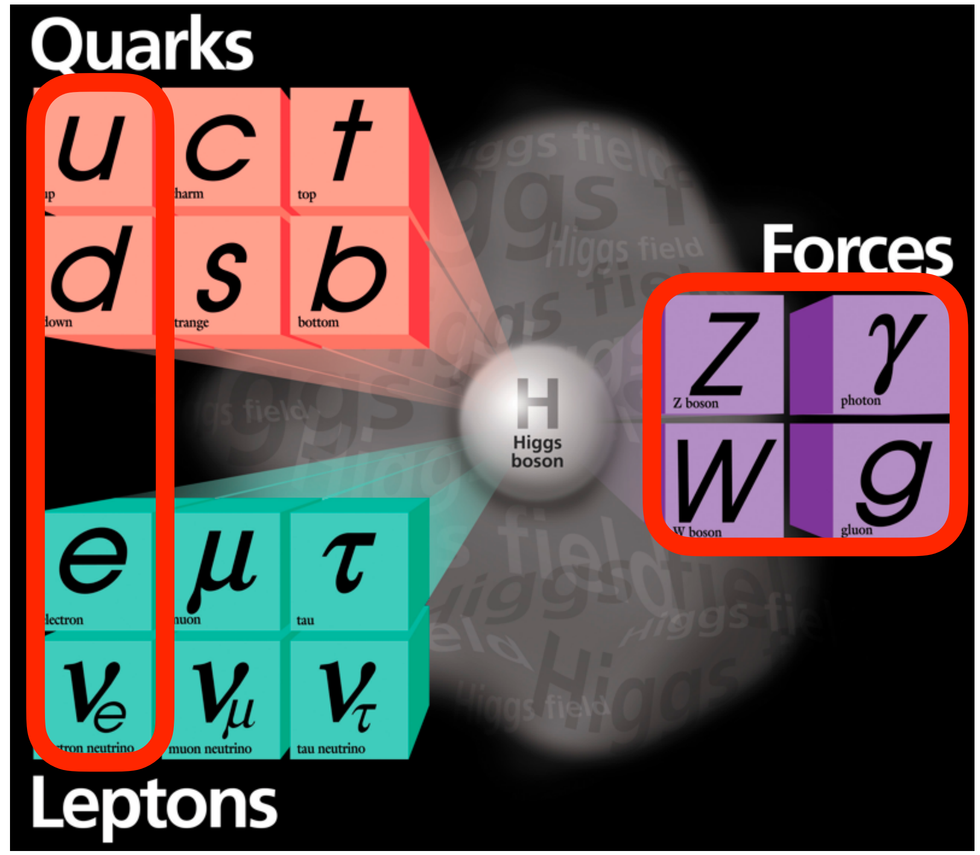
The (known) building blocks of nature

Spin 1/2:
ordinary matter
+ 2 heavier
generations

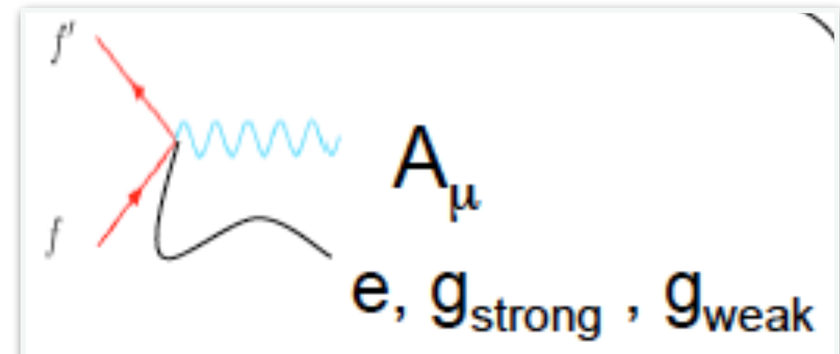


The (known) building blocks of nature

Spin 1/2:
ordinary matter
+ 2 heavier
generations



Spin 1: force carriers

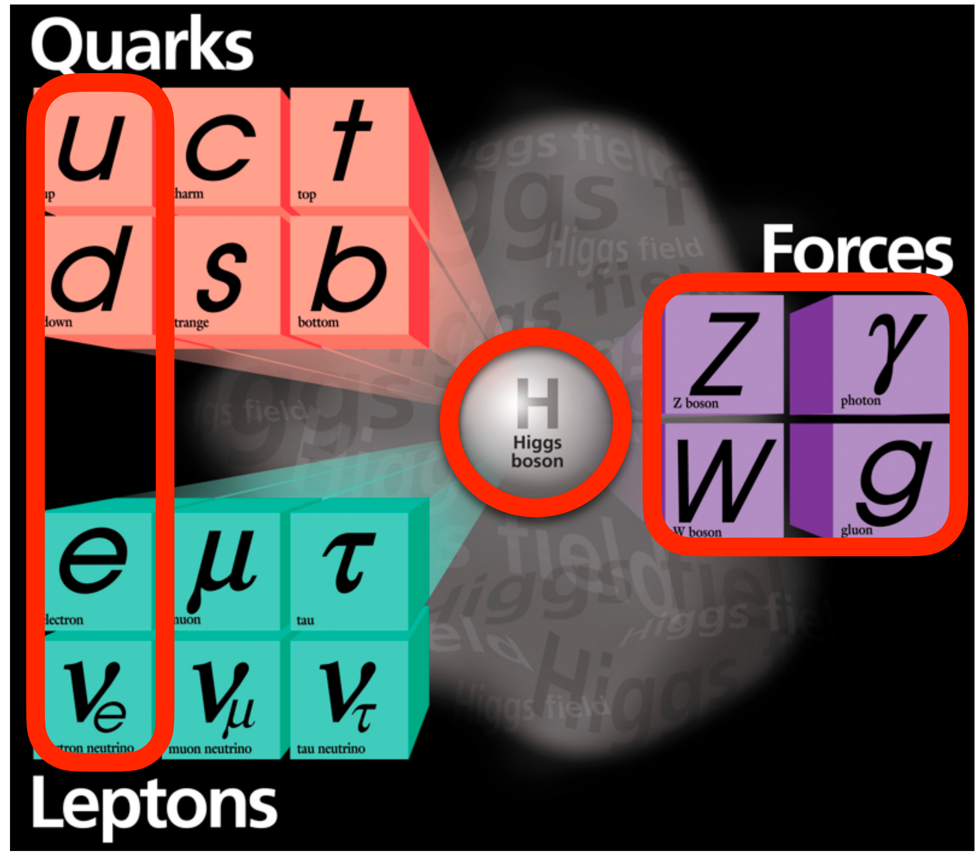


$$\mathcal{L}_I(x) \sim J_\mu(x)\, A^\mu(x)$$

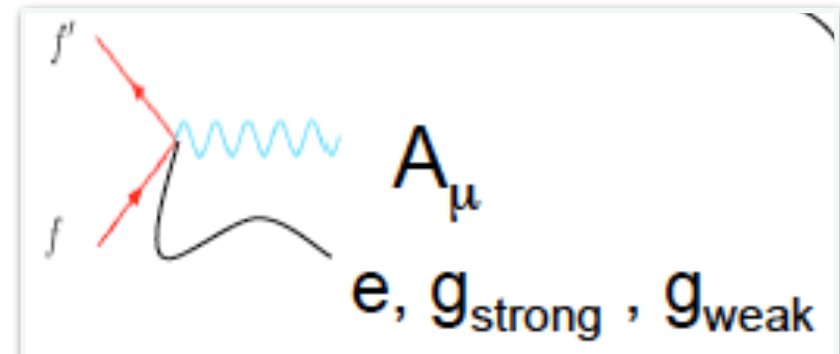
The (known) building blocks of nature

Spin 0: Higgs boson

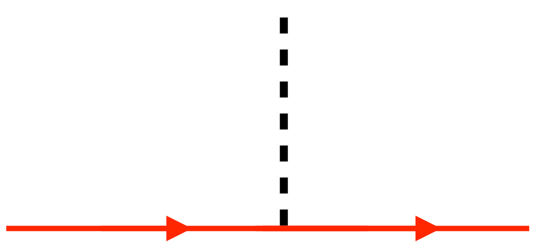
Spin 1/2:
ordinary matter
+ 2 heavier
generations

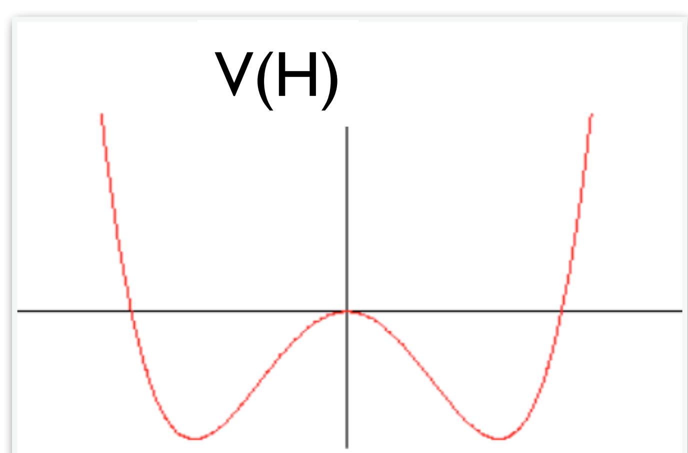


Spin 1: force carriers



$$\mathcal{L}_I(x) \sim J_\mu(x)\, A^\mu(x)$$

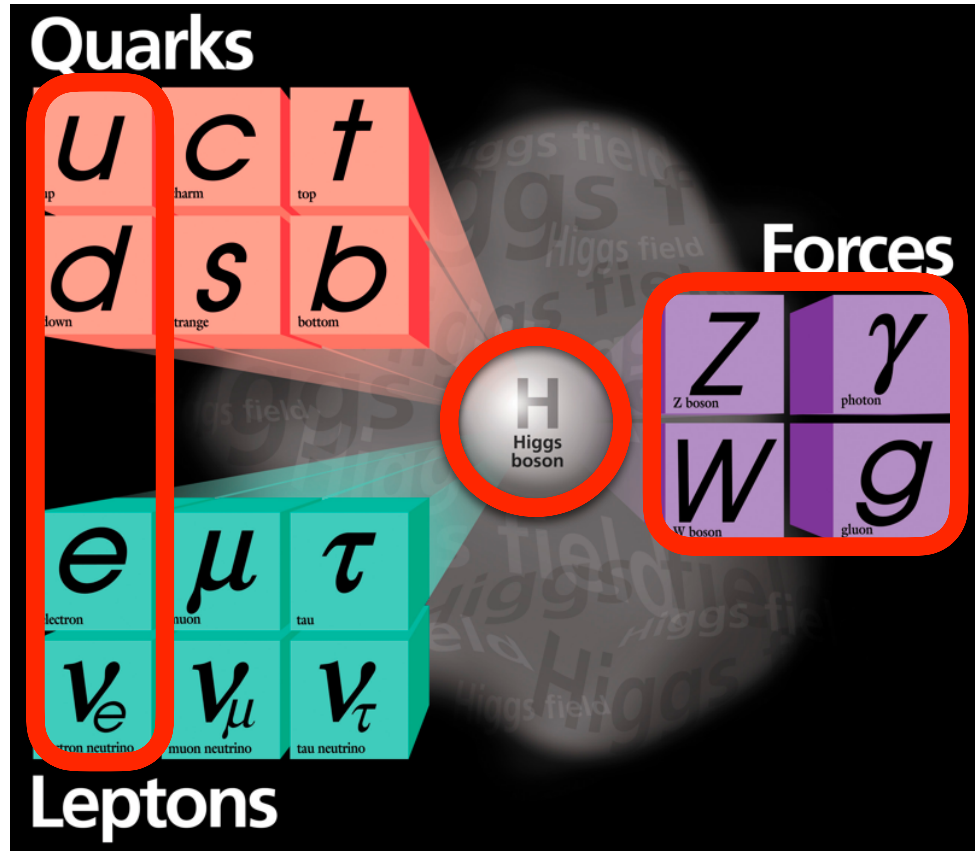




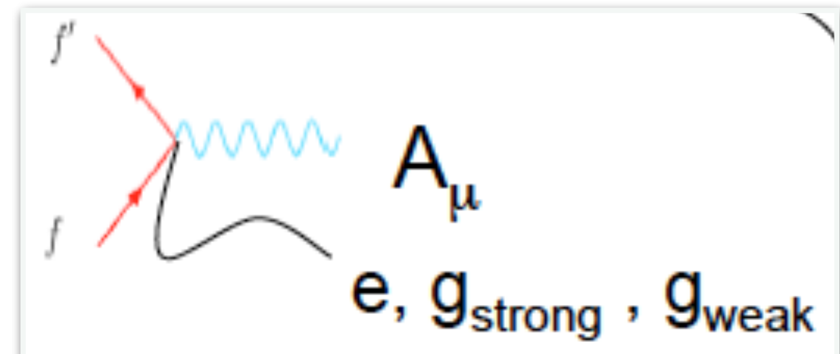
The (known) building blocks of nature

Spin 0: Higgs boson

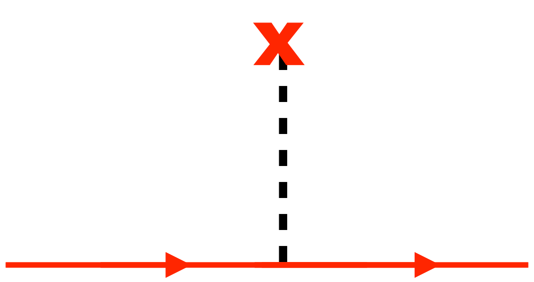
Spin 1/2:
ordinary matter
+ 2 heavier
generations



