# How Particle Physics Cuts Nature At Its Joints

Oliver Schulte

Department of Philosophy

Simon Fraser University

oschulte@sfu.ca

# The Theme

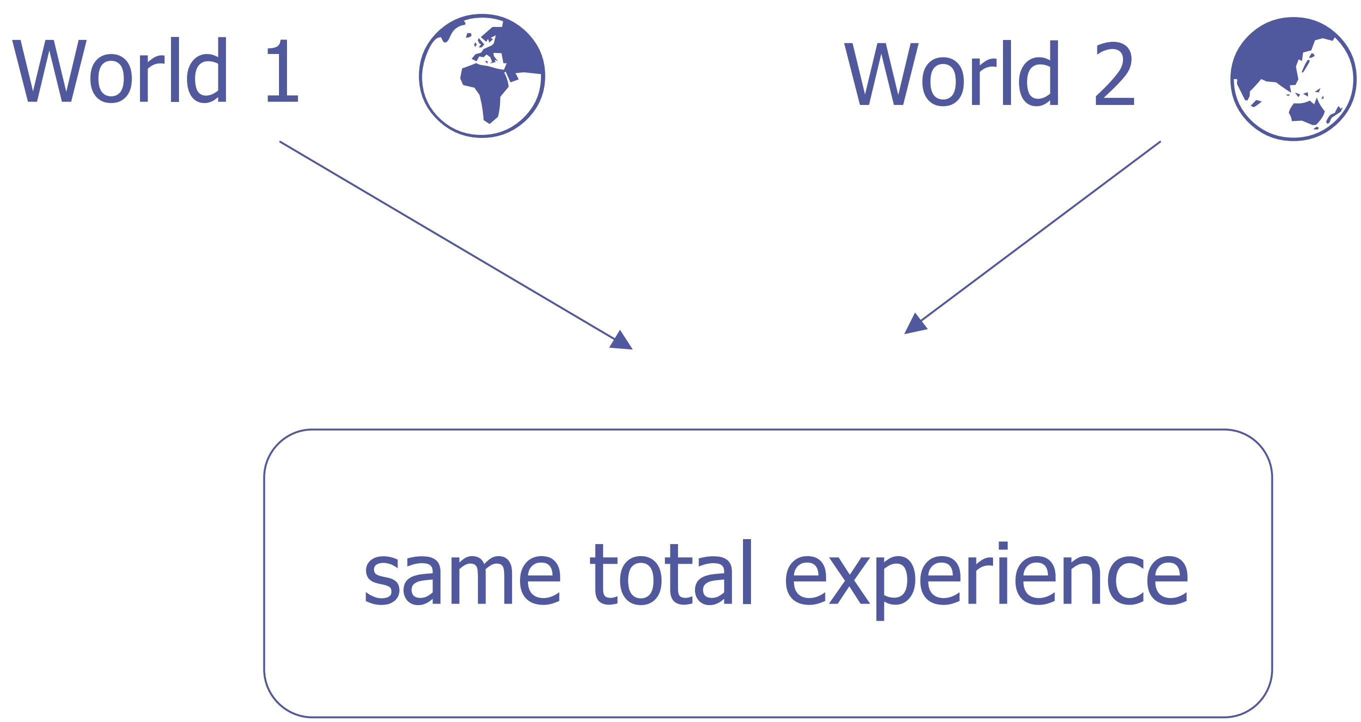
- How does *underdetermination* arise in particle physics?
- How do physicists resolve it?

