The Evidence for Conservation Principles and Particle Families

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Outline

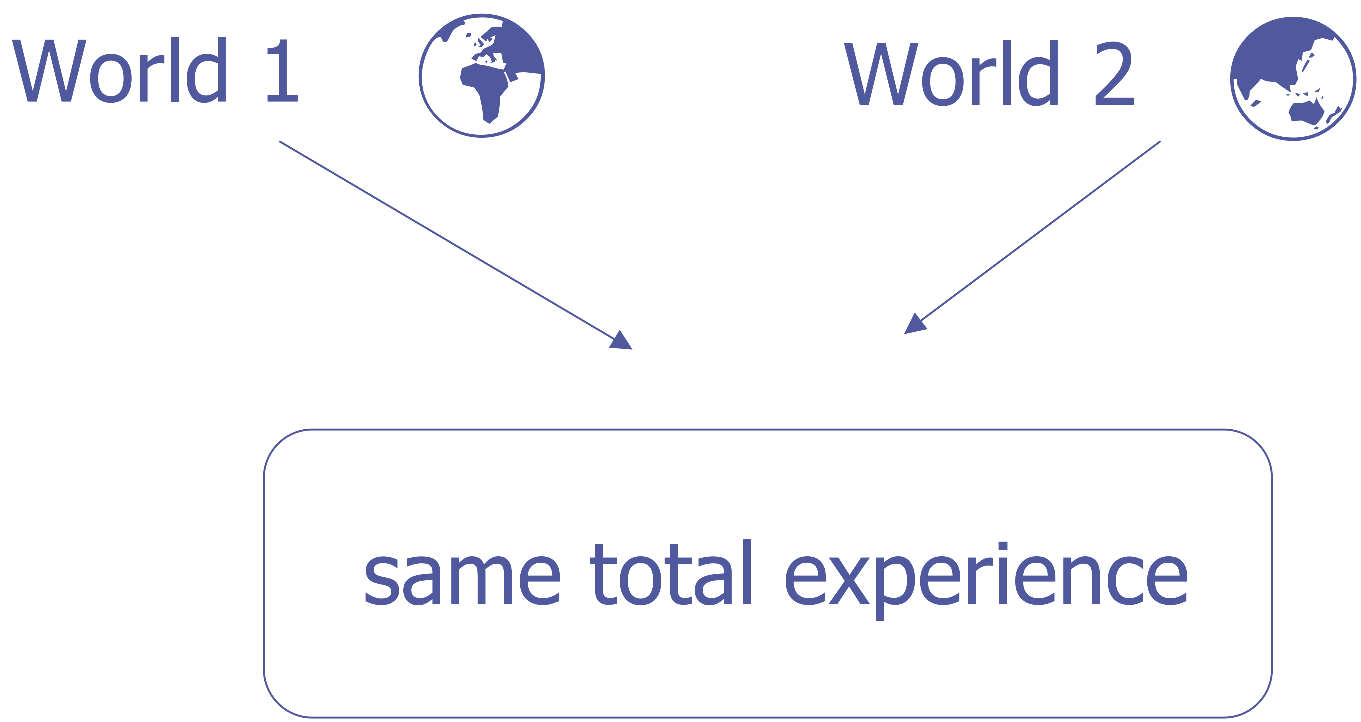
- How does *underdetermination* arise in particle physics?
- How do physicists resolve it?
- Main Result: The current data determine a **unique** set of conservation laws that govern **both** particle dynamics and particle ontology.