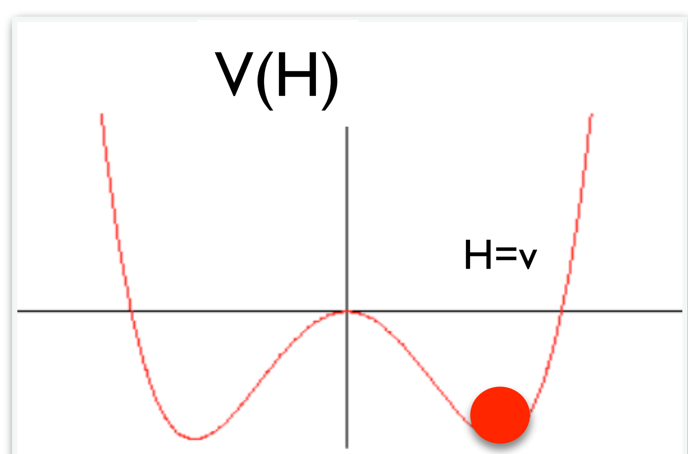
Spin 1: force carriers

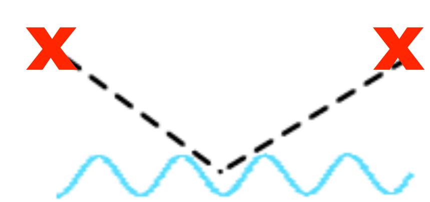


$$\mathcal{L}_I(x) \sim J_\mu(x)\, A^\mu(x)$$



Massive quarks
and leptons

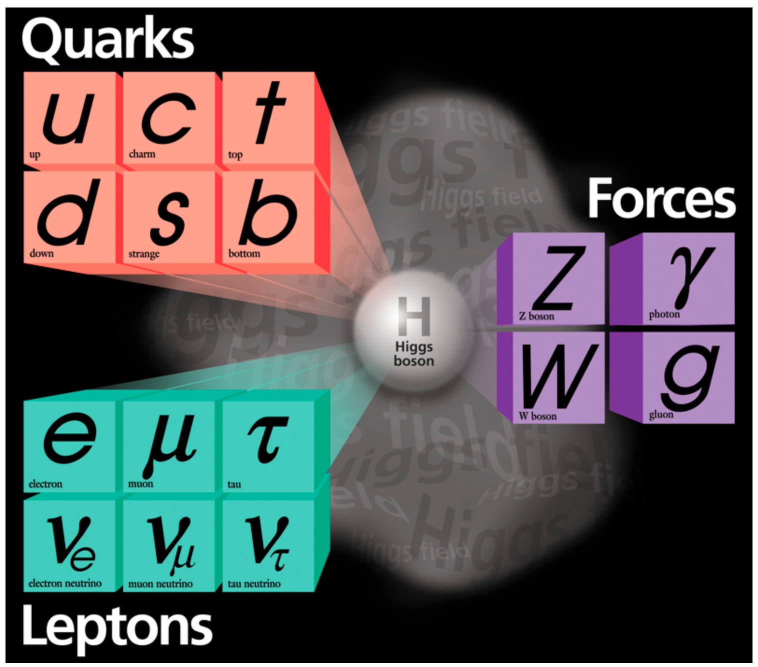


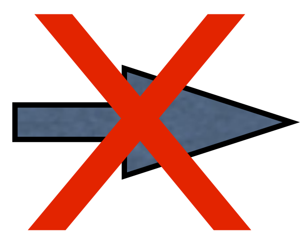


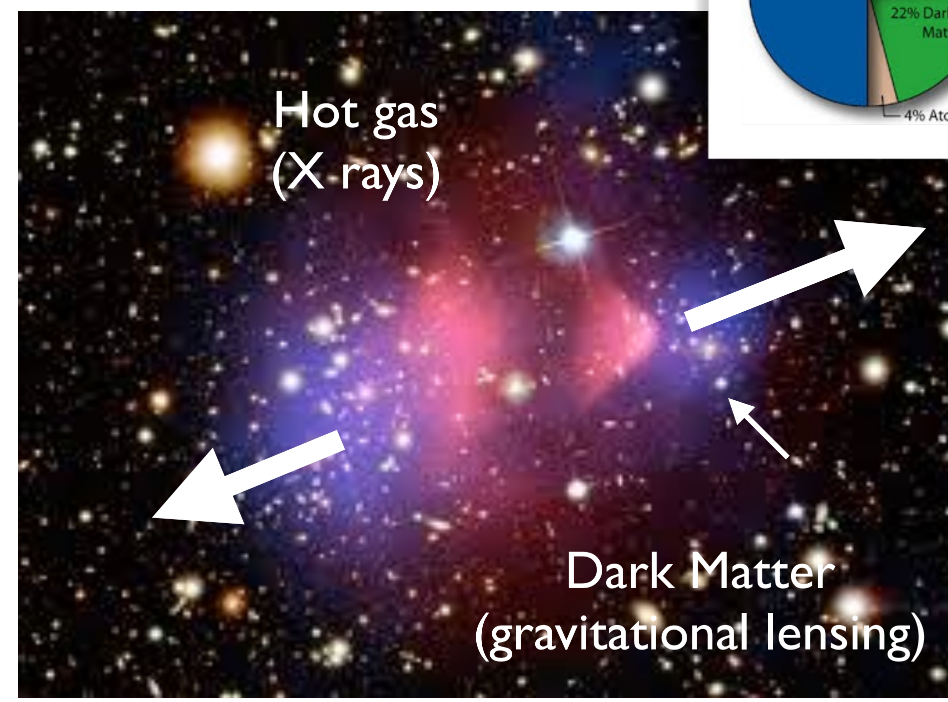
Massive EW gauge bosons
(short range weak force)

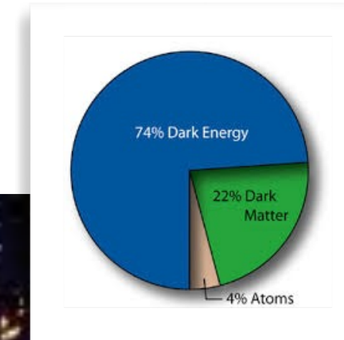
New physics: why?

- The Standard Model is remarkably successful, but …









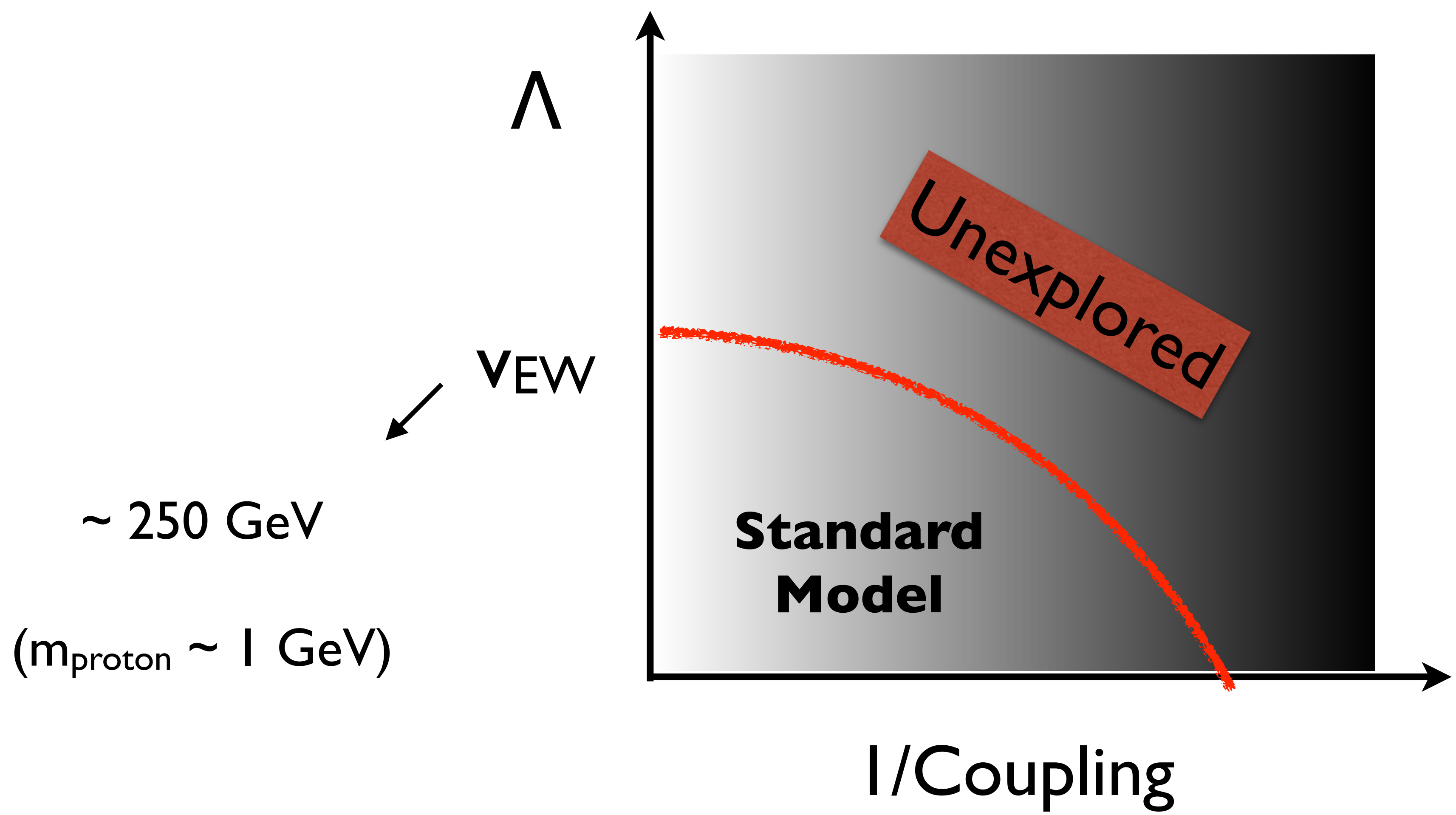
No Baryonic Matter, no Dark Matter, no Dark Energy, no Neutrino Mass

Do forces unify at high E? What is the origin of families? …

Addressing these puzzles requires new physics

New physics: where?

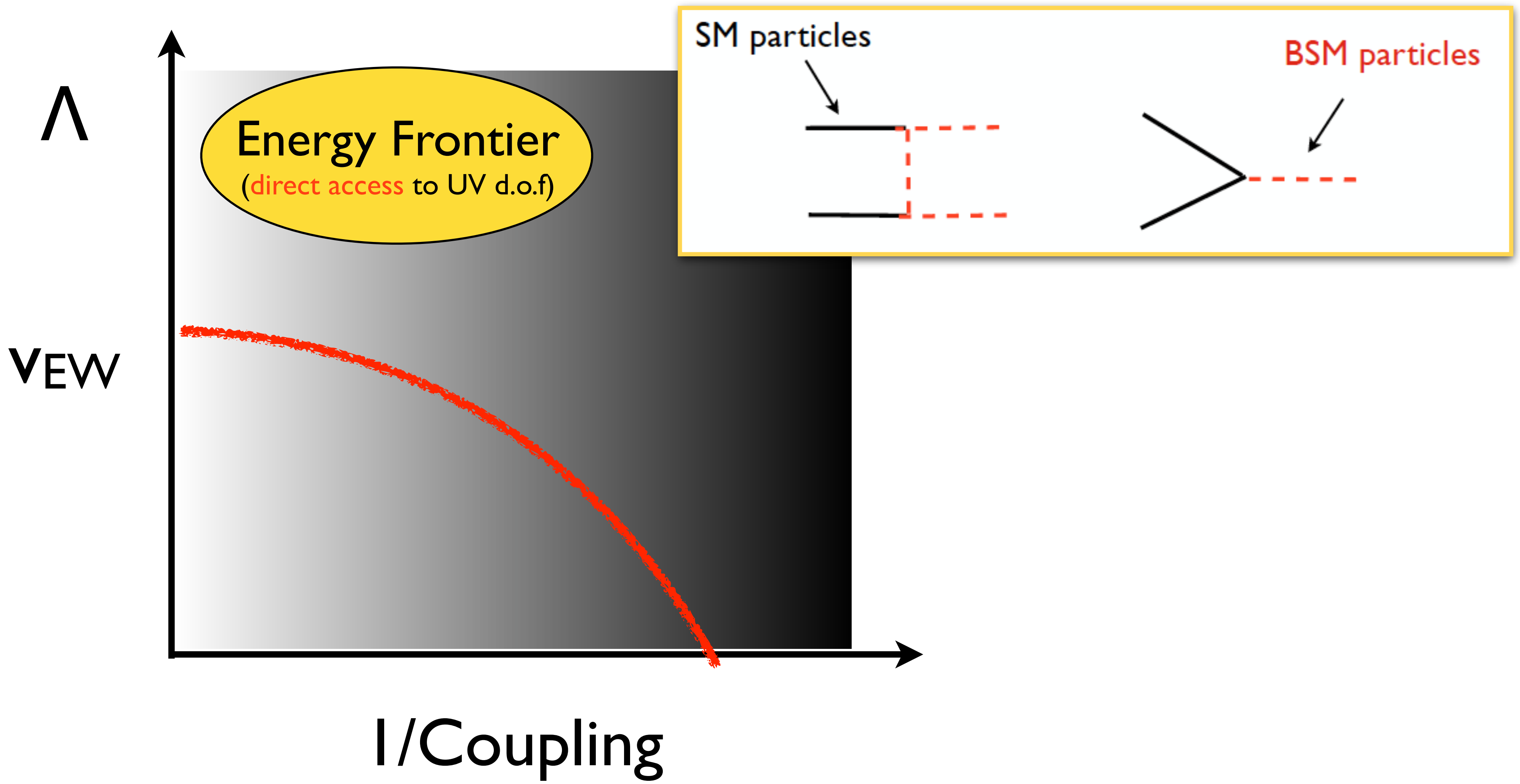
- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?



