# Chirality, particle physics, and “theory space”

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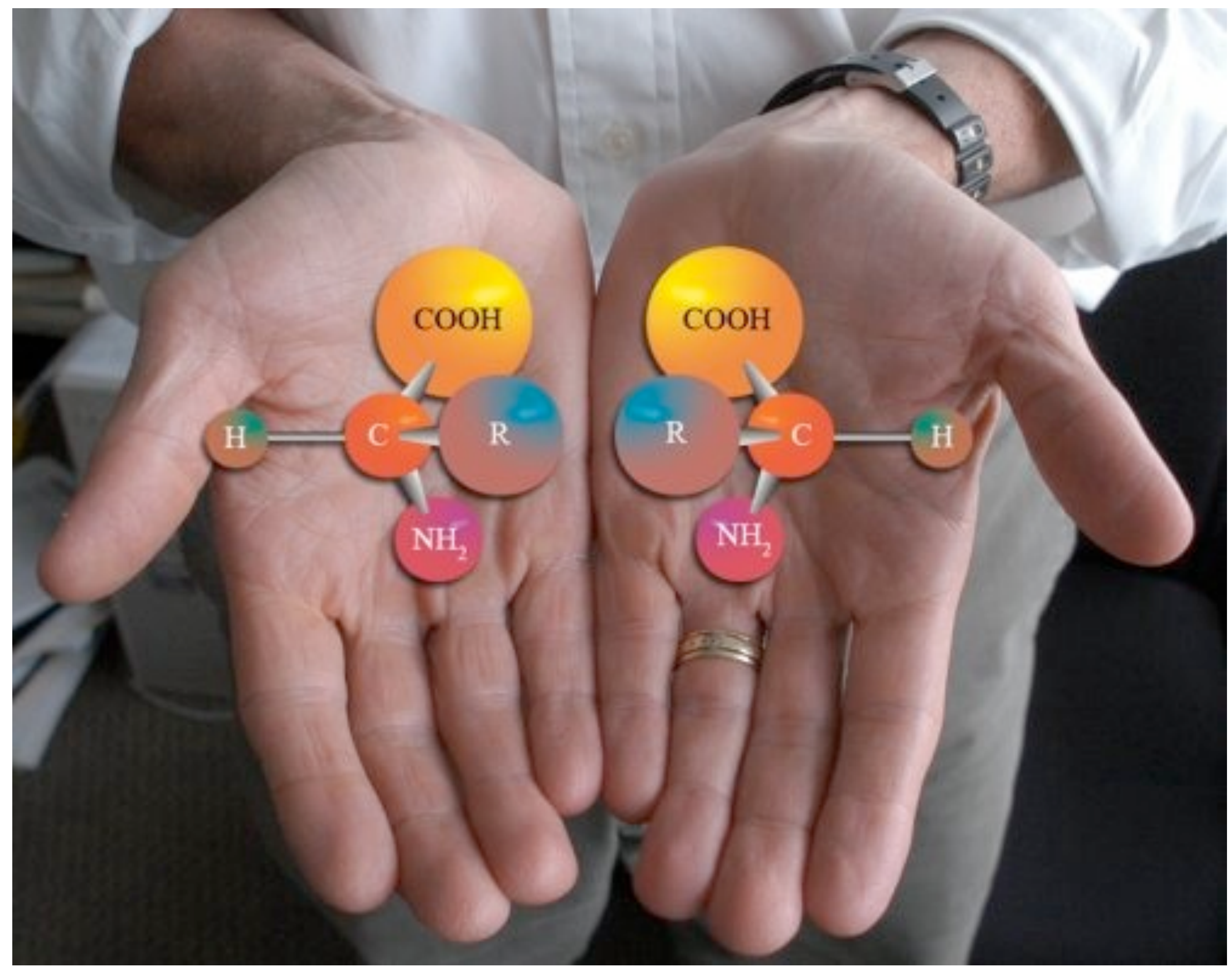
***From a theorists’ point of view, much effort in particle physics today evolves around chirality, chiral symmetry, and its breaking...***

## Lord Kelvin's definition (1904) *(first observed by Pasteur, 1848)*

*"I call any geometrical figure, or group of points,* ***chiral****, and say it has* ***chirality****, if its image in a plane mirror, ideally realized, cannot be brought to coincide by itself."*




χειρ = hand

***chirality*** **=** "handedness"

The difference between objects with left- or right-handedness is common in the **macroscopic** world.

e.g., we metabolize only right-handed glucose

Alice to Kitty:

*"...Perhaps looking-glass milk isn't good to drink...."*

In the **microscopic** world of elementary particles and the fundamental forces between them, however, the symmetry between L-(eft) and R-(ight) holds almost universally.

the four fundamental forces:

- gravity
- electromagnetism → the one most relevant for macroscopic world (chemistry/biology)
- weak interactions
- strong interactions

are blind to "chirality" - except the weak interactions

Lee, Yang (theory, 1956) Wu (experiment, 1957) spin-polarized

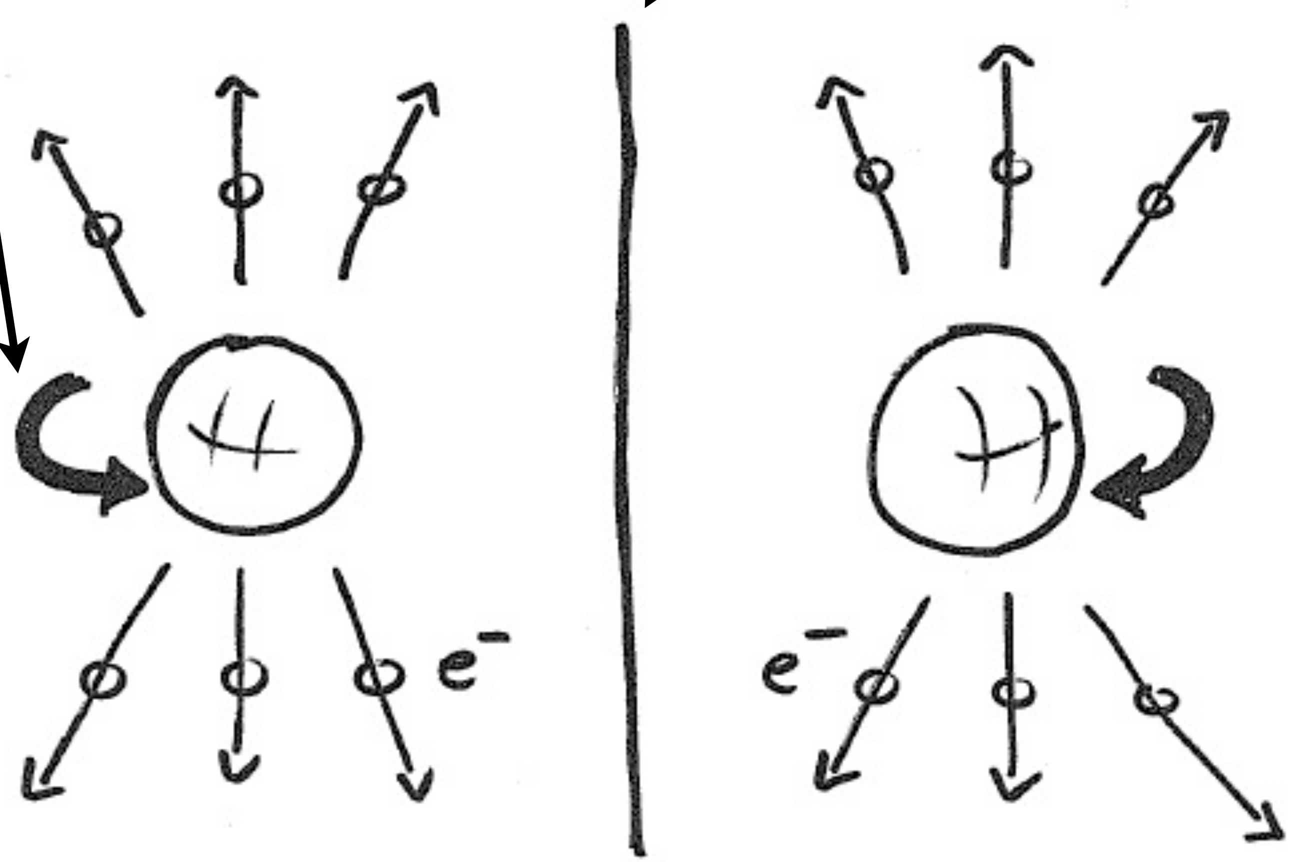
Cobalt ⟶ Nickel + electron + anti-neutrino