# Underdetermination

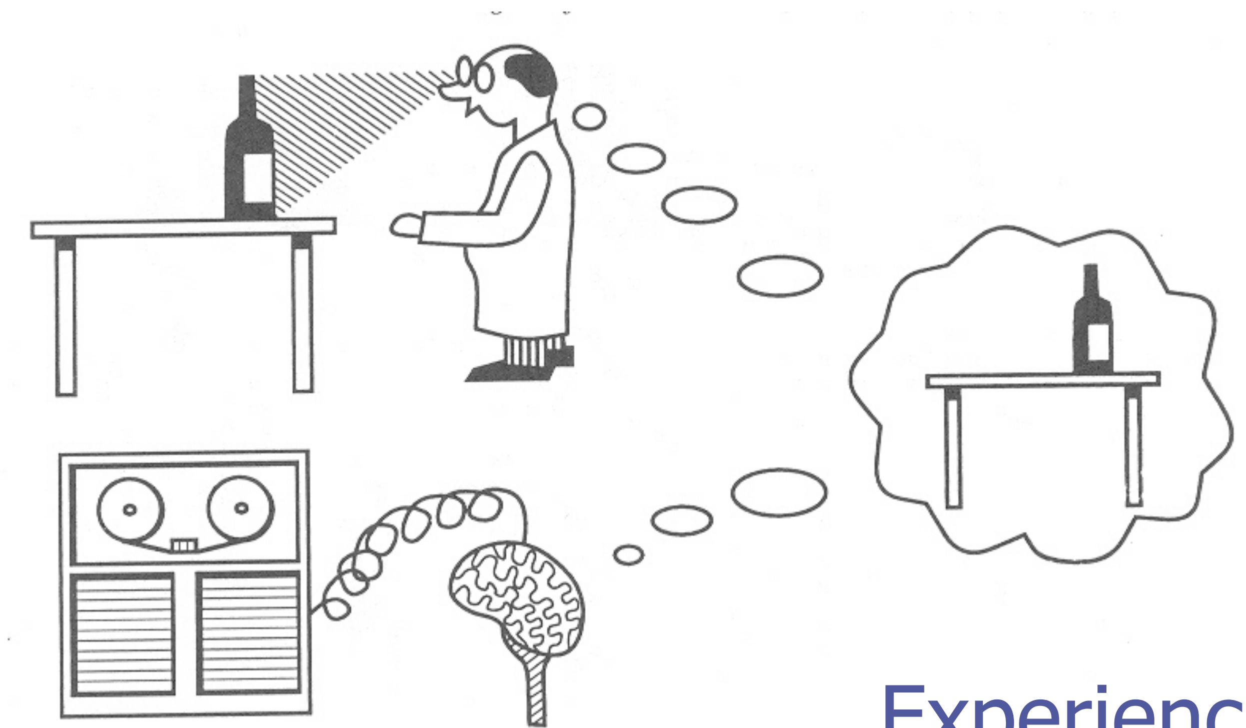
- **Global Underdetermination**: Even the total infinite data do not determine the answer to our questions.
- **Local Underdetermination**: finite data do not determine the answer to our questions.
- **Ontological Relativity**: are there objective grounds for grouping objects one way rather than another?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

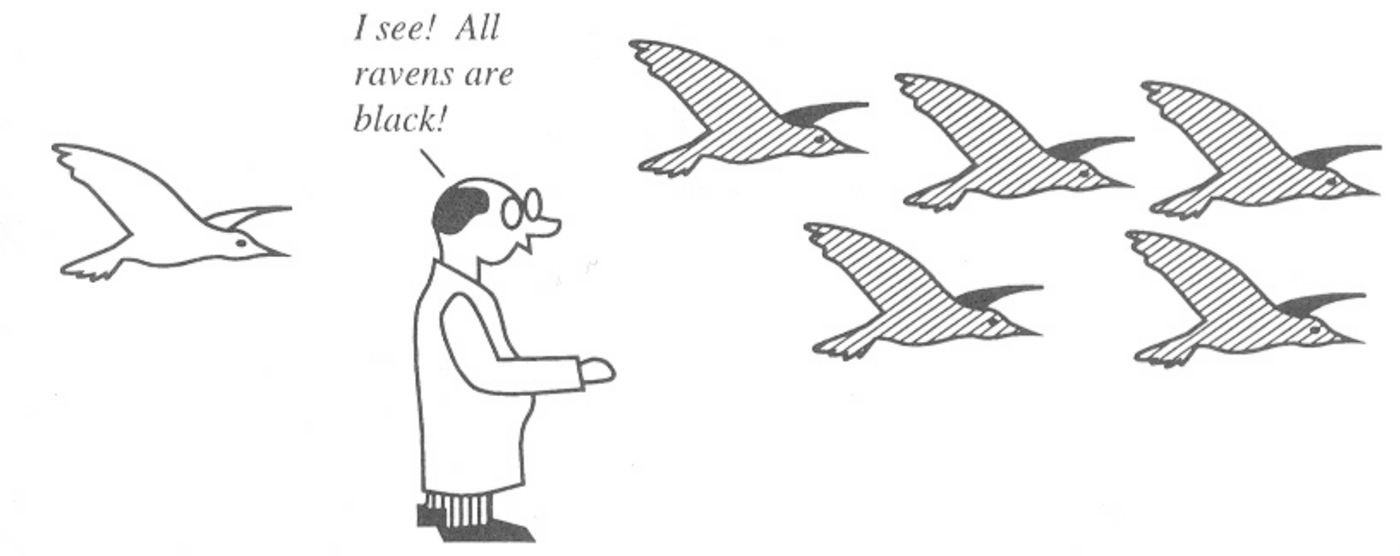
# From Metaphysics to Epistemology

- 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



# Local Underdetermination in Particle Physics

Particle Review 2005: 2v → 2p + 2e$^-$ **observed**

I see!
2v → 2p + 2e
is impossible.