New physics: how?

- Two complementary paths to search for new physics

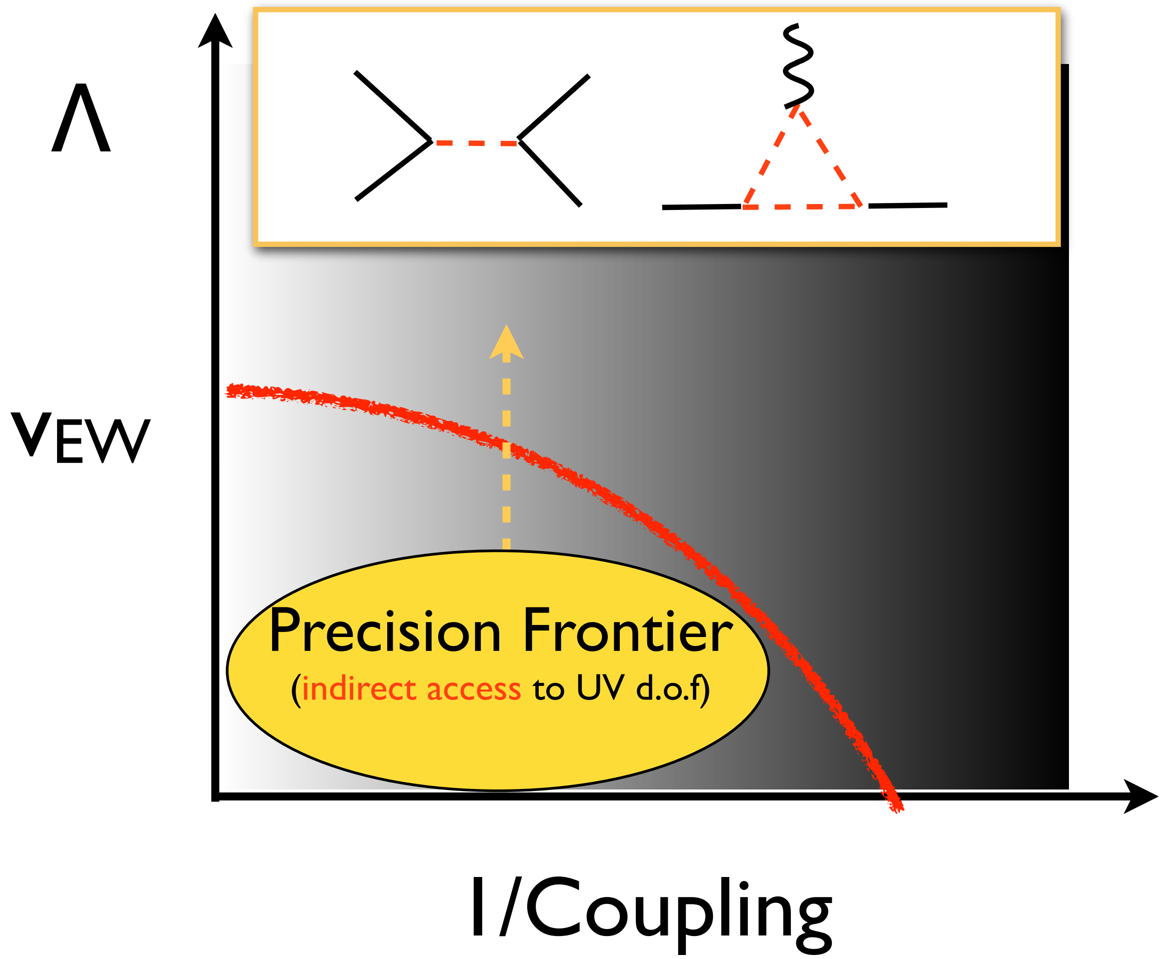
$$E = mc^2$$



New physics: how?

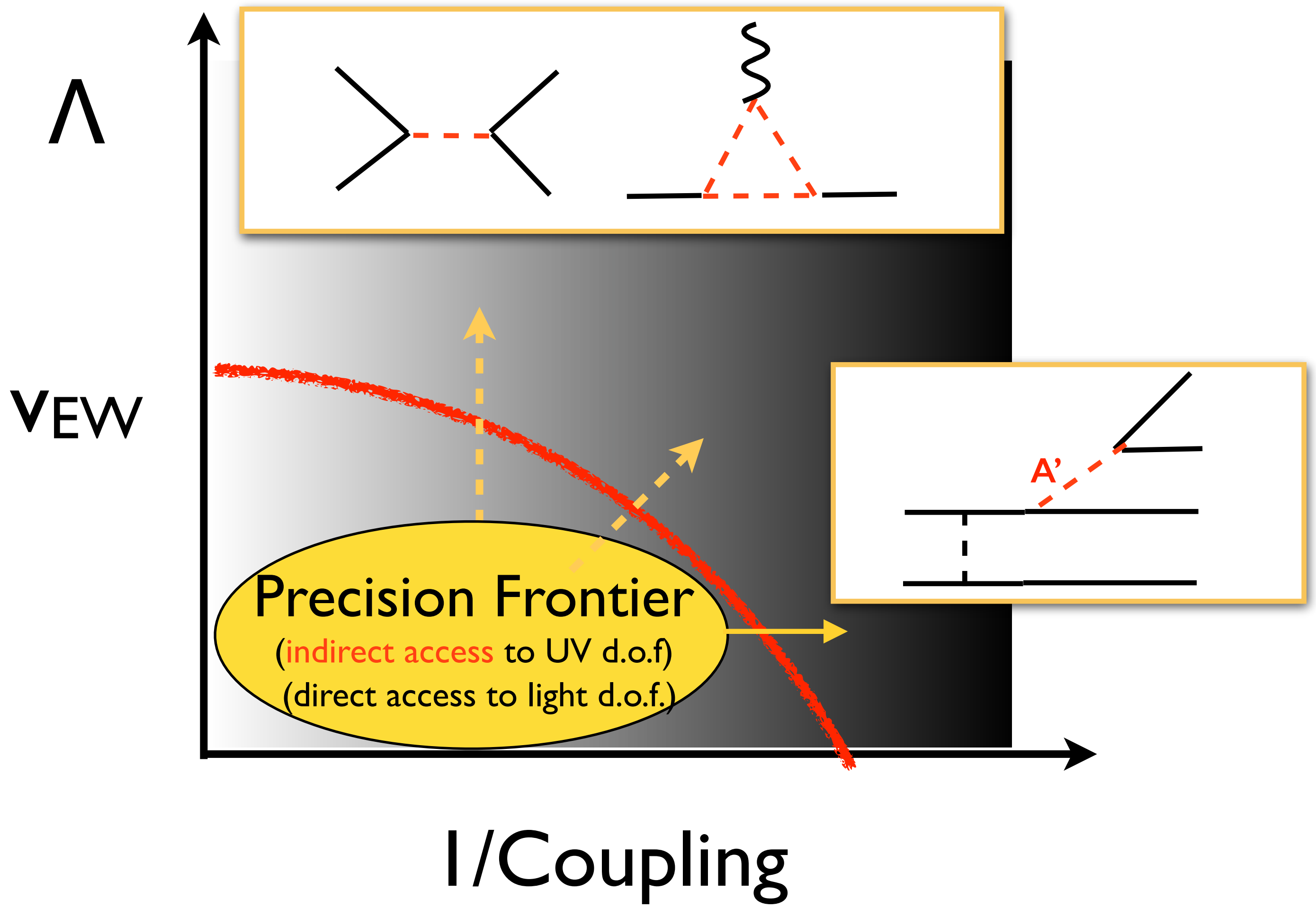
- Two complementary paths to search for new physics

$$\Delta E \, \Delta t \sim h$$



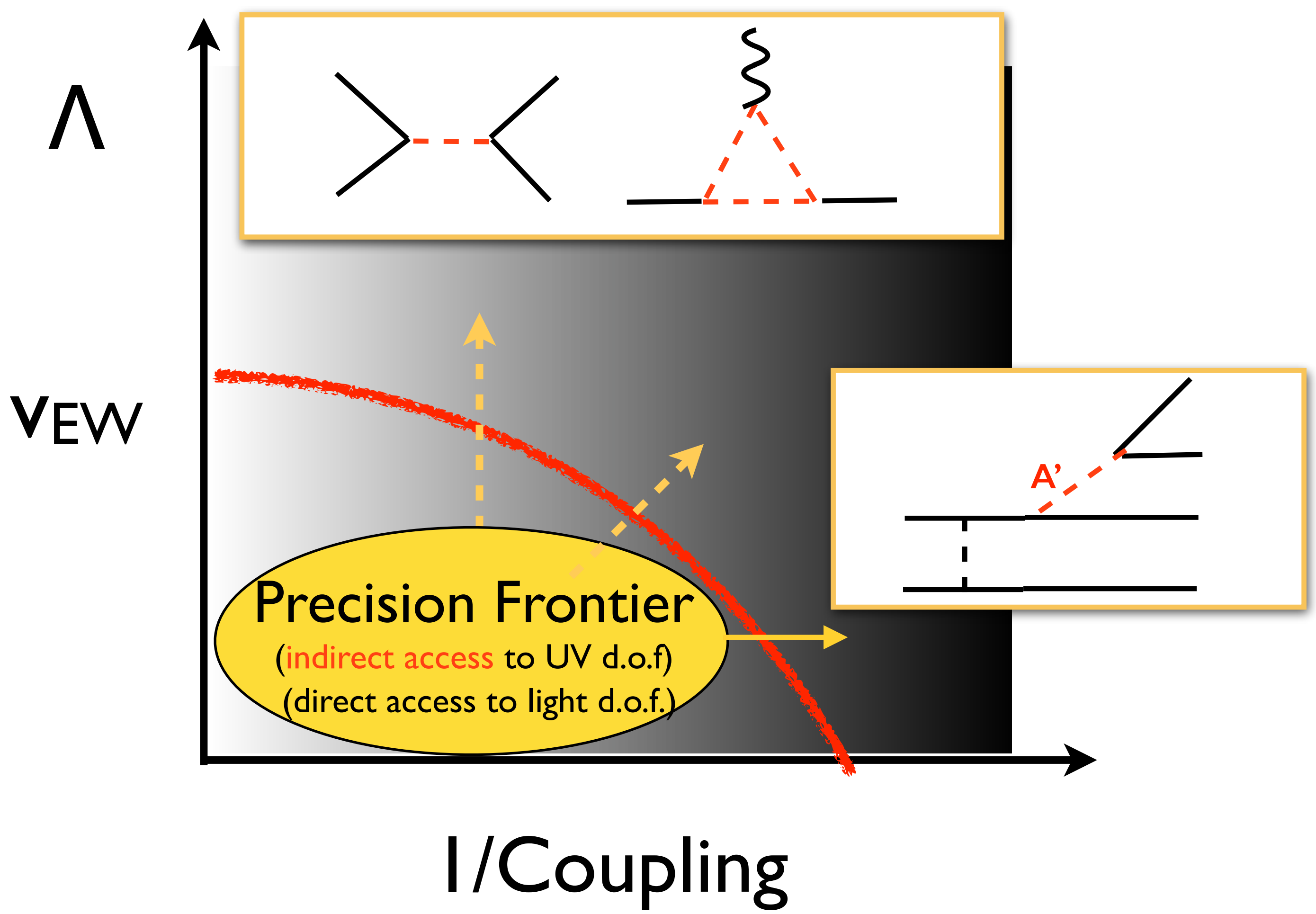
New physics: how?