27 protons
33 neutrons

28 protons
32 neutrons

spinning nucleus

mirror




in the mirror the nuclei rotate in the opposite direction

symmetry with mirror image would require equal number of electrons going up and down spin-polarized

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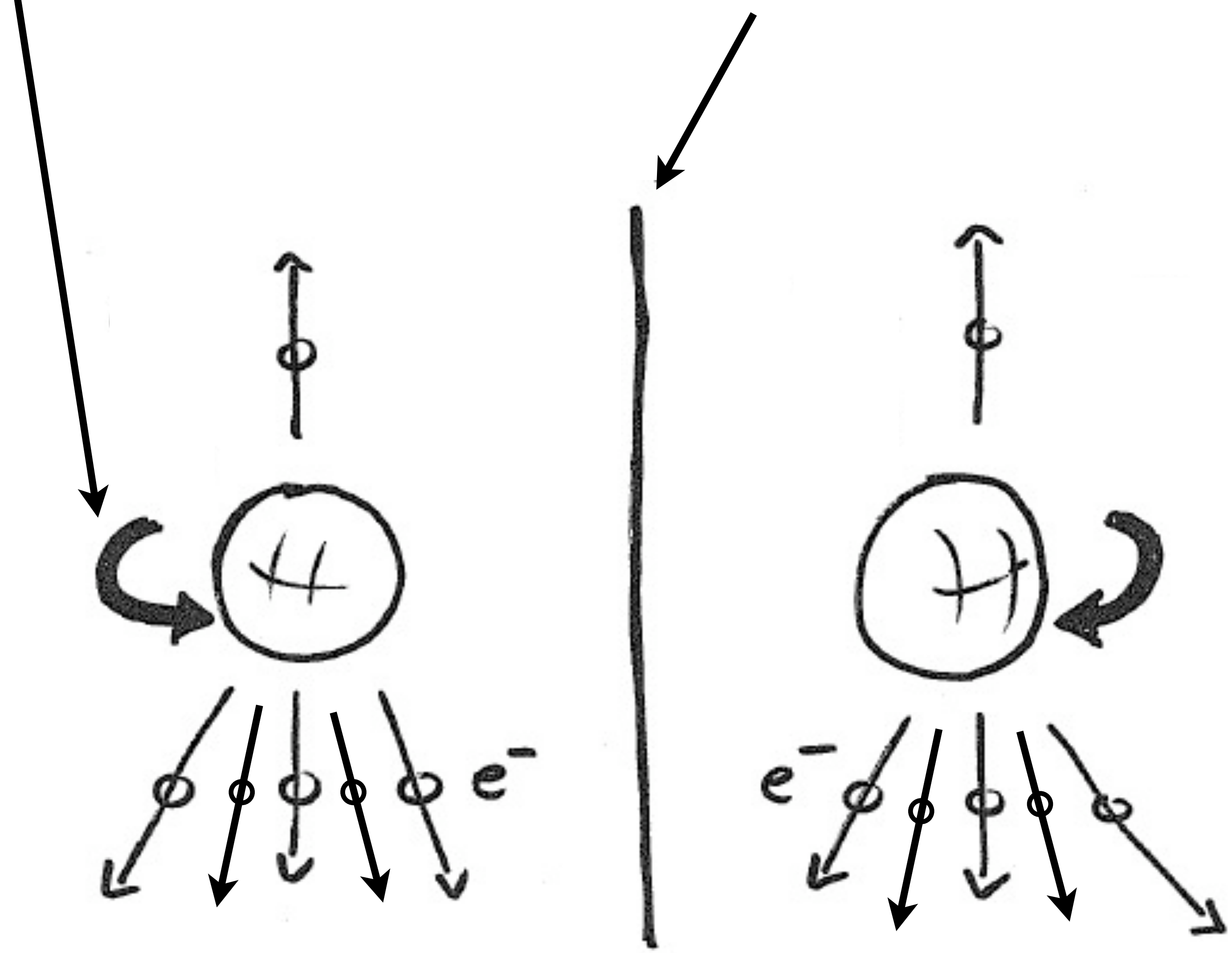


in the mirror the nuclei rotate in the opposite direction

symmetry with mirror image would require equal number of electrons going up and down

but this is not what was found!

Wu
(experiment, 1957)

thus, weak interactions are "chiral"

Wu's discovery led Gell-Mann (1958) to postulate the chiral ("V-A") structure of weak interactions, and ultimately, led to the establishment of the Standard Model of particle physics of Glashow, Salam, Weinberg (~1970).

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What, more precisely, do we mean by "chirality" in the particle physics world?

What are the "building blocks" of the Standard Model?

gauge bosons of spin-1:

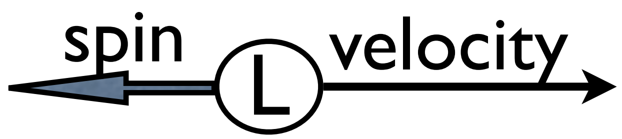
photon, gluons, W, Z

fermions of spin-1/2:

electron, muon, tau, neutrinos, quarks

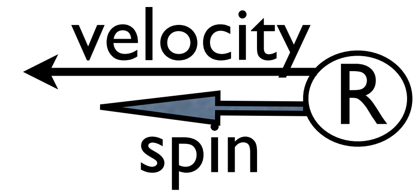
# electron, muon, tau, quarks, (neutrinos) are all "made of"

"L-handed" fermions



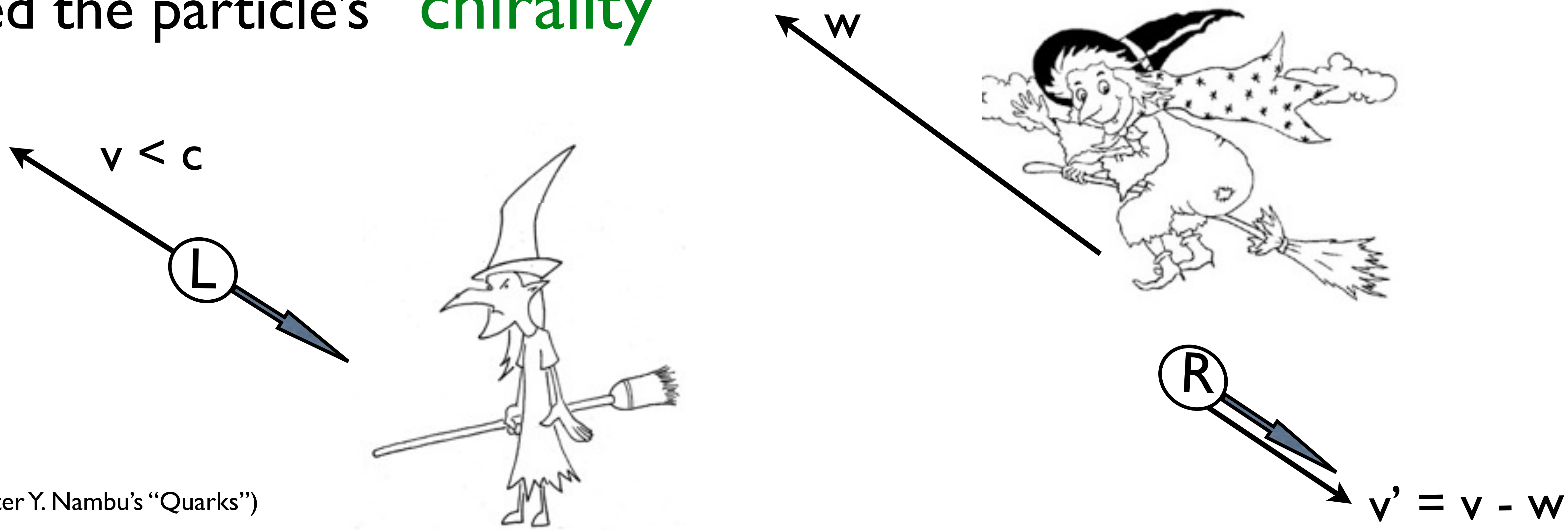

and

"R-handed" fermions




- which are mirror images of each other

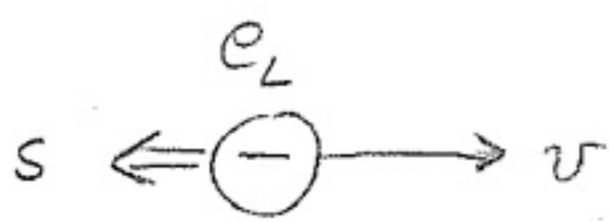
massless fermions move with speed of light - projection of spin on direction of motion is a characteristic independent of observer - called the particle's "chirality"