Underdetermination

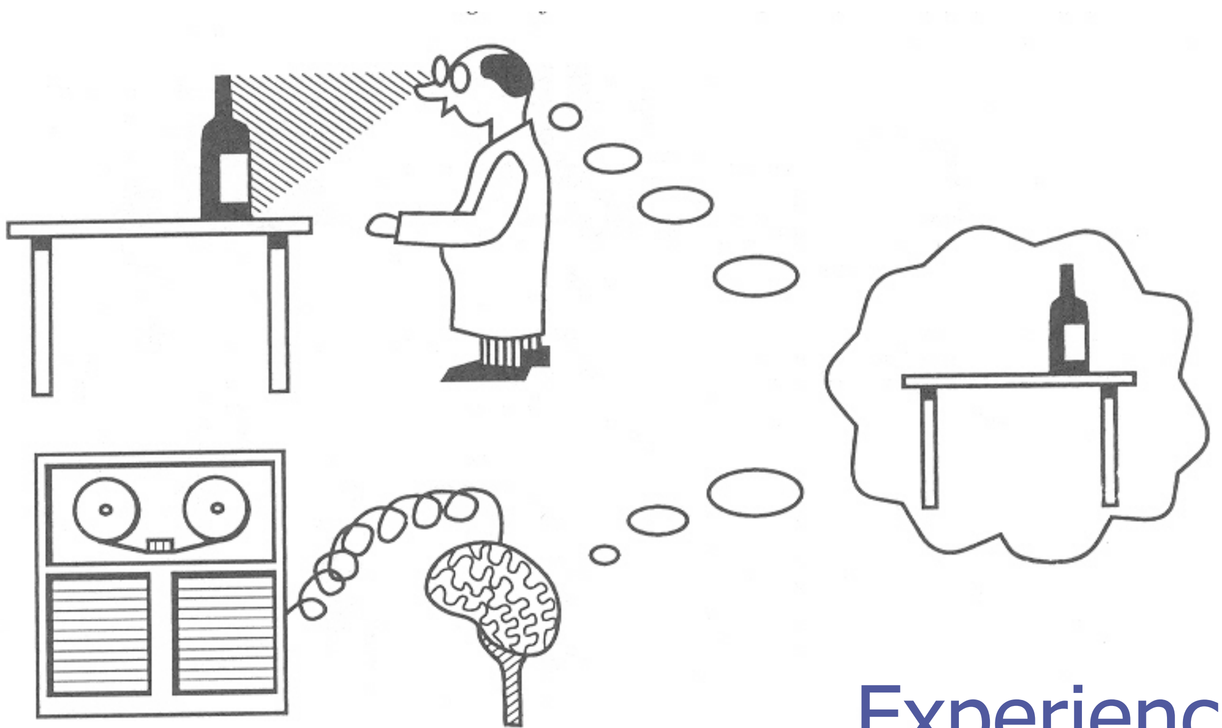
- **Global Underdetermination**: Even the total infinite data do not determine the answer to our questions.
- **Local Underdetermination**: finite data do not determine the answer to our questions.
- **Ontological Relativity**: are there objective grounds for grouping objects one way rather than another?
- **Status of Laws**: are some true generalizations special?

All these issues come up in particle physics!

Global Underdetermination: The Picture



Brain-in-the-vat Scenario



Experience

Global Underdetermination in Particle Physics (I)

World 1

$n+n \rightarrow p+p+e^-+e^-$

is possible

World 2

$n+n \rightarrow p+p+e^-+e^-$

is not possible

$n+n \rightarrow p+p+e^-+e^-$ never occurs

Response to Global Underdetermination

- Bilaniuk and Sudarshan (1969): "There is an unwritten precept in modern physics, often facetiously referred to as Gell-Mann's Totalitarian Principle… `Anything which is not prohibited is compulsory'. Guided by this sort of argument we have made a number of remarkable discoveries from neutrinos to radio galaxies."

- Ford (1963): "Everything which *can* happen without violating a conservation law *does* happen."

“Anything which is not prohibited is compulsory”

World 1

$n+n \rightarrow p+p+e^-+e^-$

is possible

World 2

$n+n \rightarrow p+p+e^-+e^-$

is not possible

$n+n \rightarrow p+p+e^-+e^-$ never occurs

From Metaphysics to Epistemology

- Kane (1986): “What is interesting is that, in committing themselves to plenitude in this restricted form, modern physicists are committing themselves to the principle that what *never* occurs must have a sufficient reason or explanation for its never occurring.”

- Nobel Laureate Leon Cooper (1970): “In the analysis of events among these new particles, where the forces are unknown and the dynamical analysis, if they were known, is almost impossibly difficult, one has tried by observing *what does not happen* to find selection rules, quantum numbers, and thus the symmetries of the interactions that are relevant.”