- Two complementary paths to search for new physics



New physics: how?

- Two complementary paths to search for new physics

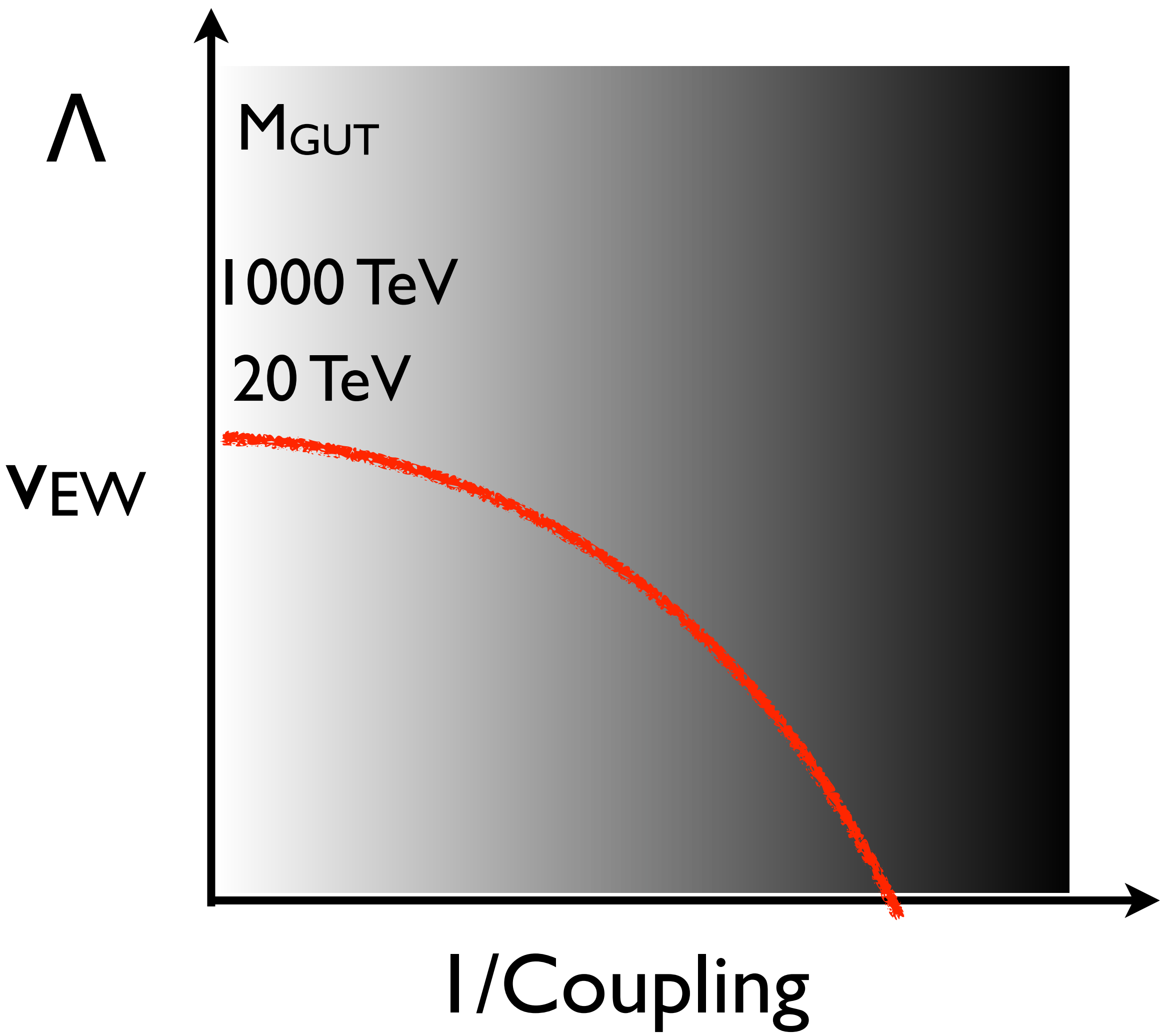


The Precision Frontier cuts across AMO, HEP & NP

Nuclear Physics plays a key role in this endeavor, through unique probes with high discovery potential

The precision frontier

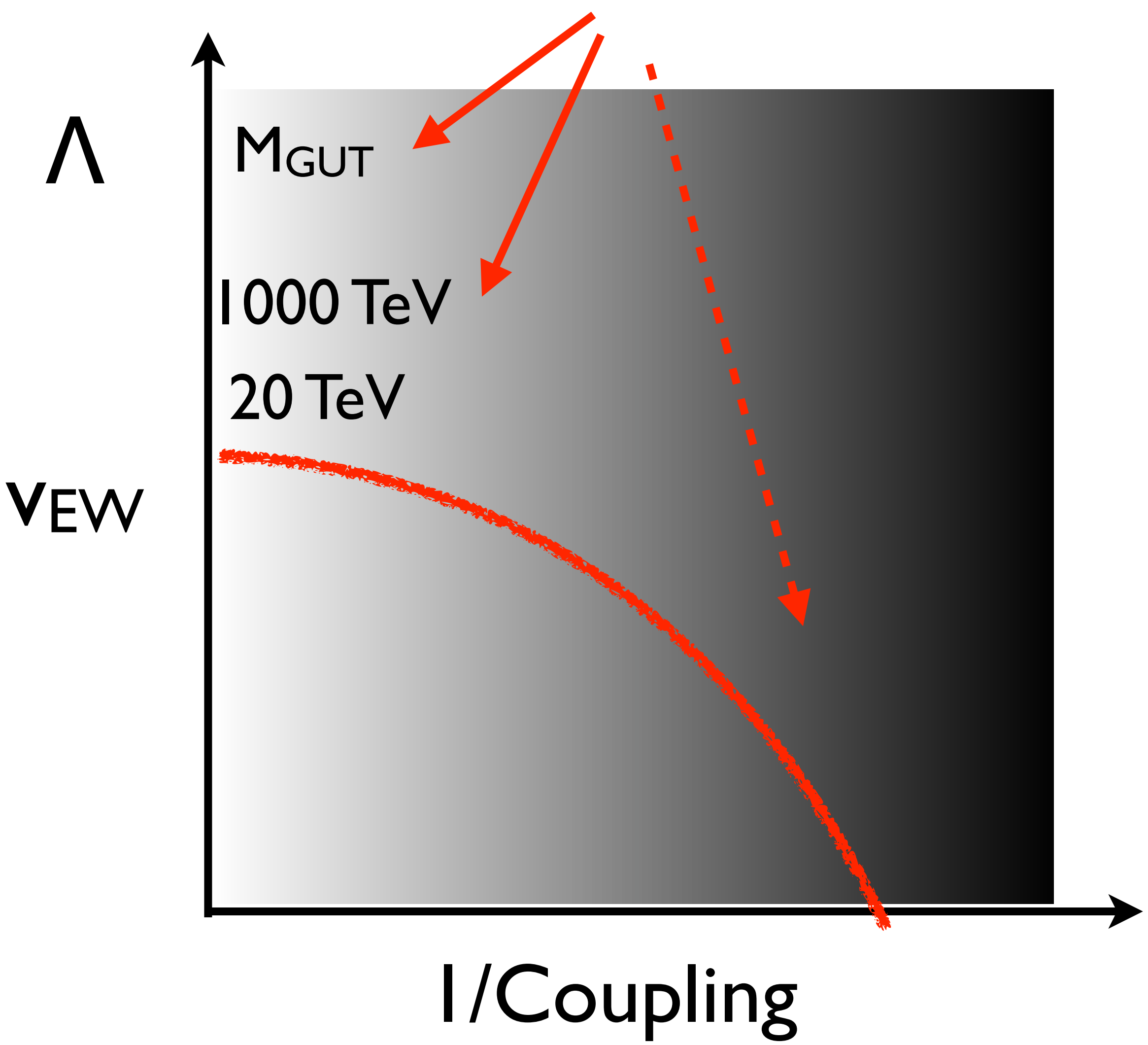
- Probes of new physics at the precision frontier can be grouped in three classes, pushing the boundary in qualitatively different ways and at different mass scales



The precision frontier

- Probes of new physics at the precision frontier can be grouped in three classes, pushing the boundary in qualitatively different ways and at different mass scales

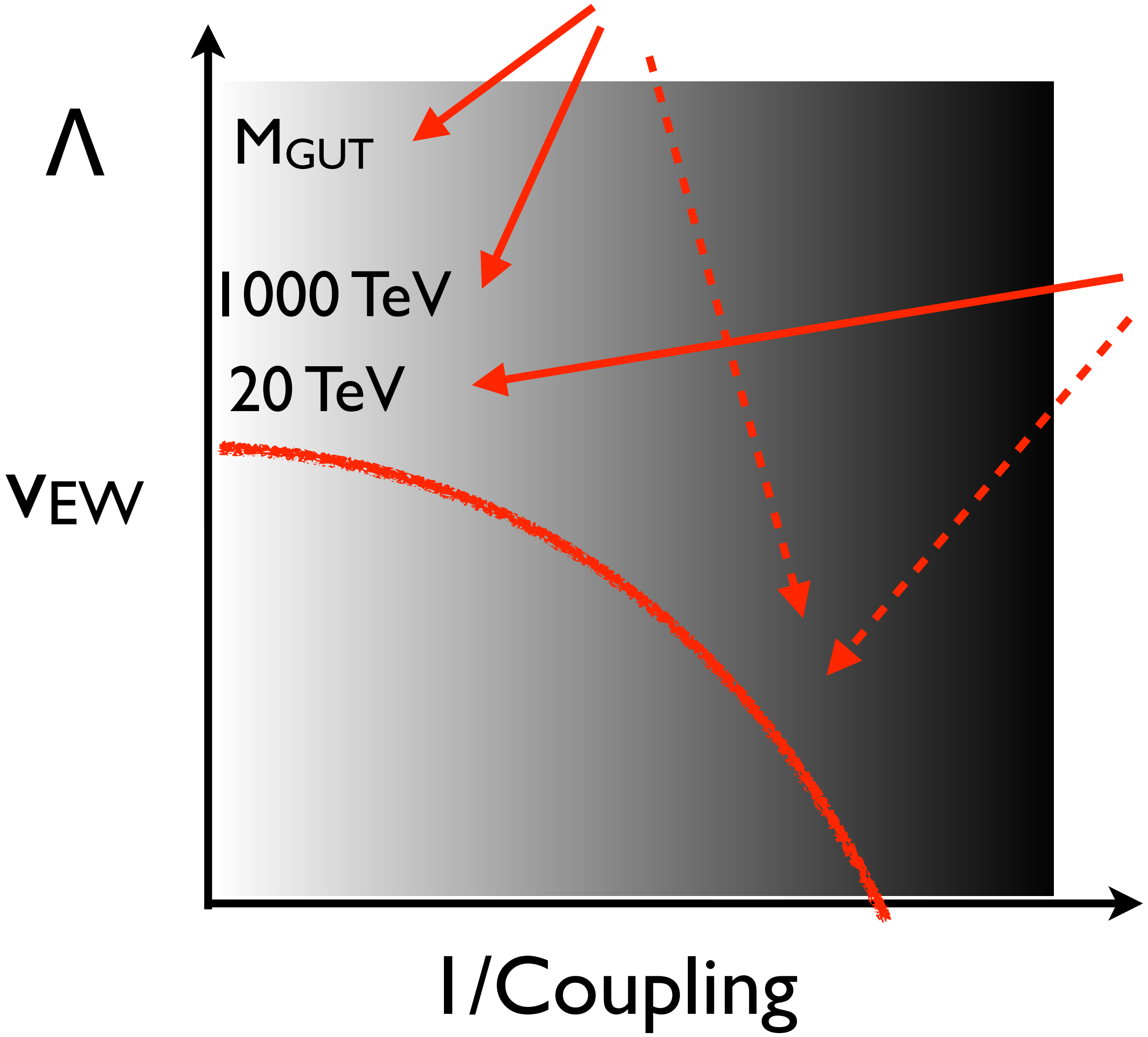
1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, EDMs, n-nbar oscillations, $\mu\to e$ conversion, $ep\to\tau X$, …



The precision frontier

- Probes of new physics at the precision frontier can be grouped in three classes, pushing the boundary in qualitatively different ways and at different mass scales

1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, EDMs, n-nbar oscillations, $\mu \to e$ conversion, $ep \to \tau X$, …