(cartoon after Y. Nambu's "Quarks")

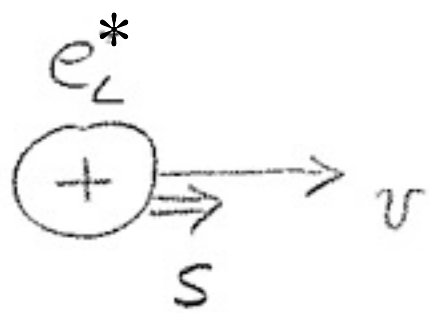
massive fermions, on the other hand, do not have definite chirality - it can look different to different observers thus, at the fundamental level, the electron is "made of"

left-handed electron

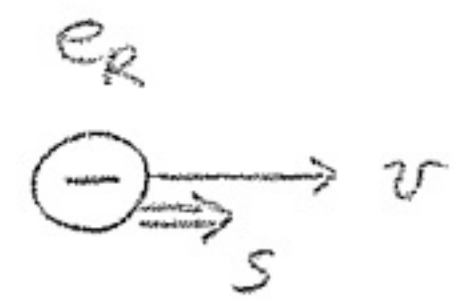



its anti-particle:

right-handed positron




right-handed electron

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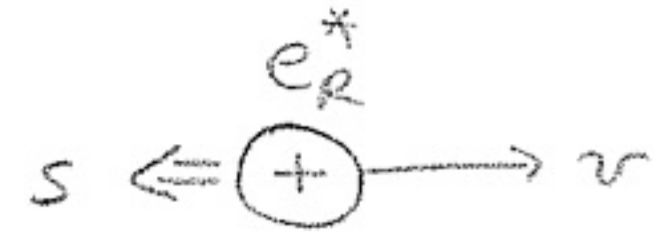



for all the rest: muon, tau, quarks (u,d,c,s,b,t) simply put the appropriate value of charge in place of +/-

for neutrinos, we do not know yet if R-handed ones exist

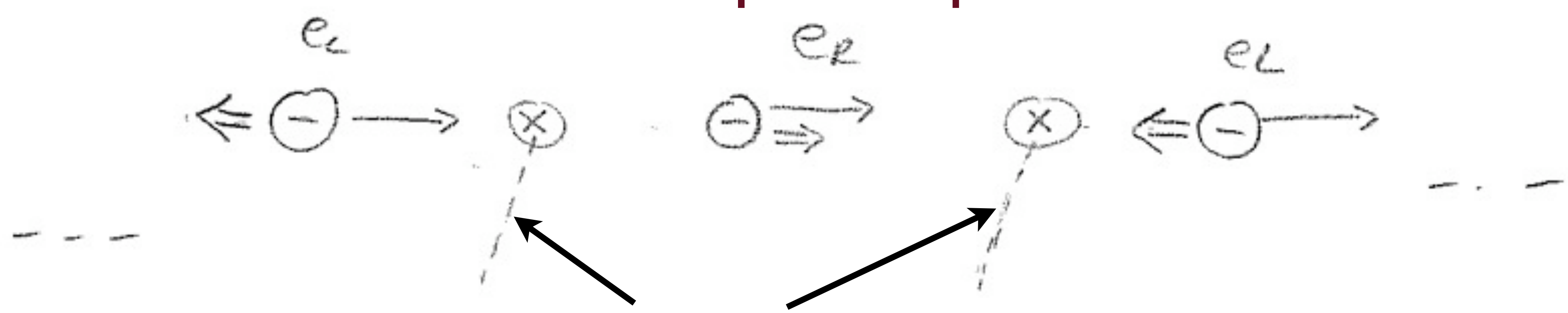
thus, apart from the neutrinos, the particle content of the Standard Model is L-R symmetric - we call it "vectorlike" or "Dirac" but, electron not massless - recall: chirality ⟶ $v = c$ (massless)

(massive) $v < c$ ⟶ ~~chirality~~

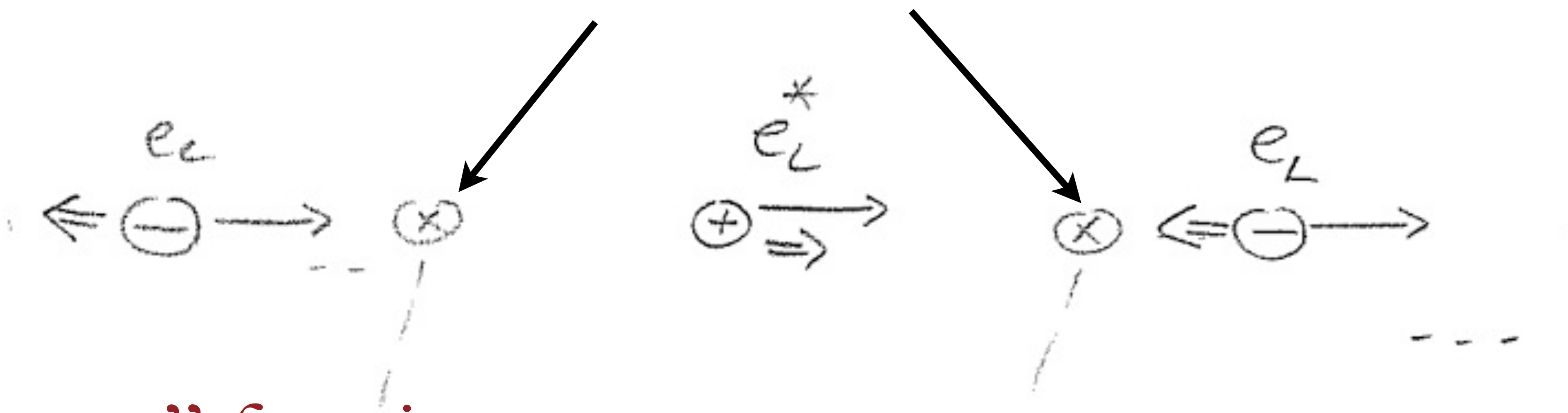
there are two ways that a fermion can be "slowed down"