Particle Review 2004: **no** 2v → 2p + 2e$^-$

Particle Review 2003: **no** 2v → 2p + 2e$^-$

Particle Review 2002: **no** 2v → 2p + 2e$^-$

I must find a conservation law
that explains this.

# Additive Conservation Principles = "Selection Rules"

| | Particle | Charge | Baryon# | Tau# | Electron# | Muon# |
|---|---|---|---|---|---|---|
| 1 | $\Sigma^-$ | -1 | 1 | 0 | 0 | 0 |
| 2 | $\overline{\Sigma}^+$ | 1 | -1 | 0 | 0 | 0 |
| 3 | $\Sigma^0$ | 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 | $\pi^+$ | 1 | 0 | 0 | 0 | 0 |
| 14 | $\pi^-$ | -1 | 0 | 0 | 0 | 0 |
| 15 | $\pi^0$ | 0 | 0 | 0 | 0 | 0 |
| 16 | $\gamma$ | 0 | 0 | 0 | 0 | 0 |
| 17 | $\tau^-$ | -1 | 0 | 1 | 0 | 0 |
| 18 | $\tau^+$ | 1 | 0 | -1 | 0 | 0 |
| 19 | $\nu_\tau$ | 0 | 0 | 1 | 0 | 0 |
| 20 | $\overline{\nu}_\tau$ | 0 | 0 | -1 | 0 | 0 |
| 21 | $\mu^-$ | -1 | 0 | 0 | 0 | 1 |
| 22 | $\mu^+$ | 1 | 0 | 0 | 0 | -1 |
| 23 | $\nu_\mu$ | 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 | $\nu_e$ | 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 no conservation principle rules out r, conjecture that r is possible.
  - If some conservation principle rules out r, conjecture that r is forbidden, and introduce a conservation principle to explain why.
- This can be justified by means-ends epistemology as *the optimal method*. (Schulte 2000 BJPS)

# Maximally Strict Conservation Principles

- **Dfn**: A set of conservation principles Q is **maximally strict** for a set of observed reactions R $\Leftrightarrow$ 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, how many maximally strict conservation theories are there?*

# The Vector Representation for Reactions

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

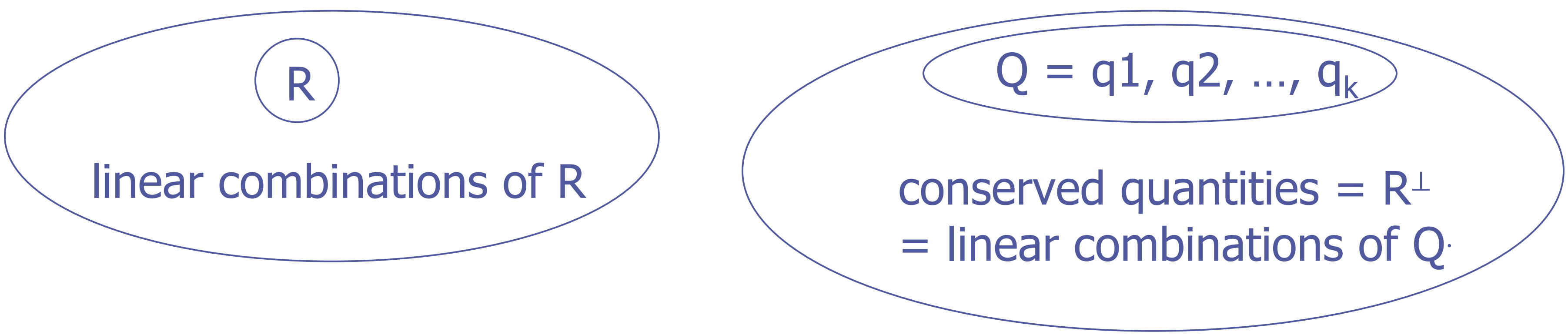
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Process | $p$ | $\pi^0$ | $\mu^-$ | $e^+$ | $e^-$ | $\nu_\mu$ | $\bar{\nu}_e$ |
| $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$ | 0 | 0 | 1 | 0 | -1 | -1 | -1 |
| $p \rightarrow e^+ + \pi^0$ | 1 | -1 | 0 | -1 | 0 | 0 | 0 |
| $p + p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