- Feynmann (1965): ”The reason why we make these tables [of conserved quantities] is that we are trying to guess at the laws of nuclear interaction, and this is one of the quick ways of guessing at nature.”

Local Underdetermination in Particle Physics

Particle Review 2005: $2\nu \rightarrow 2p + 2e^-$ **observed**

I see!
$2\nu \rightarrow 2p + 2e$
is impossible.

Particle Review 2004: **no** $2\nu \rightarrow 2p + 2e^-$

Particle Review 2003: **no** $2\nu \rightarrow 2p + 2e^-$

Particle Review 2002: **no** $2\nu \rightarrow 2p + 2e^-$

I must find a conservation law that explains this.

Additive Conservation Principles = "Selection Rules"

	Particle	Charge	Baryon#	Tau#	Electron#	Muon#
1	Σ^-	-1	1	0	0	0
2	$\overline{\Sigma}^+$	1	-1	0	0	0
3	Σ^0	0	1	0	0	0
4	$\overline{\Sigma}^0$	0	-1	0	0	0
5	n	0	1	0	0	0
6	$\overline{n}$	0	-1	0	0	0
7	p	1	1	0	0	0
8	$\overline{p}$	-1	-1	0	0	0
9	K^0	0	0	0	0	0
10	$\overline{K}^0$	0	0	0	0	0
11	K^+	1	0	0	0	0
12	K^-	-1	0	0	0	0
13	π^+	1	0	0	0	0
14	π^-	-1	0	0	0	0
15	π^0	0	0	0	0	0
16	γ	0	0	0	0	0
17	τ^-	-1	0	1	0	0
18	τ^+	1	0	-1	0	0
19	ν_τ	0	0	1	0	0
20	$\overline{\nu}_\tau$	0	0	-1	0	0
21	μ^-	-1	0	0	0	1
22	μ^+	1	0	0	0	-1
23	ν_μ	0	0	0	0	1
24	$\overline{\nu}_\mu$	0	0	0	0	-1
25	e^-	-1	0	0	1	0
26	e^+	1	0	0	-1	0
27	ν_e	0	0	0	1	0
28	$\overline{\nu}_e$	0	0	0	-1	0

Table 1: Some Common Particles and Quantum Number Assignments

Assuming Conservation Principles entails unobserved reactions

Hypothetical Scenario

observed reactions

$$\Sigma^- \rightarrow \pi^- + n$$
$$\pi^- \rightarrow \mu^- + \nu_\mu$$
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$
$$n \rightarrow e^- + \bar{\nu}_e + p$$
$$p + p \rightarrow p + p + \pi$$

not yet observed reactions

$$n \rightarrow e^- + \bar{\nu}_e$$

$$p + p \rightarrow p + p + \pi + \pi$$

↑ entailed

Response to Local Underdetermination: The Strict Inference Method

- Strict Method: suppose that reaction r has not been observed so far.
  - If there is no possible conservation principle rules out r, conjecture that r is possible.
  - If some possible conservation principle rules out r, conjecture that r is forbidden, and introduce a conservation principle to explain why.

Means-Ends Justification for Maximally Strict Inferences

Theorem. Suppose we have *n* known particles. The strict inference method is the **only** inference rule that

1. is guaranteed to eventually arrive at an empirically adequate set of conservation principles, and
2. changes its predictions at most *n* times.

Schulte 2000, BJPS. The same criteria select "all emeralds are green" in a (the?) Riddle of Induction (Schulte 1999 BJPS).

Maximally Strict Conservation Principles

- **Dfn**: A set of conservation principles Q is **maximally strict** for a set of observed reactions R ⇔ Q forbids as many <u>unobserved</u> reactions as possible.
- The strict method directs us to adopt maximally strict conservation principles.
- All maximally strict conservation principles are **empirically equivalent**.
- *For a given set of reactions, what are the maximally strict conservation theories?*

The Vector Representation for Reactions

- Fix *n* particles.
- Reaction → *n*-vector: list **net occurrence** of each particle.