clearly, both must involve chirality violation

"Dirac" fermion mass - leptons, quarks in Standard Model



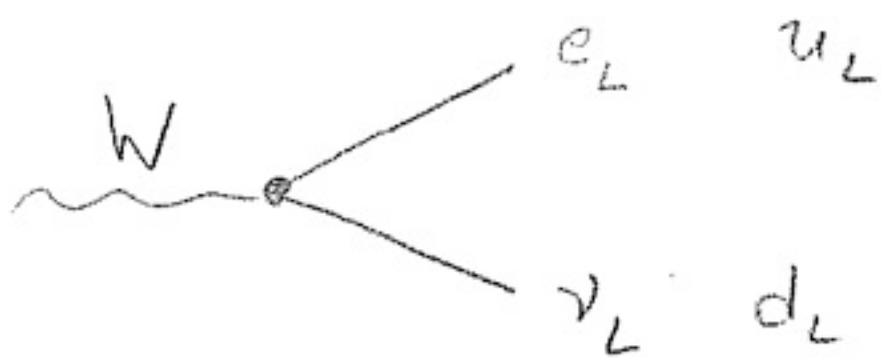

interaction with the "Higgs field" condensate "flips" chirality

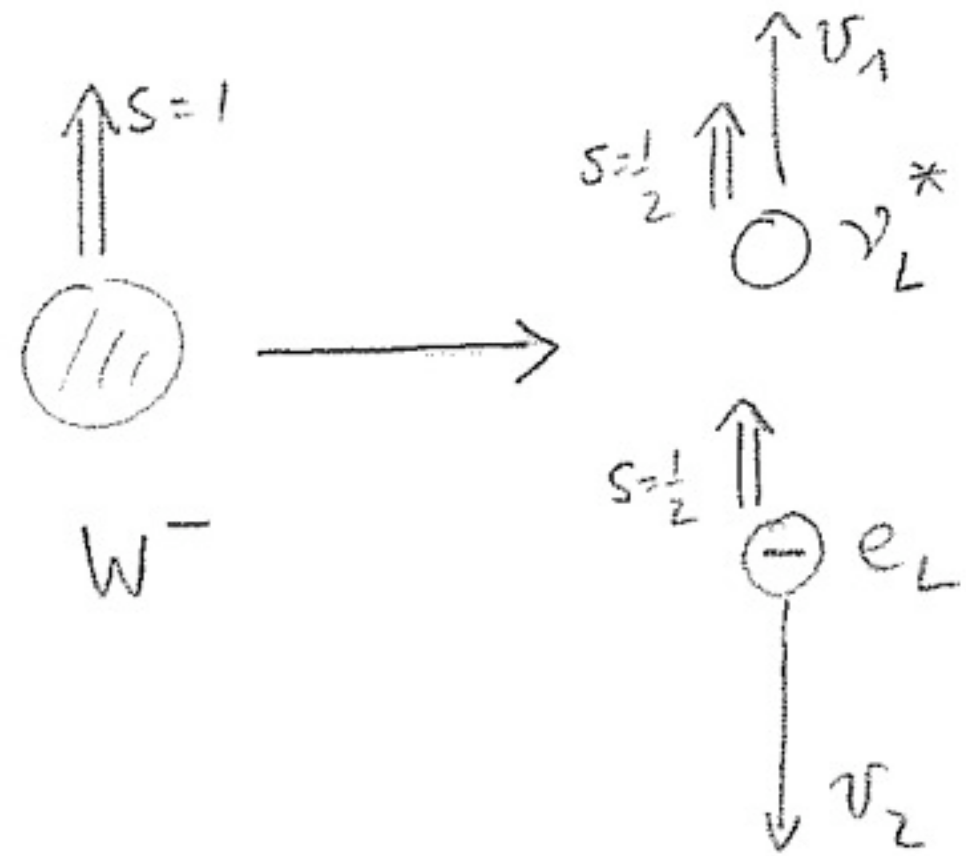



"Majorana" fermion mass

e.g., if R-handed electron didn't exist - charge would not be conserved - but a possibility for neutrinos thus, while the spectrum of the SM is L-R symmetric ("vectorlike" or "Dirac"), some of the interactions - the ones responsible for the nuclear beta decay - are not L-R asymmetric ("chiral")

W couples only to L!

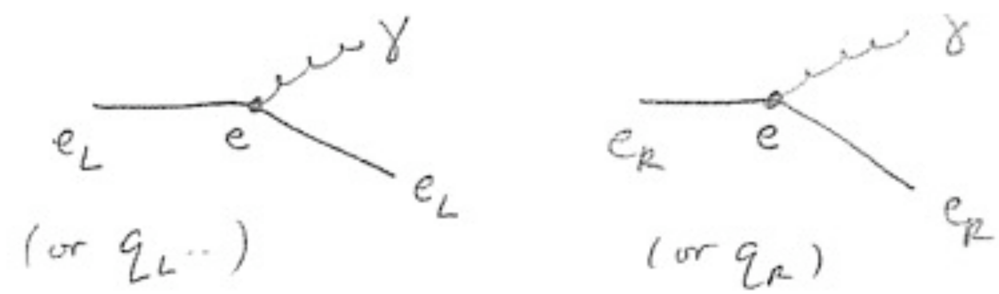


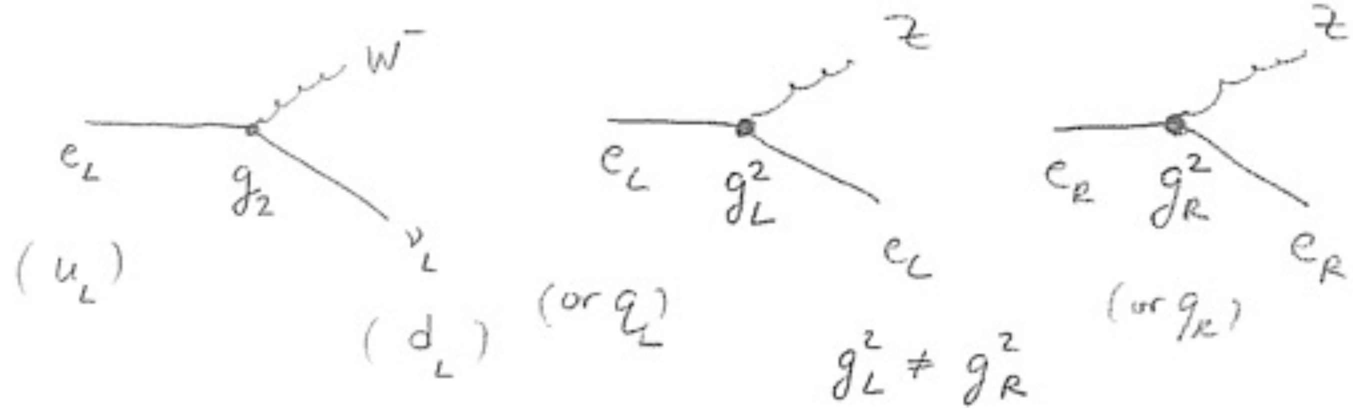

L-electron only is produced, so its velocity correlates with spin of W, which in turn "remembers" spin of neutron - part of spin-polarized Cobalt nucleus

since the nuclear beta decay interactions are very weak, it took years before parity violation was seen in summary, the Standard Model incorporates three of the fundamental forces

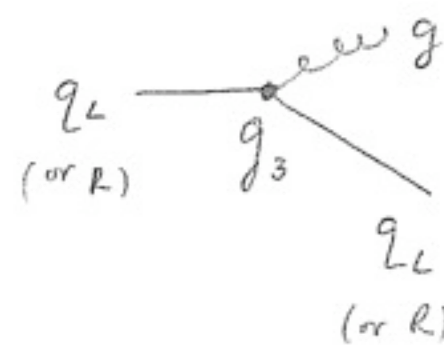
- electromagnetism



- weak interactions



- strong interactions



+ gluon self-interactions

as the names may suggest - all but the strong ones are "weak", in the sense that we can study most of their relevant aspects in "perturbation theory" in some small g:

$$H = H_0 + g\, H_I$$

For a theorist, the Standard Model is just a collection of **“gauge theories”:**

- electromagnetism — “vectorlike”, weak
- weak interactions — “chiral”, weak

(electromagnetism and weak interactions: perturbative (largely))

- strong interactions — “vectorlike”, strong “in the IR”

an arena for a host of non-perturbative techniques:

- models (quark models, instanton “liquid”, SD eqns...)
- first principles - large-N ideas, lattice

  e.g., solve H without expanding in g: $H = H_0 + g\, H_I$

The need for such non-perturbative studies of the strong interactions arises because of a peculiarity of their dynamics - "asymptotic freedom" - interactions are weak at short distances but become strong at long-distances (or, as we say, in the "IR" infrared):

- a flux tube of "glue" ("QCD string" O(1) fm thick) stretches between quarks and gives rise to a linearly-rising "confining" potential between quarks

"quarks" and "gluons" are useful to describe the short-distance behavior of the theory - but fail to capture its large-distance properties - new "emergent" degrees of freedom become relevant.