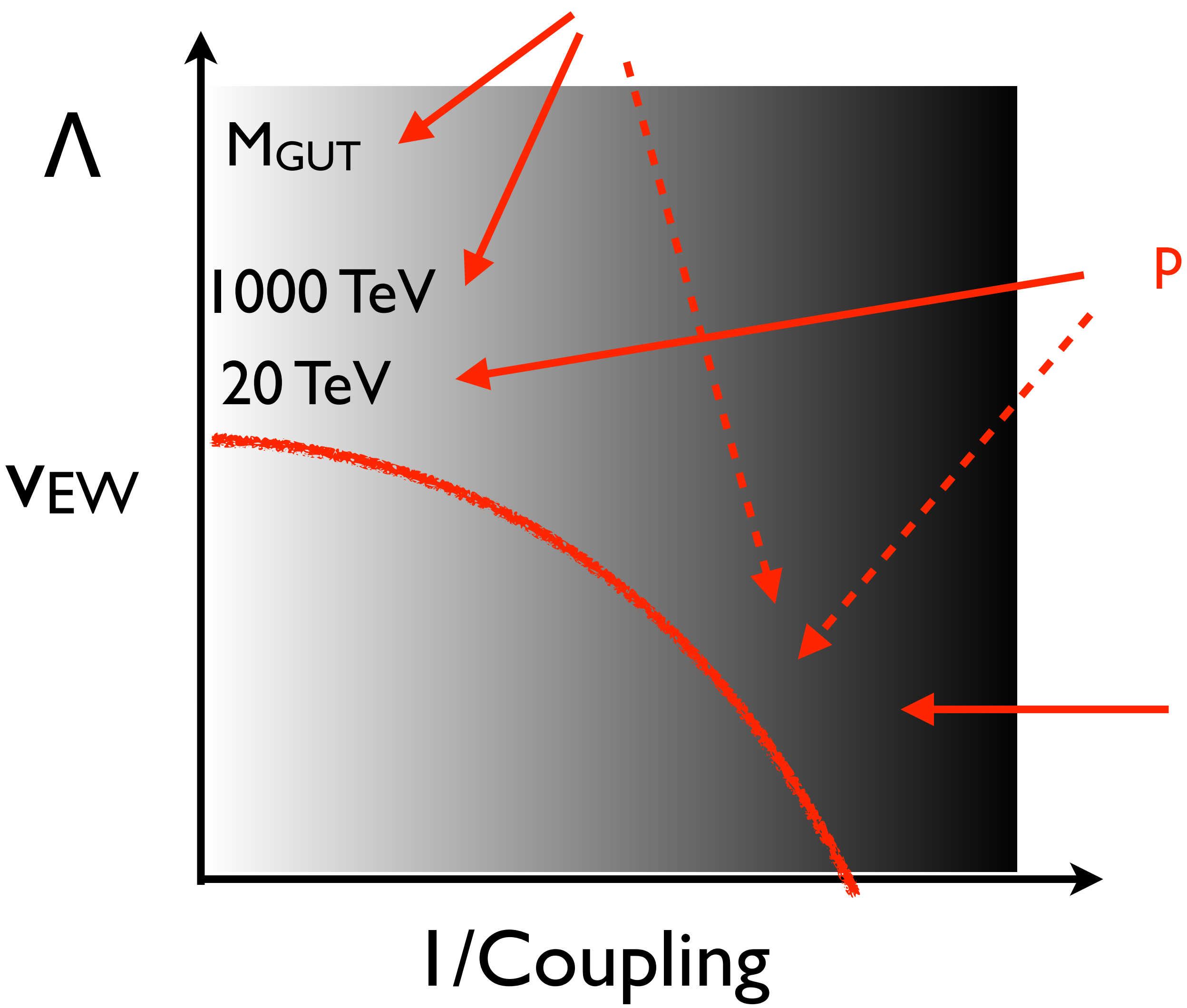


2. Precision measurements of SM-allowed processes: β-decays (mesons, neutron, nuclei), muon g-2, PV electron scattering, …

The precision frontier

- Probes of new physics at the precision frontier can be grouped in three classes, pushing the boundary in qualitatively different ways and at different mass scales

1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, EDMs, n-nbar oscillations, $\mu \to e$ conversion, $ep \to \tau X$, …



2. Precision measurements of SM-allowed processes: β-decays (mesons, neutron, nuclei), muon g-2, PV electron scattering, …

3. Searches / characterization of light and weakly coupled particles: active ν's, sterile ν's, dark sector particles and mediators, axions, …

(Strong connection with astrophysics)

Shedding light on big questions

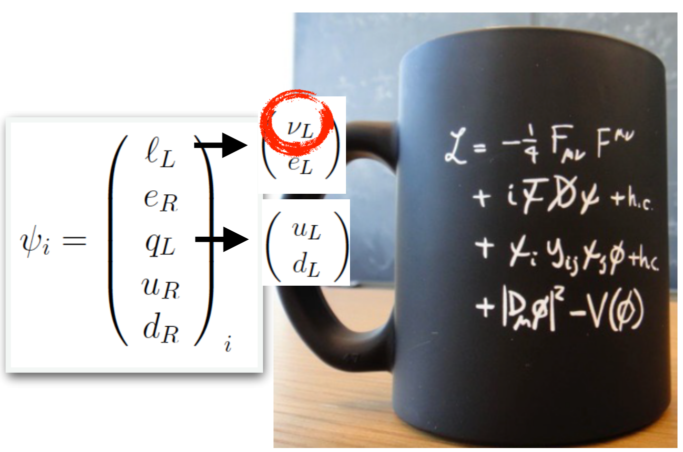
Precision probes cluster around four interconnected questions

Shedding light on big questions

Precision probes cluster around four interconnected questions

Origin of neutrino mass

The Standard Model



?

ΔL= 0

ΔL=2

No neutrino mass

Shedding light on big questions

Precision probes cluster around four interconnected questions

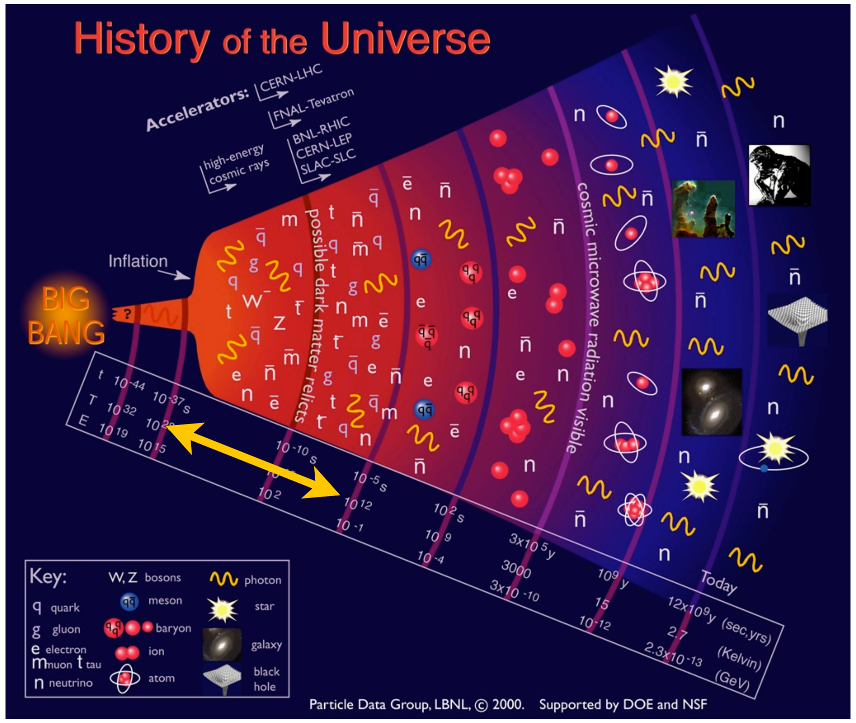
Origin of neutrino mass

Baryon asymmetry
(violation of B, L, CP)

Baryogenesis requires (Sakharov)

- B (L) violation
- C and CP violation
- Departure fro equilibrium

Baryogenesis does not work in the Standard Model

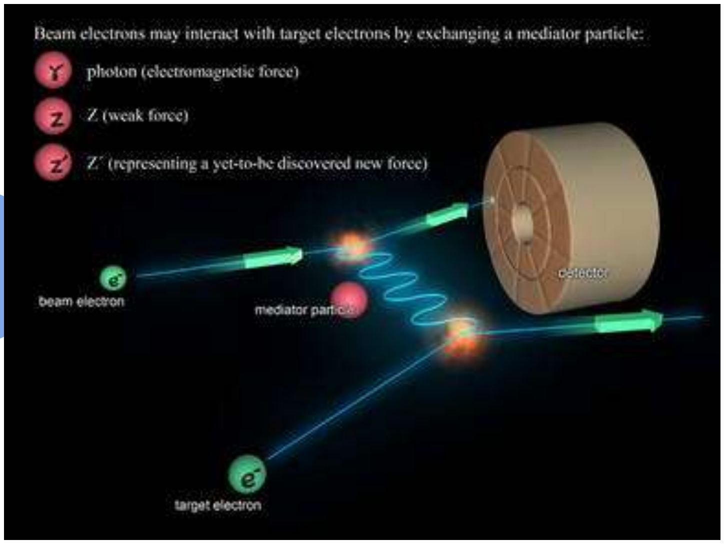


Shedding light on big questions

Precision probes cluster around four interconnected questions

Origin of neutrino mass

Baryon asymmetry
(violation of B, L, CP)



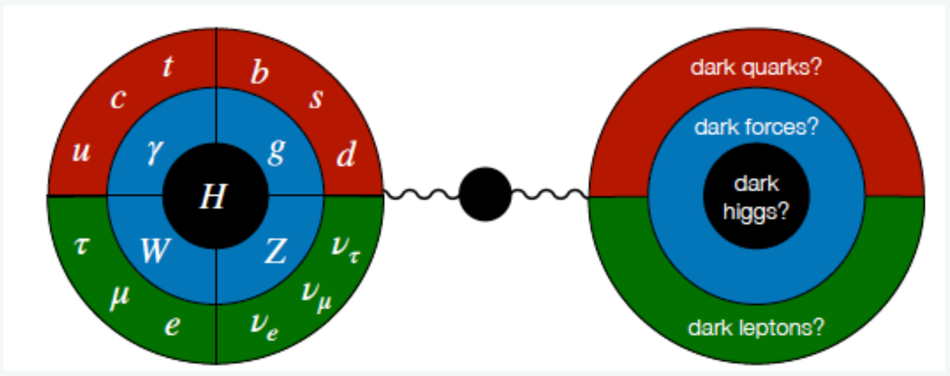
Are there new forces,
weaker than the weak force?

Shedding light on big questions

Precision probes cluster around four interconnected questions

Origin of neutrino mass

Baryon asymmetry
(violation of B, L, CP)



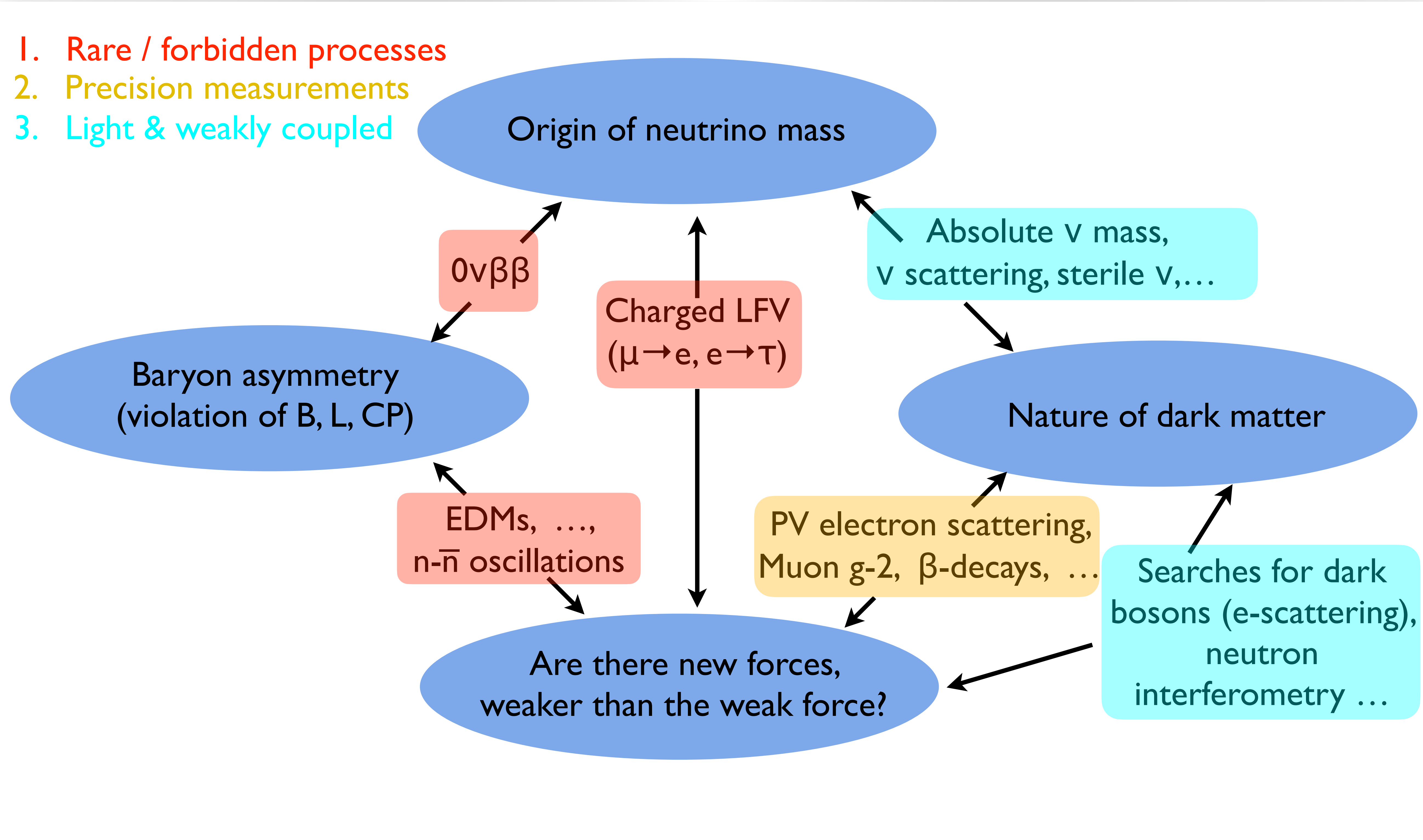
Nature of dark matter

Portals to the dark sector:
Neutrino, Vector, Higgs, Axion, …

Are there new forces,
weaker than the weak force?