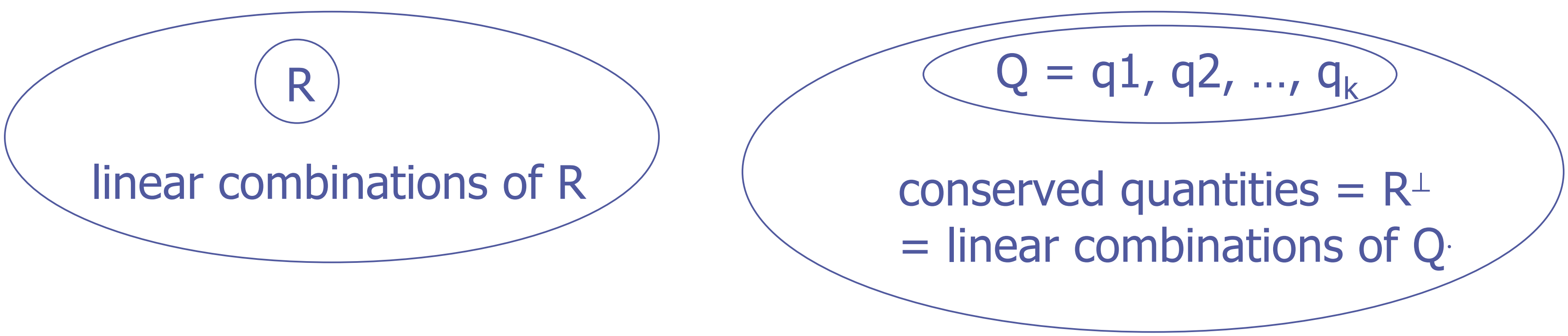
	1	2	3	4	5	6	7
Process	p	π^0	μ^-	e^+	e^-	ν_μ	$\bar{\nu}_e$
$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$	0	0	1	0	-1	-1	-1
$p \rightarrow e^+ + \pi^0$	1	-1	0	-1	0	0	0
$p + p \rightarrow p + p + \pi^0$	0	-1	0	0	0	0	0

Conserved Quantities in Vector Space

	1	2	3	4	5	6	7
Process	p	π^0	μ^-	e^+	e^-	ν_μ	$\bar{\nu}_e$
$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$	0	0	1	0	-1	-1	-1
$p \rightarrow e^+ + \pi^0$	1	-1	0	-1	0	0	0
$p + p \rightarrow p + p + \pi^0$	0	-1	0	0	0	0	0
Baryon Number	1	0	0	0	0	0	0
Electric Charge	1	0	-1	1	-1	0	0

Maximally strict selection rules Q = basis for nullspace of observations R

- **Proposition**: Q is maximally strict ⇔ span(Q) = $R^{\perp}$.
  - linear combinations of laws add no constraints and no explanatory power.
  - the more irredundant laws we add, the more nonoccurrences we explain.



Comparison with Practice

Finding: The standard laws Electric Charge, Baryon#, Muon#, Electron#, Tau# form a maximally strict set for the current reaction data.

Physicists have acted as if they are following the methodology described so far.

Global Underdetermination II

- Since a maximally strict of conservation principles is any basis for the linear space $R^{\perp}$, *for every set of observations* R *there are* ***infinitely*** *many conservation theories that make* ***exactly the same*** *predictions.*

Global Underdetermination in Particle Physics (II)

World 1

Charge, B#, E#,M#,T# are the true conservation laws

World 2

Charge, B#, E#,M#,Lepton# are the true conservation laws

exactly the same reactions are observed

These Are Not Solutions

- Lewis: what's special about the standard principles is that they are **simpler** than other empirically adequate theories.
- Reply: depends on what is meant by "simplicity". But for various obvious measures, computations show this isn't so.
- Rationalist: there must be a deeper theory from which we can derive the true conservation laws.
- Reply: Williams (1997): "these laws have no basis in fundamental physical principles".

The ontological response

- The standard principles (e.g., Baryon#) correspond to classes that are natural in the standard (quark) particle model. Thus these principles correspond to **natural kinds**.
- Skeptical/nominalist Reply: Ontology is relative. We are free to group particles differently and obtain a different set of conservation laws.

Particle Ontology $\Rightarrow$ Conservation Principles

- A particle p **carries** a quantity **q** if the value of **q** for p $\neq$ 0.
- For each class of particles, we can form a corresponding conservation principle.