(both stable particles or otherwise: proton, neutron, pion,...).

Much progress in understanding QCD - the theory of the strong interactions - has been achieved by a variety of techniques - symmetries, effective field theory, lattice, large-N, etc. (but no "solution" yet, even in simplifying limits); no doubt also aided by the nature's "analogue computer".

"Asymptotic freedom"- the growth of interactions and the associated "emergent" IR degrees of freedom - is a generic property of nonabelian gauge theories. It can lead to a IR behaviors quite distinct from QCD.

My focus here is on asymptotically free theories different from those describing the strong interactions:

- why is this interesting?
- what is (my definition of) "theory space"?
- how do we study the dynamics?

# The reason is that, despite the spectacular agreement of Standard Model predictions with experiment:

(fairly old transparency; point is to show %-level agreement)

| | | | experiment | theory | |
|---|---|---|---|---|---|
| $M_Z$ | [GeV] | LEP | $91.1876 \pm 0.0021$ | $91.1874 \pm 0.0021$ | 0.1 |
| $\Gamma_Z$ | [GeV] | LEP | $2.4952 \pm 0.0023$ | $2.4972 \pm 0.0011$ | −0.9 |
| $\Gamma(\mathrm{inv})$ | [MeV] | LEP | $499.0 \pm 1.5$ | $501.74 \pm 0.15$ | — |
| $\sigma_{\mathrm{had}}$ | [nb] | LEP | $41.541 \pm 0.037$ | $41.470 \pm 0.010$ | 1.9 |
| $R_e$ | | LEP | $20.804 \pm 0.050$ | $20.753 \pm 0.012$ | 1.0 |
| $R_\mu$ | | LEP | $20.785 \pm 0.033$ | $20.753 \pm 0.012$ | 1.0 |
| $R_\tau$ | | LEP | $20.764 \pm 0.045$ | $20.799 \pm 0.012$ | −0.8 |
| $R_b$ | | LEP + SLD | $0.21644 \pm 0.00065$ | $0.21572 \pm 0.00015$ | 1.1 |
| $R_c$ | | LEP + SLD | $0.1718 \pm 0.0031$ | $0.17231 \pm 0.00006$ | −0.2 |
| $A_{FB}(b)$ | | LEP | $0.0995 \pm 0.0017$ | $0.1036 \pm 0.0008$ | −2.4 |
| $A_{FB}(c)$ | | LEP | $0.0713 \pm 0.0036$ | $0.0741 \pm 0.0007$ | −0.8 |
| $A_b$ | | SLD | $0.922 \pm 0.020$ | $0.93477 \pm 0.00012$ | −0.6 |
| $A_c$ | | SLD | $0.670 \pm 0.026$ | $0.6681 \pm 0.0005$ | 0.1 |
| $A_{LR}$ (hadrons) | | SLD | $0.15138 \pm 0.00216$ | $0.1478 \pm 0.0012$ | 1.6 |

The New York Times May 17, 2010 **“A New Clue to Explain Existence”**

matter-antimatter symmetric initial state
(proton-antiproton collision at Fermilab) → produces more matter than antimatter
(~100x Standard Model prediction)

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**we are somewhat at a loss…**

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→

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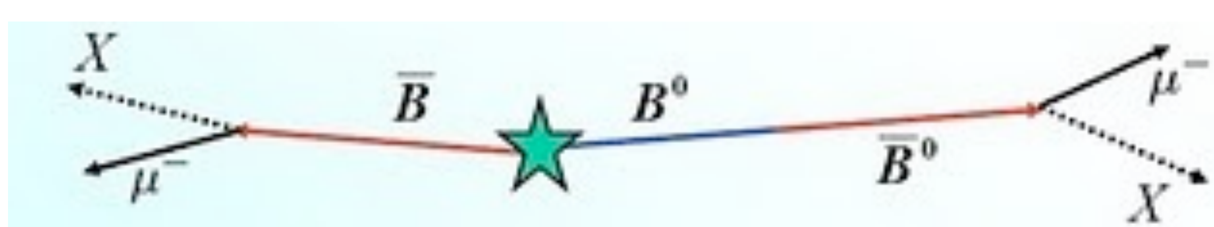
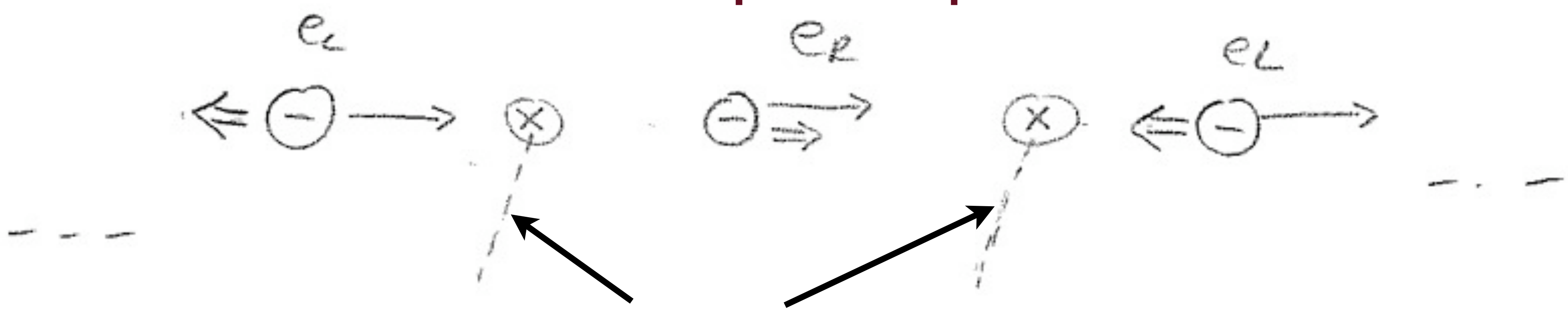


# "Dirac" fermion mass - leptons, quarks in Standard Model




chirality breaking interaction with the "Higgs field" condensate

the condensate's nature - a property of the vacuum - is not known

Precisely this unknown Higgs "phenomenon," together with the L-R asymmetry of weak interactions, links the W, Z-boson masses to the quark & lepton masses (from picture & L-only couplings of W: W "couples" to condensate, too).

Further, the fermion masses span 12 orders of magnitude below W,Z masses. We don't know why.

It is not that we do not have ways to parameterize the Higgs phenomenon (to do the theory calculations for the table shown before, one surely needs a lagrangian).

What we lack is a satisfactory picture explaining the many strange numbers describing the particle properties:

| Energy scale | gauge bosons | leptons | quarks | hadrons |
|---|---|---|---|---|
| 100 GeV | W, Z (81-90 GeV) | | top (174 GeV) | |
| 1 GeV | | tau | bottom, charm | proton, neutron, lambda, delta... |
| 100 MeV | | muon (105 MeV) | strange | pions, kaons... |
| 1 MeV | | electron (500 keV) | up, down (a few MeV) | |
| 1 meV | | neutrinos | | |
| 0 eV | photon, gluon (graviton) | | | |
| | "elementary" | | | "composite" |

$mc^2$

"emergent"

+ others not shown:

$$\frac{G_{Fermi}}{G_{Newton}} \simeq 10^{-34}$$

CKM mixing angles, CP violation phase, theta-parameter

**We have a great "working" theory - but it has 18 free dimensionless parameters, spanning about 12 orders of magnitude!** (not counting Higgs self-coupling)

In the past 30+ years, theorists have worked hard to remedy the situation - coming up with a multitude of so-called "Beyond the Standard Model" scenarios... which have raised many questions:

is "the Higgs" a fundamental scalar field?

is it a composite object?

is there strongly-coupled dynamics involved?

is there supersymmetry?

is the theory "natural"?

...

(dark matter, CP, inflation)

...

time has now come to pay the piper...