Shedding light on big questions

Precision probes cluster around four interconnected questions



Precision frontier and BSM

- Three classes of probes

  - Searches for rare / SM-forbidden processes
  - Precision measurements of SM-allowed processes
  - Search / characterization of light weakly coupled particles

- Shedding light on four interconnected scientific questions

  - Why is there more matter than antimatter in the present universe?
  - How do neutrinos get their masses and what are their values?
  - Are there new forces in nature, weaker than the weak force?
  - What is the nature of dark matter?

Precision frontier and BSM

- Three classes of probes

Topics from my research: precision tests of weak interaction

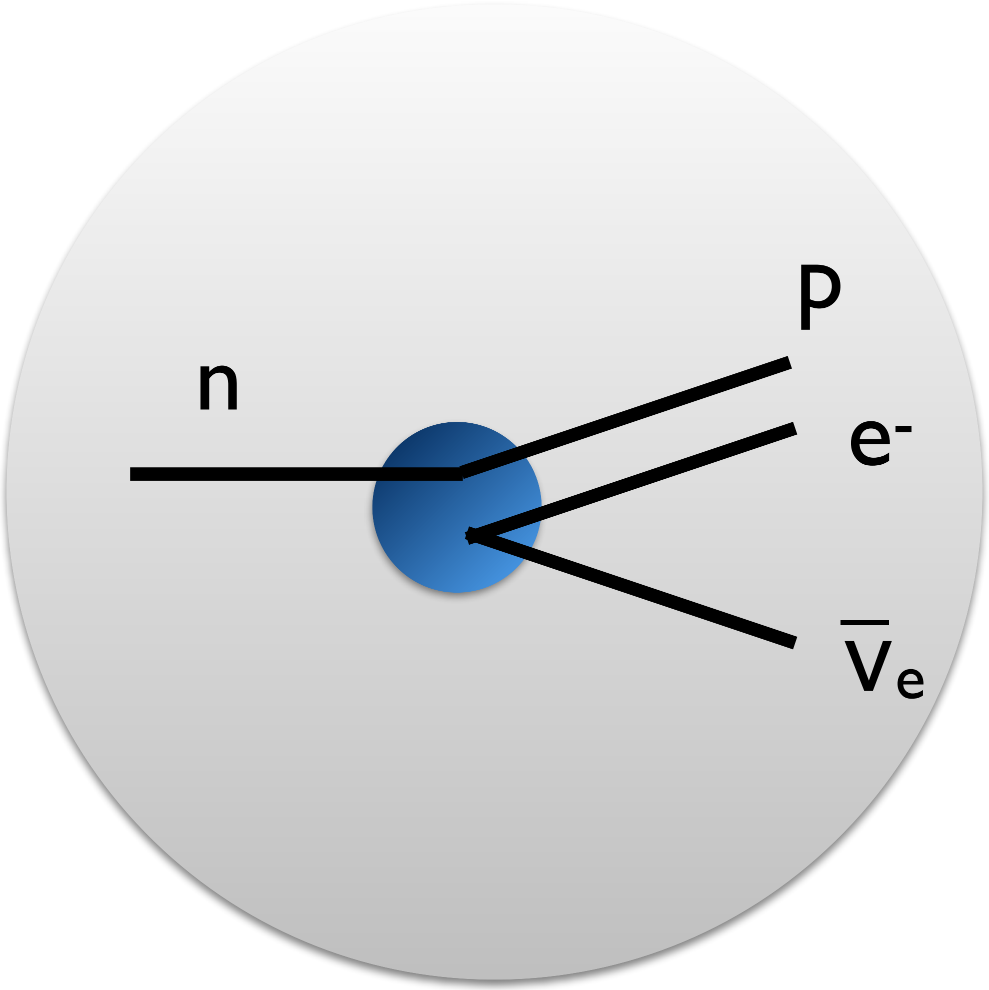
  - Searches for rare / SM-forbidden processes
  - Precision measurements of SM-allowed processes
  - Search / characterization of light weakly coupled particles

- Shedding light on four interconnected scientific questions

  - Why is there more matter than antimatter in the present universe?
  - How do neutrinos get their masses and what are their values?
  - Are there new forces in nature, weaker than the weak force?
  - What is the nature of dark matter?

Precision tests of the Standard Model with beta decays

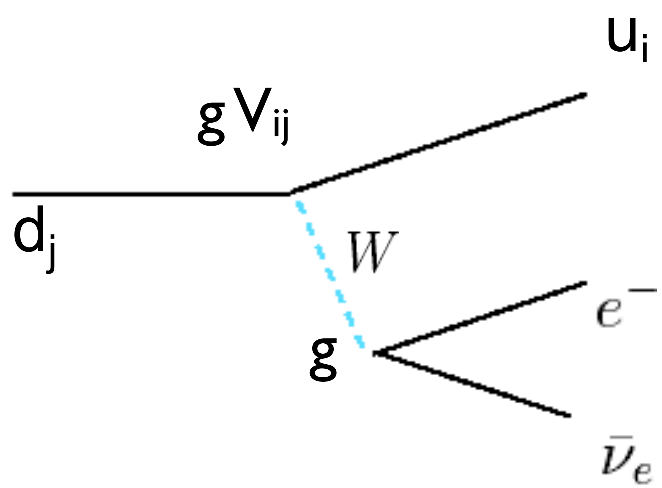
Beta decays in the SM and beyond



- Beta decays have played a central role in the development of the SM
- Nowadays: tool to challenge the SM & probe possible new physics

Beta decays in the SM and beyond

- In the SM, W exchange $\Rightarrow$ universality relations

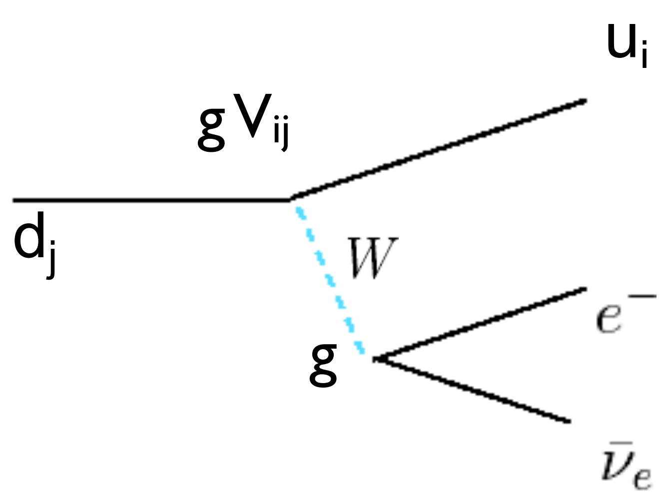


$$G_F^{(\beta)} \sim g^2 V_{ij}/M_w^2 \sim G_F^{(\mu)} V_{ij} \sim 1/v^2\, V_{ij}$$

Cabibbo-Kobayashi-Maskawa
(unitary) matrix

Beta decays in the SM and beyond

- In the SM, W exchange $\Rightarrow$ universality relations



$G_F^{(\beta)} \sim g^2 V_{ij}/M_W^2 \sim G_F^{(\mu)} V_{ij} \sim 1/v^2\, V_{ij}$

Cabibbo-Kobayashi-Maskawa
(unitary) matrix

Cabibbo universality

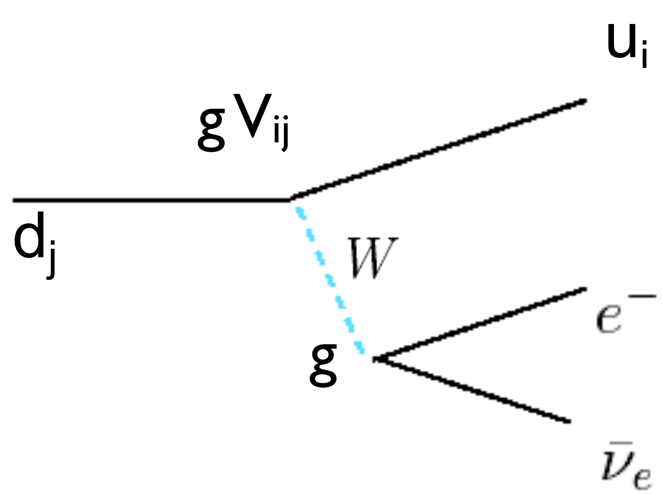
$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

$$[G_F]_e/[G_F]_\mu = 1$$

Lepton Flavor Universality (LFU)

Beta decays in the SM and beyond

- In the SM, W exchange $\Rightarrow$ universality relations



Cabibbo universality

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

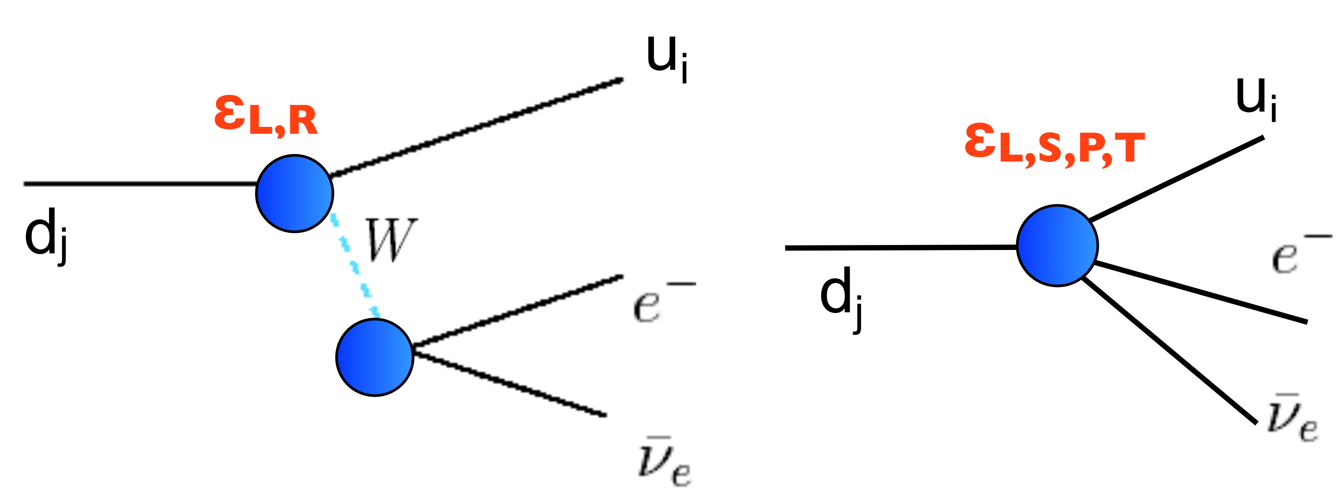
$$[G_F]_e/[G_F]_\mu = 1$$

Lepton Flavor Universality (LFU)