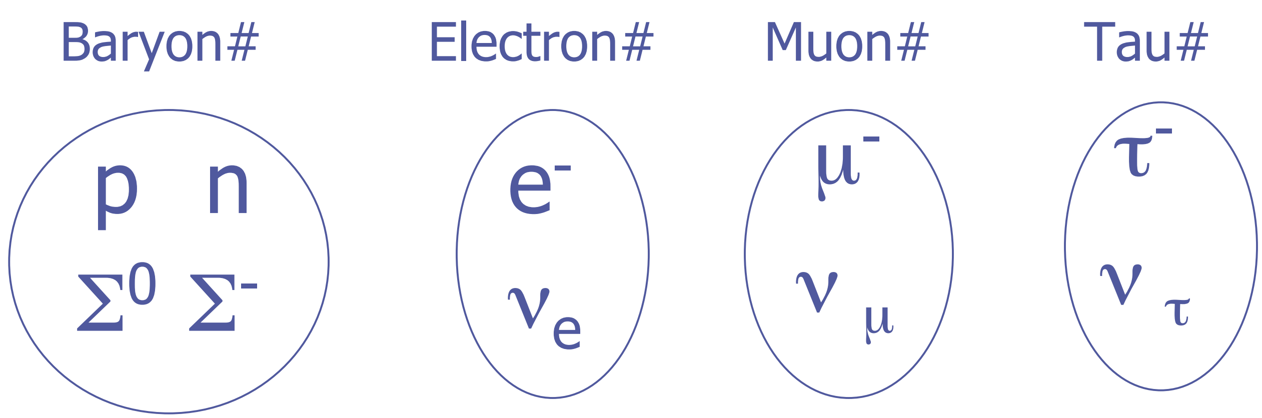


Illustration in Current Theory

	Particle	Charge	Baryon#	Tau#	Electron#	Muon#
1	Σ^-	-1	1	0	0	0
2	$\overline{\Sigma}^+$	1	-1	0	0	0
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22	μ^+	1	0	0	0	-1
23	ν_μ	0	0	0	0	1
24	$\overline{\nu}_\mu$	0	0	0	0	-1
25	e^-	-1	0	0	1	0
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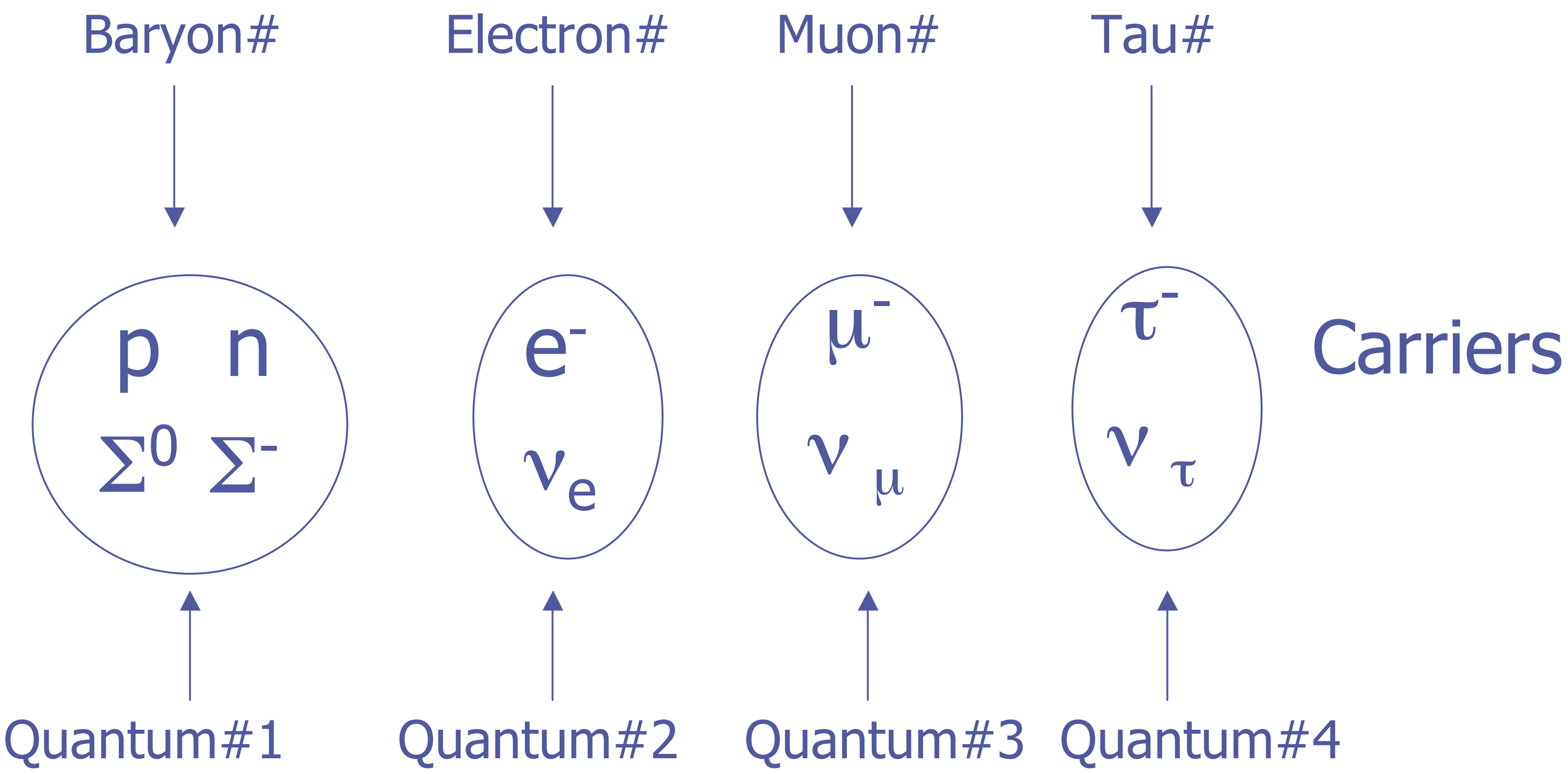
Table 1: Some Common Particles and Quantum Number Assignments