## *What will the LHC discover?*

resonaances.blogspot.com

*Blogger Jester says:*

*Higgs boson.*
*...*
*Non-SM Higgs boson.*
*...*
*New Beyond SM Particles.*
*...*
*Strong Interactions.*
*...*
*Dark matter.*
*...*
*Little Higgs and friends.*
*...*
*Supersymmetry.*
*...*
*Dragons.*
*...*
*Black Holes.*

# *What will the LHC discover?*

resonaances.blogspot.com

*Blogger Jester says:*

Here are my expectations. The probabilities were computed using all currently available data and elaborated Bayesian statistics.

*Higgs boson. Probability 80%*

*...*

*Non-SM Higgs boson. Probability 50%*

*...*

*New Beyond SM Particles. Probability 50%*

*...*

*Strong Interactions. Probability 20%*

*...*

*Dark matter. Probability 5%*

*...*

*Little Higgs and friends. Probability 1%*

*...*

*Supersymmetry. Probability 0.1%*

*...*

*Dragons. Probability* $e^{-S_{dragon}}$

*...*

*Black Holes. Probability* $0.1 * e^{-S_{dragon}}$ ...

## *What will the LHC discover?*

My purpose here is not to discuss "scenarios"
(aka "model-building" - a separate and very long subject).

Just offer a few remarks:

*Higgs boson.*
...
*Non-SM Higgs boson.*
...
*New Beyond SM Particles.*
...
*Strong Interactions.*
...
*Dark matter.*
...
*Little Higgs and friends.*
...
*Supersymmetry.*
...

we have come up with many scenarios

it is not clear which (if any) of these scenarios are true

weakly-coupled scenarios generally suffer from fine-tuning problems

e.g., $\frac{M_Z^2}{2} \sim 4{,}050 = 1{,}924{,}050 - 1{,}920{,}000 \quad (\mathrm{GeV}^2)$

strong-coupling ideas are plagued by our inability to calculate

It is important to understand the signatures of the various scenarios and their discovery potential at the LHC (many workshops).

It is also important to understand the "theory space" involved (fewer workshops).

My focus will be on this...

## *What will the LHC discover?*

*Higgs boson.*

…

*Non-SM Higgs boson.*

…

*New Beyond SM Particles.*

…

*Strong Interactions.*

…

*Dark matter.*

…

*Little Higgs and friends.*

…

*Supersymmetry.*

…

In all "scenarios" for "Beyond the Standard Model" physics, new gauge dynamics is invoked, at some scale.

(Unless "supersplit supersymmetry" turns out to be nature's choice.)

When the weak force is turned off, this gauge dynamics can be "chiral" (L-R asymmetric) or "vectorlike".

What is the "theory space" involved?

“gauge theory space” conventional wisdom:

**pure YM** - “formal” but see www.claymath.org/millennium/

**Yang–Mills Existence and Mass Gap.** *Prove that for any compact simple gauge group $G$, a non-trivial quantum Yang–Mills theory exists on $\mathbb{R}^4$ and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in* [45, 35].

[45] R. Streater and A. Wightman, *PCT, Spin and Statistics and all That*, W. A. Benjamin, New York, 1964.

[35] K. Osterwalder and R. Schrader, *Axioms for Euclidean Green's functions*, Comm. Math. Phys. **31** (1973), 83–112, and Comm. Math. Phys. **42** (1975), 281–305.

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**pure YM** - “formal” but see www.claymath.org/millennium/

**SUSY** - very “friendly” to theorists
beautiful - exact results

gauge theories with boson-fermion degeneracy: new spacetime symmetry

**applications:**
superpartner masses; supersymmetry breaking in chiral SUSY theories; metastable vacua in vectorlike theories; SUSY compositeness, flavor...

I believe that one of the most important “applications” of supersymmetry is to teach us about the many “weird” things gauge field theories could do - often very much unlike QCD:

-massless monopole/dyon condensation - confinement and chiral symmetry breaking

-“magnetic free phases” - dynamically generated gauge fields and fermions

-chiral-nonchiral dualities

-last but not least: gauge-gravity dualities

## "gauge theory space"   conventional wisdom:

| | |
|---|---|
| **pure YM** | - "formal" but see www.claymath.org/millennium/ |
| **SUSY** | - very "friendly" to theorists<br>beautiful - exact results |
| **QCD-like (vectorlike)** | - hard, leave it to lattice folks<br>(m, a, V, $) |

gauge theories with varying number of massless vectorlike fermions

**applications:**
W, Z-masses-"walking" or "conformal" technicolor
"unparticles"

- upon increasing number of fermion "flavors" believed to become conformal

- large current lattice effort (many here!) to determine phase diagram
  (phenomenological goal: predictions for parameters of effective lagrangian at LHC scale)

"gauge theory space"  conventional wisdom:

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**QCD-like (vectorlike)** - hard, leave it to lattice folks
(m, a, V, $)

**non-SUSY chiral gauge theories** - poorly understood strong dynamics
...almost nobody talks about them anymore

massless fermions with L/R asymmetric coupling

**applications:** extended technicolor (fermion mass generation); quark and lepton compositeness; speculations on W, Z, t masses by monopole condensation

- non-QCD-like behavior, e.g. "confinement without chiral symmetry breaking": massless composite fermions (probably true)

- "tumbling" - dynamical generation of different scales (no idea if true... after 30 years!)

“gauge theory space” conventional wisdom:

| | |
|---|---|
| **pure YM** | - “formal” but see www.claymath.org/millennium/ |
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| **non-SUSY chiral gauge theories** | - poorly understood strong dynamics<br>...almost nobody talks about them anymore |

moral:

**We don’t know that much about generic non-supersymmetric gauge dynamics.**

Nature’s analogue computer is not (yet) available and the theory tools are limited...

“gauge theory space”

nonperturbative tools:

**SUSY**

- ‘t Hooft anomaly matching
- “power of holomorphy”
- mass and flat direction “deformations”
- semiclassical expansions
- strings/branes
- gauge-gravity dualities

**QCD-like (vectorlike)**

- lattice
- the others mentioned already for QCD (EFT...)

**non-SUSY chiral theories**

- ‘t Hooft anomaly matching
- semiclassical expansions

“classic”:

- “MAC” (most attractive channel)
- truncated Schwinger-Dyson equations

“postmodern”:

- postulated beta functions
- extrapolating semiclassical results outside region of validity

...

“gauge theory space”

nonperturbative tools:

**SUSY**

- ‘t Hooft anomaly matching
- “power of holomorphy”
- mass and flat direction “deformations”
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**QCD-like (vectorlike)**

- lattice
- the others mentioned already for QCD (EFT...)

**non-SUSY chiral theories**

- ‘t Hooft anomaly matching
- semiclassical expansions

tools one trusts

tools you don’t really trust - unless confirmed by experiment or the tools on the left

**“voodoo QCD”**

[Intriligator]

“classic”:

- “MAC” (most attractive channel)
- truncated Schwinger-Dyson equations

“postmodern”:

- postulated beta functions
- extrapolating semiclassical results outside region of validity

...

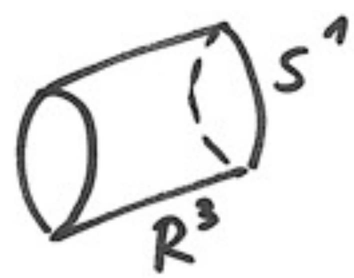
In the remaining time, I will describe a development, which is:

- relatively recent, at least in some of its twists and turns

- likely to be of some interest to people in a few of the workshops

The general theme is about infering properties of infinite-volume theory by studying (arbitrarily) small-volume dynamics.