# Conserved Quantities in Vector Space

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Process | $p$ | $\pi^0$ | $\mu^-$ | $e^+$ | $e^-$ | $\nu_\mu$ | $\bar{\nu}_e$ |
| $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$ | 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 ⇒ Conservation Principles

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

Baryon#: $p$ $n$ $\Sigma^0$ $\Sigma^-$

Electron#: $e^-$ $\nu_e$

Muon#: $\mu^-$ $\nu_\mu$

Tau#: $\tau^-$ $\nu_\tau$

# Illustration in Current Theory

| | Particle | Charge | Baryon# | Tau# | Electron# | Muon# |
|---|---|---|---|---|---|---|
| 1 | $\Sigma^-$ | -1 | 1 | 0 | 0 | 0 |
| 2 | $\overline{\Sigma}^+$ | 1 | -1 | 0 | 0 | 0 |
| 3 | $\Sigma^0$ | 0 | 1 | 0 | 0 | 0 |
| 4 | $\overline{\Sigma}^0$ | 0 | -1 | 0 | 0 | 0 |
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| 15 | $\pi^0$ | 0 | 0 | 0 | 0 | 0 |
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| 17 | $\tau^-$ | -1 | 0 | 1 | 0 | 0 |
| 18 | $\tau^+$ | 1 | 0 | -1 | 0 | 0 |
| 19 | $\nu_\tau$ | 0 | 0 | 1 | 0 | 0 |
| 20 | $\overline{\nu}_\tau$ | 0 | 0 | -1 | 0 | 0 |
| 21 | $\mu^-$ | -1 | 0 | 0 | 0 | 1 |
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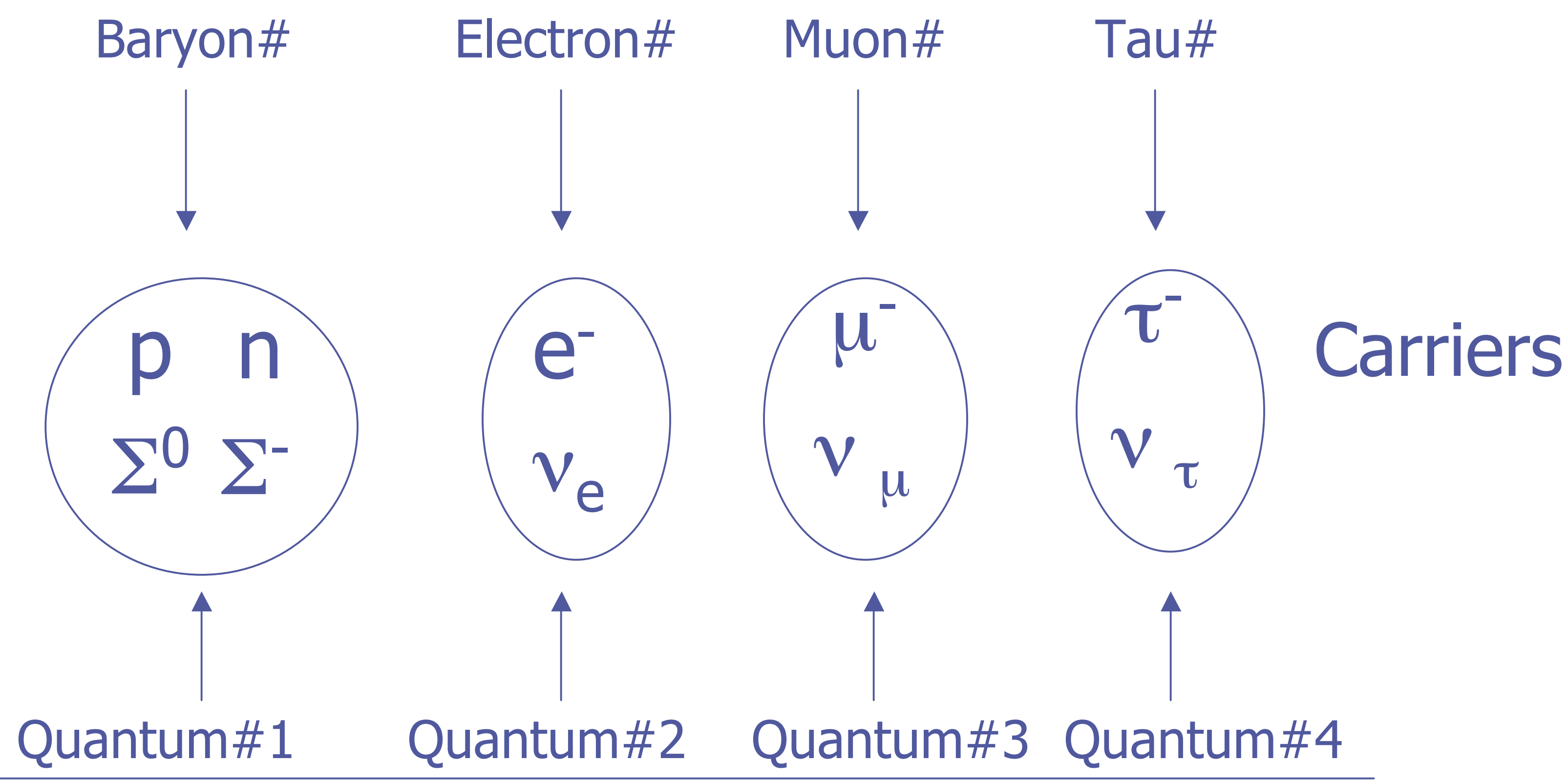
Table 1: Some Common Particles and Quantum Number Assignments