$G_F^{(\beta)} \sim g^2 V_{ij}/M_W^2 \sim G_F^{(\mu)} V_{ij} \sim 1/v^2 V_{ij}$

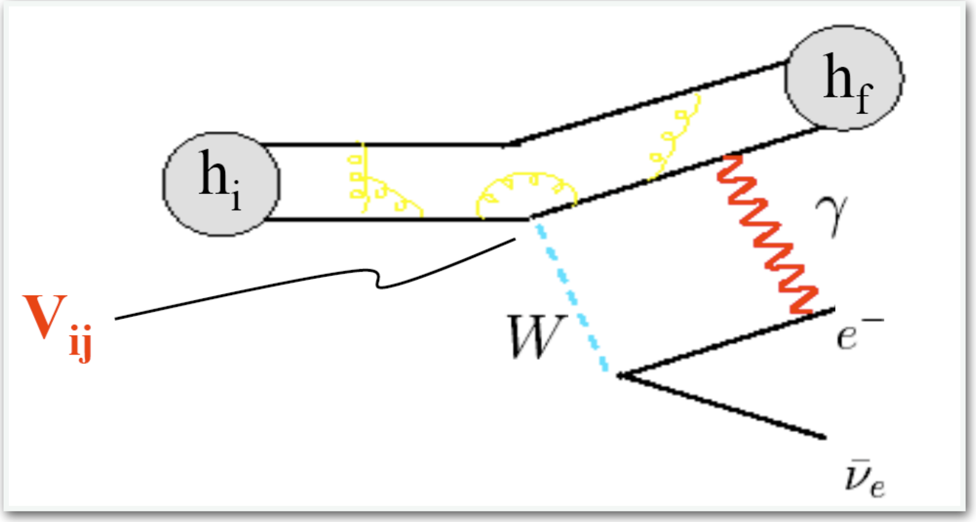
Cabibbo-Kobayashi-Maskawa (unitary) matrix

- BSM effects $\varepsilon \sim (v/\Lambda)^2$, can spoil universality. Precision of 0.1-0.01% probes $\Lambda > 10$ TeV



Probing Cabibbo universality

Extract $V_{ud}=\mathrm{Cos}\theta_C$ and $V_{us}=\mathrm{Sin}\theta_C$ from various decays
and check their squares sum to 1



$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\mathrm{had}}|^2 \times (1+\delta_{RC}) \times F_{\mathrm{kin}}$$

CKM element

Hadronic matrix element

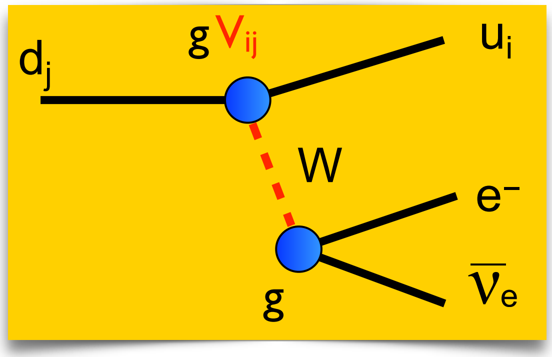
Radiative corrections: $(\alpha/\pi) \sim 2. \times 10^{-3}$ and smaller effects

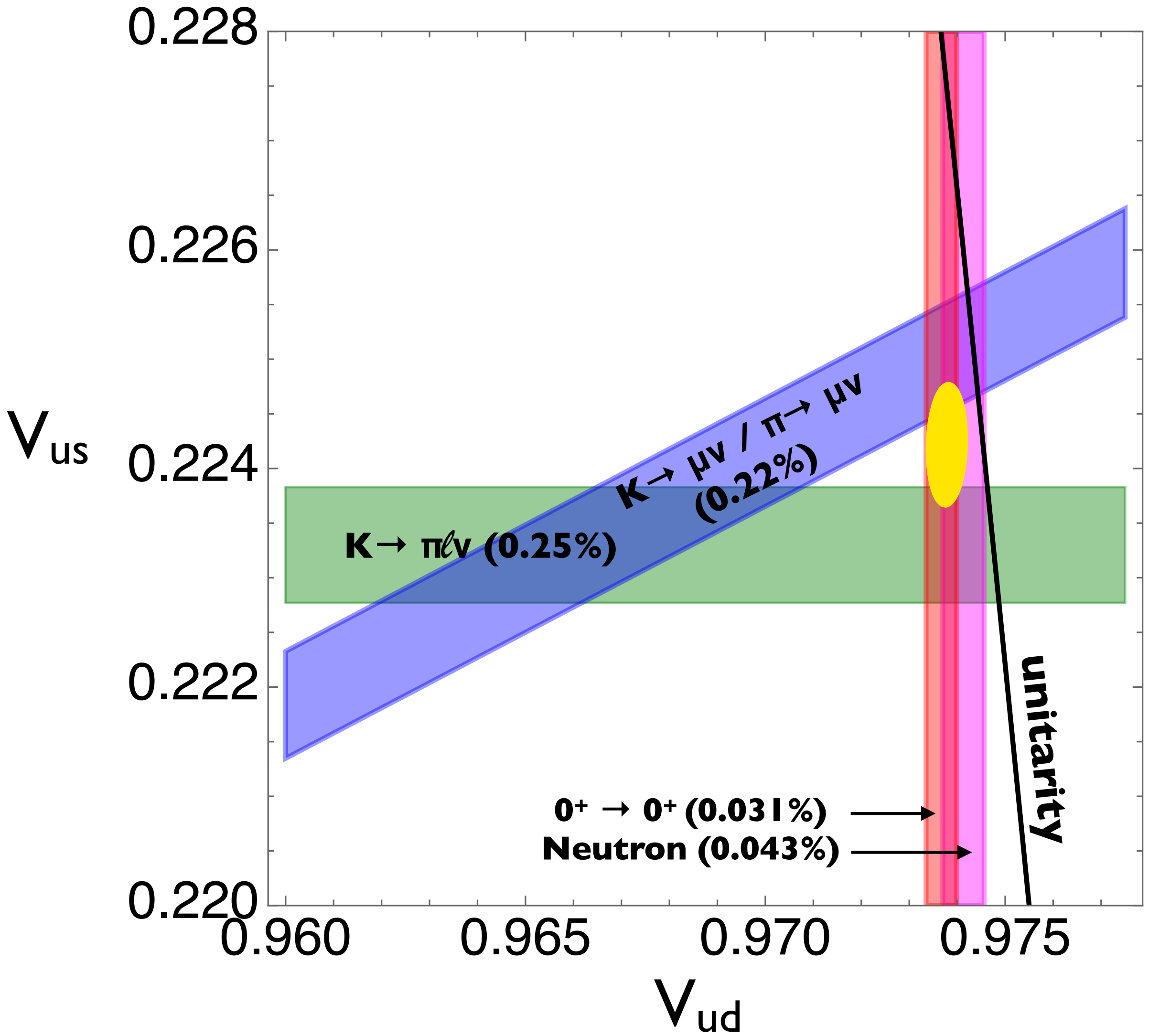
Input from *many* experiments and theory papers

β decays and CKM unitarity

$$\boxed{\Delta_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} - 1 = -15(5)\times 10^{-4}}$$

VC-Crivellin-Hoferichter-Moulson 2208.11707
and references therein

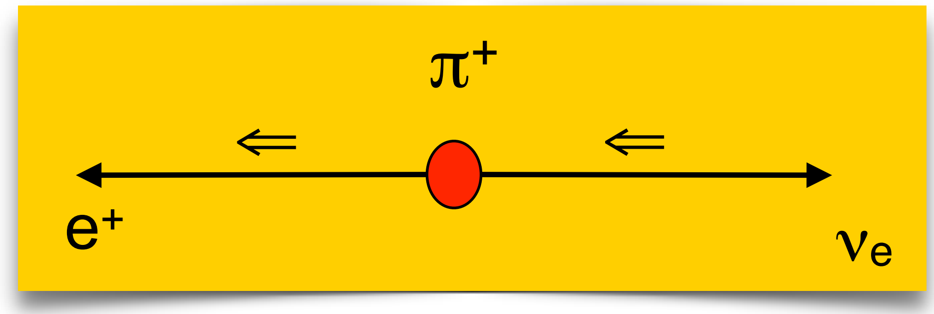




- ~3-σ 'anomaly' points toward vertex corrections with Λ~10 TeV (hard to probe even at the LHC)
- Experimental opportunities in neutron decay, nuclear decays, π & K decays, all with clear target goals
- Theory opportunities: fully controlled uncertainties in radiative corrections to neutron and nuclear decays

Pion decay and Lepton Flavor Universality

$\pi^+ \sim u\bar{d}$



- $R_{e/\mu} = \Gamma\,(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ helicity suppressed the SM (V-A), zero if $m_e \to 0$

VC & I. Rosell 0707.3439

$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015) \times 10^{-4}$$
$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$

PIENU Coll.

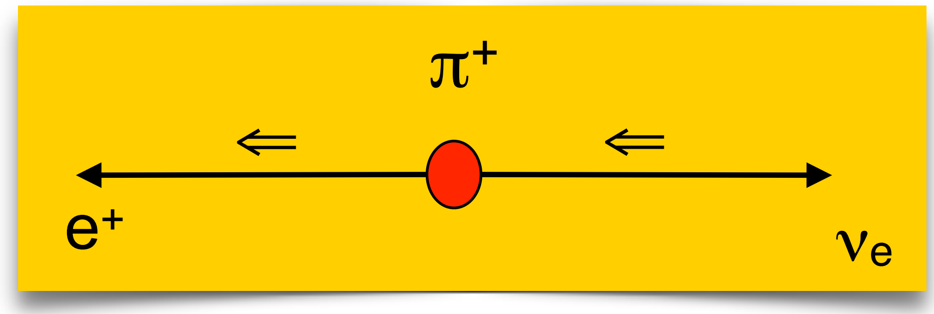
- $\sigma_{exp} \sim 15\sigma_{th} \Rightarrow$ pristine LFU test possible

> "This just demands to be tested better!
> A clean generic way to look for new physics.
> Theory vs Experiment in high precision test."

David Hertzog

Pion decay and Lepton Flavor Universality

$\pi^+ \sim u\bar{d}$



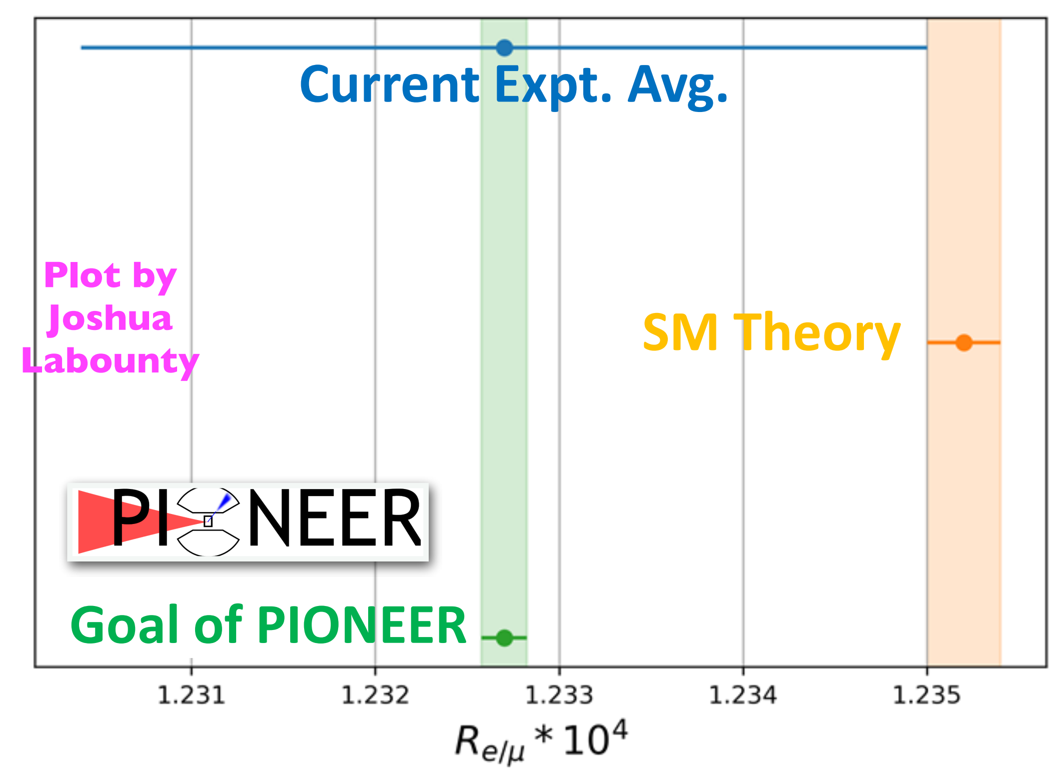
- $R_{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ helicity suppressed the SM (V-A), zero if $m_e \to 0$

VC & I. Rosell 0707.3439

$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015) \times 10^{-4}$$
$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$

PIENU Coll.