The small volume may be



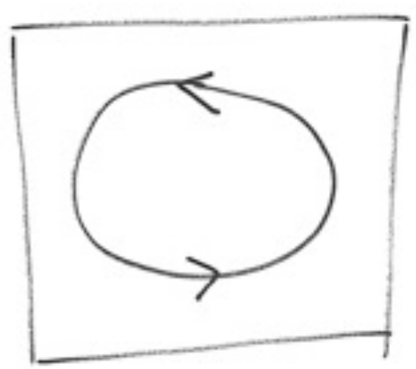

or


of characteristic size “L”

*some history:*

Eguchi and Kawai (1982) showed that loop (Schwinger-Dyson) equations for Wilson loops in pure Yang-Mills theory are identical in small-V and infinite-V theory, to leading order in 1/N, **provided**:

- "center-symmetry" unbroken
- translational symmetry unbroken (see Yaffe, 1982)



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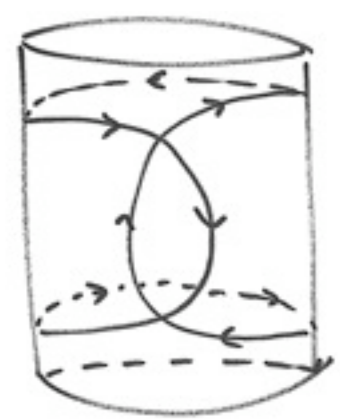


$+ \; O(1/N)$ **provided**

topologically nontrivial (winding) Wilson loops have vanishing expectation value (= unbroken center)

expectation value of any Wilson loop at infinite-L

expectation value of (folded) Wilson loop at small-L

**"EK reduction" or "large-N reduction" or "large-N volume-independence"**

If it can be made to work, **potentially exciting**, for:

1) **simulations may be cheaper** (use single-site lattice?)

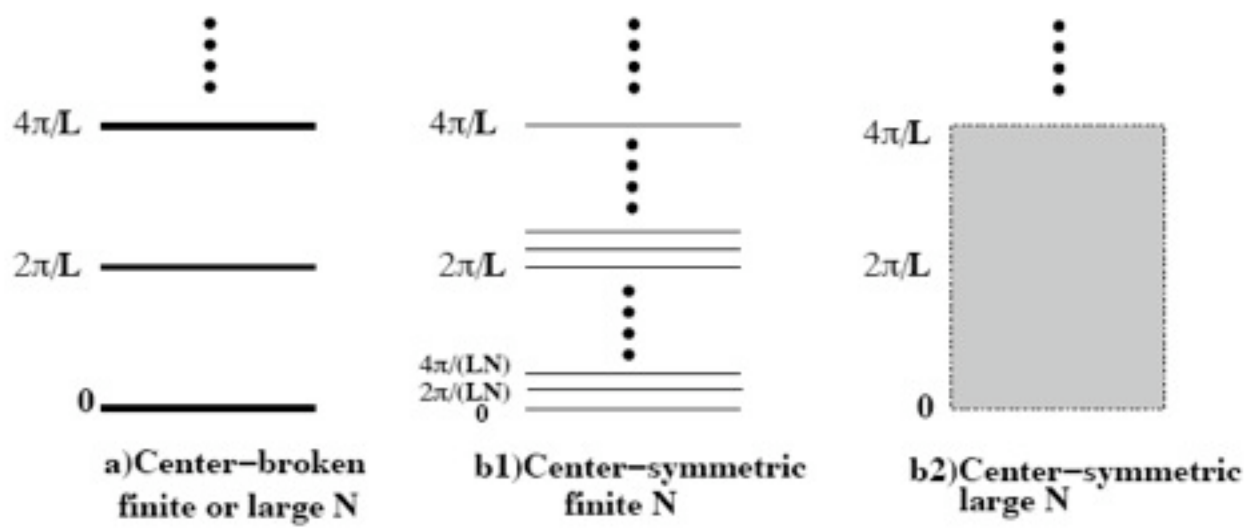
2) **raises theorist's hopes** (that small-L easier to solve?)

## Some intuition of how EK reduction works (valid at any coupling):

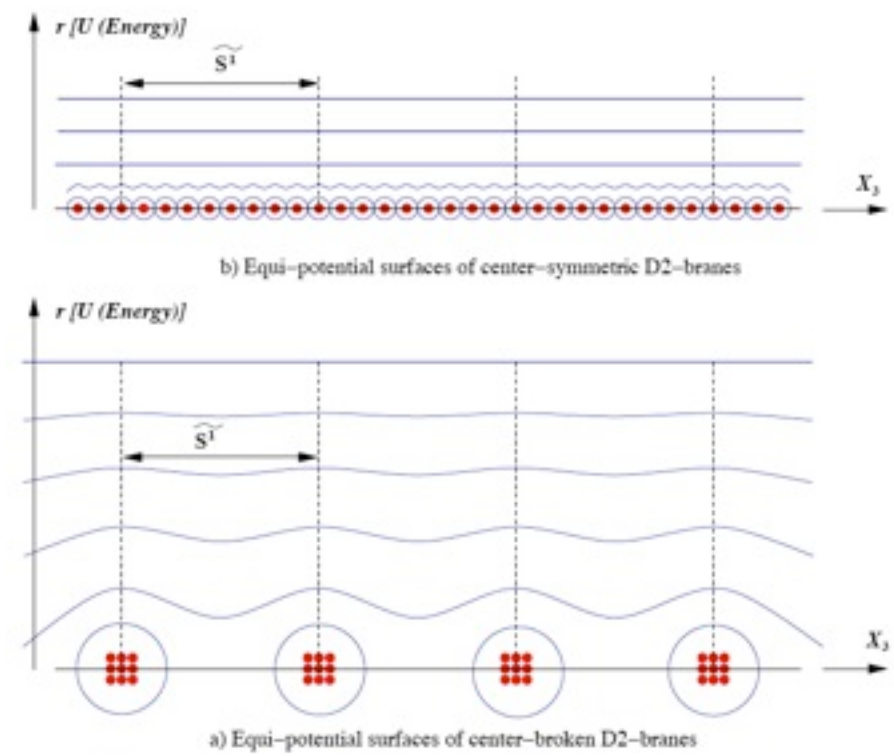
**in perturbation theory:** or **at strong coupling**:

from spectra (& Feynman graphs) in appropriate backgrounds

gravity dual of N=4 SYM - a conformal field theory - Wilson loops, appropriate correlators insensitive to box **if** center-symmetric




Parisi, Gross-Kitazawa, Das-Wadia... 1980's




$V(r) \sim 1/r$

...

Unsal, EP 2010

Bhanot, Heller, Neuberger (1982) noticed immediate problem

- center symmetry breaks for $L < L_c$ remedies: e.g., Gonzales-Arroyo, Okawa (1982) - TEK... + others later argued to have problems ... but recent 2-week-old "twists" on TEK ?

- nevertheless, "partial" reduction (i.e. $L > L_c$), can be useful (cheaper?):

e.g., Narayanan, Neuberger (2004) showed chiral symmetry breaking in QCD at large-N/small-$L>L_c$

## a "modern" large-N orbifold equivalence point of view on EK reduction

Kovtun, Unsal, Yaffe (2004)

- motivated by stringy ideas, but hold independently, using lattice-regulated loop equations

- volume-reducing "orbifold" by group of translations
  (keep only fields with right Fourier modes)

- proof that for neutral observables - uncharged under center and orbifold group - expectation values and connected correlators agree in small L and infinite-L theories [nonperturbative proof, includes also matter fields]

  "neutral" sector observables: effective size of space = N $L^d$
  "charged" sector observables: effective size of space = $L^d$

- **provided** center + symmetry used in orbifolding unbroken

(the tools are also used for proving other field theory large-N orbifold equivalences)

**a "modern" large-N orbifold equivalence point of view on EK reduction**

Kovtun, Unsal, Yaffe (2004)

Essentially, VEVs and correlators of operators that are center-neutral and carry momenta quantized in units of 1/L (in compact direction) are the same on, say  as in infinite-L theory.

calculating vevs (symmetry breaking)

- OK, even if all dimensions small

calculating spectra (for generic theories/reps)

- need at least one large dimension

... scattering for LHC

- all large dimensions (not all lunch is free)

**reduction to arbitrarily small L (single-site)** Unsal, Yaffe (2008)

if adjoint fermions (more than one Weyl) - no center breaking, so reduction holds at all L

double-trace deformations (deform measure to prevent center breaking; deformation "drops out" of loop equations at infinite-N)

used for current lattice studies of "minimal walking technicolor" (Sannino)

is 4 ...3,5... Weyl adjoint theory conformal or not?

small-L(=1) large-N simulations (2009-)

Hietanen-Narayanan; Bringoltz-Sharpe; Catterall et al

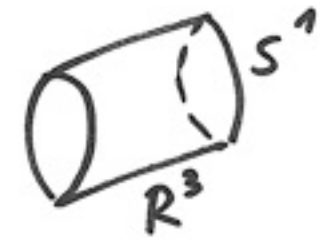
small-N large-L simulations (2007-)

Catterall et al; del Debbio et al; Hietanen et al...