Solution to Global Underdetermination II

- **Theorem**. Let q_1, q_2, q_3, q_4 be **any** quantities such that
  - {charge, q_1, q_2, q_3, q_4} classify reactions as {charge, B#, E#, M#, T#} do, and
  - q_1, q_2, q_3, q_4 have **disjoint carriers**.

  Then the carriers of the q_i **are the same** as the carriers of B#, E#, M#, T#.

The Ontology associated with Conservation Principles is Unique: Illustration



Any alternative set of 4 Q#s with disjoint carriers

Two Problems Can Be Easier Than One

- Analytic Fact: **If** there is any partition of the particle world such that the corresponding conservation principles are maximally strict, it is unique.
- Empirical Fact: there is such a partition - the one physicists give us.
- Seeking conservation laws that determine **both** dynamics and ontology **at once** determines the laws.

Extension to Unobserved Particles

- Expand the range of theories to allow the introduction of **unobserved particles**.
- Finding: to find conservation laws that make the right prediction about what **is** observed, we must introduce unobserved particles.
- $\Rightarrow$ discovery of a new (feasible?) critical experiment for testing a crucial hypothesis in current particle physics ($\nu_e \neq \bar{\nu}_e$).

Conclusions

- Both global and local underdetermination arise in particle physics.
- Remedies:

1. metaphysical principles (plenitude)
2. restrict possible theories $\Rightarrow$ conservation principles.
3. inductive principle: if process not observed so far, try to explain why process does not occur $\Leftarrow$ means-ends epistemology.
4. look for laws that account for reaction dynamics **and** particle ontology $\Rightarrow$ unique set of laws.