# 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.

# 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 (natural kinds) $\Rightarrow$ unique set of 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 critical experiment for testing a crucial hypothesis in current particle physics ($\nu_e \neq \overline{\nu}_e$).

# 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*

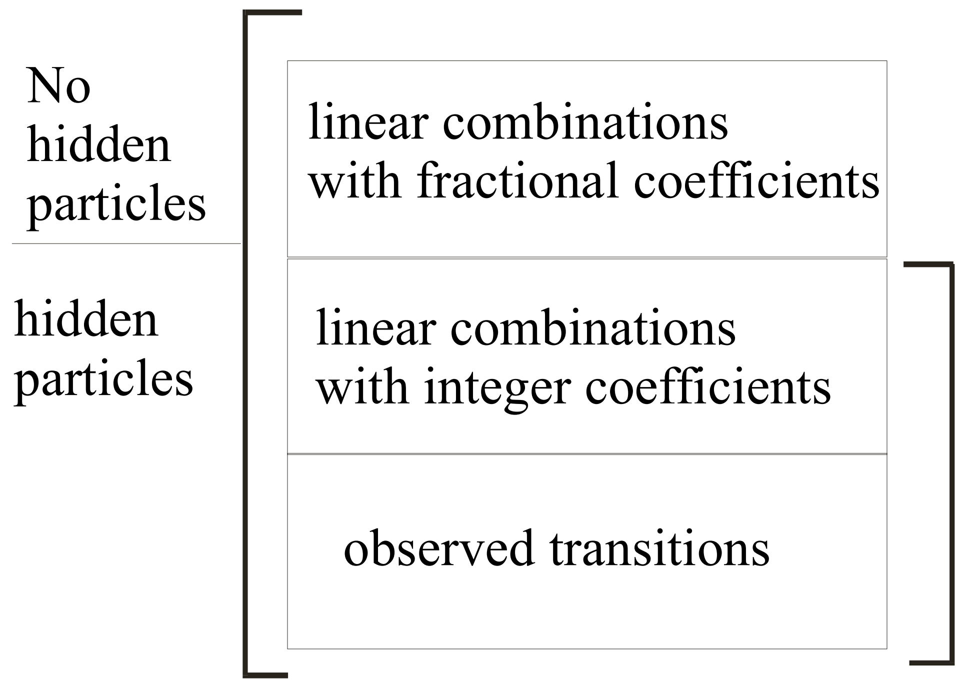
THE END

# More Particles can lead to stricter Conservation Principles

- Well-known example: if $\nu_e \neq \bar{\nu}_e$, then $n + n \rightarrow p + p + e^- + e^-$ should be possible.
- 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**."

# When do more particles lead to stricter Conservation Principles?

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



# 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 $\gamma$ Smith Normal Form of $R^T$ has a diagonal entry outside of {0,1,-1}.