(many issues to still be resolved...)

theoretical studies

Unsal;
Unsal-Yaffe;
Unsal-Shifman;
Unsal-EP 2007-9



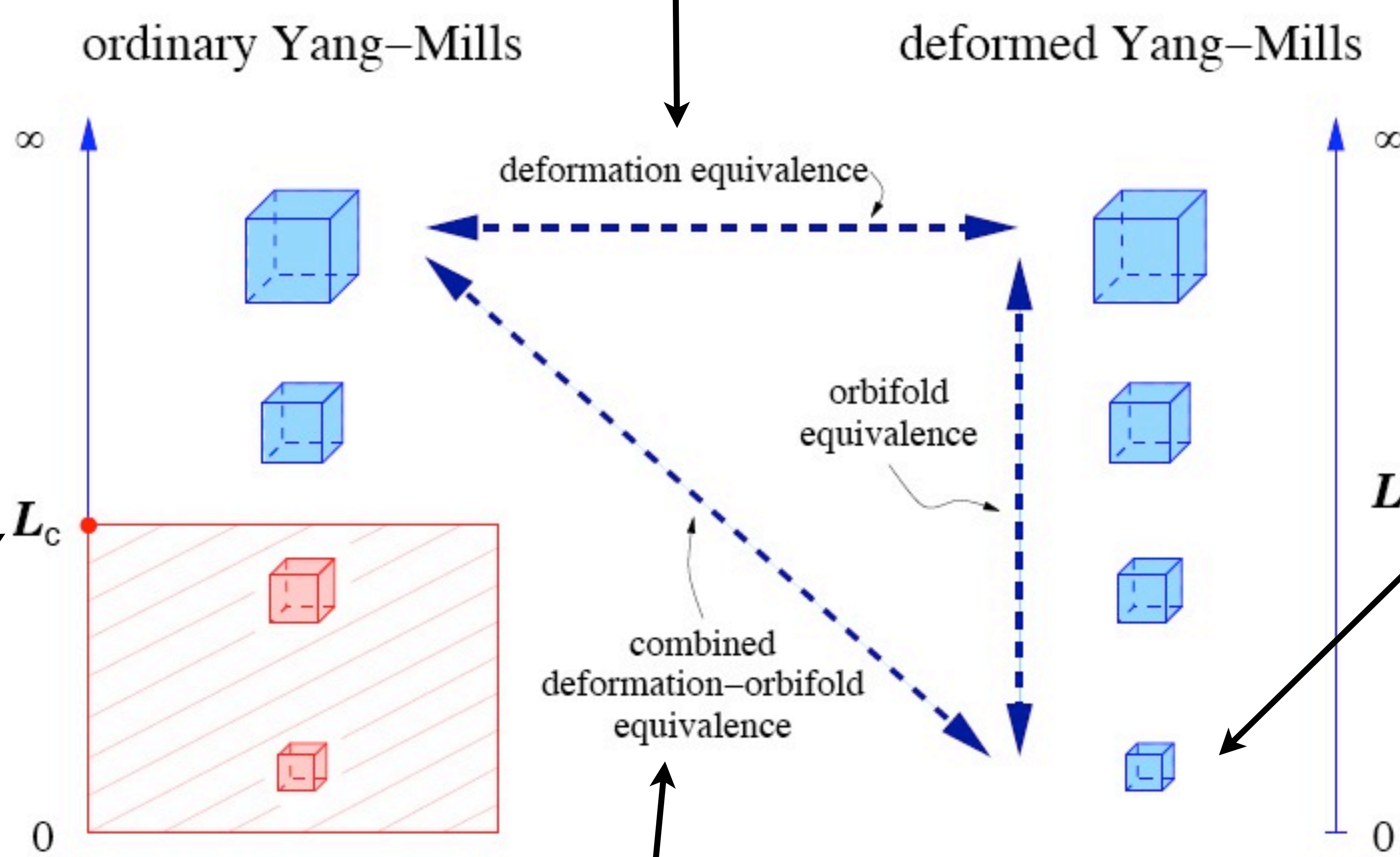

fix-N, take L-small: **semiclassical studies of confinement** - Polyakov's 3d confinement mechanism works also in a locally 4d theory, but now due to novel strange (nonselfdual) topological excitations, whose nature depends on fermion content

- for vectorlike or chiral theories

a complementary regime to that of volume independence - a (calculable!) shadow of the dynamics of the 4 dimensional "real thing"

# one last motivational slide with theoretical dreams:

use large-N "deformation equivalence" to avoid center breaking




with generic fermion representations phase transition, breaks center

now use volume-independence (valid to L=1)

**by commutativity of diagram, learn about the large-N theory you started with**

**CONCLUSION:** studying "gauge theory space" is

*a.)* fun and theoretically interesting

*and*

*b.)* may help us understand what the LHC will be trying to tell us about the short-distance properties of nature

*Higgs boson.*

**SUSY**

*Non-SM Higgs boson.*

**pure YM**

*New Beyond SM Particles*

**QCD-like (vectorlike)** *Strong interactions.*


LHC

*Little Higgs and friends.*

**non-SUSY chiral gauge theories**

*Supersymmetry.*

**CONCLUSION:** studying "gauge theory space" is

*a.)* fun and theoretically interesting

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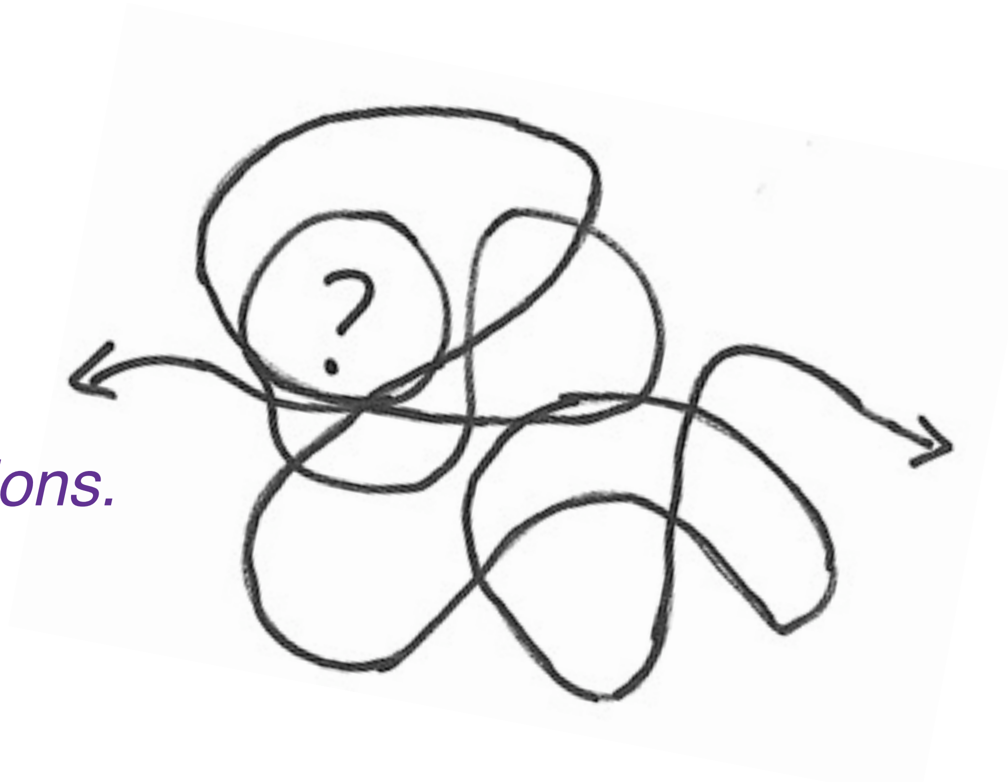


LHC