- $\sigma_{exp} \sim 15\sigma_{th} \Rightarrow$ pristine LFU test possible



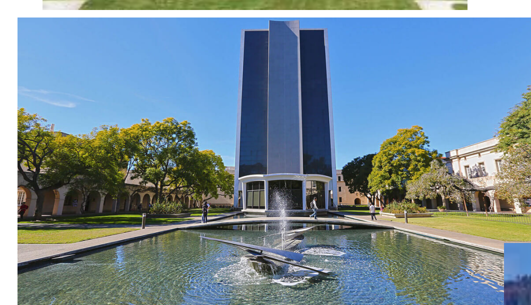
- PIONEER @ PSI will match theoretical uncertainty. Order of magnitude gap — room for surprises! Will probe scales $\Lambda_A \sim 30$ TeV or $\Lambda_P \sim 1000$ TeV (helicity!)

My career path

- Undergrad + graduate school at University of Pisa, Italy

- Visiting grad. student at UMass Amherst

- Postdoc at Vienna (Austria) + Valencia (Spain) (1.5 years each), as part of a European Training Network



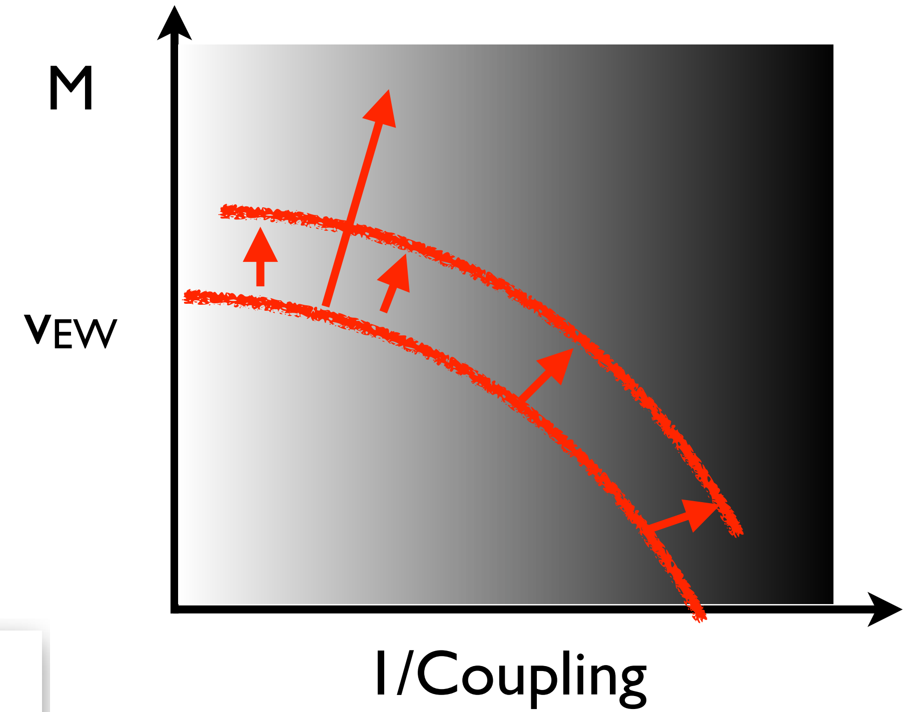
- Postdoc at Caltech (2.5 years)

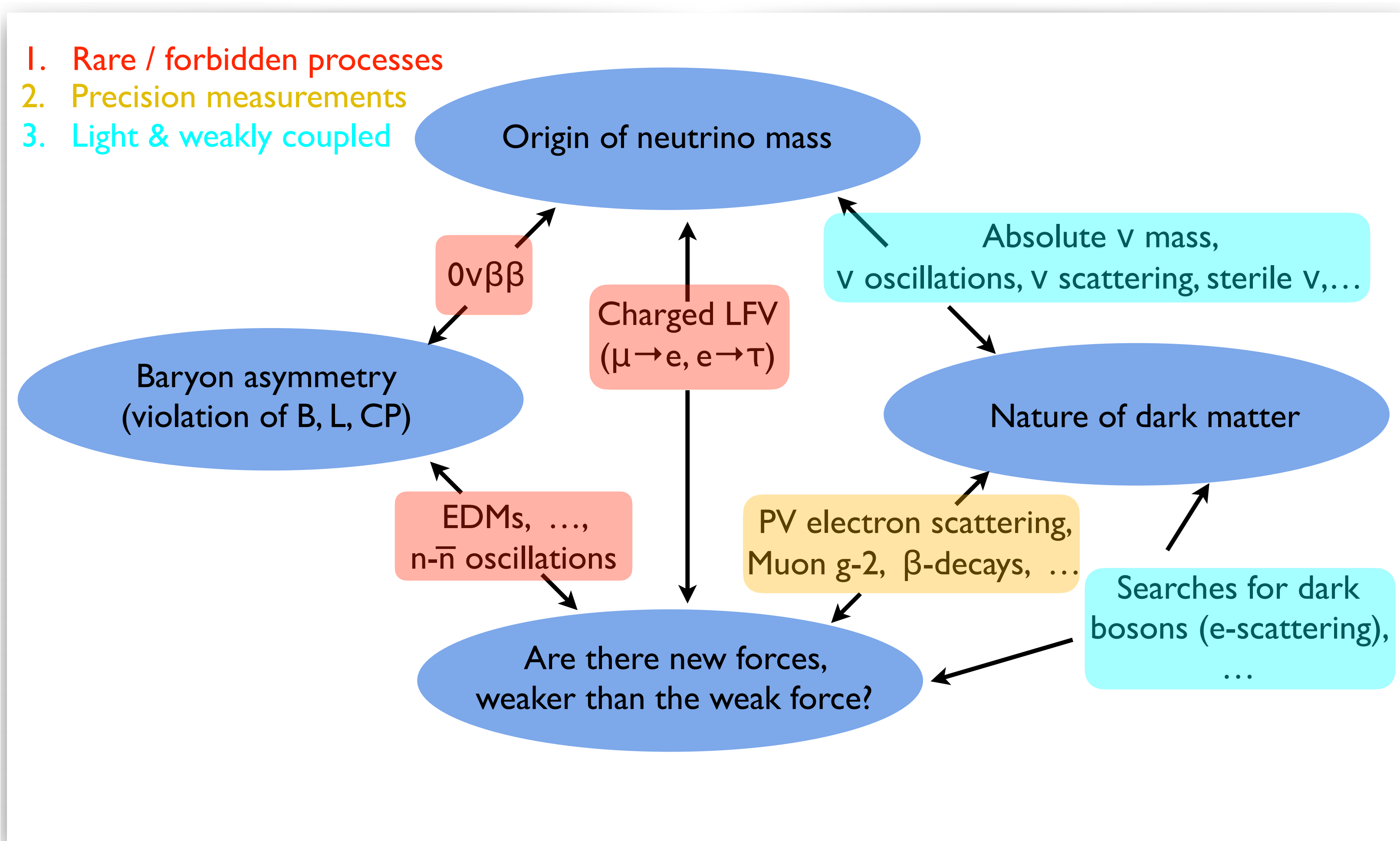
- Scientist at Los Alamos National Laboratory (16 years)

- Faculty at INT & UW Physics (2.5 years)

Concluding comments

- Precision frontier: vibrant particle and nuclear physics program (experiment and theory) probing uncharted territory in the search for new physics





- Sheds light on several unsolved mysteries about our universe

Thank you!

T. D. Lee in a drawing
by Bruno Touschek

Bruno Touschek
(1921-1978)

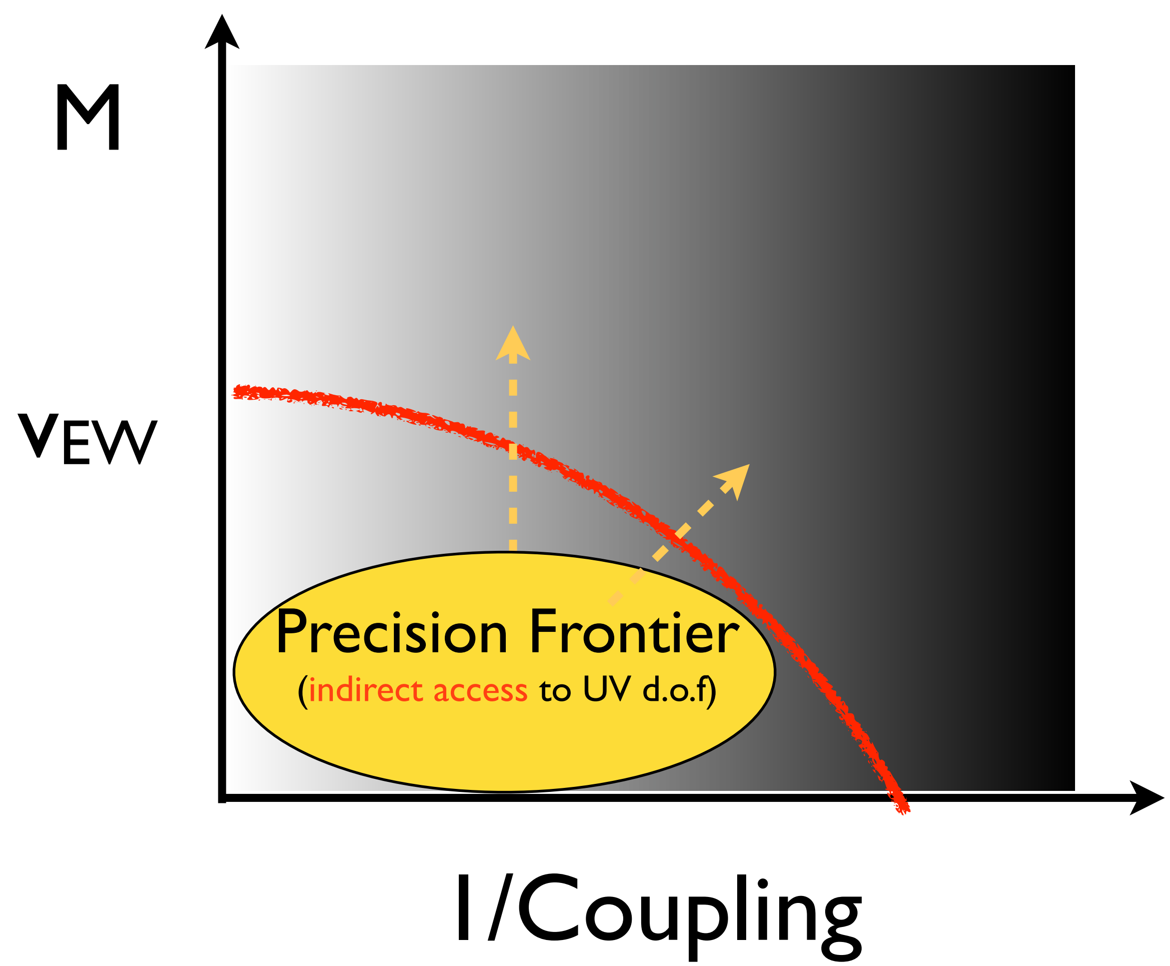
Backup

More on the precision frontier

- Practical definition: searches for new phenomena through precision measurements or the study of rare processes at low energy

- Important feature: can probe new physics originating at very high mass scale

- How so? Through quantum mechanical effects



How does it work?

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M

How does it work?

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M

You are familiar with this concept from perturbation theory in QM

$$H = H_0 + \lambda V \qquad\qquad H|n^{(0)}\rangle = E_n^{(0)}|n^{(0)}\rangle$$

$$E_n(\lambda) = E_n^{(0)} \; + \; \lambda\langle n^{(0)}|V|n^{(0)}\rangle \; + \; \lambda^2 \sum_{k\neq n} \frac{|\langle k^{(0)}|V|n^{(0)}\rangle|^2}{E_n^{(0)} - E_k^{(0)}} + O(\lambda^3)$$

$$|n(\lambda)\rangle = |n^{(0)}\rangle \; + \; \lambda \sum_{k\neq n} |k^{(0)}\rangle \frac{\langle k^{(0)}|V|n^{(0)}\rangle}{E_n^{(0)} - E_k^{(0)}} + O(\lambda^2)$$

How does it work?

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M

You are familiar with this concept from perturbation theory in QM

$$H = H_0 + \lambda V \qquad\qquad H|n^{(0)}\rangle = E_n^{(0)}|n^{(0)}\rangle$$

$$E_n(\lambda) = E_n^{(0)} + \lambda\langle n^{(0)}|V|n^{(0)}\rangle + \lambda^2 \sum_{k\neq n} \frac{|\langle k^{(0)}|V|n^{(0)}\rangle|^2}{E_n^{(0)} - E_k^{(0)}} + O(\lambda^3)$$

$$|n(\lambda)\rangle = |n^{(0)}\rangle + \lambda \sum_{k\neq n} |k^{(0)}\rangle \frac{\langle k^{(0)}|V|n^{(0)}\rangle}{E_n^{(0)} - E_k^{(0)}} + O(\lambda^2)$$

Sensitivity to high-energy states through sum over complete set of states