References

- talk posted at http://www.cs.sfu.ca/~oschulte/talks/
- "Inferring Conservation Principles in Particle Physics: A Case Study in the Problem of Induction". Schulte, O. (2000). *British Journal for the Philosophy of Science*

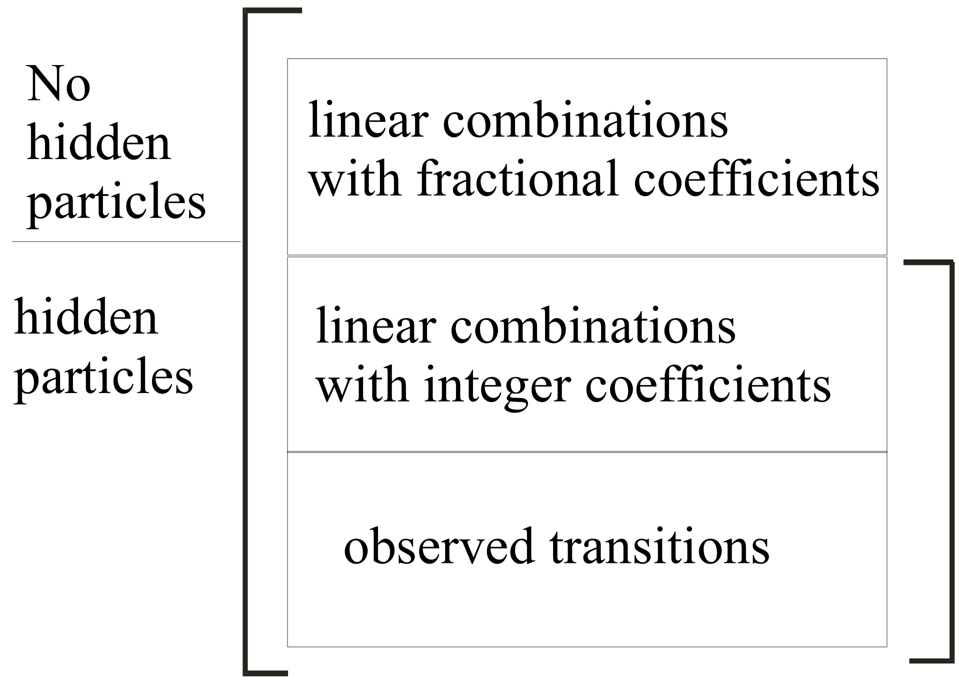
THE END

More Particles can lead to stricter Conservation Principles

- Well-known example: if $\nu_e = \bar{\nu}_e$, then $n + n \rightarrow p + p + e^- + e^-$ should be possible.
- Sometimes need to post *unobserved* particles to make correct predictions about the observed phenomena.

When do more particles lead to stricter Conservation Principles?

- **Theorem** An extra particle yields stricter selection rules for a set of reactions *R* IFF there is a reaction r such that
  1. r is a linear combination of *R*
  2. but only with **fractional** coefficients.



Application: Is the Electron Neutrino a Dirac particle?

Elliott and Engel (May 2004): "What aspects of still-unknown neutrino physics is it most important to explore? …it is clear that the absolute mass scale and whether **the neutrino is a Majorana or Dirac particle are crucial issues**."

Critical Reaction for $\nu_e \neq \bar{\nu}_e$ Discovered by Computer

Finding if $\nu_e \neq \bar{\nu}_e$, then the process $Y + \Lambda^0 \rightarrow p + e^-$ cannot be ruled out with selection rules.

Coefficient	Known Processes
½	$Y \rightarrow \mu^+ + \mu^-$
+ ½	$Y \rightarrow e^+ + e^-$
+ ½	$\Lambda^0 \rightarrow p + \pi^-$
+ ½	$\pi^- \rightarrow \mu^- + \nu_\mu$
- ½	$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$
+ ½	$\Lambda^0 \rightarrow p + \nu_e + e^-$ *
=	$Y + \Lambda^0 \rightarrow p + e^- + \mu^+ + \mu^-$

Polynomial Time Algorithm for Deciding if New Particle is Needed

Theorem (Smith 1861). Let A be an integer matrix. Then there are matrices U,V,S such that

- A = USV
- S is diagonal (*S = Smith Normal Form of A*)
- U,V are unimodular.

- **Theorem** (Giesbrecht 2004). Let R be the matrix whose rows are the observed reactions. Then a new particle is needed IFF the Smith Normal Form of R^T has a diagonal entry other than {0,1,-1}.